MINIATURIZED CASSEGRAINIAN CONCENTRATOR CONCEPT DEMONSTRATION

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INTRODUCTION

High concentration ratio photovoltaic systems for space applications have generally been considered impractical because of perceived difficulties in controlling solar cell temperatures to reasonably low values. A miniaturized concentrator system is now under development* which surmounts this objection by providing acceptable solar cell temperatures using purely passive cell cooling methods. An array of identical miniaturized, rigid Cassegrainian optical systems having a low f-number with resulting short dimensions along their optical axes are rigidly mounted into a frame to form a relatively thin concentrator solar array panel. A number of such panels, approximately 1.5 centimeters thick, are wired as an array and are folded against one another for launch in a stowed configuration. Deployment on orbit is similar to the deployment of conventional planar honeycomb panel arrays or flexible blanket arrays.

The miniaturized concept was conceived and studied in the 1978-80 time frame. Favorable results led to the present feasibility demonstration program which will span the period between 1980 and 1982. Progress in the feasibility demonstration phase made to date is reported in this paper. It is expected that the miniaturized Cassegrainian concentrator concept will be developed further in the future with space flight demonstration as a major target.

CONCENTRATOR SYSTEM DESCRIPTION

A typical solar panel of the miniaturized Cassegrainian concentrator solar array concept is illustrated in Figure 1. Groups of shallow concentrator elements are held rigidly within the gridded frame structure. The detailed design of a single element is depicted in Figure 2. The reflectors are made from relatively thick electroformed nickel in this feasibility demonstration phase. (In a later program phase, lower weight and lower cost fabrication approaches will be examined.) The solar cell radiator fin is shown as a flat square plate in Figure 1, and as a circular cup in Figure 2. This design change was made to accommodate assembly for large-scale production but is not considered final; low-cost high-volume production requirements will strongly influence the final element configuration. A materials and processes data base is presently being established that will assist in this determination.

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The nickel reflectors are coated as shown in Figure 3. The silicon monoxide (SiO) layer serves both to protect the reflector against terrestrial and space environments and to provide a high-emittance thermal control surface.

The operating temperature of the concentrator cell is controlled passively. Reference 1 describes the approach in detail; however, in brief summary it simply consists of radiating heat into space from both the front and back sides of the concentrator solar panel exactly as occurs for conventional planar arrays. Each concentrator element has a radiator fin, roughly the size of the entrance aperture, attached to the concentrator cell with a low thermal resistance bond. The radiator fin thickness is minimized for the desired cell operating temperature and the particular aperture size. The fin is radiatively coupled to the primary parabolic reflector to obtain front-side heat rejection and to reduce thermal gradients across the panel thickness. As Reference 1 demonstrates, only small diameter radiators, i.e., miniaturized elements, will result in low specific mass concentrator systems.

The concentrator element optical design, illustrated in Figure 4, results in the optical losses shown in Table 1. Under perfect sun-pointing conditions, the incident sunlight is reflected only twice without striking the tertiary reflector, also known as the light catcher cone. The light catcher cone improves the off-pointability of the concentrator element. Under conditions of perfect alignment and sun-pointing, the demonstration module concentrator elements have a theoretical geometrical concentration ratio of 163 and a nominal effective concentration ratio of 88.

EXAMINATION OF CRITICAL ISSUES

In this section the most critical issues affecting implementation of the concept are examined in four areas: optical design, thermal design, solar cell design, and assembly.

Optical Design

The initial problem of optical design was the design and procurement of a short-focal length (12.8 millimeters) nonimaging Cassegrainian system with a low f-number (0.25) and a high concentration ratio (163). Figures 5 and 6 and the performance data described below show that the initial design was successful.

The elements of the demonstration module are arranged orthogonally for assembly and test convenience only, rather than in a closely packed hexagonal pattern. Figure 5 shows the simple "spider" arrangement that supports the secondary hyperbolic reflector. The wide spider legs produce a large blockage loss contribution. No attempt was made to reduce this loss by substituting a more complex support structure since it was desired for the purpose of initial demonstration to use off-the-shelf commercial electroforming techniques without requiring complex mandrel tooling.

