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DOE/JPL/954607-3

DEVELOPMENT AND TESTING OF SHINGLE-TYPE SOLAR CELL
MODULES

Quarterly Report No. 3

By
N. F. Shepard

MASTER

April 5, 1978

Work Performed Under Contract No. NAS-7-100-954607

Space Division
General Electric Company
Valley Forge Space Center
Philadelphia, Pennsylvania

U.S. Department of Energy

Solar Energy

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DEVELOPMENT AND TESTING
OF
SHINGLE-TYPE SOLAR CELL MODULES

MASTER

JPL CONTRACT NO. 954607

PREPARED BY: N. F. SHEPARD
REPORT DATE: APRIL 5, 1978

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The JPL Low-Cost Silicon Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by Agreement between NASA and DOE.

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ABSTRACT

The fabrication and testing phase of the program to develop a shingle-type solar cell module is well underway. Six modules are currently being subjected to a qualification testing program which consists of both thermal cycling and humidity exposures followed by a mechanical integrity test to simulate wind loads.

Fabrication of the remainder of the 50 deliverable modules is proceeding.

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SECTION 1

SUMMARY

The fabrication portion of the program was delayed by late delivery of both solar cells and ASG SUNADEx glass. Early process development problems, mainly related to the bonding of solar cells to the glass coverplate with polyvinyl butyral film, also slowed the progress at the beginning of this reporting period. A laminating process which gives satisfactory PVB bonds on a repetitive basis has been established and fabrication is currently proceeding at the planned rate. To date 18 of the required 50 modules have been completed. The first six modules completed were designated as qualification units and are currently undergoing the thermal cycling portion of the qualification testing program. Figure 1-1 shows the front and rear view of one of these modules (Serial No. SM-1). Figure 1-2 shows the six qualification modules arranged to simulate an installation on a roof surface. Electrical performance measurements on module Serial Number SM-12, which was built from cells with individually measured I-V characteristics, shows that the cell bonding to the embossed glass and encapsulation with white RTV 11 results in a 7.7% increase in module maximum power output when compared to the composite bare cell performance. This module, which uses solar cells with an average bare cell efficiency of 13.3% at 100 mW/cm² insolation and at 28°C, has a measured maximum power output of 5.99 Watts under these same conditions. If this performance is reflected to the calculated Nominal Operating Cell Temperature (NOCT) of 61°C, the resulting module output yields an areal specific power output of 101 Watts/m² of module area at 100 mW/cm² insolation and at the NOCT.

(a) Front Side (Photo No. VF 78-169A)

(b) Rear Side (Photo No. VF 78-169C)

Figure 1-1. Photographs of Shingle Solar Cell Module Serial No. SM-1

Figure 1-2. Arrangement of Qualification Modules to Simulate Installation on a Roof
(Photo No. VF 78-169B)

SECTION 2

INTRODUCTION

The general scope of work under this contract involves the design, development, fabrication and testing of a solar cell module which is suitable for use in place of shingles on the sloping roofs of residential or commercial buildings. Modules of this type employ a semi-flexible substrate which is suitable for mounting on an independent rigid surface such as plywood roof sheathing. As specified in the contract statement of work, these modules shall be capable of producing an electrical power output of 80 W/m^2 of installed module area at a module temperature of 60°C with an insolation of 1 kW/m^2 . The installed weight of these shingle-type modules shall not exceed 250 kg/kW of peak power output. As a design goal these modules shall be designed for a service life of at least 15 years. An implicit requirement is that the shingle not sustain damage during the normal handling associated with installation on a roof. The vulnerability to the localized bearing loads associated with walking or kneeling on the installed shingles does not constitute a design requirement but will be assessed as part of this development effort. The program is organized into six major tasks as given below.

<u>Task No.</u>	<u>Description</u>
1	Substrate Evaluation and Testing
2	Solar Cell Tray Evaluation and Testing
3	Module Interconnection and Testing
4	Shingle Module Design
5	Fabrication and Acceptance Testing of Modules
6	Qualification Testing of Modules

Activity on the last two of these tasks is about half completed at this time. Task 6 has been recently modified by a redefinition of the mechanical integrity position of the qualification testing program.

