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Preprint

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*Presented at the 42nd IEEE Photovoltaic Specialists Conference
New Orleans, Louisiana
June 14–19, 2015*

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Conference Paper
NREL/CP-5J00-63508
August 2015

Contract No. DE-AC36-08GO28308

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Degradation in PV Encapsulation Transmittance: An Interlaboratory Study Towards a Climate-Specific Test

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Abstract — Reduced optical transmittance of encapsulants resulting from ultraviolet (UV) degradation has frequently been identified as a cause of decreased PV module performance through the life of service in the field. The present module safety and qualification standards, however, apply short UV doses only capable of examining design robustness or “infant mortality” failures. Essential information that might be used to screen encapsulation through product lifetime remains unknown. For example, the relative efficacy of xenon-arc and UVA-340 fluorescent sources or the typical range of activation energy for degradation is not quantified. We have conducted an interlaboratory experiment to provide the understanding that will be used towards developing a climate- and configuration-specific (UV) weathering test. Five representative, known formulations of EVA were studied in addition to one TPU material. Replicate laminated silica/polymer/silica specimens are being examined at 14 institutions using a variety of indoor chambers (including Xenon, UVA-340, and metal-halide light sources) or field aging. The solar-weighted transmittance, yellowness index, and the UV cut-off wavelength, determined from the measured hemispherical transmittance, are examined to provide understanding and guidance for the UV light source (lamp type) and temperature used in accelerated UV aging tests.

Index Terms — reliability, durability, thermal activation.

I. INTRODUCTION

The degradation of encapsulants used for photovoltaic (PV) modules subject to weather - the combined factors of light, especially that in the ultraviolet (UV), temperature, and moisture (relative humidity, %RH) has been examined

previously [1], [2], [3] — particularly after the incident at the Carrizo Plains concentrator installation [4]. The former studies, *e.g.*, [1], highlight the reduction in transmittance and the effect on characteristics including gel content and chemistry for poly (ethylene-co-vinyl acetate) (EVA) encapsulant. The latter studies, *e.g.*, [2], [3], confirm that the degradation of EVA results from interactions and incompatibilities between formulation additives. The module safety (IEC 61730) and qualification (IEC 61215 series) tests presently apply to only a short (up to 137 days equivalent of the IEC 60904-3 AM 1.5 global UV-B radiation dose) UV exposure. To establish module reliability for relevant, long-term use, *e.g.*, comparable to the desired lifetime of 25 years, requires greater understanding.

We are conducting a set of experiments to provide the understanding that will be used to develop weathering exposures for PV encapsulants that account for stresses in different use environments, including different terrestrial climates and mounting configurations. The effort and results for an initial set of work studying the degradation in optical transmittance of encapsulants are described here. Other portions of the work examine the effect of weathering on adhesion of glass to encapsulants or edge seals. Because no single institution had all of the resources to run the numerous exposure conditions, 15 institutions are collaborating in this work, as represented by the authors of this paper.

The goals of this encapsulant transmittance study include:

- Quantify the activation energies, E_a , for the degradation of transmittance. This includes providing a sense of the range

of the E_a that may be present by examining “known bad,” “known good,” and “intermediate” material formulations.

- Determine if there is significant coupling between relevant stress factors, *i.e.*, UV, temperature, and humidity. This will identify what factors need to be considered in an accelerated test.

- Investigate the spectral requirements for different light sources by comparing aged specimens, *i.e.*, for Xe-arc, UVA-340 fluorescent, and metal-halide lamps. One concern in addition to UV radiation was the inclusion of visible light.

II. EXPERIMENTAL

A variety of encapsulant formulations were exposed as glass/encapsulant/glass specimens under a variety of different steady state conditions. As summarized in TABLE III, six different encapsulation materials were studied in the transmittance test. The formulation additives (including their purpose, make, and relative concentration) are identified in TABLE III for the EVA samples. “N/A” is used to indicate where an additive was not present, while “?” indicates where the presence of an additive is not known. The material designation used in the figures and text is indicated at the bottom of the table. The specimens include those prone to discoloration (“known bad”), those expected to change minimally (“known good”), representatives of contemporary material (“modern”), and two formulations frequently examined in the literature. The five formulations of EVA were fabricated at Specialized Technology Resources, Inc (STR). One thermoplastic polyurethane (TPU) product from outside the PV industry known to discolor rapidly in an outdoor environment was also included.

