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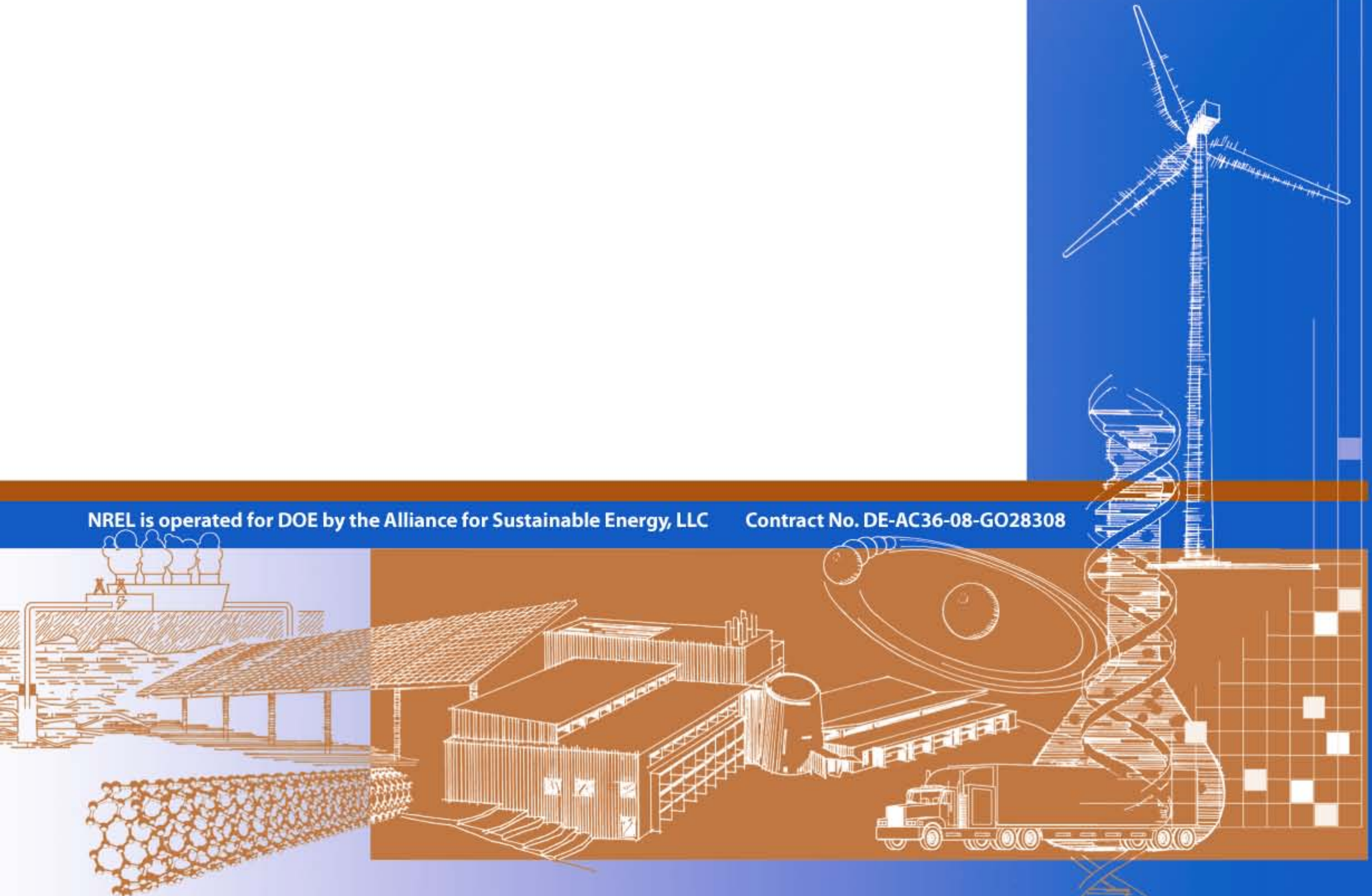
High Performance Packaging Solutions for Low Cost, Reliable PV Modules

Final Subcontract Report
26 May 2005 – 30 November 2008

B.M. Ketola and B.J. Marinik
Dow Corning Corporation
Midland, Michigan

Subcontract Report
NREL/SR-520-45903
June 2009



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Contract No. DE-AC36-08-GO28308

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PROGRAM BACKGROUND

The FY2003 procurement, Photo Voltaic (PV) Manufacturing R&D—Large-Scale Module and Component Yield, Durability, and Reliability, goals are to improve PV manufacturing processes and products while reducing costs, provide a technology foundation that supports significant manufacturing scale-up, and position the U.S. industry to meet rapidly emerging large-scale deployment and other markets. The primary focus is the enhancement of module, system component, and complete system reliability.

During this research effort, Dow Corning Corporation ("Dow Corning") will address the PV manufacturing goals of: (i) improving PV manufacturing processes and equipment; (ii) accelerating manufacturing cost reductions of PV modules; (iii) increasing commercial product performance and reliability; and (iv) scaling up U.S. manufacturing capacity. To accomplish these goals, Dow Corning has focused its efforts on developing a reduced-cost, higher-throughput, improved-performance packaging solution for U.S. PV modules manufacturers.

Dow Corning is working toward the program goals by developing quality assurance (QA) and environmental, safety, and health (ES&H) programs in keeping with local, state, and federal regulations as applicable.

PROGRAM OBJECTIVE

The overall objective of the research effort over its three-phase duration is to develop a reduced-cost, higher-throughput, improved-performance packaging solution for United States Photovoltaic ("PV") module manufacturers. The primary target of the work is to develop a packaging solution that will reduce the overall cost contribution of this component by a minimum of 25% relative to the conventional Ethyl Vinyl Acetate ("EVA")/ Poly vinyl fluoride ("PVF") batch lamination and will provide improved reliability for twenty-plus years of performance in the field. During the subcontract, Dow Corning shall formulate and optimize adhesive, encapsulant, and barrier materials for use with a broad range of current PV technologies. This effort is expected to result in improved performance encapsulation materials and the establishment of a pilot-scale, protection-system production line capable of processing full-size, single-crystalline Silicon PV modules.

SCOPE OF WORK

Phase I - Work in this phase targeted the evaluation of multiple approaches to the encapsulation solution to crystalline silicon based PV modules. Four specific approaches A-D were developed which included sheet based and liquid based options. During this phase options A and D were eliminated as possibilities due to the inability to meet the criteria for durability or reduction of cost/peak watt.

Phase II – The work in this phase targeted the optimization, scale up and application of encapsulation prototypes to thin film PV technologies. During this phase prototype C was eliminated due to the inability to meet cost/peak watt reduction. In addition, it was determined that the approach to barrier layer films did not provide any significant improvement in performance. Prototype B materials were shown to have the potential for higher manufacturing throughput by utilizing a faster cure chemistry. Prototype B materials also were shown to have the potential for higher cell efficiency by utilizing the portion of UV light blocked by EVA due to the addition of UV absorbers to minimize EVA degradation from UV exposure. The optimization of prototype B for durability was continued using IEC and UL testing criteria on mini modules. The optimized formulations were the basis to design a pilot line for the application to full size modules. Prototype B was also utilized for encapsulation with rigid thin film PV technologies.

Phase III – The work in this phase was targeted on the scaled-up material production and application on full size modules. During this phase the pilot line designed in phase II was purchased and installed at the Solar Application Development Center in Freeland, Michigan. The pilot line was used to demonstrate and optimize the application of the Prototype B encapsulation solution on full size crystalline silicon modules. These modules are being submitted to NREL or for independent IEC and UL qualification testing by module manufacturers or internally to Dow Corning. The optimized Prototype B materials were also applied to thin film PV technologies. These modules are being evaluated internally to Dow Corning for application development using IEC and UL testing criteria.

Technical Approach

In order to meet the objectives of increased durability and reduction of cost/peak watt as compared to EVA encapsulated crystalline silicon modules, literature searches and interviews with module suppliers were conducted. This resulted in a technical approach based on the following input. A new encapsulant would need to meet or beat the durability of EVA and it must deliver at least one of the following criteria: increased module efficiency, increased manufacturing throughput, or lower material costs. In addition, the solution would need to be demonstrated at a manufacturing scale.

As a result a major technical focus of the subcontract was placed on the durability of the encapsulated cells and modules. Outside testing in multiple locations is the best means of demonstrating durability but, due to the long time periods needed to demonstrate the durability, other means must be employed. Durability can also be demonstrated by evaluating coupons or modules using the standardized aging testing developed for IEC and UL qualifications. These tests are designed to analyze any changes in efficiency or power and visual defects before and after environmental aging in Damp Heat (85 °C/85 %RH), Thermal Cycling (-40 to 90 °C), and UV Exposure/Thermal Cycling/Humidity Freeze sequences.

The other major technical focus was to impact on cost per peak watt by increased cell or module efficiency, higher manufacturing throughput and reduced material cost. Increased efficiency can be directly influenced by the amount of light that reaches the cell. In order to understand if silicone can improve efficiency testing of the % Transmittance of the materials were compared against EVA. In addition, the comparison of the % Quantum Efficiency of the cell was completed to evaluate the conversion of the light to electricity by the cell. Finally, by direct comparison of EVA and Silicone encapsulated cells or module efficiencies or short circuit current (Isc).

Higher manufacturing throughput could be achieved by reducing lamination cycle times, which is significantly influenced by increased cure rates and decreased cure temperatures. Reduced cure temperatures and times would also reduce energy costs. Employing process automation and reduced material handling are other methods of increased throughput. In addition, higher throughput could be achieved if the process could improve process yield through less cell breakage or module rework.

Lower material costs can be achieved by developing formulations using high volume intermediates, and low cost production equipment. Lower labor rates can be achieved by reduced material handling. Further reduction in cost can be achieved by reducing packaging and packaging waste, which not only reduce costs but also benefit the environment. Material costs can also be minimizing by optimized silicone layer thickness and waste minimization by utilizing robotic application methods. Another approach to lowering material costs would be to eliminate or replace polyvinylfluoride back sheets. Finally, material costs can be lowered by reducing silicon usage through the use of thinner wafers or cells.

The resulting product concepts and processes taken forward in this program strived to achieve these criteria.

As a result of the industry interviews and formulation screening completed in Phase I & II the concepts shown in figure 1 were derived for the use of silicone to encapsulate PV modules.

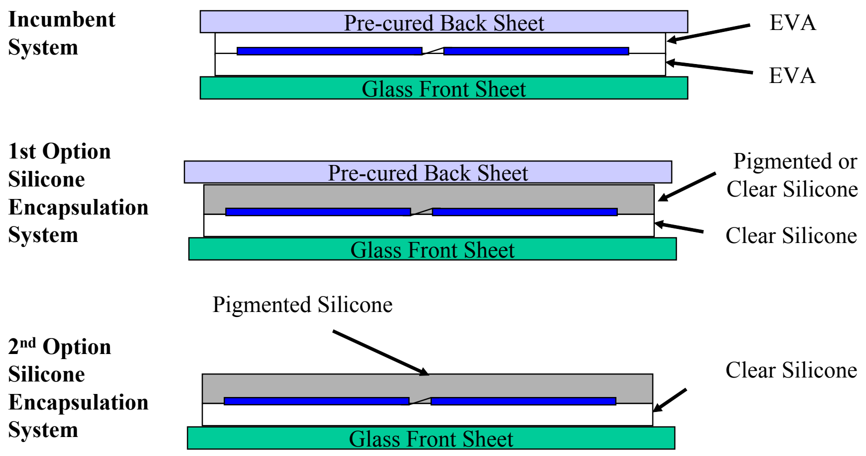

Figure 1 – Silicone Encapsulation Concepts

The first option resulted as a method to overcome the “cut test”. The “cut test” as defined in IEC 61215 proved to be a major hurdle for the second option since the silicones evaluated the cut strength was not sufficient to protect the cells and remain at a thickness that would be cost effective. Keeping the back sheet in place allowed for the passing of the “cut test” while maintaining a thickness that would allow silicones to be competitive with the cost of EVA.

Even though the “cut test” could not be met by the formulations evaluated, the second option is still of interest due to the performance of modules encapsulated with silicone only in the late 1970s and early 1980s by Solarex Corporation (BP Solar), and deployed at their facility in Frederick, MD and Georgetown University. These modules would not be a cost effective option per the materials and manufacturing methods used at the time. However, the option has the possibility to meet program goals of cost effective solution if the proper material and process could be developed. Hence, activities around this option are being explored beyond the end of this contract.

PHASE III TASK SUMMARY AND RESULTS

Task 13, Production of Prototype Cells & Circuits II

During this task functional crystalline Si cells and circuits, and thin film PV circuits that are fabricated using standard processes were needed in order to provide representative samples of the current PV technology. These circuits were evaluated for the initial performance, and packaged in appropriate materials to mitigate degradation during shipping.

