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# SPRAYLON FLUOROCARBON ENCAPSULATION FOR SILICON SOLAR CELL ARRAYS

PHASE III
FINAL REPORT

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Prepared For

NASA-JPL
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# FOREWORD

This document was prepared by the Thermophysics Group of Thermal Sciences in the Materials Sciences Laboratory of Lockheed Palo Alto Research Laboratory of the Lockheed Missiles & Space Company for NASA-JPL as a Phase III final report. The work was administered under the technical direction of Mr. E. N. Costogue, JPL Program Manager, and Dr. M. McCargo, Program Manager. The technical effort was conducted by L. G. Naes, Project Leader.

## ABSTRACT

This program was a research and development program to evaluate the Lockheed-formulated liquid transparent film-forming, fluorocarbon, SPRAYLON, protective coating for terrestrial solar cell modules.

Two modules were completed and field-tested for periods of up to two weeks. Problems developed early in the field testing which led to the shortened test period, specifically, lifting of the antireflection coating, followed in some areas by complete film delamination. It is believed that although these problems were certainly induced by the presence of the SPRAYLON film, they were not failures of the material per se. Instead, assembly procedures, module design, and cell coating quality should be evaluated to determine cause of failure.

As a consequence of these early failures, direction was received to stop all work on the program immediately. No in-depth failure analysis was performed.

## ACKNOWLEDGMENTS

Contributions by three individuals were greatly appreciated throughout this entire program.

Mr. Paul Dillard, LMSC Electrical Power-Systems, aided in the design and assembly of the SPRAYLON modules. His experience and knowledge of materials and photovoltaic systems was of great value during development testing.

Mr. Dave Vance and Dr. Stan Greenberg, LMSC Thermophysics Laboratory, were responsible for application of the SPRAYLON encapsulant. In addition, their intimate knowledge of the SPRAYLON encapsulant helped to assess some of the SPRAYLON-related problems encountered during testing.

## CONTENTS

# ILLUSTRATIONS

# TABLES

# Section 1
# INTRODUCTION

During the past 10 years, considerable effort has been spent by LPARL to help develop a low-cost, lightweight replacement for the conventional fused silica cover glass which is presently being used on extraterrestrial solar arrays.

In 1968 (Ref. 1), LMSC developed a unique solar cell cover system to directly replace the costly and cumbersome fused silica cover glasses. These covers consisted of clear FEP (fluorinated ethylene propylene) films heat-sealed directly onto the bare solar cells, at moderate pressures with temperatures in the range of 235°C to 300°C. Test results have been obtained at LMSC using 5-mil FEP films applied directly by heat-sealing techniques to solar cells. In general, the operating characteristics (I-V curves) of the bare and 5-mil FEP-coated cells have been shown to be essentially equivalent. The emittance of such coated cells ($\epsilon = 0.85$) was slightly greater than adhesive-bonded 6-mil fused quartz, $SiO_2$ ($\epsilon = 0.83$) and no significant changes in optical properties had been observed after 1500 equivalent sun hours of ultraviolet.

An improved system has been developed that could be applied by standard paint techniques (spraying, brushing, rolling, or dipping), and simultaneously provide the required optical, physical, and environmental properties. DuPont's powder coating (Ref. 2) could be used to deposit films of FEP, but the processing temperature in excess of 330°C poses the same processing problems associated with the FEP film. To alleviate many of the problems incurred in the heat-sealing process, this laboratory conceived a variation on the clear fluorocarbon film application technique. This approach, designed SPRAYLON, is based on the ability to apply a transparent fluorocarbon plastic coating from solution by conventional paint techniques followed by processing at moderate temperatures (150°C), compatible with soldered interconnects.

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Ref. 1. LMSC to NASA/Lewis Research Center, Research Brief, Mar 1968
Ref. 2. E. I. du Pont de Nemour and Co. (Inc.), Technical Products Bulletin FEP 532-5001, Wilmington, Delaware

This report describes the follow-on work, Phase III, of a continuing developmental program for the evaluation of the Lockheed-formulated liquid transparent film-forming fluorocarbon (SPRAYLON) for use as a silicon solar cell encapsulant material. Phase III of this program focuses on evaluating SPRAYLON as a potential terrestrial solar cell module encapsulant in support of the Low Cost Solar Array Project (LSA) directed by the Jet Propulsion Laboratory for the Department of Energy. This program calls for fabrication of 12 each modules, each designed to provide 18 W minimum at 18.5 V (28°C at AM1). Six each modules are to be deliverable immediately to JPL for testing at JPL's direction. Of the remaining six modules, three are to be placed into the LMSC Outdoor Solar Test Facility for a period of up to six months for outdoor field testing. The remaining three modules are to be subjected to a series of controlled environmental testing including thermal cycling, relative humidity, mechanical integrity, and warp, bow, and twist.

In preceding work, Phase I and Phase II, the efforts were directed towards the development of SPRAYLON primarily for use on extraterrestrial solar arrays. The work completed is documented in the final reports LMSC-D558143 and LMSC-D564461, both entitled, "SPRAYLON Fluorocarbon Encapsulation for Silicon Solar Cell Arrays (June 1977 and October 1977). In these reports, a complete description of pertinent optical, mechanical, physical, and environmental properties of SPRAYLON can be found.

# Section 2
# TECHNICAL PROGRAM

## 2.1 PROGRAM OBJECTIVE

The purpose of this program was to assess the Lockheed-developed SPRAYLON fluorocarbon protective film as a candidate encapsulation system in terrestrial applications. To achieve this objective, terrestrial solar photovoltaic modules incorporating SPRAYLON as the cell encapsulant were to be designed, fabricated, and subjected to a series of both field and laboratory environmental tests.

The modules acted as the test bed for the SPRAYLON evaluation. As such, no extensive study was made to optimize the module design in terms of either cost or performance. Instead, the module design developed by Lockheed under JPL Contract No. 954653, currently undergoing test at JPL as part of the Low-Cost Solar Array program, was selected as the design baseline. Changes in design were necessary in order to incorporate SPRAYLON as the encapsulant system.

## 2.2 MODULE DEVELOPMENT

The module design philosophy applied during this program was to select a design that was both compatible with an evaluation of SPRAYLON as encapsulant, and yet could interface with most of the existing hardware and tooling fabricated under JPL Contract No. 954653, Terrestrial Solar Cell Module Development. Successful test data on the module design finalized in the above contract seemed good reason to justify using it as a baseline design for the SPRAYLON module, and use of the existing hardware and tooling would help keep costs to a minimum.

A detailed description of the baseline design is found in the JPL Contract No. 954653 final report, "Transparent Superstrate Terrestrial Solar Cell Module," ERDA/JPL-954653-77/1. By way of summary, 41 cells were solder-interconnected into a single-series string with flat copper interconnects and front-surface-bonded to the back of a high-transmission glass with a clear silicon adhesive. The back of the cells were potted with a silicone which acted as both the cell and interconnect encapsulant. Solar energy was incident to the cell's active surface through the glass and adhesive layers.

In the SPRAYLON modules, the cells were mounted on the front surface of the glass substrate with SPRAYLON encapsulant providing protection over the front surface of the cells and interconnects. Some development testing was needed to determine the best encapsulation approach, e.g., over the entire module after cell-bonding or before cell-bonding on an individual cell/interconnect basis. Further, selection of adhesive, as well as application technique, had to be determined because some adhesives were incompatible with the primer used in the SPRAYLON application process.

2.2.1 Materials

2.2.1.1 Solar Cells. The main concern regarding the selection of solar cells for this program was that they be the testing medium for evaluation of the SPRAYLON encapsulant. Selection of cell vendor and particular sizing required to optimize power output were not part of this effort. Rather, the technology developed in JPL Contract No. 954653 was utilized which prompted the selection of a 3-in.-diameter cell from either Spectrolab or Optical Coating Laboratories, Inc. (OCLI).

The OCLI was selected for use in this program, primarily because of the contact deposition method. OCLI used evaporated and sintered TiPdAg contacts while Spectrolab cells used a silk-screened contact. Although SPRAYLON had been applied over cells that did have silk-screened contacts, the selection of the more rugged evaporated contacts was felt desirable. The OCLI, 3-in.-diameter cells (0.017-in.-thick) also employed a polished front surface that was coated with a silicon oxide (SiO) antireflection coating to enhance solar absorptance.

Seventeen candidate cells were sent to Lockheed Palo Alto Research Laboratory (LPARL) by OCLI for preliminary electrical and mechanical screening. The cells delivered were 3.05 in. in diameter, too large to fit into the handling tools. OCLI was notified of this problem and corrected for it with delivery of the final product.

Current-voltage relationships were made on all 17 candidate OCLI bare 3.05-in.-diameter cells. Measurements were performed at 28°C and 60°C cell temperatures at standard AM1 incident-simulated solar (100 $mw/cm^2$) with an X-25 continuous illuminator lamp. The average current output $\pm 1\sigma$ standard deviation is shown in Figs. 2-1 and 2-2. By way of summary, maximum power output per cell was 0.492 W at 0.442 V at 28°C, dropping to 0.418 W at 0.377 V.

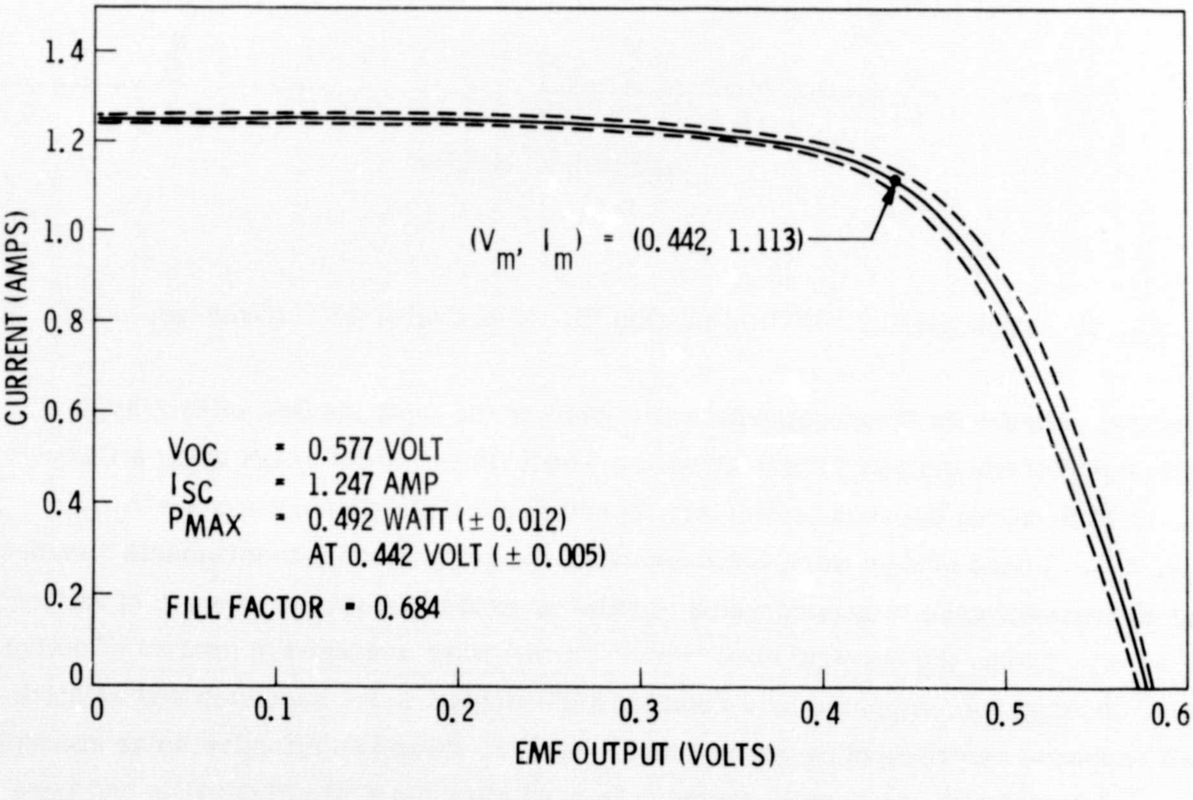


Fig. 2-1 Voltage-Current Relationship for OCLI Cells, 28°C (Average; $\pm 1\sigma$)

