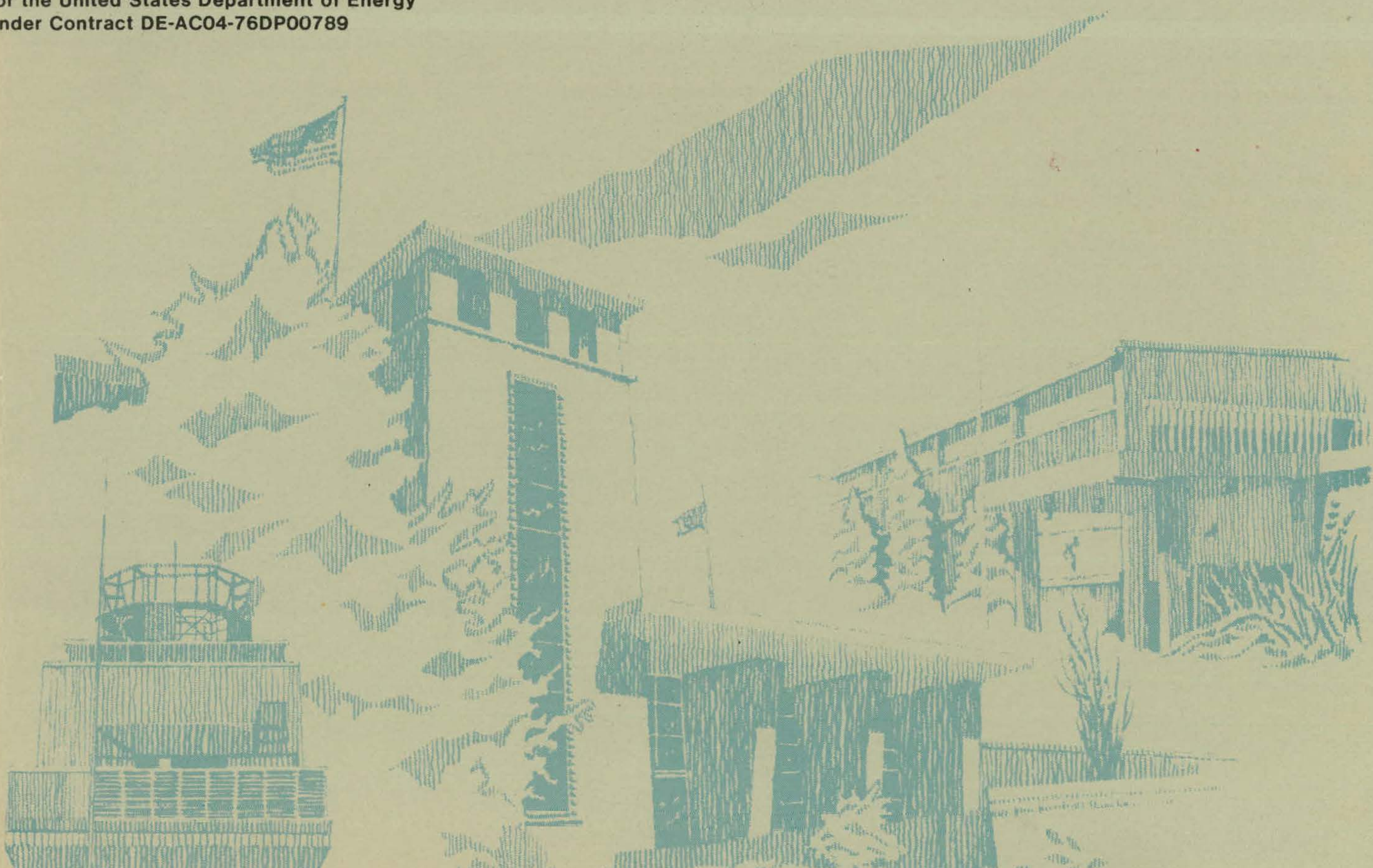
MASTER

SANDIA REPORT SAND81-1015 • Unlimited Release
Printed October 1981

Results of the PRDA 35 Qualification Tests of the Motorola Concentrating Photovoltaic Module

Daniel A. Pritchard

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789



DISCLAIMER

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: $6.00
Microfiche copy: A01

PAGES 1 to 2

WERE INTENTIONALLY

LEFT BLANK

SAND81-1015
Unlimited Release
Printed October 1981

RESULTS OF THE PRDA 35 QUALIFICATION TESTS OF THE MOTOROLA CONCENTRATING PHOTOVOLTAIC MODULE

DANIEL A. PRITCHARD
Experimental Facilities Operations Division
Sandia National Laboratories
Albuquerque, New Mexico 87185

ABSTRACT

A passively-cooled, Fresnel lens, concentrating photovoltaic module, designed and built by Motorola, Incorporated, was tested to the PRDA 35 specifications. The PRDA 35 module test program is described. Physical, electrical, and thermal characteristics of the module are presented. Module performance is shown using multiple linear regression techniques: some change was measured after environmental exposure. In addition, sample cell assemblies were evaluated for effects of severe environmental conditions. Results presented herein show the module has met the qualification goals.

CONTENTS

	Page
Introduction	7
The Motorola Photovoltaic Modules and Cell Mounts	7
The Test Facility	12
Test Program	14
Introduction	14
Voltage Isolation Tests	14
Group A Tests	17
Group B Tests	24
Group C Tests	25
Additional Tests	26
Observations	27
Summary	29
Appendix--Test Specifications	31

ILLUSTRATIONS

Figure		
1	Cut-Away View of the Motorola Photovoltaic Module	9
2	Motorola Module on a Two-Axis Tracker	10
3	Photograph of a Motorola Cell Mount	11
4	Block Diagram of the Photovoltaic Array Test System	13
5	Thermocouple Locations for MOT-385	15
6	Sample Data Printout	18
7	Maximum Output vs. Off-Axis Angle for MOT-365	19
8	Comparison of Sun Walk-Off Results with Off-Axis Results	21
9	Module Efficiency and Cell Temperatures vs. Single Lens Area Shaded	22
10	Reflux Panel and Cell Temperatures, 2 October 1980	28

TABLES

Table		Page
1	Motorola Photovoltaic Module Characteristics	12
2	Thermocouple Location Table for MOT-385	15
3	Test Schedule	16
4	Data from Sun Walk-Off Test	21
5	Performance Comparison for MOT-365	23
6	Performance Comparison for MOT-364	24
7	Performance Data for Cell Mounts 366 and 367 under One-Sun Conditions	25
8	Summary of Performance Results	27

RESULTS OF THE PRDA 35 QUALIFICATION TESTS OF THE MOTOROLA CONCENTRATING PHOTOVOLTAIC MODULE

Introduction

The Department of Energy, under Program Research and Development Announcement Photovoltaic Concentrator Application Experiments, Phase I, (PRDA 35), is sponsoring several application projects to demonstrate the utility of concentrating photovoltaic power generation systems. Prior to installation of equipment at these application sites, qualification testing is required on photovoltaic modules and components which are representative of the final design. The PRDA 35 documents define the following three groups of tests:

A. Performance evaluation of a complete module for various conditions expected during the life of the application experiment.

B. Freeze-thaw cycling of a complete module followed by hail testing.

C. Freeze-thaw cycling, temperature cycling, and ultraviolet exposure of receiver and reflector test sections.

The specifications for these three groups of tests are reproduced in the Appendix. Performance testing was done outdoors at the Photovoltaic Advanced Systems Test Facility (PASTF). Environmental tests were also handled at Sandia National Laboratories, Albuquerque (SNLA).

The Motorola Photovoltaic Modules and Cell Mounts

Two complete modules and two cell mounts were provided by Motorola for testing. The two modules are identified as MOT-364 and MOT-365; the cell mounts are identified as Cell Mount 366 and Cell Mount 367. This terminology will be used to identify these items.

Later, component changes in the MOT-364 module are described. These two changes are identified as MOT-385 and MOT-386.

Each module contains two silicon photovoltaic cells connected in series. Each cell has an active area 7 cm (2.75 inches) in diameter. One of the cell mounts in each module is fitted with a bypass diode. Two square Fresnel lenses, 61 by 61 cm (24.25 by 24.25 inches), concentrate sunlight onto the cells. MOT-364 and MOT-365 were supplied with 5.08 mm (0.200 inch) and 6.35 mm (0.250 inch) thick lenses respectively. The thin lens is used in the final design. The geometric concentration ratio is 78, with lens-to-cell spacing of 76 cm (30 inches). The Fresnel lenses are mounted on a fiberglass housing which also serves to protect the cells from the environment. A truncated conical aluminum reflector encircles the silicon cell. This reflector shields internal parts of the module from the effects of the concentrated sunlight beam when the module is pointed slightly off-axis from the sun. Figure 1 is a cut-away view of the module and Figure 2 is a photograph of the module on a two-axis tracker.

The silicon cell is bonded to an alumina wafer 0.76 mm (0.030 inch) thick which, in turn, is bonded to a 0.75 cm (0.29 inch) thick aluminum heat sink. The alumina wafer electrically isolates the photovoltaic cell from the heat sink but allows the transmission of the thermal energy. The heat sink is cooled by a passive reflux heat exchanger. The reflux heat exchanger consists of a thin aluminum envelope with a maze of interconnected passageways which are partially filled with liquid Freon™. At operating temperatures the Freon™ boils and the vapor circulates through the passageways to condense at the cooler regions, thus distributing the thermal energy over the entire panel area. The panel is passively cooled by exposure to the surrounding air.

A photograph of a cell mount is shown in Figure 3. The characteristics of the module are tabulated in Table 1.

