

Final Technical Report

Recovery Act: Organic Coatings as Encapsulants for Low Cost, High Performance PV Modules

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Recipient: PPG Industries, Inc.

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Program Objective

The objective of this project was to evaluate the feasibility of utilizing PPG's commercial organic coatings systems as efficient, modernized encapsulants for low cost, high performance, thin film photovoltaic modules. Our hypothesis was that the combination of an anticorrosive coating with a more traditional barrier topcoat would mitigate many electrochemical processes that are now responsible for the significant portion of photovoltaic (PV) failures, thereby nullifying the extremely high moisture barrier requirements of currently used encapsulation technology.

Executive Summary

Nine commercially available metal primer coatings and six commercially available top coatings were selected for screening. Twenty-one different primer/top coat combinations were evaluated. The primer coatings were shown to be the major contributor to corrosion inhibition, adhesion, and barrier properties. Two primer coatings and one top coating were downselected for testing on specially-fabricated test modules.

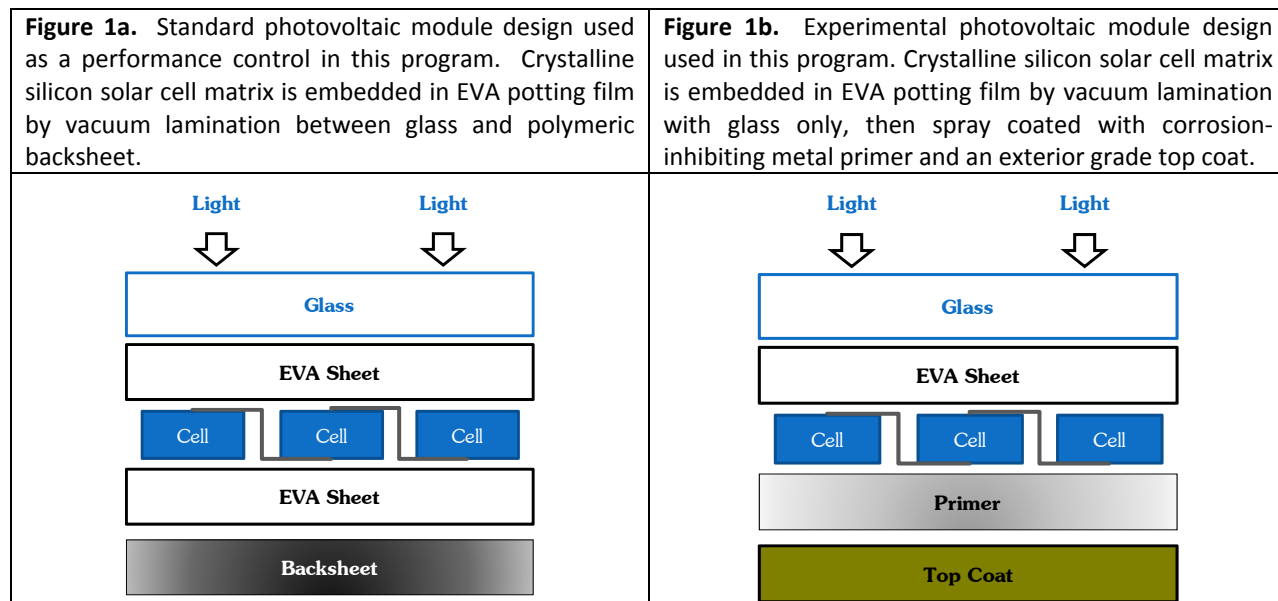
The coated test modules passed initial current leakage and insulation testing. Damp Heat testing of control modules showed visible corrosion to the bus bar metal, whereas the coated modules showed none. One of the primer/top coat combinations retained solar power performance after Damp Heat testing despite showing some delamination at the EVA/solar cell interface. Thermal Cycling and Humidity Freeze testing resulted in only one test module retaining its power performance. Failure modes depended on the particular primer/top coating combination used.

Overall, this study demonstrated that a relatively thin primer/top coating has the potential to replace the potting film and backsheet in crystalline silicon-based photovoltaic modules. Positive signals were received from commercially available coatings developed for applications having performance requirements different from those required for photovoltaic modules. It is likely that future work to redesign and customize these coatings would result in a coating system meeting the requirements for photovoltaic module encapsulation.

Detailed Summary

The Evaluation of Organic Coatings as Encapsulants for Low Cost, High Performance Photovoltaic Modules (OCE-PHOTOVOLTAIC MODULE) project was initiated in the fourth quarter of 2009 to determine if the use of a corrosion inhibiting primer coating and an exterior-durable topcoat could outperform and lower the cost of conventional potting film and back



sheet technologies that currently are used commercially for encapsulation in photovoltaic modules. We explored an experimental photovoltaic module design in which a crystalline silicon solar cell matrix was embedded into a potting film (EVA) by lamination to a glass superstrate, and then coated on the back with a corrosion inhibiting metal primer and an exterior durable top coating (Figure 1b). Performance of photovoltaic modules from this experimental design were compared to standard-design photovoltaic modules prepared using vacuum lamination of encapsulating films (Figure 1a).



Significant results from this program include:

- In Phase 1 of the program, 9 commercially available metal primer coatings and 6 commercially available topcoats were evaluated in 21 different coating design configurations. Through these evaluations, we were able to determine that:
 - The primer is the major contributor to corrosion inhibition, adhesion, and barrier properties.
 - Coating cure temperatures and coating fillers could be used to improve the moisture vapor barrier properties of these coatings.
 - In a standard photovoltaic module design, EVA potting film is highly permeable and the backsheet serves as both a moisture barrier and protective layer. In this primer-topcoat design, the coating on the cell and interconnects provides the barrier properties and the topcoat is protective.

- In Phase 2 of the program, 2 primer/topcoat configurations were down-selected from Phase 1 for evaluation according to IEC 61215 procedures with our single-solar-cell mini-module experimental test-vehicle.
 - Our freshly prepared, primer/top-coated mini-modules showed little or no leakage current and passed the Insulation Test IEC 61215 10.3.
 - After Damp Heat Test IEC 61215 10.13,
 - Mini-modules made by standard photovoltaic module design using vacuum lamination of encapsulating films showed visible brown corrosion on bus bar metal (Figure 2a) while this corrosion did not appear in mini-modules prepared using the experimental primer/top-coating systems (Figure 2b).
 - One primer/topcoat configuration retained solar power performance similar to the standard photovoltaic module design, despite showing some delamination at the EVA/solar-cell interface.
 - After Thermal Cycling IEC 61215 10.11 and Humidity Freeze IEC61215 10.12 only one mini-module from our experimental design retained its power performance. Failure modes included cracking and delamination. Delamination occurred along the metal tabs on the solar cell for one primer/topcoat configuration, but on the EVA/solar-cell interface for the other primer/topcoat configuration.

<p>Figure 2a. Busbar in standard mini-module made by lamination of solar cell as shown in Figure 1a. Corrosion is visible after damp heat testing.</p>	<p>Figure 2b. Busbar in experimental mini-module made by coating solar cell as shown in Figure 1b. No corrosion is visible after damp heat testing.</p>
	

The experimental results from this current program indicate that a relatively thin primer/topcoat configuration does have the potential to replace potting film and backsheets in crystalline silicon-based photovoltaic modules. In addition, corrosion-inhibiting primers offer the potential to improve photovoltaic module durability relative to lamination films. However, these coatings will require redesign and customization in order to meet all the requirements for photovoltaic module encapsulation. These requirements appear well within the performance

space of industrially viable organic coating technology, and further product development seems warranted.

Encapsulating a solar cell matrix within potting film by vacuum lamination between a glass superstrate and a protective backsheet (or glass substrate) remains a major process bottleneck in photovoltaic module manufacturing. Throughput is limited by the pump-down and thermal curing cycles required for laminating each module. Even with modern lamination equipment being able to accommodate more than one module at a time, photovoltaic module manufacturing currently is still limited to 10 to 25 Megawatts per production line per annum. Plant expansion requires a linear scale-up by adding more laminating lines. Results from the current program indicate that a continuous coating process has the potential to replace vacuum lamination and increase line production by an order of magnitude.

Photovoltaic module encapsulation of crystalline silicon solar cells using silicone-based liquids that were applied as coatings were evaluated as part of the US Government funded Flat Plate Solar Array Project that was managed by the Jet Propulsion Laboratory through 1986. Although results were promising, the high cost of silicone-based resins remained prohibitive. Results from the current program indicate that more conventional lower cost organic coatings have the potential to replace silicon-based resins.

Similarly, higher throughput and cost advantages for encapsulating thin film solar modules by using liquid resin were reported. However, this reported photovoltaic module design still relied on a protective backsheet laminated over the cured encapsulating resin. Results from the current program indicate that an exterior grade coating has the potential to eliminate the need for a backsheet.

