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*Presented at the National Center for
Photovoltaics Program Review Meeting
Denver, Colorado
September 8-11, 1998*



National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Work performed under task number PV806201

October 1998

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Abstract. We have conducted a series of accelerated exposure test (AET) studies for various crystalline-Si (c-Si) and amorphous-Si (a-Si) cell samples that were encapsulated with different superstrates, pottants, and substrates. Nonuniform browning patterns of ethylene vinyl acetate (EVA) pottants were observed for glass/EVA/glass-encapsulated c-Si cell samples under solar simulator exposures at elevated temperatures. The polymer/polymer-configured laminates with Tedlar or Tefzel did not discolor because of photobleaching reactions, but yellowed with polyester or nylon top films. Delamination was observed for the polyester/EVA layers on a-Si minimodules and for a polyolefin-based thermoplastic pottant at high temperatures. For all tested c-Si cell samples, irregular changes in the current-voltage parameters were observed that could not be accounted for simply by the transmittance changes of the superstrate/pottant layers. Silicone-type adhesives used under UV-transmitting polymer top films were observed to cause greater cell current/efficiency loss than EVA or polyethylene pottants.

INTRODUCTION

Reliable performance of photovoltaic (PV) modules with a 30-year service life requires that every module component and the entire assembly be durable without substantial degradation during the use period. Natural weathering testing for 20-30 years is impractical when a validation period of 2-5 years is desired for developing products with new encapsulation materials, processing methods, or both. Accordingly, artificial accelerated exposure testing (AET) has practical importance to meet this purpose. This work is the second report of our AET experiments to study issues about the reliability the PV materials and cells [1]. The objectives are to determine and separate the effects of optical degradation of the superstrate and pottant from the electrical degradation of cell components on the overall solar cell performance, to observe the degradation in adhesion of encapsulation materials, and to develop a data correlation methodology for the optical and electrical results. We used small-sized encapsulated solar cells that represent most of the features in a commercial-scale module. The "small-size" approach permits an economical way to test a large quantity of either nearly identical samples for statistical purposes or differently configured samples for ranking or comparison purposes. In this study, we also tested samples of c-Si cell, a-Si minimodules, and a new pottant, respectively, for three PV manufacturers.

EXPERIMENTAL

All of the samples studied were 5.1 cm x 7.6 cm (2 in. x 3 in.) and the c-Si solar cells were 3 cm x 3 cm. (a) ECIS samples had a c-Si cell laminated between two 3.175-mm-thick borosilicate plates with two layers of the commercial EVA formulation, A9918 or 15295. (b) Spire's samples had a c-Si solar cell, 125- μ m or 320- μ m thick, laminated with 25- μ m Tedlar or Tefzel films using a thin layer EVA pottant or silicone adhesive [2]. (c) a-Si minimodules were 3.7 cm x 7.5 cm from a PV manufacturer and were roll-laminated with a thin polymer top-film and a thin encapsulating layer. (d) Samples of Evergreen Solar's polyolefin-based thermoplastic pottants (EGS) were laminated between two borosilicate plates. The type of cell, encapsulation materials, AET, systems employed, and conditions are indicated in the tables. *The EGS samples were exposed side-by-side with ECIS samples in each AET test.* The exposures were conducted in a laboratory with a relative humidity typically in the 20%-40% range. *In-situ* c-Si cell and EVA temperatures were measured by using two custom-made sensors that had five spatially-placed thermocouples under a 3-cm x 3-cm c-Si cell and one between two EVA layers that were encapsulated similarly to the ECIS samples. The samples were characterized periodically for transmittance, color indices, fluorescence, and/or current-voltage (I-V) parameters.

RESULTS AND DISCUSSION

Case 1. ECIS c-Si Cell Samples. For ECIS (and EGS) samples, Table 1 summarizes the type of AET, conditions, pottant types, and percentage changes in the I-V parameters, transmittance (%T) integrated over the 290-792 nm and 290-1252 nm ranges, and yellowness index. The measurement error ranges and standard deviations are also included in the Table. *The efficiency changes in the c-Si cell are irregular with respect to the AET type, conditions, and %T changes!* For the ECIS samples exposed in DSET CPS systems and in an oven, where EVA did not discolor, seven cells showed a net gain in short-circuit current density (J_{sc}) or efficiency and two showed a net loss (within the measurement error range). Only one cell sample showed little change. For the cells exposed to a UV-enhanced solar simulator (UV-SS), the EVA gradually turned yellow-brown, but net efficiency gains are observed even though the %T shows a net loss of 9%-17%. More obvious efficiency decreases corresponding, though not linearly or proportionally, to large %T losses are observed for those samples exposed to the full-spectrum solar simulator (FS-SS), where the EVA rapidly turned dark brown in ~7-10 days. Here, the monitored *in-situ* temperature of the c-Si cell was ~125°C, and it was ~110°-115°C for the EVA layer in the "optical" region. Nonuniform EVA browning was observed in both the UV-SS and FS-SS exposed samples, but was more profound in the FS-SS exposed samples. This resulted in a lower photocurrent from the cell perimeter region under darkly browned EVA and a higher photocurrent from the central region under less browned EVA. For comparison, a fairly uniform EVA browning was observed over the 10-cm x 10-cm c-Si cells in field-degraded modules.