Current work is directed toward identifying practical methods of reducing the optical design losses to attain the goals shown in Table 1. The largest of the potential gains will result from an improvement in the reflective coating as indicated by Figure 7. By integrating the product of a spectral reflectance curve from this figure, the AMO solar spectrum, and the solar cell spectral response (Si or GaAs), the energy received by the solar cell after a double reflectance can be determined and, therefore, the comparative improvement obtained with candidate coatings other than aluminum. A silver coating is the obvious best choice. However, silver coatings, even with protective SiO overcoatings, are known to frequently exhibit problems in long-term terrestrial storage environments, usually due to hard-to-avoid pin holes in the SiO coating. Thus some development work will be required to make this coating system stable and economically viable.

Alignment sensitivity tests have shown that the three reflectors and the solar cell may be randomly misaligned with respect to the element's theoretical optical axis by as much as several tenths of a millimeter with no loss in element performance at normal incidence of sunlight (the Sun's ray parallel to the element's theoretical optical axis). Similarly, misalignment errors between reflectors and the cell in the direction of the optical axis up to several tenths of a millimeter are inconsequential at normal incidence.

Off-pointing tests in natural sunlight demonstrated the effectiveness of the light catcher cone (Figure 8). The off-pointing performance was good, but somewhat less than predicted analytically (for a 90 percent reflective cone surface) and from experience with alignment sensitivity measurements made with a laser in the laboratory. Several areas have been identified for potential improvements during the detailed design phase.

Thermal Design

For low earth orbit applications in which the Earth's albedo and IR emissions are significant, highly reflective high-emittance coatings are required for good thermal control. For this reason, both the spider and the aluminum radiator fin surfaces were painted with white thermal control paint. Thermal balance and thermal gradient tests in vacuum are presently under way to confirm the predicted silicon cell temperature of 80° to 100°C and cell-to-fin temperature gradients of less than 5°C. A natural sunlight test at Table Mountain, California at 8000 feet altitude and approximately 0.87 AMO sun equivalent intensity have yielded a cell temperature of 36°C with a still air ambient temperature of 19°C. This cell temperature compares favorably to similar flat plate array temperatures obtained under similar test conditions.

Solar Cell Design

The concentrator solar cell physical design, shown in Figure 9, represents a compromise in contact pad design between heat sinking and power losses in the nonilluminated cell junction area. A larger cell (with active area constant) improves heat sinking, however, it also increases power losses in the nonilluminated cell junction area. Concentrator cell designs should account for this loss mechanism and be coordinated with the application so that it is minimized. Cell dimensions are not otherwise critical except that their tolerances must be compatible with assembly tooling requirements.

An important issue in optimizing the solar cell efficiency is that the concentrated light is typically nonuniform, especially under slight off-pointing conditions (see Reference 2). Grid line design should take this into consideration.

A desirable tradeoff yet to be conducted is between cell designs with textured and polished cell active areas. While texturing will improve the absorption of light by the cell, especially the light that impinges on the cell at angles of incidence between 0 and 30 degrees, it will also raise the cell's thermal absorptance and hence its operating temperature. Reference 2 discusses textured concentrator cells in greater detail.

Presently, the concentrator demonstration module contains silicon solar cells designed for maximum performance at 100 suns. They are 8 to 10 mils thick, are made from 0.5 Ω-cm base resistivity material. Junction depth is 4000 to 5000 Å. Contacts are Ti(400 Å)-Pd(800 Å)-Ag(10 μm). The cells have evaporated aluminum back surface reflectors and SiO (800 to 1300 Å) anti-reflective coatings.

NASA's Lewis Research Center is currently working on a GaAlAs cell for the miniaturized Cassegrainian concentrator. It is planned to build elements using these cells when they become available.

Assembly

The demonstration module was assembled in a way that attempted to anticipate and solve some of the problems that might occur during large-scale production. All parts shown in Figure 10 were stacked and soldered together at one time in a vapor phase solder reflow machine. The preassembly parts inspection using laser instrumentation mentioned earlier indicated that application of standard shop practices and techniques would result in elements of similar optical performance. The four holes in the cup bottom admitted pins of an assembly fixture that held all parts together. The assembled cups were then bonded in a honeycomb panel and electrically interconnected as shown in Figures 5 and 6, respectively. The nine elements were wired so that each could be tested individually and all could be tested together in a series circuit. The primary and secondary reflectors were installed, guided and aligned by the three tabs protruding upward from the cup (shown in Figure 10).