Corrosion prevention in photovoltaic modules also was addressed as early as the Flat Plate Solar Array Project. Adhesion promoters were found to reduce moisture ingress into the photovoltaic module, and inhibit corrosion of aluminum metal on the back of the crystalline silicon solar cells. For the most part, photovoltaic module design has continued to rely on low water and oxygen permeability to delay the onset of metal corrosion. This current work indicates that metal primers have the potential to inhibit corrosion of circuit bus-bars and interconnects. Eliminating this type of corrosion could prevent certain types of open-circuit and short-circuit failure modes and improve photovoltaic module durability.

Producing electricity by photovoltaic modules holds the promise of extending the energy reserves of the United States of America. For instance, photovoltaic modules currently have an estimated *energy* payback of about 2 years. If energy from conventional resources like coal were used to make photovoltaic modules, and modules continued to produce energy for 20 to 30 years, energy production from this coal would be extended by an order of magnitude. That

is, a 10 year coal supply could extend to 100 years. Reducing photovoltaic module manufacturing costs and extending productive life of these modules is critically important for reducing the total cost-of-ownership for solar energy and shrinking the cost payback period. Results acquired during this program lend technical credence to the possibility that, with further development, module manufacturing could be transformed from its current process, now some 30 years old, to a higher throughput, lower cost continuous process using modern in-line coating technology.

By garnering funding from the Department of Energy for this program, PPG Industries enjoyed sufficient incentive to revisit the concept of coating-based encapsulation. Advantages as well as challenges associated with transforming the current photovoltaic manufacturing process to coating-based encapsulation were identified. Sufficient advantages were demonstrated to warrant continued development efforts in this technology by PPG Industries.

Comparison of Actual Accomplishments to Project Goals and Objectives

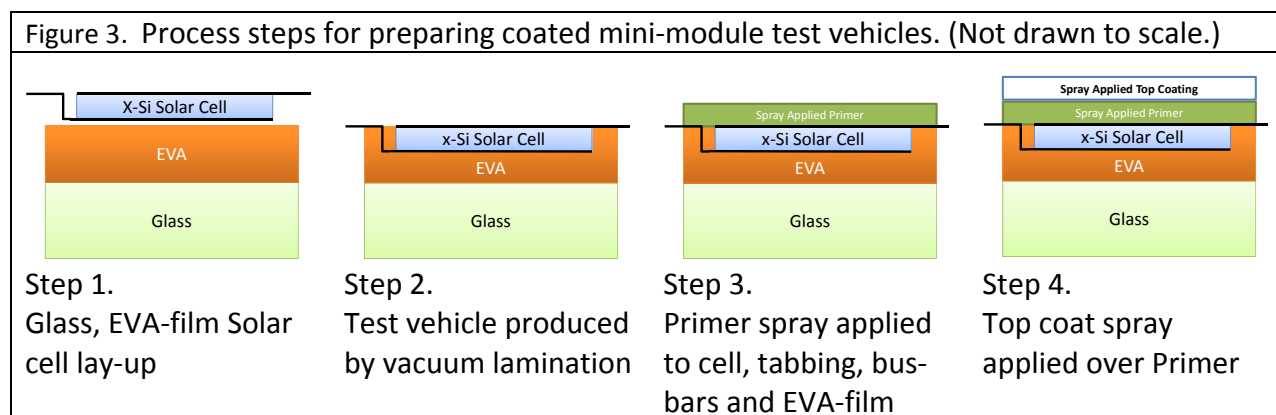
The primary objective of this program was to evaluate whether or not a coating configuration comprised of a corrosion inhibiting primer and an exterior durable topcoat could adequately protect the solar cell matrix of the photovoltaic module. Results accomplished during the course of this project demonstrated that a primer/topcoat configuration did protect metal bus-bars from corrosion during damp heat testing of single-solar-cell mini-module test vehicles. Mini-modules that were prepared using standard vacuum lamination technology with an EVA-potting film and Tedlar backsheet failed to prevent this type of bus-bar corrosion.

These coating configurations were also shown to provide adequate insulation in the mini-modules despite having considerably thinner dry-film thickness than modules that were prepared by conventional vacuum lamination with preformed films. However, the mechanical properties of these commercially-available primer/topcoat systems were inadequate for passing rigorous accelerated exposure tests, like thermal cycling and humidity freezing, which are required for photovoltaic modules. To meet these durability requirements both primers and exterior-grade top coatings will require product customization for this photovoltaic module application.

The original project goals focused on evaluating encapsulating coatings for thin-film photovoltaic modules. PPG industries had intended to coordinate this evaluation with a US-producer of amorphous silicon thin-film solar modules, BP Solar. However changes in direction at BP Solar made it impossible for PPG Industries to obtain test modules for evaluating new encapsulation concepts. Despite PPG Industries' best efforts, and help from NREL, no

alternative supplier of thin-film photovoltaic module test vehicles could be identified. An alternative test vehicle was designed using crystalline silicon solar cells rather than thin-film technology. PPG industries obtained prior approval from the Department of Energy to make this program change. Department of Energy officials indicated that research into new encapsulation technology for crystalline silicon solar modules would be welcome given the large market share that crystalline silicon photovoltaic technology enjoys.

Mini test modules, in both single and 4-cell configurations, were obtained from Spire Corporation. These were produced by vacuum laminating crystalline silicon solar cells with a glass superstrate and only a single sheet of encapsulating EVA between the solar cell and the glass. The solar cells were configured with tabs and bus-bars prior to vacuum lamination. A release film was substituted for a back encapsulating EVA film and a Tedlar backsheet. Mini-modules with EVA-film and Tedlar on the backside were also prepared by Spire to serve as control samples. Coatings were spray applied over the “half-encapsulated” test vehicles. These process steps are outlined in Figure 3.



All program primary goals and objectives were accomplished in this program. Some performance testing on test vehicles was not performed because no mini-modules fully passed damp heat and thermal cycling/humidity freeze tests. Performance evaluations that were specified in the original task schedule but not completed include hot-spot endurance, mechanical load, and outdoor exposure testing. These performance evaluations are reasonable to complete only after encapsulation candidates are shown to pass the insulation, damp heat, and thermal cycling/humidity freeze requirements. Approval for the elimination of these tasks was coordinated with Department of Energy officials responsible for managing this program.

Summary of Project Activities

1. Selection of commercially available primers and top coatings

Many of the performance requirements for photovoltaic encapsulating polymers are similar in category to those of exterior-grade organic coatings. However, electrical insulation performance characteristics such as breakdown voltage and current leakage are not commonly determined exterior coating properties. Similarly, electrical safety considerations in photovoltaic modules have led to more severe durability testing methods than are commonly required for exterior-grade coatings other than those that are used the most extreme exposure applications.

Primer and top coating candidates were selected from a pool of commercially available PPG coatings that are known to perform well in exterior exposure applications. These exterior-grade coatings are used in automotive and aerospace markets. In addition, coatings that are known to have long-term outdoor exposure durability in applications like metal roofing were selected.

The nature of the substrate materials was another important factor in selecting primer and top coating candidates for evaluation. The many-module test vehicle design dictated that the first coating layer would have adhesive interfaces simultaneously with many different materials. These interfaces included cured EVA film, aluminum on the back of the cell, tin-coated copper tabs, and solder, both on the cell and bus-bars. There was also the possibility of an interface with silicon metal on the exposed edges of the solar cell. Therefore, coatings that are known to have good adhesion to both metal and polymeric substrates were chosen.

Throughout various stages of the program 9 commercially available metal primers and 6 commercially available topcoats were evaluated in 21 different coating design configurations (Table 1).

2. Selection of test panel composition

The conductive aluminum backing, which serves as a current collector on crystalline silicon solar cells, was the principle surface interface of interest for the encapsulating coating systems that were examined in this program. Rather than attempt to re-create this baked aluminum paste surface, commercially available aluminum alloy test panels were used to simulate the solar cell interface. Three different types of aluminum alloy were selected in order to determine the affect of alloy composition on coating performance (Table 2). Alloy 5052 is relatively rich in chrome, magnesium, and iron. Alloy 6111 is relatively rich in copper and manganese. Alloy

6022 tends to be relatively low in most elemental impurities, but is somewhat higher in zinc content.

Table 1. Primers and top coatings selected for evaluation as encapsulating polymeric materials for photovoltaic modules. Table shows both configurations in which coatings were evaluated as a mono-layer and in two layer systems.

	Product ID	Description	Top Layer						
			none	Powder Topcoat (PT-1)	Powder Topcoat (PT-2)	Industrial Topcoat (LT-1)	Liquid Topcoat (LT-2)	Liquid Topcoat (LT-3)	Liquid Topcoat (LT-4)
Bottom Layer	none			x	x			x	
	ARP	Automotive Primer	x			x	x		
	CE-1	Cationic Electrocoat				x	x		
	CE-2	Cationic Electrocoat				x	x		
	AE-1	Anionic Electrocoat				x	x		
	AOP	Automotive Primer				x	x		
	ZRP	Zinc-Rich Primer				x	x		
	CP	Coil Primer							x
	AE-2	Anionic Electrocoat				x	x		
	AP-1	Aerospace Primer	x						
	AP-2	Aerospace Primer	x						

Each commercial coating is designed with a set of curing conditions appropriate for the application market in which the coating was envisioned to perform. For test panel screening, coatings were cured using these design conditions and without regard to whether or not the cure conditions would be appropriate for a photovoltaic module application.