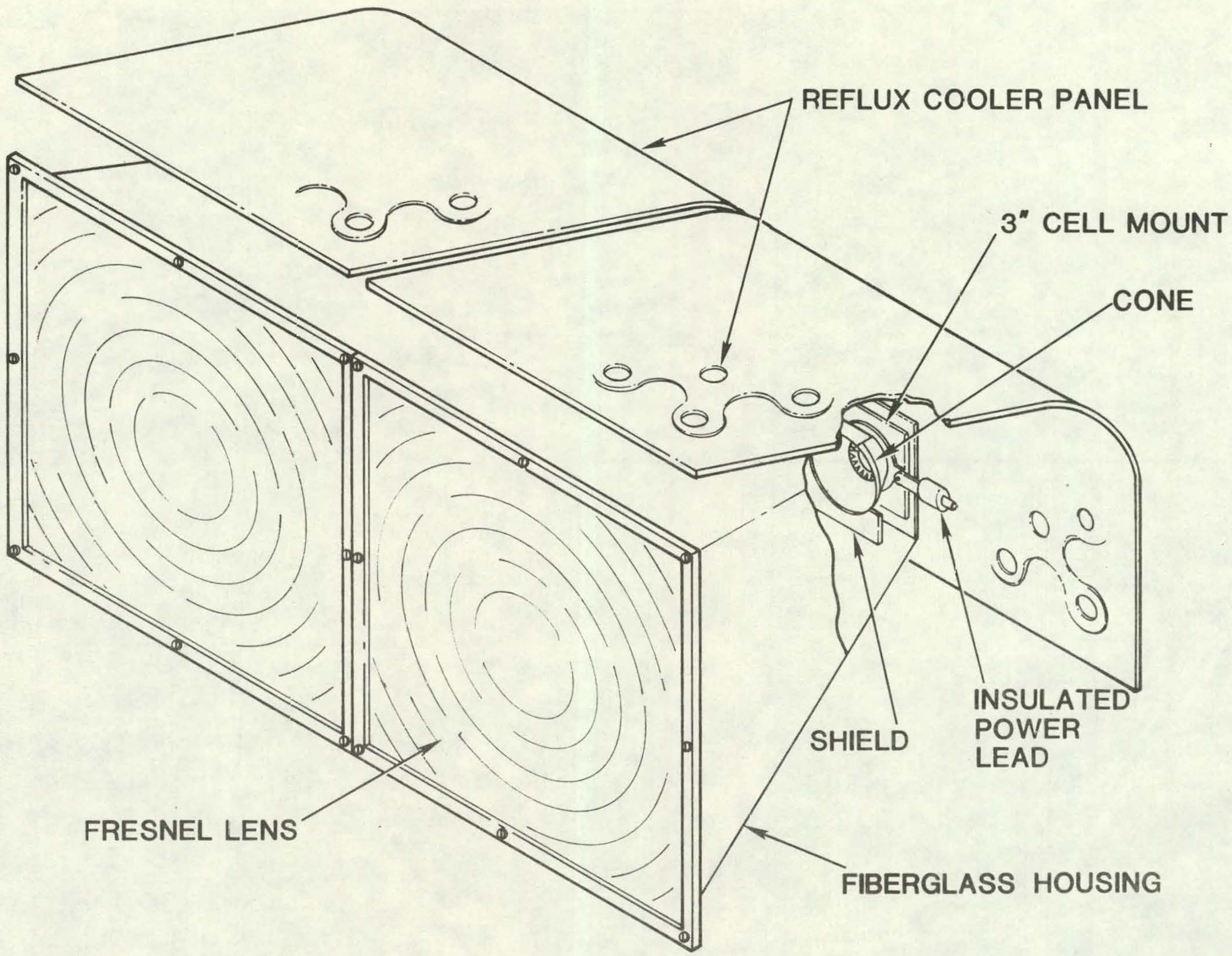


Figure 1. Cut-Away View of the Motorola Photovoltaic Module

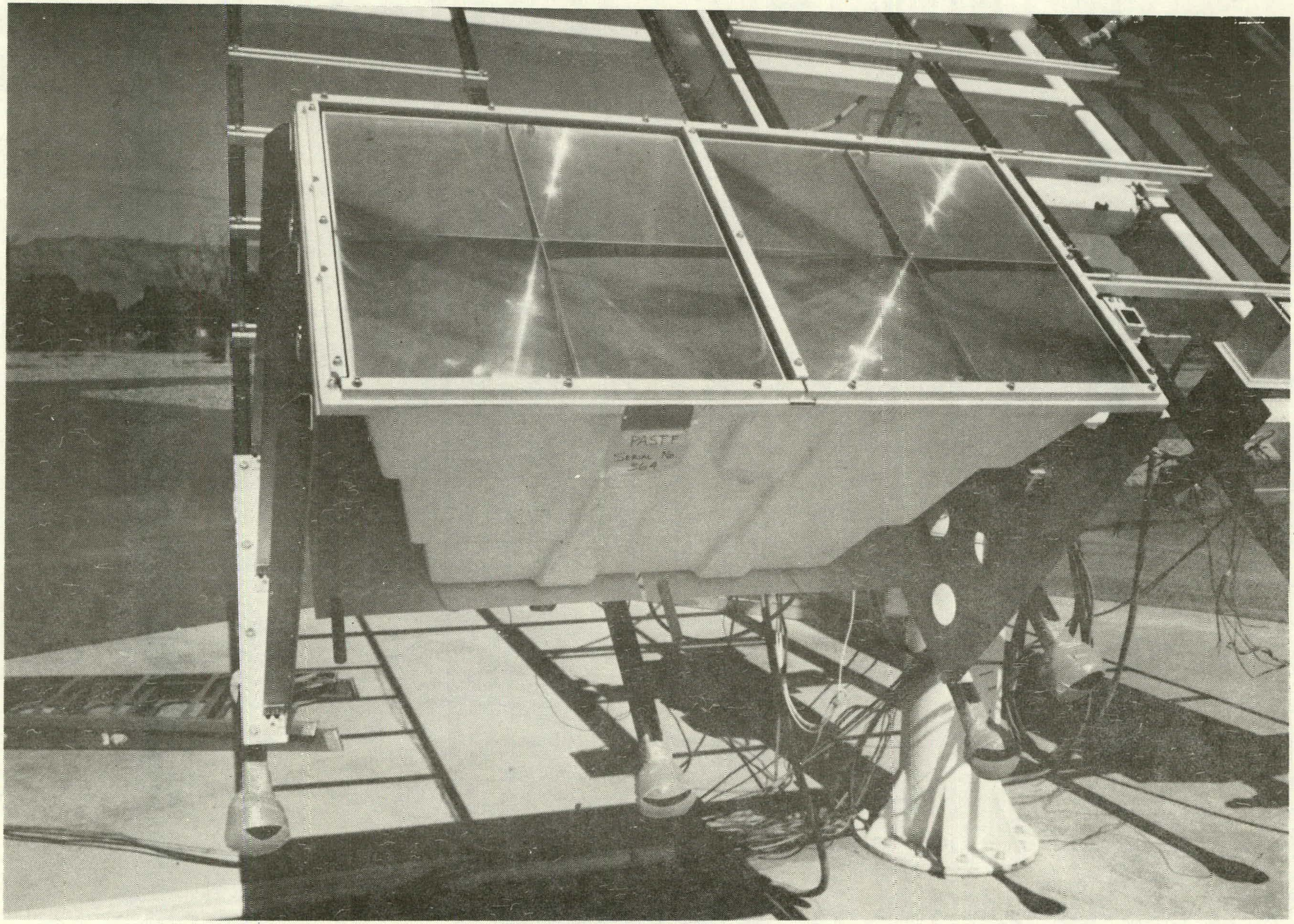


Figure 2. Motorola Module on a Two-Axis Tracker

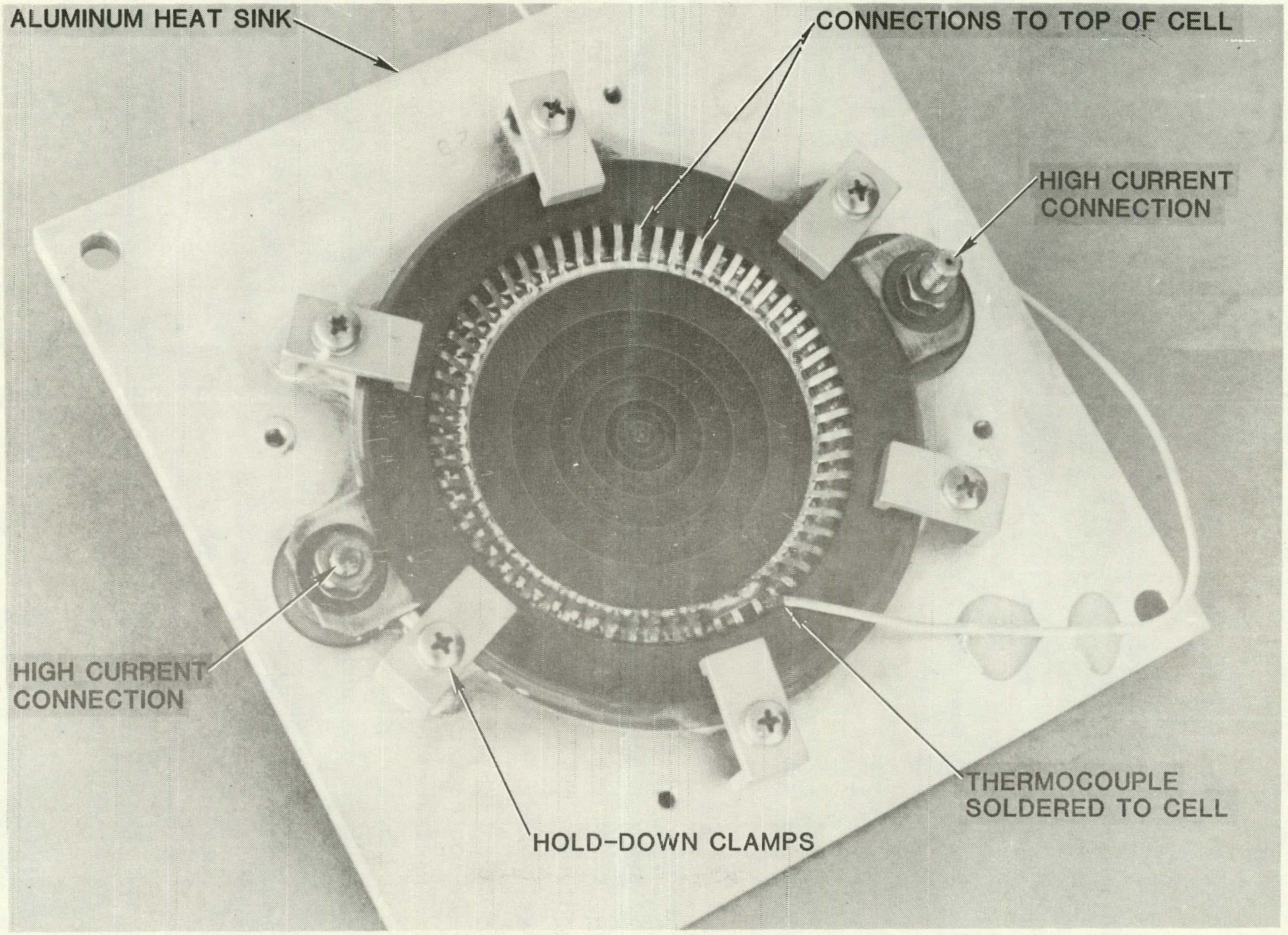


Figure 3. Photograph of a Motorola Cell Mount

Table 1

Motorola Photovoltaic Module Characteristics

- Number of point focus Fresnel lenses -- 2
- Lens size -- 61.48 cm (24.25 in.) square
- Active lens area -- 0.75 m^2 (8.1 ft^2)
- Solar cell -- 7-cm (2.75-in.) diameter, two per module
- Concentration ratio -- 78x
- Nominal peak power output -- 79.2 watts
- Average efficiency -- 10.5%
- Passive cooling
- Overall size -- 137 by 68.6 by 78.7 cm (54 by 27 by 31 in.)

The Test Facility

The PASTF provides an extensive testing capability for photovoltaic systems and system components, including cells, modules, arrays, power conversion units, and storage batteries. Several two-axis solar tracking mounts with tracking errors less than 0.1 degree are available. Each tracker is capable of carrying photovoltaic arrays with electrical output power up to approximately 1 kilowatt. Actively-cooled arrays are serviced by one of several thermal loops. Dedicated to each test item is a data acquisition system controlled by a Hewlett-Packard 9845 computer, which collects, plots, and stores the data, and controls external instruments.

A block diagram of the photovoltaic array test system is shown in Figure 4. The module is connected to a variable load. Within 24 seconds, the load is stepped from a no-load open circuit condition through the maximum power point to a short-circuit condition in about 80 steps. The current and voltage are measured at each step and plotted as the characteristic curve.

A current viewing resistor (0.01 ohms) is used to monitor the current being drawn by the load. Several other parameters are

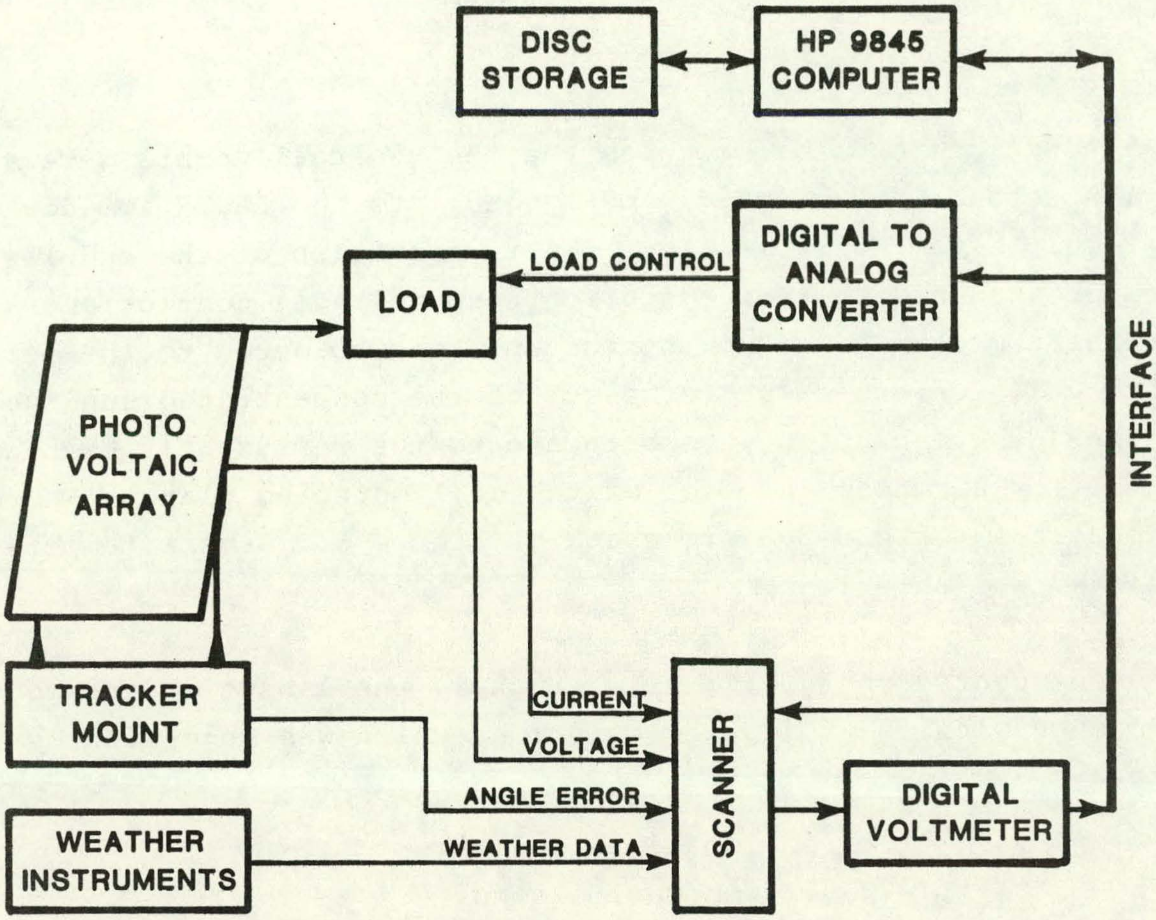


