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Photovoltaic Concentrator Technology Development Project

Sixth Project Integration Meeting

Albuquerque, New Mexico

November 5, 6, 1980

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department of
Energy under Contract DE-ACO4-76DP00789.



Sandia National Laboratories

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PHOTOVOLTAIC CONCENTRATOR TECHNOLOGY DEVELOPMENT PROJECT

Sixth Project Integration Meeting

November 5-6, 1980

Albuquerque, New Mexico

Photovoltaic Projects Division 4719
Sandia National Laboratories
Albuquerque, New Mexico 87185

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AGENDA

PHOTOVOLTAIC CONCENTRATOR TECHNOLOGY DEVELOPMENT PROJECT
SIXTH PROJECT INTEGRATION MEETING
ALBUQUERQUE, NM
November 5 and 6, 1980

Wednesday, November 5

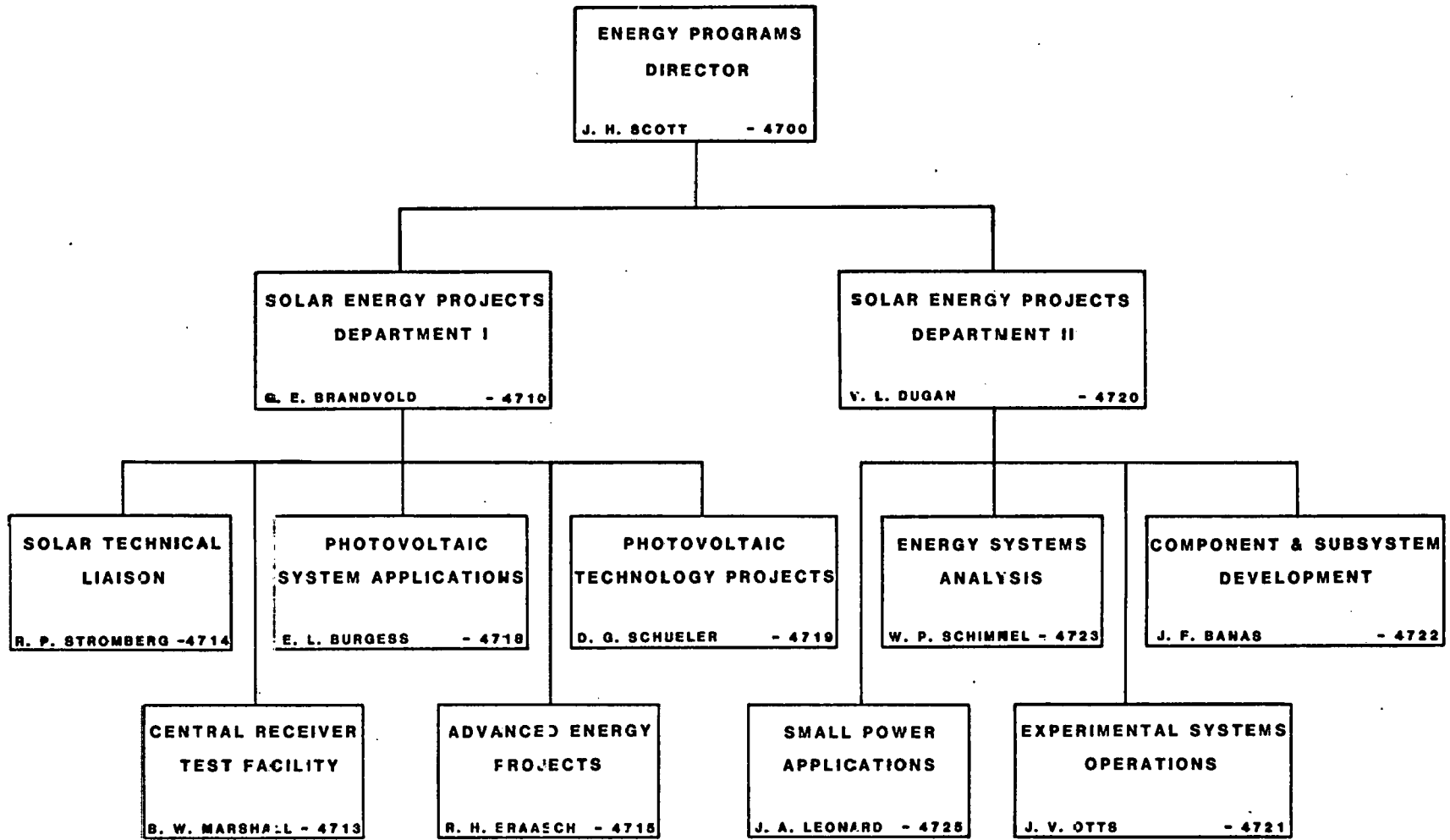
8:00 - 8:45 am	Registration	
8:45 - 10:30 am	<u>Session I: Technology Readiness for \$2.80/W_p</u>	
8:45	Introduction and Meeting Overview	Sandia
8:50	News from DOE	L. Magid/ F. Maycock, DOE
9:10	Photovoltaic Concentrator \$2.80/W _p Technology Readiness Goal	D. Schueler/ Sandia
9:30	TR80 Hardware Designs and Performance	
	Point-Focus Fresnel	B. D. Shafer/Sandia
	Line-Focus Fresnel	M. O'Neill/E-Systems
	Parabolic Trough	E. Boes/Sandia
<hr/>		
10:30 - 11:00	Coffee Break	
<hr/>		
11:00	Manufacturing Price Analysis for 1980 Commercial Technology Using SAMIS	R. Bullemer/TBA
11:20	Installed Array Price Analysis for 1982 Commercial Technology	R. Hodge/GE
<hr/>		
12:00 - 1:15	Lunch	
<hr/>		
1:15 - 5:00 pm	<u>Session II: Full-Scale PV Concentrator Array Status</u>	
1:15	SOLERAS Photovoltaic Array	S. Broadbent/Martin Marietta
1:30	MCCC and NWMJC Parabolic Trough PV Arrays	G. Hutchison/SKI

1:45	NWMJC GaAs Concentrator Array	S. Mao/UTL
2:00	Acurex/Wilcox Hospital Array	R. Spencer/Acurex
2:15	Motorola/APS Phoenix Airport Array	C. Zittle/Motorola
2:30	E-Systems/DFW Array	M. O'Neill/ E-Systems
2:45	BDM/SKI Array	W. Kaufmann/BDM
3:00	GE/Sea World Array	A. Kirpich/GE
<hr/>		
3:15 - 3:30	Break	
<hr/>		
3:30	Martin Marietta: Second- Generation Photovoltaic Array	D. Stegeman/S. Broadbent/Martin Marietta
3:55	Modelling of the First- Generation Martin Marietta Arrays	H. Gerwin/Sandia
4:15	Optimization of a Photovoltaic Concentrating Collector	A. Yasuda/Acurex
4:35	Actively Cooled Photovoltaic Array	S. Broadbent/D. Hughes Martin Marietta
<hr/>		
5:00 - 6:30	Social Hour (No Host Bar)	
<hr/>		

Thursday, November 6

8:30 - 12:00 am	<u>Session III: Modules and Optics</u>	
8:30	Development & Testing of a High- Efficiency/High Concentration Photovoltaic Module Employing AlGaAs Solar Cells	R. Owen/Varian
8:50	Performance Optimization of the ASR Optical Module	W. Meinel/ASR
9:10	Beam Splitter Module Results	P. Borden/Varian

9:30	Design & Development of a Laminated Fresnel Lens for Point- Focus PV Systems	R. Hodge/GE
9:50	A High Concentration Module Using Domed, Injection Molded Lenses	R. Scharlack/TE
<hr/>		
10:10 - 10:40	Coffee Break	
<hr/>		
10:40	Acrylic Extrusion/Embossing Process Development for the Low-Cost Production of Linear Fresnel Lenses	M. O'Neill/ E-Systems
11:00	Fresnel Lens Evaluation	C. Stillwell/Sandia
11:20	Formed Glass Reflectors	S. Martin/Sandia
11:40	Sheet Molding Compound (SMC) and Sheet Metal Reflector/ Structures	R. Champion/Sandia
12:00	Test Results from the Sandia PV Advanced Systems Test Facility	H. Gerwin/Sandia
<hr/>		
12:30 - 2:00	Lunch	
<hr/>		
2:00 - 4:30 pm	<u>Session IV: Cells and Cell Assemblies</u>	
2:00	Silicon Cell Development and Testing	R. Nasby/Sandia
2:20	AlGaAs and Multiple Junction Cell Developments	R. Chaffin/Sandia
2:40	Etched Multiple Vertical Junction (EMVJ) Cells and Assemblies	Allendorf/MA
3:00	Combined Photovoltaic/Thermal Linear Receiver	N. Shepard/GE
3:20	Advanced Cell Development and Life Testing	P. Borden/Varian
3:40	Improved Efficiency for Concentrator Cells/Arrays	S. Khemthong/ASEC
4:00	GaAs Efficiency Improvement Study	J. Cape/Rockwell
4:30	Meeting Conclusion	
5:00	Bienvenidos	



LINE ORGANIZATION STRUCTURE OF THE SANDIA SOLAR ENERGY PROJECTS

Project Structure
Photovoltaic Concentrator Technology Development Project

Task 4.0 Concentrator Cell and Cell
Assembly Development

4.1 Silicon Cells and
Assemblies

Design Optimization
Cell Fabrication and Packaging
Performance and Durability Testing
Manufacturing Development
Production Cost Analysis

4.2 Advanced Devices

Compound Semiconductors
High Efficiency Devices
Prototype Fabrication and
Evaluation
Production Cost Analysis

Task 5.0 Solar Concentrator
Development

5.1 Concentrator Module
Development

Optical Concentrator
Development
Module Design Optimization
Performance and Durability
Testing
Performance Modelling

5.2 Manufacturing Development

Production Processes
Quality Assurance
Production Cost Analysis
Large Scale Production

Task 6.0 Concentrator Array
Development

6.1 Design and Fabrication

Design Optimization
Performance Prediction
Prototype Fabrication
Production Cost Analysis
Quality Assurance

6.2 Array Evaluation

Materials and Component
Testing
Accelerated Aging
Full Scale Testing
Reliability and Lifetime
Maintenance Requirements

SANDIA PHOTOVOLTAIC PROJECTS

10-15-80

		<u>Organization Number</u>	<u>Phone 844-</u>	
Projects Manager:	SCHUELER, Don	4719	4041	
<u>Systems Definition & Development Project</u>				
Project Leader:	JONES, Gary	4719	2433	
Systems Analysis:	ALLEN, Pat	4719	8771	
	BROWNE, Doug	4719	7812	
	CASKEY, Dave	4723	7704	
	JACKSON, Jack	4719	7825	
	RIOS, Miguel	4719	2130	
Array Subsystems:	MATSH, Alex	4719	8771	
	POST, Hal	4719	2154	
Power Conditioning:	BOWER, Ward	2167	5206	
	CHU, Dahwey	4719	3043	
	COATS, Mo	2165	5206	
	ELLIOTT, Kiefer	2165	5697	
	KEY, Tom	4719	3043	
<u>System & Component Test Project</u>				
Project Leader:	GERWIN, Howard	4721	6394	
	BRAMMER, John	4721	0112	
	JANNEY, I. W.	2533	4024	
	FRITCHARD, Dan	4721	0112	
	VERARDO, Art	2533	2477	
<u>Concentrator Technology Development Project</u>				
Project Leaders:	BOES, Eldon	4719	5634	
	SHAFFER, D. D.	4719	7604	
Cell Development: (Silicon)	WEAVER, Harry	2146	8979	
	GARNER, Mike	2146	2351	
	NASBY, Robert	2146	6137	
	RODRIGUEZ, Jose	2146	6137	
	ROSE, B. H.	2146	4300	
	SEXTON, Fred	2146	2351	
	(Advanced)	CHAFFIN, Roger	5133	2609
		DAWSON, Ralph	5154	7383
		HAMMONS, B. E.	5132	3663
		WICZER, Jamie	5133	9677

SANDIA PHOTOVOLTAIC PROJECTS (Continued)

Solar Concentrators:	RAINHART, Roy	1472	6222
	STILLWELL, Charles	4719	2130
Collector Subsystems:	BEAVIS, Len	4719	2231
	EDENBURN, Mike	4723	7315
	TOGAMI, H. K.	2533	5408
<u>System Applications Project</u>			
Project Manager:	BURGESS, Ed	4718	2178
Data & Information System:	HAYENGA, Ron	2532	2701
	EVANS, Tom	2532	8867
	NAKAOKI, Cal	2532	6257
	PRUETT, Hal	2532	2807
Experimental Projects:	BIRINGER, Kent	4718	2387
	HASKINS, Dale	4718	7790
	McDOWELL, Jim	4718	7790
	ROGERS, Cal	4718	2387
<u>Other</u>			
DOE/ALO Solar Projects Division	WALKER, Ethan	ALO/SPD	8257
Solar Technical Liaison	STROMBERG, Bob	4714	8170
Solar Energy Projects Department I	BRANDVOLD, Glen	4710	6866

PHOTOVOLTAIC CONCENTRATOR \$2.80/W_p TECHNOLOGY
READINESS GOAL

D. G. Schueler
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

Technology readiness of photovoltaic collectors at a factory price of \$2.80/W_p is a major interim goal of the DOE Photovoltaic Program. According to the National Photovoltaic Program Multi-Year Program Plan of June, 1979, "Technology readiness of components is achieved: (a) with successful subscale demonstration of all the individual steps in a production process that would yield economically competitive and reliable products if produced in sufficient quality, and (b) when prototypes are available for intensive performance and reliability analysis." By reaching technology readiness for a selling price of \$2.80/W_p in 1980, it is anticipated that photovoltaic collectors could reach this price level for commercial sales by 1982. At this collector price, installed photovoltaic power system prices in the \$6-13/W_p range should be possible and this will make such systems economically competitive in many applications where conventional utility power is not available.

This meeting will begin the process of communicating and documenting the achievement of the \$2.80/W_p Technology Readiness goal by the Concentrator Technology Development Project. As a result of technology development efforts underway since 1976, a number of concentrating collector designs have been developed and components and collector subsystems built and evaluated. Specifically, three collector types (parabolic troughs, linear focus Fresnel lens, and point focus Fresnel lens) using single crystal silicon cells have successfully demonstrated performance and projected manufacturing price levels that meet this important interim goal.

DESIGN, FABRICATION, AND TESTING OF A LOW-COST, POINT FOCUS
CONCENTRATOR ARRAY*

B. D. Shafer, M. W. Edenburn, M. Garner, H. Togami
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

The primary objective of this work was to design and fabricate a point-focus photovoltaic concentrator array which will meet the 1980 goal of \$2.80 peak watt (W_p). This was to be achieved by combining each of the most cost-effective components and concepts into an optimized design. As such, it borrows heavily on various previous designs. The design employs such new concepts as planar heat sinks and studmounted cell assemblies. In addition, heat sink area and configuration were optimized for minimum energy cost. The results of this analysis lead to the conclusion that flat aluminum sheet was the most cost-effective heat sink configuration. In a similar manner, concentration ratio, cell area, and aperture area were analyzed to obtain cost effective tradeoffs.

The design that resulted has the following features. The optics are high efficiency Fresnel lenses which operate at 70X. These 17x17-cm lenses are parqueted into lens arrays with five lenses on each side for low-cost fabrication. The silicon cells are mounted on a novel type of cell assembly; a solid copper stud which incorporates a solder-bonded alumina wafer for electrical standoff, and good thermal conduction between the cell and the stud. The planar heat sink is formed into the box which comprises the module housing, thus effecting additional material savings. Details of the design effort have been published by the authors.¹

The modules are designed to be mounted on almost any type of tracking unit. Several of them could be used on a simple polar axis tracker for stand-alone applications requiring several hundred watts. At the other extreme, a tracking structure has been designed to mount 300 modules on a single turntable to produce 25,000 watts.

The module, and its components have undergone extensive testing. This includes both performance and reliability durability testing. The lenses performed at the 83-85% level, the cells at 17% efficiency at 28°C, and the first module tested had an overall efficiency of 12.0% at N.O.C.T. test conditions of 800 watts/m², 20°C ambient temperature, and 1 m/sec wind speed. The results of this testing will be reported in detail.

*This work was supported by the U. S. Department of Energy (DOE), Division of Distributed Solar Technology.

¹"Low Cost, High Performance, Point Focus Concentrator Array Design", B. D. Shafer, M. W. Edenburn, M. Garner, H. Togami, Proceedings of the 14th Photovoltaic Specialist Conference, January 1980.

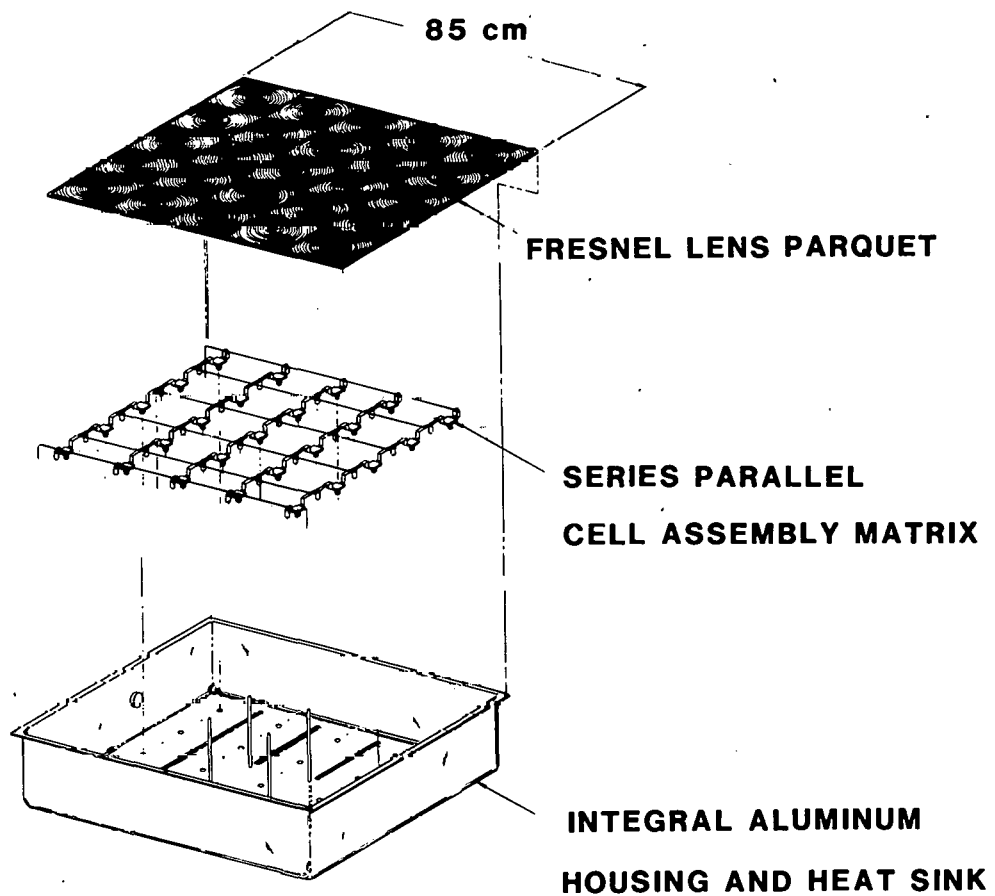


FIGURE 1. LOW COST CONCENTRATOR MODULE

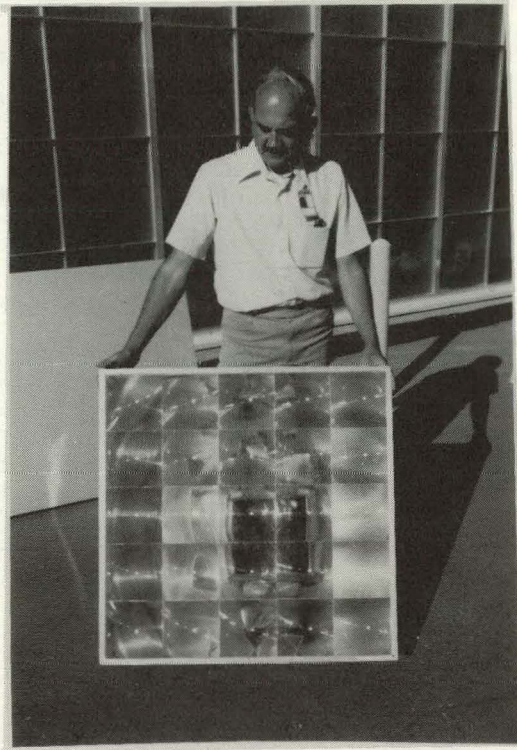


Figure 2. Low Photovoltaic Concentrator Module, Front View

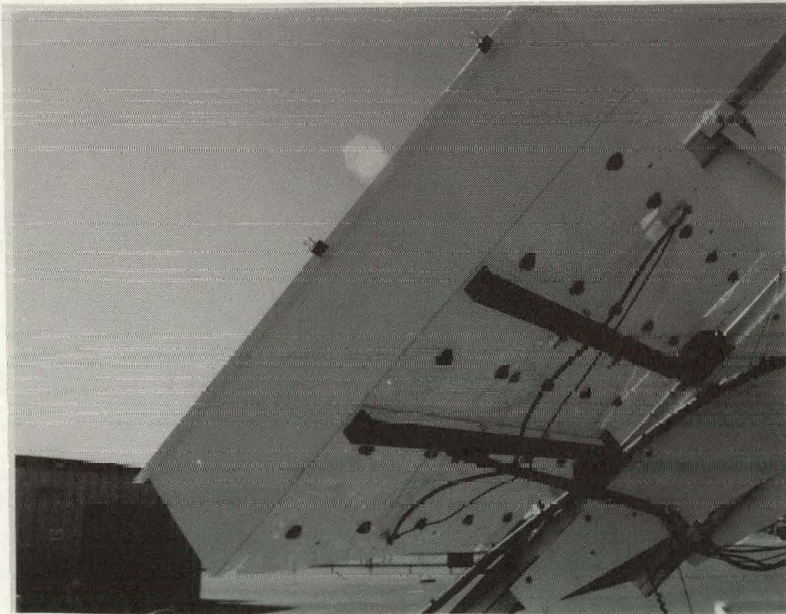


Figure 3. Low Cost Photovoltaic Concentrator Module, Back View

Table I

Comparison of Various Lens Types*

(All lenses are 290 cm²)
 (Heat Sink Temperature - 28°C)**

	<u>Actual Max Power</u>	<u>Max Power at 1000 W/m²</u>	<u>Eff.</u>
Cast Acrylic Lens	3.78 watts (899 W/m ²)	4.2 watts	14.6%
Compression Molded Lens Laminated to a Glass Superstrate	3.64 watts (894 W/m ²)	4.1 watts	14.1%
Injection Molded Lens Laminated to a Glass Superstrate	3.31 watts (891 W/m ²)	3.7 watts	12.8%

*The same cell assembly was used for all lens tests.

**The cell temperature is about 4°C above the heat sink temperature.

Table II

Typical Cell Assembly Efficiencies

(Heat Sink Temperature - 28°C)

	<u>V_{OC}</u>	<u>I_{SC}</u>	<u>Fill Factor</u>	<u>Actual Max. Power</u>	<u>Max. Power at 1000 W/m²</u>	<u>Cell Assembly Eff.</u>
Cell Mfg. A	0.697V	6.65A	0.781	3.7 W	4.1 W	17.2%
Cell Mfg. B	0.687V	6.52A	0.776	3.5 W	4.0 W	17.0%

DESIGN AND PERFORMANCE OF THE SECOND-GENERATION LINEAR FRESNEL
LENS PHOTOVOLTAIC CONCENTRATOR ARRAY

Mark J. O'Neill
E-Systems, Inc.
Energy Technology Center
P. O. Box 226118
Dallas, Texas 75266

For the past several years, E-Systems has been actively developing a novel, high-efficiency, short focal length, linear Fresnel lens solar concentrator for both photothermal and photovoltaic applications. This concentrator (U.S. Patent No. 4,069,812) offers both maximal optical efficiency and large tolerance for manufacturing errors and aberrations. In 1978-79, a first-generation combined photovoltaic/photothermal array, using the new concentrator, was designed under the DOE-funded PRDA-35 program. This first-generation array consists of ten collector modules, each 91 cm x 244 cm (3 ft. x 8 ft.) in aperture, mounted in a common 1.5-axis tracking frame. The modules utilize series-connected silicon cells, sized for a 25X geometrical concentration ratio, attached to a water-cooled copper fin-tube heat sink. Two of these modules have recently passed Sandia's qualification test program, in conjunction with E-Systems' PRDA-35 application experiment to be built at the Dallas-Fort Worth Airport. The electrical and thermal performance of these modules ranks among the highest yet measured at Sandia for silicon-based photovoltaic concentrators.

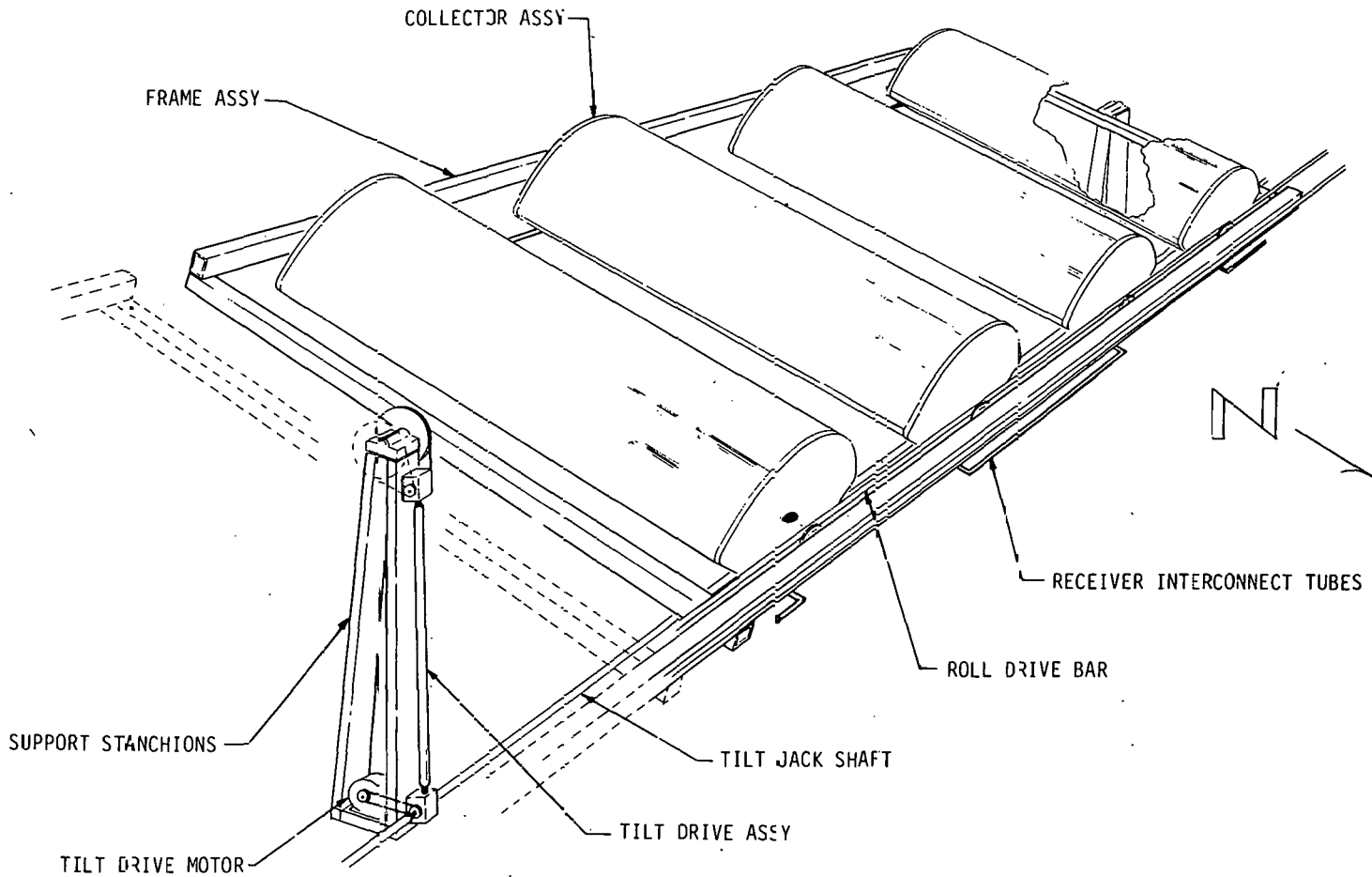
In early 1980, Sandia awarded a contract to E-Systems to generate a higher-performance, lower-cost, second-generation array design using the same linear Fresnel lens concentrator. Specific improvements include an increase in geometrical concentration ratio from 25X to 40X, the use of ASEC's automatic cell assembly machine for cell string fabrication, an extruded aluminum heat sink to replace the expensive copper assembly, a longer concentrator module to reduce assembly costs per unit aperture, a full two-axis tracking capability, and a re-engineered array configuration based upon production, installation, and system integration considerations.

The new second-generation array (Fig. 1) consists of four collector modules, each 91 cm x 305 cm (3 ft. x 10 ft.) in aperture, factory-assembled and aligned within a common support frame. These 11 m² (120 ft²) aperture arrays are then post-mounted in the field, with the capability for full two-axis tracking and inverted (lens-down) stowage. Multiple series-plumbed arrays (Fig. 2) are mechanically interconnected in long rows, with centralized drives, wiring, and manifolds (Fig. 3). Total installed system weight per unit aperture has been reduced from nearly 11 lbs/ft² to less than 9 lbs/ft². The new collector module (Fig. 4) utilizes a thinner lens and a lighter gauge sheet metal housing. The silicon cell width is optimally matched to the optical performance of the lens (Figs. 5 and 6). The receiver (Fig. 7) is designed for efficient operation over a wide range of fluid flow rates and temperatures. Two prototype collector modules (one shown in Figs. 8, 9, and 10) have been built and successfully tested. The measured electrical efficiency (η_e) and total (electrical plus thermal) efficiency (η_t) of the prototype collectors are functions of mean fluid temperature (T_{fluid}) and direct normal insolation (I_{dn}):

$$\eta_e = 0.131 - \frac{0.0005}{^\circ\text{C}} \left(T_{fluid} - 25^\circ\text{C} \right) - \frac{0.00003}{\text{w/m}^2} \left(I_{dn} - 700 \text{ w/m}^2 \right)$$
$$\eta_t = 0.62 - \frac{1.0 \text{ w}}{\text{m}^2 \cdot ^\circ\text{C}} \left(T_{fluid} - T_{ambient} \right) / I_{dn}$$

In summary, the second-generation array offers better performance and substantially lower installed system cost.

SECOND GENERATION ARRAY



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Fig. 1

TYPICAL ROW OF SECOND GENERATION ARRAY

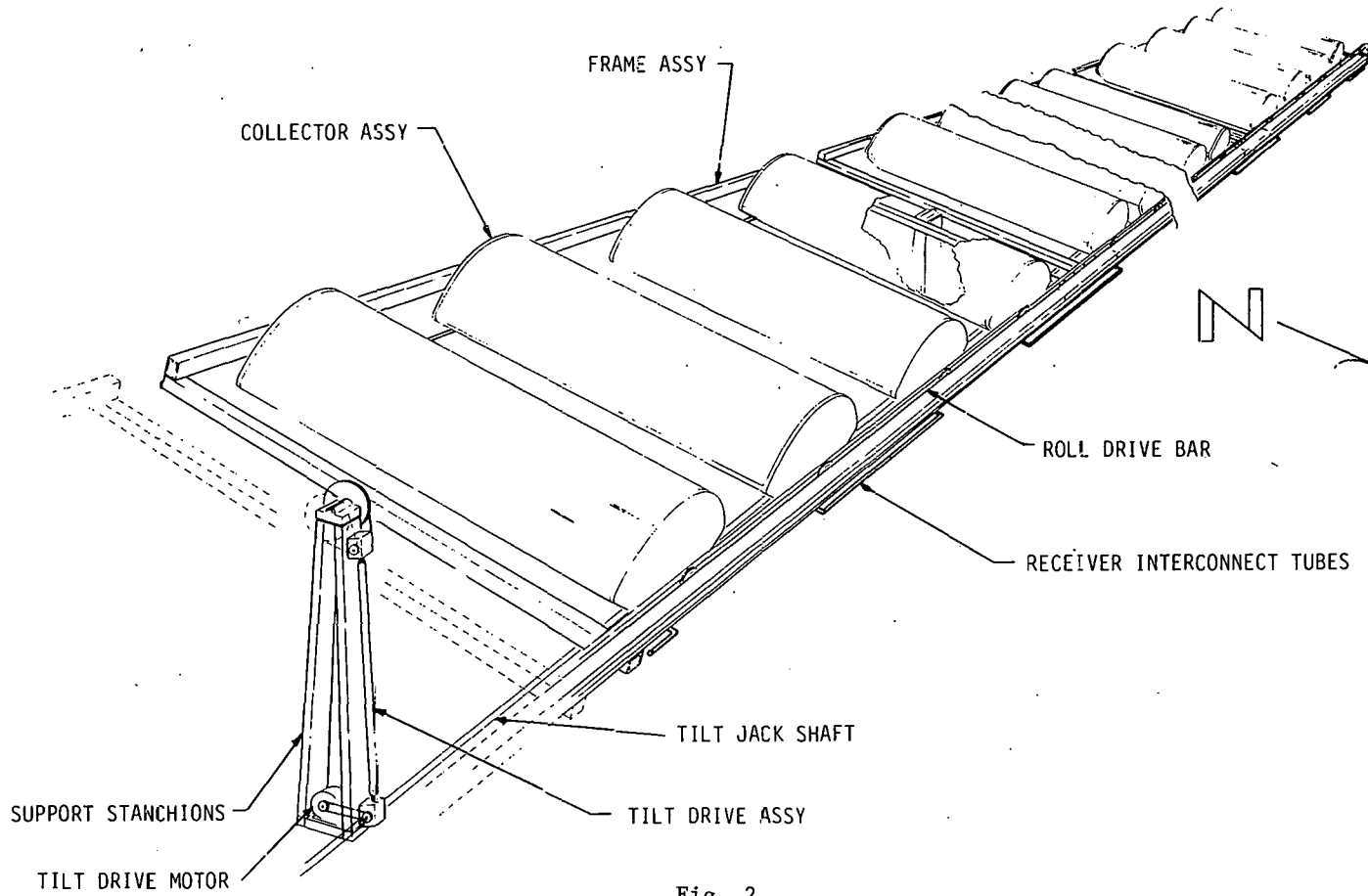


Fig. 2

TYPICAL COLLECTOR FIELD WITH SECOND GENERATION ARRAY

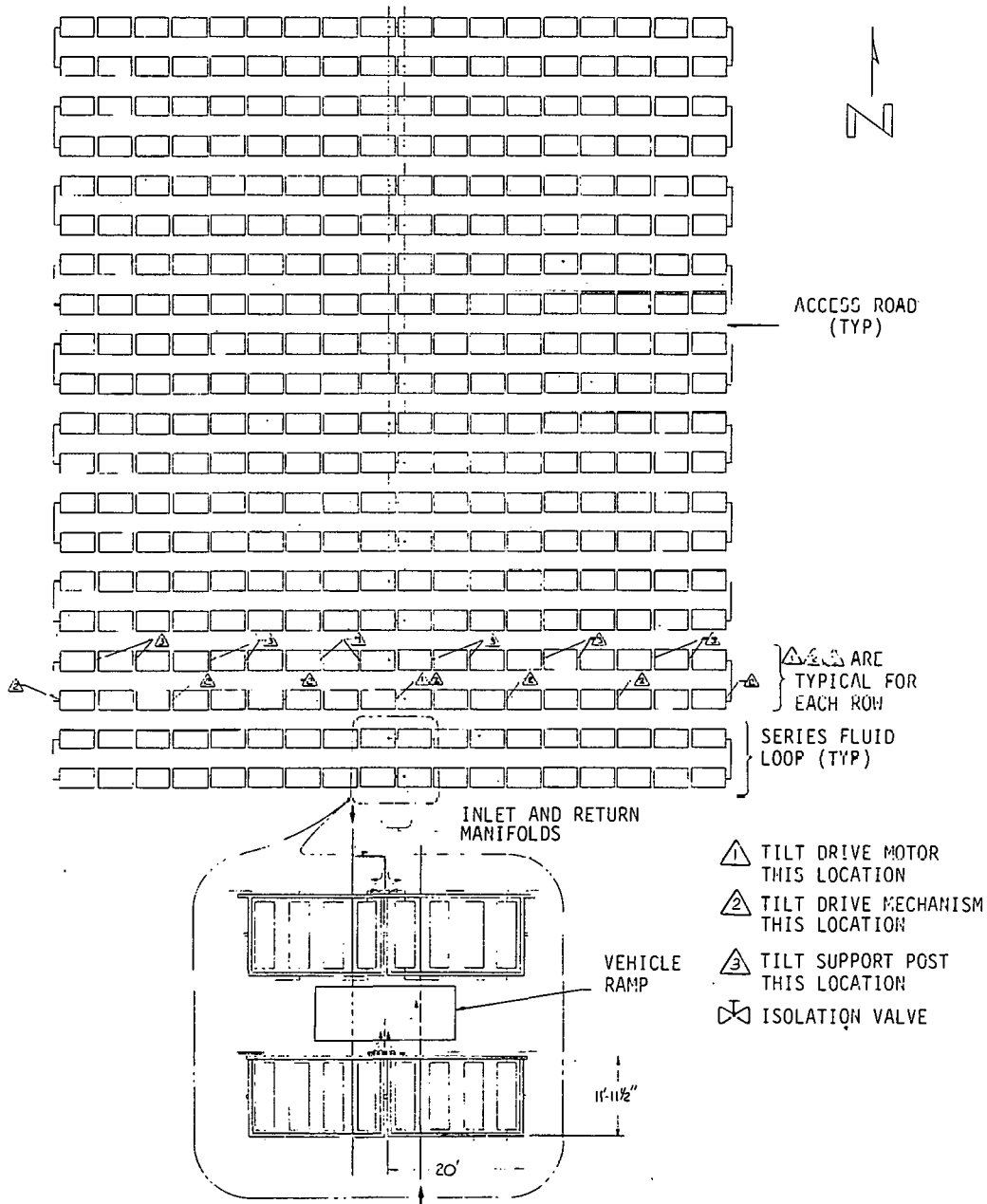


Fig. 3

PHOTOVOLTAIC COLLECTOR CROSS SECTION

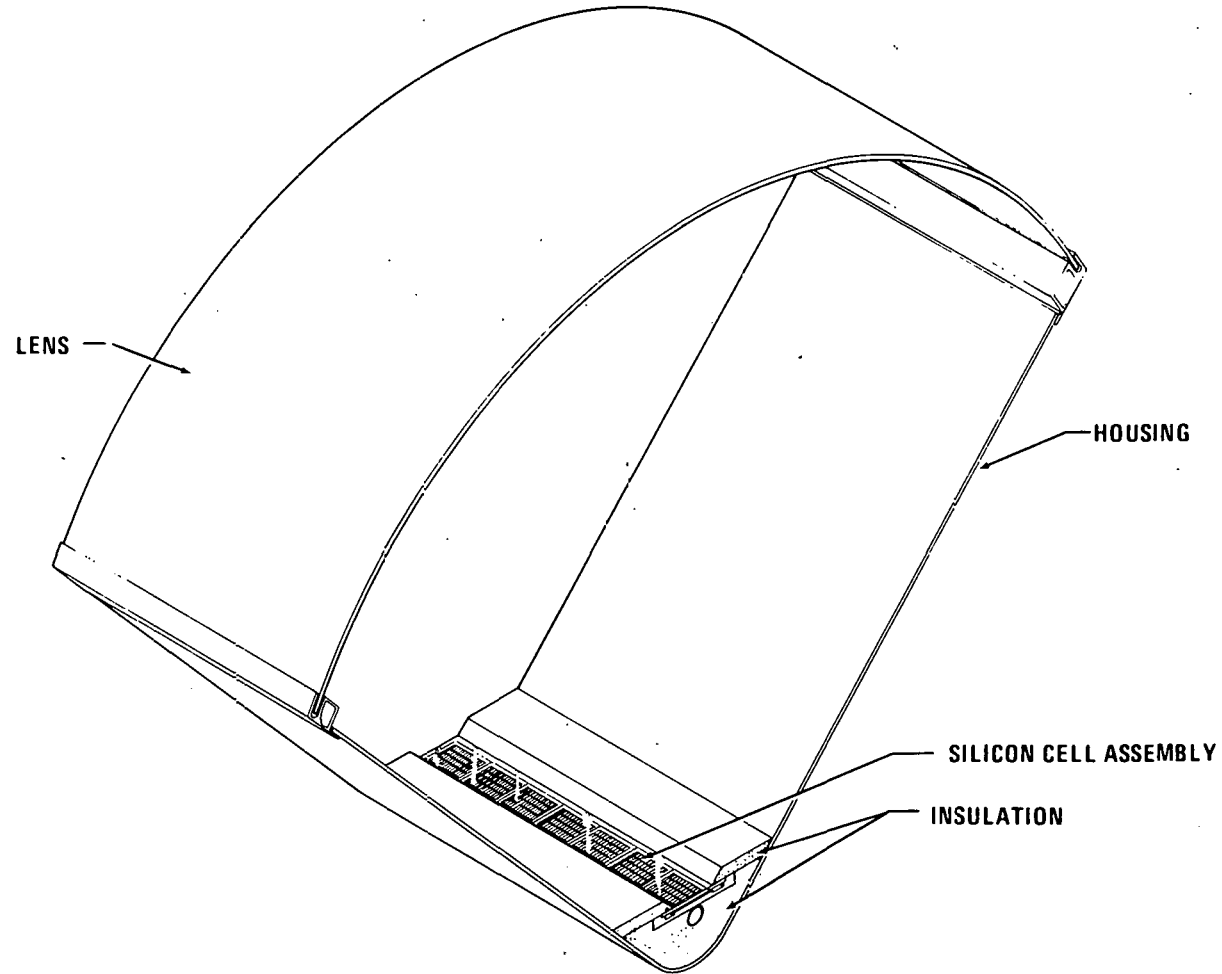


Fig. 4

COMPARISON OF PREDICTED AND MEASURED LENS FOCAL PLANE RADIANT FLUX PROFILES

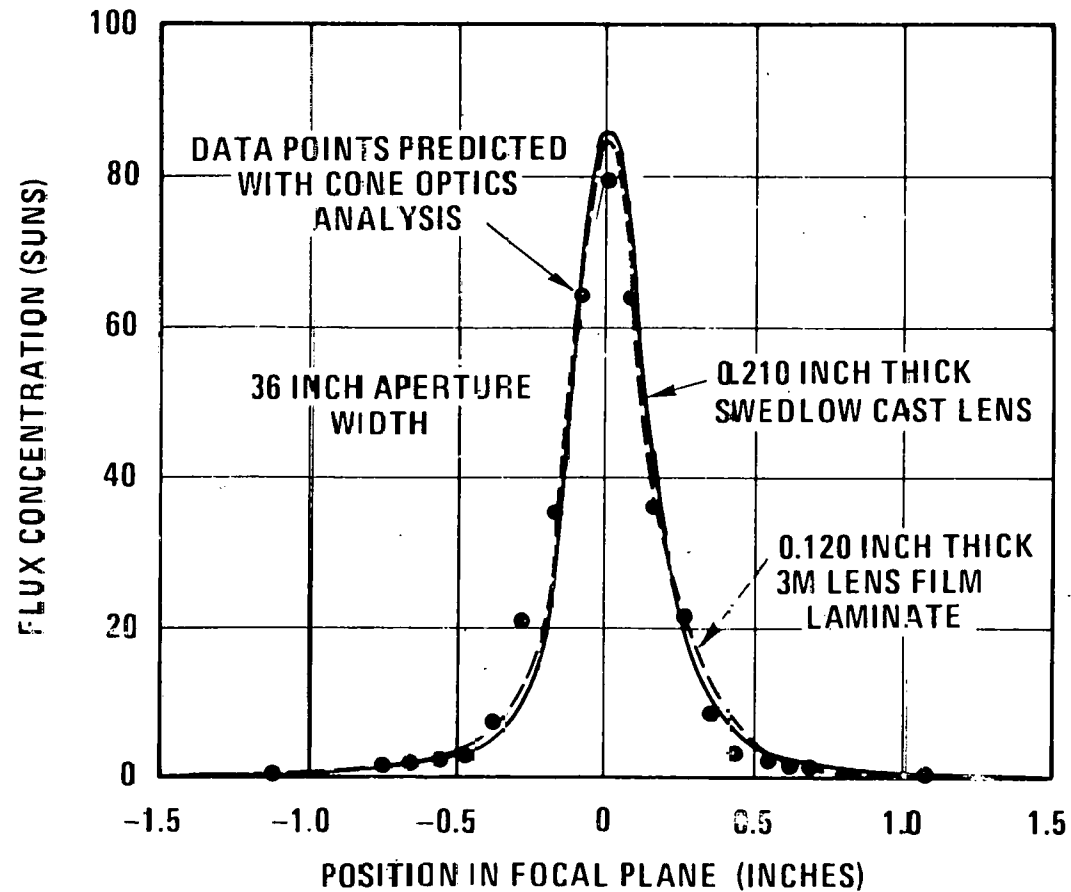


Fig. 5

MEASURED LENS OPTICAL PERFORMANCE

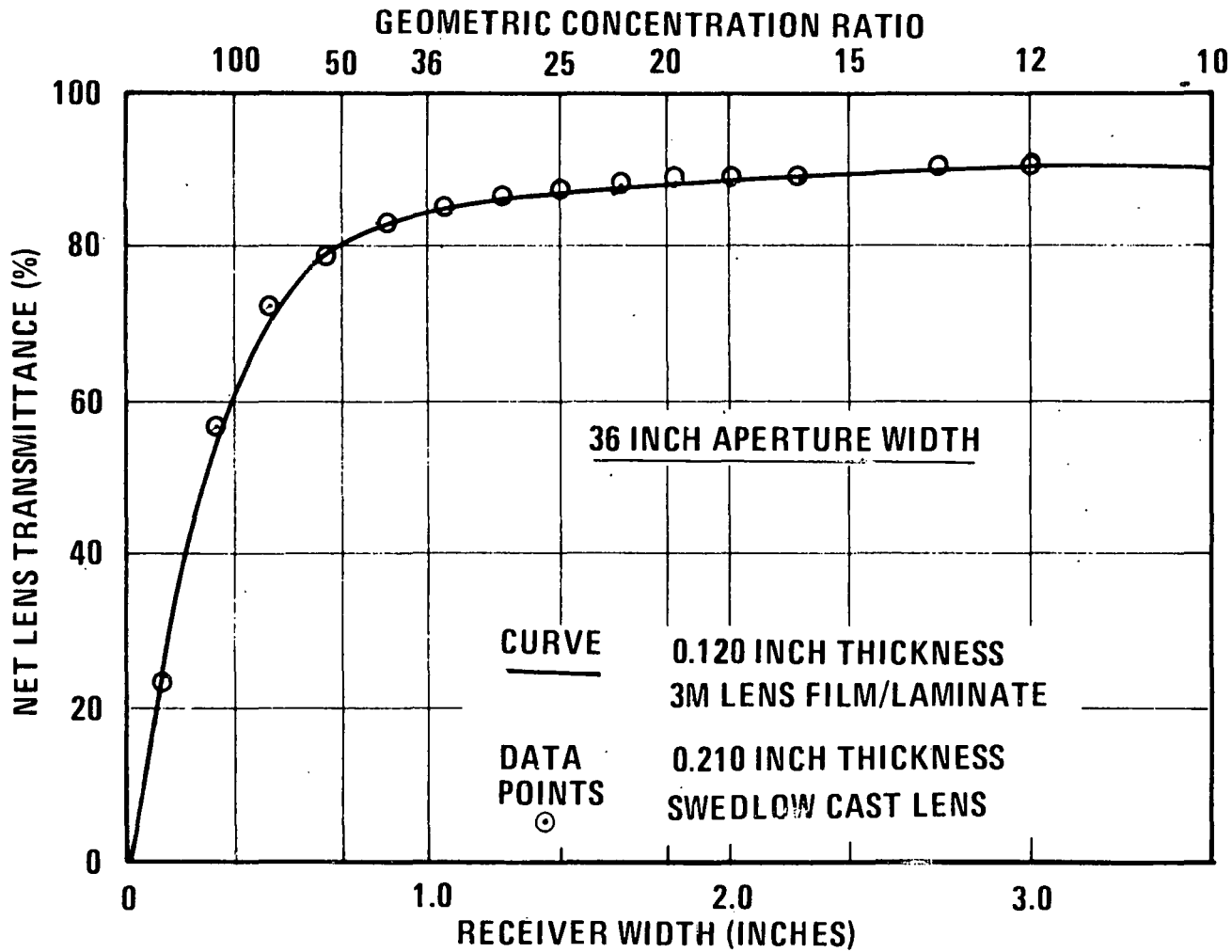
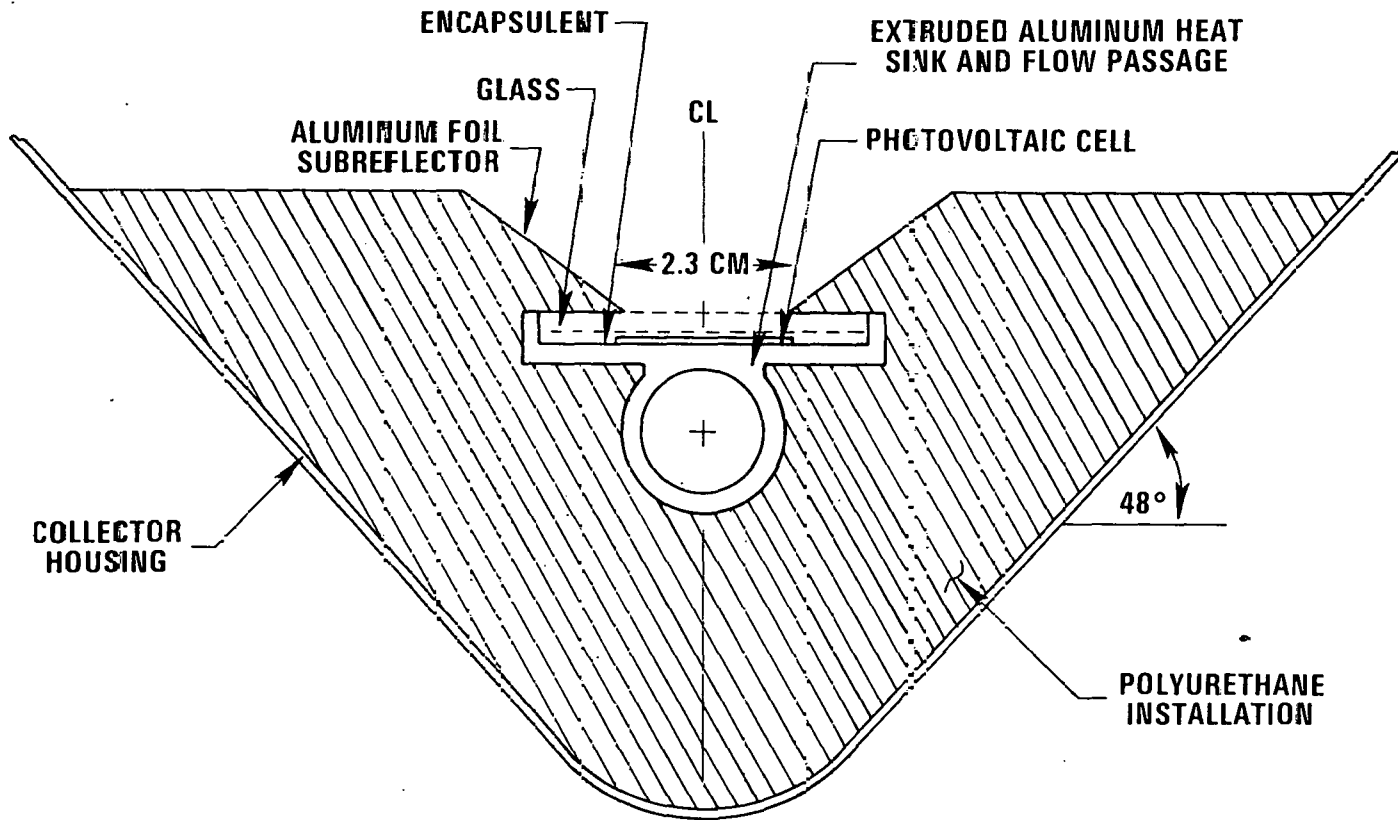


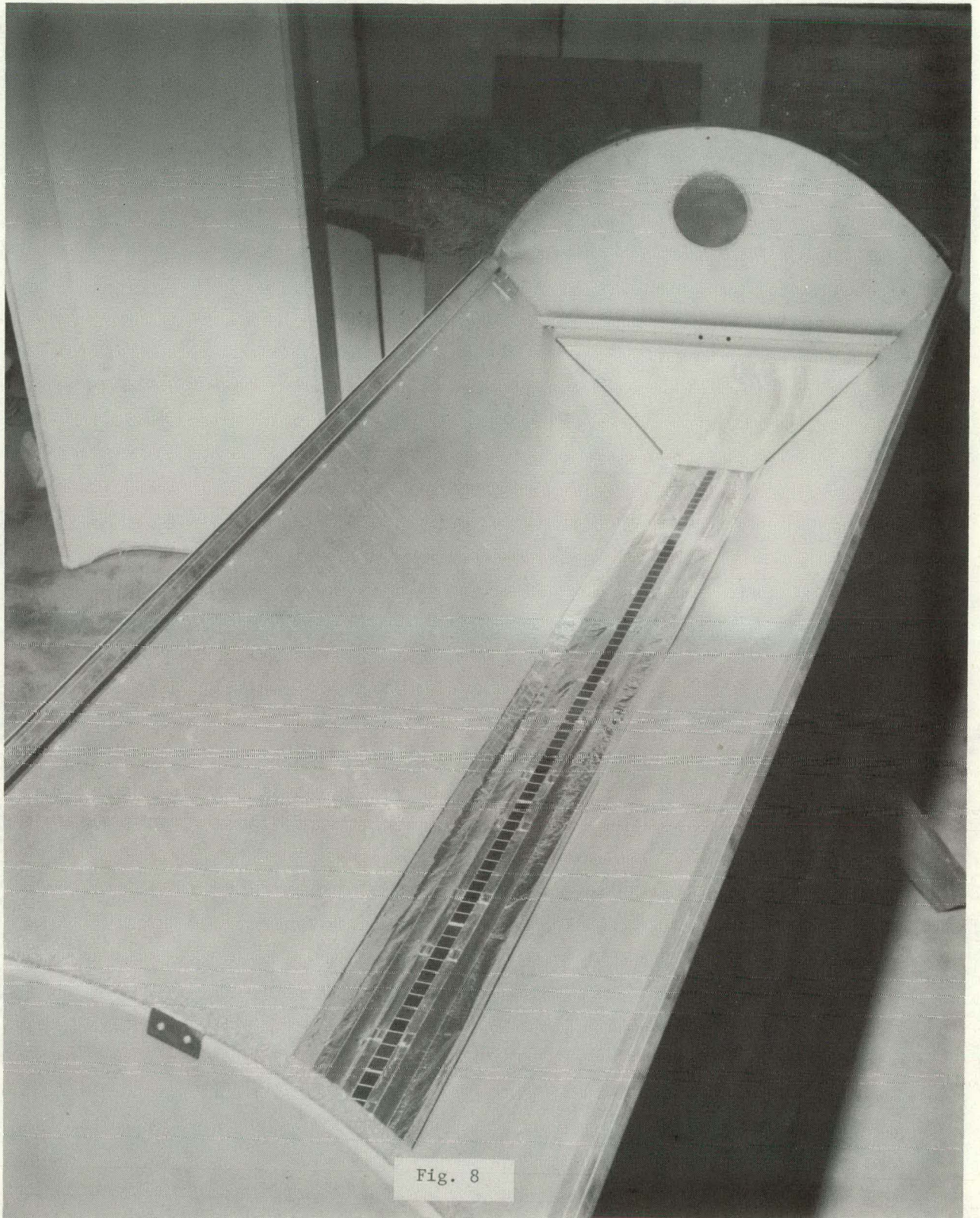
Fig. 6

FINAL RECEIVER DESIGN FOR SECOND GENERATION PHOTOVOLTAIC CONCENTRATOR



20

Fig. 7



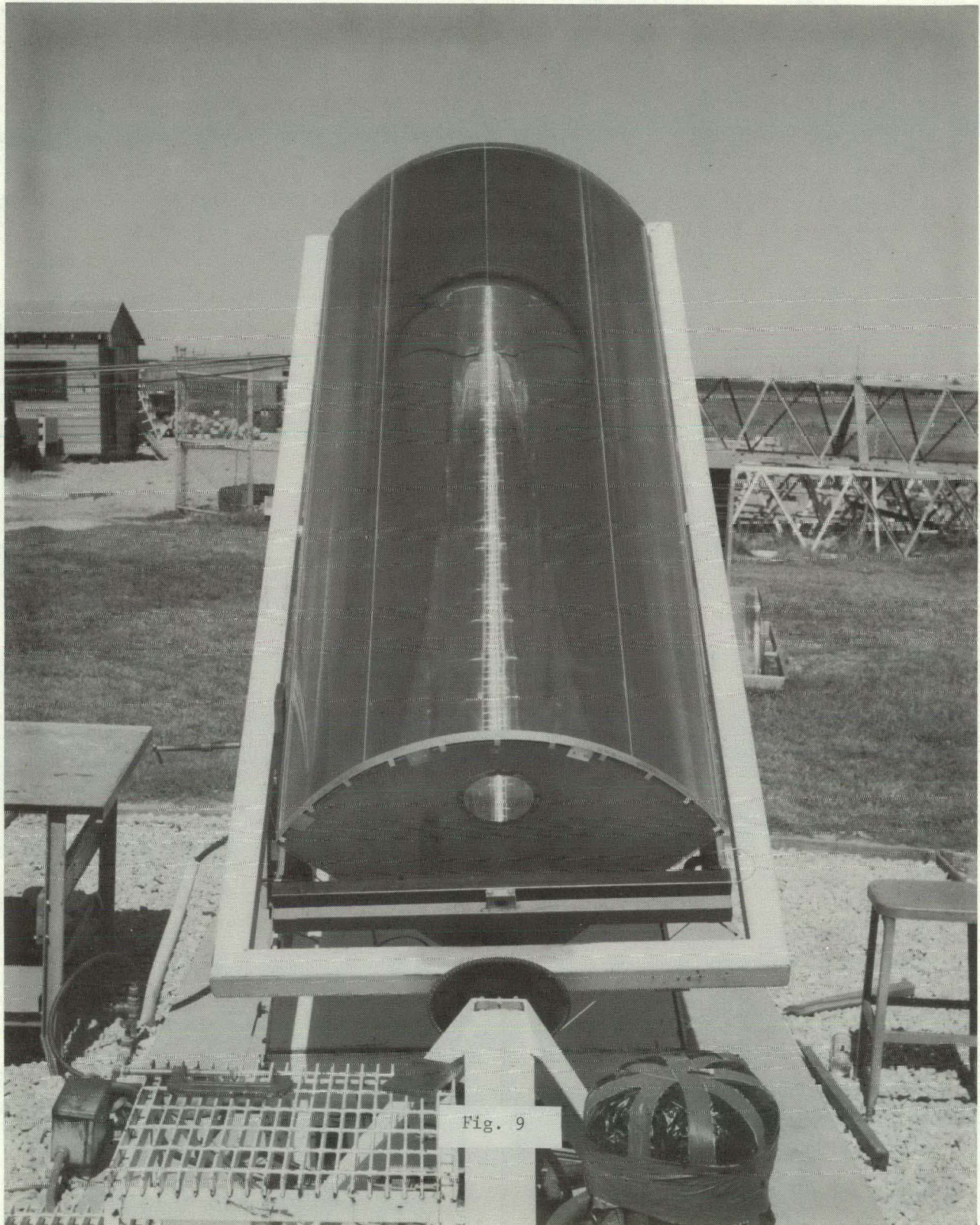
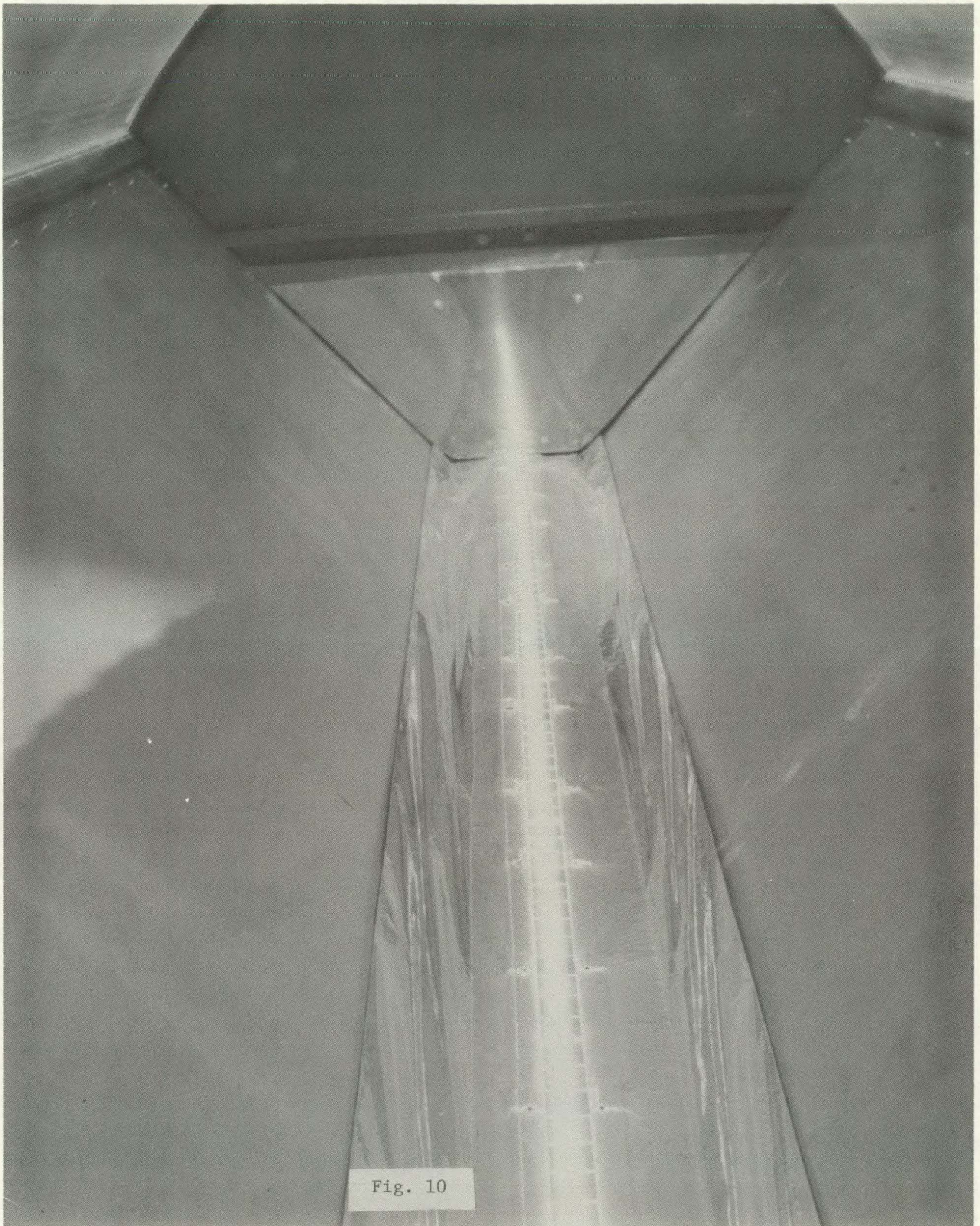


Fig. 9



PARABOLIC TROUGH: TR80 DESIGN AND PERFORMANCE

Eldon C. Boes
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

Parabolic trough photovoltaic concentrator arrays and components have been developed by several firms: Spectrolab, Acurex, Solar Kinetics, General Electric, Honeywell, Solarex, InterTechnology Solar, and Applied Solar Energy. Sandia is currently combining the experience gained from these efforts, along with the developmental achievements for solar thermal parabolic troughs, to design and fabricate a "state-of-art" PV trough.

This presentation describes the design of this PV concentrator and its developmental status. The initial durability of the design has been established by extensive environmental testing of components. Performance of this design will be projected from the analysis of measurements on various other PV trough modules.

PV TROUGH DESIGN FOR TR-80

- USES SAME PARABOLIC TROUGH CONCENTRATOR UNDER DEVELOPMENT BY DOE'S SOLAR THERMAL PROGRAM
- ORIENTATION IS NS-HORIZONTAL
- DESIGN UTILIZES THE ANALYSIS AND EXPERIENCE OF MANY PV TROUGH DEVELOPERS
- GEOMETRIC CONCENTRATION IS 40

Optical Trough Design

MODULE SIZE IS 6M X 2M

FOCAL LENGTH = 0.48M

RIM ANGLE = 92°

REFLECTOR IS SILVERED GLASS BONDED TO STEEL SHEET WHICH IS BONDED TO A STAMPED STEEL FRAME

SUPPORT IS A TORQUE TUBE ATTACHED TO END PYLONS

DRIVE LENGTH IS 24M

Optical Trough Status

FIRST 2 UNITS ARRIVED AT SANDIA IN SEPTEMBER

RMS SLOPE ERROR = 2.5 MRAD, ACCORDING TO LASER SCANS;
THIS IMPLIES AN OPTICAL EFFICIENCY OF 0.85

TEMPERATURE-HUMIDITY CYCLING AND HAIL TESTING ON
EARLIER COMPONENTS INDICATE THAT THERE ARE NO
SHORT TERM FAILURE MECHANISMS

PV Trough Receiver Design

VEE RECEIVER WITH 60° INCLUDED ANGLE

TWO CELL STRINGS USE DOUBLE BUS CELLS WITH 23 MM WIDE
ACTIVE AREA, 54 MM LENGTH

SUBSTRATE IS ALUMINUM EXTRUSION

CELLS ARE BONDED TO A GLASS SUPERSTRATE WITH PVB

THESE CELL ASSEMBLIES ARE MECHANICALLY CLAMPED TO
THE RECEIVER

ELECTRICAL ISOLATION IS INSULATING TAPE OR ALUMINA

EDGE SEALS ARE SILICON OR CLOSED CELL FGAM

PV Trough Receiver Status

PROTOTYPES ARE BEING FABRICATED BY ASEC

RECEIVER DURABILITY IS ASSURED BY ACCELERATED TESTING OF ACUREX, E-SYSTEMS AND HONEYWELL UNITS

RECEIVER PERFORMANCE PROJECTIONS:

CELL TO COOLANT ΔT : 20°C

CELL EFFICIENCY AT 50°C, 30X: 15%

RECEIVER EFFICIENCY AT 50°C CELL TEMP: 13%

NET TROUGH EFFICIENCY AT 50°C CELL: 10%

MANUFACTURING PRICE ANALYSIS
FOR 1980 TECHNOLOGY USING SAMIS

PRESENTATION ABSTRACT

By

Robert J. Bullemer

Theodore Barry & Associates
Los Angeles, California

To manage the Photovoltaic Systems Definition project effectively and to reduce parallel R&D efforts, Sandia Laboratories must continually assess the technical feasibility and verify the economic viability of new subsystem designs. Moreover, these evaluations must be made in the context of a manufacturing process sequence in an integrated factory.

In other words, Sandia must not just determine the best manufacturing process, but it must determine the best sequence of processes. For potentially large production volumes, this implies new manufacturing facilities with a high degree of automation.

The complexity of performing this continual assessment requires a planning model which is more than simply an accounting vehicle that sums plant-and-equipment cost estimates, applies an inflationary factor on current operating costs, and generates an ROI. Rather, it requires a sophisticated model that incorporates detailed data and permits evaluation of different manufacturing approaches, automated processes, plant sizes and many other parameters; it must be capable of evaluating alternative industrial systems in a context of standard assumptions, so that the impacts of those complex alternatives can be compared.

Since the candidate manufacturing processes are all in the early stages of development, and since the industry for the production of photovoltaic concentrator systems is expected to grow significantly, Sandia decided to use the SAMIS computer model to evaluate subsystem designs and calculate probable manufacturing costs in the mid 1980's.

Using SAMIS, TB&A has analyzed current manufacturing costs for two different collectors: a parabolic trough and a linear fresnel lens with annual production volumes of 37,000 m² (3.3 MW) and 55,000 m² (6.1 MW).

Based on a current solar cell price of \$1.45/cm² as input, SAMIS results in manufacturing prices of \$694/m² (\$7.71/W) for the parabolic trough and \$835/m² (\$7.59/W) for the fresnel lens.

These prices can be cut substantially by reducing the cell price and increasing the annual volume. For example, if the PV receiver price is reduced to the DOE program goal of \$3,452 (\$28/cm²), then the trough price drops to \$204/m² (\$2.27/W). Similarly, the fresnel price becomes \$355/m² (\$3.23/W).

SANDIA NATIONAL LABORATORIES

**MANUFACTURING PRICE ANALYSIS
FOR 1980 COMMERCIAL TECHNOLOGY
USING SAMIS**

Theodore Barry & Associates **TBA**

OUTLINE

SAMIS MODEL OVERVIEW

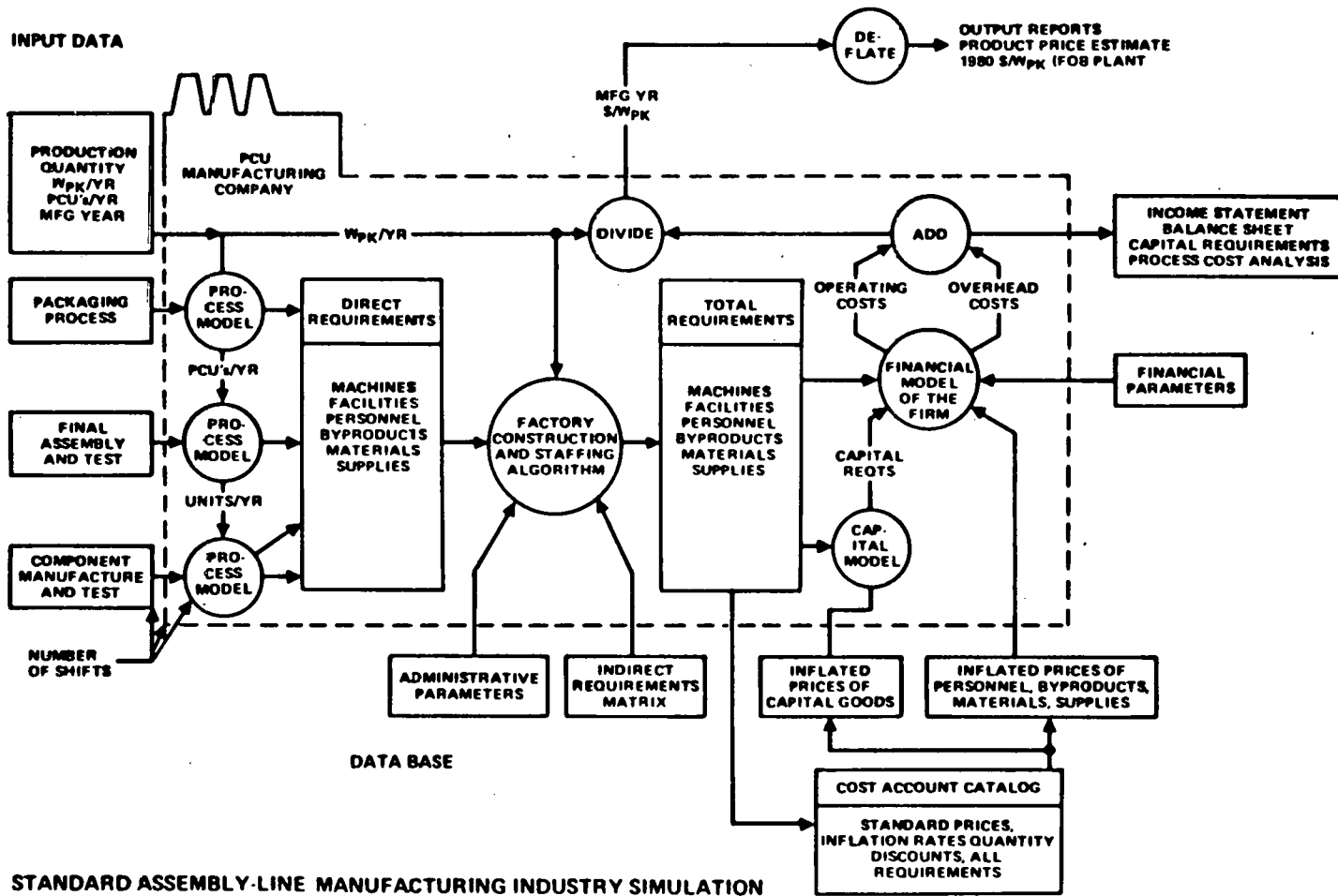
KEY FINANCIAL PARAMETERS

LINEAR FRESNEL LENS ANALYSIS

PARABOLIC TROUGH ANALYSIS

COMPARISON OF RESULTS

SAMIS MODEL OVERVIEW



STANDARD ASSEMBLY-LINE MANUFACTURING INDUSTRY SIMULATION

KEY FINANCIAL PARAMETERS

RETURN ON EQUITY	17.2%
MISCELLANEOUS G&A EXPENSE (% REVENUE)	3.0%
FACTORY OVERHEAD EXPENSE (% OF OPERATING COST)	4.0%
MARKETING AND DISTRIBUTION EXPENSE	0.0%
TAX DEPRECIATION METHOD	DDB
FACILITY LIFE	40 YEARS
INSURANCE RATE	4.0%
DEBT INTEREST RATE	12.5%
DEBT/EQUITY RATIO	20.0%
PROPERTY TAX RATE	2.0%
ACCOUNTS RECEIVABLE TIME	60 DAYS
ACCOUNTS PAYABLE TIME	60 DAYS
RAW MATERIALS INVENTORY TURNOVER	15 DAYS
FINISHED GOODS INVENTORY TURNOVER	15 DAYS
COST OF CAPITAL	15.4%
INCOME TAX RATE	50%

LINEAR FRESNEL LEN ANALYSIS MAJOR ASSUMPTIONS

COMPANY DESCRIPTION

- 1980 COMMERCIAL TECHNOLOGY
- COMBINED RECEIVER/COLLECTOR PLANT
- PV CELL PURCHASE PRICE \$1.45/cm²
- ANNUAL PRODUCTION LEVEL/2500 ARRAYS/
55,575 m²/6.1 MW_p

PRODUCT DESCRIPTION

- ACRYLIC FRESNEL LENS/PV RECEIVER
- TEN 3 FT x 8 FT COLLECTORS/ARRAY
- ARRAY AREA 22.23 m²
- ARRAY EFFICIENCY 11% (110 W_p/m²)
- GEOMETRIC CONCENTRATION RATIO 25X

MANUFACTURING PROCESSES

- 3 OPERATING SHIFTS/DAY
- 12 RECEIVER ASSEMBLY STEPS
- 21 COLLECTOR ASSEMBLY STEPS

LINEAR FRESNEL LENS ANALYSIS SAMIS MODEL RESULTS

	<u>1980 \$/m²</u>	<u>1980 \$/WATT</u>	<u>% SALES</u>
SALES	\$ 835	\$ 7.59	100%
COST OF GOODS SOLD			
• LABOR	\$ 26	\$.24	3%
• MATERIAL	645	5.86	77%
• UTILITIES	1	.01	0%
	<u>\$ 672</u>	<u>\$ 6.11</u>	<u>80%</u>
G&A			
• SALARIES	\$ 20	\$.18	
• UTILITIES	4	.04	
• SUPPLIES AND MISC	34	.31	
	<u>\$ 58</u>	<u>\$.53</u>	<u>7%</u>
DEPRECIATION	\$ 5	\$.04	1%
INTEREST ON DEBT	2	.02	0.5%
INSURANCE AND TAX	10	.09	1.5%
	<u>\$ 88</u>	<u>\$.80</u>	<u>10%</u>
INCOME BEFORE TAX	<u>\$ 88</u>	<u>\$.80</u>	<u>10%</u>
INCOME TAX	45	.41	5%
NET INCOME	<u>\$ 43</u>	<u>\$.39</u>	<u>5%</u>

*EFFICIENCY = 11% (110 WATTS/m²)

LINEAR FRESNEL LENS ANALYSIS COMPANY DESCRIPTION

ANNUAL PRODUCTION VOLUME 2500 ARRAYS/6.1 MW/55,575 m ² /			
PERSONNEL			
DIRECT	103	(66%)	39 KW/PERSON
INDIRECT	53	(34%)	356 M ² /PERSON
TOTAL	<u>156</u>	<u>(100%)</u>	
FLOOR SPACE (FT²)			
DIRECT	14,004	(15%)	64 W/FT ²
INDIRECT	82,013	(85%)	.58 m ² /FT ²
TOTAL	<u>96,017</u>	<u>100%</u>	
CAPITAL COST (1980 \$ 000)			
EQUIPMENT	\$1,276	(11%)	\$1.83/WATT
FACILITIES	6,446	(58%)	
LAND	56	(1%)	\$201/m ²
WORKING	3,409	(30%)	
TOTAL	<u>\$11,187</u>	<u>100%</u>	21% ROI
TIME PARAMETERS			
CONSTRUCTION LEAD TIME = 2 YEARS			
PRODUCTION STARTUP = 1 YEAR			

PARABOLIC TROUGH ANALYSIS

MAJOR ASSUMPTIONS

COMPANY DESCRIPTION

- 1980 COMMERCIAL TECHNOLOGY
- COMBINED RECEIVER/COLLECTOR PLANT
- PV CELL PURCHASE PRICE \$1.45/cm²
- ANNUAL PRODUCTION LEVEL/825 ARRAYS/
36,778 m²/3.3 MW_p

PRODUCT DESCRIPTION

- LINEAR PARABOLIC TROUGH/PV RECEIVER
- EIGHT 6 FT x 10 FT MODULES/ARRAY
- ARRAY AREA 44.85 m²
- ARRAY EFFICIENCY 9% (90 W_p/m²)
- GEOMETRIC CONCENTRATION RATIO 36X

MANUFACTURING PROCESSES

- 3 OPERATING SHIFTS/DAY
- 12 RECEIVER ASSEMBLY STEPS
- 8 COLLECTOR ASSEMBLY STEPS

PARABOLIC THROUGH ANALYSIS SAMIS MODEL RESULTS

	1980 \$/m ²	1980 \$/WATT	% SALES
SALES	\$ 694	\$ 7.71	100%
COST OF GOODS SOLD			
• LABOR	\$ 20	\$.22	3%
• MATERIAL	543	6.04	78%
• UTILITIES	1	.01	0%
	\$ 564	\$ 6.27	81%
G&A			
• SALARIES	\$ 15	\$.17	
• UTILITIES	3	.03	
• SUPPLIES AND MISC	28	.31	
	46	\$.51	7%
DEPRECIATION	\$ 4	\$.04	1%
INTEREST ON DEBT	2	.02	0%
INSURANCE AND TAX	8	.09	1%
	\$ 70	\$.78	10%
INCOME BEFORE TAX	\$ 70	\$.78	10%
INCOME TAX	36	.40	5%
NET INCOME	\$ 34	\$.38	5%

*EFFICIENCY = 9% (90 WATTS/m²).

PARABOLIC TROUGH ANALYSIS COMPANY DESCRIPTION

ANNUAL PRODUCTION VOLUME 825 ARRAYS/3.3 MW/36,788 m ² /			
PERSONNEL			
DIRECT	51	(66%)	43 KW/PERSON
INDIRECT	26	(34%)	478 M ² /PERSON
TOTAL	<u>77</u>	<u>(100%)</u>	
FLOOR SPACE (FT²)			
DIRECT	6,292	(14%)	73 W/FT ²
INDIRECT	38,622	(86%)	.82 m ² /FT ²
TOTAL	<u>44,914</u>	<u>(100%)</u>	
CAPITAL COST (1980 \$ 000)			
EQUIPMENT	\$ 736	(12%)	\$1.81/WATT
FACILITIES	3,115	(52%)	
LAND	29	(1%)	\$162/m ²
WORKING	2,092	(35%)	
TOTAL	<u>\$5,972</u>	<u>100%</u>	21% ROI
TIME PARAMETERS			
CONSTRUCTION LEAD TIME = 2 YEARS			
PRODUCTION STARTUP = 1 YEAR			

COMPARISON OF RESULTS

	PARABOLIC TROUGH	FRESNEL LENS
PRODUCTION VOLUME	3.3 MW _p 36,788 m ²	6.1 MW _p 55,575 m ²
ARRAY EFFICIENCY	9% 90 W _p /m ²	11% 110 W _p /m ²
MANUFACTURING PRICE		
RECEIVER	\$556/m ²	\$500/m ²
COLLECTOR	<u>138/m²</u>	<u>335/m²</u>
TOTAL	\$694/m ² \$7.71/W _p	\$835/m ² \$7.59/W _p
COST OF GOODS SOLD	81%	80%
NET PROFIT AFTER TAX	5%	5%
RETURN ON INVESTMENT	21%	21%
PERSONNEL PRODUCTIVITY	478 m ² /PERSON	356 m ² /person
CAPITAL COST	\$162/m ²	\$201/m ²

SOLERAS PHOTOVOLTAIC ARRAY

BY

MARTIN MARIETTA CORPORATION

BOX 179, DENVER, COLORADO 80201

Presented by Sidney Broadbent (303/977-0683)

The Soleras program has not been without its normal share of unanticipated development problems, although not totally unexpected, either. Throughout this development we would like to acknowledge the support and ingenuity of our major subcontractors: O.S.G. for lenses, Jim Robbins Inc. for housings and liner, Coors Porcelain for the substrates, GBC for support tubes, Morse Chain and Winsmith on drive mechanisms, ASEC for cells, Rogers for the interconnects and Bodine for the drive motors.

Considerable re-design effort was entailed to convert the prototype concept to a production version. However, the initial design was conceived with definite high volume processes in mind, for instance, the change from a vacuum formed module housing to an injection molded housing.

Other areas needing productionizing were the cell/substrate/interconnect soldering processes which have been automated with Martin Marietta funding and remain proprietary. Very considerable development effort was expended by both Martin Marietta and Coors Porcelain in developing the special substrate with an adequate thickness of copper metallization to provide satisfactory conductivity. Cells, substrates and the two basic types of interconnect are shown in Figures 1 and 2.

A conveyORIZED assembly line is ready for operation for processing heat exchangers, assembling cells substrates and interconnects, and installing housings. The housing is supplied to Martin Marietta complete with its aluminum foil liner direct from the injection molder. Martin Marietta then installs the fresnel lens at a specially vented staging area to accommodate adhesive vapors. Figures 3, 4 and 5 show this assembly area.

Figures 6 and 7 show the productionized electronic control unit with its integral sun sensor, and Figure 8 shows the drive units in course of assembly.

The arrays are shipped in four discrete sub-assemblies (1) support tube, (2) drive assembly, (3) photovoltaic modules, and (4) the electronic control unit. Assembly in Saudi Arabia comprises: attaching the drive assembly to the pedestal (6 bolts), dropping the support tube in position on rollers in the drive unit, and adding 2 restraint roller chains and a drive chain. The 32 modules are then installed, each requiring four bolts and two electrical connections. Finally, the electrical control unit is fitted and with its few electrical connections the array becomes a workable entity.

The array was shortened from 34 to 32 modules to facilitate packaging of the tube in standard 40 ft long shipping containers. Our second generation array will avoid this shortcoming.

