June 1997 • NREL/SR-520-23189

Advanced Polymer PV System

PVMaT 4A1 Annual Report
September 1995 - September 1996

J. Hanoka, R. Chleboski, M. Farber,
J. Fava, P. Kane, and J. Martz
Evergreen Solar, Inc.
Waltham, Massachusetts

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of
the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under Contract No. DE-AC36-83CH10093

NREL/SR-520-23189 • UC Category: 1280 • DE97006934

Advanced Polymer PV System

PVMaT 4A1 Annual Report
September 1995 - September 1996

J. Hanoka, R. Chleboski, M. Farber,
J. Fava, P. Kane, and J. Martz
Evergreen Solar, Inc.
Waltham, Massachusetts

NREL technical monitor: H. Thomas

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of
the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under Contract No. DE-AC36-83CH10093

Prepared under Subcontract No. ZAF-5-14271-09

June 1997

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling (423) 576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

PVMaT—Annual Report
Contract #ZAF-5-1427-09
September 1995 through September 1996

EXECUTIVE SUMMARY

The purpose of this subcontract was to produce lower module and systems costs through the innovative use of polymeric materials. The impetus behind this was the burgeoning use of polymers in such major industries as packaging and automobiles. The market demand in these industries has resulted in whole new areas of high performance but low cost plastics. This in turn has created fresh opportunities for photovoltaics.

Within this approach, our Innovative Mounting System (IMS) was developed and testing begun during the first year of this PVMaT contract. This IMS system substantially reduces the cost of installed PV systems by reducing labor and materials costs both in the factory and in field installation.

The IMS incorporates several advances in polymers, processing methods, and product design. An advanced backskin material permits elimination of the conventional aluminum perimeter frame by protecting and sealing the edge and by direct bonding of multi-functional mounting bars. Electrical interconnection is easier and more reliable with a new junction box. The feasibility of a non-vacuum, high-throughput lamination method was also demonstrated in the first year of the contract. This lamination technology is made possible because of the development of a novel transparent encapsulant with UV stabilization package that can be laminated in air and which should lead to longer field life than conventional designs.

The first-year program culminated in the fielding of prototype products with the new encapsulant, new backskin, new junction box, frameless edge seal, and Innovative Mounting System. Feedback and marketing information from potential customers has been actively solicited. Reliability and UL approval requirements have been determined and preparations made to address these. The net result is a new product which promises a $0.50/watt manufacturing and systems cost reductions as well as significantly increased system lifetime. The second year will complete refinement and testing of the encapsulant and backskin, complete the new lamination method, and refine product designs.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Some 15 years ago, following the extensive work done under JPL auspices, a Tedlar laminate backskin and an EVA encapsulant were developed for the PV industry. Each of these materials was improved over time and became accepted throughout the industry worldwide. At the time, EVA and Tedlar (a laminate, typically referred to by the Tedlar layer) were likely the best choices available, and now they have the advantage of considerable commercial experience.

Our PVMaT project builds on the enormous growth of polymeric materials and applications since the original JPL work. In particular, the explosive penetration of polymers in the packaging and automotive industries offers fertile ground for adapting advanced polymers to PV to achieve lower cost and higher performance.

This annual report documents progress for the first of two years. The project entailed four major technical areas:

1. Identification and deployment of a new backskin that allows for a frameless module and novel mounting methods;

2. Identification and deployment of a novel encapsulant that should lead to longer life and permit non-vacuum lamination;

3. Development of a continuous, high-throughput, non-vacuum lamination method; and

4. Development of an Innovative Mounting System (IMS) for PV modules that simplifies mechanical and electrical installation.

During the first year, the major developments were the backskin and IMS (#1 and #4). The ground work for the encapsulant and lamination process (#2 and #3) were also established, and, within goal #4, the design of an improved junction box was achieved. In addition to the technical work, two other important activities were included: market research and customer feedback on the new products; and discussions with UL and testing labs on safety and reliability test requirements.

NEW BACKSKIN MATERIAL

As already mentioned, a Tedlar laminate is the conventionally used PV module backskin. A typical construction is a three-part laminate: a thin outer layer of Tedlar, about 2 mils thick; a middle layer of polyester, perhaps 3-4 mils thick; and an inner layer of EVA, 3-4 mils thick. The EVA layer bonds with the EVA encapsulant in the module. The polyester serves as a barrier layer, and the Tedlar is a barrier as well as very weatherable and temperature resistant. Tedlar is a type of polyvinyl fluoride and therefore has many of the well known properties of fluorocarbon polymers.

Despite its many positive attributes, this laminate has disadvantages. It is expensive, more than $1.00 per square foot (~ $0.10 per watt). It is hard to bond to, and has been known to delaminate when mounting structures or heavy items have been bonded to it. Finally, its puncture resistance is not high because it is so thin, generally 10 mils or less.

Evergreen sought a new backskin with the following characteristics:

- Ability to eliminate the frame, but still seal and protect the edges of the superstrate glass.
- Internal stability (i.e., not a laminate) to provide a mounting platform for the Innovative Mounting System
- Higher puncture resistance
- Lower permeability
- Lower cost
- Readily available
- Manufacturable

This required a totally different kind of material than the Tedlar laminate. It had to be a thermoplastic that could be formed and melted during lamination to form an edge seal. These objectives also required choosing a commercially available resin, given the nature and size of the plastics business vis-a-vis the PV market.

Candidate materials were identified, and the search focused on modified polyolefins, many of which are used in automobiles and for which outdoor weathering data are available. One material in particular seemed to satisfy our requirements for a thermoplastic that could be formed in a lamination process under typical lamination temperatures and pressures. Furthermore, even at a 40 mil thickness, the material was still significantly lower in cost than the Tedlar laminate. Also, this material bonded readily to all adjacent surfaces.

The base resin for the new backskin is a mix of two generically similar polyolefin type materials in a synergistic combination. It can be obtained in black, with up to 5% carbon, but it can also be pigmented if desired. It can also contain mineral fillers to provide better mechanical properties. Figure 1 (p.29) shows a roll of the new backskin material.

After the identification of an appropriate candidate material, the evaluation process began. A range of test equipment was used, including an environmental test chamber (Fig 2). Three important issues were addressed: thermal creep behavior, bond strength, and environmental endurance.

Thermal creep was an important issue, because the material is a thermoplastic. For use in PV, resistance to thermal creep must be high, even at temperatures as high as 90°C. As a preliminary test, strips of 40 mil sheet were placed under a modest load of 0.5 psi and heated at 90°C for two months. These samples showed no significant creep – an encouraging early result.

The next level of evaluation addressed the material's ability to retain its creep resistance and other properties, especially electrical, after long-term exposure to temperatures higher than 90°C. A polymer's ability to maintain its physical properties after long-term exposure to elevated temperatures is known as its thermal endurance or relative thermal index (RTI). Per UL 1703, a backskin material must have an RTI of 90°C or higher. While the material first selected did not initially have a sufficiently high RTI, a modification of the material was found that increased the creep resistance to less than 5% at extreme temperatures – well above 200°C . It seems likely that the modified material will have a superior thermal endurance and be able to pass the UL qualifications.

Because of our plan to eliminate the perimeter frame and bond mounting brackets to the backskin, bond strength was another critical characteristic of the backskin. Two tests of the bond were performed: thermal creep, and static load.

Thermal creep measurements were made at 85°C with a load of 1.15 psi on a mounting component bonded to the backskin. The 1.15 psi load was selected as an initial estimate of the maximum sustainable load. Fig. 3A illustrates the set-up used. After 45 days, virtually no creep had occurred.

The bond's static load strength was tested using a set-up illustrated in Fig. 3B. For static loads, the minimum test criterion was 50 psf, as specified in module qualification tests JPL Block 5 and IEEE 1262. Roughly speaking, this corresponds to a wind speed of 125 mph. However, since UL 1703 requires a 50% safety factor, the test criterion was increased to 75 psf loading. Based on the likely worst-case dimensions of our modules, this requires a bond strength of 18.7 psi over the bond area. We bonded a mounting bracket structure to a test module, and loaded it to 18.7 psi. The sample was placed in a thermal chamber for 308 hours at 60°C. Over this time, the bond showed no degradation.

Further environmental stress tests were conducted In some cases, tests were confined to the IEEE 1262 specifications; in other cases, tests were extended well beyond these requirements.

Perhaps the most stringent of the environmental stress tests is humidity freeze. The IEEE 1262 humidity freeze test involves 10 cycles of -40°C to 85°C at 85% relative humidity (RH), the latter conditions of 85 °C and 85% RH are for 20 hours per cycle. Various kinds of samples were subjected to different degrees of exposure. Table 1 lists a subset of these tests with summarized results. Note that the samples that had undergone over 100 cycles had in effect 2000 hours (100 cycles of 20 hours) of damp heat at 85°C and 85% RH, which is another of the standard IEEE tests.

