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5101-188  
Flat-Plate  
Solar Array Project

DOE/JPL-1012-63  
Distribution Category UC -63b

# Vacuum Lamination of Photovoltaic Modules

D. R. Burger

(NASA-CR-168634) VACUUM LAMINATION OF  
PHOTOVOLTAIC MODULES (Jet Propulsion Lab.)  
22 p HC A02/MF A01 CSCL 10A

N82-19676

Unclass  
G3/44 09286

January 15, 1982

Prepared for  
U.S. Department of Energy  
Through an Agreement with  
National Aeronautics and Space Administration  
by  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

JPL PUBLICATION 81-118



1. Report No. JPL Pub. 81-118	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle VACUUM LAMINATION OF PHOTOVOLTAIC MODULES		5. Report Date January 15, 1982	
		6. Performing Organization Code	
7. Author(s) D. K. Burger		8. Performing Organization Report No.	
9. Performing Organization Name and Address JET PROPULSION LABORATORY California Institute of Technology 4800 Oak Grove Drive Pasadena, California 91109		10. Work Unit No.	
		11. Contract or Grant No. NAS 7-100	
12. Sponsoring Agency Name and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Washington, D.C. 20546		13. Type of Report and Period Covered JPL Publication	
		14. Sponsoring Agency Code	
15. Supplementary Notes Also sponsored by U.S. Department of Energy under Interagency Agreement #DE-AI01-76ET20356; identified as DOE/JPL-1012-63 and JPL Project Document 5101-188. (RTOP #776-52-61)			
16. Abstract  Vacuum lamination of terrestrial photovoltaic modules is a new high-volume process requiring new equipment and newly developed materials. Equipment development, materials research, and some research in related fields and testing methods are discussed.			
17. Key Words (Selected by Author(s)) Energy Electronics and Electrical Engineering Materials		18. Distribution Statement Unclassified - Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 24	22. Price

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**The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of  
Energy and is part of the Photovoltaic Energy Systems Program to initiate a  
major effort toward the development of cost-competitive solar arrays.**

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## ABSTRACT

Vacuum lamination of terrestrial photovoltaic modules is a new high-volume process requiring new equipment and newly developed materials. Equipment development, materials research, and some research in related fields and testing methods are discussed.

## ACKNOWLEDGMENTS

The development effort reported in this paper is based upon many concepts and materials developed by the Encapsulation Task of the Flat-Plate Solar Array Project. Edward Cuddihy of that task has given freely of his time and knowledge during this application effort.

Paul Willis of Springborn Laboratories, Inc., contributed background information on the processing and testing of the materials developed at Springborn.

Edwin P. Plueddemann of Dow Corning Corp. conceived the coupling agents and chemical-bonding philosophy so vital to this effort.

Many other industry technologists also contributed.

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## INTRODUCTION

A few years ago, most terrestrial photovoltaic (PV) modules were assembled by casting the cells in a transparent silicone substance, using a metal substrate for support. When this approach was reviewed by the Flat-Plate Solar Array (FSA) Project, development was begun on new materials that would reduce the cost and quantity of material required for encapsulation.

During development of these materials, the PV industry improved module design by eliminating metal substrates and incorporating glass superstrates to provide a hard, easily cleaned top surface. Use of glass superstrates created new material problems. Bonding some encapsulating materials proved to be a difficult problem. Elimination of visual defects, such as voids and bubbles, became necessary because of increased market sophistication. Long-term corrosion concerns became important now that thin, water-permeable polymer materials were being used to reduce cost. Discussion of these problems will start with equipment development, because improved equipment was necessary to the subsequent materials development effort. While the development was being pursued, some module design and processing problems became evident. Because these problems have a bearing upon the reliability of the lamination process, they will also be discussed.

### A. EQUIPMENT DEVELOPMENT

When modules were being assembled by casting with silicones, there were high material and labor costs and low equipment costs. Material cost reduction was sought in the development of new materials. Labor cost reduction, however, is dependent upon the development of better processes and the introduction of equipment specifically designed to use the new materials and processes. The process that seemed most suitable for the new materials was a lamination process. A typical laminated module is shown in Figure 1. Initial FSA Project involvement with lamination occurred in late 1978 at RCA Laboratories (RCA).

RCA double-glass lamination experiments showed that an autoclave was expensive and introduced air into module edges during cooldown (Reference 1). Late 1978 was also the time of contract initiation with ARCO Solar, Inc., to develop a laminator that would reduce the near-term costs of PV modules. By July 1979 a double-chamber vacuum laminator was developed, tested and put into production (Reference 2). This laminator is shown in Figure 2 and used a proven thermoplastic, polyvinyl butyral (PVB), which requires humidity- and temperature-controlled storage and handling. Other problems with PVB were high cost and high viscosity at the 150°C process temperature.