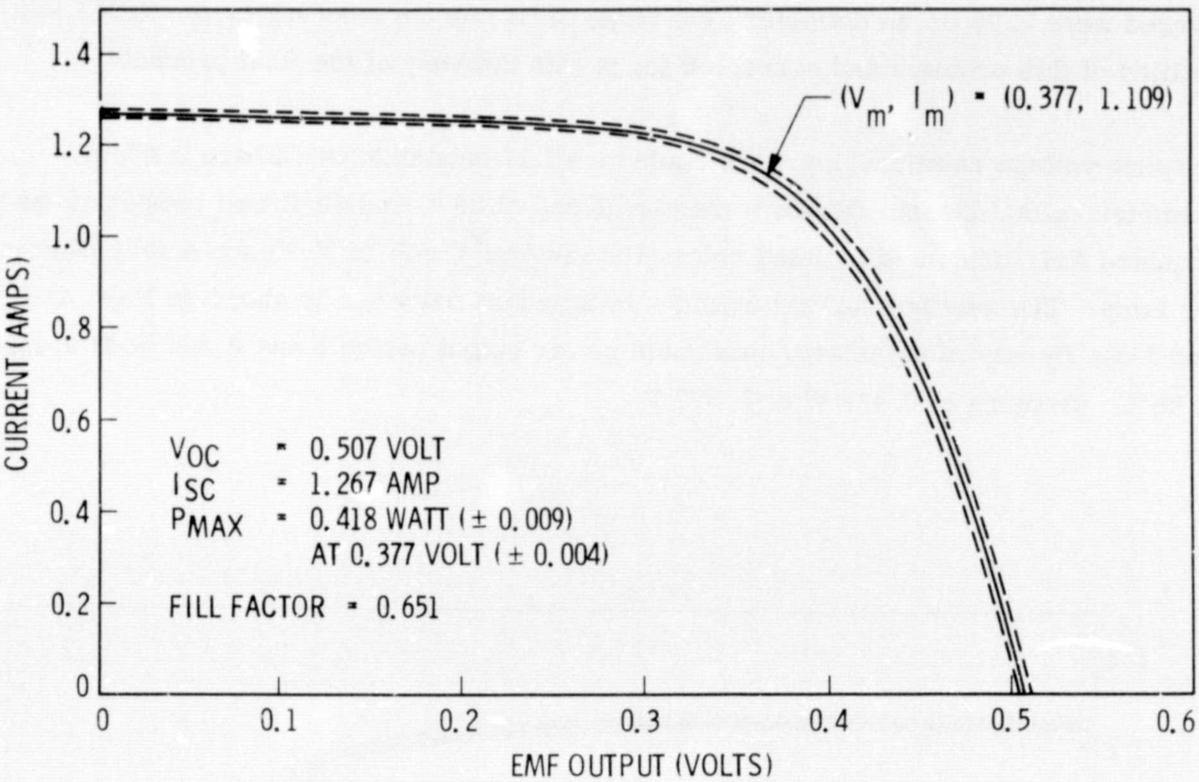


Fig. 2-2 Voltage-Current Relationship for OCLI Cells, 60°C (Average; $\pm 1\sigma$)

Spectral reflectance measurements were made on the front surface of two "typical" cells both before and after application of a 3-mil film of SPRAYLON using a Cary Model 14 Scanning Spectrophotometer. Spectral absorptance curves are shown in Fig. 2-3. These curves were evaluated from the reflectance measurements assuming no transmittance to occur, which is valid up to the bandgap wavelength of silicon (1.1 $\mu$m). Then, the spectral absorptance curves were averaged to give an effective solar absorptance, weighted by a relative AM1 incident solar spectrum and relative cell response as provided by vendor data. Results showed an effective solar absorptance of 0.88 for the bare cell, dropping to 0.86 after the SPRAYLON film had been applied giving a net change of -1.5 percent in energy absorbed. This value was used to predict the change in module electrical characteristics due to the influence of SPRAYLON.

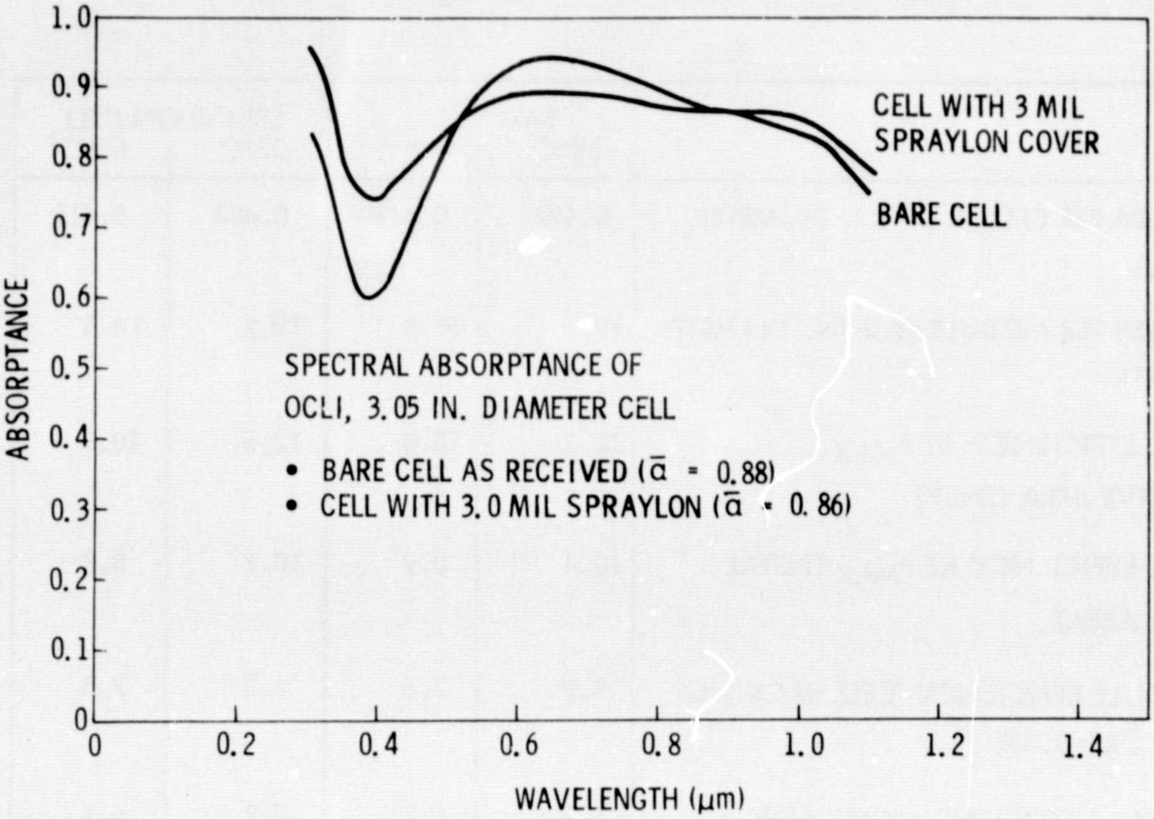


Fig. 2-3 Spectral Absorptance of OCLI 3.05 in. Diameter Cell

In Table 2-1, expected module performance and efficiency are summarized for both bare cells and cells covered with SPRAYLON. Expected performance at 28°C is 19.2 W with a module efficiency of 7.2 percent.

In addition to the 17 candidate solar cells, five cells were received that had no anti-reflection coating deposited on the cell's front surface. Spectral reflectance (converted to absorptance) measurements were performed on these cells both before and after the application of a 3-mil SPRAYLON film using the Cary Model 14 Scanning

Table 2-1

ELECTRICAL PERFORMANCE

| | BARE CELL 28°C | BARE CELL 60°C | SPRAYLON CELL 28°C | SPRAYLON CELL 60°C |
|---|---|---|---|---|
| POWER PER CELL (3.05-IN. DIAMETER CELL) | 0.492 | 0.418 | 0.484 | 0.411 |
| POWER PER MODULE (3.0-IN. DIAMETER CELLS) | 19.5 | 16.6 | 19.2 | 16.3 |
| CELL EFFICIENCY AT $P_{MAX}$ (ACTIVE AREA ONLY) | 12.7 | 10.8 | 12.5 | 10.6 |
| CELL EFFICIENCY AT $P_{MAX}$ (TOTAL CELL AREA) | 10.4 | 8.9 | 10.2 | 8.8 |
| MODULE EFFICIENCY (CELL PACKING FACTOR = 0.858) | 8.9 | 7.6 | 8.8 | 7.5 |
| MODULE EFFICIENCY (CELL AND FRAME PACKING FACTOR = 0.700) | 7.3 | 6.2 | 7.2 | 6.1 |

Spectrophotometer, see Fig. 2-4. Average solar absorptance weighted for cell response for the two cases are $\alpha = 0.66$ for a bare cell and $\alpha = 0.77$ for the SPRAYLON-coated cells, an increase of 19.5 percent. This increase in absorptance is obviously due to the intermediate index of refraction between air and silicon exhibited by the SPRAYLON ($\eta = 1.54$). It should be pointed out that the front surface of these cells was polished silicon, not texture-etched. The texture-etched cells should exhibit an even greater bare cell absorptance, quite possibly, high enough to eliminate the need for an antireflection coating. This was important because the

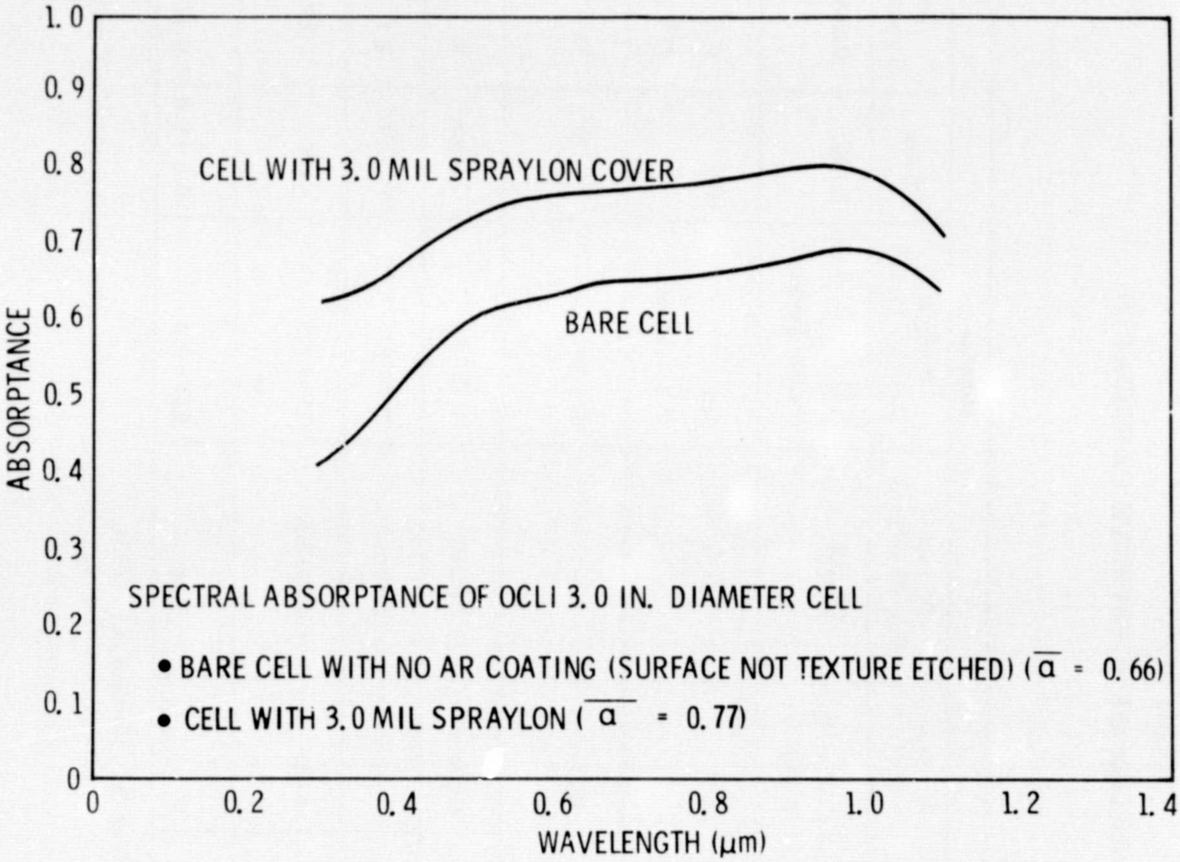


Fig. 2-4 Spectral Absorptance of OCLI 3.0 in. Diameter Cell

SPRAYLON film causes surface tensions on the order of 8000 psi to exist in the plane of the cell surfaces. This stress must be accommodated by the antireflection coating because the SPRAYLON bond is, in actuality, to the coating and not to the cell.