Table 2. Alloy compositions for test panels used for evaluating encapsulating coatings. Entries are maximum allowable content when range is not shown.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others each	Others Total	Al
5052	0.25	0.40	0.10	0.10	2.2-2.8	0.15-0.35	0.10		0.05	0.15	95.7 - 97.7
6022	0.8-1.5	0.05-0.20	0.01-0.11	0.02-0.10	0.45-0.70	0.10	0.25	0.15	0.05	0.15	Remainder
6111	0.6-1.1	0.40	0.5-0.9	0.10-0.45	0.50-1.00	0.10	0.15	0.10	0.05	0.15	Remainder

3. Coating cure conditions

The working hypothesis was that any promising performance from a commercial coating configuration would justify customizing that coating type to accommodate process requirements for photovoltaic module manufacturing. Coating configurations that were used for the initial screening on aluminum panels and their cure conditions are shown in Table 3.

Table 3. Cure conditions for initial performance screening of test panels.							
		Primer Cure Conditions before Applying Topcoat	Monocoat or Topcoat Cure Conditions				
			PT-1 Powder	PT-2	LT-1	LT-2	LT-4
Primer	none		30 min. 400 °F	10 min. 420 °F			
	ARP	30 min. 140 °F			30 min. 140 °F		
	CE-1	25 min. 335 °F			30 min. 140 °F		
	CE-2	30 min. 350 °F			30 min. 140 °F	30 min. 140 °F	
	AE-1	25 min. 225 °F			30 min. 140 °F	30 min. 140 °F	
	AOP	30 min. 350 °F			30 min. 140 °F	30 min. 140 °F	
	ZRP	20 min. 400 °F			30 min. 140 °F	30 min. 140 °F	
	CP	10 min. 475 °F					10 min. 475 °F
	AE-2	30 min. 325 °F			30 min. 140 °F	30 min. 140 °F	

4. Evaluation of aluminum corrosion performance

Corrosion was evaluated using the salt spray method (ASTM B117). Coatings on aluminum substrates were pre-scribed and placed in a salt fog chamber for 500 hours. Each coating was evaluated on duplicate panels. Exposed panels were rated for scribe creep as measured across the scribe line. Data for coatings evaluated by this method are shown in Table 4. In some cases, corrosion appeared to change with alloy composition. From these data, coating configurations with scribe creep of 0.5 mm or less were considered as potential candidates for photovoltaic encapsulation coatings.

Table 4. Corrosion of coated aluminum panels measured using salt spray exposure method ASTM B117 with 500 exposure hours. Scribe Creep measure across scribe and reported in millimeters.																
		Monocoat or Topcoat														
		PT-1 Powder			PT-2 Powder			LT-1			LT-2			LT-4 sprayable		
Aluminum Alloy		5052	6022	6111	5052	6022	6111	5052	6022	6111	5052	6022	6111	5052	6022	6111
Primer	none	0.5	1.25	2.0	25	15.5	25									
	ARP							0.25	0.5	0.5						
	CE-1							0.0	0.25	1.0	0.0	0.0	1.0			
	CE-2							0.0	0.0	0.5	0.0	0.5	3.75			
	AE-1							0.5	1.0	0.5	3.75	2.25	0.5			
	AOP							3.0	9.0	5.5	1.25	5.0	5.5			
	ZRP							8.5	11.5	8.5	9.5	11.5	10.5			
	CP													0.0	0.0	0.0
	AE-2							0.0	0.0	0.0	0.0	0.0	0.0			

5. Evaluation of adhesion following damp heat exposure

Coating adhesion performance was evaluated after exposing the coated aluminum panels to heat and humidity in accordance with test method ASTM D1735. After 500 exposure hours at 100°F and 100% relative humidity, panels were evaluated for blistering and scribe tape. Adhesion was rated on a scale of 0 to 10, with a rating of 10 being the best performance result and a rating of 0 being worst. Data for coatings that were evaluated by this method are shown in Table 5. Little variation in adhesion was observed as a function of alloy selection for the coated substrates. Coating configurations with a rating of nine or better were considered as potential candidates for further evaluation as encapsulation coatings for photovoltaic modules.

Table 5. Evaluation of adhesion of coatings on aluminum panels following humidity testing according to test method ASTM D1735. Panels were exposed for 500 hours at 100°F and 100% relative humidity.																
		Monocoat or Topcoat														
		PT-1 Powder			PT-2 Powder			LT-1			LT-2			LT-4 sprayable		
Aluminum Alloy		5052	6022	6111	5052	6022	6111	5052	6022	6111	5052	6022	6111	5052	6022	6111
Primer	none	6	8	7	8	8	8									
	ARP							10	10	10						
	CE-1							9	9	10	10	10	10			
	CE-2							2	1	0	10	9	9			
	AE-1							0	0	0	1	1	2			
	AOP							0	0	0	0	0	0			
	ZRP							-	-	-	-	-	-			
	CP													10	10	10
	AE-2							10	10	10	10	9	9			

6. Evaluation of durability from accelerated weathering tests

Durability against light induced degradation is also an important performance criterion for any polymeric encapsulating coating candidate. Light induced degradation was determined by evaluating gloss retention and color changes for coated aluminum panels after exposure to heat, light, and humidity. Tests were conducted using both weather-o-meter (WOM) and QUV-313 exposures according methods specified by SAE-J2527. Panels were evaluated after 500 and 3000 exposure hours for WOM testing. Panels were evaluated after 500, 1000 and 3000 exposure hours for QUV-313 testing. Gloss retention was evaluated at both 20° and 60° incident angles. Color shift was determined by standard CIE methods in which color coordinates L^* , a^* , and b^* are measured initially and changes are reported as the square root of the sum of the squares of the change in each coordinate, ΔE .

WOM exposure is considered to be closer to solar conditions and somewhat milder than QUV-313 which accelerates light induced degradation by exaggerating the ultraviolet light contribution of the exposure spectrum. The common cause for the loss of gloss of the coated panel is the roughening that results from light induced polymer degradation of the coating surface. This roughening causes an increase in light scattering at the coating-air interface.

Light induced degradation did not appear to be significantly affected by aluminum panel alloy selection for most coating configurations. This is not particularly surprising since our methodology primarily evaluates changes at the air-polymer interface. The result from QUV-313 exposure for the coating configuration of LT-1 over anionic electrocoat AE-2 appears to be an exception. This coating configuration appears to be more durable over the relatively pure 6022 aluminum alloy panel than over the other aluminum alloy panels based on gloss retention analysis. No attempt was made to determine the reproducibility or the mechanistic implications of this finding.

The fluorocarbon-based coil extrusion coating LT-1, used in applications such as metal roofing, has excellent 20° gloss retention after 3000 hours of WOM exposure (Table 6). This gloss retention performance appears to be independent of the primer used under this top coating. Of the other coatings that were evaluated, only LT-4 showed reasonable 20° gloss retention after 3000 exposure hours, although it still did not match the performance of LT-1.

Similar conclusions can be drawn from 20° gloss retention data from the QUV-313 exposure testing (Table 7). LT-1 appears to be very resistant to light induced degradation and shows high gloss retention all the way up to 3000 exposure hours. However, unlike results from WOM testing, QUV-313 testing revealed some durability dependence with primer selection. Both the zinc rich primer CP and anionic electrocoat AE-2 showed unusually poor gloss retention even

with LT-1 top coating. As with WOM, LT-4 was the only other coating configuration that showed reasonable gloss retention.

Using the 60° scattering angle to evaluate light-induced degradation appears to be less discriminating than using 20° gloss retention measurements. Although 60° gloss retention data for panels subjected to WOM exposure similarly leads to the conclusion that LT-1 shows superior durability, this measurement technique does not readily lead to the conclusion that either powder coatings PT-1 or PT-2 suffer significantly from light induced degradation, or that LT-4 shows significantly poorer performing than LT-1 (Table 8).

Measuring light-induced degradation by 60° gloss retention after exposure to QUV-313 test conditions similarly shows the durability benefits of LT-1, as well as a marked effect of primer selection that is not evident from data for panels supposed to WOM test conditions. Using 60° gloss retention also does not readily distinguish the poorer durability performance of LT-4 relative to LT-1.

Typically, color shifts with ΔE -values of one or less are considered indistinguishable by the human eye unless the panels are examined side-by-side. Color shifts remained relatively low for all coating configuration for panels exposed to either WOM or QUV-313 test conditions (Table 10 and Table 11). Therefore, measurement of changes in color for these coatings over and exposure period of 3000 hours does not appear to be a useful method for monitoring light induced degradation.