Some minor changes in the shingle module design have been made, as described in Section 3.1, as a result of experience gained during the early phases of the fabrication cycle.

SECTION 3

TECHNICAL DISCUSSION

The major emphasis of this discussion is on the manufacturing processes which have been developed to produce a very limited quantity of shingle modules of the design described in the last quarterly report.

3.1 DESIGN CHANGES

The module design has been changed in several areas to overcome problems which surfaced during the fabrication of the first modules. These changes include the following:

1. The use of two disks of SAFLEX SR-10 (0.030 inch total thickness) on each cell was found necessary to achieve a void-free bond of the cells to the glass coverplate. The original choice of a single 2.00-inch diameter disk of SAFLEX PT-10 was found to produce voids and bubbles during lamination. Two 1.75-inch diameter disks of SR-10, which has more plasticizer than the PT-10, were found to produce void and bubble-free bonds with reasonable control of run-out around the cell circumference. The processing steps for this cell bonding are described in Section 3.3.2.
2. The flexible printed circuit board within the substrate was made larger to cover the entire area of the substrate. This was found necessary to reduce the tendency for bubbles to form under the FLEXSEAL skins upon exposure to elevated temperatures.
3. The encapsulant was changed from RTV77 to RTV11. The RTV77 was found to be too viscous to deaerate properly.
4. The primer on the rear side of the glass coverplate and cells was changed from SS-4124 to SS-4044 followed by a spray coating of RTV108 (10 to 20 % by weight) mixed with heptane.

3.2 SOLAR CELL PERFORMANCE

The electrical performance distribution of the cells received from Spectrolab is given in Table 3-1. As measured by Spectrolab, these cells have an average electrical performance of 569 mA at 0.475 Volt when measured at 100 mW/cm² insolation and 28°C. A random sample of 66 cells from this group yielded an average performance of 595 mA at 0.475 Volt under these same test conditions when measured by GE using Terrestrial Secondary Standard No. 025 as the reference.

Table 3-1. Electrical Performance of Production Solar Cells as Measured by Spectrolab

Range of Output Current Group (mA at 0.475 V)	Quantity of Solar Cells In Group
510 - 519	69
520 - 529	95
530 - 539	108
540 - 549	115
550 - 559	120
560 - 569	127
570 - 579	164
580 - 589	147
590 - 599	146
600 - 609	97
610 - 619	72
620 - 629	27
630 - 639	13

3.3 MODULE FABRICATION

3.3.1 SOLAR CELL SOLDERING

Soldering of the interconnector to the solar cell "N" contacts is the first step in the assembly sequence. The solder-plated copper interconnector is performed with the strain relief loop prior to this step. Figure 3-1 shows the "N" contact soldering operation with the solar cell and interconnector held in the correct relative position in a soldering fixture. During process development, joints were made at several soldering iron temperatures in order to determine the effect of this parameter on the resulting contact pull strength. Table 3-2 summarizes the results of these measurements for a 45 degree pull angle between the cell and the interconnector strip. A soldering iron temperature of 590°F was found to give satisfactory results. In all cases joint failure occurred by a separation of the cell metalization from the silicon wafer.

Figure S-1. Soldering of Solar Cell "N" Contacts
(Photo No. VF78-127B)

Table 3-2. 45° Contact Pull Test Results on Spectrolab Cells

Solder Type	Soldering Iron Temperature (°F)	"N" Contact Pull Strength (grams)	Remarks
Sn 60	700	397	20% Ag/Si separation
Sn 60	700	397	80% Ag/Si separation
Sn 62	640	1049	30% Ag/Si separation
Sn 62	640	368	100% Ag/Si separation
Sn 62	590	1049	Cell broke
Sn 62	590	822	Interconnect broke at hole
Sn 62	590	709	80% Ag/Si separation
Sn 62	590	737	100% Ag/Si separation
Sn 62	590	567	100% Ag/Si separation

Following "N" contact soldering the cells are cleaned ultrasonically to remove traces of flux.