Summary and Conclusions

The work to date has identified the need for additional design optimization studies and related evaluation testing, for long-term space environmental testing, and for solar cell design and performance improvements. Nevertheless, the work accomplished thus far has demonstrated that the original assumptions and simplified mathematical models used in the formulation of the miniaturized Cassegrainian concentrator concept are valid and have predicted system performance quite well. No surprises or unusual effects have been uncovered. The fabrication of single elements and a 9-element demonstration module has demonstrated the feasibility of the concept. Several different promising approaches toward achieving low-cost design suitable for flight have been identified and are under study. Many of the critical fabrication and assembly processes that are candidates for use with this concept are currently in use in other industries and fields of endeavor. Based upon these accomplishments, it is concluded that the original multikilowatt solar array cost reduction goal of one order of magnitude is both reasonable and feasible with space performance comparable to that of state-of-the-art nonconcentrating planar solar arrays.

REFERENCES

1. R. E. Patterson, H. S. Rauschenbach, M. D. Cannady, and U. S. Whang, "Low Cost, High Concentration Ratio Solar Cell Array for Space Applications," TRW Space and Technology Group, Redondo Beach, California 90278. W. L. Crabtree, Marshall Space Flight Center, Huntsville, Alabama 35812. 16th IECEC, August 9-14, 1981.

2. H. Rauschenbach, and R. Patterson, "Design Requirements for High-Efficiency High Concentration Ratio Space Solar Cells," TRW Space and Technology Group, Space Photovoltaic Research and Technology, 1980, NASA Conference Publication 2169, October 1980.

Table 1. Optical System Transmission Comparison: Demonstration Module Versus Design Goal

<table>
<tr><th>PARAMETER</th><th colspan="2">DEMONSTRATION MODULE HARDWARE</th><th colspan="2">ULTIMATE DESIGN GOAL</th></tr>
<tr><td>PRIMARY REFLECTOR REFLECTANCE LOSS</td><td colspan="2">16%</td><td colspan="2">5%</td></tr>
<tr><td>SECONDARY REFLECTOR REFLECTANCE LOSS</td><td colspan="2">16%</td><td colspan="2">5%</td></tr>
<tr><td>SECONDARY REFLECTOR BLOCKAGE LOSS</td><td>6%</td><td rowspan="2">20%</td><td>6%</td><td rowspan="2">11%</td></tr>
<tr><td>SECONDARY REFLECTOR SUPPORT BLOCKAGE LOSS</td><td>14%</td><td>5%</td></tr>
<tr><td>OTHER LOSSES (MISALIGNMENT, ETC)</td><td colspan="2">4%</td><td colspan="2">2%</td></tr>
<tr><td>OPTICAL SYSTEM TRANSMISSION</td><td colspan="2">54%</td><td colspan="2">79%</td></tr>
</table>