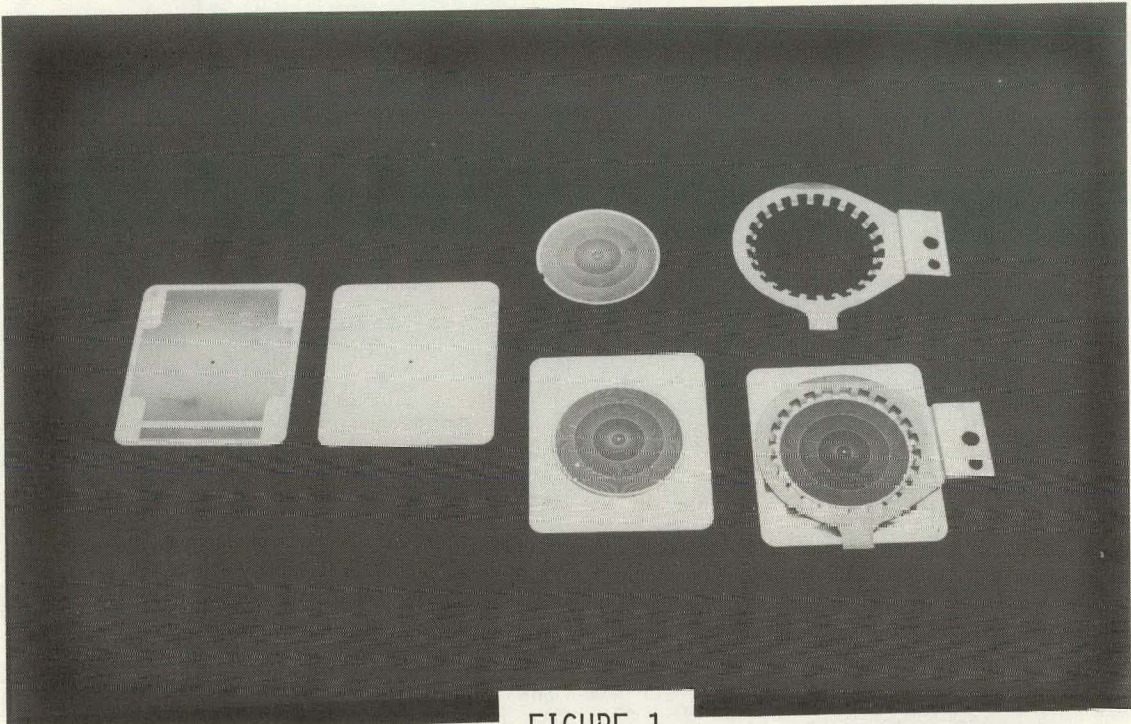


FIGURE 1

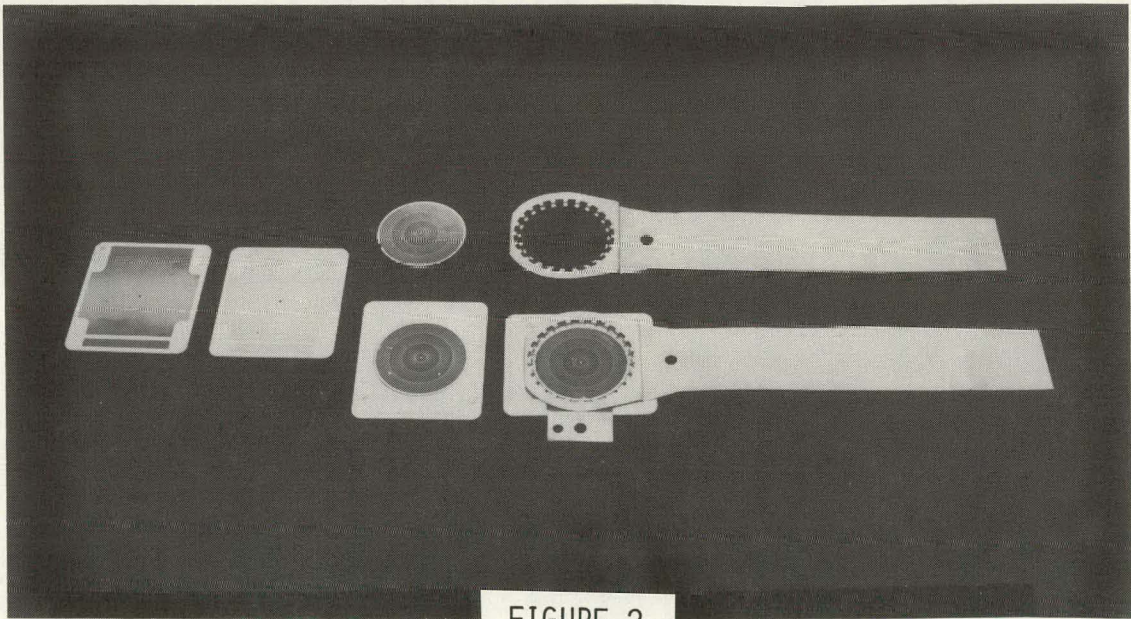


FIGURE 2



FIGURE 3

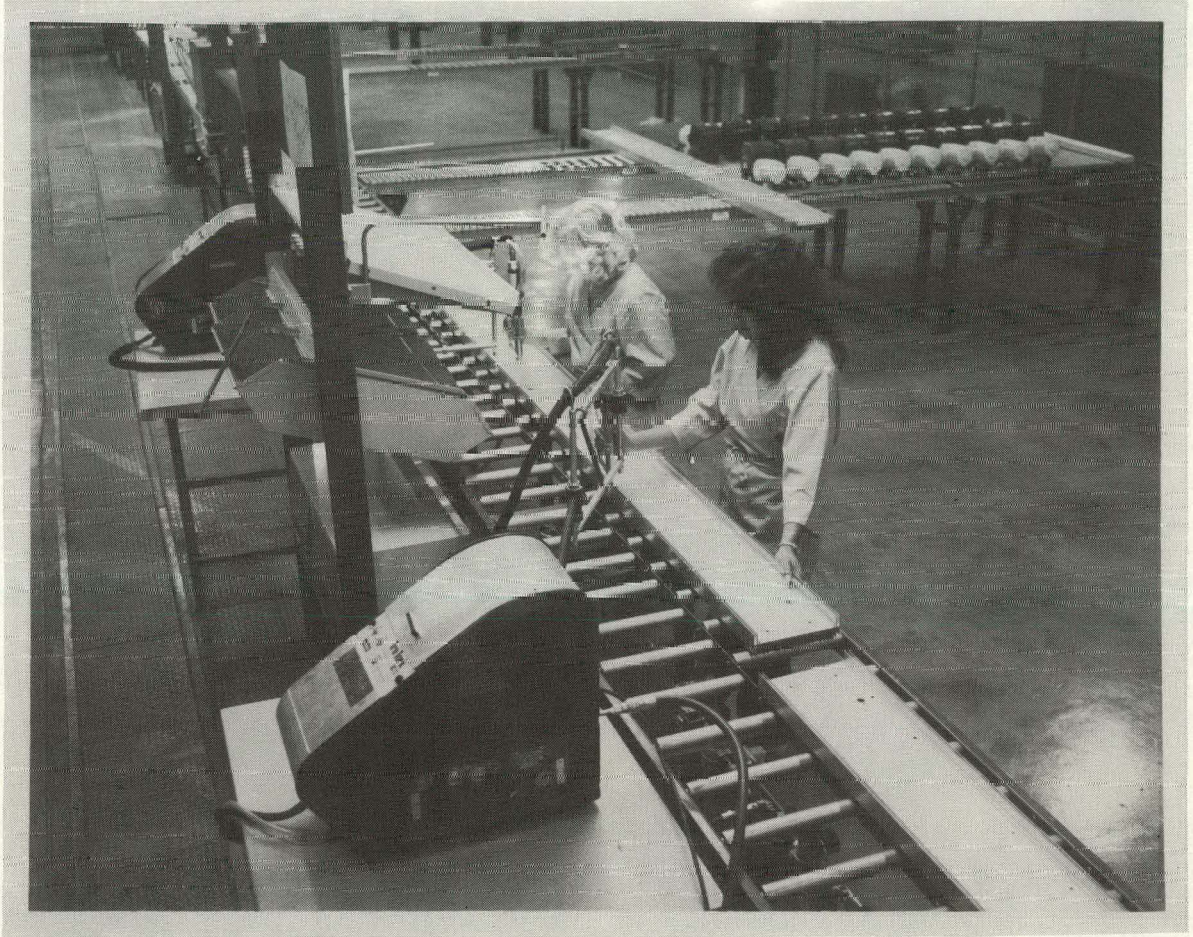


FIGURE 4

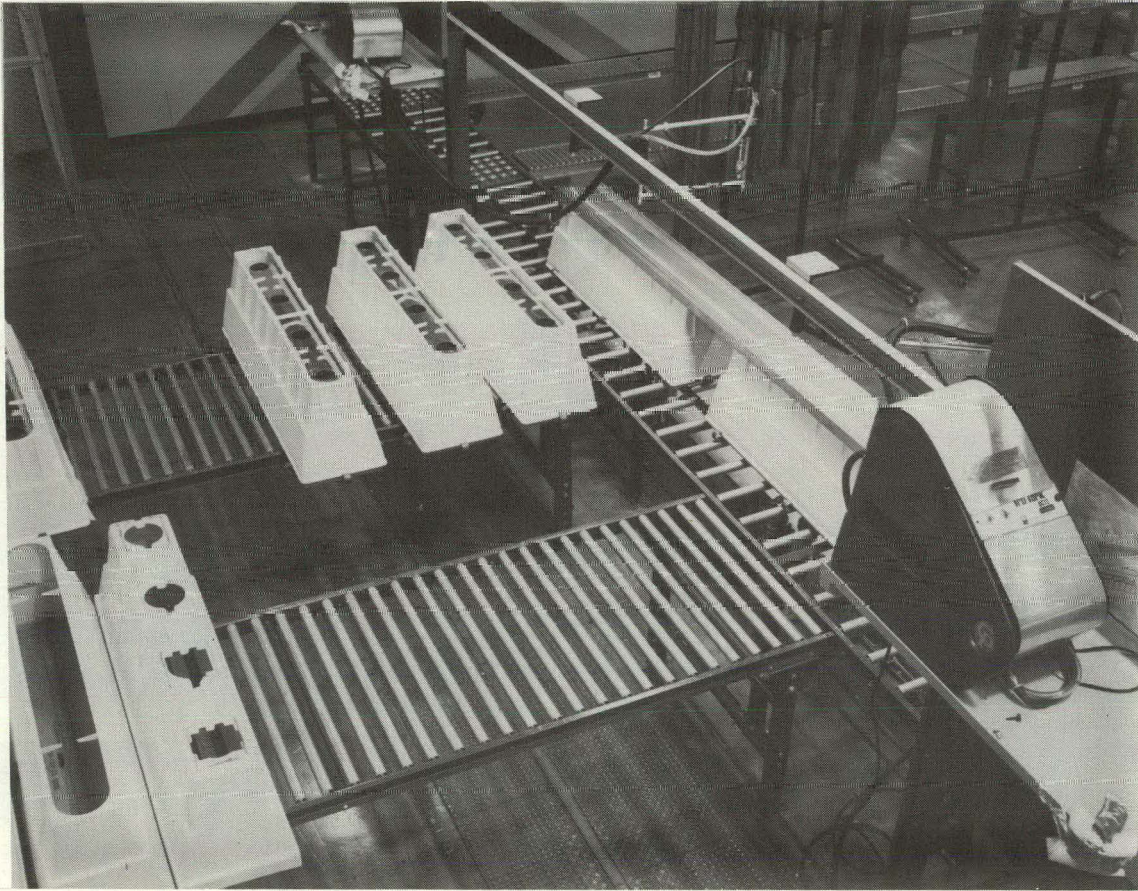


FIGURE 5

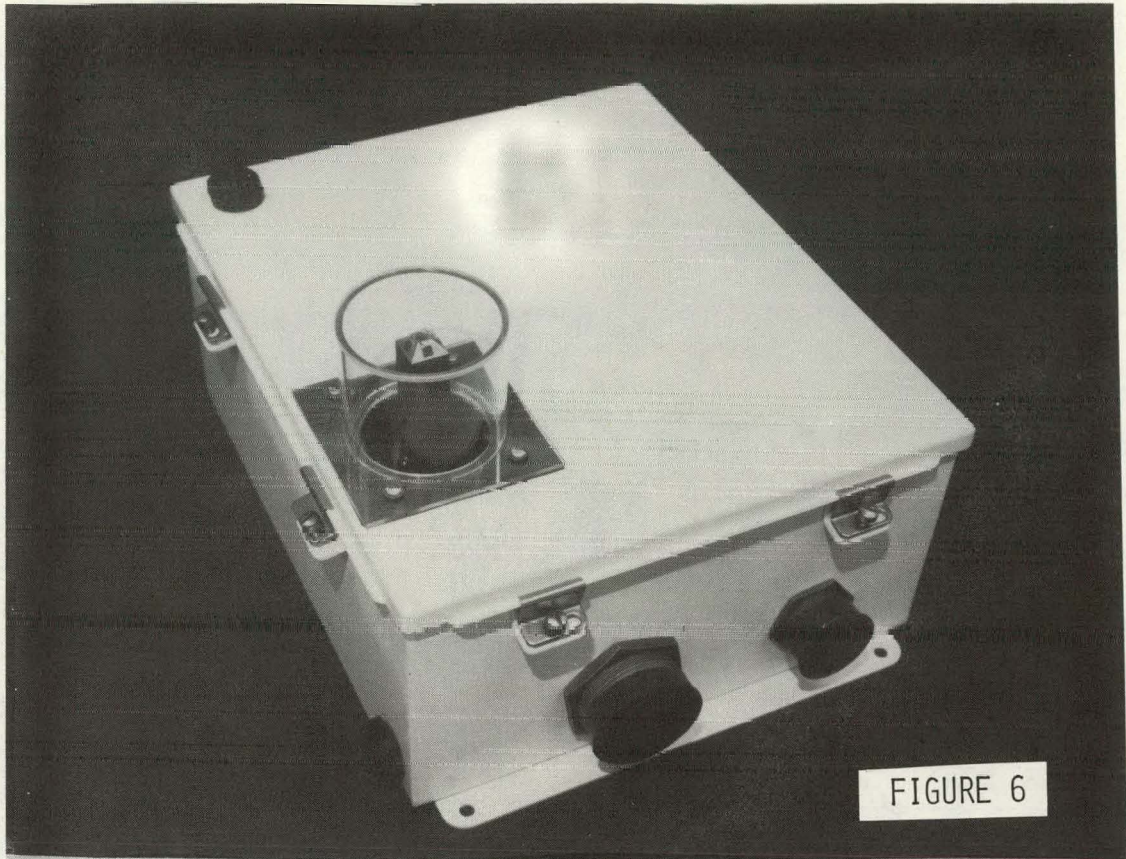


FIGURE 6

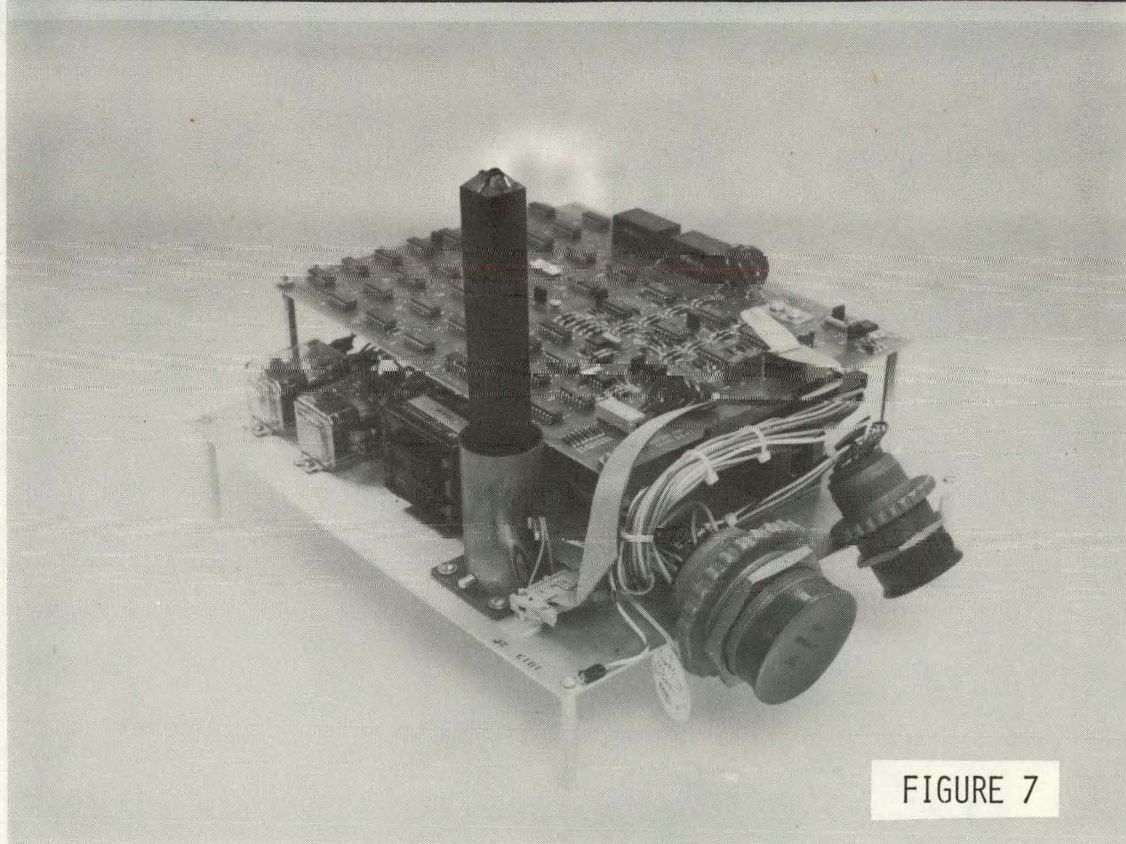


FIGURE 7

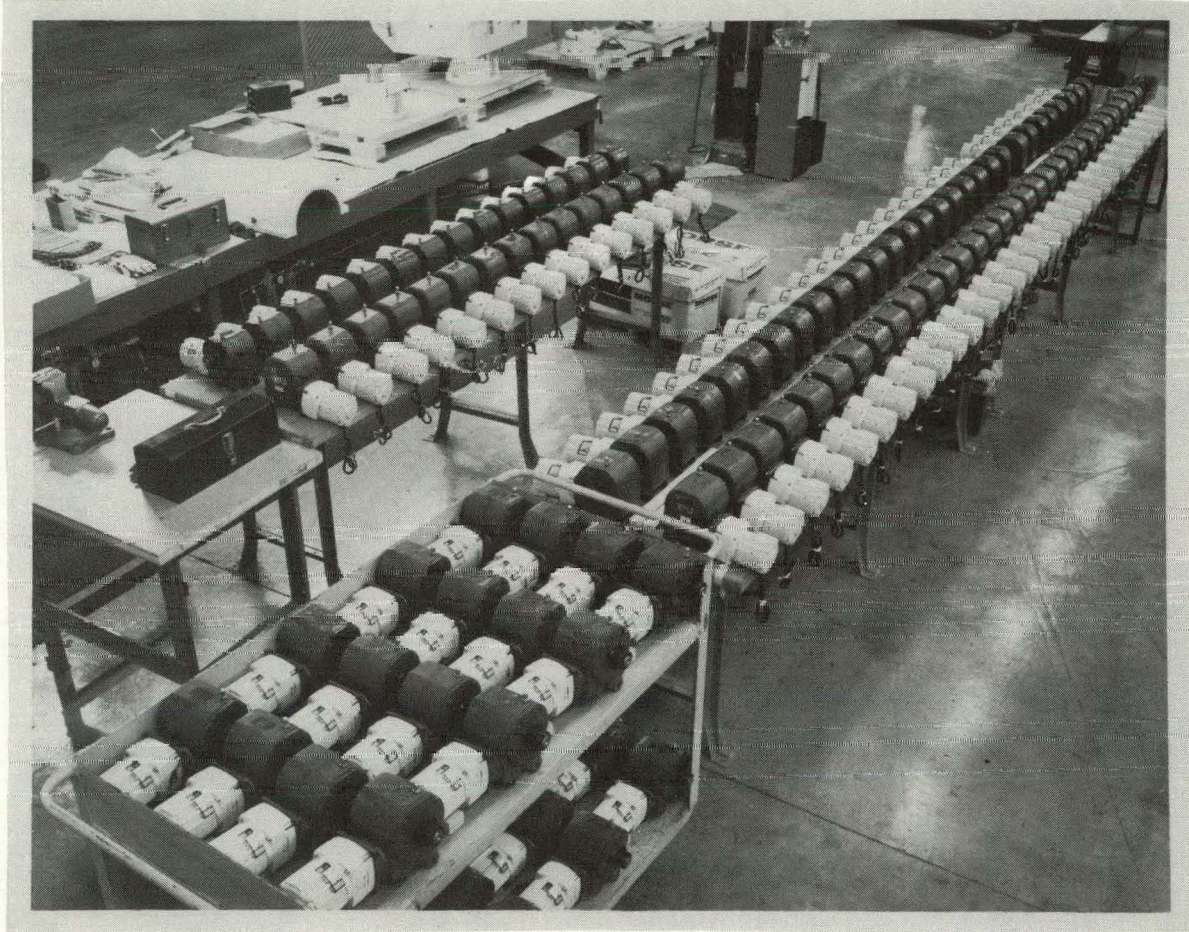


FIGURE 8

CONCENTRATING ARRAY INSTALLATION AT
MISSISSIPPI COUNTY COMMUNITY COLLEGE

by

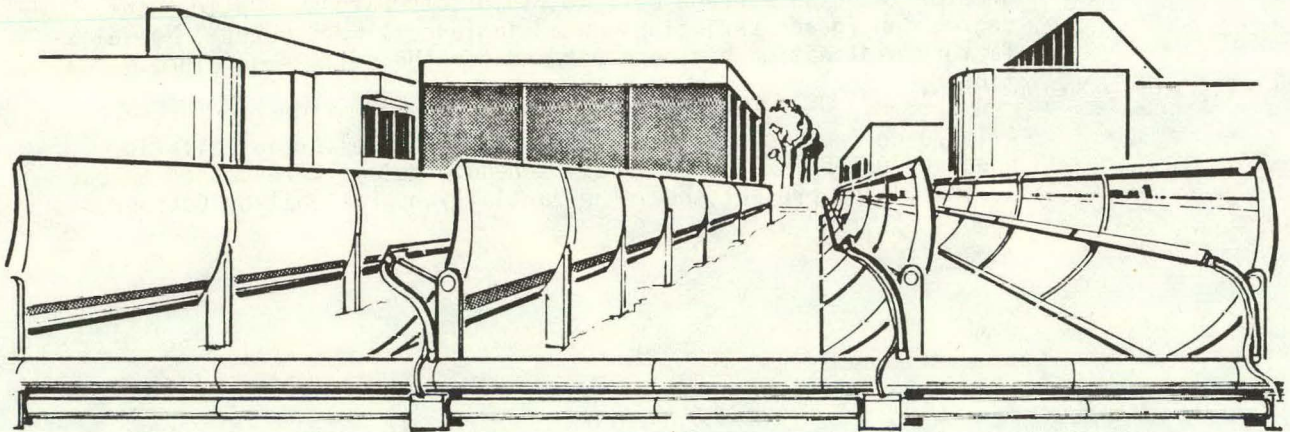
Gus Hutchison
Solar Kinetics, Inc.

The Mississippi County Community College photovoltaic receiver assembly design has been completed and all receiver substrates have been fabricated and shipped to Solarex. Chronic breakage of cell cover glass seems to have been eliminated by increasing the substrate area to match the cell area.

JPL assisted in thermal analysis of the receiver using the infrared video camera technique, followed with computer enhancement. Variations in temperature were noted from cell to cell which were greater than the average cell to fluid temperature. Up to twenty degree centigrade variations on a single cell were noted. No satisfactory explanation has been offered for the cell temperature variation.

All 270 collectors have been installed and receiver installation began on October 21, 1980. Many schedule delays were caused by bad weather. The project should be partially operational by October 31, 1980.

PROJECTS AND INSTALLATIONS



MISSISSIPPI COUNTY COMMUNITY COLLEGE

Solar Kinetics, Inc. is prime contractor and collector supplier for the photovoltaic solar concentrator system to be installed at the college's new Plytheville, Arkansas site. 38,000 sq. ft. of T-700 collectors using actively cooled aluminum receivers will produce 300 KWe peak output at 380 volt and up to 27×10^6 BTU per day of thermal energy for building space heat.

TEAM MEMBERS

SOLAR KINETICS, INC. — COLLECTORS
BDM CORPORATION — ENGINEERING
SOLAREX — PV CELL SUPPLIER
TEAM, INC. — SYSTEM INTEGRATOR

CONCENTRATING ARRAY INSTALLATION AT
NORTHWEST MISSISSIPPI JUNIOR COLLEGE

by

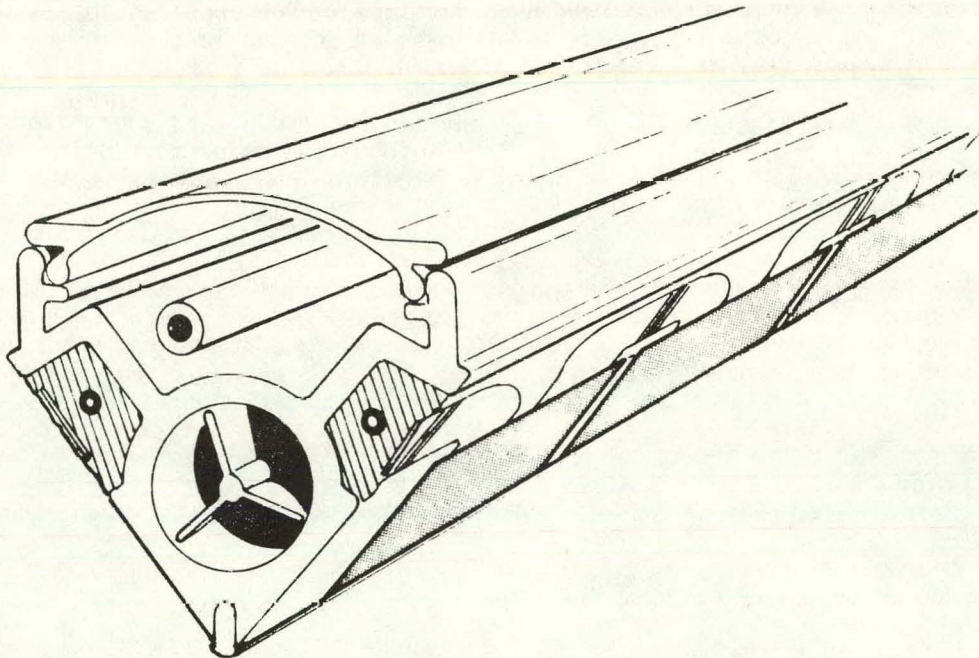
Gus Hutchison
Solar Kinetics, Inc.

The SKI Northwest Mississippi Junior College project at Senatobia, Mississippi is currently on hold. All the mechanical, electrical and concrete subcontract work has been completed. All pylons and trackers are installed. The 60 mirrors have been manufactured and are awaiting delivery release.

The delay has had a beneficial effect on the glass laminate development since some failures have occurred after eight to ten weeks. Several techniques have been developed which appear to be satisfactory and testing is in progress at SKI and in the Sandia accelerated weather chamber.

Solar Kinetics has not been advised concerning the source for PV cells and is currently awaiting that information prior to fabrication of the receivers.

PROJECTS AND INSTALLATIONS



NORTHWEST MISSISSIPPI JUNIOR COLLEGE

Solar Kinetics is prime contractor and collector supplier for the glass mirrored T-700 photovoltaic solar concentrator system to be installed at NWMJC, Senatobia, Mississippi. This system will produce 66.6 KWe peak electrical output at 84.4 volt and up to 6.0×10^6 BTU of heat for building space heat..

TEAM MEMBERS

SOLAR KINETICS, INC. — COLLECTOR SUPPLIER

BDM — ENGINEERING

TEAM, INC. — SYSTEMS INTEGRATOR

NWMJC GaAs CONCENTRATOR ARRAY

Shing Mao, UTL Corporation, Dallas, Texas

Abstract

A 50KW concentrator array using GaAs photovoltaic solar cells are designed and being installed in the test field 140 ft x 200 ft at Northwest Mississippi Junior College, Senatobia, Miss. This array consists of 16 pedestals. Each pedestal has its own two-axis tracking mechanism with direct sensing elements. On the pedestal, a panel of 16 ft x 18 ft is mounted containing 72 modules. The panels are made of light weight, aluminum alloyed structural T and I beams. The module consists of a plastic molded box, 4 Fresnel Lenses and 4 mounted GaAs cells capable to be assembled, aligned and tested at the field. The lens is 12 inch x 12 inch in size and provides insolation area approximately 11 in x 11 in. With 100 mw/sq. cm. solar insolation, each module will provide an electrical output power of 43.75 watts.

The cells are made of GaAs with AlGaAs window. A proprietary process geared for mass production has been developed and the yield over 60% has been achieved. The metal pattern is selected to be honeycone which gives the best current distribution with less than 10% insolation shadow. The cells are mounted directly on a copper tube receiver for the best electrical and thermal conduction. The tubes are connected electrically in series and thermally in parallel with active coolant circulating through the tube and maintaining the cell temperature below 100 degree C. The thermal energy of this array is not gainfully used and is dumped to the ambient via a cooling tower. The cell efficiency will be about 18%. Test result at Sandia showed that the cells are capable to generate a current over 15 amp at 500 sun. However, in field test we only obtain 10.5 amps due to the difficulty of obtaining the properly designed lens within the time frame for the project.

Further extension on this project leads to the need for tooling of the properly designed lens and the hybrid application including the utilization of the thermal power currently dumped through the coolant.

NWMJC GaAs CONCENTRATOR ARRAY

PROGRAM OBJECTIVE

- o EFFECTIVE COST
- o OPTIMUM PERFORMANCE
- o ACCEPTABLE RELIABILITY
- o EASY SERVICE AND MAINTENANCE
- o ADAPTABLE TO MASS PRODUCTION IN FOLLOW-UP APPLICATIONS
- o EXTENSION TO THERMAL AS WELL AS PHOTOVOLTAIC POWER OUTPUT FOR SYSTEM EFFICIENCY APPROACHING 50%

NWMJC GaAs CONCENTRATOR ARRAY

SYSTEM DESCRIPTION

MODULE

- o DIMENSIONS: 2' x 2' x 14"
- o NUMBER OF CELLS: 4
- o ACTIVE COOLING: 50% GLYCOL IN DI WATER.
- o ELECTRICAL CONNECTION IN SERIES
- o THERMAL COOLANT PLUMBED IN PARALLEL
- o ELECTRICAL OUTPUT: 43.75 WATTS

PANEL

- o DIMENSIONS: 16' X 18'
- o TWO-AXIS TRACKING PEDESTAL
- o CONSISTS OF: 72 MODULES OR 288 CELLS
- o ELECTRICAL OUTPUT: 3150 WATTS

SYSTEM

- o CONSISTS OF: 16 PANELS ON PEDESTALS
- o FIELD SIZE 140 x 200 FT²
- o ACTIVE COOLING WITH COOLING TOWER
- o SYSTEM ELECTRICAL OUTPUT: 250V, 200 AMP. or 50KW.

NWMJC GaAs CONCENTRATOR ARRAY

TRACKING AND PEDESTAL

- o FIVE ELEMENTS WITH CLOUD & EVENING SENSING.
- o ACCURACY TO ± 0.25 DEGREE MEAN WINDOW WIDTH.
- o DRIVEN BY TWO 1/8 HP. MOTORS.
- o ABLE TO SUPPORT 2000 LBS.
- o MODE OF OPERATIONS:

AUTOMATIC: ACTIVE TRACKING THE SUN IN AZIMUTH & ELEVATION.

PROGRAMMED: TRACING THE DIURNAL SUN POSITION IN AZIMUTH ONLY DURING CLOUD.

SUNRISE CAPTURE: RETURN TO SUNRISE CAPTURE POSITION BEFORE SUNRISE.

MANUAL: MANUALLY OVERRIDE ALL OTHER MODES AND DRIVE BOTH AZIMUTH AND ELEVATION TO DESIRED POSITION AT A RATE 35 DEGREES PER MINUTE.

NWMJC GaAs CONCENTRATOR ARRAY

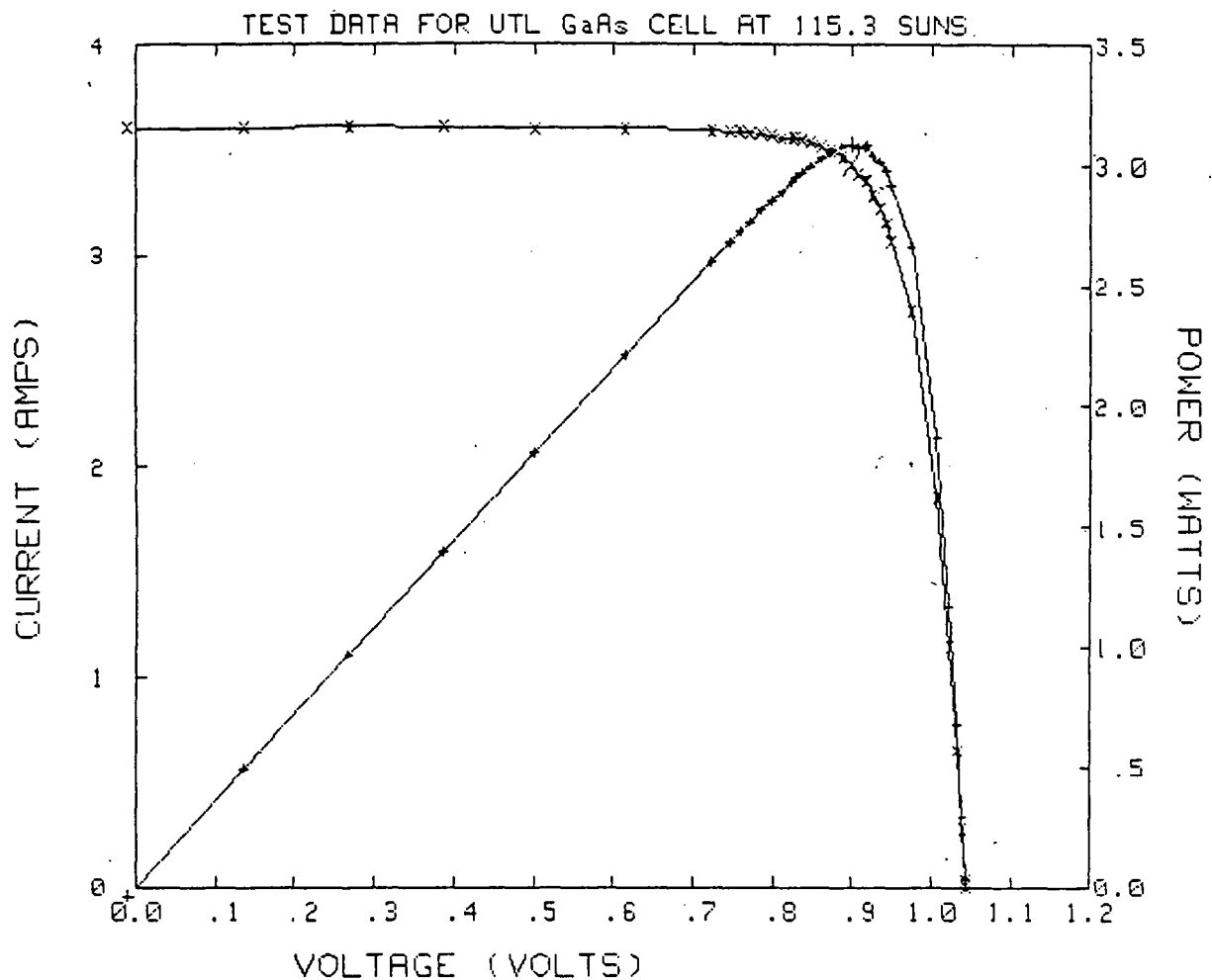
OPTICAL SYSTEM EFFICIENCY

LENS TRANSMISSION	0.86
EDGE LOSS*	0.92
SCATTERING	0.95
OVERALL OPTICAL EFFICIENCY	0.7516
INSOLATION ON 11.5" x 11.5" AREA	85.3 watts
INSOLATION ON CELL	64.0 watts
CELL OUTPUT	10.94 watts (17.1%)

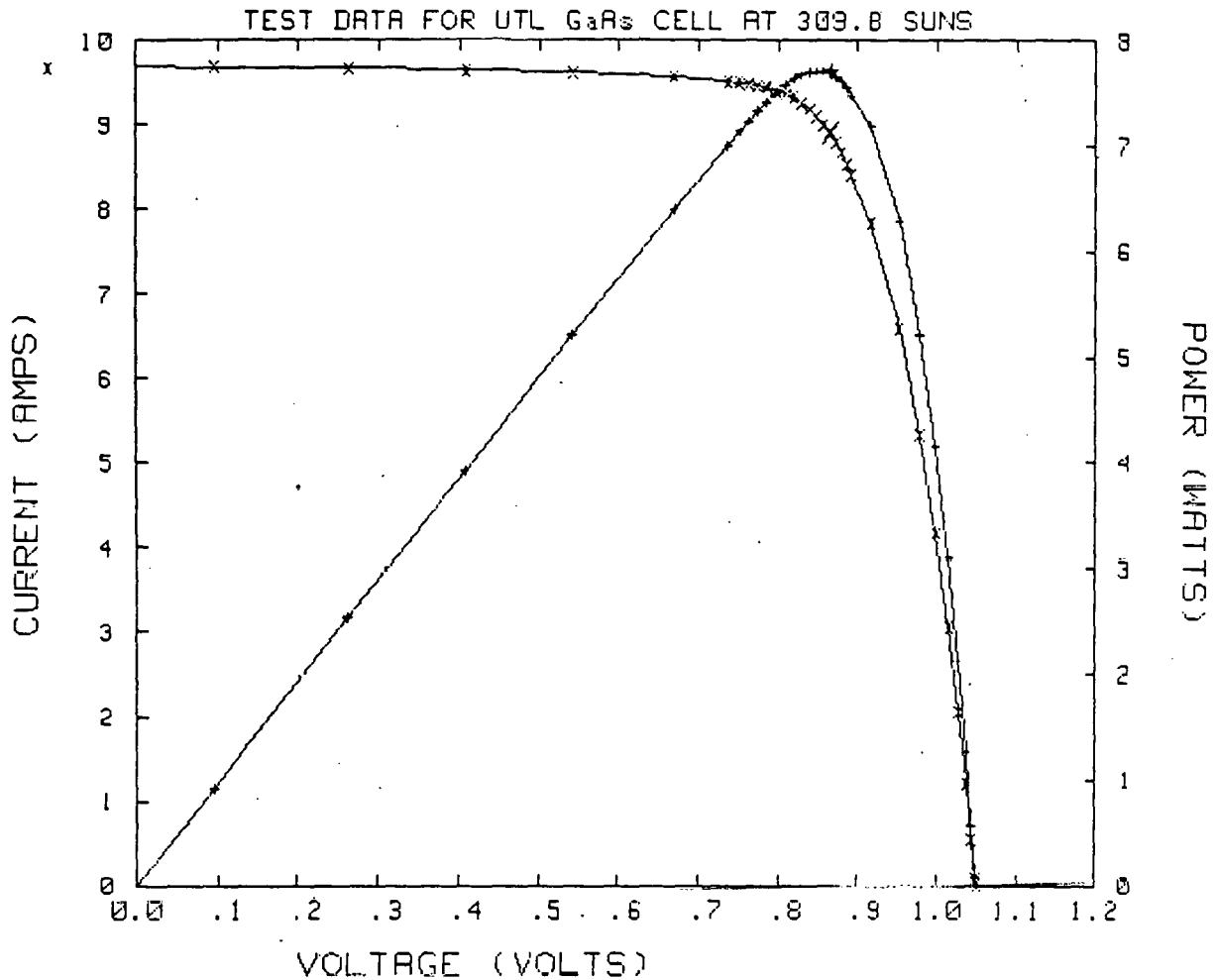
NWMJC GaAs CONCENTRATOR ARRAY

GaAs CELLS STRUCTURE

- o SUBSTRATE n^+ GaAs, 10^{18} cm^{-3}
- o FIRST EPI-LAYER: n GaAs, 10 μm thick, 10^{17} cm^{-3}
- o SECOND EPI-LAYER: p^+ GaAs, about 2 μm thick, $2 \times 10^{18} \text{ cm}^{-3}$
- o WINDOW EPI-LAYER: p^+ AlGaAs, about 0.07 μm thick, $3 \times 10^{18} \text{ cm}^{-3}$
- o METAL PATTERN: HONEYCONE, line width 5 μm . side length 3 mils.
- o SILVER PLATING: 4 μm thick.
- o CELL DIAMETER: 0.54 inch
- o CELL AREA: 1.4775 cm^2



TYPE OF TEST=	CONCENTRATOR
CELL DESCRIPTION=	UTL GaAs
CELL NUMBER=	D 60 B 211
CELL SIZE=	1.4700 SQ.CM
EFFICIENCY=	18.19 %
CONCENTRATION RATIO=	119.37X
# 100 mW/SQ.CM SUNS=	115.29 SUNS
FILL FACTOR=	8.1898E-01
BEGINNING CELL TEMP=	35.56 DEG. C
ENDING CELL TEMP=	47.14 DEG. C
OPEN CIRCUIT VOLTAGE=	1.0442E+00 VOLTS
S.C. CURRENT=	3.6057E+00 AMPS
MAX POWER=	3.0835E+00 WATTS
VOLTAGE AT MAX POWER=	8.9861E-01 VOLTS
CURRENT AT MAX POWER=	3.4314E+00 AMPS
CURRENT DENSITY AT SHORT CRKT=	2.4529E+00 AMPS/SQ.CM.
CURRENT DENSITY AT S.C./#SUNS=	2.1277E-02 AMPS/SQ.CM/SUN
S.C. CURRENT/#SUNS=	3.1277E-02 AMPS/SUN
NIP INSOLATION=	93.60 mW/SQ.CM.
SINGLE SUN INSOLATION=	96.58 mW/SQ.CM.
SINGLE SUN S.C. CURRENT=	3.0207E-02 AMPS
AMBIENT TEMP=	31.66 DEG. C
DATA FILE NAME=	181623
PARAMETER FILE NAME=	181624
DATE= (Mo-Day-Yr)	9-18-00 DISK #3
TIME= (Hr:Min:Sec)	16:23:23



TYPE OF TEST=	CONCENTRATOR
CELL DESCRIPTION=	UTL GaAs
CELL NUMBER=	D 60 B 211
CELL SIZE=	1.4700 SQ.CM
EFFICIENCY=	16.92 %
CONCENTRATION RATIO=	320.75X
# 100 mW/SQ.CM SUNS=	309.78 SUNS
FILL FACTOR=	7.5748E-01
BEGINNING CELL TEMP=	46.03 DEG. C
ENDING CELL TEMP=	51.65 DEG. C
OPEN CIRCUIT VOLTAGE=	1.0501E+00 VOLTS
S.C. CURRENT=	9.6890E+00 AMPS
MAX POWER=	7.7067E+00 WATTS
VOLTAGE AT MAX POWER=	8.6521E-01 VOLTS
CURRENT AT MAX POWER=	8.9073E+00 AMPS
CURRENT DENSITY AT SHORT CRKT=	6.5912E+00 AMPS/SQ.CM.
CURRENT DENSITY AT S.C./#SUNS=	2.1277E-02 AMPS/SQ.CM./SUN
S.C. CURRENT/#SUNS=	3.1277E-02 AMPS/SUN
NIP INSOLATION=	91.89 mW/SQ.CM.
SINGLE SUN INSOLATION=	96.58 mW/SQ.CM.
SINGLE SUN S.C. CURRENT=	3.0207E-02 AMPS
AMBIENT TEMP=	31.80 DEG. C
DATA FILE NAME=	181631
PARAMETER FILE NAME=	181632
DATE= (Mo-Day-Yr)	9-18-80 DISK #3
TIME= (Hr:Min:Sec)	16:31:35

ACUREX, WILCOX HOSPITAL ARRAY

Bob Spencer
Acurex Corporation
485 Clyde Avenue
Mountain View, California 94042
(415) 964-3200

ABSTRACT

Acurex Corporation has developed an efficient, durable, actively cooled photovoltaic receiver for application to a parabolic trough concentrator array. This design provides several potentially attractive benefits for commercial and industrial applications, in addition to the electrical energy delivered. The electrical aperture efficiency is better than flat plate modules, and it provides thermal energy for process heat. Costly cell area is dramatically reduced, and commercial pricing readiness may be achieved sooner than with flat plate photovoltaic arrays.

The design effort was organized to optimize the receiver to three primary criteria:

- Performance
- Environmental stability
- Cost

The receiver performance was modeled for normal incidence from previous receiver prototypes. We performed laser ray trace characterizations of our production trough at both Acurex Corporation and at Sandia Laboratories. The results were used to computer model the energy flux distribution at the receiver. Several receiver parameters were then optimized for performance and cost to define the top level design constraints.

The receiver mechanical design incorporated environmental resistance and maintainability within the performance envelope. In addition, the mechanized assembly of the receiver components was considered to allow for future cost reduction. The primary concerns for environmental survival are:

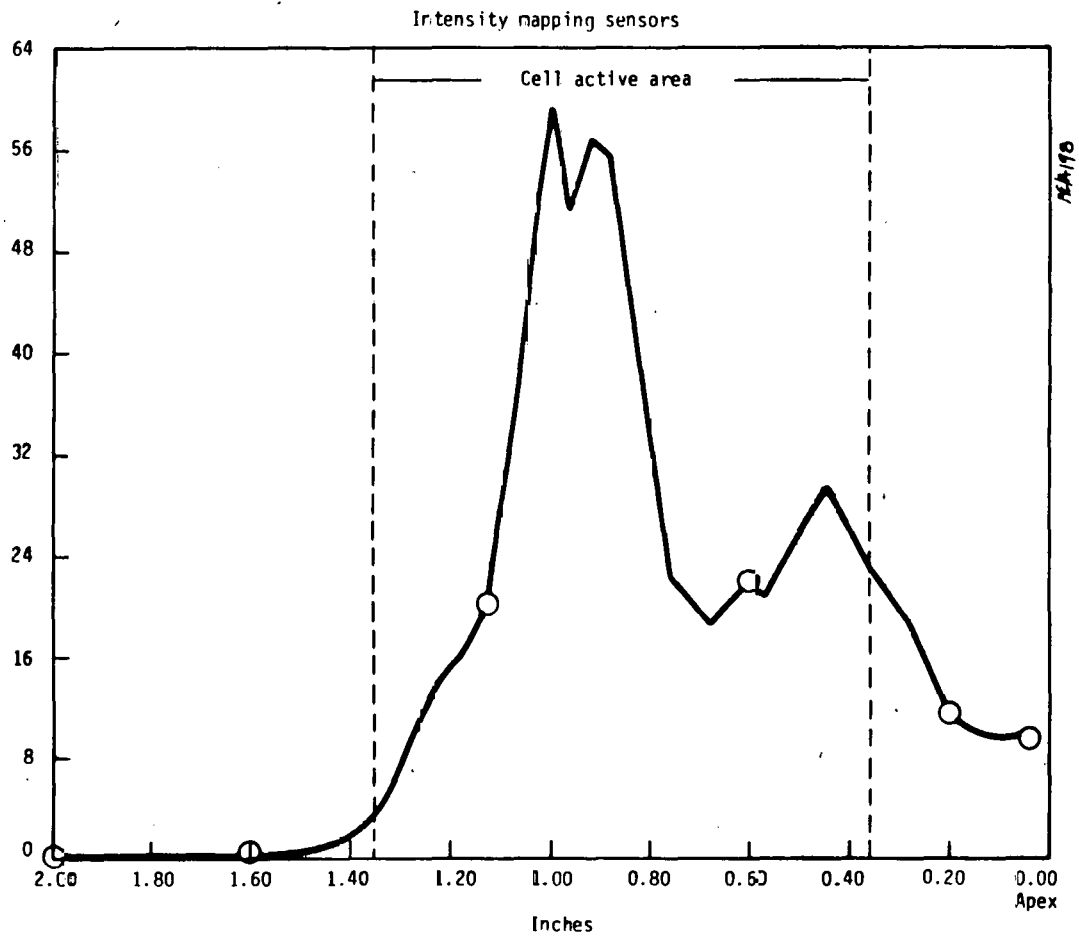
- Thermal cycling -- differential expansion and upper temperature limits of the design
- Moisture protection of the cells and wiring
- Ultraviolet degradation of components
- Electrical isolation

Field maintenance requires that broken cells or wiring components be easily replaced. The major design hurdle in this task was maintaining moisture and electrical isolation and effective cell cooling with replaceable modules.

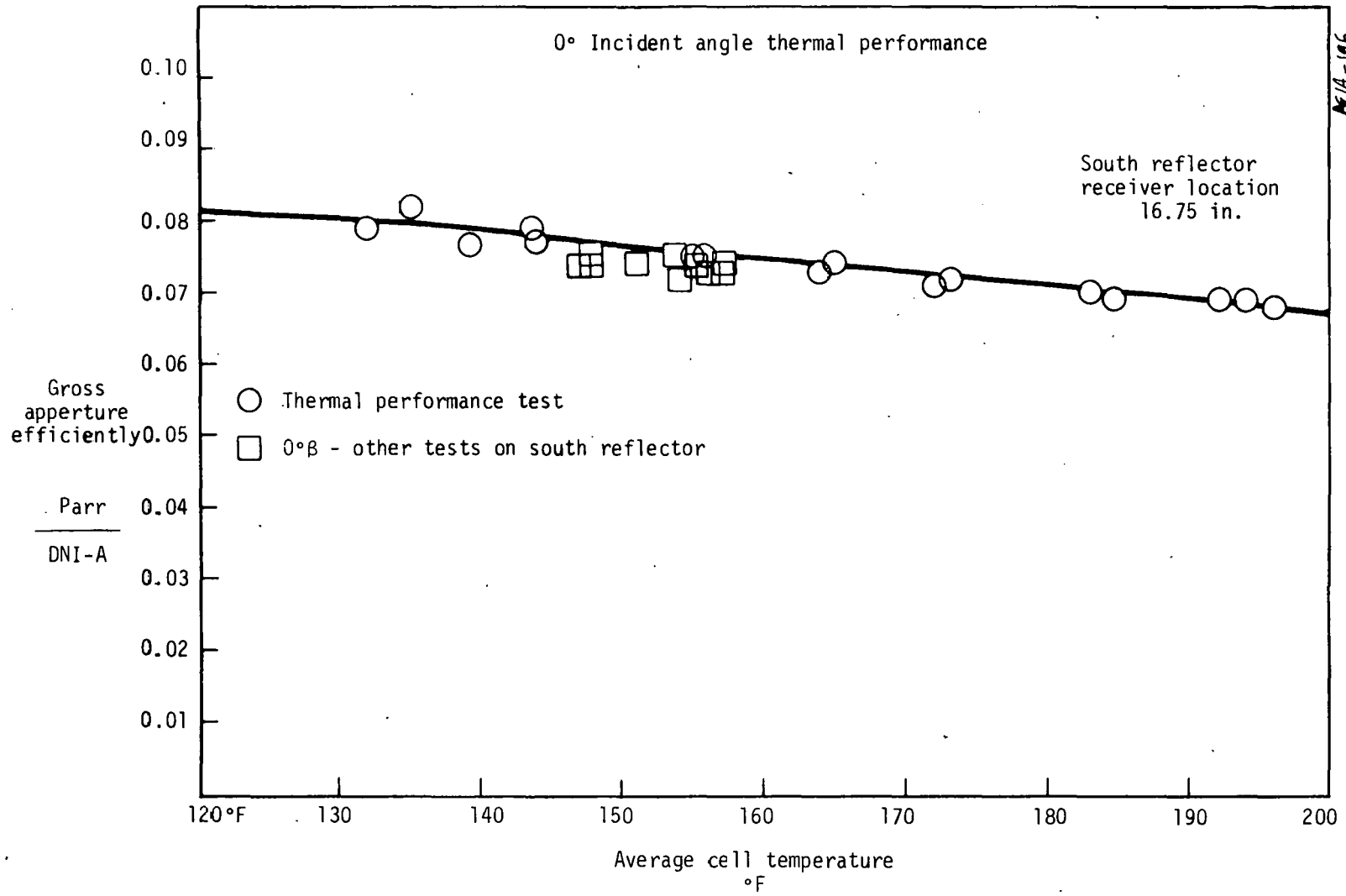
The three full length (10 ft) receiver sections were tested for performance evaluation and for extended exposure to concentrated light.

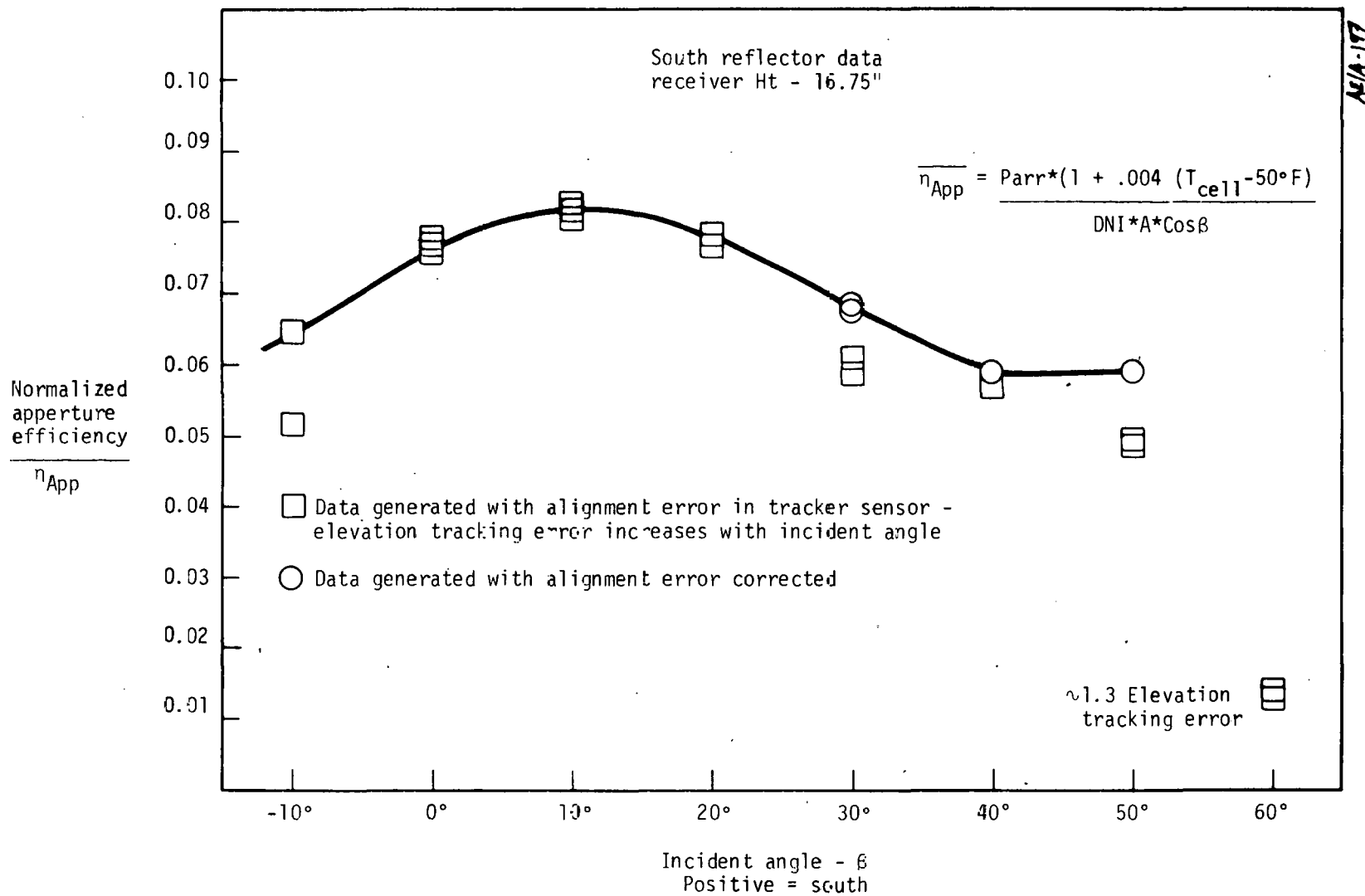
The receivers were also tested for environmental stability by Sandia labs. Sample sections were exposed to temperature cycling and to freeze-thaw cycling without significant performance reduction. All samples withstand application of 1750 VDC with no more than 50 μ A leakage current.

Acurex's concentrating photovoltaic array has achieved aperture efficiencies in testing of 10.7 percent at $\beta = 10^\circ$, $T_{cell} = 50^\circ\text{C}$, and $H_i = 800 \text{ w/m}^2$, with average efficiencies of 10.2 percent. The cell-to-coolant differential temperature is 24°C at $H_i = 1000 \text{ w/m}^2$ and the design flowrate. This provides a thermal efficiency of 52 percent at the field design outlet temperatures of 190°F (88°C).

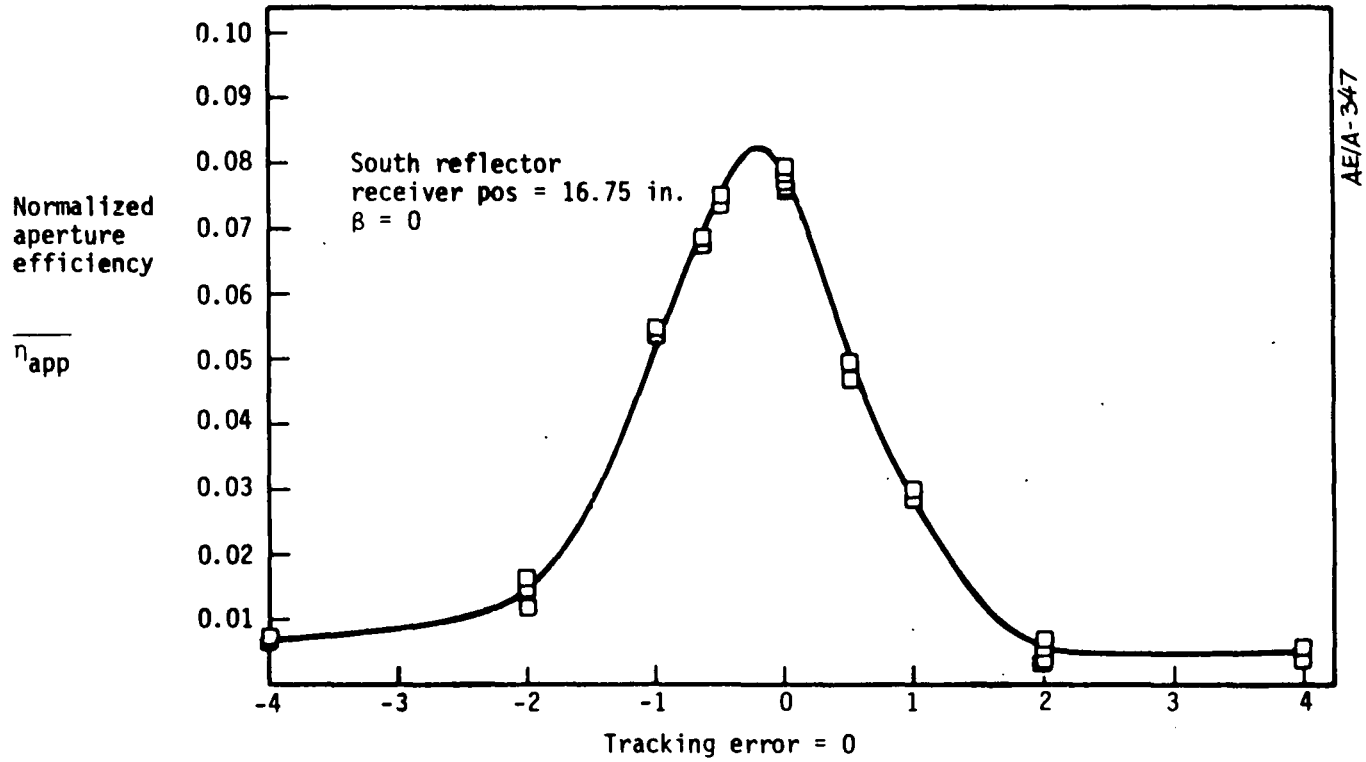


Two-Dimensional Flux Map

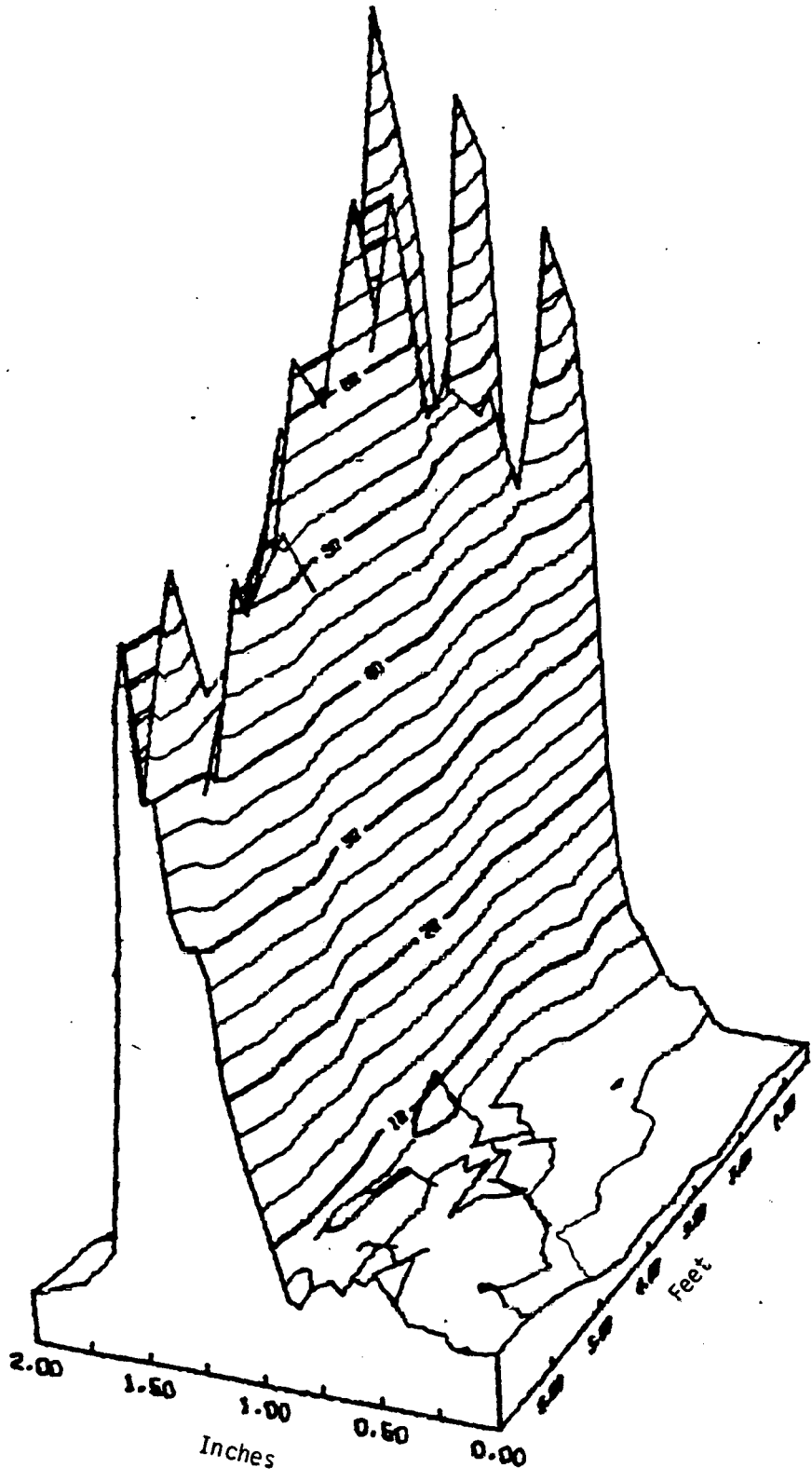




Receiver Efficiency Versus Incident Angle (Declination)



Receiver Efficiency Versus Pointing Error



Three-Dimensional Flux Map

MOTOROLA/APS PHOENIX AIRPORT ARRAY

by

C. Zittle
Motorola Inc.
Scottsdale, AZ

ABSTRACT

In February of 1980 Arizona Public Service and Motorola Inc. were awarded a contract by the Department of Energy to design, build and test a photovoltaic concentrator system with a peak power output of 225 kW. The system includes power conditioning for converting the photovoltaic DC to AC for introduction into the utility grid. The system is being constructed on a 7 acre site at the Phoenix Sky Harbor International Airport in Phoenix, AZ and will supply power to a portion of a recently completed terminal building.

The basic concentrating module utilizes a 24 inch square acrylic fresnel lens focusing energy on a 3 inch diameter silicon solar cell. The cell is mounted on a disc of alumina for electrical isolation while maintaining low thermal resistance. Each cell has a peak output of 42 watts at 1 kW/M^2 insolation and 28°C ambient temperature.

One module consists of two lens/cell mount combinations packaged in a fiberglass housing. A funnel shaped reflective cusp is mounted over the solar cell to improve the off-axis performance of the module. The cell mount is passively air cooled using a unique closed loop boiling freon cooling panel.

One hundred and fifty-six modules are mounted on a large two-axis sun tracking array. Each array has a peak output of 13 kW of DC power.

The module recently successfully completed a series of environmental tests at Motorola and module hardware was submitted to Sandia Laboratories for testing late in September.

One completed operating array will be constructed at Motorola's plant site. All material for the array is on order and the array is planned to be completely assembled ready for DC power testing by mid-January, 1981.

MOTOROLA CONCENTRATOR ARRAY

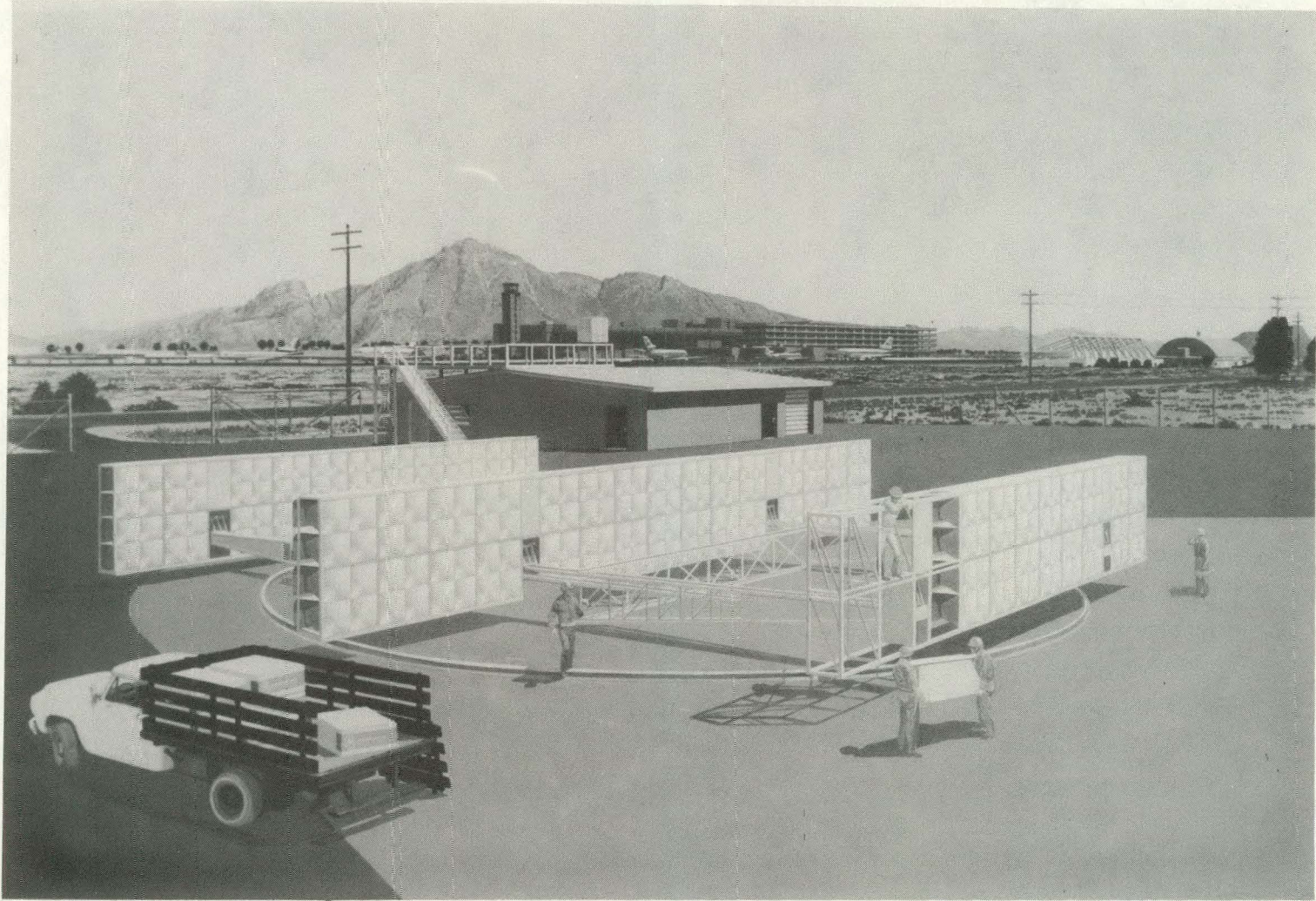
- SUPPORTS 156 POINT FOCUS FRESNEL LENS MODULES (TWO 3 INCH DIAMETER SILICON SOLAR CELLS PER MODULE)
- PEAK POWER OUTPUT - 13 KW
- TWO AXIS TRACKING
- SUPPORT RAIL DIAMETER - 51.5 FT
- THREE SUBARRAYS, EACH 64 FT LONG X 10 FT HIGH

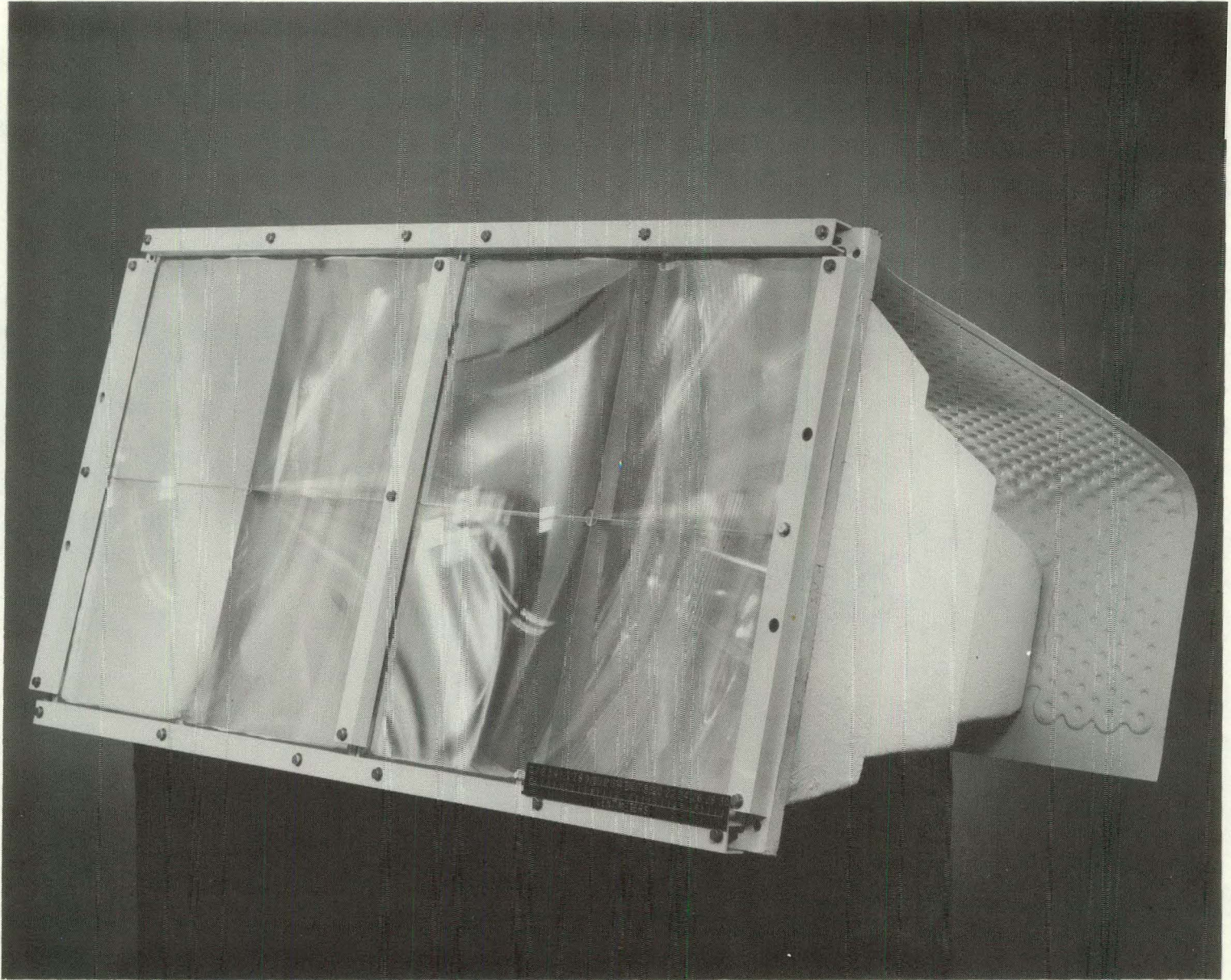
MODULE SPECIFICATIONS

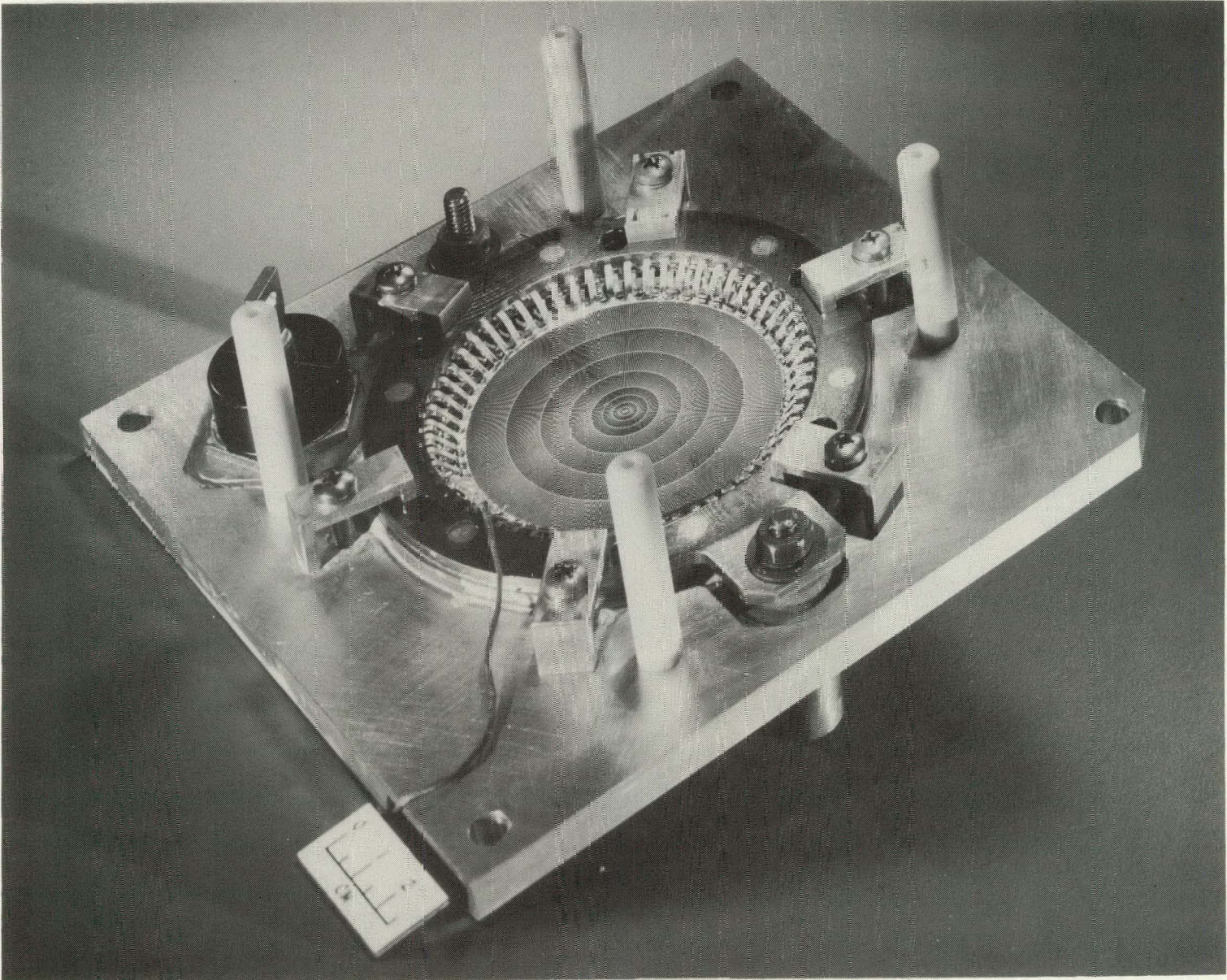
- POWER (STANDARD CONDITIONS) 83.4 WDC
- CONCENTRATION RATIO 79X
- ΔT , CELL TO AMBIENT 30° C
- SIZE 54 X 27 X 31 IN.
- WEIGHT 67 LB
- ENVIRONMENT
 - MODULE -6° C TO 55° C,
RH > 85%
 - CELL MOUNT -6° C TO 120° C

MOTOROLA CONCENTRATOR ARRAY STATUS

- CONCENTRATOR MODULE SUCCESSFULLY COMPLETED ENVIRONMENTAL TESTS AT MOTOROLA
- CONCENTRATOR MODULE HARDWARE SUBMITTED TO SANDIA LABORATORIES FOR TESTING - TEST PROGRAM STARTED SEPT 24, 1980
- CRITICAL PROJECT REVIEW PLANNED FOR MID NOV, 1980
- ALL MATERIAL ON ORDER FOR ONE COMPLETE ARRAY
- ARRAY FOUNDATION CONSTRUCTION STARTED OCT 6, 1980
- ARRAY SCHEDULED TO BE COMPLETED AND READY FOR DC POWER TESTS BY MID JAN, 1981







DESIGN AND PERFORMANCE OF THE E-SYSTEMS/DFW AIRPORT LINEAR FRESNEL
LENS PHOTOVOLTAIC CONCENTRATOR ARRAY

Mark J. O'Neill
E-Systems, Inc.
Energy Technology Center
P. O. Box 226118
Dallas, Texas 75266

For the past several years, E-Systems has been actively developing a novel, high-efficiency, short focal length, linear Fresnel lens solar concentrator for both photothermal and photovoltaic applications. This concentrator (U.S. Patent No. 4,069,812) offers both maximal optical efficiency and large tolerance for manufacturing errors and aberrations. In 1978-79, as part of the DOE-funded PRDA-35 program, E-Systems designed a first-generation combined photovoltaic/photothermal array using the new concentrator. In 1979-80, under a continuation of the PRDA-35 program, E-Systems built, tested and delivered to Sandia two collector modules for a full battery of qualification tests. These modules have now passed the qualification test program, and have demonstrated excellent electrical and thermal performance levels. Pending final DOE approval, E-Systems plans to manufacture, install and operate a 25 kw (electric), 140 kw (thermal), application experiment at the Dallas-Fort Worth (DFW) Airport, using 245 square meters of the linear Fresnel lens concentrators.

The DFW photovoltaic system (Fig. 1) will utilize eleven modular arrays of ten collector modules each. Each array (Fig. 2) consists of ten 91 cm x 244 cm (3 ft. x 8 ft.) aperture area concentrator modules, mounted in a common 1.5-axis tracking frame. The basic array design is adapted from a previous purely thermal array design (Fig. 3), which has been tested for the past two years at E-Systems in Dallas. The collector module (Fig. 4) consists primarily of the lens, receiver, and sheet metal housing. The receiver (Fig. 5) utilizes series-connected silicon cells, sized for a 25X geometrical concentration ratio, attached to a water-cooled copper fin-tube heat sink. The photovoltaic cell assembly (Fig. 6) was developed by ASEC. During in-house testing of the two qualification modules, it was determined that the lens flux profile (Fig. 7) was excessive for the cells being used; electrical resistance losses caused the cell-string fill factor to be low. Therefore the lenses were reconfigured by effectively splitting the lens in half and defocussing the halves to provide a double-peak flux profile (Fig. 7). This defocussing is achieved by leaving a 1.3 cm (0.5 in.) centerline gap between 3M lensfilm strips during their lamination to the plexiglass substrate sheet which forms the outer surface of the lens.

At Sandia, the two qualification modules were subjected to a variety of cycling tests and accelerated exposure tests to verify the reliability and durability of the modules in an outdoor environment (Fig. 8). Additionally the electrical efficiency (Fig. 9) of these collector modules was measured by both E-Systems and Sandia under a variety of operating conditions, with extremely close correlation of results. The total efficiency (electrical plus thermal) of the modules was also measured at E-Systems (Fig. 10). These modules have now passed all of the qualification testing at Sandia, and have demonstrated performance levels among the highest yet measured for silicon-based photovoltaic concentrators.

25 KW DALLAS/FORT WORTH AIRPORT PHOTOVOLTAIC SYSTEM

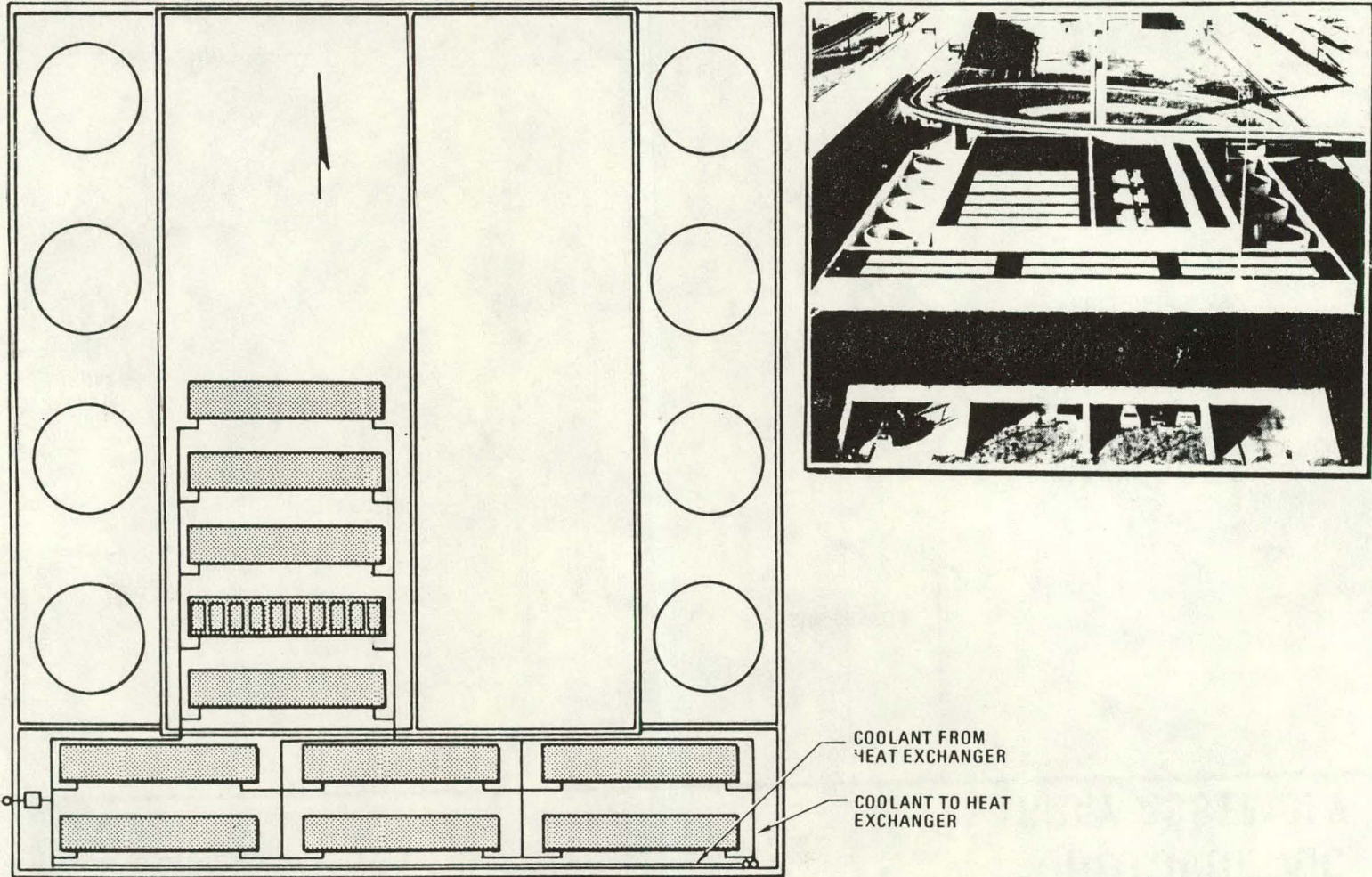


Fig. 1

PHOTOVOLTAIC ARRAY ASSEMBLY

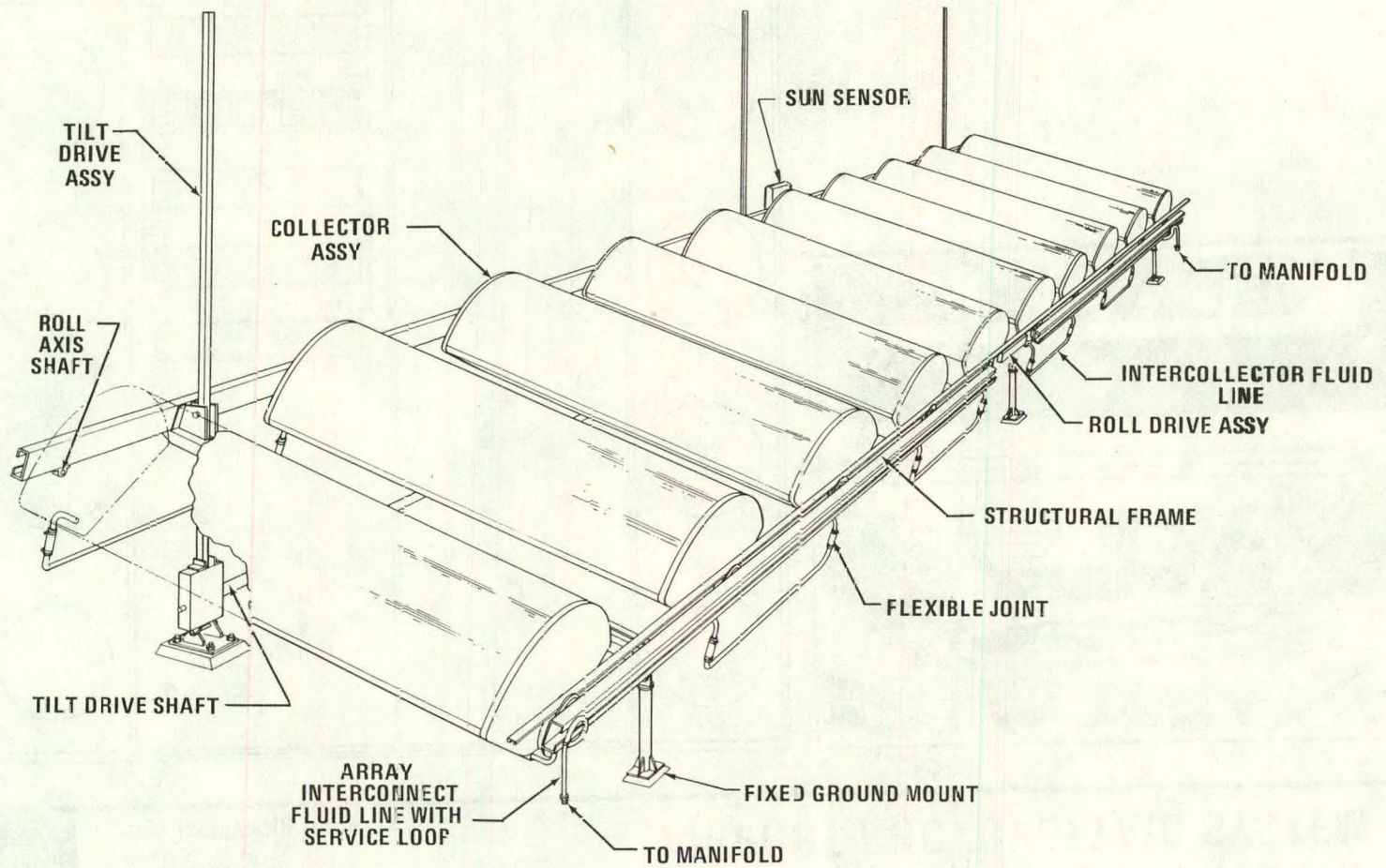


Fig. 2



Fig. 3



PHOTOVOLTAIC COLLECTOR CROSS SECTION

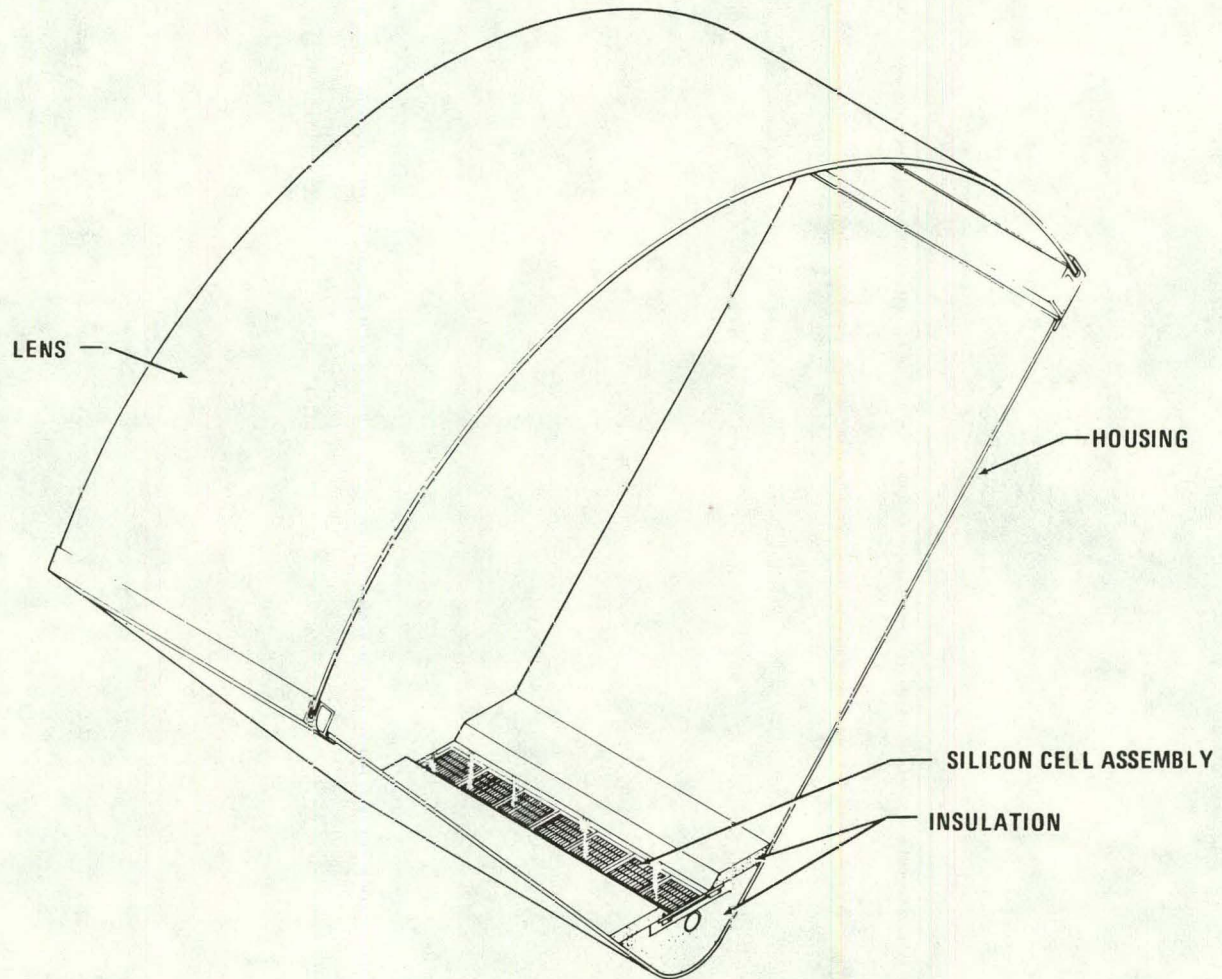


Fig. 4

PHOTOVOLTAIC RECEIVER SCHEMATIC

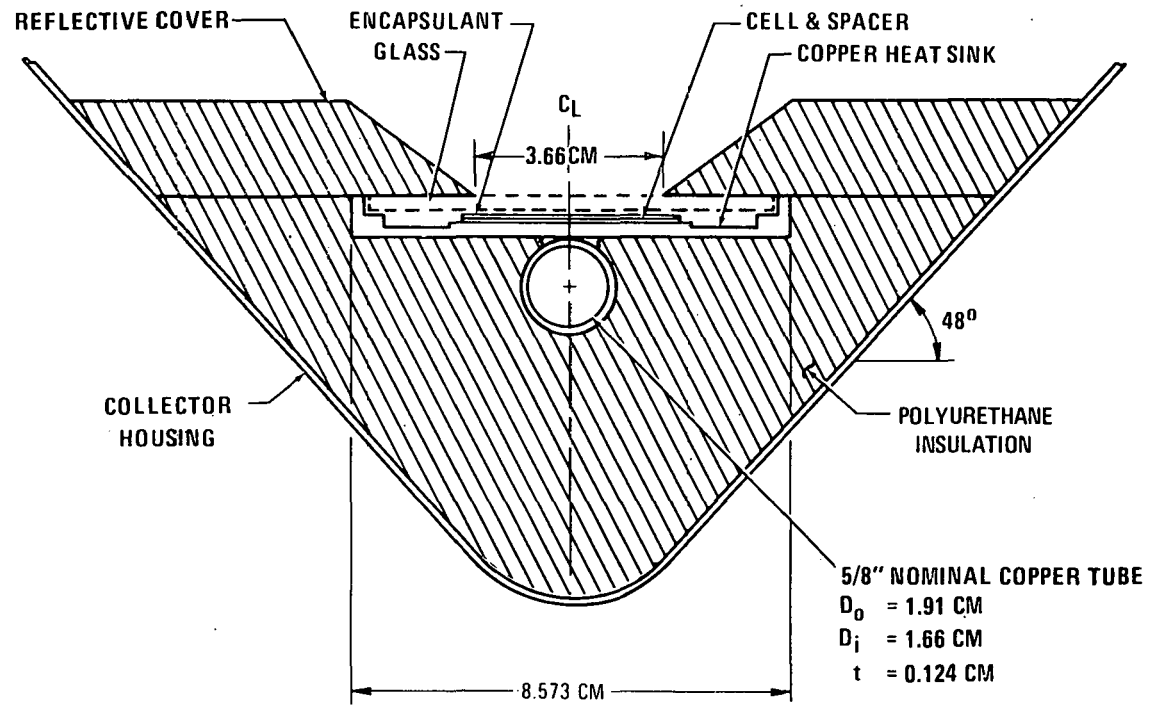


Fig. 5

PHOTOVOLTAIC CELL ASSEMBLY

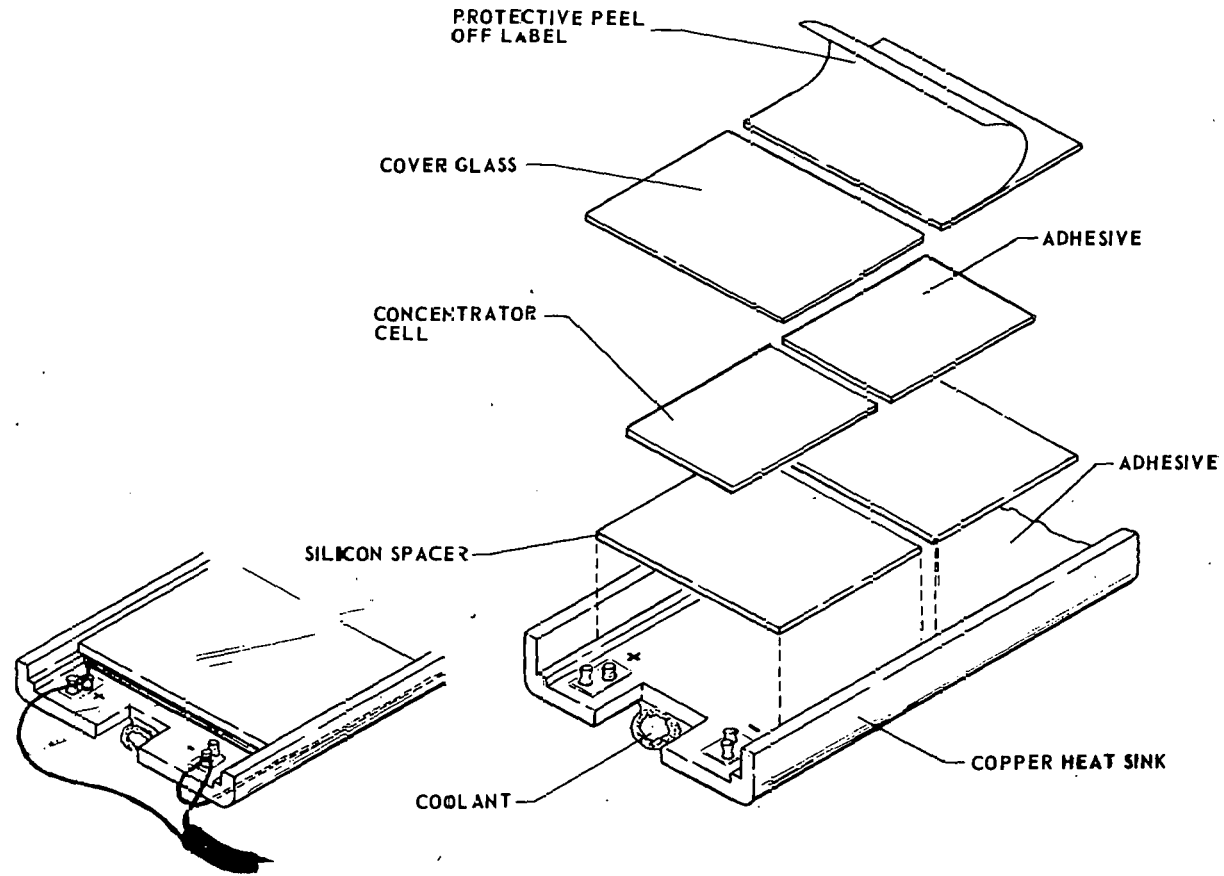


Fig. 6

MEASURED LENS FOCAL PLANE RADIANT FLUX PROFILES

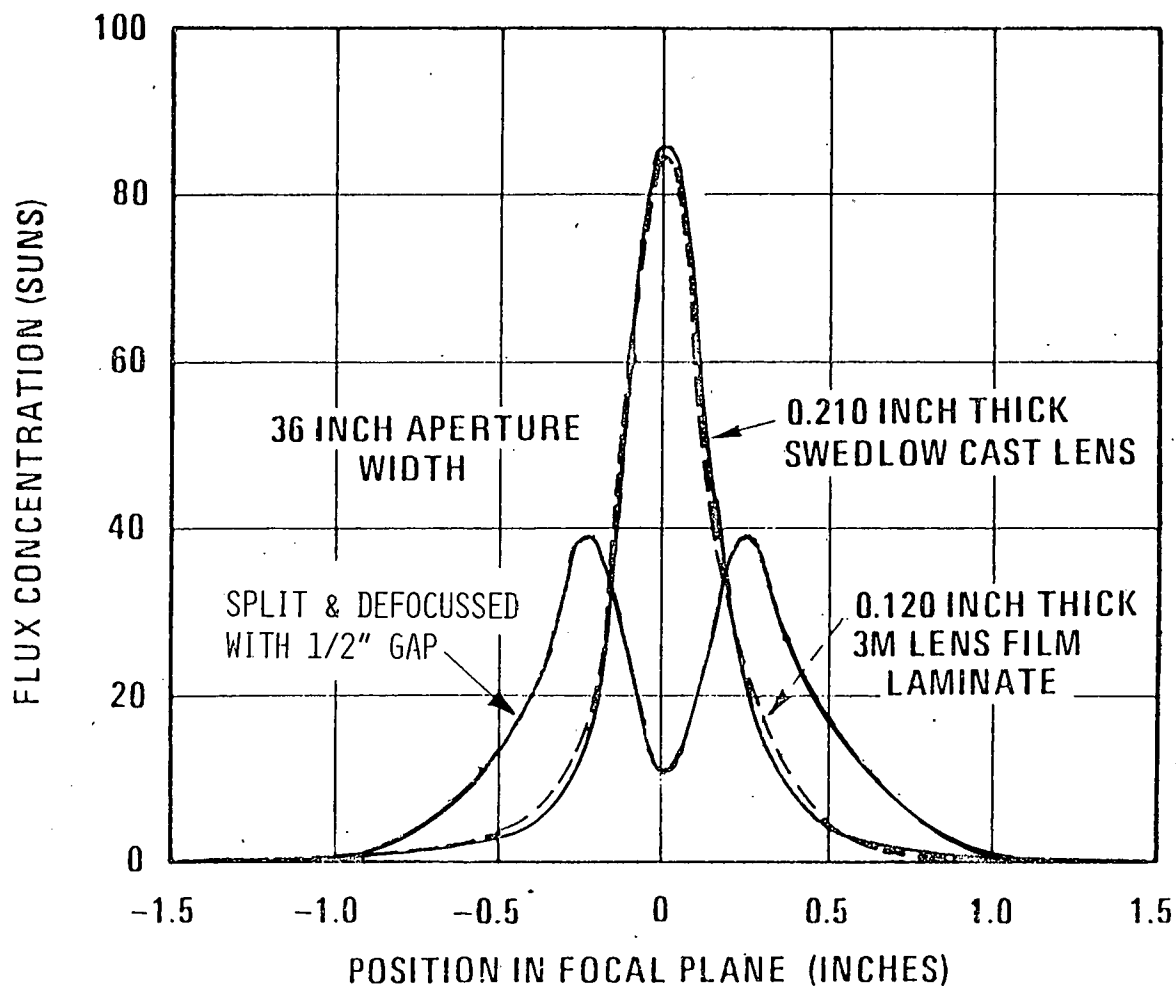


Fig. 7

FULL COLLECTOR MODULE TESTS

- o CONTINUOUS PERFORMANCE MEASUREMENTS - MAY TO SEPT. 1980
- o OFF-AXIS BEAM DESTRUCTION
- o PARTIAL SHADING
- o THERMAL SHOCK
- o FREEZE/THAW CYCLING (4 WEEKS, -6°C TO 55°C , 100⁰ R.H.)
- o HAIL IMPACT - 1 INCH BALLS AT TERMINAL VELOCITY

SMALL RECEIVER SAMPLE TESTS

- o TEMPERATURE CYCLING (4 WEEKS, -6°C TO 120°C)
- o VOLTAGE ISOLATION (1500 VDC)

SMALL LENS SAMPLE TESTS

- o SALT SPRAY
- o TEMPERATURE CYCLING (4 WEEKS, -6° TO 50°C)

RESULTS

- o PERFORMANCE OF MODULES, RECEIVER SAMPLES, AND LENS SAMPLES WAS NEGLIGIBLY AFFECTED BY THESE EXPOSURES

MEASURED ELECTRICAL EFFICIENCY OF PRDA-35
 QUALIFICATION MODULE

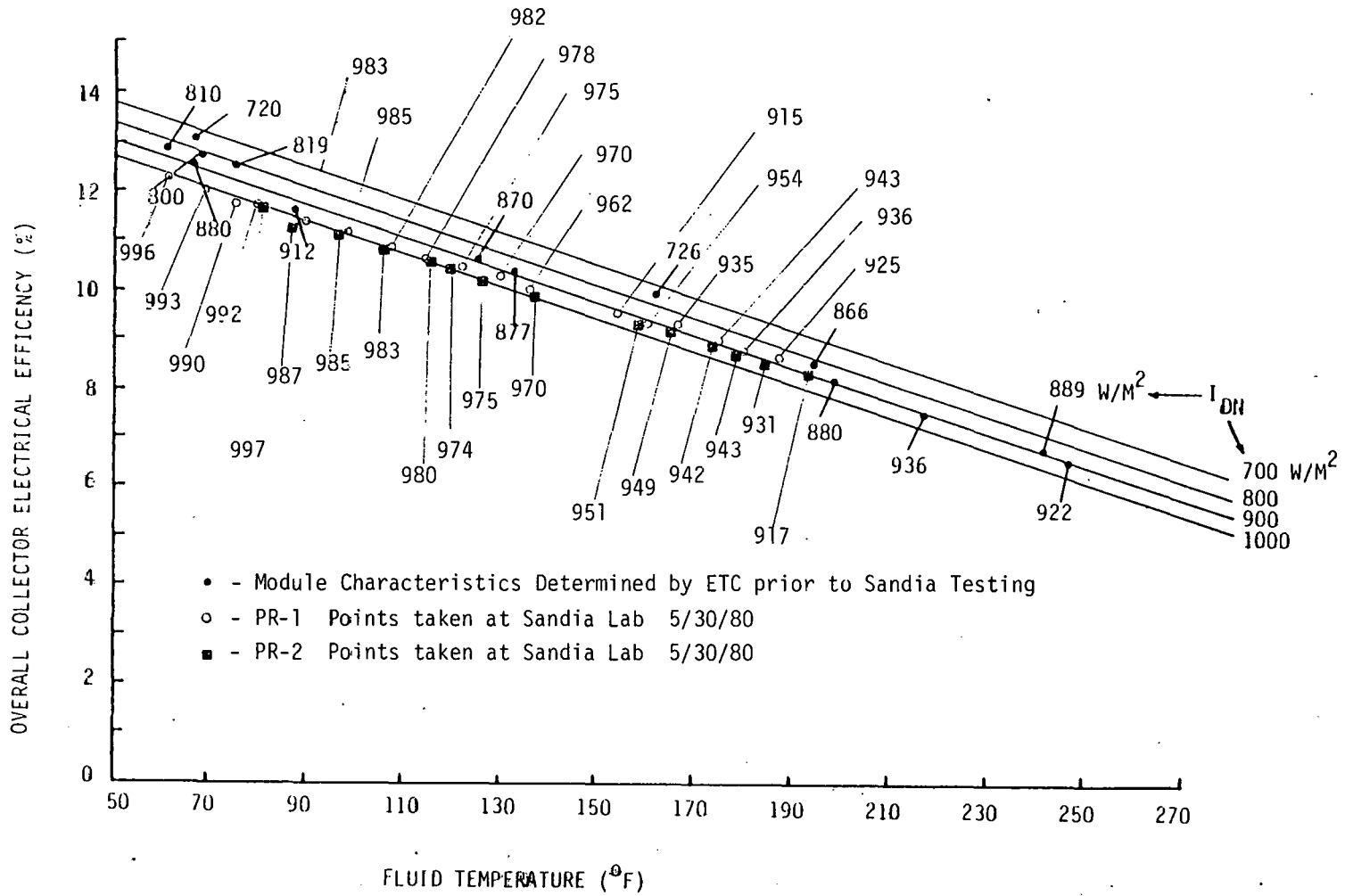
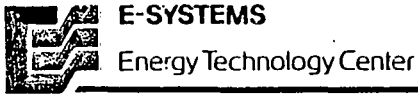


Fig. 9

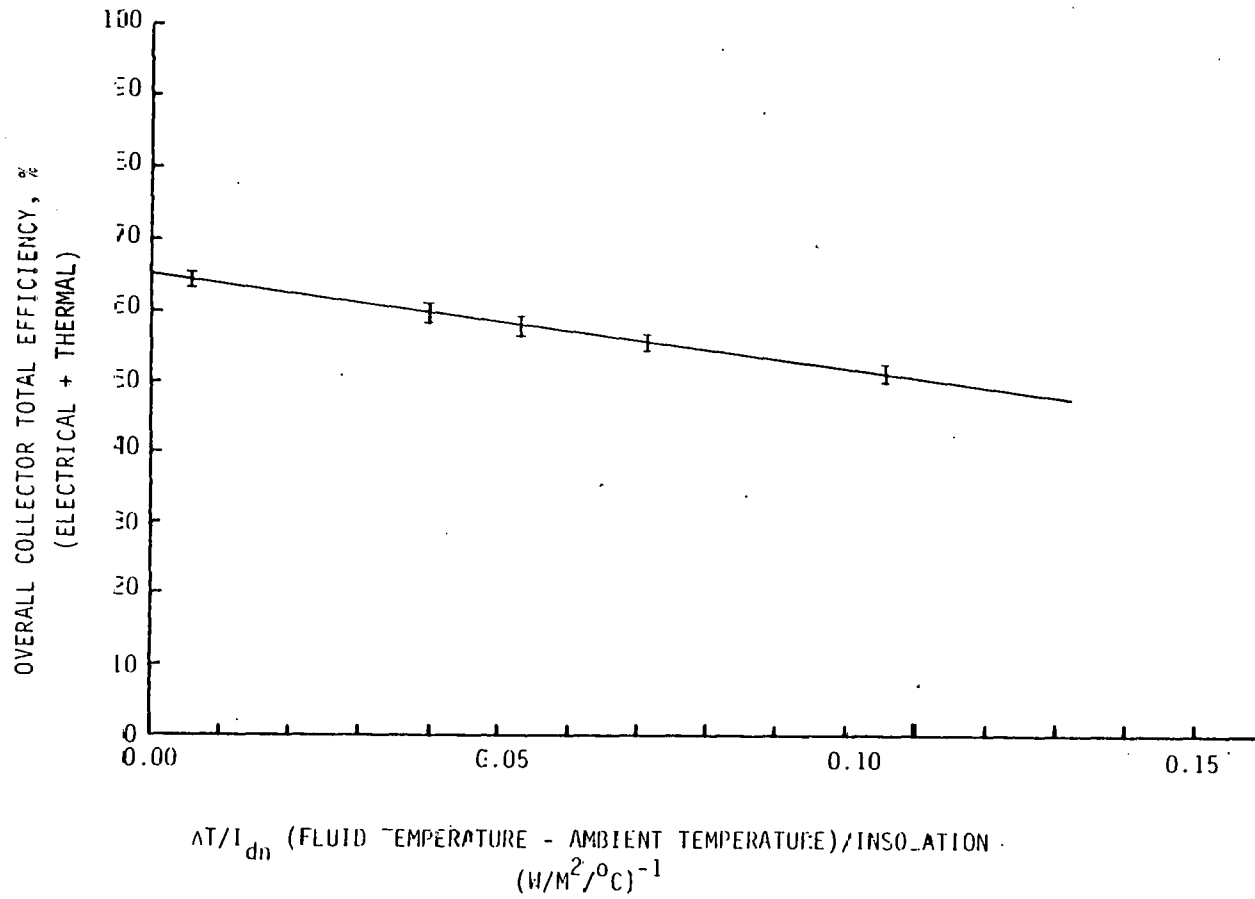


Fig. 10

GE/SEA WORLD SOLAR ARRAY

BY

GENERAL ELECTRIC COMPANY

ADVANCED ENERGY PROGRAMS DEPARTMENT

P.O. BOX 8661

PHILADELPHIA, PA 19101

CONTRACT NO.: DE-AC04-80ET 20627
PRINCIPAL INVESTIGATOR: A. KIRPICH
(215) 962-5837
CONTRACT VALUE: 3,386,250
CONTRACT DURATION: JUNE 1980 THRU NOVEMBER 1981

PROJECT DESCRIPTION: The GE/Sea World PV Concentrator Application Experiment uses a solar array consisting of three azimuth-tracking turntables onto each of which are mounted 24 elevation tracking parabolic trough collectors. The collectors are 7 x 30 feet in size and are designed for a geometric concentration ratio of 34:1. Solar cells are Vee-mounted along a liquid cooled receiver. Operating temperatures are in the range of 200°F in order to utilize the thermal byproduct for operating an absorption chiller unit.