2.2.1.2 Substrate. Several candidate substrate materials were considered including glass, aluminum plate, PC board, and acrylics. Table 2-2 shows a summary of pertinent material properties for these materials. In the case where the cells were mounted on top of the substrate, the primary substrate requirements were

Table 2-2

MATERIAL PROPERTIES OF SUBSTRATE CANDIDATES

| Property, Units | Material | | | | | |
|---|---|---|---|---|---|---|
| | Glass. | Aluminum 6061 | PC Board Glass Fiber/Epoxy | Plexiglas (Acrylic, #5.68) | Epoxy | Lexan (Polycarbonate) |
| Cost, \$1 in.$^3$ or (\$ per 2 ft x 2 ft x 1/8 in piece) | (2.60) | 0.07 (6.50) | (17.60) | 0.02 (13.00, 3/8 in.) | 0.025 | 0.043 |
| Weight, lb for 2 ft x 2 ft x 1/8 in. piece | 6.5 | 7.1 | 5.1 | 9.3 (3/8 in. thick) | 4.9 | 9.6 (3/8 in. thick) |
| Coefficient of thermal expansion, per °F x $10^{-6}$ (Silicon = 2.6) | 4.7 | 13.1 | – | 30 – 40 | 10 – 20 | 18 – 38 |
| Luminous Transmittance (1/8 in.), % | 90 | Opaque | Opaque | > 92 | Opaque | 88 |
| Modulus of Elasticity in Flexure, $10^5$ psi | 100 | – | 28 – 31 | 3.5 – 5 | 15 – 25 | 3.1 – 5 |
| Maximum Recommended Service Temperature °F | 550 | > 500 | 450 – 500 | 155 – 190 | < 400 | < 250 |
| Water Absorption (24 hr), % | 0 | 0 | 0.10 | 0.3 – 0.4 | 0.3 – 0.8 | 0.12 – 0.19 |

(a) Primary Source: Materials Selector 76, Rheinhold Publishing Co., Stamford, CT, 06904.

good structural rigidity and strength over a wide temperature range, a good coefficient of thermal expansion match with the silicon solar cell, and low cost.

The substrate selected was 1/8-in.-thick ASG Industries, Sunadex, low-iron content tempered-glass. The glass was precut by the manufacturer to 44.25-in. by 8.75-in. sizes, enabling utilization of most of the existing assembly tooling.

Suitable optical properties also were required of the substrate material to help maintain as cool a module temperature as was practical. Specifically, either a high solar transmittance or reflectance coupled with a high room-temperature emittance was desirable.

Using the optical properties listed in Table 2-3, a one-dimensional thermal analysis was performed to determine steady-state cell temperatures. Under an assumed worse-case 100 $mW/cm^2$-incident solar heat flux at an ambient (still air) temperature of 32°C, it was found that the cells would reach 68.8°C. If a 2- and 5-MPH wind were allowed to be incident to the front surface of the module, the cell temperature would drop to 61.4°C and 53.3°C, respectively (2- to 5-MPH wind velocity conditions are expected most of the time in the outdoor LPARL Solar Test Facility). In addition, a sensitivity analysis under zero velocity wind conditions showed the cell temperature to change 0.45°C/mW of incident solar isolation and 0.87°C/°C change in ambient air temperature.

Table 2-3
SPRAYLON MODULE OPTICAL PROPERTIES

| | |
|---|---|
| Cell/SPRAYLON Solar Absorptance | 0.86 |
| Cell/SPRAYLON Infrared Emittance | 0.87 |
| SUNADEX Solar Transmittance | 0.91 |
| SUNADEX Solar Reflectance | 0.09 |
| SUNADEX Infrared Emittance | 0.85 |

2.2.1.3 Adhesive. The general properties required of the cell-to-substrate adhesive include:

- Compatibility with SPRAYLON application
- Good adhesion between the glass and solar cells
- Low modulus over wide temperature range enabling bond integrity during thermally induced stresses
- Ability to cure in large, thin unexposed areas
- Low moisture permeability

The baseline design used Dow Corning Sylgard 184; however, procedure problems encountered during assembly forced a change to a "B"-staged epoxy cloth. Three-mil, AF126 pre-pegged epoxy cloth was selected for use on the SPRAYLON module.

2.2.1.4 Interconnects. The interconnect design incorporated in this program was the in-plane stress-relieved design developed under JPL Contract No. 954653. A slight modification was made in the N-tab attach point design because of a slightly different grid pattern OCLI had selected for these cells. The change affected only that portion of the interconnect over the N-side grid and should not have changed any of the stress relief characteristics of the interconnect.

In Fig. 2-5, the interconnect outline is shown in position between two adjacent cells. Redundant connections to both the N and P contacts were made on each cell by two-each 0.105-in.-wide bus lines. Attachment on both the N and P contact was made by a solder junction using SN96 high-melting temperature solder and MIL-F-14256 Type RMA mildly activated resin flux.

The interconnects were chem-milled (etched) from 1 oz of copper foil (0.0014-in. thick). A multiple-image artwork pattern was used as the plate tool so that approximately 40 interconnects per sheet were produced. Then, the etched interconnect was solder-tinned in a batch process and hot-wax reflowed to obtain a thin 0.0005-in. uniform coating. The net interconnect thickness would be less than 0.003-in.

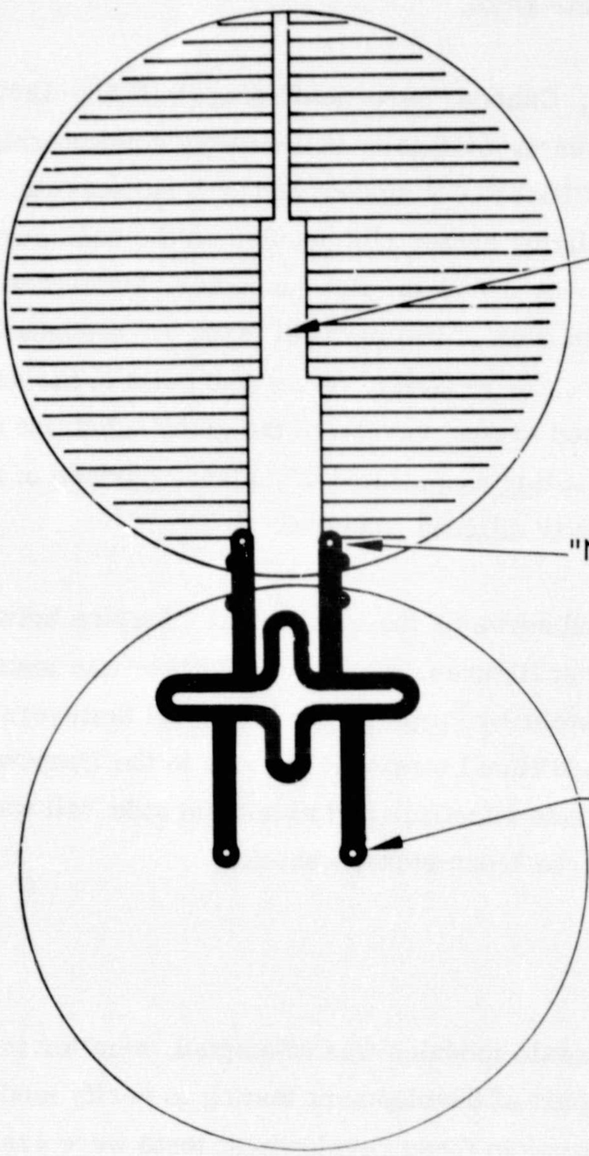


Fig. 2-5 Interconnect Configuration

Removal of the individual interconnects from the copper frame was performed by hand with a sharp razor blade or X-Acto knife.

2.2.1.5 Miscellaneous Hardare. Cannon "sure-seal" plug (P/N 120-1807-000) and receptacle (P/N 120-1805-000), environmentally self-sealing connectors provided the electrical interface between the SPRAYLON module and JPL harnessing. These connectors were mounted on a stabilizing center rib, located on the back surface of the module. Four-strand, 0.003-in. by 0.060-in. flat conductor, Mylar-insulated cabling wired to have two-each strands in each of two parallel leads for redundancy was soldered to the N and P surface, respectively, on the end cells in the string. The flat conductor cabling was wrapped around the end of the glass substrate and brought to the center connectors. The cabling was affixed to the back surface of the module with Dow Corning Sylgard 184 clear silicone adhesive.

To provide structural rigidity and serve as the mechanical interface between the SPRAYLON module and JPL's test fixtures, the glass substrate was installed into a rigid aluminum frame, held together by "pop" rivit mechanical fasteners. The center rib referred to above provided additional torsional siffness to the framework. Attached at the glass edges between the glass substrate and aluminum side rail was 1/16-in., 3 M-4516 foam tape, which absorbs front-surface shock.

2.2.2 Subsystem Testing

Before construction of any full-scale modules was attempted, smaller three-string cell modules were produced as part of development testing to verify module assembly procedures. Problems encountered in these development tests were examined and potential solutions verified by further three-string cell-module construction. A summary of the three-string cell-module testing follows, giving the module configuration employed, results derived from the test, and any comments regarding either the test or direction that should be taken on further development tests.

2.2.2.1 The first three-string cell module was produced to evaluate the bonding technique that should be employed to secure the interconnect tabs to the cell. The original concept called for the SPRAYLON encapsulation process to be the last assembly operation, the cells having been interconnected already and bonded in place.

The SPRAYLON process requires solvent flashoff at 350°F for periods of up to 20 min. Typically, thermal gradients of several degrees occur in ovens large enough to accommodate these modules (9 in. by 44 in.). For the more conventional SN62 solder which melts at 361°F, gradients toward higher temperatures could be destructive.

Configuration. Three-each three-string cell modules on a single pane of glass were fabricated. Each three-cell stringer utilized a different candidate interconnect tab bonding technique: solder (using SN62), solder (using SN96), and spot-welding. SN62 solder is the more conventional solder melting at 361°F while SN96, which contains 3.5 percent silver, melts at 430°F. Spot-welding was considered because it was felt that SN96 might cause application problems associated with its higher melting point, in which case a second alternative to SN62 solder should be included in this test.

The interconnected cells were bonded to the glass with Dow Corning Sylgard 184 silicone adhesive. A metered amount of adhesive was applied to the back surface of each cell in the string. Then, the glass was laid onto the cell string, spreading the adhesive by manually forcing the cell to the glass, at no time allowing the adhesive to come within 1/4-in. from the cell's edge. After the adhesive had fully cured, the three-string cell modules were encapsulated with SPRAYLON over the cell's front surface, cell edge, interconnects, and glass top surface.

Results: With respect to the cell bonding approach to be used, none of the techniques exhibited a failure during this test. SN96 solder proved to be as easy to use as the SN62 solder and was selected for use on all further modules.