Milestone	**Description**
M-3.13.1	Completion of production for functional mono-crystalline Si cells and circuits required for fabrication of modules, and functional multi-crystalline Si cells and circuits required for fabrication of modules.
M-3.13.2	Completion of 30 thin-film PV devices for use in evaluation of encapsulation materials.

Strategy

The production of crystalline circuits was completed by multiple partners to ensure a representative supply from the industry. The mini-modules were supplied first to evaluate and optimize the encapsulation system. Then full size circuits or matrices were acquired for module production with the optimized encapsulation system. The major issues for shipping matrices were the handling, packaging and shipping without damage. To solve this issue a “sandwich” package design was developed by Dow Corning to transport the matrices. This design was successful in transporting 72 cell matrices without damage from multiple suppliers in multiple locations.

Mono-crystalline Cells, Strings and Matrices

The first source, supplier 1, sent 125 mm x 125 mm mono-crystalline cells, 3 cell strings, 32 cell matrices and 72 cell matrices at no charge to the contract. Because of concerns with potential damage when measuring IV the strings and matrices were not evaluated prior to shipment.

Supplier 2 also sent 125 mm x 125 mm cells to evaluate and optimize the encapsulation system. Two sets of 100 cells of multi-crystalline were supplied. The cells specifications are as follows:

Cell Type: 125 mm

Eff. = 14.93%
Isc = 5.002 Amp
Voc = 608 mV
Ipmax = 4.67 Amp
Vpmax = 498 mV
FF = 76.5 %

The single and multi crystalline cells were encapsulated in three cell as well as four cell configurations. The four cell configurations were soldered together at Dow Corning for encapsulation experiments.

Evaluation and optimization of the encapsulation system was accomplished by encapsulating the cells using option 1 shown in Figure 1. The encapsulated cells were evaluated by visual inspection and IV power analysis using a Spire 240 A Sun Simulator at Dow Corning. The encapsulated cells were then subjected to environmental aging at Damp Heat (85 °C/85% RH), Thermal Cycle (-40 to 90 °C), and UV/Thermal Cycle/Humidity Freeze conditions. Due to the concerns over customer confidential information the results from this testing will be reported as % change from initial.

The 32 cell and 72 cell matrices were encapsulated using the optimized formulations derived from the single cell and multi cell strings. The encapsulation of the matrices was used to optimize the pilot line encapsulation process developed in Task 12.

Milestone	**Description**
M-3.13.2	Completion of 30 thin-film PV devices for use in evaluation of encapsulation and barrier materials

Strategy

The production of thin film circuits was completed by multiple partners to ensure a representative supply from the industry. Mini-modules were supplied first to evaluate and optimize the encapsulation system. Then full size circuits were or will be acquired for module production with the optimized encapsulation system.

Task Results

Supplier 1

Fifty cells (modules) were sent from rigid thin film Supplier 1. These were used in encapsulation trials, and environmental aging studies, and compared to incumbent encapsulant materials as control samples.

A second shipment of twenty cells (modules) was sent using a silicone based insulating tape from the rigid thin film supplier. In addition, a laminated module was received as standard reference for the Spire 240 A Sun Simulator.

The modules were visually inspected and characterized using the Spire 240 A Sun Simulator prior to and after encapsulation as well as after environmental aging studies. These results were reported as % change in Pmax.

Supplier 2

Supplier 2 sent 20 – 30 cm x 30 cm modules and back glass for adhesion and encapsulation mock ups. These will be used to develop adhesion testing and demonstrate the use of prototype B formulations with these types of modules.

In addition, 58 modules were sent from Supplier 2 for DOEs studying electrical connection and insulator composition. In addition, a laminated module was received as standard reference for the Spire 240 A Sun Simulator.

The modules were visually inspected and characterized using the Spire 240 A Sun Simulator prior to and after encapsulation as well as after environmental aging studies. These IV results were reported as % change in Pmax.

Task 14, Device Protection & Packaging System Evaluation for Thin-Film PV on Glass

This task is designed to evaluate the application of the protection system, Developed in Phase I and optimized in Phase II, on thin film devices provided by alternative suppliers. The encapsulated devices will be evaluated for protection against environmental aging. In order to optimize the protection system for thin-film applications, the materials and processes will be applied the to additional thin film devices and perform the characterization tests.

Milestone	**Description**
M-3.14.1	Demonstration of the protection system developed for single-crystalline Si cells on thin-film PV on glass cells in order to verify applicability of system to a broader range of thin-film PV technology
M-3.14.2	Demonstration of an optimized protection system on thin-film PV on glass cells in order to verify applicability of system to a broader range of PV technology

Strategy

The target for this task is to evaluate the potential benefits of silicone encapsulation versus EVA, and the various technologies to prevent moisture ingress using these modules. Research papers have recently been questioning EVA as the best encapsulant for thin film technologies[1,2,3,4]. A major issue is corrosion potential due to acetic acid generation. Another issue that is known in the industry is "dark loss" or drop in initial efficiency from elevated temperatures during the lamination cycle. In addition, there is some suspicion that the high modulus of the EVA can cause high stresses during thermal changes which could result in premature failure. The use of perimeter seals has been proposed as a potential solution for moisture ingress[1,2,3] from the edges in a glass on glass construct. However the use of perimeter seals do add a processing step which can slow production, add cost and can potentially cause issues with stress build up in traditional lamination.

It is theorized that silicone can address several of these issues. Based on Dow Corning experience in the electronics and automotive industries, it is well known that silicones, when properly formulated, can prevent corrosion in electronic devices. From this experience it has been learned that moisture ingress is not an issue for corrosion if the encapsulation material has good adhesion with no void spaces for condensation of moisture. In addition, there has to be ionic contamination, such as metallic ions, acetic acid or acidic peroxide by-products, associated with condensed moisture to promote corrosion mechanisms. Silicones have been formulated to excel in adhesion, with good rheological properties to prevent void spaces, having low in ionic content, and do not form ionic materials due to the chemical make up and cure mechanisms.

Silicones can be formulated with multiple cure chemistries that can significantly lower the cure temperature, some as low as room temperature, and significantly reduce the cure times. This not only helps with “dark loss”, but can also significantly increase throughput. In addition, the proper cure chemistry and rheology can possibly eliminate traditional lamination techniques.

Finally, silicones can be formulated for much lower modulus and have inherently lower Glass Transition Temperature (Tg) to provide stress relief during thermal changes over temperatures ranging from -40 to >150 °C.

The strategy employed by this task will attempt to demonstrate the potential benefits of silicone over EVA based on these properties.

Task Results

In Phase II the evaluation of thin film modules from Supplier 1 was started. The crystalline encapsulant formulation prototype B was applied to the several modules and tested using humidity freeze conditions. Surface defects were noted during this testing. Visual observation seemed to indicate that the surface defects were associated with the tape used as the insulator under the lead foil. It was theorized that the acrylic adhesive was a possible factor. Experiments that were completed to replace the tape also indicated that the surface defects were associated with the acrylic adhesive used on the tape. As a result modules were prepared with silicone adhesive insulator tape by the supplier. The modules were then prepared with prototype B. The modules were then subjected to HF cycling. Modules with acrylic tape adhesive were included in the study. The IV response to HF cycling as measured by percent change in Pmax is presented in Figure 2.

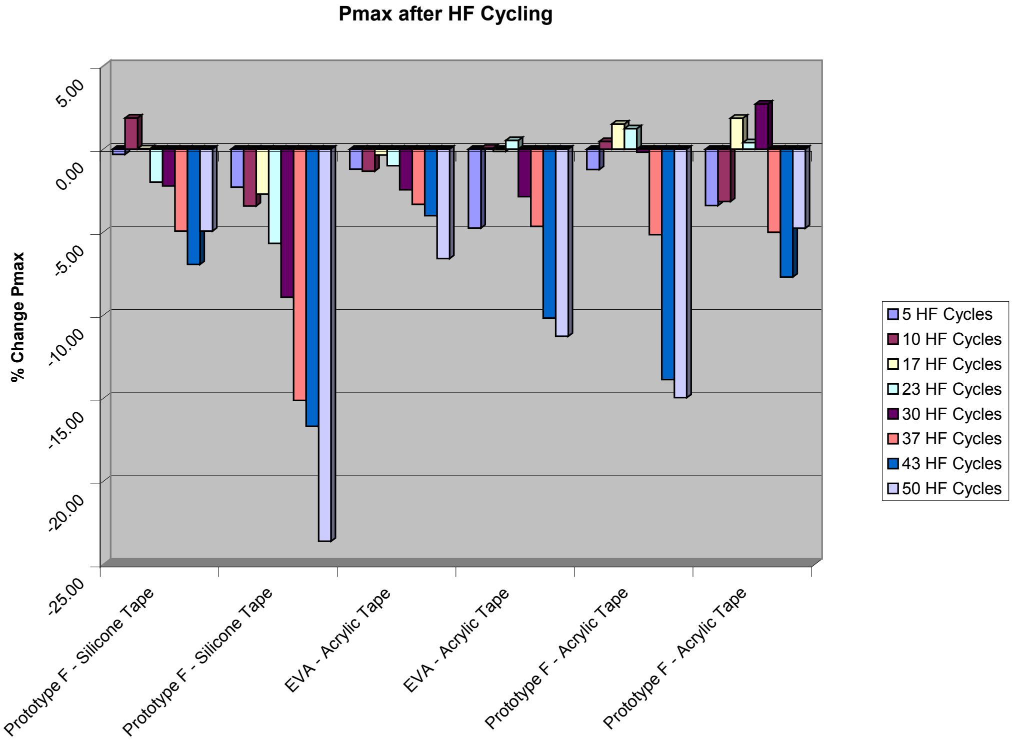

Figure 2 – Rigid Thin Film Response to Humidity Freeze Cycling

The data indicated that percent change Pmax performance was acceptable for all modules up to thirty cycles. To understand if there were any major differences in IV performance after further cycling the modules continued to be aged. Significant Pmax degradation took place for at least 1 of the samples from each configuration at each of the next intervals. The Pmax degradation correlated with a drop in FF or Voc which could be attributed to increases in resistance and degradation of the PV device respectively.

It should be noted that the above data should be used for qualitative purposes only due to the fact that the unencapsulated modules with acrylic adhesive tape had been stored for an extended period of time.

Visual observation of the two Prototype B modules with silicone tape had minimal surface defects, and essentially no defects in the silicone. Surface defects developed along the edge of the modules when observed at 50 cycles, and the silicone showed minor adhesion loss at the perimeter.

Visual observation of the Prototype B modules with acrylic tape was showing surface defects under the insulating tape and along one edge of the module after 22 cycles. The surface defects out to 50 cycles did not change significantly after being first observed. The silicone defects again showed minor defects along the edge.

Visual observations of the EVA modules revealed significant surface defects on the edges of the modules after 22 cycles. At 30 cycles one module was showing significant delamination of the EVA from the metallization layer. In addition, the EVA was very hazey along the perimeter. The delamination continued to grow in size out to 50 cycles, and the corners began to delaminate. In addition, the surface defects had continued to increase. In the areas along the long edge of the module and near the junction box hole the PV material appeared to be blistered or delaminating from the front glass.

The results of the experiment lead to the search for the root cause of the surface defects. It was theorized that the surface defects could be a function of loss of adhesion which allowed moisture to migrate to the PV material. Experiments were performed by varying Prototype F formulations with different adhesion promoter packages on small samples cut from a module. These samples were subjected to 85 °C and 85% RH conditions and inspected for surface defect formation. These experimental results revealed that optimizing the adhesion package can have a significant impact on surface defects.

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Lap shear adhesion was utilized and the samples were prepared as shown in the Figure 3.