CURRENT STATUS: On the basis of exploratory tests conducted during Phase I of the PCAE program on prototype collector and receiver hardware, design modifications have been introduced toward minimizing cell-to-fluid temperature drops and reducing manufacturing costs. Both receiver and collector segment hardware are being fabricated presently for approval testing to be conducted by Sandia.

KEY RESULTS TO DATE: Prototype hardware tested during Phase I indicated an electrical efficiency of 7.5 percent at a fluid temperature of 180F. An improvement to 10 percent electrical efficiency is anticipated as a result of higher basic cell efficiency (16.5% versus 14.5%) and a reduced cell-to-fluid temperature drop. At a fluid temperature of 120F, an electrical efficiency of 11.5 percent is anticipated.

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83.2



**GENERAL
ELECTRIC**

SYSTEM CONCEPT (3 TURNTABLES)

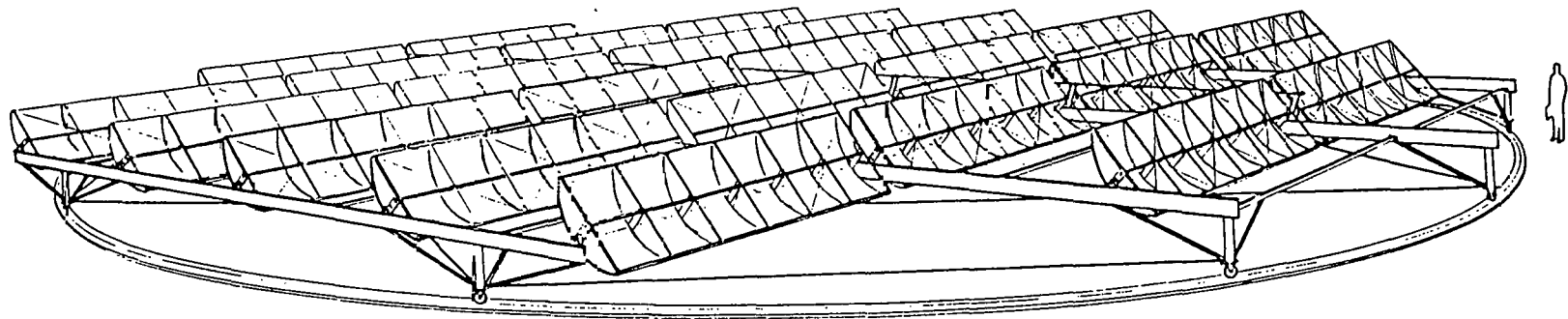


**SEA
WORLD**

PHYSICAL SUMMARY		PERFORMANCE SUMMARY	
SITE AREA, ACRES	2	ARRAY VOLTAGE	360 VDC ± 12%
NUMBER TURNTABLES	3	INVERTER VOLTAGE	277/480 VAC
NUMBER COLLECTORS (2.1 X 9.2 M EACH)	72	PEAK ARRAY OUTPUT, KW	130
NUMBER SOLAR CELLS (3.5 X 6 CM EACH)	20,736	PEAK SYSTEM OUTPUT, KW	
SOLAR CELL AREA (M ²)	37.3	PV SYSTEM	92
APERTURE AREA (M ²)	1289	CHILLER EQUIV.	69
TURNTABLE SWEEP DIAMETER (M)	46		161
MAX HEIGHT ABOVE GROUND (M)	2.5	GROSS ANNUAL ELECTRICITY (MWH)	153
		ANNUAL PARASITICS (MWH)	35
		ANNUAL THERMAL OUTPUT (MBTU)	1.89 X 10 ³
		ANNUAL COOLING OUTPUT (TON-HRS)	1.19 X 10 ⁵
		ANNUAL EQUIV. ELECTRICITY TO PRODUCE COOLING (MWH)	89
		ANNUAL DIRECT NORMAL INSOLATION (MWH)	1773
		SYSTEM EFFICIENCY, $\frac{153 - 35 + 89}{1773} =$	11.7%



TURNTABLE CHARACTERISTICS



83B

- PEAK PV RATING: 37.3 KW
- 24 - 7 x 30-FT. PARABOLIC COLLECTORS
- WATER-COOLED SEGMENTED SOLAR CELL RECEIVER; 3.5 x 4 CM SOLAR CELLS IN 216 SERIES x 2 PARALLEL MATRIX IN EACH COLLECTOR
- I-BEAM & BOX-BEAM TURNTABLE FRAMEWORK WITH DIAGONAL ROD BRACING
- $\pm 1^\circ$ AZIMUTH TRACKING WITH 2 MOTORIZED WHEELS ON TURNTABLE PERIPHERY
- $\pm 0.1^\circ$ ELEVATION TRACKING WITH A ALL COLLECTORS GANGED TO SINGLE DRIVE
- COLLECTOR WEIGHT: 18,000 LBS
OTHER WEIGHT: 16,000 LBS
- MECHANICAL INTERFACES:
 - PINTLE BEARING
137.2-FT & 83.5-FT DIAMETER
 - CONCRETE TRACKS
 - 3-INCH WATER SUPPLY & RETURN THROUGH SPIRAL HOSES AT PINTLE
- ELECTRICAL INTERFACES THROUGH SPIRAL CABLING AT PINTLE:
 - 360 VDC PV OUTPUT
 - 120 VAC SERVICE POWER
 - 5-WIRE SIGNAL LINK

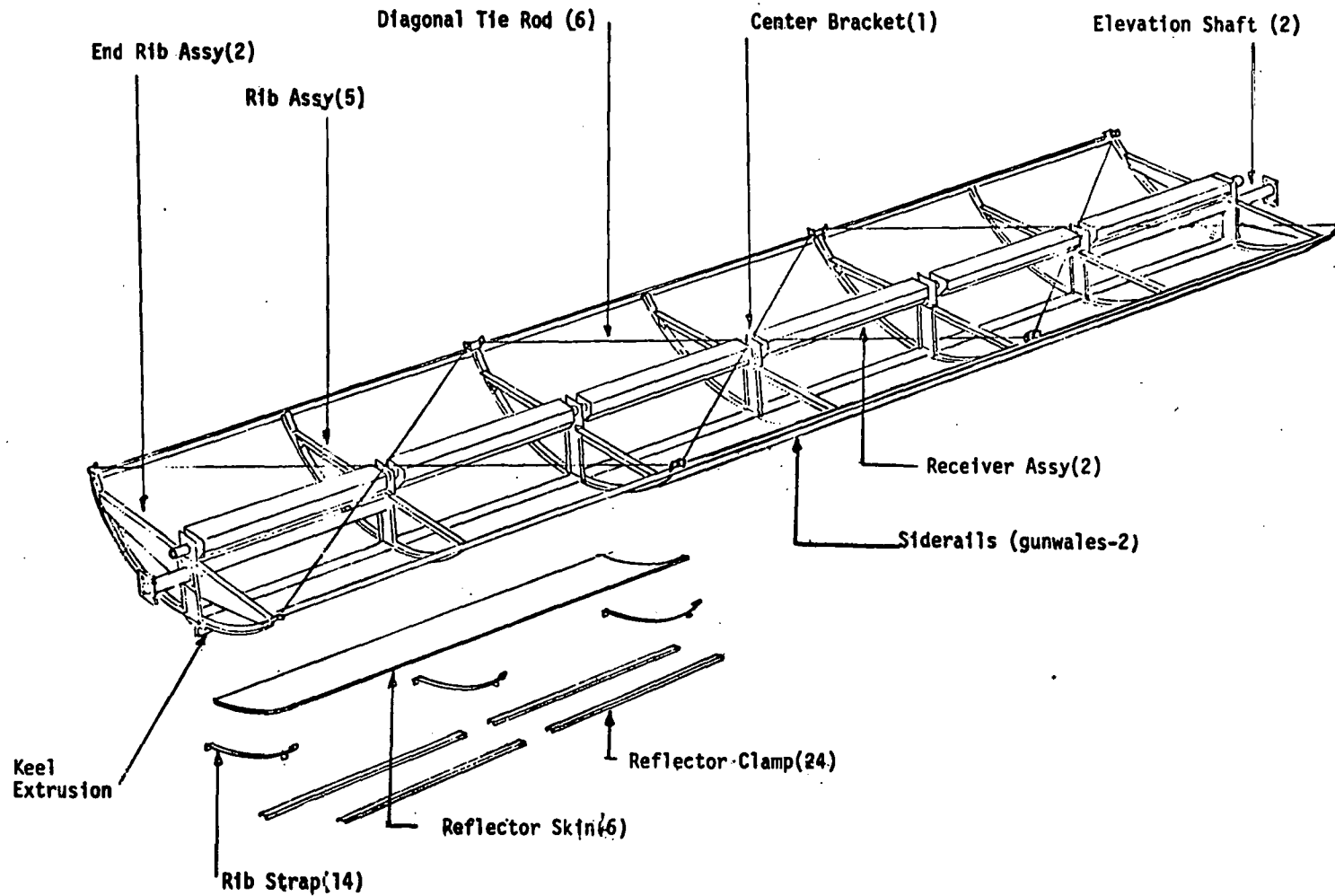


**GENERAL
ELECTRIC**

COLLECTOR ASSEMBLY



**SEA
WORLD**



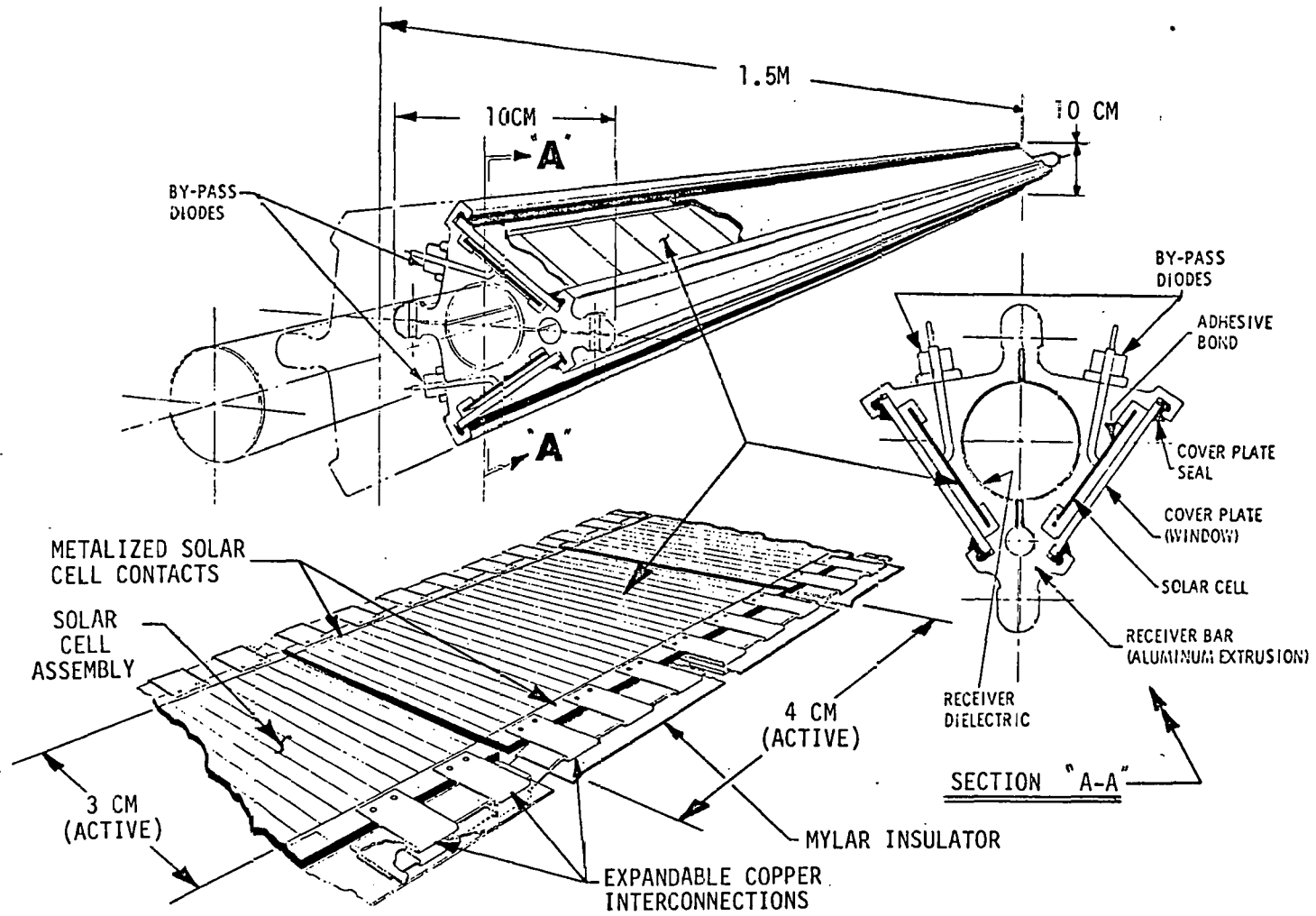
83C



PHASE I DESIGN
SOLAR CELL RECEIVER



83D



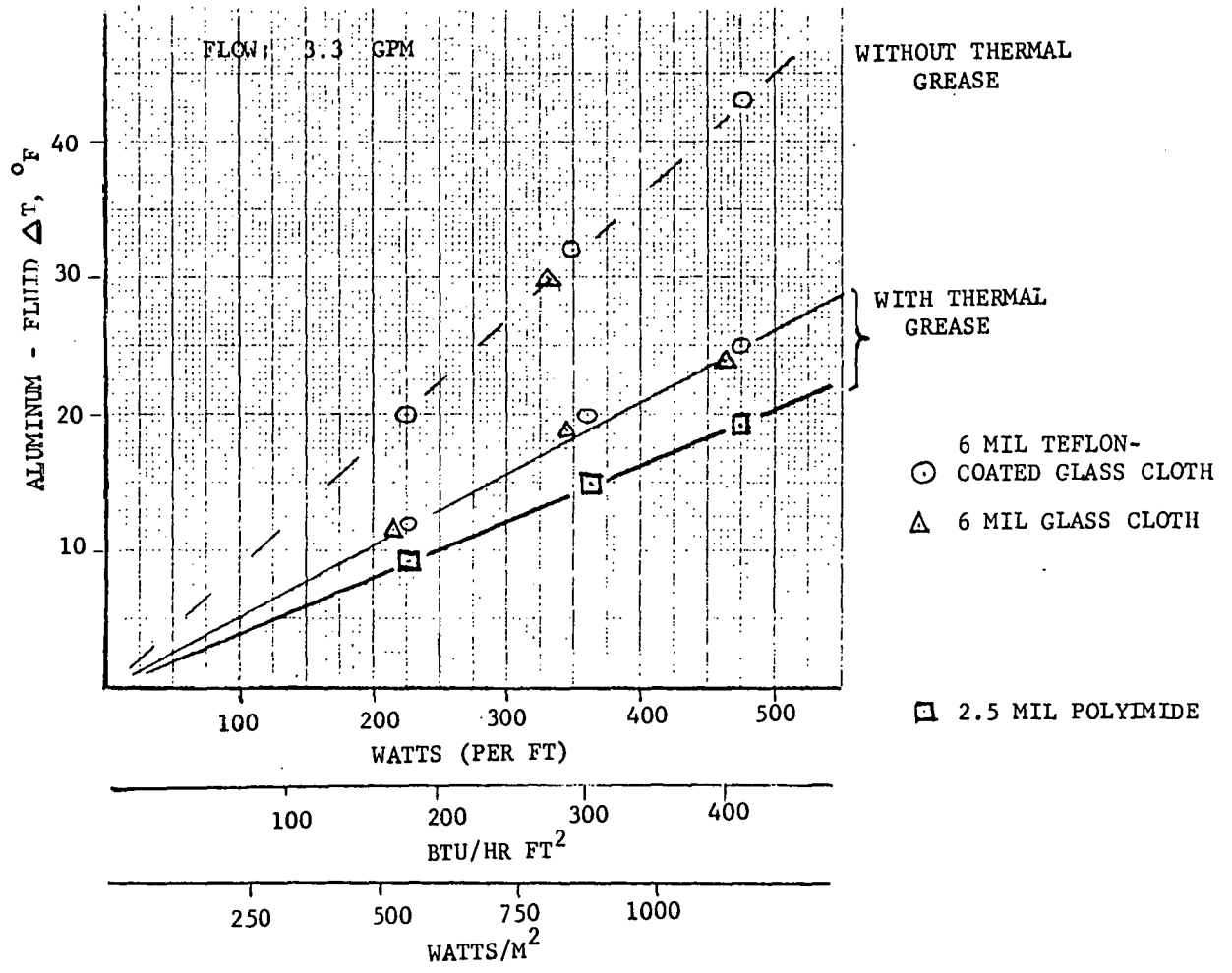
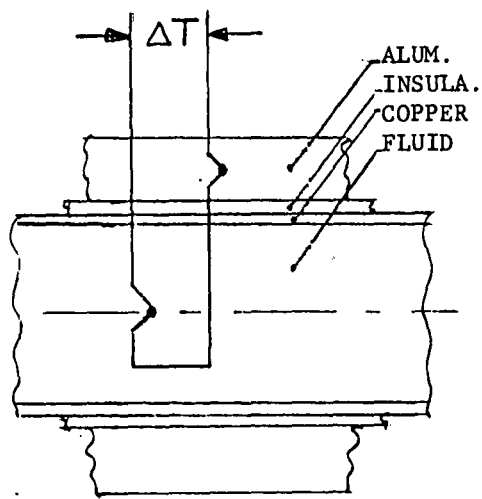


PHASE I RESULTS

SOLAR CELL RECEIVER TEMPERATURE DROP TESTS



83E





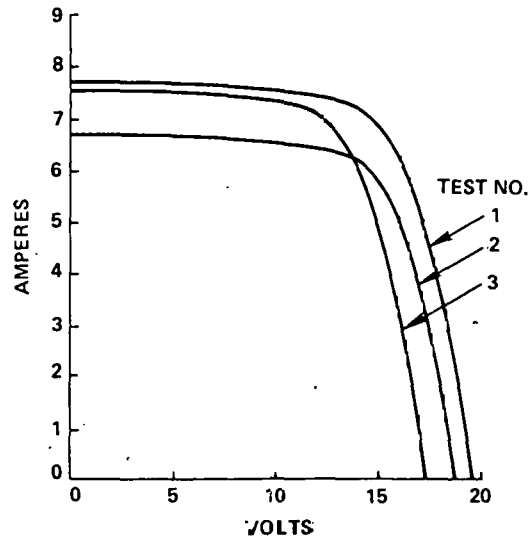
PHASE I RESULTS
COLLECTOR SEGMENT TESTS



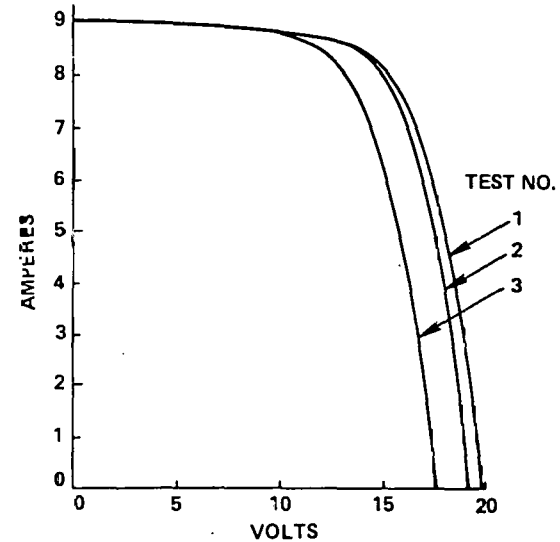
- FLOW: 3.1 GPM
- APERTURE AREA (PER RECEIVER HALF): 1.491 m²

TEST NO.	TIME	INSOLATION kW/m ²	PV OUTPUT WATTS	PV EFFICIENCY	PREDICTED PV EFFICIENCY*	TEMPERATURE, °C					THERMAL EFFICIENCY	
						AMBIENT	FLUID IN	FLUID OUT	ALUM. SUBSTRATE	CELL		WIND SPEED, KPH
1	1/3/79 AM	.846	104	8.24%	8.87%	-10	46.9	47.4	63	89	35	16.2%
2	1/3/79 PM	.738	89	8.03%	8.54%	-9	64.3	65.2	72	102	18	33%
3	1/4/79 AM	.825	88	7.13%	7.64%	-4	80.9	82.0	91	125	4	37%

*BASED ON TEST INSOLATION AND CELL TEMPERATURE INPUTS TO FIGURE 2-10.



(a) TEST DATA (TRANSPOSED FROM X-Y PLOTTER)



(b) TEST DATA ADJUSTED TO 1 kW/m² INSOLATION



SOLAR CELL RECEIVER
STATUS AT CONCLUSION OF PHASE I



- PERFORMANCE: 80% OF PREDICTED OUTPUT
- EXCESSIVE CELL-TO-SUBSTRATE TEMPERATURE DROP
- MANUFACTURING PROCESSES NOT FULLY DEFINED

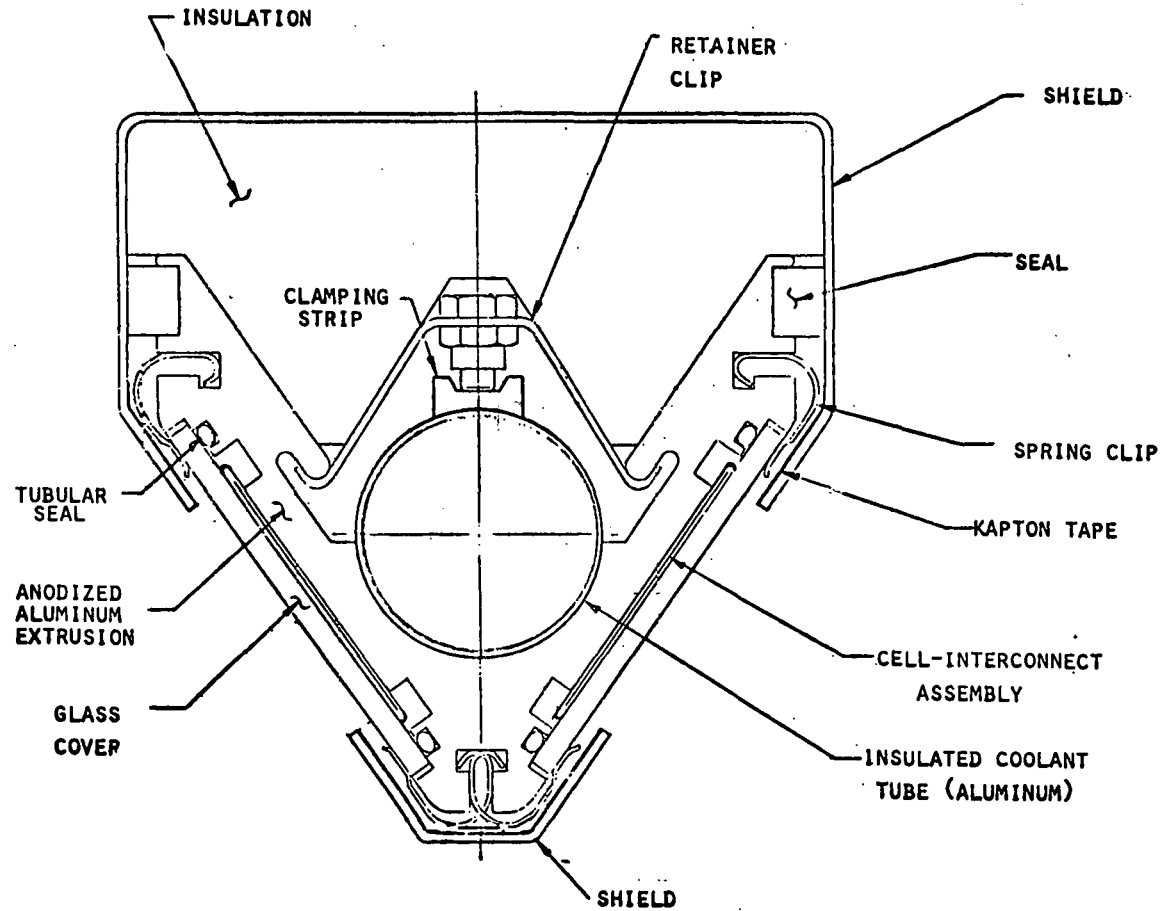


SOLAR CELL RECEIVER
PHASE II DESIGN UPDATE

- SINGLE EXTRUSION (VS. SPLIT DESIGN)
- 3.5 x 6 CM CELLS (VS. 3.5 x 4 CM)
- MECHANICAL CELL-TO-SUBSTRATE CONTACT (VS. ADHESIVE BOND)
- UNIFIED EXPANDABLE INTERCONNECT (VS. 2-PIECE APPROACH)



PHASE II DESIGN
SOLAR CELL RECEIVER



83T

SECOND GENERATION PHOTOVOLTAIC ARRAY

BY

MARTIN MARIETTA CORPORATION

BOX 179, DENVER, COLORADO 80201

Principal Investigators: Sidney Broadbent (303) 977-0683 and
Richard Stegeman (303) 977-0678

The approach to optimization for the 2nd Generation P.V. module was influenced by 3 primary factors. First, it was to be an evolution from the previous P.V. concept of point focus, Fresnell optics, passive cooled, planar silicon cells etc., which helped to narrow the areas of investigation to one primarily of improving the optics and cell performance to minimize cost per watt based on first generation experience as to what the real cost drivers were.

Secondly, to accommodate the intricate way in which the various system parameters interacted with each other to affect bottom line output, it would be necessary to generate a computer program that could predict the output by involving the total system dynamics. This was done and resulted in the capability to understand the impact of changes in specific design parameters on total performance, including the cost data generated on first generation, to give cost/watt impact. (Refer to Fig. 1 for Flow Diagram)

Then, thirdly, considering the multitude of design parameters, it was necessary to systematically fix various aspects of the design as they revealed their optimum values and thereby zero in on the final design.

The design developed as follows: It was determined that an F number of 1.24 gave maximum use of the target area because it minimized the target excursions due to tracking errors at any combination of lens size or concentration level (Ref. Fig. 2). Fixing F number we then addressed cell size and conclusively showed that we could achieve a minimum cost per watt with a "2 cm" cell ($\frac{1}{4}$ of a 3" mother wafer) over the entire range of lens sizes and concentration levels in contention (Ref. Fig. 3). The next to be defined was the optimum lens size which was narrowed to a range between 8" and 8.25" by the minimum cost per watt (within 3¢/watt) for the range of ambient conditions to be expected annually at Albuquerque (Ref. Fig. 4). It then was specifically defined to be 8.16" by the physical aperture constraints imposed by the tube and drive assembly capabilities (Ref. Fig. 5).

Knowing the optimized primary optical parameters, the last remaining optimization was the simplification of the housing design, heat sink, and tube mounting technique, which are discussed below. Design characteristics tabulated in Fig. 6.

The resulting design shows a reduction in cost/watt for the total system of 37% over the first generation.

Apart from the foregoing module design/cost optimization several gross cost savings can be achieved by simple design changes providing we have sufficient analytical and test background experience to safely incorporate them, for instance: the porosity that our current module spacing involves reduces azimuth torque by a factor of three, thus greatly reducing drive unit size and cost, but it involves a loss of 13% of array area. On the second generation array we plan to use this 13% of array area for energy collection but still maintain array porosity by staggering the modules on the support tube as shown in Figure 7. At the same time we intend to mount the modules directly upon the support tube assembly, dispensing with the continuous heat exchangers and dispensing with up to 1200 lbs. of aluminum per array. Individual heat ex-

changers would be used as shown in Figure 8.

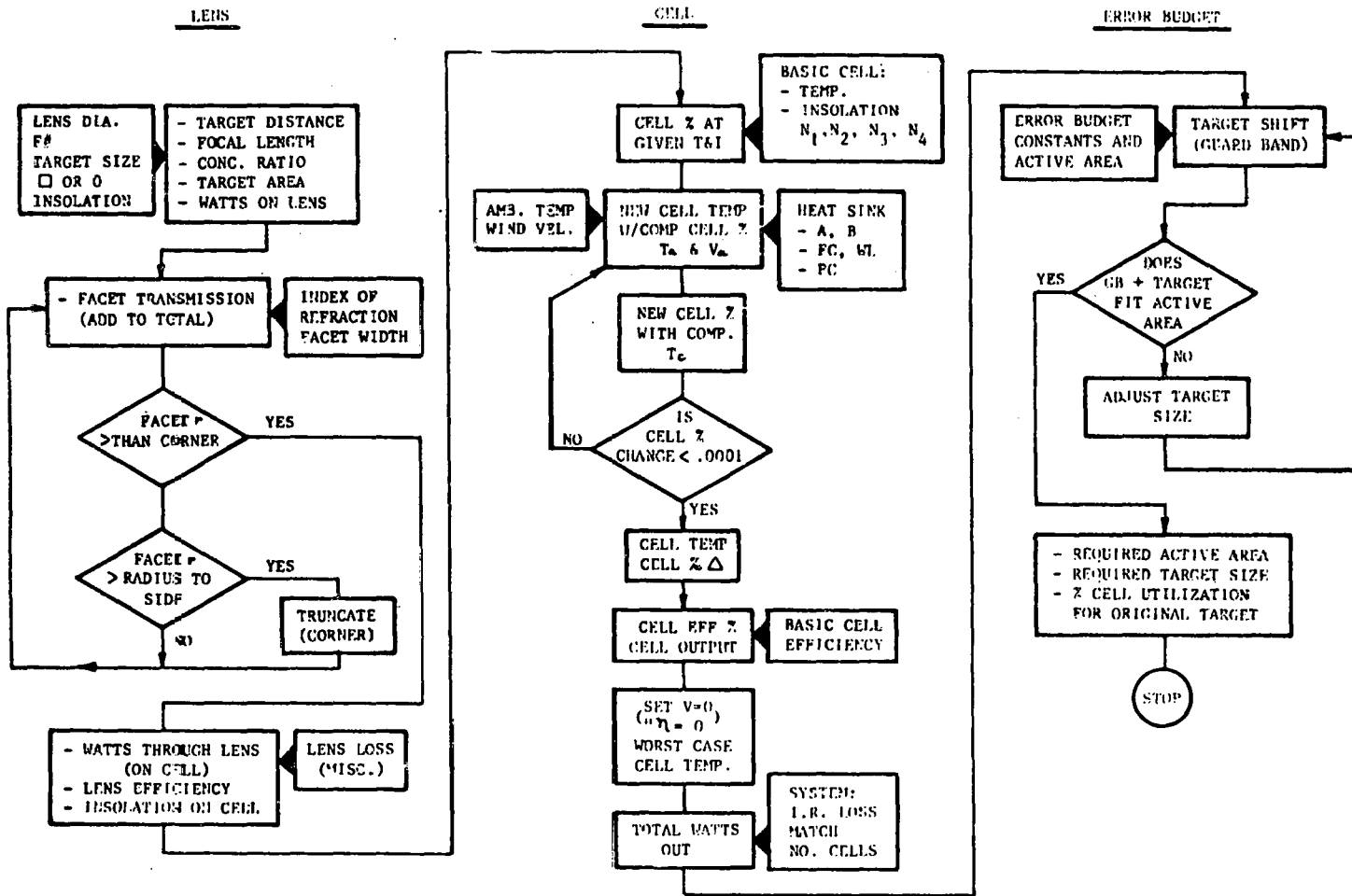
Housings would include tandem rows of 7 cells enabling the housing to be formed with a central reinforcing channel which is also used as an attachment means to the support tube assembly. Direct attachment to the tube was considered but the stress levels were too great for the ABS (Rovel) material preferred on the housing. A separate mounting member was devised as shown in Figure 9 which attaches separately to the support tube located by molded-in dowels and attached very simply by band clamps. This presents dovetail snouts either side of the support tube on which the housings slide on to and latch in position. These mountings would be injection molded in a glass reinforced plastic, probably polycarbonate, in order to accommodate stress levels.

A further 10% increase in array area is planned and is viewed as commensurate with drive mechanism improvements, however, wind tunnel testing will be undertaken before exact proportions of the array are finalized.

Figures 10 and 11 show the combined cell/substrate/interconnect/heat exchanger assemblies that we contemplate for this second generation.

The drive mechanism will remain substantially as produced for the Soleras program except that the control electronics will be incorporated in the drive mechanism housing with only the sun sensor mounted on the array. This minimizes the amount of electrical cabling and service loops.

PROGRAM FLOW DIAGRAM

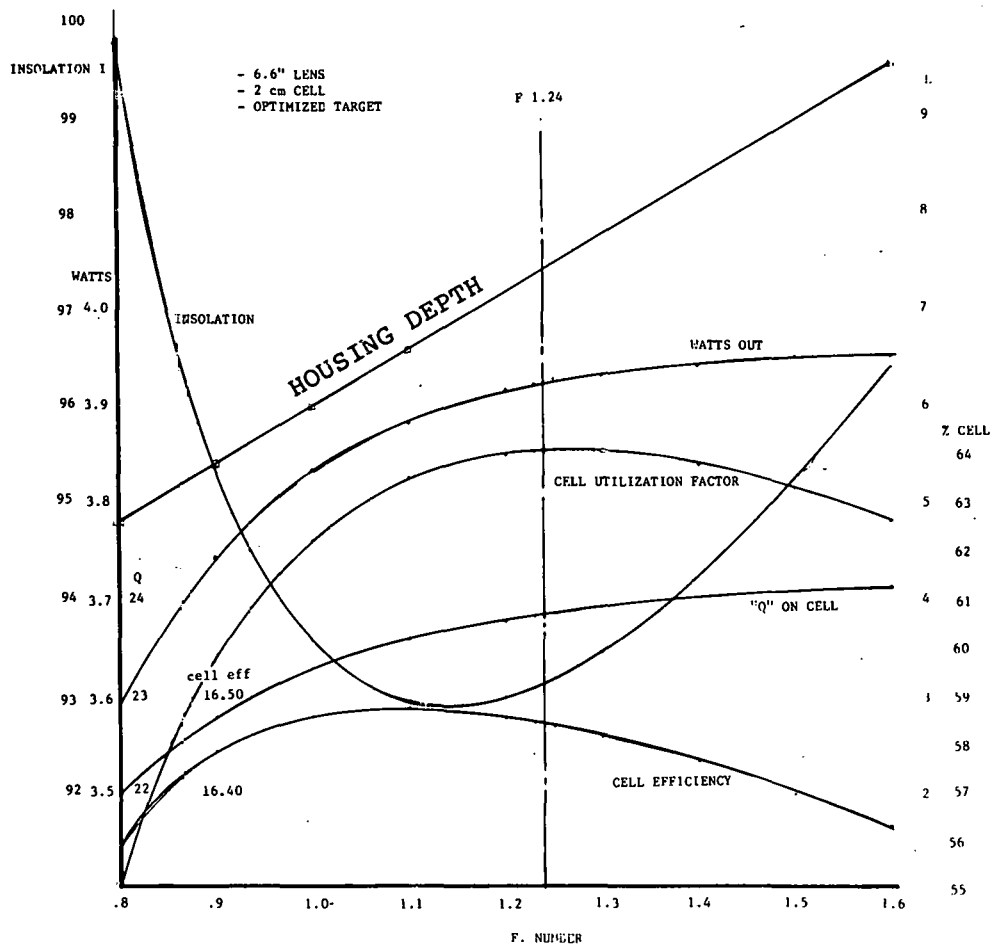


86

MARTIN MARIETTA

FIGURE 1

2ND GENERATION PCA OPTIMUM F NUMBER STUDY



MARTIN MARIETTA

FIGURE 2

CELL SIZE COMPARISON

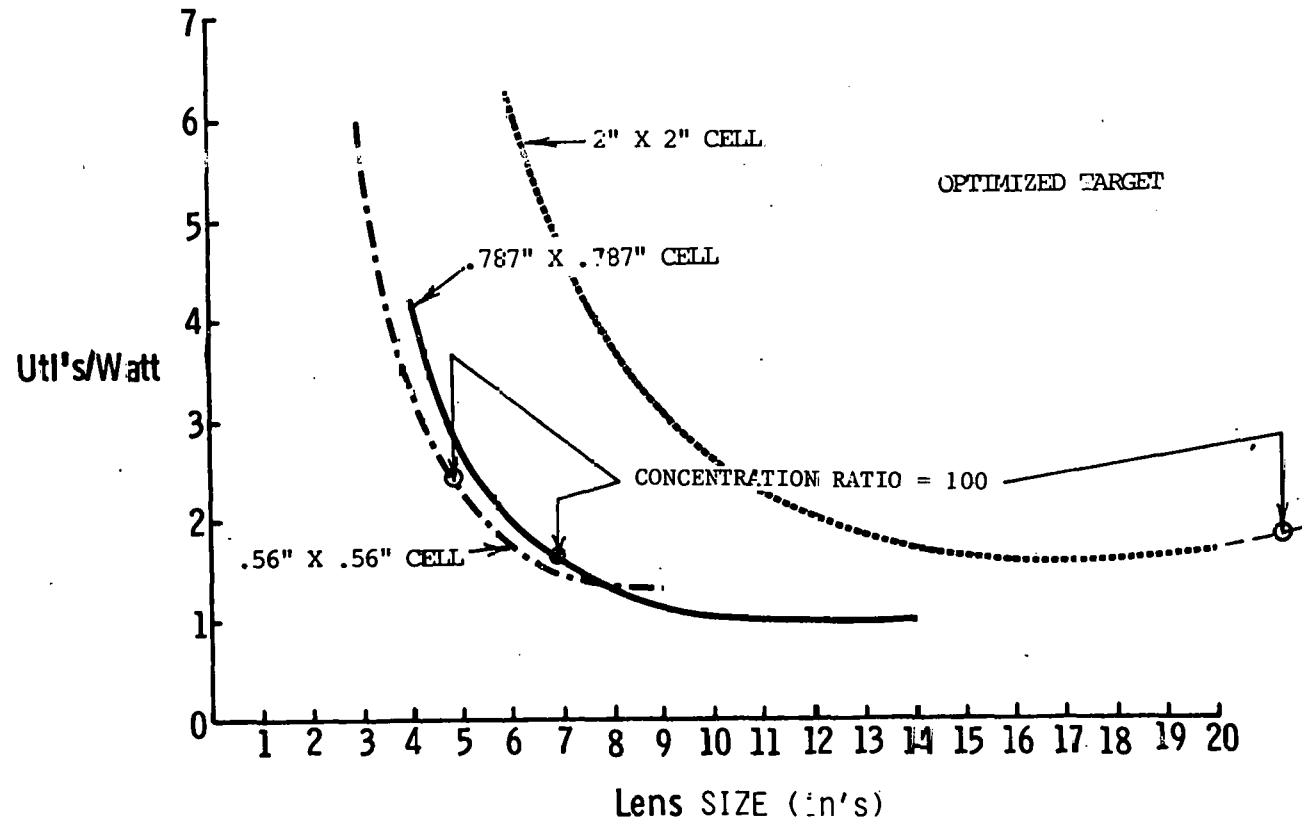
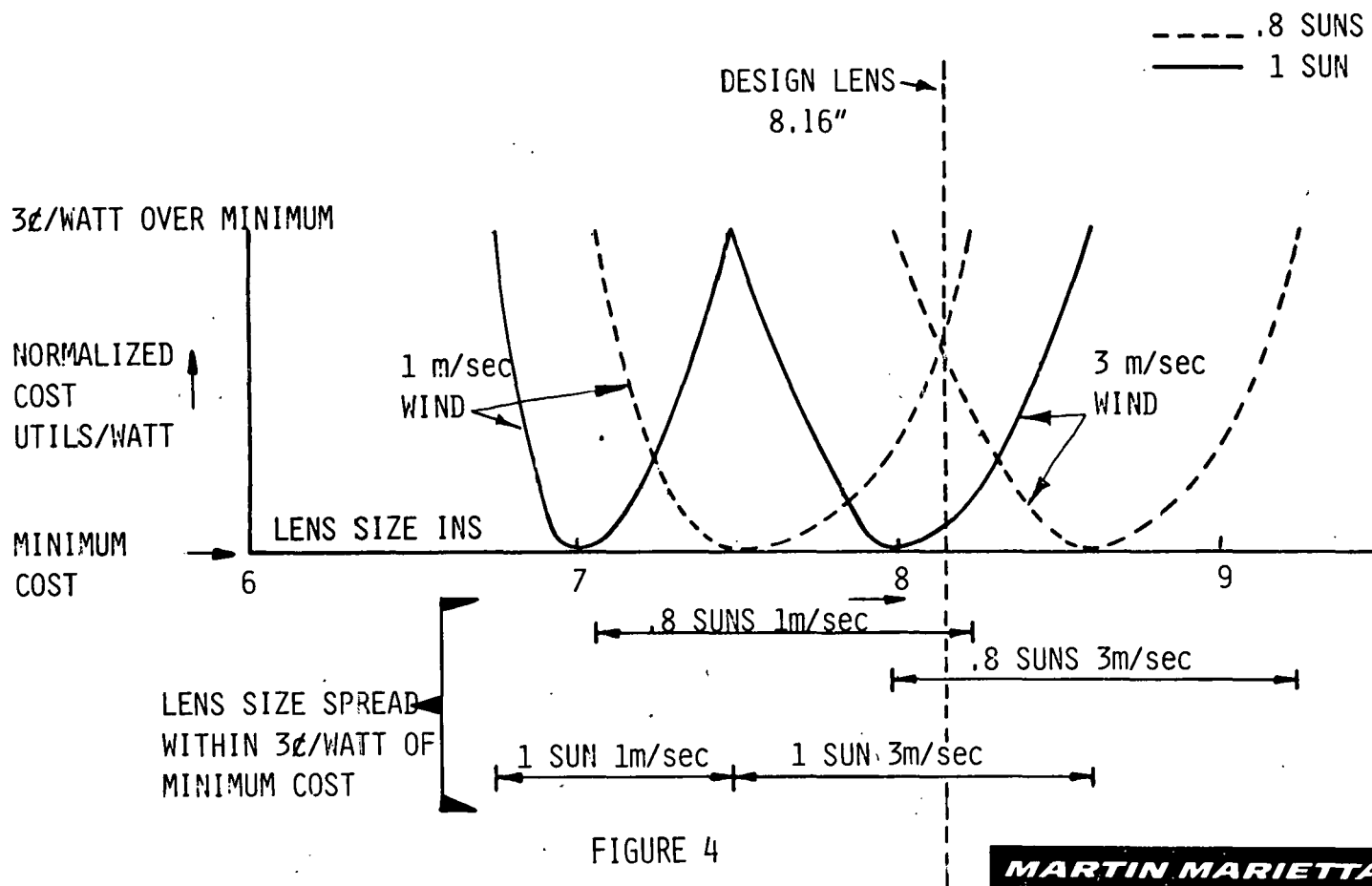


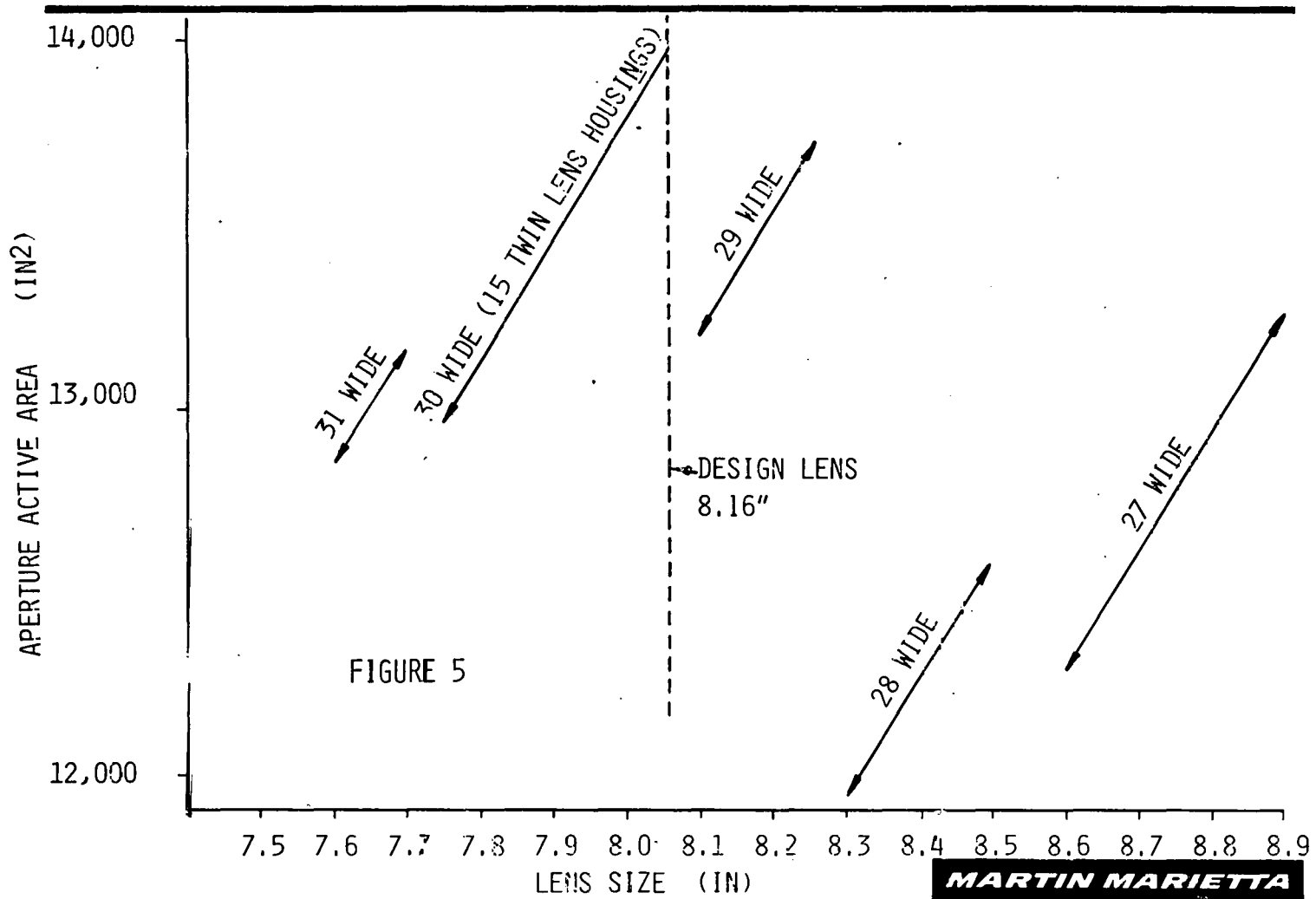
FIGURE 3

MARTIN MARIETTA

LENS COST OPTIMIZATION AT VARIOUS AMBIENT CONDITIONS:



LENS SIZE OPTIMIZATION FOR MAXIMUM APERTURE WITHIN ARRAY SIZE CONSTRAINTS
(250 LONG SEGMENTS)



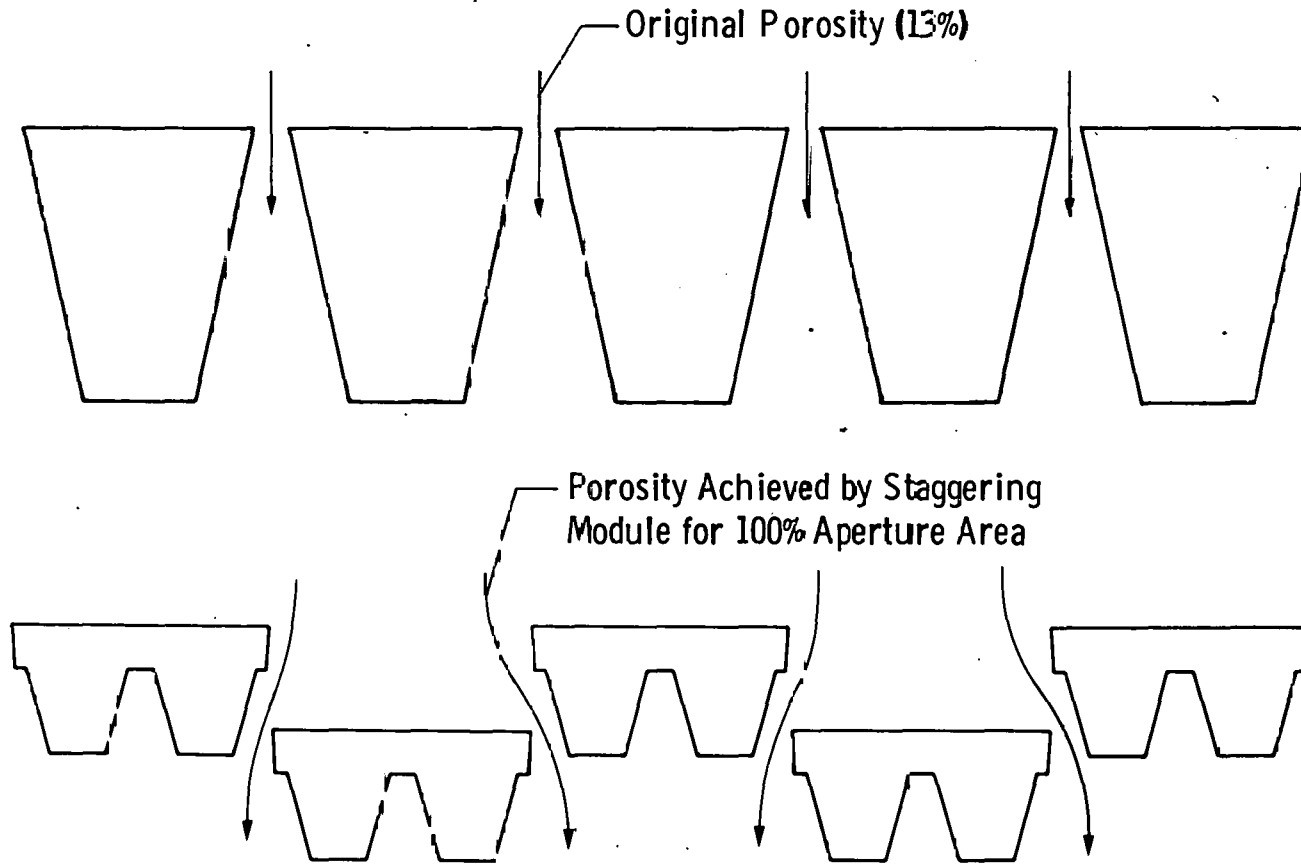
SUMMARY - OPTIMIZED DESIGN AND PERFORMANCE CHARACTERISTICS

LENS SIZE	8.16" SQUARE
CELL SIZE	1.05" SQUARE
CELL ACTIVE AREA	.89" SQUARE
CELL IMAGE AREA	.696" SQUARE
GEOMETRIC CONCENTRATION RATIO (BASED ON ACTIVE AREA)	84
GEOMETRIC CONCENTRATION RATIO (BASED ON IMAGE AREA)	138
MODULE SIZE	7 TANDEM LENSES
ARRAY SIZE	840 LENSES
HEAT EXCHANGER WEIGHT/CELL	.24 LBS.
ARRAY OUTPUT (BASED ON .8 SUNS 3 M/SEC WIND 15.077 CELL EFFICIENCY 28°C)	3.476 K WATTS

FIGURE 6

MARTIN MARIETTA

2nd GENERATION PCA - 13% ADDITIONAL APERTURE AREA FOR SAME SIZE ARRAY



92

FIGURE 7

MARTIN MARIETTA

2nd GENERATION MODULE

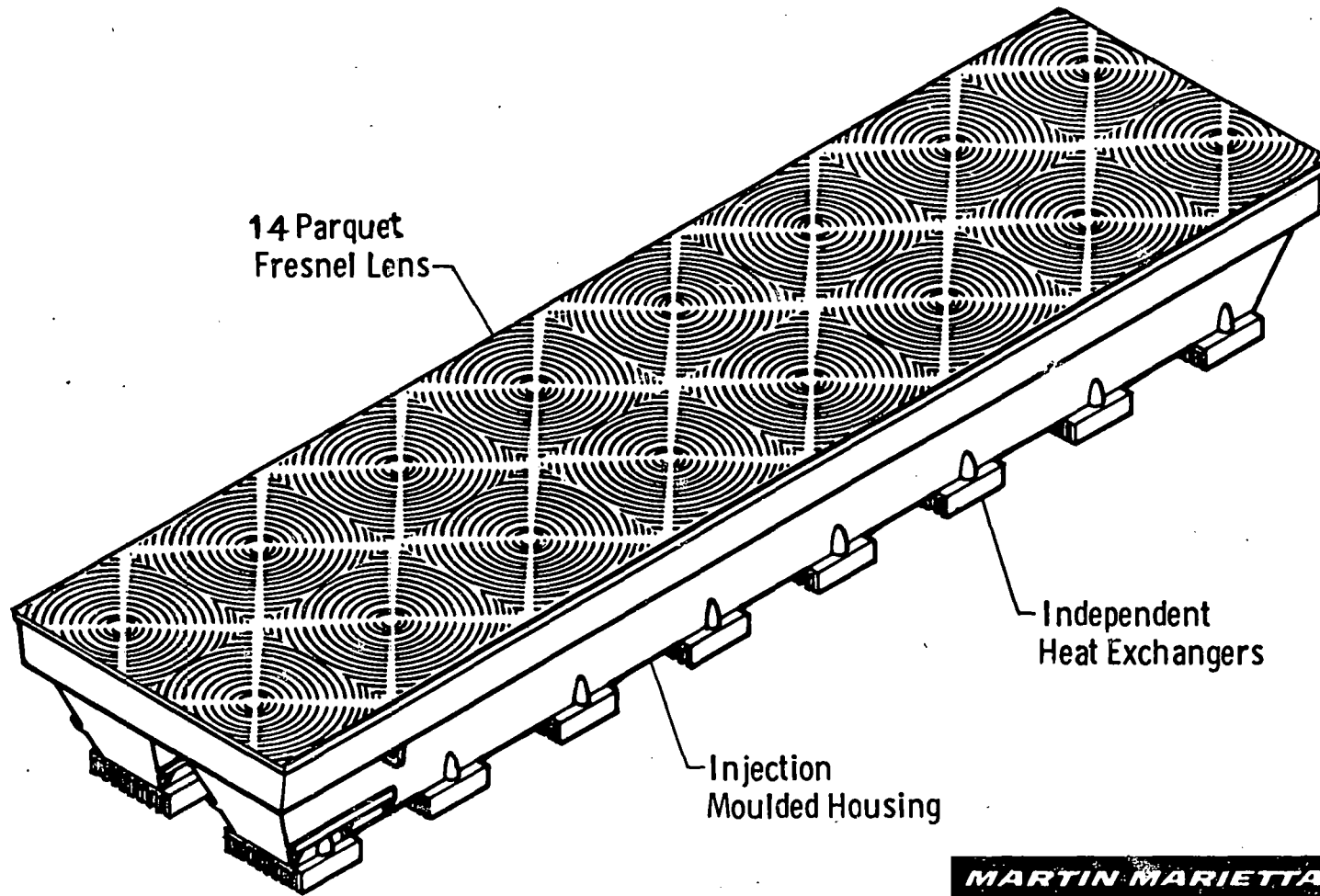


FIGURE 8

2nd GENERATION - FORWARD & AFT SADDLE CONFIGURATION

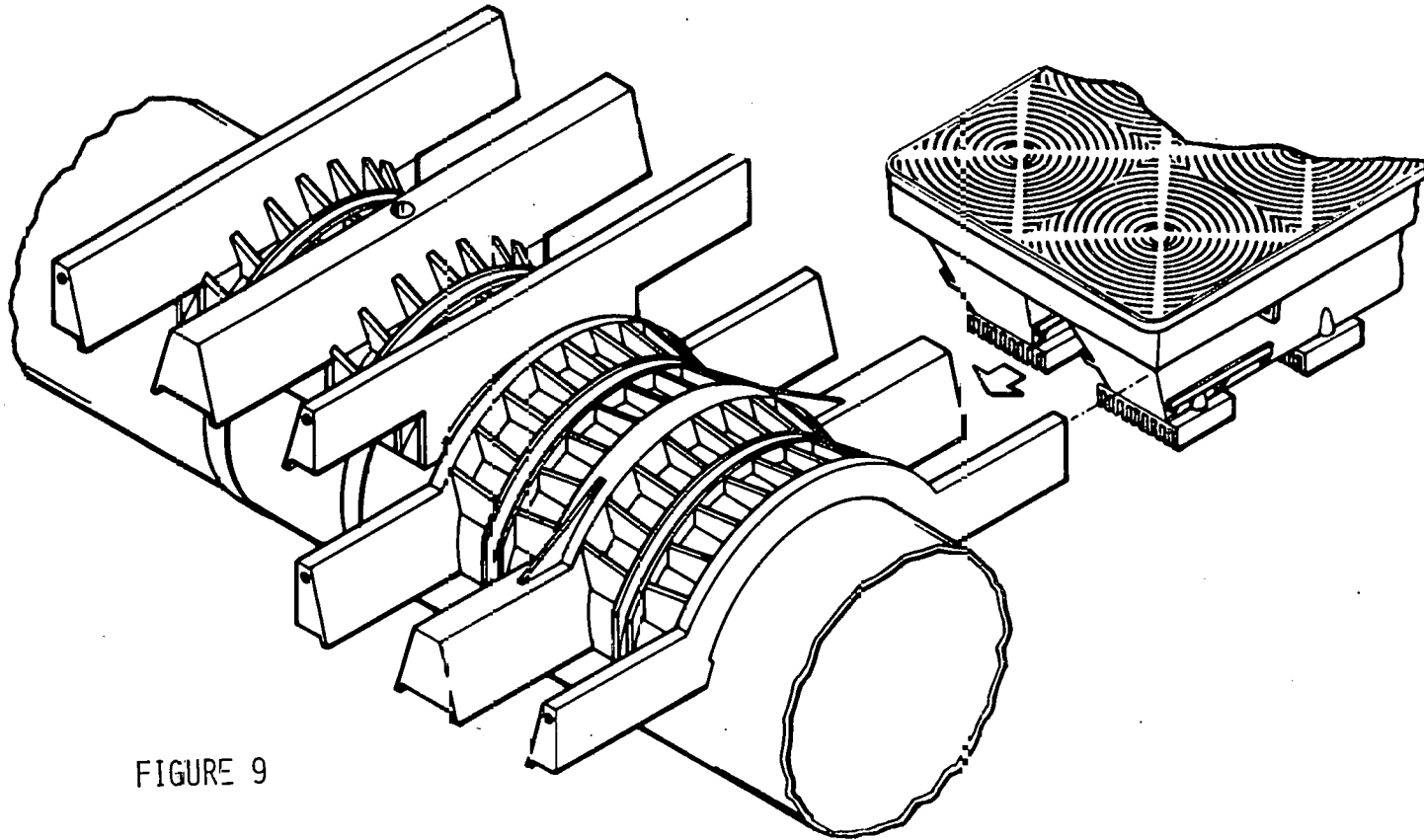


FIGURE 9

MARTIN MARIETTA

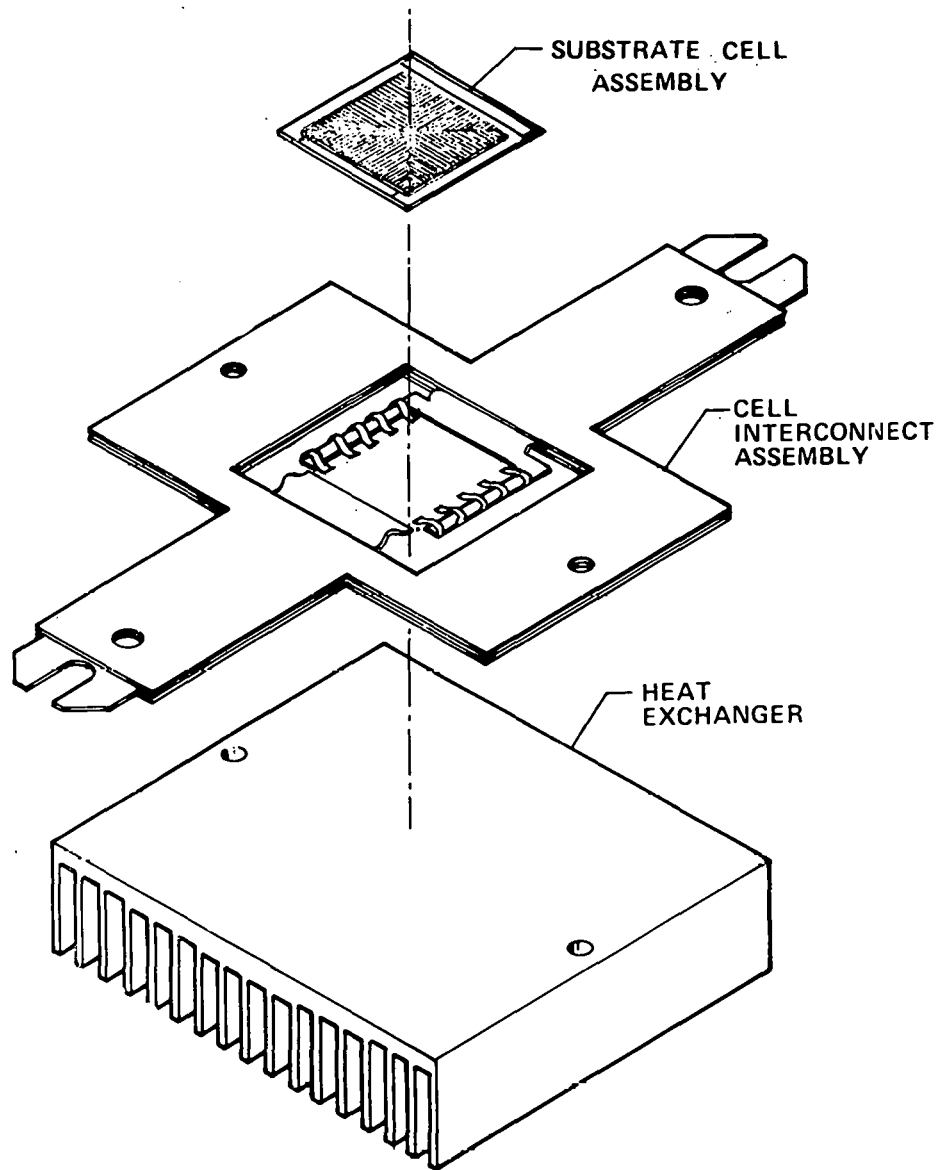


FIGURE 10

CELL INTERCONNECT
ASSEMBLY TYPE 1

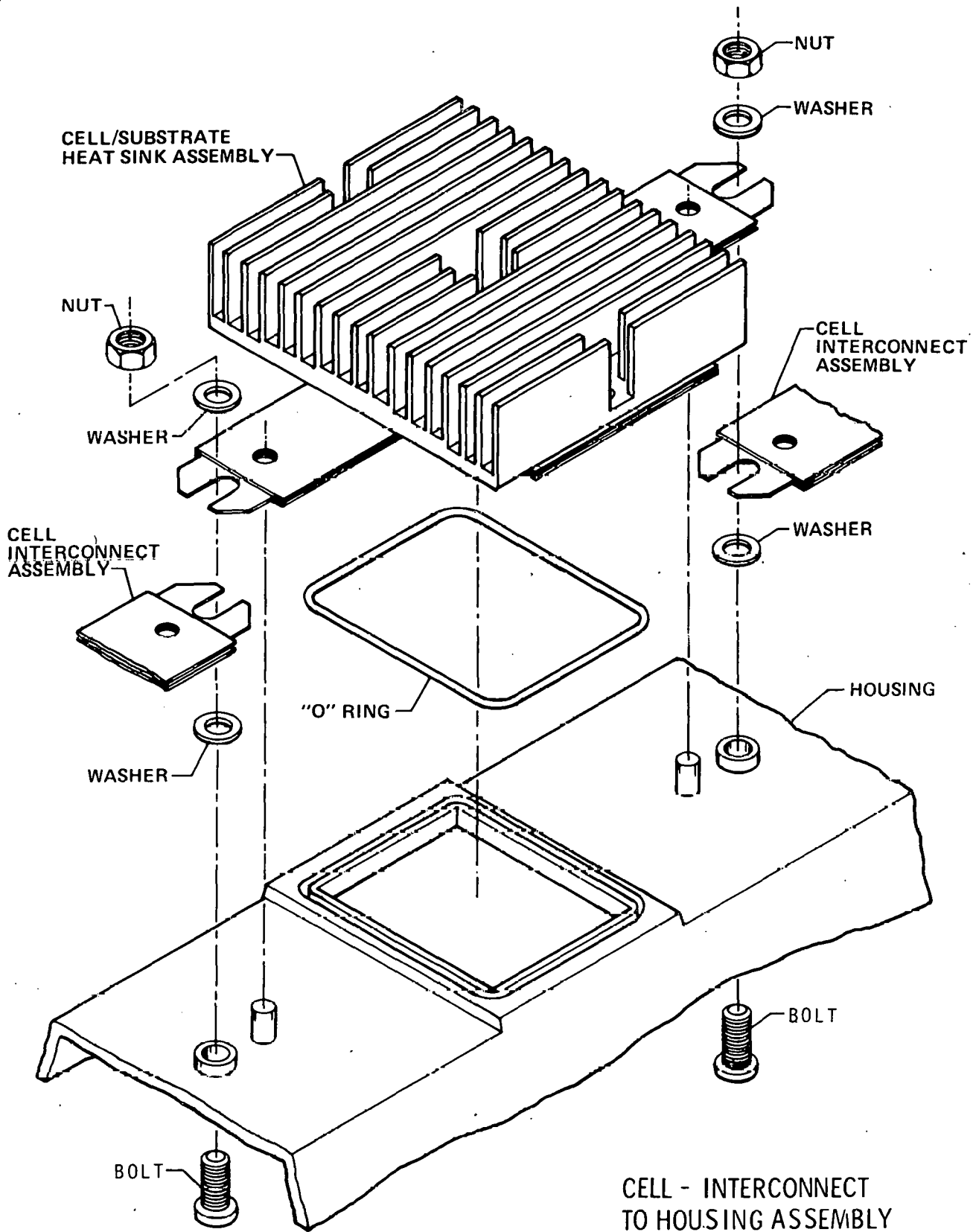


FIGURE 11

MODELLING OF THE FIRST GENERATION
MARTIN MARIETTA ARRAYS*

H. J. Gerwin, Division 4721
Sandia National Laboratories
Albuquerque, New Mexico 87185

ABSTRACT

Two photovoltaic arrays, built by Martin Marietta, have been tested extensively during this past summer. The point focus, passively-cooled modules in these arrays employ a common heat sink design of extruded aluminum fins. To evaluate the heat sink effectiveness, the modules were separated into four groups according to the number of fins they have. Temperatures were monitored on the heat sinks. Representative plots of the results are shown in Figures 1 and 2.

Performance testing of the arrays was continued throughout the day for several days. Data from the current-voltage (I-V) scans are being analyzed for relationships between efficiency and various uncontrolled parameters such as insolation, air temperature and wind speed. The I-V scans were repeated at intervals of every few minutes to improve the statistical value of the data. Two basic approaches to correlating the data are multiple regression analysis and separation of variables. Currently, we are developing both techniques so that there is a check on the system. If the multiple regression approach proves successful, all the data can be used and the results can be translated to other environmental conditions with greater confidence. An example of the in-process analysis is shown in Figure 3.

*This work was supported by the U. S. Department of Energy.

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97.2

MMC 2,3,4,7 FIN OUTBOARD AND AMBIENT AIR

DATE JULY 25, 1980

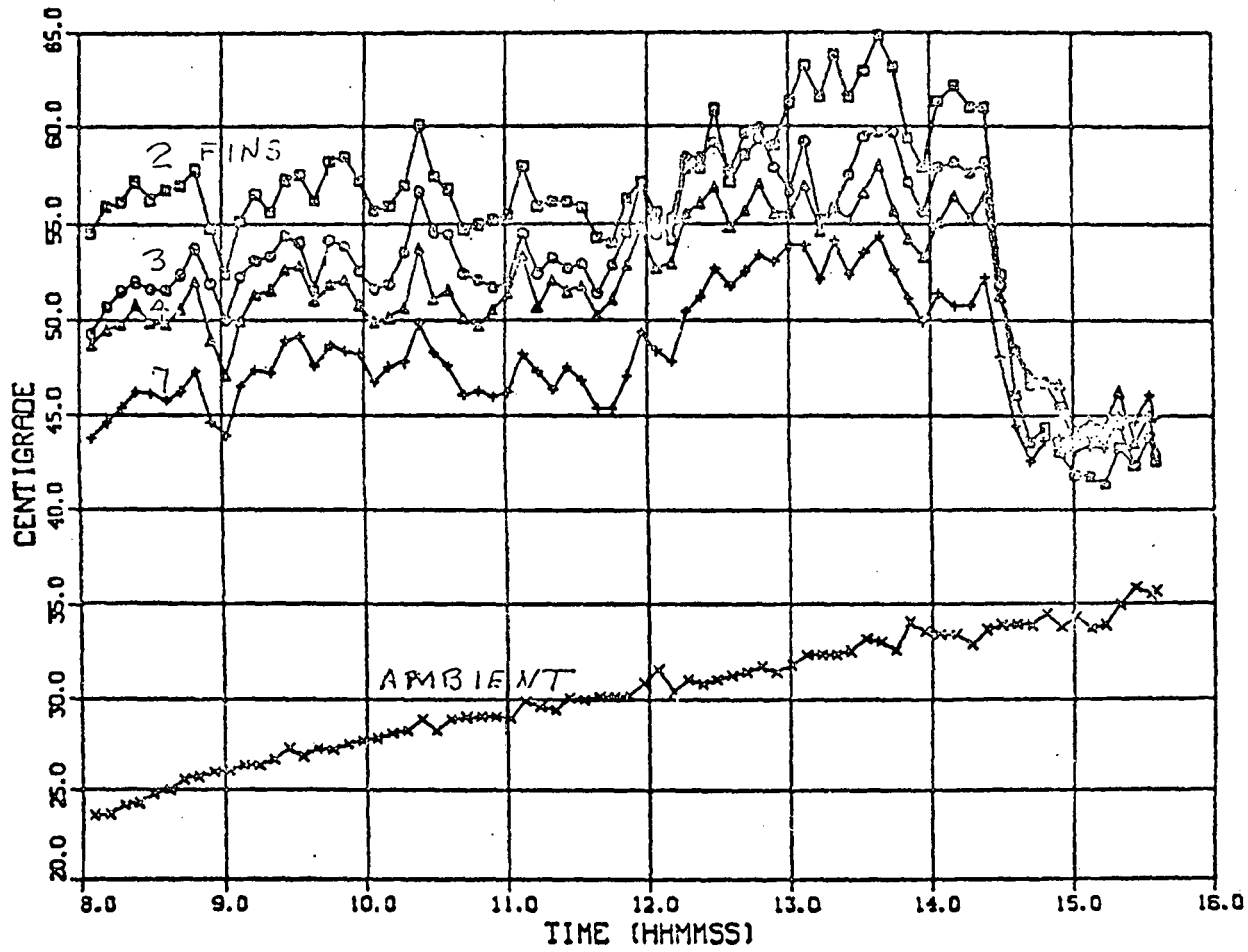


FIGURE 1

MMC 2,3,4 AND 7 FIN BASE TEMPERATURES

DATE : JULY 25, 1980

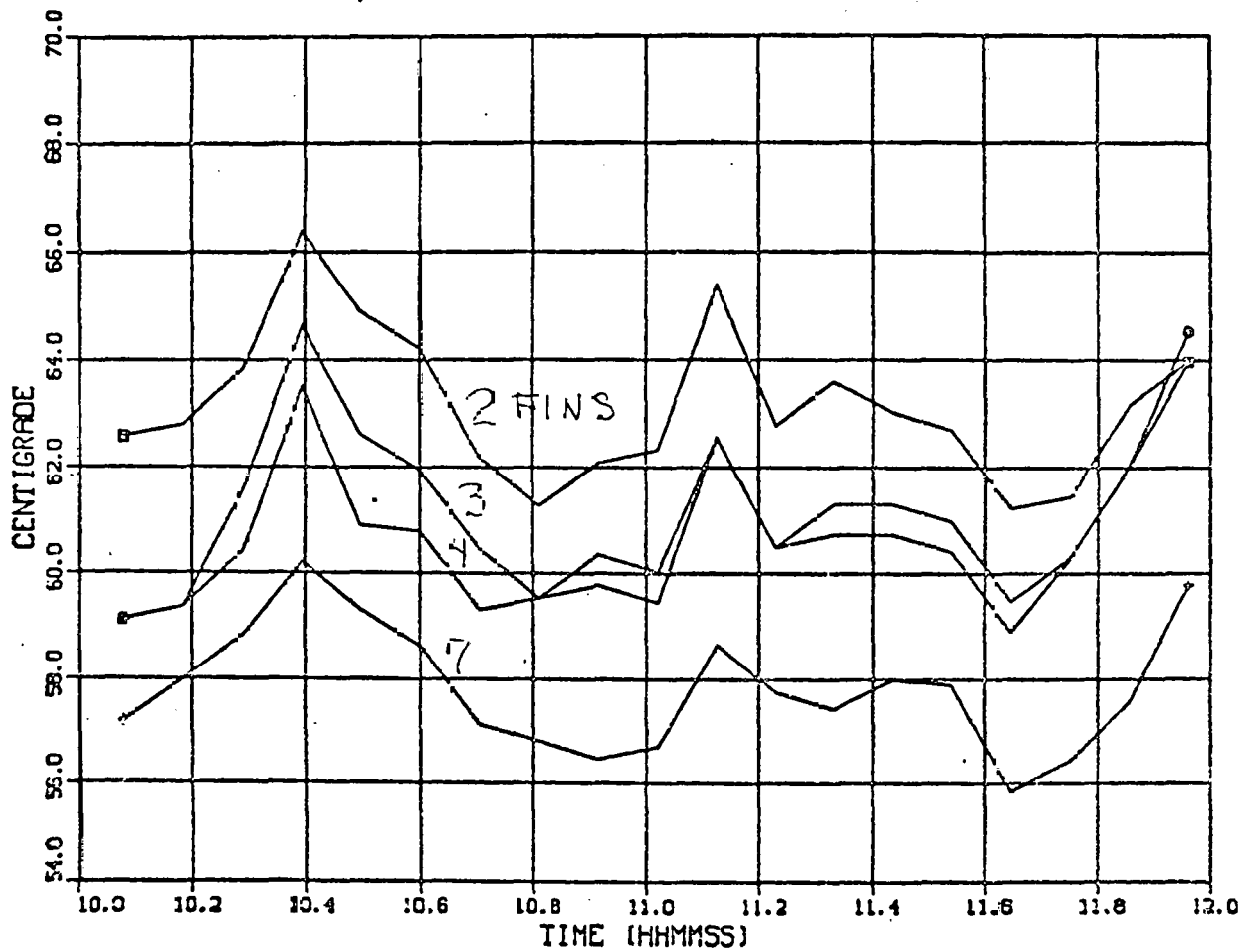


FIGURE 2

MMC NWE EFF. VS DNI: 1345-1600 HRS

AUGUST 11, 1980

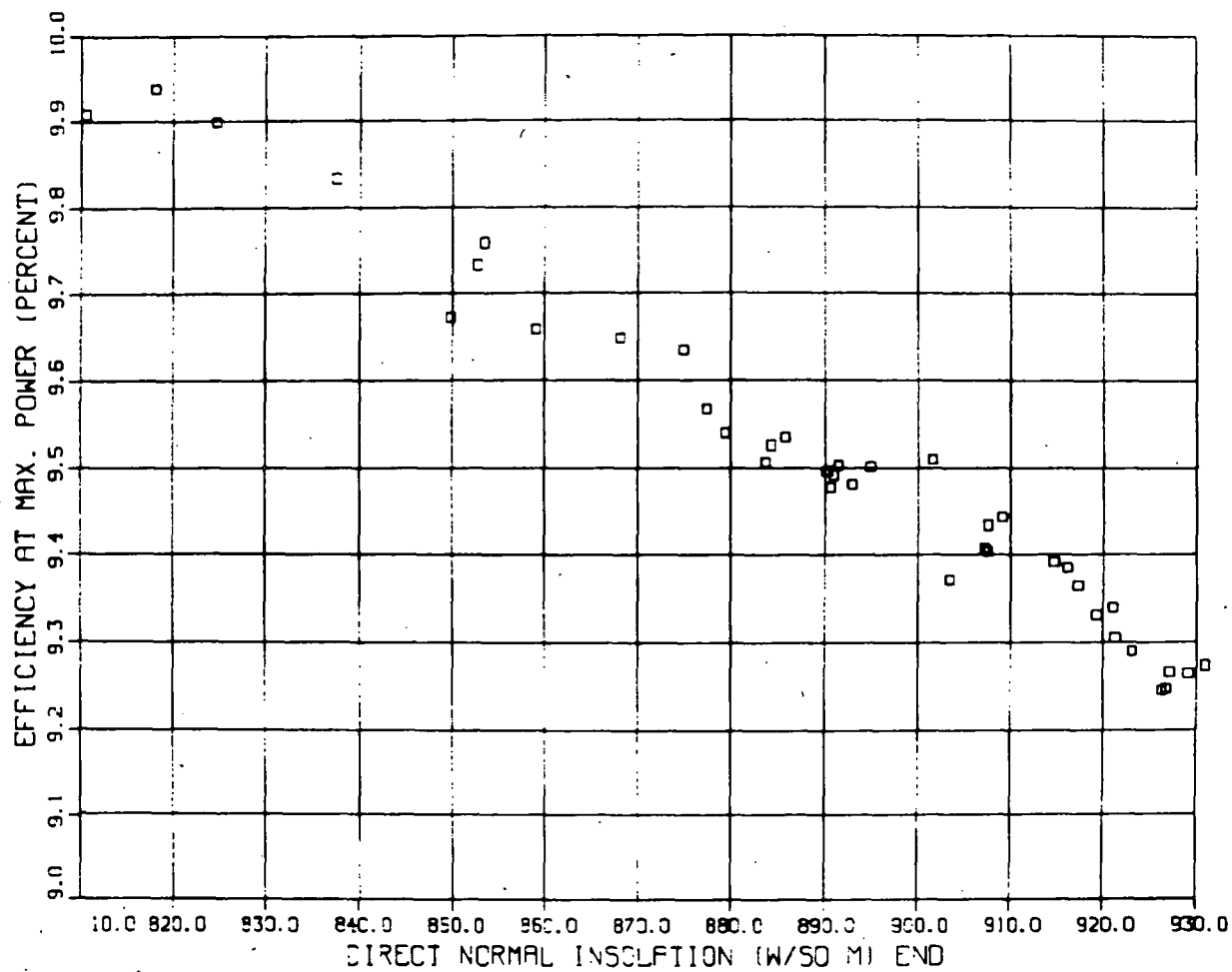


FIGURE 3

OPTIMIZATION OF A PHOTOVOLTAIC
CONCENTRATING COLLECTOR

A. Ken Yasuda
John I. Kull
Acurex Corporation
Alternate Energy Division
485 Clyde Avenue
Mountain View, California 94042

ABSTRACT

A photovoltaic concentrating collector was designed and optimized for the application of photovoltaic cells to a line focus concentrating collector. The primary design variables evaluated were the concentrator and receiver tube configurations, both of which impact optical efficiency. The optical efficiency is the performance figure of merit and is defined by

$$\eta_{opt} = F_B \rho_T \gamma CG F_{ECL}$$

where, F_B = receiver tube blockage factor
 ρ_T = reflective surface reflectivity
 γ = intercept factor
 CG = cell cover glass transmissivity
 F_{ECL} = extrinsic cell loss factor

A computer model was developed to compute optical efficiency for the various trough configurations. The code computes the energy distribution at the focal plane for any trough or receiver geometry. This information is tabulated so the energy incident upon a cell located anywhere along the focal plane can be obtained.

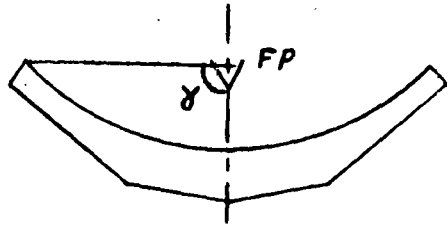
Alternative trough configurations included varying the collector rim angle, or creating two focal regions by changing the cross-sectional shape of the trough.

The receiver assembly used a 2.5 cm double bus cell. This selection was based on earlier optimizations and analysis. The receiver design optimization examined various cell locations on the receiver tube, receiver tube included angle, and receiver tube location.

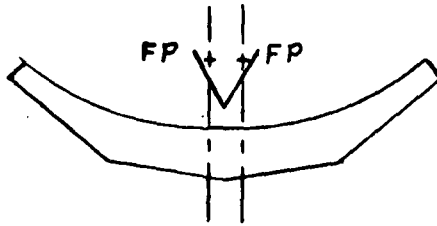
Results of the study show the optimum rim angle to be 90°. For each rim angle, there is an optimum receiver tube location and included angle. The optimum included angle is 44° with the apex of the receiver tube 0.63 in below the focal point.

The split displaced trough was selected as the best design. It has a higher optical efficiency than the continuous parabola because it allows greater flexibility in cell placement. This is particularly important when the reflective surface has slope errors and does not conform to a perfect parabola.

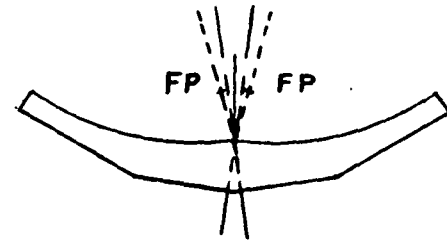
Another important conclusion of this study was the dramatic effect of surface slope error on optical performance. All modeling and optimization was done with slope error data from an actual collector. Assuming a perfect reflector with no slope error, a performance increase of 6.9 percent could be achieved.