Table 6. Evaluation of light induced degradation by exposure to weather-o-meter (WOM) according to test method SAE J2527. Degradation Response 20°- Gloss retention %

Topcoat or Monocoat	Aluminum Alloy	Exposure Hours	Primers								
			none	ARP	CE-1	CE-2	AE-1	AOP	ZRP	CP	AE-2
PT-1 Powder	5052	500	100								
		3000	50								
	6022	500	100								
		3000	50								
	6111	500	100								
		3000	0								
PT-2 Powder	5052	500	117								
		3000	57								
	6022	500	*								
		3000	*								
	6111	500	*								
		3000	*								
LT-1	5052	500		95	96	95	97	94	93		94
		3000		98	96	92	99	102	97		94
	6022	500		95	96	97	94	97	95		89
		3000		95	99	97	94	96	94		94
	6111	500		100	91	95	94	93	93		90
		3000		103	91	97	96	93	93		94
LT-2	5052	500			75	76	75	75	78		73
		3000			8	9	8	6	9		5
	6022	500			76	75	77	72	73		73
		3000			7	7	8	6	8		5
	6111	500			76	73	77	74	94		70
		3000			7	8	10	8	11		6
LT-4 sprayable	5052	500								104	
		3000								81	
	6022	500								109	
		3000								86	
	6111	500								104	
		3000								79	

* Delamination from substrate after 500 hours

Table 7. Evaluation of light induced degradation by exposure to QU-313 according to test method SAE J2527. Degradation Response 20°- Gloss retention %

Topcoat or Monocoat	Aluminum Alloy	Exposure Hours	Primers								
			none	ARP	CE-1	CE-2	AE-1	AOP	ZRP	CP	AE-2
PT-1 Powder	5052	500	100								
		1000	80								
		3000	20								
	6022	500	100								
		1000	100								
		3000	33								
	6111	500	100								
		1000	100								
		3000	0								
PT-2 Powder	5052	500	1108								
		1000	92								
		3000	42								
	6022	500	104								
		1000	88								
		3000	32								
	6111	500	109								
		1000	91								
		3000	39								
LT-1	5052	500		95	100	100	100	94	74		102
		1000		95	95	97	96	90	53		95
		3000		100	97	103	101	102	55		59
	6022	500		97	100	100	102	96	59		98
		1000		97	95	100	98	91	57		91
		3000		103	108	103	98	91	56		72
	6111	500		100	95	97	102	99	68		100
		1000		97	88	97	100	93	62		95
		3000		107	95	103	108	91	58		46
LT-2	5052	500			36	22	33	21	14		16
		1000			4	3	9	0	3		3
		3000			1	1	1	1	1		1
	6022	500			32	20	35	22	10		27
		1000			4	3	9	0	3		5
		3000			1	1	1	1	2		1
	6111	500			32	23	23	19	12		26
		1000			5	4	0	0	3		3
		3000			1	1	1	1	1		1
LT-4 sprayable	5052	500								104	
		1000								100	
		3000								72	
	6022	500								104	
		1000								100	
		3000								74	
	6111	500								100	
		1000								76	
		3000								70	

Table 8. Evaluation of light induced degradation by exposure to weather-o-meter (WOM) according to test method SAE J2527. Degradation Response 60°- Gloss retention %											
Topcoat or Monocoat	Aluminum Alloy	Exposure Hours	Primers								
			none	ARP	CE-1	CE-2	AE-1	AOP	ZRP	CP	AE-2
PT-1 Powder	5052	500	102								
		3000	90								
	6022	500	102								
		3000	90								
	6111	500	106								
		3000	90								
PT-2 Powder	5052	500	91.5								
		3000	82								
	6022	500	*								
		3000	*								
	6111	500	*								
		3000	*								
LT-1	5052	500		103	101	103	101	103	102		103
		3000		107	102	102	104	107	104		102
	6022	500		105	101	101	103	101	100		105
		3000		106	104	105	101	102	104		102
	6111	500		100	104	102	101	101	104		105
		3000		110	100	107	104	102	101		104
LT-2	5052	500			106	105	106	107	106		106
		3000			43	44	44	36	45		36
	6022	500			105	105	105	107	106		106
		3000			41	41	43	36	43		35
	6111	500			106	107	105	108	97		105
		3000			47	41	43	42	49		36
LT-4 sprayable	5052	500								91	
		3000								97	
	6022	500								98	
		3000								90	
	6111	500								94	
		3000								91	

* Delamination from substrate after 500 hours

Table 9. Evaluation of light induced degradation by exposure to QUV-313 according to test method SAE J2527. Degradation Response 60°- Gloss retention %

Topcoat or Monocoat	Aluminum Alloy	Exposure Hours	Primers								
			none	ARP	CE-1	CE-2	AE-1	AOP	ZRP	CP	AE-2
PT-1 Powder	5052	500	95								
		1000	81								
		3000	15								
	6022	500	91								
		1000	83								
		3000	17								
	6111	500	95								
		1000	81								
		3000	24								
PT-2 Powder	5052	500	106								
		1000	98								
		3000	65								
	6022	500	104								
		1000	95								
		3000	60								
	6111	500	105								
		1000	96								
		3000	64								
LT-1	5052	500		97	102	101	100	97	80		103
		1000		97	99	97	98	94	64		97
		3000		115	106	112	11	116	101		84
	6022	500		99	102	100	102	99	69		100
		1000		99	99	100	100	96	72		95
		3000		115	115	112	110	106	97		101
	6111	500		100	99	98	103	101	70		103
		1000		96	96	98	101	97	83		97
		3000		118	105	113	116	104	92		68
LT-2	5052	500			76	66	73	62	57		58
		1000			30	23	44	5	18		21
		3000			4	3	3	3	3		3
	6022	500			72	61	75	63	42		70
		1000			28	25	44	4	14		34
		3000			31	3	4	3	3		3
	6111	500			74	67	67	60	50		71
		1000			31	32	43	4	16		27
		3000			4	3	4	3	3		3
LT-4 sprayable	5052	500								105	
		1000								101	
		3000								81	
	6022	500								105	
		1000								101	
		3000								80	
	6111	500								103	
		1000								100	
		3000								79	

Table 10. Evaluation of light induced degradation by exposure to weather-o-meter (WOM) according to test method SAE J2527. Degradation Response ΔE											
Topcoat or Monocoat	Aluminum Alloy	Exposure Hours	Primers								
			none	ARP	CE-1	CE-2	AE-1	AOP	ZRP	CP	AE-2
PT-1 Powder	5052	500	0.3								
		1000	1.1								
	6062	500	0.7								
		3000	1.4								
	6111	500	0.3								
		3000	1.2								
PT-2 Powder	5052	500	0.2								
		3000	2.1								
	6062	500	*								
	6111	500	*								
LT-1	5052	500		0.3	0.2	0.2	0.1	0.1	0.2		0.2
		3000		0.8	0.5	0.6	0.4	0.4	0.4		0.7
	6062	500		0.3	0.2	0.2	0.1	0.1	0.2		1.9
		3000		0.6	0.5	0.5	0.5	0.4	0.4		2.0
	6111	500		0.3	0.2	0.2	0.1	0.1	0.2		0.2
		3000		0.6	0.5	0.5	0.4	0.4	0.5		0.5
LT-2	5052	500			0.2	0.1	0.2	0.1	0.2		0.1
		3000			0.8	0.8	0.7	0.7	0.8		0.8
	6062	500			0.2	0.1	0.2	0.2	0.2		0.1
		3000			0.8	0.8	0.7	0.7	0.9		0.8
	6111	500			0.2	0.1	0.1	0.2	0.2		0.1
		3000			0.9	0.8	0.7	1.0	0.9		0.8
LT-4 sprayable	5052	500								0.6	
		3000								0.8	
	6062	500								0.3	
		3000								0.5	
	6111	500								0.4	
		3000								0.5	

Table 11. Evaluation of light induced degradation by exposure to QUV-313 according to test method SAE J2527. Degradation Response ΔE

Topcoat or Monocoat	Aluminum Alloy	Exposure Hours	Primers								
			none	ARP	CE-1	CE-2	AE-1	AOP	ZRP	CP	AE-2
PT-1 Powder	5052	500	0.4								
		1000	0.7								
		3000	5.3								
	6062	500	0.4								
		1000	0.6								
		3000	5.0								
	6111	500	0.2								
		1000	0.5								
		3000	6.8								
PT-2 Powder	5052	500	0.6								
		1000	1.0								
		3000	1.7								
	6062	500	0.6								
		1000	0.8								
		3000	2.1								
	6111	500	0.5								
		1000	0.9								
		3000	1.9								
LT-1	5052	500		1.2	0.8	0.8	0.6	0.7	0.8		2.0
		1000		1.4	1.1	1.0	0.94	1.0	1.1		2.1
		3000		2.2	1.9	1.8	1.7	27.6	1.8		2.5
	6062	500		1.2	0.7	0.8	0.6	0.5	0.8		2.1
		1000		1.3	1.0	1.1	1.0	1.0	1.2		2.2
		3000		5.3	1.7	1.8	1.9	1.8	1.8		2.4
	6111	500		1.0	0.8	0.8	0.6	0.7	0.8		2.1
		1000		1.2	1.1	1.1	1.0	1.0	1.1		2.3
		3000		2.5	1.7	1.9	1.9	1.8	1.7		2.7
LT-2	5052	500			0.4	1.2	0.3	0.3	0.3		0.5
		1000			0.3	1.2	0.3	0.4	0.3		0.6
		3000			0.3	1.2	0.4	0.3	0.3		0.4
	6062	500			0.3	0.3	0.3	0.3	0.3		0.4
		1000			0.3	0.4	0.3	0.4	0.4		0.5
		3000			0.3	0.3	0.3	0.3	0.3		0.5
	6111	500			0.3	0.3	0.3	0.3	0.3		0.5
		1000			0.3	0.3	0.4	0.4	0.3		0.6
		3000			0.3	0.3	0.4	0.3	0.4		0.4
LT-4 sprayable	5052	500								0.3	
		1000								0.4	
		3000								0.5	
	6062	500								0.1	
		1000								0.2	
		3000								0.3	
	6111	500								0.2	
		1000								0.3	
		3000								0.4	

7. Evaluation of moisture barrier properties

For coating systems to hold promise as a viable replacement for encapsulating films in crystalline silicon photovoltaic modules, component coating layers must provide adequate barrier protection from moisture and oxygen to prevent corrosion during decades of outdoor exposure.