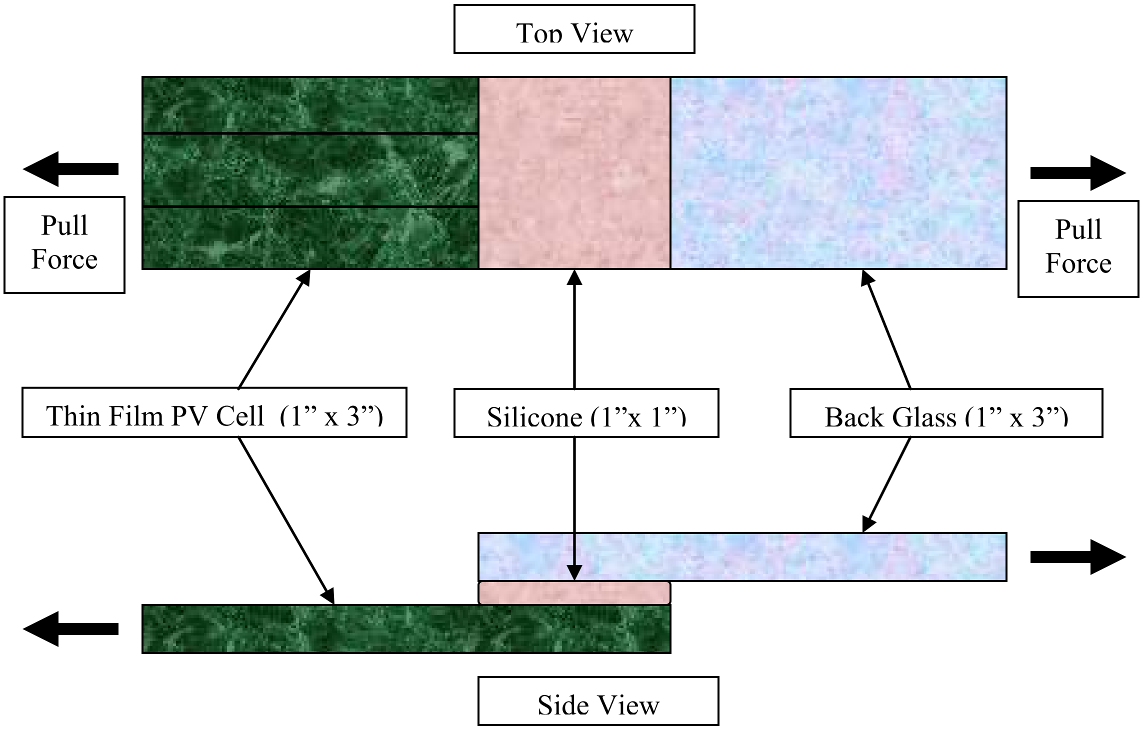


Figure 3 - Lap Shear Adhesion Test Sample Configuration

Samples from supplier 1 prepared in Task 7 were tested to determine if the coatings applied using the APPLD technology will have a benefit for this application. Samples were prepared for adhesion testing from coated, coated with heat treatment, and uncoated substrates using the Prototype B formulation used in the module testing above. The samples were subjected to 85 °C/85 %RH conditions to compare the adhesion and surface defect formation. The results of the adhesion testing are shown in Figure 4. Visual inspection of the samples after three weeks at 85 °C/85 %RH showed that the defect formation in the coated samples was much improved over the uncoated samples. However after seven weeks in 85 °C/85 %RH conditions the only samples that showed no defects were the samples that had been heat treated. Unfortunately the module supplier noted that the heat treatment at this stage of the processing would most likely degrade module performance and would not be an acceptable processing step. Since this method of adhesion promotion did not meet the customer criteria, and it would have an extra processing step this approach was abandoned. Instead, adhesion improvement was pursued by evaluating adhesion promoter packages.

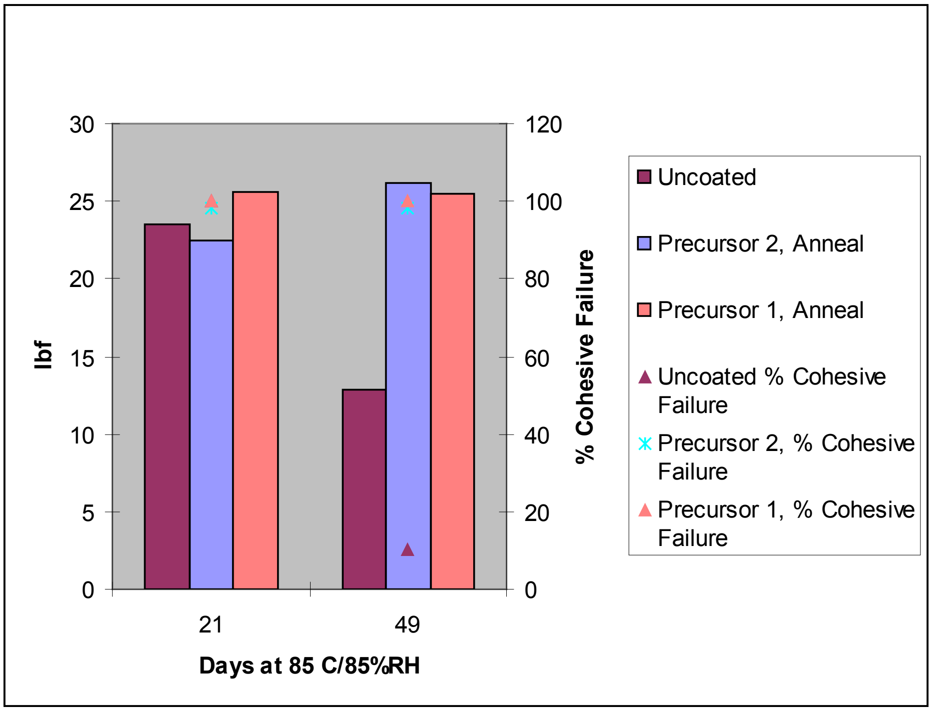


Figure 4 – Lap Shear Adhesion Results of APPLD coated samples

Prototype B formulations using various adhesion promoter packages were prepared using materials provided by supplier 2, and tested by lap shear adhesion testing before, and after aging at room temperature and in 85 °C/85 %RH conditions. These were tested ~1 week intervals to monitor the changes adhesion in both conditions. The results of the adhesion testing are shown graphically in Figures 5 and 6.

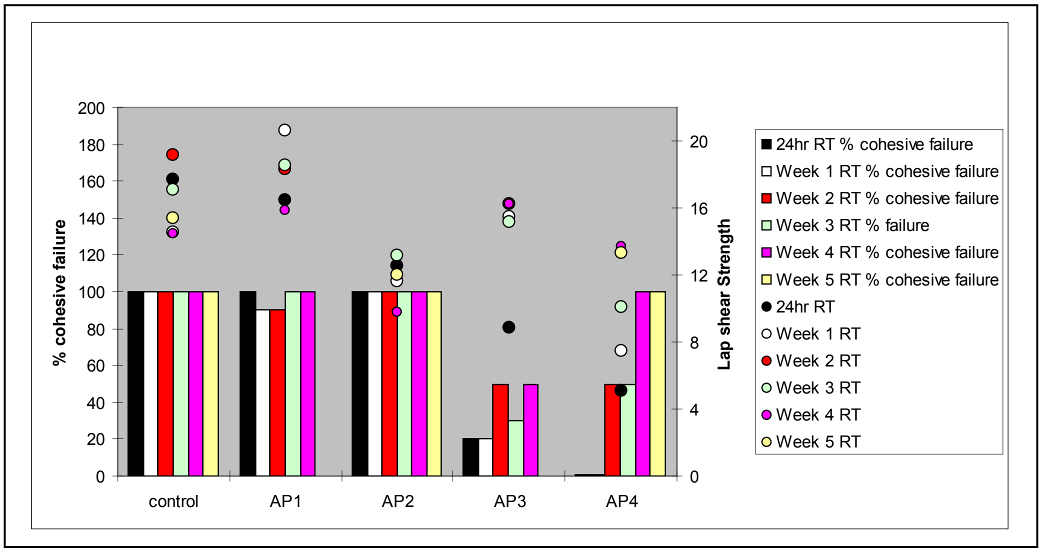


Figure 5 - Rigid Thin Film Lap Shear Adhesion Testing Results with Prototype B9 – Room Temperature Aging

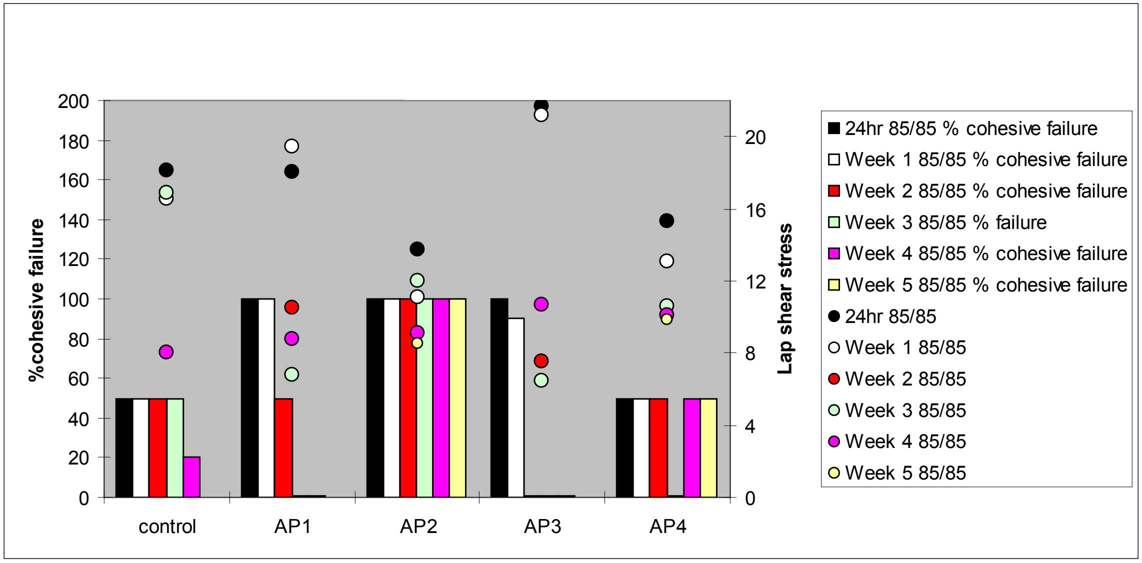


Figure 6 - Rigid Thin Film Lap Shear Adhesion Testing Results with Prototype B9 – 85 °C/85 %RH Aging

Based on this data Prototype B9 with AP2 showed the best performance in RT and 85 °C/85 %RH. This adhesion package would be brought forward in further testing.

A second Prototype B formulation, B10, was also prepared tested for adhesion at RT and 85 °C/85 %RH aging conditions for at least 6 weeks with tests at 1 week intervals. The results of the testing are shown in Figures 7 and 8.

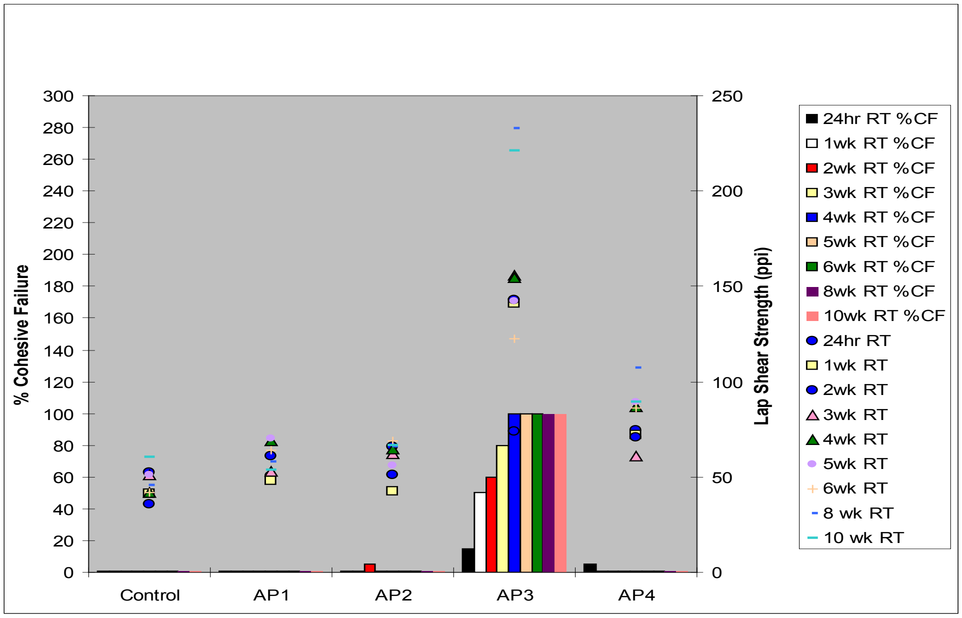


Figure 7 - Prototype B10 Adhesion Testing Results – RT Aging

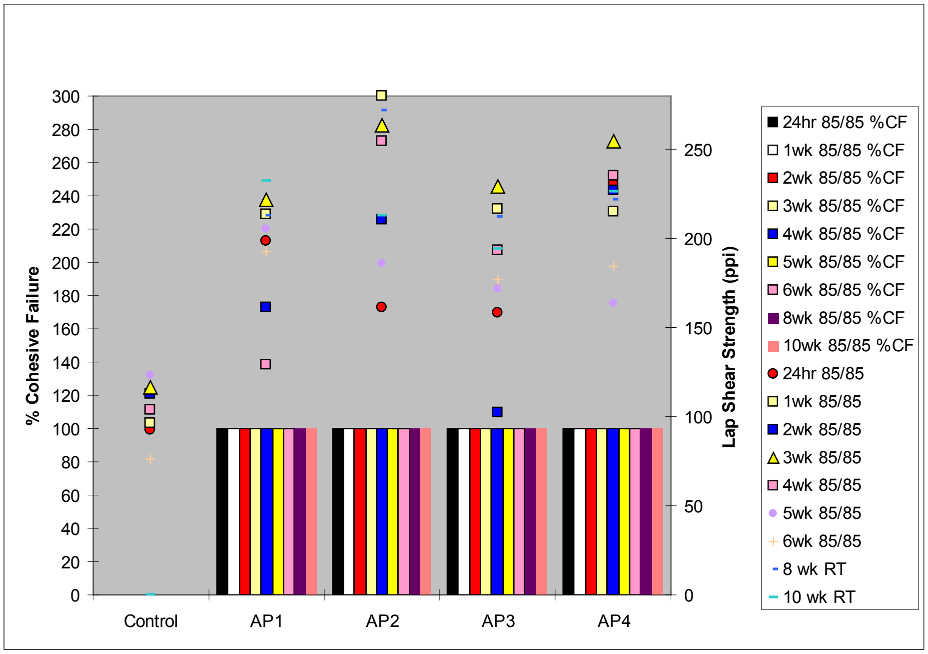


Figure 8 - Prototype B10 Adhesion Testing Results – 85 °C/85 %RH Aging

Based on the fact that RT adhesion develops over time with AP3 seems to be best suited for this formulation. This adhesion package will be used in future encapsulation of rigid thin film PV modules.

