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LARGE SCALE PRODUCTION TASK OF THE LOW COST
SILICON SOLAR ARRAY PROJECT

Final Report

December 29, 1976

Work Performed Under Contract No.
NAS-7-100-PO-BQ-649005

Spectrolab, Incorporated
Sylmar, California

MASTER

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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LARGE SCALE PRODUCTION TASK
of the
LOW COST SILICON SOLAR ARRAY PROJECT

P.O. BQ-649005
DRD No. MA006
FINAL REPORT

prepared for
Jet Propulsion Laboratory
Pasadena, California

prepared by
Spectrolab, Inc.
Sylmar, California

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December 29, 1976

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TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	1
II. DESIGN	2
III. QUALIFICATION TESTS AND PREPRODUCTION ACTIVITIES	4
IV. PRODUCTION ACTIVITIES	13
V. PRODUCTION EVALUATION MODULES	17
VI. RECOMMENDATIONS	20

I. INTRODUCTION

2000 solar power modules capable of producing over 10 kW of peak power were delivered by Spectrolab, Inc., during the period March to October 1976. These modules were comprised of twenty 2-inch diameter silicon solar cells embedded in a silicone elastomeric potting compound on an aluminum T beam extrusion with a glass cover plate and were typical of standard commercial products being manufactured during that time period. These modules have good structural and thermal dissipation characteristics, but difficulties were encountered with respect to delamination of the encapsulant material, low electrical breakdown resistance and humidity sensitivity. The extensive environmental test program and subsequent analytical analysis of results has provided a great deal of new knowledge of the module design. It has shown there were many limitations with this particular commercial module which were not known at the start of the program and should provide a good basis for developing an improved module in the future. Design modifications that have been recommended to improve reliability and reduce cost, include the elimination of metal substrate, replacement of silicone with a more suitable encapsulant, larger module size and use of series-parallel circuit configurations.

II. DESIGN

The module originally proposed by Spectrolab was a typical commercial module design comprised of 20 solar cells (2" diameter) in series connection attached to a T shaped anodized aluminum extrusion substrate by means of an epoxy cement with a fiberglass cloth layer to support the cells and coated with a commercially available silicone conformal coating. The minimum power output was 5 watts at 9.4 volts. Module outline dimensions were 27.50 inches in length, 4.88 inches in width, and the module weight was 2.5 pounds.

Prior to the execution of the contract, Spectrolab had completed an extensive evaluation of various module encapsulation systems. As a result, Spectrolab proposed a revised and improved design which was being incorporated at that time into the commercial product line. In the revised design the cells were supported on Dextilose paper and embedded in Sylgard 184 silicone rubber with a glass cover pane. This modification, which was accepted by JPL resulted in a weight increase to 3.5 pounds.

Metal fatigue difficulties encountered during the preproduction evaluation led to the use of an S bend wire interconnect between the solar cell circuit and module terminals. RTV 615 was qualified as an encapsulant alternative to Sylgard 184. The resultant module design is shown in Figure 1 (Drawing 060513G).

5 AMP NOMINAL
HARD FACE
ROUND CELL MODULE

TABULATION

DASH NO.	VOLTS	NO. OF CELLS	LENGTH	WT.-LBS	FRAME NO.
-1	2	6 SERIES	9.37	1.2	060420-1
-2	4	12	15.90	2.0	-2
-3	6	18	22.43	2.8	-3
-4	8	24	28.95	3.6	-4
-5	10	30	35.48	4.4	-5
-6	12	36	42.12	5.2	-6
-7	14	42	48.65	6.0	060420-7
-8	6	1	20 SERIES	26.12	3.2 060418

4 INSULATING PAPER (ITEM 9) CUTOFF A TERMINAL END OF MODULE IS OPTIONAL. BOTH ACCEPTABLE CONFIGURATIONS ARE SHOWN.

3 -B CONFIGURATION DOES NOT HAVE CELL SPACERS (ITEM 17).