Table 1. Results of Humidity Freeze Tests

Sample Number	*Number of Humidity Freeze Cycles*	*Sample Description*	*Results*
1	173	5" x 5" coupon with new backskin and edge seal	Edge seal still very intact Cracks on rear of backskin
3	145	24" x 17" module with 24" long metal mounting component bonded to backskin	All bonds and seals fine Cracks in backskin in one corner
11	53	Same as #1 except with modified backskin and metal mounting stud bonded to backskin	All bonds and edge seal fine
17a	40	5" x 5" coupon with Tedlar backskin, conventional edge seal, and Al frame	All bonds and edge seal fine
17b	40	5" x 5" coupon with new backskin and edge seal	All bonds and edge seal fine

This testing program suggests excellent performance of the new material. Samples #1 and #3, which were tested to failure with 173 and 145 humidity freeze cycles, still show excellent edge sealing but some cracking. These cracks only appeared after these extraordinarily long numbers of humidity freeze cycles and in both cases originated in the corner of the module. There is some suspicion that these two modules were inadvertently dropped on the corner while the module was at a temperature of ~ 85°C and this could have caused the subsequently observed cracking. Samples #3 and #11 also indicate that the excellent bond of the metal mounting component to the backskin is unaffected by the cumulative environmental exposure. Sample #11 showed that the modified backskin material (cf. P.7 of this report) also displayed strong bond strengths to a metal mounting component. Also, samples #17a and #17b, a direct comparison between Tedlar and the new backskin, show no differences as yet after 40 cycles. Finally, the samples with very long exposures, such as #1 and #3, show yellowing of the EVA, which was the encapsulant in all samples listed in Table 1. This yellowing is likely due either to water vapor or oxygen ingress and is a useful visual criterion for sealing effectiveness. This criterion was employed in a general way to compare the permeability of the modified backskin material vs. that of Tedlar. Qualitatively and visually, no difference has yet been seen.

NOVEL ENCAPSULANT

Two objectives motivated the development of an alternative encapsulant to EVA. First, we sought an encapsulant with process advantages, in particular, one which could be laminated in air. Second, we wanted an encapsulant with better product performance, particularly UV stability.

It should be noted that EVA is presently the most widely used PV encapsulant, does function effectively in many PV applications, and is undergoing continuous improvement. Nevertheless, our search for a better encapsulant is motivated by EVA's inherent limitations, many of which stem from the use of organic peroxide. The organic peroxide, either Lupersol 101 or TBEC, is added to EVA to promote cross-linking during lamination. Without cross-linking, the low melting point of ELVAX 150 with 33% vinyl acetate unduly increases the likelihood of thermal creep at temperatures as high as 90°C. However, the use of the organic peroxide results in substantial disadvantages:

A key requirement is lamination in a vacuum, which has led to the batch lamination process widely in use.

The peroxide is not totally consumed during lamination and, over time, can promote polymer degradation.

The peroxide requires extrusion of the EVA, when formed into sheets, at a low enough temperature to avoid premature cross-linking in the extruder screw. This creates, at least for TBEC, a rather narrow processing window for forming sheets of EVA.

In addition to issues stemming from use of organic peroxide, EVA has two other limitations: currently available EVA formulations can discolor under strong, extended sunlight exposure, which reduces conversion efficiency; and, since EVA has ester functionality (as opposed to the acid functionality of our new encapsulant), its bond strength to adjacent surfaces will be weaker and exhibit adhesive failure rather than cohesive failure. "Adhesive failure" means that the interface bond strength fails first while "cohesive failure" means that the interface bond strength is so strong that the polymer itself fails first (cf: <u>Handbook of Adhesives</u>, ed. By I. Skeist, 3rd ed, 1990, Van Nostrand Reinhold, p. 54).

Similar to the backskin development, finding an alternative encapsulant was aided by the enormous development of the transparent polymer packaging industry since EVA was adapted for PV. As a result, co-polymers of polyolefins, the most widely used packaging materials, were studied carefully. Given the size of the PV market relative to the polymer industry, we again aimed to adapt existing materials rather than invent new ones.

The first-year results were highly promising. A candidate encapsulant material was selected, and much work done on a suitable UV stabilization package. Initial testing is complete, with more testing remaining for the second year.

In the first part of this task, discussions were held with several resin manufacturers. In addition, we gathered together several consultants who were experts either on resin properties or UV stabilization.

The list of possible resins was narrowed first to two candidate materials, and finally to one material. The selected encapsulant material was made into 18 mil sheet. It is somewhat stiffer than EVA, has a much higher melting point, and poses no particular shelf life issues. Fig. 4 shows a roll of this material. This initial lot of the material did not have stabilizers. Thermal creep tests wherein 1" x 6" strips of the encapsulant were placed in a convection oven for 30 days at 90 °C indicated no significant creep.

The early experiments done with this material are promising, albeit preliminary. The material laminates well in both the vacuum laminator and in the alternative non-vacuum lamination process (discussed later in this report). Although not necessarily longer or more complicated, the optimal vacuum lamination cycle is clearly different than for EVA. Its peak lamination temperature will be somewhat higher, and the point at which the bladder pressure is begun is also at a higher temperature than for EVA. Lamination cycles for EVA and the new encapsulant are shown schematically in Fig. 5.

Choice of an encapsulant resin, however, is only half the problem. The other half is to select and test a UV additive package in such a resin. In general, the packaging industry is not very concerned about UV stability, so this area required a considerable amount of work.

The first task relating to additives was to identify an outside testing laboratory to perform initial screening tests for possible UV stabilizers. The list of qualified labs was narrowed to four, including an adjunct lab to the University of Massachusetts at Lowell. One lab was eliminated after a site visit because of inadequate capabilities, and, ultimately, two labs were invited to bid. The one chosen submitted the most detailed as well as the lowest cost bid.

A listing of all likely additives and samples of each were obtained from four different stabilizer suppliers. Initially, there were 16 possibilities.

Solubility was the first major criterion to be studied. We devised a solubility test procedure, which was subsequently implemented by the testing lab. Extruded film, about 2" wide and 0.030" thick, was made for each possible stabilizer. Two concentrations, 0.5% and 0.75%, were then added for each. Two phases of solubility tests were then performed, as follows.

During the first phase of solubility analysis, all samples were placed into sealed jars at 65°C for one month. Samples were then examined for evidence of surface exudation, cloudiness, or yellowing – all indicators of lack of solubility. This analysis reduced the number of possible stabilizers to 8.

In the second phase of the solubility study, combinations of the additives were tried in various samples and in a somewhat broader range of concentrations: 0.1% to 0.75%. Samples were again placed in sealed jars, but at 70°C (instead of 65°C, as in the earlier test) for one month.

From these studies, several possible combinations of additives emerged as attractive candidates for UV stabilization. One, in particular, uses a new type of stabilizer, which works on a somewhat different chemical basis than the others and may prove to be the best. Detailed discussions with the technical director of its manufacturer supports a good prognosis. Of course, field tests under sunlight will be the ultimate criterion.

At the end of Phase I, experimental quantities of the new encapsulant incorporating one of the stabilization packages have been received, and early testing initiated. Also, UVA - 340 bulbs have been received to begin accelerated UV exposures to compare the new encapsulant to EVA. As can be seen in Fig. 5a, these bulbs provide an excellent simulation of the UV portion of the solar spectrum.

ALTERNATIVE LAMINATION METHOD

Conventional PV lamination employs EVA in a vacuum method involving a silicone rubber bladder. By its nature, the vacuum process is a batch process, not conducive to large-scale manufacturing, and typical vacuum lamination equipment is expensive.

In contrast, we are developing a continuous, non-vacuum lamination process, expected to be lower cost and more easily scaled. In this Phase I of the subcontract we demonstrated feasibility with experimental equipment and laid the groundwork for establishing a manufacturing process in the second year.

During this first year, we acquired a "benchtop" non-vacuum laminator used in applications other than PV. The laminator was modified to test the feasibility of continuous lamination for crystalline silicon PV modules. Demonstrating feasibility required the following:

1. The availability of a non-EVA encapsulant that could be heated in air;
2. Sufficient heat and pressure for the encapsulant to melt and flow;
3. Sufficient heat and pressure for the backskin to bond; and
4. Demonstration that lamination could be done without cracked cells, or trapped air or bubbles.

The first task was to improve the equipment. The laminator was significantly modified to allow for more controlled and repeatable pressure and a wider range of speed control. Also, a large-area platen was constructed and connected to the equipment to preheat the glass.

Next, lamination was demonstrated in three discrete operations. First was pre-lamination of the encapsulant to the glass. Second was lamination of the middle layers, particularly the silicon solar cells. Third was lamination of the backskin. Fig. 6 illustrates these three steps. The non-EVA encapsulant for this early work was not the one which was later developed (described above). Instead, we used a commercially available co-polymer of polyethylene without UV stabilizers, so that work could begin on the novel lamination method before the new encapsulant was available. When the best conditions were found, this pre-lamination concept was shown to be viable and was therefore used subsequently.