Several samples were encapsulated using prototype B9 and B10 formulations to develop the encapsulation method. The successfully encapsulated modules were subjected to Humidity Freeze Cycling to understand the response of the modules to the aging conditions. Samples prepared with Prototype B9 showed some surface defects. Samples prepared with Prototype B10 showed no surface defects. After discussing the results with the supplier it was determined that conclusions from this study could not be drawn since the modules were not of acceptable quality.

As a result another set of modules were supplied for use in a DOE to study adhesion promoters and module assembly techniques. These samples were encapsulated using the B9 and B10 formulations. Samples were then characterized visually and by IV and put into 85 °C/85 %RH aging for 1000 hours. Intermediate testing results show no degradation of the modules at ~400 and 700 and 1000 hr testing intervals. The data is shown graphically in Figure 9.

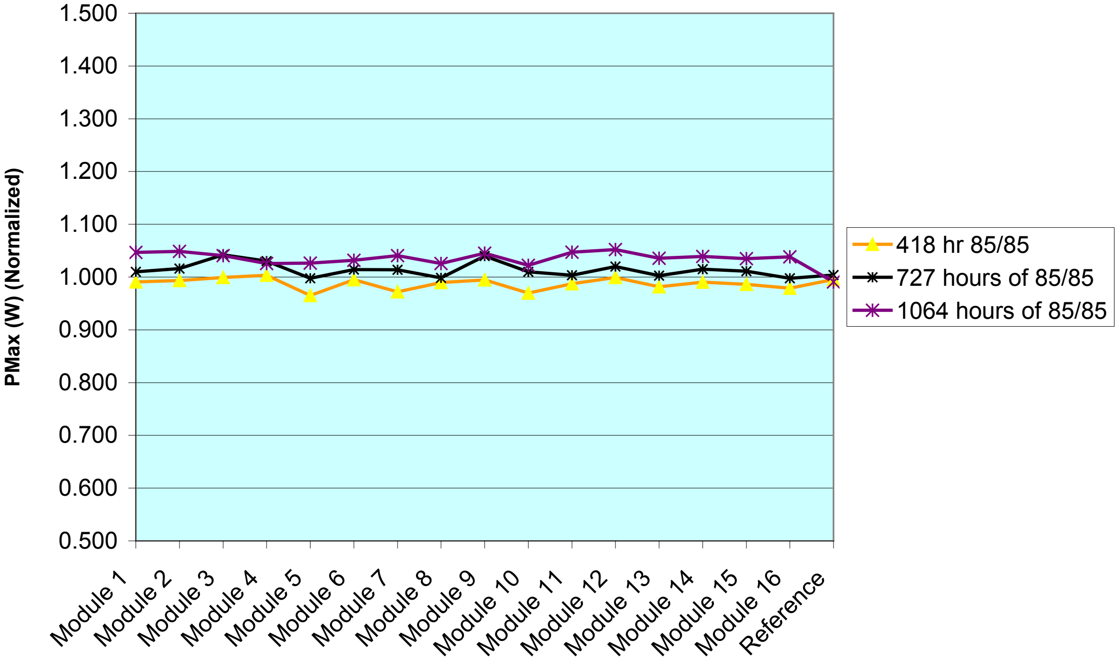


Figure 9 – Rigid Thin Film PV Pmax Response to Damp Heat Aging

Visual inspection of the modules has shown no major defects after aging. The pictures below are representative of two samples prepared for Rigid Thin Film Testing. These have been prepared with two versions Prototype F 9 and Prototype F10.

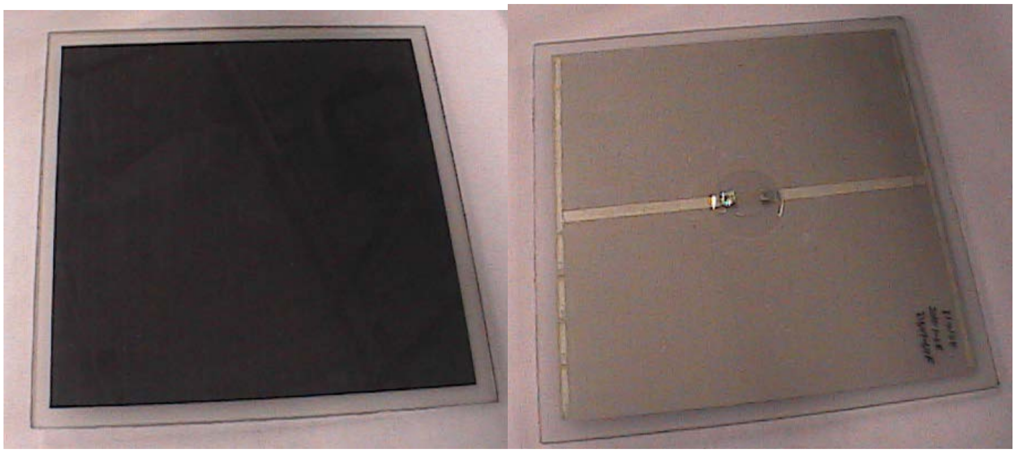


Figure 10 - Rigid Thin Film Module Prepared with Prototype B9 – Post 1000 hr 85 °C/85 %RH aging.

Figure 11 - Rigid Thin Film Module Prepared with Prototype B10 – Post 1000 hr 85 °C/85 %RH aging.

The modules from Supplier 2 have shown very good IV response to the 85 °C/85 %RH conditions with essentially no degradation in Pmax. Based on these results, plans are being made for full size panels to be tested on the pilot line described in Tasks 12, 15 and 17.

Task 15, Protection System Scale-Up

A major goal of this task will be the scale-up activities for the pilot-scale, protection-system production line through production-run trials of the collective system. During this task the tools for the application of the adhesive and encapsulant will be designed, installed and started up. Following start up and calibration, protective system trials will be completed and the protection-system performance tested as compared to previous evaluation results.

Milestone	**Description**
M-3.15.1	Completion of scale-up and calibration of pilot-scale, protection-system production line, as needed to demonstrate benefits, including the barrier, adhesive, and encapsulant tools

Strategy

The encapsulation system development during Phase I and II resulted in the concepts depicted in Figure 1. The materials selected for these concepts are based on prototype B formulations, which are liquids. Because of the use of liquid materials, a completely new system of material application needed to be developed as compared to EVA sheet applications. To demonstrate the liquid application system a pilot line has been designed based on a conceptual production line shown schematically in Figure 12.

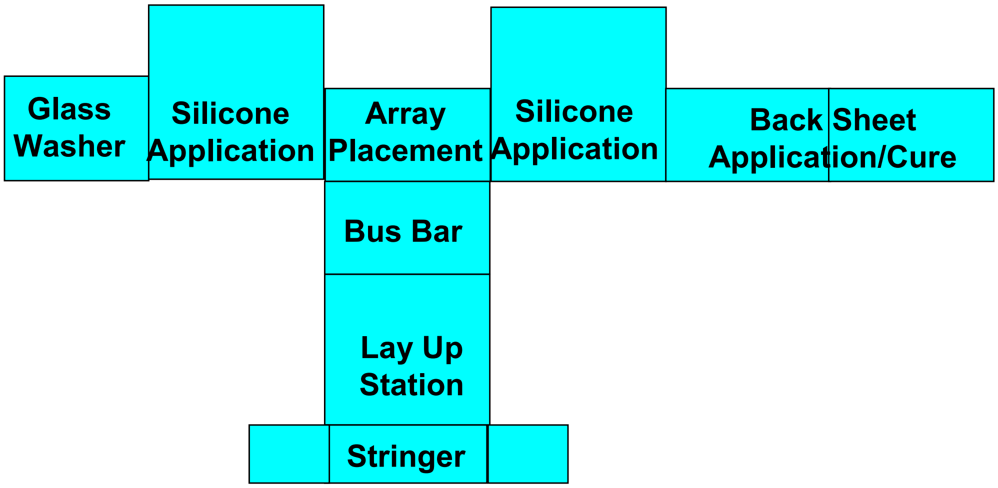


Figure 12 – Manufacturing Concept for Application of Prototype B Encapsulation

In order to handle multiple types and sizes of modules the pilot line was designed with a high degree of flexibility in mind. In addition, the line was designed to be a semi continuous operation with electronic communication capability, where capable, between pieces of equipment. The resulting pilot line consists of glass staging, silicone dispensing, array placement, back sheet placement and curing. Details of the unit operations equipment operation is provided below.
The picture in figure 13 shows the actual pilot line that has been installed at the Dow Corning Solar Application Center in Freeland, Michigan.

Figure 13 – Picture of the Pilot Line for Prototype B Application

Glass Staging, Silicone Application and Cure Equipment

In Phase II of the contract the design and specifications for the glass staging, dispensing and curing equipment were completed and sent to prospective suppliers. The glass staging equipment was designed as an inspection station to simulate the outlet of a glass washing operation. The two dispensing tools were designed to dispense a layer up to 0.5 mm thick over an area as large as 1.2mm x 1.8mm in less than 2 minutes. Cure equipment was designed for autonomous conveying and curing of laminates at temperatures up to 150 °C in less than 2 minutes. Quotes for staging, dispensing and curing equipment for the adhesive and encapsulant layers, and curing were then acquired, and the equipment was then ordered based on the cost and timeliness of delivery. Equipment demonstrations completed at the selected equipment supplier that revealed some necessary changes to meet desired process throughput targets. Final quotes were issued and purchase orders were then issued for this equipment with expected delivery in Q4 2007. Due to delays at the manufacturer and modifications to approve the equipment design and operation delivery was accomplished in Q1 2008. The equipment was installed in Q1 2008 and started up in Q2 2008. Optimization of dispense methods were conducted in preparation for crystalline matrices being sent from suppliers in Q2 and Q3 2008. This dispensing optimization focused on the dispense speed, coating thickness variation control and pattern accuracy. Curing optimization focused on optimizing cure conditions at less than 150 °C resulting in a bubble free product.

Cell/Array Placement Apparatus

Cell placement was determined to be a potential bottle neck for the increased throughput desired. A proprietary and potentially patentable prototype was designed to demonstrate a faster application method. The prototype was developed and used successfully in single cell and multiple cell coupons. A provisional patent was submitted on the design. A prototype capable of handling multiple strings or matrices was then designed. As with the dispensing equipment this apparatus was developed with the capability to handle multiple sizes of module designs as well as keeping unit operation times below a 2 minute maximum. In addition, the equipment was designed to simulate matrices supplied by standard stringing and lay up operations. Particular attention was paid to transporting without cell damage and precise locating and aligning the glass and cells. A quote for the apparatus was acquired, and a purchase order was initiated with anticipated delivery in Q4 2007. During a trip to the manufacturer to approve the design equipment changes were identified. The completion of these modifications changed the equipment delivery schedule to Q1 2008. The equipment was delivered, installed and started up in Q1 2008. The apparatus was used successfully with 32 cells by Q2 2008 and 72 cell matrices by Q3 2008. The equipment start up focused on the accurate placement of matrices without cell damage. Due to the novelty of the cell placement design, the prototype was highly manual in operation and depended heavily on mechanical alignment. Although this design met the specification of less than 2 minute unit operation, the equipment needs further development to automate the design, making it capable for manufacturing processes.