Figure 4. Block Diagram of the Photovoltaic Array Test System

measured at the same time as each I-V curve (e.g., pyrheliometer, ambient air temperature, dewpoint, wind velocity and direction, and temperatures at various points on the module). A more complete description of the data acquisition system is available in a separate report, SAND79-2186.

Due to the high current (~90 amperes) and the low voltage (~1 volt) of the Motorola module, a special load was designed and constructed. This load, which is similar in design to the one described above, has current, voltage, and power ratings of 125 amperes, 30 volts, and 750 watts, respectively.

Test Program

Introduction

The two photovoltaic modules and the two cell mounts were visually inspected, photographed, and logged into the PASTF immediately upon receipt from Motorola, Inc. Instrumentation of the modules consisted of standard four-wire (current and voltage) connections and several thermocouples. One thermocouple was soldered to the periphery of each cell surface so as to be out of the concentrated sunlight. Additional thermocouples were attached to the reflux heat exchangers near the top and near the back of the cell mounting plate. Thermocouple locations for MOT-385 are shown in Figure 5. Sample temperatures are listed in Table 2.

Once mounted on the two-axis tracker, the lenses of the module were washed with the following solution, which was suggested by Motorola:

1 gallon distilled water
10% isopropyl alcohol
A few drops of mild liquid soap
2 to 5% ammonia

Washing was followed by a rinse with deionized water.

Since the selected lens design for the module had previously been subjected to and had passed the hail test, this test was not repeated under the Group B category in this series. The ultraviolet exposure tests were waived for the same reason. Cell mounts 366 and 367 were exposed only to temperature cycling. The test schedule is listed in Table 3.