An answer to these problems was sought in a material that would cure at process temperatures. One possible solution was to develop a thermosetting polymer, but these polymers place more stringent temperature requirements on a laminator. The original ARCO Solar laminator used long, slender tungsten-filament lamps as a heat source and shiny aluminum strips to adjust for uniformity. This approach works well with a thermoplastic-like PVB, but was considered to be too variable and limited for research into thermosetting materials and substrate module designs.

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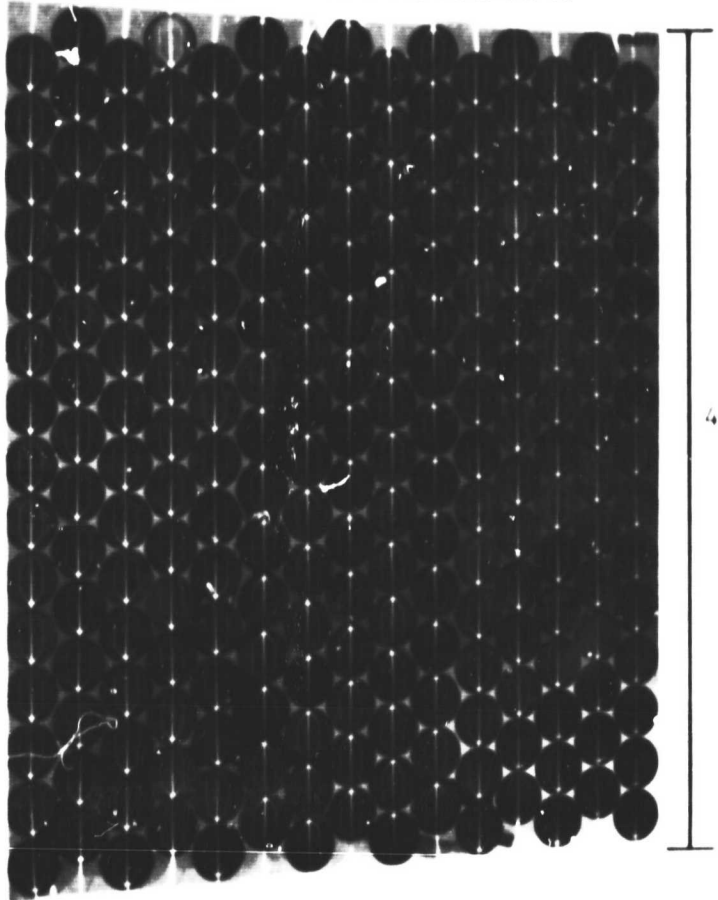


Figure 1. Typical Laminated Module

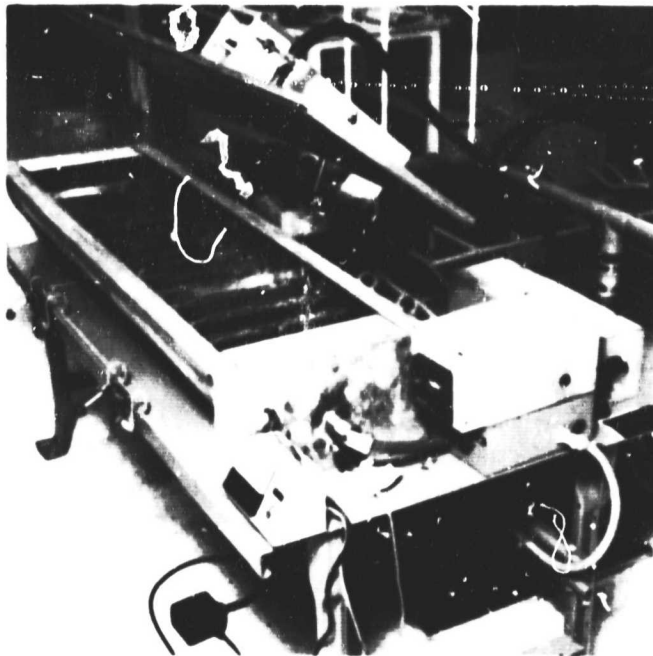


Figure 2. Original ARCO Solar Laminator

A resistive strip heater was considered as a possible inexpensive, improved heat source. Wire-wound strip heaters are commonly made with surface-temperature variations of less than  $\pm 2\%$  (when measured on top of a 0.125-in.-thick glass plate). Another well controlled heat source would be a heated oil system. This system also would have the capability of cooling down the product before opening the laminator.

The Process Development Area (PDA) of the Project received two ARCO Solar-developed laminators at the end of the contract. One of these laminators was modified for use with a strip heater (Figure 3). This configuration, with a boost-and-buck autotransformer power supply, as shown in Figure 4, was used successfully for some process verification and materials survey experiments. Assessment of future research needs and present equipment capabilities led to additional modifications of the laminator.

