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

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IEEE Photovoltaics Specialists Conference 2015 ("IEEE PVSC 42")

Area 11: Module materials and Component Reliability

#972; 11:00-11:15 Fri, 2015/6/19, Hyatt Regency - New Orleans, Strand 10 (Level 2)

NREL/PR-5J00-64628

Goal and Activities for PVQAT TG5 (UV, T, RH)

- PV safety, qualification tests (61215, 61646, 61730-2) presently prescribe up to 137 days equivalent IEC 60904-3 AM 1.5G UV-B radiation dose. This is << 25 years!
- **TG5 Goal**: develop UV- and temperature-facilitated test protocol(s) that may be used to compare PV materials, components, and modules relative to field service.

Applications:

- IEC 62892 (climate- and configuration-specific weathering).
    1. General UV weathering test.
    2. Start of "Leg 2" test series to query delamination. (UV→DML→HF10→DH500)

- IEC 62788-7 (PV materials and components weathering).
  Accelerated aging test(s) for encapsulation, backsheet, adhesives…

Motivation for the k_d Interlaboratory Experiment (PVQAT TG5 US)

- Knowing E_a is critical to prescribing & interpreting a *UV- and T*-mediated test.
- Unfortunately, E_a is not known for the UV degradation of common PV materials.

$$k_d = A\left[\frac{T}{T_0}\right]^n e^{\left[\frac{-E_a}{RT}\right]}$$

Arrhenius representation for rate of Δ characteristic

Goals for the interlaboratory experiment:

1. Quantify E_a.
   Provide a sense of the range of E_a by examining "known bad," "known good," and "intermediate" material formulations.

2. Determine if there is significant coupling between relevant aging parameters, *i.e.,* UV, temperature, and humidity.
   What weathering parameters must be considered in a standardized test?

3. Investigate the spectral requirements for UV light sources, *i.e.,* by comparing specimens aged by Xe-arc, UVA-340, metal-halide.
   Is visible light required (e.g., enabling photobleaching)?

The Materials Used in the k_d Experiment

- Discoloration of encapsulation somewhat studied in the literature:
  - ⇒We have a sense of the general rate of degradation.
  - ⇒Use historical (literature) and contemporary formulations.

- 6 Materials examined in interlaboratory study:
  - Compare peroxide used for cross-linking (module manufacture).
  - Compare type or use of UV absorber.
  - TPU formulation: not for PV, but chosen as a reference material.

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)

Encapsulation materials being compared in the transmittance (discoloration) experiment.

Interlaboratory Effort Enables a Wider Range of Study

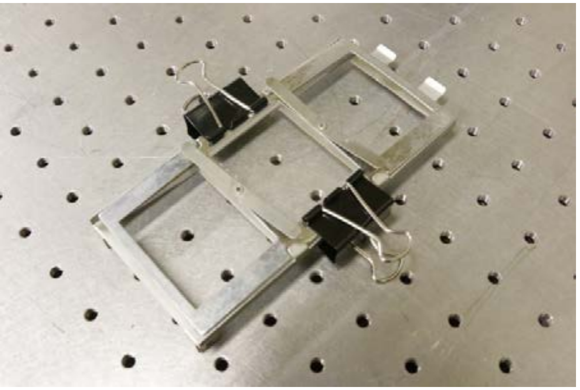
- Indoor aging is expensive. No institution has all the resources or bandwidth to apply the complete set of parameters TG5 wanted to examine.
- Discoloration studied at (14) -*volunteer*- institutions.
- Example: compare similar instrument models (*e.g*., Ci5000 & QSUN XE3).

- Standard condition (60°C chamber ambient) to compare a broad variety of light sources.
- Baseline irradiance of 1.0 $W{\cdot}m^{-2}{\cdot}nm^{-1}$ at 340 nm for UV sources.

