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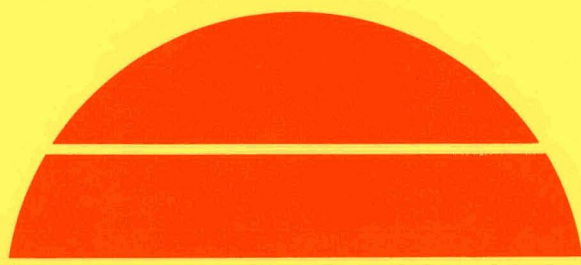
**LARGE SCALE PRODUCTION TASK: LOW COST  
SILICON SOLAR ARRAY PROJECT**

Final Technical Report

September 1978

Work Performed Under Contract No. NAS-7-100-954587

Spectrolab, Incorporated  
Sylmar, California



**MASTER**

**U.S. Department of Energy**

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**Solar Energy**

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FINAL TECHNICAL REPORT

SPECTROLAB, INC.

Contract No. 954587

DRD No. MA006

Large Scale Production Task  
Low Cost Silicon Solar Array Project

September 1978

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## 1. INTRODUCTION

The solar cell module design used by Spectrolab, Inc. for the previous (46 kW) procurement utilized solar cells encapsulated in a silicone elastomer on an aluminum "T" beam substrate with a glass cover plate protecting the elastomer. That module design had exceptionally good structural and thermal dissipation characteristics. However, difficulties were encountered with respect to delaminations, electrical breakdown to the metal substrate and humidity sensitivity. In addition the use of liquid silicone encapsulant did not appear to be a readily controllable and satisfactory production process, the aluminum extrusion limited the design with respect to size and shape, and the metal substrate intensified thermal coefficient mismatch and delamination problems.

Recognizing the potential problems with the T beam design, Spectrolab had initiated a company funded program to evaluate and develop an alternative and improved design concept. In this program several design concepts were evaluated and compared with each other and with the baseline aluminum extrusion design. They were compared in respect to potential for low cost and automation, protection against weathering, potential for array efficiency as a function of weight and area, potential for design flexibility and exposure to electrical breakdown or leakage to ground. This evaluation program narrowed attention to design concepts involving glass as the primary structural and weather resistant component of the module. The leading specific design structure consisted of the solar cell circuit embedded in poly vinyl butyrate by lamination between a glass front surface and a polyester film rear surface (Figure 1). Preliminary evaluation of this structure in high humidity and thermal cycle was promising, and extensive field experience with similar structures in architectural and automotive applications was favorable.

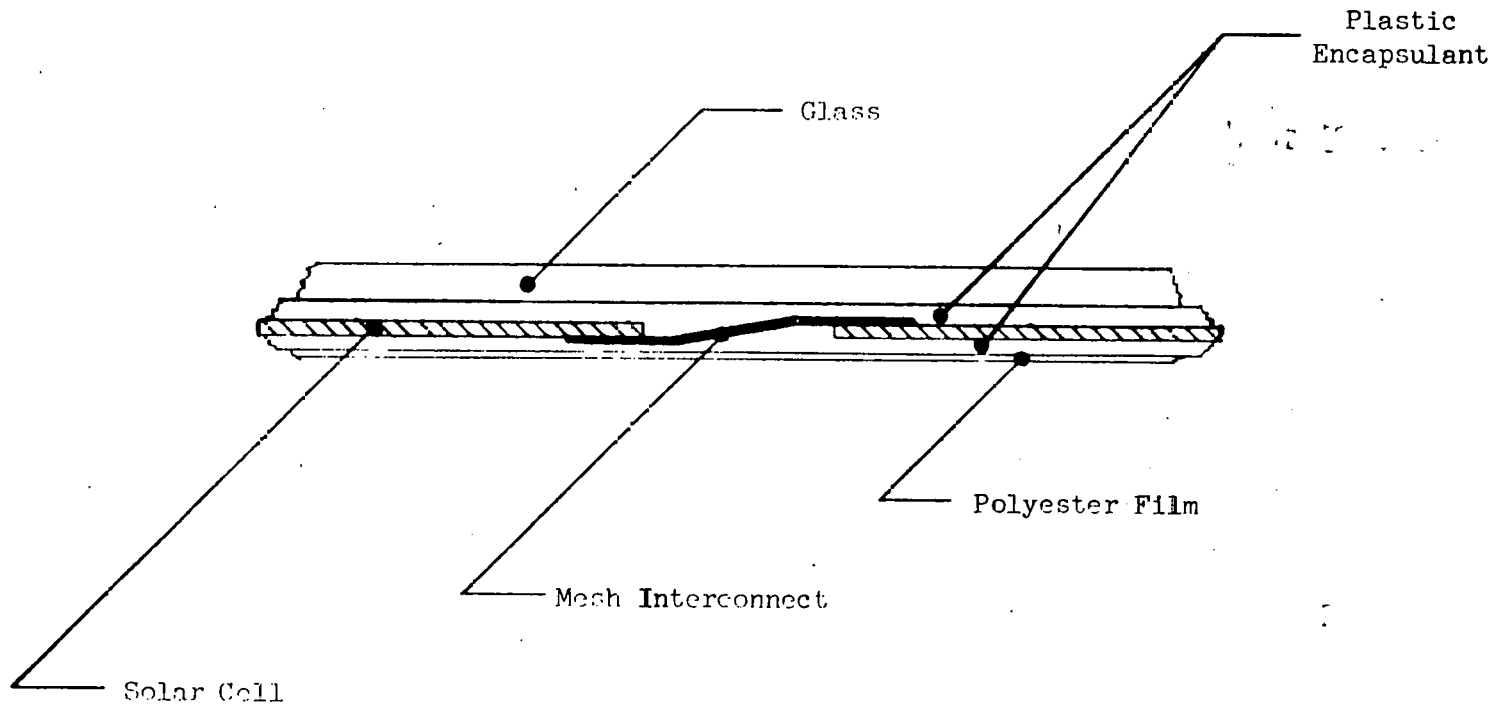


Figure 1. Cross-Section of Laminate Structure

Despite limited experience with this design concept, Spectrolab decided to propose it for this JPL contract. The specific design proposed was comprised of 120 2" diameter cells in a series-parallel configuration. The laminate was mounted in an aluminum frame with a neoprene gasket providing the requisite mechanical strength with flexibility. The resulting module size of 15 by 46 inches permits three modules to be neatly fitted into the 46 inch square subarray specified by JPL. The design as modified to accommodate subsequent experience is shown in Figure 2.