TABLE 1. Change (%) of I-V Parameters, Transmittance, and Yellowness Index for Encapsulated Si Cells and an EGS Pottant by AET Treatments

Sample ID	Superstrate	Pottant Type	Substrate	Time (h)	V _{oc} (%)	V _{max} (%)	J _{sc} (%)	J _{max} (%)	FF (%)	P _{max} (%)	%T (%)	Rate (%T/h)	Net YI Change	Rate (YI/h)
Measurement Error Range (+-%):					0.99	1.85	2.35	3.38	1.11	1.75	0.63		4.79	
Standard Deviation/Average (%):					0.55	1.85	1.87	2.01	0.66	1.39	0.35		3.23	
AET: Oven/0 UV sun/85°C											(290-792nm)			
ECIS-03	Boro ¹	15295P ²	Boro	1581	-0.58	-3.08	-2.88	-2.38	-2.04	-5.38	-0.72	-4.55E-2	1.02	6.47E-4
ECIS-07	Boro	15295P	Boro	1216	-0.14	-3.34	11.70	9.00	-5.60	5.30	-2.23	-1.83E-1	0.56	4.59E-4
ECIS-19	Boro	A9918P ²	Boro	925	0.10	0.00	6.61	6.94	0.20	6.88	-0.76	-8.21E-2	0.19	2.08E-4
EGS-07	Boro	EGS ³	Boro	1216							-0.39	-3.17E-2	0.36	2.96E-4
EGS-08	Boro	EGS	Boro	1216							-0.16	-1.34E-2	0.33	2.74E-4
AET: DSET CPS Tabletop Exposure System #2/~1 UV sun/BPT=60-65°C														
ECIS-04	Boro	15295P	Boro	1188	-0.14	-2.15	11.72	12.57	-1.26	10.19	-1.50	-1.26E-1	-0.02	-1.41E-5
ECIS-16	Boro	A9918P	Boro	906	-1.17	-4.29	4.98	-8.42	-15.55	-12.37	-0.68	-7.51E-2	0.35	3.87E-4
EGS-01	Boro	EGS	Boro	1188							-0.44	-3.66E-2	-0.32	-2.69E-4
EGS-02	Boro	EGS	Boro	1188							-0.12	-9.90E-3	-0.29	-2.47E-4
AET: DSET CPS Tabletop Exposure System #3/~1 UV sun/BPT=80-85°C														
ECIS-05	Boro	15295P	Boro	1186	-0.42	-1.94	13.33	11.44	-3.17	9.32	-1.13	-9.52E-2	0.38	3.17E-4
ECIS-17	Boro	A9918P	Boro	904	-0.71	-3.55	4.50	4.88	-2.46	1.17	-1.69	-1.87E-1	1.68	1.86E-3
EGS-03	Boro	EGS	Boro	1186							-0.73	-6.14E-2	-0.23	-1.90E-4
EGS-04	Boro	EGS	Boro	1186							-0.76	-6.40E-2	-0.20	-1.65E-4
AET: UV-enhanced Solar Simulator (UV-SS) #2/~7.5 UV suns/BPT=85°C														
ECIS-06	Boro	15295P	Boro	849	-0.07	-0.68	6.38	6.53	-0.45	5.79	-17.43	-2.05E+0	26.76	3.15E-2
ECIS-08	Boro	15295P	Boro	1186	-0.60	1.29	6.76	3.07	-1.61	4.42	-16.13	-1.36E+0	24.23	2.04E-2
ECIS-22	Boro	A9918P	Boro	870	-2.70	-3.85	2.91	8.04	3.73	3.84	-9.28	-1.07E+0	18.84	2.17E-2
EGS-05a	Boro	EGS	Boro	872							-4.01	-4.60E-1	-0.04	-4.19E-5
AET: Full Spectrum Solar Simulator (FS-SS) #3/~9.0 UV suns/BPT~145°C (T(EVA) ~ 110-115°C)														
ECIS-09	Boro	15295P	Boro	1082	-1.14	-2.07	-16.11	-17.79	-2.90	-19.46	-50.43	-4.66E+0	61.19	5.66E-2
ECIS-10	Boro	15295P	Boro	1082	-2.55	-4.40	-16.90	-18.02	-3.25	-21.62	-45.14	-4.17E+0	54.09	5.00E-2
ECIS-18	Boro	A9918P	Boro	805	-2.26	0.23	-22.76	-23.50	1.51	-23.35	-32.76	-4.07E+0	38.68	4.80E-2
EGS-06	Boro	EGS	Boro	746	(Severe delamination in 250 h)						-3.79	-5.08E-1	1.89	2.54E-3

¹ Boro: borosilicate of 3.175-mm thick.