Table 12. Moisture Vapor Transfer Rate (MVTR) of coatings over ITO-coated PET film. MVTR of ITO-PET film = 1.10, Permance = 5.44 Values: MVTR as g/m ² ·day, DFT dry film thickness as mils, Permeance as g·mil/m ² ·day													
		Monocoat or Topcoat											
		PT-1			PT-2			LT-1			LT-2		
		Powder			Powder								
		MVTR	DFT	Permeance	MVTR	DFT	Permeance	MVTR	DFT	Permeance	MVTR	DFT	Permeance
Primer	none	0.44	10.7	4.7	0.40	7.1	2.9						
	ARP							0.06	9.1	0.55			
	CE-1							2.25	7.7	17.4	2.31	2.6	17.4
	CE-2							2.27	8.2	18.7	2.24	8.2	18.5
	AE-1 ¹							-	-	-	-	-	-
	AOP							-	-	-	0.06	8.4	0.51
	ZRP ²							-	-	-	-	-	-
	CP ³												
	AE-2 ⁴							-	-	-	-	-	-

Footnotes for Table 12.

¹AE-1 ITO-PET had insufficient conductivity for applying this coating by electrodeposition.

²ZRP Primer did not form a continuous film on ITO-PET substrate.

³CP Cure temperature too high for PET film

⁴AE-2 ITO-PET had insufficient conductivity for applying this coating by electrodeposition.

Measuring moisture vapor transfer rates (MVTR) was attempted by applying and curing a coating over indium tin oxide coated polyethylene terephthalate film (Table 12). The original hypothesis was that by knowing the MVTR of the coated and uncoated ITO-PET films, the MVTR of the coating could be calculated. ITO-PET was chosen so that the same substrate could be used for both spray applied and electrodeposited coatings. While in some cases such as LT-1 over ARP or LT-2 over AOP MVTR was clearly reduced by application of a coating, in most cases the coating application and curing processes led to an overall increase in MVTR. Several coating system could not be applied at all due to either cure conditions that were inappropriate for PET insufficient conductivity from the ITO-PET to allow for electrodeposition.

Consequently, this approach to measuring barrier properties was abandoned in favor of developing a method to measure MVTR on freestanding films prepared from individual coatings.

By the time it became clear that measuring MVTR over ITO-PET film would not lead to the desired outcome, many coating configurations could be eliminated by evaluation of results from other performance criteria. Therefore, only a limited set of coatings was evaluated as freestanding films. These coatings instead were evaluated as individual films and in two layers, primer/topcoat configurations. The effect of cure conditions on moisture barrier properties was also examined (Table 13).

Table 13. Moisture Vapor Transfer Rate (MVTR) of coatings as freestanding films.
Values: MVTR as g/m²·day, DFT dry film thickness as mils, Permeance as g·mil/m²·day

				Topcoat or Monocoat								
				none			LT-1			LT-2		
Primer	Description	Cure time (hr)	Cure Temp (°F)	MVTR	DFT	Permeance	MVTR	DFT	Permeance	MVTR	DFT	Permeance
none		168	r.t				35	1.9	68	82	1.9	162
none		0.5	140				25	2.0	49	91	1.8	166
none		0.5	250				24	1.8	44	71	2.0	141
ARP	Automotive Primer	168	r.t	35	1.3	45	11	4.0	46	21	3.2	67
ARP	Automotive Primer	0.5	140	34	1.2	39	10	3.8	38	16	3.3	52
ARP	Automotive Primer	0.5	250	19	1.2	23	7.3	3.7	27	14	3.0	42
AP-1	Aerospace Primer	168	r.t	16	1.9	29	10	3.1	30			
AP-1	Aerospace Primer	0.5	140	12	1.9	23	7	3.1	21			
AP-1	Aerospace Primer	0.5	250	7	2.0	14	7	3.0	21			
AP-2	Aerospace Primer	168	r.t	20	1.3	26	10	2.9	31			
AP-2	Aerospace Primer	0.5	140	12.	1.9	23	8	3.1	25			
AP-2	Aerospace Primer	0.5	250	13	1.2	15	7	2.8	20			

Moisture vapor transfer rates for standard polymer films used to encapsulate crystalline silicon in photovoltaic modules also were measured in order to benchmark the performance of these encapsulating coating. As-received EVA film was found to have a permeance of 458 g·mil/m²·day, and EVA film that had undergone a vacuum lamination process showed only a marginal decrease in permeance to 399 g·mil/m²·day. Tedlar backsheet was found to have a permeance of 30 g·mil/m²·day.

Permeance values of freestanding films for each individual coating, as well as each bilayer primer/topcoat configuration, were lower than EVA film. In most cases, coating permeance was an order of magnitude lower than EVA film. Furthermore, most of the coatings and coating systems that were evaluated had permeance values similar to that of Tedlar.

These MVTR results indicated that LT-1 generally had better moisture barrier properties than did LT-2. Significantly lower permeance values also were achieved by using higher cure temperatures for short duration. This is consistent with the concept that higher crosslink density is achieved at higher cure temperatures, and that higher crosslink density increases film resistance to moisture permeation.

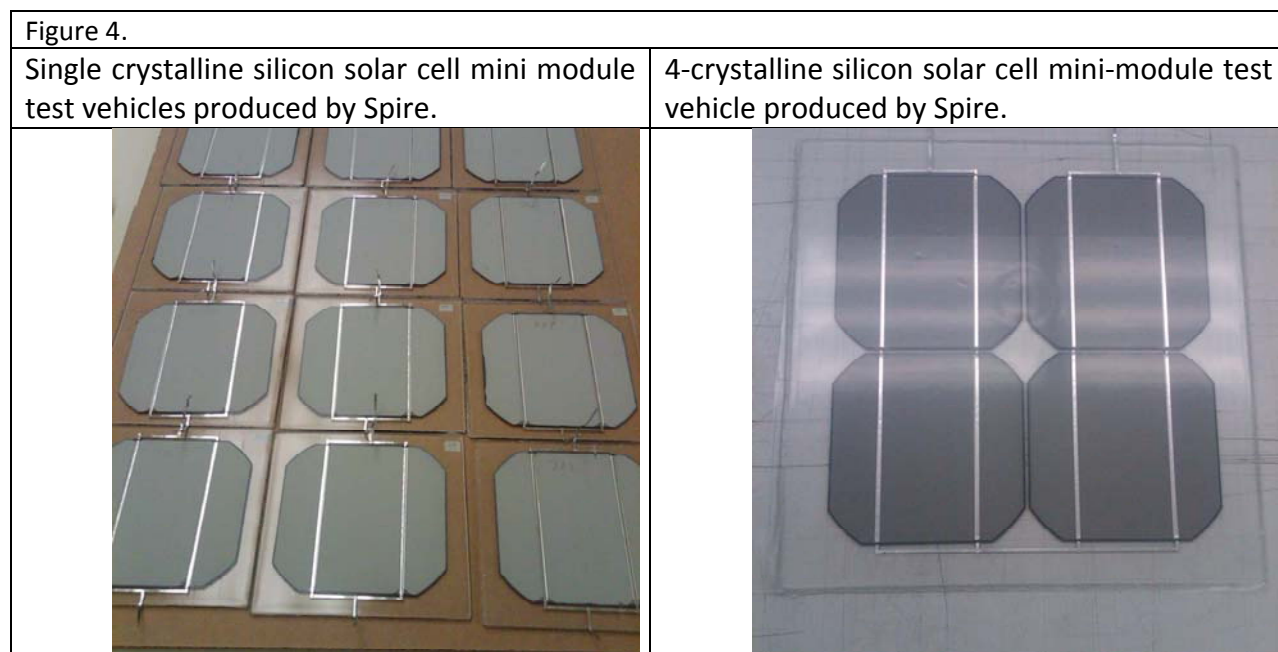
Interestingly, permeance values for primer/topcoat bilayer films were in each case similar to permeance values for the primer alone. This led to this hypothesis that the primer would be the major contributor to barrier properties in our encapsulating coating photovoltaic mini-module test vehicle design. In some ways this points to the unique feature of this encapsulating coating design because EVA potting film that is used in standard photovoltaic modules has very poor barrier properties, and both exterior durability and barrier properties are provided by a Tedlar backsheet. The experimental primer/topcoat design puts a corrosion inhibiting coating with good barrier properties directly into the solar cell matrix.