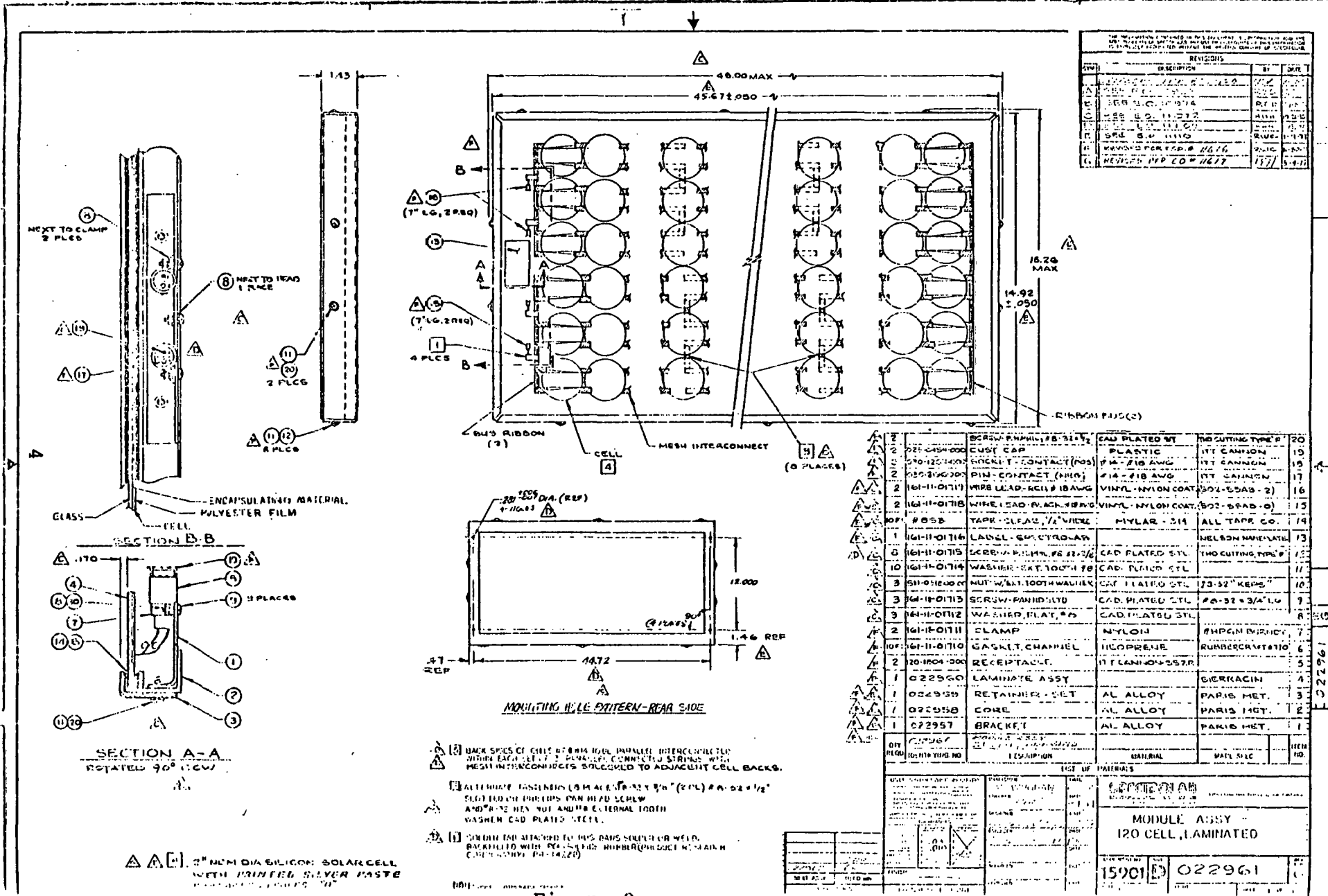


Figure 2

## 2. DESIGN

### A. Encapsulant

Polyvinyl butyrate (PVB) is a thermoplastic hydrocarbon based on the polyethelene chain. It has been used as an interlayer for laminating glass sheets together in safety glass for automotive and architectural applications for many years. Such structures have now been subjected to a wide variety of environmental exposure for over 20 years without evidence of bubble formation or discoloration, and only limited delamination effects. It is readily available in sheets of appropriate thickness and good optical quality. It is a relatively elastic material capable of withstanding the  $-40^{\circ}$  to  $90^{\circ}$ C thermal cycle requirement, but with a substantially lower rate of moisture transmission than that of silicones.

### B. Module Surfaces

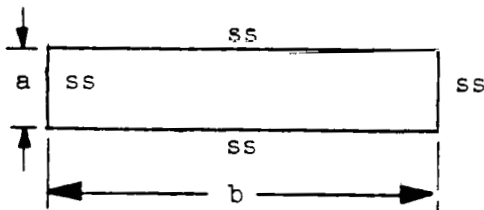
The selection of glass for the front face of the module was based on its desirable attributes of light transmission, weatherability, mechanical strength, low thermal expansion and prior use with PVB in automotive and architectural applications. In order to support the 50 pound per square foot loading requirement a standard 0.120 inch glass thickness is required. Stress analysis is given in Table 1.