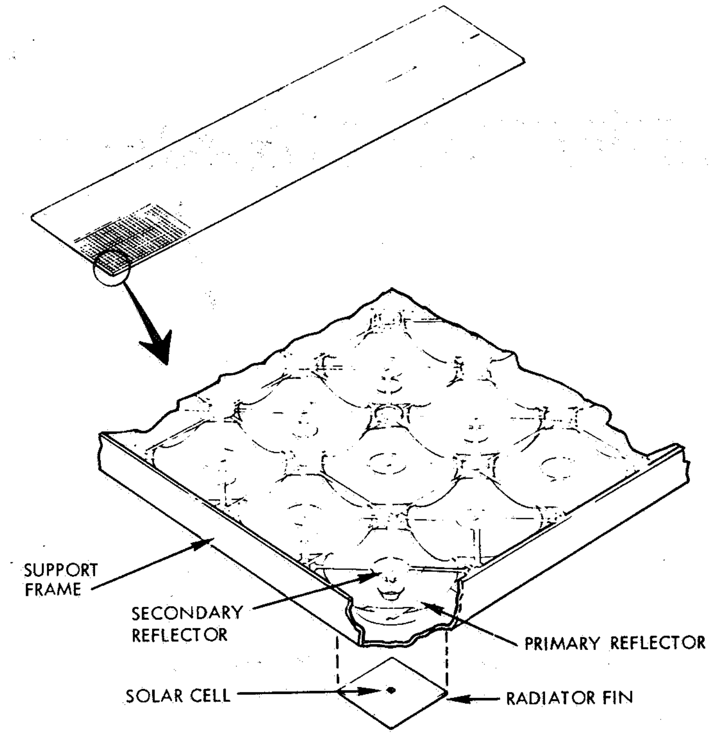


Figure 1. Mounting of Concentrator Element or Subassemblies into Panel Frame

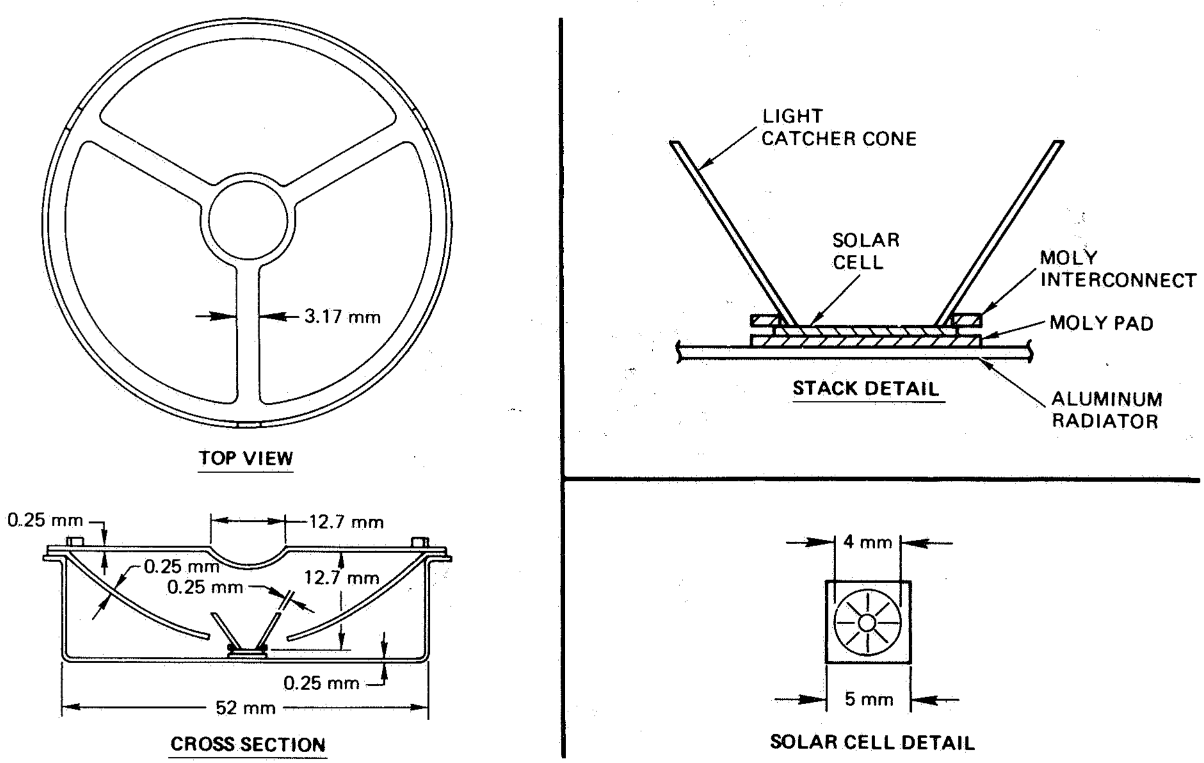


Figure 2. Baseline Concentrator Element Design