Independent of the bonding, two problems regarding the SPRAYLON used in this configuration appeared. The first item was primarily a cosmetic problem, and can be seen in Fig. 2-6.

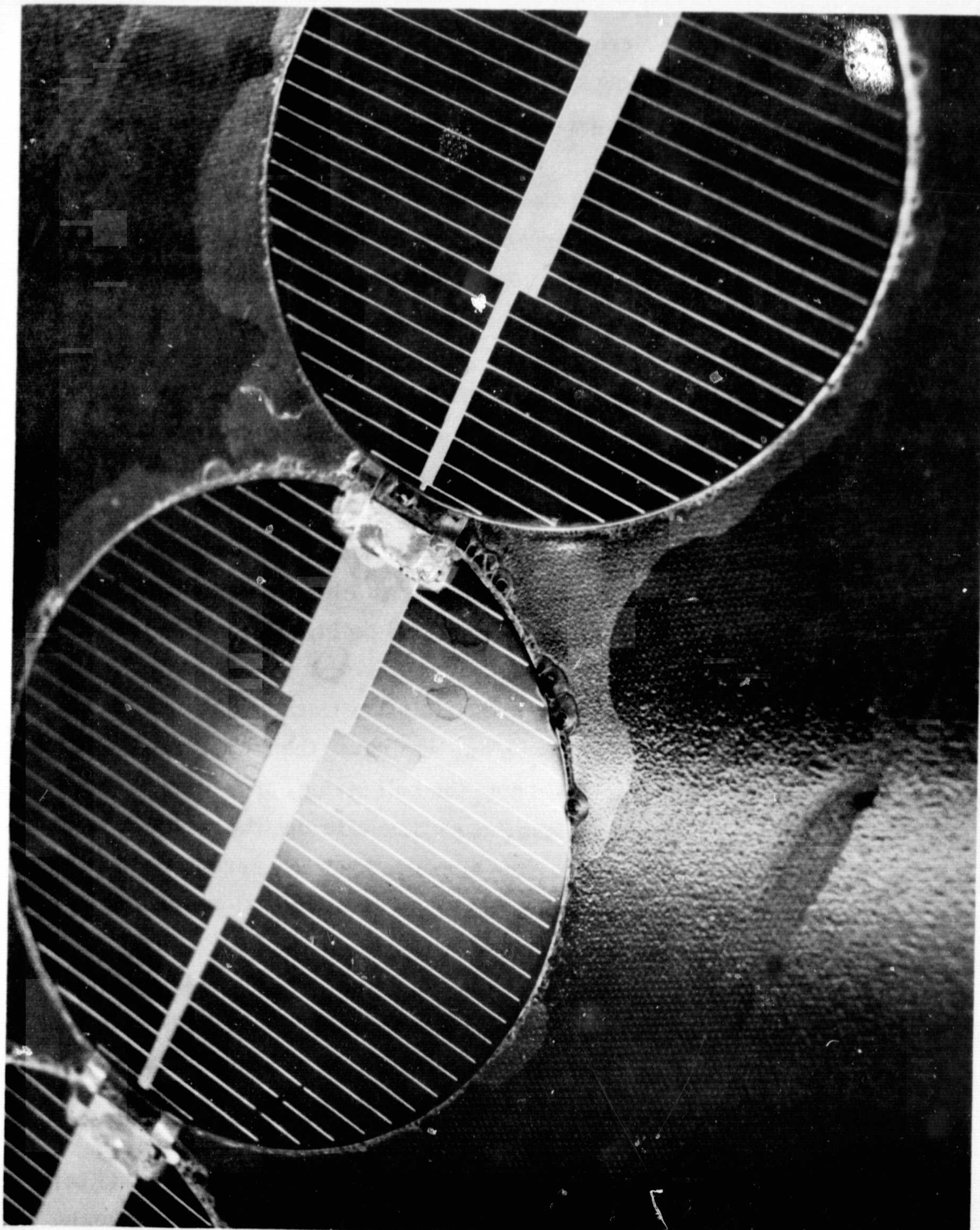

Fig. 2-6 SPRAYLON Edge-Bubbling and Delamination

The liquid SPRAYLON formed a thin membrane over the edge of the cell, which completely enclosed a volume of air under that part of the cell where there was no adhesive. During the SPRAYLON cure process, this trapped air, when heated, will tend to drive through the liquid SPRAYLON film, forming bubbles at the cell edge. After all the SPRAYLON solvents have been driven off, the film retains the contour given by these heated gases.

This effect could be reduced by minimizing the volume of trapped gases, i.e., by allowing the adhesive to come out closer to the cell edge. However, this approach was not recommended because of an incompatibility that existed between the SPRAYLON solvents and silicone adhesives.

The second problem had the potential for being the more critical of the two. Specifically, SPRAYLON delamination was found to occur across portions of the glass surface near the cell edge which propagated from ~ 1 mm initially to approximately 10 mm within one week. (No further delamination could be determined after this time.) This effect also can be seen in Fig. 2-6 as the lighted area between adjacent cells in the area of the interconnect.

Two possible reasons exist that could explain the propagation of the delaminated areas. The most obvious reason is poor adhesion. If the surfaces are not impeccably clean from all residues, silicones especially, it is known that the bond strength between SPRAYLON and glass will be poor, if it exists at all. The bare glass was cleaned and primed before assembly and good adhesion was verified away from the cells by a qualitative peel strength test. In areas near the cell, the potential did exist to have silicone residues driven from the adhesive during the 250°F bakeout contaminating the glass surface, thus causing a poor SPRAYLON-to-glass bond.

A second explanation for the film delamination near the cell edge is the non-coplanar feature of the cell and glass substrate top surfaces. In covering both the cell and glass, the SPRAYLON film must undergo a 0.023-in. step at the interface. When first applied to the surface, the SPRAYLON was very conformal at this interface as well as during the curing operation when the SPRAYLON solvents were driven off by bakeout at 350°F. To produce a very specular surface which was desirable over the front surface of the solar cell, the assembly was removed from the oven and quick-quenched in water at room temperature. This quench leaves the film in tension at room temperature, with surface stresses that are normally around 5000 psi at 70°F, varying between 3500 psi to 8500 psi over a typical day. These stresses are normally restricted to the plane of the cell or glass substrate. However, at the cell/glass substrate interface, the 0.023-in. step tended to complicate the stress pattern and add a third-dimensional component. It is believed that by now, having stresses distributed in all three dimensions, a peel stress was developed at the cell's edge which tended to pull the film away from the substrate, leaving an area of delamination around the circumference of the cell. Because this delaminated film was still in tension, peel stresses on the glass remained causing continued delamination over a period of time until the combined normal peel component and film tension were less than the bond strength, at which time peeling ceased. This effect would be enhanced by substrate warping caused by handling, wind, loading, etc.

2.2.2.2 To test for the influence of silicone contamination, a second mule was constructed which eliminated the silicone adhesive as the problem variable.

Configuration. The three cells were interconnected together using SN96 high-melting temperature solder. This will be the usual practice from now on. The interconnected cells were bonded to the glass with Furane Plastics Epibond 123/9615-10 two-part epoxy which does not exhibit any bonding incompatibilities with SPRAYLON once fully cured. As with the previous module, the adhesive was restricted to within 1/4-in. from the cell's edge. SPRAYLON encapsulation was over the cell's front surface, cell edge, interconnects, and glass top surface.

Results: The delamination pattern described above was found to repeat itself on this module. Again, right after encapsulation, only a small amount of delamination very near the cell's edge (on the glass) could be seen. However, after one week, the delamination had propagated to the extent shown in Fig. 2-6.

As a consequence, the feeling was that the primary cause of delamination was not by poor adhesion between the SPRAYLON and glass due to residual contaminants developed during the encapsulation process. Rather, it was believed that the step function incurred by the film was the most probable cause of the edge delamination on the glass of the two three-string modules.

The impact that the delamination had on the SPRAYLON modules was that the encapsulation approach had to be reevaluated. Covering the entire module after the cells had been bonded to the substrate did not appear likely unless the cells were recessed to eliminate the step at the cell's edge, which is impossible with the glass substrate. Rather than make a radical change in the module design by going to a different substrate in which the cells could be recessed (which also would require a modification of the tooling aids and handling fixtures), it was decided to encapsulate the cell and interconnect on an individual basis before bonding to the substrate.

In all of the following subsystem three-string cell-module development tests, the cells/interconnects were pre-encapsulated with SPRAYLON before bonding to the substrate. The N-tab interconnects were soldered to the bare cell using SN96 solder. Then, SPRAYLON was applied to the cell and interconnect subassembly over the cell's front surface, edge, outer back surface (inner 2-in. diameter of the back surface was left bare) and both front and back surfaces of the interconnect, out to, but excluding the P-side solder tabs. After encapsulation, the cells were laid sun-side down in a cell/interconnect registration tool (CIRT) and the P-contacts were soldered in place with SN96 solder to connect the string.

2.2.2.3 The proposed module assembly approach calls for the interconnected cells to to lie sun-side down in the cell/interconnect registration tool. The registration tool was placed in one side of a two-stage vacuum fixture, on a 1-mil Teflon diaphragm which separated the vacuum spaces in the vacuum tool. Once in the vacuum fixture, Dow Corning Sylgard 184 adhesive was applied to the back surface of each cell, after which the glass was laid over the registration tool (not yet in contact with the cells). The top of the vacuum tool was laid in position and both vacuum spaces (top and bottom) were evacuated.

After approximately 20 minutes of pumpout required to completely outgas the adhesive, the volume opposite the glass side of the vacuum tool was backfilled with air to 1 atm. The 1-atm pressure differential across the Teflon diaphragm forced the cells against the glass with uniform loading, spreading the adhesive. After an additional 15-min pumping to remove all trapped voids in the adhesive, the 1-atm pressure differential was removed. The cells remained held to the glass by the adhesive surface tension.

The glass with cells attached was removed from the vacuum fixture and all excess adhesive was cleaned from around the cell's edge while still uncured.

Configuration: This module used the proposed assembly sequence as described above.

Results: The potential energy stored in the large-area P-side interconnect (with SPRAYLON) during compression was much greater than the surface tension of the adhesive. When the vacuum was removed, the cell released from the glass substrate so far that the excess adhesive around the cell perimeter did not fill all the voids created. As a consequence, "crab legs" and "bubbles" appeared, exposing unprotected parts of the cell's back surface.

This problem did not occur in the baseline module design — probably because the N-side interconnect (the side bonded to the glass) was of a much smaller area. Also, material thickness was smaller because the interconnect material was bare.

2.2.2.4 To eliminate the problem of the cell's releasing off the glass surface, the interconnect design could be changed to incorporate a smaller area under the cell. With this approach, however, came the question of the planar, stress-relief characteristics of the redesigned interconnect as well as the quantitative reduction in the elastic properties of the redesigned interconnect.

The additional design, fabrication, and development testing necessary for such a change did not make this approach feasible for this program. Instead, a more direct approach was considered whereby the adhesive was cured while installed in the vacuum tool under pressure.

The main problem with curing in the vacuum tool was containment of the adhesive. Any excess adhesive squeezed out beyond the cell's edge left uncontained also would bond the cell interconnect registration tool to the glass substrate. A technique was required to isolate the adhesive from the registration tool during assembly.

Configuration: Before the cells were laid into the cell interconnect registration tool for connecting the P-side interconnect tab, a thin polyethylene release film was laid on the registration tool. The adhesive does not bond to the film. Therefore, after bonding, the film can be removed easily from the glass surface.

Result: By curing the adhesive while in the vacuum tool, the "crab legs" and "bubbles" were eliminated successfully. However, examination of the adhesive residue clearly indicated a need to contain the adhesive flow. In the area between cells over the interconnects, a very rough surface (high dirt accumulation potential) was left because the polyethylene film wrinkled badly when put under vacuum. The film also caused the excess adhesive to wick up onto a major portion of the front surface of the cell, which required cleanup.