During the fabrication of the prototype modules it was found that the reflection and transmission characteristics of the glass-PVB system resulted in about 7% reduction of circuit power output. The loss was largely due to absorption in the float glass, which has a relatively high iron content. A low iron sheet glass obtained from ASG Industries was used for the production run.

Polyester film was selected as a protective membrane for the back surface to reduce cost and weight, and to provide more freedom to

TABLE 1

GLASS STRESS CALCULATION



Annealed Glass:

- a = 14.5 in
- b = 45.25 in
- t = 0.120 in
- E =  $10^7$  #/in<sup>2</sup>
- w = 0.35 #/in<sup>2</sup>

Strength = 6500-8500 #/in<sup>2</sup>

Ref. Timoschenko, Theory of Plates and Shells, Pg. 118.

$$\begin{aligned}
 b/a = 3 \quad M_{\max} &= 0.1139 wa^2 \\
 &= 0.1189 (0.35) (14.5)^2 \\
 &= 8.75 \\
 \sigma_{\max} &= 6M/t^2 \\
 &= 6 (8.75) / (0.120)^2 \\
 &= 3645 \text{ #/in}^2 \text{ (Elastic Supported Sides } c \approx 4000 \text{ psi)} \\
 y_{\max} &= 0.1335 wa^4/Et^3 \\
 &= 0.1335 (0.35) (14.5)^4 / 10^7 (0.120)^3 \\
 &= 0.12 \text{ in}
 \end{aligned}$$

withstand thermal stresses. The resulting transparency of the laminate limits energy absorption to the area actually occupied by the cell circuit, and hence limits the temperature rise.

The thermal path from cells to the module surface is about the same as the previous design. However the stem and base of the aluminum "T" extrusion of the previous design served as a thermal dissipator not present in the laminate design. Cell temperature should therefore be slightly higher with the new design. An experimental determination confirmed that this temperature differential between the two designs is about  $10^{\circ}\text{C}$  as shown in Figure 3.

### C. Circuit

The solar cell circuit contained 3 strings of 40 series connected, 2 inch diameter solar cells with parallel interconnections at each end and in the center. This configuration was modified in the final design review to add four additional equally spaced parallel interconnections.

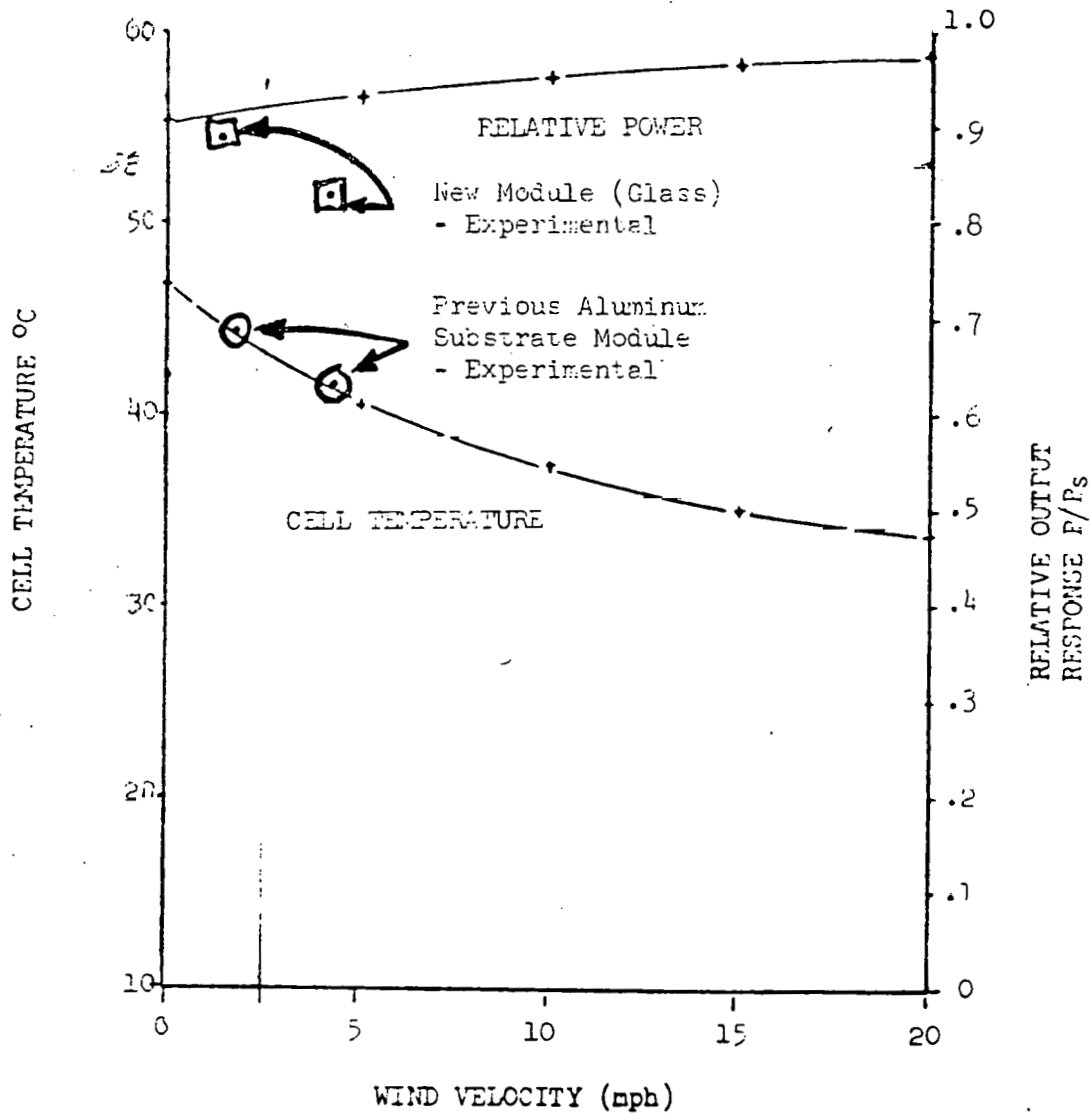
Each cell was provided with two parallel front ohmic metallization conductors which are electrically connected by the collector grid metallization. This redundant metallization pattern provided solder pads for two interconnects between each series cell, thus providing redundant series interconnections. Solder plated expanded copper mesh was used for series interconnects in the Spectrolab design. This selection provided a long fillet path which can be readily inspected and avoids problems due to thermal coefficient mismatch, but increases the difficulty of flux removal.