2 SEE TABULATION BLOCK

1 PER JPL SPECIFICATION S-342

4		CELL SPACER 3	NYLON		17
4		TAB LOOP CONNECTING	COPPER	SOLDER PLATED	16
2	00619	STRESS RELIEF LOOP	COPPER	AWG #22 GA	15
1		IDENTIFICATION TAG			14
AR 161-11-0151		ENCAPSULATING RESIN	SILICONE	SYLGARD 184 OR GE 615 RESIN	13
AR		SPACER	SILICONE		12
1	060518	COVER PANE	GLASS		11
1	00235	INSULATION	PAPER	DEXTILOS	10
AR 161-11-00617		MESH, INTERCONNECT	COPPER	SOLDER PLATED	9
2	MS15795-806	#6 FLAT WASHER	CRES		8
2	MS35338-136	#6 LOCKWASHER	CRES		7
2	MS35619 264	#6-32 HEX NUT	CRES		6
1	060364-2	TERMINAL, RED			5
1	060364-1	TERMINAL, BLACK			4
2	060411	MODULE END	LEXAN PLASTIC		3
2	161-11-01279	ROUND SOLAR CELL		2" NOMINAL DIA	2
1	2	FRAME, MODULE	6063-T5 AL ALY	EXTRUDED	1

III. QUALIFICATION TESTS AND PREPRODUCTION ACTIVITIES

When fabrication of the prototype modules was initiated two difficulties had been encountered with Sylgard 184. Firstly, a supply shortage occurred in which difficulty was encountered in obtaining the material. Secondly, there developed a technical problem in the available material. This difficulty took the form of abnormal cure characteristics resulting in spontaneous delamination of the Sylgard 184, primarily at the cell surfaces, during the late stages of curing and accompanied by or precipitated by the evolution of gases.

Extensive experimental evaluations undertaken to identify and eliminate the problem caused several months' delay in the program. This study and evaluation succeeded in establishing that a variation of susceptibility was associated with the Sylgard lot identity. In order to get the production programs underway, Sylgard lots which did not exhibit spontaneous cell delamination were identified and used to fabricate 20 prototype modules. At the same time RTV 615 was being evaluated as an alternative encapsulant. Four modules which had been fabricated with RTV 615 for engineering evaluation were included in the environmental test exposures conducted by Spectrolab on 10 prototype modules fabricated with Sylgard 184. The environmental test sequence to which the modules were subjected was: thermal cycling, 100 cycles -40°C to +90°C; and 168 hours exposure to 90% relative humidity at 70°C.

Despite the care taken in Sylgard lot selection, thermal cycling resulted in extensive delamination of the Sylgard 184 from cell, aluminum and glass surfaces of the prototype modules. The engineering modules (made with RTV 615) also showed some delaminations, but the areas were much smaller in size than was the case with Sylgard 184. Thermal cycling was also found to induce fatigue deformation and fracture in the interconnect mesh, especially in those regions between the cell circuit and the module terminals. Fatigue fracture adjacent to the terminals resulted in complete separation of the conductor in two modules.

The subsequent humidity test resulted in serious degradation of electrical output of the prototype modules fabricated with Sylgard 184. The four engineering modules fabricated with RTV 615 performed much better in the humidity test, with no module showing degradation greater than 1.6%. The results of environmental testing of both the JPL prototype modules (Sylgard 184) and engineering test modules (RTV 615) are summarized in Tables 1-3. The Spectrolab test experience with the prototype modules was confirmed by JPL test of ten prototype modules.

Spectrolab proposed to correct the deficiencies and improve the quality of the modules by replacing the copper interconnect mesh between the terminals and the cell string with an S shaped copper wire attached to solid copper straps at the terminals and cells and to include RTV 615 as an alternate encapsulant material. Before beginning production, Spectrolab undertook environmental testing of 10 prototype modules fabricated with RTV 615 and S bend lead wires. These tests revealed the solid copper strap attachment to the cells to be a point of design weakness which caused cells to fracture in four of the ten modules during thermal cycle. Some delamination was observed, but the size of delaminated areas was again small compared with the previous experience with Sylgard 184. There was no significant degradation during humidity exposure and no failures other than broken cells associated with the solid copper tabs on the cells. The results of this set of environmental tests are summarized in Tables 4 and 5.