2.2.2.5 To eliminate any wicking onto the front surface of the cell, the polyethylene film had to be discarded. Further, the quantity of adhesive had to be kept to a minimum to eliminate excessive seepage.

Configuration: The volume of adhesive required for a bond covering the cell area with a thickness sufficient to accommodate the interconnect was metered onto the back surface of each cell. This adhesive was smoothed over the back of the cell surface by hand to aid in obtaining a uniform bond thickness. To keep any excesses from coming into contact with the cell/interconnect registration tool, 0.060-in. studs were placed on the CIRT to act as a spacer between the glass and registration tool.

Result: The adhesive could not be controlled to flow uniformly. Instead, a preferential flow towards the interconnect side resulted, leaving voids in some edge areas and excess between the cells near the interconnects. The studs successfully kept the adhesive away from the CIRT, but seepage over the cell's front surface remained a problem rquiring cleanup.

2.2.2.6 Insufficient containment of the adhesive demonstrated itself to be the main problem in assembly of the above development module tests. An adhesive was needed that would not appreciably flow during the assembly process.

Configuration: The use of Dow Corning Sylgard 184 adhesive was discarded. Instead, a 5-mil layer of General Electric SR-56 contact cement was used.

Results: Excellent containment of the adhesive was achieved using GE SR-56 contact cement. However, high and low areas formed during the adhesive application resulted in only localized contact, giving an unacceptable bond uniformity. GE SR-56 contact cement was discarded as a potential adhesive candidate for this application.

2.2.2.7 Using the contact cement demonstrated the workability of assembly procedure once adhesive containment was realized. What was required was to define an adhesive which provided a good, uniform bond.

Configuration: On the back surface of each cell, 2.5-in.-diameter pads of 3-mil, AF 126 pre-pegged epoxy cloth were placed. This "B"-staged epoxy required heating to 250°F for one hour under minimum pressure. By assembling in the vacuum tool, the pressure requirement could be met. To bring the temperature up to 250°F, a 500-W resistance heater blanket was constructed and inserted on the back of the glass surface.

Results: Using AF 126 pre-pegged epoxy cloth, excellent bond uniformity and adhesive containment were achieved. This configuration produced the first completely acceptable three-string cell module during development tests and was selected to represent the approach to be used on the full-size, 41-string cell modules.

## 2.3 MODULE DESIGN

The module design developed for this program used 41 pre-encapsulated 3-in.-diameter cells furnished by OCLI. The cells were soldered together into a single series using flat, stress-relieved copper interconnects. The interconnects were soldered to the cells with SN96 solder which melts at 430°F.

The string was laid in three groups of 14, 13, and 14 cells as shown in Fig. 2-7. As can be seen, the single string is connected in a redundant electrical path from positive to negative terminal.

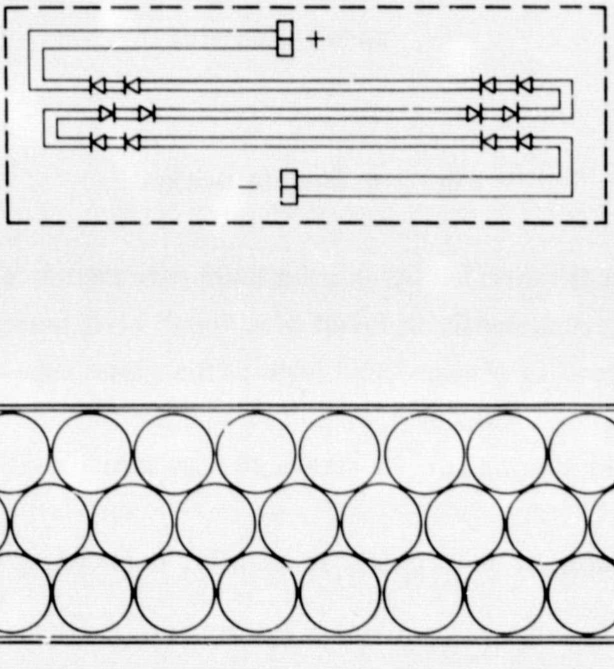


Fig. 2-7 Schematic Diagram

In Fig. 2-8, a side view of the module is shown. The OCLI solar cells are mounted to a 44.25-in. by 8.75-in. by 0.125-in. ASG Industries Sundex glass substrate. Each cell rests on a 2.5-in.-diameter by 3-mil pad of epoxy adhesive. As shown, the epoxy pad does not extend to the cell's edge. Surrounding the cell's front surface, edge, outer back surface, and interconnect is the SPRAYLON encapsulant. Although not shown in this figure, a small air gap exists between the SPRAYLON applied to the cell's back surface and the glass. This gap goes in only to the epoxy interface.

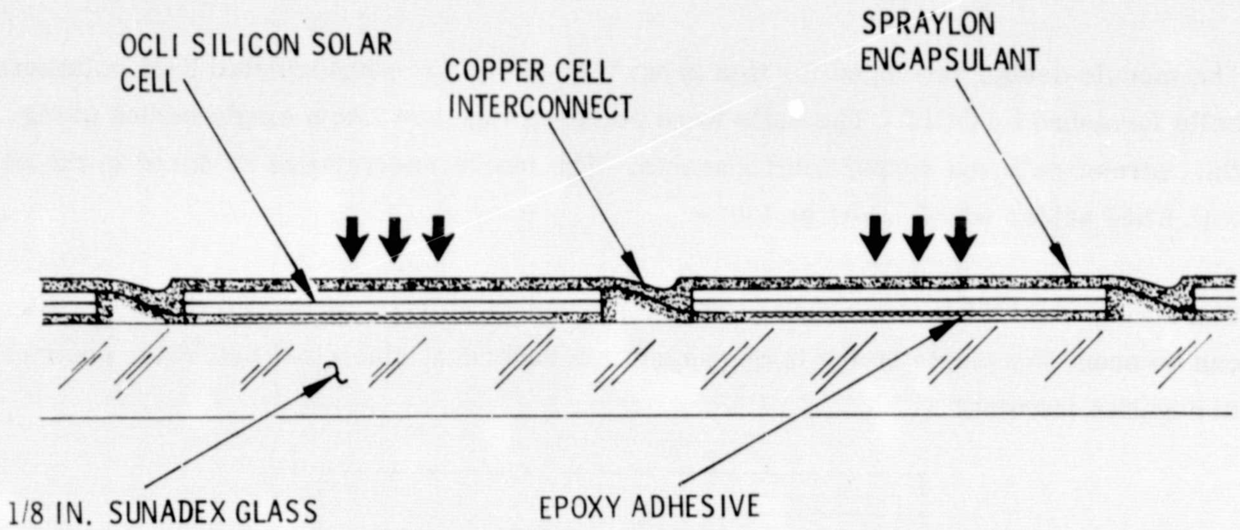


Fig. 2-8 Module Design

The structural support is provided by an aluminum extruded side rail, end rail, and center rib which are mechanically secured with "pop" rivit fasteners. In Fig. 2-9, the detail in the side rail is shown. The edge of the glass substrate is striped with 1/8-in. 3M Foam Tape No. 4516 on both the top and the bottom. The tape acts as a shock absorber between the module substrate and the more rigid framework.

Expected electrical output at 28°C (AM1) is 19.2 W, decreasing to 16.3 W at 60°C (AM1).

## 2.4 MODULE FABRICATION

The module assembly procedure adopted as a result of the three-string cell-module development tests is summarized.

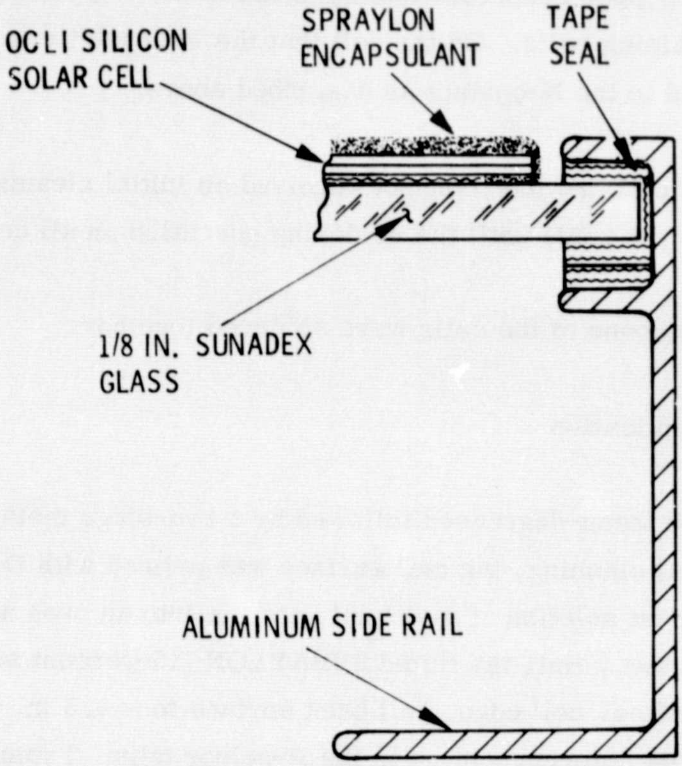


Fig. 2-9 Module Design (Side Rail)

2.4.1 N-Side Interconnect Junction

Forty photo-etched copper interconnects were trimmed from their frame by an X-Acto knife or razor blade. The interconnects were cleaned with methyl alcohol, as were the virgin, as received, OCLI solar cells, and two-each flat four-strand copper conductors. Thirty-eight cells were laid sun-side up in the Cell/Interconnect Registration Tool (CIRT), after which the interconnects were laid in place. Each cell was rotated until the grid contact pattern aligned itself with the interconnect N-side solder tabs. Then, the interconnects were soldered to each of the N-side cell contacts with SN96 solder, using mildly activated resin flux (MIL-F-14256 Type RMA) to promote wetting.

The flat, four-strand copper conductor was soldered to the N-contact and P-contact on either of the two remaining cells. On the cell that the P-contact was made, an interconnect also was soldered to the N-contact as described above.

After soldering, each cell and interconnect received an initial cleaning with methyl alcohol, and then was put aside until the soldering operation on all cells was finished.

Note that at this point, none of the cells were soldered together.

### 2.4.2 SPRAYLON Application

Each of the cells were freon-degreased followed by a two-stage methyl alcohol cleaning. Immediately after final cleaning, the cell surface was primed with Dow Corning Z6020 silicone in a 0.1-percent solution of methanol, and put into an oven at 350°F for a 5-min primer flash-off. At this point, the liquid SPRAYLON (15-percent solids) was metered onto the cell front surface, cell edge, cell back surface to ~ 0.5 in. from the edge, as well as both sides of the interconnect up to the P-solder tabs. Typically, application on the back surfaces and edges are made first, followed by a bakeout at 200°F for 5 min. This low-temperature bakeout allowed for partial setting of the film so that the cell could be turned over for application of SPRAYLON to the front surface without flowing of the film on the back surface. Then, the encapsulated cell was placed in a 350°F oven for 20 min for complete solvent flash-off.

For a specular film, the cells were removed from the oven after 20 min of bakeout, and immediately quenched in a bath of water at room temperature. If a slower cooldown were allowed, a diffuse film having a lower solar transmittance by approximately 4 percent would result.

### 2.4.3 P-Side Interconnect Junction

The back surface of each cell in the area where the P-side solder junction was to be made was cleaned with a light abrasive (Koh-I-Lon Drafting Film Eraser) to remove any residual SPRAYLON primer, followed by a swabbing with methyl alcohol. Each cell was laid successively into the CIRT, sun-side down, laying the extended P-contact over the back of the adjacent cell until all 41 cells were registered in the CIRT. The two electrically redundant P-tabs were soldered to the back surface of the adjacent cell, again using SN96 solder with MIL-F-14256 Type RMA flux to promote wetting. Once completed, the cell string is freon-degreased to remove residual flux using the CIRT now as a handling tool.