It was estimated that the circuit output would be 26 watts at 15.8 volts and  $60^{\circ}\text{C}$  (30 watts at 18.5 volts and  $28^{\circ}\text{C}$ ) as shown in Figure 4. This would provide a subarray output of 78 watts at

Figure 3

PREDICTED CELL TEMPERATURE AND RELATIVE  
RESPONSE VERSUS WIND VELOCITY

For: Wind velocity from the South  
Irradiance = 100 mW/cm<sup>2</sup>  
Ambient Temperature = 23°C



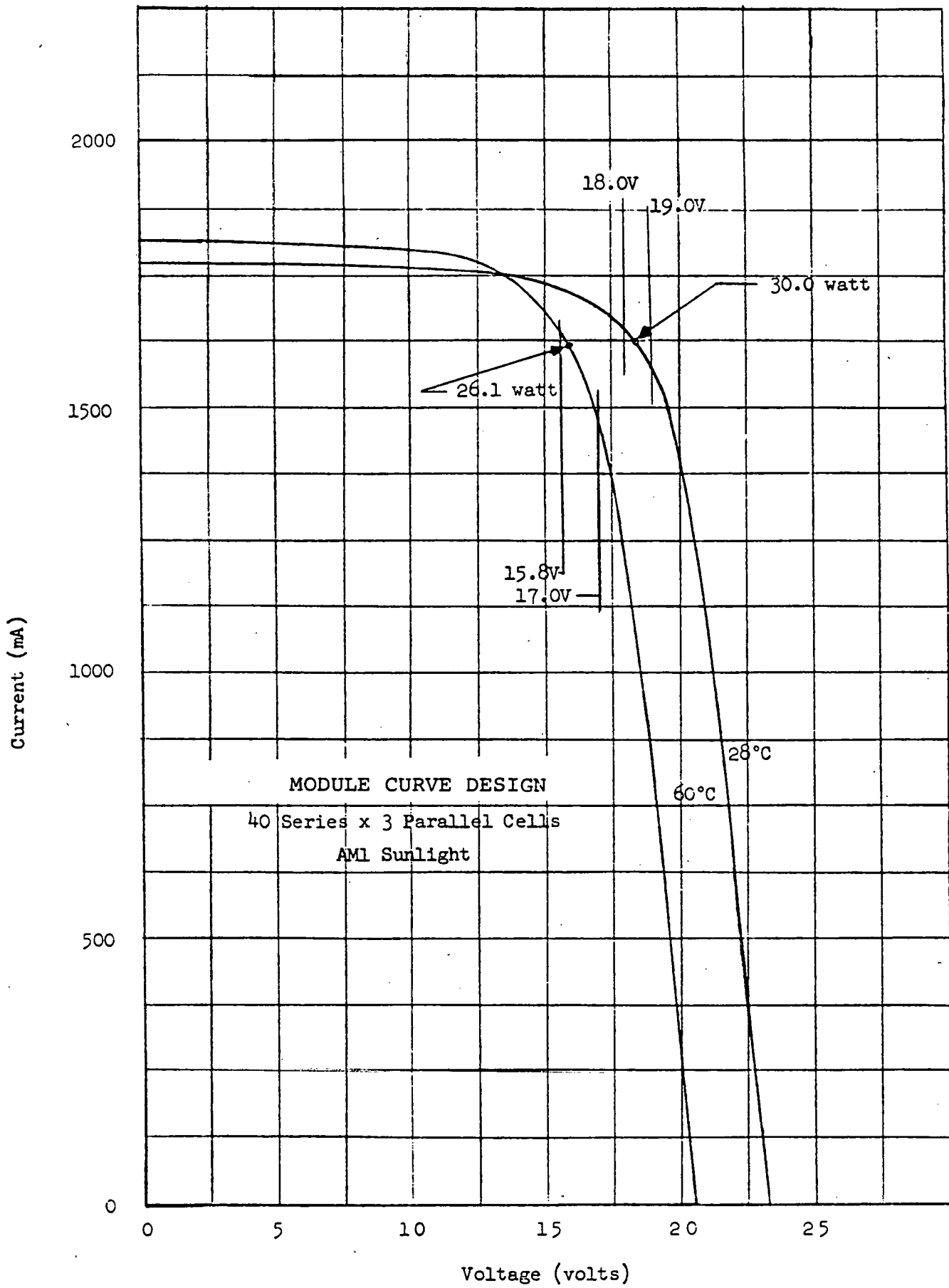


Figure 4

60°C, well above the 60 watts which were required by the JPL specification. The actual performance of the 30 prototype modules fabricated was found to be 28.6 watts at 18.5 volts and 28°C (Table 2). During the subsequent production run there was a continuing increase in the module output, the final lots having average module power in excess of 26 watts at 60°C.