The description here is primarily focused on materials exposed at the National Renewable Energy Laboratory (NREL) in two devices: a Ci5000 by ATLAS Material Testing Technology LLC, *i.e.*, Xe lamp with “Right Light” filter; and the NREL “UV Suitcase” (a custom chamber using UVA-340 fluorescent lamps from Q-Lab Corp.). The Ci5000 used exposure settings of $1.0 \text{ W}\cdot\text{m}^{-2}\cdot\text{nm}^{-1}$ at 340 nm, with the indoor chamber temperature set point of 60°C , the black panel temperature uncontrolled, and the chamber controlled to 30% RH, resulting in a measured sample temperature of $\sim 63^\circ\text{C}$. The UV Suitcase was set at $1.0 \text{ W}\cdot\text{m}^{-2}\cdot\text{nm}^{-1}$ at 340 nm, with a chamber temperature of 60°C and uncontrolled %RH, resulting in a measured sample temperature of $\sim 55^\circ\text{C}$. Exposure times are reported for the cumulative radiant exposure, H , provided for the wavelength range $295 \leq \lambda \leq 360 \text{ nm}$ so that the results may be more readily compared between Xe and UVA-340 sources, as suggested in Ref. [5].

Weathering specimens were made by first laminating a 36.8-cm x 36.8-cm silica/encapsulant/silica stack using a thickness-specific removable layer to ensure good ($0.45 \pm 0.03 \text{ mm}$) thickness uniformity. Lamination was carried out for 8 minutes at 145°C . The resulting samples were then diced into 5.1-cm x 5.1-cm coupons using an abrasive water jet saw. Diced specimens were then preconditioned in temperature/humidity chambers for 1 month to achieve a

baseline moisture concentration in the polymer similar to that applied in indoor aging. Silica glass (transmitting above 202 nm) was used rather than industry-standard soda-lime glass (transmitting above 295 nm), so that the glass would not attenuate UV radiation.

Transmittance measurements were obtained at 0, 15, 30, 45, 60, 75, 90, 120, and 180 days cumulative exposure. Transmittance measurements were obtained at the center and periphery (within $\sim 0.5 \text{ cm}$ of the edge) for each of the specimens. Measurements were performed using spectrophotometers equipped with an integrating sphere according to the procedure in IEC 62788-1-4 [6], with the 1-nm incremented measurement beginning from 200 nm rather than the default minimum of 280 nm. Transmittance values are reported as either the representative solar weighted transmittance of photon irradiance, τ_{RSW} [6], directly related to module performance, yellowness index (YI), a mathematical treatment of the same spectral data which quantifies the change in color perceived by a human observer, or the UV cut-off wavelength, λ_{cUV} , which quantifies when the material becomes transmitting. YI is a more acute indicator than the characteristic of τ_{RSW} , with the threshold for interlaboratory repeatability of 0.27 vs. 0.63%, respectively [6]. Each data point is the average of the measurements for three replicate specimens with the corresponding error bounds for one standard deviation.

III. RESULTS

All samples showed signs of degradation through the experiment. The loss of transmittance with age for the materials exposed to UVA-340 is compared in Fig. 1. τ_{RSW} is reduced after 180 days by 3.4% and 2.3% for TPU and EVA-A, respectively, but is increased by 1.0% for EVA-C. τ_{RSW} changed by $<1\%$ for the other materials. In contrast, the specimens aged in the Ci5000 exhibited τ_{RSW} reductions of 5.1% and 2.3% at 180 days for TPU and EVA-A, respectively.