Cracking of the crystalline silicon solar cells was a potential issue. This turned out not to be a problem when the appropriate conditions were found. The key was to reheat the encapsulant following pre-lamination so it was soft enough to cushion the cells under pressure.

Another technical issue was the elimination of bubbles due to trapped air, particularly between cells or around the electrical leads. Bubbles could be avoided through variations in temperature, pressure, machine speed, and the durometer of the silicone used to transmit the pressure. (Durometer is a measure of the hardness of an elastomer.) The temperature had to be high enough that the encapsulant would flow only slightly for steps 1 and 2 (in Fig. 6), but not so high in step 2 that craters or bubbles would form between the cells. A low durometer silicone also helped.

When samples of the new encapsulant first became available at the end of the first year, it was found that higher temperatures were needed to make this material flow (see Fig. 5), and it was difficult to reach these required temperatures with the present equipment. Rather than redesign a portion of the current machine, we will redesign the entire machine to complete this work in year two. Accordingly, at the very end of year one, plans were initiated for a total redesign to make a prototype machine with better capabilities.

With very modest equipment, the feasibility of non-vacuum lamination was firmly demonstrated. Furthermore, the range of process control for the prototype machine was also clearly established and provided an excellent foundation for the design of such a machine.

REDUCED SYSTEMS COST

A major objective of this PVMaT contract was to develop an innovative product that would reduce PV's mechanical and electrical installation costs, both in the factory and in the field. We concentrated on three areas:

Junction box design;

Replacement of the perimeter aluminum frame; and

An Innovative Mounting System (IMS).

The original concept was a snap-together mounting system with a frameless module and an integral junction box. The junction box was to be of the same material as the new backskin and also to have a so-called "living hinge." After the Phase I work began, we had extensive discussions with plastics design engineers and a structural engineer. The result of these discussions was a change from the initially suggested approach. For module mounting, a slide rail concept was embraced because it afforded much greater strength than the original snap-together system. For the junction box, very high mold costs in successfully deploying a living hinge necessitated a different J-box design and material than originally proposed. As will be shown, the alternatives chosen turned out to work very well for us.

Junction Box Design

Market research conducted amongst three different integrators, and several distributors, indicated that, from the customer's perspective, the junction box is one of the most important features of a module. It is the place that installers electrically connect to the product, and therefore size, layout, and related features directly determine installation time and "hassle." Furthermore, poor junction box design can lead to unreliable or unsafe connections.

We began with an extensive evaluation of current industry practice and then interviewed potential customers (system integrators and distributors) on the strengths and weaknesses of current designs. This analysis led to our junction box design, whose attributes are listed in Table 2.

After developing and evaluating several design concepts, we proceeded to use rapid prototyping methods so well developed in the polymers industry. The first step was solid or 3-D modeling. From this computer model, 3-D drawings were generated and used for initial feedback. After several iterations, including further customer interaction, a desirable junction box design emerged. From these discussions, the idea of a molded-in terminal block was explored. Since we had little experience with terminal blocks, we had discussions with and ultimately obtained engineering support from a leading terminal block and connector company.

Table 2. Features of Evergreen Solar's Junction Box

- Large size
- Sturdy
- No loose parts
- Box location and lid don't interfere with panel rail
- Hinged lid with a single, captive screw
- Lid stays open to desired position
- Field and factory wiring under separate terminals
- Molded-in terminal strip
- Spacing of terminals adequate for standard wire terminations
- Spare terminals for multiple module wiring configurations
- Clamp plates accept two #10 wires
- Dual voltage capability
- Rated for 600 volts DC
- Conduit capable
- 4 knock-outs
- Built-in fuse capability
- Better sealing and protection for leads

The combination of this iterative work and the 3-D solid modeling then led to the rapid prototyping of the junction box. This was performed using a stereolithographic method (called SLA) to form full-size physical prototypes with a light-sensitive polymer (not the polymer which would be used in production). The SLA forms a prototype using the 3-D solid modeling and the appropriate computer program to guide a laser beam to form the actual physical model from the light sensitive polymer. The prototypes were again shown to customers for final comments. Modifications to improve the design were made, the final design was prepared, and an injection mold was ordered to form parts.

We believe that the final design, shown in Fig. 6, will be very well received by customers. It incorporates all of the target features listed in Table 2.

Elimination of the Perimeter Aluminum Frame

The perimeter frame traditionally protects and seals the edges and offers mounting points. After the junction box, customers commonly identify the frame as the next most important feature. Just as the junction box is the electrical point of connection, so the frame is the mechanical point of connection.

The aluminum frame is a significant cost element, about $0.25/watt (materials and labor), often the second most expensive material in a module after silicon. Thus a viable method for eliminating the aluminum frame has long been recognized as very desirable. Of course, eliminating the frame poses the challenges of protecting and sealing the edges and offering mounting options. Several frameless modules have been produced over the years, but none have become accepted among the standard power modules for the industry's most demanding applications.

In the work done during the first year, protecting and sealing the edges was accomplished in a simple and straightforward manner. The backskin material itself was used for both these purposes without the need for any additional sealants or adhesive polymers. As described earlier, the seal has been tested in environmental stress tests more severe than required for IEEE 1262 and related tests. Results so far have been excellent, indicating that the seal holds up quite well under both humidity freeze and damp heat conditions.

The polymer seal also provides physical protection for the glass edges. This was tested in a fixture that allowed a 13" x 13" module with tempered glass and the backskin wrapped around the edge to be dropped 24 inches onto a rounded pin. The glass withstood this impact 10 times before it cracked.

Innovative Mounting System

Elimination of the perimeter frame requires not only acceptable edge sealing and protection, but an alternative mounting method. The method selected takes advantage of one of the most useful attributes of the new backskin material: its unusual ability to bond strongly to a variety of other materials, including glass, metal, and other polymers. Our next task was to develop a variety of mounting components, either polymer or metal, to bond directly to the backskin.

As with the junction box, we began with customer input and a review of industry practices. Jefferson Shingleton, a consulting design and structural engineer with substantial PV systems experience, was critical to this effort. The goal was to develop a mounting approach to meet the highest performance requirements of multi-module panels in extreme conditions, while also offering flexibility for small systems or less demanding requirements.

Several different mounting systems were developed, with both metal and polymer mounting components. The best of the concepts is a slide bar that permits rapid but robust integration of multiple modules onto a standard panel rail with no screws. It also incorporates a bolt track for mounting one or many modules in any fashion that can accommodate standard mounting bolts. The slide bar system was prototyped and reviewed with key distributors and system integrators.

The first major system to be developed used an aluminum slide bar directly bonded to the backskin. Figs. 7, 8 and 9 show two 40 watt size frameless modules made with the new backskin and metal mounting components in three different configurations. Fig. 7 shows the modules on a novel ground-mounted structure consisting of simple components that could be assembled by any homeowner. (This structural design, also designed by Mr. Shingleton, is the prototype AC Module system for Evergreen Solar's TEAM-UP project.) Fig. 8 shows two modules with similar mounting components bonded onto the backskin but now placed on a roof using the roof jack concept from Ascension Technology. Fig. 9 illustrates a ground-mount system using a ballasted tray concept also from Ascension Technology and again with two 40 watt modules with the new backskin, edge protection, and metal mounting components. Fig. 10 shows a close-up of the new quick-connect connectors used with the system in Fig. 9.

The installations shown in Figs. 7, 8, and 9 incorporate an IMS that meets the original objectives of reducing factory manufacturing cost (by replacing an expensive frame with a less expensive slide bar), and reducing field installation cost (by installing quickly and with no screws). And yet the system design has the same flexibility and robust performance of conventional frames.

By the end of the first year, we had selected a design for the mounting bracket. Several prototypes and one working system were completed with machined components, and an extrusion die for the aluminum slide bar is being fabricated early in the second year for further testing and customer feedback.

UL AND CODES

In order to ensure that the IMS is safe and reliable, we have spent significant resources reviewing applicable codes and qualification tests. From this review, two key areas have emerged, the electrical interconnection requirements (junction box) and the backskin material. Each will be discussed below.

The IMS module must meet the requirement of the National Electrical Code (NEC), pass the standard qualification tests (IEEE 1262 and IEC 1215), and be listed with UL. To ensure this, we began early discussions with Jodi Smyth at UL and other knowledgeable industry experts, particularly regarding the junction box. The key objectives were to ensure that the junction box would be safe, reliable and allow the final module to be UL listed.

Several meetings were held at UL, and key questions addressed included the spacing of leads on the molded-in terminal strip to guarantee a 600 volt rating, connection of the module leads to the box, and the junction box polymer material. Because of these discussions, the design was modified slightly, and a better material for the box was chosen. We also participated in the NEC Task Force to become fully familiar with current and emerging code issues. It was this participation that led to developing the fusing option in our junction box, a first (to our knowledge) in the industry.