2.4.4 Bonding Cells to Glass Substrate

The adhesive used to bond the cells to the glass substrate was a 3-mil AF 126 pre-pegged epoxy cloth. Prior to assembly, the roll of adhesive was removed from a cold-storage area and brought to room temperature, at which point the material became ply-able and workable. Once at room temperature, the sheet was unrolled and the required number of pads were cut from the sheet using a 2.5-in.-diameter "cookie-cutter." Each pad was laid onto the center back of each cell which remained face-down in the CIRT after the freon-degreasing.

The two-stage transparent vacuum fixture was separated and one-half laid, outer surface-down, in the assembly area. A 1-mil Teflon diaphragm was laid over the entire exposed inner surface, after which the CIRT with cells and epoxy pads was placed over the dia-phragm. The glass substrate was cleaned by freon-degreasing and swabbed with methyl alcohol across the entire surface. The cleaned glass substrate was laid onto the CIRT, centering on the alignment indicators located on the CIRT. Note that the cell registers were recessed so that the cells and adhesive did not yet make contact with the glass.

A flat resistance heater blanket with a built-in thermistor was placed on the back sur-face of the glass. This heater was used to raise the adhesive temperature during the cure cycle. Then, the second half of the vacuum fixture was installed over the entire assembly, clamping the edges to ensure a good vacuum seal.

A vacuum (1 atm) was pulled in the bottom volume which tended to tighten the Teflon diaphragm and removed any wrinkles. Then a vacuum was pulled on the top volume.

After pressure equilibrium, the bottom volume was back-filled slowly to ambient pressure, creating a pressure differential in the tool which, through the diaphragm, forced the cells against the glass with a uniformly distributed load.

Only after the cells were firmly pressed to the glass was the contact heater turned on. The power was adjusted to give a slow, linear warm-up from room temperature to 250°F in 2 hr. Then, the temperature was maintained at 250°F for 1 hr followed by an uncontrolled cooldown to room temperature (i.e., power turned OFF). When the temperature dropped below 100°F, the pressure differential was removed, and the glass substrate with bonded cells was removed from the vacuum fixture.

### 2.4.5 Mechanical Assembly

After the bonding operation was completed, strips of 3M Foam Tape No. 4516 were laid on both the top and bottom side edges along the full length of the glass. Then, the edges were fitted into the extruded aluminum side rails.

The flat conductor cabling was wrapped around each respective module end and guided toward the center back of the module. The cabling was affixed to the glass substrate temporarily with double-back Kapton tape until the final operation. With the flat conductor wrapped over the edge of the substrate, both end rails were positioned next to the side rails and secured in place with 3/16-in.-diameter "pop" rivets.

The two-each electrical connectors were mounted to the center rib after which the center rib was mounted to the side rail, again, secured by 3/16-in.-diameter "pop" rivets. Then, two-each electrical connector pins were crimped into two-each of the four-strand conductor for each cable which made a redundant current path. Each of the connector pins were installed into the mounted connector receptacle. Finally, the flat conductor cabling was potted to the back of the glass substrate with Sylgard 184 to complete the module assembly.

## 2.5 MODULE TESTING

Two complete modules were fabricated as described in Section 2.4, STM 7701-01 and STM 7701-02. The voltage-current relationship of both modules was determined followed by a period of outdoor field testing. Problems arose during the course of the field testing which forced an early end of the testing phase of this program.

### 2.5.1 Electrical Testing

Electrical testing on both modules was performed a the Large-Area Pulsed Solar Simulator (LAPSS) facility in Sunnyvale. The test hardware and procedure used is described in Appendix A.

The module current-voltage relationship for Modules STM 7701-01 and STM 7701-02 was measured under simulated AM1 incident solar irradiation (100 mW/cm$^2$) at both 28°C and 60°C. These relationships are shown in Figs. 2-10 and 2-11. As can be seen, the maximum average power output of these two modules at 28°C is 20.1 W at 18.8 V, decreasing at 60°C to 18.2 W at 16.8 V. This measured performance is 5 percent higher than the predicted module output discussed in Section 2.2.1.1.

### 2.5.2 Environmental Testing (Field Test)

Both Modules STM 7701-01 and STM 7701-02 were placed in the Lockheed Outdoor Solar Test Facility for preliminary environmental susceptibility testing. A description of this facility, including testing capabilities, is included in the Appendix.

Module STM 7701-01 was tested outdoors for a period of four days and Module STM 7701-02 for a period of fifteen days. The environment during these exposure times was that of nearly continuous rainfall or high relative humidity with overcast. At the end of the exposure period, three distinct, although not necessarily unrelated, failure modes were observed on both modules.

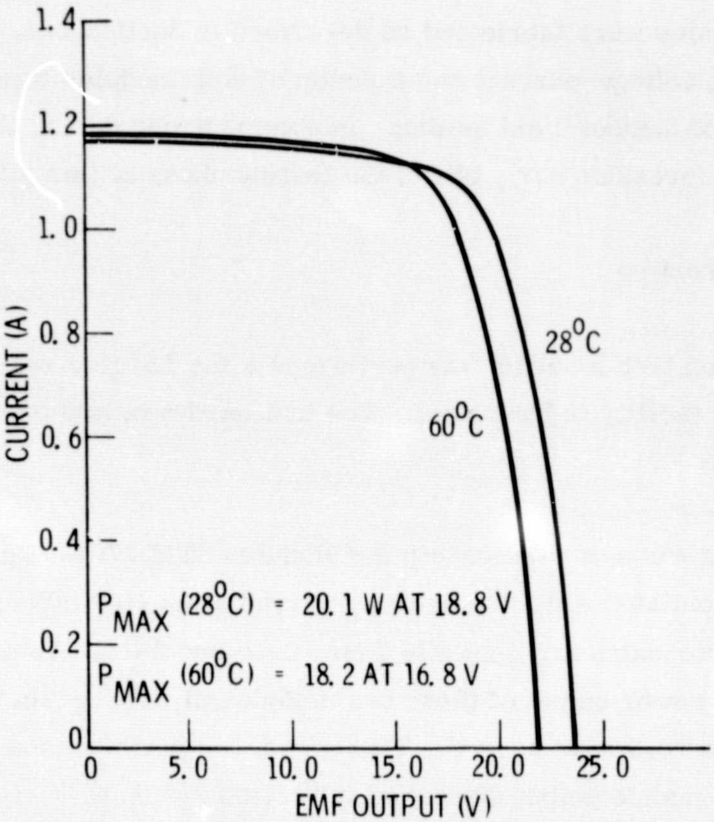


Fig. 2-10 Voltage-Current Relationship – Module STM 7701-01

2.5.2.1 Fungus Growth. This first failure was primarily a cosmetic failure because the module performance was affected in no way. A fungus developed under that part of the cell not bonded to the glass. The back surface of a portion of Module STM 7701-02 is shown in Fig. 2-12, showing the growth observed after fifteen days of outdoor testing.

The 2.5-in.-diameter epoxy adhesive pad is shown centered beneath the 3.0-in.-diameter cells, leaving a 1/4-in. annulus around the outer edge of the cell which is not bonded to the glass. This portion of the cell was protected with SPRAYLON so that

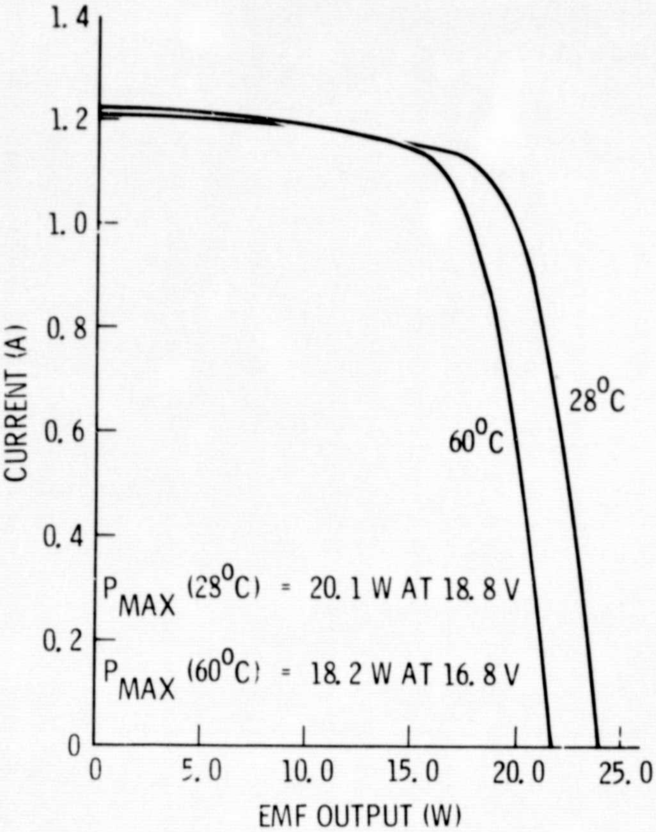


Fig. 2-11 Voltage–Current Relationship – Module STM 7701-02

no degradation of the cell material proper was expected. The 1- to 3-mil gap between the SPRAYLON-covered portion of the cell and glass substrate evidently made an excellent trap for spores and organisms to grow.

2.5.2.2 Antireflection Coating Separation. A separation of the AR coating film at the cell surface occurred on approximately 50 percent of all cells over at least a small area of the cell. Separation on a typical cell is shown in Fig. 2-13. The separation took the form of a difference in the surface coloration of the cell. Instead of the bluish