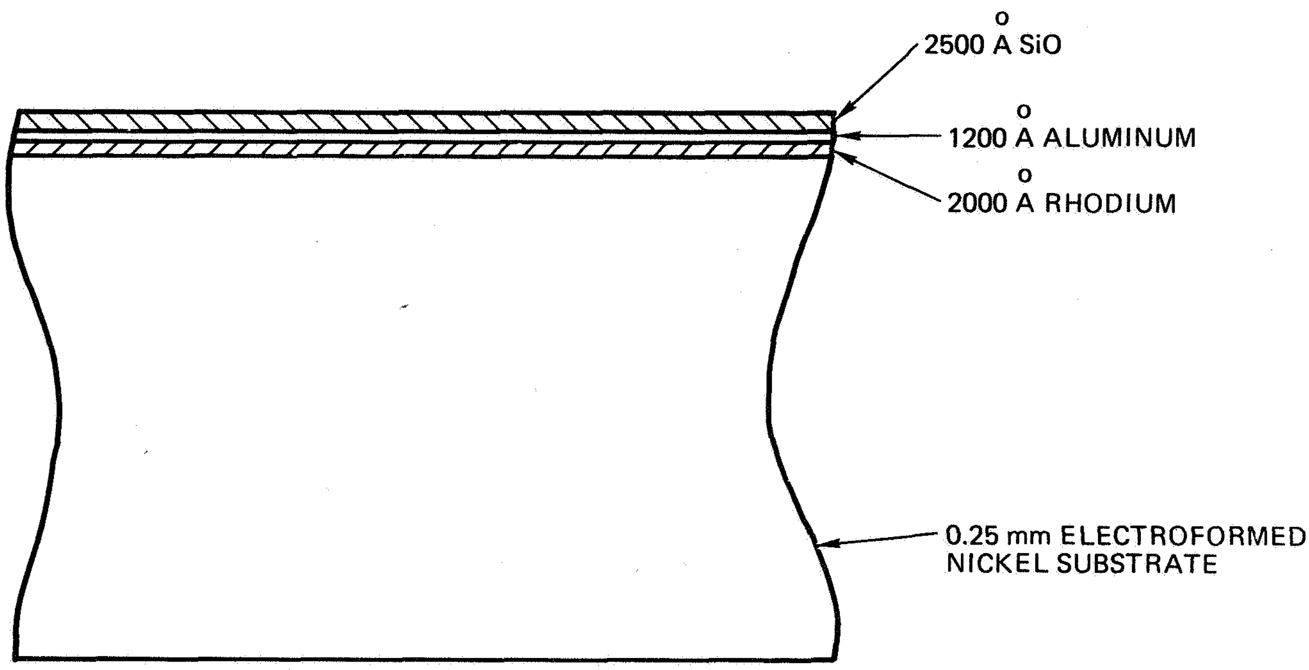


Figure 3. Reflector and Coating Configuration

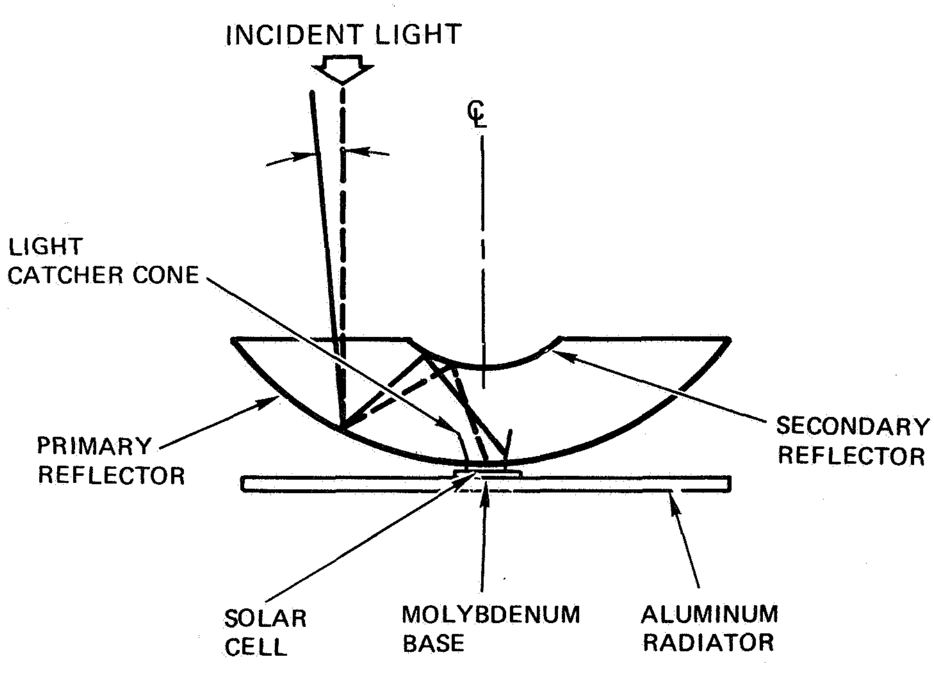


Figure 4. System Schematic

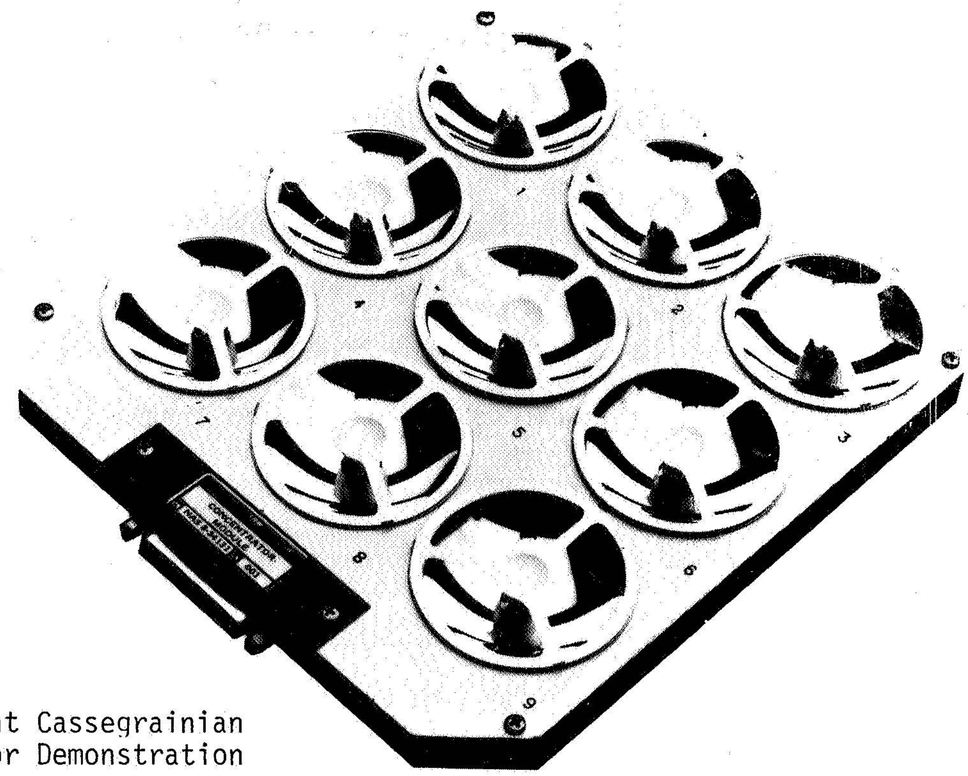