Measurements made by JPL on 10 modules indicated that the thermal power slope ( $m = -0.1391$ ) is somewhat greater than had been anticipated. The average output at 15.8 volts and 60°C was 23.2 watts for 10 modules tested (Table 3), however this data is related to a different light level test condition. Voltage at maximum power at 60°C was found to fall between 14.9 and 15.8 volts. Due to the small change in power output near the maximum power point of the I-V curve, the peak power output was 22.9 watts at 15.8 volts by the JPL measurements.

#### D. Frame

The laminate was held by a neoprene gasket in an aluminum frame comprised of a U channel extrusion core on which the laminate rests, with angle retainers which bolt to the core for capturing the laminate. The frame cross section is shown in Figure 5. The frame stress analysis is given in Table 4.

#### E. Leads and Connectors

Electrical contact was made through lead wires with nylon coated vinyl insulation. For the 30 preproduction modules which were produced these lead wires were brought out between the glass and the polyester film during lamination. During final assembly a curved channel was routed out of the PVB to direct the wire away from the metal frame. After mounting the connectors, which held the lead wires in position, this area was backfilled with a polysulfide rubber to hold the wires in the channels.

Table 2

POWER OUTPUT

Intensity 100 MW/cm<sup>2</sup> based on Spectrolab Std. 1014

SN	* P <sub>18.5V, 28°C</sub>	** P <sub>15.8V, 60°C</sub>	SN	* P <sub>18.5V, 28°C</sub>	** P <sub>15.8V, 60°C</sub>
	Watts	Watts		Watts	Watts
4003	28.9	24.45	4023	26.7	22.25
4004	29.0	24.55	4024	29.2	24.75
4006	29.0	24.55	4025	30.1	25.65
4007	29.6	25.15	4026	29.2	24.75
4008	29.2	24.75	4027	29.2	24.75
4009	28.5	24.05	4028	28.9	24.45
4011	28.9	24.45	4029	29.0	24.55
4012	28.1	23.65	4030	29.5	25.05
4013	28.1	23.65	4031	29.6	25.15
4014	26.8	22.35	4032	30.0	25.55
4016	23.9	19.45	4034	28.9	24.45
4018	27.8	23.35	4035	28.9	24.45
4019	28.9	24.45	4036	27.8	23.35
4020	29.4	24.95	4037	27.8	23.35
4021	28.1	23.65	4038	29.1	24.65
			<u>P</u>	28.6	24.15

\*Measured values

\*\*Calculated using a temperature coefficient of -0.139 watts/°C

Table 3

VOLTAGE AND POWER VS. TEMPERATURE

Data Measured by JPL using Z Series Standard Cell

S/N	SLOPES		28°C		60°C		Approx. P@15.8V
	M (V <sub>mp</sub> )	M (P <sub>m</sub> )	V <sub>mp</sub>	P <sub>m</sub>	V <sub>mp</sub>	P <sub>m</sub>	
04012	-.0773	-.1236	17.47	26.67	15.00	22.71	22.50
04018	-.0910	-.1428	18.03	27.24	15.12	22.64	22.55
04019	-.0900	-.1416	18.38	27.75	15.50	23.47	23.35
04021	-.0336	-.1335	17.86	26.80	15.17	22.45	22.36
04023	-.0815	-.1360	17.51	25.76	14.90	21.35	20.86
04025	-.0905	-.1448	18.50	28.86	15.60	24.23	24.14
04026	-.0916	-.1489	18.58	28.18	15.55	23.51	23.42
04028	-.0354	-.1371	18.50	27.93	15.77	23.49	23.53
04029	-.0372	-.1465	18.28	27.96	15.48	24.30	23.04
04035	-.0836	-.1350	18.13	27.50	15.45	23.18	22.99
04003	-.0859	-.1389	18.44	27.95	15.64	23.52	23.50
04009	-.0360	-.1357	18.09	27.16	15.31	22.82	22.50
Average	-.0835	-.1391	18.15	27.48	15.37	23.24	22.90
Std. Dev.	.0047	.0066	.38	.82	.27	.81	.84
% S.D.	5.4	4.8	2.1	3.0	1.8	3.5	3.7