Back Sheet Placement Apparatus

In order to maintain the desired throughput, it was desired to have a continuous application of the back sheet. Research in this area revealed a device that could cut and apply the back sheet in line. A unit was found to be in storage at Spire Corporation and available for purchase. The back sheet placement apparatus was purchased from Spire. Since this had been in storage and needs some modification for use with the proposed encapsulation system it was sent to the manufacturer to be started up and modified. A trip to the manufacturer to approve the changes was completed in Q4 2007. Minor modifications were identified, and the equipment was scheduled to be shipped in Q1 2008. The equipment was delivered in Q1 2008 and installed and started up in Q2 2008. The equipment is being used when roll quantities of back sheet are being used for encapsulation trials of matrices. Optimization focuses on the alignment of the back sheet to be laminated, and hole size and location for the junction box leads.

Milestone	Description
M-3.15.2	Completion of protective-system trials, comparing the protection-system performance to previous evaluation results

Strategy

Adhesive Layer

Phase I results had shown that Prototype B (Liquid Silicone) was the best candidate to take forward for the adhesive layer primarily based on optical properties as shown in Figures 14 and 15. In addition, %QE analysis of silicone versus EVA was completed at NREL (Figure 16) which showed the significant gains in % QE in the Ultra Violet (UV) region.

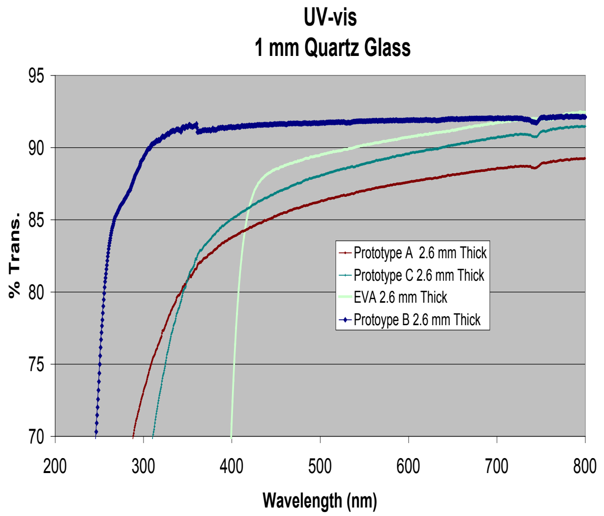
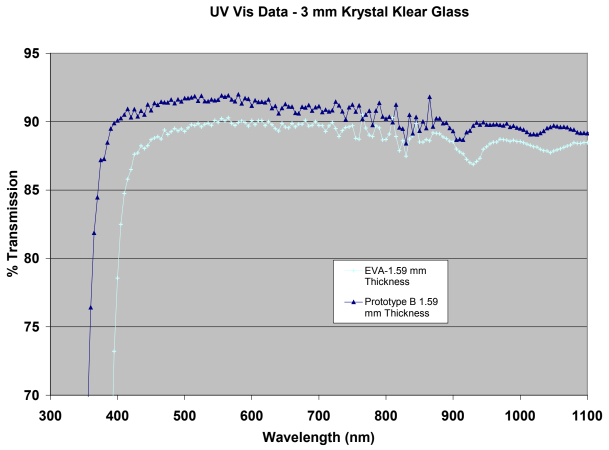
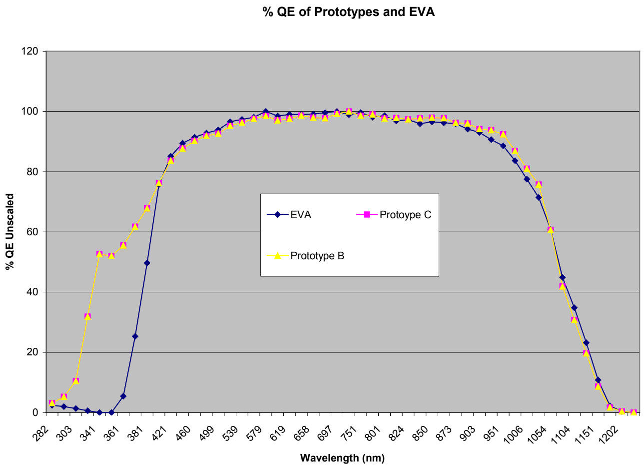


Figure 14 - Encapsulation Prototypes % Transmission Measured at Dow Corning Corporation



Courtesy Mike Kempe @ NREL

Figure 15 - Encapsulation Prototypes % Transmission Hemispherical Measurement at NREL



Courtesy of Tom Moriarty @ NREL

Figure 16 - %QE Analysis of Silicone and EVA encapsulated single-crystalline Cells

In Phase II the efficiency improvement of cells encapsulated with silicone over EVA was demonstrated using Supplier 3 cells as shown in Figure 17.

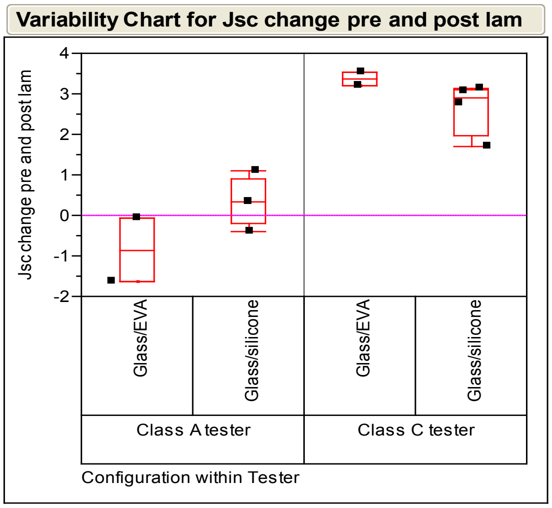


Figure 17 - Efficiency Gain Pre and Post Encapsulation vs. IV Tester

As shown in Figure 17 the demonstration of the improved Isc response required the proper IV testing equipment. This is due to the fact that most AM1.5 cell testers are designed to filter out the wavelengths below 400 nm. As can be noted in Figures 1, 2 and 3 a significant portion of the efficiency benefit for silicones are realized at wavelengths below 400 nm. This is a challenge to showing the efficiency improvements with silicone at the module level. Until a Sun Simulator is developed to include a comparison of EVA and silicone encapsulated modules in a multi module array will need to be done in direct sunlight to quantify any gains in efficiency or power output.

Encapsulant Layer

Prototypes B & C (Thermoplastic Copolymer) were chosen for the encapsulant layer due the options for application methods and cure system/speed (Figure 18) that allow for the potential of increased throughput and the elimination of traditional laminator processing.

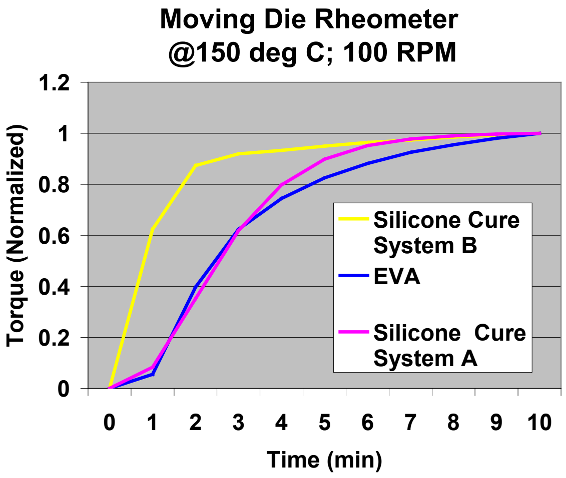


Figure 18 - Cure Rate vs. Cure System

As a result of the choices for the adhesive and encapsulant layers two encapsulation concepts, shown in Figure 19, were then developed.

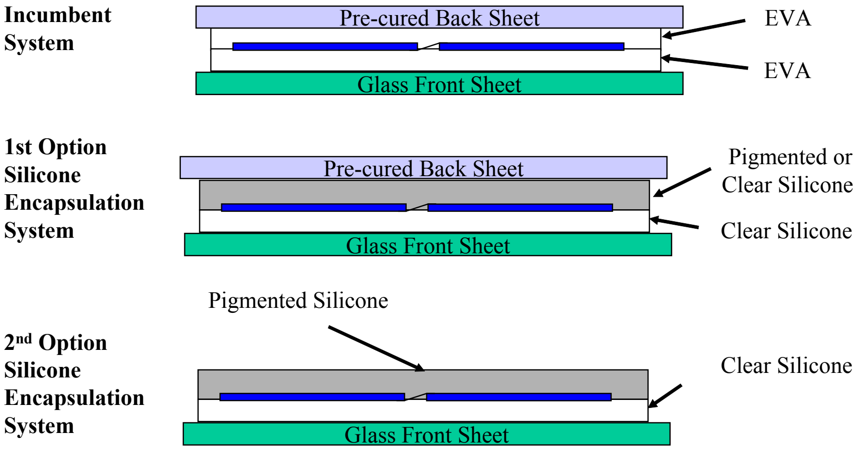


Figure 19 – Encapsulation Concepts

The first option primarily targeted liquid silicone (Prototype B) as the encapsulant and adhesive layers. The second option primarily targeted Prototype B for the adhesive layer and a copolymer (Prototype C) in sheet form as the encapsulant layer. The potential to use Prototype C depended heavily on the economic evaluation. It was theorized that the use of prototype C would require the elimination of the back sheet to allow for economic benefit. Attempts to eliminate the back sheet did not result favorably due to the lack of protection during cut test analysis without a prohibitively thick encapsulant layer. This discovery eliminated prototype C a viable material for option 2.

These options were evaluated in Phase II by evaluating encapsulating cells then exposing the cells to Humidity Freeze (HF) Cycling as a screening test. Options that passed the HF screen then would be then subjected to industry standard testing of 1000 hrs 85 °C/85 %RH, 200 Thermal Cycles (TC) and 420 hrs UV/50 TC/10 HF Cycles for final selection. The samples were evaluated for visual defects and characterized at the supplier for changes in efficiency or using a

Spire SPI 240 AL Sun Simulator at Dow Corning for change in performance before and after aging conditions testing.

Another key factor used for the prototype selection was based on economic evaluation of formulation options to ensure the cost of the material would achieve the goal of 25% reduction of $/Wp. This analysis not only focused on material usage and cost, but utilized a Cost of Ownership Model that emphasized gains from increased cell efficiency, and production throughput.

Task Results

The encapsulation system development during Phase I and II resulted in the concepts depicted in Figure 20.

1st Option - Encapsulation

A two layer model (1st Option) using silicone adhesive and encapsulant layers and pre-cured back sheet are the primary focus. The two layers are based on a curable liquid silicone two part formulations

These formulations were used to assemble 4 cell strings and subjected to Humidity Freeze Cycling as a screening exercise. Visual observation of the screening samples revealed some defects in the adhesive layer under the bus bars and where the tabbing is interconnected at the edge of the cells as well as some delamination of the back sheet was observed around the perimeter after 33 cycles of Humidity Freeze. This is shown in the picture in Figure 21.

Figure 21 – Back Sheet Delamination after Thirty Three Humidity Freeze Cycles

Formulation optimization was pursued to improve these issues. This exercise focused primarily on the adhesion of the encapsulant to the glass and back sheets.

When the four-cell string had passed Humidity Freeze Cycling, six more strings were constructed and subjected to industry standard testing of 1,000 hours 85 °C and 85 %RH, 200 TC and 420 hrs UV/50 TC/10 HF. The results of the IV testing are shown in the Figure 22.

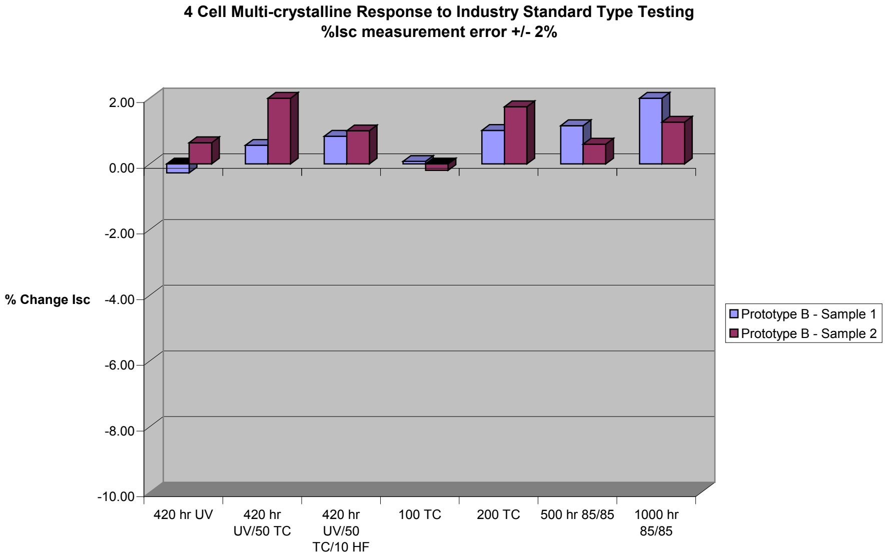


Figure 22 – Mutlicrystalline cell IV Response to Industry Standard Testing

As with the four-cell string humidity freeze screening, the IV results were satisfactory with all three types of the testing. Similarly, visual observation of the samples revealed defects in the adhesive layer under the bus bars and where the tabbing is interconnected at the edge of the cells. And the 85 °C/85 %RH sample showed some adhesion issues with the silicone and the back sheet was around the perimeter.