PARABOLIC TROUGH
CONTINUOUS



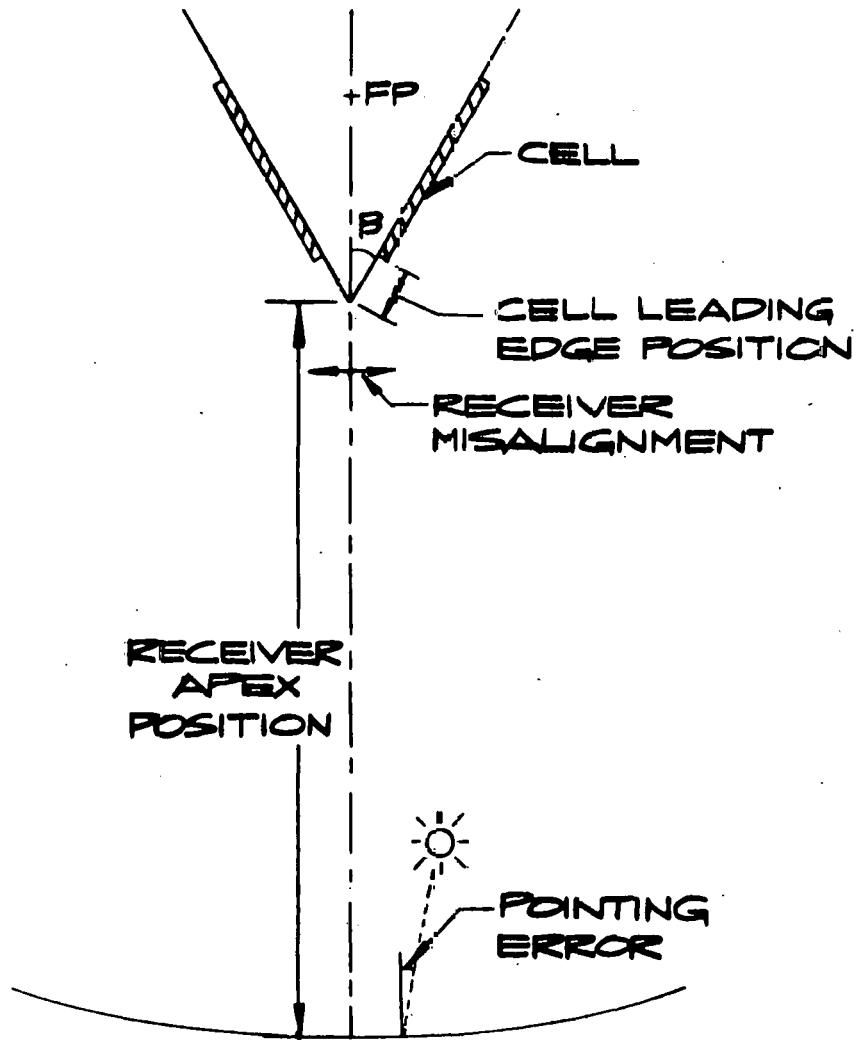
SPLIT TROUGH
DISPLACED



SPLIT TROUGH
CANTED

- VARIABLE PARAMETERS
- RIM ANGLE (α)
- REFLECTOR SLOPE ERROR

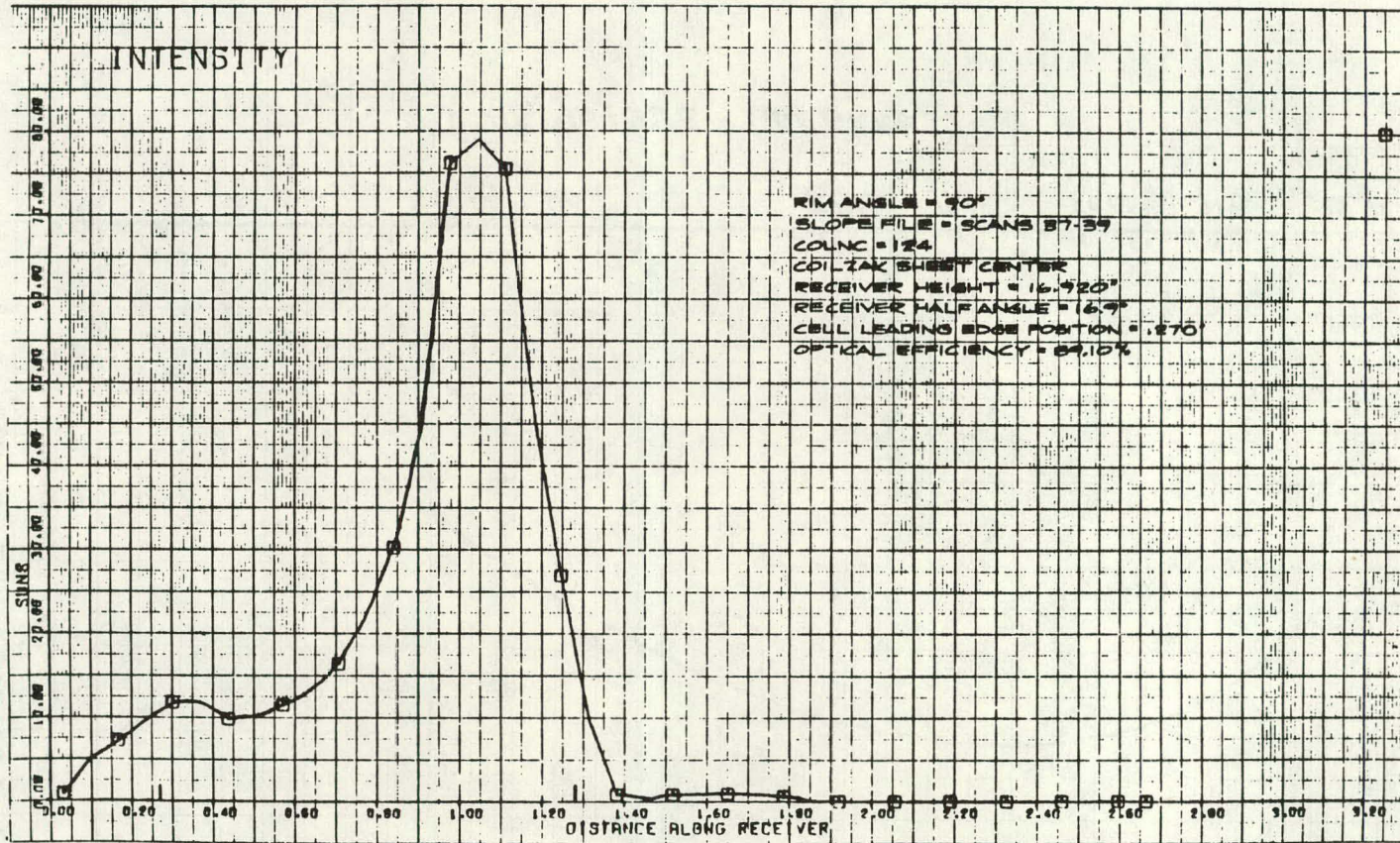
Fundamental Trough Configurations



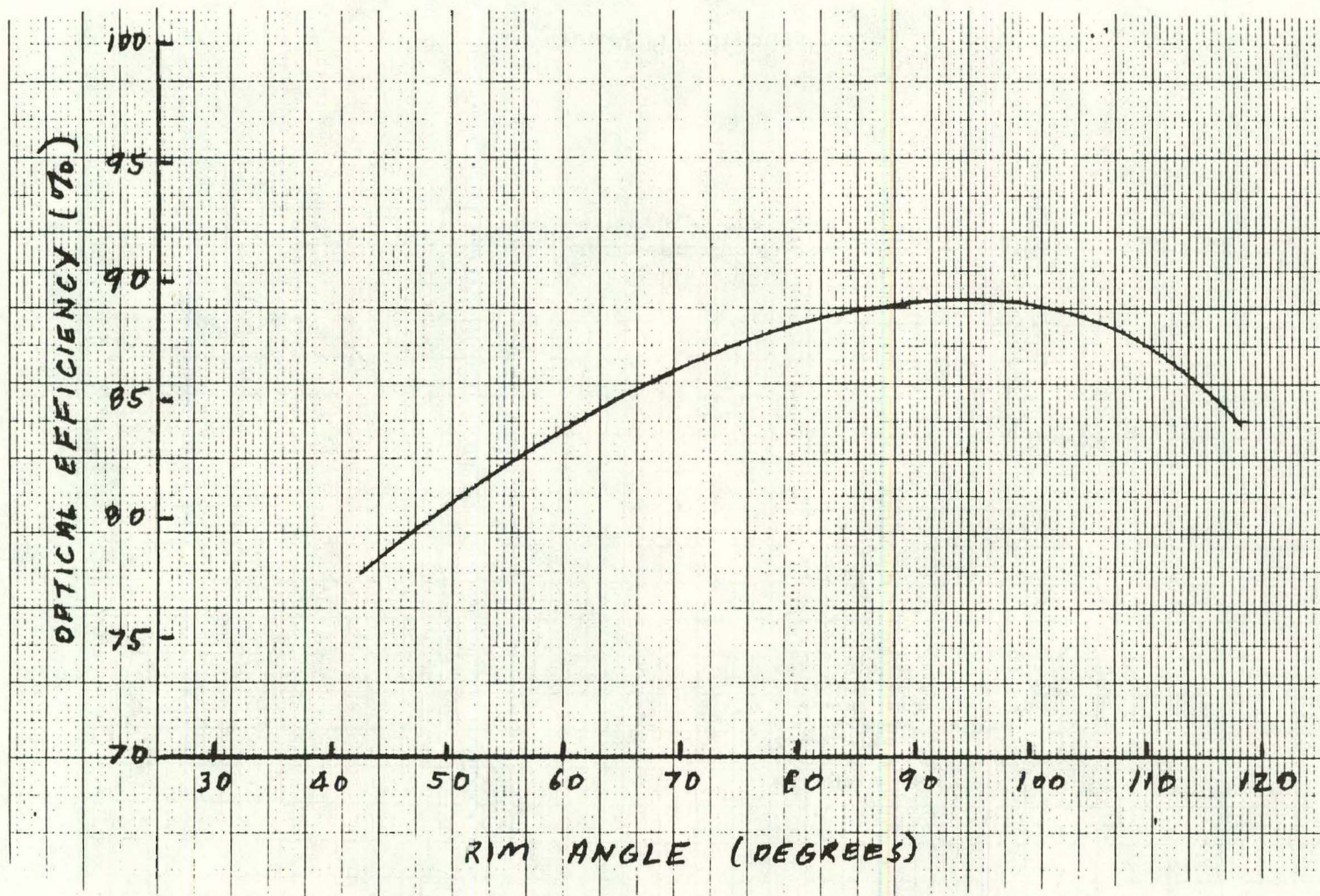
● VARIABLE PARAMETERS

- RECEIVER APEX POSITION
- CELL LEADING EDGE POSITION
- RECEIVER INCLUDED HALF ANGLE (β)
- RECEIVER MISALIGNMENT
- POINTING ERROR

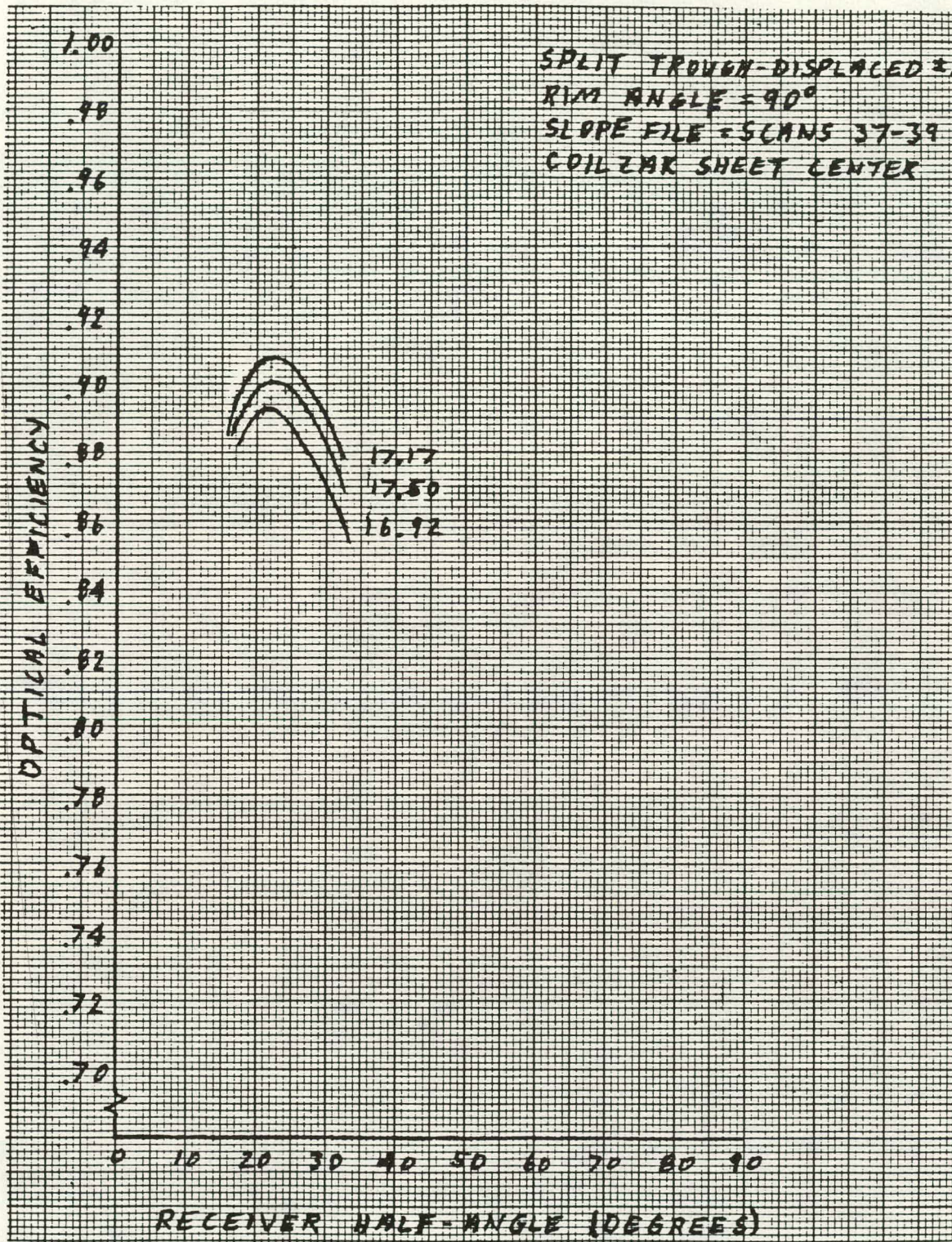
Receiver Tube Geometry



Typical Flux Distribution



Optical Efficiency Versus Rim Angle



Optical Efficiency Versus Receiver Angle

ACTIVELY COOLED PHOTOVOLTAIC ARRAY

BY

MARTIN MARIETTA CORPORATION

BOX 179, DENVER, COLORADO 80201

Principal Investigator: Sidney Broadbent (303) 977-0683

The design approach adopted to convert the Martin Marietta passively cooled array to an actively cooled array was described at the 5th Project Integration Meeting including the revised cell-substrate-interconnect design. Figure 1 illustrates the array, while Figures 2 thru 4 illustrate the heat exchanger cell/substrate/interconnect assemblies and the complete module assembly. Array completion has been delayed due to process developmental problems associated with substrate production and cell and interconnect soldering.

Our original substrates were metalized using an initial layer of either Tungsten or Molybdenum to which nickel would be plated to provide a satisfactory bond for a final copper deposit of substantial thickness (.001^u) to minimize our series resistance. Many processing techniques were tried including electroless vs electroplated nickel deposits, different rinsing and inter-process baking operations with minimal success, the failure mechanism being corrosion through the copper from electrolytes trapped in the porosities of earlier metalizations.

An alternative method of copper attachment to the alumina substrate was finally proven eminently satisfactory using a copper paste screen onto the substrate and fired. This however, also involved long and tedious development on the part of the supplier and involved delamination of the copper and the inability to apply a satisfactory solder coating. The problems were overcome by strict attention to process control of furnace atmospheres, temperatures, and copper paste composition. Excellent results are now obtained with a method eminently adaptable to high volume, low cost automated techniques.

The process involves the "tape method" of ceramic handling, wherein, the substrate thickness is limited to .035 thickness with appreciable out-of-flatness tolerances. Our latest substrate also differs from the original in that it is unground and does not have corner holes for hold down bolts. Our method of hold down using stainless steel clips has proved very successful, completely eliminating the corner racking problem we previously experienced.

Successful soldering of cell to substrate demands the application of precise thickness of solder to avoid excessive exuding of solder from beneath the cell. In the Martin Marietta design any such excess of solder raised the possibility of shorting to the interconnect fingers, however, by providing a .020 margin of bare silicon at the cell perimeter this shorting problem was minimized.

Figures 2 thru 4 illustrate the cell/substrate/interconnect assemblies fastened to the heat exchange. A film of Wakefield thermal grease is applied between underside of substrate and the heat exchanger. The trailing edge of one interconnect is resistance or inductively soldered to the N metalization of the adjacent substrate. A .003 thick Kapton film is bonded to the heat exchanger beneath the interconnects for electrical isolation. Alternatively, it may be bonded to the underside of the interconnect.

Modules are in course of assembly to the structural tube and tested under tracking mode. Excellent image targeting has been achieved and a performance improvement of up to 20% has been achieved compared to the original passively cooled arrays. A typical IV curve for a four cell module is given in Figure 5. We expect to present complete array performance test results at the PIM.

ACTIVELY COOLED PHOTOVOLTAIC ARRAY

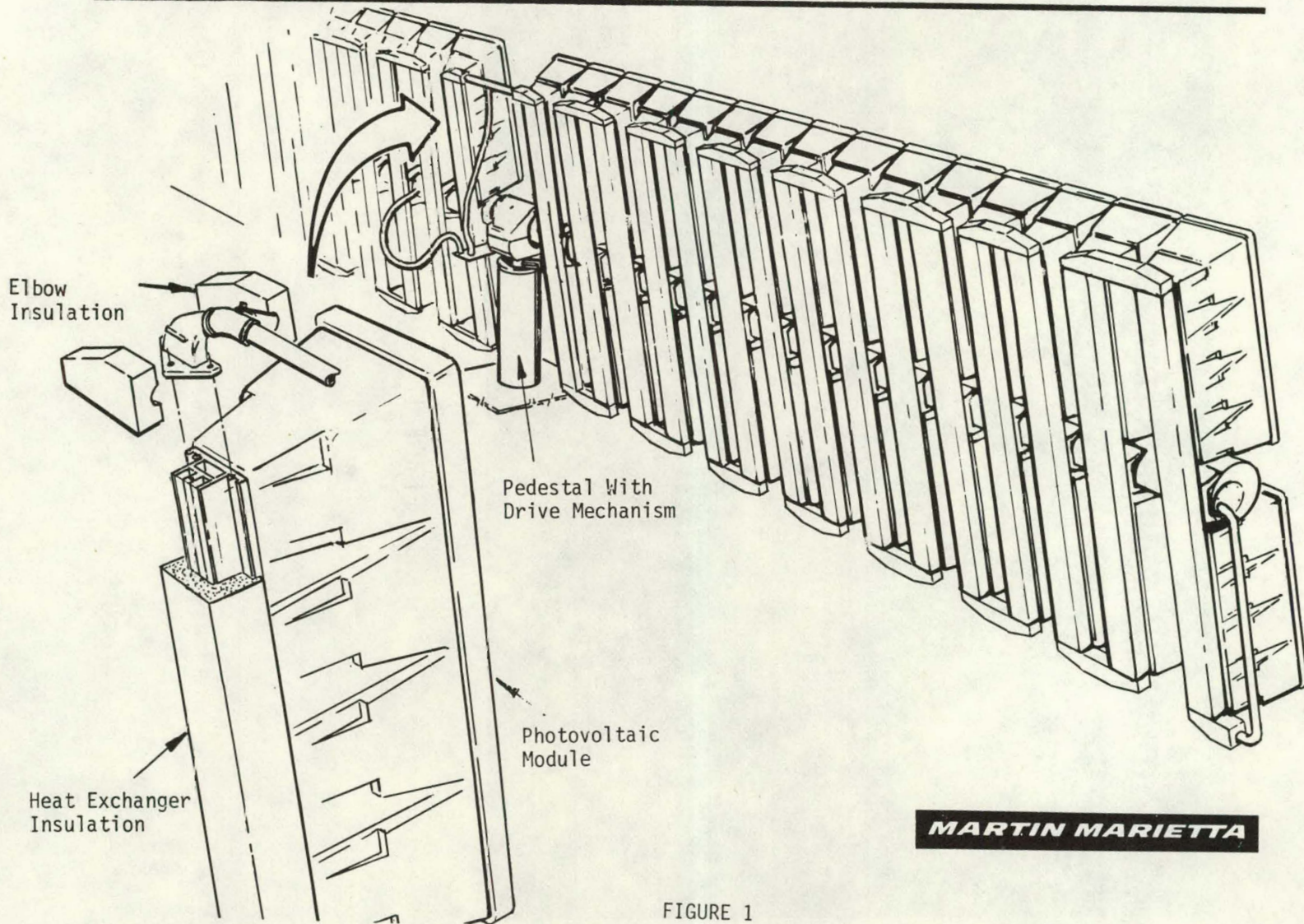


FIGURE 1

105

PHOTOVOLTAIC CONCENTRATOR ARRAY

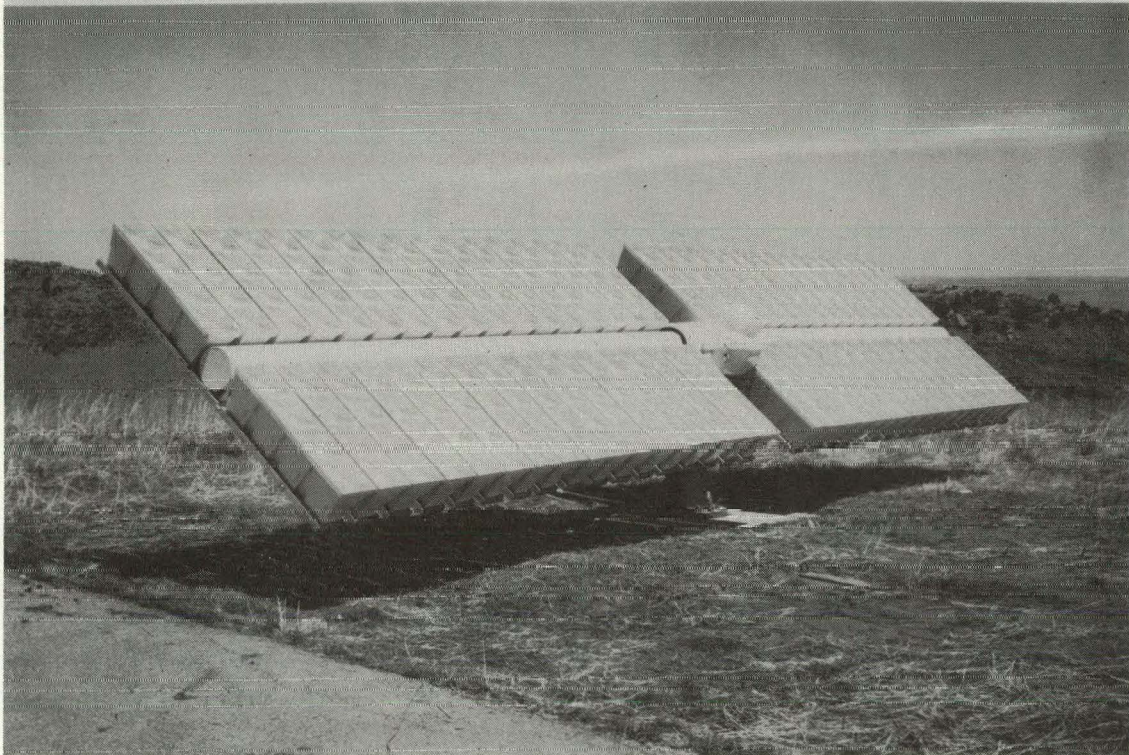


FIGURE 1

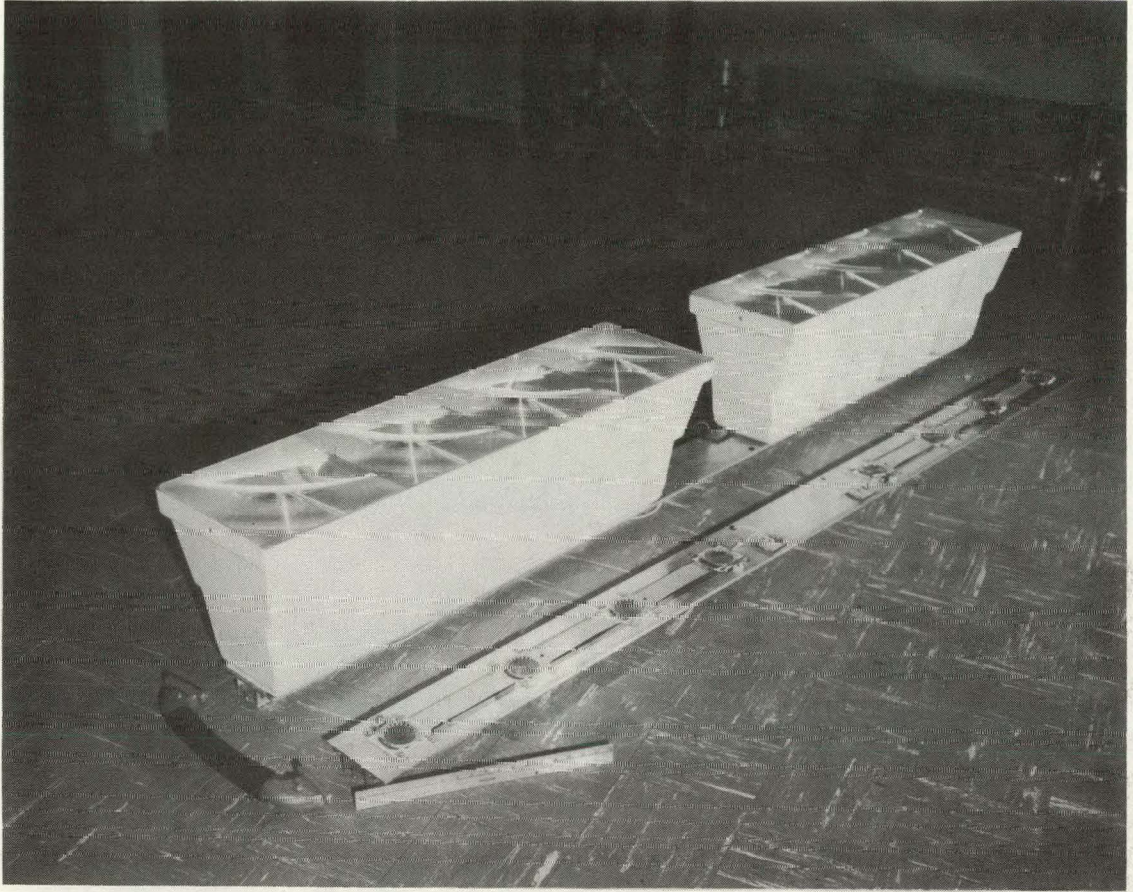


FIGURE 2

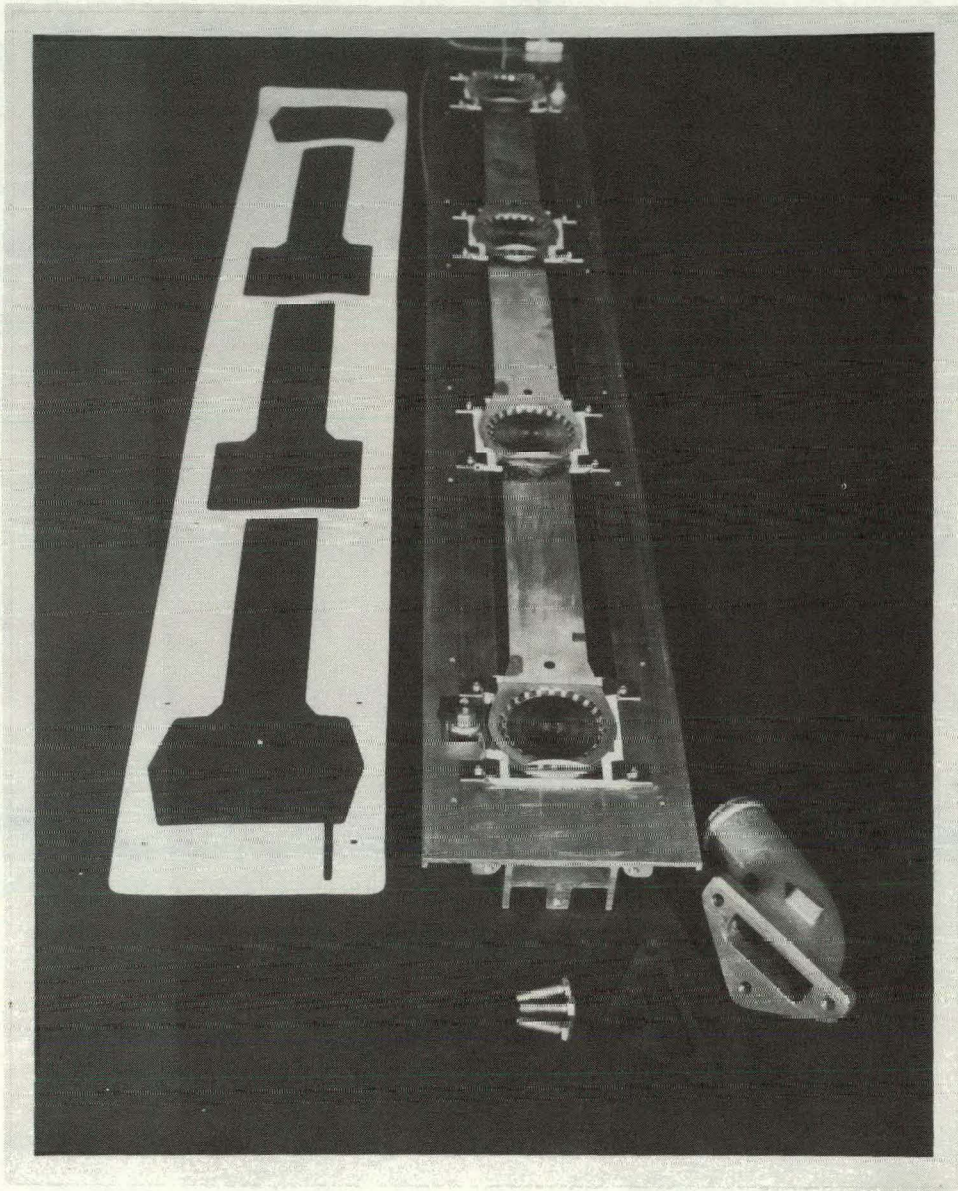


FIGURE 3

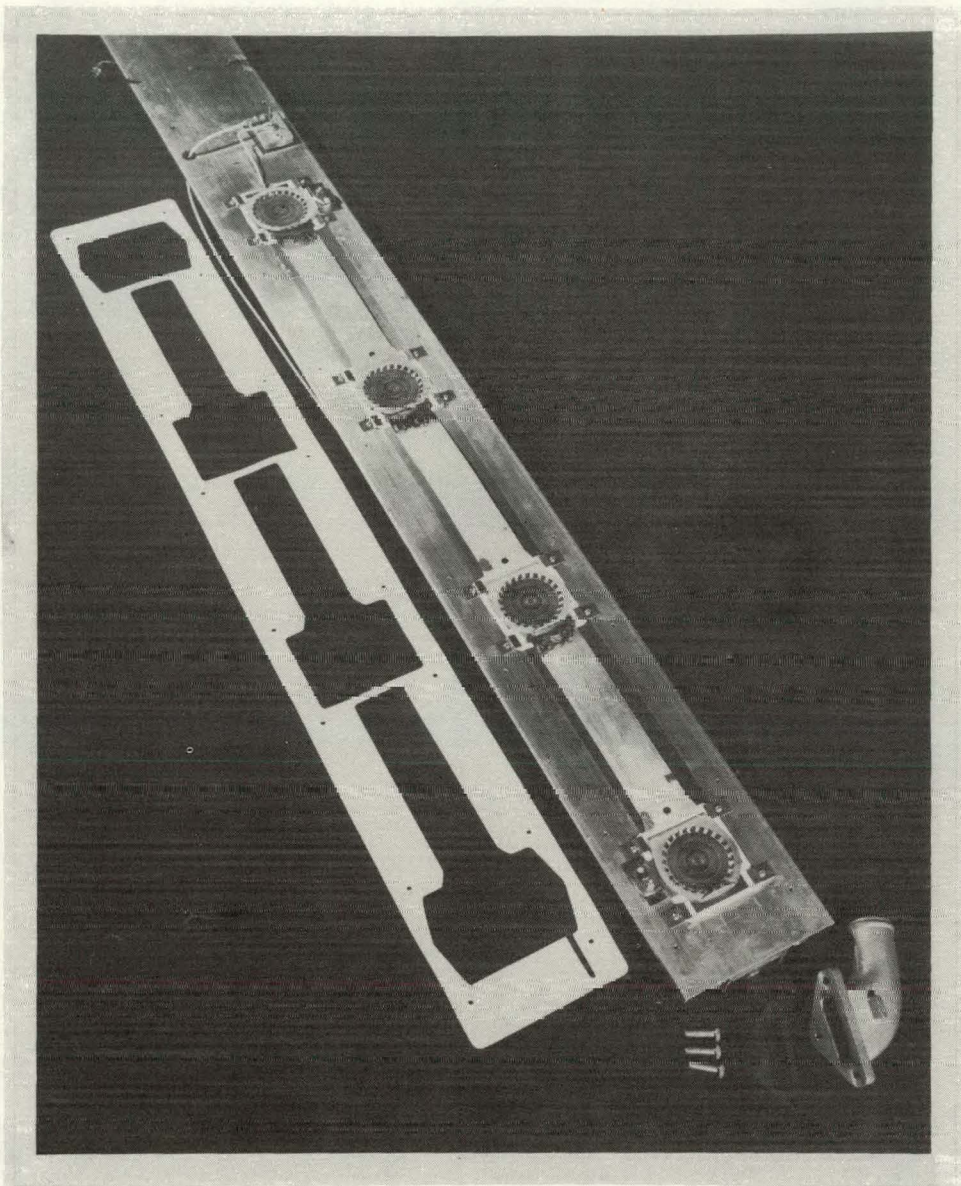
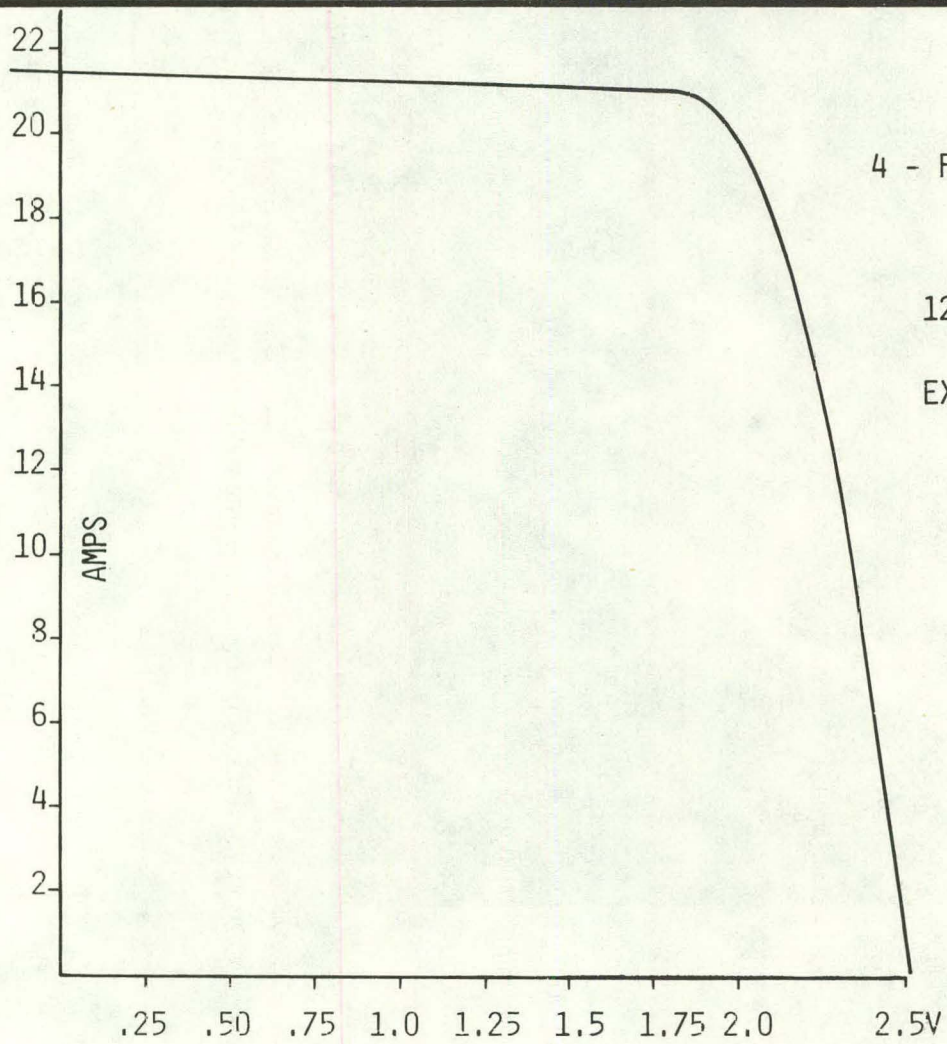


FIGURE 4

110

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ACTIVELY COOLED PHOTOVOLTAIC ARRAY - MODULE IV CURVE



4 - FLOAT ZONE CELLS/MODULE
.935 SUNS
.746 FILL FACTOR
12.69 EFFICIENCY AT 28°C

EXTRAPOLATED FROM TEST DATA:
AVERAGE CELL TEMP 47.5°C
CELL/SUBSTRATE T 8°C

FIGURE 5

MARTIN MARIETTA

DEVELOPMENT AND TESTING OF A HIGH-EFFICIENCY/
HIGH-CONCENTRATION PHOTOVOLTAIC MODULE
EMPLOYING AlGaAs/GaAs SOLAR CELLS

by

Richard J. Owen

Varian Associates, Inc.
611 Hansen Way
Palo Alto, CA 94303

ABSTRACT

The objectives of Varian's development program were to design, manufacture, and test an advanced module employing high-concentration (400 suns) Fresnel lenses, AlGaAs/GaAs cells, and jet impingement cell cooling. The module efficiency goal was 14%.

The basic design approach was to select a module configuration employing a minimum of components; one that could be easily handled and assembled into larger arrays. The module employs a monolithic, acrylic lens panel containing twelve optical elements (0.687 m² active area) focused on twelve AlGaAs/GaAs solar cells. The lens panel and cells are supported by a molded, polycarbonate structural foam housing. An aluminum heat shield mounted inside the housing protects components from exposure to concentrated sunlight during periods of off-axis tracking. An injection molded polysulfone coolant manifold contains flow passages and nozzles for directing coolant to the back of the cells. The 67 pound module mounts easily at four points to a two-axis tracking structure. The module was also designed for thermal energy recovery from the ethylene glycol/water coolant if desired.

Two prototype modules were fabricated. Since molding tooling was not available for this phase of the program, the lens panel was approximated by installing discrete lenses in a machined acrylic "holder", and the housing and coolant manifold were fabricated by bonding together sheet material.

High efficiency packaged AlGaAs/GaAs concentrator solar cells were fabricated for the program in the Varian pilot production line. These cells used organometallic-vapor phase epitaxial (OM-VPE) material. All cells underwent and passed humidity and thermal cycling tests before incorporation into the modules. No cell degradation was observed.

The prototype modules were mounted and tested on Varian's solar tracker. The measured performance exceeded the program goals. The modules produced approximately 90 W_p at a solar flux of 760 W/m² and demonstrated a sunlight-to-electrical power conversion efficiency level of 16.45%, the highest ever achieved with a photovoltaic concentrator in a module configuration. Significantly, the Varian module performance was at a coolant inlet temperature of 50^o C and reflected the deduction of power required for coolant pumping. The module efficiency is 17.1% when corrected to a coolant inlet temperature of 28^o C.

Conceptual array designs using the module were also created during the program.

MODULE DEVELOPMENT PROGRAM (2 MODULES)
(SANDIA CONTRACT NO. 42-7248)

- OBJECTIVE: DESIGN, MANUFACTURE, AND TEST AN ADVANCED PV CONCENTRATOR MODULE USING A HIGH CR FRESNEL LENS, AlGaAs/GaAs CELL, AND JET IMPINGEMENT COOLING SUBSYSTEM
- ORIGINAL GOALS: 14% MINIMUM MODULE EFFICIENCY (50° C COOLANT INLET TEMPERATURE), COST-EFFECTIVE DESIGN (10⁵ M² OF APERTURE/YEAR), DURABLE (20-YEAR LIFE)
- EXTENSION GOALS: EXTENDED MODULE TESTING (INCLUDING THERMAL ENERGY RECOVERY) DETAILED ARRAY DESIGN USING DEVELOPED MODULE
- CONTRACT AMOUNT: \$190,201 (ORIGINAL CONTRACT)
\$ 74,967 (CONTRACT EXTENSION)
- CONTRACT AMOUNT: FEBRUARY 1980 - FEBRUARY 1981
(INCLUDES 4-MONTH EXTENSION)

MODULE DESIGN APPROACH

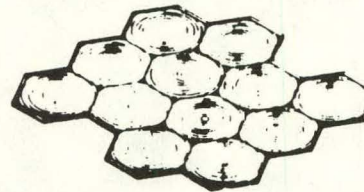
- SIMPLIFY DESIGN/IMPROVE RELIABILITY BY REDUCING NUMBER OF PARTS
- SELECT SIZE TO BE TRULY "MODULAR", EASILY HANDLED BY TWO PEOPLE
- DESIGN FOR EASE OF ASSEMBLY INTO ARRAYS OF VARIOUS SIZES/POWER LEVELS
- DESIGN FOR HIGH VOLUME PRODUCTION
- DESIGN FOR ULTIMATE USE IN HIGH TEMPERATURE, "TOTAL ENERGY" SYSTEM
- DESIGN PROTOTYPE MODULE TO SIMULATE PRODUCTION MODULE SO DATA IS VALID
(PRODUCTION TOOLING NOT AVAILABLE)

ADVANCED MODULE CONCEPT

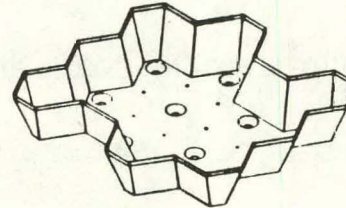
ELEMENTS

MODULE

FRESNEL LENS
(ACRYLIC)



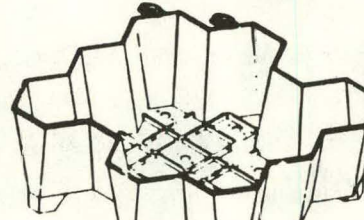
THERMAL SHIELD
(THIN ALUMINUM)



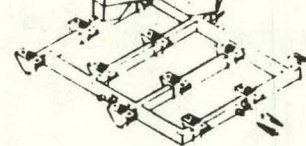
AlGaAs/GaAs SOLAR CELL HOLDERS
(POLYSULFONE)



HOUSING
(POLYCARBONATE STRUCTURAL FOAM)



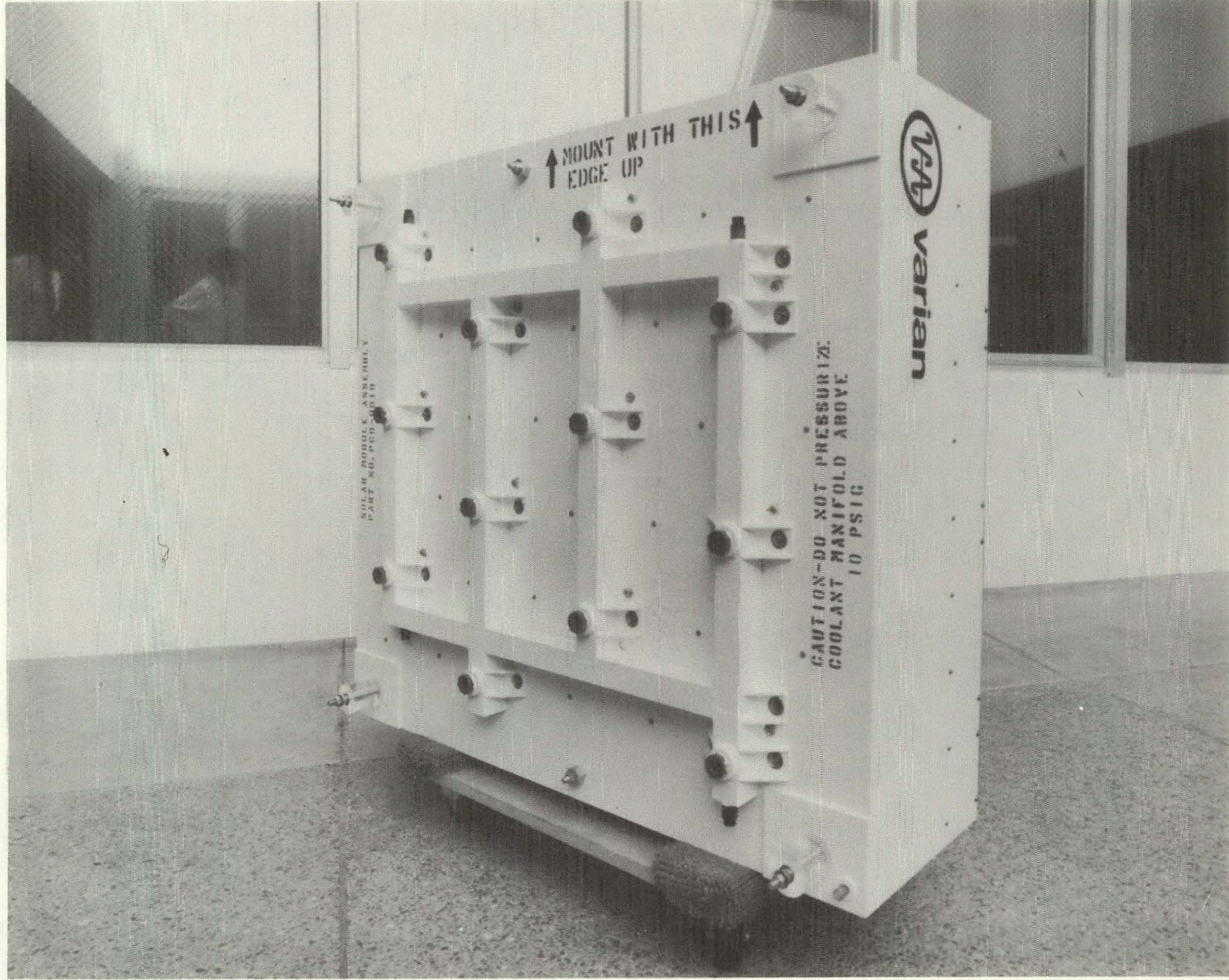
COOLANT MANIFOLD
(POLYSULFONE)

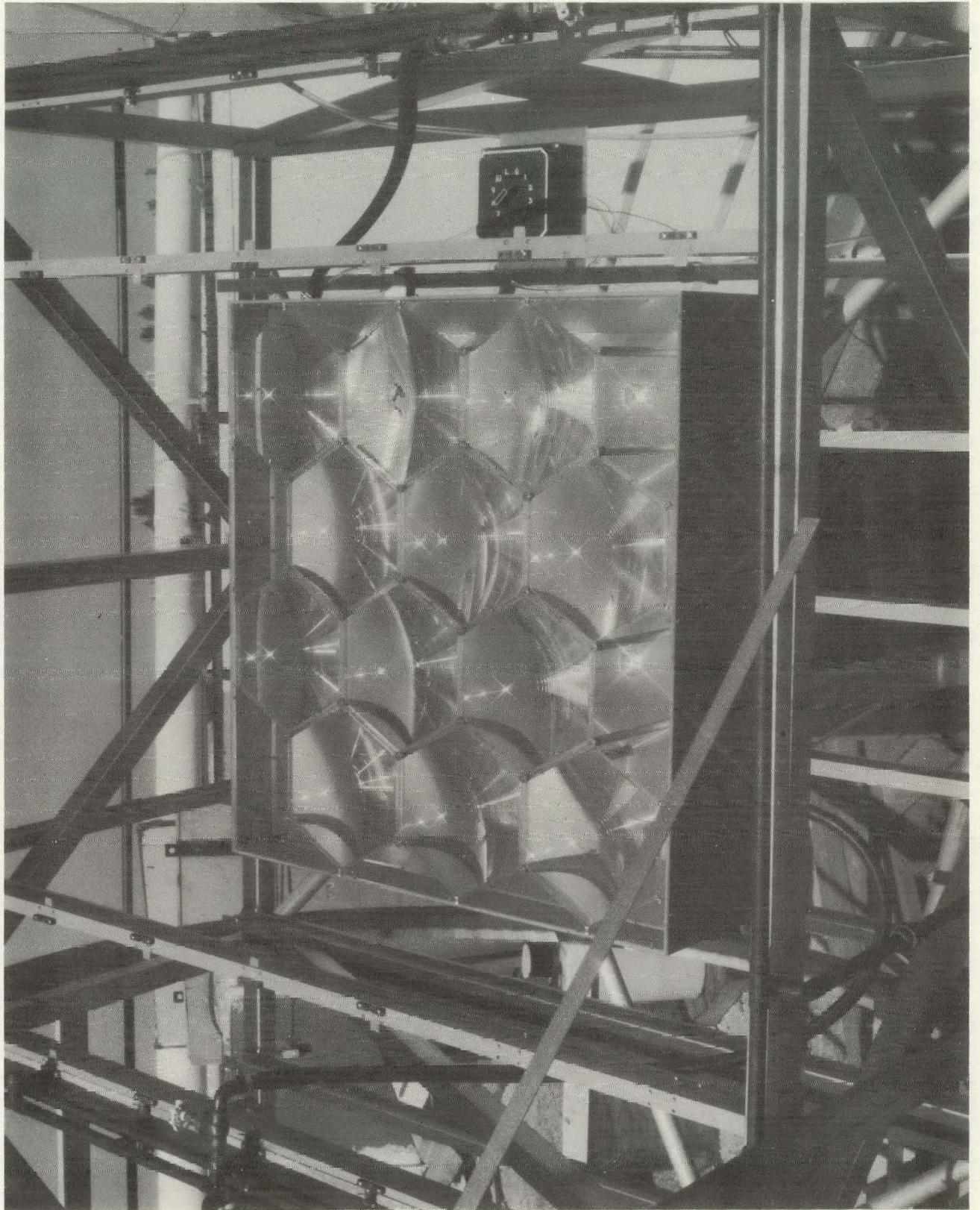


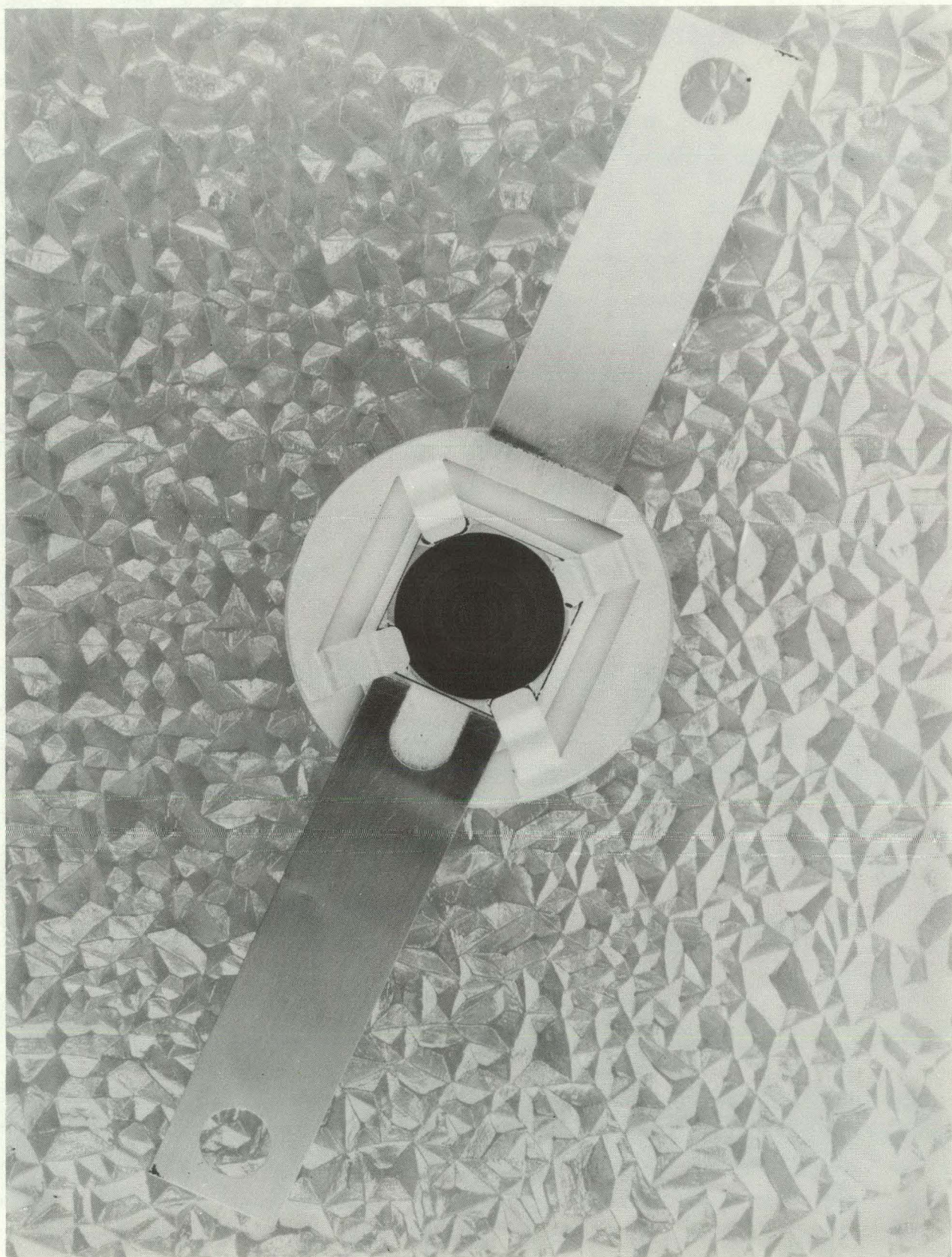
PROTOTYPE MODULE DESIGN/PERFORMANCE CHARACTERISTICS

- CELLS 12 OM-VPE AlGaAs/GaAs, 0.49-INCH DIAMETER ACTIVE AREA,
 $\eta_c = 20.3 - 23.5\%$
- LENSES: 12 CURVED-GROOVE FRESNEL (η_T 80%, EFFECTIVE CR = 377)
FIXED FOCAL LENGTH AT MAXIMUM POWER POINT (32.7 CM)
- ACTIVE APERTURE: 0.687 m²
- SIZE: 1 X 1 X .43 METERS
- WEIGHT: 87LB, DRY, 97LB, WITH COOLANT (PROTOTYPE)
60LB, DRY, 66LB, WITH COOLANT (PRODUCTION)
- COOLING: ACTIVE (JET-IMPINGEMENT) WITH ETHYLENE GLYCOL/WATER
(50/50 MIXTURE), 1 - 2 GALLONS/MINUTE
- INTERCONNECT WIRING: 3 SERIES/4 PARALLEL
- PCWER PRODUCED: 100 W @ 50° C COOLANT INLET TEMPERATURE AND 1000 W/m²
INSOLATION (2.6 VOLTS, 38.8 AMPS)
- TRACKING ACCURACY REQUIRED: ± 0.2 DEGREE





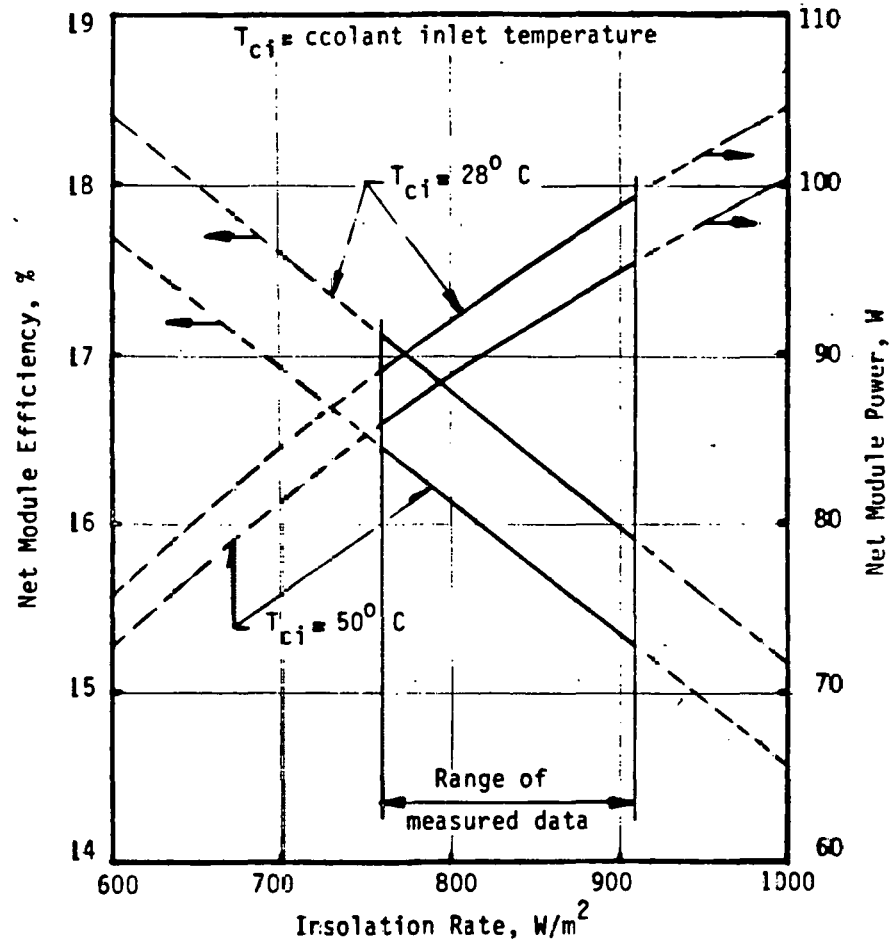




MODULE COMPONENT TESTS

- LENS/CELL SPACING: 32.7 cm (\pm 0.25 cm) FOR MAXIMUM POWER
- LENS TRANSMISSION: 80% AT MAXIMUM POWER SPACING
- LENS ENVIRONMENTAL TESTING: 5% LOSS IN TRANSMISSION AFTER 15 CYCLES FROM -30 TO 75° C (3 HOUR CYCLE) AND 15 HOURS AT 65° C AND 95% RH
- CELL ENVIRONMENTAL TESTING: NO DEGRADATION AFTER 15 CYCLES FROM -30 TO 125° C (4 HOUR CYCLE), 50 HOURS AT 65° C AND 95% RH, AND IMMERSION IN BOILING WATER FOR SEVERAL HOURS
- CELL COOLING SUBSYSTEM TESTING: NOZZLE DIAMETERS OF 0.14, 0.24, AND 0.32 CM
NOZZLE-TO-CELL SPACING OF 1 AND 2 DIAMETERS
VARIOUS COOLANT FLOW RATES
EMPIRICAL RELATIONSHIP FOR PREDICTING ΔT_{BL} (CAN BE HELD TO 10° C OR LESS). SMALLER NOZZLE MORE EFFECTIVE THAN LARGER

NET MODULE EFFICIENCY AND GENERATED POWER



CONCLUSIONS

- 16.45 - 17.1% EFFICIENCY IS HIGHEST EVER ACHIEVED WITH A PV CONCENTRATOR IN A MODULE CONFIGURATION
- EFFICIENCY GOAL OF 14% EXCEEDED IN A 6-MONTH PROGRAM CONDUCTED ON SCHEDULE AND WITHIN BUDGET
- AlGaAs/GaAs PACKAGED CELLS ROUTINELY PRODUCED WITH EFFICIENCIES OF 21 - 23% (AT 50° C)
- MODULE DESIGNED TO OPERATE IN A "TOTAL ENERGY" MODE (THERMAL ENERGY RECOVERY)

PERFORMANCE OPTIMIZATION OF THE ASR OPTICAL MODULE

by

Arizona Scientific Research
10121 Catalina Hwy.
Tucson, AZ 85715

Contract No.: 13-5162
Principal Investigator: Wally Meinel
Contract Amount: 235,016
Contract Duration: June 1979 - Jan 1981

PROJECT DESCRIPTION

This project is part of the Concentrator Technology Development Program at Sandia. There are three tasks involved in this project. Task One calls for design performance optimization for the ASR Optical Module. This optimization minimizes all loss mechanisms, both optical and electrical while keeping the design cost effective. Task Two is for fabrication and testing of six prototype modules utilizing the information generated in Task One, and for maximizing the module efficiency. Task Three calls for module production cost estimates at two production volumes, $10^5 \text{ m}^2/\text{year}$ and $10^7 \text{ m}^2/\text{year}$. This costing will be used to determine the cost effectiveness of the ASR Optical Module design.

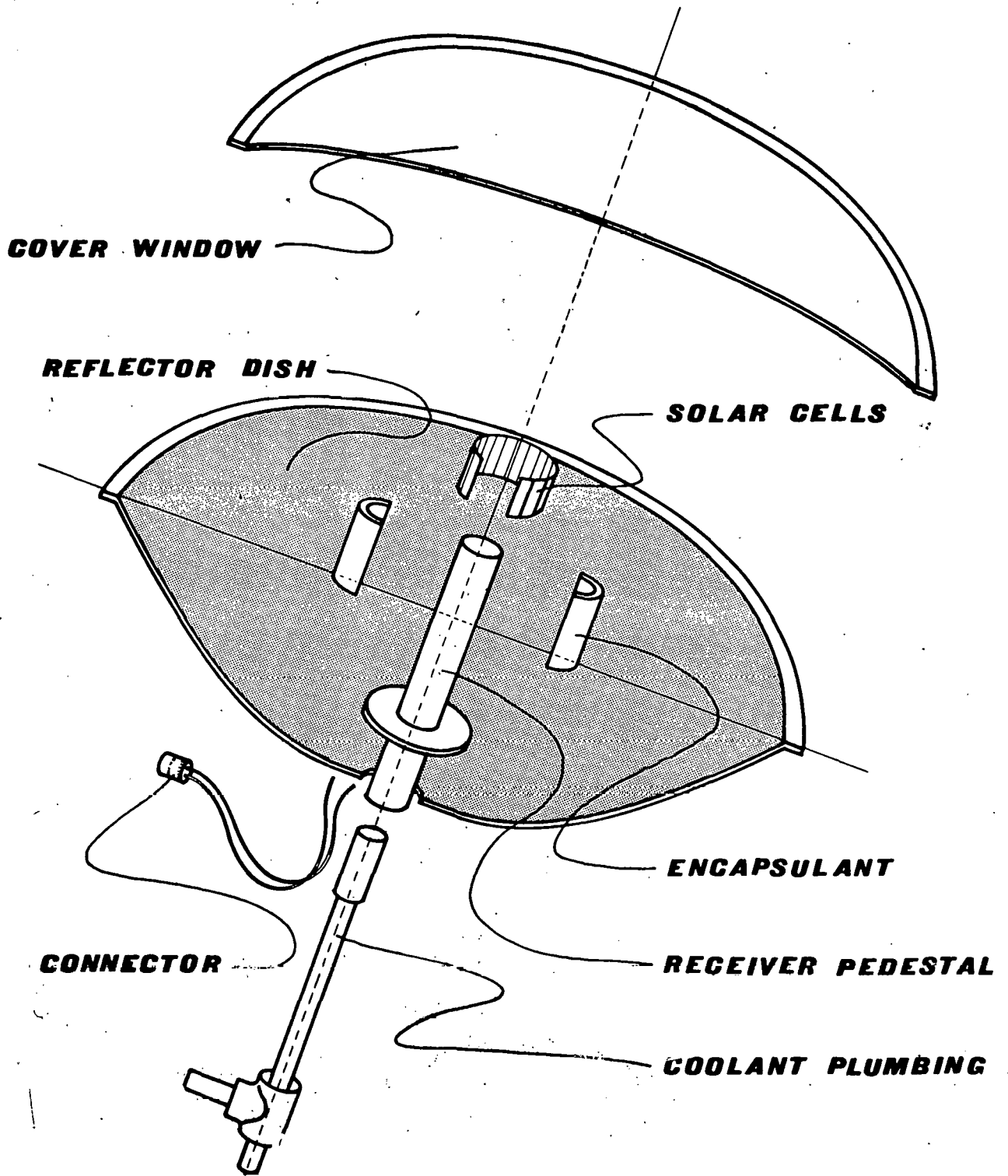
CURRENT STATUS

The design optimization is completed, the prototype receivers have been fabricated and solar cells have been mounted. The reflector dish and manufacturing cost estimates are in the process of completion. Testing and evaluation of the prototype units will follow.

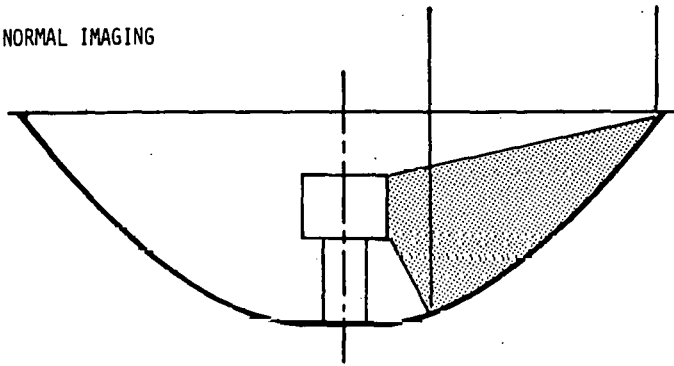
KEY RESULTS

The design for prototype fabrication consists of a 32.5" diameter dish. The central receiver is 2.1" in diameter with 20 solar cells connected in series. The solar cells are .395" wide by 2.4" long and operate at a concentration of 50X. The cells are overlapped to provide a dense array. The dish consists of a fiberglass-balsa wood laminate with aluminum metalization. A window is to be placed over the dish to provide environmental protection. Process verification tests were carried out for each part of the prototype design. The tests were: 1) solar cell efficiency, 2) cell laydown, 3) cell encapsulation, and 4) dish substrate.

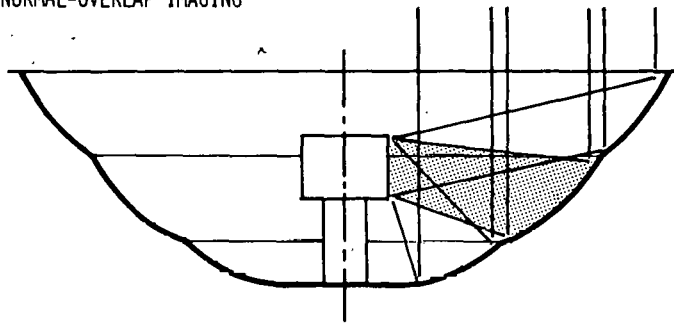
ASR OPTICAL MODULE



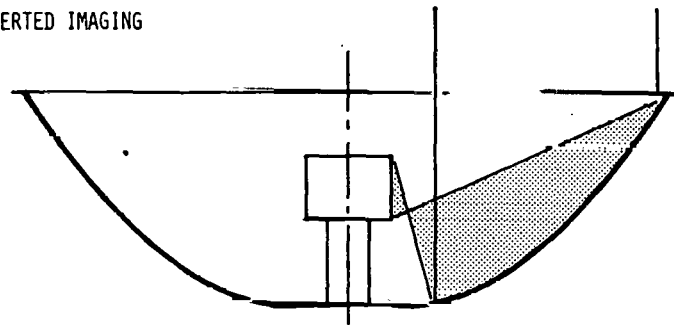
NORMAL IMAGING



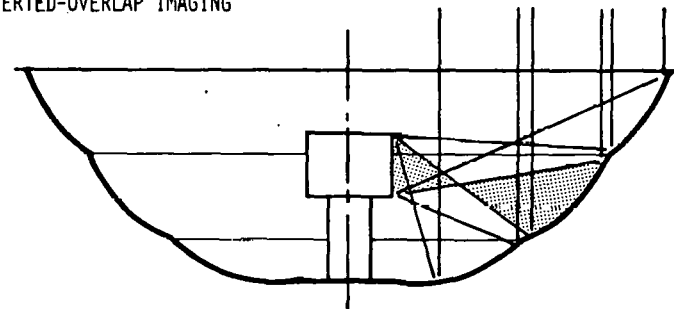
NORMAL-OVERLAP IMAGING

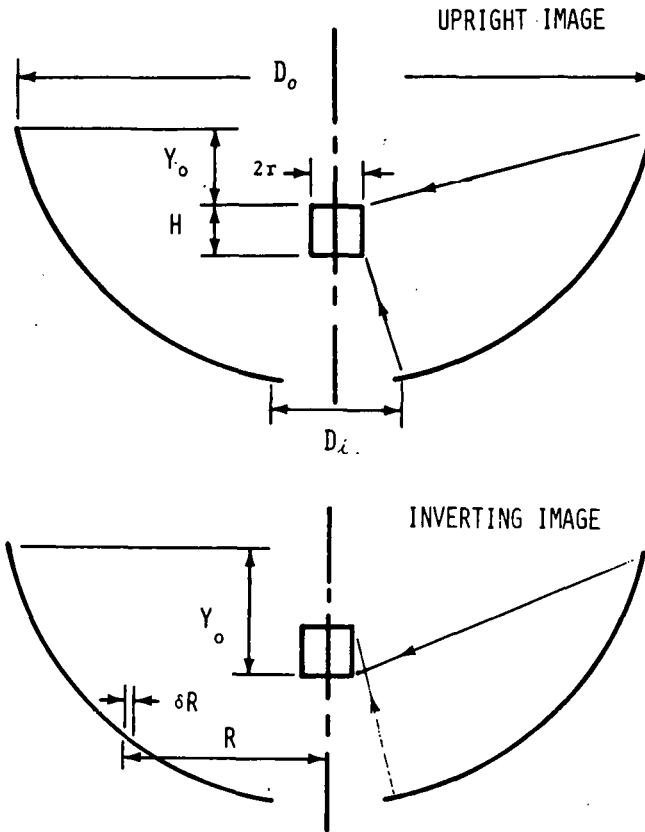


INVERTED IMAGING



INVERTED-OVERLAP IMAGING



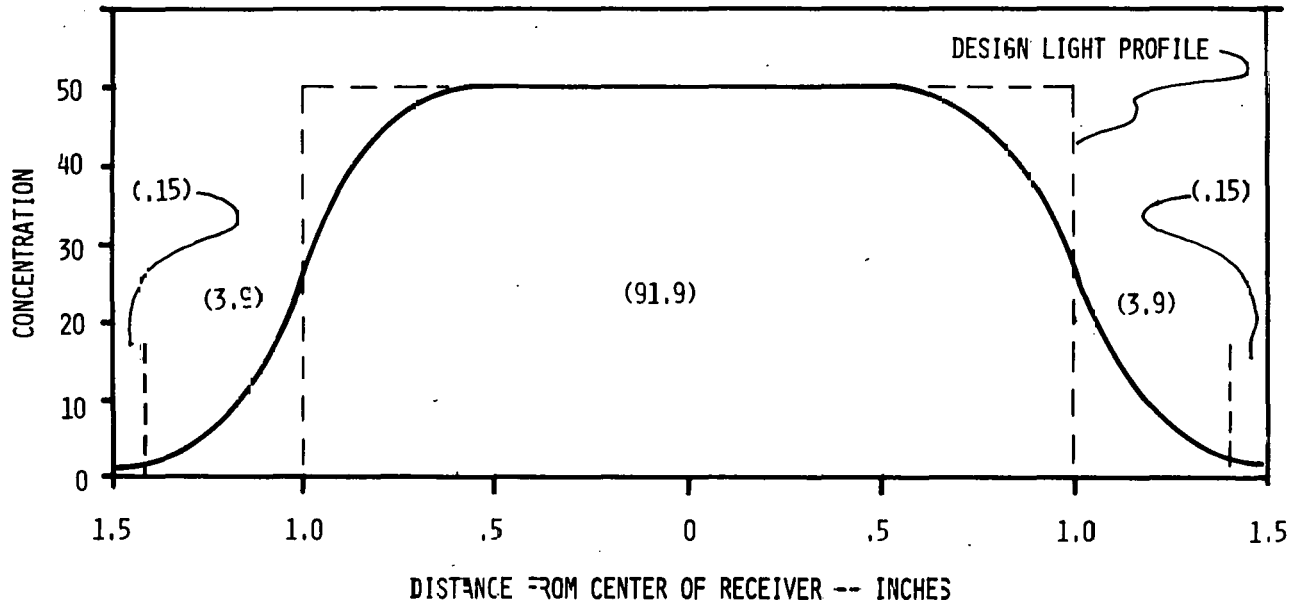


THE EQUATION FOR CONCENTRATION RATIO IS:

$$K = \frac{(D_o - D_i)}{2rH} \left[\frac{D_o}{2} - \frac{(D_o - D_i)}{4} \right]$$

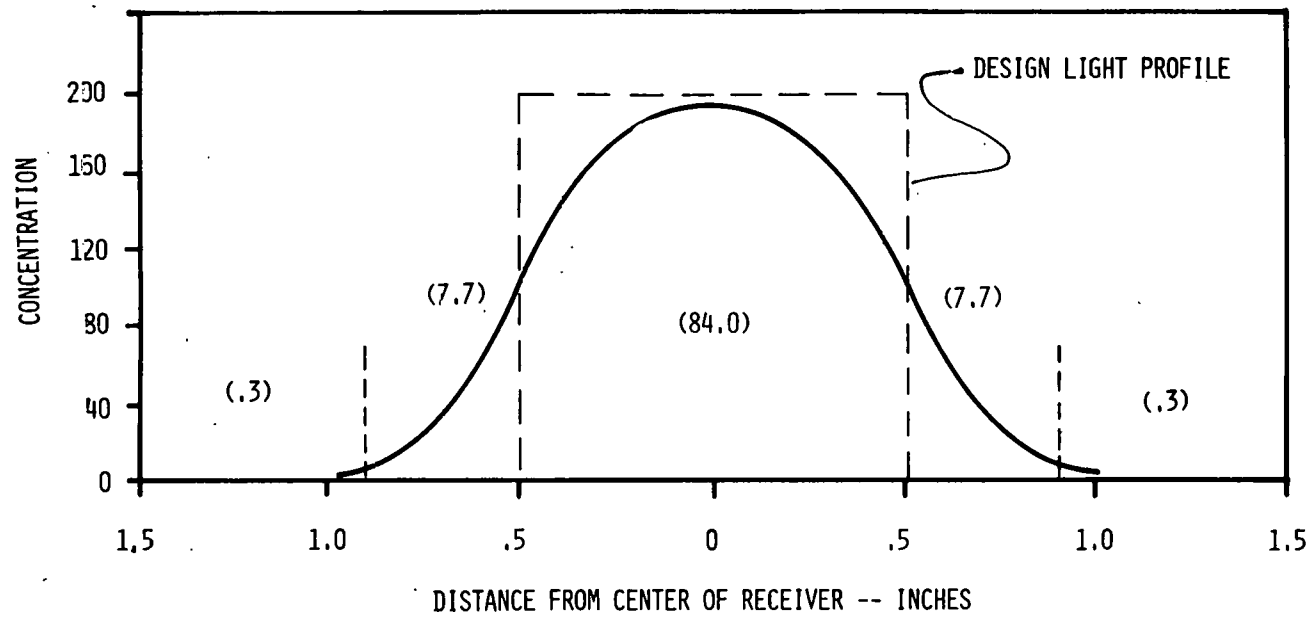
THE EQUATION FOR UNIFORM CONCENTRATION IS:

$$K = \frac{2R \, dR - (dR)^2}{2rdH}$$



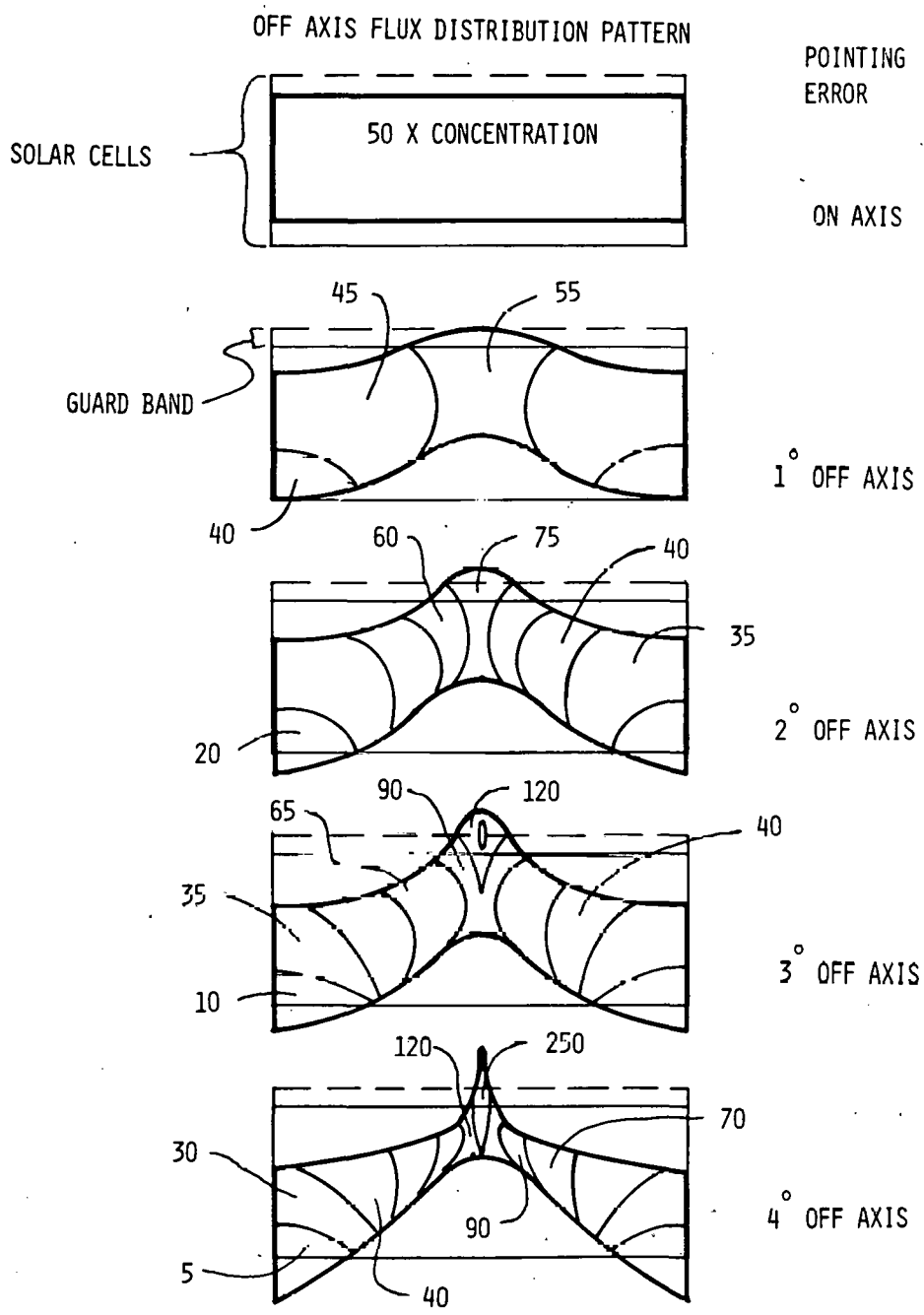
FINAL DESIGN AXIAL LIGHT DISTRIBUTION

THE NUMBERS IN PARENTHESES INDICATE THE PERCENT ENERGY CAPTURED IN EACH SECTION. THE LIGHT DISTRIBUTION WAS DETERMINED BY THE CONVOLUTION OF SUN SHAPE, SPECULARITY ($\sigma=0.34^\circ$) AND SLOPE ERROR ($\sigma=0.4^\circ$) WITH THE DESIGN LIGHT PROFILE. NOTE THE UNIFORM CONCENTRATION IN THE CENTRAL 1".

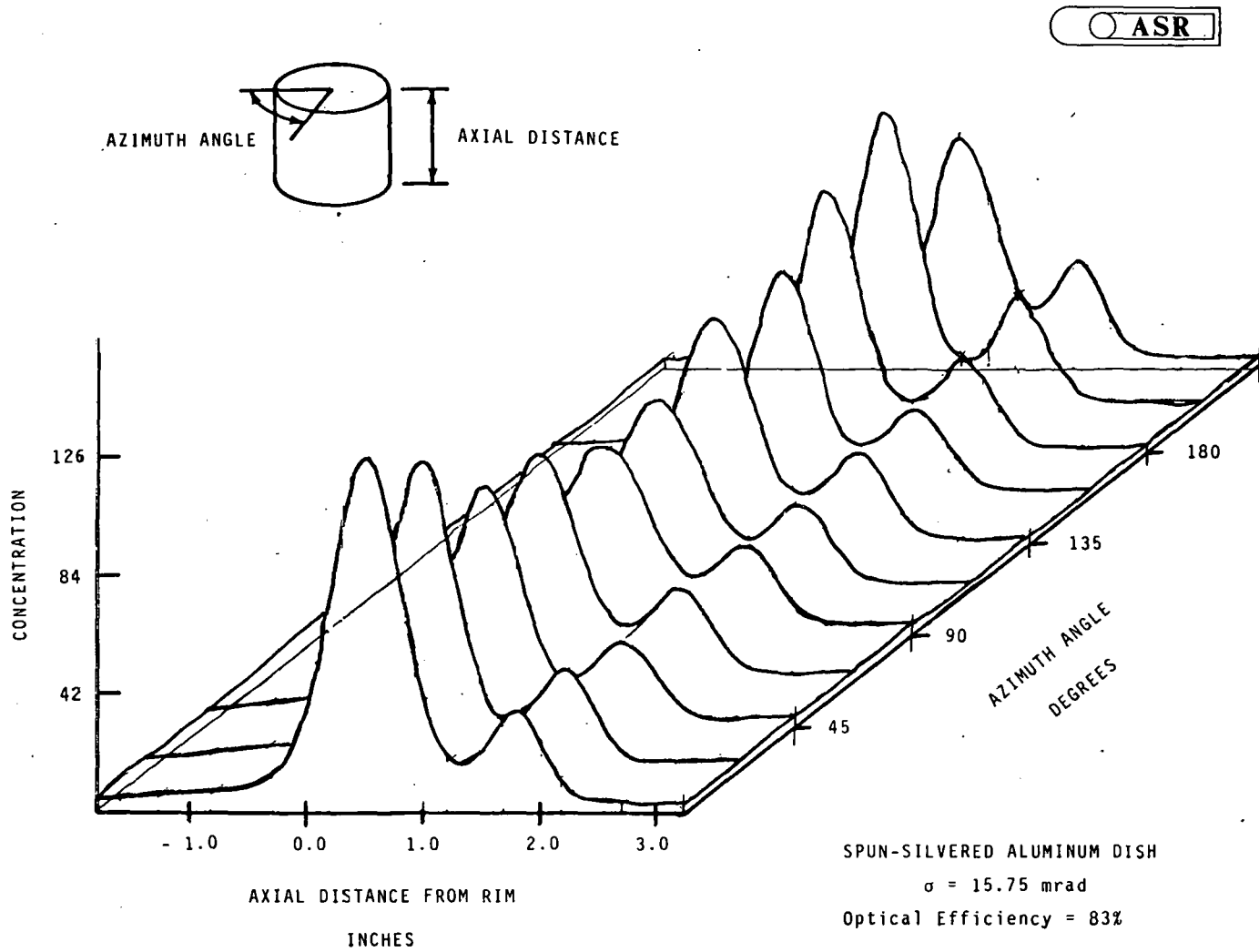


LIMITING CASE FOR UNIFORM LIGHT DISTRIBUTION

THE NUMBERS IN PARENTHESES INDICATE THE PERCENT ENERGY CAPTURED IN EACH SECTION. THE LIGHT DISTRIBUTION WAS DETERMINED BY THE CONVOLUTION OF SUN SHAPE, SPECULARITY ($\sigma=0.34^\circ$) AND SLOPE ERROR ($\sigma=0.4^\circ$) WITH THE DESIGN LIGHT PROFILE. A RECEIVER LONGER THAN 1" WILL HAVE A CENTRAL SECTION WITH UNIFORM CONCENTRATION.



THE OFF AXIS IMAGE DEGRADATION IS SHOWN.
(THE CYLINDRICAL SURFACE IS UNFOLDED)



BEAM SPLITTER MODULE RESULTS

Paul Gregory, Peter Borden and Osborne Moore
Varian Associates, Inc.
Palo Alto, CA 94303

A ten-unit, 20-cell beam splitting module has been built and tested, yielding an efficiency of 20.34% with 839 W/m² insolation and 37°C coolant inlet temperature. Each of the ten units consists of a f4.2 curved-groove fresnel lens mounted above a dichroic filter, which ideally reflects light below 1.65 eV to a silicon cell and transmits light above 1.65 eV to a 20% AlGaAs cell. The effective concentration on each cell is about 240 suns, which is the ratio of lens to total cell areas. The units are made of acrylic, with aluminum heat shields and a common aluminum I-beam support. The cells mount in plastic jet impingement coolers.

Both types of cell have a 1/3" diameter radial grid pattern and are packaged in the standard Varian ceramic baseplate package. The silicon cells have a 0.7-micron deep emitter to enhance red response. The substrates are high-resistivity 111 FZ material. These cells test at 15-16% efficiency at 400 AM2 suns, full spectrum. The AlGaAs cells are grown with LPE and have some variations in bandgap (1.58-1.68 eV) due to the extreme sensitivity of AlGaAs growths by LPE to the concentration of aluminum in the melt. In actual operation, the AlGaAs cells contribute about 14.8% to module efficiency and the silicon cells contribute about 5.6%.

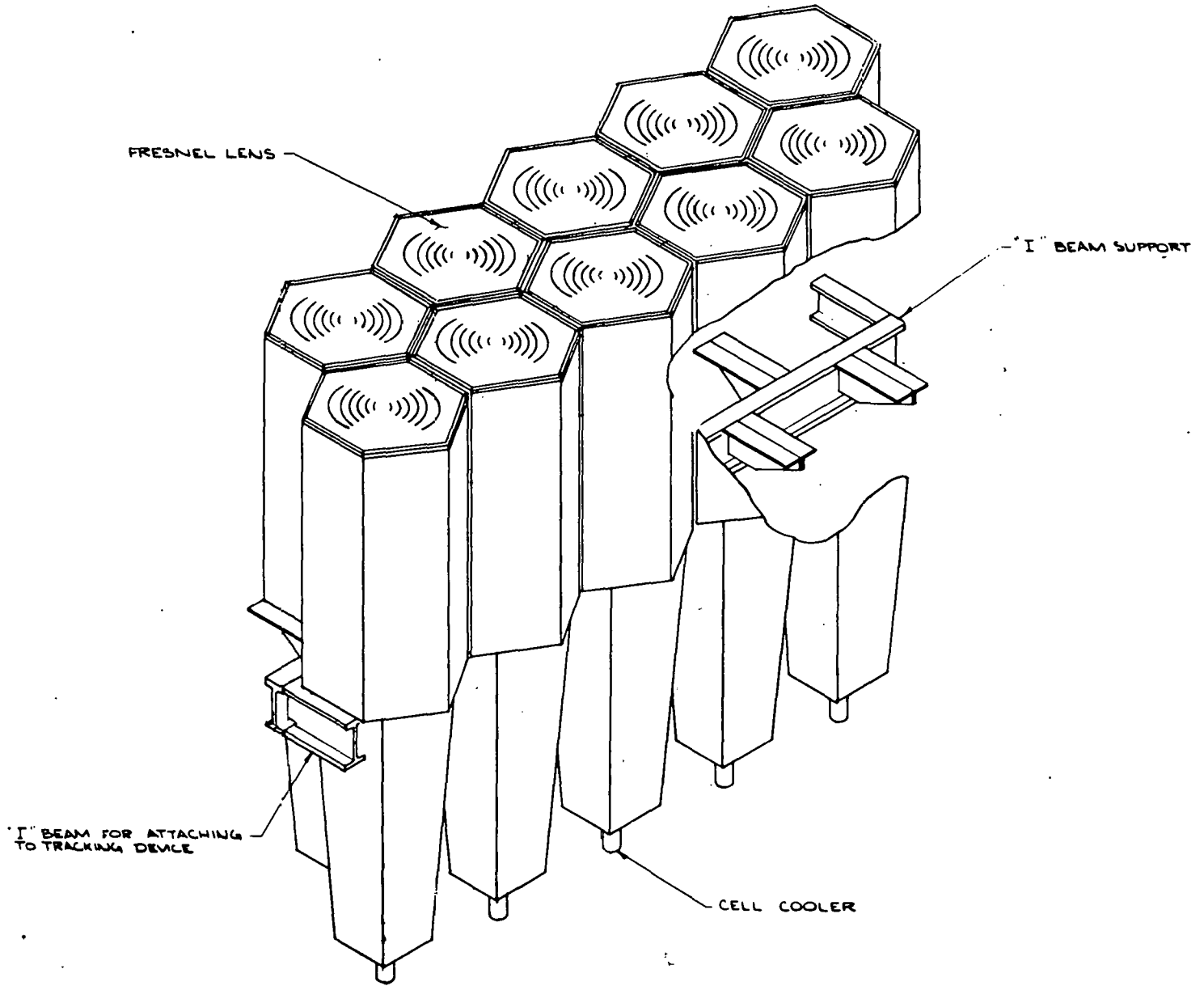
The module is wired for a single electrical output. This is possible because the peak power voltage of an AlGaAs cell is close to double that of a silicon cell. The configuration is three parallel strings, one with ten silicon cells and two with five AlGaAs cells each. A typical output at peak power is about 8.5 amps and 6 volts.

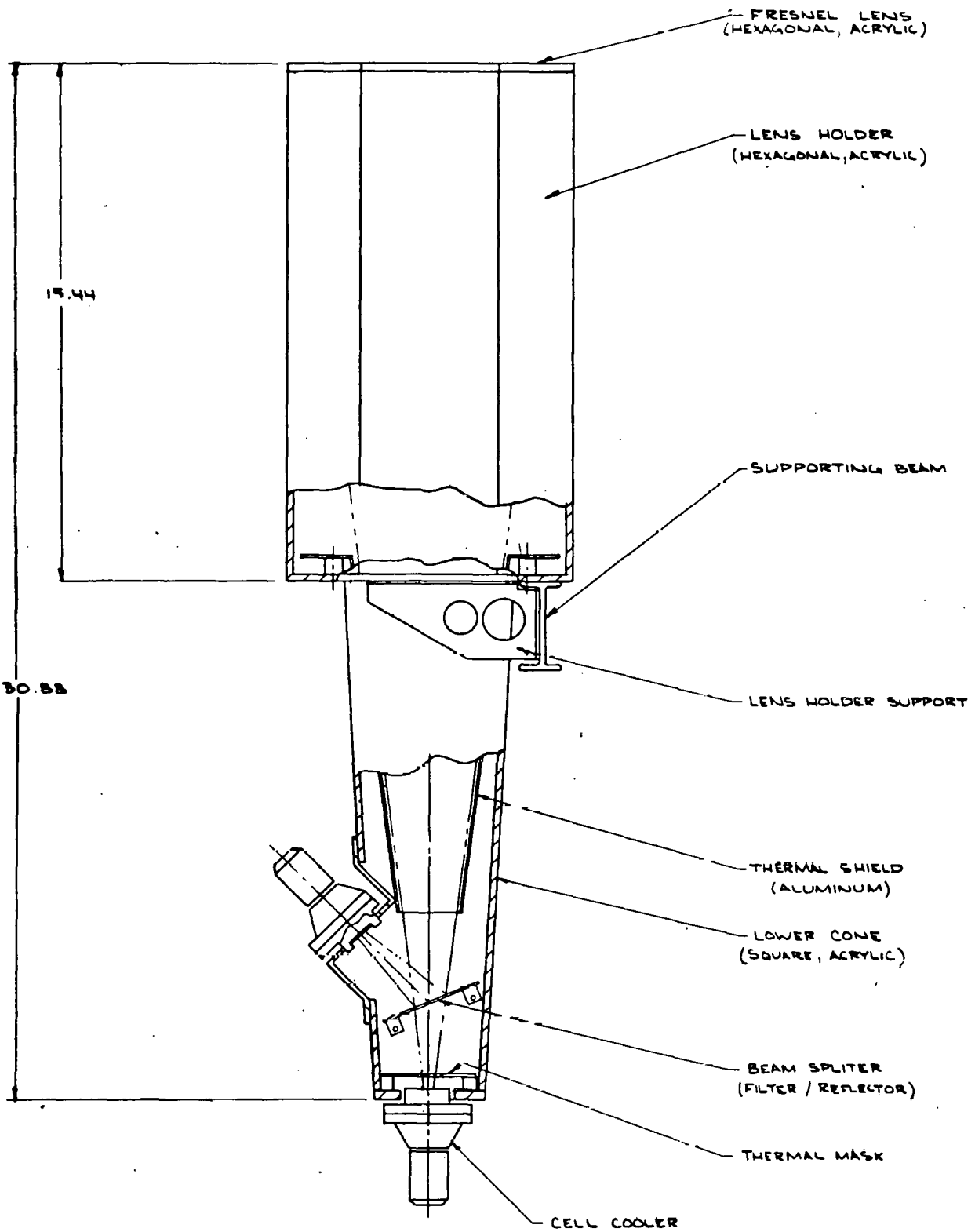
Various loss mechanisms have been identified. A major one is in the filters, which are about 90% transmissive to the AlGaAs cells and have a cutoff at about 1.55 eV, so that a significant amount of below-bandgap light transmits to the AlGaAs cells. In 1978, Varian had reported 27.0% efficiency from a single converter, a result which did not include lens loss. Taking into account lens transmission of 80% and loss due to the low filter cutoff, the estimated cell plus filter efficiency is 27.3%, in good agreement with the earlier result.

The system in its present form embodies deficiencies which we believe limit its practical value. The first of these is the cost of the filters. These require multiple-layer dielectric coatings to provide a sufficiently sharp cutoff and are hence expensive to fabricate. The second is the complexity of the long focal length, multiple element optical system, which makes alignment and optimization time consuming.

The significance of the module is that it is the first demonstration of the concept of spectral splitting at the module or array level, and shows the gain in efficiency possible by such an approach. Furthermore, while this module may not be cost effective, it has the advantage that its component parts may be individually chosen, aligned, and isolated. In this sense, it represents a tool for measuring what can be expected from other spectrum splitting approaches, such as stacked or monolithic cells.

This work was sponsored under Sandia contract SAND-13-0308.