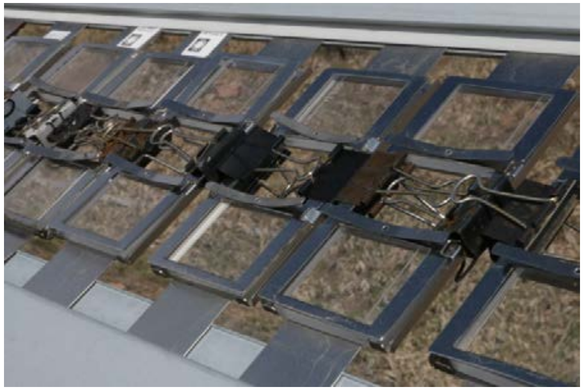
- Rate of indoor degradation will ultimately be compared against field data to determine site-specific acceleration factors.
- Outdoor data will verify the validity of indoor weathering.

Details of the k_d Methods and Experiment: Encapsulation Transmittance Test

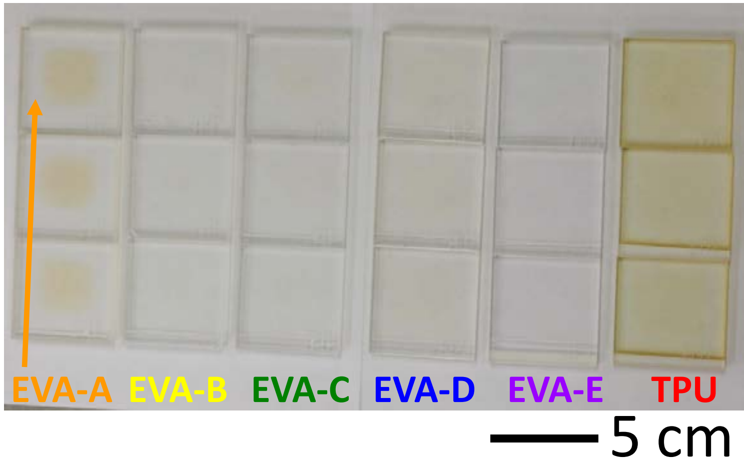
- Silica/polymer/silica coupon specimens measured using a spectrophotometer (with integrating sphere).
- Measure at specimen center (anaerobic, minimal O_2) and periphery (aerobic).
- Analyze: solar-weighted transmittance, yellowness index, and UV cut-off λ.



Specimen in sample holder for indoor aging at NREL.



Specimens on outdoor rack, aging in Golden, CO at NREL.



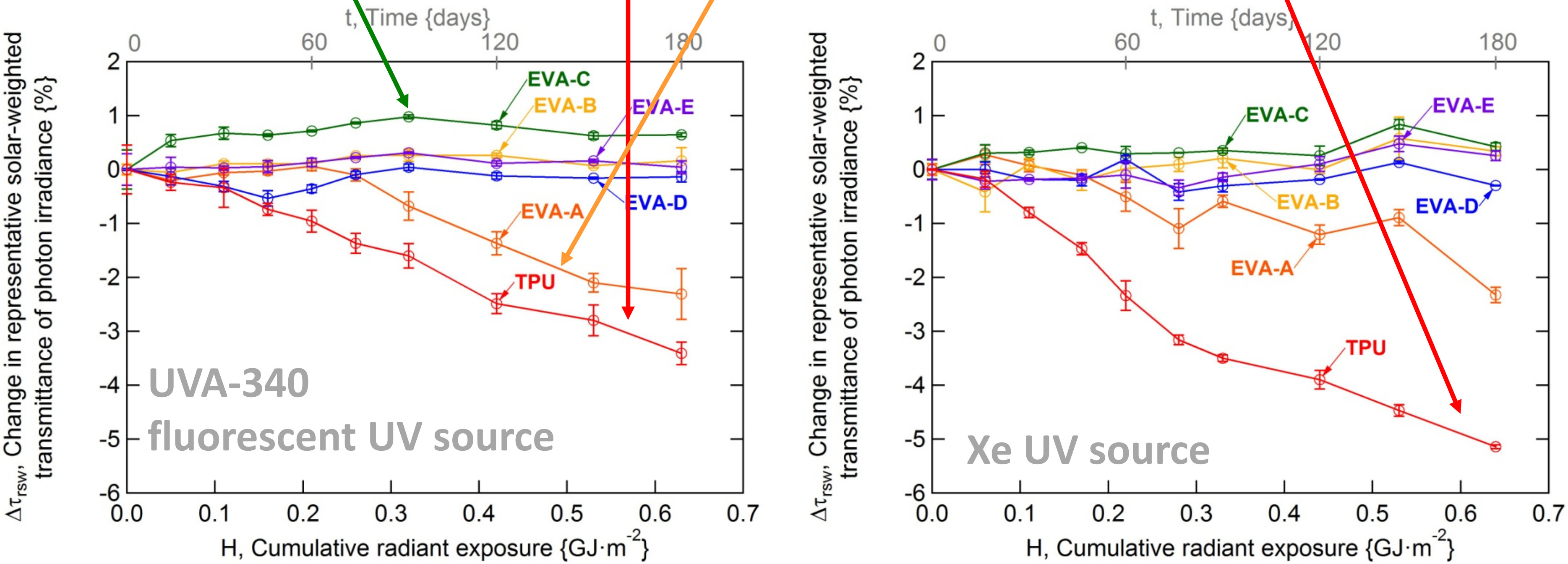
Visual appearance of the NREL UV Suitcase aged specimens at 180 days.