Experience with the laminator showed that the heavy aluminum base plate, a large thermal mass, caused control-response problems. The 0.25-in. Transite plate also caused some control problems, because it was close to the controller thermocouple. Thermal mass keeps the chamber temperature high during the unload-load cycle, which can start the cure cycle earlier than desired. The controller temperature must be manually adjusted to prevent the temperature of the laminant adhesive-encapsulant from overshooting. An inexpensive, mechanically stiff thermal insulation system that would not out-gas during exposure to processing temperatures as high as 175°C was required. Figure 5 shows the laminator modifications required to achieve the desired thermal isolation and improved controllability. An unusual material application was the use of glass marbles as insulation. Table 1 shows typical laminant and controller temperature readings before and after the thermal isolation modification. There was an improvement in warm-up time and in tracking. This design presents a nearly balanced thermal load above and below the strip heater (Figure 6) that should allow good tracking, regardless of the desired time-temperature cycle.

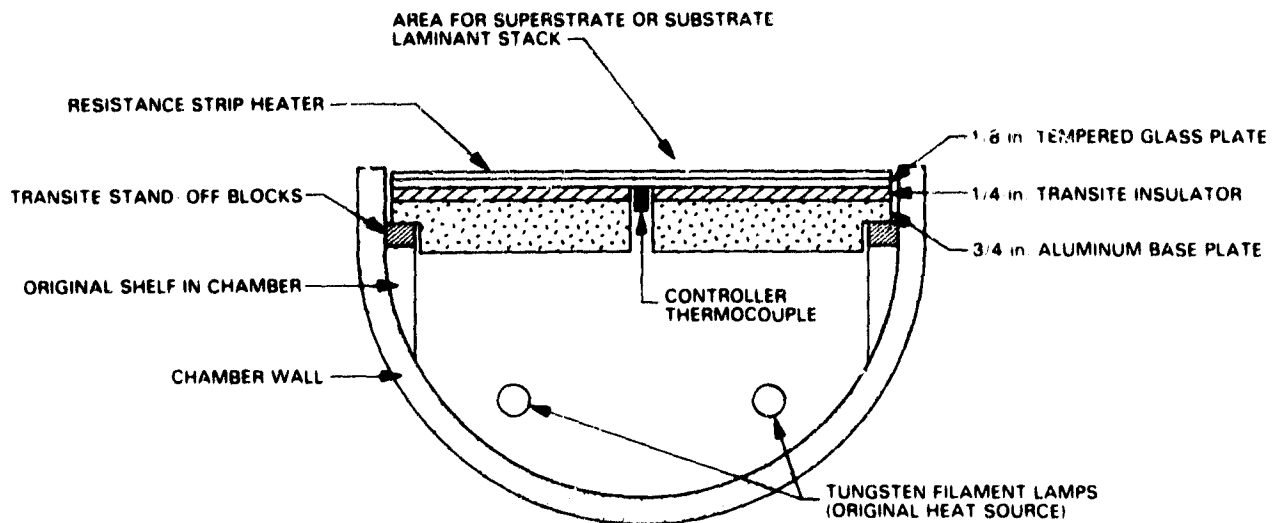