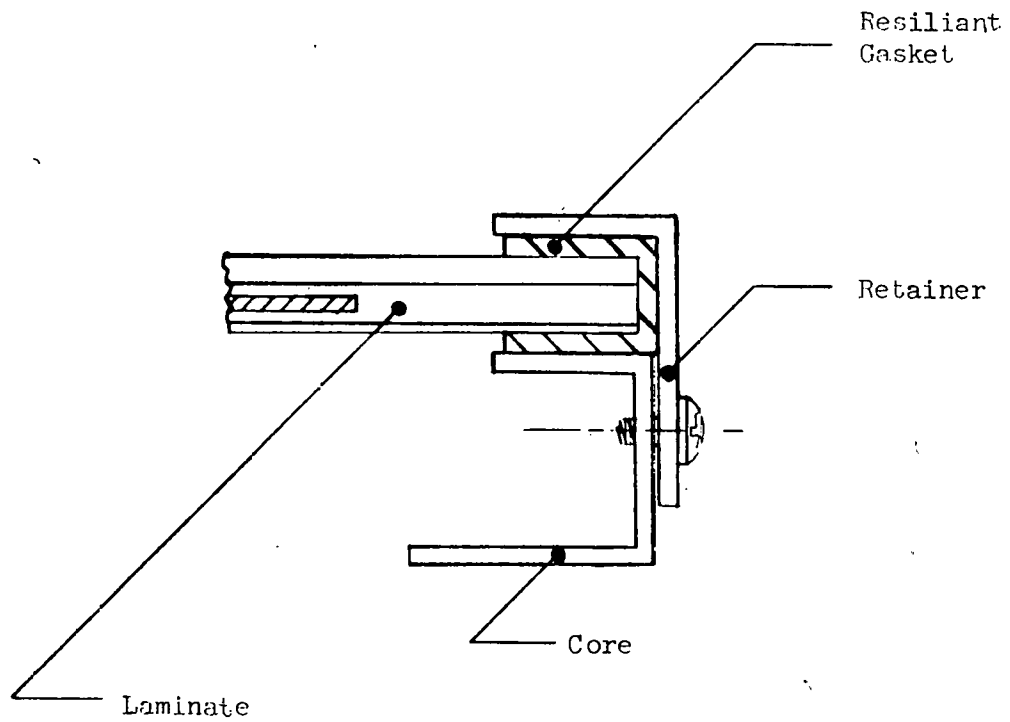
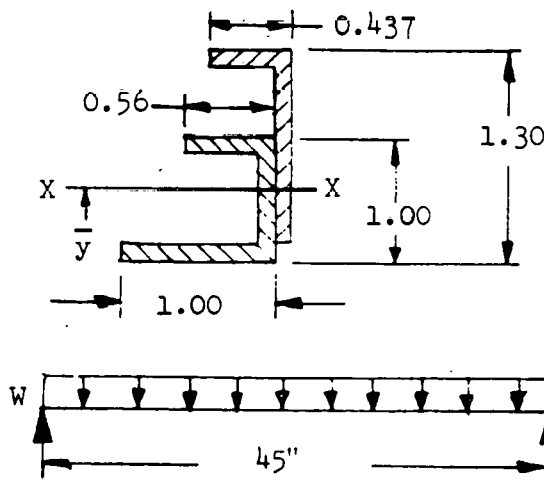


Figure 5

Frame Cross-Section

TABLE 4

FRAME STRESS CALCULATION



$$\bar{y} = \frac{\sum A_i y_i}{\sum A_i}$$

$$\bar{y} = 0.57$$

$$I_{xx} = \sum \left[ \frac{b_i t^3}{12} + A_i (y_i - \bar{y})^2 \right]$$

$$I_{xx} = 0.058$$

$$w = 50 \text{ lb/ft}^2 \times \frac{45 \times 15}{144} \times \frac{1}{45} \times \frac{1}{2} = 2.6 \text{ lb/in}^2$$

$$M_{\max} = \frac{wL^2}{8} = 658 \text{ in lb}$$

$$\sigma_{\max} = \frac{Mc}{I} = \frac{658 (1.3 - 0.57)}{0.058}$$

$$= 8232 \text{ lb/in}^2$$

$$y_{\max} = \frac{5}{384} \frac{wL^4}{EI} = \frac{5}{384} \frac{(2.6)(45)^4}{10^7 (0.058)}$$

$$= 0.24 \text{ in.}$$

This arrangement sometimes resulted in damage to the wire insulation during lamination and during trimming after lamination, and was modified during the final design review. In the new configuration used during the production run, small solder tabs were provided at the ends of the circuit. After lamination, the polyester film and PVB were excavated to expose the solder tabs. Lead wires were soldered to the tabs, and the openings backfilled with polysulfide rubber. This method eliminated damage to the insulation and provided a more positive method of routing the wire to avoid accidental contact with the metal frame.

After passing through expansion loops, the lead wires were brought to weatherproof bipolar connector receptacles (ITT Cannon Sure Seal, SS2R) which was secured to an aluminum bracket by means of nylon mounting clips. Two connector receptacles and two sets of lead wires provided a redundant external electrical connection.

### 3. QUALIFICATION TESTING

#### A. Final Electrical Test

The power at STC of the prototype modules is reported in Table 5. All of the modules which were fabricated are included in this tabulation except those rejected for major physical defects (broken glass, broken cells, overlapping cells). All measurements were referenced to Spectrolab standard cell 1014. Subsequent to the completion of these measurements and shipment of the modules, Spectrolab received from JPL a special standard cell Z-15. This standard cell was found to read about 7.5% high when used on the LAPSS. The JPL measurements reported in Table 3 used a related standard cell which was reported by JPL to also read about 4 or 5% high. Since standard cell 1014 was used for the initial measurements, the subsequent measurements after environmental exposure were also made using 1014 as the calibration standard.

All modules passed the 1500 volt stand off test and the 100 volt resistance to grounded frame test. The measured values of resistance to ground for the 10 modules which were environmentally tested by Spectrolab are reported in Table 5. The observed values are all in excess of  $1.4 \times 10^9$  ohms.

#### B. Estimated 60°C Subarray Performance

Applying the average slope ( $-0.139$  watts/°C) reported in Table 3 to the average module power in Table 5 gives an average module power at 60°C of 24.1 watts. Estimated power at 60°C for individual modules is given in Table 1. The average subarray power would be 72.3 watts.

Table 5

POWER OUTPUT AT 28°C

Intensity 100 MW/cm<sup>2</sup> Based on Spectrolab Std. 1014

<u>SN</u>	<u>P<sub>18.5V</sub></u> <u>Watts</u>	<u>R<sub>1000V</sub></u> <u>G Ohms</u>	<u>SN</u>	<u>P<sub>18.5V</sub></u> <u>Watts</u>	<u>R<sub>1000V</sub></u> <u>G Ohms</u>
4003	28.9	-	4023	26.7	-
4004	29.0	2.7	4024	29.2	2.1
4006	29.0	-	4025	30.1	-
4007	29.6	1.4	4026	29.2	-
4008	29.2	1.4	4027	29.2	2.6
4009	28.5	-	4028	28.9	-
4011	28.9	-	4029	29.0	-
4012	28.1	-	4030	29.5	-
4013	28.1	1.6	4031	29.6	2.2
4014	26.8	-	4032	30.0	-
4016	23.9	2.2	4034	28.9	2.1
4018	27.8	-	4035	28.9	-
4019	28.9	-	4036	27.8	-
4020	29.4	2.4	4037	27.8	-
4021	28.1	-	4038	29.1	-

Average Power = 28.6 watts.