In order to have a UL listed module, the backskin material needs to be certified for this particular application. At the end of the first year of the contract, we developed a test program, in conjunction with UL, to have the backskin material tested and certified. The tests will begin early in the second contract year, and a provisional certification can be obtained within a few months after tests commence. Details on this testing follow.

In general, there are four basic areas that UL tests:

- Flammability,
- Ultraviolet (UV) radiation resistance,
- Water immersion and exposure, and
- Resistance to hot wire ignition.

In order to demonstrate compliance in these four areas, several individual tests are required. Of these tests, the full-length RTI (Relative Thermal Index—see p. 7 of this report) and UV radiation resistance tests are long-term and very demanding.

The RTI of a material is an indication of the material's ability to retain physical properties when exposed to elevated temperatures for an extended period of time. In essence, it is the material's thermal endurance. For a backskin material, three physical properties are tested: mechanical with and without impact (tensile strength with impact and tensile strength) and electrical (dielectric strength).

Physically, samples of the material and a control sample (one with known degradation performance) are subjected to extended thermal treatments at four elevated temperatures. We have chosen to test samples at 110°C, 120°C, 130°C, and 140°C. Periodically (every three days for the 140°C tests and every 28 days for the 110°C tests), samples are removed and their physical properties tested. When the properties degrade to one-half the original value, the sample has failed. Failure time versus temperature is plotted on a semi-log scale. Linear regression is used to estimate the temperature at which the sample would fail at 100,000 hours. It is this temperature that determines the material's RTI for that property. For PV applications, a backskin must have an RTI of at least 90°C or 20°C higher than the operating temperature of the module, whichever is greater, for the three properties discussed.

In addition to the RTI tests, these same properties are tested for UV radiation resistance and water immersion tests. For the UV tests, samples are exposed to a xenon arc lamp for 1,000 hours. To pass, the materials properties cannot degrade to less than 70% of the original value. For water immersion, samples are placed in 70°C water for 7 days, then dried for 14 days and tested. In this case, passing requires that the samples have not degraded to less than 50% of original values.

MARKETING ANALYSIS

The final topic for this report is the market research regarding the new product designs. As mentioned briefly above, customers were involved early in the development both of the junction box and the IMS. Most of the focus was on the IMS, which is the greatest departure from conventional industry practice. In total, 31 personal and telephone interviews were conducted with 25 individuals from 14 companies. The interview guide is in Table 3.

The purpose of this research was to assess the interest in, benefits of, and concerns about the PVMaT product under development. The product was described as a module and associated hardware that promotes easier multi-module panelization. In approximately half of the interviews, samples of our current prototype were shown.

Both system integrators (and associated consulting engineers) and distributors were interviewed. System integrators tend to be the more sophisticated users of multi-module panels, while distributors sell a greater volume of modules into multi-module applications.

Findings are summarized below.

Table 3. Interview Guide

Rank the importance or cost of field BOS labor and materials:

- Panelize: structural; power
- Erect structure
- Mount panels, structural; power
- Grounding wiring
- Other (shipping, logistics, etc.)

Multi-module panel applications:

- What fraction of your projects use 4-8 module panels?
- Wiring configurations (parallel/serial)?
- Who panelizes: you or your customers?
- Field or factory?

Benefits of and concerns about innovative mounting system (IMS):

- Frameless module
- Polymer mount structure
- Quick mount
- Plug connector

Cost of BOS Labor and Materials

In all the following, the term "panelization" refers to combining and mounting several PV modules.

Regarding panelization cost, we found that structural cost exceeds electrical cost, and materials cost roughly balances labor cost. Total panelization costs ranged from $0.40/W to over $1.00/W for integrators. Distributors estimated higher costs because of small installations by installers who do panelization infrequently and more typically in the field than in an indoor factory or staging setting. Potential savings are therefore greater on smaller jobs with less specialized installers.

Inexpensive panelization, which is the goal of the IMS, competes against large (200+ watts) modules for multi-kW applications. The benefits of large modules vs. inexpensive panelization differed markedly between system integrators and distributors. System integrators like large modules, because they have the sophistication and ability to ship and handle large modules for large projects. On the other hand, distributors view large modules as a disadvantage, because they can't be conveniently shipped or handled. Distributors suggested keeping modules below 100W; 120W was viewed as too big, and over 200W was viewed as "useless, even for large systems." Distributors strongly preferred a better means of panelization to large modules.

Particularly for ground-mounted systems, the structure itself is a major cost component, and an IMS is unlikely to affect it much. The weight of the PV array has little to do with structural costs; wind loading is the major driver.

Grounding is an important and overlooked issue. Grounding wiring is far more expensive than power wiring if the installer is required to jumper every module frame. Therefore, there are major benefits to simplifying or eliminating grounding.

Both system integrators and distributors viewed shipping and handling costs as an important factor. One distributor stated that shipping costs are typically 8% of module cost.

Multi-module Panel Applications

Integrators use multi-module panels for virtually 100% of their work. Distributors are unsure, but estimate that multi-module panels are between half and three-quarters of their sales. However, integrators' projects are big, typically 2 to 200 kW; while integrators' customers' projects tend to be small, typically 0.5 to 2 kW.

Distributors never panelize, their customers do; whereas integrators always panelize themselves, although sometimes with project-specific contract labor. Integrators almost always panelize in a protected environment: either a factory or staging area. Distributors' customers are more likely to panelize in the field. Although distributors don't panelize themselves, they are in a position to influence the module selection based on customer's installation cost.

This research has broadened our focus from large to also encompass small systems. Small multi-module systems may benefit from improved panelization more than large systems, because system integrators, who are large, sophisticated, repeat-users, have already developed methods for streamlining panel costs. In contrast, small-system customers typically don't use specialized labor or facilities, rely more on manufacturers' high-priced panel rails, and do panelization under more challenging field conditions.

Benefits of and Concerns About IMS

All said they're eager for and open to the concept of frameless modules, although somewhat skeptical because of prior experience with poor products. Other manufacturers' modules without frames or junction boxes have either been discontinued due to inferior performance, or sold into low-power, low-expectation applications. However, the market is continually demanding simpler modules because of their expectations of lower price.

Frameless modules might have less lip at the front edge (as in a traditional aluminum frame), and the lip catches soil and impedes snow slide-off. Thus, frameless modules can be expected to produce modestly more kWh per kW over the long-term.

If we take away the frame, think about how the customer will pick up a module. Modules need handles. The j-box might become the default handle.

Click, slide, snap, turn, or plug panelization lowers labor cost not only by reducing hours, but by reducing the hourly wage of the installer by permitting the use of lower skilled installers. For example, in many cases a plug connector permits a roofer or mechanical laborer to electrically interconnect at the same time as physical installation, instead of using an electrician. Quick-connect panels promote the trend toward packaged systems, which less trained installers will assemble.

Frameless modules must be able to withstand full environmental challenges: heat, humidity, and structural. The IMS product must be UL-approved.

Beware requiring customers to use a panel rail that is either more expensive or more difficult to procure than normal.

There were more concerns about innovative connectors than about innovative structures. Many customers may not value reduced material and labor costs of a plug connector. Customers need wiring flexibility (series/parallel, return wire, conduit or not, etc.). Customers might not want us to pick the wire. The electrical system might not work with the bolt track mounting concept of our current IMS design concept. Plugs are more difficult to use with conduit.

On the other hand, the IMS might enable some customers who typically use conduit to do without. Conduit is very often used more for physical wire protection (against rodents, for example) than for weather protection. Thus, a panel rail designed for dual use as a wiring raceway may supplant conduit in some cases.

Some thought frameless modules might increase packaging cost, if modules are too fragile. Others thought it might reduce packaging cost and shipping cost, because of slimmer profile and lighter weight.

In summary, there was strong market interest in our Innovative Mounting System, primarily because of customers' expectations of lower module and BOS costs. While there is some skepticism and high expectations, customers' reactions to our early prototypes were extremely positive. More than one interviewee declared the prototype the most promising frameless concept they had seen.

APPENDIX: Summary of Milestones and Deliverables

Note: The main body of the preceding text discusses each of the following milestones and how they were met. [Page numbers refer to the preceding text.]

ESI m-1.1.1 Complete preliminary sketches and design specifications for the complete IMS. (Subtask1.1) [p. 12-21]

ESI m-1.1.3 Complete Subtask 1.1[p. 12-21]

ESI m-1.1.4 Complete data collection for base resin of backskin. (Subtask 2.1) [p. 5]

ESI m-1.1.5 Obtain sample encapsulant materials (Subtask 3.1) [p. 9-11]

ESI m-1.1.6 Complete selection of one or two encapsulant resins.

(Subtask 4.1) [p. 9-11]

ESI m-1.1.7 Complete 'creep' test on candidate encapsulants. (Subtask 4.1) [p. 10]

ESI Milestone m-1.1.8 Complete Subtask 4.1 [p. 9-11]

ESI Milestone m-1.2.1 Complete selection of base resin for backskin (Subtask 2.1) [p. 6]

ESI Milestone m-1.2.2 Demonstrate bonding and coverage of candidate encapsulant using alternative lamination method. (Subtask 3.1)

This task was completed on 3/31/96 with the submission of Deliverable D-1.4. [p. 11-12]

ESI Milestone m-1.2.3 Complete Subtask 3.1.