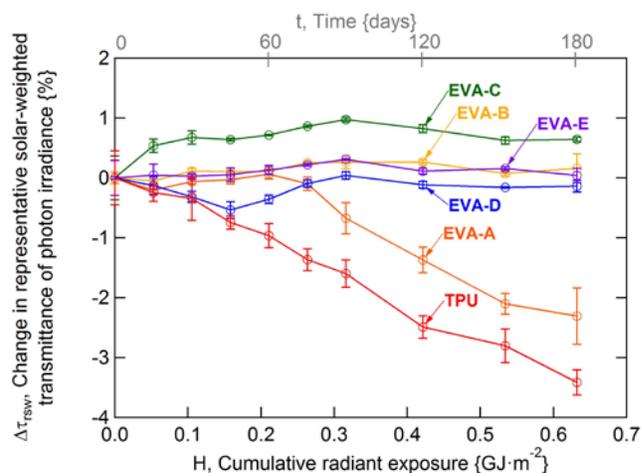


Fig. 1. Change in transmittance with radiant exposure (H) for the center of coupons aged in the NREL UV Suitcase (UVA-340 lamps, with the chamber controlled at 60°C and uncontrolled %RH).

The discoloration with age for the materials examined is compared in Fig. 2. Some of the materials show a sustained increase in YI over the course of exposure, while others show a discrete inflection in the data (material label is underlined in the figure). Inflections were not always obvious in the τ_{rsw} data (e.g., compare EVA-D in Fig. 2), which indicates the utility of the examination of YI . Different behaviors were observed for the UVA-340 and Xe weathering. Inflections were observed for EVA-A, EVA-C, and EVA-D aged in UVA-340 (Fig. 2), but only EVA-D and TPU demonstrate an inflection in YI when aged using a Xe source (not shown).

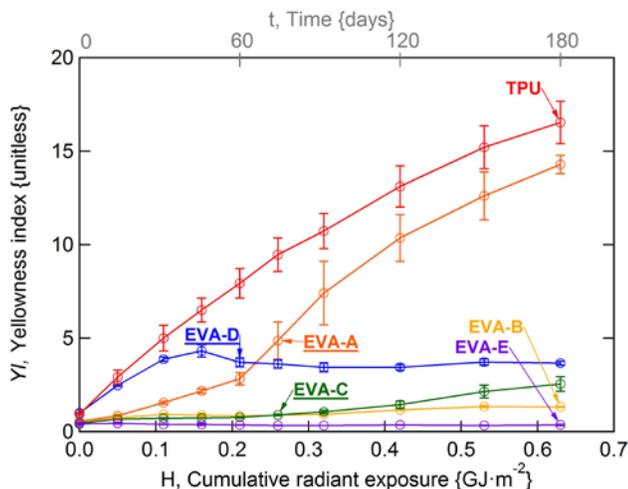


Fig. 2. Change in YI with H for the center of coupons aged in the NREL UV Suitcase (UVA-340 fluorescent lamps, with the chamber controlled at 60°C and uncontrolled %RH).

The results in Fig. 2 may be compared to the literature, which has historically focused on YI . In Ref. [3], a change in YI of ~ 56 was observed for the STR product PHOTOCAP A9918P/UF (similar to EVA-A), while a ΔYI of ~ 30 was observed for 15295P/UF (similar to EVA-B). Weathering exposures in that study achieved a similar radiant exposure, but with a lower irradiance level ($0.55 \text{ W}\cdot\text{m}^{-2}\cdot\text{nm}^{-1}$ at 340 nm) and higher applied temperature. The experiment in Fig. 5 identifies that temperature enables greater ΔYI such as observed in Ref. [3]. Consider that the 70°C chamber temperature would result in a sample temperature up to $\sim 15^\circ\text{C}$ higher than specimens in this study (measured at 63°C for the Ci5000 aged samples).

Inflections as observed in the data profiles in Fig. 2 are generally associated with degradation modes occurring via multiple chemical mechanisms. Two different behaviors are noted here: in some cases, e.g., EVA-A in Fig. 2, a steeper slope follows an initial period of more gradual sustained change; in other cases, EVA-D Fig. 2, a steady degradation is observed in the early stages of exposure, followed by a stabilization.

The material specific spectral transmittance (hemispherical transmittance, τ_h { % }) results are shown in Fig. 3 for all the material types aged using UVA-340. The transmittance of TPU and EVA-A is greatly reduced above 400 nm, with a

corresponding increase in YI . EVA-D is affected similarly, but to a lesser extent. The change in the transmittance spectra for TPU and EVA-A is consistent with the decreased transmittance with age for these materials in Fig. 1. The UV transmittance (below 400 nm) is increased for EVA-E, EVA-C, and EVA-A. For EVA-C, the increase in τ_h at ~ 350 nm specifically facilitates the increase in its τ_{rsw} with age.