To understand the impact of the visual defects the four-cell string samples were put back into the environmental chambers and continued to be aged well beyond IEC or UL standards. The results of which are quite positive with minimal degradation of Pmax as shown graphically in Figure 23.

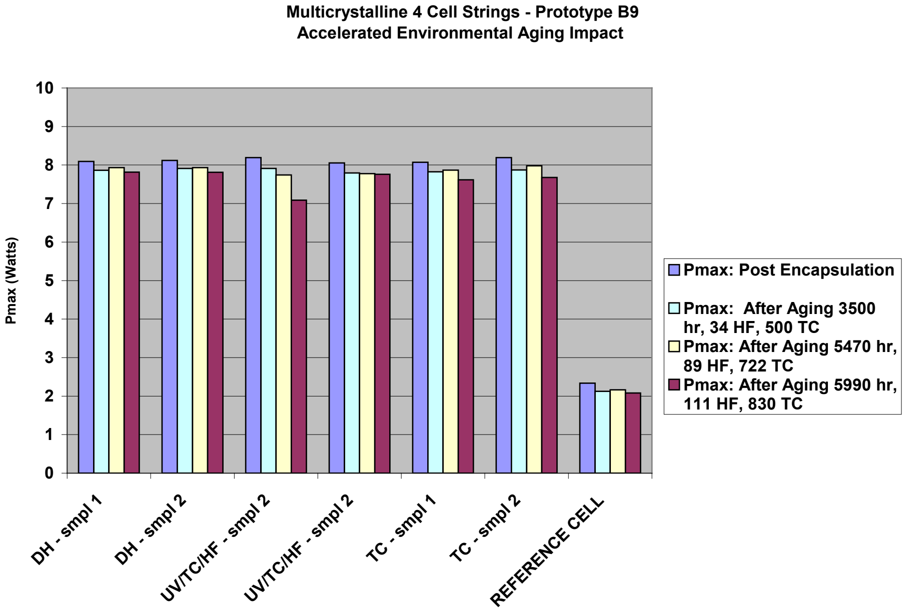


Figure 23 - Mutlicrystalline cell IV Response to Extended Industry Standard Testing

To improve the visual observation defect issues formulation optimization was pursued. These experiments were completed with single cell constructs. These constructs were placed in Humidity Freeze Cycling, and were observed at regular intervals for changes in appearance. The physical observations indicated that visual defects were resolved at a single cell level.

In parallel to the above experiments the adhesion promoter packages were screened in the encapsulant layer formulations. Samples have been tested by preparing samples for 180 degree (angle) peel testing. The test method schematic is shown in Figure 24.

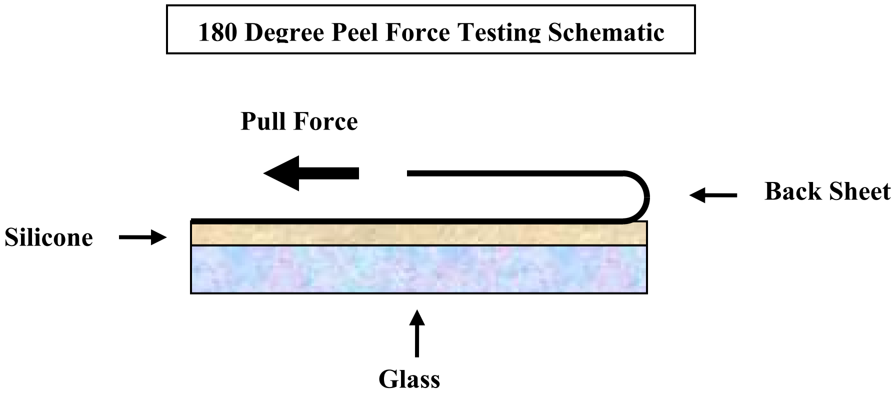


Figure 24 – 180 Degree Peel Adhesion Schematic Representation

These samples were tested for initial adhesion and tested at regular intervals after aging at room temperature and 85 °C/85 %RH conditions. The result of this testing is shown graphically in Figure 25.

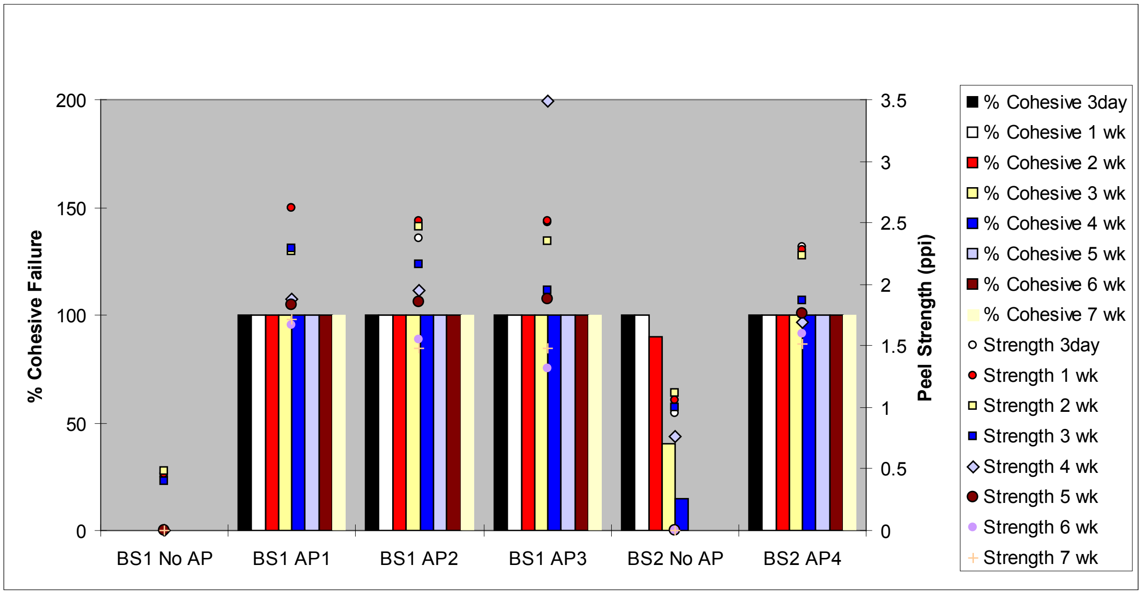


Figure 25 – Adhesion by 180 Degree Peel Testing of Back Sheet w/ Prototype B9 at 85 °C/85 %RH Aging

Several samples performed well in this testing. AP4 was chosen to be used in future formulation development and scale up. Cells and four-cell strings were then encapsulated using prototype B9 and AP4. These were then submitted for the Damp Heat, Thermal Cycling, and UV/Thermal Cycling /Humidity Freeze aging. IV performance, discussed below, and visual observations of the samples confirmed the improvement in adhesion performance with no delamination of back sheets in the samples tested in environmental aging. As a result of the adhesion the testing of the cells and mini strings the B9 formulation with AP4 was targeted to be used on the 72 cell arrays being shipped from supplier 1 and 2 as discussed under Task 17.

Supplier 1

In phase II an issue with low temperature cycling was discovered while applying the option 1 encapsulation solution to supplier 1 cells. A root cause analysis of the issue was pursued for the first several months of Phase III.

The root cause analysis continued with an evaluation of the back sheets. The results are shown in Figure 26.

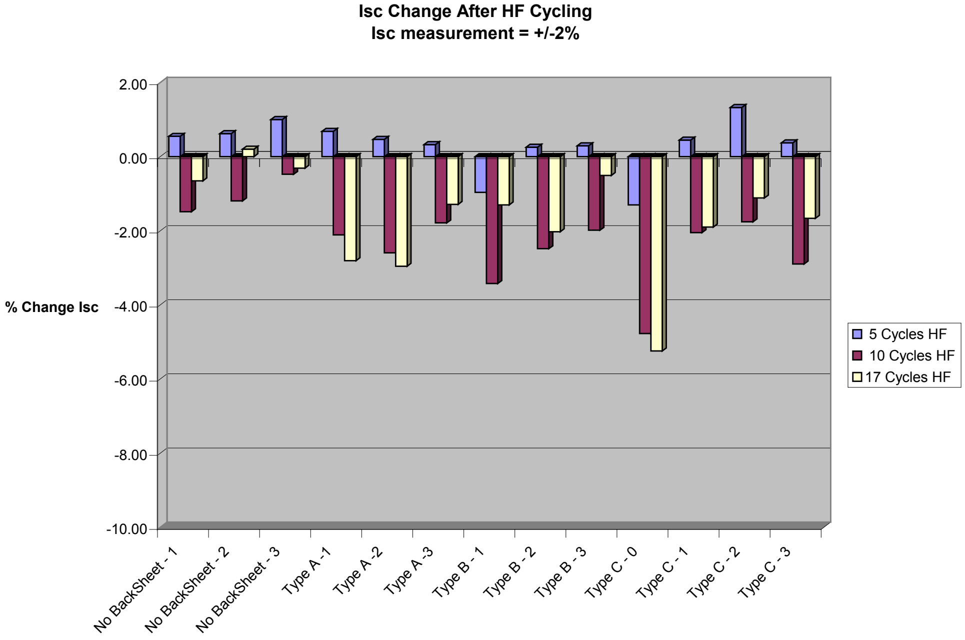


Figure 26 – Back Sheet Comparisons by Response to Humidity Freeze Cycling

This data seemed to indicate the best results are achieved by not using a back sheet. This was seen as a clue to the root cause of the issue. The issue could be due to higher stress when the back sheet is present or trapping of moisture. Experiments to further investigate these theories as potential root causes were completed.

An experiment was completed to test the stress induced from different back sheets exposed to thermal cycling to minimize the effects of moisture. The data shown in the Figure 27 indicated that the stress induced from temperature cycling without significant moisture present did not cause degradation at up to 100 cycles.

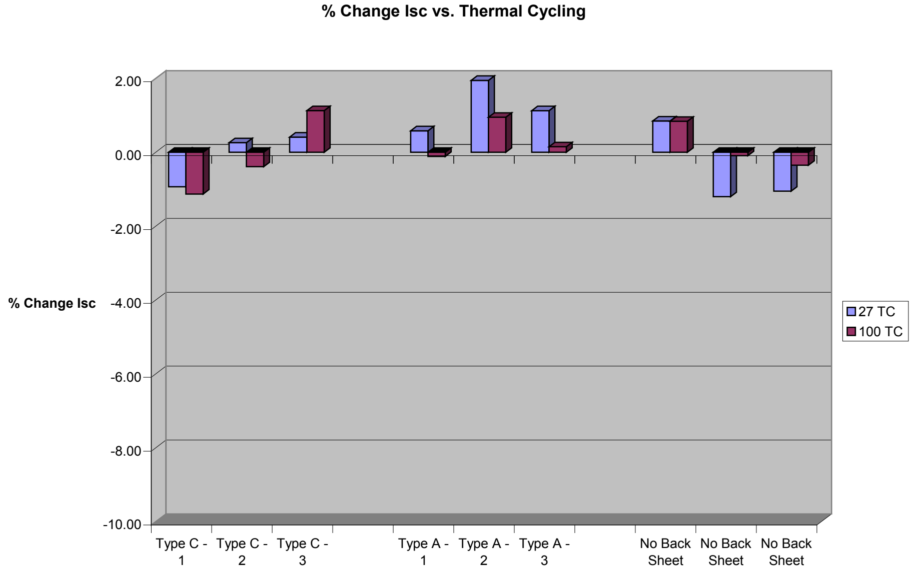


Figure 27 – Back Sheet Comparison by Response to Thermal Cycling

Another set of experiments was started to evaluate the effects of moisture by preparing cells with a moisture impermeable edge seal with a glass back sheet. These cells were characterized at the supplier and were exposed to Humidity Freeze conditions. The results from the first 10 cycles are shown in Figure 28.