Figure 3. Laminator Modified for Strip Heater

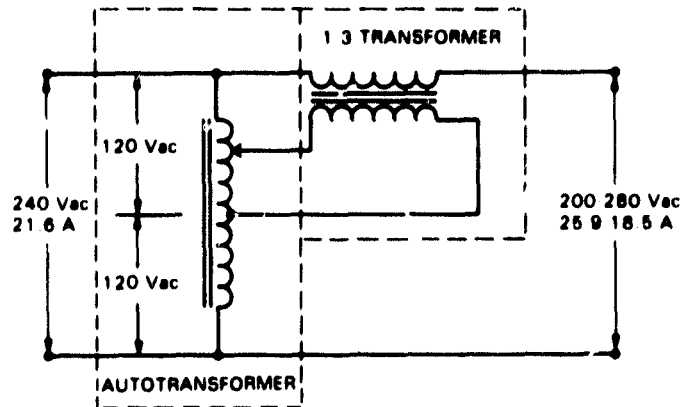


Figure 4. Boost-and-Buck Autotransformer Power Supply

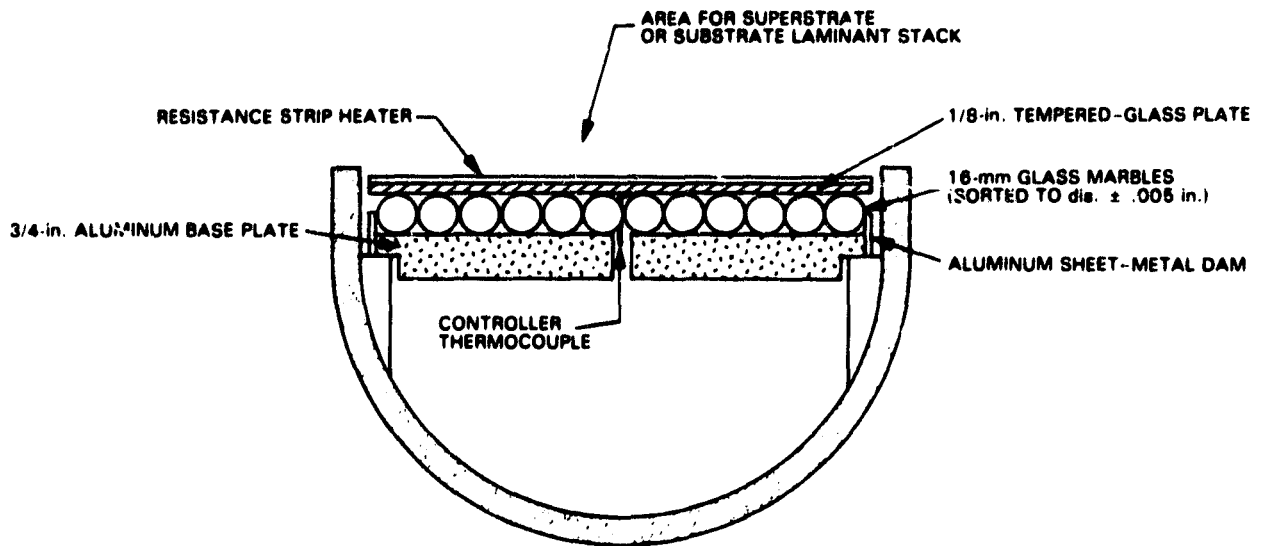


Figure 5. Laminator With Improved Thermal Isolation

Table 1. Glue-Line and Platen Temperatures

Time, min	Before Thermal Isolation		After Thermal Isolation	
	Controller Thermocouple, °C	Laminant Thermocouple, °C	Controller Thermocouple, °C	Laminant Thermocouple, °C
0-5	100 <sup>a</sup>	93.0	90 <sup>a</sup>	77.0
6	105	103.0	100	85.6
7	112	117.0	110	100.0
8	120	129.4	125	116.0
9	131	141.1	136	128.8
10	139	151.4	146	140.4
11	145 <sup>b</sup>	160.0	155 <sup>b</sup>	151.0
12	149	166.9	156	156.0
13	150	171.3	158	159.9
14	150	173.3	159	161.0
15	150	173.6	159	162.5
16	150	172.5	159	163.0
17	150	170.6	159	163.3
18	150	168.2	159	163.5
19	150	165.6	159	163.5
20	150	163.0	160	163.5
21	150	160.6	160	163.4
22	150	158.5	160	163.3
23	150	156.7	160	163.2
24	150	155.4	160	163.2
25	150	154.4	160	163.1
26	150	153.7	160	163.0
27	150	153.2	160	162.9
28	150	153.1	160	162.8
29	150	153.1	160	162.7
30	150	153.2	160	162.6

<sup>a</sup>Heater was turned on at increased voltage at 5 min for fast warm-up.

<sup>b</sup>Voltage was reduced to line voltage.