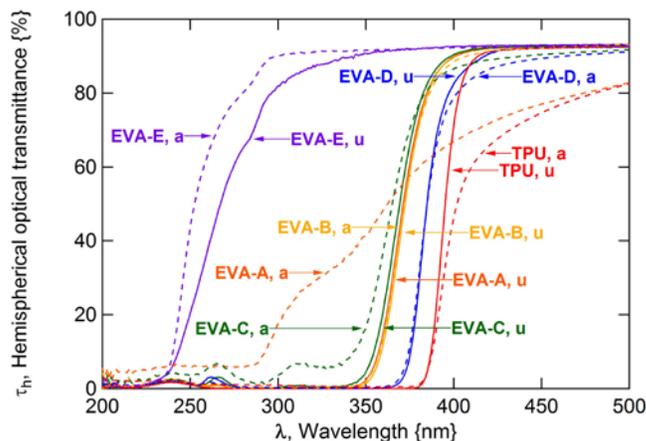


Fig. 3. The UV spectral transmittance of the encapsulation materials examined. The subscript $-u$ (solid lines) indicates the data for unaged specimens, while the subscript $-a$ (dashed lines) indicates the data for specimens aged for 6 months in the NREL UV Suitcase.

The spectral data are summarized for the two UV sources in TABLE I for the characteristics of τ_{rsw} , YI , and λ_{cUV} . A qualitative explanation of the observed changes is also provided in the table. The data in TABLE I evidence sometimes complex disparities between the materials, e.g., for EVA-C an *increase* in YI (associated with formation of new optically absorbing species) counter-intuitively occurs at the same time as an *increase* in transmittance (associated with the loss of absorbing species). This is explained by the transmittance spectra in Fig. 3 for aged EVA-C by the increase in the spectral bandwidth below the λ_{cUV} , occurring along with a decrease in the transmittance above the λ_{cUV} .

TABLE I
COMPARISON OF CHANGE IN PERFORMANCE BETWEEN UV SOURCES.

MATERIAL	UV Suitcase (UVA-340)		Ci5000 (Xe)			QUALITATIVE EXPLANATION	
	$\Delta\tau_{\text{rsw}}$ { % }	ΔYI { unitless }	$\Delta\lambda_{\text{cUV}}$ { nm }	$\Delta\tau_{\text{rsw}}$ { % }	ΔYI		$\Delta\lambda_{\text{cUV}}$ { nm }
EVA-A	-2.1	+13.7	-64	-2.1	+7.9	-6	TBD
EVA-B	+0.1	+0.9	-1	+0.3	+0.4	-1	Little change
EVA-C	+0.6	+2.1	-11	+0.4	+1.1	-5	Loss of additive
EVA-D	-0.1	+2.7	-1	-1.6	+2.9	-1	Formation of degradation product
EVA-E	0.0	-0.1	-1	+0.2	0.0	-3	Loss of additive
TPU	-3.1	+15.6	-20	-4.6	+17.2	-1	Formation of degradation product

The following are formulation-specific observations from Fig. 1, Fig. 2, Fig. 3, and TABLE I:

- TPU was visibly yellow after weathering, with a corresponding decrease in τ_{rsw} and increase in YI . Spectra for UVA-340 or Xe aged specimens show a similar reduction in transmittance above λ_{cUV} , with a more severe rounding of the cut-on profile for TPU aged using Xe ($\Delta YI = 17.2$), than UVA-340 ($\Delta YI = 15.6$).

- EVA-E increased in spectral bandwidth near ~ 240 nm, the λ_{cUV} , but there was little to no change in τ_{rsw} or YI (spectral weighting is low for the UV-C wavelength range).

- EVA-B and EVA-D were affected similarly, with optical absorbance increasing slightly at ~ 390 nm (EVA-D was more affected than EVA-B); the results are qualitatively the same for both UVA-340 and Xe weathering.

- EVA-C and EVA-A both showed greater differences from aging for the UVA-340 exposures.