Voltage Isolation Tests

Initial screening of the test items was done using the Voltage Isolation Test. Both modules and both cell mounts were subjected to this test. All items passed the 1,600-volt requirement with less than

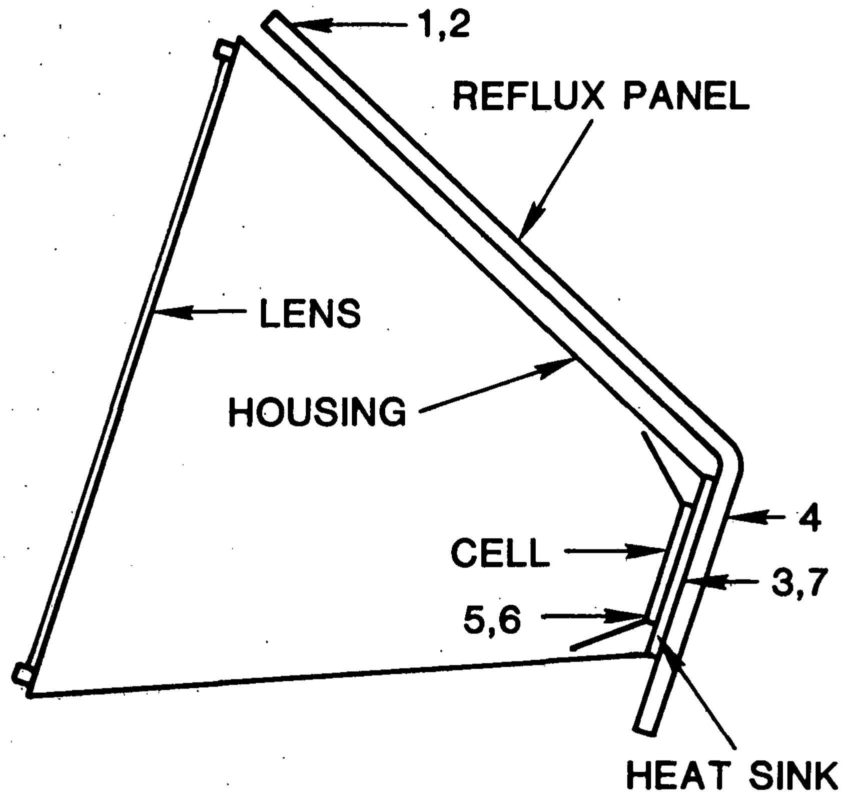


Figure 5. Thermocouple Locations for MOT-385

Table 2

Thermocouple Location Table for MOT-385

Thermo-couple No.	Data Item No.	Location on Module	Sampled Temperatures (°C) (14:27 PM, 12/11/80)
1	32	Left Panel Top	16.5
2	33	Right Panel Top	16.8
3	34	Right Panel Behind Cell Center	35.1
4	35	Left Panel, 7 cm from TC #7	22.6
5	36	Right Cell Surface	35.5
6	37	Left Cell Surface	34.7
7	38	Left Panel Behind Cell Center	34.9
--	8	Ambient Air	7.1

Table 3

Test Schedule

Tests	Test Dates
Group A Module Tests (MOT-365)	
1. Voltage Isolation	9/22/80
2. Initial Performance Characterization	10/3 - 10/9
3. Partial Lens Shading (left side to center)	10/10
4. Partial Lens Shading (center to left side)	10/18
5. Sun Walk-Off	10/20
6. Off-Axis Performance	10/20
7. Thermal Shock (Focus-Defocus Cycling)	10/23
8. End Performance Characterization	11/10 - 11/14
9. Operating Life (Maximum Power Loading)	10/23 - 10/29
Group B Module Tests (MOT-364)	
1. Voltage Isolation	9/22
2. Initial Performance Characterization	9/29 - 10/2
3. Freeze - Thaw Cycling	10/3 - 10/27
4. End Performance Characterization	11/3 - 11/7
Group C Component Tests (Cell Mounts)	
1. Voltage Isolation	9/22
2. Initial Performance Characterization	10/9
3. Temperature Cycling	10/10 - 11/5
4. End Performance Characterization	11/6 - 11/20
Additional Module Tests	
1. Full Concentration Characterization	12/11 - 12/18
2. Freon™ 11 Reflux Cooler Panels	12/23

5 μA leakage current. The cell assembly with the bypass diode was tested with both sides of the diode held at test potential to check insulation between the diode and the aluminum plate.

Group A Tests

MOT-365 was subjected to the Group A Tests. MOT-365 was mounted on a two-axis tracker, and initial performance data were collected during the period 3 October to 9 October 1980. Testing was conducted during periods when the insolation level exceeded 800 W/m^2. I-V curves were measured at intervals of approximately 6 minutes. Other relevant data were recorded concurrently and are shown with a typical I-V curve in Figure 6.

A multiple linear correlation analysis was performed to relate module efficiency (η_{el}) to the direct normal insolation (I_{DN}) and the cell temperature (T_c). This resulted in the regression equation

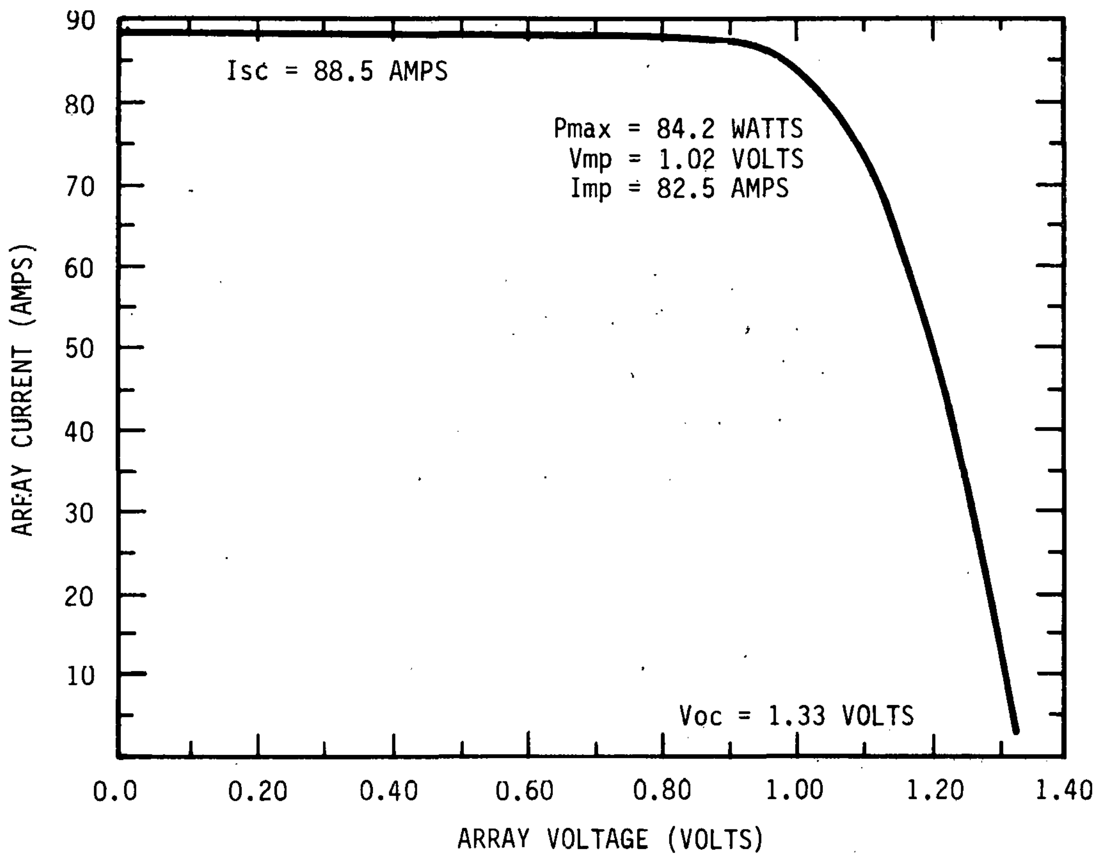
$$\eta_{el} = 10.58 - 0.062\ (T_c - 328) + 4.066 \left(1 - \frac{I_{DN}}{1000}\right)$$

η_{el} in percent
T_c in degrees Kelvin
I_{DN} in watts/meter^2

The correlation coefficient was $R^2 = 0.931$.

The off-axis performance tests were conducted after completing measurement of initial performance. The tracking device was adjusted to track the sun at a preset offset angle in either elevation or azimuth. The maximum power output was measured under these conditions.

The results of the off-axis performance tests on MOT-365 are shown in Figure 7 in which the electrical output is plotted against the offset angle for both elevation and azimuth. Different environmental conditions existed for the two tests, but the elevation data



MOT MODULE WITH B-12 & C-57 CELLS
EFFICIENCY TEST MAX POWER
TEST RUN AT 10:35:04 DEC 11, 1980

DIRECT NORMAL INSOLATION	=	987	W/SQ M (START)	987	W/SQ M (END)
TOTAL HORIZONTAL INSOLATION	=	498	W/SQ M (START)	499	W/SQ M (END)
AMBIENT TEMPERATURE	=	3.3	DEG C		
DEW POINT	=	-8.8	DEG C		
WIND SPEED	=	.5	M/SEC (INST.)	.3	M/SEC (AVE.)
WIND DIRECTION (CW FROM NORTH)	=	352	DEG (INST.)	3	DEG (AVE.)
TEST PAD	=	450			
MANUFACTURER'S CODE	=	MOT			
TEST ITEM MODEL NUMBER	=	5			
TEST ITEM SERIAL NUMBER		385			
TEST ITEM RECEIVAL DATA	=	801209			
TEST ITEM APERTURE.	=	.754 SQ M			
TEST CODE	=	1			
ELECTRICAL EFFICIENCY	=	11.3 %			
FILL FACTOR	=	.72			

THERMOCOUPLE TEMPERATURE DATA (DEG C)