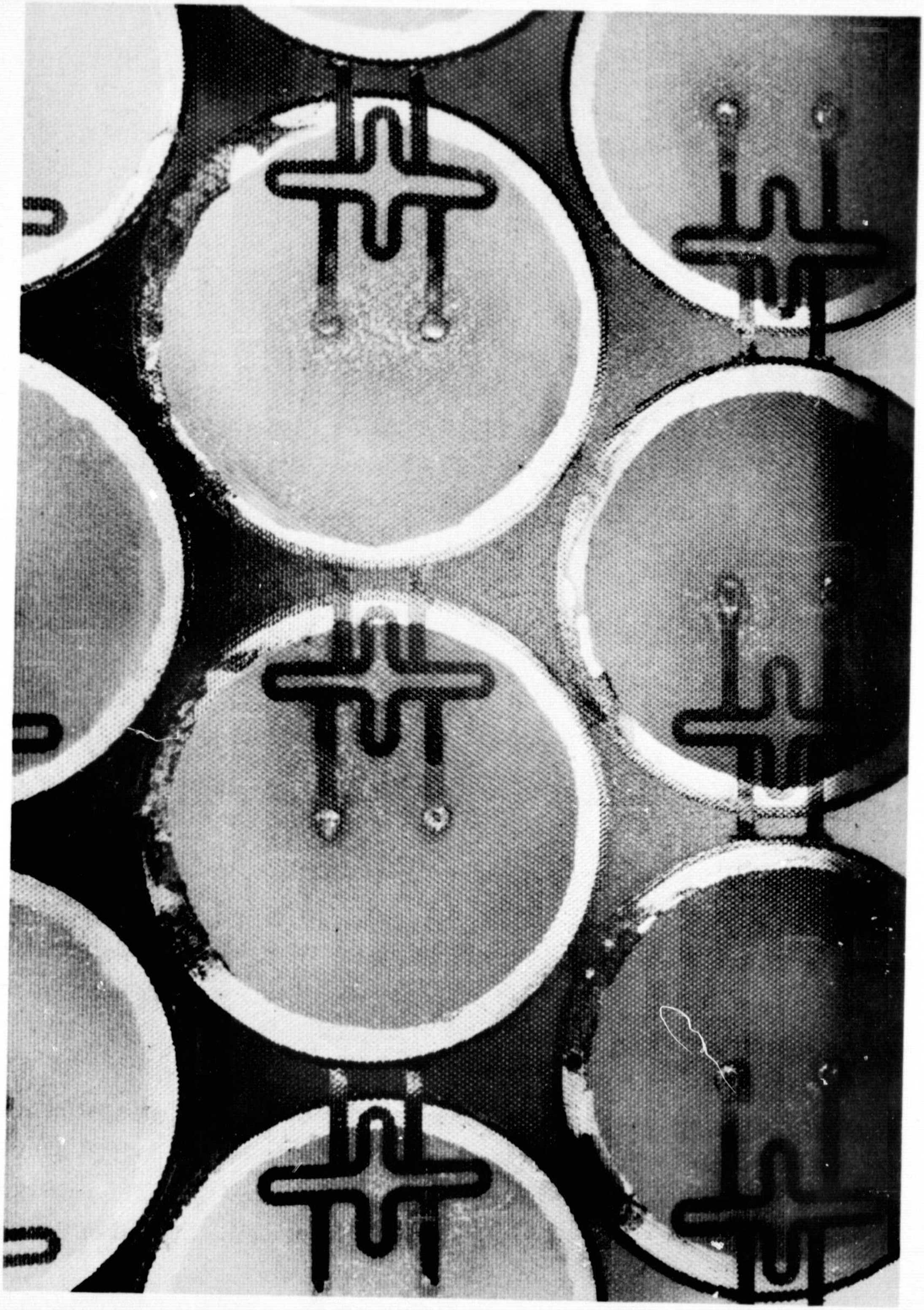

Fig. 2-12 Fungus Growth Under Portion of Cell Not Bonded to Glass

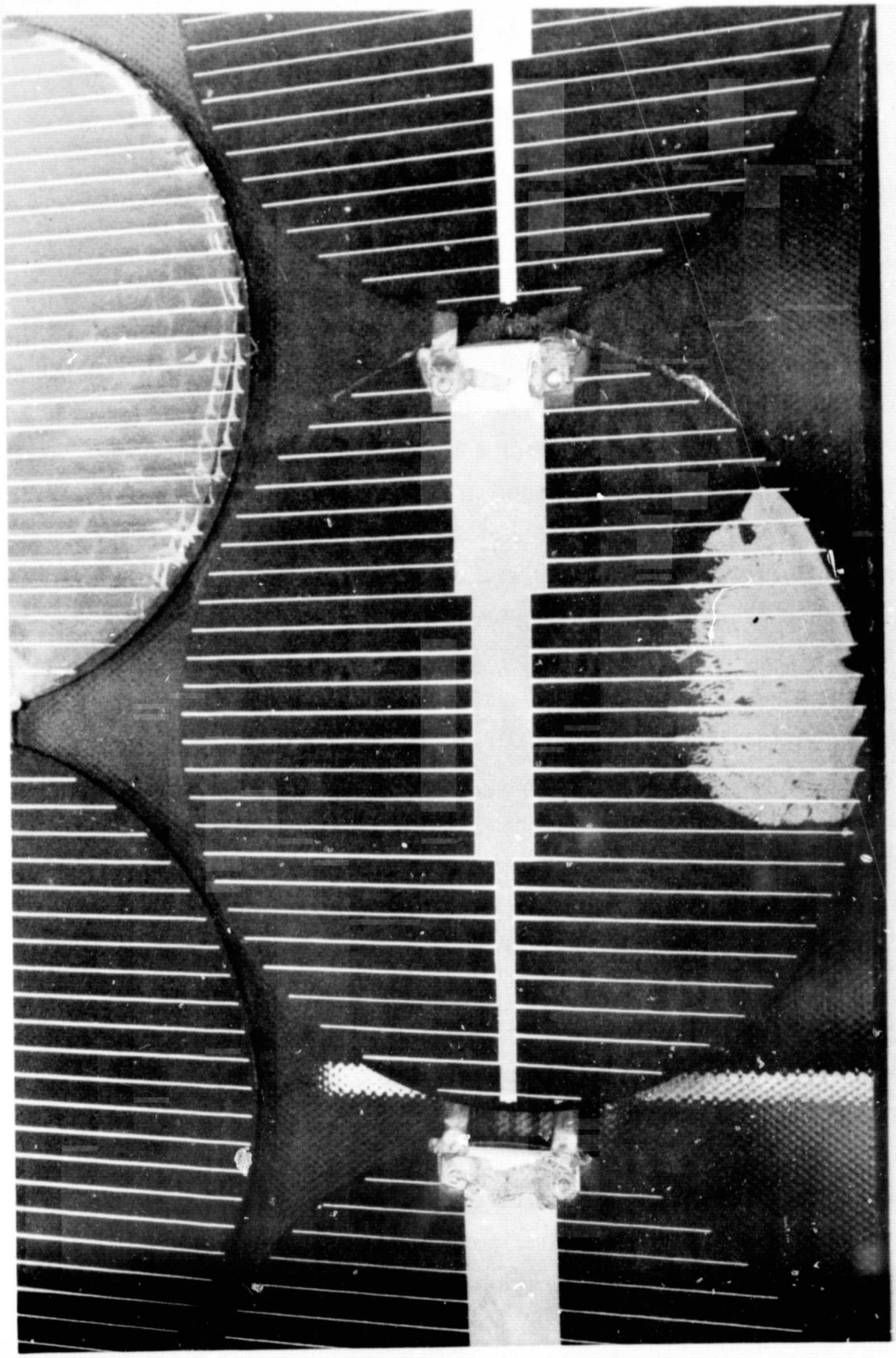

Fig. 2-13 Antireflection Coating Separation From Cell

color observed when the AR coating was intact, the gray color of the bare silicon material was seen. Physically, this was the only change that can be observed. The SPRAYLON did not show any signs of failure; the surface still appeared to be conformal to the cells' surface, showing no evidence of "coming up."

Further, in all of the antireflection coating separations, the first observation was made near the cell edge.

It was believed that the cause of this failure was the surface stresses induced by the SPRAYLON film, forcing a failure of the cell/antireflection coating bond. On the surface of the cell, the SPRAYLON film was in tension having surface stresses of between 5000 psi at 70°F and 3500 psi at 40°F. Over a typical overcast and rainy day, surface stress excursions of 3500 psi can take place. Further, near the edge of the cell, the potential exists that stress concentrations may increase this daily variation by a factor of two or three. It is proposed here that these stresses may be high enough to cause a failure of the antireflection coating bond to the cell.

This effect could be even more pronounced if this bond were weakened during the assembly process by contaminants. Specifically, it was known that small pinholes might exist in the SiO antireflection coating, forming microscopic cavities where contaminants such as solder flux residue could accumulate. During cleaning, it was probable that complete removal of these contaminants could not be achieved. Over a period of time, the presence of this residue might degrade the bond between the cell and antireflection coating in the area around the pore.

2.5.2.3 <u>SPRAYLON Film Delamination.</u> On approximately 10 percent of the cells, the SPRAYLON film had either partially or completely delaminated from the cell's surface as a consequence of the field testing.

The delamination of the SPRAYLON followed a general pattern in all but two isolated cases. The first observation was the antireflection separation from the cell's surface, as described in Section 2.5.2.2. Once a region of separation was defined, the delamination began by a cutting of the SPRAYLON film at the edge of the cell. In Fig. 2-14, the cut SPRAYLON had been turned up slightly in order to see this effect. At this point, adhesion was still good over that portion of the cell where separation of the antireflection coating had not yet taken place.

Once the initial cutting of the film at the cell's edge had been made, complete delamination over the whole surface of the cell occurred generally within two days. After this time, no bond existed between the SPRAYLON film and the cell. Further, the cut at the edge had propagated almost completely around the circumference of the cell, so that only the film laid on the cell, held in place at a single point in the area of the interconnect.

Figure 2-15 shows a cell after the SPRAYLON film had been pulled off. The gray areas again depict those areas where the antireflection coating had been separated. By comparison, Fig. 2-16 shows the SPRAYLON film removed from the cell in Fig. 2-15. The residue from the antireflection coating on the SPRAYLON film can be seen. The fact that the antireflection coating was removed with the SPRAYLON film strongly suggests that the delamination be initiated by the antifeflection coating separation.

The only evidence which might lean toward a compromise in the SPRAYLON adhesion came in the delaminations which occurred on those two cells with no apparent separation of the antireflection coating. In Fig. 2-17, one of these cells is shown. Of interest here is that the delamination appeared to have grown from the inside out. That is, the edges near the interconnect showed a good bond while the delamination existed over the center. This is contrary to the problems associated with the antireflection coating separating where the damage began at the edge and worked its way around the cell.

These two cases appeared to be the result of improper priming of the cell's surface. Examination of the cell's surface showed irregular interference patterns which generally occurred under these circumstances.

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Fig. 2-14 SPRAYLON Delamination – Partial Film Removal