Evaluation of individual coatings and primer/top coating systems on aluminum panels and free films led to the following parameters for down-selecting the best candidates for further testing in crystalline silicon photovoltaic mini-module test vehicles:

- Primers function to inhibit corrosion, promote adhesion, and provide a moisture barrier protection.
- Top coatings provide durability and accelerated weathering performance.
- LT-1 outperformed all other commercially available topcoats that were evaluated.
- Higher cure temperatures significantly lower moisture permeance and could allow a coating system to meet performance requirements with lower total film thickness.

8. Mini-module test vehicle design

Mini-modules were produced by vacuum laminating crystalline silicon solar cells with a glass superstrate and only a single sheet of encapsulating EVA between the solar cell the glass. The solar cells were configured with tabs and bus-bars prior to vacuum lamination. A release film was substituted for a back encapsulating EVA film and a Tedlar backsheet. Both single cell and 4-cell mini-modules were prepared by Spire Corporation (Figure 4). Mini-modules with EVA-film and Tedlar on the backside were also prepared by Spire Corporation to serve as control samples.



Coatings were spray applied over these “half-encapsulated” test vehicles. These process steps are outlined in Figure 3.

9. Evaluation of coatings as encapsulants with crystalline silicon based photovoltaic mini-module test vehicles

Two primer/top coating bilayer configurations were selected for further evaluation using single crystalline silicon solar cell mini-module test vehicles. The two of the most promising primers, refinish primer ARP and aerospace primer AP-1, were each spray applied and cured on the back of mini-module test vehicles. The best performing top coating, LT-1, was then spray applied over each primed mini-module and cured. In this way, the encapsulation performance of two different primers and only one top coating was evaluated.

International standard IEC 61215, second edition, 2005-2004 entitled "Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval" was used as a guide for all mini-module performance evaluations. Discussions with NREL staff helped to identify the tests which would probe the most critical performance criteria, and therefore which should be run first. Only these critical performance tests were completed within the scope of this project.

a. Visual Inspection - Test Procedure IEC 61215 -10.1

Each single solar cell mini-module test vehicle was inspected for the visual defects as described in IEC 61215-10.1.2. No cracked or broken cells were observed. The surfaces were not tacky, and no failures were found in adhesive bonding. There was no delamination or bubbles. No faulty interconnections or electrical termination were found. In general, there were no observable conditions that would be expected to negatively affect performance.

b. Maximum Power Determination – Test Procedure IEC 61215-10.2

The maximum power (P_m) and fill factor (FF) for each single cell mini-module test vehicle was measured using a PPG Industries in-house solar simulator according to standard procedures that are described in IEC 61215-10.2.3, and using simulated solar irradiance of 1 sun. Each mini-module was measured before and after durability testing. P_m and FF were also measured at various time intervals during each test to monitor the performance progression.

c. Insulation Test – Test Procedure IEC 61215 10.3

Dry current leakage was determined for each single cell mini-module test vehicle according to standard test procedures that are described in IEC 61215-10.3.4. Since the test vehicles contain only one solar cell and have a maximum system voltage that does not exceed 50 V, and applied voltage of 500 V was used for this test as described in step 10.3.3c. All freshly prepared mini-modules passed the test requirements that are specified in section IEC 61215-10.3.5. That is, insulation resistance and not exceeding 400 M Ω , and 40 M Ω per m². This insulation test was performed before and after durability testing, and at various time intervals during durability testing to monitor performance progression.

d. Damp Heat Test – Test Procedure IEC 61215 10.13

Durability to high temperature and high humidity exposure was determined by subjecting the single silicon solar cell mini-module test vehicles to the damp heat test procedure as described in section 10.13.2 of the international standard IEC 61215. Mini-modules were exposed to 85°C

and 85% relative humidity for duration of 1000 hours. In order to provide a more statistically relevant performance perspective, each of the two experimental bilayer coating configurations was tested in triplicate (that is, three coated mini-modules that were presumed to be identical per each coating configuration).

Mini-modules also were withdrawn from the damp heat chamber for evaluation at time intervals 330 hours and 660 hours to determine how performance was progressing with time throughout the duration of the test. These modules were then returned to the damp heat chamber to continue the testing. Three mini-modules that were prepared by conventional vacuum lamination using EVA encapsulating films and clear Tedlar backsheet were subjected to damp heat testing simultaneously with the experimental coated mini-modules to serve as performance controls for comparison.

One of each configuration of the experimental coated mini-modules and one control mini-module that was prepared by conventional vacuum lamination were exposed to ambient, room temperature conditions with no humidity control. Pm performance for these control mini-modules was measured each time along with the mini-modules that were subjected to the damp heat test to establish how much Pm performance measurement drifts from random effects over time. There did appear to be a slight downward drift in Pm performance over the 1000 hour test period even for samples that were not subject to the damp heat testing. In general, all mini-modules showed about 1100 mW of power at Pm. Experimental coated mini-modules showed roughly the same Pm output as the control backsheet laminated mini module (Table 14). Similar conclusions were drawn from FF data.

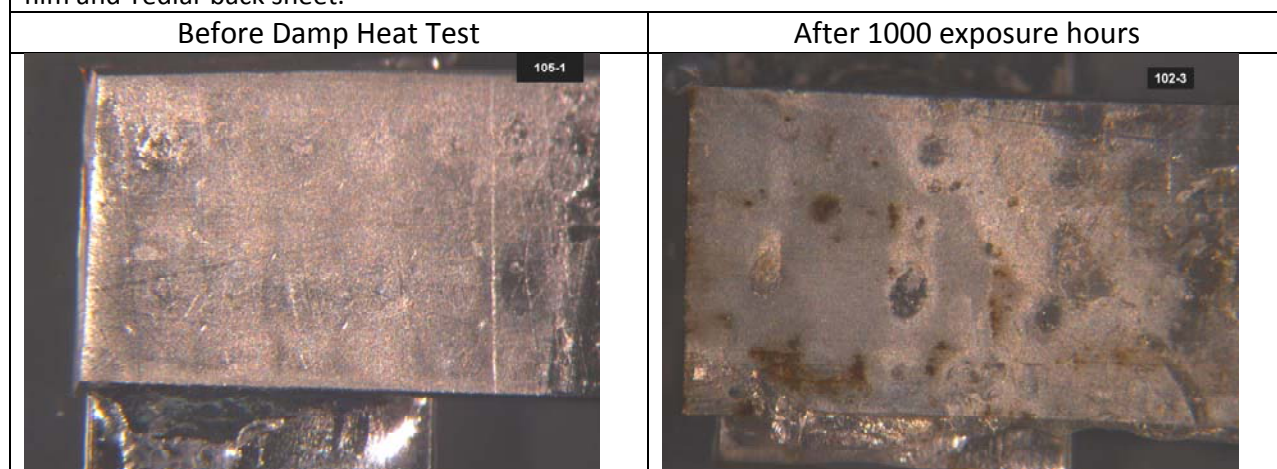
Table 14. Pm for control mini-modules that were subjected only to ambient room temperature conditions, but re-measured each time along with damp heat tested mini-modules. Data show some small drift in Pm measurement over time.						
			Hours into Damp Heat Testing			
			0	330	660	1000
Min-Module Description	Mini-module ID	Pm of mini-module when initially prepared	Pm of control mini-modules			
control	105	1136	1142	1124	1093	1073
AP-1	304	1130	1134	1119	1123	1100
ARP	317	1133	1108	1081	1079	1072

Similarly, the control mini-modules that had been prepared by conventional vacuum lamination showed less than a 5% loss in maximum power output over the entire 1000 hour duration of the damp heat test (Table 15). Similar results were observed for fill factor measurements. These changes could be well within the random drift of measurements using the solar simulator method as mentioned above.