T/C# 1 = 16.1	T/C# 2 = 21.4	T/C# 3 = 42.7	T/C# 4 = 22.5
T/C# 5 = 47	T/C# 6 = 35	T/C# 7 = 35.9	

AZIMUTH TRACKING ERROR	=	.03	DEGREES
ELEVATION TRACKING ERROR	=	-.03	DEGREES

Figure 6. Sample Data Printout

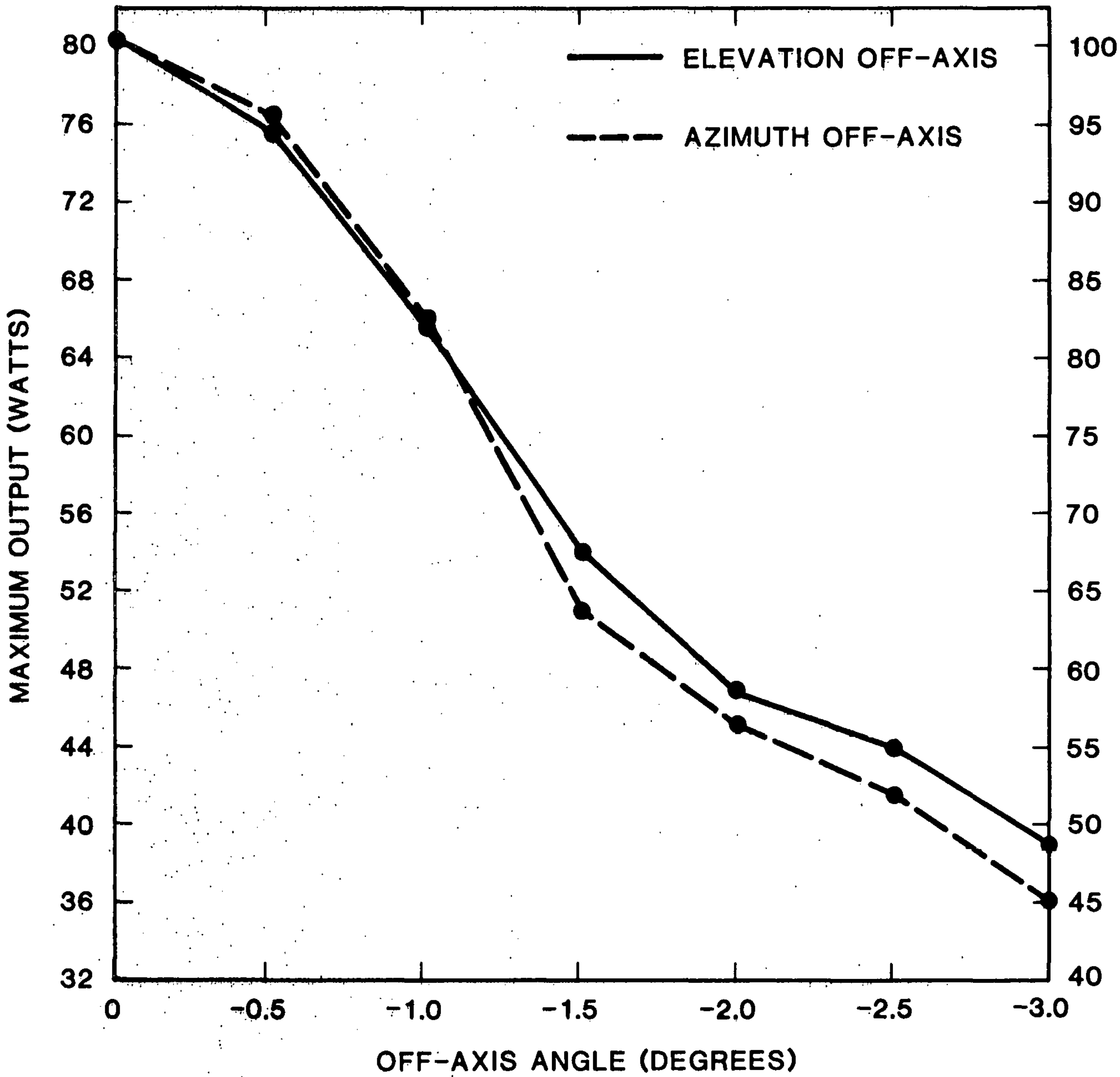


Figure 7. Maximum Output vs. Off-Axis Angle for MOT-365

have been adjusted to the azimuth conditions by the following formula:

$$P_{adj} = P_{test} + K_1(I_{adj} - I_{test}) + K_2(T_{adj} - T_{test})$$

where

P_{adj} = Corrected maximum power output
P_{test} = Maximum power from test conditions
K_1 = 0.0574 (From MOT-365 initial multiple regression analysis)
I_{adj} = Adjusted value of insolation
I_{test} = Insolation from test conditions
K_2 = 0.425 (From MOT-365 initial multiple regression analysis)
T_{adj} = Adjusted value of average cell temperature
T_{test} = Average cell temperature from test conditions

This procedure yielded results for both tests which are nearly identical, due largely to the symmetry of the module. Note that output drops to 95% of maximum for an offset angle of 0.5 degree.

The "Thermal Shock and Off-Axis Beam Destruction Test" as described in the Appendix (Item 5, Group A Tests) was divided into two separate tests. "Thermal Shock" is the focus-defocus cycling part. The "Sun Walk-Off" test is meant to have similar properties to the "Off-Axis Beam Destruction" part of the specification. Here, the tracker is halted in its operation and, as the sun "moves" off the module axis, its focused image travels off the solar cell, hence the name "sun walk-off." Since the sun moves approximately 1/4 degree per minute, the off-axis position of the sun can be estimated, and the efficiencies achieved in this test can be compared with the corresponding efficiencies observed in the off-axis test. The data from the sun walk-off test is listed in Table 4. A comparison of the sun walk-off results with the off-axis results is shown in Figure 8.

In the lens shading tests, only one of the two lenses of the module was subjected to shading. Opaque strips of paper were taped over

Table 4

Data from Sun Walk-Off Test

Time	Max Power (watts)	EFF (%)	Off-Axis Angle (approx.) degree	Percent Output
947	76.3	10.95	0	100
948	75.4	10.94	0	100
949	72.6	10.67	.25	97.5
950	68.4	10.11	.50	92.4
951	65.3	9.62	.75	87.9
952	60.6	8.97	1.00	82.0
953	55.1	8.16	1.25	74.6
954	49.6	7.34	1.50	67.1
956	42.0	6.20	2.00	56.7
958	37.0	5.38	2.50	49.2
1000	33.3	4.79	3.00	43.8
1002	29.0	4.20	3.50	38.4

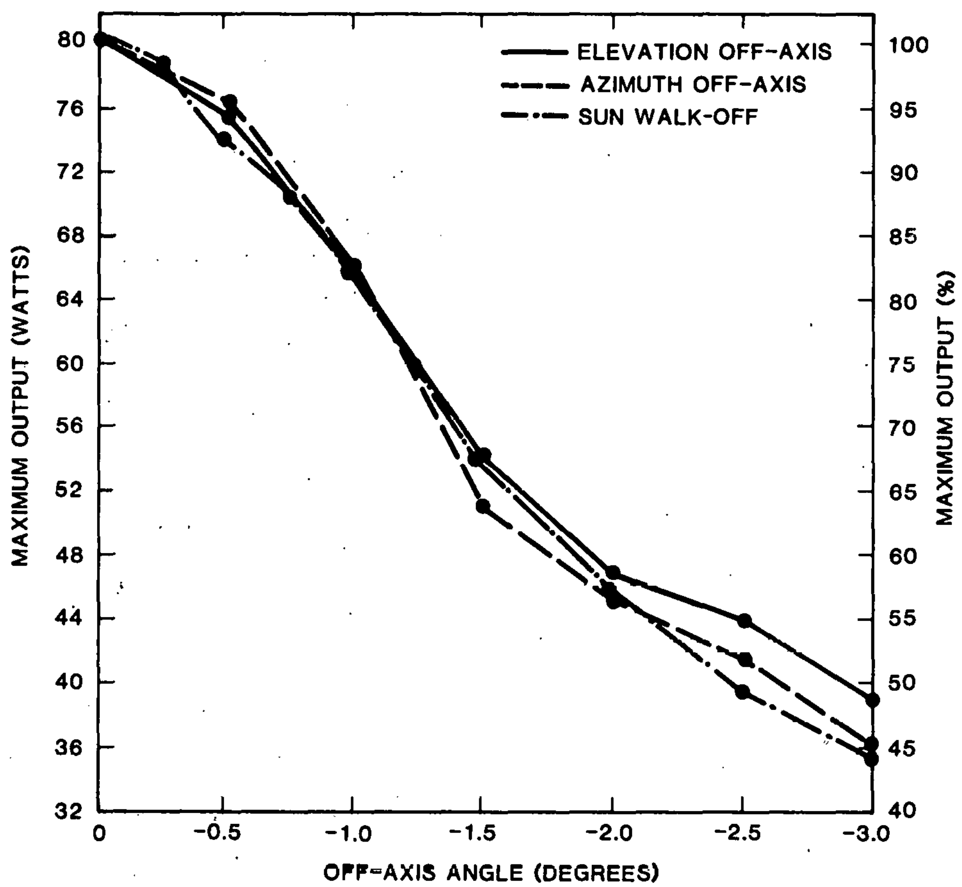


Figure 8. Comparison of Sun Walk-Off Results with Off-Axis Results

the lens to block out varying percentages of insolation. The output of the module was measured as a function of the lens area covered. The test was performed twice: first by progressively shading the left lens, starting from the left side, and then by progressively shading the same lens starting from the right side. No appreciable difference in characteristics was seen. Typical results are shown in Figure 9.