Soldering of the "P" contact at three places per cell occurs following bonding of the 19-cell array to the glass coverplate. No positioning fixture is required for this operation since the cells are securely bonded to the glass with the PVB film.

3.3.2 SOLAR CELL BONDING

The bonding of the solar cells to the embossed surface of the tempered glass coverplate is the next assembly step. The 19 cells are loaded in the module bonding fixture as shown in Figure 3-2. This fixture, which has a pocket for each cell, controls the linear positioning of each cell within the module as well as the angular orientation of each cell. A series of holes drilled into an internal cavity permits the later application of vacuum to the space between the fixture and the glass coverplate. A thermocouple has been embedded within the fixture to enable monitoring of plate temperature during the subsequent bonding operation.

Figure 3-2. Loading of Bonding Fixture
(Photo No. VF73-127A)

Two disks of 1.75-inch diameter SAFLEX SR-10 polyvinyl butyral are next centered on the top of each solar cell. One surface of this product is grooved to enhance the escape of air during vacuum lamination. This surface of each of the two disks is placed in contact with the glass or solar cell.

A glass coverplate is positioned on top of the cells and PVB disks and taped to the bonding fixture around the perimeter with high temperature TEFLON tape. This fixture is then placed on a preheated hot plate as shown in Figure 3-3 (a). An insulation blanket is placed on top of the glass to reduce heat loss from the coverplate surface as shown in Figure 3-3 (b). A thermocouple is placed at the center of the module between the glass coverplate and insulation blanket. The insulation blanket reduces the temperature difference between the fixture and the glass coverplate and produces a more uniform flow-out of the PVB from cell-to-cell across the module.

Table 3-3 gives the temperature-vacuum profile which has been developed to give satisfactory bonds with two disks of SAFLEX SR-10 as described above. Figure 3-4 shows front and rear views of the glass coverplate for Module Serial No. SM-2 following cell bonding and soldering of the interconnectors to the "P" contacts.

Initial attempts to bond cells to the glass coverplate with a single disk of 2.00-inch diameter SAFLEX PT-10 proved to be unsuccessful in terms of the repeatability of obtaining a void-free lamination. The thickness of the PVB was doubled by adding another 2.00-inch disk of PT-10 to each cell. This approach was successful in eliminating the large area voids in the lamination, but bubbles continued to be a problem. Attempts were made to dissolve these bubbles by subjecting the coverplate assemblies to an autoclave cycle which consisted of a pressure of 180 psi at 300°F. The coverplates were maintained at this temperature and pressure for at least 30 minutes before the temperature was allowed to decrease. The pressure was maintained until the coverplate temperature was below 120°F. This cycle was successful in eliminating entrapped bubbles, but in some cases these bubbles reappeared following overnight soak at ambient conditions. Some yellowing of the PVB where it runs out around the circumference of the cells was also a result of the autoclave cycle. Since this autoclave step is

(a) Without Insulation Blanket (Photo No. VF78-127G)

(b) With Insulation Blanket (Photo No. VF78-127E)

Figure 3-3. Solar Cell Bonding Operation

Table 3-3. Typical Cell Bonding Cycle

Elapsed Time (minutes)	Fixture Temperature (°F)	Coverplate Temperature (°F)	Vacuum (in. Hg Gauge)	Remarks
0	75	75	0	Place on hot plate
6	150	110	5	
14	200	170	10	
16	220	190	20	
22	250	225	27	
38	285	266	0	Vent for 2 minutes
40	285	268	27	
84			0	Remove for hot plate and cool

an expensive addition to the processing sequence, efforts were made to obtain bubble-free bonds directly. To this end, the change to SAFLEX SR-10, which has more plasticizer and better flow characteristics at lower temperature, has resulted in satisfactory bonds without the need for an autoclave processing step. Experiments with the diameter of the SR-10 disks, which included 2.00, 1.87, and 1.75 inch diameters, has led to the selection of two 1.75-inch diameter disks. This selection provides nearly bubble-free bonds with limited run-out around the cell circumference and virtually no underrun.