Table 15. Pm for control mini-modules that were prepared by conventional vacuum lamination.			Hours into Damp Heat Testing			
			0	330	660	1000
Min-Module Description	Mini-module ID	Pm of mini-module when initially received	Pm of mini-modules			
control	105	1136	1142	1124	1093	1073
control	304	1130	1134	1119	1123	1100
control	317	1133	1108	1081	1079	1072

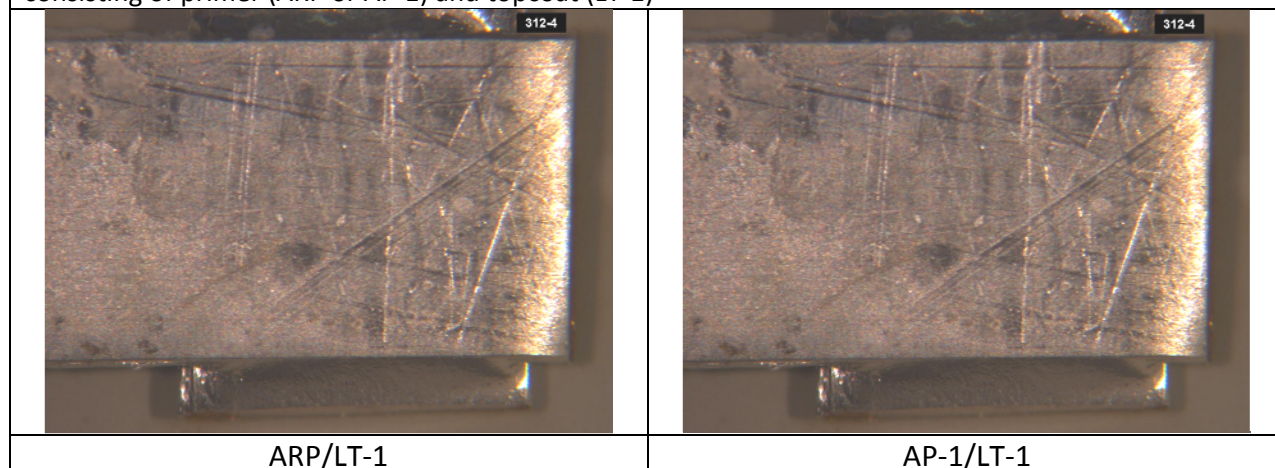
However, visual inspection of these control mini-modules showed significant levels of corrosion along the metal tabbing and bus-bars. This corrosion was evident from dark brown and yellow spots and marketing all along the metal tabbing materials. Corrosion of the bus-bar corner position before and after damp heat testing is shown in Figure 5.

Figure 5. Photograph showing corrosion of bus-bar before and after 1000 exposure hours in damp heat testing of mini-module test vehicles that were prepared by conventional vacuum lamination with EVA-film and Tedlar back sheet.



By contrast, visual inspection of mini-module test vehicles that were prepared using the primer/topcoat bilayer configuration as a replacement for EVA-film/Tedlar vacuum lamination showed no bus-bar corrosion (Figure 6). These results would appear to validate the initial hypothesis that corrosion inhibiting primers can reduce metal corrosion in photovoltaic modules.

Figure 6. Photograph showing no corrosion of bus-bar after 1000 exposure hours in damp heat testing of mini-module test vehicles that were prepared by using an encapsulating coating bilayer configuration consisting of primer (ARP or AP-1) and topcoat (LT-1)

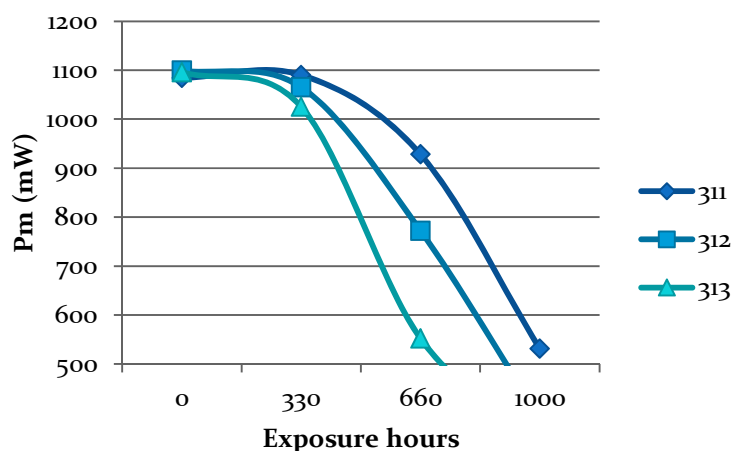


Experimental single crystalline-silicon solar cell mini-module test vehicles that had been coated in a bilayer configuration using refinish primer ARP and LT-1 topcoat showed stable Pm output performance only to about 300 exposure hours in the damp heat test (Table 16). Beyond 330 hours output performance rapidly declined and modules failed insulation testing (Figure 7). Analysis of fill factor data resulted in identical conclusions. In addition, two of these mini-modules failed the dry insulation test after 330 exposure hours.

Table 16. Pm for control mini-modules that were coated with ARP primer and LT-1 topcoat.			Hours into Damp Heat Testing			
			0	330	660	1000
Mini-Module Description	Mini-module ID	Pm of mini-module when initially prepared	Pm of mini-modules			
ARP	311	1148	1084	1090	928	531
ARP	312	1147	1099	1065	772	390
ARP	313	1134	1096	1025	552	351

Visual inspection of the failed mini-modules revealed that the coating had delaminated at the metal tabbing interface. This failure appeared to be particularly pronounced at the interfacial edge of the tabbing with EVA front sheet (Figure 8).

Figure 7. Maximum power output at 1 sun irradiance over the course of 1000 exposure hours to damp heat testing. Data shows rapid performance decline after only 330 exposure hours.



Experimental mini-module test vehicles that had been coated in a bilayer configuration comprised of aerospace primer AP-1 and a LT-1 topcoat showed stable maximum power output after 1000 exposure hours in the damp heat test (Table 17).

Figure 8. Photograph of backside of mini-module coated with refinish primer ARP and LT-1 top coat after 1000 exposure hours in damp heat test. Visual inspection reveals delamination and corrosion along the metal tabbing interface.



Table 17. Pm for control mini-modules that were coated with AP-1 primer and LT-1 topcoat.			Hours into Damp Heat Testing			
			0	330	660	1000
Mini-Module Description	Mini-module ID	Pm of mini-module when initially prepared	Pm of mini-modules (mW)			
AP-1	318	1129	1120	1111	1107	1081
AP-1	319	1126	1121	1105	1109	1083
AP-1	320	1141	1122	1129	1129	1113

Comparison of both power output performance, Pm, and fill factor of these coated mini-modules shows that the bilayer coating configuration using AP-1/LT-1 had similarly stable damp heat test durability to the control mini-modules that were prepared by conventional vacuum lamination using EVA film and Tedlar backsheet. Further comparison shows that the AP-1/LT-1 bilayer coating configuration clearly outperforms the ARP/LT-1 bilayer coating configuration in this damp heat durability test (Figure 9).

However, visual inspection indicated that the AP-1/LT-1 coated had suffered delamination during the damp heat testing exposure period. The failure mode appeared primarily at the edge of the solar cell at the silicon-EVA interface (Figure 10). This delamination could be caused by a mismatch in the thermal expansion properties between EVA front sheet and the coating.

Figure 9. Power output (Pm) and fill factor comparison after Damp Heat testing for mini-modules that were prepared either by coating with AP-1 primer/LT-1 topcoat or ARP/LT-1 topcoat or by conventional vacuum lamination using EVA/TPT-Tedlar backsheet. Charts show that AP-1/LT-1 performs similarly to the control, while ARP/LT-1 degrades rapidly after 330 exposure hours.

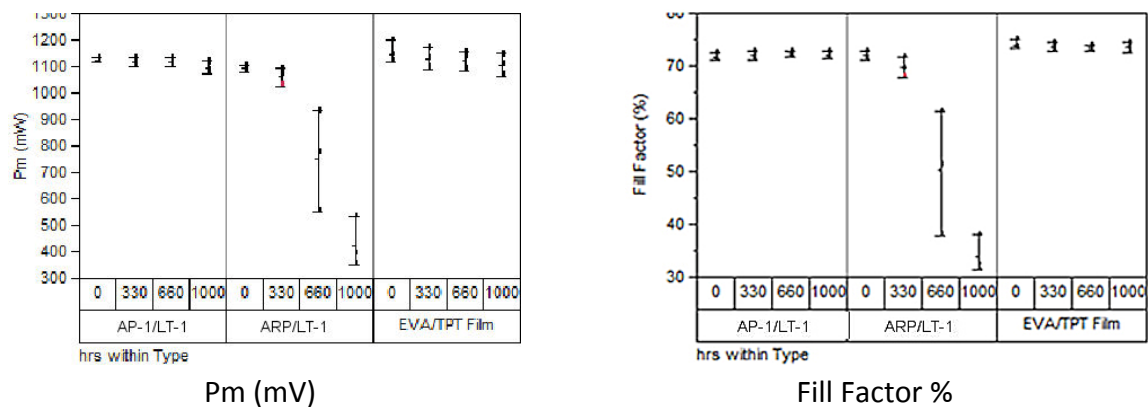
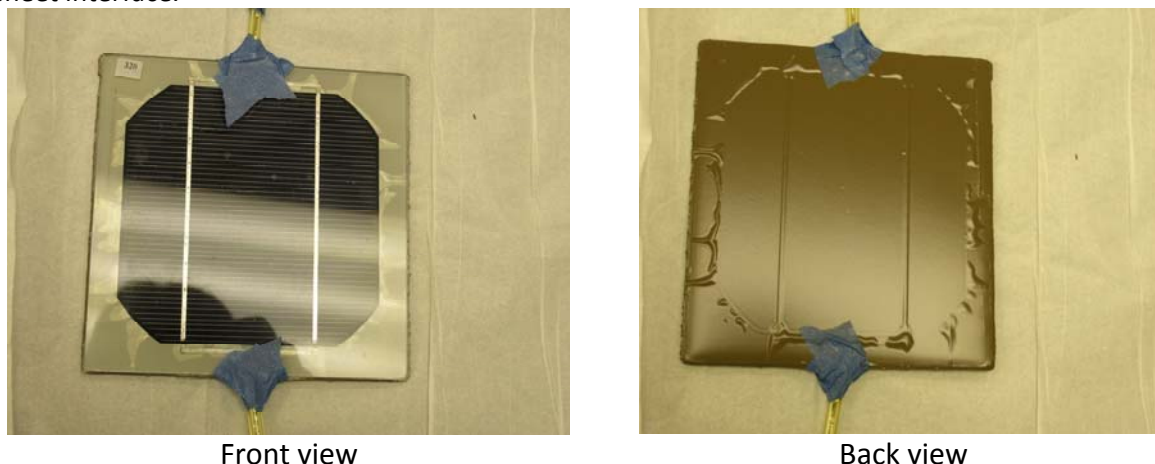