Completed.

ESI Milestone m-1.3.1 Complete selection of fillers and additives for the candidate backskin. (Subtask 2.2)

Two levels of mineral filler (12% and 20%) were studied in the base resin mixture chosen in Milestone m-1.2.1. The higher level was known to give better creep resistance, but poorer bonding—the lower level just the reverse. Tests indicated that the creep resistance with the lower level was fine (Milestone m-1.1.7), so this concentration was chosen—since bond strength was deemed very important. A UV stabilization package with an excellent track record for 60 month exposures in south Florida was used. [p. 6]

ESI Milestone m-1.3.3 Complete definition of Evergreen's sheet converter requirements. (Subtask 2.3)

The ideal sheet converter would be someone who can make large volume, low cost manufacturing runs, but also, at the same time, lower volume prototype runs. We have located a converter who seems to satisfy both needs. The technical director for the converter has interacted with the PI of this project, Dr. Jack Hanoka, very successfully, and has indicated his interest in continuing this relationship. [p.11]

ESI Milestone m-1.3.4 Demonstrate bonding and coverage of the encapsulant without stabilizers, with the backskin. (Subtask 3.2)

This task had two potential areas of concern: 1. Would the new encapsulant and backskin bond together, and 2. Would the alternative lamination process be able to facilitate this bond. The encapsulant without stabilizers was bonded to the backskin with both the vacuum lamination process and the alternative lamination method. Bonding with the backskin in the vacuum laminator has produced an extremely strong bond—although no quantitative peel strength tests have yet been made. One of the reasons for the very high bond strength is the high chemical compatibility between the encapsulant and the backskin. Both materials were deliberately chosen with this in mind. High bond strength will translate into better sealing of the overall module.

This task was completed upon the submission of Deliverable D-1.5 on 7/16/96.

ESI m-1.3.5 Complete Subtask 3.2

Completed.

ESI m-1.3.6 Determine the optimized stabilization package for the new encapsulant. (Subtask 4.2)

The principal task was to determine the solubility of a large number of possible additives for UV stability. From an even larger list, 16 possible candidate additives were identified and studied. In the first phase of this study, these were added to the encapsulant in concentrations of 0.5% and 0.75% and then tested for solubility. The solubility tests were conducted on different extruded strips of the encapsulant material containing each concentration. Samples were then placed in sealed jars at 65^0 C for a period of four weeks. Solubility was then determined by the lack of evidence of either surface exudation, cloudiness, or yellowing. From this first phase, the number of possible additives was reduced to eight.

In a second phase, the eight candidate stabilizers were again added to new formulations of the encapsulant material and subjected to another month of solubility studies but this time with various desired combinations of the stabilizers added to the same samples. The temperature was increased to 70^0 C and again sealed jars over a month's duration were employed. From this second phase, an optimized UV stabilization package was chosen.

A newer stabilizer, using very different chemistry than all the other stabilizers, was discovered late in the program. Solubility for it was determined to be satisfactory. It will be used in a later phase in Year II. It has the potential of very high UV stability. [p. 10-11]

ESI m-1.4.1-A Samples sent for outdoor testing. (Subtask 4.4)

This milestone has not been completed and has been deferred into Year II. See Milestone m-1.4.11 for a complete explanation.

ESI Milestone m-1.4.1 Demonstrate initial feasibility of initial prototype IMS. (Subtask 1.2)

On this task, Evergreen changed its original design concept based on customer feedback and structural challenges. The goals were to design a quick mount module and an all polymer support structure. Evergreen succeeded on the first goal, albeit with a different design than originally conceived, and significantly modified the second goal. [p. 12]

ESI m-1.4.2 Complete performance tests on the initial prototype. (Subtask 1.2)
[p. 7-8, Table 1]

ESI Milestone m-1.4.3 Complete Subtask 1.2

Completed.

ESI Milestone m-1.4.4 Complete Phase I portion of the effort under Task 1.

Completed.

ESI Milestone m-1.4.5 Complete survey of resin makers for recommendations for a sheet converter. (Subtask 2.3)

This has been covered in Milestones m-1.1.5, m-1.1.6, and m-1.3.3.

ESI Milestone m-1.4.6 Complete the Phase I portion of the effort under Task 2. (Task 2)

Completed.

ESI Milestone m-1.4.7 Demonstrate the feasibility of the alternative lamination process: make prototype modules incorporating new mini-modules (single-cell coupons) with new encapsulant & backskin, without additives, fillers and/or stabilizers. (Subtask 3.3)

This has been done. A small module about 10" square has been made this way and 6 coupon size modules with single cells have been made.

ESI Milestone m-1.4.8 Complete modifications to benchtop laminator. (Subtask 3.3)

Three principal modifications had to be made to the benchtop laminator. A new motor and gearing were added to the machine so as to be able to control the sample speed through the machine more accurately and also the sample temperature. Secondly, the pressure controls and pistons were modified very significantly to allow for higher and more reproducible pressure applied during lamination. Thirdly, a preheat platen to warm the glass was constructed and deployed successfully. [p. 11-12]

ESI Milestone m-1.4.9 Complete Subtask 3.3

Preliminary modifications to the alternative laminator have been completed and prototype mini-modules have been made. Additional mini-modules will be made (when a new run of the encapsulant material, with UV stabilizers is completed) and tested in Year II of the contract. Also, additional modifications may be required in Year II to further improve the process.

ESI Milestone m-1.4.10 Complete the Phase I portion of the effort under Task 3. (Task 3)

See explanation in Milestone m-1.4.9.

ESI Milestone m-1.4.11 Complete preparation of the prototype encapsulant for testing. (Subtask 4.3)

This has been deferred into Year II to be fully completed. As it turned out, the first prototype run of the encapsulant material with the UV stabilization package was run incorrectly by the sheet converter. (It was run on an off shift while the technical director was away at a conference.) The material we received exhibits very anomalous behavior and so the whole run needs to be repeated—this is being done as quickly as possible.

ESI Milestone m-1.4.12 Complete Subtask 4.2

Completed.

ESI Milestone m-1.4.13 Complete Subtask 4.3

The first run of encapsulant, with the stabilization package was made. However, as previously described in Milestone m-1.4.11, an additional run will be required early in Year II.

ESI Milestone m-1.4.14 Complete the Phase I portion of the effort under Task 4. (Task 4)

Full completion of this task has been delayed until Year II.

ESI Milestone m-1.4.15 Complete initial testing of the alternative encapsulant. (Subtask 4.4)

Deferred into Year II—see the remarks for Milestone m-1.4.11.

Deliverables for Phase I

ESI D-1.2 Deliver samples of the candidate encapsulant, without stabilization package. 6-10 each. December 31, 1995 (Subtask 4.1)

Completed 1/23/96.

ESI D-1.4 Deliver sample new encapsulant, without stabilization package, bonded to glass 6-10 each March 31, 1996 (Subtask 4.1)

Completed 3/29/96.

ESI D-1.5 Deliver sample of new encapsulant, without stabilization package, prelaminated with backskin (without additives and fillers) demonstrating bonding and coverage required for IMS. (Subtask 3.2) 6-10 each June 30, 1996.

Completed 7/16/96.

ESI D-1.6 Deliver sample of new encapsulant with optimized package of stabilizers with supporting test data, 6-10 each September 20, 1996.

Completed 10/9/96. Additionally, samples from the next run of sample encapsulant will be provided when available. See Milestone m-1.4.13.

ESI D-1.7 Deliver initial prototype of the IMS. 1 each September 20, 1996 (Subtask 1.2)

Completed 10/9/96.

ESI D-1.8 Deliver samples of encapsulant sheet laminated to glass. (Subtask 3.1) 6-10 each September 20, 1996.

Completed 10/9/96.

ESI D-1.9 Deliver 'mini-modules' incorporating: the candidate backskin without stabilizers fillers, etc.; the alternative encapsulant; and PV cell for testing. 6-10 each September 20, 1996.

This deliverable has been delayed until early in Year II. The reason is because of concerns about the error in the running of the candidate encapsulant by the extruder. See explanation under Milestone m-1.4.13

ESI D-1.10 Deliver report summarizing initial accelerated test results for the backskin and encapsulant. 2 each September 20, 1996.