User summary:

- Geometry: silica/polymer/silica (3.2 mm/0.5 mm/3.2 mm).
- Size: 2" x 2".
- Quantity: 3 replicates of 6 materials (pre-conditioned), and 1 reference (not pre-conditioned).
- Aging: 0, 15, 30, 45, 60, 75, 90, 120, 150, 180 cumulative days (indoors).
  or 0, 1, 2, 3, 4, 5 years (outdoors).
- Measurements (non-destructive): repeatedly age and measure at each laboratory/test site.

UVA-340 vs. Xe: A Comparison of τ_{rsw} With Age

- Representative solar weighted transmittance (τ_{rsw}) evaluated for $300 \leq \lambda \leq 1250$ nm.
- TPU affected more in Xe ($\Delta\tau_{rsw}$ -5.1%) than UVA-340 ($\Delta\tau_{rsw}$ -3.4%).
- EVA-A affected continuously for Xe, delayed for UVA-340. Same $\Delta\tau_{rsw}$ -2.3%.
- EVA-C improved ($\Delta\tau_{rsw}$ 1.0% for UVA-340)!



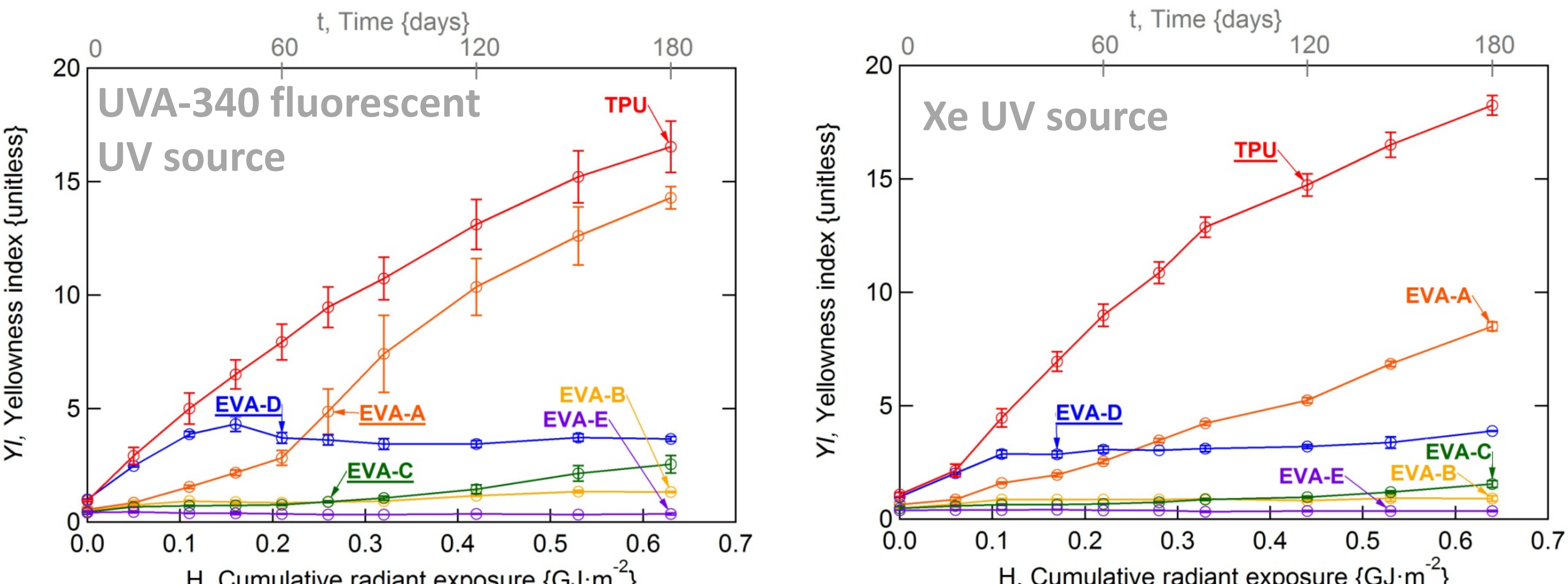
Change in τ_{rsw} with *H* for the NREL aged transmittance coupons (center measurements).
The data points have been connected to guide the eye.
***This presentation: H* shown for $295 \leq \lambda \leq 360$ nm.**