One further design modification was made to correct the cell breakage problem. This modification replaced the solid copper solder tabs on the cells with short lengths of interconnect mesh to which the S bend lead wires were soldered. Production was then initiated with this modification, but to check the effectiveness of the modifications, the first 20 modules were subjected to the environmental test sequence, 10 at Spectrolab and 10 at JPL. The corrective action taken to eliminate cell breakage was completely effective, however, some electrical degradation during humidity testing was still observed in the environmental tests conducted by Spectrolab indicating an inherent limitation in this particular module design. Test results are summarized in Tables 6 and 7.

Table 1

Comparison of Electrical Performance
After 100 Thermal Cycles -40°C to +90°C
and 168 Hours 90% Relative Humidity 70°C

JPL MODULES 060513-8 REV. A

Module Serial Number	I @ 9.4V Before T Cycle (mA)	I @ 9.4V After T Cycle (mA)	ΔI (mA)	Change (%)	I @ 9.4V After Humidity (mA)	ΔI (mA)	Change %
5042	534.2	534.9	+0.7	+0.1	524.6	-9.6	-1.8
5060	564.2	546.7	-17.5	-3.1	517.0	-47.2	-8.4
5062	534.4	Open	Open	Open	Open	Open	Open
5065	540.0	Open	Open	Open	Open	Open	Open
5068	539.8	522.1	-17.7	-3.3	404.9	-134.9	-25.0
5071	555.6	545.7	-9.9	-1.2	382.1	-208.5	-37.5
5076	560.4	560.3	-0.1	0	468.3	-92.1	-16.4
5079	556.6	560.3	+3.7	+0.7	415.2	-141.4	-25.4
5081	561.6	514.4	-47.2	-8.4	416.6	-145.0	-25.8
5082	561.5	570.9	+9.4	+1.7	437.7	-123.8	-22.0
0377 *	559.2	556.8	+7.6	+1.4	559.7	+0.5	+0.1
0382 *	559.6	558.6	-1.0	-0.2	550.9	-8.7	-1.6
0386 *	536.9	541.6	+4.7	+0.8	531.3	-5.6	-1.0
0388 *	566.1	570.3	+4.2	+0.7	562.9	-3.2	-0.6

*Engineering test module fabricated with RTV 615.

Table 2

SUMMARY OF FATIGUE INSPECTION
AFTER THERMAL CYCLE

JPL MODULE 060513-8 REV. A

<u>Module #</u>	<u>Red Term.</u>	<u>Black Term.</u>	<u>Intercell</u>
388*	yes	yes	1
382*	no	yes	no
377*	yes	no	2
386*	yes	yes	no
	3/4	3/4	3/76 (3.9%)
	75%		
5071	yes	yes	no
5068	no	no	no
5082	yes	yes	2
5042	yes	yes	2
5079	yes	yes	no
5076	no	yes	no
5060	yes	yes	2
5062**	yes	yes	no
5065**	yes	yes	1
5081	no	yes	no
	7/10	9/10	7/190 (3.7%)
	80%		

*Engineering test module fabricated with RTV 615.