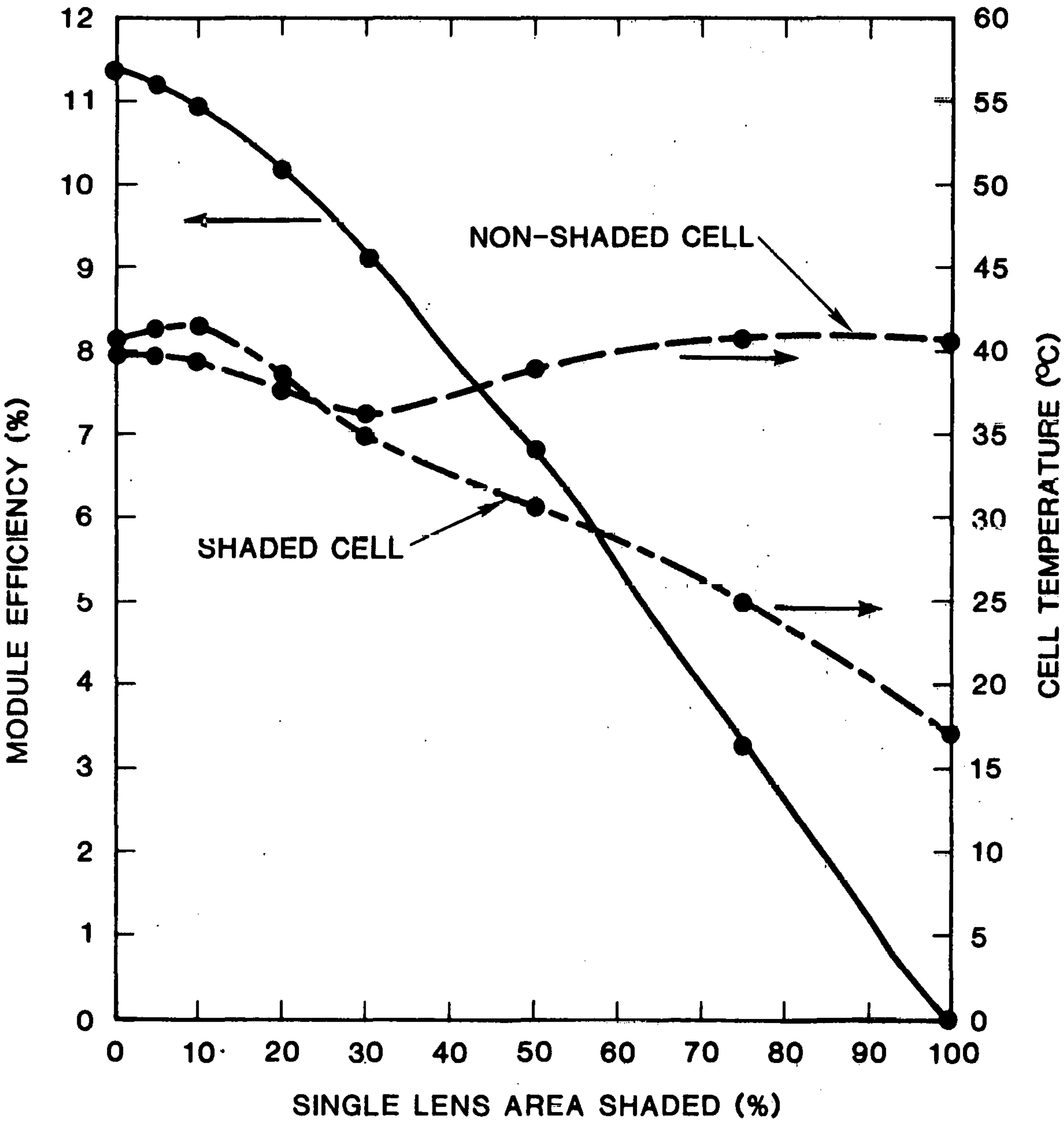


Figure 9. Module Efficiency and Cell Temperatures vs. Single Lens Area Shaded

After completion of the lens shading tests, the end performance was determined from tests conducted during the period 22 October to 29 October 1980. A total of 60 I-V curves was recorded, together with the other relevant data. The same procedures as used for the initial performance data were used for the collection of the end performance data. The regression equation obtained from the end performance data was

$$\eta_{el} = 10.09 - 0.065\ (T_c - 328) + 1.544 \left(1 - \frac{I_{DN}}{1000}\right)$$

with a correlation coefficient of $R^2 = 0.890$.

Using values of 1,000 W/m^2 for direct normal insolation and 55°C for cell temperatures, the end performance of MOT-365 can be compared to its initial performance. The performance comparison is shown in Table 5.

Table 5

Performance Comparison for MOT-365
at I_{DN} = 1,000 W/m^2 and T_c = 55°C

	Initial	End	% Difference
P_{max}	79.77 W	76.08 W	-4.6%
η	10.58%	10.09%	-4.6%

The comparison shows that the effect of the Group A tests, which were designed to identify design weaknesses, was a 4.6% reduction in efficiency. This is within the PRDA 35 qualification goal of less than 5% decrease.

Group B Tests

The MOT-364 module was subjected to the Group B tests. The initial performance characterization of MOT-364 was determined from data acquired in the period 30 September through 2 October 1980. A total of 149 I-V curves were recorded. The multiple linear regression equation derived from this data was

$$\eta_{el} = 10.89 - 0.040\ (T_c - 328) + 3.311 \left(1 - \frac{I_{DN}}{1000}\right)$$

with a correlation coefficient of $R^2 = 0.920$.

After subjecting MOT-364 to freeze-thaw cycling in the environmental exposure chamber, its performance was again measured during the period 30 October through 7 November 1980. A total of 252 data points was collected during that period. Multiple linear regression analysis yielded the following correlation:

$$\eta_{el} = 10.53 - 0.057\ (T_c - 328) + 3.488 \left(1 - \frac{I_{DN}}{1000}\right)$$

with $R^2 = 0.910$.

Using the same reference conditions (1,000 W/m² and 55°C) as before, the end performance can be compared to the initial performance as shown in Table 6.

Table 6

Performance Comparison for MOT-364 at I_{DN} = 1,000 W/m² and T_c = 55°C

	Initial	End	% Difference
P_{max}	82.11 W	79.39 W	-3.0%
η	10.89%	10.53%	-3.0%

The comparison shows an efficiency degradation of 3.0% for MOT-364 as a result of the freeze-thaw cycling in an environmental chamber. As in the Group A Tests, this is within the goal of less than 5% decrease.

Group C Tests

The performance of cell mounts 366 and 367 was measured under one-sun conditions (no concentration). After completion of the temperature cycling program, the performance was again measured. The results of the performance tests are shown in Table 7.

Table 7

Performance Data for Cell Mounts 366 and 367 under One-Sun Conditions

ID No.	Temp. Cycle	Cell Surface	I_{dn} (W/m²)	Temp. (°C)	P_{max} (W)	Eff (%)	P_{norm} (W)
366	Before	Clean	951	30.3	.446	12.2	.470
			940	29.8	.440	12.2	.468
			938	30.3	.439	12.2	.469
			934	30.7	.437	12.2	.469
			925	30.8	.432	12.2	.469
	After	Dirty	954	25.9	.430	11.8	.443
			954	26.5	.423	11.7	.437
			960	27.4	.426	11.6	.439
			960	27.0	.430	11.8	.442
			960	27.6	.424	11.5	.437
		Clean	900	15.7	.427	12.4	.446
			937	15.5	.450	12.6	.451
			920	15.3	.440	12.6	.449
367	Before	Clean	950	24.8	.330	9.0	.340
			950	24.6	.333	9.1	.343
			955	25.0	.336	9.1	.344
			956	25.5	.335	9.3	.344
			960	25.7	.335	9.1	.343
	After	Dirty	982	23.8	.349	9.3	.346
			984	23.7	.350	9.3	.346
			980	23.5	.348	9.2	.345
			950	23.7	.349	9.5	.358
			987	23.7	.352	9.3	.347

The symbol, P_{norm}, in Table 7 is the maximum power normalized to an insolation value of 1,000 W/m^2 and a cell temperature of 30°C. The normalization equation used was:

$$P_{norm} = \left[P_{max} - P_{max}(4.2 \times 10^{-3})(30 - T_c)\right] \frac{1000}{I_{DN}}$$

where T_c = cell temperature during test
and I_{DN} = direct normal insolation during test

This procedure was suggested by Motorola, Inc.

Comparison of the normalized maximum power, P_{norm}, for the two cell mounts shows a 4.3% degradation of output power after the effects of temperature cycling for cell mount 366 and a slight improvement in performance for cell mount 367.

Additional Tests

In addition to the required PRDA 35 tests, two additional tests were conducted; the first evaluated the performance of the two cell mounts when incorporated into a module, and the second the effect of using a lower boiling temperature Freon™ in the reflux cooler panels.

Cell mounts 366 and 367 were mounted in a module, and the performance of the module was measured in the same manner as for MOT-364 and MOT-365. This new module was identified as MOT-385. The reflux cooler panels of this module were then exchanged for a new pair. The original panels used Freon™ 113 as the coolant. The new panels, the result of a design change by Motorola, used Freon™ 11, which has a lower boiling temperature than Freon™ 113. This module with the new reflux panels, and incorporating cell mounts 366 and 367, was identified as MOT-386. The performance of this module was also measured. The regression equations for MOT-385 and MOT-386 are included in Table 8 which summarizes the data for all of the module performance tests.

Table 8

Summary of Performance Results

		No. of Data Points	η_{el} Regression Equation	Correlation Coefficient, R^2	Efficiency (%) at I_{DN} = 1,000 (W/m^2) T_c = 55 (°C)
MOT 365 Group A Tests	Initial	183	$\eta_{el} = 10.58 - 0.062\ (T_c - 328) + 4.066 \left(1 - \frac{I_{DN}}{1000}\right)$	.931	10.58
	End	60	$\eta_{el} = 10.09 - 0.065\ (T_c - 328) + 1.544 \left(1 - \frac{I_{DN}}{1000}\right)$	.890	10.09
MOT 364 Group B Tests	Initial	149	$\eta_{el} = 10.89 - 0.040\ (T_c - 328) + 3.311 \left(1 - \frac{I_{DN}}{1000}\right)$	.920	10.89
	End	252	$\eta_{el} = 10.53 - 0.057\ (T_c - 328) + 3.488 \left(1 - \frac{I_{DN}}{1000}\right)$	.910	10.53
MOT 385 (With cell mounts 366 and 367)		135	$\eta_{el} = 10.82 - 0.035\ (T_c - 328) + 3.104 \left(1 - \frac{I_{DN}}{1000}\right)$	.972	10.82
MOT 386 (With Freon 11)		43	$\eta_{el} = 10.30 - 0.054\ (T_c - 328) + 2.721 \left(1 - \frac{I_{DN}}{1000}\right)$	.903	10.30

Observations

As mentioned earlier, the cells are cooled by means of reflux heat exchanger panels. When the cells are heated as a result of concentrated illumination, the energy is transferred into the panel and causes the Freon™ to boil. This boiling action spreads the energy over the entire panel area. At times, one panel was observed to be boiling, while the other was not, particularly when the ambient temperature was low. This observation was verified by simultaneous recordings of temperatures of both the right and left reflux panels and of the right and left cells. An example of these data in Figure 10 shows that during the morning hours the left cell was operating at a temperature about 15°C higher than the right cell, while the left panel was cooler by about 5°C than the right panel. At noon the temperature of the left cell drops abruptly until it is approximately the same as the right cell. Concurrently the left panel temperature rises until it is approximately the same as that of the right panel. This condition is maintained through the remainder of the test. It appears from this record that boiling of the Freon™ in the left panel did not begin until noon and, from then on, it functioned normally.