Figure 10. Photograph showing delamination at the edge of the solar cell along the silicon-EVA front sheet interface.



e. Thermal Cycling Test - Test Procedure IEC 61215 10.11

Durability to thermal cycling between -40 °C and 85 °C was determined by subjecting the single cell mini-module test vehicles to the thermal cycling test procedure as described in section 10.11.3 of the international standard IEC 61215. Cycling was repeated for 50 cycles. Samples were analyzed only after all 50 cycles were completed, and no analysis was performed at intermediate cycling intervals.

As expected, the control mini-modules that had been prepared by conventional vacuum lamination using EVA film and Tedlar backsheet showed good durability in the standard thermal cycling test. The mean output power (P_m) from the three control mini-modules declined less than 2% after 50 thermal cycles (Table 18).

Similarly, the experimental mini-module test vehicles that had been coated with the ARP primer/ LT-1 bilayer configuration showed about a 2% decline in mean output power (P_m) after completing 50 thermal cycles. Fill factor data led to similar conclusions. These mini-modules also passed the dry insulation testing (Table 19). However, visual inspection revealed that there were some cracks in the coating. Some cracks seemed to emanate from the soldered corners of the bus-bar which could indicate that coating cure conditions were too severe.

Table 18. Pm for control mini-modules that were prepared by conventional vacuum lamination using EVA-film and Tedlar backsheet after Thermal Cycling and humidity Freeze Tests.

Mini-Module Description	Mini-module ID	Pm of mini-modules (mW)			
		As-received	Before starting thermal cycling	After Thermal Cycling for 50 cycles	After Humidity Freeze for 10 cycles
control	106	1124	1119	1090	1067
control	107	1085	1095	1080	1087
control	108	1145	1142	1120	1118

Experimental mini-module test vehicles that were coated with the AP-1 primer/LT-1 bilayer configuration showed mixed results after 50 cycles with large variation between the three different samples. One mini-module retained over 98% of its initial power output (Pm). Another mini-module retained only about 91% of its initial power output. A third mini-module retained only about 80% of its initial power output, and actually failed the dry insulation test (Table 19). Visual inspection revealed that there were some cracks in the coating with this bilayer configuration as well.

f. Humidity Freeze Test - Test Procedure IEC 61215-10.12

Durability to thermal cycling between -40 °C and 85 °C with 85% relative humidity was determined by subjecting the single silicon solar cell mini-module test vehicles to the Humidity Freeze test procedure as described in section 10.12.3 of the international standard IEC 61215. Cycling was repeated for 10 cycles. Samples were analyzed only after all 10 cycles were completed, and no analysis was performed at intermediate cycling intervals.

Table 19. Pm after Thermal Cycling and Humidity Freeze Tests for mini-modules that were prepared by coating with a bilayer configuration of either ARP/LT-1 (ARP) or AP-1/LT-1 (AP-1).

Mini-Module Description	Mini-module ID	Pm of mini-modules (mW)			
		Before coating	After coating	After Thermal Cycling for 50 cycles	After Humidity Freeze for 10 cycles
ARP	314	1103	1075	1030	954
ARP	315	1158	1125	1106	1041
ARP	316	1116	1078	1062	986
AP-1	301	1146	1125	1111	1102
AP-1	302	1145	1137	912	842
AP-1	303	1131	1091	989	938

Mini-modules that had completed Thermal Cycling for 50 cycles were used for this Humidity Freeze Test in accordance with IEC 61215.

As expected, the control modules that were prepared by conventional vacuum lamination showed good durability for Humidity Freeze testing. Over 99% of mean output power (P_m) was retained for these 3 control modules after 10 cycles (Table 18).

Mini-modules prepared by coating with a bilayer configuration comprising refinish primer ARP and top coat LT-1 retained only 97% of their mean output power (P_m) (Table 19). In addition, 2 out of the 3 of these mini-modules failed insulation testing, and some additional cracking was observed beyond that which had resulted during Thermal Cycling.

Experimental mini-module test vehicles that have been coated with the AP-1 primer/LT-1 bilayer configuration showed mixed results after 10 cycles with large variation between the three different samples. One mini-module retained over 99% of its initial power output (P_m) and passed the dry insulation test. Another mini-module retained only about 92% of its initial power output and passed the dry insulation test. A third mini-module, that had already failed the dry insulation test after Thermal Cycling, retained about 95% of its initial power output (Table 19). Visual inspection revealed that some additional cracks had formed in the coating with this bilayer configuration.

10. Summary

The experimental results from this current program indicate that a relatively thin primer/topcoat configuration does have the potential to replace potting film and backsheet in crystalline silicon-based photovoltaic modules. In addition, corrosion inhibiting primers offer the potential to improve photovoltaic module durability relative to lamination films. However, this study was restricted to commercially available coatings that were originally developed for totally different applications. These coatings will require redesign and customization in order to meet all the requirements for photovoltaic module encapsulation. These requirements appear well within the performance space of industrially viable organic coating technology, and further product development seems to be warranted.

Encapsulating a solar cell matrix within potting film by vacuum lamination between a glass superstrate and a protective backsheet (or glass substrate) remains a major process bottleneck in photovoltaic module manufacturing. Throughput is limited by the pump-down and thermal curing cycles required for laminating each module. Even with modern lamination equipment being able to accommodate more than one module at a time, photovoltaic module manufacturing currently is still limited to 10 to 25 Megawatts per production line per annum. Plant expansion requires a linear scale-up by adding more laminating lines. Results from the

current program indicate that a continuous coating process has the potential to replace vacuum lamination and increase line production by an order of magnitude.

Photovoltaic module encapsulation of crystalline silicon solar cells using silicone-based liquids that were applied as coatings were evaluated as part of the US Government funded Flat Plate Solar Array Project that was managed by the Jet Propulsion Laboratory through 1986. Although results were promising, the high cost of silicone-based resins remained prohibitive. Results from the current program indicate that more conventional lower cost organic coatings have the potential to replace silicon-based resins.

Similarly, higher throughput and cost advantages for encapsulating thin film solar modules by using liquid resin were reported. However, this reported photovoltaic module design still relied on a protective backsheet laminated over the cured encapsulating resin. Results from the current program indicate that an exterior grade coating has the potential to eliminate the need for a backsheet.

Corrosion prevention in photovoltaic modules also was addressed as early as the Flat Plate Solar Array Project. Adhesion promoters were found to reduce moisture ingress into the photovoltaic module, and inhibit corrosion of aluminum metal on the back of the crystalline silicon solar cells. For the most part, photovoltaic module design has continued to rely on low water and oxygen permeability to delay the onset of metal corrosion. This current work indicates that metal primers have the potential to inhibit corrosion of circuit bus-bars and interconnects. Eliminating this type of corrosion could prevent certain types of open-circuit and short-circuit failure modes and improve photovoltaic module durability.

Producing electricity by photovoltaic modules holds the promise of extending the energy reserves of the United States of America. For instance, photovoltaic modules currently have an estimated *energy* payback of about 2 years. Reducing photovoltaic module manufacturing costs and extending productive life of these modules is critically important for reducing the total cost-of-ownership for solar energy and shrinking the *cost* payback period. Results acquired during this program lend technical credence to the possibility that, with further development, module manufacturing could be transformed from its current process, now some 30 years old, to a higher throughput, lower cost continuous process using modern in-line coating technology.

By garnering funding from the Department of Energy for this program, PPG Industries enjoyed sufficient incentive to revisit the concept of coating-based encapsulation. Advantages as well as challenges associated with transforming the current photovoltaic manufacturing process to coating-based encapsulation were identified. Sufficient advantages were demonstrated to warrant continued development efforts in this technology by PPG Industries.