**Open

Table 3

SUMMARY OF CELL + GLASS + ALUMINUM DELAMINATION
AFTER THERMAL CYCLE

JPL MODULE 060513-8 REV. A

Sylgard 184 Modules

11

13

6

7

6

10

10

12

11

14

$\Sigma = 100$

Avg = 10 Defects per module

G.E. 615 Modules

7

8

6

6

$\Sigma = 27$

Avg = 6.75 Defects per module

Table 4

Results of Thermal Cycle and Humidity Test
of Solar Power Modules
Made with RTV 615 and S Bend Terminal Leads

Mod. SN	I @9.4V Before T Cycle mA	I @9.4V After T Cycle mA	ΔI	Change %	I @9.4V After Humid. mA	ΔI	Change %
5115	568.3	433.6	-125.0	-22.0	435.5	-132.7	-23.4*
5121	563.5	449.3	-114.2	-20.3	459.1	-104.4	-18.5*
5123	569.2	565.4	-3.8	-0.2	562.9	-6.3	-1.1
5124	572.1	501.0	-71.1	-12.4	514.5	-57.6	-10.1*
5125	576.8	335.2	-241.6	-41.9	339.0	-237.8	-41.2*
5126	567.5	571.6	+4.1	+0.7	539.8	-27.7	-4.9
5133	573.8	572.7	-1.1	-0.2	570.9	-2.9	-0.5
5134	562.5	567.6	+5.6	+0.9	540.0	-22.5	-4.0
5135	569.5	567.8	-1.9	-0.3	568.6	-0.9	-0.2
5136	559.7	563.3	+3.6	+0.6	559.9	+0.2	0

*Broken Cells

Table 5

Summary of Visual Defects after Thermal Cycle and Humidity Test of
Solar Power Modules Made with RTV 615, S Bend Terminal Leads

<u>S/N</u>	<u>Glass Delam.</u>	<u>Cell Delam.</u>	<u>Terminal Delam.</u>	<u>Fatigue</u>	<u>Cracked Cells</u>
5115	2	5	-	1	1
5121	4	3	2	4	1
5123	3	-	2	3	-
5124	7	4	1	1	1
5125	6	6	1	-	2
5126	6	-	-	1	-
5133	3	2	-	3	-
5134	2	2	1	2	-
5135	5	-	2	2	-
5136	3	-	-	3	-
Σ	41	22	9	20	5
$\bar{x}$	4.1	2.2	0.9	2.0	.5
Modules Affected	10	6	6	5	4

Table 6

Comparison of Electrical Performance after 100 Thermal Cycles
-40°C to +98°C and 168 Hours 90% Relative Humidity 70°C

JPL Modules 060513-8, Revision G

Mod. SN	I @9.4V Before T Cycle mA	I @9.4V After T Cycle mA	I mA	Change %	I @9.4V After Humid. mA	I mA	Change Percent
5161	555.7	539.3	-16.4	-3.0	473.9	-81.8	-14.7
5174	574.3	569.9	-4.4	-0.8	536.0	-38.3	-6.7
5235	579.2	578.3	-0.9	-0.2	573.5	-5.7	-1.0
5251	581.3	583.4	+2.1	+0.4	571.2	-10.1	-1.7
5257	554.9	551.5	-3.4	-0.6	533.5	-21.4	-3.9
5277	570.3	567.4	-2.9	-0.5	541.2	-29.1	-5.1
5297	551.3	551.0	-0.4	-0.1	553.3	+1.9	+0.3
5300	537.9	533.1	-4.8	-0.9	473.2	-64.7	-12.0
5384	554.6	548.6	-6.0	-1.1	501.3	-53.3	-9.6
5393	565.7	569.8	+4.1	+0.7	564.2	-1.2	-0.3

Average degradation for ten modules: -5.5%

Table 7

Summary of Visual Defects After Environmental Test

JPL Modules 060513-8, Revision G

<u>S/N</u>	<u>Glass Delam.</u>	<u>Cell Delam.</u>	<u>Terminal Delam.</u>	<u>Fatigue</u>	<u>Lifted Tab</u>
5161	2	5	1	1	0
5174	5	6	0	0	0
5235	4	5	0	2	0
5251	5	9	0	0	0
5257	0	8	2	0	0
5277	1	7	0	1	0
5297	6	5	0	0	0
5300	4	5	0	0	2
5384	5	7	0	2	1
5393	1	7	2	0	0
Σ	33	64	5	6	3
$\bar{x}$	3.3	6.4	0.5	0.6	0.3
Modules Affected	9	10	3	4	2

IV. PRODUCTION ACTIVITIES

A total of 2000 modules were produced and shipped. The initial production shipment was made on May 28, 1976 and consisted of 80 modules. The complete delivery history is given in Table 8.