- EVA-C was more affected by the UVA-340 ($\Delta\lambda_{\text{cUV}} = -11$ nm for UV Suitcase) than Xe ($\Delta\lambda_{\text{cUV}} = -5$ nm for Ci5000) spectrum. Transmittance reduction from discoloration ($\Delta YI = 2.1$ and $\Delta YI = 1.1$) was outweighed by the increased spectral bandwidth, increasing transmittance by $a\tau_{\text{rsw}}$ of 0.6% and 0.4% for EVA-C in UVA-340 and Xe, respectively. The increase in τ_{h} at ~ 350 nm (Fig. 3) specifically facilitates the net increase in τ_{rsw} with age (Fig. 1) for EVA-C. Additional transmittance peaks are also observed for UVA-340 aged EVA-C at ~ 262 nm and ~ 312 nm.

- Significant changes occur in the EVA-A spectrum after UVA-340 exposure, where a much greater change is observed ($\lambda_{\text{cUV}} = -64$ nm) than for Xe ($\lambda_{\text{cUV}} = -6$ nm). In addition to the large change in spectral bandwidth (defined in Ref. [6] for the τ_{h} of 10%), a more severe rounding of the cut-on profile was observed for EVA-A aged using UVA-340 ($\Delta YI = 13.7$) than for Xe ($\Delta YI = 7.9$). Additional failure analysis will be performed for these specimens to understand the underlying changes (e.g., depletion of UV absorber) in their chemistry.

IV. DISCUSSION

Implications concerning degradation mode(s). The spectral changes after weathering imply changes in the concentration of components within the base material, consistent with a model that may include both loss of species due to degradation or migration and the addition of by-product species. For example, the reduced transmittance for TPU follows from the formation of chromophore by-product species. For EVA-C, the shift in λ_{cUV} to lower wavelengths is likely related to loss of UV absorber due to degradation and/or diffusion. Similarly, the shift in λ_{cUV} to lower wavelengths for EVA-E, likely follows from the loss of formulation additives.

For EVA-A and EVA-C, additional insight follows from the difference in results between the Ci5000 and UV Suitcase. While the intensity of irradiance for both devices was set equal at the 340 nm, the Xe exposure will provide the same photon spread below 340 nm, plus additional radiation at

wavelengths above 340 nm, where UVA-340 emits less radiation [7]. Any photochemistry initiated in the UV Suitcase will therefore also occur in the Ci5000, with additional photochemical reactions initiated at the higher wavelengths possible. The data in TABLE I suggest that the EVA-A and EVA-C samples are degraded more for UVA-340 than for Xe weathering, which itself is an unlikely result. Greater discoloration implies the formation of optically absorbing chromophore species. The difference for EVA-A may result from a photobleaching process, enabled by the longer wavelengths of light present from a Xe source.

The lack of change for EVA-E suggests that the observed degradation of the other EVA samples is related to the additives, due either to incompatibility or UV-vulnerability. For example, the reduced transmittance for EVA-A follows from the formation of chromophore species, whereas the increased transmittance for EVA-C or EVA-E suggests the decomposition or loss of volatile species. This finding is consistent with Refs. [2] and [3], where for example the discoloration of A9918P/UF (similar to EVA-A) was attributed to an interaction between the Lupersol 101 (curing agent), Naugard P (AO), and Tinuvin 770 (UV absorber) in Ref. [2]. Examination of the data in Fig. 2 suggests that the UV absorber is the ultimate source of discoloration for many of the EVA formulations examined (YI does not increase when an absorber is absent, as in EVA-E). From Fig. 2, Tinuvin 770 is foremost affected by Lupersol 101 (present in EVA-A), then Naugard P (present in EVA-B). Additive-facilitated degradation is fundamentally different from the intrinsic UV degradation of EVA, e.g., following directly from the formation of unsaturated species such as polyenes as suggested incorrectly in Ref. [1] or in academic studies examining unformulated EVA.

All of the data described above come from measurements made at the center of the specimens. Additional data were taken at the specimen edges. Visible discoloration could be observed at the anaerobic center of the EVA-A and EVA-D specimens, with no observed discoloration (and minimal change in τ_{rsw} , YI , and λ_{cUV}) at the periphery. This is consistent with the literature, where an oxygen-enabled photobleaching is identified for EVA at the periphery of PV cells [2], [3].