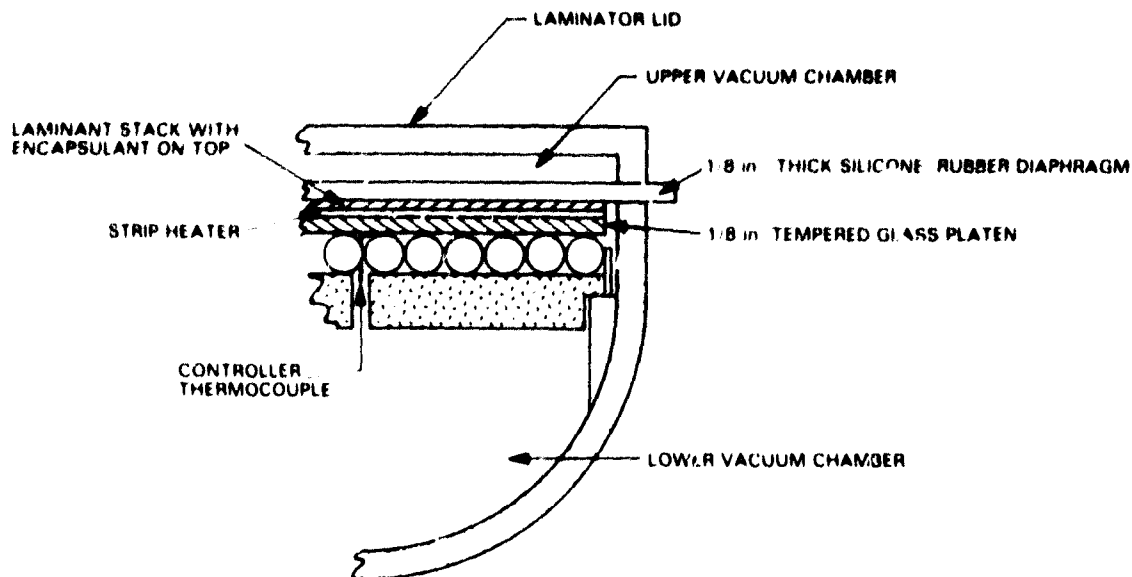


Figure 6. Balanced Thermal Load on Strip Heater

Additional laminator changes that were implemented included:

- (1) Applying a vacuum to the top chamber of a double-chamber vacuum laminator just before raising the upper chamber (lid) to remove a completed module (see Figure 3). This allows the silicone-rubber diaphragm to be attached to the upper chamber, which reduces handling and keeps the diaphragm weight off the laminant stack during evacuation of the lower chamber.
- (2) Attaching the controller thermocouple to the bottom of the 0.125-in. aluminum platen by laminating. This was done and this improved thermal coupling enhanced the performance of the laminator.

One measure of the utility of the present laminator is its acceptance by other researchers. Test programs now scheduled on the laminator include:

- (1) New encapsulating materials evaluation.
- (2) Substrate encapsulation studies.
- (3) Preparation of water permeation study samples.
- (4) Evaluation of module design developed under JPL contract.

- (5) Encapsulant-to-metal primer-compound research.
- (6) Preparation of electrostatic samples.

Because of the equipment development success, a new, larger laminator is being designed to explore problems inherent in fabricating the larger PV modules envisioned for the mid-1980s. A 4-ft square laminator area is anticipated that would be compatible with the 1.2-m square designs or any smaller configurations. The most expensive part of a large laminator is the chamber that must withstand the atmospheric pressure load. Presently, the lowest-cost vacuum chamber that has been considered uses standard hemispheric pressure vessel-end caps costing about \$300 each (including a 2-in.-wide flange). The stand for the chamber would be a short cylinder from the same supplier.

Support and insulation of the platen was also a problem, and the use of marbles seems to be an inexpensive choice because about \$200 of marbles would provide support, thermal isolation, and have the added advantage of easy transport and modification of the chamber. Marbles also reduce the volume of the vacuum chamber and thereby reduce pump-down time and energy.

## B. MATERIALS RESEARCH

Design of a PV module that will withstand 20 years of exposure to a variety of terrestrial environments creates many problems. An FSA Project cost allocation of \$14/m<sup>3</sup> for encapsulation, superstrate or substrate and edge-seal/gasket places an additional burden on the encapsulation materials, because the glass superstrate alone has a projected cost of about \$10/m<sup>2</sup>.

Details and background on early materials research efforts have been published (References 3, 4, 5, 6 and 7). A detailed discussion of present encapsulation materials will be published soon (Reference 8). This report covers the application testing of developed materials and other requirements for successful vacuum lamination.

### 1. Ethylene Vinyl Acetate System

The first new lamination material developed by the FSA Project was compounded by Springborn Laboratories, Inc. (SLI) from an ethylene vinyl acetate (EVA) feedstock available from Du Pont. Compared with PVB, EVA costs about one-third as much, has much lower viscosity at process temperature, and has no humidity-control requirement during processing.

Early laminator experience uncovered problems with curing and adhesion of FVA. The original material from SLI also would adhere to itself, or block. Subsequent material delivered from Du Pont did not block, and had one waffled surface, which enhanced air removal during vacuum pumpdown.

There is more than one correct cure cycle for EVA. Like most polymers with peroxide promoters, it is good practice to raise the bond-line temperature rapidly to avoid peroxide decomposition before an adequate cure has been obtained. One cure cycle that has been proven uses two steps, one at 100°C for evacuation and adhesion, the other at 150°C for long-term oven cure.

This cycle provides a high throughput with only one laminator. A description of the cure cycle used for materials testing is:

Evacuation for 5 min, then 25 min of cure with the top chamber bled to atmosphere. During the 25-min cure, the first 8-10 min is required to raise the encapsulant temperature to 160°C, where it is maintained to the end of the cycle. Modules are then removed without being cooled. Modules fabricated with this cure cycle show even and complete curing and no bubbles.