The distribution of power output of the modules shipped is shown in Figure 2. The distribution appears to have a large kurtosis coefficient, probably caused by a relatively narrow distribution which wandered rather widely during the production run. The average power output under standard test conditions (AM1, 28°C) was 5.29 watts per module with a standard deviation (uncorrected for kurtosis) of 0.3 watts.

During the production phase a number of operational problems were encountered in the assembly and electrical test areas for both these modules and other commercial products. These problems led to an expansion of the module assembly area and a complete reconstruction of the electrical test area. These revisions included the provision of air conditioning in the test area, removal of system assembly activities, enclosure of the Large Area Pulse Solar Simulator in a baffled black tunnel, and the installation of a folding mirror to permit testing circuit assemblies and modules mounted in the horizontal position. These modifications were underway during the latter part of the production phase and were nearing completion as the last modules were being shipped.

Substantially all of the modules were fabricated with RTV 615 as the encapsulant. Some lot to lot variability of the curing time characteristics of RTV 615 was encountered. This resulted in a tendency of some lots of RTV to entrap abnormally large amounts of air in bubbles under the glass cover pane. This tendency was minimized by refining assembly techniques to reduce the amount of air trapped in the RTV prior to mounting the cover pane. By the end of the production run, a substantial reduction had been achieved in the incidence of entrapped bubbles. At one point in the production run a supply shortage of RTV was encountered and it was necessary to fabricate some modules with Sylgard 184 encapsulant.

Table 8

Shipping Schedule

<u>Date</u>	<u>Invoice #</u>	<u>Qty.</u>	<u>Cum. Qty.</u>	<u>Comment*</u>
3/31	9283	10	10	Prototype, Spectrolab Eval.
5/18	9434	10	20	Prototype, JPL Eval.
5/28	9496	10	30	To JPL Eval.
5/28	9497	80	110	
6/25	9581	109	219	
7/16	9657	220	439	
7/28	9720	1	440	Prod. Eval. Module to JPL
7/30	9730	186	626	
7/30	9731	20	646	To JPL Eval.
8/10	9760	44	690	
8/27	9863	555	1245	
9/24	9997	216	1461	
9/30	10021	250	1711	
10/22	10215	280	1991	
		9	2000	Prod. Evaluation to JPL

*All modules shipped to Lewis Research Center unless otherwise indicated.

Figure 2. Distribution of Module Power Output
Module 060513-8, Rev. G

The module design delivered for this contract (Dwg. 060513) was a Spectrolab commercial model and had been designed for use in relatively low voltage systems. During the production phase it was reported to Spectrolab by JPL that electrical breakdown at voltages in the range of 100-500 volts in some modules precluded use in some planned applications involving high voltages. JPL had determined that some modules had small pointed bits of interconnect mesh which had been deformed and were pointing down toward the aluminum substrate. These projecting barbs were found to be sites of electrical breakdown. A technique was developed for rolling the backside of the mesh to flatten projecting pieces of mesh immediately prior to mounting the circuit on the substrate. This procedure was applied to 746 modules shipped on invoice number 9997, 10021 and 10215 (Table 8). To date there has been no subsequent data available to indicate the efficacy of this procedure for improving the voltage breakdown characteristics of the modules.

V. PRODUCTION EVALUATION MODULES

During the production run sample modules were picked at random (1 module for each kilowatt of module capacity produced) to be tested in the environmental test sequence described in Section III.