Figure 5. Nine-element Cassegrainian Concentrator Demonstration Module

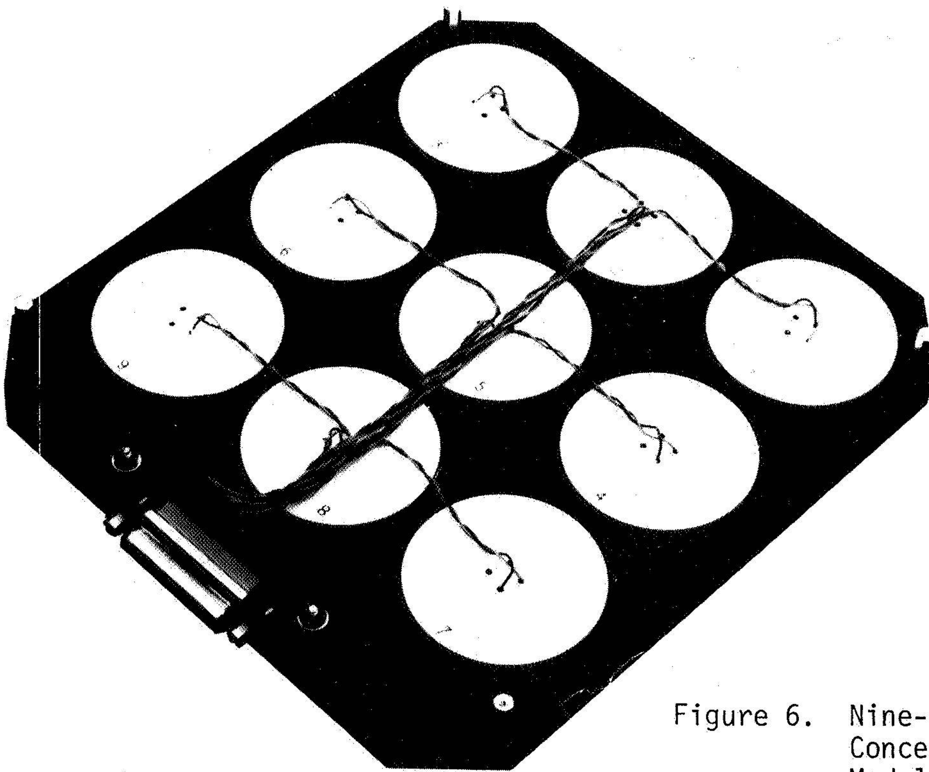


Figure 6. Nine-element Cassegrainian Concentrator Demonstration Module (Back View)