This deliverable has been delayed until early in Year II. The reason is because of concerns about the error in the running of the candidate encapsulant by the extruder. See explanation under Milestone m-1.4.13

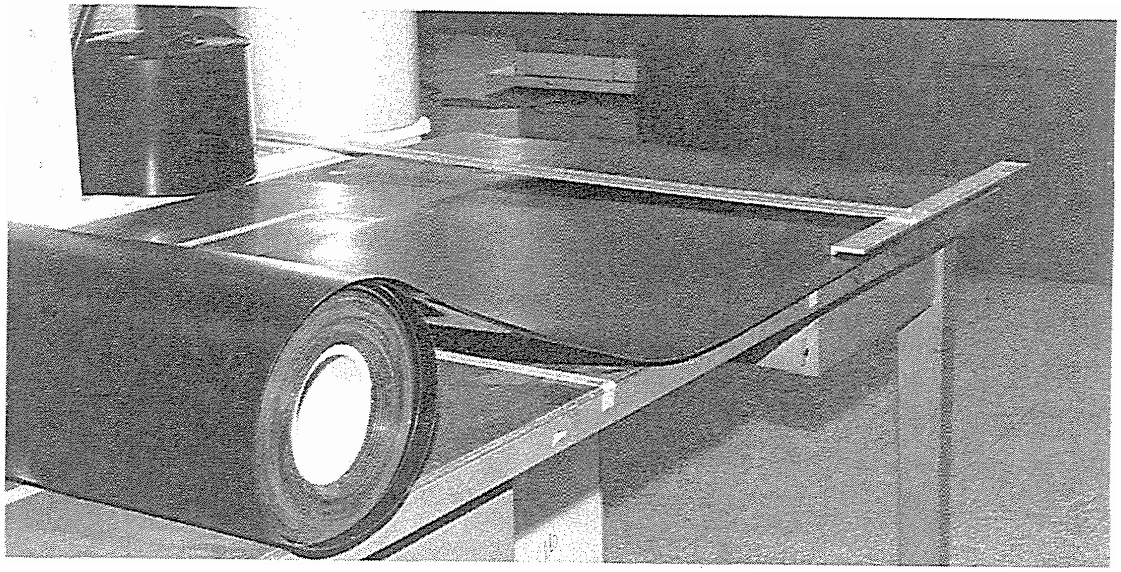

Fig. 1. Roll of the New Backskin

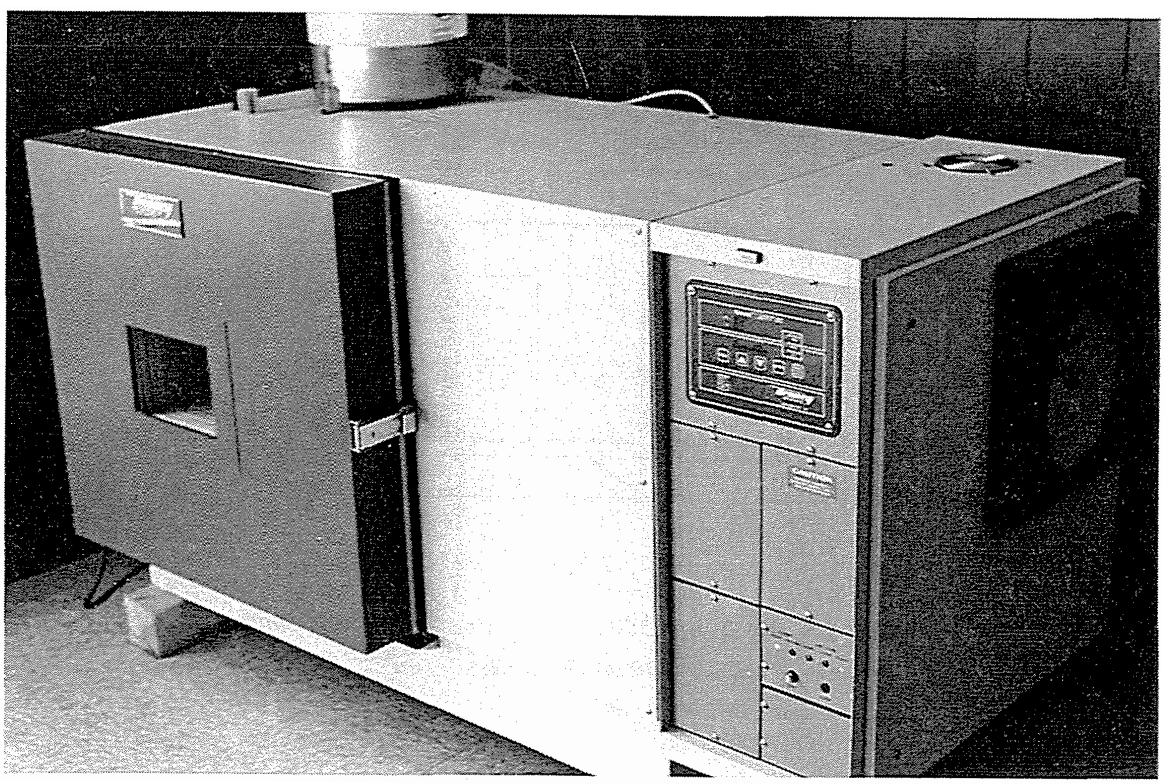

Fig. 2. Environmental Test Chamber

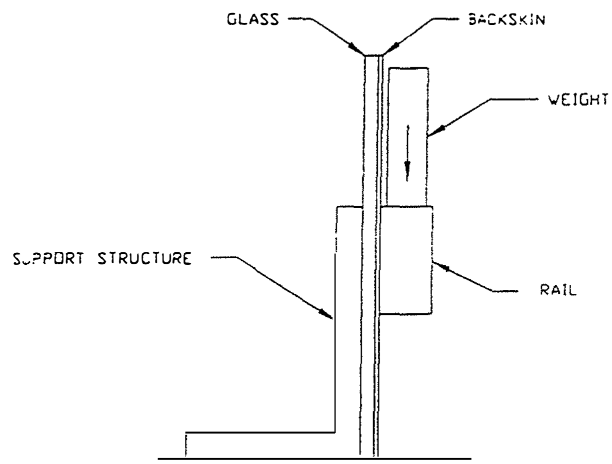

FIGURE 3A. Thermal creep test arrangement for the new backskin material.

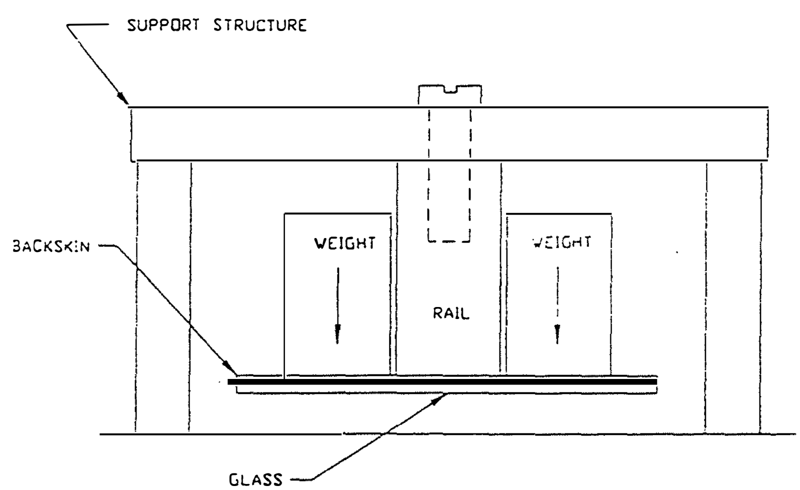

FIGURE 3B. Set up for static load testing of the aluminum slide rail for the frameless module.