UVA-340 vs. Xe: Insights From *YI*

- Yellowness index (*YI*) calculated from measured τ_h.
- Repeatability: *YI* (0.27) < τ_{rsw} (0.63).
  YI is overt indicator of degradation trends.

- Many instances of ~linear change with time.
- Inflection (Δslope) in some profiles: EVA-A (UVA-340); EVA-C (UVA-340); TPU (Xe).
- Initial yellowing to stable-state for EVA-D (UVA-340 & Xe).

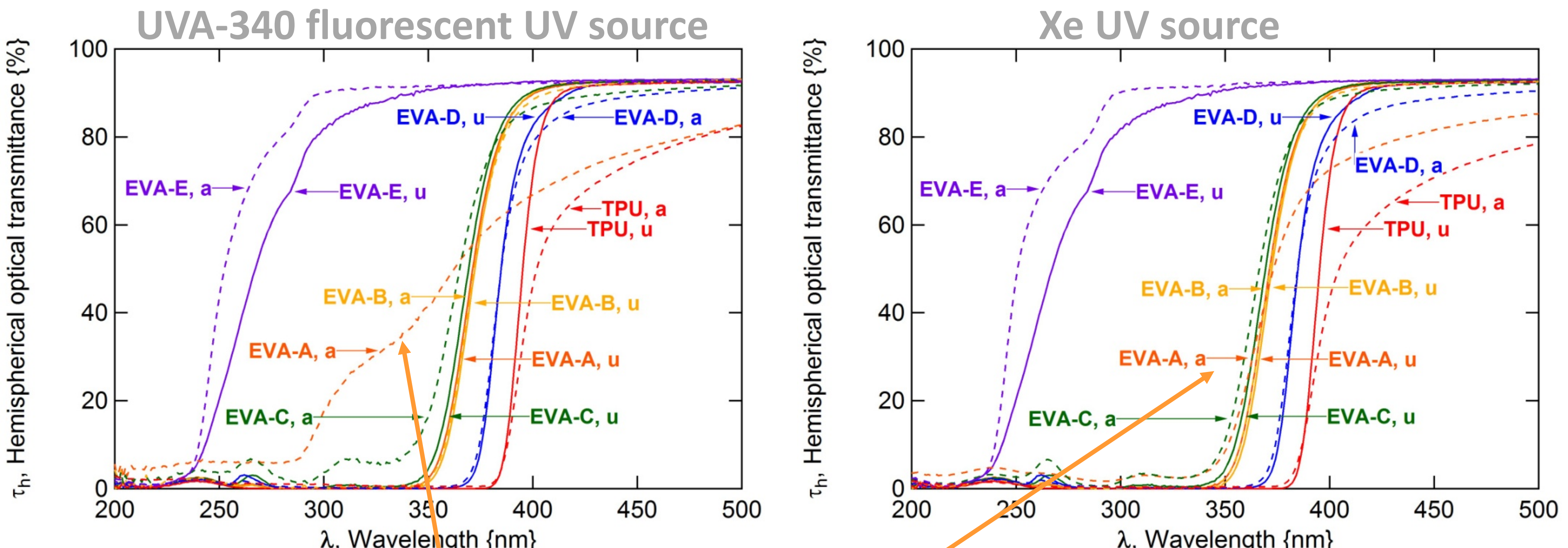
$\Rightarrow$Effects of aging are dominated by interactions between additives, not base material!