I-V PLOT FOR CELL #
 20.34 Efficiency
 839 Insolation:
 8.60 Isc
 .835 Fill Factor
 6.375 Voc
 45.785 Peak Power

Module IV curve

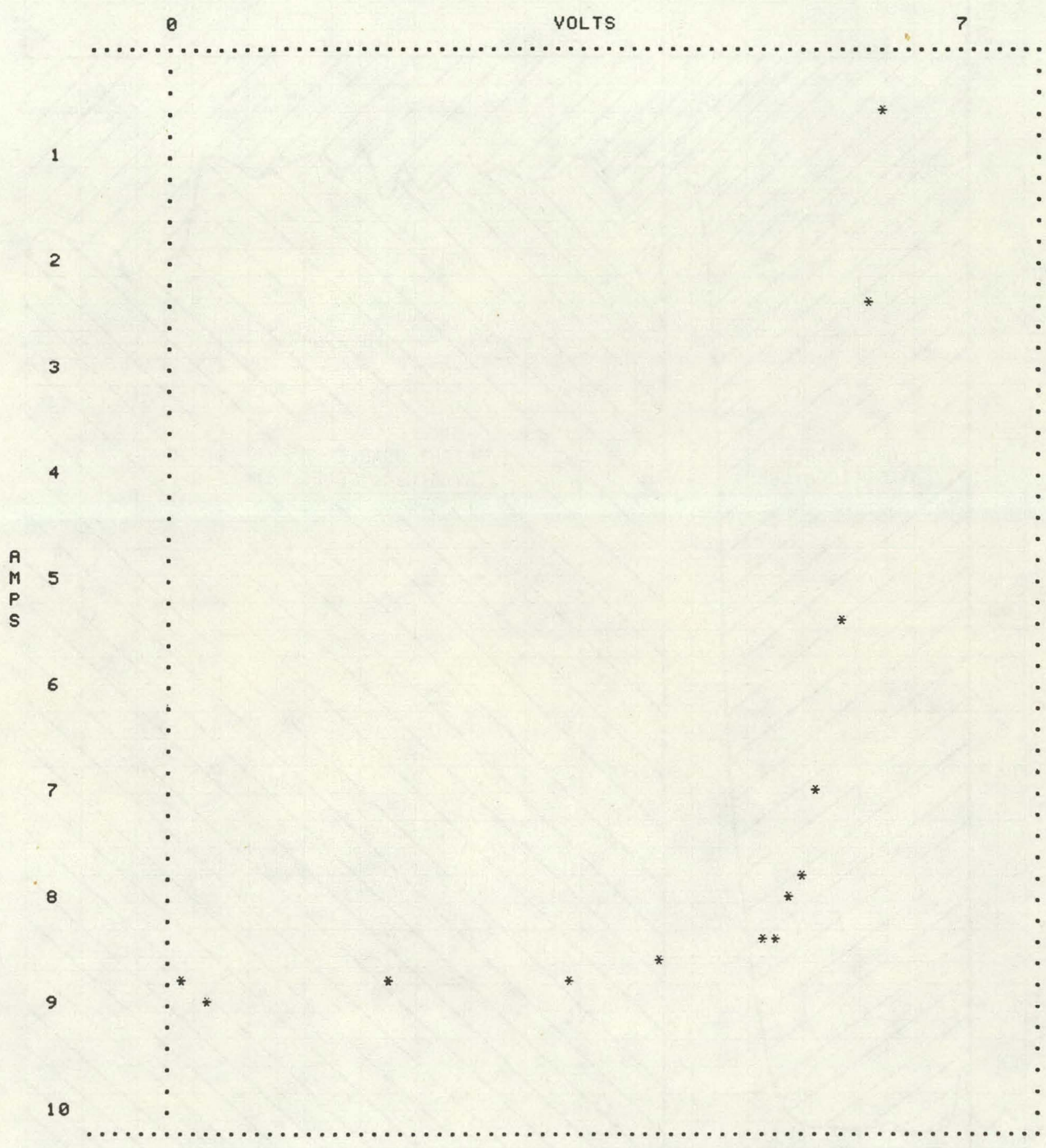
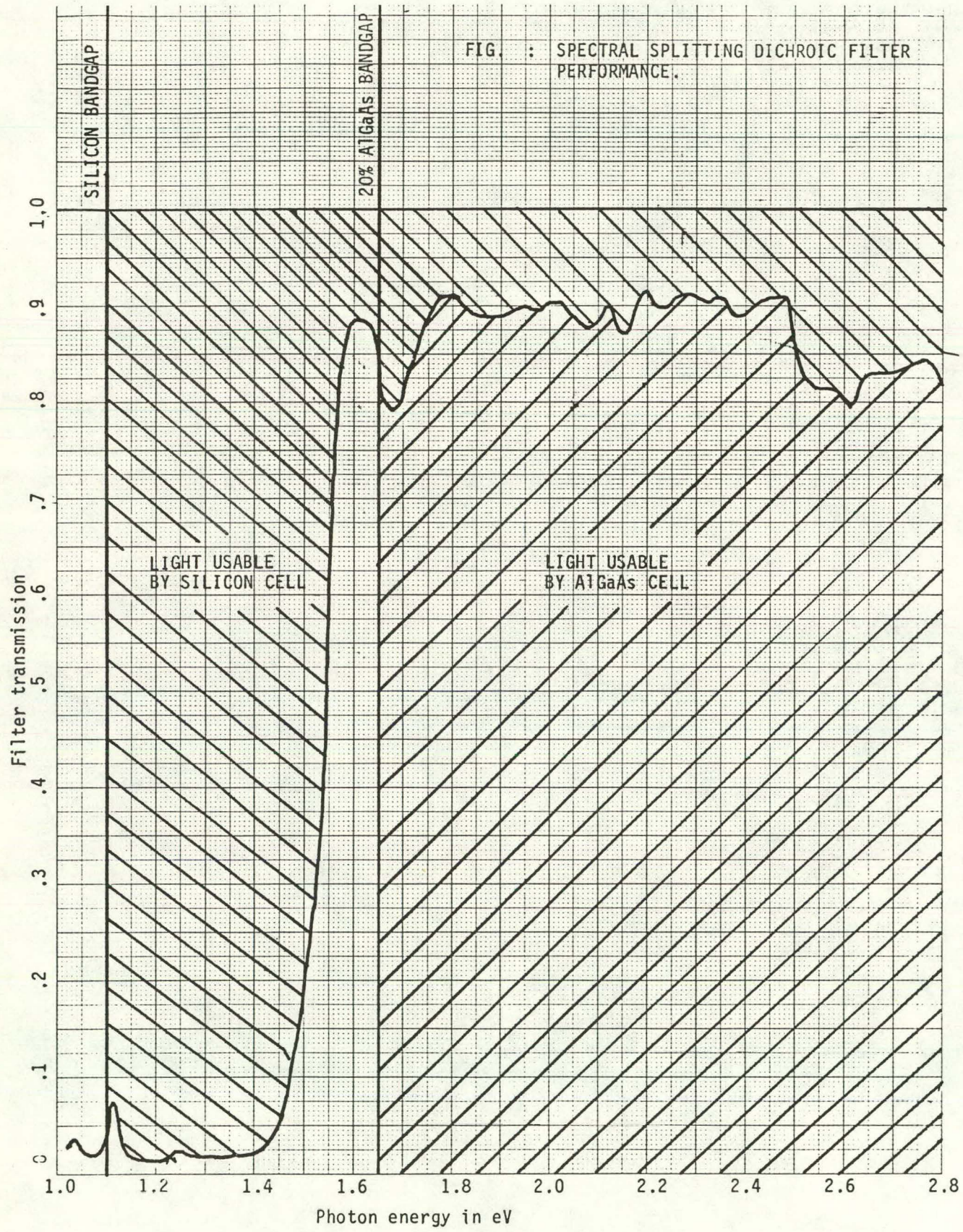
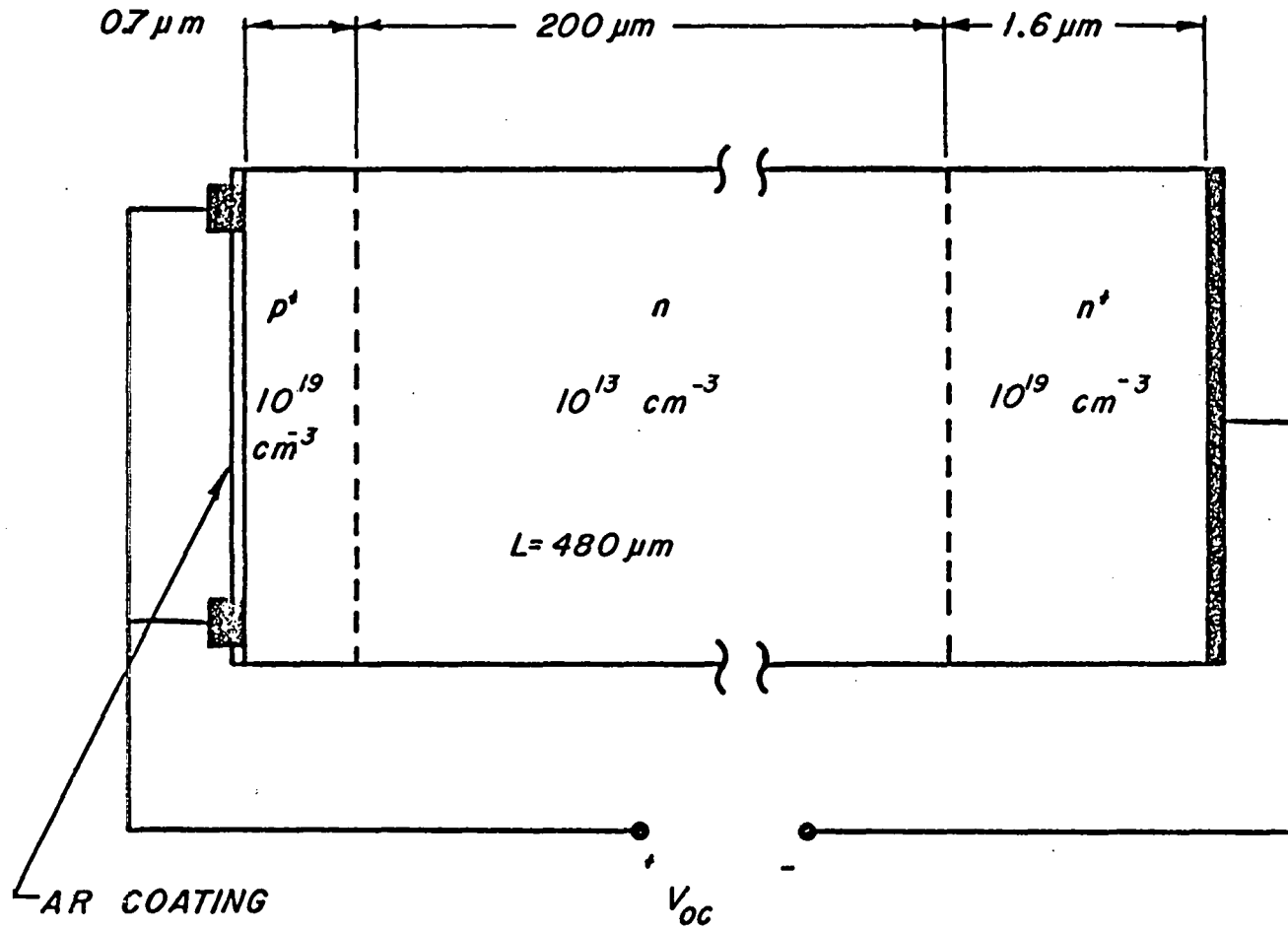


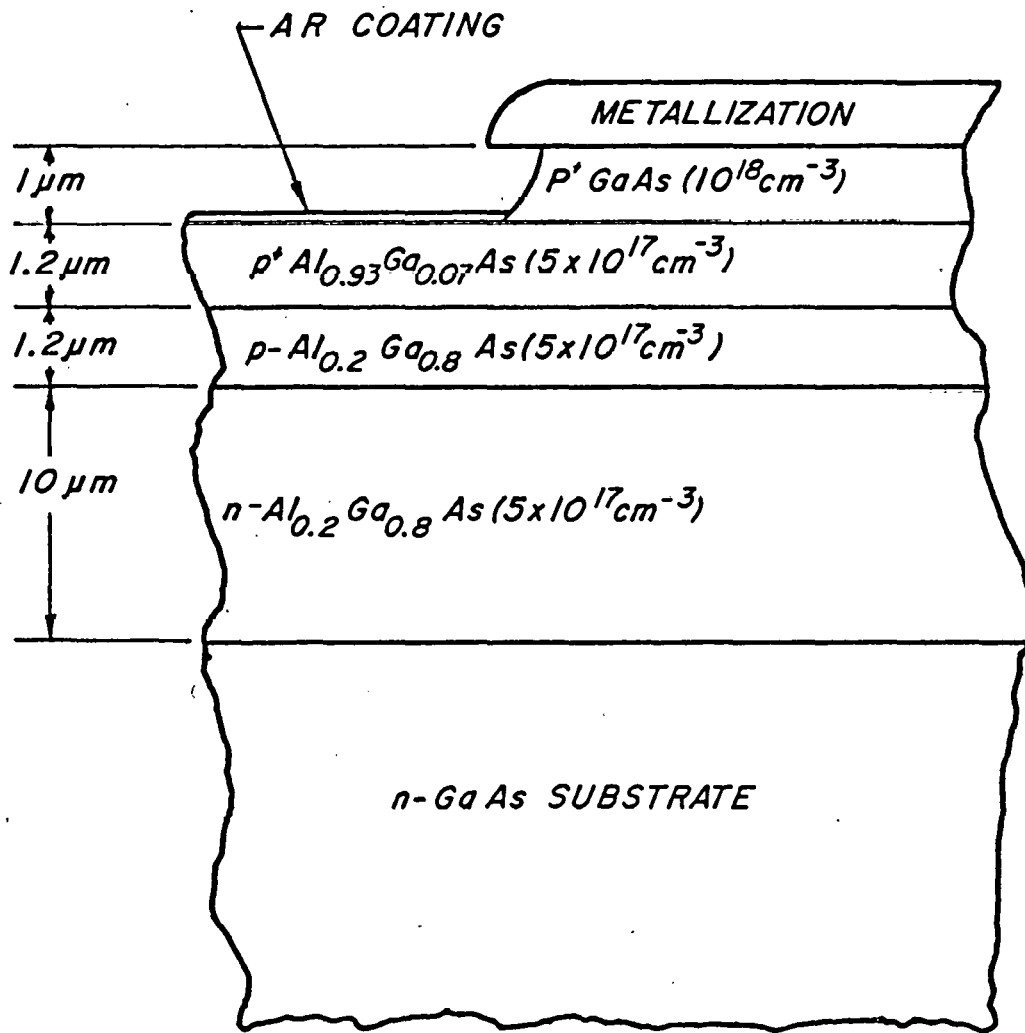
FIG. : SPECTRAL SPLITTING DICHOIC FILTER PERFORMANCE.



SCHEMATIC CROSS SECTION OF Si SOLAR CELL



SCHEMATIC CROSS-SECTION OF 1.65 eV SOLAR CELL



Schematic Cross-Section of 1.65eV Solar Cell.
 Dopings are in units of (cm^{-3})
 Dimensions are in microns.

DESIGN AND DEVELOPMENT OF A LAMINATED
FRESNEL LENS FOR POINT FOCUS
PV SYSTEMS

BY

GENERAL ELECTRIC COMPANY
P.O. BOX 8661
PHILADELPHIA, PA 19101

PRINCIPAL INVESTIGATOR: R. C. HODGE

CONTRACT NO.: 46-0063

CONTRACT AMOUNT: \$171,800

CONTRACT TERM: OCTOBER 19, 1979 TO
JULY 18, 1980

PROJECT DESCRIPTION

The objective of this program was to design and investigate the technical feasibility of a laminated parquet point focus Fresnel lens using injection molded flat Fresnel lens elements. The program addressed three basic areas; lens design and tooling fabrication, lamination design development, injection molding of prototype lenses, and subsequent lens testing.

CURRENT STATUS

A 6.65 inch square, flat Fresnel lens was designed with a geometric concentration ratio of 120. This lens represents the basic optical element in a glass superstrate flat Fresnel lens laminate assembly. This program dealt with the development of a 7 inch square prototype laminate lens assembly. A subsequent program is planned to develop a full-size 5 x 5 parquet lens assembly. The lamination design effort screened candidate glass superstrates and adhesives. Over one hundred 6.7 inch square Fresnel lenses were molded using conventional injection molding techniques. Prototype laminate lens assemblies were then fabricated using the selected glass and adhesive. Both optical transmission and accelerated environmental exposure tests were then performed on these prototype assemblies.

KEY RESULTS

A laminated point focus Fresnel lens assembly was defined which has a potential direct manufacturing cost of less than a \$1/ft² and a lens transmission efficiency of greater than 80%. The lamination approach permits the use of a glass superstrate, with its proven durability, and a thin (< .080 inch) plastic Fresnel lens. The lens design was validated by testing compression molded control lenses. Transmission efficiencies of 84-86% and a flux uniformity of 1.18 (I_p/I_{avg}) were measured.

Final injection molding trial lenses exhibited transmission efficiencies of 73-75%. This represented a 40% improvement from the initial molding trials. Insight gained into lens and mold design as well as optimum process parameters indicates that injection molded lens with transmission efficiencies of 80% are feasible.



LAMINATED INJECTION MOLDED
POINT FOCUS FRESNEL LENSES

SIXTH PROJECT INTEGRATION MEETING
PHOTOVOLTAIC CONCENTRATOR TECHNOLOGY DEVELOPMENT PROJECT
SANDIA LABORATORIES
NOVEMBER 5 and 6, 1980

GENERAL ELECTRIC COMPANY
ADVANCED ENERGY PROGRAMS DEPARTMENT



PROGRAM OBJECTIVE/BASIC AREAS



OBJECTIVE

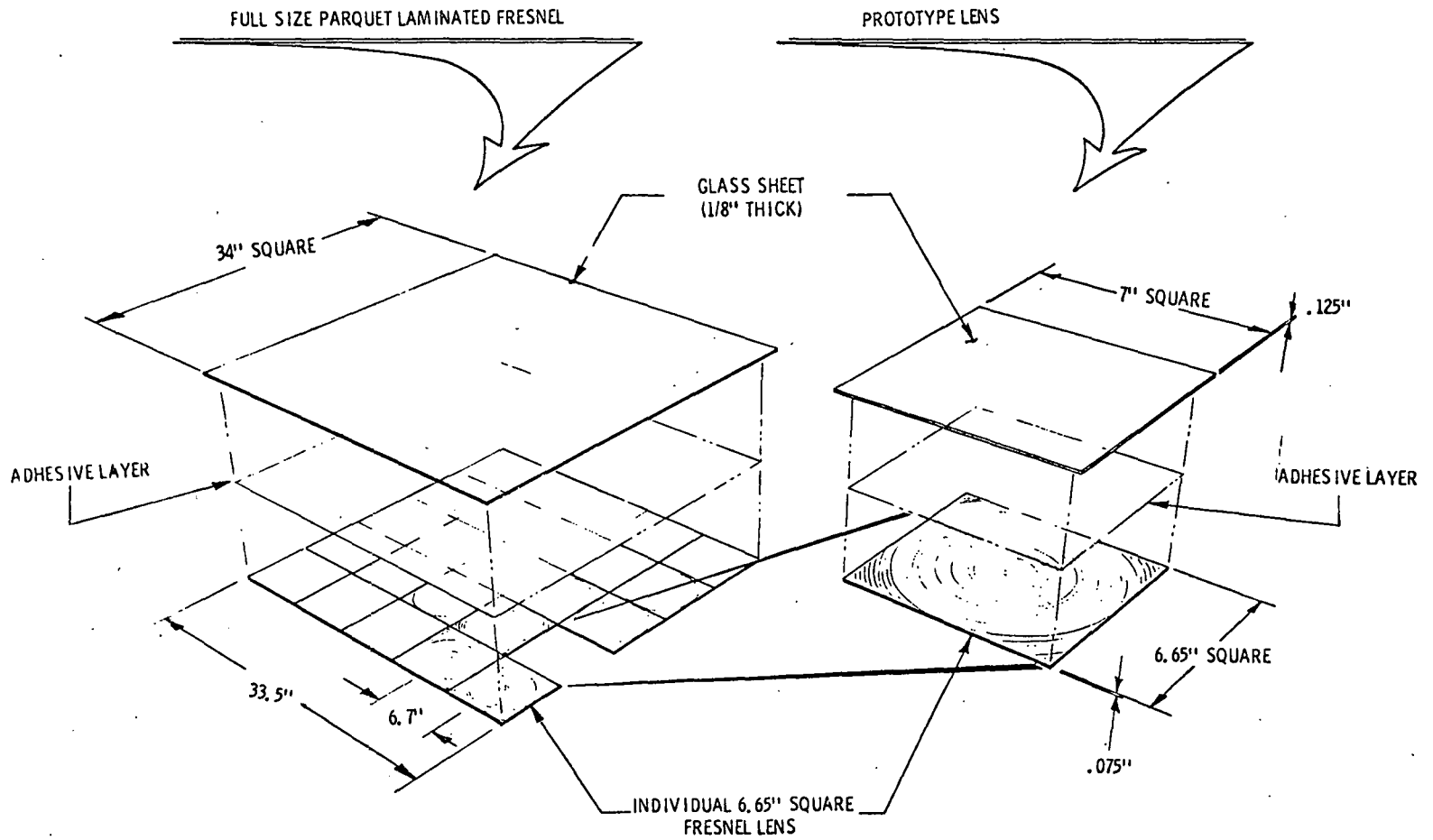
DESIGN AND INVESTIGATE THE TECHNICAL FEASIBILITY OF A LAMINATED POINT FOCUS FRESNEL LENS PARQUET USING INJECTION MOLDED INDIVIDUAL LENSES.

BASIC AREAS

1. LENS DESIGN AND TOOLING FABRICATION
2. LAMINATION PROCESS DEVELOPMENT
3. LENS MOLDING AND EVALUATIONS
4. LENS COST ANALYSIS



LAMINATED FRESNEL LENS DESIGN





**GENERAL
ELECTRIC**

DESIGN REQUIREMENTS/DESCRIPTION



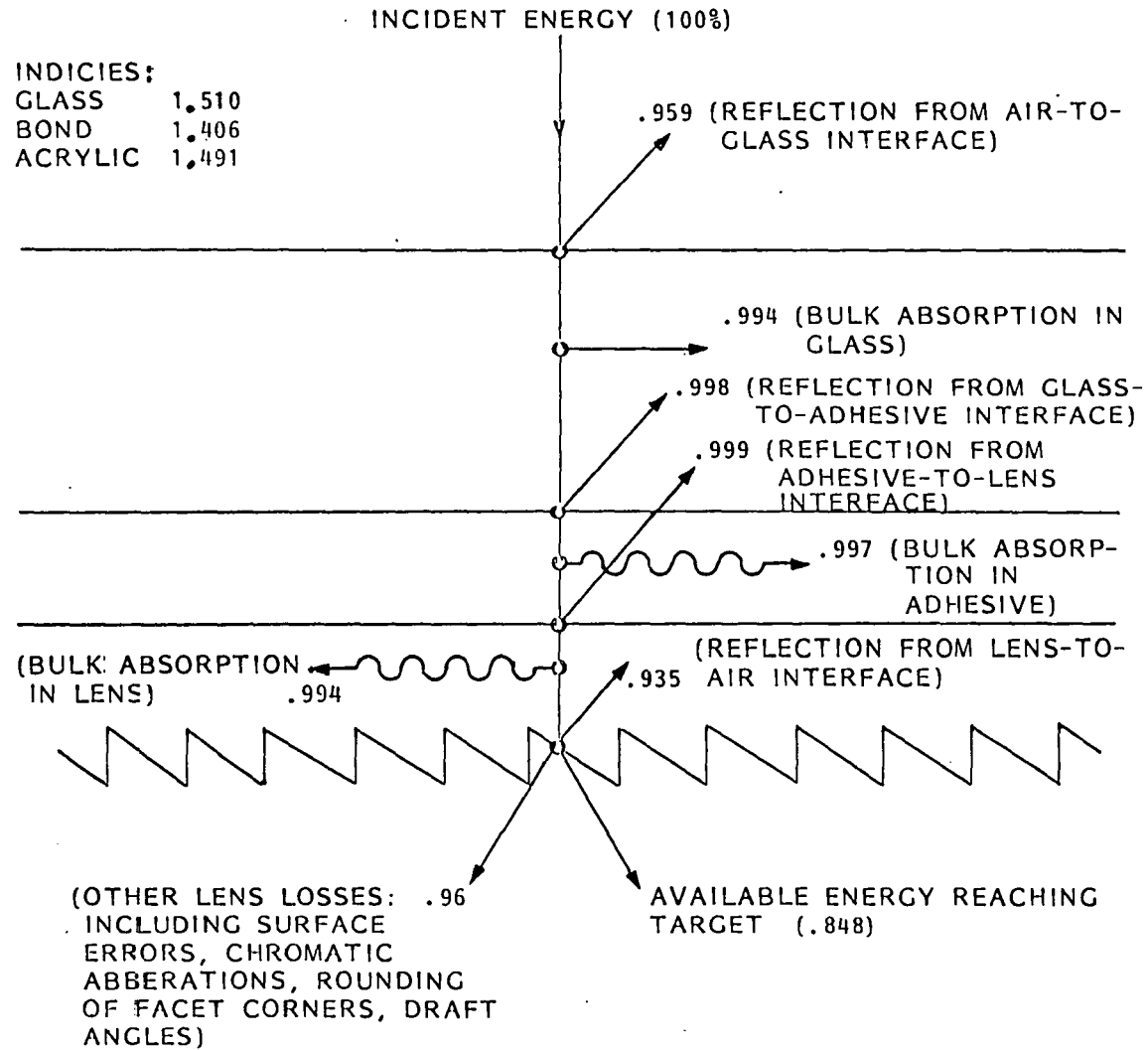
Fresnel Lens Design Requirements

Parameters	Requirements ^①
Individual Fresnel Lens Size	6.70 inches square
Distance from Lens to Cell	7.37 inches (F/1.1)
Illumination Target Size	0.61 inches square
Flux Distribution at Focal Plane	Peaks < 2X I _{ave.} ^②
Overall Lens Efficiency	> 80 %
Energy Incident on the Lens	Energy Within Target Area
Thermal Cycling Exposure	1000 cycles -30 to +50°C
Hall Impact Resistance	1.00 inch diameter Iceballs at 55 mph
^① Specified By Sandia ^② This is a goal	

Lens Assembly Design Description
Fresnel Lens <ul style="list-style-type: none"> • 0.075-inch thick injection molded acrylic - 6.65-inch square • 7.37 lens-x-cell distance (conc. ratio - 120) • 2° draft angle • Facet spacing - 0.015-inch
Glass Superstrate <ul style="list-style-type: none"> • Schott B-2#0 "Solawit" annealed glass (3 mm thick) • 92% transmission • Survives 90 mph winds/1.00 inch hair impact at 55 mph • Low cost
Lamination Adhesive <ul style="list-style-type: none"> • GE-534-04 liquid silicone adhesive 9 0.003-inch thick • Bond flexibility/added bond integrity with primer • Lamination process simplicity • Low cost



LENS ASSEMBLY LOSS BUDGET





LENS PERFORMANCE DATA



UNMASKED EFFICIENCY*

CONTROL LENS	83-85%
LAMINATED CONTROL LENS ASSEMBLY	82-84%
INJECTION MOLDED LENS	72-75%
LAMINATED INJECTION MOLDED LENS	72-74%

ACRYLIC EXTRUSION/EMBOSSING PROCESS DEVELOPMENT FOR THE LOW-COST
PRODUCTION OF LINEAR FRESNEL LENSES

Mark J. O'Neill
E-Systems, Inc.
Energy Technology Center
P. O. Box 226118
Dallas, Texas 75266

For the past several years, E-Systems has been actively developing a novel, high-efficiency, short focal length, linear Fresnel lens solar concentrator for both photothermal and photovoltaic applications. This concentrator (U. S. Patent No. 4,069,812) offers both maximal optical efficiency and large tolerance for manufacturing errors and aberrations. The modular design of the system requires linear lenses with aperture dimensions of 91 cm (36 in) width by 244 cm (96 in) length. Of all methods available to manufacture such lenses, including casting, compression molding, injection molding, profile extrusion, etc., the method offering highest performance at least cost should be continuous extrusion/embossing of acrylic plastic. After partially successful, company-funded process development efforts in 1977 and 1978, E-Systems was awarded a contract from Sandia in 1979 to adapt the extrusion/embossing process to full-size, high-quality linear Fresnel lens production.

The lens to be produced is the convex concentrator used in E-Systems' combined photovoltaic/photothermal collector (Fig. 1). This lens has several unique features (Fig. 2) making it particularly suitable for low-cost production. One of these features is the ability to tolerate rounded prism peaks (Fig. 3), which represent the most troublesome defect in extrusion/embossed lenses. In order to accurately evaluate the performance of lenses produced by extrusion/embossing, E-Systems has developed a focal-plane flux-scanning apparatus (Fig. 4). For a performance baseline, this test apparatus was used to measure the flux profiles (Fig. 5) of the same E-Systems lens produced by two alternate processes, casting (Swedlow) and a proprietary 3M process. Integration of the flux profiles for these two lenses provides net optical efficiency (net transmittance) as a function of receiver width (Fig. 6). Both lenses (Swedlow and 3M) provide essentially the same performance, characterized by 87% optical efficiency for a receiver width of 3.66 cm (1.44 in), which represents a 25X geometrical concentration ratio. Thus 87% lens efficiency at 25X geometric concentration ratio was selected as the performance goal for the extruded/embossed lenses.

Optical Sciences Group (OSG) was selected to design and build the diamond-turned, high quality embossing roll (Fig. 7). The roll is water-cooled during the embossing process via internal flow passages (Fig. 8). K-S-H, Inc., the largest extrusion/embossing firm in the U. S., was selected to install the embossing roll in one of their production extrusion lines and to conduct trial production runs of lenses. To date, K-S-H has conducted five trial runs, with lens sample evaluations complete for the first four of these runs. (Samples from the fifth run are currently in transit.) Measured performance for the first trial run (Fig. 9) indicated that the first embossed lenses had excellent prismatic angular accuracy, producing the proper size image, but that badly rounded prism peaks caused the net lens transmittance to be low, about 60% at 25X. Better results have been achieved with each succeeding trial run (Fig. 10), with current lens efficiency levels of about 72% at 25X. While the performance goal has yet to be achieved, steady progress has been demonstrated and the project team members are confident of further improvement in later runs. Furthermore, since the extruded/embossed lenses cost only about one-third as much as lenses produced by the other processes, full performance equality is not required for cost/performance viability.

PHOTOVOLTAIC COLLECTOR CROSS SECTION

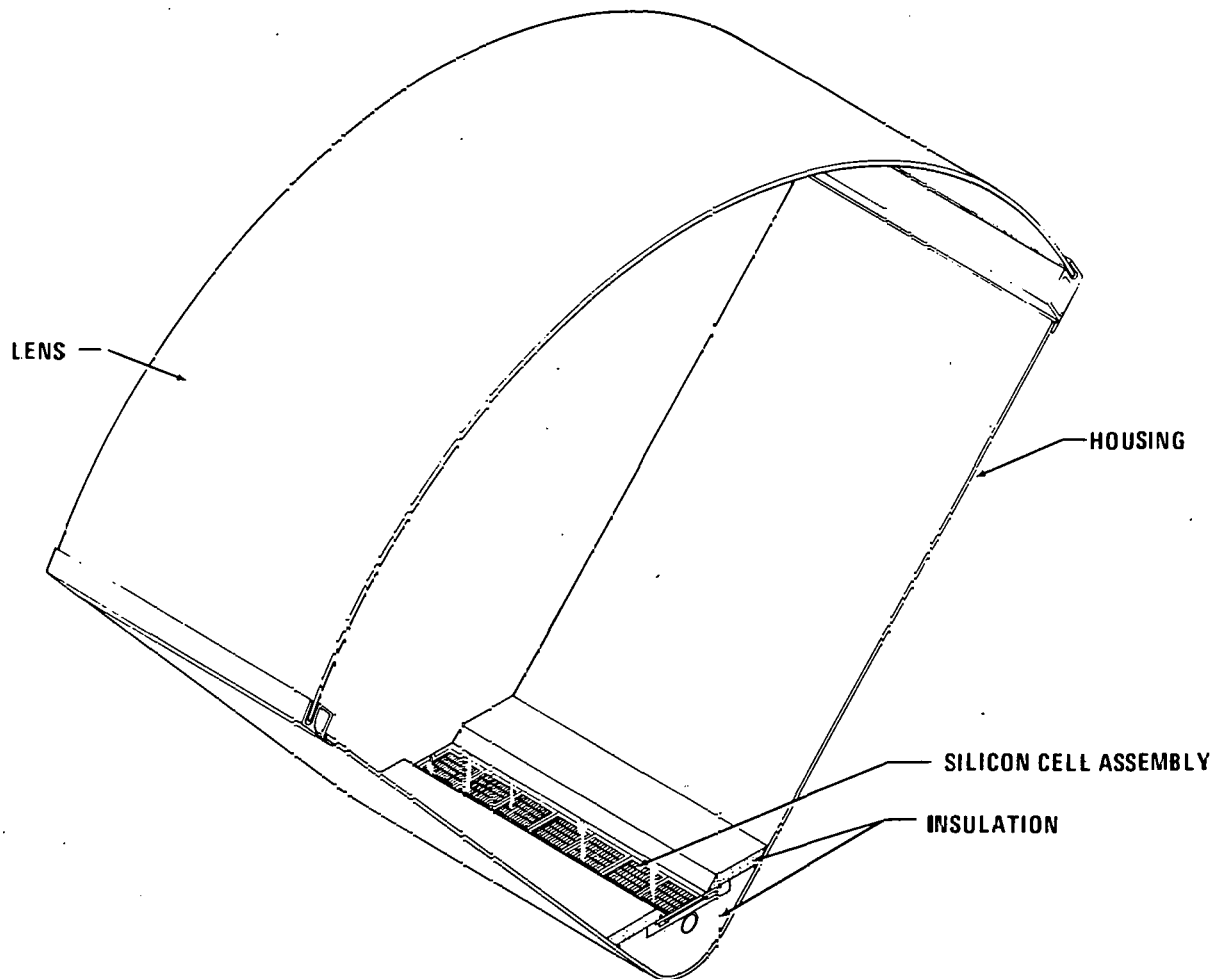


Fig. 1

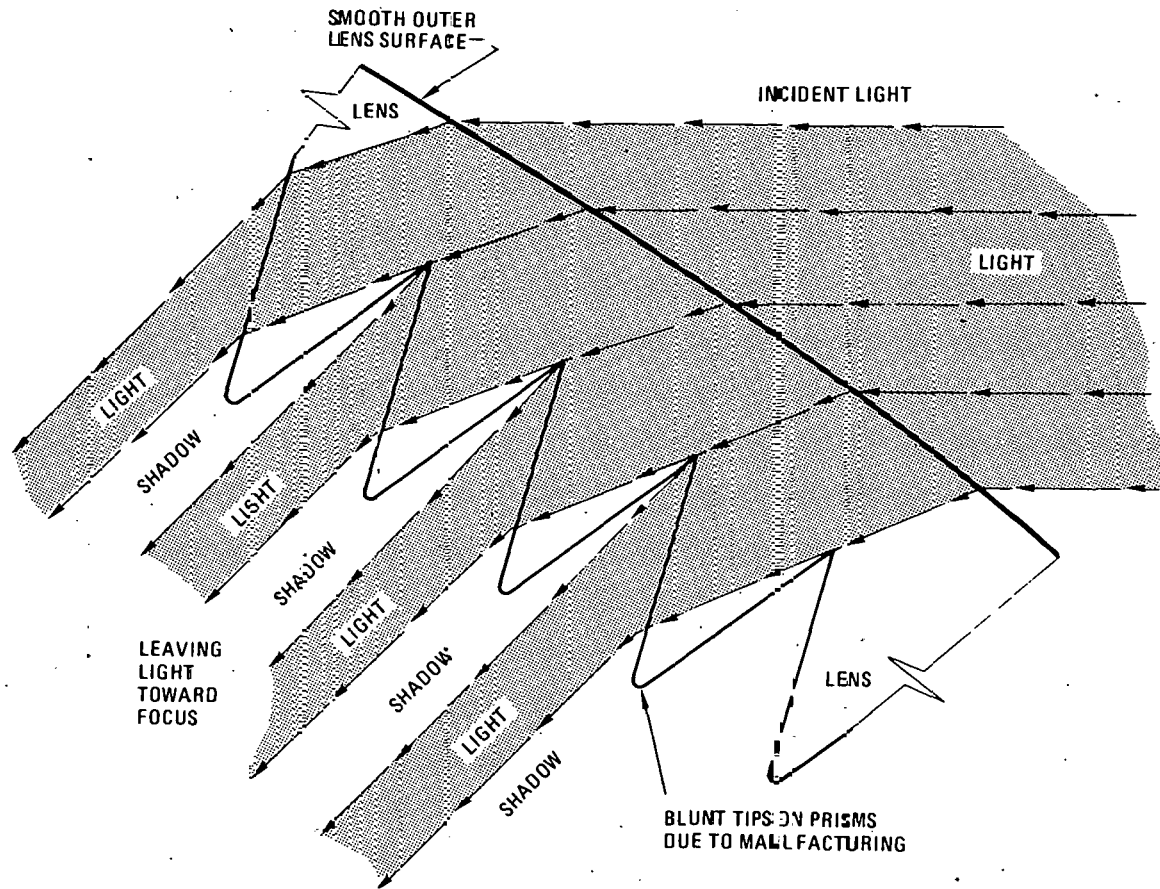
UNIQUE LENS DESIGN

- MAXIMUM POSSIBLE TRANSMITTANCE FOR EACH PRISM
- MAXIMAL TOLERANCE FOR ERRORS
 - SLOPE ERRORS
 - ROUNDED PRISM PEAKS
 - PRISM ANGLE ERRORS
- SMALLER SOLAR IMAGE
 - FINITE SUN
 - CHROMATIC ABERRATION
- SHORTER FOCAL LENGTH
 - 45 DEGREE RIM ANGLE
 - F/NO. 0.5 RATHER THAN 1.0
- ALLOWS MORE COMPACT, LIGHTER, CHEAPER COLLECTOR MODULE
 - 5 LBS/FT² RATHER THAN 10 LBS/FT²
 - REDUCED WEIGHT AND WIND LOADS ON SUPPORT STRUCTURES AND DRIVES
- U.S. PATENT 4,069,812 24 JANUARY 1978

Fig. 2



MAGNIFIED VIEW OF PRISMS SHOWING PRISM FACE OVEREXTENSION TO MINIMIZE OPTICAL LOSSES DUE TO BLUNT TIPS

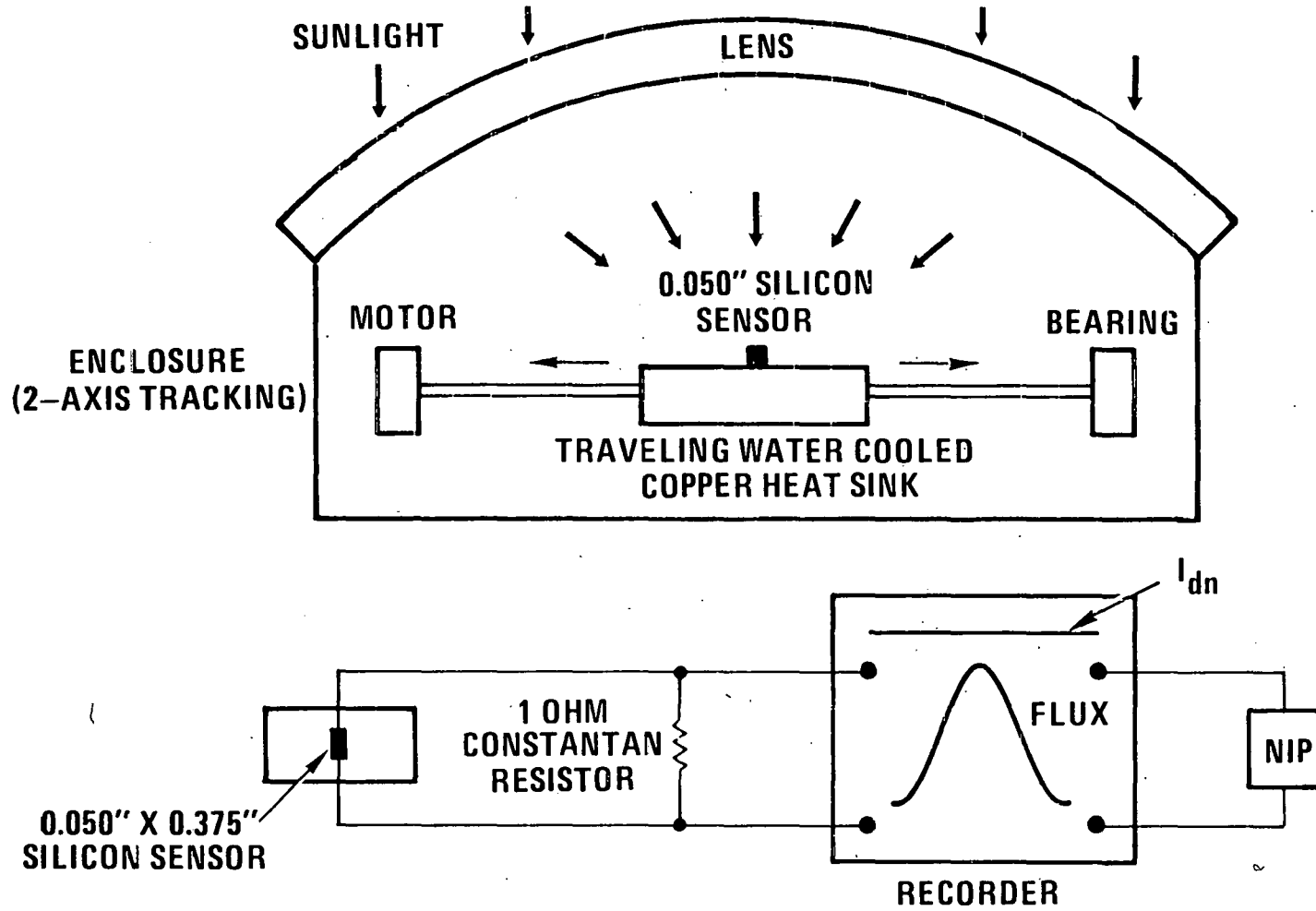


148

ETC36879-26

Fig. 3

LENS FLUX TEST APPARATUS



149

Fig. 4

COMPARISON OF PREDICTED AND MEASURED LENS FOCAL PLANE RADIANT FLUX PROFILES

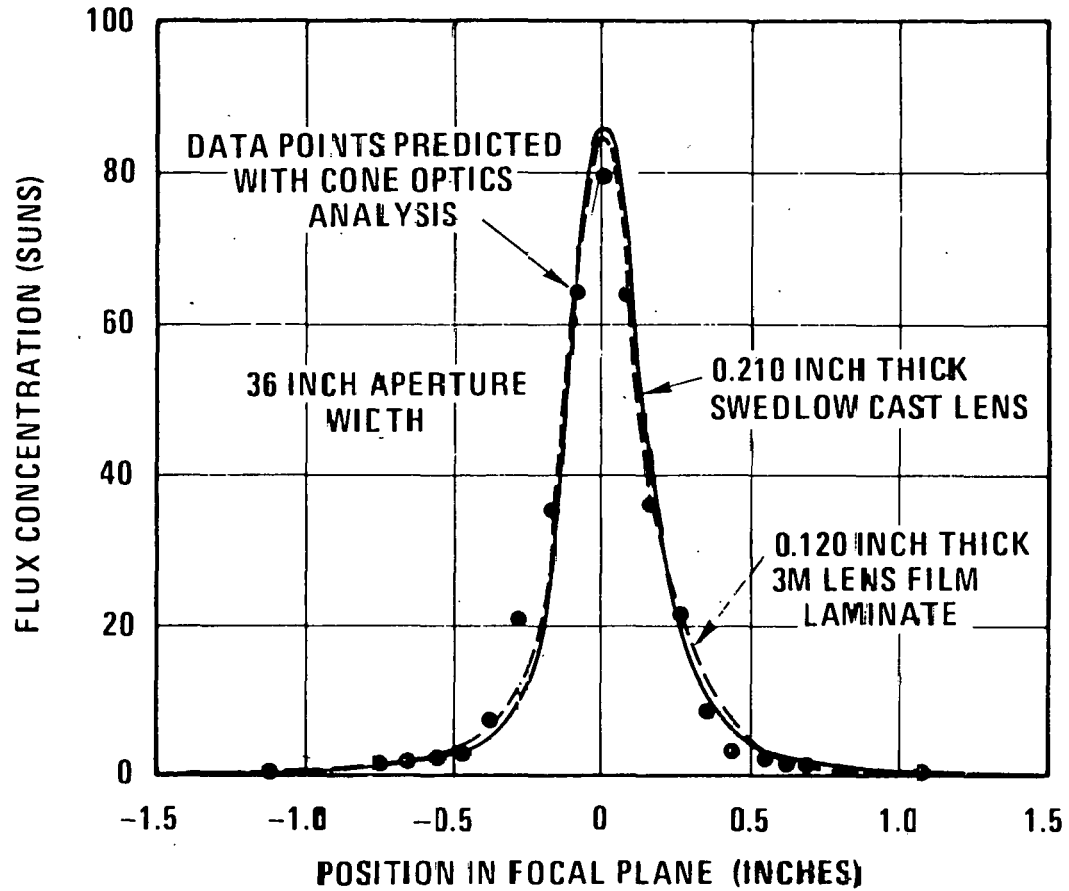


Fig. 5

MEASURED LENS OPTICAL PERFORMANCE

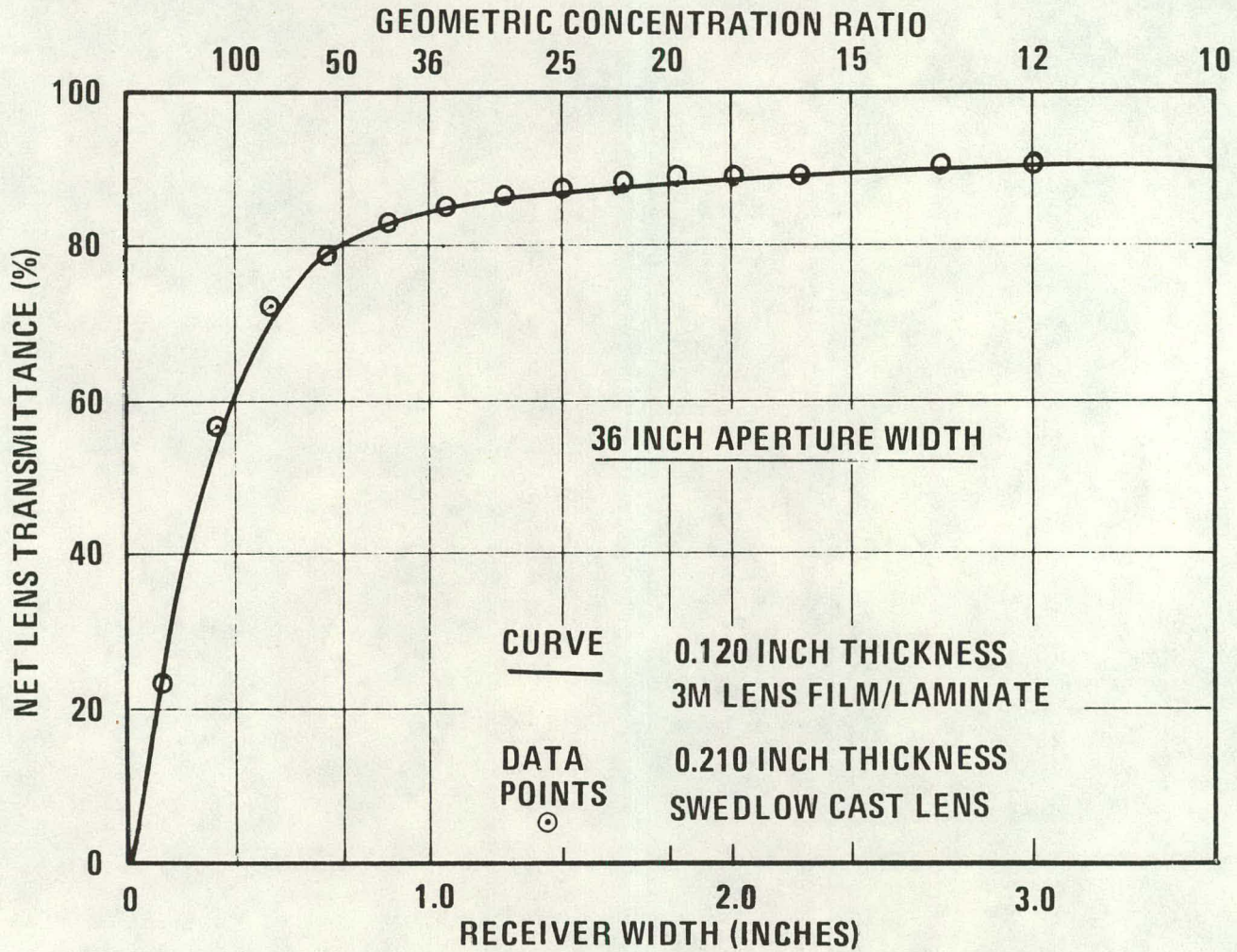


Fig. 6

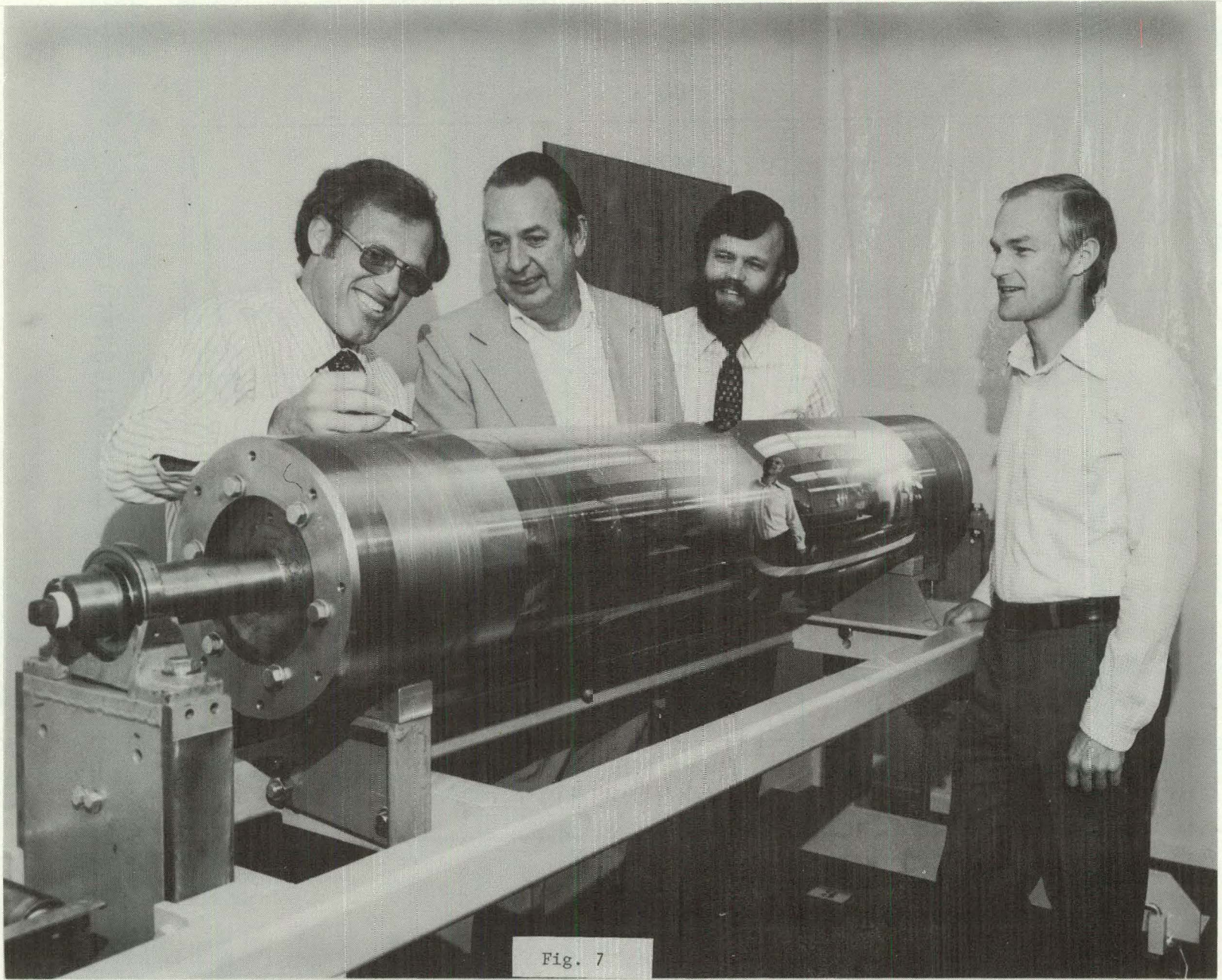


Fig. 7



Fig. 8

MEASURED LENS FOCAL PLANE RADIANT FLUX PROFILES

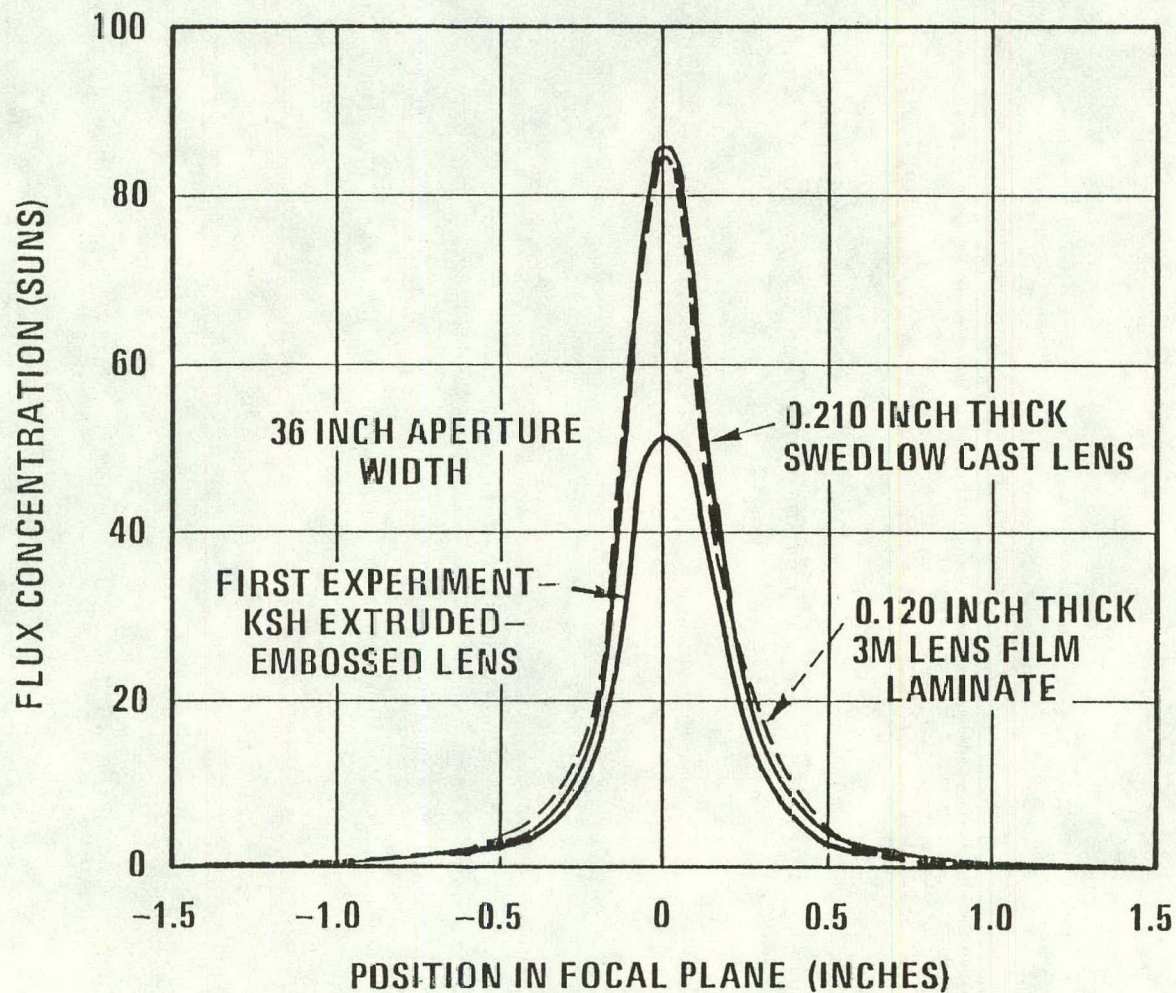


Fig. 9

EXTRUSION/EMBOSSING TRIAL RUN RESULTS
TO DATE

<u>TRIAL RUN NUMBER</u>	<u>DATE MEASURED</u>	<u>LENS EFFICIENCY (AT 25X)</u>
1	OCTOBER 1979	60%
2	DECEMBER 1979	65%
3	MARCH 1980	70%
4	MAY 1980	72%

FRESNEL LENS EVALUATION

Charles B. Stillwell
Photovoltaic Projects Division 4719
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

Sandia is developing a capability to evaluate the performance of point focus Fresnel lenses. This capability will be installed in the Photovoltaic Test Area.

Currently, the evaluation is performed using polar axis sun tracking systems designed primarily for solar cell evaluation. Two such systems are operational at Sandia, neither of which is in the PV test area. A new system is now being designed and fabricated and is to be installed in the PV test area about March 1981. For lens evaluation, these systems are utilized to obtain the normalized solar cell short circuit currents for single sun and lens concentrated sun to determine the lens efficiency. System efficiency can also be obtained by obtaining both the power input and the output power at the maximum power point.

A second method for Fresnel lens evaluation being developed is a portable polar axis sun tracking lens analyzer. This system is operational; however, it is still undergoing refinements to provide the desired capabilities. It is expected that it will be installed in the PV test area by about January 1981. This system utilizes a silicon photodiode to sweep the cell plane image produced by a point focus Fresnel lens. Data sampled during the sweeps is then used to provide lens efficiency and 1-D, 2-D, and 3-D concentration intensity profiles. Currently, the lens efficiency numbers are incorrect and various techniques are being tried to improve the system calibration. With the use of filters, this system can provide spectral sensitivity data. A solar simulator source for use with the system is planned.

The profile data from the lens analyzer is now being used to investigate solar intensity profiles on various systems and to compare profiles for different lens designs for the same system. They are also being utilized with the lens and system efficiencies obtained from the cell tests to investigate the relationship between the profiles and the efficiencies.

POINT FOCUS FRESNEL LENS EVALUATION
AT
SANDIA NATIONAL LABORATORIES

TWO TECHNIQUES UTILIZED

- CELL TESTER
- LENS ANALYZER

CELL TESTER

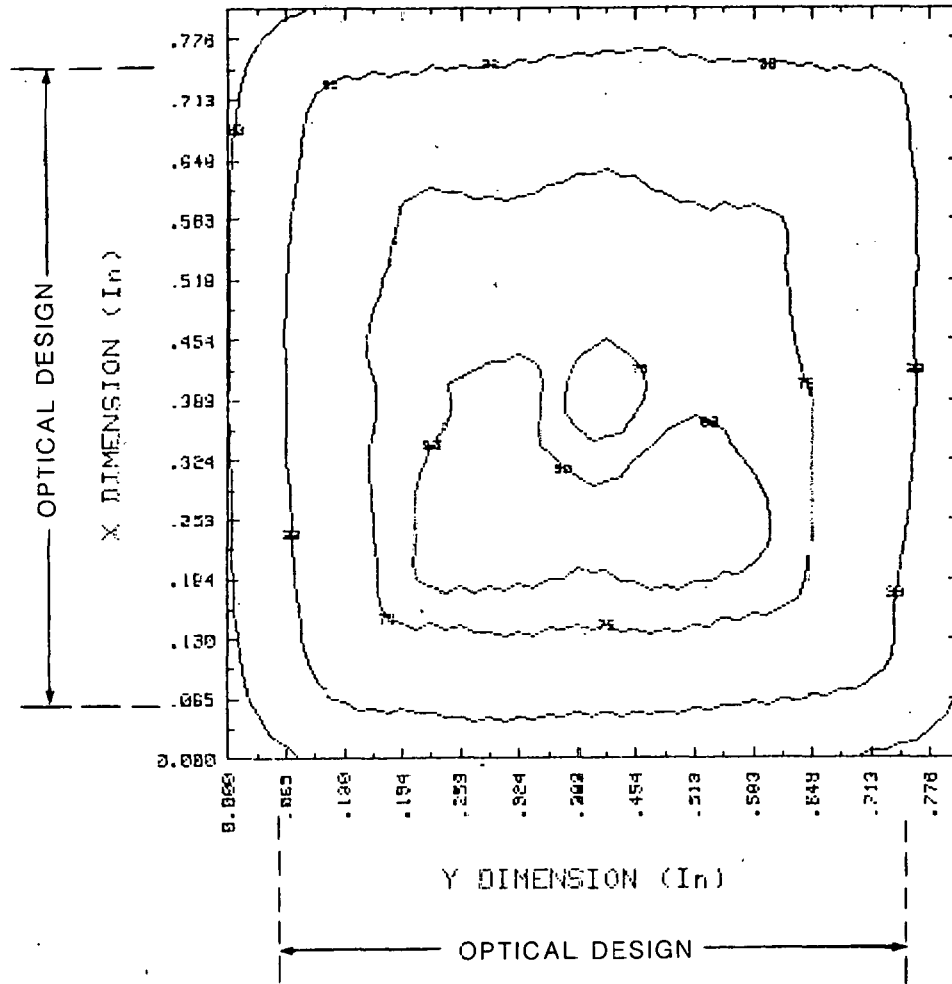
- POLAR MOUNTED SUN TRACKER
- TESTS LENS AND CELL COMBINATION
- OBTAINS CELL I-V CHARACTERISTICS
- LENS EFFICIENCY
 - USE SOLAR CELL SHORT CIRCUIT CURRENT (I_{sc})
 - I_{sc} NORMALIZED (NI_{sc}) WITH NIP OR STD. CELL
 - $\eta_L = \frac{C_M}{C_G} = \frac{NI_{sc}/C_G}{NI_{sc}}$
- SYSTEM EFFICIENCY
 - $\eta_s = \frac{P_{MP}}{P_{IN}}$
- TWO TESTERS OPERATIONAL
 - CELL DEVELOPMENT DIVISIONS
- NEW TESTER FOR PV TEST AREA
 - DESIGN & FABRICATION IN PROGRESS
 - INSTALLATION APPROX. 3/81

LENS ANALYZER

- PORTABLE POLAR AXIS SUN TRACKER
- TESTS ONLY LENSES
- MAPS CELL PLANE
 - SILICON PHOTODIODE SWEEPS CELL PLANE
 - PHOTODIODE I_{sc} SAMPLED DURING SWEEPS
 - SAMPLED I_{sc} COMPARED TO REFERENCE DIODE SINGLE SUN I_{sc}
 - CONCENTRATION (C_M) CALCULATED AND STORED FOR EACH DATA SAMPLE
- HAS SPECTRAL SENSITIVITY CAPABILITY
- OUTPUT
 - 1D, 2D, 3D CONCENTRATION PROFILES
 - LENS EFFICIENCY

$$\eta_L = \left(\sum_{x,y=1}^N C_M \right) + (N^2 \times C_G)$$

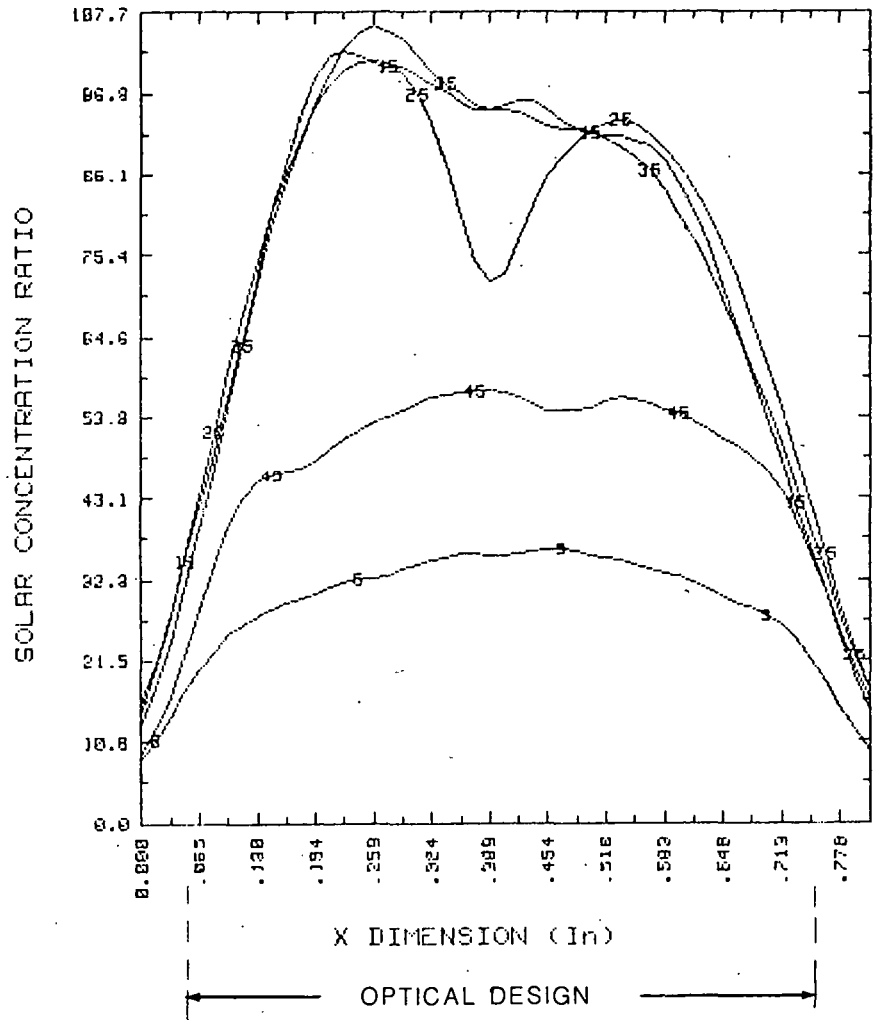
- STATUS
 - OPERATIONAL, BUT
 - LENS EFFICIENCY INACCURATE
 - CALIBRATION TECHNIQUES IMPROVING
 - TO BE INSTALLED IN PV TEST AREA
 - APPROX. 1/81
 - SUN SIMULATOR PLANNED



PLOT OF CONTOURS(%)
10
33
75
90
OF FILE GCPF7

Image dimensions =
.61, .61
Lens Efficiency =
67.19%
Scan efficiency =
88.75%

TYPICAL 2-D CONTOUR PLOT
LENS ANALYZER

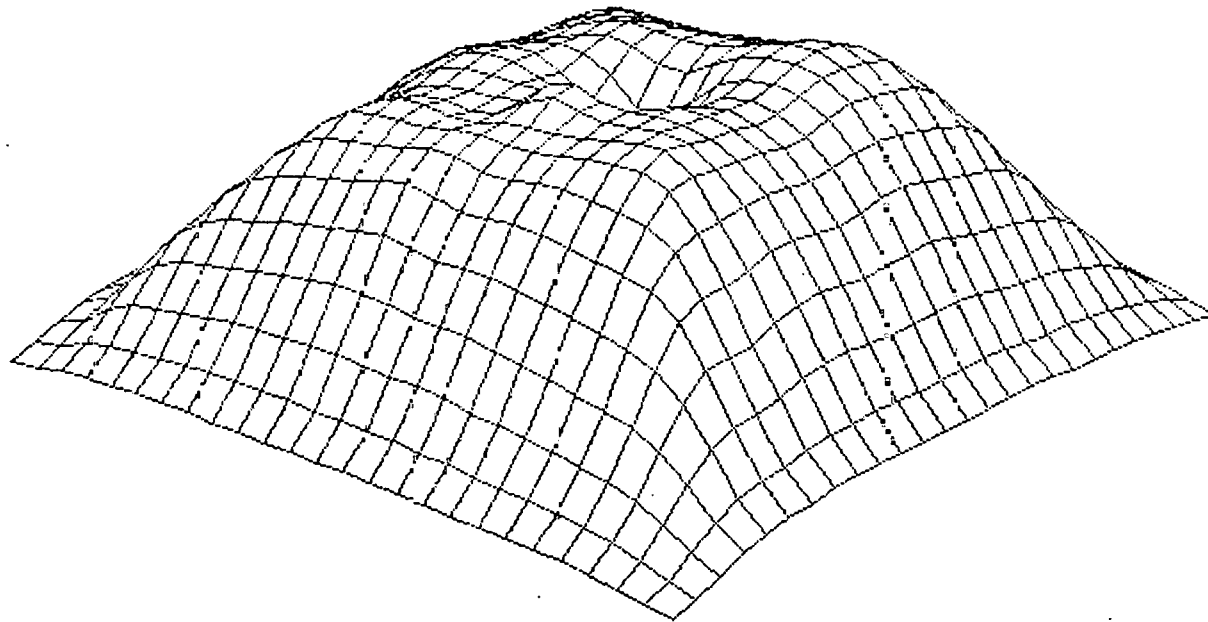


PLOT OF LINES:
 5
 15
 25
 35
 45
 OF FILE .GCPF7

Image Dimensions -
 .610, .610
 Lens efficiency -
 67.19%
 Ave concentration =
 82.70

Scan Efficiency =
 88.75%
 Max scan conc =
 107.68
 Ave scan conc =
 57.50%

TYPICAL 1-D INTENSITY PLOTS
 LENS ANALYZER



3-D PLOT OF FILE GCPF7

E1 = 25 Az = 40
Scan Efficiency = 88.75%

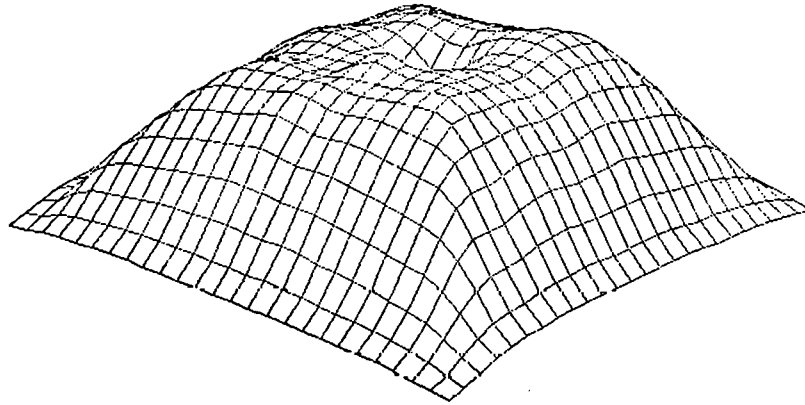
TYPICAL 3-D INTENSITY PROFILE
LENS ANALYZER

DEFINITION OF EFFICIENCY

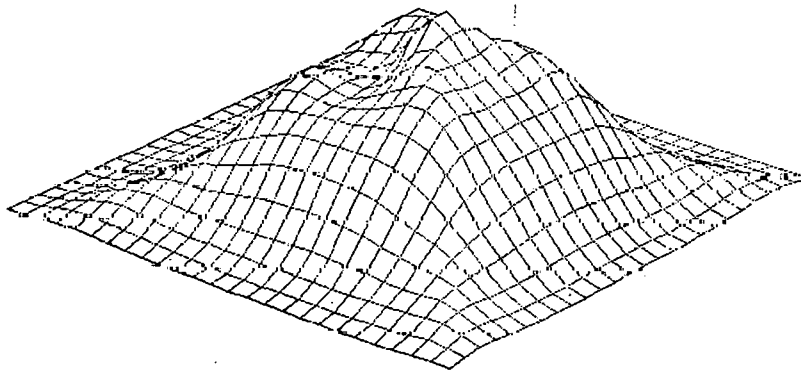
- LENS EFFICIENCY (η_L)
 - RATIO, CONCENTRATED TO UNCONCENTRATED NORMALIZED I_{sc}
 - GENERALLY USED FOR LENS EVALUATION

- SYSTEM EFFICIENCY (η_s)
 - AT MAX. POWER POINT OF CELL I-V CURVE
 - RATIO, MAX. OUTPUT POWER TO INPUT POWER

- MAX. η_L DOES NOT ASSURE MAX. η_s
 - CELL FILL FACTOR
 - CELL ILLUMINATION INTENSITY PROFILE



LENS 1



LENS 2

LENS DESIGN COMPARISON

DATA UTILIZATION

- CELL TESTER AND LENS ANALYZER DATA
- LENS PROFILE COMPARISONS
 - LENS 1 BROAD AND FLAT
 - LENS 2 NARROW AND PEAKED
- LENS EFFICIENCIES (η_L)
 - LENS 2 MORE EFFICIENT
 - FULL CELL AND OPTICAL DESIGN
- SYSTEM EFFICIENCIES (η_s)
 - LENS 2 MORE EFFICIENT
- $\Delta\eta_s$ NOT AS GREAT AS $\Delta\eta_L$
 - FLATTER PROFILE FOR LENS 1

FORMED GLASS REFLECTORS

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ABSTRACT

A straightforward concept for a parabolic trough solar collector utilizes thermally formed and laminated glass mirrors which are supported by a steel structure. Automotive windshield technology demonstrates that glass can be thermally formed to shape and laminated using high volume production techniques. Relative to potential application to solar collectors, laminated mirrors for heliostats at the CRTF have indicated excellent protection of the silver from the environment. Metal stamping technology appears applicable for fabrication of the support structure because of good contour accuracy and potentially low costs in production.

A mockup of the trough concept has been made. The glass mirrors are approximately 1 m x 1 m aperture. Twelve mirrors will be mounted on a steel support structure to provide a 2 m x 6 m aperture trough. The support structure will consist of a thin walled torque tube with sheet metal ribs to support the glass. It is currently planned to bond the glass directly to the support structure with a resilient adhesive. An alignment fixture will be required to position the glass during bonding.

Ford and PPG have recently completed developments to thermally form glass to a two meter parabola. Ford gravity sagged 2.3 mm thick Ford low iron float glass from the Barstow heliostat glass run and 1.5 mm-thick Corning 0317 glass. PPG gravity sagged and also press formed PPG glass in thicknesses of 2.3 mm and 1.5 mm. The developments demonstrated that glass can be thermally formed using high volume production type techniques. Accuracy of the glass in the free state does not yet meet the $1\sigma = 2.5$ milliradian slope error goal, but indications are that improved optical surface accuracy could be achieved with continued development. Five samples of glass have been bonded to honeycomb trough segments, and all showed slope errors of less than the 2.5 mr goal. Accuracy of the present glass appears adequate for low pressure bonding. Further development is currently underway to make thermally formed laminated glass mirrors.

Ford performed cost studies which showed prices for the thermally formed glass ranging between $\$9.69/\text{m}^2$ and $\$334/\text{m}^2$ depending upon production levels and the glass used. These prices do not include silvering.

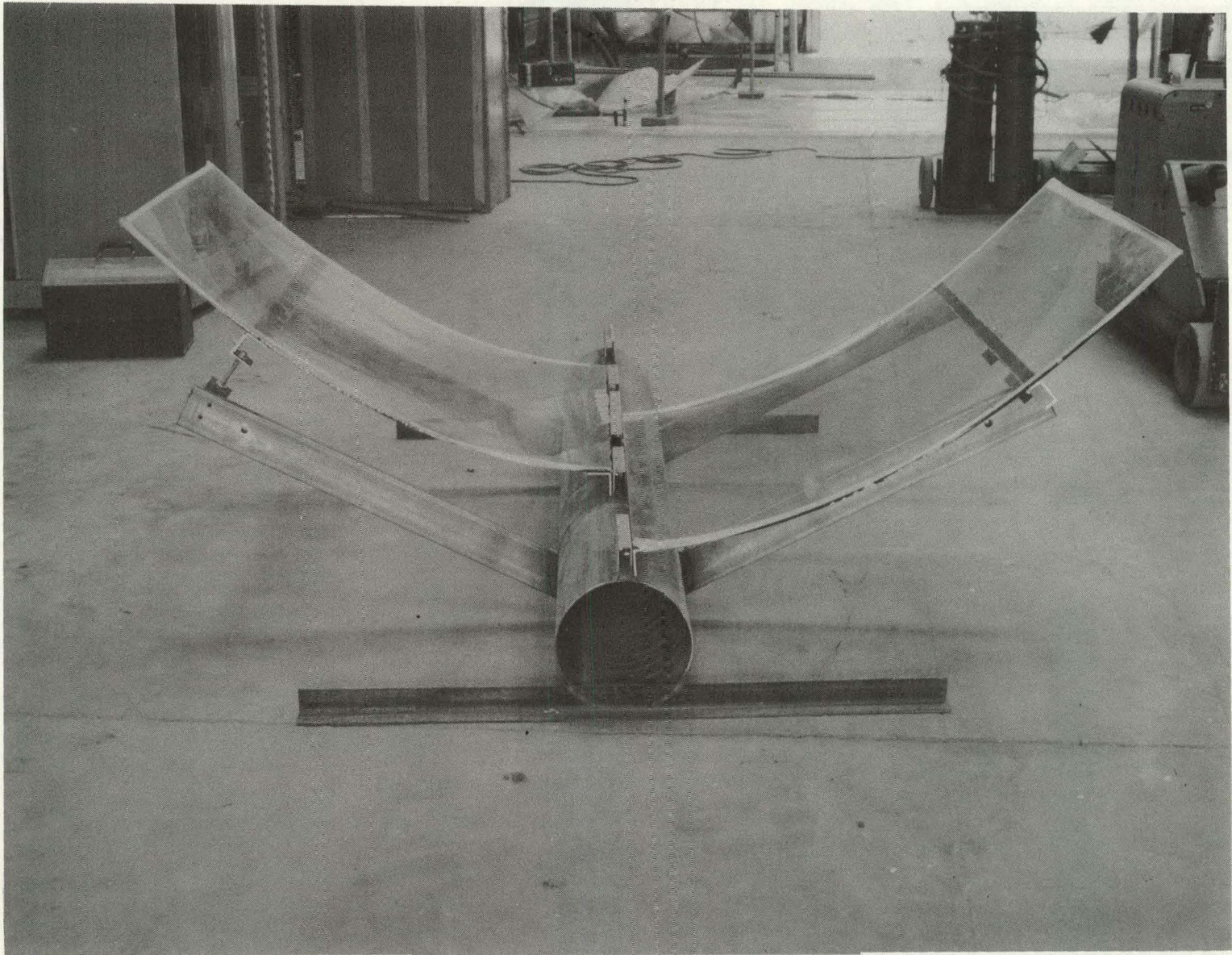
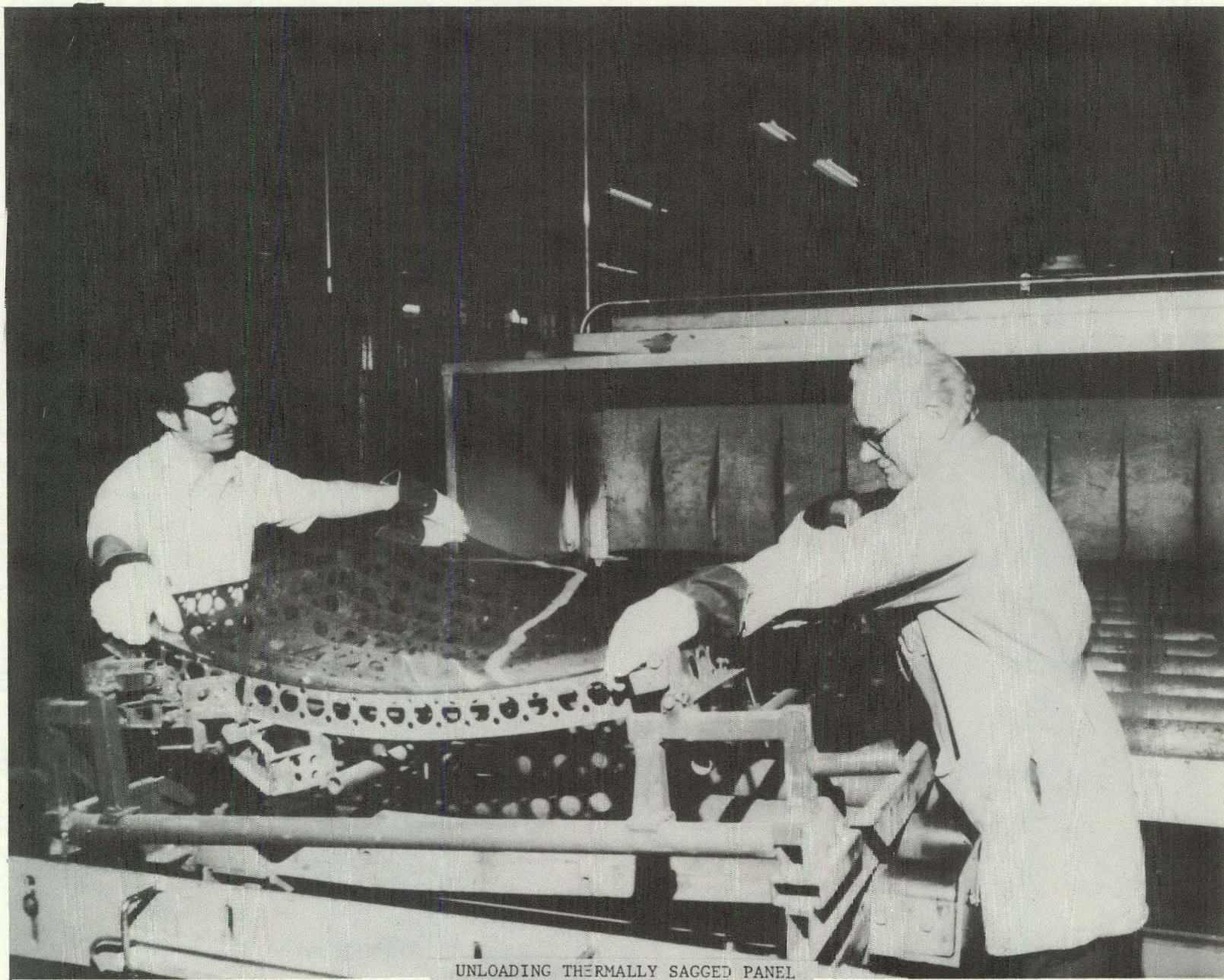


FIGURE 1 - GLASS LAMINATE MOCKUP



UNLOADING THERMALLY SAGGED PANEL
FROM FORMING FIXTURE

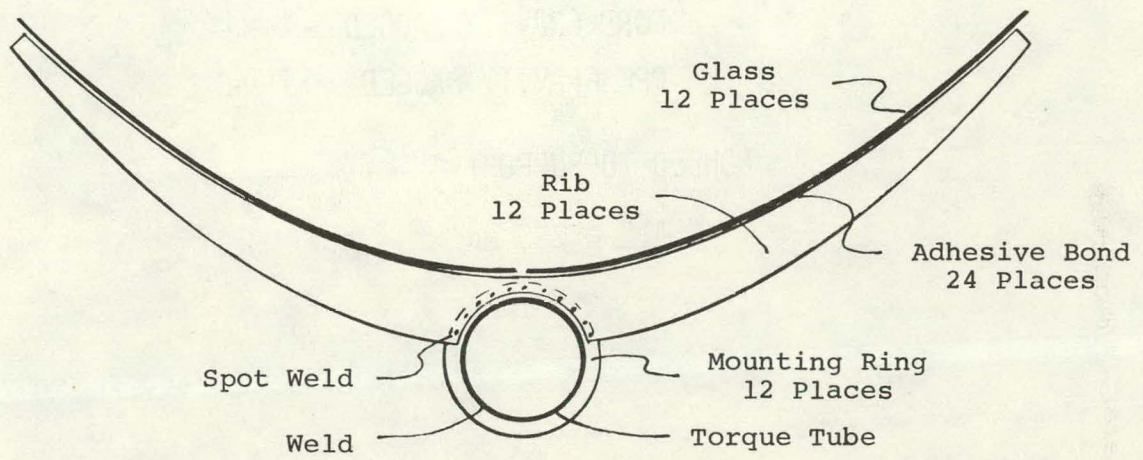


FIGURE 4 - GLASS LAMINATE - RIB MOUNTING

SLOPE ACCURACY

FREE STATE ON SUPPORT

PPG PRESS FORMED ≈ 3 MR

FORD GRAVITY SAGGED ≈ 4 MR

PPG GRAVITY SAGGED ≈ 7 MR

BONDED TO SUPPORT

ALL ≤ 2.5 MR

REFLECTIVITY

(AIR MASS = 1.5)

FORD LOW-IRON (2.3 MM) $\approx 89\%$

PPG (1.5 MM) $\approx 87\%$

CORNING 0317 $\approx 94\%$

SCHOTT B270 $\approx 94\%$

THERMALLY FORMED GLASS
PRICE ESTIMATES PER SQUARE FOOT

ANNUAL REQUIREMENTS	FABRICATION METHOD	LOW IRON CONTENT (0.06%)	NORMAL IRON CONTENT (0.10%)
LOW VOLUME LEVEL (10,000 SQ. FT.)	PROTOTYPE FACILITY	\$31.00	\$9.82
INTERMEDIATE VOLUME LEVEL (1,000,000 SQ. FT.)	"GREENFIELD" GRAVITY BEND FACILITY	\$ 7.14	\$6.02
	EXISTING WINDSHIELD BENDING FACILITY	\$ 2.96	\$1.84
HIGH VOLUME LEVEL (50,000,000 SQ. FT.)	"GREENFIELD" GAS HEARTH FACILITY	\$ 1.42	\$0.90

*FREIGHT EXCLUDED

SOURCE: FORD GLASS DIVISION

SHEET MOLDING COMPOUND (SMC) AND SHEET METAL REFLECTOR/STRUCTURES

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Component & Subsystem Development Division 4722
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Sheet Molding Compound Reflector/Structures

Introduction

Molding with sheet molding compound (SMC) is a potential fabrication technology for the manufacture of parabolic trough reflector structures. SMC is a polyester resin material with chopped fiber-glass reinforcement along with appropriate fillers and modifiers. Parts of SMC are typically molded at 300°F and 600 to 1000 psi in 3 to 5 minute cycle times. SMC molding is a semi-high volume production process. It offers potential for low cost.

Early investigations of trough panels molded of SMC indicated that they met the slope error accuracy requirement as well as being stable in accelerated environmental testing. With this promise, two subsequent development efforts have been undertaken; one with Haveg Industries, Santa Fe Springs, California, and one with the Budd Company, Ft. Washington, Pennsylvania, to investigate molding of silvered glass mirrors into SMC panels as an integral part.

Reflector trough panels of SMC and glass appear to offer two advantages over other fabrication techniques:

- (1) The molding in of the reflector eliminates the secondary bonding operation,
- (2) The encapsulation of the second surface silver provides a good long-term environmental capability.

The molding project at Haveg was initiated with the following objectives:

Primary: To determine the survivability of 2 x 4 ft. sheets of chemically strengthened glass and sagged glass in the molding process.

Secondary: To determine:

- . Effects of molding on the silver coating of the mirror
- . Bi-material response of glass and SMC which have different expansions
- . "Sink" at the ribs
- . Effect of the glass (a poor thermal conductor) on the flow and cure of the SMC

- . Environmental stability and durability of the combination
- . Processing parameters--how to handle the glass, pre-heating, and how to load the charge.

The units molded at Haveg (Figure 1) were 2 x 4' in size with .050" and .060" thick glass mirrors. Rib height was 1 7/8" in a peripheral and centerline pattern. The thickness of the SMC face behind the glass was nominally .155" thick. The SMC material contained 30% chopped fiberglass. Glass sheets were slightly smaller than the 24 x 48" face dimension so that a narrow lip of SMC was molded all around the edge of the glass to provide a better grip on the glass and to decrease the shear stresses at the interface.

In the molding process, the glass was preheated to 260°F and placed in the mold; the SMC charge was set on top of the glass. The pressure produced by mold closure held the glass against the mold face and prevented resin from running under the glass.

Molding Results

Six all-SMC units were molded successfully at Haveg. Four sagged glass units were attempted but resulted in major fracture of the glass.

Eleven units were molded with chemically strengthened glass; one resulted in dicing of the glass, but that was due to grit underneath the glass during molding. Of the ten which survived the molding process, eight were unqualified successes. The glass was flush with the front molded surface; the SMC bonded to the protective paint over the silver and copper coatings on the back surface of the glass. The remaining two units suffered silver/glass delamination.

Evaluation of Molded Units

The molded panels were evaluated in four areas:

1. Surface contour accuracy determined with a laser ray trace inspection.
2. Measurement of mechanical properties of the material, throughout the part.
3. Thermochemical analysis (degree of cure, component volume fraction, filament orientation and content, etc.)
4. Accelerated thermal cycling of some units.

A laser ray trace inspection system provides an accurate measurement of the focal length of the best fit parabola, the rms slope error (in milliradians) and essentially a contour

map of the slope errors. We could thus establish the initial condition of a part and measure all subsequent changes quite accurately.

Environmental Testing

After laser ray trace (LRT) inspection of all units to establish the baseline condition, some units were subjected to accelerated thermal cycling between -20°F and + 130°F. These units were subsequently removed from the test chambers and reinspected with the LRT at weekly and, later, monthly intervals.

The thermal cycling produced an unexpected decrease in the focal length of the panels. In several weeks, a semi-stable state was reached at focal lengths of 30.9"; original was ~31.35". The cycling produced some type of stress relief or creep which allowed the change. This area is not understood.

With the feasibility of molding glass mirrors into SMC panels established, a contract was placed with The Budd Co. to scale up the 2 x 4' parts to a 1 x 1 m panel which could be assembled and tested in a 2 x 6 m collector unit. All of the problems had not been solved, but,

- (1) Molding of strengthened glass was feasible
- (2) The environmental capability looked very good
- (3) Slope error accuracy was essentially within budget
- (4) Bi-material and creep areas need additional investigation.

1 x 1 m Panels

The project at The Budd Company specified the design and fabrication of tooling suitable for production of 1 x 1 m SMC trough panels and also fabrication of molded-in glass mirrors. (Figures 2 and 3). Again the requirements included molding of all-SMC units and units with sagged and chemically strengthened glass. The experience with the bi-material effect in the Haveg units contributed to the design of the tooling at Budd.

Zinc alloy tooling was produced and a series of moldings completed. Several major problems have been encountered, including:

- (1) Delamination of the silver from the glass in small areas during the molding process.
- (2) Lack of adhesion between the mirror and the SMC.
- (3) Lack of a good grip of the SMC along the edges of the glass.

- (4) Incomplete fill of the mold.
- (5) Positioning of the glass within the mold.

An SMC material with a 40% chopped fiberglass content was selected to provide molded material with higher modulus, higher strength and lower thermal expansion. The thermal expansion characteristic is important to minimize the bi-material response of the laminate structure. Material properties of samples cut from molded panels are within specification and are relatively consistent.

The charge pattern as well as press closure rates appear to be important to achieving full fill of the mold and good adhesion of the SMC to the mirror. The Budd units, unlike the Haveg units, indicate that the poor thermal conductivity of the glass is affecting the flow of the SMC during molding.

Units with chemically strengthened glass mirrors have been produced for evaluation. Complete success in molding glass mirrors into SMC panels has not been achieved. The chemically strengthened glass mirrors have survived the pressure and temperature of molding; yet one or more of the problem areas listed above have been encountered in every molded part.

Additional development efforts are in progress. Each parameter is being reassessed to attempt to optimize the material, the coating, or the process to achieve good parts. The next molding series will be conducted in late 1980.

Sheet Metal Reflector/Structures

Introduction

Steel sheet metal represents a low cost, readily available material and technology for high volume production. The adaptation of sheet steel to solar reflector panels raises questions regarding:

- (1) The accuracy of stamped sheet metal panels
- (2) Integration of the reflector material into the structure
- (3) Environmental protection of the steel for long life
- (4) Integration of the reflector/structure with the supporting torque tube.

This paper will describe the design requirements and the development efforts for sheet metal reflector structures.

A contract has been placed with The Budd Company, Technical Center, Ft. Washington, Pennsylvania, to investigate the fabrication and assembly techniques for sheet metal panels. The design requirements for this concept included:

1. Survival in 80 mph winds.
2. Operation in 25 mph winds within specified deflection limits due to wind and gravity.
3. Survival of other weather conditions.
4. Contour accuracy of the reflective surface within an error budget of 3 milliradians rms.
5. Long-term, low maintenance life of reflector structure in its outdoor environment.
6. Low cost materials and fabrication.

Concept

The present design (Figures 4 and 5) consists of a stamped frame panel to provide structural stiffness and a parabolic panel and reflector on the front. Figure 6 illustrates the concept of multiple panels on a torque tube to form a parabolic trough reflector.

The automobile industry has long used sheet metal stampings to provide low cost structures at high production volumes. A typical example is the hood of modern automobiles, consisting of a smooth contoured front panel and a rear stiffening panel joined by bonding or spot welding.

Several configurations of stamped panels and reflectors are being assembled for test and evaluation; these include sagged glass, chemically strengthened glass, and laminates of glass and steel, all with second surface silvering. Appropriate finishes (primers, paints, electrogalvanizing, aluminizing) must be included in the evaluation of the long-term environmental capability of such structures.

Tooling

Fabrication of the rear stiffening panel utilized normal automotive prototype techniques. Stamping dies were made of zinc alloy, as opposed to more expensive steel dies for production. All trimming and cut-out operations were performed by hand.

An accurate assembly fixture was designed and produced for holding the parts in an accurate contour while the bonding or

spot welding operations were performed. This fixture was also used in the bonding of the glass mirrors to the steel structure.

Prototype Units

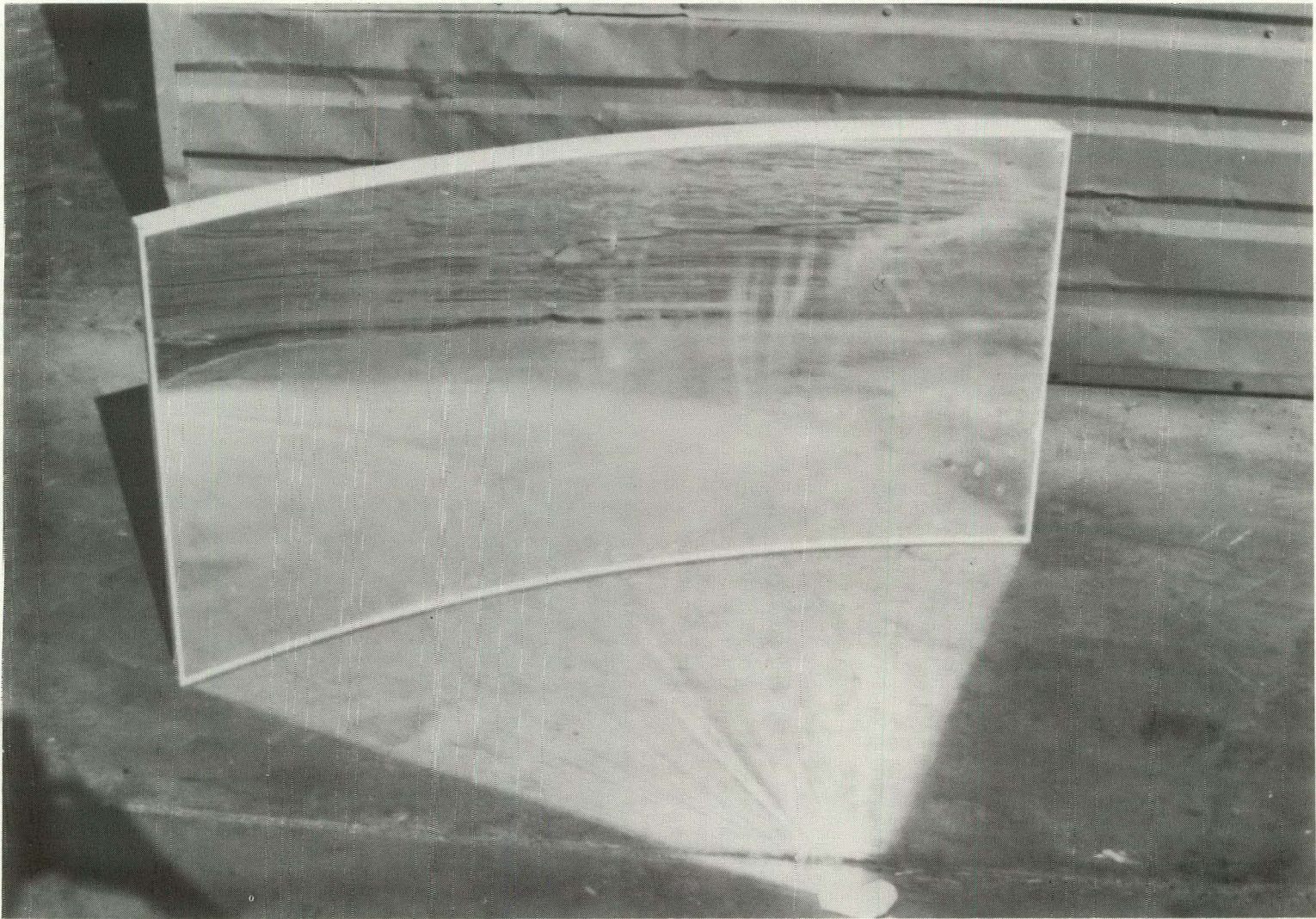
Two prototype units have been assembled utilizing the prototype tooling and assembly fixtures. These units have been inspected by 3-dimensional equipment to establish the variation from specified parabolic coordinates and also with the optical laser ray trace systems at Sandia. Both units were less than 3.0 milliradians rms (2.98 and 2.40 milliradians).