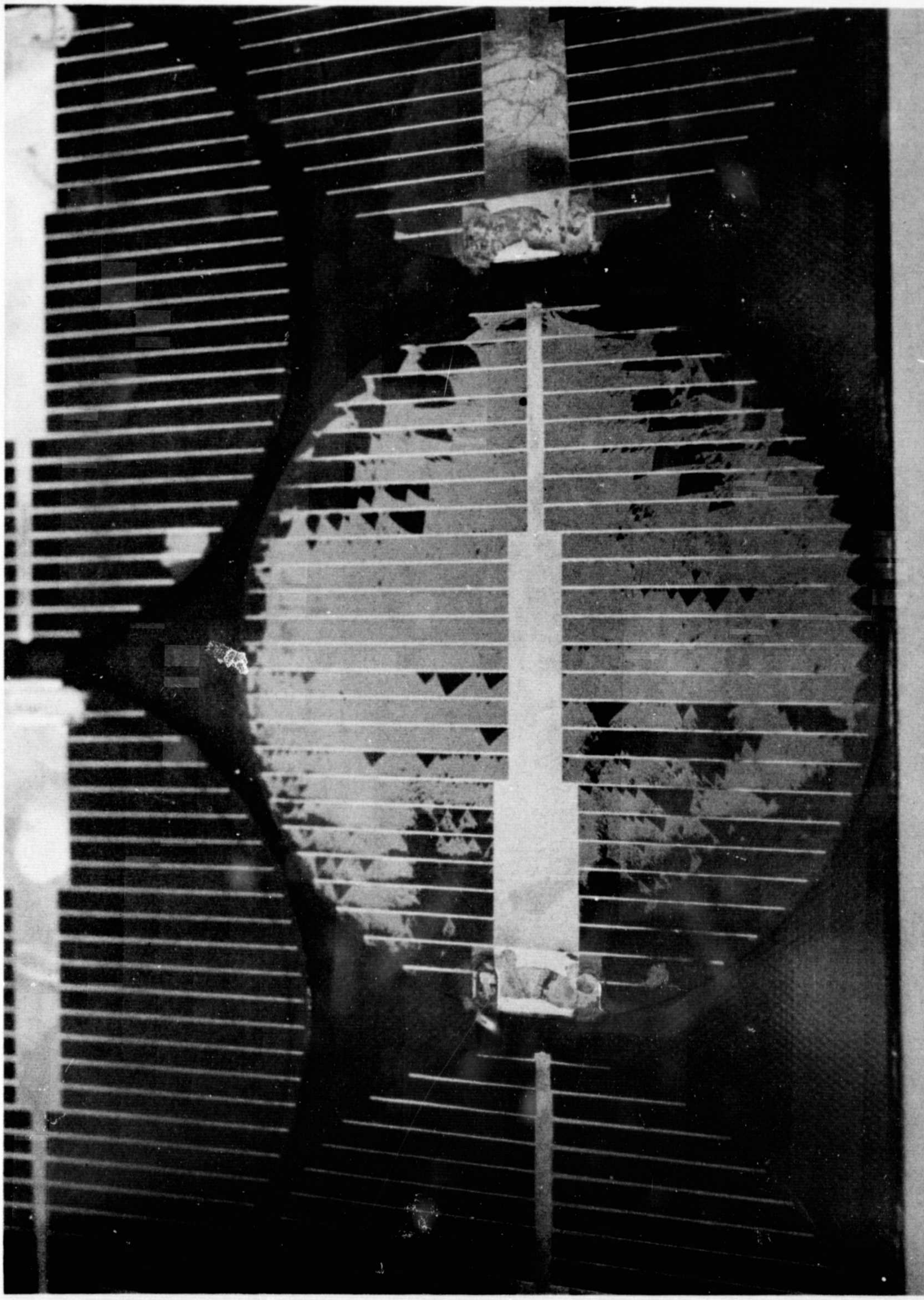

Fig. 2-15 SPRAYLON Delamination – Total Film Removed

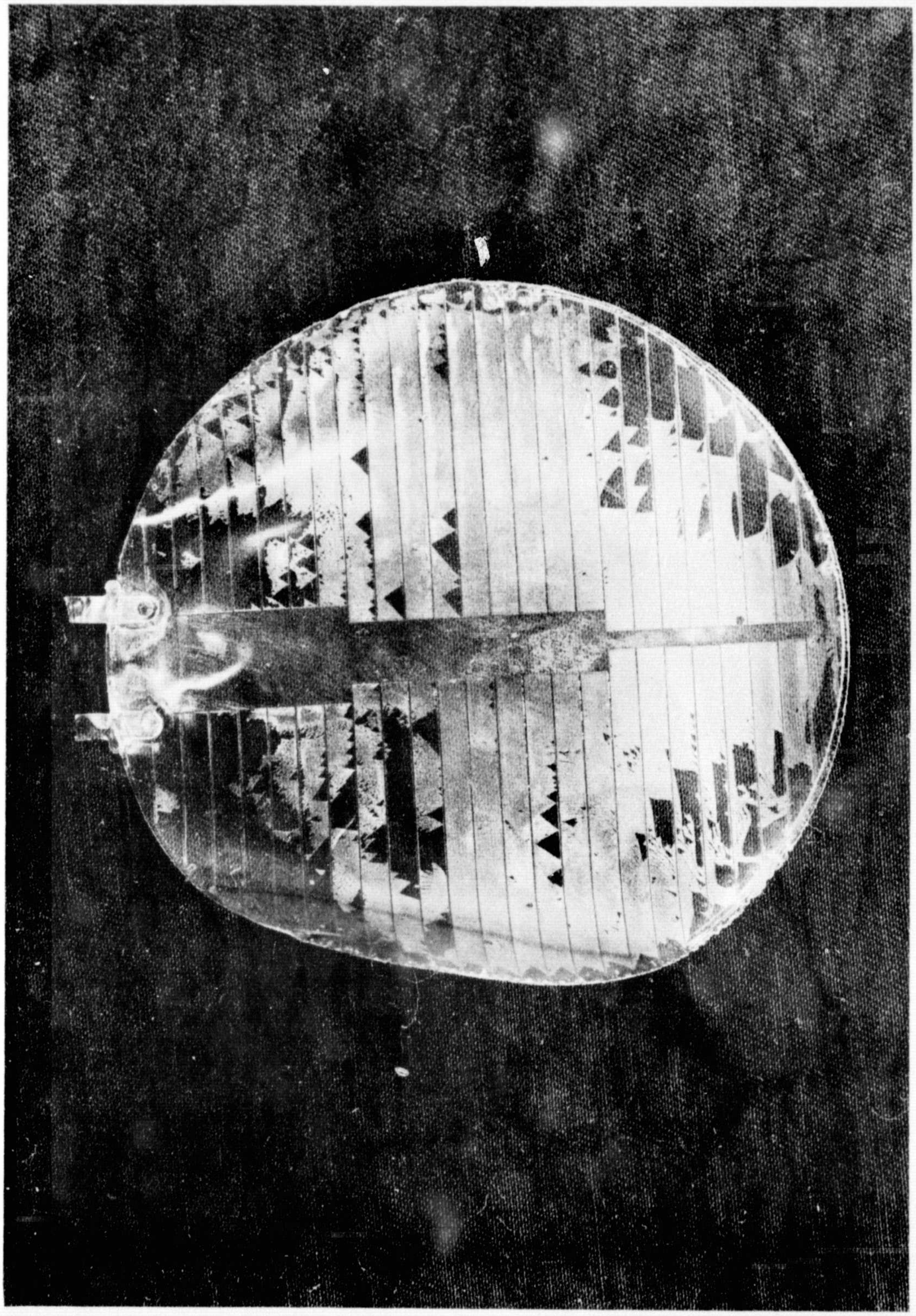

Fig. 2-16 SPRAYLON Film Removed From Delaminated Cell

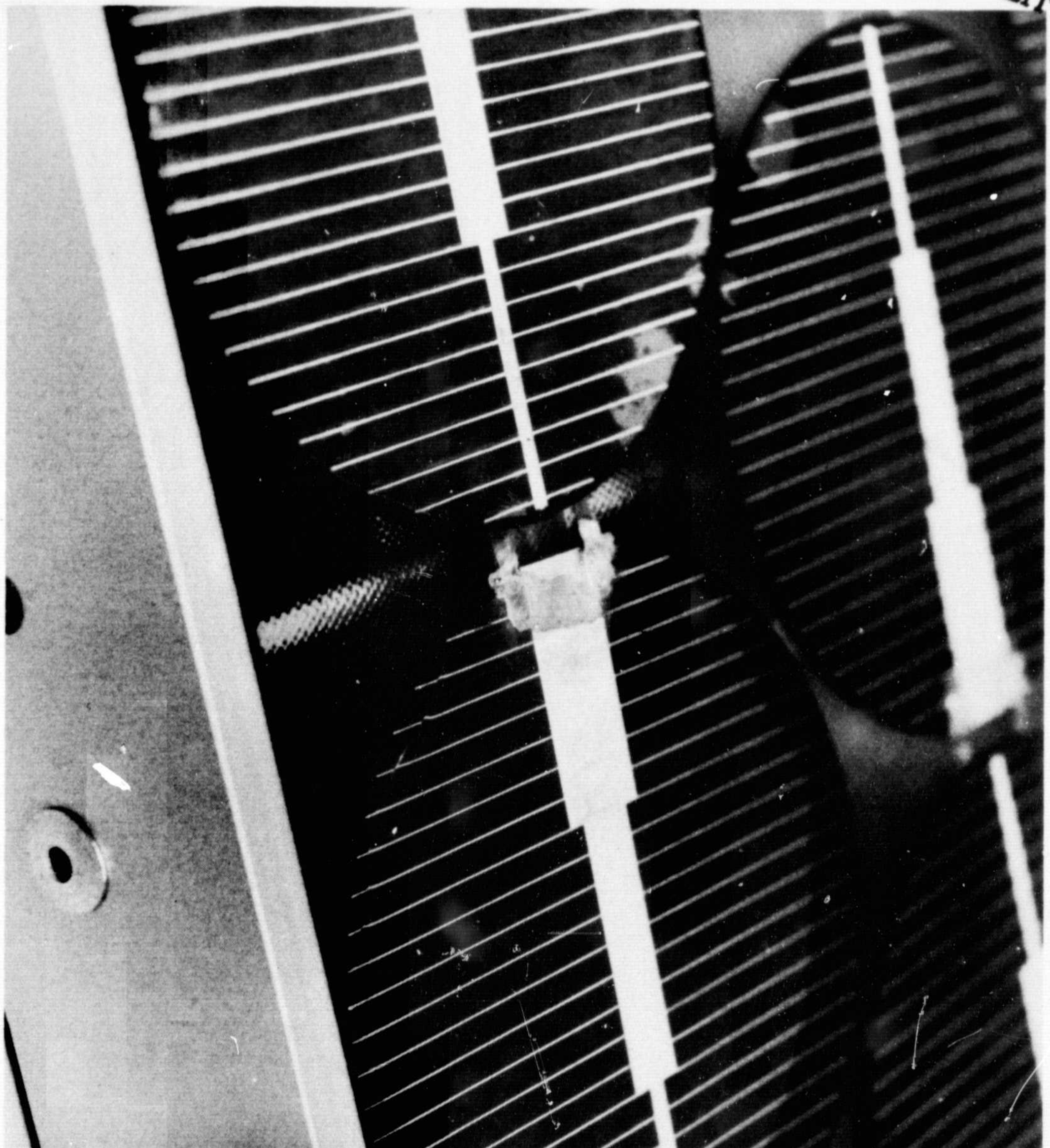

Fig. 2-17 SPRAYLON Delamination – No Antireflection Coating Separation

# Section 3
# CONCLUSIONS AND RECOMMENDATIONS

The failures that occurred during the outdoor environmental module testing caused the program to be terminated prematurely. It is believed that these failures were not a failure of the SPRAYLON encapsulant material itself, but rather were a failure induced by the particular design selected in this program to evaluate SPRAYLON. Specifically:

- The delamination of the SPRAYLON film over the cell's front surface is believed to be caused by the separation of the antireflection coating.
- The separation of the antireflection coating from the front surface of the cell is believed to be a failure of the coating bond to the cell, induced by the SPRAYLON film. The bond may or may not be weakened by any of the assembly procedures.

As a consequence of these failures, it is not recommended at this time to discard SPRAYLON as a viable candidate for a terrestrial photovoltaic solar cell module encapsulant. Instead, it is recommended that:

- Studies be performed to assess the influence of the antireflection coating bond strength on module failures
- Consideration be given to the use of bare (no AR coating) texture-etched cells on cell efficiency with SPRAYLON encapsulation
- Additional material property measurements be performed as related to terrestrial environments, specifically, peel strength (wet), peel strength (dry), effect of film uniformity, moisture sensitivity, and edge effects
- Evaluation of SPRAYLON be considered on a sub-module basis utilizing design sensitivity to SPRAYLON constraints, for example, cell surface coplanar with substrate, conformal coating entire substrate/cells with back surface venting to eliminate trapped gases.

# Appendix
# TESTING AND FABRICATION AIDS

## A.1 ELECTRICAL TESTING FACILITIES

Electrical testing at the module level was performed at the Large-Area Pulsed Solar Simulator (LAPSS) facility in Sunnyvale. The LAPSS provides a uniform, spectrally balanced pulse of light (pulsed xenon) to the test object, and subsequently electronically loads the module during illumination, and records and conditions the data for rapid retrieval. The current-voltage relationship of the module is plotted out on an X-Y recorder.

The illumination is directed vertically onto a calibrated area with registration marks for location of the module position. A test cable is connected to the module output terminals and the current read at ten preselected voltage levels including open-circuit, short-circuit, and 18.1-V (the expected maximum power voltage at 28°C). The equivalent electronic output is determined using a secondary standard calibrated by JPL to adjust the LAPSS intensity to give 100 mW/cm$^2$, AM1 at 28°C.

## A.2 FIELD TESTING FACILITIES

Outdoor environmental testing was performed at the Lockheed Solar Test Facility in Palo Alto. This facility is designed for outdoor testing and evaluation of both photovoltaic and thermal solar collectors. The facility includes a complete weather station (temperature, wind speed and direction, and relative humidity) meeting all NBS standards as well as a calibrated diffuse and total pyranometer. For in situ testing of photovoltaic modules, a Spectrolab D550 Load Bank is available to monitor current voltage module characteristics without removing the modules from the outdoor test racks.

## A.3 TOOLING AND FABRICATION AIDS

Tooling and fabrication aids were necessary to either ensure dimensional tolerances on critical items, provide an easy handling mechanism for the delicate cell-string during assembly, or act as an aid during the testing phase of the module. Tooling required on this program included:

- Photo templates for etching the OCLI interconnect pattern
- Cell/Interconnect Registration Tool (CIRT) which was used to register relative cell and interconnect position during soldering operations. The tool also acted as a handling fixture during module assembly.
- Contact heater pad required for assembly bonding process
- Two-stage transparent vacuum fixture for bonding cells to the glass substrate
- Temperature control test fixture for maintaining uniform module temperature during indoor current-voltage testing

The last two items were manufactured under JPL Contract No. 954653 and made available for use on a rent-free basis. The remaining items were manufactured specifically for this contract.