² Commercial EVA formulation: Fast-cure EVA 15295P and slow-cure EVA A9918P, where P stands for silane-primed.

³ EGS samples do not contain c-Si solar cells and are laminated single layer.

Case 2. Spire's c-Si Cell Samples. The thin c-Si cells were used by Spire to fabricate lightweight PV modules, as described in detail by M. Nowlan et al. [2]. The c-Si cells were laminated between two layers of air-permeable Tedlar or Tefzel polymer films. In an earlier work, we reported studying various encapsulation schemes, including the polymer/solar cell/polymer configuration [3]. Upon AET in a DSET system, the film laminates were not discolored because of photobleaching of the EVA or silicone adhesive [3,4]. A few films wrinkled upon exposure, but no delamination was observed. Table 2-Part I summarizes the encapsulation materials for each of the samples, the changes in the I-V parameters, and the small net increase in %T. As with the ECIS samples, the cells' I-V parameters also exhibit irregular changes. The most unusual observations are on cell samples D1-2 and D2-1 that were laminated with silicone adhesive and UV-transmitting Tefzel. The two cells showed, respectively, a 23% vs. 24% loss in J_{sc} , a 16% vs. 28% loss in P_{max} (or efficiency), but a 5.0% vs. 6.6% increase in %T. In contrast, the D1-2 and D2-2 cells that were also laminated with silicone, but with UV-screening Tedlar, did not show such large loss in efficiency.

Case 3. a-Si Minimodules. Table 2-Part II shows the encapsulation materials, changes in I-V parameters, discoloration, and delamination observed for the exposed a-Si minimodules. All polymer top-films (polyester and nylon) turned light yellow or a darker yellow. The top-film on two samples was delaminated from the a-Si layer, and the nylon top-film on another sample was substantially wrinkled. The a-Si minimodules degraded as expected upon light exposure. A larger decrease in I_{max} and P_{max} occurred on the sample laminated with a thicker (3.0-mil) UV-screening polyester. As with the Spire samples, the a-Si sample laminated with silicone adhesive showed an efficiency loss of 20.6%, the largest of any cell.

The irregularity in the results presented in Tables 1 and 2 indicates that optical transmittance loss alone is not sufficient to explain the exact cause(s) or to pinpoint the electrical degradation mode(s) responsible for the cell efficiency changes upon AET treatments. To obtain a better interpretation, presently, we are performing detailed analysis of the dark/light I-V data to determine the changes in the series resistance (R_s), shunt resistance (R_{sh}), and diode quality factor (n). Such analysis may be useful because the changes in the fill factor (FF) are also irregular, but mostly negative, suggesting an increase in the cell series resistance. The UV-transmitting Tefzel films may have permitted UV-induced photochemical reactions of the silicone adhesive and produced yet unidentified by-products that caused chemical degradation of the c-Si and a-Si cells and metallic components.

Case 4. Evergreen Solar's Thermoplastic Pottant. The AET results are shown in Table 1. When exposed in an oven in the dark or to ~ 1 UV sun at a black panel temperature (BPT) of 60°-65°C or 80°-85°C for 900-1200 h, both EGS films and EVA remained clear. The thickness of the laminated EGS films is typically $\sim 10 \pm 2$ mil as compared to a thickness of $\sim 20 \pm 2$ mil for the EVA layer in the optical region of the ECIS samples. Assuming a linear %T loss versus AET time for convenience, then the EGS film showed a slightly lower %T loss rate than EVA (*the thickness difference is not considered*). Under more severe AET conditions using solar simulators, EVA

TABLE 2. Change (%) of I-V Parameters, Transmittance, and Adhesion for Encapsulated c-Si Cells and a-Si Minimodules by AET Treatments