Evaluation

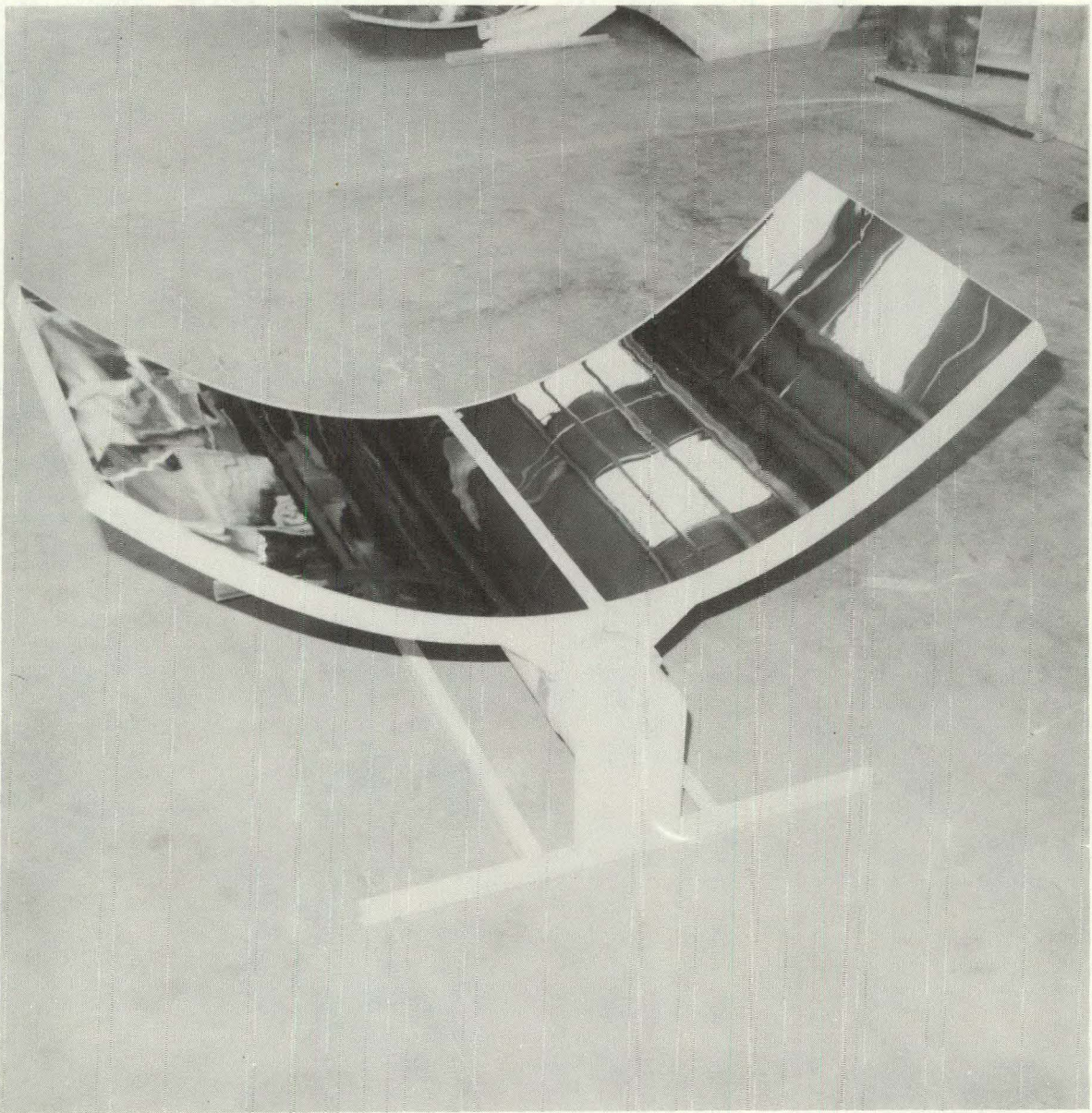
One unit has been instrumented with strain and deflection gages and tested under weight loading conditions to simulate high wind loads. The data are being used in correlating with a finite element stress analysis. These outputs will be used to assess design adequacy or refinements. Environmental testing (thermal cycling, etc.) is underway.

Conclusions

All processes used for this design appear to be adaptable for low cost, high volume production. With an environmental capability for such structures established by the automotive industry, it appears that this concept offers an accurate, long life, low cost, high volume approach to production of reflector structures.





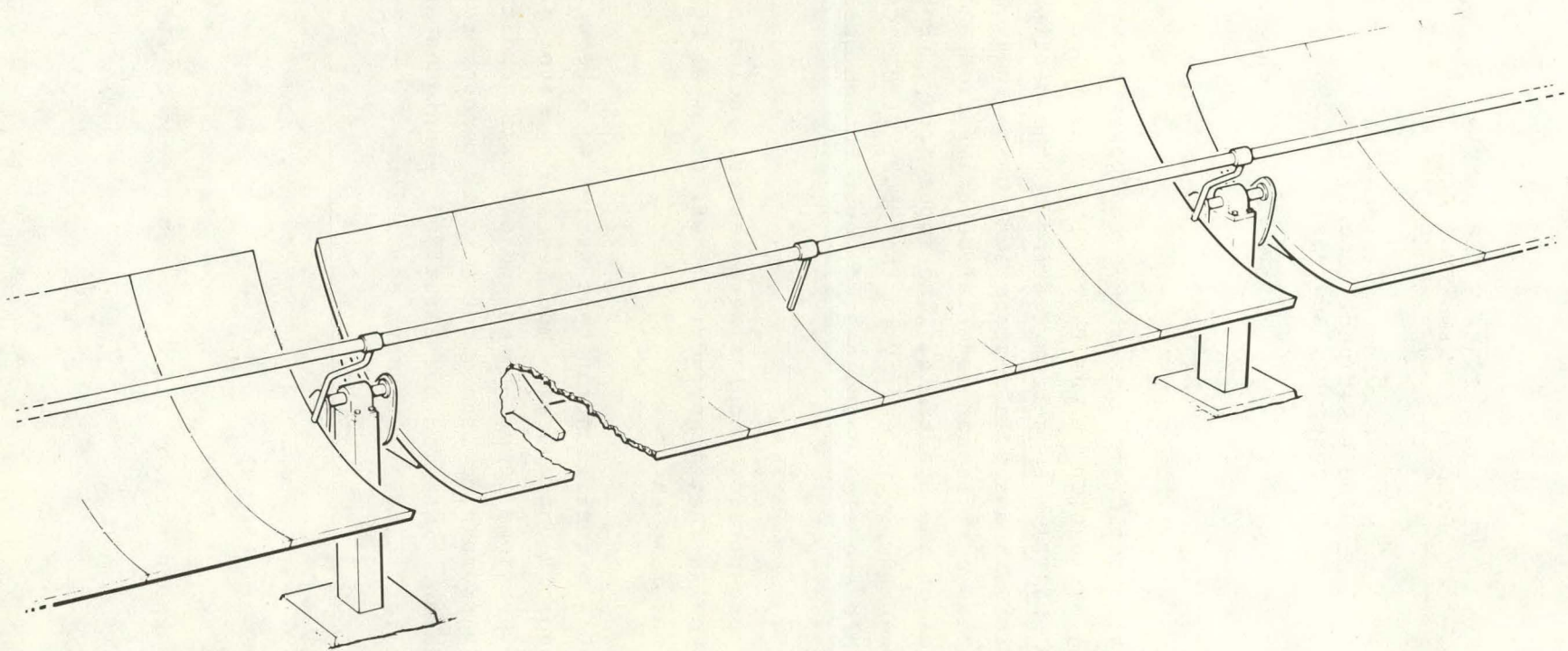




181



**2m X 6m PARABOLIC TROUGH
MODULE DESIGN CONCEPT**



183

TEST RESULTS FROM THE SANDIA
PV ADVANCED SYSTEMS TEST FACILITY*

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Albuquerque, New Mexico 87185

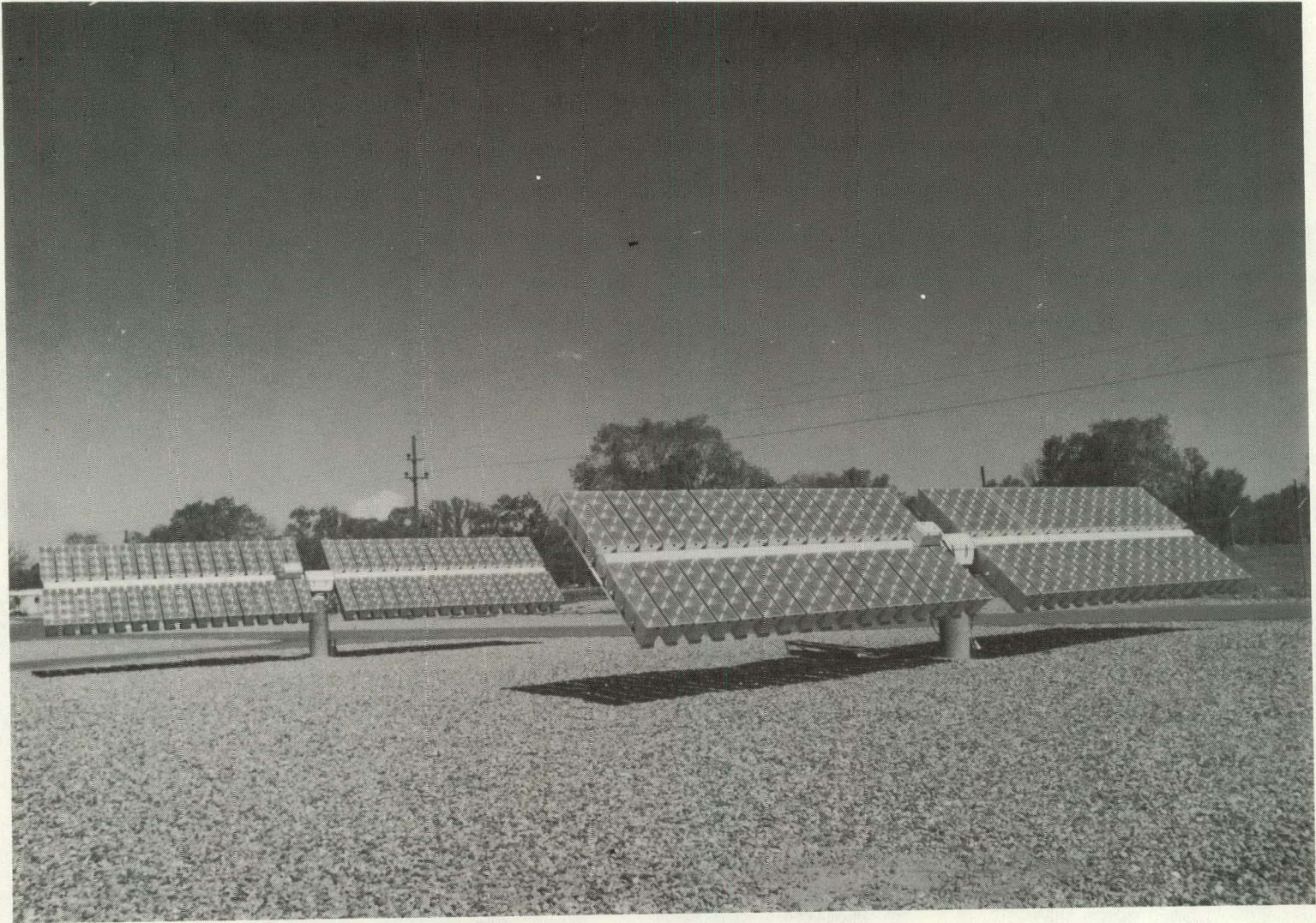
ABSTRACT

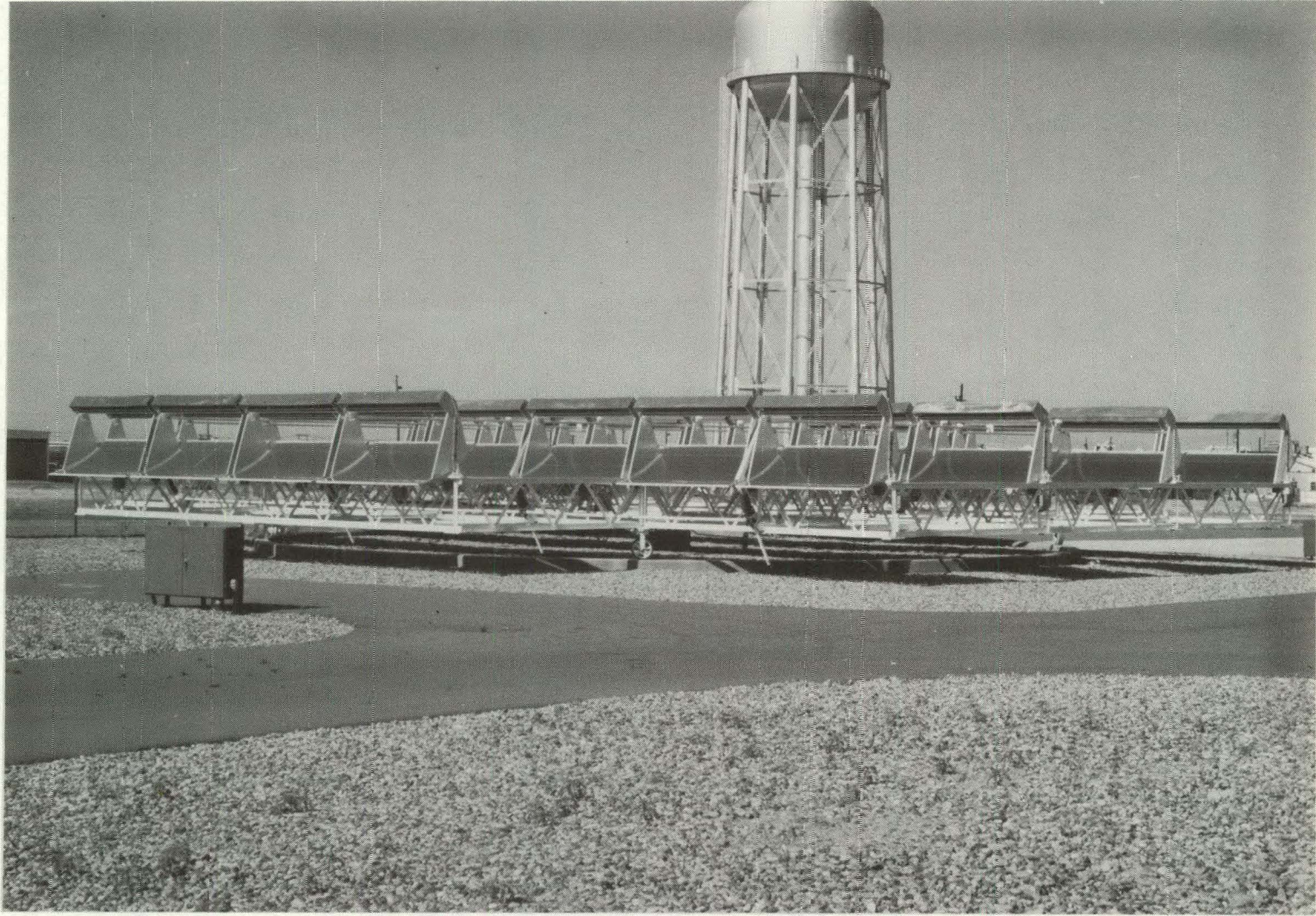
Concentrator cells, modules arrays and power inverters are undergoing evaluation at the Photovoltaic Advanced Systems Test Facility (PASTF). Long-term testing of the Martin Marietta point focus arrays shows some degradation due to individual module problems, whereas a reflector material deterioration has affected the performance of the Spectrolab line focus array. Both of these arrays have been supplying energy to the power grid. Gemini and Abacus inverters are also being tested, even though operating below their capacity.

Several concentrator modules were tested, including one with Varian's GaAs cells that measured 15.7% efficient at 800 w/m² and 23°C coolant temperature.

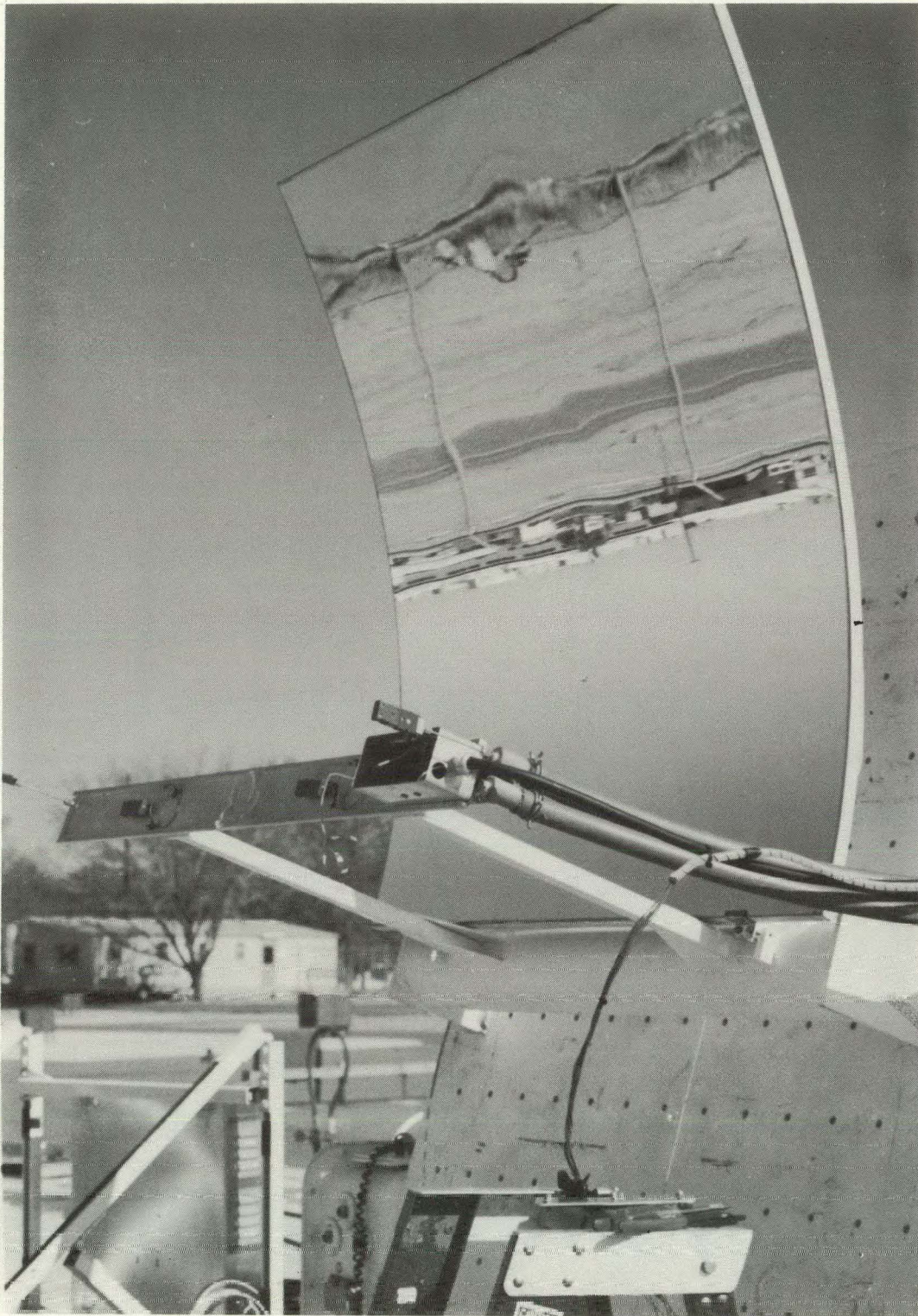
Three PRDA 35 qualification test series were begun. E-Systems, Acurex and Motorola concentrator modules and receiver subassemblies were tested at various temperatures and off-axis conditions. Peak efficiencies were running from about 6 to 12 percent for the different modules. Specific normalization techniques are being developed for reporting at standard conditions.

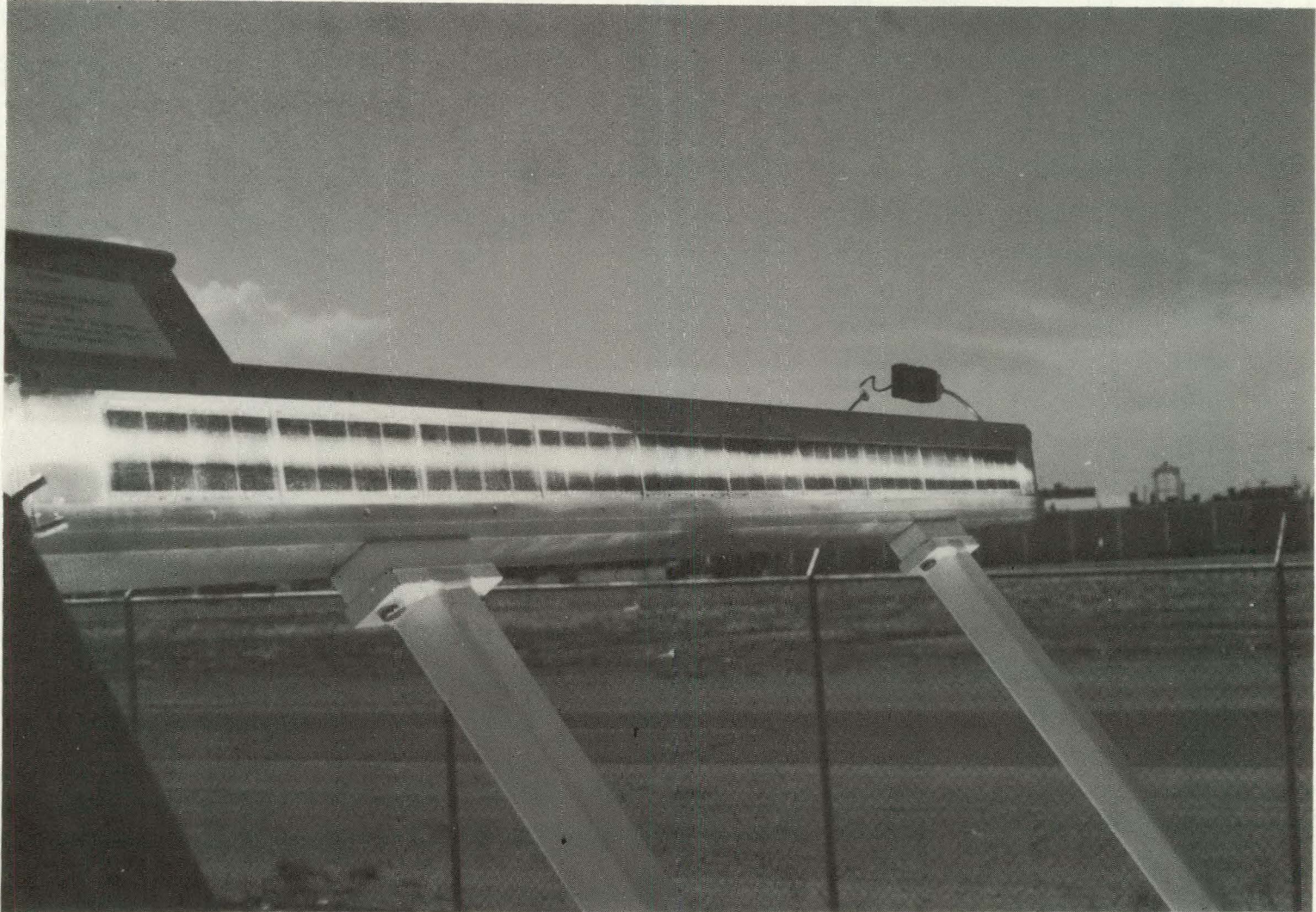
*This work was supported by the U. S. Department of Energy.

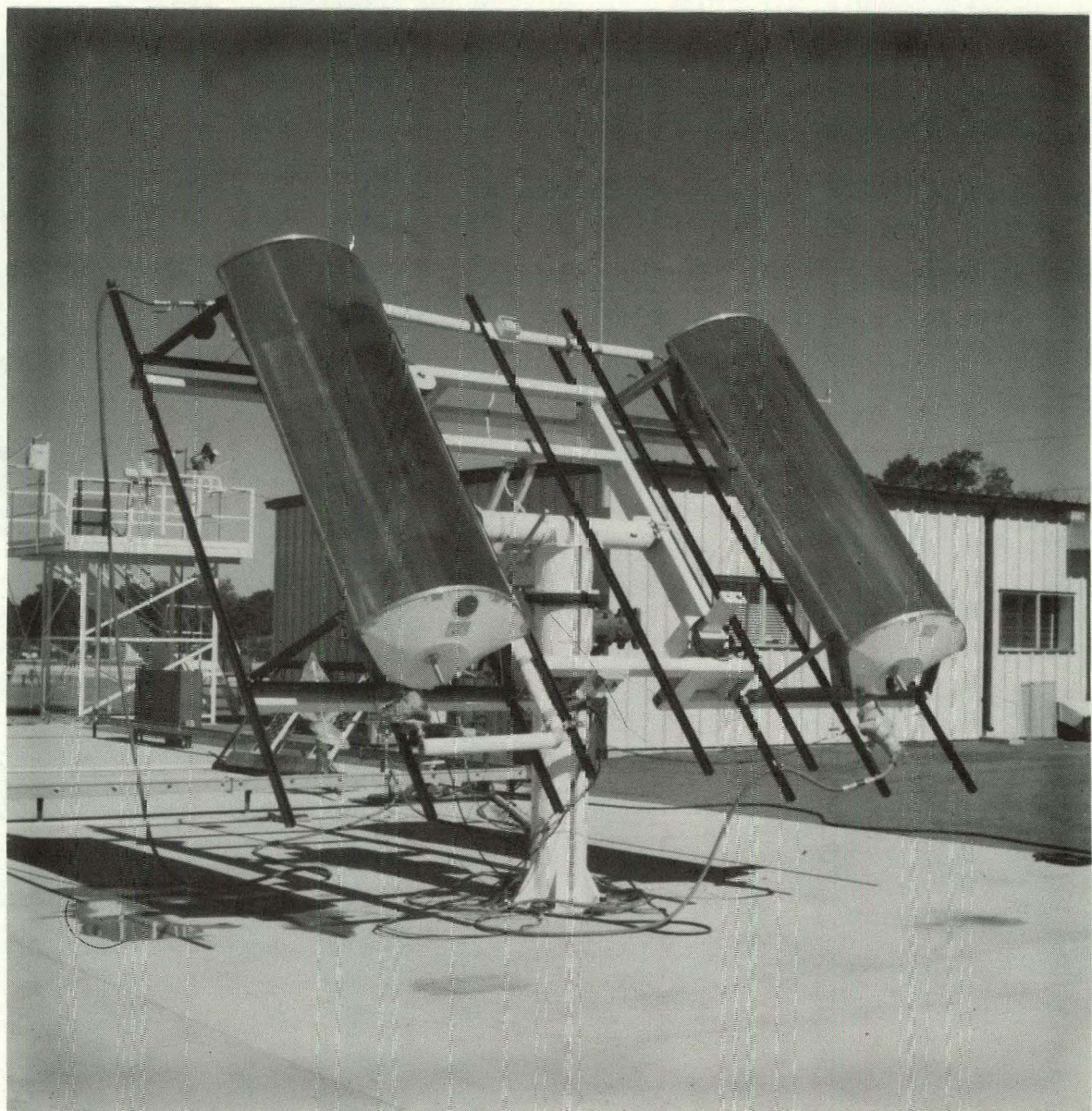


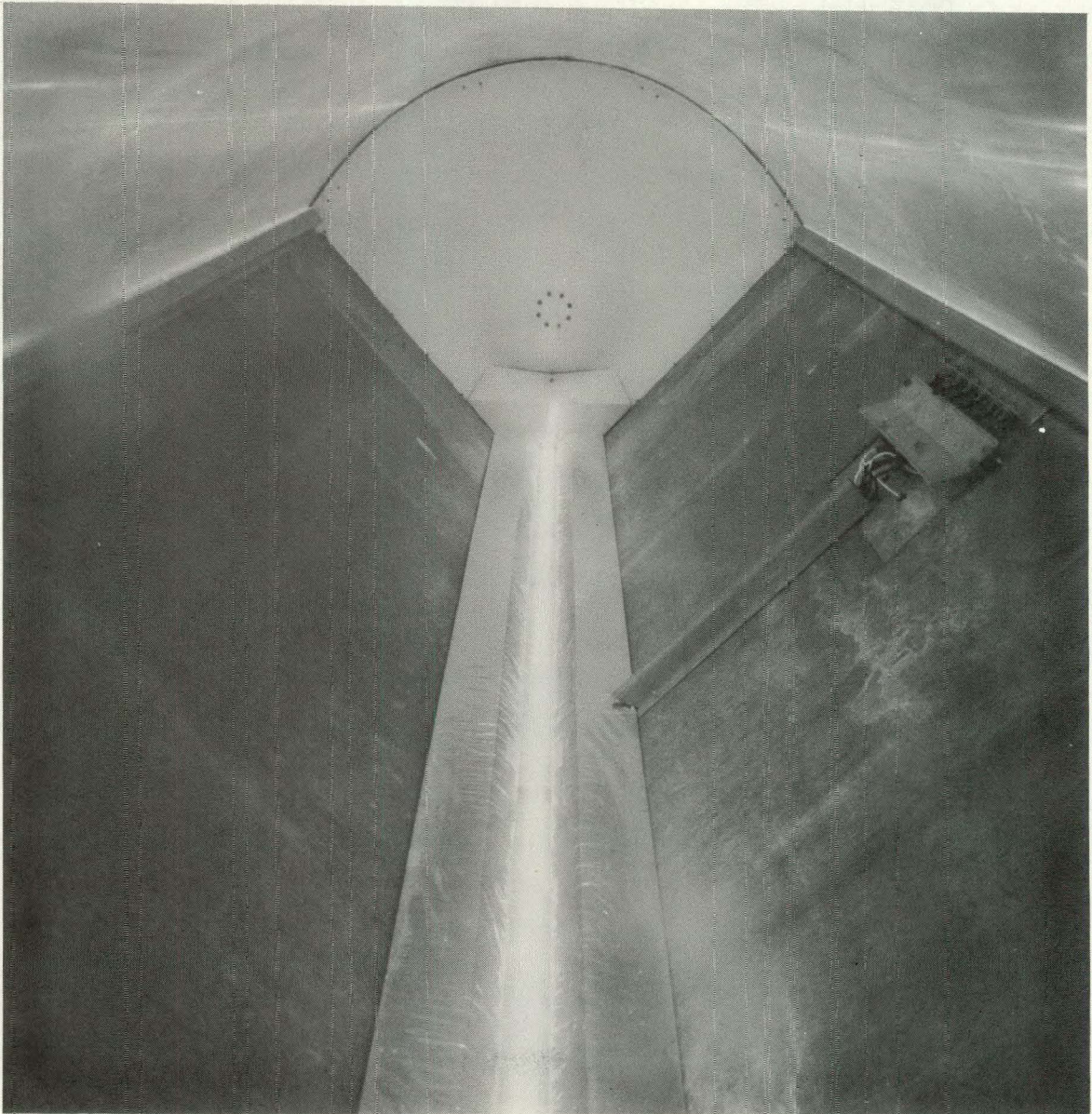


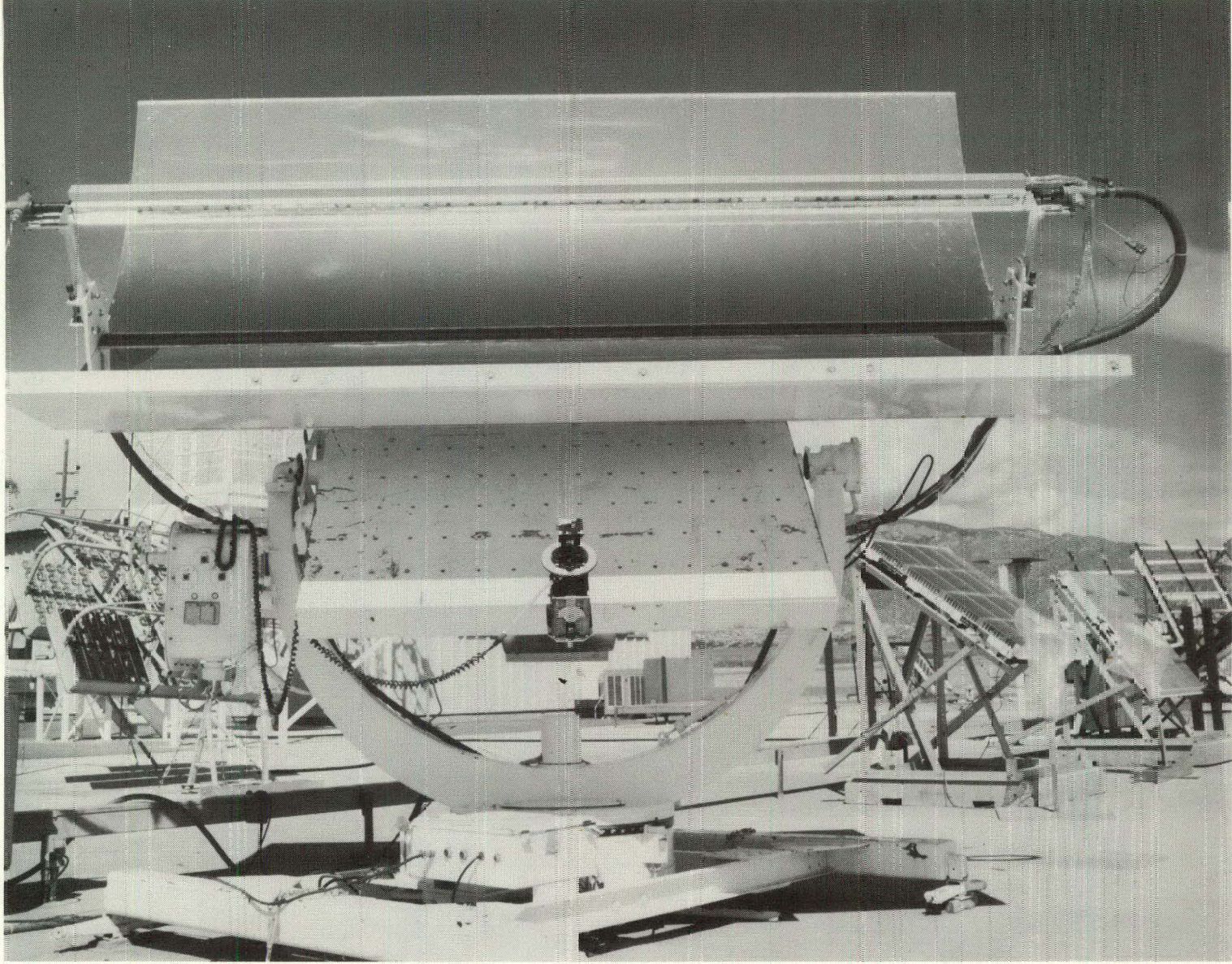


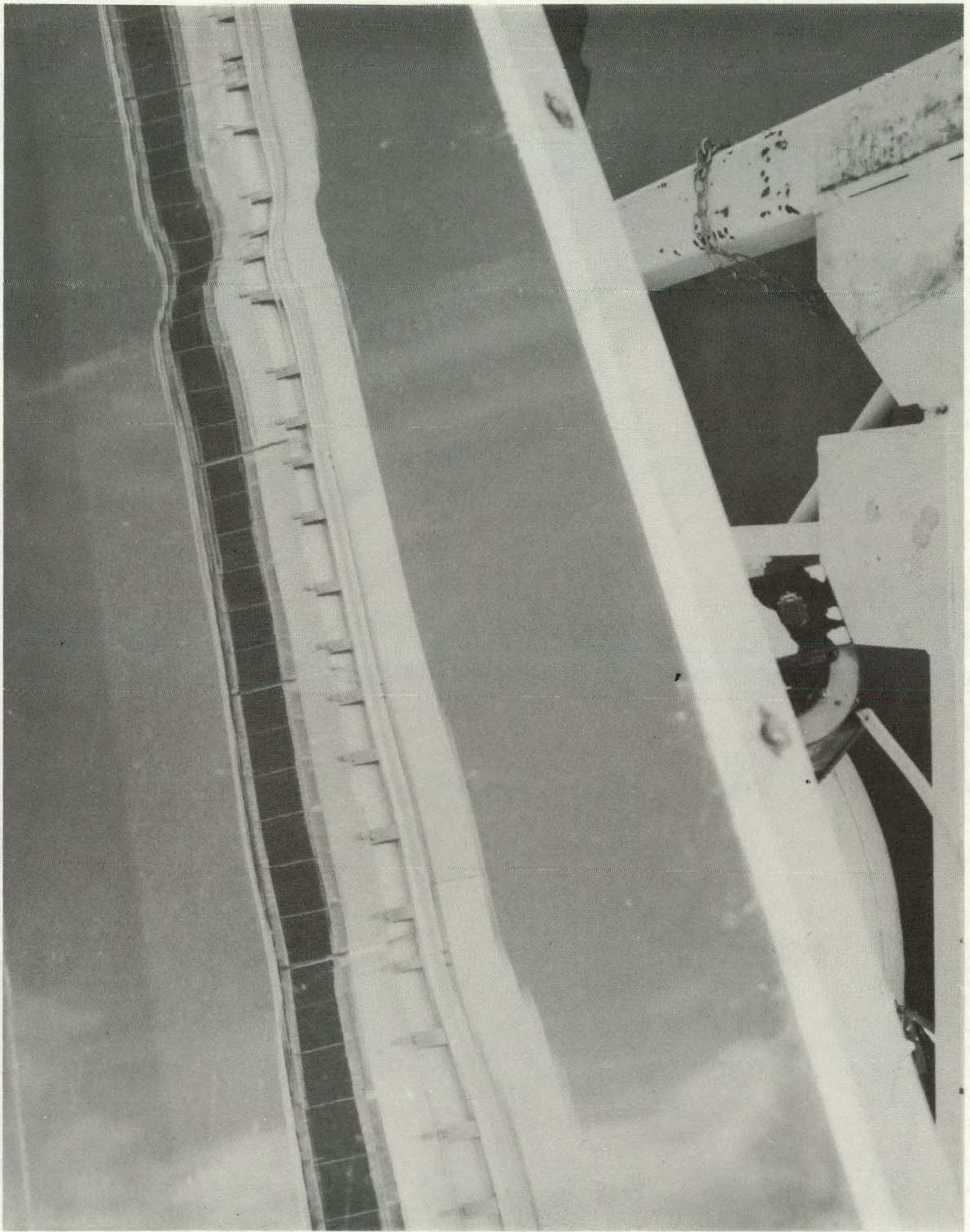


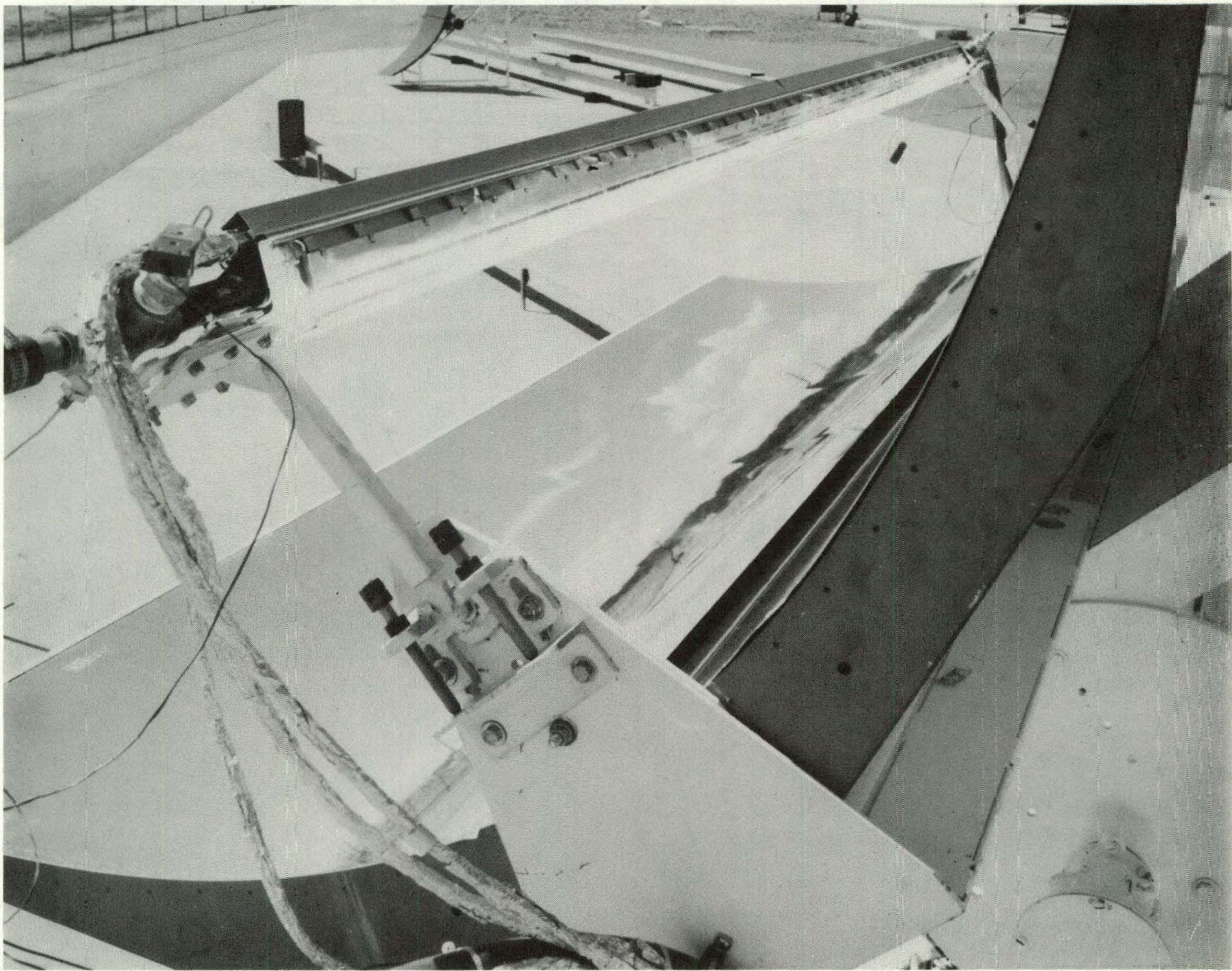












SILICON CELL DEVELOPMENT AND TESTING*

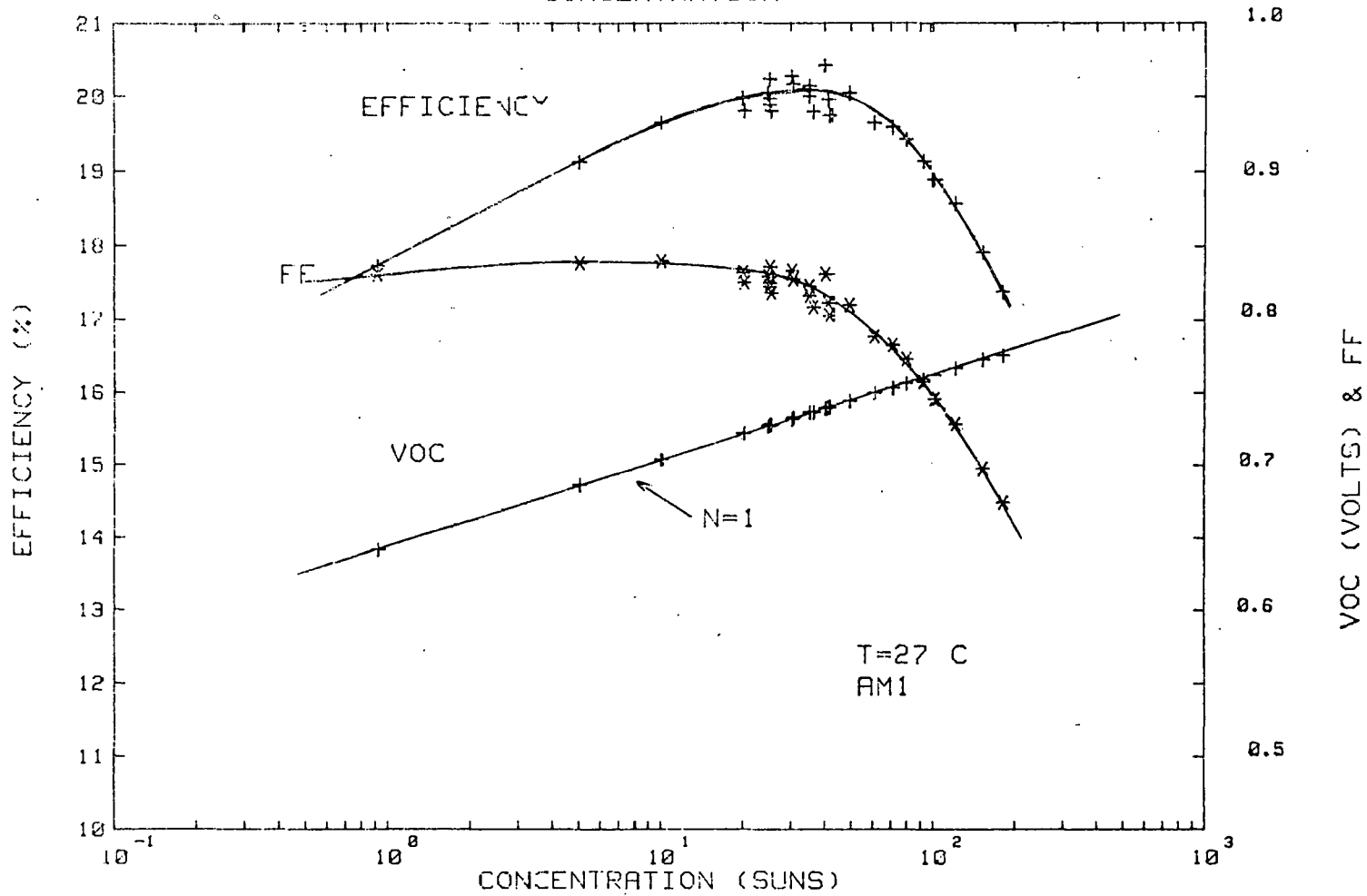
R. D. Nasby
Sandia National Laboratories, Albuquerque, NM 87185

Increased energy conversion efficiencies have been obtained recently on cells fabricated at Sandia National Laboratories. Efficiencies of 20% at 27°C have been measured on the best cells. These peak values occurred near concentrations of 30 and 70 suns for cells with different grid patterns and with cell areas of 4.2 and 0.81 cm², respectively. In addition, a one-sun efficiency of 18.1% was measured on a cell designed for use at low concentrations, less than 10 suns, in a luminescent solar concentrator system.

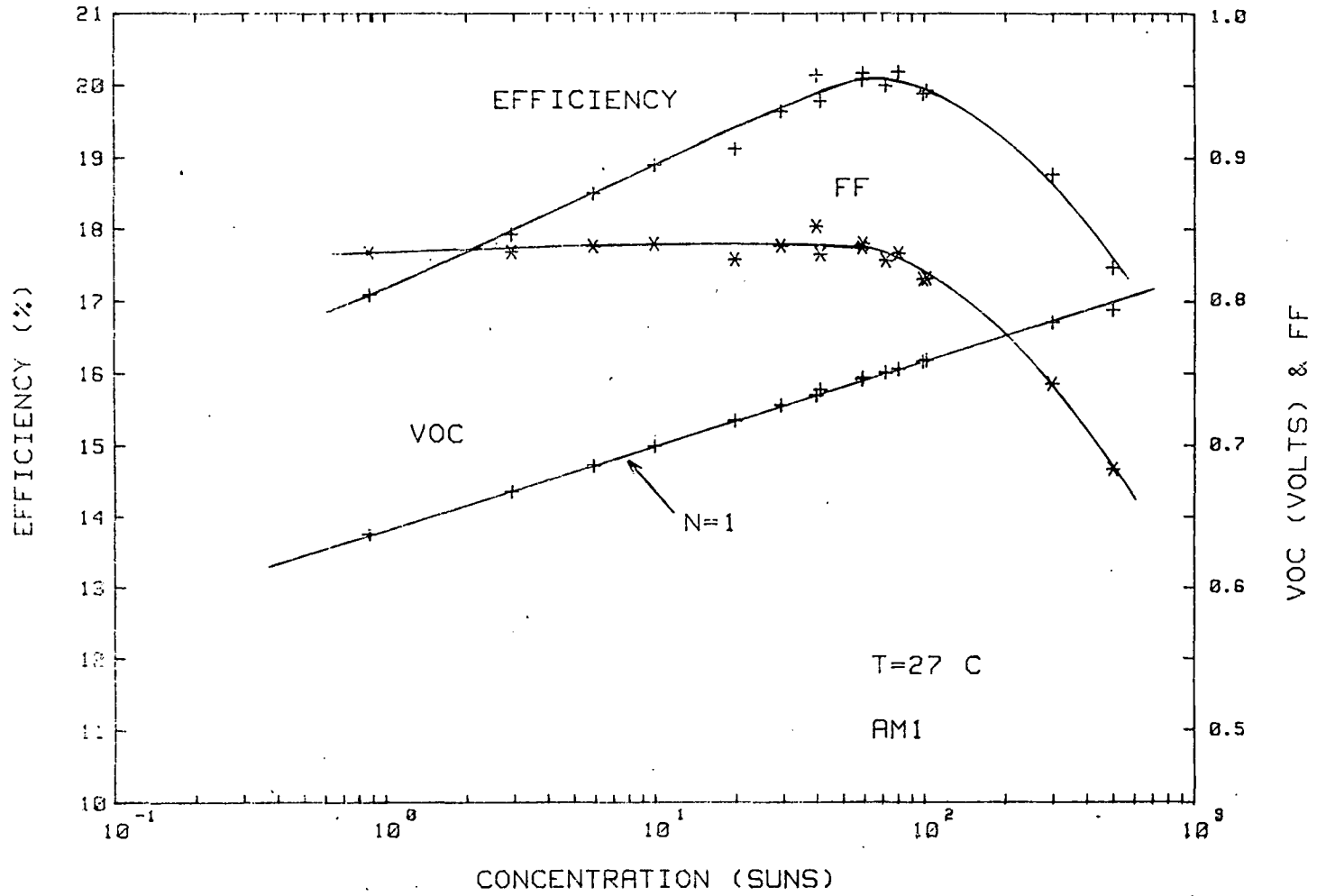
The cells are p⁺nn⁺ cells fabricated on 0.3 Ω-cm float-zone silicon wafers. The cell processing is very similar to that used in fabricating the p⁺nn⁺ BSF cells previously reported. The BSF cells were fabricated on 10 Ω-cm base material and yielded maximum conversion efficiencies approaching 19%. The decrease in base resistivity results in an increase in open circuit voltage and fill factor which more than compensates for the decrease in short circuit current. The maintenance of a high fill factor to higher concentrations is one reason for the improved performance. The fill factor equalled 0.85 at the peak efficiency for the 0.3 Ω-cm base cell as compared to 0.77 for the 10 Ω-cm base cell.

*This work was supported by the U. S. Department of Energy, DOE.

S1305A-31
 EFFICIENCY-FILL FACTOR-OPEN CIRCUIT VOLTAGE
 VS
 CONCENTRATION



S0413A2-2
EFFICIENCY-FILL FACTOR-OPEN CIRCUIT VOLTAGE
VS
CONCENTRATION



Abstract

A_lGaAs and Multiple Junction Cell Developments*

by

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Introduction

This paper discusses three main aspects of Sandia's interest in A_lGaAs and advanced multijunction cells. (1) Interests and goals; (2) Current Contracts and (3) In-house research activities at Sandia.

Interests and Goals

A_lGaAs cells are of interest because of their higher efficiency than silicon and as building blocks for multi-junction cells. Figure 1 shows a plot of allowed cell costs vs concentration to achieve the 70¢/Wp goal. From the figure we see that a 15% efficient array (possibly made up of 19% efficiency silicon cells) would allow cell + heatsink (receiver) costs of only 10¢/cm². On the other hand a 25% array efficiency (possibly made up of 29% efficient A_lGaAs cells) allows receiver (cell + heatsink) costs of ~ \$2.00/cm². This is a factor of 20 increase over the 19% silicon cell. This type of analysis continues to keep our interest alive in high efficiency A_lGaAs cells and multiple junction devices. To this end we are planning contract funding of ~ \$550K in FY81 to support improved efficiency A_lGaAs cells and mechanically stacked or spectral split development efforts.

Current Contracts

We are presently supporting work on the effects of the GaAs substrate on cell efficiency, A_lGaAs cell life tests and advanced mechanically stacked and spectral splitting techniques - see Figure 2.

In-House Research

Present in house research activities include:

- a) Array Modeling - computer simulations of array performance of series connected cells.
- b) Series Resistance - development of new techniques for series resistance measurements using flash testing.
- c) Thermal Impedance - studies of economic factors of heatsink impedance at high concentrations.
- d) Performance Evaluation - operation of facility to measure efficiency of contractor developed cells (up to 1500X)

*This work sponsored by the U.S. Department of Energy (D.O.E.) under contract DE-AC04-76-DP00789.

[†]A U.S. Department of Energy facility.

EFFICIENCY-COST TRADEOFFS FOR
 CONCENTRATING PHOTOVOLTAIC ARRAYS
 \$0.70/W_p TECHNOLOGY - NO THERMAL CREDIT

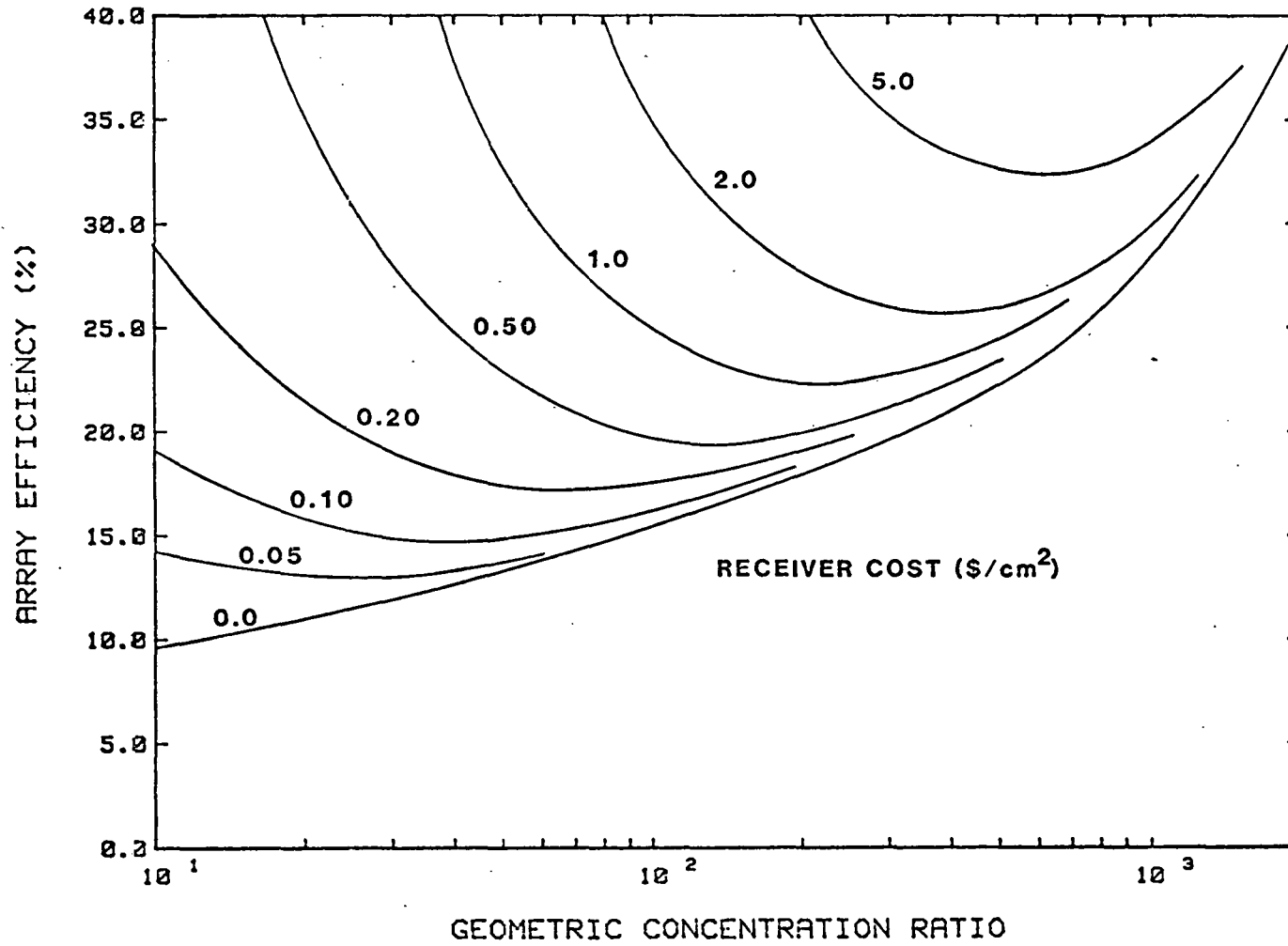


FIGURE 1.

<u>A&GaAs and Advanced Cell Contracts (\$K)</u>		
	<u>FY80</u>	<u>FY81</u>
Spectral Splitter		200
Life Test	350	
A&GaAs Efficiency Improvement Study	350	
Cover Glass Research		100
Diffusion Barriers	35	45
To be Placed	--	~ \$200K

Figure 2.

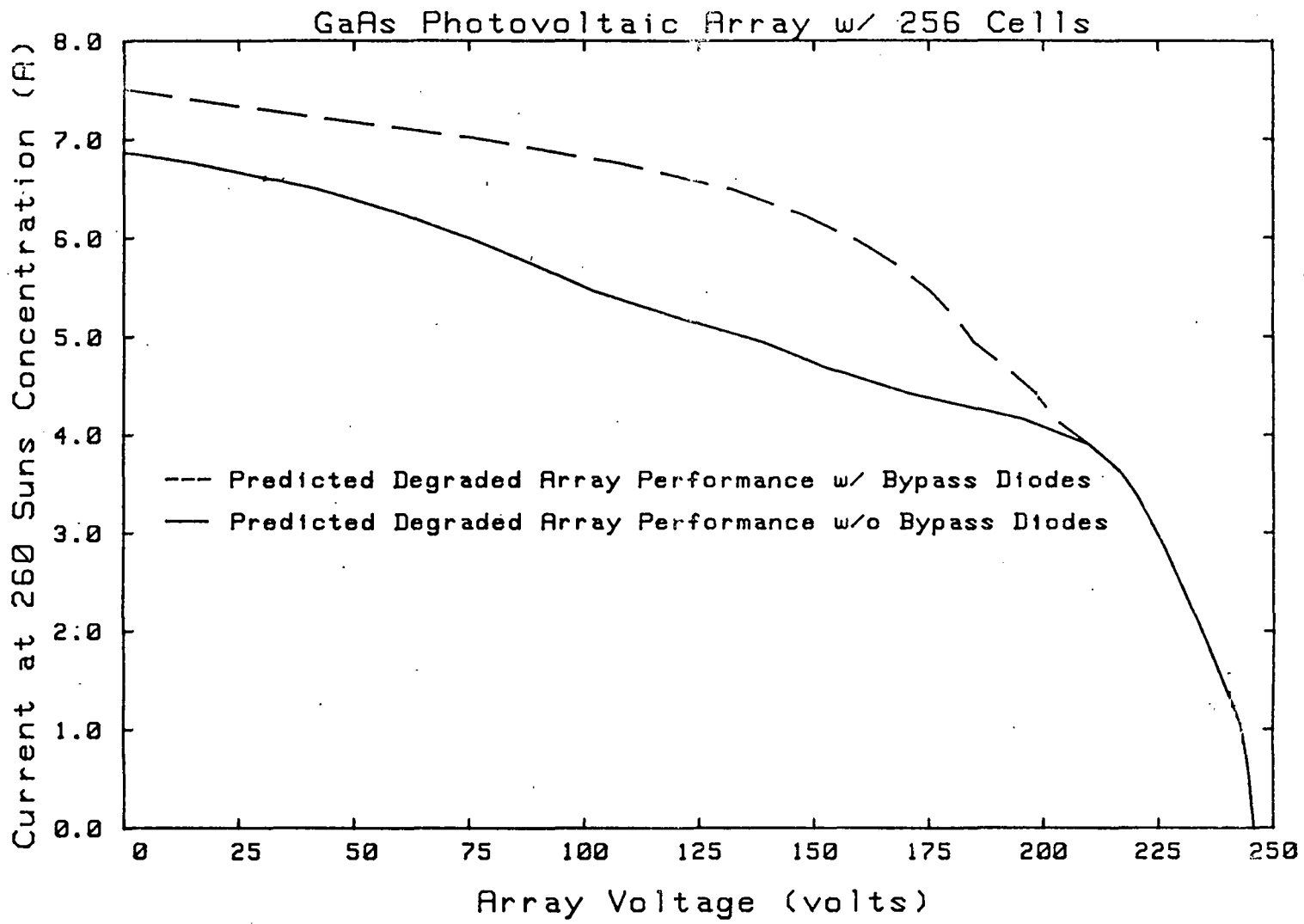
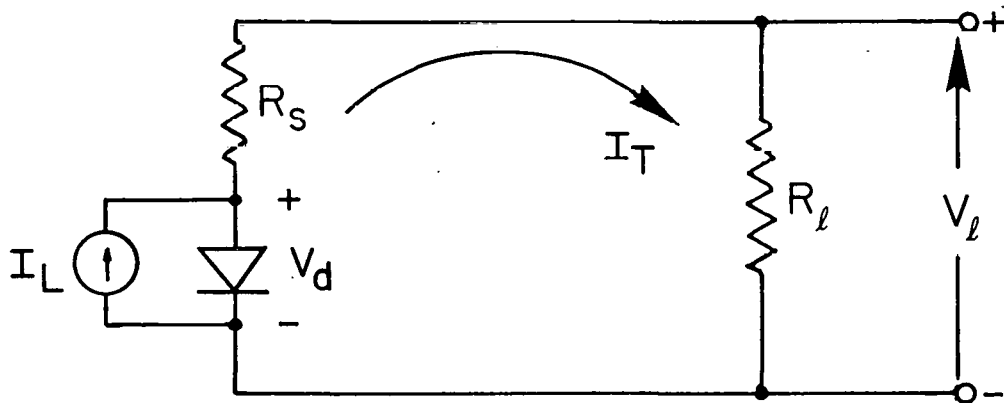
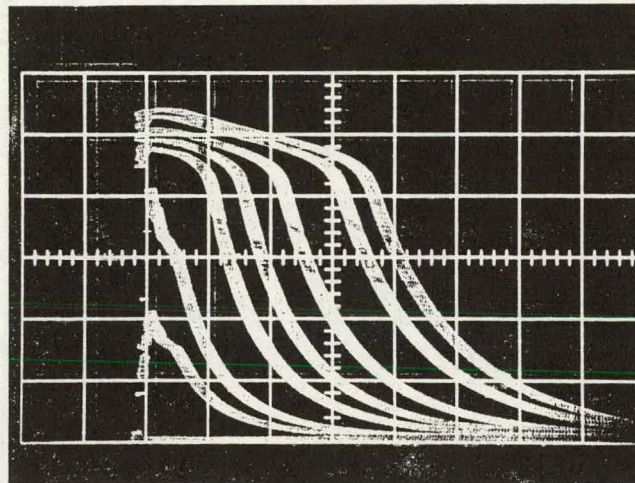


Figure 3



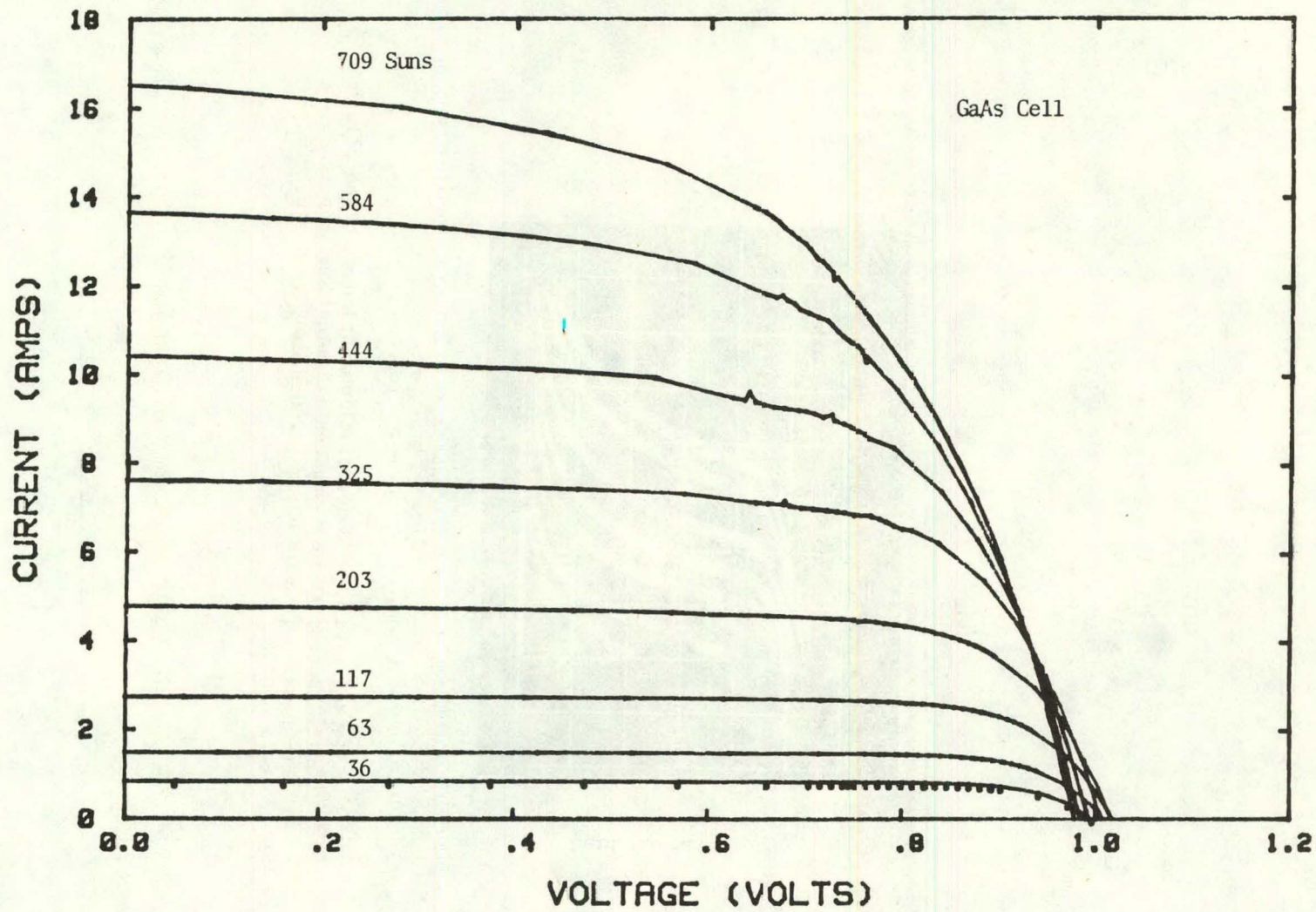
At Saturation: $I_S(R_L + R_S) \cong V_{oc}$

Cell Current →



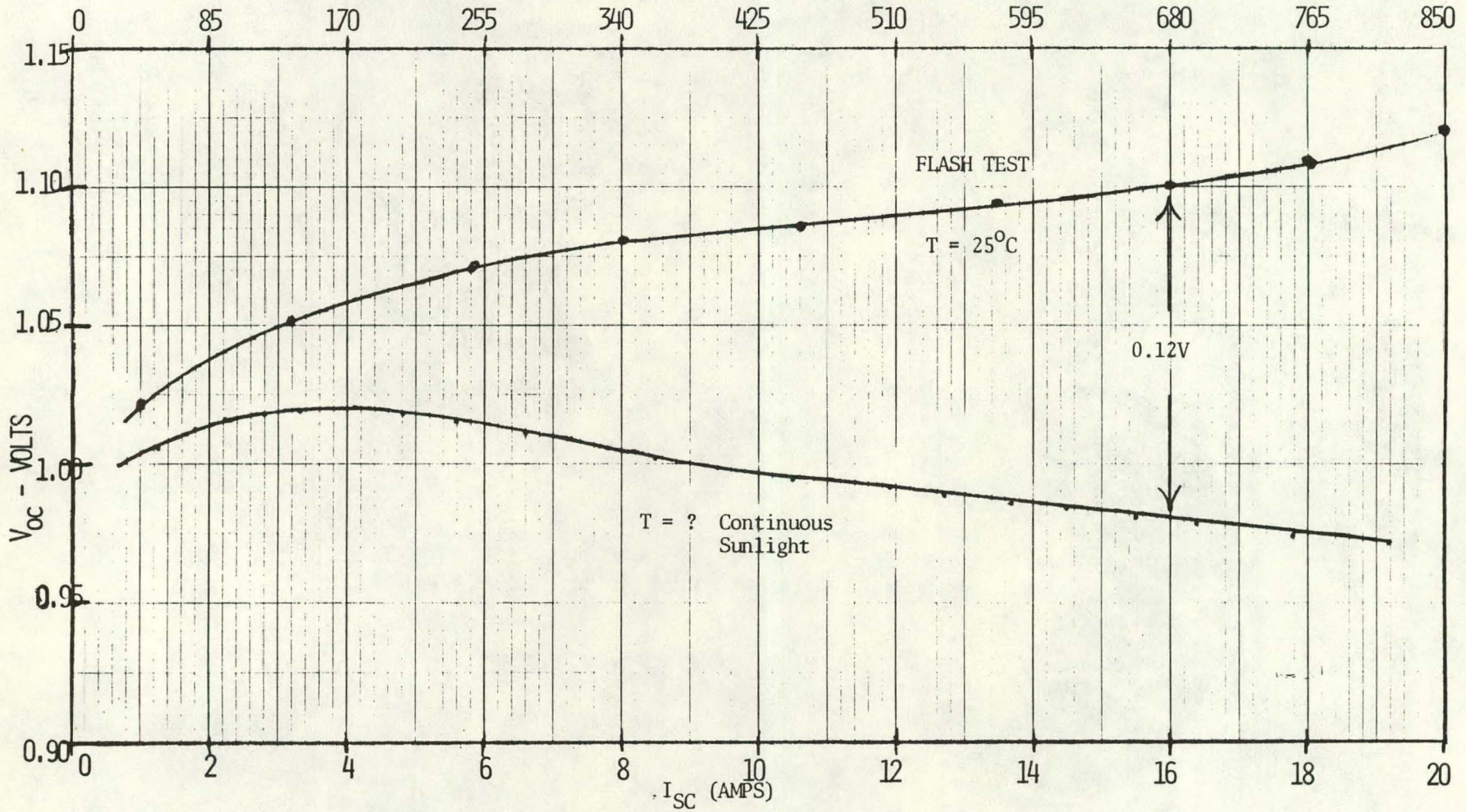
Time →

Solar cell time response to illumination with photoflash unit. Bottom trace = weakest illumination, top trace = strongest. (scales horiz = $200\mu\text{s}/\text{div}$, vert = $0.2\text{V}/\text{div}$). $R_{\ell} = 0.079\Omega$.

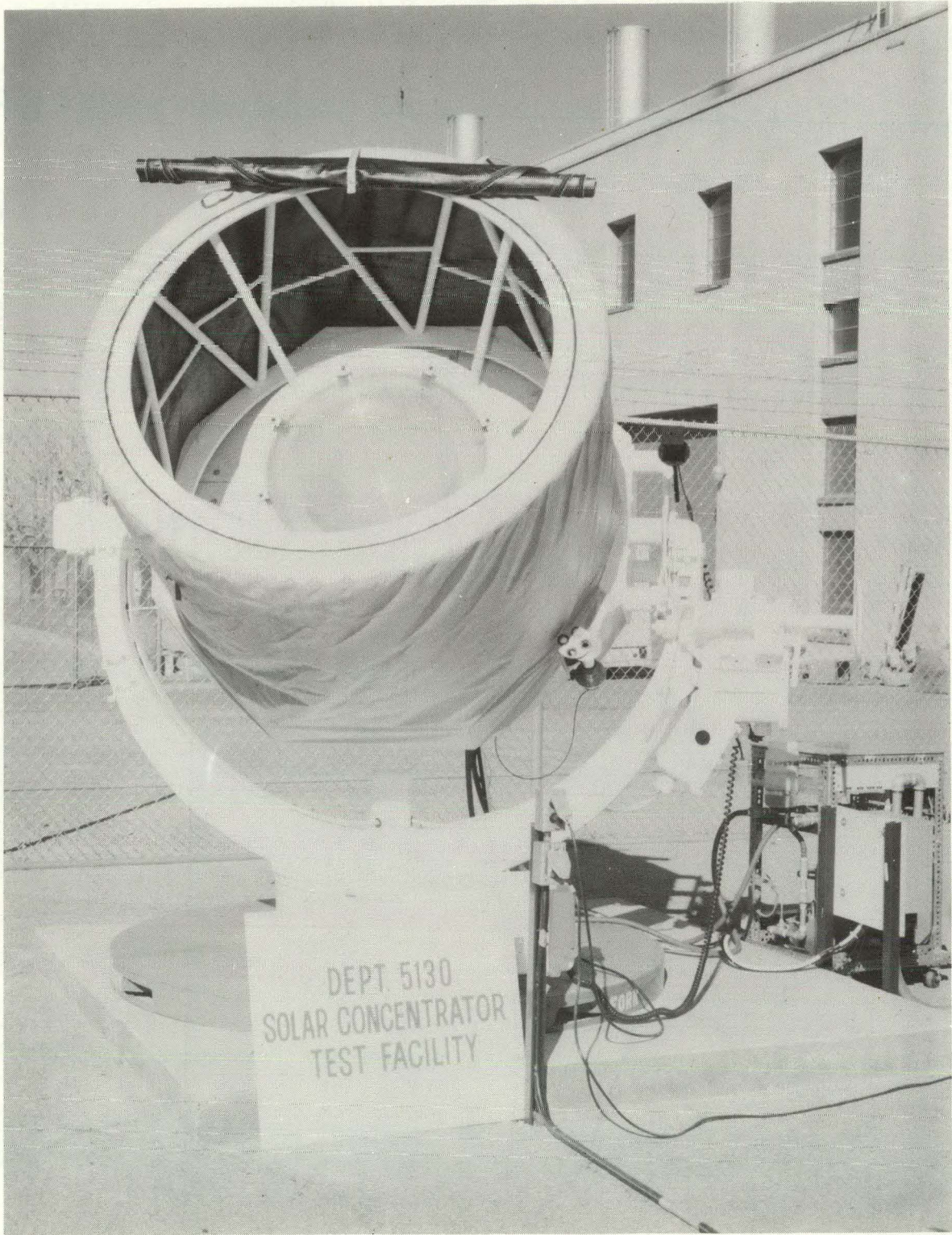


I-V Characteristics of 1.27 cm dia GaAs concentrator cell on water cooled heatsink.

INSOLATION - SUNS



V_{oc} vs I_{sc} (insolation) for GaAs concentrator measured at 25°C (by flash test) and in continuous sunlight.



ETCHED MULTIPLE VERTICAL JUNCTION (EMVJ) CELLS AND ASSEMBLIES

Dr. George P. Allendorf and Robert I. Frank

Microwave Associates, Inc.
43 South Avenue
Burlington, Massachusetts 01803
617-272-3000

In the area of the etched multiple vertical junction (EMVJ) solar cell, work has proceeded toward an optimization of the basic structure (Figure 1). In this structure, vertical grooves are etched into the silicon wafer from the top surface. Boron is then diffused into these grooves. The wafer is passivated, metallized and diced. During operation, photo-generated carriers diffuse from the bulk silicon directly through the junction, into the thick metallization on the walls of the etched grooves, and out to the top electrode. This provides a structure with a very small series resistance, permitting the efficiency to increase with increasing concentration. Over the last year, three structures have been fabricated and tested, using the same basic design concepts (Figure 2). A square cell with grooves etched from the top surface, and with narrow buss stripes on either end of the grooves was fabricated. Thermally grown SiO_2 was used as an anti-reflection coating. This class of cells generally showed efficiencies of about 17.1% at 500 suns. The fill factor rolled off rather quickly beyond these intensities (Figure 3). The second class of device utilized essentially the same basic structure but a larger buss area which completely surrounds a circular active area was instituted to facilitate top bonding of these cells. Improved performance was observed for these (over the former cells) in that the efficiency levelled out at about 18.5% from approximately 600 to 1000 suns, and the fill factor rolled off much more slowly (Figure 4).

During this period, optimization of certain processes, which would improve overall cell performance was proceeding. Work was initiated in improving the AR coating: a thin thermal oxide, annealed, followed by silicon nitride deposition, resulted in flatter laser scans (plotting I_{sc} versus distance). Obscured area due to metallization "spillover" during plating of the vertical grooves was reduced from ~13% of the active area to about 9%.

Two very important factors became apparent during this period: the effect of the unpassivated edges of the chips on current collection and the effect of base resistance (R_B) due to loss of conductivity modulation at higher intensities. The former affects J_{sc} and fill factor primarily, while the latter has more of an effect on fill factor. High

surface recombination velocity at the edges has been observed directly by monitoring I_{sc} as a laser beam is scanned across the chip surface near the edge. A third class of cell was fabricated to lessen these effects. Overlapping grooves were etched from both sides of the wafer (Figure 5). Boron is diffused into the grooves on one side, and phosphorus into the grooves on the other side. Data for this device as a function of intensity will be presented. In general, a marked improvement in FF behavior with intensity, especially above 500 suns, has been observed (Table I). The effect of the cell edges, however, has not yet been completely eliminated.

Future tasks in the areas of metallization, improved AR coatings, edge passivation, and cell geometry (e.g. junction area) will be described. In addition a developmental program to design and fabricate solar cell packages is underway. This program has two major aspects: (1) the design and fabrication of a reliable, potentially low-cost hermetic package using one-step all brazed construction, and (2) the development of a reliable, low-cost method of making electrical connection to the top and bottom contacts of an EMVJ cell. Progress has been made on both these tasks and the results will be described.

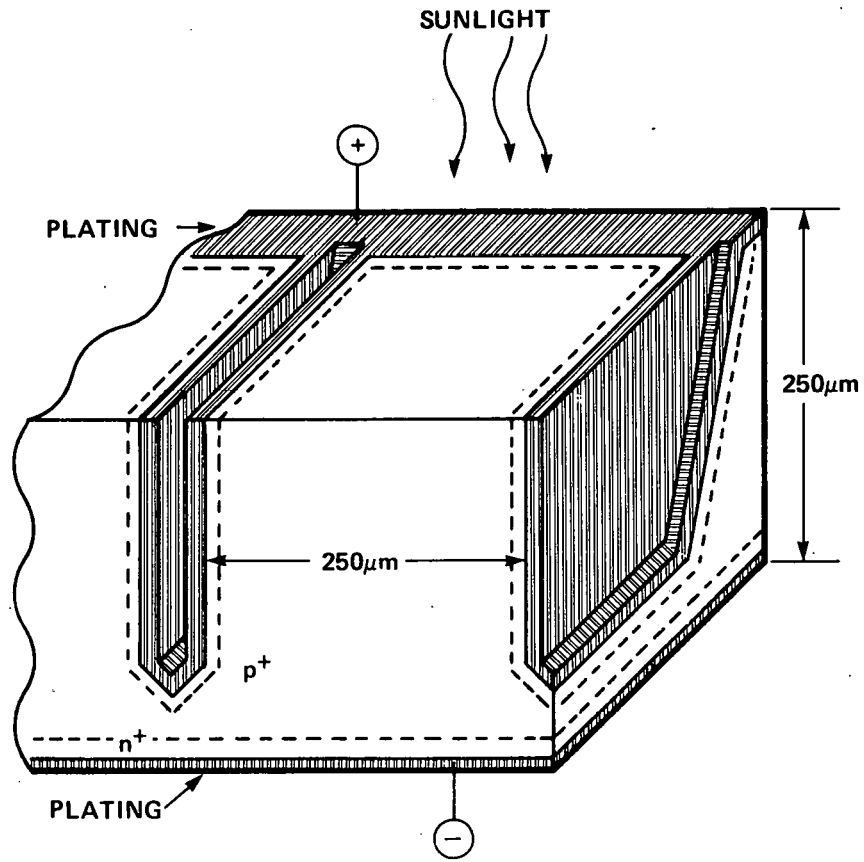


FIGURE 1. BASIC STRUCTURAL FEATURES OF THE FRONT-GROOVED ETCHED MULTIPLE VERTICAL JUNCTION (EMVJ) CELL.

D-19106A

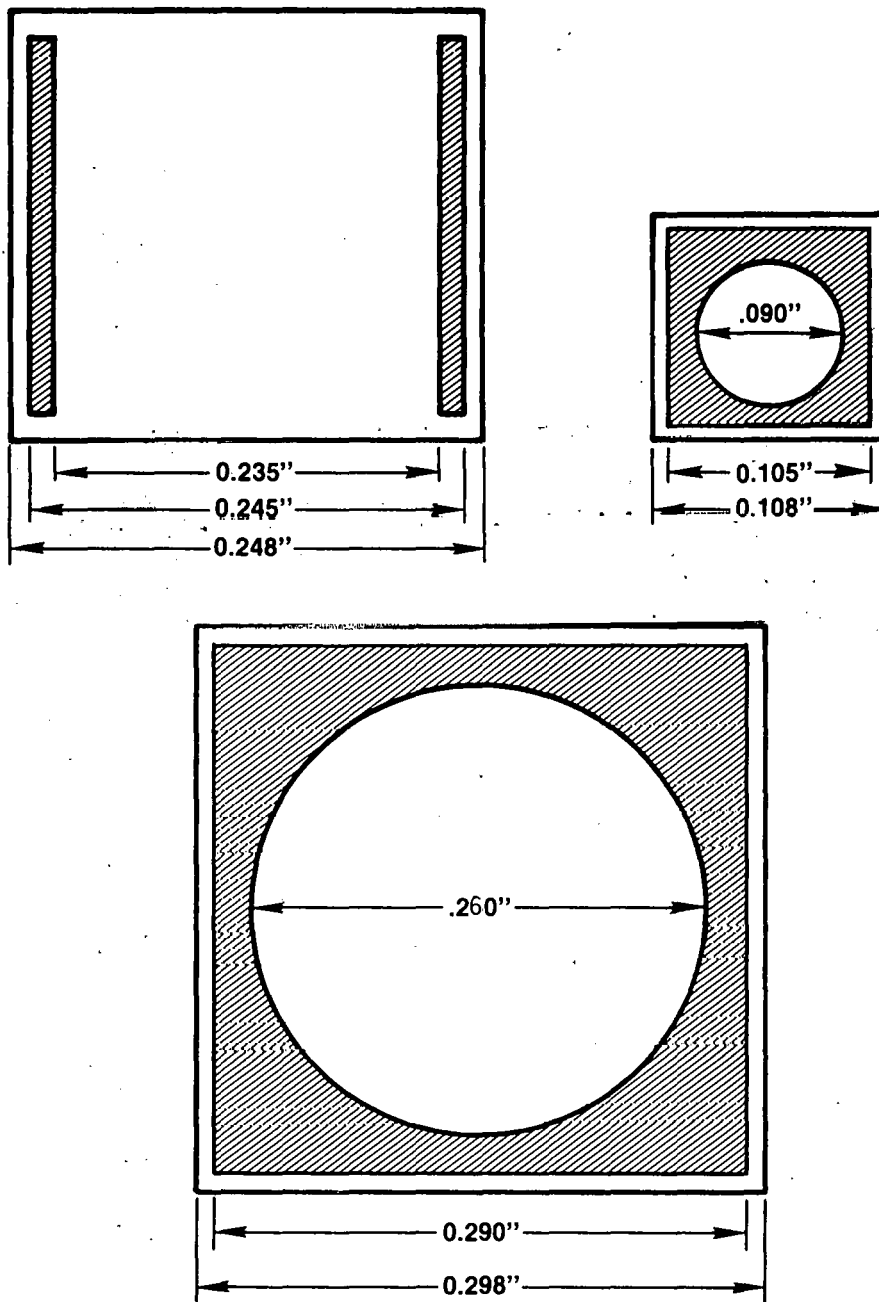


FIGURE 2 . TOP SURFACE LAYOUT AND SIZE OF TEST CELLS

D-19593

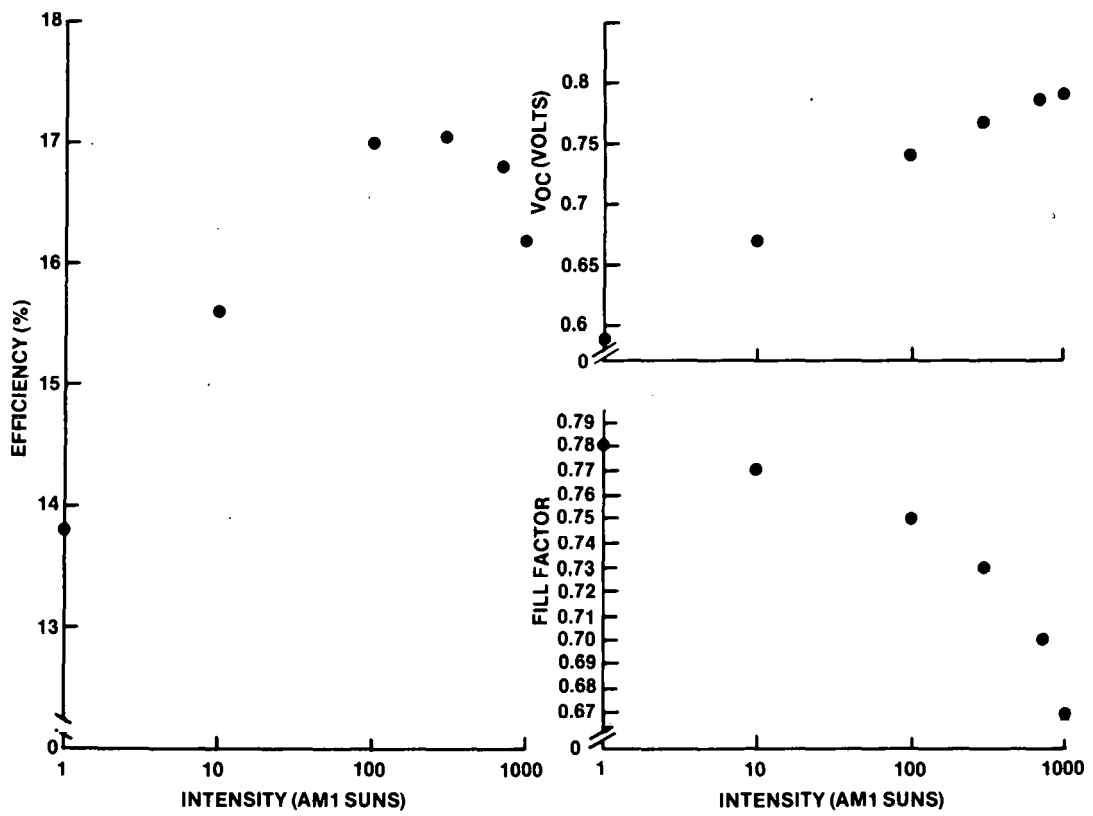


FIGURE 3 . HIGH INTENSITY PERFORMANCE OF 0.25" SQUARE CELL

D-19577

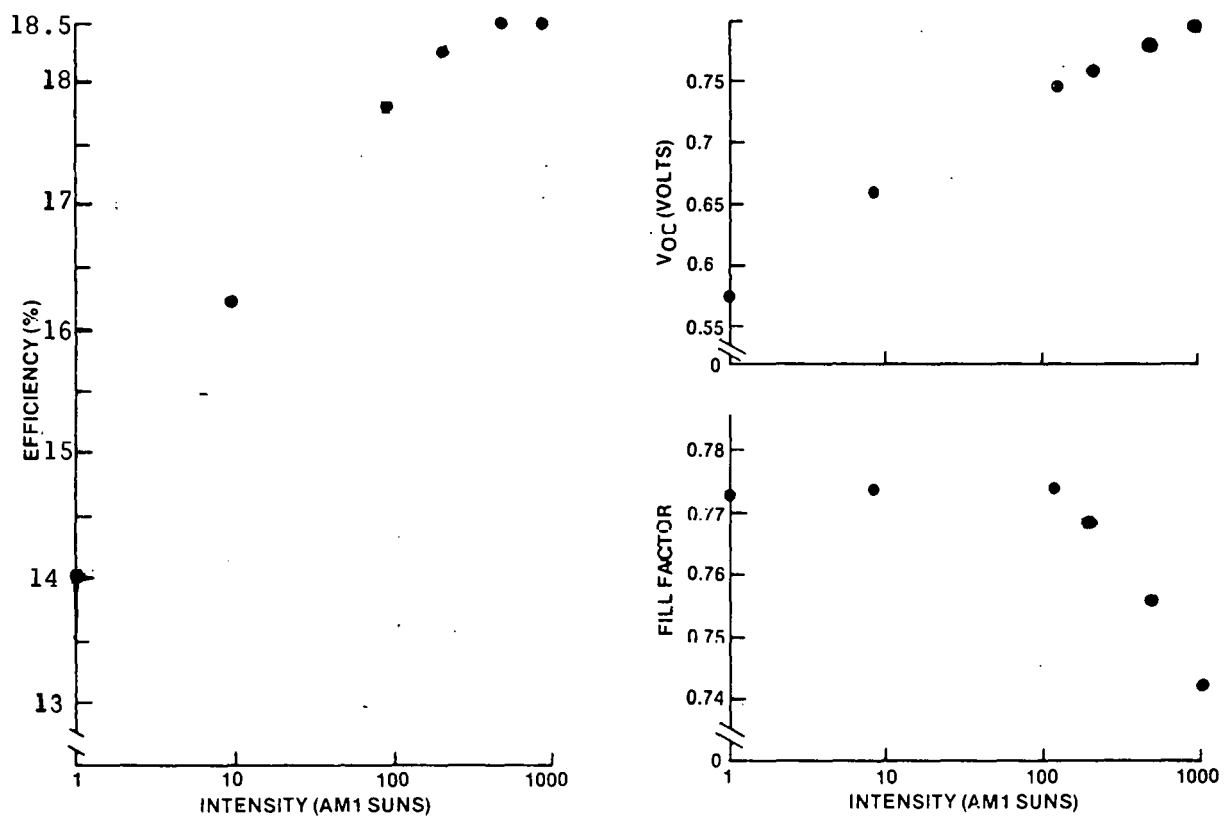


FIGURE 4. HIGH-INTENSITY PERFORMANCE OF A 0.260" DIAMETER EMVJ CELL.

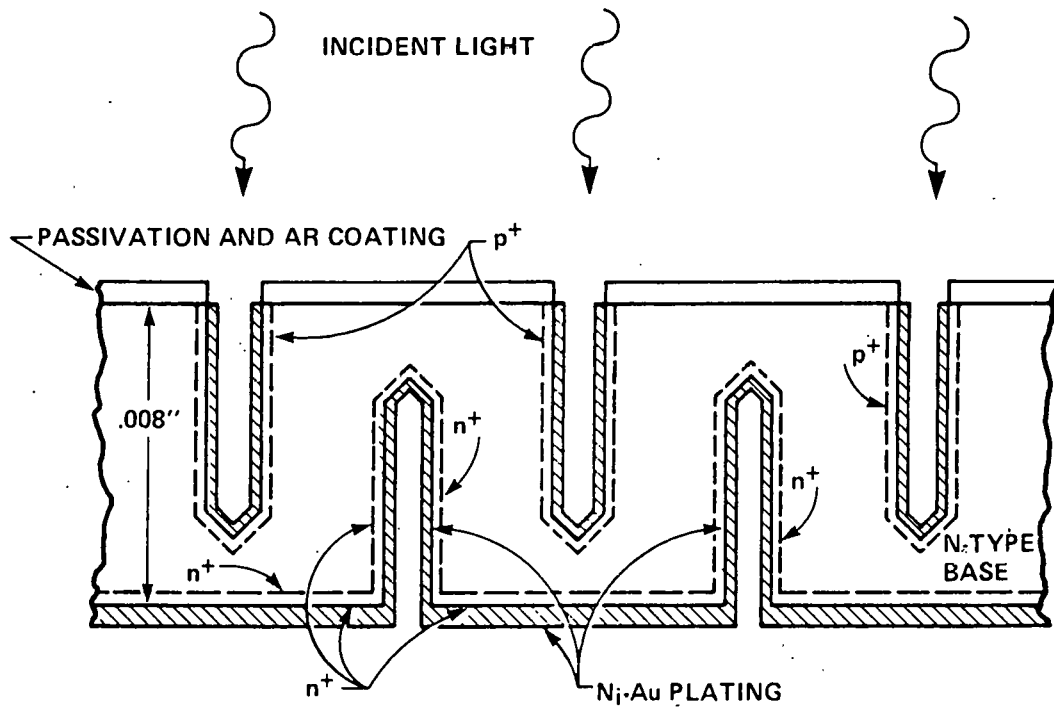


FIGURE 5. CROSS-SECTION OF EMVJ CELL WITH p^+ AND n^+ GROOVES ETCHED FROM OPPOSITE SIDE OF WAFER

D-16601B

TABLE I

FILL FACTOR VERSUS INTENSITY FOR A
FRONT-BACK GROOVED CELL

<u>INTENSITY(SUNS)</u>	<u>FILL FACTOR</u>
1	0.768
50	0.759
100	0.764
300	0.765
600	0.760
800	0.757
1000	0.753
1400	0.750

COMBINED PHOTOVOLTAIC/THERMAL
LINEAR RECEIVER

BY

GENERAL ELECTRIC COMPANY
ADVANCED ENERGY PROGRAMS DEPARTMENT
P. O. BOX 8661
PHILADELPHIA, PA 19101

CONTRACT NO.: 13-8893
PRINCIPAL INVESTIGATOR: NEAL F. SHEPARD, JR.
(215) 962-5839
CONTRACT VALUE: \$93,234
CONTRACT DURATION: OCTOBER 1979 TO SEPTEMBER 1980

PROJECT DESCRIPTION. This project involves the design, fabrication and testing of a combined thermal/photovoltaic linear receiver which employs an outer glass shroud with a transparent coolant fluid passing over the active surface of solar cell circuits which are mounted within this tube. This receiver is designed to be optically compatible with the Sea World reflector design with a geometric concentration ratio of 34:1. Two five foot long prototype receivers are to be fabricated and tested as part of this program.