Adhesion is a more difficult problem. There are many chemically different interfaces in a laminant stack: glass-EVA, 1-solar cell surface (oxidized silicon or some antireflection (AR) coating), cell back-surface metallization-EVA, EVA-back sheet, and EVA-bus bars (copper or tinned copper). Each of these interfaces is important, because mechanically good adhesive bonds will often fail by delamination after exposure to humidity in the field. Water vapor will permeate through polymers and, if there is a non-chemically bonded surface, water may collect and cause failure by displacement. Tables 2, 3, and 4 provide details of some of the research efforts in adhesion.

A material survey was made using EVA and EMA encapsulants and Korad 63000, Scotchpar 20CP and Tedlar 200BS 30WH as back sheets. Table 2 shows the detailed results of this survey. Primed and unprimed surfaces and a new Du Pont Adhesive, 68040, were investigated. This survey showed good glass bonding with SLI Primer All861-1, and showed the need for a primer. The only back sheet that adhered to EVA was Tedlar with Adhesive 68040. Earlier tests showed good mechanical bonding to untreated Tedlar but poor humidity performance.

Because the glass-to-EVA interface bonding problem seemed to be solved when all samples exhibited adherent and persistent bonds, the focus of the effort was shifted to back-sheet adhesion. An additional series of tests (see Table 3) confirmed the good results of Tedlar with the Du Pont Adhesive 68040. Korad 63000 may be a useful material, but cure temperatures during lamination caused some degradation. Additional tests on this acrylic sheet may be run. A polyester film, Scotchpar 20CP, was interesting, because it would be less expensive than a polyvinyl fluoride film, such as Tedlar. This test series showed that a new primer or adhesive was needed for the Scotchpar film.

Fortunately, E. P. Plueddemann of Dow Corning Corp. had already developed and patented a primer for polyester films. Table 4 shows the excellent results achieved using this primer, EVA and Scotchpar. Because Project material cost objectives can be met using a polyester film, additional application research efforts in back sheet adhesion were not pursued. Additional samples of both the EVA/68040/Tedlar and the EVA/Cymel Primer/Scotchpar systems were prepared for adhesion tests described in a later section.

## 2. Ethylene Methyl Acrylate System

A new encapsulant adhesive, ethylene methyl acrylate (EMA), is under development. Preliminary work showed excellent adhesion of EMA to glass when the glass is primed with All861-1. Long-term soaking in cold water reduced the adhesion. Additional work and samples are needed.



Table 2. Material Survey

Sample No.	Encapsulant	Back Sheet	Class Primer	Back-Sheet Adhesive	Encapsulant-Glass Peel, g	Back Sheet-Encapsulant Peel, g
1	EVA	Korad 63000	None	None	Not tested	185
2	EVA	Korad 63000	All861-1	All861-1 Primer	2,900	370
3	EMA	Korad 63000	None	None	Not tested	0
4	EMA	Korad 63000	All861-1	All861-1 Primer	4,300	Adherent, but brittle
5	EVA	Scotchpar 20CP	None	None	Not tested	55
6	EVA	Scotchpar 20CP	All861-1	All861-1 Primer	7,000	590-680
7	EMA	Scotchpar 20CP	None	None	Not tested	110
8	EMA	Scotchpar 20CP	All861-1	All861-1 Primer	10,000	3,200; broke
9	EVA	Tedlar 200BS 30MH	None	68040	Not tested	Adherent; couldn't peel
10	EVA	Tedlar 200BS 30MH	All861-1	68040 and All861-1 Primer	5,100	Adherent; couldn't peel
11	EMA	Tedlar 200BS 30MH	None	68040	Not tested	Adherent; couldn't peel
12	EMA	Tedlar 200BS 30MH	All861-1	68040 and All861-1 Primer	7,000	4,400; broke

Table 3. Back-Sheet Adhesion

Sample No.	Encapsulant	Back Sheet	Glass Primer	Back-Sheet Adhesive	Back Sheet-Encapsulant Peel
A-1	EVA	Scotchpar 20CP	A11861-1	68040	0
A-2	EMA	Scotchpar 20CP	A11861-1	68040	0
A-3	EVA	Korad 63000	A11861-1	68040	Adherent, but brittle
A-4	EMA	Korad 63000	A11861-1	68040	Adherent, but brittle
A-5	EVA	Tedlar 200BS 30WH	A11861-1	68040	Adherent; couldn't peel
A-6	EMA	Tedlar 200BS 30WH	A11861-1	68040	Adherent; couldn't peel
A-7	EVA	Gel test	None	-----	-----
A-8	EMA	Gel test	None	-----	-----
A-9	EVA	Tedlar/68040/ EVA combination	A11861-1	(68040)	Adherent; couldn't peel
A-10	EMA	Tedlar/68040/ EVA combination	A11861-1	(68040)	Adherent; couldn't peel
A-11	EVA	Gel test	None	-----	-----
A-12	EVA	Scotchpar 20CP	A11861-1	1359	0
A-13	EVA	Korad 63000	A11861-1	1359	Adherent, but brittle