Rate analyses. A degradation rate comparison can be applied to compare the effects of different weathering conditions. For example, the transmittance data for EVA-A and TPU, the materials with the greatest change in τ_{rsw} , are shown in Fig. 4. The slopes determined for the six materials are listed in TABLE II. A linear fit, fixed to the origin, was applied in the analysis. While a simple linear dependence is assumed here, as used to distinguish the inflections in Fig. 2, a more complicated functional dependence might instead be applied to analyze the data. For the transmittance curves with an inflection, the initial data points before the perceived inflection were used, as shown in Fig. 4 and summarized in TABLE II. The ratio of the slopes for the UVA-340 and Xe exposures provides a means to compare weathering between the different materials. As in the inset of Fig. 4, the relative degradation rate (k_{H} , unitless) follows as the ratio of the slopes

of the linear fit, *i.e.* the multiplier that is required to scale the data for UVA-340 aged specimens parallel to the data profile for Xe aged specimens. (A k_H of 1 would indicate that τ_{rsw} is changing at the same rate for both Xe and UVA-340 sources.) The change in τ_{rsw} did not exceed the repeatability threshold of the measure for EVA-B and EVA-E; therefore, no k_H value is given, “N/A.”

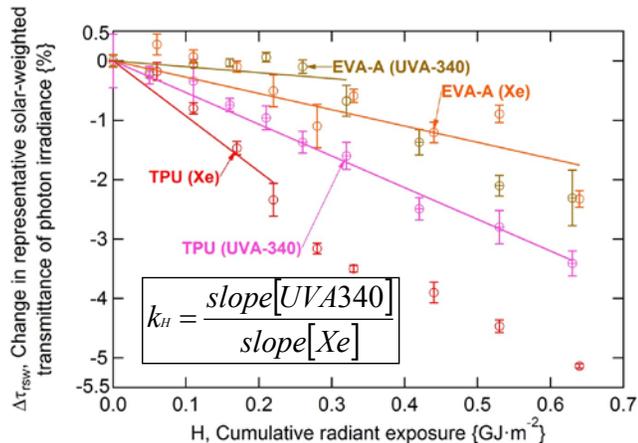


Fig. 4. Comparison of change in transmittance for EVA-A and TPU with light source (Xe in Ci5000 or UVA-340 in UV Suitcase). The default temperature of 60°C was applied in each chamber, with the %RH maintained at 60% or uncontrolled, respectively.

TABLE II

SUMMARY OF RESULTS OF RELATIVE DEGRADATION RATE ANALYSIS.

MATERIAL	RANGE OF ANALYSIS, UVA-340 {GJ·m ⁻² }	RANGE OF ANALYSIS, Xe {GJ·m ⁻² }	k_H (for τ_{rsw}) {unitless}
EVA-A	0-0.32	0-0.64	0.08
EVA-B	0-0.63	0-0.64	N/A
EVA-C	0-0.42	0-0.64	3.4
EVA-D	0-0.63	0-0.64	1.1
EVA-E	0-0.63	0-0.64	N/A
TPU	0-0.63	0-0.28	0.6

The k_H of 0.08 for EVA-A aged in UVA-340 indicates that the degradation in the UV Suitcase is significantly slower than for the Ci5000 at the start of the experiment. Different chemical mechanisms likely regulate the initial degradation of EVA-A in Xe and UVA-340 weathering. By the end of exposure, the overall reduction in transmittance is, however, similar for Xe and UVA-340. In retrospect, for TPU, an k_H value on the order of $1.4^{-1} = 0.7$ might be ideally expected in Fig. 4, based on the $\sim 10^\circ\text{C}$ greater specimen temperature for the Xe chamber [8].

Thermal activation is being examined directly in ongoing exposures at 3M, with the same irradiance level and %RH applied in three similar Ci5000 chambers operated at different temperatures. The interim results are shown in Fig. 5 for EVA-A. The effect of temperature on aging is strong, where the reduction of 10.5% at 80°C at $H = 0.44 \text{ GJ}\cdot\text{m}^{-2}$ in Fig. 5 exceeds that of 2.3% at the end of the experiment for EVA-A

in Fig. 1. Increased degradation with temperature is observed for the other materials except EVA-E, where no significant $\Delta\tau_{rsw}$ was observed. Coupling between UV degradation and temperature was anticipated from field observations, *e.g.*, increased discoloration at local hot spots in modules, such as: warm solder joints; proximate locations to the junction-box; and sometimes even the module front, above the name plate sticker.