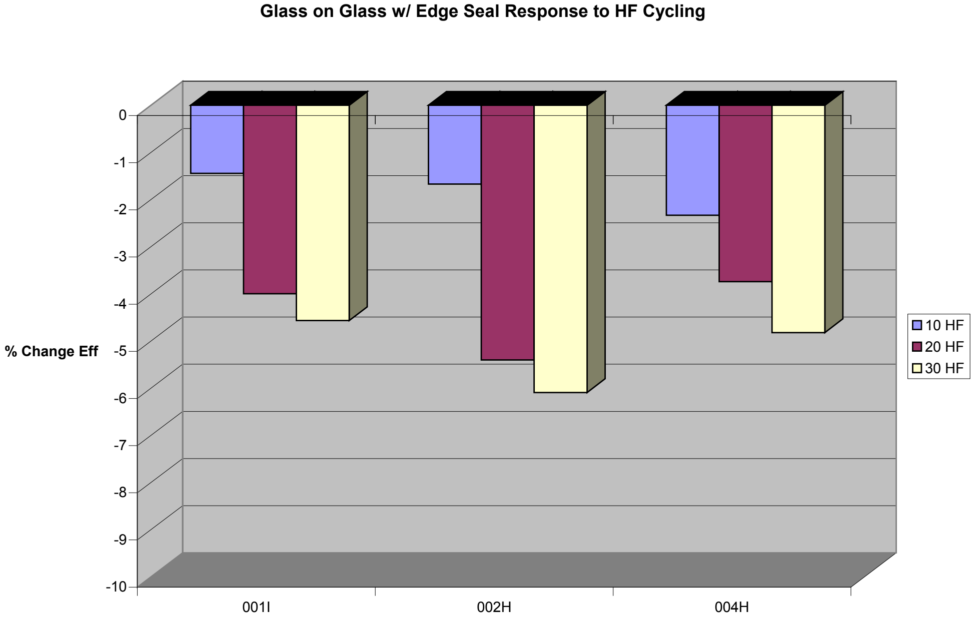


Figure 28 – Effect of Moisture Barrier on Humidity Freeze Cycling

The results were positive with good response out to 30 cycles. In addition, repeats of glass on glass with and without the edge seal were prepared to confirm the results above. The data in the in Figure 29 showed that the samples without edge bead fail within 10 cycles, and those with edge bead do not. Sample Edge Bead 3 seemed as though it may be failing. Inspection of the cell indicated a potential path for moisture through the edge bead.

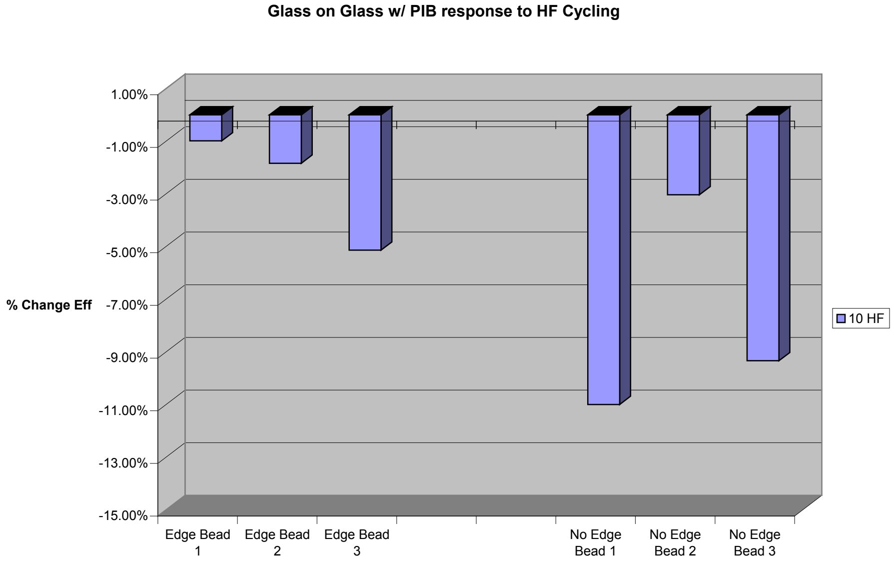


Figure 29 – Cell Response to Humidity Freeze Cycling With and Without PIB Edge Bead

Another experiment to confirm the results of the edge bead test using cells prepared with a special layer was completed. This was conducted with 3 cell strings characterized at the supplier before and after HF cycling. The results of the testing are shown in Figure 30.

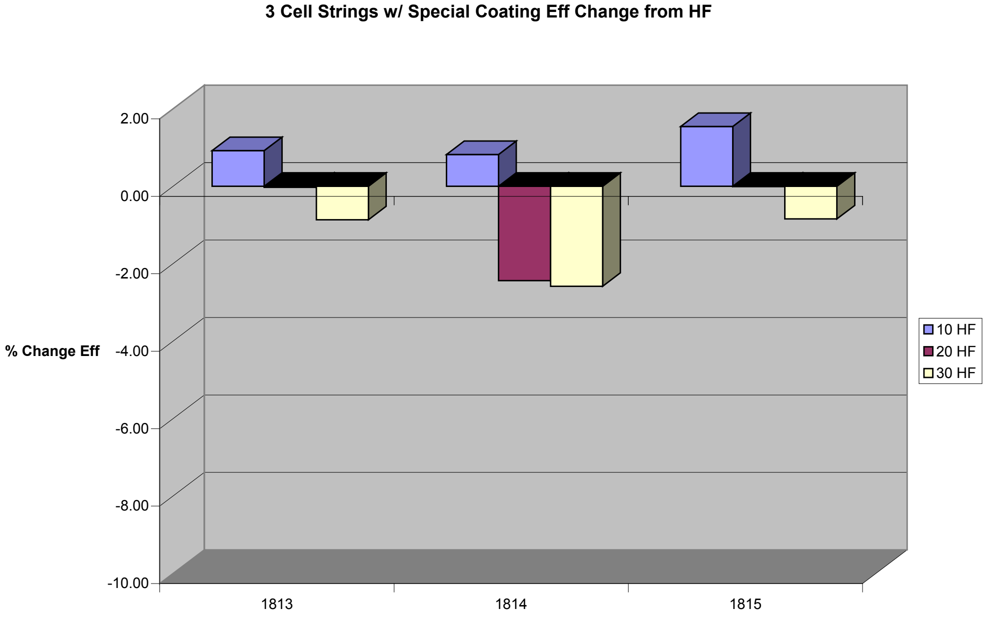


Figure 30 – Coated Cell Response to Humidity Freeze Cycling

The results out to 30 cycles showed a strong indication that the coating works effectively with Prototype B.

With the positive results from the above experiments a new set of 3 cell strings with special coating was prepared and subjected to the 420 hr UV/50 TC/10 HF, 200 TC & 1000 hr 85%RH/85 °C testing sequences. Testing of the cells has shown no significant degradation of cell performance as shown graphically Figure 31.

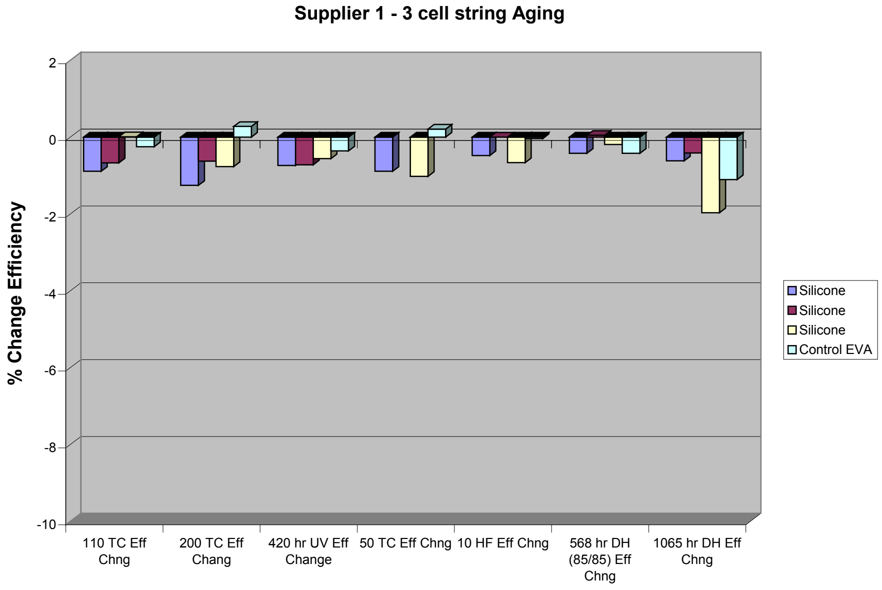


Figure 31 – Three Cell Strings Response to Standard Industry Testing

All aging conditions showed acceptable levels of degradation. These samples continued to be aged, and monitored periodically. The results of the continued aging can be seen in the graphs in Figures 32, 33 and 34.

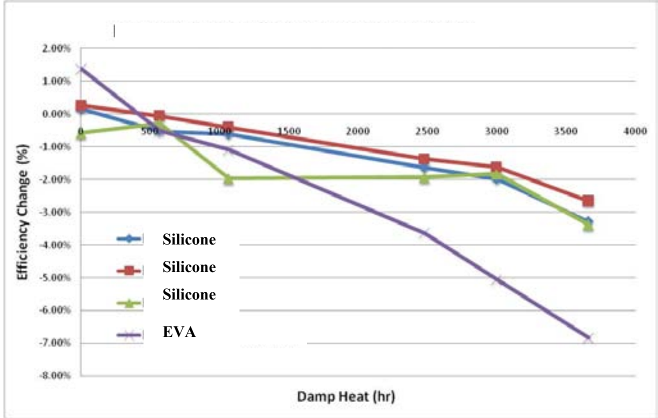


Figure 32 – Three Cell String IV Response to Extended Damp Heat Conditions

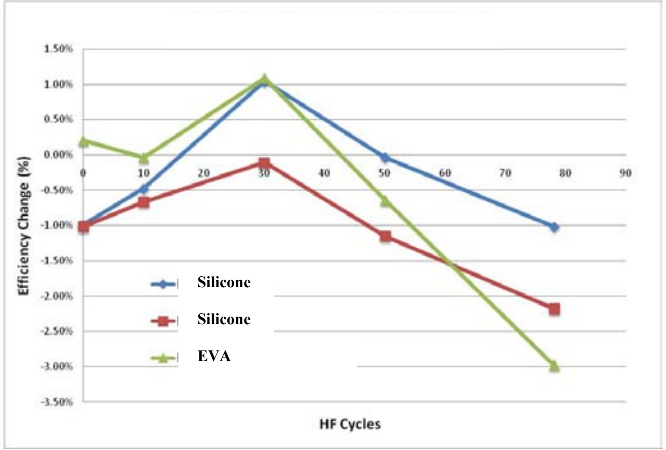


Figure 33 – Three Cell String IV Response to Extended Humidity Freeze Conditions

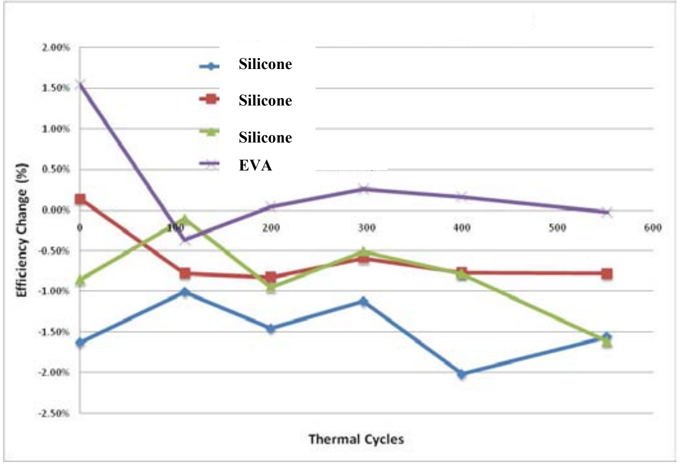


Figure 34 – Three Cell String IV Response to Extended Thermal Cycling Conditions

According to this data, the Damp Heat condition at 2,500 hours, and at 3,600 hours indicate a more significant loss of power for the EVA encapsulated module where as the silicone encapsulated modules seem to be maintaining. The power degradation appears to be starting in the EVA encapsulated module at 78 Humidity Freeze Cycles as well. However no degradation can be seen in either encapsulation material out to 550 cycles. These modules continue to be aged.

2nd Option – Encapsulation

In order to achieve a lower cost encapsulation method the elimination of the back sheet is a potential route to reduce cost. In addition, work done with silicones and no back sheet has shown promise in protecting amorphous silicon mini-modules during damp heat conditions. This is believed to be a result of the inherent ability for silicone to “breath” coupled with low moisture solubility, low ionic content and good adhesion. These properties have proven successful in protecting electronic devices and should be applicable to PV modules.

Previous attempts to eliminate the back sheet have met with failure for various reasons. The lack of thickness control and cut test resistance have been two major reasons observed when trying to use this approach with silicones for this project. Study of these issues has continued to develop a method of back sheet elimination. A proprietary and potentially patentable approach has been discovered and will be pursued for the rest of this contract.

To maximize the potential of this approach a design of experiment was performed to optimize the formulation based on material rheology, cured properties and cut test response. The optimized formula will be applied to cells for encapsulation method optimization and response to aging studies.

Two formulations from the optimization were used to encapsulate single cells. The appearance of these cells was not acceptable due to uneven coating which is believed to be unacceptable for cut resistance. The formulation and application techniques are being reevaluated to improve upon this issue. Formulations from this reevaluation have been prepared and were used in encapsulation trials. The test showed what is believed to be acceptable cut resistance, but a current leakage test needs to be established to evaluate the cut strength. Equipment for this test is being purchased and methods for completing single cell testing are being developed.