Table 4. Results of 7-Day Water Soak Test

Coupon No.	Encapsulant	Primer <sup>a</sup>	Back Sheet	Results <sup>b</sup>
C-1	EVA	Cymel	Scotchpar 20CP	Peels
C-2	EVA	Cymel	Scotchpar 20CP	Sample given away
C-3	EVA	Cymel	Korad 63000	Peeled after cure
C-4	EVA	Cymel	Korad 63000	Peeled after cure
C-5	EVA	68040	Tedlar 200BS	Adherent
C-6	EVA	68040	Tedlar 200BS	Adherent
C-7	EVA	68040	Tedlar 200BS	Adherent
C-8	EVA	68040	Tedlar 200BS	Adherent
C-9	EVA	68040	Tedlar 200BS	Adherent
C-10	EVA	68040	Tedlar 200BS	Adherent
C-11	EVA	68040	Tedlar 200BS	Adherent
C-12	EVA	68040	Tedlar 200BS	Adherent
C-13	EVA	68040	Tedlar 200BS	Adherent
E-1	EMA	Cymel	Scotchpar 20CP	Peels
E-2	EVA	Cymel	Acrylar	Brittle
E-3	EVA	A-11861-1	Acrylar	Peels
E-4	EMA	Cymel	Acrylar	Peels
E-5	EMA	A-11861-1	Acrylar	Peels
E-7	EMA	68040	Tedlar 100BG 30UT	Peels after cure
E-8	None	68040	Tedlar 200BS	Peels
E-9	None	68040	Tedlar 200BS	Peels

<sup>a</sup>Primer consists of Cymel 303 (American Cyanamid), 90 parts; Du Pont Z-6040, 10 parts; methanol; 300 parts.

<sup>b</sup>After 7-day soak unless otherwise noted

Tests with Tedlar and Adhesive 68040 showed adhesion to EMA. However, adhesion after cold-water soak was poor. This problem is being investigated.

The same primer that was used to bond EVA to a polyester was also tried in bonding EMA to a polyester. This system also degraded after long-term soaking in cold water. Korad 63000 has adhered to EMA, but the resulting back sheet was brittle.

### C. TESTING METHODS

The original lamination materials development was started with a process verification test program.

The EVA verification effort was based on a Spectrolab, Inc., process (Reference 9), which had a laminant material sequence of:

- (1) 1/8-in. tempered glass.
- (2) 0.005-in. Craneglas 230.
- (3) 0.018-in. clear EVA.
- (4) Cells.
- (5) 0.005-in. Craneglas 230.
- (6) 0.018-in. white-pigmented EVA.
- (7) 0.005-in. Craneglas 230.
- (8) 0.003-in. Mylar.

Four minimodules (Serial Nos. M-1 to M-4) were successfully laminated, using this process and the cure cycle described above. An evaluation of the modules by a quality-assurance inspector showed some small bubbles at the junctions of the cell interconnect and the 0.010-in.-thick copper parallel bus bars and some delaminated areas because of incomplete solder-flux removal. Adhesion of the EVA to the glass superstrate was excellent; the peel test samples broke before peeling. The reason for this strong bond was the use of Primer All861-1. Peel tests were not made of the EVA-to-Mylar bond because it was so poor. Even though there were some problems, the basic lamination process was considered to be verified because there was good EVA-glass adhesion and no cell cracking.

During the process verification testing, the number of sheets of Craneglas 230 was varied to determine process sensitivity. As a result of these tests, it was found that only the Craneglas sheet between the cells and the white-pigmented EVA was necessary. Individual module designs may require more sheets of Craneglas. Another area of investigation was the use of pigmented EVA. A simpler lamination process was found by using all-clear EVA and a white-pigmented back sheet.

A gel test, recommended by SLI, was made on EVA coupon samples produced when the original four modules were made. Because unpolymerized EVA is soluble in toluene, weighted samples were placed in 60°C toluene for 2 h, and the resultant solution and sample was poured through weighed filter paper. After filtration, the samples were dried in a 90°C circulating-air oven for 5 h. The percentage of EVA remaining is a measure of the degree of gelation or polymerization during cure. SLI specifies a nominal 80% gel with 65% as the lower limit. The gel test on the samples produced above showed better than 95% gelation.

Peel-test samples were prepared by cutting through the layer to be tested using a 0.25-in. wide template. The desired layer was then peeled back by cutting when necessary. Peel strength was measured using a Unitek Micropull I, Model 6-092. Several adherent samples had a cohesive strength above the 5-lb limit of the test equipment, so these samples were tested using a calibrated spring scale. After some testing, it was noted that if a peel-test sample could be easily prepared the sample had substandard adhesion. Some thin film samples were so adherent or so brittle that a sample could not be prepared. These situations are noted in the attached tables.