Range 23.9 - 30.1 watts.

### C. Environmental Test Results

The results of environmentally testing 10 modules are reported in Table 6. All of the modules except SN 04008 satisfied the requirements of less than 5% degradation after the specified sequence of thermal cycle, humidity, and mechanical testing.

Module SN 04008 had cumulative degradation of 4, 5, and 7 percent after thermal cycle, humidity and mechanical testing respectively. Because of the large change after thermal cycle, this module was given a detailed microscopic examination at that point. One of the redundant interconnect mesh was found to be parted except for two strands which were observed to have cracks extending partially through. Parted ends were observed to be solder plated and to have divergent surfaces indicating that the defect existed in the original mesh. Another mesh in this module was observed to have what appeared to be etch grooves with a pattern orientation identical with that of the parted mesh. Investigation revealed that the mesh used had been fabricated by chemical milling rather than the mechanical slit and expand method customarily used. It was concluded that the observed defects originated during the chemical milling from a linear scratch in the photoresist. Further it appeared that the failed mesh had been weakly connected by plating which failed during the environmental exposures. This failure mode was eliminated during the production run by avoiding the use of chemically milled mesh.

Module SN 04013 had an unusually large series of changes, first upwards then downward. This module was given a detailed microscopic examination after completion of the test sequence, however nothing was observed which could account for these data.

Table 6

SUMMARY DATA - ENVIRONMENTAL TESTING

Module No.	Initial			After Thermal Cycling				After Humidity				After Mechanical			
	Power @ 18.5V Watts	IR	HV	Power @ 18.5V Watts	% Change From Initial	IR	HV	Power @ 18.5V Watts	% Change From Initial	IR	HV	Power @ 18.5V Watts	% Change From Initial	IR	HV
04004	28.5	OK	OK	28.9	+1	OK	OK	28.9	+1	OK	OK	28.8	+1	OK	OK
04007	29.6	"	"	29.6	0	"	"	29.6	0	"	"	29.4	-1	"	"
04008	29.2	"	"	28.1	-4	"	"	27.8	-5	"	"	27.2	-7	"	"
04013	28.1	"	"	28.3	+1	"	"	28.1	0	"	"	27.9	-1	"	"
04016	24.1	"	"	24.8	+3	"	"	24.1	0	"	"	23.4	-3	"	"
04020	29.2	"	"	29.2	0	"	"	29.2	0	"	"	29.5	+1	"	"
04024	29.2	"	"	29.2	0	"	"	29.2	0	"	"	29.4	+1	"	"
04027	29.2	"	"	29.2	0	"	"	29.2	0	"	"	29.2	0	"	"
04031	29.6	"	"	29.6	0	"	"	29.6	0	"	"	30.1	+2	"	"
04034	28.9	"	"	28.9	0	"	"	28.9	0	"	"	28.8	0	"	"

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All Data Measured at Standard Test Conditions 28°C 100 mW/cm<sup>2</sup>

IR = Insulation Resistance Test > 100 Meg ohm at 1000 VDC

HV = High Voltage Breakdown Test > 1500 VDC

After completion of the test, an investigation of the mechanical loading test facility in cooperation with Don Moore of JPL revealed that excess spacing of the mattress expansion region resulted in incomplete loading, with gaps between the air mattress ridges. This, when corrected for a slight excess pressure, resulted in a net deficiency in loading of about 12 or 13%.

Although not required by the specification, the electrical insulation resistance was measured after each environmental test. In all cases the observed values exceeded the  $1 \times 10^8$  ohm specification. The voltage withstanding test was conducted before and after completion of the test sequence. All modules passed in both cases.

Visual inspections were made at the completion of fabrication. All irregularities observed were recorded on module maps. The major defects observed, for which modules were rejected, were broken glass, broken cells, and overlapping cells with associated areas of unpressed PVB. Minor discrepancies noted consisted of small bubbles, stains, chipped cells, mesh distortion, scratches and inclusion of foreign material. Similar visual inspection were made after the completion of each environmental test. Some buildup of white material on the aluminum frame and glass face, believed to be a carbonate deposit, was observed after humidity testing. No other significant changes were observed except the parted mesh previously discussed.

#### 4. PRODUCTION ACTIVITIES

A total of 980 modules were produced and shipped. The initial production shipment was made on August 5, 1977 and consisted of 37 modules. The complete delivery history is given in Table 7.

The distribution of power output of the modules shipped is shown in Figure 6. The average module power output at AML, 100 mW/cm<sup>2</sup> solar irradiance and 60°C cell temperature was 26.30 watts with a standard deviation of 0.76 watts. There was a gradual increase in average module power output during the course of deliveries as a result of small improvements and optimization of the cell manufacturing processes. The initial shipment had an average output of 25.45 watts. The shipment on November 23, 1977, midway through the deliveries had an average output of 26.50 watts and the shipment on March 11 near the end of the deliveries had an average output power of 27.18 watts. The increase of the initial shipment from the average power of 24.15 watts in the prototypes was primarily due to the use of low iron sheet glass in the production run as compared with the use of float glass for the prototypes.

##### A. Problems Encountered

Subsequent to completion of the 30 prototype modules and prior to beginning production some changes were observed at JPL in output power of some of these modules after storage in the laboratory. Extensive evaluation and measurements after various kinds of treatment were made at both Spectrolab and JPL. Although some problems were discovered with test equipment, results were inconclusive and it was not possible to specify a cause for the observed instabilities.