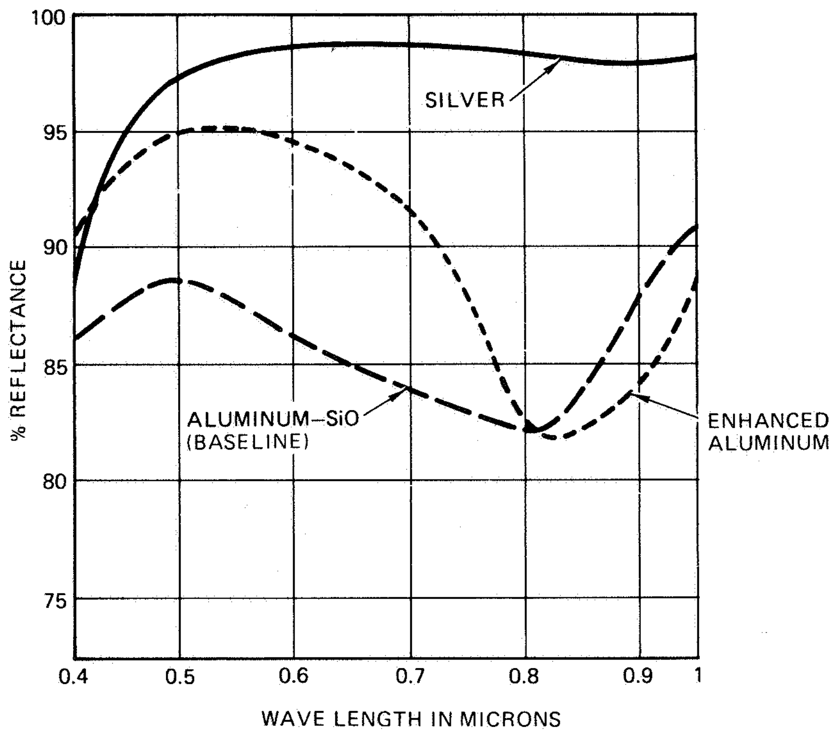


Figure 7. Alternate Reflector Coatings Offer Improved Reflectance

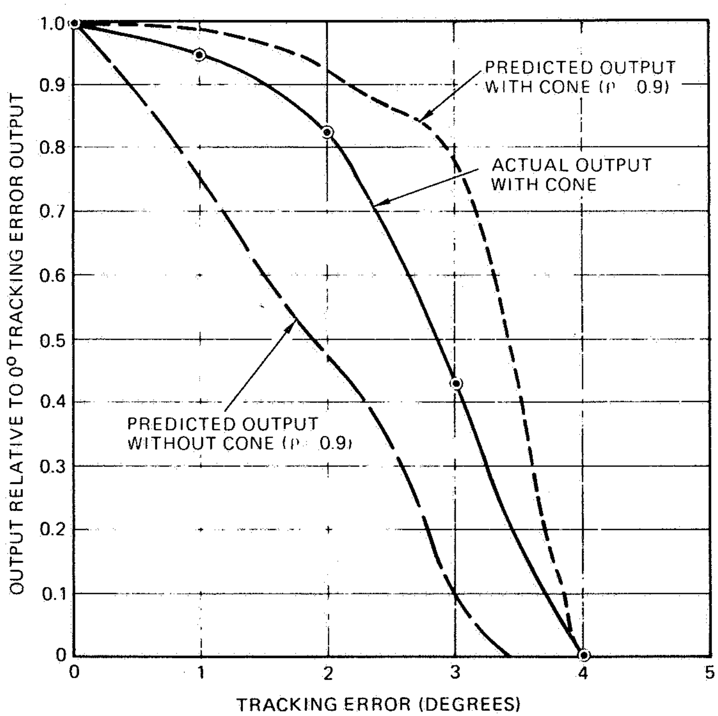
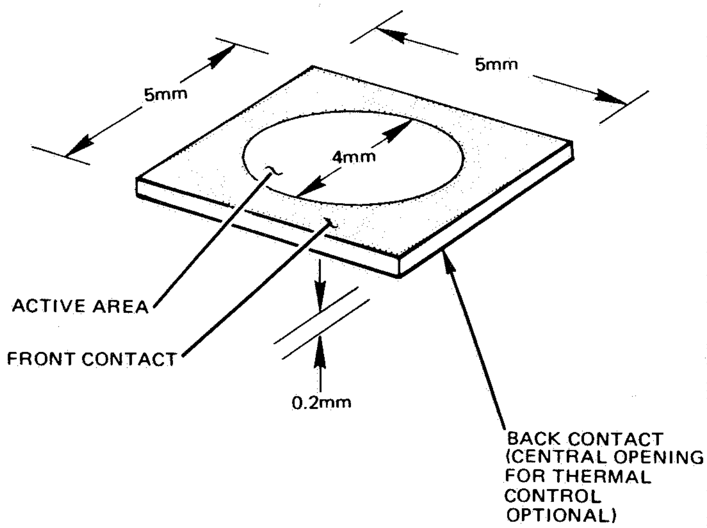


Figure 8. Single Element Off-Pointing Test Results



PARAMETER	REQUIREMENT
EFFICIENCY AT $28^{\circ}C$, 100 SUNS	20%, Si 30%, Ga As
NORMAL OPERATING TEMPERATURE	$80^{\circ}C$