Performing a peel test after lamination should be considered as only a good screening test; it is not sufficient for material selection. Plueddemann recommends a 7-day soak in room-temperature water as an additional test, with final peel tests demonstrating cohesive failure rather than adhesive failure (Reference 10). All of the laminants made at JPL have been subjected to the 7-day room-temperature water-soak test. Table 4 summarizes the results of 7-day room temperature water soak tests.

#### D. OTHER LAMINATION-RELATED EFFORTS

The first lamination efforts were mechanically successful but visually unsuccessful. Many bubbles and voids were found that were related to solder joints. Another visual problem was cell misalignment and poor placement. Both of these problem areas were not caused by the lamination process but would have a profound effect on the marketability and field service-life of the final laminated product.

##### 1. Solder-Flux Removal

Removal of soldering flux residues is an established process in the printed-circuit-board and electronic-assembly industries. The quality of the lamination process is dependent upon chemical bonding of all surfaces within the laminant, so very clean cell-string assemblies are required. Proper removal of flux residues requires solvents that can remove both polar and non-polar soluble contaminants, so use of proprietary flux-removal solvents was indicated. Because cell interconnects provide flux traps (especially the Motorola Inc. and ARCO Solar combination bus bar-interconnect designs), it was decided to try ultrasonic cleaning followed by vapor degreasing. Six cell-string assemblies for minimodules and four assemblies for 1 x 4-ft modules were first cleaned in Kester 5345 Rosin Residue Remover using a Sonix IV Model SS-104 Ultrasonic Cleaner. Subsequently, these same cell-string assemblies were cleaned in Kester 5120 vapor degreasing solvent using an Electrovert, Inc., Degrestil Model LCD-18 vapor degreaser. The assemblies were first introduced to the vapor zone, then were dipped in the cold-solvent tank and finally were removed slowly through the vapor zone. These cell strings showed no delaminated areas or bubbles after being laminated with EVA. Cell strings that were only swab-cleaned for flux removal showed both bubbles and delamination when laminated using identical process parameters.

Because flux is such a concern, one contractor is exploring ultrasonic bonding (Reference 11), using prepunched aluminum interconnects that are attached to electroplated copper cell metallization with a seam welder. Others are examining fluxless bonding concepts, such as vapor-phase solder reflow.

## 2. Material Handling

Several operations are required between cell stringing and lamination. Typically, these are:

- (1) Attach (solder) bus bars to cell-string ends.
- (2) Electrical test.
- (3) Flux removal.
- (4) Apply primer.
- (5) Lay up laminant stack.

During these operations, proper material handling is important to avoid breaking cells or straining the cell interconnects. Those operations that required dipping in a solution and vertical withdrawal for draining (e.g., flux removal and primer application) were especially difficult. There was no simple way to support the cell strings without interfering with the action of the liquids. Lack of proper support strains the interconnects, which affects module layup and may also lead to later thermal-cycling fatigue failures.

If the cell strings are cleaned right after their assembly, the flux removal operation would be simpler. After cell stringing, the parallel bus bars must be attached. If these are soldered, it may be possible to remove the flux from the bus-bar ends without handling the whole assembly. Another approach would be to ultrasonically bond or to spot weld the interconnects to the bus bars.

Application of a primer by dipping the cell string assembly is the most feasible operation, but with 4-ft-long cell strings it is awkward. The priming operation must come after all joining operations, because the primer binds to surfaces and may inhibit mechanical adhesion. The Encapsulation Task of the FSA Project is exploring inclusion of the primer in EVA so that glass and cell-string-assembly priming may be unnecessary.

## E. CONCLUSIONS

The following conclusions can be drawn from efforts to date:

- (1) Vacuum lamination is an acceptable process for manufacturing void-free PV modules, if matched with correct materials and used with a qualified cure cycle.

- (2) Conceptual design of a large (4 x 4-ft) vacuum laminator indicates the potential for an inexpensive piece of capital equipment.
- (3) Material research by the Encapsulation Task of the JPL FSA Project has been applied to actual laminated systems with good results. One laminant system has been developed that shows excellent adhesion and resistance to delamination after being soaked for 7 days in cold water.
- (4) Gel tests are useful in determining proper cure cycles.
- (5) Peel tests are only partially useful. Most laminant systems exhibit either very low or very high adhesion after a 7-day soak in cold water. The soak test may not be a sufficient predictor for 20-yr service life; however, it may be considered as a screening test for systems that should receive additional effort.
- (6) Complete removal of solder flux is presently considered to be necessary to ensure long-term laminant adhesion. A process change to avoid solder flux is thereby encouraged.
- (7) Handling damage to cells and interconnects is a major problem that requires more process and automation effort.

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