Temperature trends were analyzed using an Arrhenius fit [8], Fig. 5 inset. An activation energy on the order of $\sim 60 \text{ kJ}\cdot\text{mol}^{-1}$ is presently estimated for the loss of τ_{rsw} observed for EVA-A. In comparison, the range of $10\text{--}40 \text{ kJ}\cdot\text{mol}^{-1}$ is typically observed for the photodegradation of structural polymers and coatings [8]. It should be noted that the effect of polymer morphology on degradation rate is not well established, whereas *cross-linked* EVA undergoes a melt transition at $\sim 60^\circ\text{C}$. In comparison, maximum annual temperatures from 70°C – 90°C are readily anticipated within rack- and roof-mounted modules in hot, dry locations [9]. Additional examination within the interlaboratory study will assess if moisture contributes significantly to UV degradation.

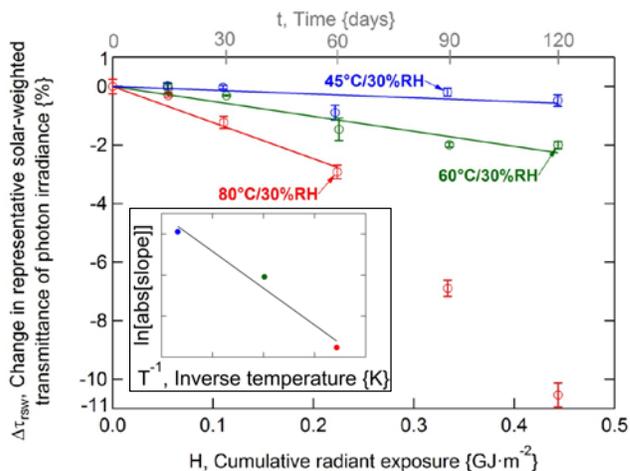


Fig. 5. Comparison of change in transmittance with applied temperature for EVA-A. The same default irradiance and %RH conditions were used in separate Xe chambers, maintained at 45°, 60°, or 80°C. The slope from linear trendline fits (through the origin, prior to an inflection in the data profile) was examined using an Arrhenius analysis.

Perspective on Xe and UVA-340 UV sources. The k_H values notably ($>\pm 10\%$) differing from unity as well as the changes in slope (τ_{rsw} vs. H , or YI vs. H) specific to the combination of light source used and the material examined suggest that Xe and UVA-340 sources may not always be applied equally for accelerated aging of encapsulation. The results for EVA are an important benchmark, because many of the encapsulation products on the PV market also share a polyethylene chemistry base. The example of EVA-A, which demonstrates a substantial change in spectral bandwidth for UVA-340 that does not occur for Xe, calls for further study.

Perspective on applied temperature. The ongoing experiment will verify if a temperature greater than 60°C can

be applied to reduce the test duration. Roof-mounted modules, however, may temporarily achieve a temperature of 105°C in hot desert locations [9]. In addition to their maximum temperature, roof-mounted modules in a desert location may spend a significant amount of their lifetime above 90°C. In contrast, an accelerated test might be designed for lesser temperatures that are sustained for prolonged duration. For example, a chamber test temperature of 70°, 80°, or 90°C might be applied for indoor weathering. These test temperatures would importantly elevate specimens above the melt transition temperature for EVA.

V. CONCLUSIONS

The UV photodegradation of the optical transmittance of PV encapsulation materials is under examination. Key interim results of the interlaboratory study include the following:

The change in optical performance, unique to each formulation examined, identifies that discoloration follows primarily from the formulation additives Lupersol 101, Naugard P, Tinuvin 770, or Tinuvin 123 rather than the base resin.

Regarding the use of Xe and UVA-340 light sources, a change in slope (the apparent degradation rate) was observed for specific combinations of UV sources and test materials, indicating different rate controlling mechanisms within the experiment. Analysis of the relative degradation rates demonstrates that Xe and UVA-340 sources cannot be presumed as equal alternates for purposes of accelerated weathering. The appearance of apparent greater damage to one of the EVA formulations (EVA-A) under UVA-340 exposure calls for further study.