TEMPERATURE CYCLING RANGE	$-100^{\circ}C$ TO $+100^{\circ}C$
TEMPERATURE CYCLES	60,000 CYCLES
SOLAR ABSORPTANCE	≤ 0.75
ANGLE OF INCIDENCE	0 TO 30°, 20° NOMINAL
RADIATION TOLERANCE	PROTONS 1 TO 10 MeV

Figure 9. Concentrator Solar Cell Reference Design and Requirements

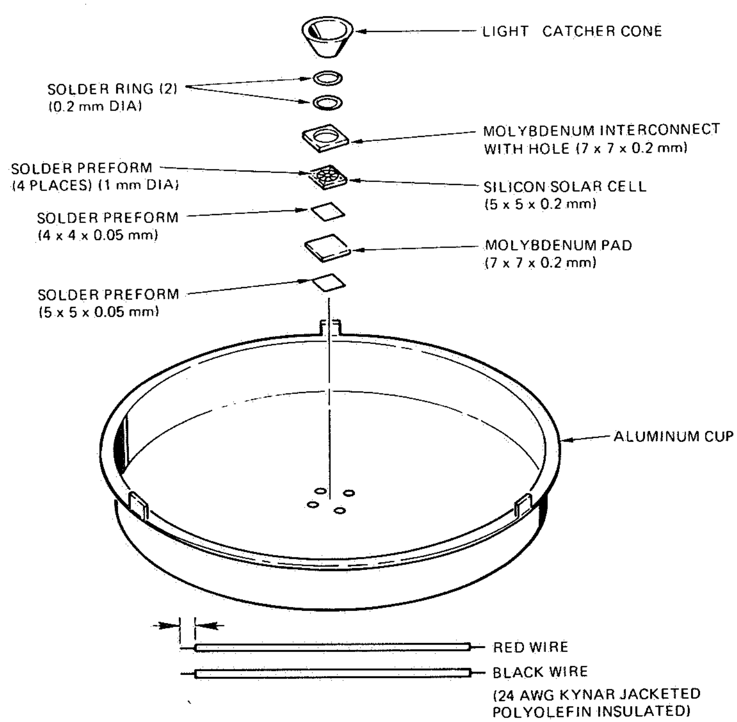


Figure 10. Cell Stack Assembly Parts Diagram