3.3.3 SUBSTRATE LAMINATION

The lamination of the semi-flexible substrate, which is the next step in the processing sequences, involving bonding the outer FLEXSEAL skins to the epichlorohydrin foam core and to the two-sided flexible printed circuit board. The B. F. Goodrich FLEXSEAL contact adhesive system, which was selected for this application, has been found to give satisfactory results if care is exercised when the initial contact is made between the adhesive-coated surfaces. Waxed paper is slipped between these surfaces so that proper alignment can be achieved before contact is made. This paper interlayer is then gradually pulled out while the surfaces are rolled together along a line to minimize the amount of entrapped air pockets.

(a) Front (Photo No. VF78-127H)

(b) Back (Photo No. VF78-127C)

Figure 3-4. Coverplate/Solar Cell Assembly for Module Serial No. SM-2

The flexible printed circuit board substrate material has been made large enough to cover the entire area of the foam core. This change was found necessary to reduce the formation of bubbles under the FLEXSEAL skins when the module is exposed to elevated temperatures.

3.3.4 MODULE ENCAPSULATION

The encapsulation of the module and the bonding of the rear TEXTOLITE cover are both accomplished using RTV11. The rear side of the glass coverplate and solar cells are primed with SS-4044 followed by a spray coating of RTV108 (10 to 20% by weight mixed with heptane). The RTV11 is mixed, deaerated and poured over the rear surface of the glass coverplate assembly. The material is spread over the entire glass surface until the height of the silicon just covers the interconnector strain relief loops. The spread RTV11 is again deaerated in a large vacuum enclosure to remove entrapped bubbles. The RTV11 is allowed to cure before the rear TEXTOLITE cover, which has been previously primed with SS-4044, is bonded on using RTV11 as the adhesive.

3.4 MODULE ELECTRICAL PERFORMANCE

Table 3-4 summarizes the electrical performance measurements made to date using the Large Area Pulsed Solar Simulator (LAPSS) with JPL-supplied Terrestrial Secondary Standard No. 025 used as the reference cell. Figure 3-5 is an example of one such I-V characteristic as obtained using this simulator. The median performance of the modules measured to date is 5.90 Watts at the maximum power point.

Module Serial Number SM-12 has been built using solar cells which has been previously serialized and illuminated to determine the I-V characteristic for each cell. The use of these cells permits the accurate determination of the absolute gain due to covering and encapsulation. Table 3-5 gives the voltage reading for each cell at four current values which bracket the maximum power point of the cells. The sum of the values for all 19 cells at each of these four currents yields the composite module characteristic with no coverplate. The overall module performance with bare cells is 5.56 Watts at the maximum power point voltage of 9.25 Volts. This equates to an average bare cell efficiency of 13.3 % based on a nominal total solar cell area of 419.2 cm².

Table 3-4. Summary of Module Electrical Performance Measurements *

Module Serial Number	I _{SC} (mA)	V _{OC} (Volts)	V _{MP} (Volts)	P _{MAX} (Watts)
SM-1	705	11.3	9.10	5.32
SM-2	720	11.7	9.30	6.05
SM-3	702	11.7	9.30	5.90
SM-4	713	11.8	9.30	6.01
SM-6	719	11.7	9.25	5.79
SM-7	707	11.5	9.25	5.68
SM-10	713	11.7	9.30	5.92
SM-12	713	11.7	9.30	5.99
SM-18	702	11.7	9.40	5.88
SM-19	697	11.6	9.30	5.83
SM-21	706	11.6	9.40	6.02
SM-22	706	11.6	9.30	5.91
SM-23	704	11.6	9.30	5.90

* At 100 mW/cm² using Terrestrial Secondary Standard No. 025 as the reference cell. Cell temperature corrected to 28°C.

Figure 3-5. I-V Characteristic for Module Serial Number SM-4

Following the bonding of these cells to the embossed surface of an ASG SUNADEx glass coverplate with PVB film, the I-V characteristic of the entire module was measured before encapsulation with RTV11. Figure 3-6 shows this characteristic both before and after encapsulation with the white silicone pottant. Prior to encapsulation the enhancement in maximum power output is calculated to be 2.3% based on the composite characteristic of the 19 bare solar cells. Following encapsulation, this enhancement is increased to 7.7% compared to the same composite bare cell characteristic.