Regarding the applied temperature, a significant thermal activation was observed. An activation energy on the order of ~60 kJ·mol⁻¹ is presently estimated for the degradation of EVA-A. Because the encapsulant degradation study has so far shown high activation energies, the temperature set point of a laboratory exposure will be an important factor in establishing

a correlation with PV field use. The ongoing experiments will provide foundational work to explore if degradation modes change at elevated temperatures and how these correlate to application environments.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

REFERENCES

- [1] A. W. Czanderna and F. J. Pern. "Encapsulation of PV Modules Using Ethylene Vinyl Acetate Copolymer as a Pottant: A Critical Review," *SOLMAT*, 43, 101-181, 1996.
- [2] W. W. Holley and S. C. Agro, "Advanced EVA-based encapsulants: Final report," NREL, Golden, CO, Rep. NREL/SR-520-25296, 1998.
- [3] C. G. Reid, et. al., "UV Aging and Outdoor Exposure Correlation for EVA PV Encapsulants," *Proc. SPIE*, 2013, 8825-7.
- [4] A. L. Rosenthal and C. G. Lane, "Field-test results for the 6 MW Carrizo Solar Photovoltaic Power-Plant", *Solar Cells*, vol. 30, 563-571, 1991.
- [5] S. Fowler, "Developing steady state exposure conditions in an ASTM G154 fluorescent UV test chamber for backsheet materials," *Proc. NREL PVMRW*, 2014.
- [6] D. C. Miller et. al., "Examination of An Optical Transmittance Test for Photovoltaic Encapsulation Materials," *Proc. SPIE*, 2013, 8825-8.
- [7] D. C. Miller et. al., "Durability of Polymeric Encapsulation Materials for Concentrating Photovoltaic Systems," *Prog. Photovoltaics: Research and Applications*, vol. 21, no. 4, pp. 631-651, 2013.
- [8] J. E. Pickett et. al., "Effects of Temperature on the Weathering of Engineering Thermoplastics," *Polym. Deg. Stab.*, vol. 93, pp. 684-691, 2008.
- [9] D. C. Miller et. al., "Creep in Photovoltaic Modules: Examining the Stability of Polymeric Materials and Components," *Proc. IEEE PVSC*, 262-268, 2010.

TABLE III
SUMMARY OF THE SPECIMEN MATERIALS EXAMINED.

INGREDIENT	DESCRIPTION	MAKER	MASS [g]					
Elvax PV1400	EVA resin, 33 wt% Vac	E. I. du Pont	100	100	100	100	100	N/A
Z6030	silane primer, gamma-methacryloxy propyl trimethoxysilane	Dow-Corning Corp.	0.25	0.25	0.25	0.25	0.25	?
TBEC	curing agent, OO-Tertbutyl-O-(2-ethyl-hexyl)-peroxycarbonate	Arkema Inc.	N/A	1.5	1.5	1.5	1.5	?
Lupersol 101	curing agent, 2,5-Bis(tert-butylperoxy)-2,5-dimethylhexane	Arkema Inc.	1.5	N/A	N/A	N/A	N/A	?
Tinuvin 329	UV absorber, benzotriazole type	BASF Corp.	N/A	N/A	N/A	0.3	N/A	?
Cyasorb UV-531	UV absorber, benzophenone type	Cytec Industries Inc.	0.3	0.3	0.3	N/A	N/A	?
Tinuvin 770	hindered amine light stabilizer (HALS)	BASF Corp.	0.1	0.1	0.1	N/A	N/A	?
Tinuvin 123	non-basic aminoether-hindered amine light stabilizer (NOR-HALS)	BASF Corp.	N/A	N/A	N/A	0.1	0.1	?
Naugard P	anti-oxidant (AO), phosphite containing	Chemtura Corp.	0.2	0.2	N/A	N/A	N/A	?
		Designation (Note)	EVA-A (known bad, "slow cure")	EVA-B (improved, "fast cure")	EVA-C (known good)	EVA-D (modern)	EVA-E (no UV absorber)	TPU (known bad)