Task 16, Evaluation of Protection System with Thin-Film PV on Flexible Substrate

This task shall evaluate the application of encapsulation and barrier materials previously developed for application on thin film PV devices on flexible substrates. Thin-film PV on flexible substrates will be purchased. The protection system developed to date shall be applied and be evaluated using the test methods established under Task 5 as well as performing characterization tests. The expected result of this task includes the materials and processes for a protection system application to a broader range of PV technology, including additional flexible, thin-film technologies.

Milestone	Description
M-3.16.1	Demonstration of the protection system developed in Task 14 on thin-film PV on flexible substrate cells in order to verify applicability of system to a broader range of thin-film PV technology

Strategy

The plan for this task was to use the protection system for the crystalline application directly on flexible substrates. In phase II several suppliers were targeted and were approached for this activity. Unfortunately, an agreeable method of testing was not able to be reached. This is mainly due to customers that were either not interested in working with a silicone solution, not willing to ship samples outside their facility, or not willing to change their design to accommodate a liquid silicone solution. Discussion of this issue with NREL has resulted in an option to seek out flexible thin film cells from an NREL subcontractor.

The team pursued contacts at flexible thin film suppliers in an effort to gain access to at least a small supply of flexible, thin-film PV for evaluation of the encapsulation system on flexible cells. Contact was made at each organization. NDAs were established and a Statement of Work was submitted to both potential suppliers. One supplier agreed to the work as long as all samples were sent back to their facility for testing.

Task Results

Twenty cells were received from the supplier. The first ten were used for development and practice of the application techniques. The second ten were used for the actual test samples. Both sets of cells were characterized by IV analysis at the supplier prior to shipment. All of the samples were encapsulated using the adhesive and encapsulant layers using two configurations. The first configuration used a clear fluoropolymer front sheet and an opaque white polyvinylfluoride laminate back sheet. The second configuration used a glass front sheet and an opaque white polyvinylfluoride laminate back sheet. As of this writing, the encapsulated cells were shipped back to the supplier for visual inspection and IV analysis after encapsulation, and subsequent environmental aging in Damp Heat, Thermal Cycle and UV/Thermal Cycle/Humidity Freeze conditions. The data from these tests will be sent by the supplier at the intervals of intermediate testing.

Task 17, Module Fabrication

The Subcontractor shall apply protective coating systems to full-size modules fabricated using crystalline Si cells on glass. The Subcontractor shall demonstrate the scaled-up material production and application process for the newly developed protection system for use in fabricating full-size, crystalline Si modules. Through a lower-tier subcontract, the Subcontractor shall ensure that a lower-tier subcontractor fabricate crystalline Si cells for use in the modules. The Subcontractor, in collaboration with a lower-tier subcontractor, shall assemble and test the complete modules prior to delivery to NREL. The Subcontractor shall characterize the performance of the protection system utilizing standard evaluation techniques. The expected result of this task is the fabrication of ten, crystalline Si PV modules.

Milestone	Description
M-3.17.1	Completion of full-size, single-crystalline Si modules and multi-crystalline Si mini-modules utilizing the protection system developed

Strategy

The pilot line was installed and started up in Q1 2008. Optimization and encapsulation trials began in Q2 and continue to be run through Q4.

The pilot line was designed to handle matrices up to 125 mm x 72 cell or 156 mm x 60 cell modules. It was designed without a stringing operation specifically to allow the testing of the encapsulation system with the standard stringing operations presently in use at the suppliers. This required shipment of strings or matrices prepared on the suppliers stringing and lay up operations. Handling, packaging and shipping of the matrices without damage was a hurdle to overcome. Specialized packaging was designed and constructed to allow damage free shipment and compatibility with the cell placement apparatus operation. Once this packaging was successfully developed matrices were shipped from the suppliers for testing on the pilot line.

In addition to the matrices used to make the deliverable goal, extra matrices for optimization of the handling and alignment operations in the cell placement apparatus were included in the planning.

In addition, glass and back sheet materials were also sent from the matrix suppliers. Both materials were shipped in standard containers. The back sheet was supplied in roll form long enough in length for use on the continuous back sheet placement tool. Glass would be cleaned by washing with water and soap and allowed to dry by air. A light wipe with IPA to increase drying rates would be employed prior to placing into the pilot line. Back sheet materials were typically used as is from the roll.

Finished laminates of acceptable quality would be characterized by IV testing at Dow Corning using a Spire 4600 Sun Simulator. These would be sent to the respective suppliers for IV characterization and testing.

Task Results

Supplier 1

As of this report both 125 mm x 32 cell and 125 mm x 72 cell matrices have been received from Supplier 1.

Pilot Line trials began in Q2 2008 using 32 cell arrays sent from Supplier 1. Most of these modules were used to optimize the cell placement handling and alignment accuracy. In addition, the optimization of silicone thickness and dispense patterning of the adhesive and encapsulant layers was performed to ensure complete bubble free encapsulation. Several modules were successfully completed with minimal defects such as bubbles. Because of damage sustained during handling and the poor alignment most of the modules were not characterized. Modules of sufficient visual quality were sent to NREL as a part of this task deliverable.

Pilot line trials for 72 cell matrices from supplier 1 were encapsulated in Q4 2008. As with the 32 cell modules matrices were used for practice in processing for alignment and handling. Due to the optimization of the handling of the 32 cell modules fewer matrices were damaged. The remaining matrices were successfully laminated. These laminates were IV tested at Dow Corning. The data showed normal functionality. The laminates were sent to the supplier for characterization and testing compared to EVA encapsulated modules. Sun Simulator IV characterization data at the supplier confirmed the data on the Dow Corning Sun Simulator. The results will not be reported here as it is proprietary information to the supplier.

Supplier 2

Plans for the delivery of 72 matrices from the supplier 2 were made in Q2 2008. Packaging for 72 cell matrices was prepared and shipped to the supplier in early Q3 2008. The matrices were received in late Q3 2008. Encapsulation trials on the pilot line were run in Q3 and Q4 2008. Early trials encountered issues with cell handling and alignment. This was primarily due to the transfer of modules from the shipping package to the cell placement apparatus, and the alignment of the cell strings after transfer. This was overcome by better techniques and attention to realignment of the strings prior to placing the matrix into the cell placement apparatus.

Similar to supplier 1 trials, several matrices were used for practice in processing for matrix alignment and handling. Two matrices were then successfully encapsulated utilizing the prototype B formulations described in Task 15. A picture of a module is presented in figure 35. The resulting laminates were shipped to supplier 2 to evaluate compatibility with framing and junction box application. Once this testing was completed the remaining matrices were encapsulated and shipped to supplier 2 for characterization and environmental aging testing. In addition, several single cell coupons were sent to supplier 2 for accelerated UV aging testing. These will be aged to simulate 20 years of UV exposure and tested at the supplier. Due to the extended length of this aging the results from this testing will not be available for this report.

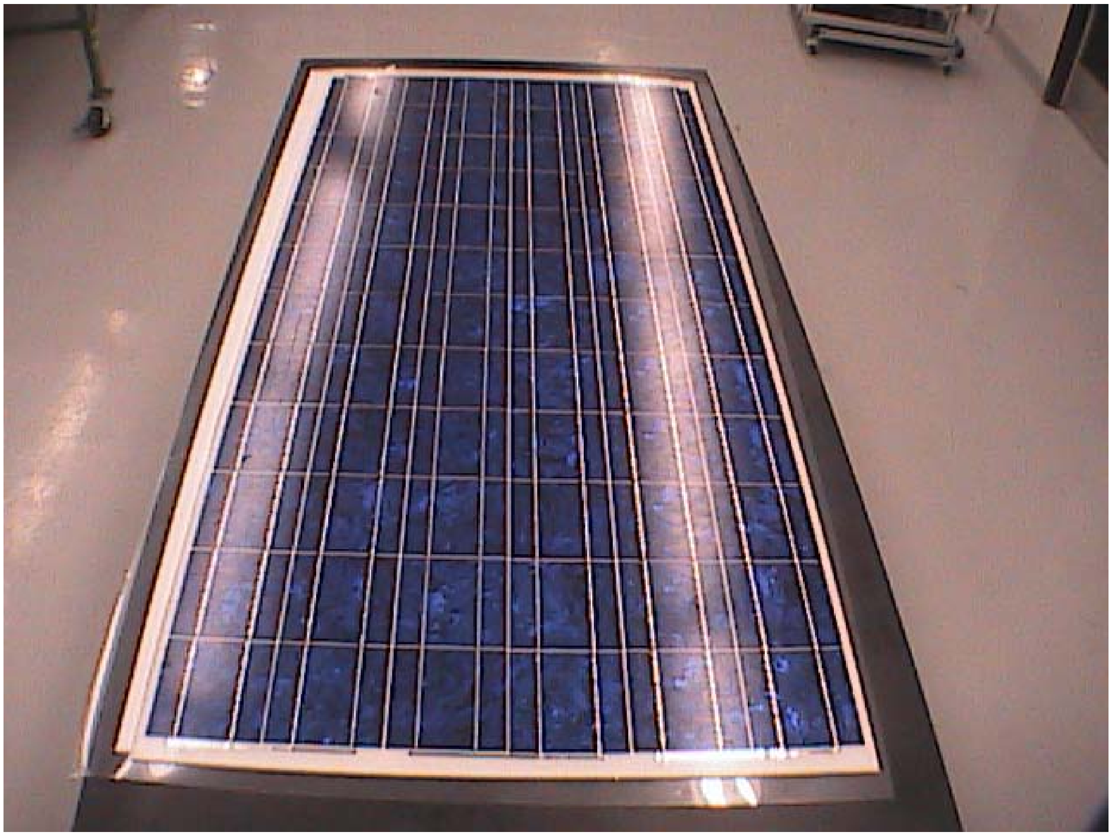


Figure 35– Silicone encapsulated module prior to shipment.

PHASE III SUMMARY

The work in Phase III was based on the development and optimization of prototype formulations in Phases I & II using single cell and multi cell strings that were subjected to IEC and UL testing standards for simulated environmental aging. In Phase III the prototype formulations were further optimized by improving adhesion to substrates. In addition to the formulation optimization, application methods were developed and optimized for successful encapsulation using liquid-based materials. The application methods developed included methods to maximize process throughput and minimize silicone usage to help reduce the cost of modules on per peak watt basis. In addition, evaluation of the percent transmittance of silicone and EVA showed a potential benefit for solar cell efficiency. This was supported by the analysis of cell quantum efficiencies after encapsulation with EVA and silicone. Furthermore the efficiency improvement was successfully measured on cells encapsulated with silicone and EVA. This work will be further investigated by comparing full size module power output in side by side outdoor testing.

The optimized prototype B formulations and application method were also applied to rigid thin film PV technologies. Extended aging testing in Damp Heat or 85 °C/85 %RH has shown minimal power degradation of 30 x 30 cm modules from Supplier 2. Further testing is planned for full size modules beyond this contract. When encapsulating rigid thin film modules from supplier 1, variable results have been seen when subjected to environmental aging testing. Further evaluation of these modules will continue beyond this contract.

The optimized prototype B formulations and application methods have been applied to flexible thin film PV cells. These cells are under evaluation at the cell supplier. A decision to pursue this encapsulation system with the flexible will be made by the supplier depending on the results of the evaluation.

As a result of successful encapsulation testing a pilot line to demonstrate the encapsulation method on modules up to 72 x 125 mm cells was designed in Phase II and installed and started up in Phase III. The pilot line has been used to successfully encapsulate crystalline matrices and rigid thin film modules with prototype B formulations. The full sized modules are being evaluated against testing standards at the suppliers or internally.

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14. ABSTRACT *(Maximum 200 Words)*

The overall objective of the research effort over its three-phase duration is to develop a reduced-cost, higher-throughput, improved-performance packaging solution for United States Photovoltaic ("PV") module manufacturers. The primary target of the work is to develop a packaging solution that will reduce the overall cost contribution of this component by a minimum of 25% relative to the conventional Ethyl Vinyl Acetate ("EVA")/ Poly vinyl fluoride ("PVF") batch lamination and will provide improved reliability for twenty-plus years of performance in the field. During the subcontract, Dow Corning shall formulate and optimize adhesive, encapsulant, and barrier materials for use with a broad range of current PV technologies. This effort is expected to result in improved performance encapsulation materials and the establishment of a pilot-scale, protection-system production line capable of processing full-size, single-crystalline Silicon PV modules.

15. SUBJECT TERMS
PV; high performance; packaging solution; low-cost; reliability, modules; manufacturer; crystalline silicon; ethyl vinyl acetate; poly vinyl fluoride;

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