CURRENT STATUS. All contract work effort has been completed and the final report has been published. Two prototype receivers were fabricated and one of these was integrated with the prototype Sea World reflector and subjected to a series of electrical performance tests using Synfluid (2 centistoke) as the coolant.

KEY RESULTS TO DATE. A module electrical efficiency of 9.2 percent was measured with a 50°C inlet coolant temperature.

PRESENTATION
AT THE
SIXTH CONCENTRATOR PROJECT INTEGRATION MEETING
NOVEMBER 5-6, 1980

COMBINED PHOTOVOLTAIC/THERMAL
LINEAR RECEIVER

N. F. SHEPARD

GENERAL ELECTRIC COMPANY
ADVANCED ENERGY PROGRAMS DEPARTMENT
P. O. BOX 8661
PHILADELPHIA, PA 19101



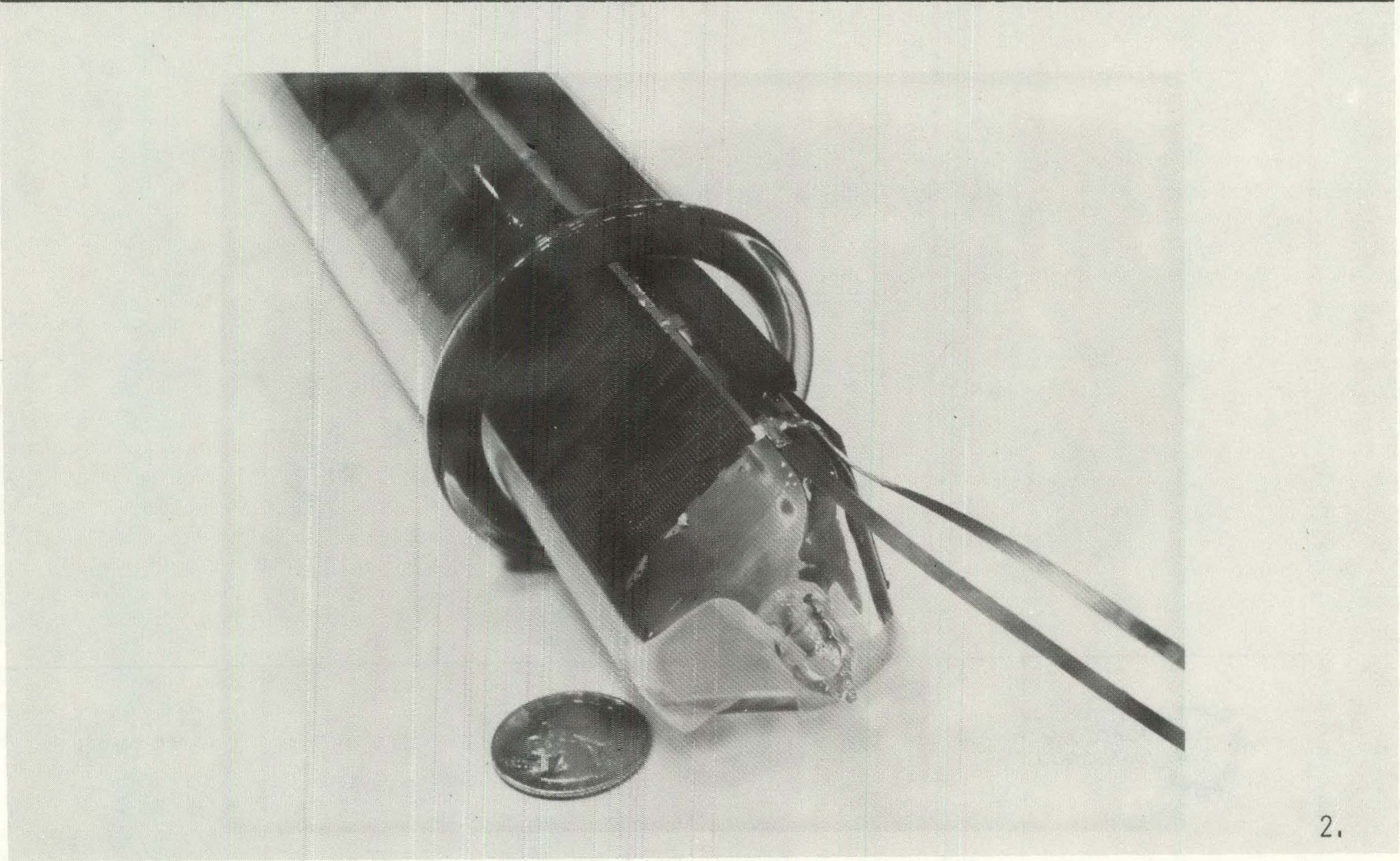
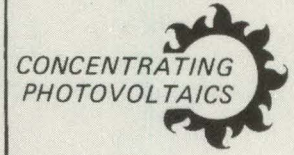
CURRENT STATUS



- CONTRACT WORK EFFORT COMPLETED
- FINAL REPORT ISSUED (SAND80-7138)
- ASSEMBLED TWO 5 FT. LONG PROTOTYPE RECEIVERS
- INTEGRATED ONE RECEIVER WITH THE SEA WORLD PROTOTYPE TROUGH
- COMPLETED PERFORMANCE TESTING USING SYNFLUID COOLANT

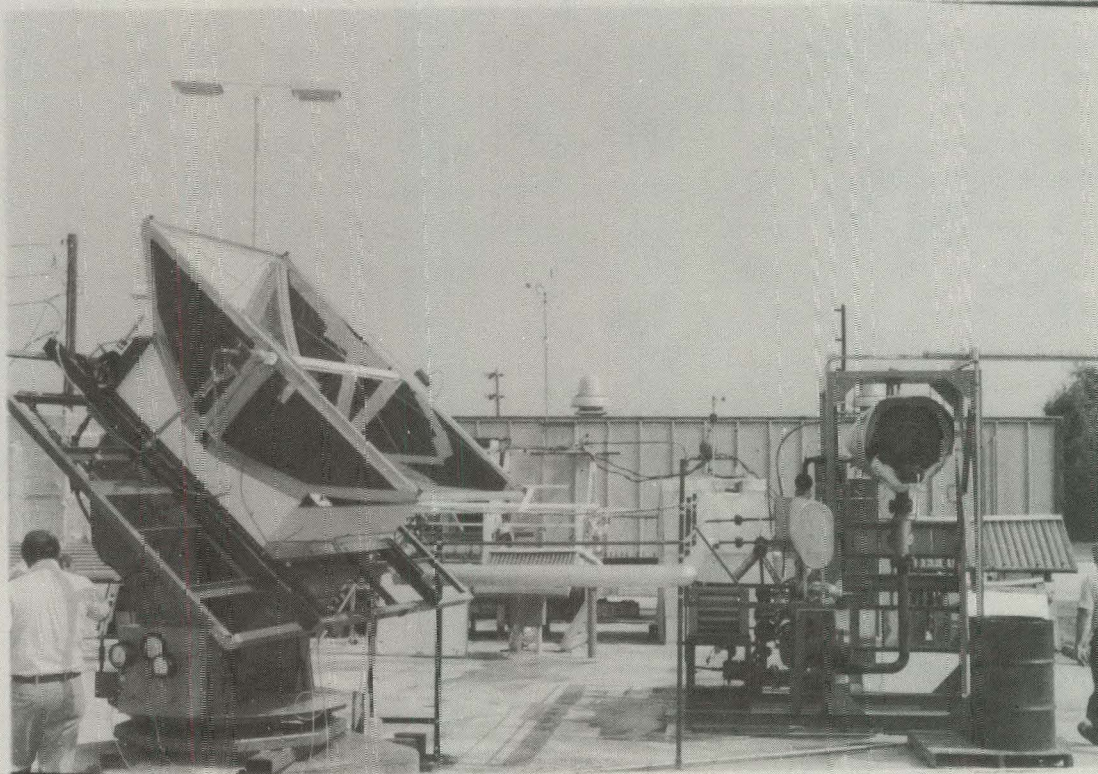


COMBINED PHOTOVOLTAIC/THERMAL
LINEAR RECEIVER



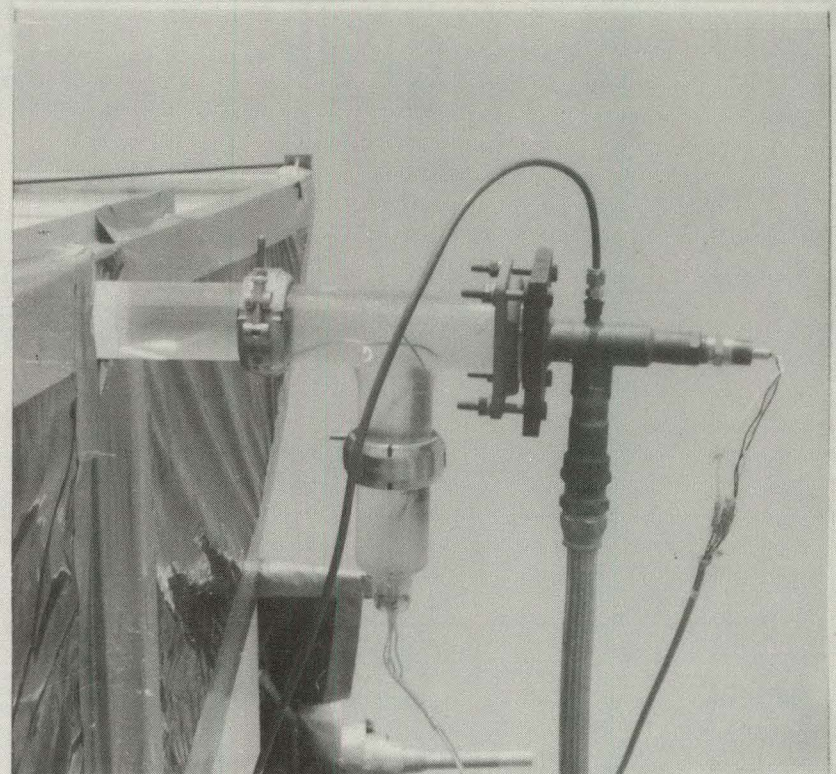
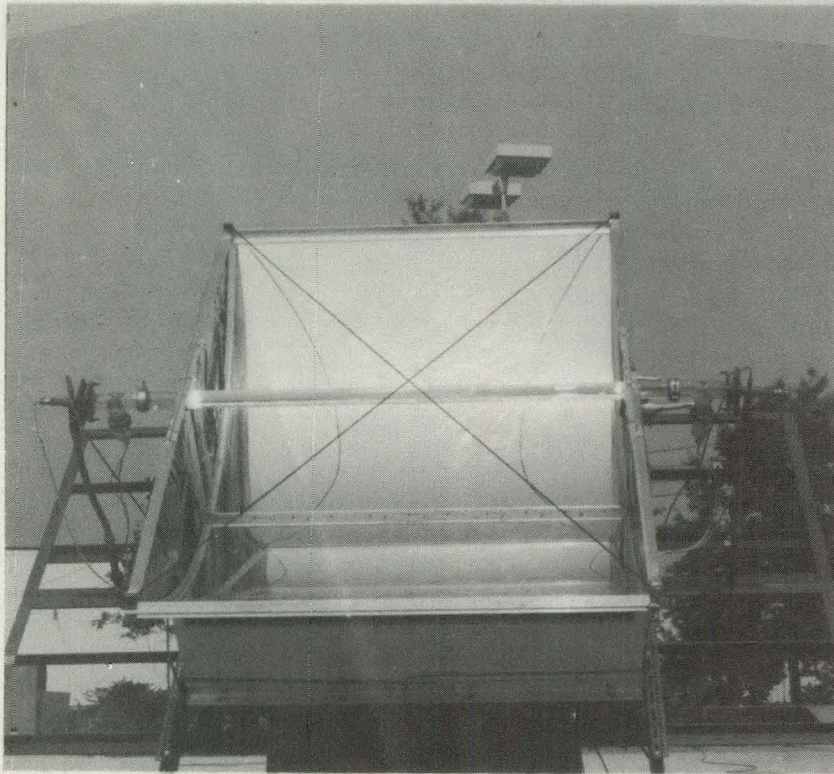
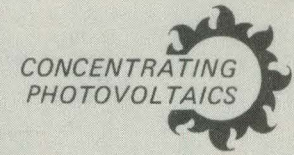


LINEAR RECEIVER
TEST SET-UP



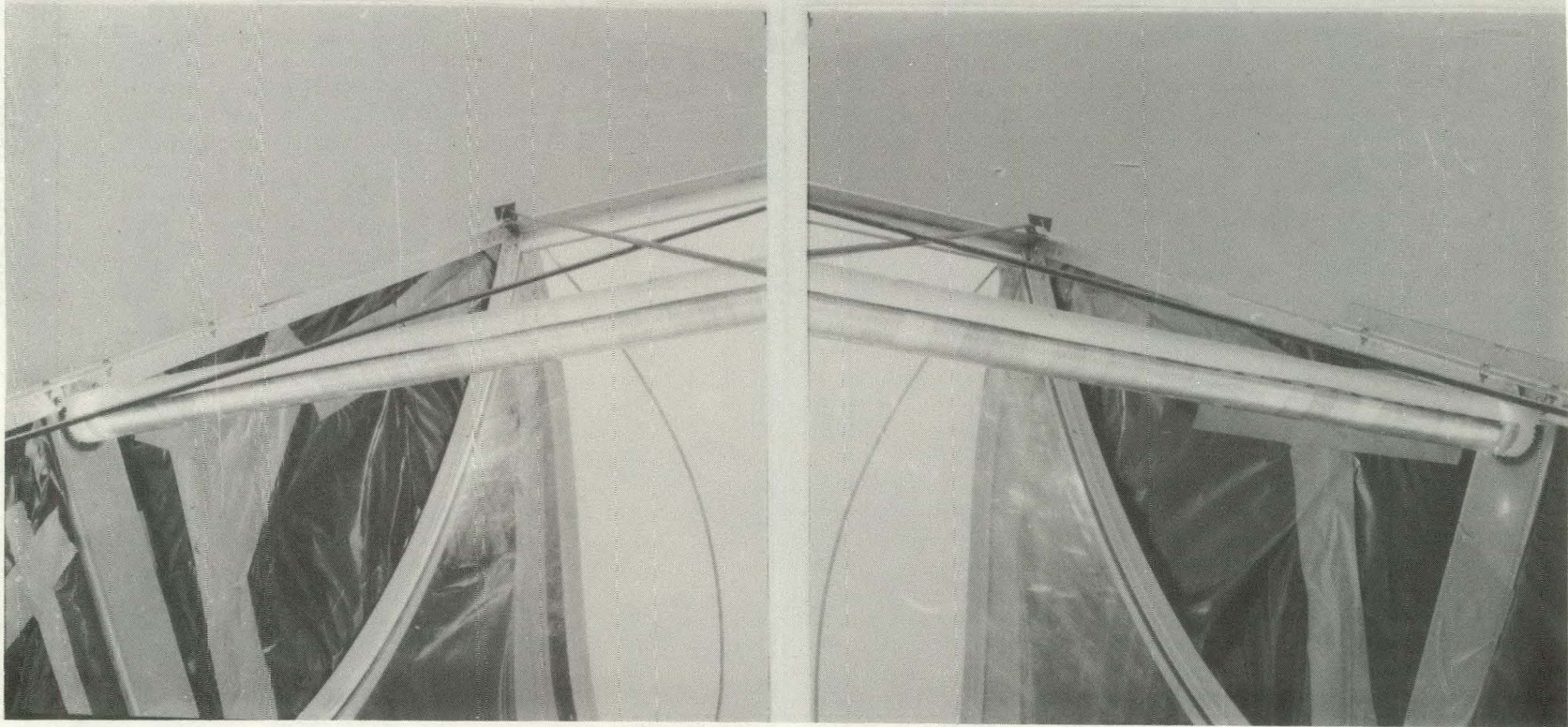
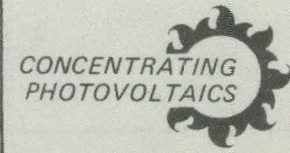


LINEAR RECEIVER
TEST SET-UP





LINEAR RECEIVER
TEST SET-UP

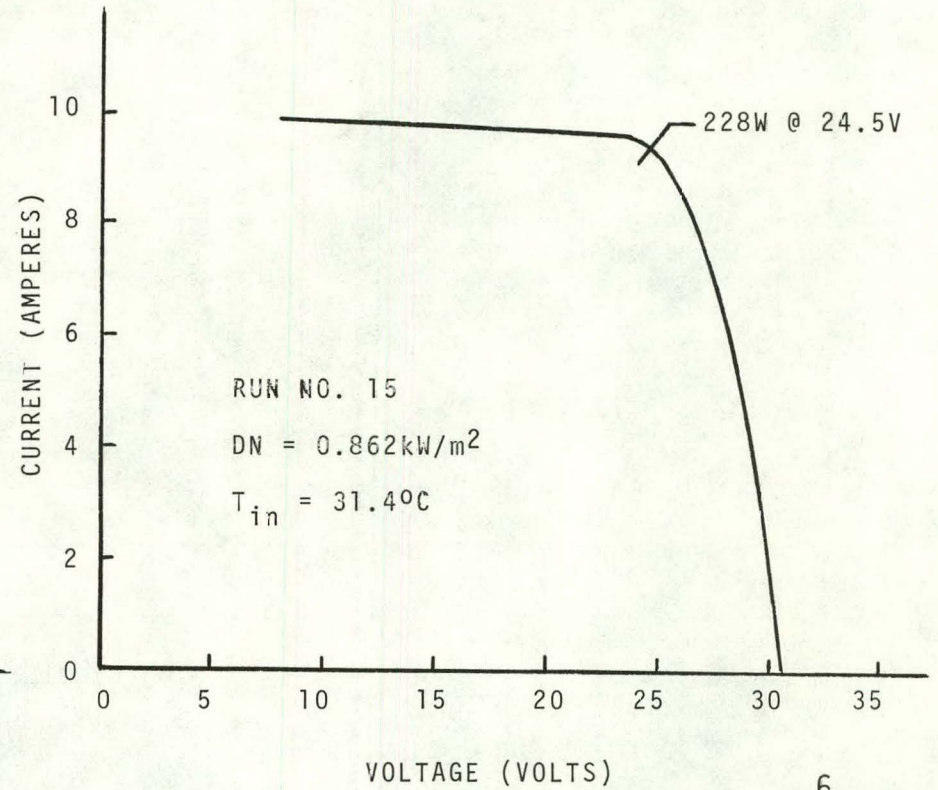
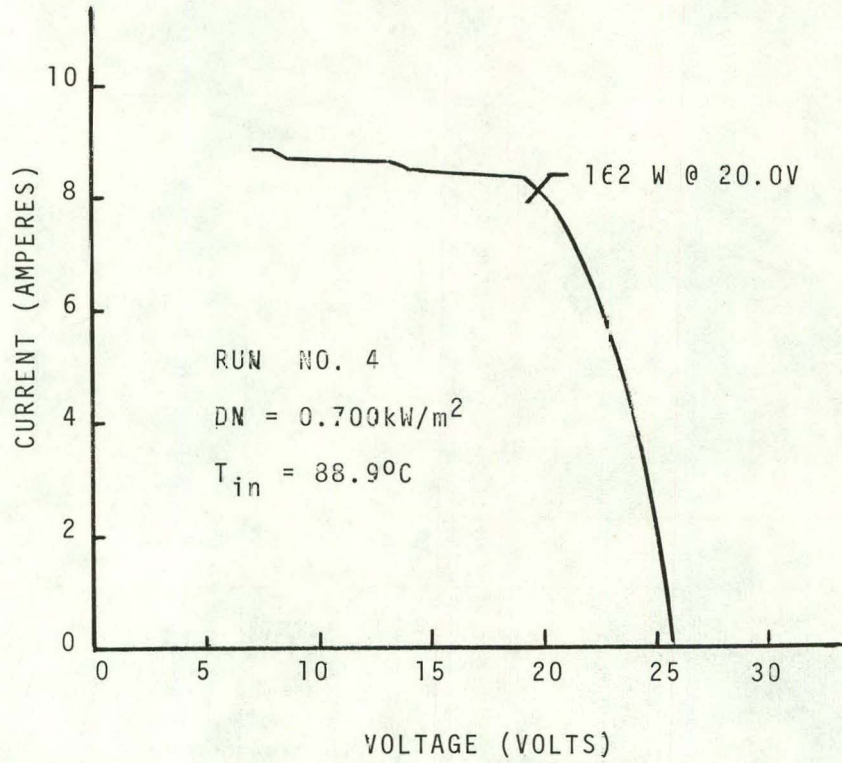




TYPICAL MODULE
I-V CHARACTERISTICS



222

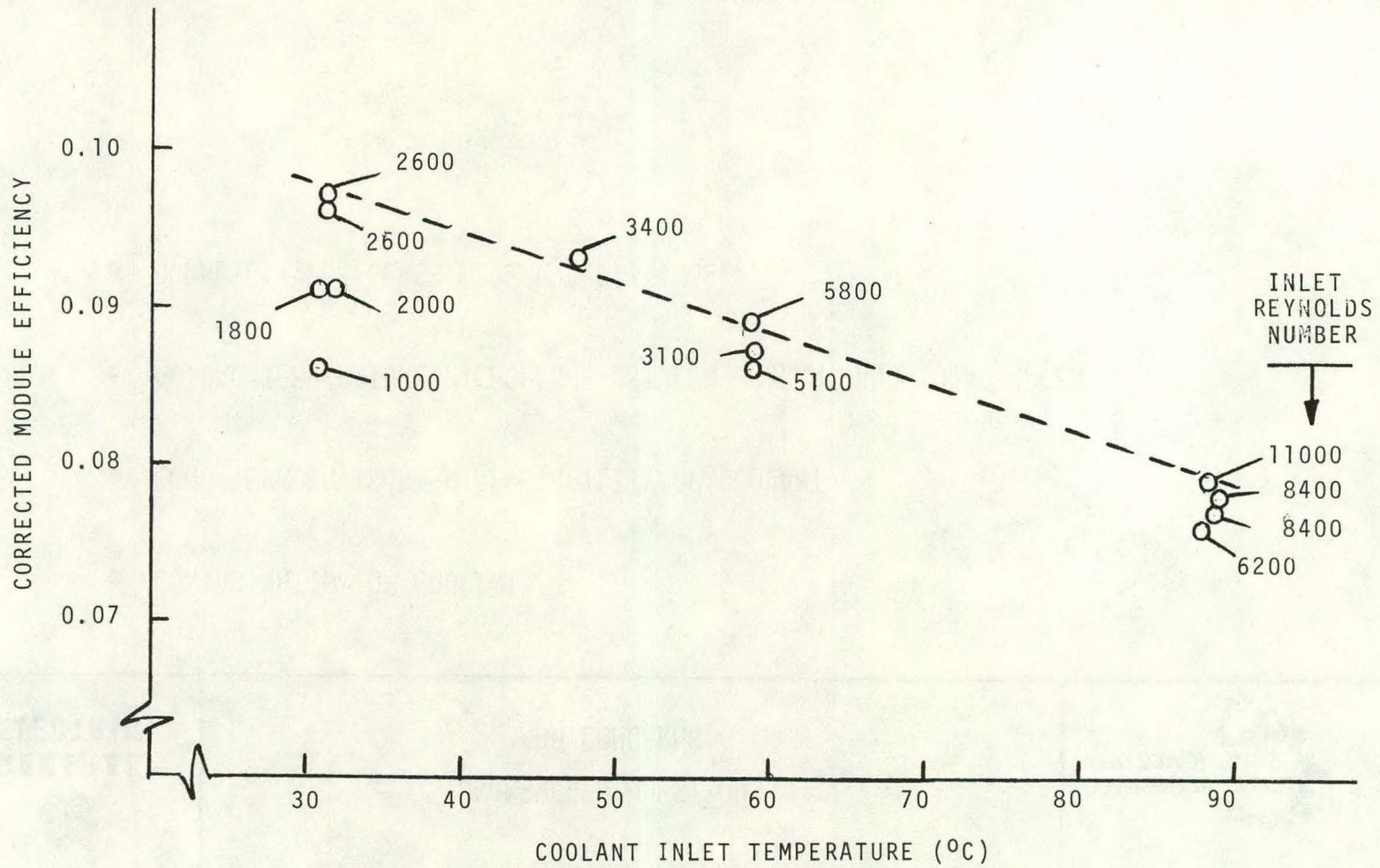




MODULE PERFORMANCE



223

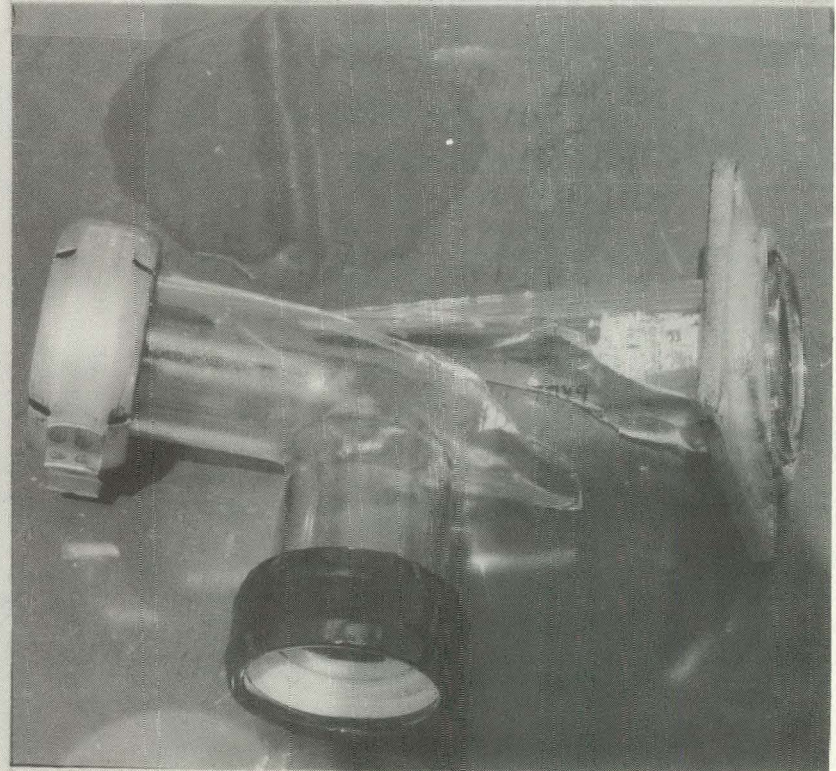




UNANSWERED QUESTIONS
AND CONCERNS



- CONTAMINATION OF COOLANT
- LONG-TERM ENVIRONMENTAL STABILITY OF COOLANT
- ACTUAL TEMPERATURE DIFFERENCE BETWEEN COOLANT AND SOLAR CELLS
- DURABILITY OF GLASS PIPE AND FITTINGS



ADVANCED CELL DEVELOPMENT AND LIFE TESTING

Peter Borden, Paul Gregory and Ram Saxena
Varian Associates, Inc.
Palo Alto, CA 94303

Varian has been engaged in the development, pilot production, and life testing of high-efficiency packaged AlGaAs/GaAs solar cells for point focus applications. This talk describes cell fabrication and packaging, production yields, and the environmental stability of these devices.

An important aspect of the cell fabrication process has been the use of Organometallic Vapor Phase Epitaxy (OM-VPE) to grow the active layers on single-crystal GaAs. Unlike liquid phase techniques, this provides uniform, reproducible layers with excellent morphology. In addition, the process is readily scaled up for high throughputs.

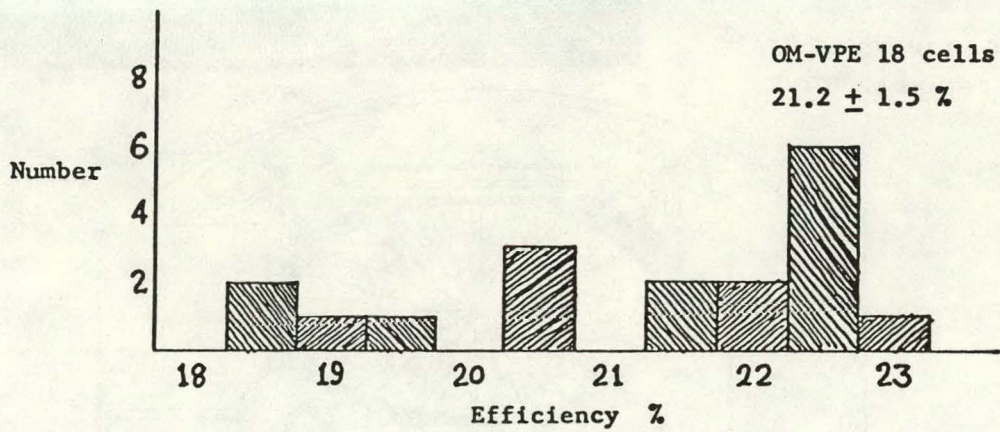
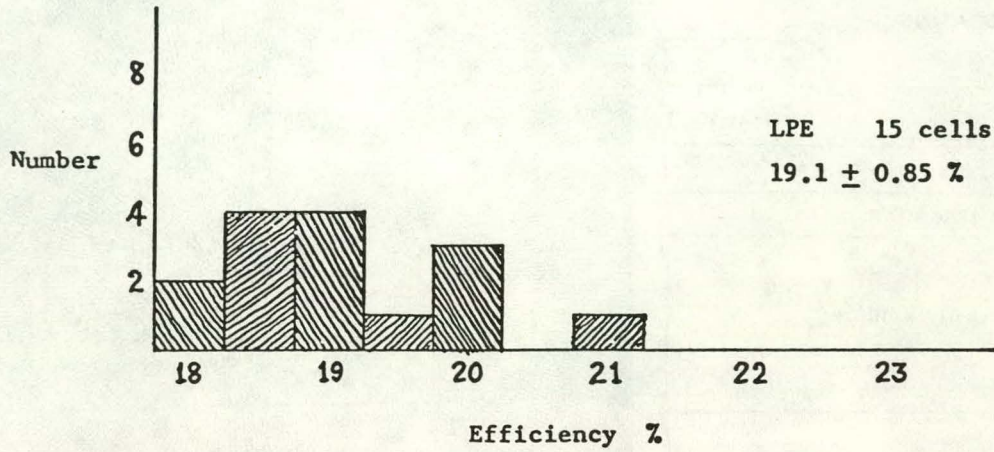
The cell dies are formed with routine photolithography, plating, and AR coating techniques. A unique feature is the point focus package in which the cell die are bonded. This consists of an alumina baseplate with a fired-in metallized pattern and brazed copper lead tabs. The cell is soldered to the alumina with a Ag-Sn solder. To reduce voids, this is done in a vacuum. The lead frame contacting the top of the cell is bonded with a Pb-In paste solder.

To test cells at concentration after fabrication, we have set up a computer-based flash tester. This unit uses a standard photo strobe to flash the cell with a pulse of light that can vary from a few to over a thousand suns intensity by adjustment of the cell-strobe spacing and the intensity. For each flash, the computer sets an active load; in this manner, the complete cell IV characteristic can be plotted. Experience to date with AlGaAs/GaAs cells over the past nine months indicates a very close correlation between room-temperature flash test results and efficiencies measured under concentrated sunlight with a cell coolant temperature of 50°C, with the differences arising due to spectral variations between the xenon source and the sun.

Largely because of the quality of OM-VPE layers, cell yields have been high. For example, 18% was chosen as the cutoff efficiency for the AlGaAs module program at Varian. Of the OM cells fabricated for this program, the yields of packaged cells at 400 suns and 50°C were 83% above 18%, 63% above 20%, and 43% above 22%. The average efficiency of the 12 cells delivered for the first module was 21.7%; the average of the 12 cells in the second module fabricated was 22.1%.

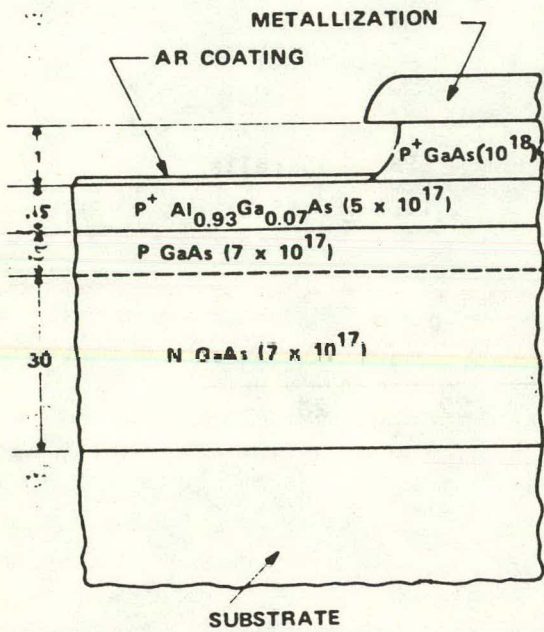
A variety of life tests have been carried out, mostly on unpackaged cells. These have included storage at 400°C and 425°C in nitrogen, thermal cycling between room temperature and 400°C, and storage in air at 250°C. In the static test, most failures occurred after about 600 hours at 400°C. Significant degradation in the thermal cycling test occurred only after 400 cycles. The cells stored in air at 250°C have shown only minor degradation after 1600 hours at temperature. An important point of concern had been oxidation of the cell's AlGaAs window layer. It is believed that this is correlated with the thickness of the layer. As evidence, OM cells with 1500 angstrom window layers have been kept in a humidity chamber at 65°C for 290 hours, followed by 8 hours in boiling water with no degradation.

LPE - OM VPE Comparison

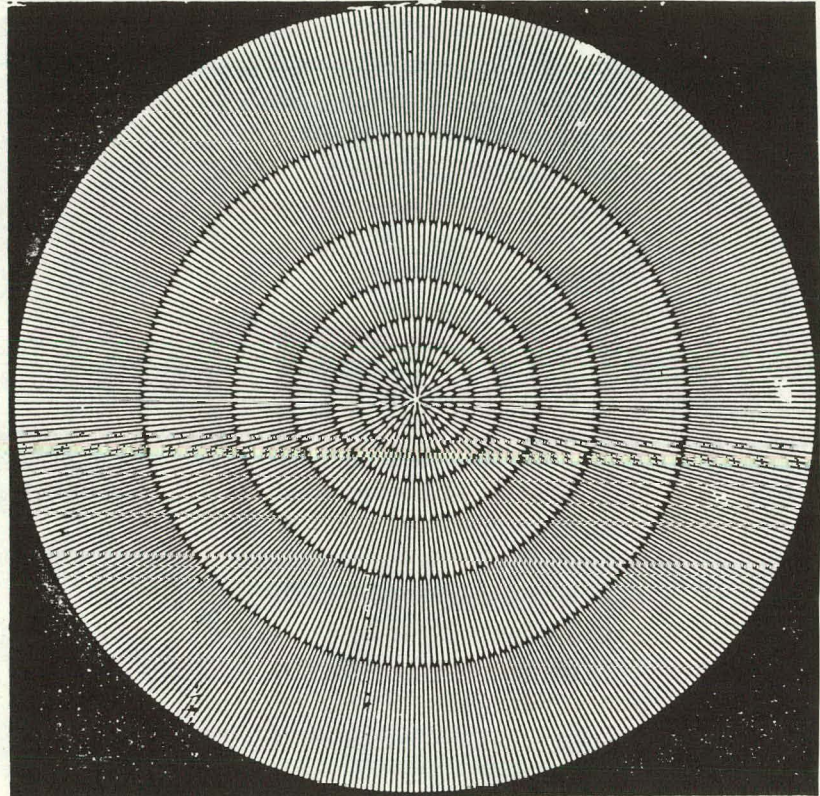


SOLAR CELL FABRICATION AND PACKAGING

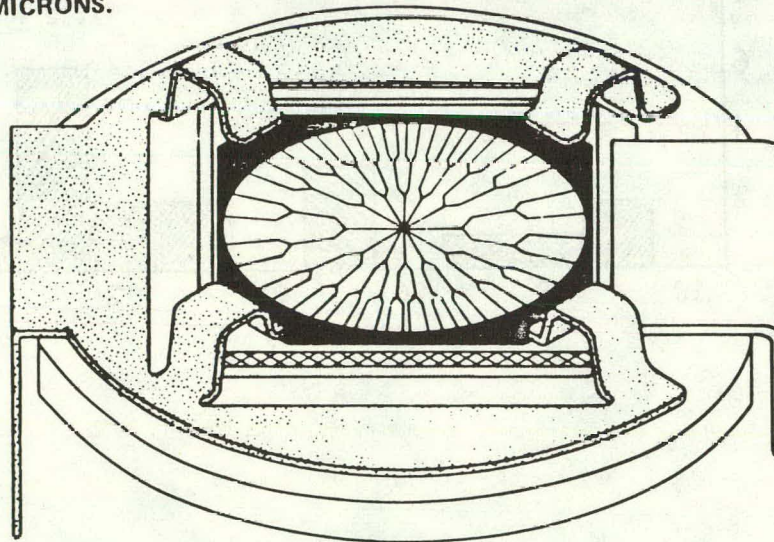
SCHEMATIC CROSS-SECTION OF GaAs SOLAR CELL



CONTACT GRID STRUCTURE

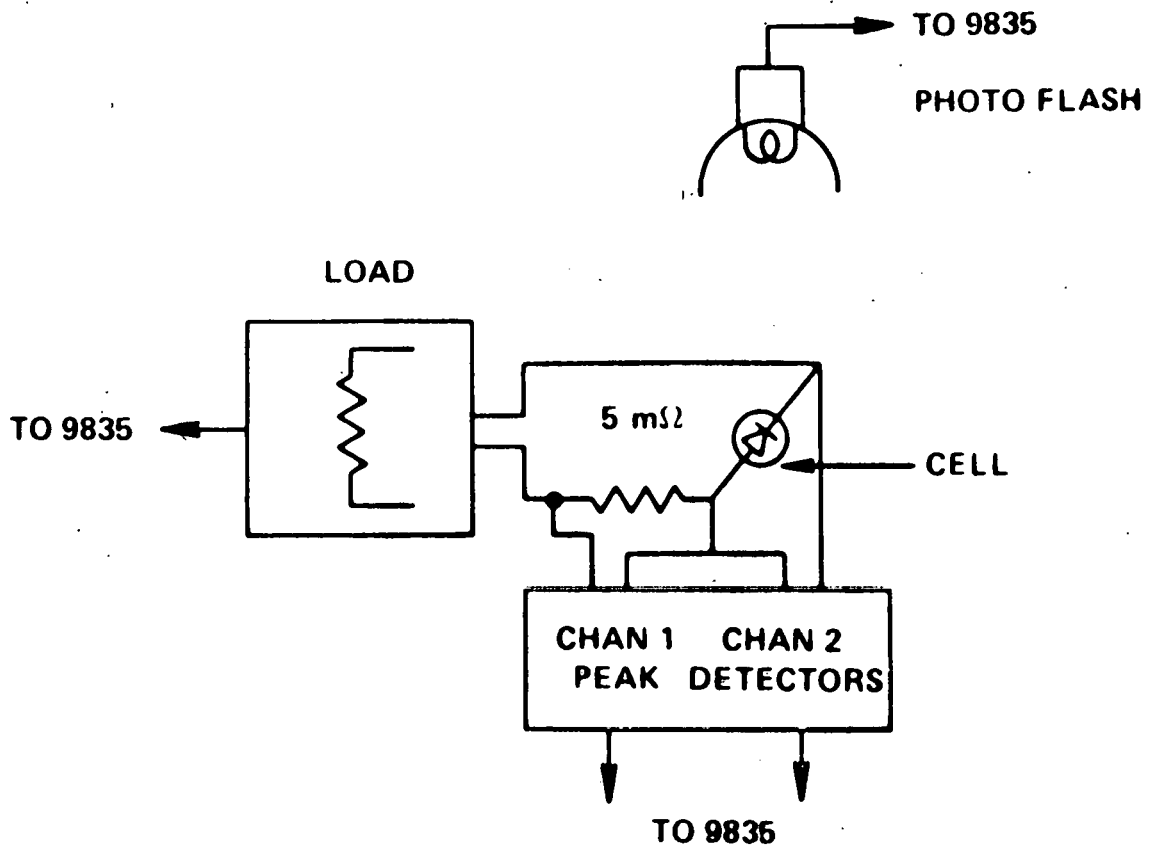


DOPINGS ARE IN UNITS OF (CM⁻³).
DIMENSIONS ARE IN MICRONS.

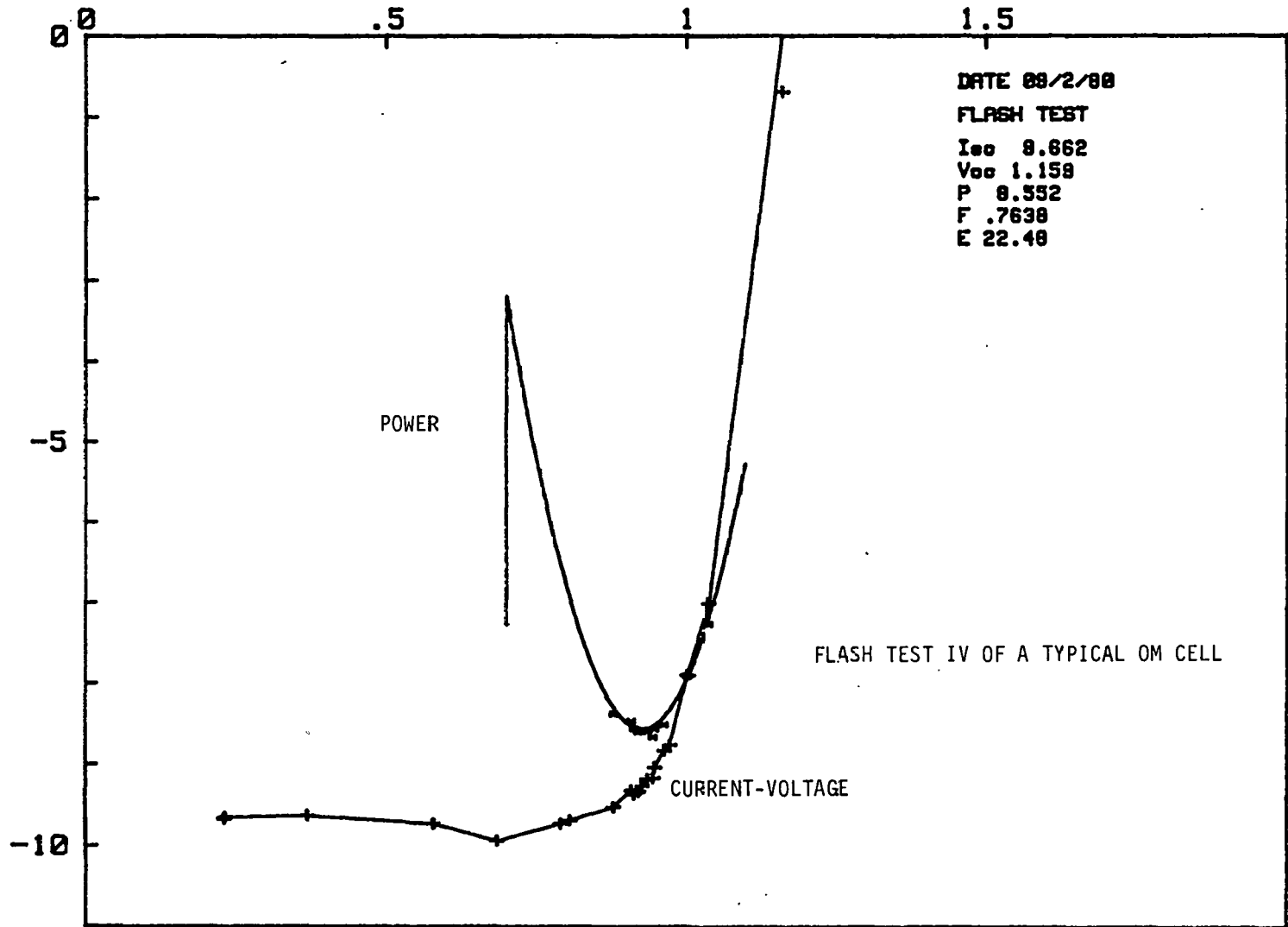


PACKAGED CELL

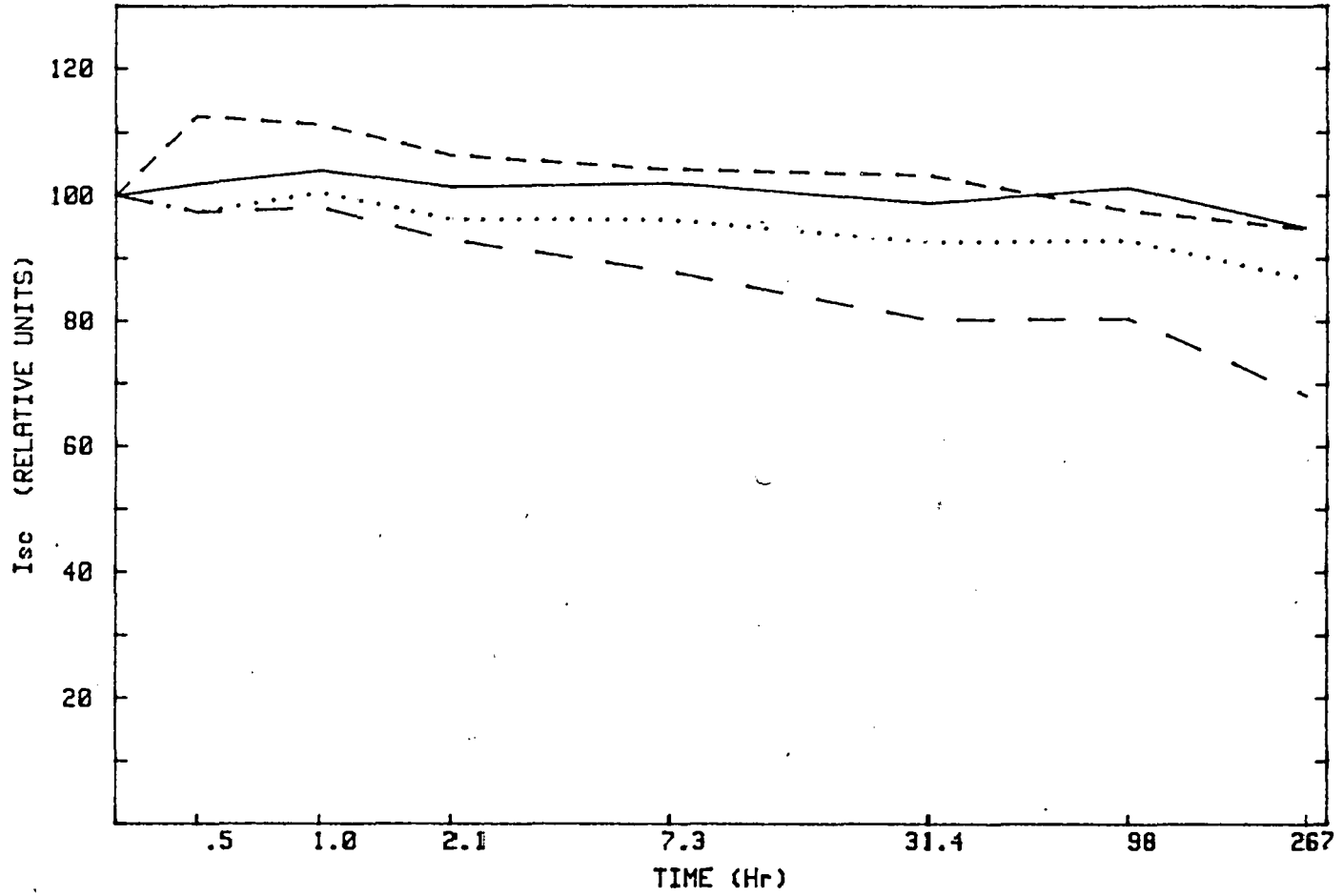
FLASH TESTER



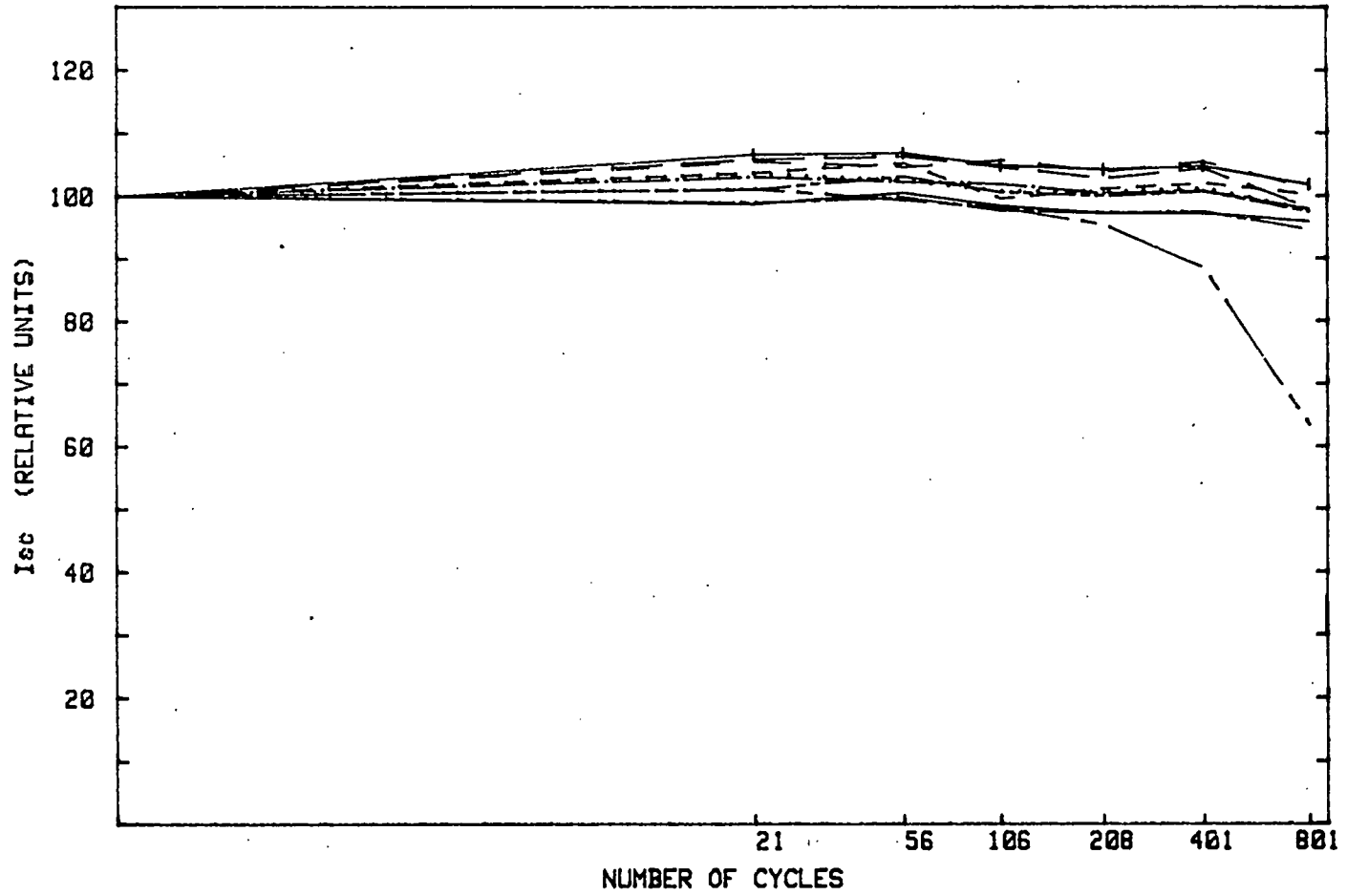
CELL OM791#3



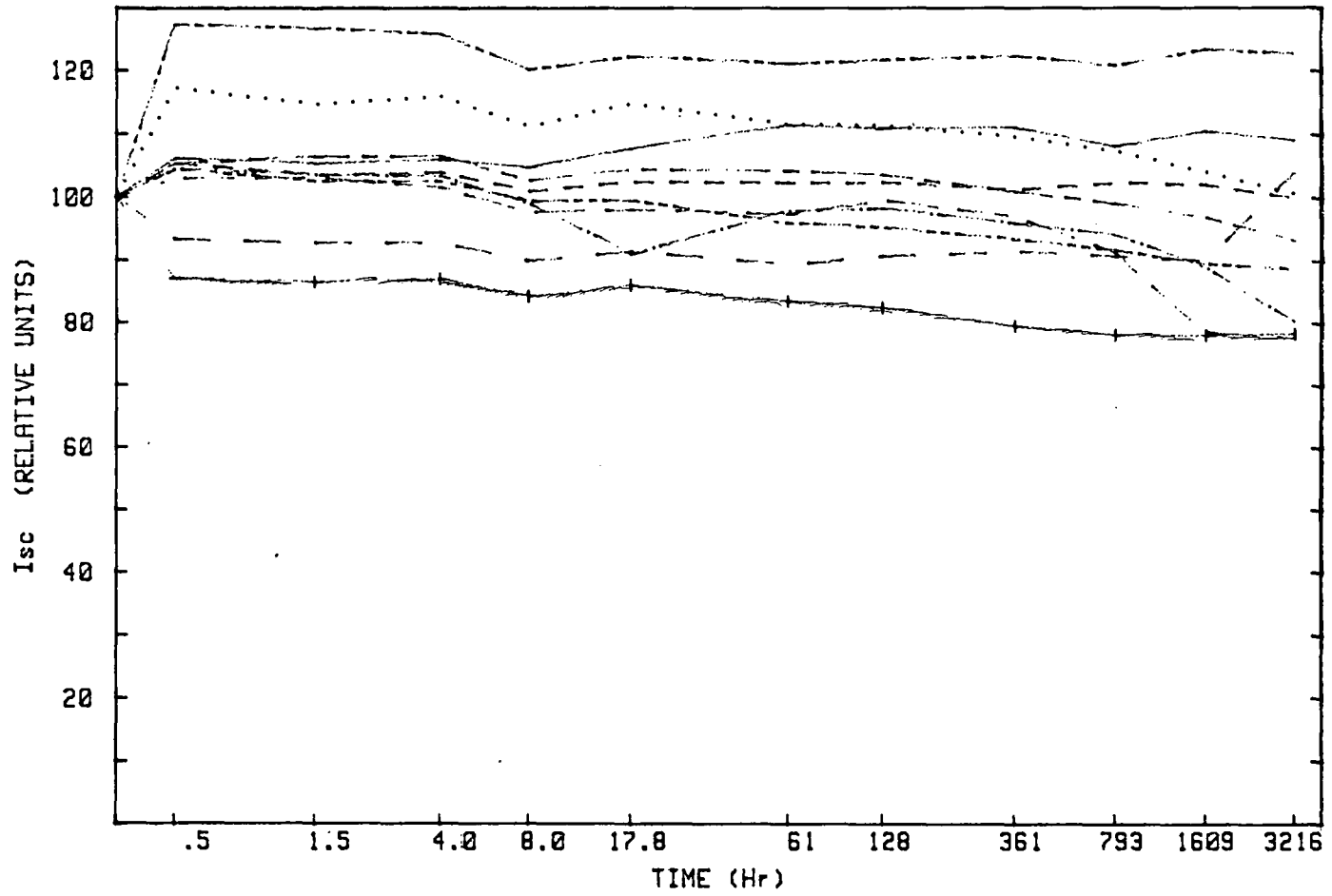
HEATED IN NITROGEN AT 425C, CELLS LOOSE: I_{sc}



CYCLED 25-400C IN NITROGEN: I_{sc}



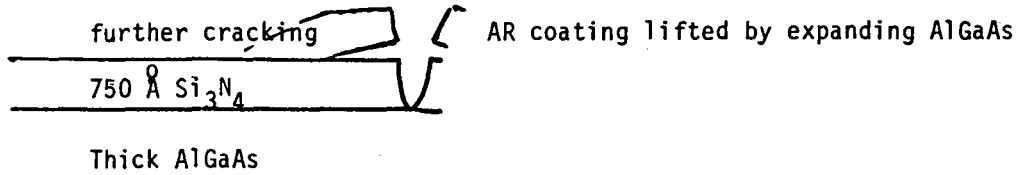
HEATED IN AIR AT 250C: I_{sc}



EFFECT OF AlGaAs OXIDATION ON AR COATING DELAMINATION

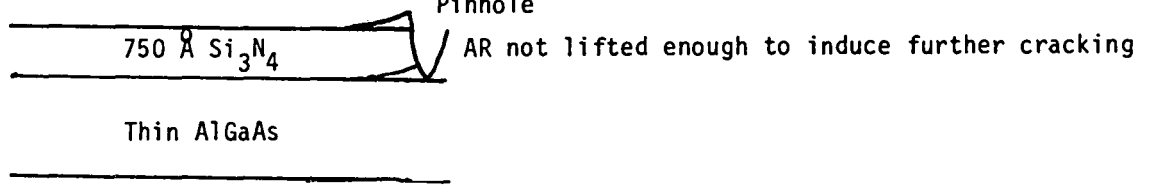
LPE CELLS

Pinhole



OM CELLS

Pinhole



IMPROVED EFFICIENCY FOR CONCENTRATOR
CELLS/ARRAYS

BY

Applied Solar Energy Corporation
15251 E. Don Julian Road
City of Industry, Ca. 91746

Contract No.: Sandia 49-2670
Principal Investigator: S. Khemthong
(213) 968-6581, Ext. 333
Contract Amount: \$299,303
Contract Duration: April 4, 1980 - April 4, 1981

Project Description

The overall goals are to increase the efficiency of silicon cells at high insolation levels, and to improve concentrator array technology.

The detailed goals for cell improvement include a systematic parametric optimization of both N+/P and P+/N configurations, with development of improved grid formation technology. For array improvement, an automated cell assembly machine will be further developed.

The cell parameters under study include N or P-type silicon, FZ or CZ grown, with resistivity in the range 0.1 to 1.5 ohm-cm, thickness range 2 to 12 mils, with polished or textured surfaces and using BSF and BSR processes.

Current Status

A) Successful process sequences giving high efficiency cells have been developed for both configurations. The grid pattern used to date is shown in Figure 1; slight improvements in the photomask have been made.

For both configurations, textured surfaces led to increased cell shunting with reduced CFF at one-sun levels; as expected Voc was slightly lower ($\sim 10\text{mV}$) and Jsc was about 6% higher.

Computer predictions for performance of these cells at high insolation levels have been confirmed. Above 10X, the high shunt leakage for textured cells becomes negligible and the performance of textured cells becomes comparable, despite low efficiency at 1X (Figure 2)

Difficulty was experienced for the N+ BSF processing, but this step has now been improved.

At $\sim 40\text{X}$, the program has given the following results:

N+/P/P+ Cells	η_{Polished}	$\sim 19\%$
	η_{Textured}	$\sim 20\%$
P+/N/N+ Cells	η_{Polished}	$\rightarrow 19\%$
	η_{Textured}	$\sim 18.5\%$

Figure 3 shows I-V curves for the best cells.

Future Plans

Further increases are sought by improved BSF processing, reduction of non-illuminated PN junction area, passivation, and use of improved grid formation methods. For the latter, dry film resist methods have produced rectangular section lines 15-20 μm wide and $\sim 15 \mu\text{m}$ high.

B) Array Assembly

Several modifications to an earlier assembly machine have been completed. The length of the machine was reduced, and the components were mounted on a single aluminum plate. A print-on flux dispenser was installed. The parting die was modified to allow either or both sides of the interconnector strip to be used for diode installation.

A small rotary straightener was installed between the parting and cut-off dies, to ensure straight out-feed of the finished array segments.

In a demonstration run, the machine performed well, confirming all expectations. Figures 4 through 6 show the machine and completed arrays.

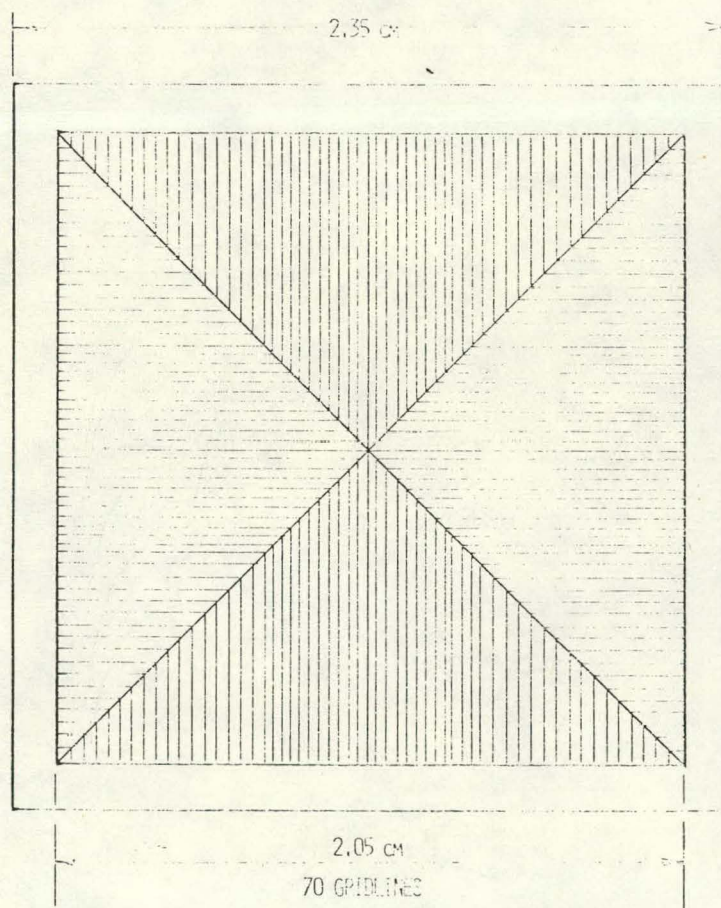


FIGURE 1. FRONT CONTACT AND GRID PATTERN FOR HIGH INSOLATION CONCENTRATOR CELL.

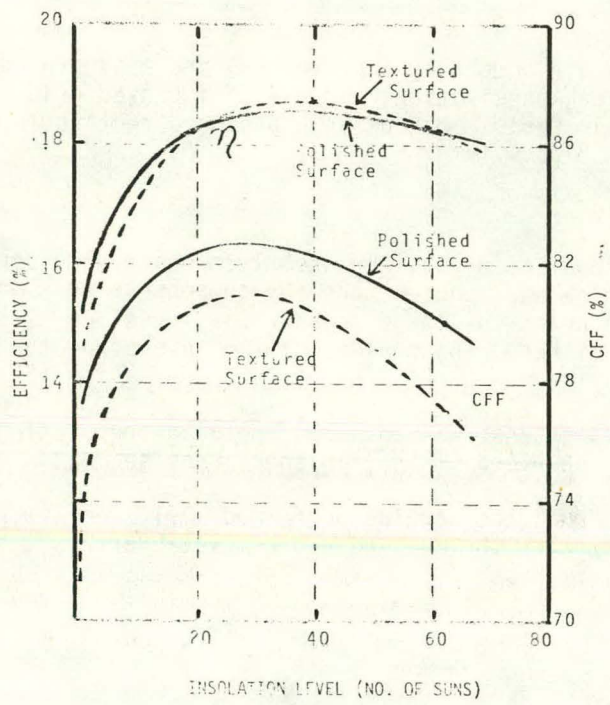


FIGURE 2: EFFICIENCY AND CFF vs INSOLATION LEVEL OF POLISHED AND TEXTURED SILICON CONCENTRATOR CELL AT 28°C.

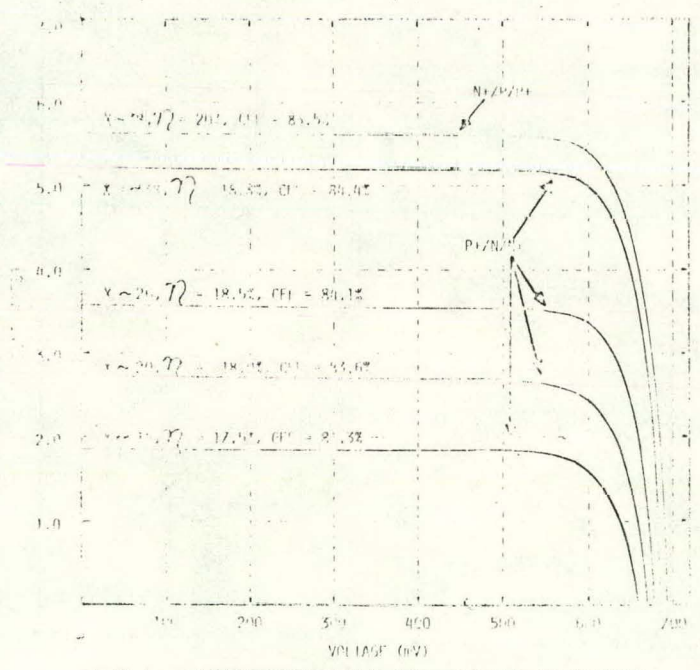


FIGURE 3: I-V CHARACTERISTICS OF N+/P/P+ and P+/N/N+ CONCENTRATOR CELL AT HIGH INSOLATIONS AND 28°C.

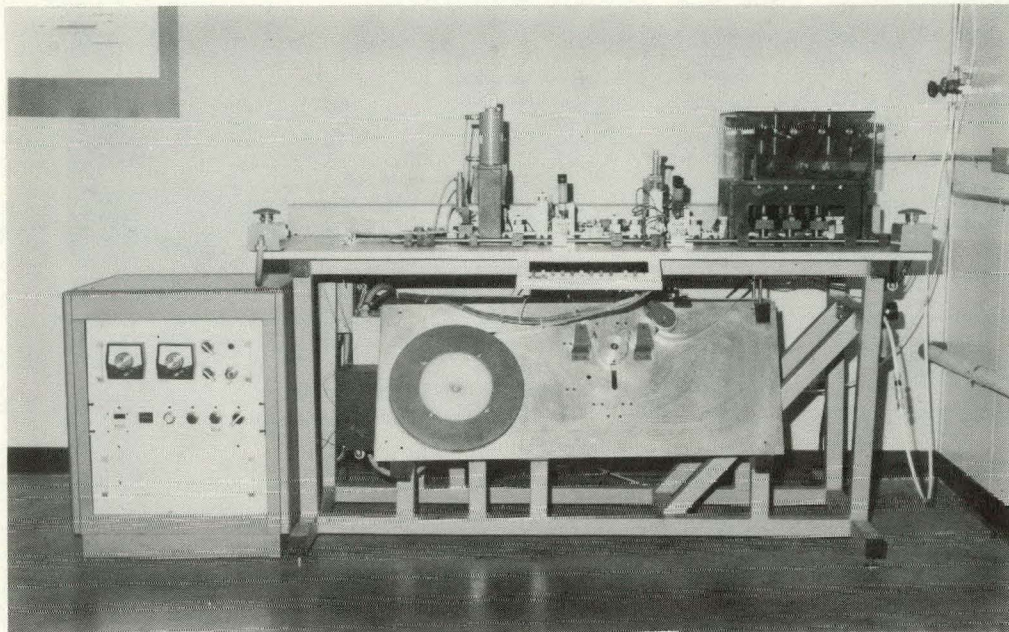


FIGURE 4
OVERALL VIEW OF ARRAY ASSEMBLY MACHINE

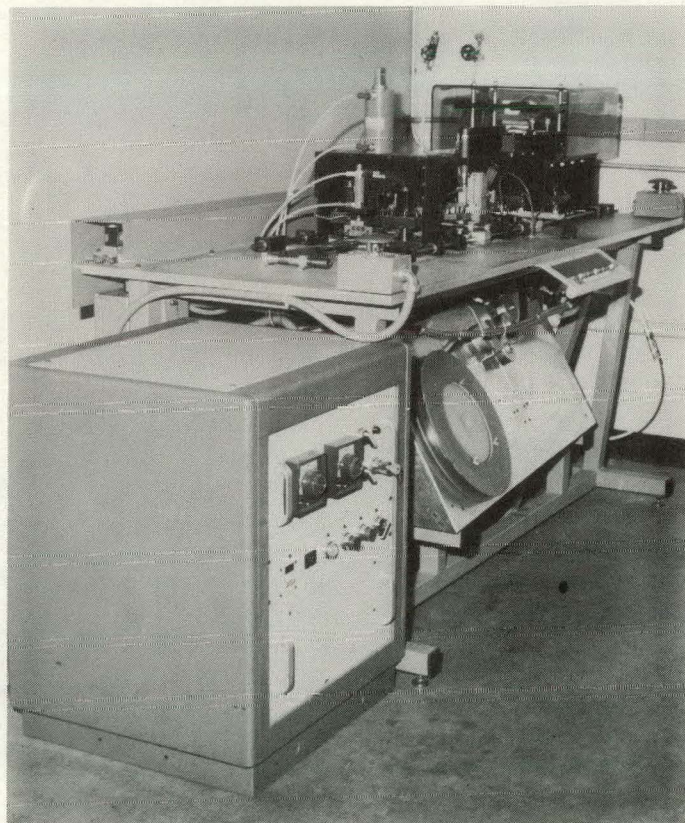


FIGURE 5
ANOTHER VIEW OF THE MACHINE

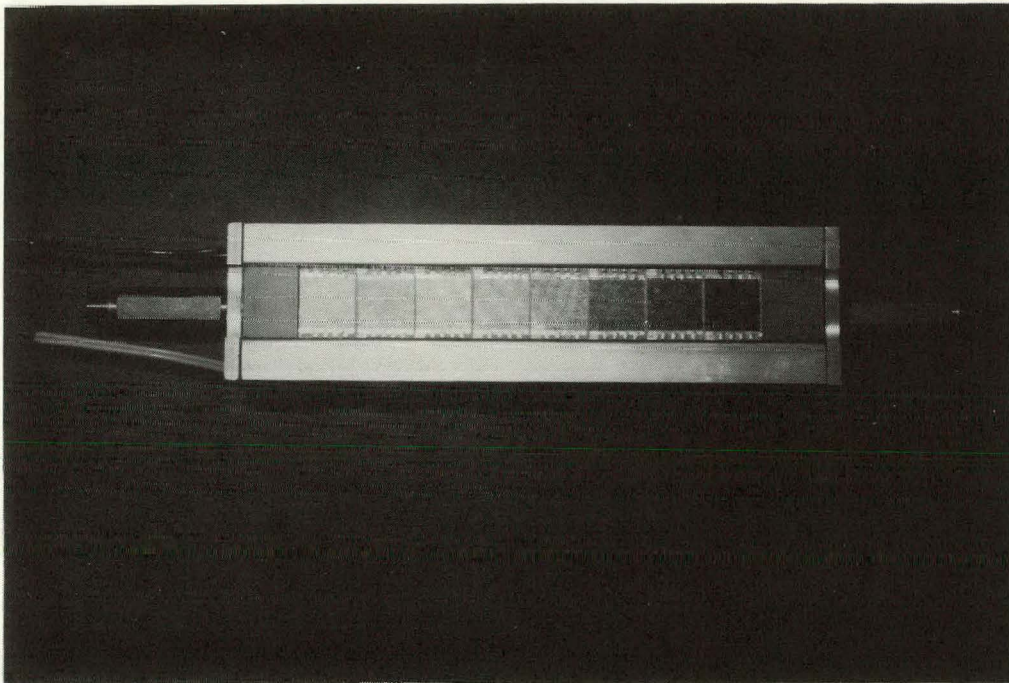


FIGURE 6 (a)
AN ASSEMBLED ARRAY SEGMENT (8 CELLS)

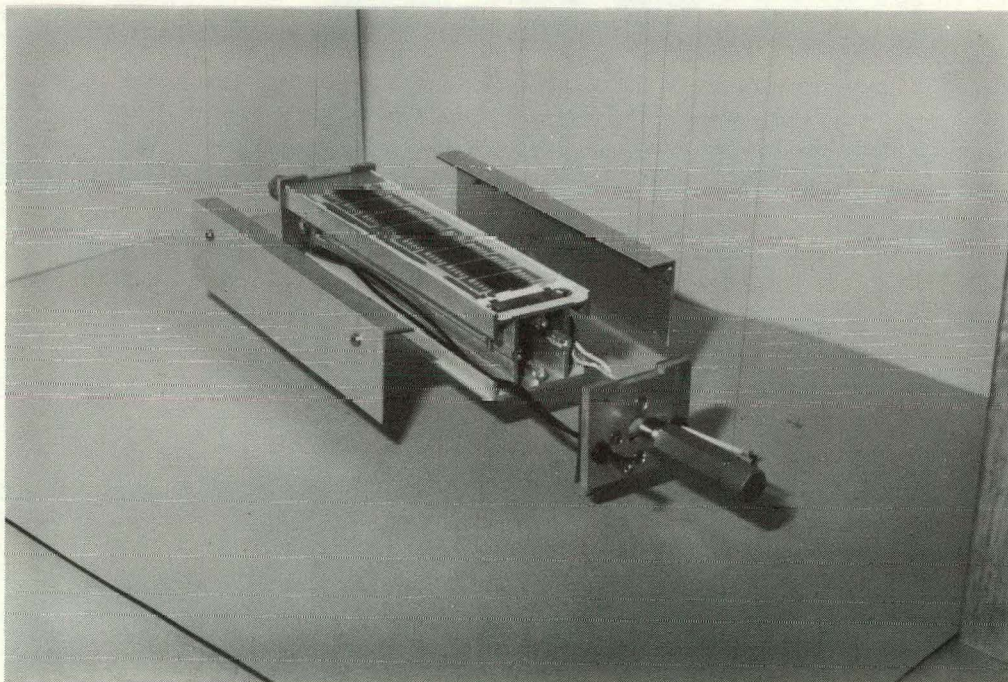


FIGURE 6 (b)
ASSEMBLED SEGMENT, MOUNTED WITH COOLING (EXPLODED VIEW)

GaAs EFFICIENCY IMPROVEMENT STUDY

Rockwell International Electronics Research Center
Thousand Oaks, California 91360

Principal Investigator: J. A. Cape
Program Manager: S. W. Zehr

PROJECT DESCRIPTION

The goal of this program is the achievement of high yields of high efficiency GaAs concentrator cells. To this end, the project is focused on identifying the efficiency limiting factors in cell materials and cell processing, and improving materials growth and cell fabrication methods so as to mitigate these factors. Specifically, the program plan calls for (1) developing an in-house capability for directly synthesizing up to 3" diameter GaAs boules by the liquid encapsulant method, (2) establishing 2" and 3" diameter MO-CVD (metal organic chemical vapor deposition) epitaxy as the method of solar cell layer growth, (3) studying the defects in the GaAs substrate and epigrown layers and correlating materials quality with the cell efficiency, and (4) as material evidence for the results of this program, delivering a minimum number (150) 1 cm. diameter concentrator cells meeting specified performance characteristics.

CURRENT STATUS

Drawing on the experience of several years in MO-CVD, we have recently completed the development of a MO-CVD facility devoted to solar cell materials growth. Special emphasis has been placed on very fine temperature and flow control for the constituent gases. This in turn results in exceptional control of composition and layer thickness for the active GaAs layers and the window AlGaAs layer. Calibration runs have recently been completed and thus far 6 wafers with 10 μ m n-buffer layers have been processed as solar cells. All show AM1 (100 mW solar simulator) efficiencies greater than 20%. We are currently experimenting with reduced growth temperature. Cells grown at 650°C appear to have greater mobilities with good layer morphology, independent of substrate quality.

Evidence from EBIC data on thick LPE layers, grown at 750°C and 900°C will be described which is interpreted in terms of the diffusion of recombination centers from the substrates into the epi-layers. These centers evidently act to reduce the diffusion length and hence the short circuit current of the cells. Growth at 650°C apparently greatly reduces these effects. A second category of defects is thought to be responsible for poor junction quality and cell leakage problems frequently encountered with LPE grown cells. This problem appears to be almost non-existent with our MO-CVD growths.

A Metals Research LEC crystal puller is on line growing up to 3" diameter boules for solar cells. A separate concurrent project is focused on achieving highest quality GaAs with this facility.

A novel pulse-illumination test system has been recently completed. Fully automated and computer controlled, the system enables forward or reverse, light or dark I-V curves to be obtained at up to 30 amps maximum cell current and/or 10,000 SUNs maximum illumination. In particular, concentrator cell series resistance values are easily measured with this system.

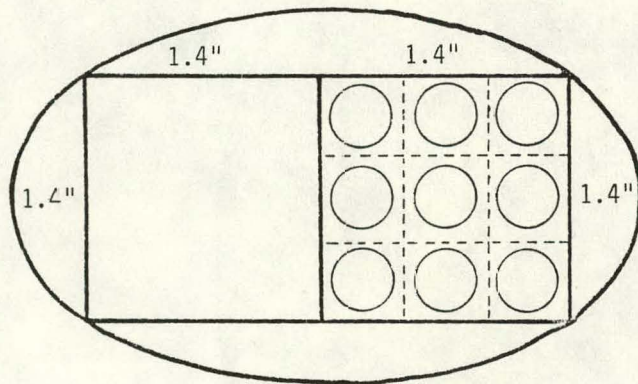
ACCOMPLISHMENTS

- 2" MO-CVD FACILITY OPERATIONAL
- LOW TEMPERATURE GROWTH EXPLORED
- 1.4" x 1.4" 9-CELL WAFER PROCESSING
- SUBSTRATE-DEFECT DIFFUSION EFFECTS STUDIED
- SERIES ARRAYS STUDIED
- PROCESSING IMPROVED
- HIGH YIELD OF HIGH EFFICIENCY CELLS OBTAINED

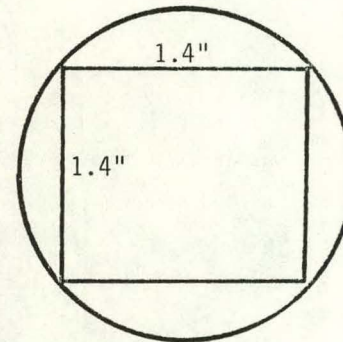
GAAs EFFICIENCY IMPROVEMENT STUDIES

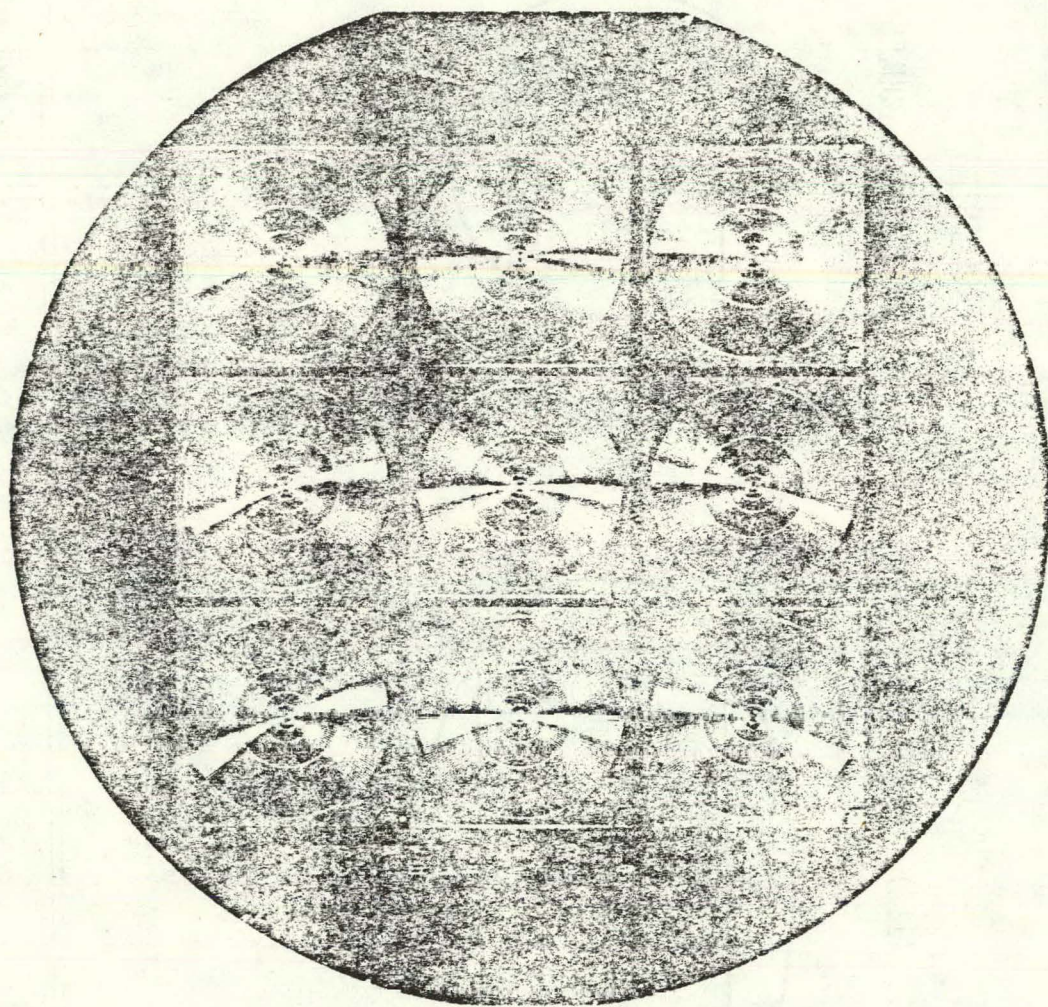
CURRENT 1.4" x 1.4" 9-CELL WAFER PROCESSING

2.2" (111) BOULES

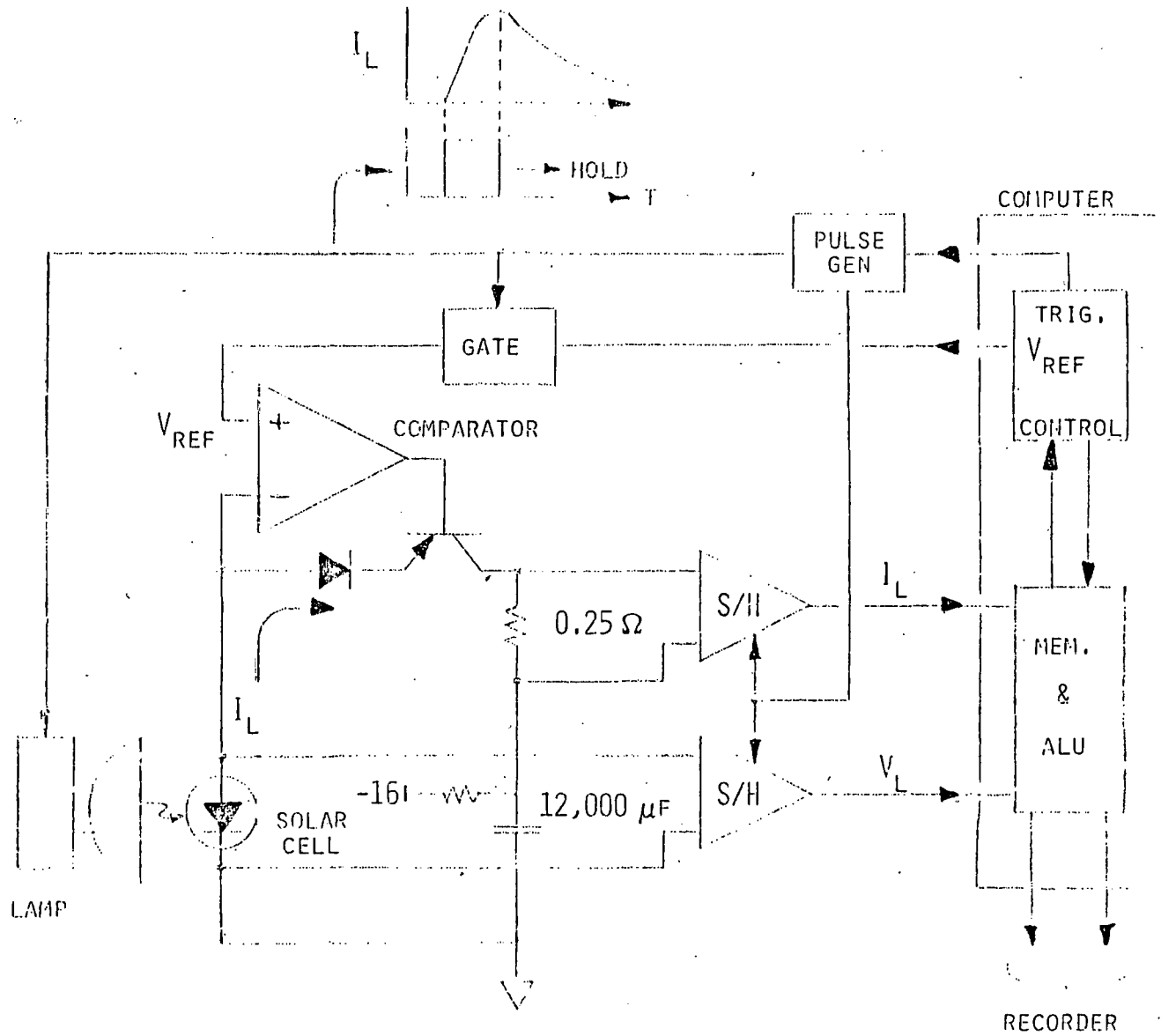


2" (100) BOULES



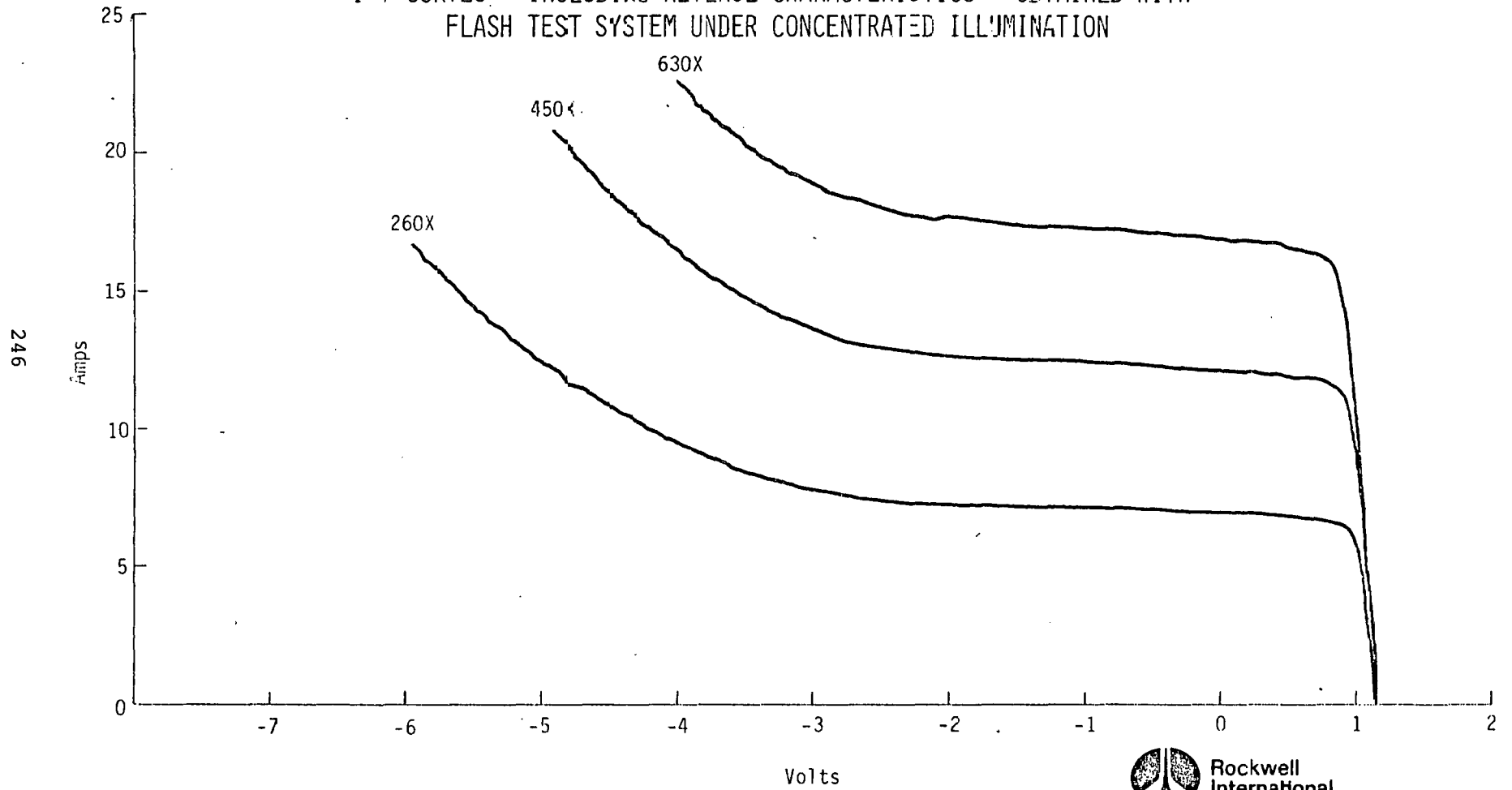


SCHEMATIC FOR HIGH CONCENTRATION FLASH ILLUMINATION I-V TEST SYSTEM



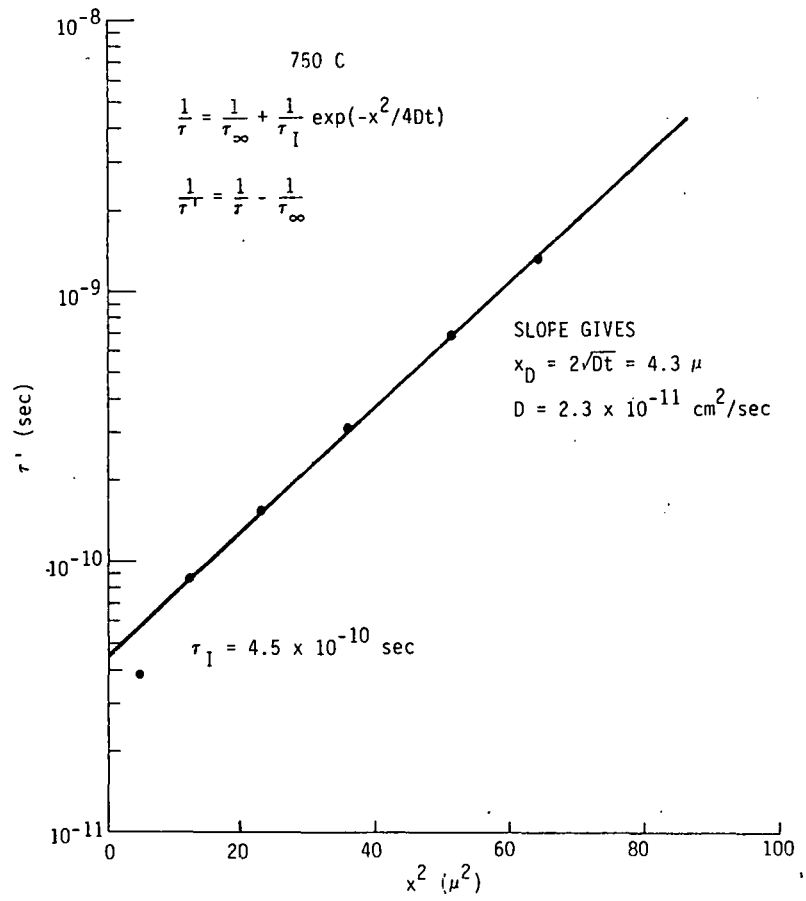
GAA'S EFFICIENCY IMPROVEMENT STUDIES

I-V CURVES - INCLUDING REVERSE CHARACTERISTICS - OBTAINED WITH
FLASH TEST SYSTEM UNDER CONCENTRATED ILLUMINATION



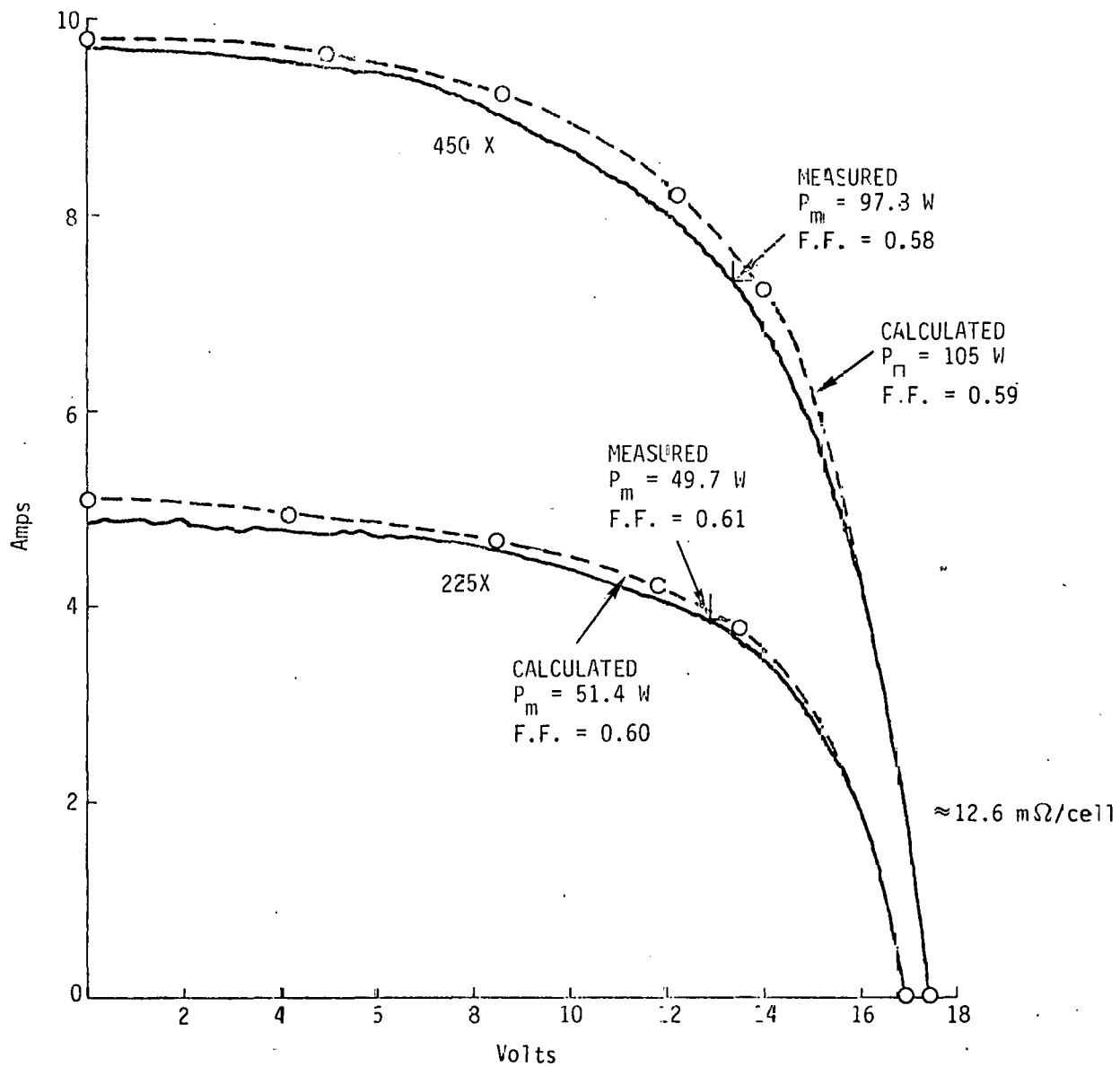
GaAs EFFICIENCY IMPROVEMENT STUDIES

SUBSTRATE-DEFECT DIFFUSION IN GaAs BUFFER LAYER



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COMPARISON OF MEASURED AND CALCULATED I-V CURVES FOR 16-CELL SERIES STRING



CONTRACTOR STATUS SUMMARIES

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ADVANCED PHOTOVOLTAIC TROUGH CONCENTRATOR DEVELOPMENT

by

Acurex Corporation
485 Clyde Avenue
Mountain View, California 94042

Contract Number: 13-9493
Project Manager: Dariush Rafinejad
(415) 964-3200 Ext. 3534
Project Engineer: Bob Spencer
(415) 964-3200 Ext. 3441
Contract Amount: \$235,695
Contract Duration: November 1979 -- December 1980

Project Description

The program has two objectives. First is to develop a single axis photovoltaic, parabolic collector which combines high efficiency, effective cell encapsulation, and improved array life. The second goal is to provide prototype reflector and receiver hardware to Sandia for testing.