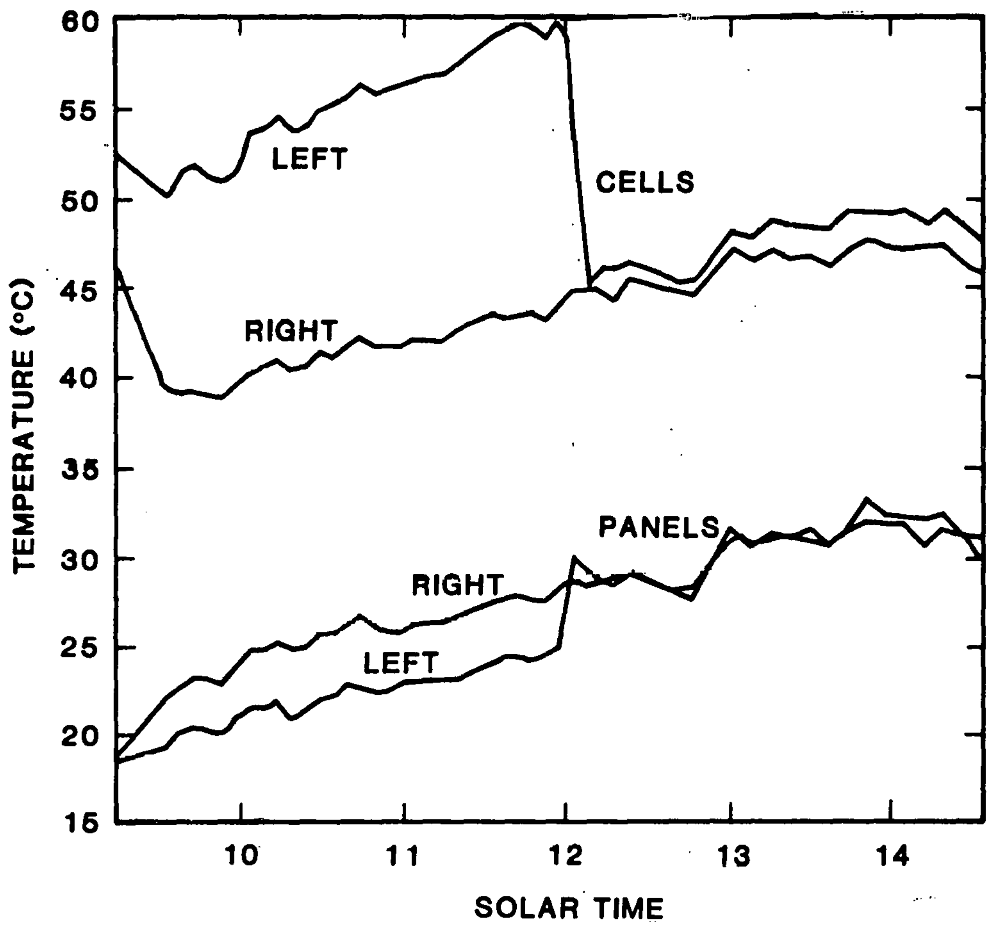


Figure 10. Reflux Panel and Cell Temperatures, 2 October 1980

During the time that the Freon™ is not boiling, heat transfer from the cell to the reflux panel is only by conduction and most of the area of the panel is ineffective. The cell temperature is, therefore, high. Once boiling is initiated, heat is more efficiently transported over the panel area and the cell temperature is reduced. Cell temperature differences of 20°C were common when one reflux panel failed to boil. For some tests, the operation of both reflux panels was desired; boiling was induced by agitating (tapping) the panel. The data used in regression analyses were the average of both cell temperatures.

This uneven operation of the reflux panels was the primary reason for the switch from Freon™ 113 to Freon™ 11 by Motorola, Inc.

Summary

A concentrating photovoltaic collector developed by Motorola has been tested and evaluated at the PASTF. This design, which utilizes a point focus Fresnel lens concentrator and a Freon™-assisted passively-cooled receiver, has been put through a PRDA 35 qualification test program during a three month period. The results presented herein show the module has met the goals of the qualification requirements to which it was subjected. The module output was found to be approximately 80 watts at 1,000 watts/m^2 insolation and 55°C cell temperature, giving an overall efficiency of 10.5 percent. The module is well sealed, which helped minimize environmental degradation. The Freon™-assisted reflux panels used in cell cooling functioned well, keeping cell temperatures low without using a large amount of aluminum as a heat sink.

APPENDIX

Test Specifications

Introduction

This test specification establishes the test procedures and performance levels for testing PV array module hardware. Three groups of tests are defined:

1. Performance evaluation of a complete module for a number of conditions expected to occur during the life of the application experiment,
2. Accelerated freeze-thaw cycling of a complete module followed by hail testing, and
3. Accelerated freeze-thaw cycling, temperature cycling, and ultraviolet exposure of receiver and reflector test sections.

A standard set of test levels is specified for each group of tests.

Test Procedures

As the test hardware is received, it shall undergo visual inspection to establish the as-received physical condition. Each hardware item shall then be placed into one or more of the following test categories for performance and accelerated environmental testing.

<u>Group A Tests</u>

The hardware required for this group of tests is one module. The following test sequence shall be followed:

1. Voltage Isolation -- The output terminals of the module shall be short-circuited during the performance of this test. Test

leads from a suitable dc voltage power supply shall be connected with the positive lead on the module terminals and the negative lead on the receiver tube or heat sink. A voltage of twice the system voltage plus 1,000 volts shall be applied at a rate not to exceed 500 V/s and then held at the test voltage for one minute. The module shall be observed during the test for signs of arcing or flashover.

Requirement: Leakage current shall be monitored and shall not exceed 50 μA.

2. Off-Axis Performance of One-Axis Tracking Arrays -- The module shall be mounted on a tracker which can track the sun in the azimuth direction with different elevation angle adjustments. The module maximum power shall be measured as a function of off-axis angle.

Goal: The maximum power* for a given off-axis angle shall not fall below 95% of the value predicted from array performance modeling.

3. Continuous Performance Measurements -- The module shall be installed on a two-axis tracker, loaded electrically, and operated continuously for a period of 3 weeks. The electrical load shall be either a maximum power tracking load or a resistive load of such a value as to allow approximately maximum power transfer at solar noon on a clear day. The initial maximum power shall be established. The output power, cell temperature, and solar insolation shall be recorded at intervals of 10 minutes or less. At least three times per day, the complete current-voltage characteristics shall be measured (midmorning, noon, and midafternoon). At the end of the 3-week test period, the mirror or lens shall be cleaned and the maximum power measured.

Goal: The maximum power after cleaning shall be not less than 95% of the initial maximum power.

*Throughout this test specification, maximum power shall be as defined in the section on Test Definitions.

4. Partial Shading Tests -- While operating the module at the maximum power point, selected cells shall be shaded, both partially and fully.

   Requirement: After the shading tests are complete, there shall be no degradation in module performance as a result of partial or full shading of the cells.

5. Thermal Shock and Off-Axis Beam Destruction -- The module shall be slowly brought into and out of focus 50 times. The rotation shall be through the angle of focus plus or minus 45°. The module shall be moved completely out of focus (image misses all parts of module), fixed in defocused position, and held while the sun's image moves across the module completely. The maximum power shall be remeasured after these tests.

   Requirement: No visible damage that could lead to power degradation shall be observed.

Group B Tests

The hardware required for this group of tests is one module. This module may consist of the same concentrator as used in the Group A tests and a second detachable receiver which is mounted on the Group A test concentrator for electrical measurements. The following test sequence shall be followed:

1. The module shall be mounted on a 2-axis tracker and the initial maximum power established.

2. The complete module or detachable receiver shall be placed in the environmental test chamber for 4 weeks and subjected to the standard freeze-thaw cycle defined later in the section on Test Definitions.

3. After the 4-week period in the environmental chamber, the module or receiver shall be reinstalled on the two-axis tracker and the maximum power measured.

Goal: The maximum power shall be not less than 95% of the initial value established in Step 1. In addition, no visual damage shall be observed.

4. The complete module shall be removed from the tracker and hail-tested in the stowed position. The hail test shall be as defined in the section on Test Definitions.

5. The module shall be reinstalled on the two-axis tracker and the maximum power measured.

   Goal: The maximum power shall be not less than 95% of the initial value established in Step 1. In addition, no visual damage shall be observed.

Group C Tests

The hardware required for this group of tests includes, in the case of line-focusing-type modules, 1-foot receiver sections and sections of lenses or reflectors. Complete modules are required for the point-focusing-type modules. Three types of tests shall be performed.

Temperature Cycling -- The following test sequence shall be followed:

1. The maximum power at one-sun conditions (no concentration) of one of the 1-foot receiver sections or complete modules shall be measured to establish the initial maximum power.