Part I. AET: DSET CPS Tabletop Exposure System #2/~1 UV Sun/BPT~60-65°C/1188 h

c-Si Cell ID	Cell Thick- ness (μm)	Top Film	Pottant Type	Bottom Film	V _{oc} (%)	V _{max} (%)	J _{sc} (%)	J _{max} (%)	FF (%)	P _{max} (%)	Transmittance (%)	
											290-790nm	290-1500nm
A1-2	320 +/- 50	Tedlar*	EVA*	Tedlar	-0.82	-3.30	3.96	- 5.69	-11.52	- 8.78	0.37	-0.50
A2-2	125 +/- 25	Tedlar	EVA	Tedlar	-0.51	-2.83	9.19	10.34	- 1.30	7.20	1.10	1.06
B1-1	320 +/- 50	Tefzel*	EVA	Tefzel	0.00	-1.26	4.63	6.04	0.12	4.74	2.14	1.53
B2-1	125 +/- 25	Tefzel	EVA	Tefzel	-0.36	-2.32	7.30	8.02	- 1.35	5.48	1.57	1.26
C1-2	320 +/- 50	Tedlar	Silicone*	Tedlar	-0.59	-3.51	6.39	10.82	1.10	6.90	1.09	0.52
C2-2	125 +/- 25	Tedlar	Silicone	Tedlar	-1.17	-1.87	4.14	- 0.29	- 4.91	- 2.19	1.25	0.07
D1-2	320 +/- 50	Tefzel	Silicone	Tefzel	-1.04	-0.65	-22.69	-15.43	9.90	-15.95	6.60	3.75
D2-1	125 +/- 25	Tefzel	Silicone	Tefzel	-0.52	-1.30	-22.87	-27.18	- 6.34	-28.13		
D2-1		Tefzel	Silicone	Tefzel	-0.24	-1.30	-25.46	-27.71	- 4.08	-28.66		
D2-1		Tefzel	Silicone	Tefzel	-0.34	2.16	-23.54	-29.82	- 5.96	-28.32		
		(3 measurements for D2-1):			-0.36	-0.14	-23.96	-28.24	- 5.46	-28.37	5.01	2.67

* The c-Si solar cells are laminated between 25 μm UV-screen Tedlar or 25 μm Tefzel with 90 μm EVA or 50 μm Silicone transfer adhesive

Part II. AET: DSET CPS Tabletop Exposure System #1/~1 UV Sun/BPT~60-65°C/1235 h

a-Si Cell ID	Area (cm ²)	Top Film	Pottant/ Adhesive	V _{oc} (%)	V _{max} (%)	J _{sc} (%)	I _{max} (%)	FF (%)	P _{max} (%)	Film Color	Adhesion
F57S6-1	20.65	PES*	EVA	-1.81	-4.68	- 9.38	- 3.83	3.04	- 8.34	Light yellow	Delaminated
		(1.5 mil)	(0.5 mil)								
F57S11-2	20.46	UV-PES	PE*	-2.10	-3.13	- 9.08	- 5.37	3.05	- 8.31	Light yellow	Delaminated
		(1.0 mil)	(2.0 mil)								
F57S18-3	20.67	UV-PES*	PE	-4.20	-7.33	-10.80	-10.76	-2.95	-17.11	Light yellow	
		(3.0 mil)	(2.0 mil)								
F55S28-4	20.27	Nylon	Silicone	-1.69	-7.27	-14.10	-14.40	-6.00	-20.61	darker yellow	Wrinkled
		(1.5 mil)	(1.5 mil)								

* PES: polyester; UV-PES: UV-screen polyester; PE: polyethylene thermal set adhesive.

discolored to yellow-brown or dark brown, but the EGS film did not discolor. The %T loss rates for the EGS films were 3-4 times less than the EVA when exposed to 7.5 UV suns at a BPT of 85°C and was ~8 times less when exposed to 9.0 UV suns at a BPT of ~145°C. In the latter conditions, however, the EGS film exhibited severe coral-like delamination from the borosilicate plate in ~250 h, which might have resulted from a melting point of 100°-110°C for the thermoplastic material. Our results show the EGS films are photochemically stable against UV-induced browning, in good agreement with other results reported recently by Hanoka [5]. However, the EGS films may require improvement in the adhesion strength for their modules to operate at high temperatures.

CONCLUSIONS

We have reported the results of a series of AET studies for various Si cell samples that were encapsulated with different superstrates, pottants, and substrates. Irregular changes in the J_{sc} , FF, and cell efficiency were observed for all tested c-Si cell samples, which cannot be simply attributed to the %T loss of the superstrate/pottant. More detailed analysis of the light/dark I-V and electrochemical impedance data is under way. Different kinds of delamination were observed separately on a-Si minimodules and for EGS films at high temperatures. Silicone adhesives used under UV-transmitting polymer top-films seem to cause a greater loss in cell current and efficiency. The new pottant used by EGS may avoid adhesion failure and be a good pottant if the modules are not used at high operating temperatures. To continue the AET studies, we are preparing a large-scale "matrix experiment" using a large number of variously encapsulated c-Si cells for AWT in weatherometers. We are also investigating the issues of nonuniform EVA browning patterns observed in the ECIS samples.

ACKNOWLEDGEMENTS

The authors thank A. Czanderna and R. Hulstrom for their support of this work and K. Emery, H. Field, and D. Dunlavy for the assistance in the I-V measurements. This work was supported by the Department of Energy under Contract No. DE-AC36-83CH10093.

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