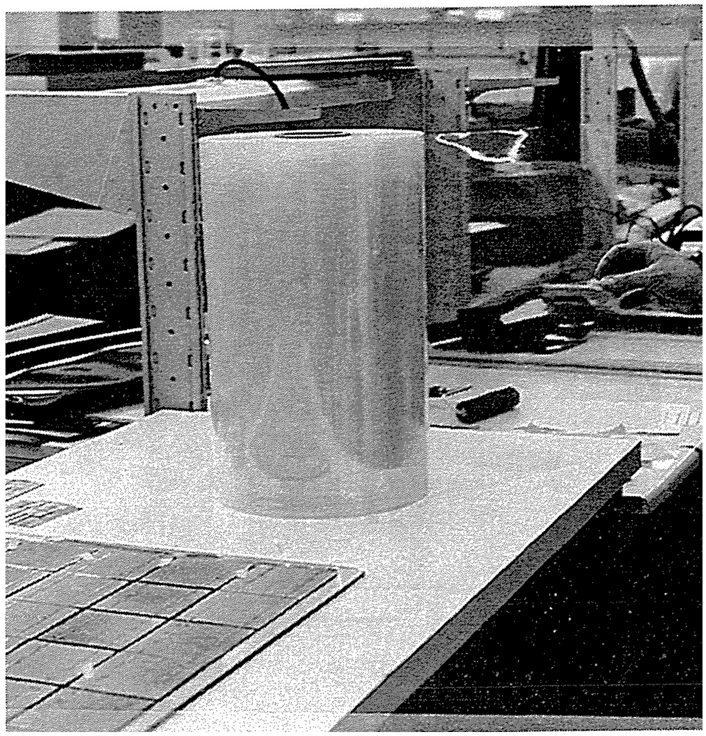

Fig. 4. Roll of the New Encapsulant Material

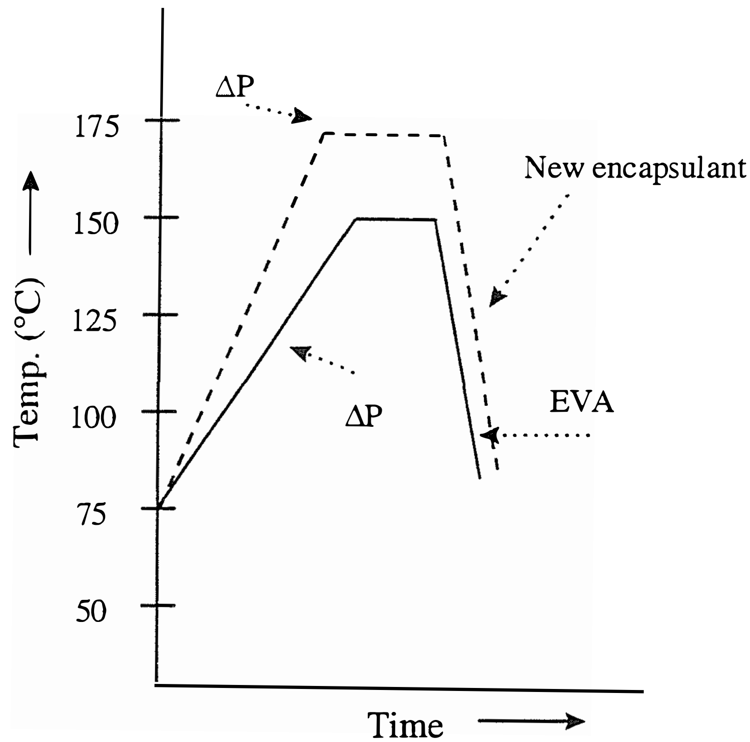

Fig. 5. Lamination Cycles for EVA and for the New Encapsulant

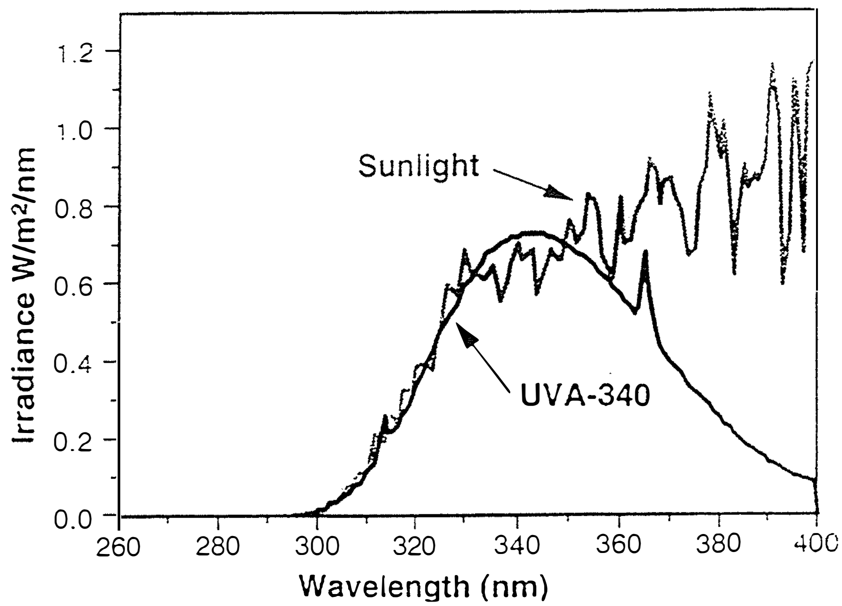

Fig. 5a. Spectrum for UVA Lamps vis a vis the Solar Spectrum

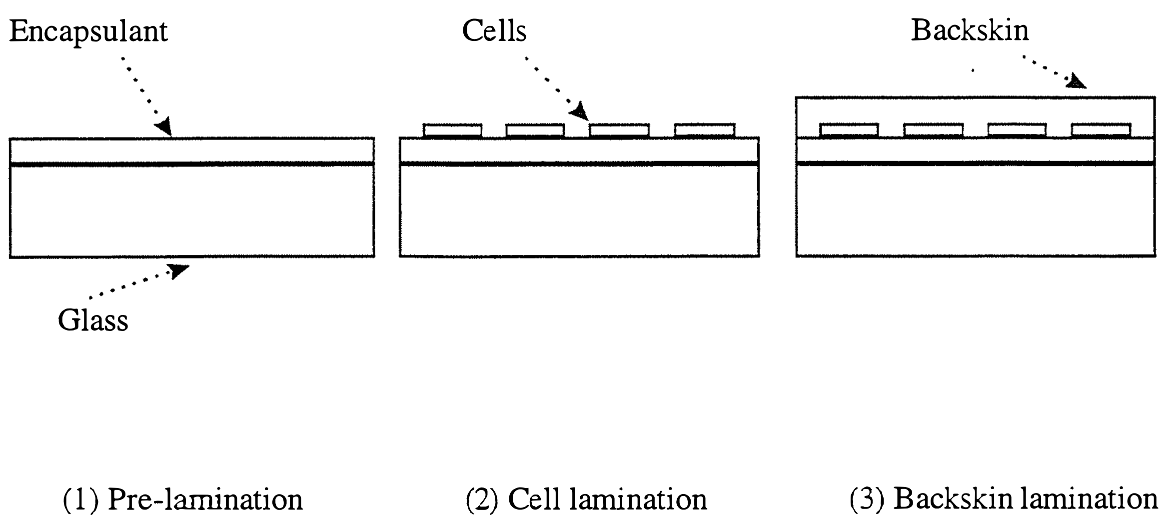

Fig. 6. Schematic of the Alternative Lamination Process

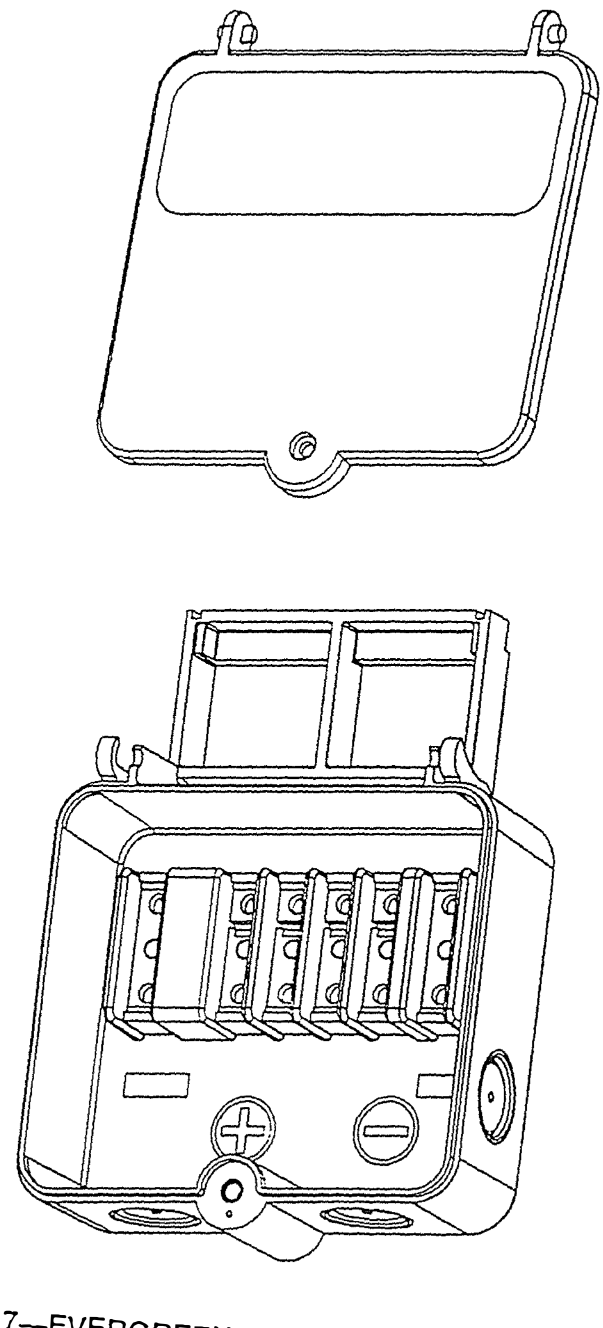

FIG. 7—EVERGREEN'S NEW JUNCTION BOX

FIG. 8—MODULE MOUNTING USING ONE VARIATION OF THE IMS

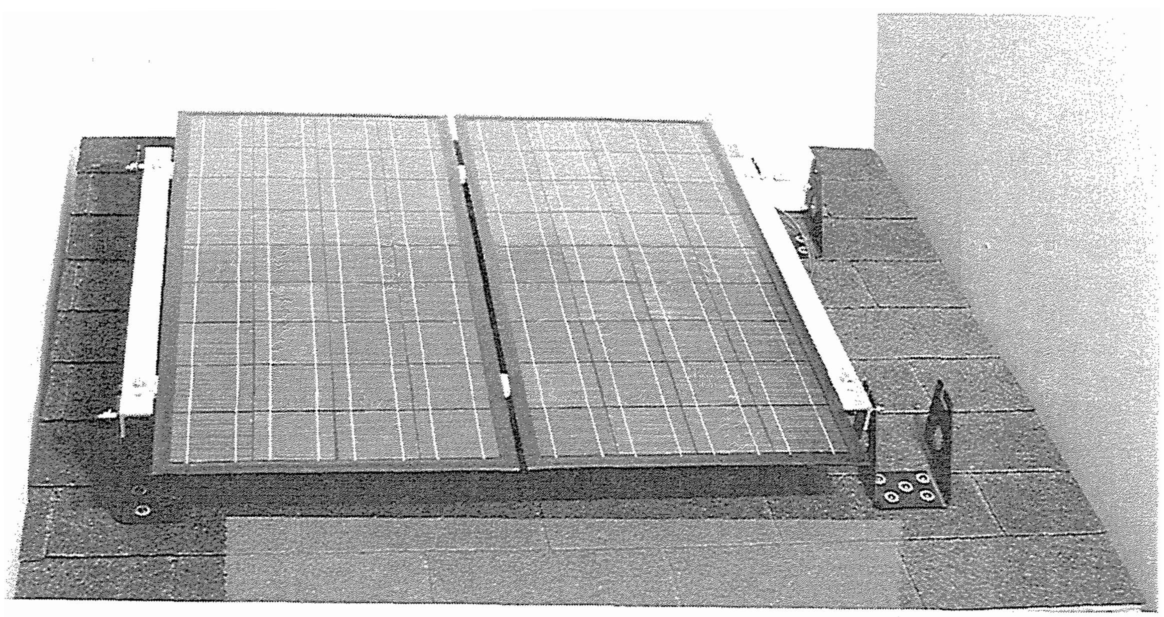

Fig. 9. Roof Mounting using Another Variation of the IMS

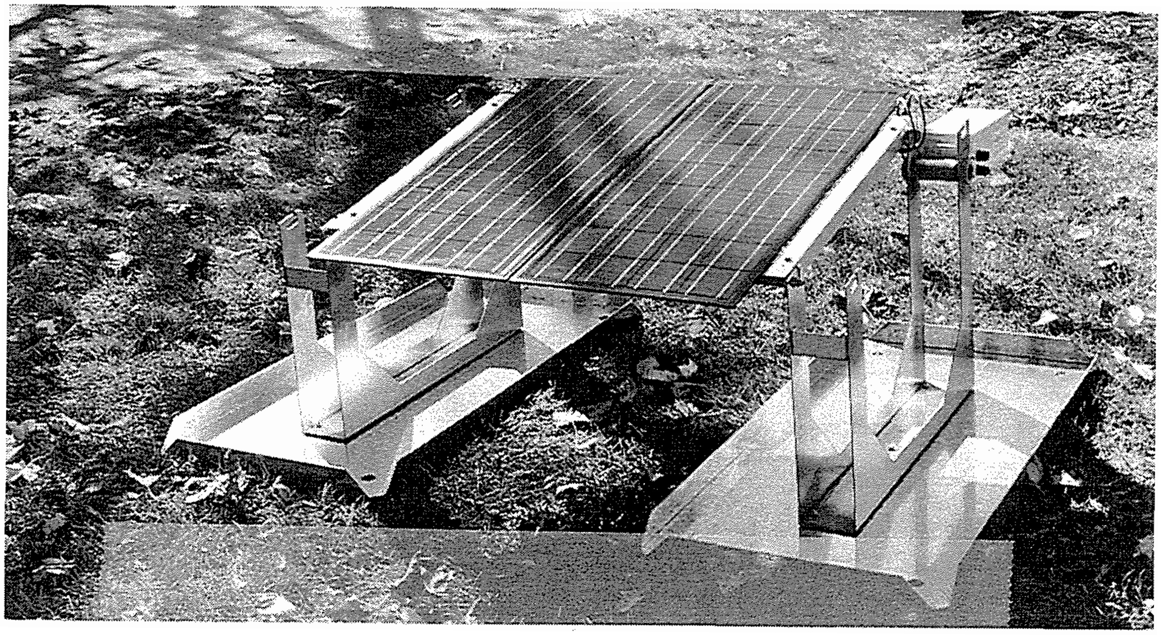

Fig. 10. Tray/Ballast Mounting using the IMS

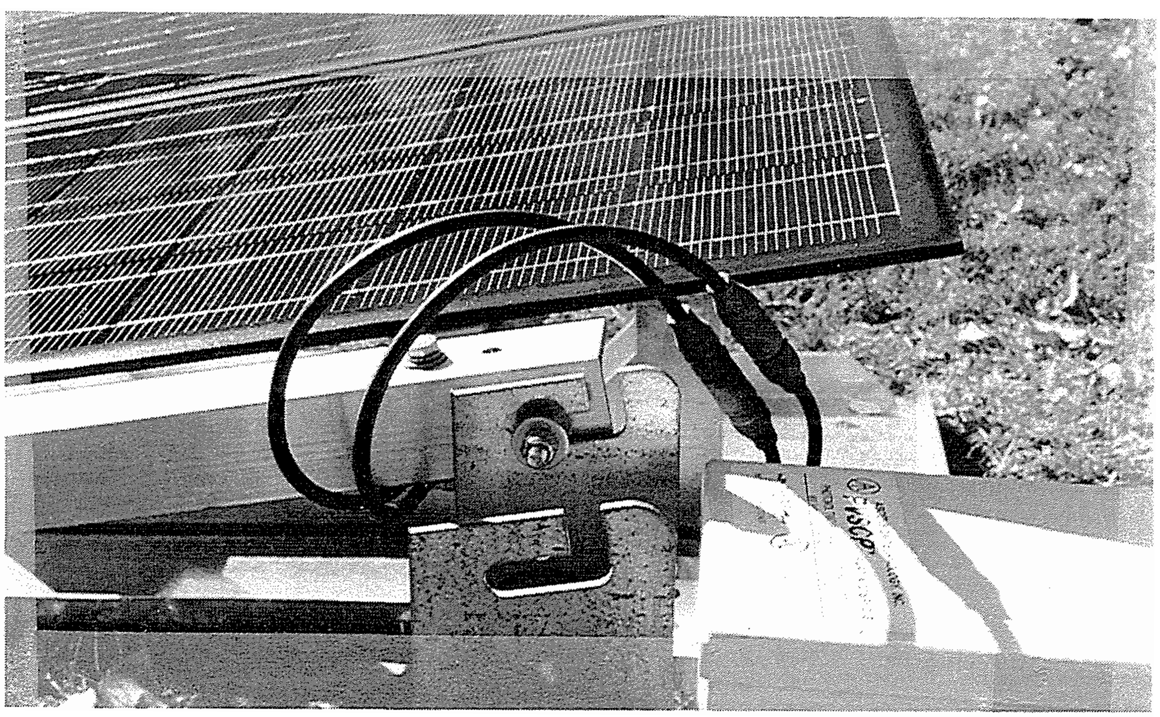

Fig. 11. Quick Connects

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1997	PVMaT 4A1 Subcontract Annual Report, September 1995 - September 1996

4. TITLE AND SUBTITLE

Advanced Polymer PV System: PVMaT 4A1 Subcontract Annual Report, September 1995 - September 1996

5. FUNDING NUMBERS

C: ZAF-5-14271-09
TA: PV705101

6. AUTHOR(S)

J. Hanoka, R. Chleboski, M. Farber, J. Fava, P. Kane, and J. Martz

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Evergreen Solar, Inc.
211 Second Ave.
Waltham, MA 30332

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SR-520-23189

DE97050821

11. SUPPLEMENTARY NOTES

NREL Technical Monitor: H. Thomas

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
	UC-1280

13. ABSTRACT *(Maximum 200 words)*

This annual report documents progress for the first year of a 2-year Photovoltaic Manufacturing Technology subcontract. The project entailed four major technical areas: identification and deployment of a new backskin that allows for a frameless module and novel mounting methods; identification and deployment of a novel encapsulant that should lead to longer life and permit nonvacuum lamination; development of a continuous, high-throughput, nonvacuum lamination method; and development of an innovative mounting system (IMS) for PV modules that simplifies mechanical and electrical installation. The major developments were the backskin and IMS. Researchers also established the groundwork for the encapsulant and lamination process and designed an improved junction box. In addition to the technical work, two other important activities were included: market research and customer feedback on the new products, and discussions with Underwriters Laboratories and testing labs on safety and reliability test requirements.

14. TERMS

photovoltaics ; Photovoltaic Manufacturing Technology ; PVMaT ; nonvacuum lamination ; advanced polymers ; frameless modules ; innovative mounting system (IMS)

15. NUMBER OF PAGES
40

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL