June 1999 • NREL/SR-520-24911

Subcontractor Report

# Advanced Polymer PV System

## PVMaT 4A1 Final Report
## September 1995 — December 1997

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### 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.

Using this approach, a new backskin material instead of Tedlar™ (Tedlar is a Dupont trademark) or Tedlar™ laminate was developed and tested. This new backskin material allowed for the making of a frameless module and novel mounting methods. The latter is referred to as our Innovative Mounting System (IMS). This IMS system in conjunction with the frameless module 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. The advanced backskin material permits elimination of the conventional aluminum perimeter frame, it serves to protect and seal the module edge, and allows for direct bonding of multi-functional mounting bars. Electrical interconnection is easier and more reliable with a new junction box that Evergreen has designed after soliciting user feedback.

A new transparent encapsulant material, to replace EVA, was developed and tested as part of this subcontract. Early results indicate it will have a number of advantages over EVA, not least of which is better resistance to degradation under light exposure. This new encapsulant can be laminated in air, and so has also allowed for the development of a continuous, non-vacuum lamination process as well.

The program culminated in the fielding of prototype products with the new encapsulant, new backskin, new junction box, frameless edge seal, and IMS. Feedback and marketing information from potential customers has been actively solicited. Reliability and UL approval requirements have been determined and a number of these already addressed. The net result is a new product that promises a 20% manufacturing and systems cost reduction as well as significantly increased system lifetime, as compared to a conventional Al framed module and mounting.

Basically, all the goals of the program were met. A considerable amount of proprietary technology emerged from the program, seven patents were filed, and two have already been granted.

## INTRODUCTION

Our PVMaT project builds on the enormous growth of polymeric materials and applications since the original JPL work done some fifteen years ago in developing Tedlar™ backskin material and EVA as a transparent encapsulant material. 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 final report documents the progress made on this project which was about twenty-seven months in total duration. 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 module service life and permit non-vacuum lamination;
3. Development of a continuous, high-throughput, non-vacuum lamination method; and
4. Reduced systems costs through development of innovative mounting systems for PV modules that simplify mechanical and electrical installation and which utilize an improved junction box design.

## NEW BACKSKIN MATERIAL

Tedlar™ 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 also a barrier layer as well as being 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 hard to bond to, and has been known to delaminate when mounting structures or heavy items have been bonded to it. Its puncture resistance is not high because it is so thin, generally 10 mils or less and the thin Tedlar™ layer is dictated by the high cost of Tedlar™ itself. And its use, in conjunction with an aluminum frame, also requires the use of an elastomeric edge seal.

Evergreen sought a new backskin with the following characteristics:

- Ability to eliminate the aluminum frame, but still seal and protect the edges of the superstrate glass.
- Higher puncture resistance.
- Readily available and manufacturable.
- Lower permeability.

## Choice of a new backskin material

The basic approach used in identifying a new backskin material was to survey commercially available polymers and then to investigate what modifications to these materials were necessary for the particular needs of PV modules. Evergreen determined at the outset that attempts to develop a new resin which satisfied all the above requirements through working with one of the large polymer companies would not be fruitful. The volume requirements of the PV industry would not be large enough to interest any of these companies. Instead, a material which was already in use in other major industries was identified. This was a material for which outdoor weathering data was already available. It was selected for our application and then suitable modifications were made to it to satisfy the particular PV module requirements.

The material chosen is a thermoplastic which could be formed during the lamination process itself so as to seal and frame the module edges and obviate the need for an aluminum frame and any other edge sealant. The backskin is 0.040” thick (about 1 mm) over the rear surface of a module, and at the modules’ edges it is about 0.125” thick (about 3 mm). The thicker edge is made possible through the molding of the material in the lamination process. A roll of the 0.040” thick sheet of this material is shown in Figure 1. (All figures are at the end of the text.)

## Thermal creep behavior

Since the new backskin material is a thermoplastic, thermal creep was an important issue. For PV applications, particularly architectural ones, temperatures as high as $90^{o}C$ can be reached in a module, and so thermal creep resistance at temperatures at or even above $90^{o}C$ is necessary. Furthermore, part of UL test 1703 is a Relative Thermal Index (RTI) test that must be passed by backskin material in PV modules to obtain UL approval. This test determines creep resistance at high temperatures ($\sim150^{o}C$), and relates this back to mechanical and electrical properties at temperatures of $\geq 90^{o}C$. A backskin material must have an RTI of $\geq 90^{o}C$. The test is stringent and easily eliminates a large number of polymers as candidate backskin materials.

In our case, as indicated above, we have found that, with suitable modification of the selected material, this test would likely be passed. In fact we have subjected 1” x 6” strips of the backskin material with a nominal load of 1 psi to temperatures over $300^{o}C$ and found that the maximum creep measured, even at these extremely high temperatures, was $\leq 5\%$. After this test the material was somewhat stiff but still in surprisingly good condition. As of this writing the RTI tests with UL have just been started. Based on our in-house experiments we expect no problems.

Subsequent to the end of the subcontract period, Evergreen frameless modules were subjected to UL spread of flame and burning brand fire tests and passed for a Class C fire rating.

## Bond strength

Two aspects of bond strength were studied. First was the strength of the bond between the backskin material and the superstrate glass as the backskin wraps around the edge of the module and is bonded to the front glass surface. Second was the question of the bond strength between the backskin material and any mounting components we choose to bond to it.

## Backskin-Glass Bond Strength

In the case of the backskin-glass bond, an accelerated test was devised which was found to be useful in optimizing the process to provide maximum bond strength at this interface. The test involved an initial soak in water followed by freezing so as to form ice all over the module. With non-optimized processing conditions, particularly too low of a lamination temperature and inadequate surface preparation of the glass, it was possible to produce bond-failure after 7-9 such immersion-freeze cycles. On the other hand, optimizing the bond formation process produced exceptionally strong bonds. These bonds were tested to failure and it was found that between 180 and 200 such cycles were required before failure was observed in any of the samples. Surface preparation of the glass comprised two items. One was good cleaning of the as-received glass surface, and the other was the use of an appropriate silane coupling agent. Silane coupling agents promote very strong bonds between polymers and glass surfaces when deployed correctly.

A further accelerated test done subsequent to the subcontract period involved subjecting 5”x5” “mini modules” with the frameless design and new backskin material to immersion in boiling water for up to one week in duration. This can be viewed as a very severe test of polymer bond strength. With suitable improvements in the silane coupling agent formulation and in the lamination process, a very strong bond could be obtained even after this extreme exposure. Bond strength was determined in this case semi-qualitatively by using a $90^o$ peel and measuring force necessary to break the bond. A comparison sample which did not receive these latest improvements in forming the bond failed after four days of boiling water immersion. On the other hand, the sample with the improvements could barely be peeled away, even with a full week of boiling water immersion.

Based on our plan to eliminate the usual aluminum perimeter frame and bond aluminum mounting brackets directly to the backskin, the bond strength of the resulting backskin-aluminum interface was clearly important. Two tests of the bond of aluminum mounting components were performed: thermal creep and static load. Thermal creep measurements were made at $85^oC$ with a load of 1.15 psi on a mounting component bonded to the backskin and the set-up shown in Figure 2. The 1.15 psi load was selected as an initial estimate of the maximum sustainable load. After 67 days, virtually no creep had occurred. The test was then conducted at $90^oC$ for 26 days and again no creep was detected—indicating an excellent bond.

## Backskin-Mounting Components Bond Strength

For static loads, the minimum test criterion was 50 psi, 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 psi loading. Based on the likely worst-case and the dimensions of our test modules, this required a load of 18.7 psi over the bond area. As seen in Figure 3, 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 $60^oC$. Over this time the bond showed no degradation.

We then increased the severity of this test by repeating it a higher loading of 19.3 psi for 216 hours at $70^oC$, then for 168 hours at $80^oC$, and finally for 144 hours at $90^oC$—all under the increased load. In all these cases no bond weakening could be detected. This test was continued to see at which temperatures >90°C bond weakening will finally occur, i.e., it was tested to failure and it was found that this occurred somewhere between 95°C and 100°C.

Small test modules with the new backskin, the frameless design, and, in some cases, with aluminum mounting components bonded onto the back, were then subjected to environmental stress tests. To perform these tests, Evergreen acquired an environmental test chamber. In some cases tests were confined to the IEEE 1262 specifications, and in other cases tests were extended well beyond these requirements. One of 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 85-85 for 20 hours. Various kinds of samples were subjected to different amounts of exposure. Even after more than 100 humidity-freeze cycles, the edge seal and mounting component bond strength suffered no degradation. Damp heat (85-85) for 2000 hours is another of the standard tests. This was not done but it is interesting to note that 100 humidity-freeze cycles contains within it 2000 hours of damp heat, albeit not all at one time.

Two module samples were tested to failure and exhibited some cracks in the backskin material after about 145 humidity-freeze cycles. Another, somewhat unrelated test was done in which a small 5 x 5 size “coupon” with the frameless module construction and the new encapsulant was immersed in water at room temperature for over twelve months. This sample showed no adverse effects due to this prolonged immersion.

Permeability

In terms of permeability, no reliable quantitative measurements have yet been made with the new backskin vis-à-vis Tedlar™ backskin. However, a qualitative test was done which did indicate that the permeability was, at minimum, no worse than that of the Tedlar™. This qualitative test was made possible by the observation that modules made with EVA and Tedlar™, as control modules, exhibited yellowing of the EVA after a very long number (on the order of 100) of humidity-freeze cycles. Clearly, some oxygen and water vapor can permeate through the Tedlar™ to produce yellowing. No light was present in the environmental test chamber, so this was evidently not an example of photo-oxidation but instead probably just thermal and/or moisture induced oxidation. Using this observation, identical test samples of a Tedlar™ module with an aluminum frame and a frameless module with the new backskin and each containing EVA were subjected to humidity-freeze cycles. This experiment encompassed somewhat fewer than 100 cycles, but no yellowing of the EVA was observed for either module. This experiment will be continued beyond the scope of this subcontract.

## NOVEL ENCAPSULANT

Two objectives motivated the development of an alternative encapsulant to EVA. First, we sought an encapsulant with process advantages—in particular, one that 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 was motivated by EVA's inherent limitations, some of which stem from the use of an organic peroxide. The organic peroxide, either Lupersol 101 or TBEC (TBEC is becoming almost universally used), 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 of temperatures as high as $90^{o}$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.

- When EVA is formed into sheets, the peroxide requires extrusion of the EVA 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 and adds to the cost of making the material.

In addition to issues stemming from use of organic peroxide, EVA has one other limitation: currently available EVA formulations can discolor under strong, extended sunlight exposure. Over time, this reduces conversion efficiency.

EVA has ester functionality (as opposed to the acid functionality of our new encapsulant), and, consequently, its bond strength to adjacent surfaces might not be as strong, and might 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: Handbook of Adhesives, ed. By I. Skeist, 3rd ed, 1990, Van Nostrand Reinhold, p. 54). However, it should be noted that tests done by Michael Quintana et al at Sandia Labs [2] have indicated some cohesive failure for EVA modules. And data by Plueddemann [3] in his book also indicate cohesive failure for EVA on glass. So this putative difference remains to be demonstrated.

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 results were highly promising. A candidate encapsulant material was selected, much work was done on a suitable UV stabilization package, and tests were initiated on accelerated UV exposure. 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 eventually to a single candidate material. The selected encapsulant material was made into 18 mil sheet. The resulting sheet is somewhat stiffer than EVA, has a much higher melting point, and poses no particular shelf life or handling issues. From a manufacturing and handling point of view, the latter are not trivial concerns. For example, EVA is very tacky and soft before it is laminated and must be removed from a release sheet before use. Also, it has to be stored in dark, sealed, plastic bags. The higher melting point also means that chemical cross-linking can now be obviated.

Figure 4 shows a roll of the new encapsulant material. Thermal creep tests wherein 1” x 6” strips of the encapsulant were placed in a convection oven under nominal load for 30 days at 90$^{o}$C indicated no significant creep, indicating that the decision to avoid chemical cross-linking was warranted.

The material laminates well in both the vacuum laminator and in the alternative non-vacuum lamination process (discussed in this report in the section labeled “Continuous Lamination Method”). The possible vacuum lamination cycles are clearly different than for EVA and may, in general, offer a wider processing window. Peak lamination temperatures can be similar to that for EVA.

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. This has the result that there is not very much published material on UV stabilizers for the material we chose and so this area required a considerable amount of work on our part.

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 finally to one, and they were chosen because they had 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 sixteen 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 0.03 thick, was made containing each possible stabilizer at two concentrations, 0.5% and 0.75%. 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$^{o}$C for one month. Samples were then examined for evidence of surface oxidation, cloudiness, or yellowing—all indicators of lack of solubility. This analysis reduced the number of possible stabilizers to eight. 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$^{o}$C (instead of 65$^{o}$C, as in the earlier test) for one month.

## UV Stability

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. A detailed discussion with the technical director of its manufacturer supports a good prognosis. Of course, field tests under sunlight will be the ultimate criterion.

Quantities of the new encapsulant containing a UV stabilization package were then made and testing of this material was begun. For UV stability, three such tests were conducted, and in all cases the new encapsulant was tested alongside cross-linked TBEC EVA. The latter was laminated so as to form 75% to 80% gel content. In one such test, four samples of each encapsulant were laminated between 50 x 75 mm. glass slides and then subjected to mirror enhanced sunlight exposure in Arizona. The enhancement amounts to between 5x and 7x of normal sunlight. Edges of the sample were not sealed in any way. The samples are air cooled to prevent excessive heating. 18 mil thick EVA and 18 mil thick new encapsulant were used. A widely used measure of yellowing is the change in yellowness index ($\Delta$YI) as specified in a standard ASTM test, D2244. For the samples in Arizona, $\Delta$YI is measured every month, after the samples are carefully washed. This test has been continued subsequent to the end of the subcontract and results are shown in Figure 5 for 14 months of exposure. The results to date indicate that the EVA is increasing in yellowness at a much faster rate than the new encapsulant. It should be noted that the $\Delta$YI values are still quite low relative to what is visible to the naked eye.

A second test that has been done is to expose bare samples of the new encapsulant and TBEC EVA to UV in a QUV machine with UVA bulbs. The sample size in this case is about 3” x 10”. The spectrum of UVA bulbs is shown in Figure 6. It can be seen that the UV part of the solar spectrum up to about 350 nm is closely simulated. In this test the bulbs are run at approximately 20% higher intensity than sunlight and the ambient temperature is kept at $50^oC$ with the QUV machine. All of this is designed to accelerate degradation effects, of course. To further uniform exposure, the sample positions are rotated periodically. The caveat here, as is so for all accelerated tests of this type, is that extrapolation from the accelerated results must be done cautiously. For this reason we are doing both indoor simulation and outdoor acceleration and will await final results after several years of such tests. In the case of the QUV test, it should be noted that this is a very widely used accelerated test for polymer stability under UV.

At the time of writing this report a total of about 13,000 hours of exposure in the QUV machine have been in effect. After about 4000 hours, there was visible yellowing in the EVA samples and not in the new encapsulant samples. However, there also seemed to be some photo-bleaching effects on the EVA samples (see papers by Pern and Czanderna [4,5]) so this visible yellowing was not a steady phenomenon which could always be observed.

In any case, another very widely used measure of polymer degradation, that of tensile strength decrease, was used on both sets of samples from the QUV machine after 7000 hours of exposure and again after 13,000 hours of exposure. Control samples which had not received any exposure were also used. The results are shown in Figure 7. The difference in tensile strength after exposure is very striking. The new encapsulant samples exhibited about a 10% drop, while the EVA samples underwent a drop in tensile strength to about 70% of the initial value. Polymer degradation is accompanied by breakup of the polymer chains and this is then reflected in reduced tensile strength.

A third set of accelerated tests, exposure to various types of Xenon simulated sunlight, were conducted by John Pern and Steve Glick at NREL, and were presented subsequent to this subcontract period [6]. In their experiments, samples of Evergreen's new encapsulant and EVA were laminated between 2" x 3" pieces of borosilicate glass and then exposed to different accelerated UV light conditions at various temperatures (what they term "black panel temperature").

In general, their results agreed with our accelerated tests in that Evergreen's new encapsulant showed significantly lower ΔYI values than for TBEC EVA. The following table is abstracted from their paper and lists two of their experiments.

| Sample | Time (h) | Exposure system and temperature | | Ave. ΔYI |
|---|---|---|---|---|
| **EVA** | 849-1186 | ≅ 7.5 UV Suns | 85$^{o}$C | 25.5 |
| **New Encap** | 872 | ≅ 7.5 UV Suns | 85$^{o}$C | -0.4 |
| **EVA** | 1082 | ≅ 9 UV Suns | 110-115$^{o}$C | 57.6 |
| **New Encap** | 746 | ≅ 9 UV Suns | 110-115$^{o}$C | 1.89 |

**Table 1. Selected Results of Xenon Exposure by NREL on the New Encapsulant and on EVA**

For the last set of numbers, with a temperature of 110-115$^{o}$C, the new encapsulant samples showed severe delamination after about 250 hours. This temperature exceeds the melting temperature of the encapsulant so this effect is not too surprising.

To summarize all the accelerated UV exposure tests so far, they all consistently show a much slower degradation rate for Evergreen's new encapsulant vis-à-vis EVA.

<u>Other Properties of Evergreen's New Encapsulant</u>

There are two additional properties of the new encapsulant which render it different than EVA. One is that it feels less "rubbery" than EVA, and, in sheet form, is stiffer.

The other major difference is in the optical properties of the two materials. When laminated between glass plates, EVA looks very clear and transparent. The new encapsulant, on the other hand, has a less transparent appearance. But this difference does <u>not</u> mean a difference in the amount of light which reaches the solar cell. The new encapsulant, because of its molecular structure, tends to form nano-crystallites of the basic polymer material when it is cooled after being melted and these non-crystallites serve as scattering centers. The result is a significant Raleigh scattering effect (degree of scattering is inversely proportional to the fourth power of the wavelength) and a bluish appearance, not unlike the color of the sky. The result is that the <u>total</u>

amount of light reaching a solar cell laminated with the new encapsulant is not less than that for EVA. Furthermore, the scattering may actually produce more light reaching the cell. Some very initial measurements of $J_{sc}$ before and after lamination under glass with the new encapsulant and with EVA are shown in Figure 8.

## CONTINUOUS 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 necessarily conducive to continuous large-scale manufacturing, and typical vacuum lamination equipment is expensive.

With a view towards ultimately doing large scale manufacturing without having a room full of vacuum laminators, we have developed a continuous, non-vacuum lamination process, expected to be lower cost and more easily scaled. The method and equipment is based on internally heated, rubber coated rolls. The pressure between the rolls can be varied as well as the temperature of the rolls. The upper roll is also covered with a release material, which will not stick to other polymers. Figure 9 shows a drawing of the prototype equipment developed in this project. To develop some sense of scale, the apparatus is about 7 feet high at the highest point. The prototype shown in Figure 9 has a single heated roll section. The final machine will ultimately have three such sections, all linked together in one continuous machine. The basic process which will be done using this method involves three separate steps, schematically shown in Figure 10. First, the new encapsulant is pre-laminated into a pre-heated glass superstrate. The pre-heat region is marked as such in Figure 9. The glass superstrate moves on a series of edge rollers until an encapsulant sheet of the appropriate size is placed on it and then the two, the glass and the encapsulant, go through the heated rolls whereby the encapsulant softens sufficiently to melt and bond to the glass under the heat and pressure of the heated rolls.

This second step will be the bonding of the cells onto the encapsulant layer. This will also be accomplished by running everything through a second set of heated rolls. The final step will be the bonding and melting of the backskin onto the module. If a second layer of encapsulant is desired (which would be between the backs of the cells and the backskin) then this can be pre-laminated onto the backskin. In the process we have developed at Evergreen, the need for a second encapsulant layer can be eliminated and the cells can be directly bonded to the backskin material. If not, then the backskin itself is laminated in this final step through the heated rolls. The process development for the formation of the edge seal in the frameless module design in the continuous laminator still needs further work. Forming this edge seal has been shown to be possible with our original, bench top lamination machine, but clearly needs more development before it can be done on the prototype machine. In any case, as an interim measure, the edge formation can be done in a short sequence in a vacuum laminator following the continuous lamination steps to do everything else.

### Technical issues in connection with the continuous lamination method

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 Figure 10), but not so high in step 2 that craters or bubbles would form between the cells. A low durometer silicone also helped.

To summarize, with very modest equipment the feasibility of non-vacuum lamination for crystalline solar cells, such as Evergreen's String Ribbon cells, 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 a full-fledged mass production machine.

## REDUCED SYSTEMS COST—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.

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. Also, from these discussions, the advantages of a molded-in terminal block became apparent.

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. Table 2 lists the features of Evergreen's junction box.

**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 block
- 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 final junction box, shown in Figure 11, was very well received by customers. It incorporates all of the target features listed in Table 2, and constitutes what we believe is one of the best designed if not the best junction box in the industry.

## REDUCED SYSTEMS COST—FRAMELESS MODULE

Using the new backskin material and the new encapsulant and the appropriate lamination conditions, we can now obtain an edge-sealed and frameless module directly from the lamination step. This possibility occurs due to the unique properties of both the new backskin material and the new encapsulant. The backskin material is a modified polyolefin with a certain amount of mineral content as an additive. The resulting material is still a thermoplastic but a limited one whereby the flow under heat and pressure can easily be controlled such that an edge seal and an attractive “framed” appearance can both be easily achieved in the lamination step itself. Furthermore, the backskin material has been demonstrated to be capable of forming strong bonds directly to the rear surfaces of solar cells. This capability means that a layer of encapsulant between the backskin and the cells can now be eliminated. Also, the backskin material bonds very well with the new encapsulant material. The net outcome of all this is a frameless module which eliminates the need and cost of an aluminum frame, an additional edge sealant material, and a second layer of encapsulant behind the cells.

The innovative mounting system which was finally chosen utilizes aluminum “slide bars” which are bonded onto the backskin of the module and extended a slight distance beyond the edge of the module. The completed frameless module with aluminum slide bars can then be mounted by simply sliding the module over pieces of C-channel [1], as indicated in Figure 12.

Following successful completion of reliability tests in 1998, Evergreen is planning to market frameless modules as developed under this PVMaT program. The modules will be produced in two standard sizes, 30W and 60W. These modules will be made with String Ribbon solar cells, using Evergreen’s own proprietary technology in both growing silicon ribbon and in low-cost cell processing [7]. Figure 12 shows 60W modules where the “framing” effect of the backskin wrapping around to the front of the module and bonding to the glass superstrate can be seen. To develop a feel for scale, the String Ribbon cells in this module are 5.6 cm x 15 cm. These modules are at a beta site for a utility in Texas. Also shown are the components for the mounting structure.

As mentioned above (page 7) in connection with the development of the backskin material, it is quite easy to bond aluminum mounting brackets to the backskin material constituting the frameless module. In particular, simple, extruded slide bars of aluminum can be bonded directly to the backskin of the module and the module then slid into place over C channel, obviating any need for screws, nuts or bolts. A gauge of the strength of the bond between the slide bars and the backskin can be gleaned from this example: when trying to pry such a slide bar off of a module after it had been bonded, the aluminum itself was bent while the bond seemed undisturbed.

The backskin material allows for an entire spectrum of mounting possibilities. Using the slide bar concept and “C” channel, modules can be readily roof-mounted. One example, using Ascension Technology’s ballasted roof mounting brackets, is shown in Figure 13. We have successfully bonded a bent aluminum plate for a pole mount and tested it for bond strength with no apparent problems. We have also successfully and easily bonded large area flat head aluminum bolts. Finally, the backskin material can be heat-bonded to other polymers in such a way as to produce a module with no junction box and with the emerging leads sealed to the backskin material, from the edge of the module. Figure 14 illustrates a module made this way. The potential advantages of such a module are several. Its entire profile thickness is about 8 mm, so it can be packed very tightly for shipment and thus dramatically reduce shipping costs. An increase of packing density over a conventional module with a junction box and an aluminum frame of about 5-fold can thus be realized. For small modules whereby a junction box can be avoided, installation can be very simple.

A more recent possible application of the frameless module is in its use as a PV roofing tile. The backskin material can again be used to form a frameless module except that now, more of the backskin material is used to cover that portion of the front of the tile which is the overlap region for the next tile. Figure 15 shows some prototype roofing tiles made this way.

## 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.

**Table 3. Interview Guide**

- Rank the importance or cost of the 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

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.

### Cost of BOS Labor and Materials

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

Regarding panelization costs, 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 ever module frame. Therefore, there are major benefits to simplifying or eliminating grounding. It might be added here that in future work, Evergreen will investigate the use of polymeric slide bars instead of aluminum—thus 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 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.

It 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 environment 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 cost 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.

## OVERALL PROJECT SUMMARY

The culmination of the project and the key deliverable was a frameless module with the new backskin material, the new encapsulant, the new junction box, and laminated using the continuous lamination method. A 30-Watt size module with Evergreen's String Ribbon solar cells and Evergreen's proprietary technology used to make the cells were delivered to NREL prior to the completion of the subcontract.

In general, the project was very successful and all the basic goals were reached. A considerable amount of testing will be continued for the new encapsulant and UL approval for the frameless module will be soon sought.

Two papers have already been published based on this work, and three more are slated for publication. Two of these will be in the Proceedings of the 2nd World PV Conference held in July 1998 in Vienna and the third will be published in the AIP Proceedings of the NCPV review meeting held in Denver, September 1998. Seven patents were filed and two have already been issued. A detailed listing follows on the next page.

A total estimated saving of 20% for manufacturing cost is a result of this project. Modules based on the technology developed under this subcontract have been fielded in test sites both in the Northeast and the Southwest U.S.

# REFERENCES

[1] J. I. Hanoka, et al, 26th IEEE PVSC, Anaheim, CA 1997.

[2] M. A. Quintana, D. L. King and N. G. Dhere, Presentation at PV Performance and Reliability Workshop, Lakewood, CO, 1996. See also Proceedings of PV Module Durability and Long Term Exposure Symposium, February 1998, Cocoa, FL.

[3] E. P. Plueddemann, Silane Coupling Agents, 2nd Ed., Plenum, 1982, p. 157

[4] F. J. Pern and A. W. Czanderna, Sol. Energy Mater. Sol. Cells, 25 (1992) 3-23.

[5] F. J. Pern, Sol. Energy Mater, U.S. Sol. Cells, 41/42 (1996) 587-615.

[6] F. J. Pern and S. H. Glick, NCPV Meeting, September 1998, Denver.

[7] R. Janoch et al, 26th IEEE PVSC, Anaheim, CA 1997.

# APPENDIX

## Summary of papers and patents

**Papers**—To date, two papers have been presented and published:

1. Advanced Polymer PV System, J. I. Hanoka, P. M. Kane, R. G. Chleboski, and M. A. Farber, NREL/SNL PV Program Review, Lakewood, CO 1997, A/P Conf. Proceedings 394, p. 859.

2. Low Cost Module and Mounting Systems Developed through Evergreen Solar's PVMaT Program, J.I.Hanoka, P. E. Kane, J. Martz, and J. Fava, 26th IEEE PVSC, Anaheim, CA 1997.

**Patents**—Filed under this contract (Note: CIP below means Continuation In Part):

1. Solar Cell Modules with Improved Backskin and Methods for Forming Same. Issued as U.S. patent #5,741,370.

2. Solar Cell Modules with Integral Mounting Structure and Methods for Forming Same. Issued as U.S. patent #5,762,720.

3. Encapsulant Material for Solar Cell Modules and Laminated Glass Applications. Pending.

4. CIP on 3. Pending.

5. UV Light Stabilization additive Package for Solar Cell Module and Laminated Glass Applications. Pending.

6. Solar Cell Roof Tile and Method of Forming Same. CIP of #1. Pending.

7. Methods for Improving Polymeric Materials for use in Solar Cell Applications. Pending.

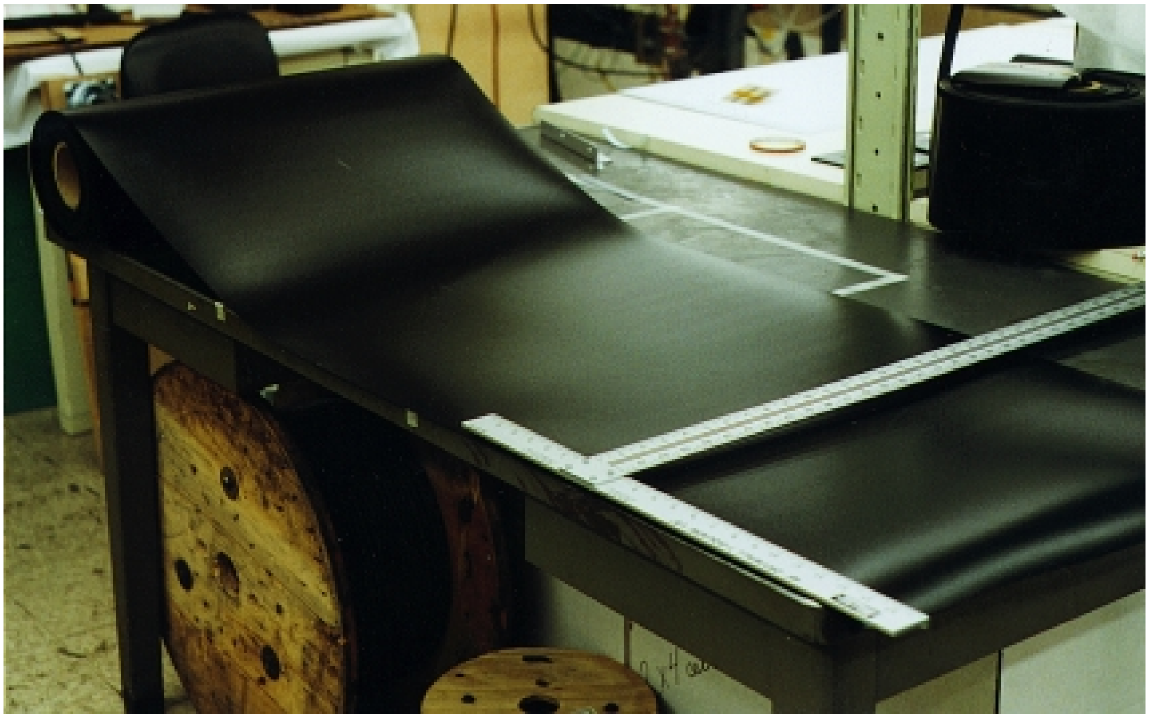

Figure 1.  Roll of the New Backskin

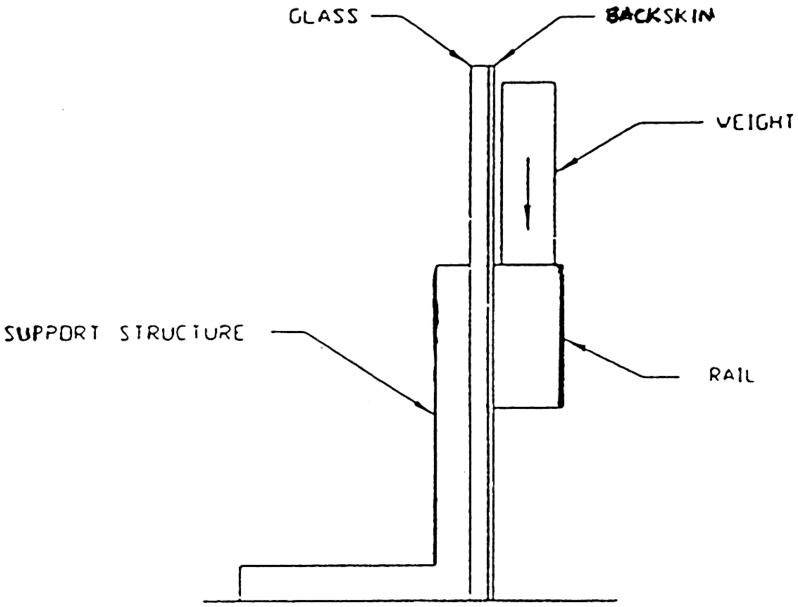

Figure 2. Thermal creep test arrangement for the new backskin material

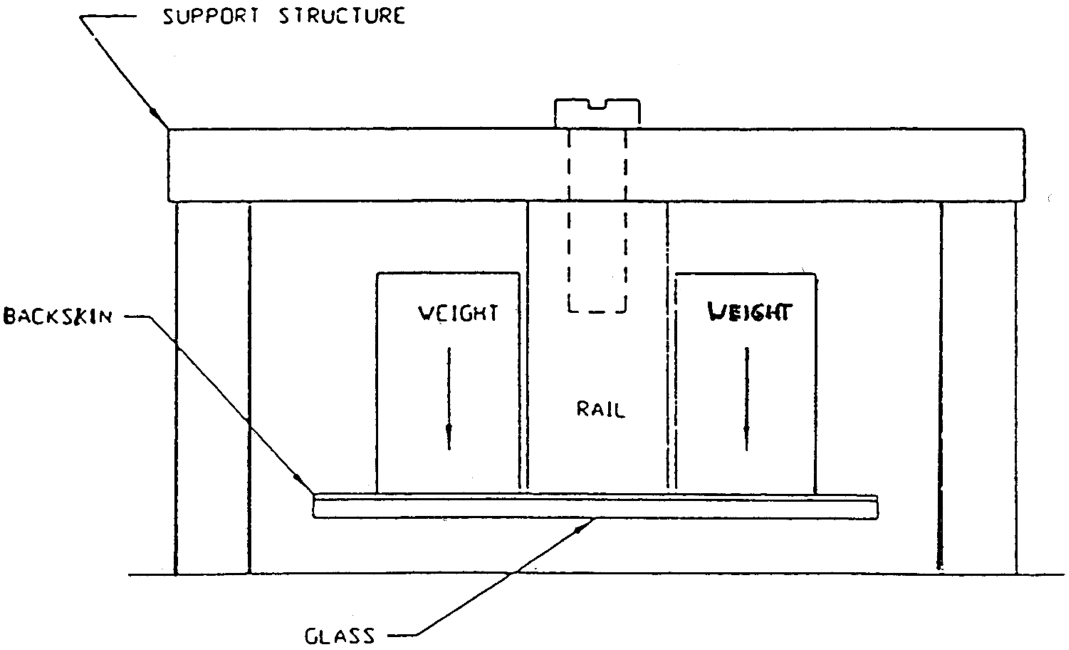

Figure 3. Set-up for static load testing of the aluminum Slide rail for the frameless module

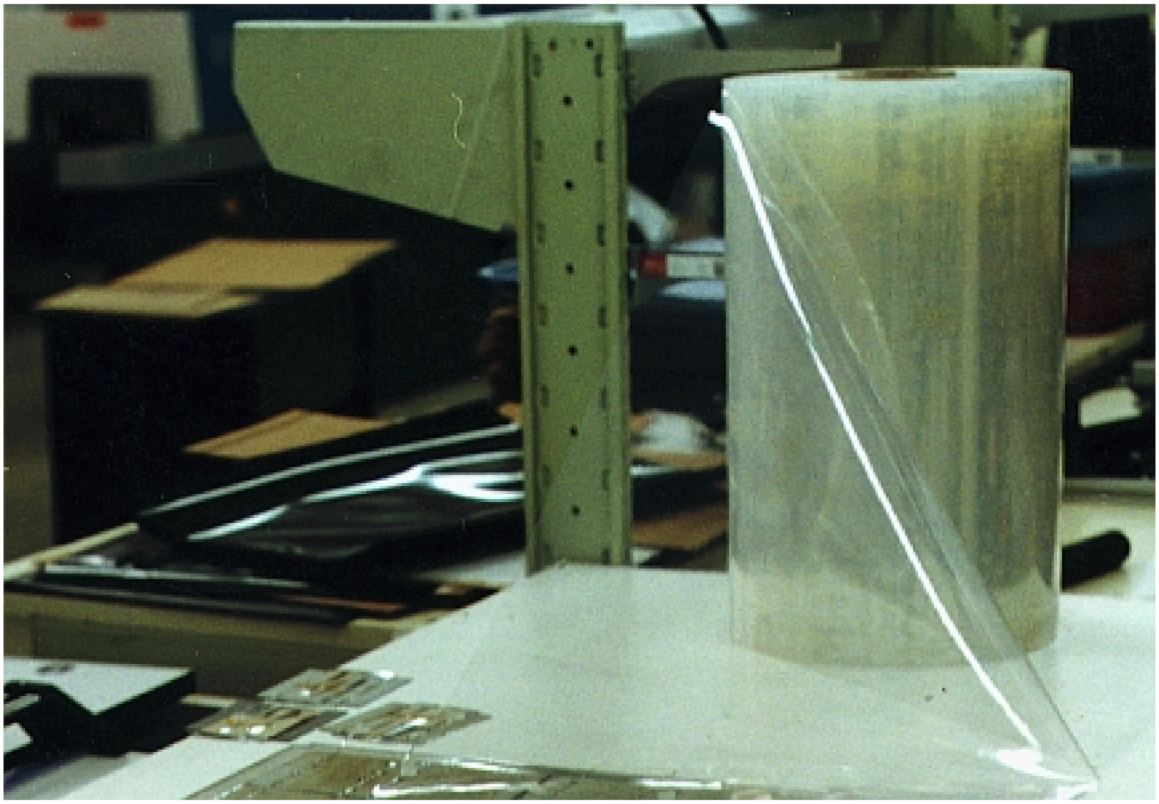

Figure 4.  Roll of the New Encapsulant Material

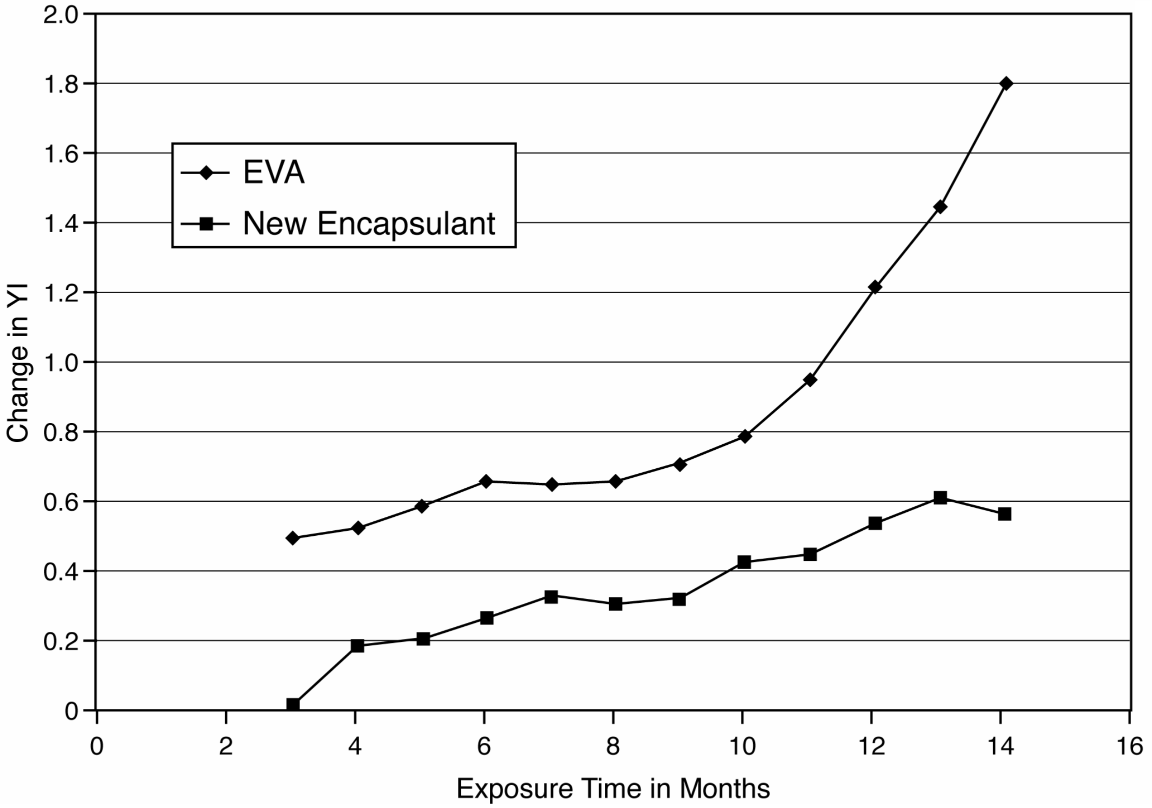

**Figure 5. Yellowness Change under enhanced Arizona Sunlight**

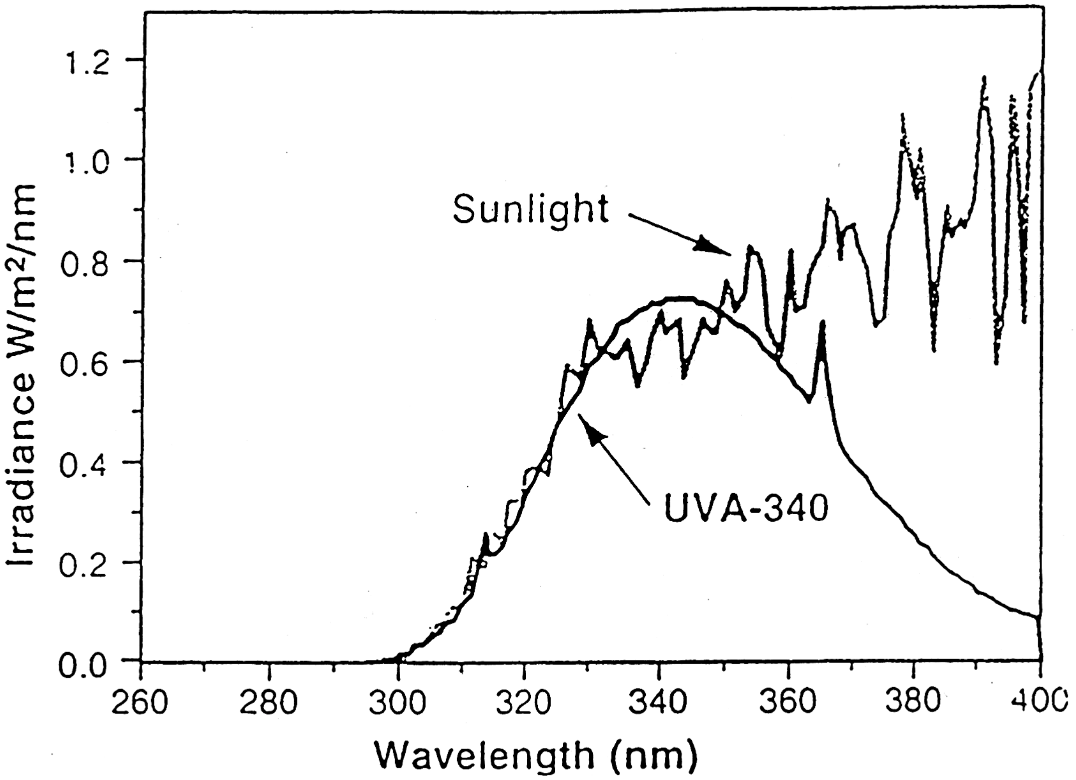

**Figure 6. Spectrum for UVA Lamps vis-à-vis the Solar Spectrum**

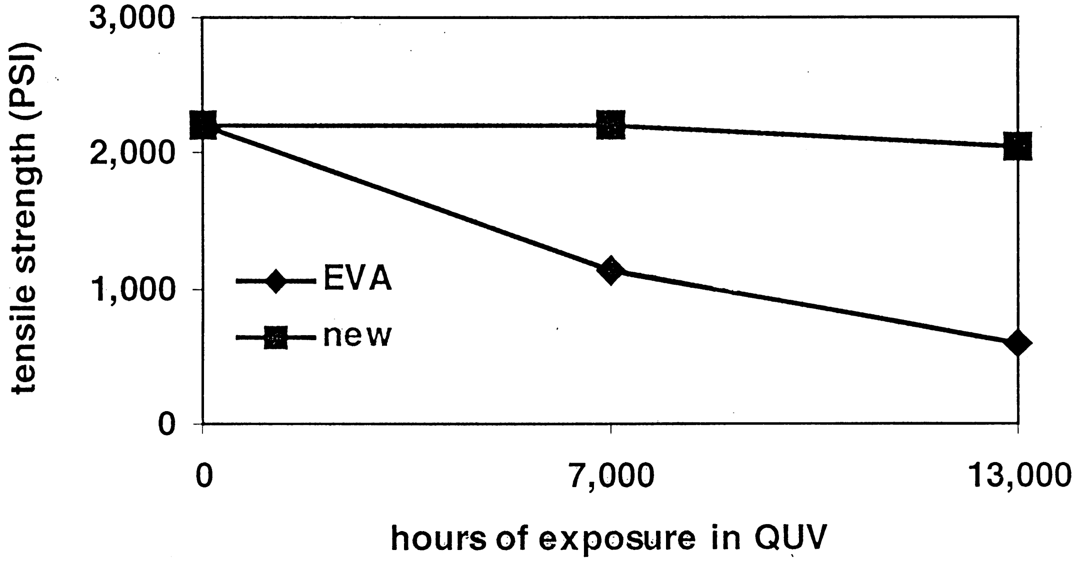

Figure 7. Tensile strength vs. UVA exposure (1.2x @ 50°C)

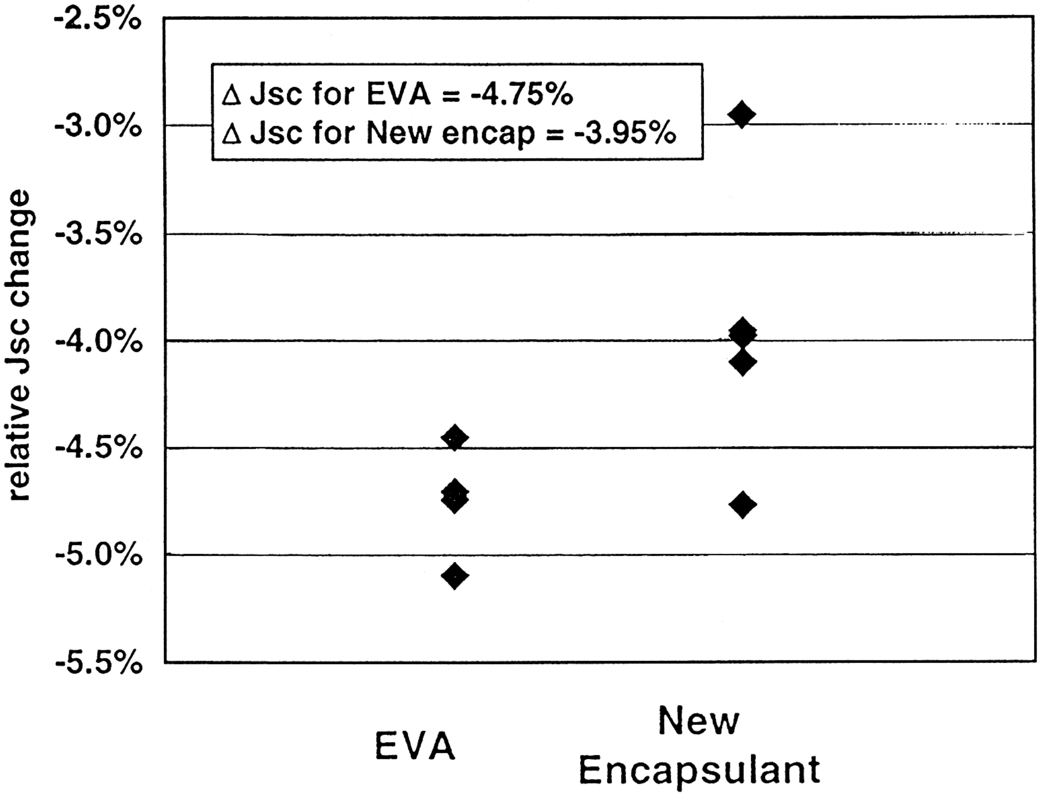

Figure 8. $J_{SC}$ after encapsulation with glass

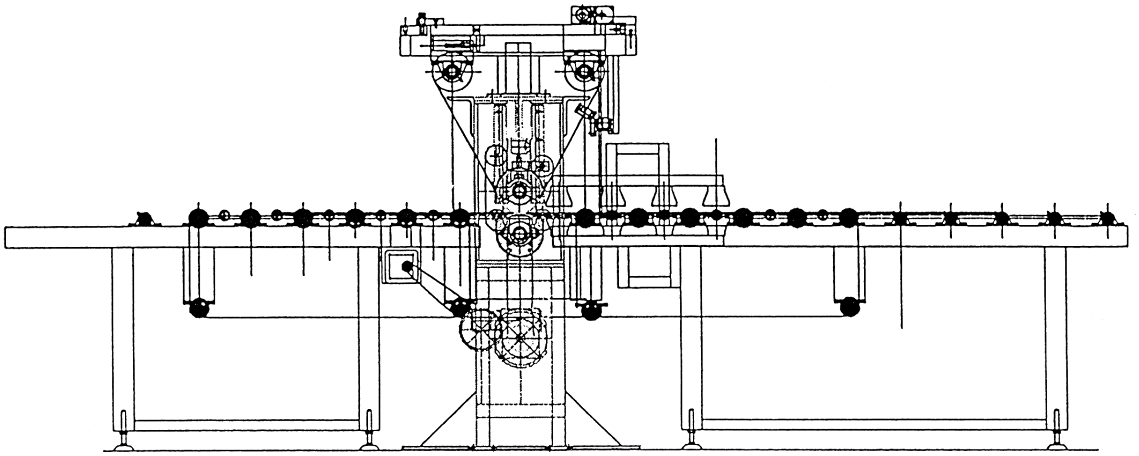

Figure 9. Drawing of the Prototype Continuous Lamination Equipment

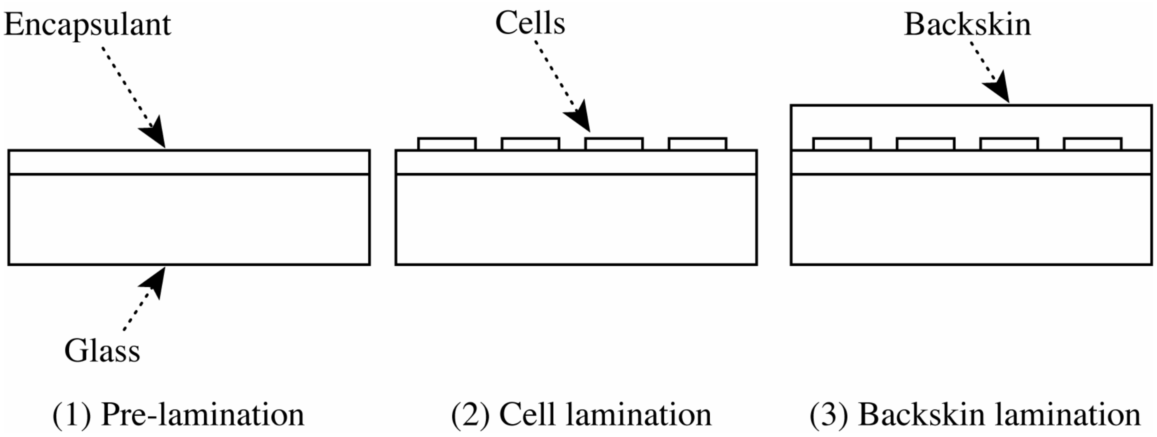

Figure 10. Schematic of the Alternative Lamination Process

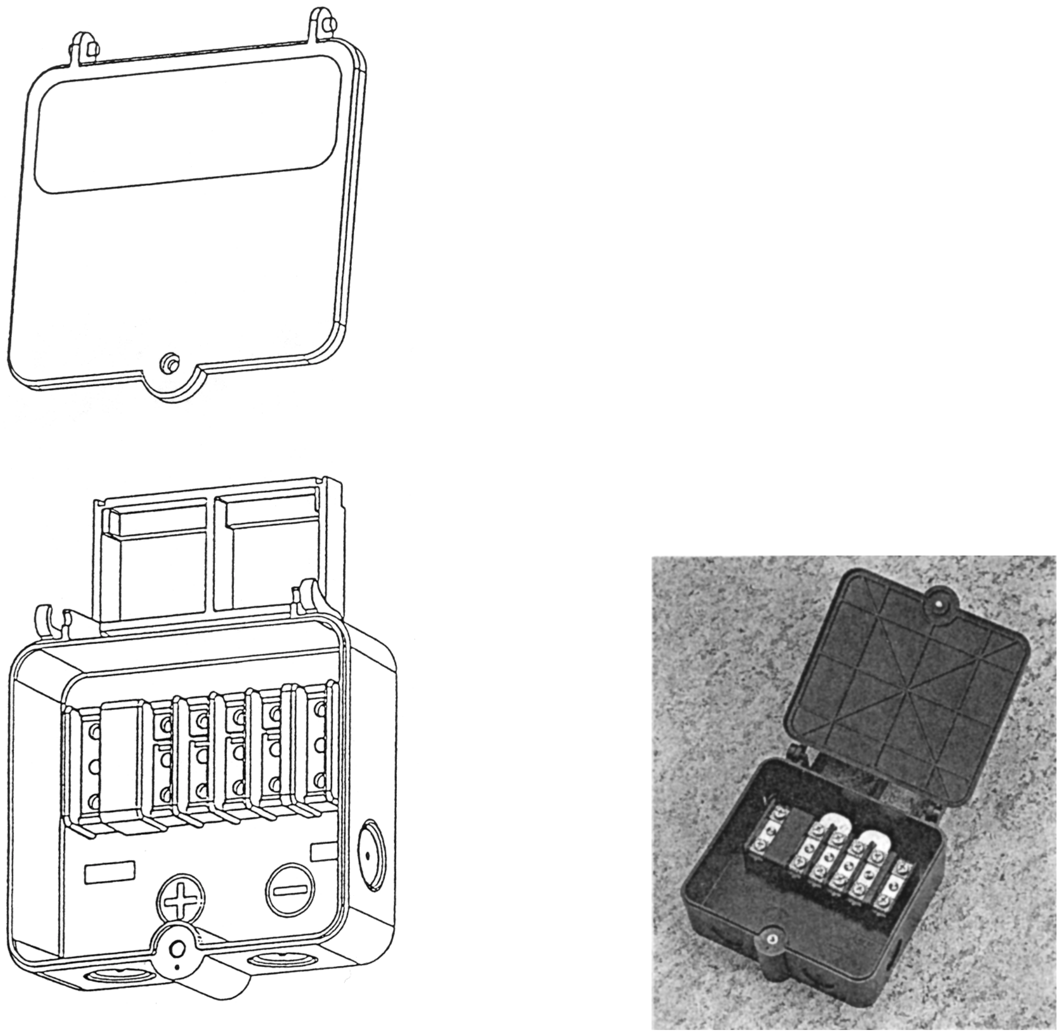

Figure 11. Evergreen's New Junction Box

**Figure 12. Four 60 Watt Evergreen frameless modules mounted at a Texas Utility (Top)**

**Mounting components (Bottom)**

**Figure 13.  Roof Mounting using another variation of the IMS**

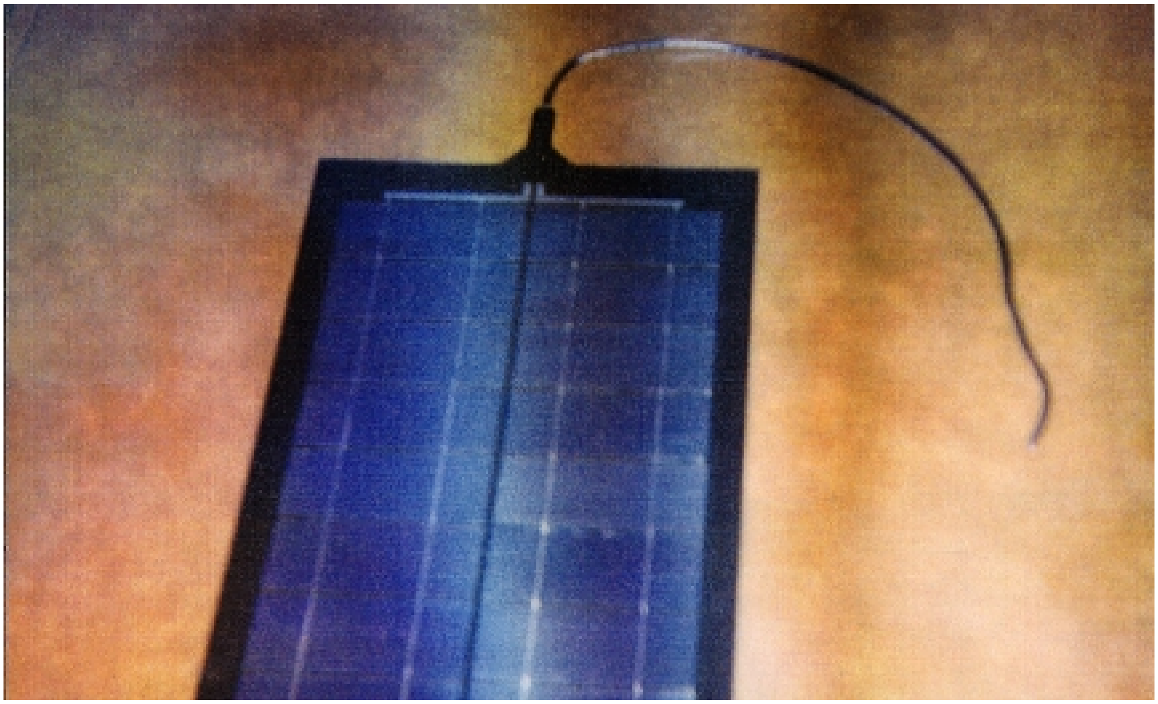

**Figure 14. Module with leads bonded directly onto the backskin material**

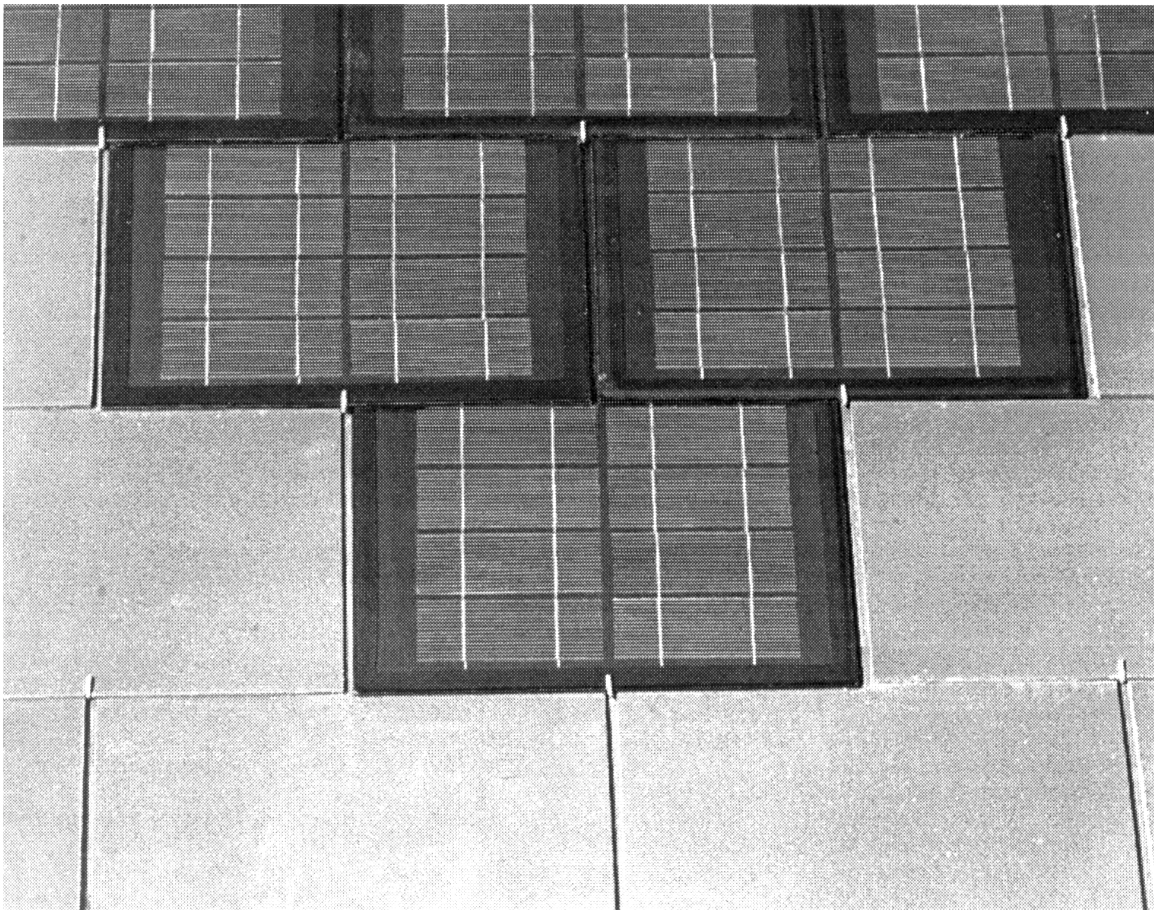

**Figure 15. PV Roofing Tiles using the Frameless Module Concept**

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13. ABSTRACT *(Maximum 200 words)*

This document reports on work performed by Evergreen Solar, Inc. under this Photovoltaic Manufacturing Technology (PVMaT) subcontract. The purpose of this subcontract was to produce lower module and systems costs through the innovative use of polymeric materials. The impetus behind this approach 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. These developments created fresh opportunities for photovoltaics. Using this approach, a new backskin material instead of Tedlar™ (Tedlar is a Dupont trademark) or Tedlar™ laminate was developed and tested. This new backskin material allowed us to make a frameless module and novel mounting methods. The latter is referred to as an Innovative Mounting System (IMS). This IMS system, in conjunction with the frameless module, 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. The advanced backskin material permits elimination of the conventional aluminum perimeter frame, serves to protect and seal the module edge, and allows for direct bonding of multi-functional mounting bars. Electrical interconnection is easier and more reliable with a new junction box that Evergreen has designed after soliciting user feedback. A new transparent encapsulant material, to replace ethylene vinyl acetate (EVA), was developed and tested as part of this subcontract. Early results indicate it will have a number of advantages over EVA, not least of which is better resistance to degradation under light exposure. This new encapsulant can be laminated in air and has also allowed for the development of a continuous, non-vacuum lamination process. The program culminated in the fielding of prototype products with the new encapsulant, new backskin, new junction box, frameless edge seal, and IMS. Feedback and marketing information from potential customers has been actively solicited. Reliability and UL approval requirements have been determined and a number of these already addressed. The net result is a new product that promises a 20% manufacturing and systems cost reduction, as well as significantly increased system lifetime, as compared to a conventional Al-framed module and mounting. A considerable amount of proprietary technology emerged from the program, seven patents were filed, and two have already been granted (1998).

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