2. The 1-foot receiver section or complete module shall then be placed in the temperature chamber for a 4-week period and subjected to the standard temperature cycle defined later in the section on Test Definitions.

3. After the 4-week period in the temperature chamber, the 1-foot receiver section or complete module shall be retested at one-sun conditions to establish maximum power.

   Goal: The maximum power shall be not less than 95% of the initial value established in Step 1. In addition, no visual damage shall be observed.

4. The spectral reflectance or transmission of one of the reflector or lens sections shall be established.

5. The reflector or lens section shall then be placed in the temperature chamber for a 4-week period and subjected to the standard temperature cycle as in Step 2 above. Note: Steps 2 and 5 may be done simultaneously.

6. After the 4-week period in the temperature chamber, the reflector or lens section shall be retested to establish spectral reflectance or transmission.

   Goal: The spectral reflectance or transmission shall be not less than 95% of the initial value established in Step 4. In addition, no visual damage shall be observed.

Ultraviolet (uv) Exposure -- The following test sequence shall be followed:

1. The maximum power at one-sun conditions (no concentration) of one of the 1-foot receiver sections or complete modules shall be measured to establish the initial maximum power.

2. The 1-foot receiver section or complete module shall then be placed in the ultraviolet exposure facility and subjected to the standard accelerated exposure cycle as defined later in the section on Test Definitions.

3. After the accelerated ultraviolet exposure cycle, the 1-foot receiver section or complete module shall be retested at one-sun conditions to establish maximum power.

   Goal: The maximum power shall be not less than 95% of the initial value established in Step 1. In addition, no visual damage shall be observed.

4. The spectral reflectance or transmission of one of the reflector or lens sections shall be established.

5. The reflector or lens section shall then be placed in the ultraviolet exposure facility and subjected to the standard

accelerated exposure cycle as in Step 2 above. Note: Steps 2 and 5 may be done simultaneously.

6. After the accelerated ultraviolet exposure cycle, the reflector or lens section shall be retested to establish spectral reflectance or transmission.

   Goal: The spectral reflectance or transmission shall be not less than 95% of the initial value established in Step 4. In addition, no visual damage shall be observed.

Freeze-Thaw Cycling -- The following test sequence shall be followed:

1. The spectral reflectance or transmission of one of the reflector or lens sections shall be established.

2. The reflector or lens section shall then be placed in the environmental test chamber for a 4-week period and subjected to the standard freeze-thaw cycle defined below in the section on Test Definitions.

3. After the 4-week period in the environmental chamber, the reflector or lens section shall be retested to establish spectral reflectance or transmission.

   Goal: The spectral reflectance or transmission shall be not less than 95% of the initial value established in Step 1. In addition, no visual damage shall be observed.

Test Definitions

Maximum Power -- The maximum product of current times voltage obtained by adjusting the array operating point. For purposes of comparison of this maximum power from test to test it shall be corrected to a cell temperature of 28°C (82.4°F) and a solar insolation of 1,000 W/m^2.

Standard Freeze-Thaw Cycle -- Temperature and humidity cycling with a temperature excursion from -6°C to 55°C, a relative humidity reaching 100% at 5°C, and three cycles per 24-hour period.

Hail Test -- A salvo of 1-inch hail balls at terminal velocity and angles-of-incidence from 0° to 45°.

Standard Temperature Cycle -- For receiver sections, a temperature excursion from -6°C to 120°C with one cycle every 2 hours; for reflector or lens sections, a temperature excursion from -6°C to 50°C with one cycle every 2 hours.

Standard Accelerated Ultraviolet Exposure Cycle -- 30 mW/cm^2 for 300 hours from ultraviolet lamps.

DISTRIBUTION:

TID-4500-R66, UC-63 (304)

A. D. Little, Inc.
Attn: W. Peter Teagan
Acorn Park
Cambridge, MA 02140

Acurex Corporation
Aerotherm Group
Attn: D. Radinadjad
485 Clyde Avenue
Mountain View, CA 94042

Albuquerque Operations Office (3)
U.S. Department of Energy
Attn: J. A. Morley
E. A. Walker
D. C. Graves
Albuquerque, NM 87185

Applied Solar Energy Corp.
15251 E. Don Julian Road
Box 1212
City of Industry, CA 91749
Attn: K. Ling
T. Brawley

Arizona Public Service Co. (5)
Attn: Joe McGuirk
411 North Central Avenue
Phoenix, AZ 85036

Arizona State University
College of Engineering
Attn: C. E. Backus
Tempe, AZ 85281

Battelle-Columbus Laboratories
Attn: D. C. Carmichael
505 King Avenue
Columbus, OH 43201

Clemson University
College of Engineering
Attn: Prof. J. W. Lathrop
Clemson, SC 29631

Congressional Research Service
Library of Congress
Attn: H. Bullis
Washington, DC 20540

Division of Photovoltaic Energy Systems (4)
U.S. Department of Energy
600 E Street, NW
Washington, DC 20585
Attn: A. S. Clorfeine
A. D. Krantz
L. M. Magid
M. B. Prince

DSET
Attn: G. A. Zerlaut
P.O. Box 185
Phoenix, AZ 85029

Electric Power Research Institute
Attn: Frank Goodman
P.O. Box 10412
Palo Alto, CA 94303

E-Systems, Inc.
Energy Technology Center
Attn: D. Yakil
P.O. Box 226118
Dallas, TX 75222

Fresnel Optics Division
Alliance Tool Corporation
Attn: Helmut Walter
1300 Mount Reed Blvd.
Rochester, NY 14606

General Electric Company (3)
Attn: R. C. Hodge
A. S. Kirpich
N. F. Shepard, Jr.
P.O. Box 8661
Philadelphia, PA 19101

Jet Propulsion Laboratory (4)
4800 Oak Grove Drive
Pasadena, CA 91103
Attn: R. Forney
J. Hesse
R. Baisley
J. Praver

DISTRIBUTION (Continued)

Kaman Sciences Corporation
Attn: D. M. Jardine
1500 Garden of the Gods Road
P.O. Box 7463
Colorado Springs, CO 80933

Lea County Electric Cooperative
Drawer 1447
Lovington, NM 88260
Attn: P. Felbe

Martin Marietta Corporation
Denver Division
Attn: Sidney Broadbent
Matthew Imamura
Box 179
Denver, CO 80201

Microwave Associates, Inc.
Attn: S. Deem
108 Turquoise Avenue
Balboa Island, CA 92622

MIT-Energy Laboratory
Attn: R. Tabors
E38-411
Cambridge, MA 02139

MIT-Lincoln Laboratory
Attn: M. Pope
P.O. Box 73
Lexington, MA 02173

Monegon, Ltd.
Attn: H. L. Macomber
4 Professional Drive
Suite 130
Gaithersburg, MD 20760

Motorola, Inc. (5)
Government Electronics Division
Attn: T. Sarphie
8201 E. McDowell Road
Scottsdale, AZ 85252

Naval Civil Engineering Lab
Attn: G. Watson, Code L-63
Ft. Hueneme, CA 93042

New Mexico State University
New Mexico Solar Energy Institute
Attn: V. Risser
Box 3SOL
Las Cruces, NM 88003

Oak Ridge National Laboratory
Attn: S. Kaplan
P.O. Box X
Oak Ridge, TN 37830

Optical Science Group
Attn: John Eggers
24 Tiburon Street
San Rafael, CA 94901

Oregon Solar Institute
Attn: James E. Mollé
637 S. E. Harrison Street
Portland, OR 97214

Research Triangle Institute
Attn: R. M. Burger
P.O. Box 12194
Research Triangle Park, NC 27709

Science Applications, Inc.
8400 Westpark Dr.
McLean, VA 22101
Attn: Y. Gupta

Solar Kinetics, Inc.
Attn: Gus Hutchison
P.O. Box 47045
Dallas, TX 75247

Solar Energy Research Institute (3)
Attn: H. Lauffenburger
Library (2)
1617 Cole Blvd.
Golden, CO 80401

Solarex Corporation
Attn: R. C. Hamilton
1335 Piccard Drive
Rockville, MD 20850

Solar Power Corp.
20 Cabot Road
Woburn, MA 01801
Attn: R. Addiss

DISTRIBUTION (Continued)

Texas Tech University
Center for Energy Research
Attn: W. M. Marcy
Lubbock, TX 79409

The Aerospace Corporation
Attn: B. Siegil
R. Fling
P.O. Box 92957
Los Angeles, CA 90009

The BDM Corporation
Technology Applications Center
Attn: W. R. Kauffman
2600 Yale Boulevard, S.E.
Albuquerque, NM 87106

U.S. Department of Energy
20 Massachusetts N.W.
Washington, D.C. 20545
Attn: A. Krantz

University of Texas at El Paso
Department of Metallurgical Engineering
Attn: Steve Stafford
El Paso, TX 79968

Varian Associates, Inc.
Attn: Henri J. R. Maget
611 Hansen Way
Palo Alto, CA 94303

2532 R. Hayenga
4700 J. H. Scott
4710 G. E. Brandvold
4714 R. P. Stromberg
4720 D. G. Schueler
4721 W. P. Schimmel
4721 H. J. Gerwin
4721 T. D. Harrison
4721 D. A. Pritchard (20)
4721 R. M. Workhoven
4724 E. C. Boes
4724 M. W. Edenburn
4724 B. D. Shafer
4726 E. L. Burgess
4726 All (6)
3141 L. J. Erickson (5)
3154-3 C. H. Dalin (3)
For DOE/TIC (Unlimited Release)

Org.	Bldg.	Name	Rec'd by	Org.	Bldg.	Name	Rec'd by

Sandia National Laboratories