Table 7

<u>Date</u>	<u>No. of Modules</u>
8-5-77	37
8-24-77	12
8-26-77	15
9-7-77	19
9-22-77	29
9-30-77	14
10-21-77	20
10-28-77	80
11-16-77	40
11-23-77	133
1-11-78	108
1-16-78	74
1-27-78	133
2-10-78	60
2-17-78	75
2-23-78	30
3-10-78	95
3-24-78	6
Total	980

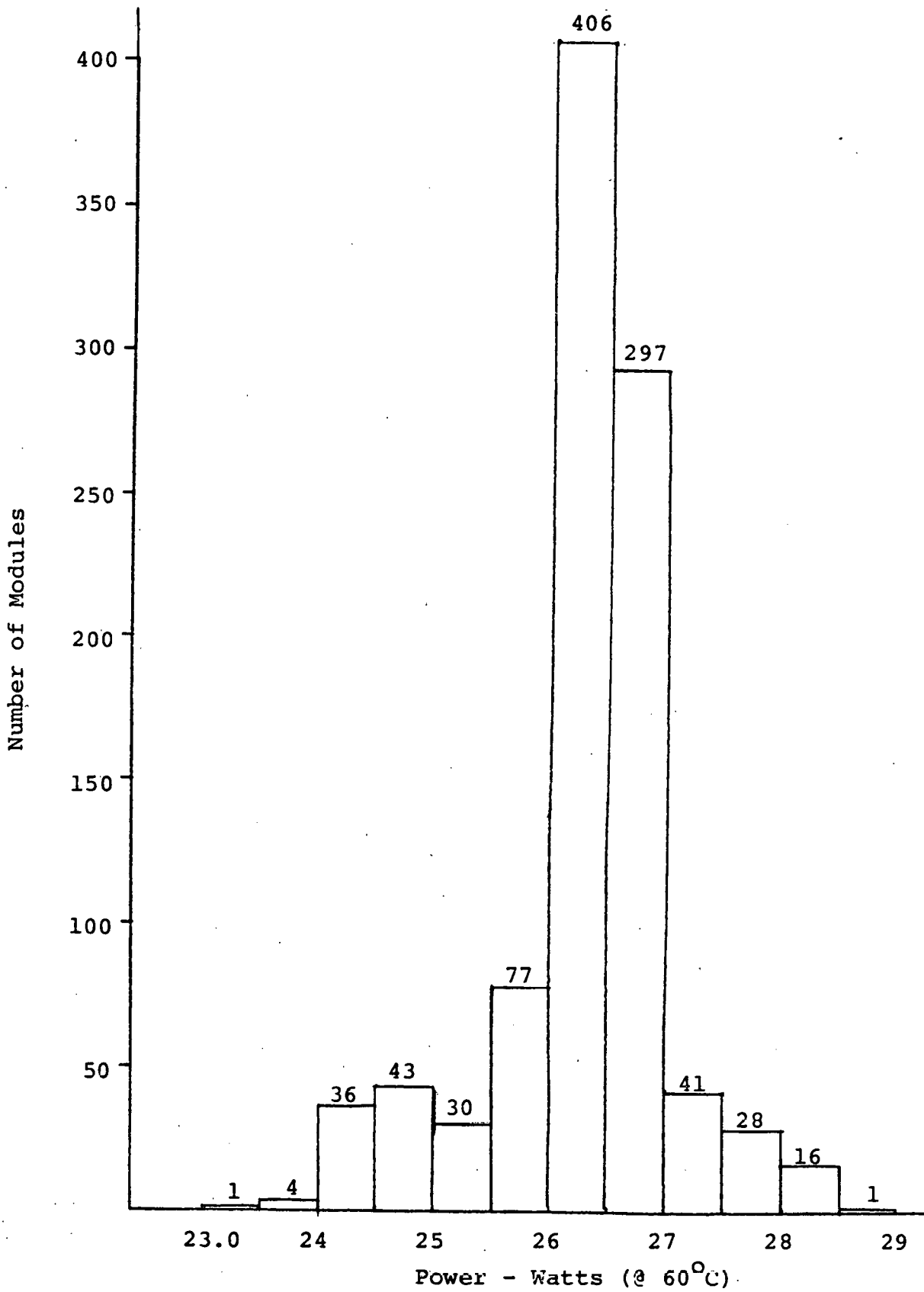


Figure 6. Distribution of Module Output Power

The cells used in the prototype modules were made with screen printed metallization treated by HF rinse. Cells made by this process were known to be humidity sensitive, and at JPL's request, Spectrolab agreed to start the production run with cells made with evaporated Ti-Pd-Ag metallization.

It was believed that such cells would be inherently more stable than the screen printed. Considerable difficulties were encountered with the vacuum metallization process arising from non-uniformity of deposition.

In the meantime Spectrolab had continued development work with screen printing and had succeeded in modifying that process to eliminate the HF rinse. These cells were found to be resistant to humidity exposure. Production was shifted from the evaporated metallization to the new screen printing process.

In the lamination process difficulties were encountered with bubble formation and with broken cells. The former was solved by providing improved channels for the escape of gasses to the vacuum system during the lamination cycle. The broken cell problem was somewhat more difficult to resolve. It was found that most of the cell breakage was occurring in handling prior to the layup for lamination. This problem was compounded by the large number of cells in the circuit. The problem was brought under control by discipline introduced by a careful quality assurance inspection immediately prior to lamination layup.

## 5. RECOMMENDATIONS FOR FUTURE DIRECTIONS

Based on experience obtained from the preproduction module tests, the following recommendations are made:

1. Use of larger cell size to reduce cost.
2. Use of a one-piece aluminum extrusion frame to reduce assembly time and costs.