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AN UPDATE ON THE DEVELOPMENT OF A LINE-FOCUS REFRACTIVE CONCENTRATOR ARRAY

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ABSTRACT

Concentrator arrays offer a number of generic benefits for space (i.e. high array efficiency, protection from space radiation effects, minimized plasma interactions, etc.). The line-focus refractive concentrator concept, however, also offers two very important advantages: (1) relaxation of precise array tracking requirements to only a single axis and (2) low-cost mass production of the lens material. The linear refractive concentrator can be designed to provide an essentially flat response over a wide range of longitudinal errors for satellites having only single-axis tracking capability. New panel designs emphasize light weight, high stiffness, stowability and ease of manufacturing & assembly. This paper will address the current status of the concentrator program with special emphasis on the design implications, and flexibility, of using a linear refractive concentrator lens as well as detail the recent fabrication of prototype hardware.

INTRODUCTION

During the past two years, NASA Lewis, ENTECH and JX Crystals have been working on a refractive line-focus PV concentrator array for space applications (ref. 1). The linear-focus concentrator array for space is directly comparable to ENTECH's current line of terrestrial PV concentrator systems, and benefits from the operational and manufacturing knowledge gained by years of experience in this field. This concentrator concept is based on the same general principles as the point-focus mini-dome Fresnel lens concentrator (ref. 2,3) and offers many of the same advantages of the point-focus system. In addition to the generic benefits offered by PV concentrator systems for space (i.e. high array efficiency, inherent protection from space radiation effects, minimized interactions with the space plasma, etc.), the linear concept offers two very important advantages: (1) relaxation of precise array tracking requirements to only a single axis and (2) low-cost mass production of the concentrator lens material.

While the program is still pushing to maintain high array performance (i.e. high efficiency, low weight & volume, etc.) as its primary goal, greater emphasis is being put on manufacturability and overall array and spacecraft system cost reductions. Since the last report on this technology, low-cost, roll-to-roll production of the concentrator lens material has been demonstrated. New array structure designs are also being developed. The new array designs emphasize light weight, high stiffness, low thermal distortions and ease of manufacturing & assembly.

LINEAR CONCENTRATOR LENS DESIGN

As mentioned previously, the linear concentrator is based upon the same general lens design as the mini-dome Fresnel lens concentrator. The lens, currently made from silicone, has a curved, smooth outer surface with individually tailored linear Fresnel facets along the inner surface. (Refer to Fig. 1). The curvature of the outer surface and the Fresnel facets are designed such that the angles at which the light enters and exists the lens are equal, producing a condition that maximizes optical efficiency while minimizing the effects of radial shape errors. Thus, the lens is very tolerant to shape errors due to manufacturing, assembly or operational thermal distortions. The lens can also be easily designed to adjust the desired flux profile on the cell. (A double-hump design is currently used). This design flexibility has minimal impact to the overall design of the panel and array structure.

One of the major concerns facing photovoltaic concentrator systems is the precision of sun-pointing required. A key advantage of the linear refractive concentrator is the ability to modify the lens/cell design to obtain the necessary off-track design profile required for a specific mission without significantly affecting the basic array design. Because of the linear nature of the lens design, pointing errors along the longitudinal (length-wise) axis of the lens are much more tolerant to off-tracking than errors along the lateral (critical) axis. Errors along the critical axis are on the order of a few degrees and are highly dependent upon the lens/cell configuration, concentration ratio and the use of optical secondaries.

Fig. 2 demonstrates what happens when a linear lens is off-pointed along the longitudinal axis for the current lens design (40 degree rim angle). In Fig. 2a, light rays from the sun enter the curved lens and are then focused on to the cell within a specific flux profile. As the array begins to off-track along the longitudinal axis the focal length begins to effectively "shorten" (in a two-dimensional visualization). As this happens, some of the outer rays begin to move off the cell. Fig. 2b shows what happens for a 10 degree longitudinal error. At this angle the focal "shortening" is small and most of the light still hits the cell. The effective loss on lens optical efficiency is minimal. As the off-tracking error is increased (Figs. 2c. & 2d.), the effective "shortening" becomes more pronounced and the lens optical efficiency begins to decrease.

To illustrate the flexibility of the linear refractive concentrator lens, the effects of both lateral and longitudinal errors are plotted in Fig. 3 for two different lens designs. Lens optical efficiency refers to the amount of sunlight that actually falls on the photovoltaic cell and includes all reflection losses associated with the lens. Please note that these plots are for two specific designs and that optical secondaries were not included. (The use of optical secondaries will significantly increase tolerance along the lateral (critical) axis and cell concentration ratio along the longitudinal axis). The purpose of Fig. 3 is to qualitatively illustrate the variability of off-tracking tolerance as a function of the combined lens/cell design.

Fig. 3a shows a 3-dimensional plot of lens efficiency as a function of tracking error for the current lens design (40 degree rim angle). Note the much greater degree of tolerance along the longitudinal axis for a line-focus design. Still, the decrease in lens efficiency is fairly symmetric about the "on sun" position. Fig. 3b shows the same plot for a lens/cell design that is "single-axis tracking" (i.e. can accommodate errors of $\pm$ 23.5 degrees along the longitudinal axis without significant power loss). Note the difference in the shape of the plots. Also note that, unlike certain point-focus concentrator systems, there is still a significant amount of power available as the array begins to move off the sun. The "single-axis tracking" design could be used to provide an essentially flat response over a wide range of longitudinal errors for those satellites having only single-axis tracking capability. However, the cost of this added off-tracking capability is usually a decrease in concentration ratio (i.e. increased cell area). Thus, a true optimization of the lens/cell design is dependent upon a number of array, system and mission level factors (i.e. cell cost, array cost, radiation damage, single axis vs. double-axis tracking, contingency requirements, etc.). The plots in Fig. 3 represent the start of a detailed analysis to evaluate and quantify these relationships.

Fig. 4 illustrates how the design calculations compare to actual measured performance. Fig. 4 shows the calculated curve of geometric concentration ratio as a function of sun-pointing error tolerance along the lateral axis. As noted previously, to effectively improve the sun-pointing tolerance of the array, the geometric concentration ratio on the cell must decrease (i.e. cell area must increase). Also plotted on the chart are measured data points from both the current linear lens design for space and one of ENTECH's production level terrestrial concentrators. (The range on the measured values correspond to optical lens efficiencies in the range of 90 to 95%.) Note that the measured points follow the predicted values quite well, being slightly above the predicted curve in all cases.

PROTOTYPE HARDWARE DEVELOPMENT

Fig. 5 shows some of the early prototype hardware developed under the linear concentrator program. The photograph shows a single linear lens with a cell receiver assembly that uses gallium arsenide/gallium antimonide (GaAs/GaSb) tandem cells (ref. 4) and molded optical secondaries. Further optimization and fabrication of the cell receiver assembly is currently under way at JX Crystals.

The lens in Fig. 5 was one of the first lenses produced and was fabricated by hand using a single tool to mold the unit. Since that time, low-cost, mass production of the lens material has been demonstrated. Because the Fresnel facets run linearly along the inner surface of the lens, the linear lens is very easy to fabricate and lends itself to roll-to-roll fabrication techniques. (The lens can be fabricated in a flat form and then curved to the proper shape upon integration with the array structure). Fig. 6 shows a 200 ft. roll of lens material fabricated by 3M to ENTECH specifications. The lens fabrication process is similar to that used by ENTECH on their large terrestrial linear modules. The roll contains five linear lenses side-by-side, which, by proper design of the spacing between lenses, could be mounted to the array structure as a single unit.

Significant progress has also been made on the development of an array structure. Fig. 7 shows different views of an array panel that was recently fabricated. The structure was made from carbon composite material to minimize weight and the effects of thermal distortions. An important point to note is that the structure achieves its stiffness from the honeycomb panel on the back of the structure, while the lenses are held accurately in place above the cell plane with a minimal amount of supporting structure. This design allows for a number of options with regard to reducing the stowed panel thickness by rotating the lenses down.

Optimization of the panel structure indicates that a total panel weight of < 2 kg/m^2 is readily achievable. Estimates for both the panel mass and performance are given in Table I. With a cell operating efficiency of around 25% and an optical lens performance of 90%, an array efficiency corresponding to 300 watts/m^2 is achieveable. This provides a panel specific power of 150 watts/kg. Based on this, a specific power of > 100 watts/kg at the array level should be achievable in the near-term.

SUMMARY

The line-focus refractive concentrator array is a novel photovoltaic array concept that offers two very important advantages compared to some other concentrator concepts: (1) relaxation of precise array tracking requirements to only a single axis and (2) low-cost mass production of the lens material. This means that the linear refractive concentrator can be designed to provide essentially constant power for satellites using only single-axis tracking. Low-cost, roll-to-roll production of the lens material has been demonstrated and new panel designs, emphasizing light weight, high stiffness, stowability and ease of manufacturing & assembly, are currently being fabricated and tested.

REFERENCES

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2. M.F. Piszczor and M.J. O'Neill, "Development of a Dome Fresnel Lens/Gallium Arsenide Photovoltaic Concentrator for Space Applications," *Proc. of 19th IEEE Photovoltaic Specialist Conf.*, New Orleans, LA, May 1987, pp. 479-484.

3. M.F. Piszczor et al., "A High-Performance Photovoltaic Concentrator Array: The Mini-Dome Fresnel Lens Concentrator with 30% Efficient GaAs/GaSb Tandem Cells," *Proc. of 22nd IEEE Photovoltaic Specialist Conf.*, Las Vegas, NV, October 1991, pp. 1485-1490.

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Mass Estimate of the Line-Focus Fresnel Lens Concentrator Panel				
Element	Thickness	Density	Part Area/Aperture Area	Mass/Aperture Area
	(microns)	(g/cu.cm.)		(kg/sq.m.)
Lens Glass Superstrate	50	2.50	1.20	0.15
Silicone Fresnel Lens	200	1.00	1.20	0.24
Composite Structure	375	1.80	1.60	1.08
Cells & Cover Glasses	1250	2.50	0.07	0.22
Miscellaneous				0.31
Total				**2.00**
Panel Performance Estimate				
Cell Efficiency at Operating Temp.	Lens Efficiency	Packing Factor	Areal Power	Specific Power
(%)	(%)	(%)	(W/sq.m.)	(W/kg)
18	90	95	211	105
20	90	95	234	117
22	90	95	258	129
24	90	95	281	141
26	90	95	305	152
28	90	95	328	164
30	90	95	352	176

Table I. Mass & Performance Estimates for a Linear Refractive Concentrator Panel

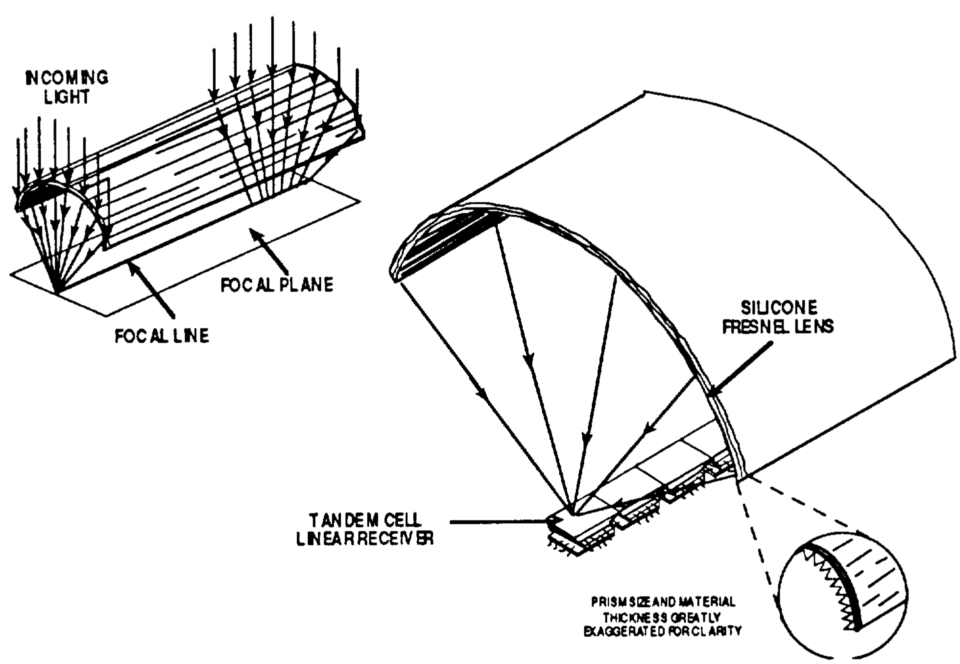

Fig. 1. Sketch of line-focus refractive concentrator components detailing operation and construction of the lens/cell element.

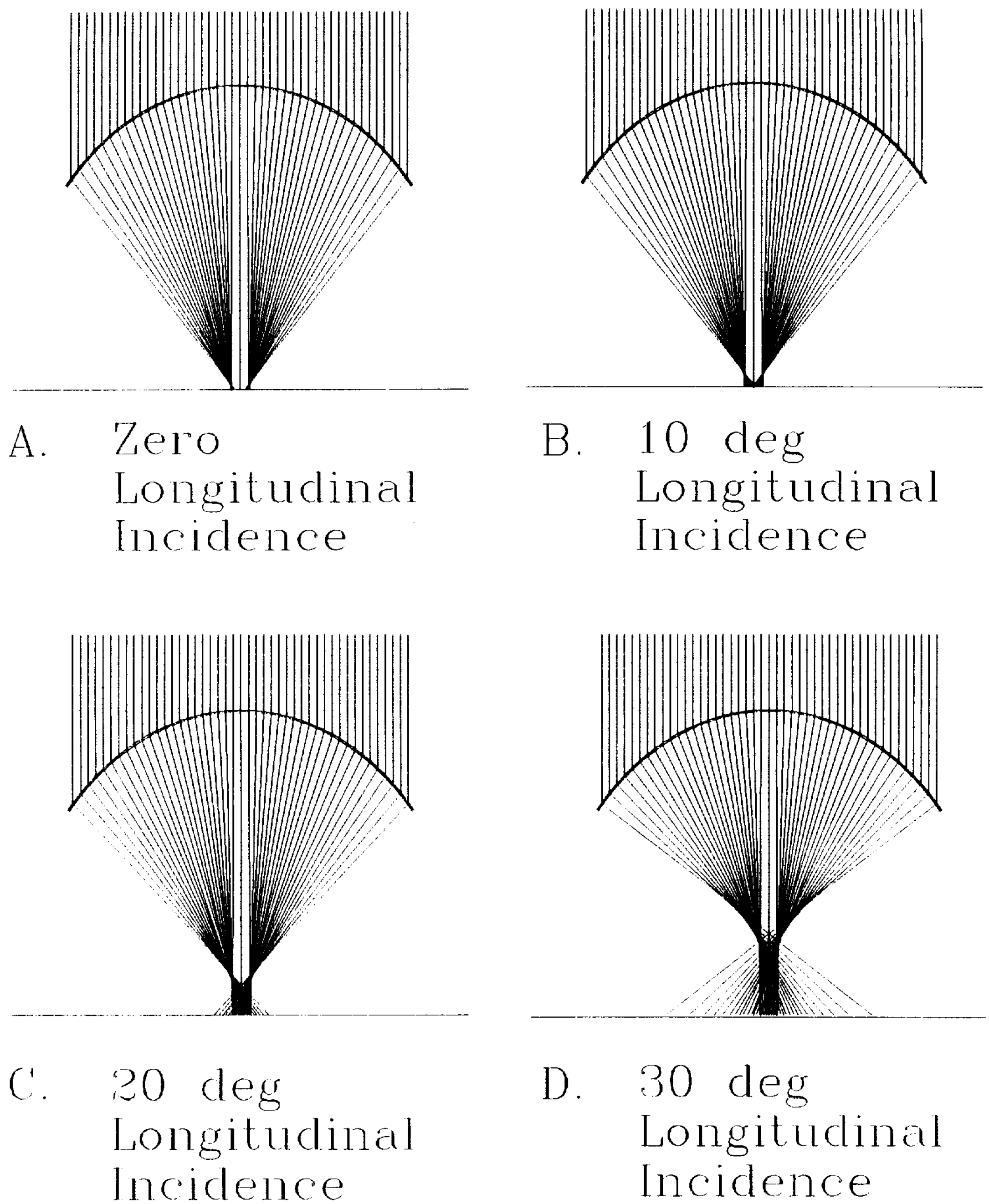

Fig. 2 - Effective 2-Dimensional Visualization of Focal Length Shortening Due to Off-Pointing Along the Longitudinal Axis

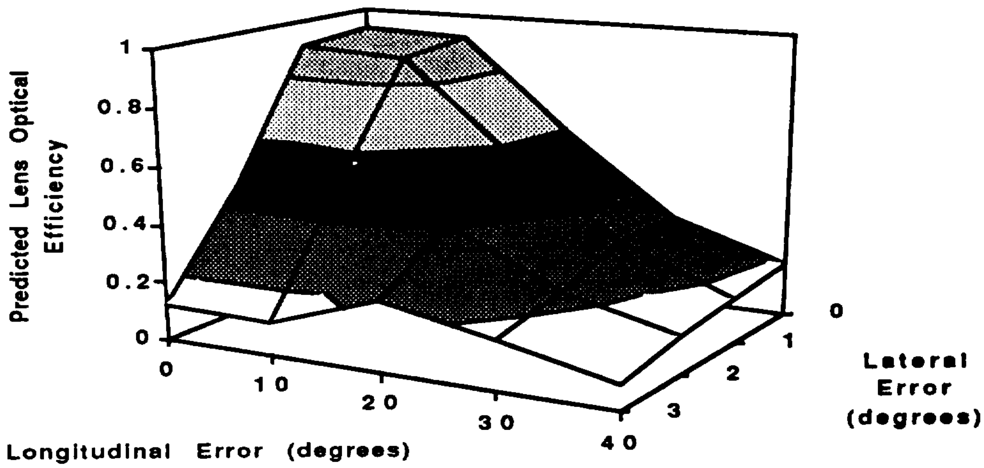

Fig. 3a. Predicted optical lens efficiency vs. off-pointing for a linear refractive concentrator. (Current lens design without an optical secondary.)

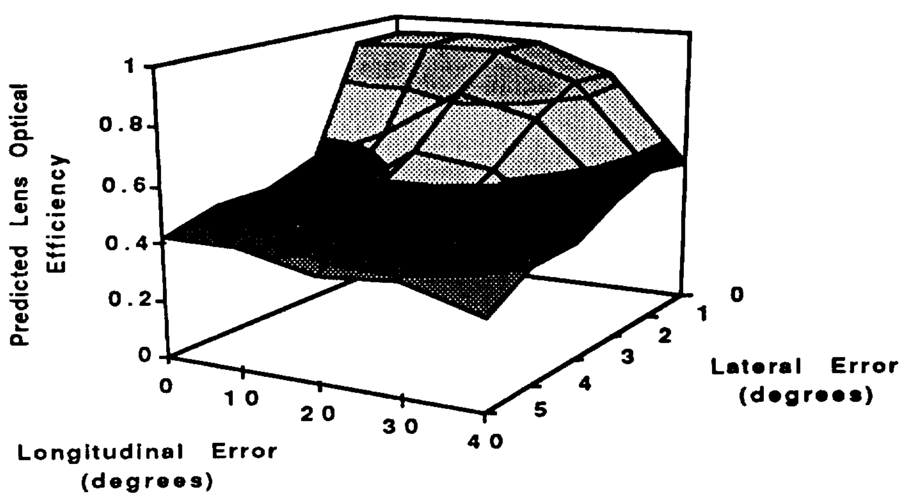

Fig. 3b. Predicted optical lens efficiency vs. off-pointing for a linear refractive concentrator. (Single-axis tracking lens design without an optical secondary.)

Calculated and Measured Geometric Concentration Ratio vs. Sun-Pointing Error Tolerance for Production-Version Line-Focus Lens (40 deg Rim, Designed for +/- 1 deg Tolerance at 15X) with No Secondary Optics

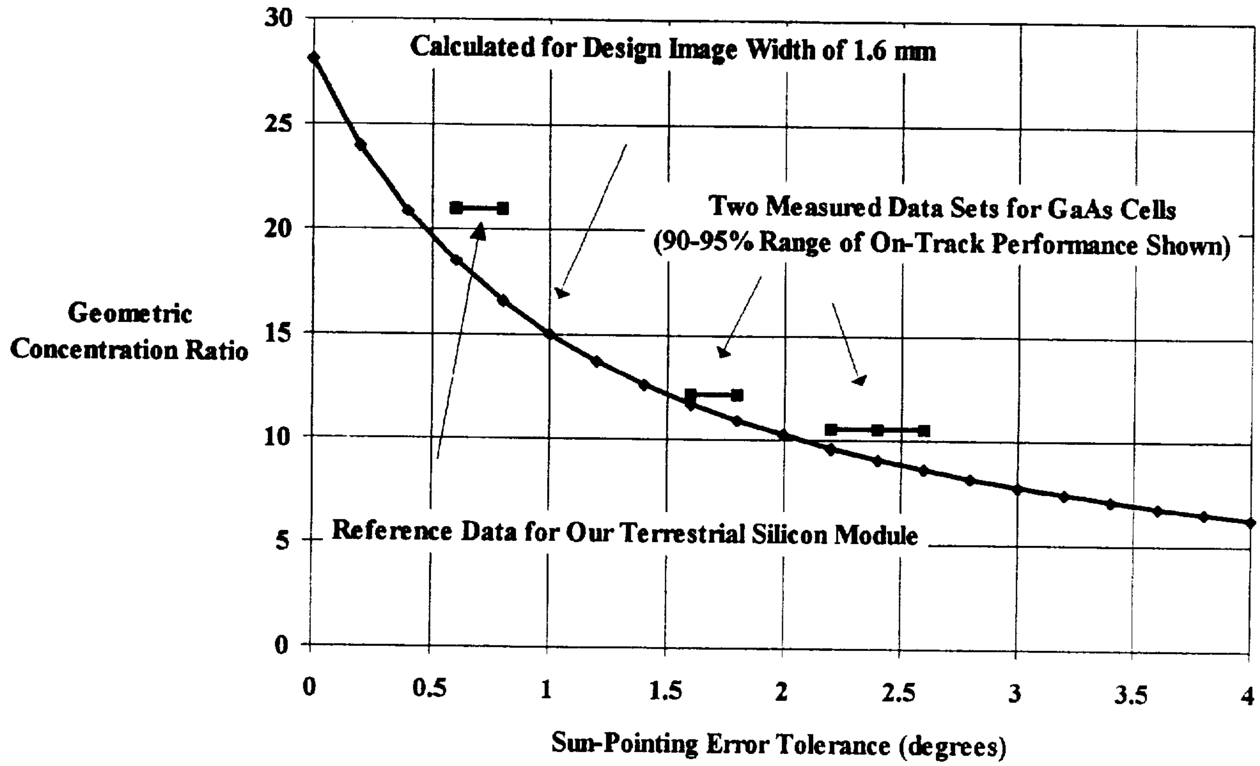

Fig. 4. Calculated vs. Measured Design Values for Linear Refractive Concentrators

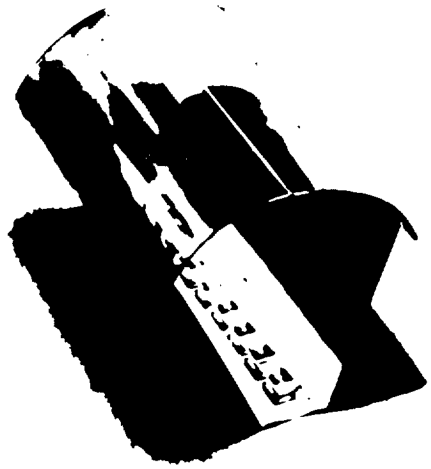

Fig. 5. Early prototype of linear refractive concentrator element. Photograph shows a single linear lens and a GaAs/GaSb tandem cell receiver with optical secondaries.

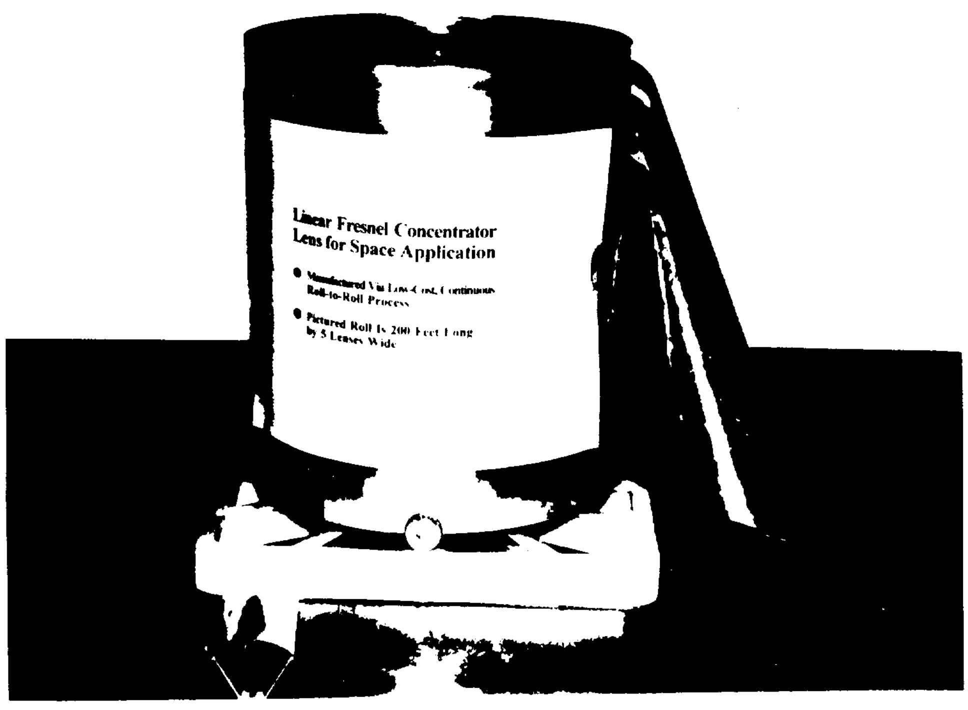

Fig. 6. A 200 ft. roll of linear con.lens material. The 5-element wide roll was fabricated by 3M using a low-cost, roll-to-roll manufacturing process.

Fig. 7a. Prototype linear concentrator panel structure recently fabricated. Note that the stiffness of the carbon composite panel is achieved from the honeycomb panel on the back of the structure.

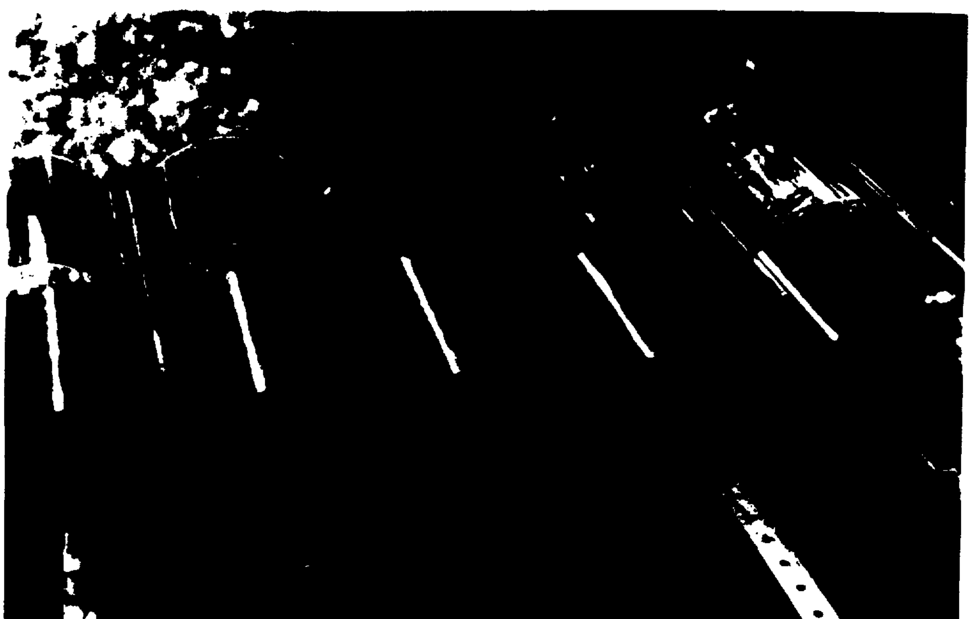

Fig. 7b. Prototype linear concentrator panel structure with linear lenses in place focusing light onto the back panel. Lens elements are a single unit cut from the 200 ft. roll of lens material.