It should be noted that this is the net enhancement, which includes the transmission and reflection losses associated with the glass and PVB. The exposed surface of the glass coverplate was untreated. The addition of a suitable antireflective coating to this outside surface could further augment the module output by an additional 1.5 to 2.0%.

Table 3-5. Performance of Individual Solar Cells in Module Serial No. SM-12 *

Cell Position	Cell Identification Number	Voltage at Specified Current (Volts)			
		575 mA	600 mA	625 mA	650 mA
1	580-1	0.497	0.485	0.466	0.432
2	590-1	0.504	0.488	0.460	0.350
3	590-2	0.497	0.485	0.467	0.440
4	590-3	0.504	0.490	0.468	0.420
5	600-1	0.508	0.493	0.470	0.410
6	600-1	0.512	0.500	0.485	0.452
7	590-8	0.503	0.487	0.460	0.400
8	570-13	0.495	0.480	0.456	0.400
9	600-2	0.508	0.495	0.473	0.420
10	610-1	0.502	0.492	0.474	0.442
11	610-2	0.507	0.495	0.476	0.437
12	580-2	0.495	0.480	0.454	0.390
13	580-5	0.500	0.487	0.460	0.385
14	620-1	0.499	0.486	0.469	0.435
15	580-3	0.500	0.488	0.470	0.423
16	580-7	0.499	0.482	0.452	0.350
17	580-9	0.499	0.485	0.456	0.375
18	580-12	0.498	0.484	0.465	0.407
19	590-10	0.500	0.483	0.455	0.375
Total Voltage		9.52	9.27	8.84	7.74
Measured on SM-12 Before Encapsulation		9.72	9.50	9.00	8.00
Measured on SM-12 After Encapsulation		10.00	9.80	9.30	9.22

* At 100 mW/cm² insolation and at 28°C

Figure 3-6. I-V Characteristics of Module Serial No. SM-12
Before and After Encapsulation

SECTION 4

CONCLUSIONS

A shingle module, which uses solar cells with an efficiency of 13.3 % at 100 mW/cm² insolation and at 28°C, will produce an areal specific power output of 101 Watts/m² of exposed module area at the calculated Nominal Operating Cell Temperature (NOCT) of 61°C. This high specific power output can be attributed to the efficient packing of the circular cells within the hexagon shape and to the enhancement of the output due to the reflected light from the embossed glass pattern in the white interstices. An enhancement of 7.7 %, compared to bare cell performance, has been measured on a shingle module of this design. Another way of looking at this enhancement is that the white interstices, which amount to 87 cm² per module, perform as solar cells with an efficiency of about 5%.

SECTION 5

RECOMMENDATIONS

An outdoor exposure test of an assembly of shingle modules would seem appropriate to determine if the design is watertight for roof slope angles from 30 to 40 degrees. The simulated roof section to be built for the mechanical integrity testing could be adapted for this purpose by constructing a small gable roof with this test specimen as the south facing surface. Additional dummy modules, which do not contain solar cells, could be added to cover the available area.

SECTION 6
NEW TECHNOLOGY

The following New Technology disclosures have been reported to JPL:

1. Descriptive Title: A Zero Depth Solar Photovoltaic Concentrator
Date Submitted: November 14, 1977
Name of Innovator: N. F. Shepard, Jr.
References: Quarterly Report No. 2-DOE/JPL 954607-78/2, pages 3-14, 3-15, 6-1
2. Descriptive Title: Interconnector for Overlapping Solar Cell Modules
Date Submitted: March 23, 1975
Name of Innovator: N. F. Shepard, Jr.
References: Quarterly Report No. 2-DOE/JPL 954607-78/2, pages 3-11, 3-13, 3-29, 3-32, 3-33, 3-34
3. Descriptive Title: Embossed Glass-Covered Shingle Solar Cell Module
Date Submitted: March 23, 1978
Name of Innovator: N. F. Shepard, Jr.
References: Quarterly Report No. 2-DOE/JPL 954607-78/2, pages 1-1, 1-2, 3-1 through 3-16