We have divided the program into tasks to simplify attainment of these goals:

- Task 1 -- Array Optimization. This task includes all analytical efforts to optimize array configuration.
- Task 2 -- Advanced Reflector Development. This task includes two specific goals. First to develop thin glass mirror laminates. We are laminating three manufacturers' thin glass mirrors to metal backing sheets for use as concentrator reflective surfaces. The second goal is a modification of our existing trough design for FEK reflectors.
- Task 3 -- Advanced Receiver Development. This task will design and produce advanced photovoltaic receivers for testing.

Current Status

Tasks 1 and 2 are complete and Task 3 is 70 percent complete. Final reports for Tasks 1 and 2 are being prepared and cell modules for Task 3 receiver are on order.

Key Results to Date

An efficient trough with VEE-receiver has been designed and tested. Task 1 optimization shows that a 44° receiver apex included angle and 90° trough rim angle are optimum. The reflective surface slope error has a dramatic effect on optical performance. Glaverbell thin glass with acrylic bond to a metal backing is found to be an acceptable reflective surface.

NOVEL CONCENTRATOR DEVELOPMENT PROGRAM

by

Acurex Corporation
485 Clyde Avenue
Mountain View, California 94042

Contract Number: 07-6922
Project Manager: Dariush Rafinejad
(415) 964-3200 Ext. 3534
Project Engineer: Tim Muller
(415) 964-3200 Ext. 3442
Contract Amount: \$227,759
Contract Duration: November 1977 -- December 1980

Project Description

The program investigates the feasibility of producing low cost photovoltaic concentrators using sealed beam headlamp technology. The scope includes conceptual design, prototype fabrication, optimization for high-volume production, and cost estimating.

Current Status

The technical effort is complete and final report is in preparation. The prototype array has been fabricated, tested at Acurex and delivered to Sandia.

Key Results to Date

A two-axis tracking, point focus and actively cooled array using headlamp technology has been developed and tested. A gross aperture efficiency of 7 percent has been measured. An effective cell cooling design has been achieved. A cell-to-coolant temperature of 80°F at design flow rate was measured.

The array cost is projected to be significantly higher than expected. Significantly different design approach such as larger aperture area, lighter weight material have to be used to achieve a cost effective array.

IMPROVED EFFICIENCY FOR CONCENTRATOR
CELLS/ARRAYS

BY

Applied Solar Energy Corporation
15251 E. Don Julian Road
City of Industry, Ca. 91746

Contract No.: Sandia 49-2670
Principal Investigator: S. Khemthong
(213) 968-6581, Ext. 333
Contract Amount: \$299,303
Contract Duration: April 4, 1980 - April 4, 1981

Project Description

The overall goals are to increase the efficiency of silicon cells at high insolation levels, and to improve concentrator array technology.

The detailed goals for cell improvement include a systematic parametric optimization of both N+/P and P+/N configurations, with development of improved grid formation technology. For array improvement, an automated cell assembly machine will be further developed.

The cell parameters under study include N or P-type silicon, FZ or CZ grown, with resistivity in the range 0.1 to 1.5 ohm-cm, thickness range 2 to 12 mils, with polished or textured surfaces and using BSF and BSR processes.

Current Status

A) Successful process sequences giving high efficiency cells have been developed for both configurations. The grid pattern used to date is shown in Figure 1; slight improvements in the photomask have been made.

For both configurations, textured surfaces led to increased cell shunting with reduced CFF at one-sun levels; as expected Voc was slightly lower (7-10mV) and Jsc was about 6% higher.

Computer predictions for performance of these cells at high insolation levels have been confirmed. Above 10X, the high shunt leakage for textured cells becomes negligible and the performance of textured cells becomes comparable, despite low efficiency at 1X (Figure 2)

Difficulty was experienced for the N+ BSF processing, but this step has now been improved.

At ~ 40X, the program has given the following results:

N+/P/P+ Cells	η Polished	~	19%
	η Textured	~	20%
P+/N/N+ Cells	η Polished	→	19%
	η Textured	~	18.5%

Figure 3 shows I-V curves for the best cells.

Future Plans

Further increases are sought by improved BSF processing, reduction of non-illuminated PN junction area, passivation, and use of improved grid formation methods. For the latter, dry film resist methods have produced rectangular section lines 15-20 μm wide and $\sim 15 \mu\text{m}$ high.

B) Array Assembly

Several modifications to an earlier assembly machine have been completed. The length of the machine was reduced, and the components were mounted on a single aluminum plate. A print-on flux dispenser was installed. The parting die was modified to allow either or both sides of the interconnector strip to be used for diode installation.

A small rotary straightener was installed between the parting and cut-off dies, to ensure straight out-feed of the finished array segments.

In a demonstration run, the machine performed well, confirming all expectations. Figures 4 through 6 show the machine and completed arrays.

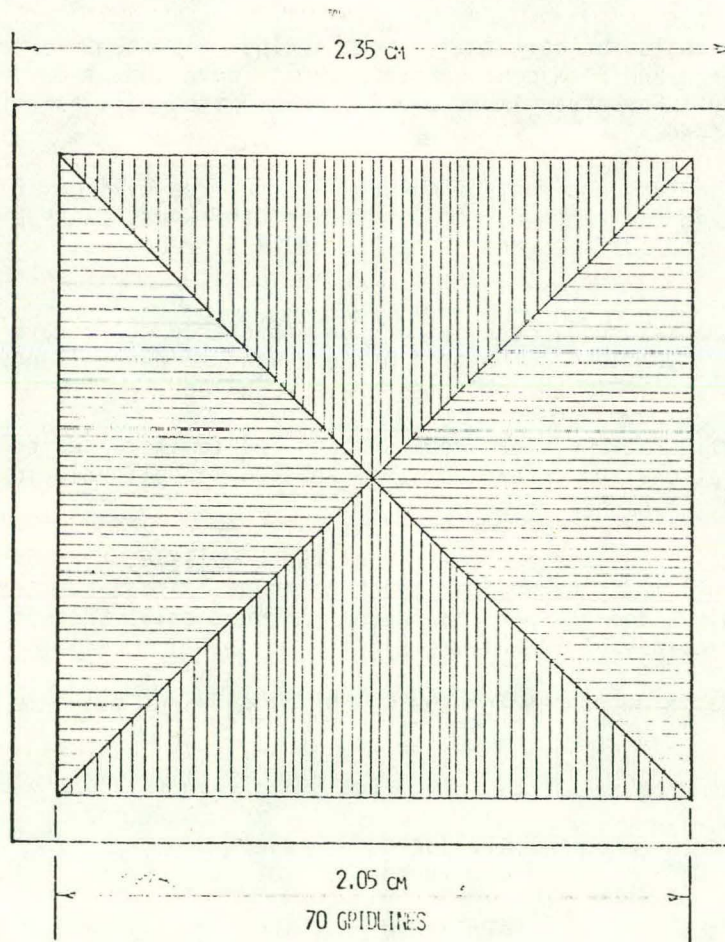


FIGURE 1. FRONT CONTACT AND GRID PATTERN FOR HIGH INSOLATION CONCENTRATOR CELL.

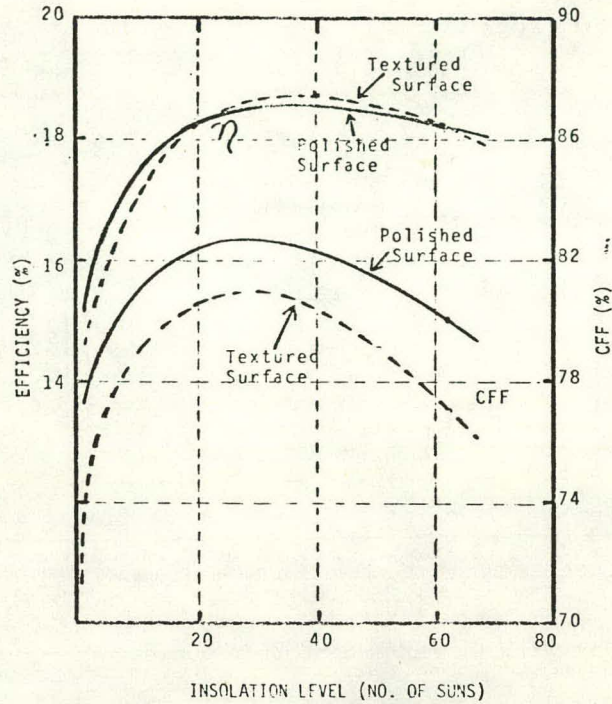


FIGURE 2: EFFICIENCY AND CFF vs INSOLATION LEVEL OF TEXTURED AND POLISHED SILICON CONCENTRATOR CELL AT 28°C.

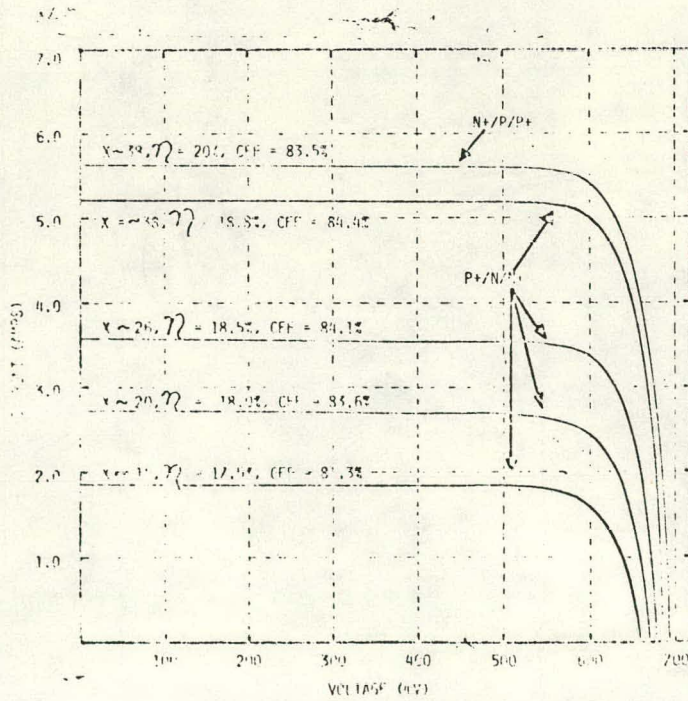


FIGURE 3: I-V CHARACTERISTICS OF N+/P/P+ and P+/N/N+ CONCENTRATOR CELL AT HIGH INSOLATIONS AND 28°C.

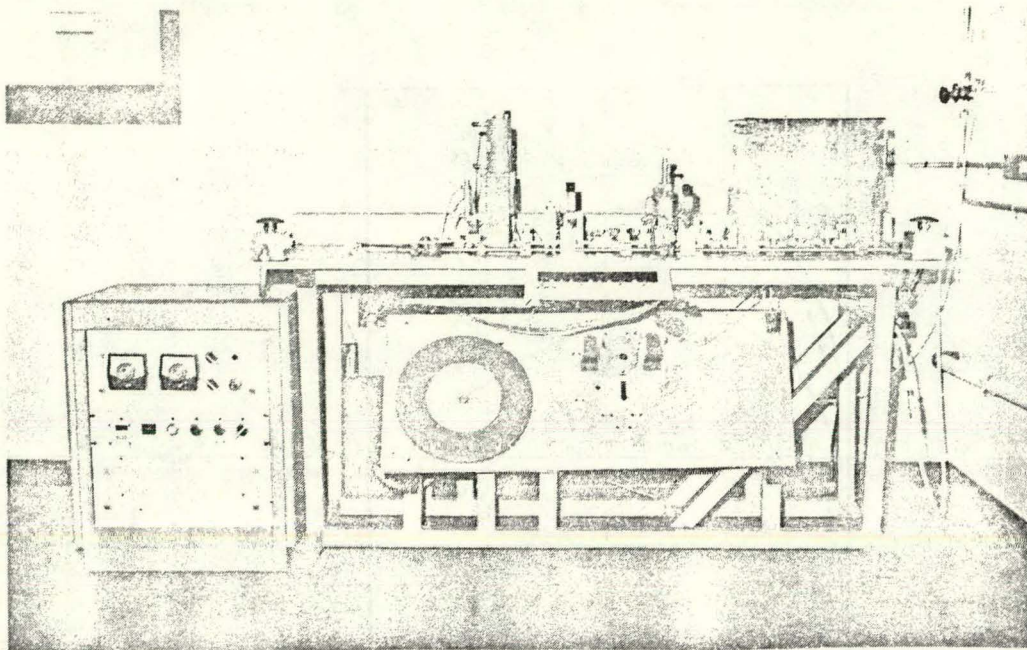


FIGURE 4
OVERALL VIEW OF ARRAY ASSEMBLY MACHINE

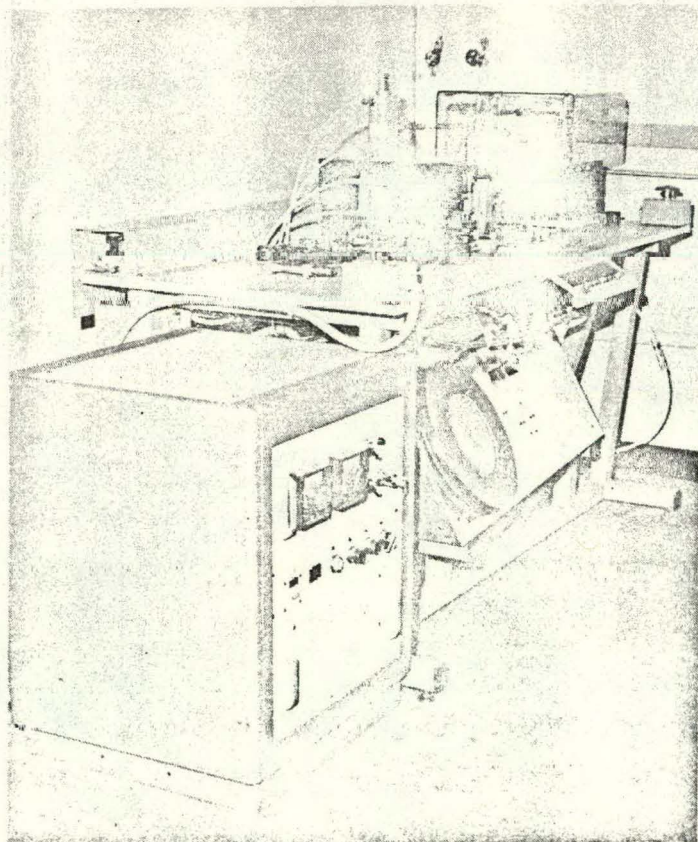


FIGURE 5
ANOTHER VIEW OF THE MACHINE

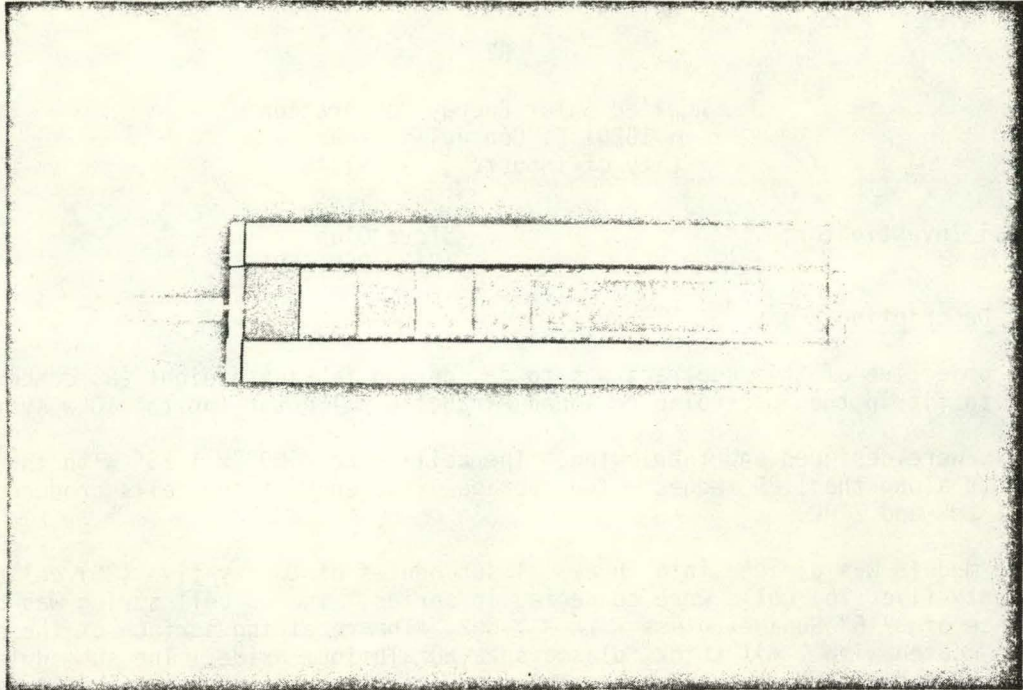


FIGURE 6 (a)
AN ASSEMBLED ARRAY SEGMENT (8 CELLS)

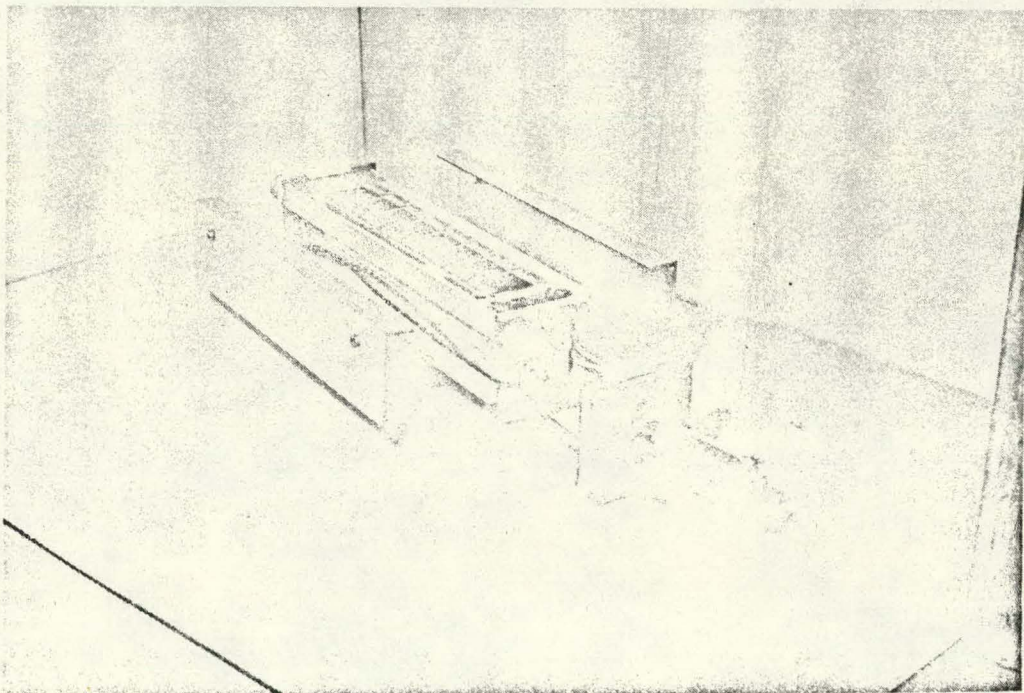


FIGURE 6 (b)
ASSEMBLED SEGMENT, MOUNTED WITH COOLING (EXPLODED VIEW)

FABRICATION AND DELIVERY OF EIGHT CONCENTRATOR MODULES

BY

Applied Solar Energy Corporation
15251 E. Don Julian Road
City of Industry, Ca. 91746

Principal Investigator:

Steve Olah
(213) 968-6581

Project Description

The objective of this contract was to design and fabricate eight (8) concentrator modules to fit in the Spectrolab designed Parabolic Collector for the 10kw system.

Cells were designed and fabricated. The cells were 2.09" x 1.25" with the two N-contacts along the 1.25" edges. The average efficiency of the cells produced was 14.5% at 20x and 27°C.

Each module was divided into three (3) submodules of twenty-five (25) cells each. All seventy-five (75) cells were connected in series. The 25 cell string was bonded to a piece of 3/16" Sunadex glass with RTV-602. The receiving surface of the extrusion was coated with 7 mil thick, plasma sprayed aluminum oxide. The submodules were bonded to the substrate with high thermal conductivity adhesive Eccosil 4954, manufactured by Emerson and Cumming, Inc.

Eight modules were fabricated and delivered to Sandia Laboratories.

DESIGN AND FABRICATION OF LINEAR CONCENTRATOR

BY

Applied Solar Energy Corporation
15251 E. Don Julian Road
City of Industry, Ca. 91746

Principal Investigator: Steve Olah
(213) 968-6581

Contract No.: 62-9828

Project Description

The objective of this contract is to design and fabricate phototype concentrator modules to be used in a parabolic collector.

The design requirements were:

- a) Double bus bar cell, minimum efficiency of 14% at 28^oC and 30X concentration.
- b) By-pass diode protection.
- c) Cell protection from terrestrial environment.
- d) Mechanical support of the cell string assembly.
- e) "V"-shaped aluminum extrusion, standard plumbing connection.
- f) 1500VDC electrical isolation between cell and extrusion.
- g) Cell module to be one and two meters in length.
- h) Operating coolant fluid temperature range of 30^oC to 70^oC.

The design of the module assembly and components was completed and approval has been received from Sandia Laboratories.

Purchase orders have been placed to acquire the components.

PERFORMANCE OPTIMIZATION OF THE ASR OPTICAL MODULE

by

Arizona Scientific Research
10121 Catalina Hwy.
Tucson, AZ 85715

Contract No.: 13-5162
Principal Investigator: Wally Meinel
Contract Amount: 235,016
Contract Duration: June 1979 - Jan 1981

PROJECT DESCRIPTION

The ASR Optical Module consists of a dish that concentrates sunlight onto a central receiver which is parallel to the optical axis. The intensity profile is uniform along the receiver to maximize the concentrator cell efficiency. This project identifies and minimizes optical loss mechanisms, identifies potential low-cost manufacturing processes, and fabricates six modules using the best candidate materials. A cost estimate for high volume production rates is also projected.

CURRENT STATUS

The design optimization is completed, the prototype receivers have been fabricated and solar cells have been mounted. The reflector dish and manufacturing cost estimates are in the process of completion. Testing and evaluation of the prototype units will follow.

ASU CONCENTRATOR CELL TESTS
(Contract No. 49-1510)

by

Arizona State University
Tempe, AZ 85281

Principal Investigator: C.E. Backus (602) 965-1725 R.W. Sanderson (602) 965-6145
Contract Amount: \$149,950
Contract Duration: January 1 - December 31, 1980

Project Description. This contract is a continuation of research at ASU during the last few years which generates and evaluates information on all aspects of photovoltaic concentrator systems. The objective of these investigations is to provide a body of data that others can use for the design of specific concentrator systems. Major areas receiving attention at this time are the evaluation of concentrator cells at high concentration and the evaluation of testing procedures for both individual cells and for concentrator modules. Investigations into the linearity of short-circuit current with irradiance, temperature coefficients of electrical performance parameters under high irradiance, and methods of correcting one-sun current reference data to a standard spectrum are currently in progress.

Temperature Coefficients Under High Irradiance. Temperature coefficients of efficiency, open-circuit voltage, and short-circuit current have been investigated over concentrations from 1-100 suns for n/p cells of 0.15, 0.4 and 1.5 ohm-cm base resistivity. Results indicate that the low resistivity material performs better under changing temperature conditions at all intensities, as expected. The low resistivity cells tested give efficiency results which are less sensitive to temperature and relatively constant in temperature coefficient behavior at irradiances up to 100 suns.

Over the temperature range tested (0-100°C), the temperature coefficients of efficiency, open-circuit voltage, and short circuit current were independent of temperature, as shown in Figs. 1 and 2.

Calculation of Cell Currents at Reference Irradiance Conditions. The atmospheric influence on the terrestrial solar spectrum can cause variations in the measured ratio of short-circuit current to intensity of 10% or more. To enable accurate comparison of silicon cell performance characteristics, it is important that measured data recorded under some arbitrary solar spectrum be referenced to some reference irradiance condition. One means for accomplishing this is to use matched reference cells. A second approach has been developed at Arizona State University which can be used in situations where the validity of the reference cell technique is questionable. Concurrent pyrheliometric measurements, both unfiltered and utilizing at most three cut-off filters, and measurement of cell short-circuit current are input to a simple computer model which generates an approximate spectral response for the cell. This approximate spectral response is then convoluted with any desired reference spectrum to predict the reference value of the cell short-circuit current. Theoretical and experimental evidence show that the predicted reference current is typically within $\pm 1\%$ of the true value. This technique may be used only for cells whose principal energy source is the direct solar beam, making it ideal for concentrator applications. Further, the reference current prediction can be made for any number of cells connected in some series/parallel fashion, which may or may not be operating at some non-zero condition.

Short-Circuit Current vs. Intensity. In almost all concentrator applications the short-circuit current of the cells are used as a measure of incident intensity. An investigation has been made of the correctness of this assumption by two different techniques: spectral response measurement and neutral density filter measurements. The spectral

response of several silicon solar cells was measured under illumination levels going from approximately .01 sun up to 125 suns for 11 different wavelengths distributed over the solar spectrum. The spectral response was found to increase with increasing concentration for each of the wavelengths. The effect on the spectral response varies with the type of cell, but has shown an error in short-circuit current that could be as high as 6-8% in concentrations of 100-125 suns. Figure 3 shows typical experimental results for different intensities of concentration. All n/p concentration cells tested showed a slight increase of short circuit current per unit intensity at high concentrations. In many cells the incorrectness of the assumption of constant short circuit current to intensity ratio will result in errors of only 1-2%.

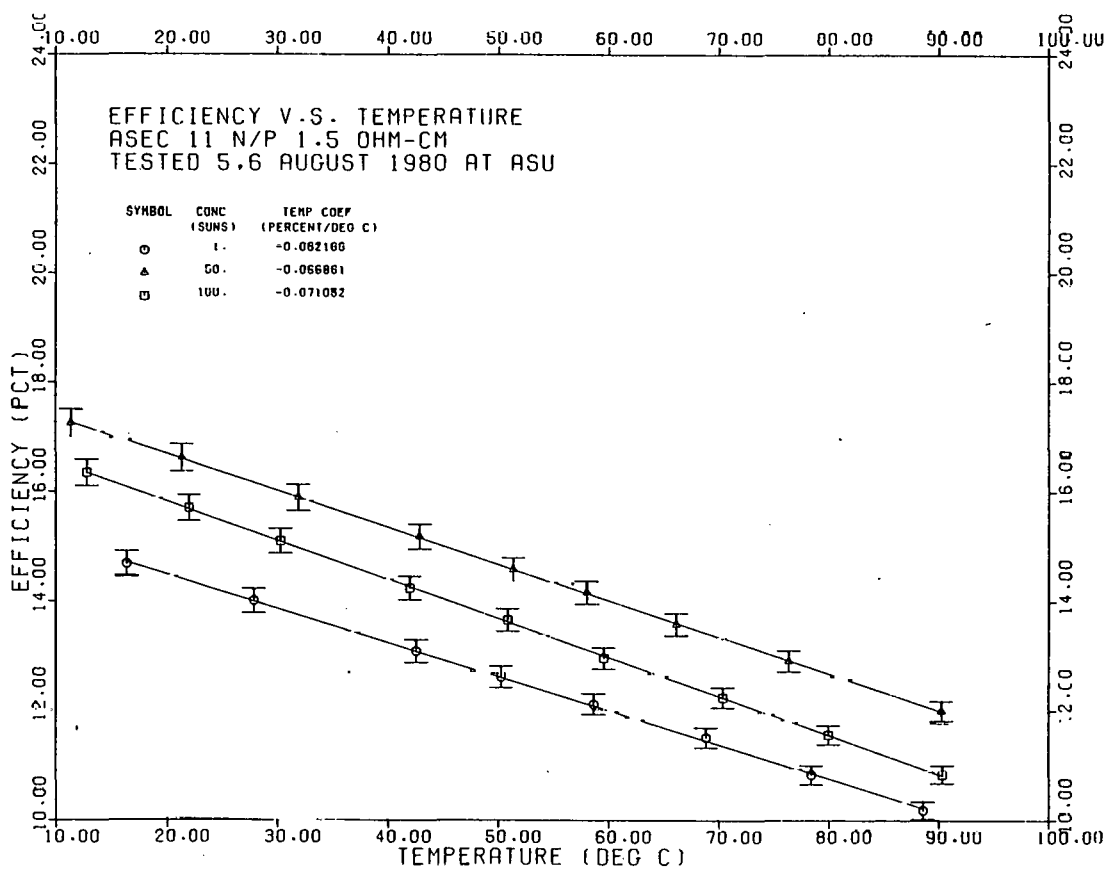


Fig. 1

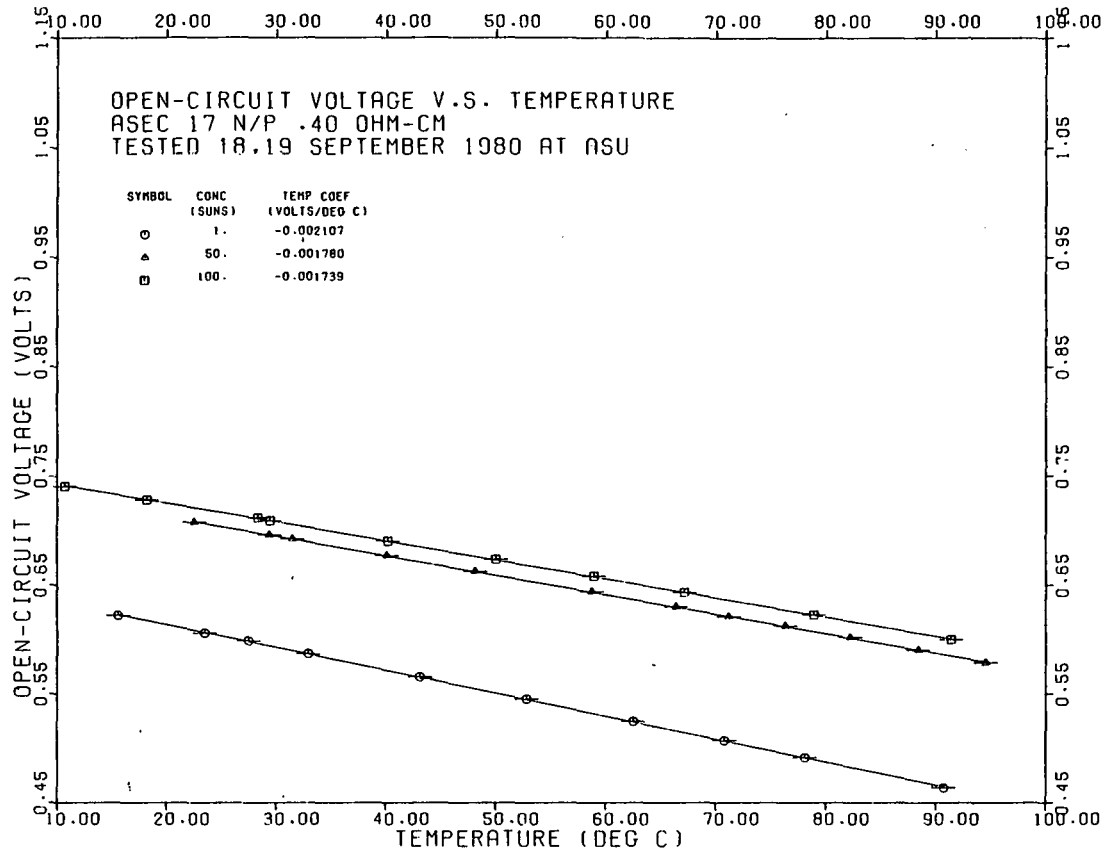


Fig. 2

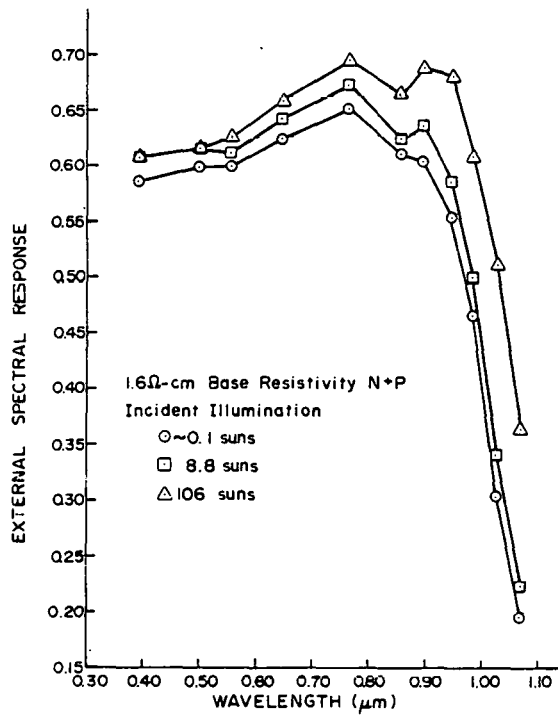


Fig. 3. Spectral response vs. wavelength for 1.6 Ω-cm cell at indicated concentrations

PLASTIC FILM PHOTOVOLTAIC CONCENTRATOR

by

Boeing Engineering and Construction Company
625 Andover Park West
Tukwila, Washington 98188

Project Manager: D. K. Zimmerman
Term of Contract: 4-25-79 to 10-31-80
Contract Amount: \$203,597

Status Summary

An investigation into the use of plastic film for a photovoltaic concentrator is described. Boeing Engineering and Construction (BEC) is presently under contract with Sandia Laboratories to design, fabricate and evaluate a photovoltaic concentrator system utilizing a plastic film reflector. BEC has previously evaluated plastic film concentrators. A 2 m diameter parabolic concentrator (with focal length/diameter = 1/2) was evaluated in Sandia Contract 05-4467 with laser scans and a solar simulation test. This earlier work established that large gore angles (20°) could be used to achieve a high efficiency, high concentration ratio parabolic plastic film concentrator. Laser ray scanning tests of a 4.57 m diameter concentrator and $f/D = 1/2$ provided similar conclusions. The purpose of the present contract was to determine the most practical configuration of the concentrator for use with an annular photovoltaic receiver, and to design, fabricate, and test the concentrator.

Various combinations of reflector shapes and photovoltaic module geometries were analyzed using a ray trace optical computer model. The best concentrator configuration was found to have a cylindrical photovoltaic module and a deep dish reflector capable of providing uniform flux on the cylindrical module surface. This configuration provides a good compromise between energy capture, depth of reflector, solar cell module layout, energy incidence angle on the cells, and active reflector area.

Several reflectors were fabricated with gore-shaped segments of .05 mm (.002 inch) thick aluminized polyester film, which had a specular reflectance of 86% at a cone angle of .14° (2.5 mr). The reflector is supported by a lightweight fiberglass shell and stabilized with a slight negative pressure. The reflector has a geometric concentrator ratio of 145, selected to achieve 100 suns on the solar cells.

Optical evaluations of the reflectors were performed using a laser ray trace technique in order to determine local variations in surface errors and to relate observed errors with physical features of the reflector. The laser ray was reflected from the reflector surface onto a simulated photovoltaic module. The observed laser image on the module was then compared with the design intercept point to determine the local surface error, and the density of the images on the module provided a map of the expected solar intensity on the solar cells.

Results of the fabrication and testing showed that the deep-dish concentrator configuration is considerably more difficult to implement than the previously evaluated shallow paraboloids. An initial attempt using 20° gore angles showed substantial wrinkling along the gore seams. Subsequent analysis using a newly available version of the NASTRAN computer program indicated the wrinkling would be acceptably small with a 15° gore angle. This configuration was then fabricated and is currently being tested using the laser ray tracing procedure. The 15° gores do suppress the wrinkling problem. However, preliminary test data indicate less accurate shape control than previously attained.

THIN-FILM BARRIERS

by

California Institute of Technology
Electrical Engineering Department
Pasadena, California 91125

Contract No.: 13-6199
Principal Investigator: Marc-A. Nicolet
(213) 795-6811 ext. 1803
Contract Amount: \$149,500.
Contract Duration: 19 July 1980 - 18 July 1981

Project Description - Investigate thin-film diffusion barriers for metallization schemes by a two-pronged approach:

- Test thin films on devices to demonstrate relevance.
- Undertake basic studies to characterize the thin films and further the understanding of thin-film barriers.

The contract is in its second-year extension.

Current Status - We have upgraded our sputtering system by introducing a throttle valve between the diffusion pump and the LN₂ trap, so as to be able to proceed with the sputtering cycle without having to close the high vacuum valve. The resistivity of the TiN layers obtained with this improved system is substantially reduced and approaches that of commercially produced films. We have also improved the gas supply system and are now able to sputter with two premixed gases of a known concentration ratio. With this arrangement, we have been able to confirm the rapid transition of the deposited layer as a function of the partial pressure of N from TiN to N-doped Ti. A systematic investigation of the metallurgical diffusion barrier property of TiN and HfN is now being undertaken to assess the role of the deposition parameters on this property of the sputtered films.

Preliminary experiments have been undertaken to evaluate the diffusion barrier properties of TiN on GaAs, to determine the temperature coefficient of resistivity of TiN, and to estimate the electronic work function of TiN.

The processing steps and the electrical measurements needed to determine the contact resistivity of sputtered TiN films on solar-cell-type silicon have been worked out. The results obtained have been useful; we next intend to repeat these measurements systematically for several nitride layers on silicon. A handicap is the lack of a photolithography laboratory at Caltech. We benefitted from assistance by Applied Solar Energy Corporation and Jet Propulsion Laboratory on that matter.

The testing of the barrier layers on commercial cells has been executed in collaboration with Applied Solar Energy Corporation. We appreciate and acknowledge this cooperation.

Key Results - No degradation of a solar cell could be observed after a 600°C, 10 minute heat-treatment in flowing nitrogen ambient when the cell was provided with a TiN-Ti-Ag metallization scheme and the reactively sputtered TiN layer was $\approx 1700 \text{ \AA}$. The conventional Ti-Pd-Ag metallization scheme failed under the same annealing treatment.

The contact resistivities of sputtered TiN and Ti-TiN films on solar-cell-type silicon was measured. For the n⁺Si-Ti-TiN system, a contact resistivity of $9 \times 10^{-4} \text{ } \Omega\text{cm}^2 \pm 50\%$ was obtained. A heat treatment of 700°C, 30 minutes decreases this value by one order of magnitude and the interposed Ti fully reacts with Si and forms a TiSi₂ layer. An extrapolation based on these measurements suggests that this contact system should be acceptable for Si solar cells with concentrations upto 100 times. The contact resistivity of the n⁺Si-TiN contact system was $2 \times 10^{-3} \text{ } \Omega\text{cm}^2 \pm 50\%$ and remained constant after annealing upto 700°C for 30 minutes. This value is adequate for non-concentrator cells.

Thin ($\sim 1.5 \text{ k}\text{\AA}$) bilayers of Cu and Ni evaporated in good ($\lesssim 10^{-7}$ Torr) and in poor ($\sim 10^{-5}$ Torr) vacuum have been annealed for 15 minutes in a flowing nitrogen atmosphere. The films strongly mix above about 600°C and very substantial inter-diffusion is observed at 450°C. We conclude that Ni film of the order of k \AA thickness deposited in vacuum is not a diffusion barrier to Cu.

Sputtered TiN layers are not stable against oxidation, but below 400°C, no significant oxide is formed during annealing in pure oxygen. At 550°C, layers of the order of k \AA in thickness are oxidized in a matter of hours. The kinetics seems to be diffusion-limited, but the oxidation rate varies noticeably from sample to sample in a non-controllable way.

Metallurgical tests based on backscattering spectrometry data indicate that HfN behaves similarly to TiN in respect to diffusion barrier properties on silicon. The result suggests that most early transition metal nitrides should form diffusion barriers in the same way as TiN does.

DEVELOPMENT OF A SECOND-GENERATION LINEAR
FRESNEL LENS PHOTOVOLTAIC CONCENTRATOR ARRAY

By

E-Systems, Inc.
Energy Technology Center
P. O. Box 226118
Dallas, Texas 75266

Principal Investigator: Mark J. O'Neill
(214) 272-0515, x3830
Contract Number : 46-5791
Contract Amount : \$349,396
Contract Term : February 1980-February 1981

Project Description - For the past several years, E-Systems has been actively developing a novel, high-efficiency, short focal length, linear Fresnel lens solar concentrator for both photothermal and photovoltaic applications. This concentrator (U. S. Patent No. 4,069,812) offers both maximal optical efficiency and large tolerance for manufacturing errors and aberrations. In 1978-79, a first-generation combined photovoltaic/photothermal array, using the new concentrator, was designed under the DOE-funded PRDA-35 program. This first-generation array consists of ten collector modules, each 91 cm x 244 cm (3 ft. x 8 ft.) in aperture, mounted in a common 1.5 axis tracking frame. The modules utilize series-connected silicon cells, sized for a 25X geometrical concentration ratio, attached to a water-cooled copper fin-tube heat sink. Two of these modules have recently passed Sandia's qualification test program, in conjunction with E-Systems' PRDA-35 application experiment to be built at the Dallas-Fort Worth Airport. The electrical and thermal performance of these modules ranks among the highest yet measured at Sandia for silicon-based photovoltaic concentrators.

In early 1980, Sandia awarded this contract to E-Systems to generate a higher-performance, lower-cost, second-generation array design using the same linear Fresnel lens concentrator. Specific improvements include an increase in geometrical concentration ratio from 25X to 40X, the use of ASEC's automatic cell assembly machine for cell string fabrication, an extruded aluminum heat sink to replace the expensive copper assembly, a longer concentrator module to reduce assembly costs per unit aperture, a full two-axis tracking capability, and a re-engineered array configuration based upon production, installation, and system integration considerations.

Current Status - The new second-generation array design has been completed. Two prototype collector modules of the new design have been built and successfully tested. Material procurement and fabrication efforts are currently underway for a nominal 4 kw prototype system which will be completed, tested, and delivered to Sandia in 1981.

Key Results - The second-generation array consists of four collector modules, each 91 cm x 305 cm (3 ft. x 10 ft.) in aperture, factory-assembled and aligned within a common support frame. These 11 square meter (120 square feet) aperture arrays are then post-mounted in the field, with the capability for full two-axis tracking and inverted (lens down) stowage. Multiple series-plumbed arrays are mechanically interconnected in long rows, with centralized drives, wiring, and manifolds.

Overall system weight per unit aperture has been reduced from nearly 11 lbs/ft² to less than 9 lbs/ft². Despite a reduction in silicon area by nearly 40%, the two prototype collectors electrically outperform the first-generation collectors by about 5 to 15%, depending upon operating temperature. In summary, the second-generation array design provides a large reduction in installed system cost per unit aperture, as well as a significant improvement in system performance.

DEVELOPMENT OF A LOW-COST EXTRUSION/EMBOSSING
PROCESS FOR A LINEAR FRESNEL LENS
PHOTOVOLTAIC CONCENTRATOR

By

E-Systems, Inc.
Energy Technology Center
P. O. Box 226118
Dallas, Texas 75266

Principal Investigator: Mark J. O'Neill
(214) 272-0515, x3830

Contract Number : 13-2359

Contract Amount : \$213,923

Contract Term : January 1979-December 1980

Project Description - For the past several years, E-Systems has been actively developing a novel, high-efficiency, short focal length, linear Fresnel lens solar concentrator for both photothermal and photovoltaic applications. This concentrator (U. S. Patent No. 4,069,812) offers both maximal optical efficiency and large tolerance for manufacturing errors and aberrations. The modular design of the system requires linear lenses with aperture dimensions of 91 cm (36 in) width by 244 cm (96 in) length. Of all methods available to manufacture such lenses, including casting, compression molding, injection molding, profile extrusion, etc., the method offering highest performance at least cost should be continuous extrusion/embossing of acrylic plastic.

The overall objective of this development effort is to adapt the low-cost extrusion/embossing process to the production of high-quality linear Fresnel lenses for photovoltaic concentrator applications. Specific objectives are to design and build a full-size, diamond-turned, prismatic embossing roll, to install this roll in a production extrusion line, and to conduct an iterative process development program including trial production runs, sample lens optical performance measurements, and process modifications, in repeating cycles.

Current Status - Under subcontract to E-Systems, Optical Sciences Group (OSG) designed and fabricated the full-size embossing roll. Also under subcontract, K-S-H, Inc., the largest extrusion/embossing firm in the U. S., installed the roll in one of their production lines. To date, K-S-H has conducted five trial production runs, with an additional run planned before year's end. Using a sun-tracking, focal-plane-scanning, lens flux profile measurement apparatus, E-Systems has evaluated lens samples from the first four trial runs, and will evaluate samples from the fifth run upon their receipt.

Key Results - The performance figure-of-merit selected for the lens samples is the net optical efficiency of the lens at a geometric concentration ratio of 25:1. The performance goal is 87%, the value already demonstrated for the same lens produced by compression-molding (OSG), by casting (Swedlow), and by a proprietary process (3M). Test results for the extruded/embossed lenses from the first four trial runs are shown in the table on the following page.

<u>Trial Run Number</u>	<u>Date Measured</u>	<u>Lens Efficiency</u>
1	October 1979	60%
2	December 1979	65%
3	March 1980	70%
4	May 1980	72%

While the performance goal has yet to be achieved, steady progress has been demonstrated. Furthermore, since the embossed lenses cost only about one-third as much as lenses produced by the alternate processes, full performance equality with the other processes is not required for viability.

SECOND GENERATION PHOTOVOLTAIC TWO-AXIS TRACKING SYSTEM (27 KWe NOMINAL RATING)

By

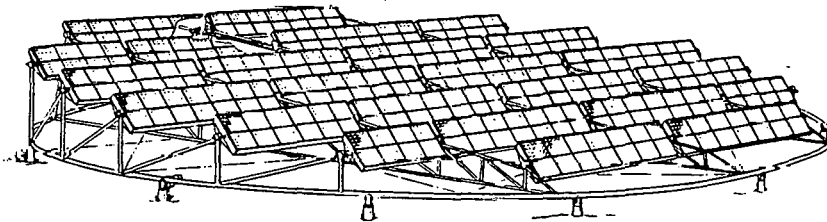
Ford Aerospace & Communications Corporation
3939 Fabian Way
Palo Alto, Ca. 94303

Contract No:	13-9495
Program Manager:	Howard J. Sund (415) 494-7400 Ext. 4594
Contract Amount:	\$230,796
Contract Duration:	December 1979 to February 1981

PROJECT DESCRIPTION

The goal of this program is to develop a two-axis tracking, photovoltaic concentrator structure which has been optimized to produce the lowest cost per KWh of energy while supporting point focus fresnel lens modules. The finalized array is to represent a more reliable, improved performing system that, when adapted to high volume production, will approach the near-term design goal of producing power at \$2.80 per peak watt. Specifically, this contract proposes to meet the following objectives:

- Perform system trade studies and optimize the support structure in order to collect the maximum amount of solar energy at the lowest structural/mechanical cost.
- Generate detailed design drawings and specifications for the tracking structure along with the foundation criteria.
- Provide estimated costs of the tracking structure based on a production rate of 10^5 to 10^6 square meters of aperture per year.
- Fabricate, install and functionally checkout the prototype assembly at Sandia's facility in Albuquerque, N.M.



CURRENT STATUS

System optimization trade studies were performed using a computer program which calculated the effective optical aperture as a function of varying structural array geometry, i.e. diameter (64', 85', 128' and 191'), tilt angle (0° , 10° , 20° , 30°) and a packing factor range (0.25 - 1.00). The total number of parameter combinations generated by the computer was 680. For each of these configurations, a minimum full illumination angle was also calculated (5° to 40°). Utilizing the TMY (Typical Meteorological Years) tape data for Albuquerque, the computer was also programmed to print out the energy collected per year for each of the geometric configurations under examination. Detailed production cost analyses were performed on a selected baseline configuration and these costs were then extended via appropriate formulas or equations to cover the number of geometric configurations under consideration. Having the total energy collected and the cost of each configuration, the lowest "cost per kWh" structure was identified.

This optimized tracking structure has been completely analyzed and detailed. Vendor quotations for the fabrication and installation of the prototype unit have been received and are now being reviewed. Preliminary production cost estimates have also been generated.

KEY RESULTS

The system trade studies identified the optimized tracking structure configuration as having the following parameters:

- 85 foot diameter
- Seven modular rows (0.46 packing factor)
- 0° tilt angle
- 312 parquets (34" x 34") totaling 225 M^2
- 27.0 KW_e peak power rating at 1000 W/M^2
- Minimum full illumination angle = 27.5°

The resulting design has several key cost-effective features such as an inexpensive timber pile foundation, a unique "inverted" rotating track concept, lightweight tubular truss structural members, secondary wire rope bracing and innovative non-lubricated nut elevation drive actuator assemblies. All components have been designed for 20 year life with negligible scheduled maintenance and the design lends itself to high volume manufacturing techniques and to lower labor-intensive field installation.

Preliminary installed production cost estimates of the selected tracking structure, including the foundation but excluding the fresnel modules themselves, resulted in a cost of $\$65.7/\text{M}^2$ which equates to $\$0.55$ per peak watt for the structure itself. This particular tracking structure, which supports 225M^2 of point focus fresnel modules, collects 285 kWh/M^2 of energy per year for a typical Albuquerque type environment.

DESIGN AND DEVELOPMENT OF A LAMINATED
FRESNEL LENS FOR POINT FOCUS
PV SYSTEMS

BY

GENERAL ELECTRIC COMPANY
P.O. BOX 8661
PHILADELPHIA, PA 19101

PRINCIPAL INVESTIGATOR: R. C. HODGE

CONTRACT NO.: 46-0063

CONTRACT AMOUNT: \$171,800

CONTRACT TERM: OCTOBER 19, 1979 TO
JULY 18, 1980

PROJECT DESCRIPTION

The objective of this program was to design and investigate the technical feasibility of a laminated parquet point focus Fresnel lens using injection molded flat Fresnel lens elements. The program addressed three basic areas; lens design and tooling fabrication, lamination design development, injection molding of prototype lenses, and subsequent lens testing.

CURRENT STATUS

A 6.65 inch square, flat Fresnel lens was designed with a geometric concentration ratio of 120. This lens represents the basic optical element in a glass superstrate flat Fresnel lens laminate assembly. This program dealt with the development of a 7 inch square prototype laminate lens assembly. A subsequent program is planned to develop a full-size 5 x 5 parquet lens assembly. The lamination design effort screened candidate glass superstrates and adhesives. Over one hundred 6.7 inch square Fresnel lenses were molded using conventional injection molding techniques. Prototype laminate lens assemblies were then fabricated using the selected glass and adhesive. Both optical transmission and accelerated environmental exposure tests were then performed on these prototype assemblies.

KEY RESULTS

A laminated point focus Fresnel lens assembly was defined which has a potential direct manufacturing cost of less than a \$1/ft² and a lens transmission efficiency of greater than 80%. The lamination approach permits the use of a glass superstrate, with its proven durability, and a thin (< .080 inch) plastic Fresnel lens. The lens design was validated by testing compression molded control lenses. Transmission efficiencies of 84-86% and a flux uniformity of 1.18 (I_p/I_{avg}) were measured.

Final injection molding trial lenses exhibited transmission efficiencies of 73-75%. This represented a 40% improvement from the initial molding trials. Insight gained into lens and mold design as well as optimum process parameters indicates that injection molded lens with transmission efficiencies of 80% are feasible.

COMBINED PHOTOVOLTAIC/THERMAL
LINEAR RECEIVER

BY

GENERAL ELECTRIC COMPANY
ADVANCED ENERGY PROGRAMS DEPARTMENT
P. O. BOX 8661
PHILADELPHIA, PA 19101

CONTRACT NO.: 13-8893
PRINCIPAL INVESTIGATOR: NEAL F. SHEPARD, JR.
(215) 962-5839
CONTRACT VALUE: \$93,234
CONTRACT DURATION: OCTOBER 1979 TO SEPTEMBER 1980

PROJECT DESCRIPTION. This project involves the design, fabrication and testing of a combined thermal/photovoltaic linear receiver which employs an outer glass shroud with a transparent coolant fluid passing over the active surface of solar cell circuits which are mounted within this tube. This receiver is designed to be optically compatible with the Sea World reflector design with a geometric concentration ratio of 34:1. Two five foot long prototype receivers are to be fabricated and tested as part of this program.

CURRENT STATUS. All contract work effort has been completed and the final report has been published. Two prototype receivers were fabricated and one of these was integrated with the prototype Sea World reflector and subjected to a series of electrical performance tests using Synfluid (2 centistoke) as the coolant.

KEY RESULTS TO DATE. A module electrical efficiency of 9.2 percent was measured with a 50°C inlet coolant temperature.

MANUFACTURING COST ANALYSIS OF 1980 PV ARRAYS

BY

GENERAL ELECTRIC CO.
P.O. BOX 8661
PHILADELPHIA, PA 19101

PRINCIPAL INVESTIGATOR: R. C. HODGE
(215) 962-5949

CONTRACT NO: 62-6547

CONTRACT AMOUNT: \$173,300

CONTRACT TERM: JULY 17, 1980 TO
APRIL 16, 1981

PROJECT DESCRIPTION

The overall objective of this program is to verify that photovoltaic concentrator technology has reached the point of Technology Readiness as defined by the DOE \$2.80/Wp energy cost goal. This verification will be accomplished by investigating the production and installation cost potential of the following 1980 vintage PV concentrator hardware designs:

- E-Systems' linear Fresnel
- Sandia's TR-80 Point-focus Fresnel
- Sandia's 1-axis N-S horizontal parabolic trough

With an assumed production rate of $10^5 \text{ m}^2/\text{year}$, appropriate production processes for each array will be defined, and factory and life cycle costs of the arrays will be estimated. As available, actual hardware test data will be used to estimate adjusted peak watt and annual energy collection performance.

The program consists of three (3) major tasks. The first task is to compile available array design detail, and estimate each array's performance potential. The second task is to define high volume production processes and estimate associated manufacturing costs. In addition, the total installed and life cycle array costs will be estimated. The third task will formulate a conceptual plant design for the most attractive array approach. This effort will include the generation of a conceptual plant layout showing major equipment location, floor space and utility requirements, assembly, test and inspection stations.

CURRENT STATUS

Manufacturing and installation cost analyses have been completed for the Fresnel arrays. Detailed production process definitions are being generated for the 1-axis parabolic trough. Selection of the most attractive array for production plant layout design will be made in conjunction with Sandia upon completion of the 1-axis trough costing analysis.

KEY RESULTS

Salient program groundrules and design guidelines have been defined. Detailed part and assembly drawings, part lists and material specifications have been compiled for the selected 1980 PV array designs. Assuming the prescribed annual production rate make/buy analyses have been made for the Fresnel arrays. Production processes/costs for the "make" items and vendor quotes on the "buy" items have been generated. The cell cost quotes were provided by Applied Solar Energy Corporation. Direct manufacturing costs and FOB factory sell prices have been determined for the Fresnel arrays. Cost estimates have been generated for the installation of a 400-kW system for each concentrator as well as a 1980 vintage flat plate array in a Southwestern site. Array field layout, major installation steps, and material and labor requirements were estimated. Array energy outputs were predicted for an Albuquerque location and the resultant array energy costs have been calculated based on the total installed array costs.

ACTIVELY COOLED PHOTOVOLTAIC ARRAY

BY

Martin Marietta Corporation

P. O. Box 179

Denver, Co. 80201

Contract No.: 13-8778
Principal Investigator: Sidney Broadbent
(303) 977-0683
Contract Amount: \$261.2K
Contract Duration: July 19, 1970 - December 31, 1980

Project Description - The design and fabrication of an actively cooled version of Martin Marietta's existing passively cooled photovoltaic array. This involved the following analysis, design and testing:

- o Thermal analysis evaluating cooling system options & minimization of pumping and insulation losses.
- o Design trade-off analyses for maximum cost effectiveness and reliability.
- o Incorporation of a 2nd generation cell/substrate/interconnect design for improved cell performance and volume production.
- o Modification of electronic controls to include over-temperature and pressure loss over-ride sensing and de-steer provisions.
- o Module and array testing.

Current Status - The array is in final stages of assembly. Electronic controls are complete and have been satisfactorily tested in conjunction with the testing of individual photovoltaic modules.

Key Results to Date - Processing techniques have been perfected to guarantee satisfactory cell/substrate/interconnect attachments with minimized series resistance. Resulting performance improvements compared to our original design amounts to as much as 20%.

2ND GENERATION PHOTOVOLTAIC ARRAY
BY
MARTIN MARIETTA CORPORATION
P. O. BOX 179 DENVER, COLORADO 80123

Contract No.: 46-3018
Principal Investigator: Sidney Broadbent
(303) 977-0683
Contract Amount: \$353.3K
Contract Duration: March 1980 - March 1981

Project Description - The objective of this program is to develop the current Martin Marietta Array design into a more cost effective concept with certain design constraints that limit geometric concentration ratios to 100, that silicon cells and planar fresnal lenses be utilized and that the array remains of the central pedestal mounted variety. The redesign effort would reconsider array proportion, automated production methods and alternative control systems. Five prototype modules will be produced for test evaluation at both MMC and Sandia Laboratories.

Current Status - A comprehensive computer analysis embodying all significant cell, lens and heat exchanger characteristics together with insolation and wind magnitudes and known imaging errors due to manufacturing tolerances has been developed which in conjunction with detailed cost data derived from our Saudi Arabian production program, optimizes lens size, "f" number and target size for minimum cost/watt. Design effort proceeded concurrently on a more cost effective cell laydown technique, individual heat sinks with integral interconnects and simplified mounting of the module to the support tube.

Key Results to Date - Using a optimized lens of 8.16" square an "f" number of 1.24 and concentration ratios of 84 a cost reduction of 37% \$/watt is predicted on the basis of 1000 arrays.

DEVELOPMENT OF SOLAR CELL ASSEMBLIES

BY

Microwave Associates, Inc.
43 South Avenue
Burlington, Massachusetts 01803

Contract No: 46-2034

Principal Investigator: D. Hobbs, 617-272-3000, Ext. 1911

Contract Amount: \$199,273

Contract Duration: October 1979 to November 1980

Project Description - The objectives of this developmental contract are given in the following four tasks:

- Task 1 - Develop one or more cell assembly designs for prototype fabrication.
- Task 2 - Fabricate assemblies from such designs. Optimize the assembly reliability and performance with respect to cell interconnection methods and bonding.
- Task 3 - Investigate alternative cooling methods for substrate.
- Task 4 - Deliver sample assemblies to Sandia Laboratories.

Current Status - A hermetic assembly design has been chosen, and piece parts received. The design features a one-step brazing process to form the entire package assembly except for a glass window. The cell and window are then inserted and the assembly is completed using a lower temperature solder process.

Key Results to Date - Silicon solar cell chips have been mounted in the packages. Measurements are being made on the electrical and thermal properties of the cell and assembly.

EMVJ SILICON CELL DEVELOPMENT

BY

MICROWAVE ASSOCIATES, INC.
43 South Avenue
Burlington, Massachusetts 01803

Contract No: 13-0361

Principal Investigator: Dr. G. Allendorf, 617-272-3000, Ext. 1558

Contract Amount: \$339,769

Contract Duration: November 1978 to November 1980

Project Description: The objectives of this developmental contract are to fabricate silicon concentrator cells which have an efficiency greater than 18% at concentrations higher than 50 suns. In this Etched Multiple Vertical Junction (EMVJ) design, diffusions and metallizations are both embedded in deeply etched grooves normal to the cell surface. As a result, there is no current flow within the junction planes, and the surface area available for metallization is very large compared to the obscured surface area.

Current Status: The geometrical layout and size for the 150 cells to be delivered to Sandia have been largely determined. The overall size of the silicon chip will be 0.3 by 0.3 inches, with an active cell area in the center with a diameter of 0.25 inches. Metallization experiments have resulted in plated groove walls greater than 0.2 mils thick. These "buried" grid conductors have a total resistance of less than 15 milliohms. Various device design parameters are being studied in order to optimize cell efficiency.

Key Results to Date: Silicon cells with top grooves spaced at 8 mil centers, and with metallization obscuring 0.8 mils per groove have been fabricated and measured using laboratory mounting assemblies. These cells have given an efficiency of 18.5% from 600 to 1000 suns at a heat sink temperature of 27°C, (with $V_{OC} = 0.790$ and $FF = 0.74$ at 1000 suns). The AR coating was silicon dioxide (only).

CONCENTRATOR SOLAR CELL DEVELOPMENT

by

Motorola Incorporated
Semiconductor Group
5005 East McDowell Road
Phoenix, Arizona 85008

Contract No:	28-1065
Principal Investigator:	Larry Grenon (602) 244-6414
Contract Amount:	\$197,762
Contract Duration:	June 1980 - August 1981

This program is a continuation of a silicon concentrator solar cell development effort that has been in existence at Motorola since early 1978. The fundamental goal of the program is to establish a low cost, manufacturable process capable of producing high efficiency concentrator solar cells for applications of nominally 100X or less. A further goal of the program is to identify a baseline process in which solar cell parameters can be accurately measured and to incorporate new, more cost effective processes as they are developed. Additionally, processes and potential processes selected for use in the manufacturing of silicon concentrator solar cells are selected for their compatibility with the processes being developed for 1-sun solar cells. This is believed to be the best approach for achieving DOE cost objectives.

The current approach to manufacture silicon concentrator solar cells at Motorola utilizes a diffusion process into 0.3 Ω -cm, P-type, <100>, float zone substrates. Cells are texture etched and use low pressure chemical vapor deposited silicon nitride as the anti-reflection layer. Patterning of the layer utilizes R-F plasma etching techniques through either a photolithographically defined pattern or by mechanical masking of the pattern. The metal structure is established by plating of nickel and copper. Both electrolytic and electroless plating processes are being evaluated for electrical and mechanical properties. Each of these manufacturing processes are directly related to current or proposed low cost cell processing techniques and have demonstrated the capability of producing silicon concentrator solar cells with peak conversion efficiencies of near 19%, AM1.

SOLAR CELL TESTING
AND EVALUATION

By

North Carolina A&T State University
Department of Electrical Engineering
Greensboro, N.C. 27411

Contract No.: 62-1523
Principal Investigators: Elias K. Stefanakos
Ward J. Collis
(919 379-7760)
Contract Amount: \$20,800
Contract Duration: May 1 - December 31, 1980

Project Description: This research project involves the testing of Si and GaAs solar cells under natural and simulated sunlight conditions. The natural sunlight testing facility entails the construction of a solar concentrator system. This system utilizes a plane mirror mounted on a tracking stand and a fixed parabolic concentrating mirror (47 cm diameter, 230 cm focal length). The testing of solar cells is to be performed over an ambient to 180°C temperature range. In one cell mounting design, the cell block is maintained at a constant elevated temperature by a temperature-controlled oil heat transfer system. A second cell mounting approach does not employ liquid cooling, and is intended for the high temperature (>100°C) test range. In this configuration, a rotary solenoid actuated reflective shutter adjacent to the cell plane controls the average temperature of the cell mounting block (which is insulated thermally from the structural support). Thus, the cell is exposed to transient, high concentration illumination. A computer controlled data acquisition system will synchronize the cell I-V measurements with the shutter-open intervals.

For the testing of single solar cells with simulated sunlight (Xenon), a test fixture containing a cell mounting block which incorporates both a coolant loop and electrical heaters is being developed. This system can be cycled between temperature extremes $\sim -100^\circ\text{C}$ to 150°C while the cell is contained in an N₂ environment. During the temperature cycling the cell can be under light or electrical bias. The physical and electrical behavior of the cell will be observed during the test duration to determine degradation mechanisms.

Current Status: The solar tracking concentrator system has been constructed and tested to a limited extent. The reflective shutter mechanism has been used to determine the transient temperature behavior of a concentrator-type GaAs solar cell with thermocouples bonded to the cell surface busbar, and to the copper mounting block. The installation of the oil heat transfer system is complete except for the cell mounting block fabrication and fluid connections.

The test chamber for temperature cycling has been constructed with heating and liquid nitrogen coolant control systems.

Both of these testing facilities require solar cells in order to proceed with actual tests.

Key Results to Date: The solar concentrator tracking system is operating very well with a negligible deviation of the concentrated sun image on the test plane over several hours.

The shutter temperature control system operates with fairly large temperature transients (15-20°C) at the cell surface. This technique may be useful for studying thermal transients in concentrator cells under partly cloudy conditions.

AN INTERDIGITATED BACK CONTACT SILICON SOLAR CELL
FOR USE IN CONCENTRATED SUNLIGHT

by

Purdue University
West Lafayette, IN 47907

Principal Investigator: Richard J. Schwartz
(317) 749-2467
Contract No.: 13-2304
Contract Amount: \$74,913.00
Contract Duration: January 1980 to
January 1981

Project Description: The purpose of this program is to provide general analytic support to the design of IBC cells; to develop a two dimensional code to be used in the analysis and design of IBC solar cells; and to provide cell characterization on completed cells.

Current Status: A two dimensional code which is applicable to IBC cells is under development. At the present time the code is operational for equilibrium conditions and for low intensity operation of the cells. The rate of convergence of the program is slow and current work is directed toward reducing the amount of machine time required so that the code will become a useful design tool.

Key Results: Work on the proper formulation of the transport equations to be used in the heavily doped regions of the solar cell has been completed. The transport equations have been formulated in terms of two experimentally determinable parameters, which, when incorporated into the model, correctly account for the effects of degeneracy, bandgap narrowing, and possible density-of-states changes which occur under heavy doping conditions. These results have been accepted for publication. One further result of this work is the clarification of the interpretation of experimentally determined bandgap narrowing parameters and a clarification of those operating conditions for which a knowledge of the asymmetry factor is required for proper device modeling. It was shown, that under conditions at which solar cells are expected to operate, a knowledge of the asymmetry factor is not required in order to correctly predict the terminal characteristics.

SUPPORT FOR COMMERCIALIZATION
OF A PHOTOVOLTAIC CONCENTRATOR SYSTEM

by

Spectrolab, Inc.
12500 Gladstone Avenue
Sylmar, CA 91342

Principal Investigator: Ronald W. Opjorden
(213) 365-4611
Contract Number: 07-7168
Contract Amount: \$140,914
Contract Term: July 31, 1980

Project Description

The project supports the commercialization of a 500 watt, single axis, polar mount photovoltaic concentrator array utilizing passively cooled photovoltaic modules and dual parabolic primary mirrors. The effort includes the fabrication, installation, and evaluation of a representative system, and environmental tests by Sandia of key portions of the system. A production cost estimate for 10 MW (peak power) yearly production rates is also included.

Current Status

All design and developmental work is complete. Temporary installation and performance evaluation at Spectrolab has taken place. Permanent installation at Sandia is pending.

Key Results

The original 500 watt (nominal) output rating has been reduced to 350 watts. This change was made due to limitations on the maximum length that a one-piece parabolic trough honeycomb mirror could be manufactured without a dedicated facility. The overall length of the cell string was reduced to accommodate shorter optics, allowing the optical design to remain unchanged. That is, the full field of view in the declination axis, $\pm 25^\circ$ from local latitude angle was maintained.

Preliminary outdoor testing indicates system performance meets design goals. Results of these tests also indicate that the difference in operating temperature between an inexpensive clear anodizing and an expensive dark anodizing on the heat sink extrusion is essentially nil for this system.

A commercially available single axis tracking electronics package which sells for about \$300 performs nearly as well under most ambient conditions as units which cost many times as much. Thus, a simple, "bare bones" tracker is functionally as effective as much more highly sophisticated units.

Careful consideration of voltage/current options, tracking drive machinery, the degree to which the system is shop-fabricated, and the best method to adjust for local latitude angle is needed to minimize production cost.

SOLAR CELL ARRAY DEVELOPMENT

Spire Corporation
Patriots Park
Bedford, MA 01730

Contract No.: 46-2042C

Program Manager: Peter R. Younger

Contract Amount: \$74,000

Project Description - This program is directed at the design, development, fabrication and testing of line focus concentrator cell assemblies to be retrofitted to Sandia provided aluminum heat sinks of the Spectrolab design. Four 8-foot long assemblies are to be fabricated. Each will contain 75 series connected cells measuring 1.25 x 2.09 inches. Performance specification is 13 percent efficiency at 20 suns at 27°C.

Current Status - The cell contact grid design has been completed. Initial cells, produced by ion implantation, have average efficiencies in excess of 17 percent at 25 suns at 27°C. Production of the 300 cells required for the deliverable hardware is in progress. Multiple-tab cell interconnectors of nickel plated copper have been designed and fabricated. These are soldered to the cells at four points per inch of cell length on each side. Low power dissipation by-pass diodes have also been fabricated. An encapsulation system consisting of tempered low iron glass top cover and ethylene vinyl acetate (EVA) encapsulant has been developed.

Key Results - Line focus concentrator cells have been fabricated for low concentration applications. At 25 suns they have the following average performance:

<u>Temperature</u>	<u>Efficiency</u>
27°C	17.3%
50°C	16.2%
82°C	14.1%

DEVELOPMENT OF FABRICATION TECHNIQUES FOR
INTERDIGITATED BACK CONTACT CELLS,
USING SILICON AND GERMANIUM

Spire Corporation
Patriots Park
Bedford, MA 01730

Contract No.: 49-2715

Principal Investigator: Stephen N. Bunker

Contract Amount: \$202,799

Contract Duration: May 1980 - April 1981

Project Description - The interdigitated back contact configuration for concentrator solar cells offers considerable promise for producing high efficiency devices capable of operation beyond 100 suns. The contact design utilizes thick back contact fingers for minimal series resistance and removal of shadowing of the front surface. Devices are being fabricated using ion implantation in conjunction with furnace annealing. Research into design refinements as well as the use of a germanium substrate is also being performed.

Current Status - IBC cells are currently being fabricated using both a simplified three-mask process and a more complex four-mask process. The first cells will be ready for test in November. In addition, conventional test cells are being fabricated on germanium wafers.

Research has been centered on defining a gettering process to maximize carrier diffusion length and front surface modification techniques to improve efficiency. Test lots have been prepared using conventional cells to assess the effects of different thicknesses of grown oxides on open circuit voltage and AR coatings to determine the compatibility of surface modifications with electrostatic bonding of cover glass, and to test the possible use of texture etching to improve efficiency.

DEVELOPMENT OF A LAMINATED
GLASS - PLASTIC FRESNEL LENS

by

Swedlow, Inc.
12122 Western Avenue
Garden Grove, California

Contract No.:	13-5165
Program Manager:	Lawrence Matalon
Contract Amount:	\$106,475
Contract Duration:	October 4, 1979 - June 13, 1980

PROJECT DESCRIPTION

The objective of this program is to design, develop, manufacture and test candidate laminated glass-plastic Fresnel lenses for photovoltaic applications. The design portion of the program will concentrate on the selection and properties testing of candidate plastic facet materials. The development activities will include processes and tooling to produce laminated Fresnel lenses. Thirty laminated lenses will be produced and evaluated for optical and environmental performance. Ten of these lenses will be delivered to Sandia with the test results.

CURRENT STATUS

The originally proposed activities have been completed. A short time extension has been granted to expend the remaining program funds on evaluation of additional material candidates which show promise.

During the plastic facet material screening process, only flexible, transparent materials were selected based on coefficient of expansion related warpage problems experienced in previous laminated lens development programs. Screening tests for candidate materials included optics, weatherability, polymer material costs, and processability. Soda-lime float glass was used for development studies due to the price of low iron glass in small quantities. All development articles were finally produced from flexible molds via a casting process. Separation problems were experienced with the other manufacturing techniques evaluated.

Environmental testing of the candidate lens materials resulted in discoloring, delamination, and in some cases, dissolving of the plastic material. Only the silicon materials provided good all around optical performance after testing. The final program results should be available in several months.

DESIGN AND DEVELOPMENT OF CAST ACRYLIC
FRESNEL LENS CONCENTRATOR ARRAYS

by

Swedlow, Inc.
12122 Western Avenue
Garden Grove, California 92645

Contract No.: 13-5166
Program Manager: C. M. Childers
Contract Amount: \$101,854
Contract Duration: September 1979 -
November 1980

Project Description

The objective of the program is to design and fabricate cast acrylic point-focus Fresnel lens arrays to be used in Sandia's latest photovoltaic demonstration unit. These concentrator arrays are meant to demonstrate the technology readiness of actual hardware for the 1980 goal of \$2.80/W. Each module in the unit will support two 86cm. x 86cm. acrylic lens array castings having 25 - 17cm. x 17cm. square lens elements apiece.

Lens design parameters were chosen to maximize the cost-effectiveness of the entire module at the expense of some lens efficiency. The 10.72cm. lens cell spacing results in an undesirable $\left(\frac{\text{design focal length}}{\text{lens diameter}}\right)$ ratio of .77 at the lens corners, but decreases the module depth, thereby decreasing its cost.

Current Status

Ten individual prototype lenses were delivered to Sandia this July to undergo optical testing. Swedlow's in-house testing of these lenses revealed a 79% transmission efficiency over a 1.5cm. x 1.5cm. square target at the design lens-cell spacing of 18.72cm.

One of four 25-lens arrays has been sent to Sandia for module testing. The balance will be cast, assembled, and shipped by November 1, 1980.

Contract Summary
HYBRID AZIMUTH TRACKING INTERMEDIATE PHOTOVOLTAIC CONCENTRATOR
Contract No. 62-6536

The nine-month contract was started on Sept. 1, 1980. During the first six weeks of the project the final design was completed and materials ordered.

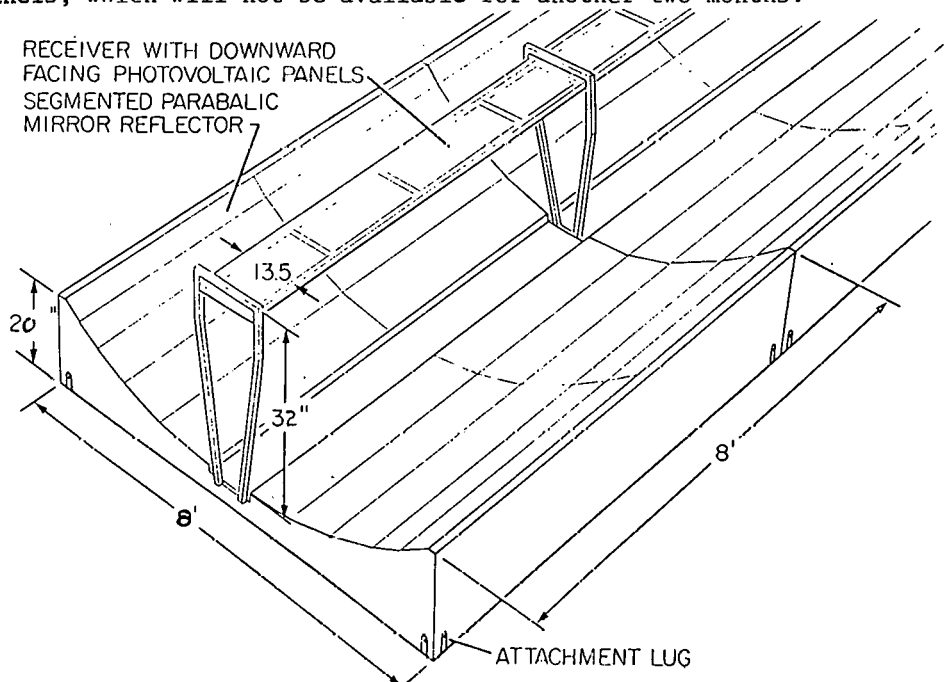
Basically the contract calls for the construction and testing of a floating nine-module (8 x 8 ft) intermediate concentrator which tracks the sun in an azimuthal mode by rotating on a four-inch pool of water. Since the collector, as shown below, is low profile and continuously supported by water, it can be constructed primarily of inexpensive polystyrene, reinforced with rectangular steel tubing. The nine-module system is based on a four-module design now in operation on a U.S. Bureau of Mines reclamation project in Northern Arizona.

A further evaluation of test data on one-sun photovoltaic panels indicated that a 5 to 6x-sun concentration level was the point of diminishing returns for the one-sun panels commercially available on the market. Therefore, an eight ft wide concentrator will be used, which will give a 6x-sun concentration. The thin back-surface mirrors originally slated for the project were found to be difficult to cut. Therefore, back-surfaced 3/32" mirrors will be used instead. This will result in a slightly less efficient reflective surface. These two modifications will reduce the expected 4.4 kwp production from the prototype. However, reduction in cost of the already inexpensive intermediate concentrator system should more than offset the reduction in production, so a relatively low cost per adjusted peak watt should be obtained. The reduction in cost of the concentrator has come about because of (1) the development of an inexpensive peripheral drive and (2) the use of styrefoam, protected with filon plastic, rather than the more expensive fibreglassed polyurathane for the platform float.

Accomplishments to date include the following:

1. Completion of final design
2. Ordering of all materials, including the photovoltaic panels
3. Completion of steel ring for the 35 ft diameter shallow pond
4. Development and testing of peripheral drive which rides on above ring.

It is expected that the rest of the concentrator system will be completed within two or three weeks, with the exception of the final mounting of the photovoltaic panels, which will not be available for another two months.



RESEARCH AND DEVELOPMENT WORK ON THE VGMJ SILICON SOLAR CELL*

Richard M. White, Department of Electrical Engineering
and Computer Sciences, and the Electronics Research
Laboratory, University of California, Berkeley

This project is concerned with the VGMJ (V-Groove Multi-Junction) single-crystal silicon concentrator solar cell. The cell is formed by field-assist bonding an oxidized silicon wafer 50 to 100 microns thick onto a glass disk perhaps 500 microns thick, producing by photolithography 50-micron wide parallel openings in the oxide, and then etching with an orientation-dependent etch, such as ethylene-diamine with pyrocatechol (EDP), to form the V-shaped grooves. Subsequent ion implantation of boron and phosphorous into alternate faces of the grooves produces n^+ and p^+ regions. After the implants are annealed, titanium and aluminum electroding is evaporated onto the silicon wafer to form a series-connected multi-junction cell. Following test in artificial light and AM1 sunlight, the cell is to be brought into close contact with a matching V-groove etched silicon block up to 250 microns thick which is to serve as a thermal conducting block to take excess heat out of the cell.

This second silicon block may be used in an active cooling mode where water is circulated behind and in contact with its un-etched flat surface. Or, one of two passive cooling approaches may be used. In the first, the heat transfer silicon block is soldered to a copper or aluminum member which is essentially a conventional heat sink for convecting and radiating heat to the ambient. In the second passive approach, the flat surface of the heat transfer block is the thermal input member for a gravity-aided heat pipe (or thermo-siphon).

To date work on the cell has been directed toward parts of the cell fabrication process, including the following:

- (1) The field-assist bonding of silicon to glass. Initially 7070 glass was used and bonding occurred in an air furnace at more than 500°C. Experiments with an evacuated chamber and RF heating, and with pyrex glass at a much lower temperature, show this technique to be effective and desirable. The use of two protective silicon wafers in the bonding apparatus have reduced the previous tendency for particles of the graphite susceptors to imbed themselves in the glass, adversely affecting its optical quality.
- (2) Lifetime improvement has been observed by oxidizing the starting float-zone silicon wafers in an atmosphere containing TCE (trichloroethylene). Indications of lifetime are obtained from our microwave measurement apparatus, in which a CW 10.5GHz RF signal is reflected by the wafer in process as a strobe light flashes briefly.
- (3) Wafers thinned to 100 microns have been received recently for use in making test cells. Microwave measurements show considerable variations in lifetime from wafer to wafer, and those with highest lifetimes are now being oxidized in a furnace into which TCE is bubbled.
- (4) Again, through the use of the microwave measurement system, we have determined what appears to be a suitable annealing schedule for removing damage introduced during the implantation.
- (5) In a test set of cells, a rectifying I-V characteristic was obtained under probing before electroding, but the measurements after evaporation of electroding suggested some unwanted conductive shunt paths existed on the intact oxide strips. We are attempting to remove these paths chemically to permit testing these cells in full sunlight.

In addition, we have obtained very encouraging results in heat transfer studies, which we shall report later.

* This work is supported by Sandia Contract No. 49-2603.

CONCENTRATOR SOLAR CELL DEVELOPMENT

Department of Electrical Engineering
University of Florida
Gainesville, FL 32611

Contract No.: 28-1161

Principal Investigator: Jerry G. Fossum
(904) 392-4921

Contract Amount: \$57,751

Contract Duration: 5/31/80 - 5/30/81

Project Description

The project is intended to promote the development of high-efficiency, cost-effective silicon concentrator solar cells, and to advance the understanding of the fundamental physics of these cells. It involves a working interaction between the University of Florida and Sandia Laboratories' Photovoltaics Division. Cells are fabricated in both Sandia's Semiconductor Device Laboratory (SDL) and Florida's semiconductor processing facility.

Current Status

An analytic model for minority-carrier transport in heavily doped regions of silicon solar cells, supported by numerical analyses, has been developed, and is being used to suggest optimal designs of p^+ and n^+ regions that minimize the carrier recombination losses occurring in these regions. A study of simple processing technologies to produce cost-effective, high-efficiency silicon concentrator solar cells has been begun.

Key Results to Date

Theoretical analysis of carrier transport in heavily doped regions of silicon has suggested that the suppression of recombination losses in these regions is more easily achieved in p^+ regions than in n^+ regions. Experimental results, including data taken from solar cells fabricated in the SDL, support this suggestion.

Experimental results derived from cells fabricated at Florida indicate that it is not practical nor feasible to fabricate, in mass, extremely long-carrier-lifetime cells, e.g., the BSF cell, in unsophisticated processing facilities using simple technology. The yields of such processes are quite low, and consequently the processes cannot be cost-effective. Since highly sophisticated technology appears to be cost-ineffective for solar cells, the only viable alternative for achieving cost-effectiveness is to fabricate shorter-carrier-lifetime cells, i.e., lower-resistivity cells, using simple technology.

Based on experiments involving the fabrication of p^+n cells using unsophisticated boron sources, i.e., spin-on silicafilms and polymer films and solid boron-nitride wafers, it appears that the use of borosilicafilms may be the only simple way to fabricate p^+ emitters with enough flexibility to enable design optimization via tailoring the doping profile. Borosilicafilms are not as "clean" as gaseous sources, e.g., diborane; but they are acceptable in the fabrication of low-resistivity cells.

Impurity gettering, for example by phosphorus diffusion, is critical, even in the fabrication of low-resistivity cells, when unsophisticated facilities and technologies are used. Without the getter, surface-related and junction-space-charge-region recombination currents can be excessive and can severely limit the cell voltage and efficiency.

Preliminary results of an experimental-theoretical study of the feasibility of a simple, low-temperature ($<500^\circ\text{C}$) thermal oxidation process to passivate the surface of a shallow-junction silicon solar cell suggest that such a process, which would succeed the electrode deposition and precede the AR-coating deposition, could yield cell-efficiency improvements comparable to those obtained with higher-temperature thermal oxides. In addition to reducing the surface recombination velocity, the low-temperature oxidation will anneal and improve the bulk properties, e.g., carrier diffusion length, of some cells.

ACCELERATED AGING OF GaAs/AlGaAs CONCENTRATOR SOLAR CELLS

by

Varian Associates, Inc.
611 Hansen Way
Palo Alto, CA 94303

Contract No: 13-5674
Principal Investigator: Paul Gregory
(415) 493-4000, Ext. 3433
Contract Amount: \$403,760
Contract Duration: July 1979 -- October 1980

Project Description - A comprehensive program to determine the degradation modes of AlGaAs/GaAs solar cells is under way. Devices under test include both mounted and unmounted cells, as well as ohmic contact and electromigration test patterns. The battery of experiments include storage at elevated temperatures in N₂, air and high humidity ambients, thermal cycling, exposure to extreme concentrations (4000-10,000 suns), and operation at 1000 suns and elevated temperatures.

Current Status - The following experiments are in progress or have been completed:

- o Thermal storage at 400°C in N₂, complete after 3000 hours.
- o Thermal storage at 425°C in N₂, complete after 270 hours.
- o Thermal cycling 25-400°C in N₂, complete after 800 cycles.
- o Thermal storage at 250°C in air, over 3000 hours to date.
- o Thermal storage at 320°C in air, over 100 hours to date.
- o Ohmic contacts stored at 400°C in N₂, 200 hours.
- o AlGaAs corrosion tests: storage of cells at 65°C, 95% relative humidity and immersion in boiling water.
- o AlGaAs corrosion studies: immersion of wafers in boiling water with varying AlGaAs layer thickness.
- o Cell fabrication: 99 1/3-inch cells fabricated for accelerated aging program in last 6-month period.

Key Results to Date - The cells are proving to be quite rugged. Several hundred hours at 400°C in N₂ were required to produce cell failures. Cells held at 425°C in N₂ failed after 100 to 270 hours. Cells held at 250°C in air have shown only small changes after over 3000 hours at temperature. The cells held at 320°C in air have developed some cosmetic defects, but no important decreases in output after 100 hours at temperature.

Corrosion studies have shown organometallic (OM)-grown cells to be much more resistant to AlGaAs corrosion than are liquid phase epitaxially (LPE)-grown cells. The improved corrosion resistance of the OM cells is tentatively attributed either to the good surface morphology of the OM cells or to the thickness of the AlGaAs layer used in the OM cells.

DEVELOPMENT AND TESTING OF A HIGH-EFFICIENCY/
HIGH-CONCENTRATION, PHOTOVOLTAIC MODULE
EMPLOYING AlGaAs/GaAs SOLAR CELLS

by

Varian Associates, Inc.
611 Hansen Way
Palo Alto, CA 94303

Contract Number: 42-7248
Principal Investigator: Richard J. Owen
(415) 493-4000, Ext. 4186
Contract Amount: \$190,201 (original contract)
\$ 74,967 (contract extension)
Contract Duration: February 1980 - February 1981
(includes 4-month extension)

Project Description - The original six-month technical program had the following objectives:

- design a photovoltaic concentrator module employing a high-concentration, curved facet, acrylic Fresnel lens, a high-efficiency, packaged AlGaAs/GaAs cell, and a jet impingement cell cooling subsystem. Design goals are 14 percent conversion efficiency, 20-year life, and cost-effectiveness.
- conduct performance/durability tests on molded lenses and packaged cells.
- fabricate two identical prototype modules.
- evaluate the operational characteristics of both modules mounted on a tracking structure. Tests will include power output, thermal distributions, and structural deflections.
- deliver one module to Sandia for additional test and evaluation.
- develop a preliminary, conceptual array design employing the selected module configuration.

The program has been extended for an additional four months in order to accomplish the following tasks:

- redesign the module for tooled production in limited quantities (approximately 100 modules would be required for a three-array development program).
- revise the existing prototype module design so that it can be operated at high coolant temperatures (up to 100^o C) for recovery of thermal energy.
- perform extended testing of the unmodified prototype module to gather additional data under various environmental and operating conditions.
- modify the module and test to evaluate new design features and operational characteristics at high coolant temperature.

A two-month reporting period will follow the completion of the ten-month technical effort.

Current Status - The initial six-month technical effort was successfully completed in August 1980 with the fabrication and testing of two 100 watt, actively cooled, prototype modules, each employing twelve 400-sun Fresnel lenses and AlGaAs/GaAs cells. One module was shipped to Sandia for further testing which is now in progress.

Extended testing of the second prototype has now been started at Varian. Module redesign and detailed array design activities are also proceeding.

Key Results to Date - The prototype modules were mounted and tested on Varian's solar tracker. The measured performance exceeded the program goals. The modules produced approximately 90 W_p at a solar flux of 760 W/m² and demonstrated a sunlight-to-electrical power conversion efficiency level of 16.45%, the highest ever achieved with a photovoltaic concentrator in a module configuration. Significantly, the Varian module performance was at a coolant inlet temperature of 50° C and reflected the deduction of power required for coolant pumping. The module efficiency is 17.1% when corrected to a coolant inlet temperature of 28° C.

Other significant results were as follows:

1. An advanced module was designed. The module employs a monolithic, acrylic lens panel containing twelve optical elements (0.687 m² active area) focused on twelve AlGaAs/GaAs solar cells. The lens panel and cells are supported by a molded, polycarbonate structural foam housing. An aluminum heat shield mounted inside the housing protects components from exposure to concentrated sunlight during periods of off-axis tracking. An injection molded polysulfone coolant manifold contains flow passages and nozzles for directing coolant to the back of the cells. The 67 pound module mounts easily at four points to a two-axis tracking structure. The module was also designed for thermal energy recovery from the ethylene glycol/water coolant if desired.
2. Jet impingement was determined to be an effective way to actively cool the cells, and an empirical relationship was developed for predicting coolant boundary layer temperature drop.
3. High efficiency (21-23 percent) packaged AlGaAs/GaAs concentrator solar cells were fabricated for the program in the Varian pilot production line. These cells used organometallic-vapor phase epitaxial (OM-VPE) material. These cells were subjected to severe environmental conditions, including 15 cycles between -30 and 125° C (4 hour cycle), storage at 95% relative humidity and 65° C for 50 hours and immersion in boiling water for several hours. No cell degradation was observed.
4. A conceptual array design using the advanced module was created.

ENGINEERING DEVELOPMENT OF A TWO-AXIS TRACKING LINEAR CONCENTRATOR ARRAY

By

Solarex Corporation
1335 Piccard Drive
Rockville, Maryland 20850

Contract No. 42-7317
Principal Investigator: Roy Gibson (301)948-0202 x 230
Contract Amount: \$81,955
Contract Duration: November 1979 - October 1980

Project Description - We have characterized the performance of a low rim angle, glass mirror, parabolic trough type concentrator with the aim of determining which components of the system need modification in order to permit improvement of the overall system.

The analysis included:

- Testing of overall system efficiency, both optical & thermal
- Evaluation of two types of sagged glass mirrors one being of foam backed construction
- Measurement of mirror contours
- Measurement of the two-axis variation in silicon cell performance
- Ways of optimizing the cell width, mirrors slope error, and receiver design

Current status - The program is near completion and a model of an innovative receiver design is being tested.

Key Results to Date - A receiver cooled by a silicone liquid which flows directly over the back of the silicon cells, interconnects and bus bars was designed. In addition, the silicon cells are mounted on the back of Sunadex glass plate instead of having individual cover slides. Furthermore, the cells are connected in parallel interdigitated groups along the length of the receiver in order to minimize the effects of optical non-uniformity. The fabrication and testing of a full receiver is planned.

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