Electrical and visual test results for the production evaluation modules are reported in Tables 9 and 10 respectively. Three facts stand out in these data: (1) Electrical degradation was more severe and extensive than in the previous pre-production tests. (2) There was more extensive electrical degradation after thermal cycle than in the previous test. (3) The electrical degradations were largely inexplicable in terms of visual defects.

Module 06379 degraded about 11% in thermal cycle. On visual inspection one of the interconnect mesh was found to have 8 of 13 strands with fatigue cracks. The fatigue cracks are, however, suspect as an absolute explanation for the degradation because Module 06668 with a similar fatigue condition degraded by only 4% in thermal cycle, while other modules have large degradation in thermal cycle with no evidence of fatigue damage. Thus, Modules 06676 and 07009 show no fatigue damage and Module 06427 shows only a minor amount.

Considering the humidity test effects, degradation in the cases of S/N 06111, 06379, 06676 and 06427 is perhaps associated with delamination of the aluminum silicone interface adjacent to the terminals. However, this leaves the degradation in the case of S/N 05649, 03787, 04686 and 07009 unexplained. In all cases the extent of cell and glass delamination was, as judged by previous tests, too small to contribute to the humidity degradation.

In an attempt to find another explanation for the degradation, cells were immersed in the components of the silicon potting compound and heated to accelerate any chemical reaction which might occur. Some degradation was observed for cells immersed in RTV 615 hardener for 72 hours at 125°C. This observation is suggestive of chemical reactivity, however, the evidence is not conclusive at this time and extensive analytical testing is beyond the scope of this particular program.

Table 9

Production Evaluation Sample
Electrical Test Results

<u>S/N</u>	<u>I₉₄₀ Original</u>	<u>I₉₄₀[*] after T.C.</u>	<u>% Change</u>	<u>I₉₄₀^{**} After Humidity</u>	<u>% Change</u>
05191	567 mA	562 mA	- 0.9	548 mA	- 3.3
05649	525	558	+ 4.4	457	-13.0
06111	542	522	- 3.7	433	-20.1
06379	539	480	-10.9	343	-36.4
06676	569	476	-16.3	273	-52.0
03787	533	505	- 5.3	428	-19.7
06427	530	477	-10.0	380	-28.3
04686	545	530	- 2.8	456	-16.3
06668	599	575	- 4.0	480	-20.0
07009	532	390	-26.7	194	-63.3

* 100 cycles -40°C to +90°C

** 218 hours 90% R.H., 70°C

Table 10

Production Evaluation Sample
Visual Inspection Results

<u>S/N</u>	<u>Fatigue of Interconnect (good strand/total)</u>	<u>Al Delamination at Terminals</u>	<u>Cell* Delam.</u>	<u>Glass* Delam.</u>
05191	-	-	-	-
05649	none	none	6	0
06111	none	extensive	8	6
06379	1 (8/13)	moderate	7	3
06676	none	extensive	7	2
03787	1 (1/15)	none	6	1
06427	1 (2/14)	extensive	10	0
04686	none	none	4	1
06668	1 (8/14)	none	3	0
07009	none	minor	4	2

*Cell and glass delaminations were all of a minor nature.

VI. RECOMMENDATIONS

As a result of the extensive testing and analysis performed on the modules made in this program, Spectrolab has been able to obtain a great deal of knowledge of the strengths and the limitations of this particular commercial module design and as a result has been able to come up with some recommendations. The recommendations below should help solar cell module designers to develop modules with improved performance, reliability and lower cost.

- A. Eliminate metal substrates in order to improve resistance to electrical breakdown to ground.
- B. Replace silicone encapsulant materials with a more suitable encapsulant. Besides being high cost materials requiring processing methods which will be difficult to automate, silicones have shown technical deficiencies including lot to lot variability in characteristics, high permeability to moisture, a tendency toward poor adhesion (delamination), and a suspected absence of chemical inertness.
- C. Move toward larger size modules to achieve economies of scale.
- D. Use series-parallel circuit configurations to achieve a narrower distribution of module power and more efficient use of the available cell power.