Change in τ_{rsw} with *H* for the NREL aged τ coupons (center measurements).
The data points have been connected to guide the eye.
This presentation: data shown for average of 3 replicates, with error bars for 1 S.D.

UVA-340 vs. Xe: Insights From the τ Spectra

- EVA-A, EVA-D, and TPU show a significant rounding of the UV cut-off (shifted ↓, right) and increased *YI* corresponding to Δvisual appearance.
- Likely explained by chromophore formation (from peroxide, AO, and UV absorber).



UV spectral transmittance for the NREL aged τ coupons (center measurements).
$-_u$ (solid lines) indicates unaged specimens; $-_a$ (dashed lines) indicates specimens aged for 6 months.

- For EVA-B, EVA-C, EVA-E, the UV cut-off wavelength is instead decreased (shifted left) and there is an increase in τ. τ_{rsw} is increased for EVA-C about ~350 nm.
- Likely explained by the loss of additive(s) with age.

- EVA-A: is UV absorber lost for UVA-340 source? VIS required (photobleaching for Xe)?

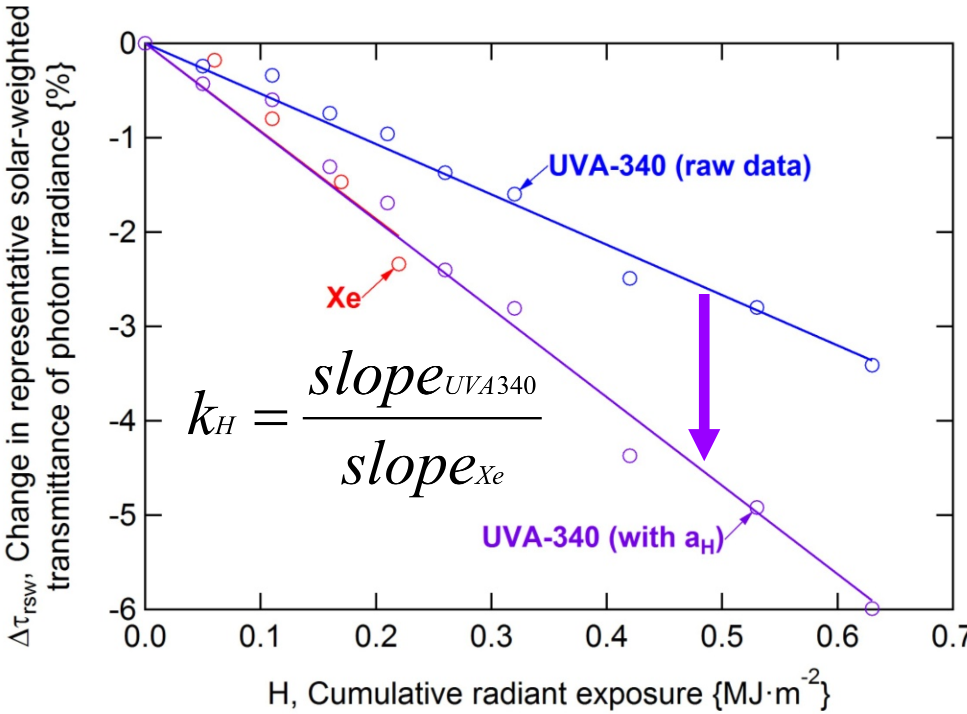
Methods of Analysis for the k_d Data

- Verify what data may be analyzed.

e.g., delayed loss of formulation additive.

- Here: consider inflections in $\Delta\tau_{rsw}$ or *YI* data.

- Degradation rate (linear) or shift factor (logarithmic) comparison may be used to examine different test conditions, *e.g.*, UV sources.
- Example: what k_H is required map the UVA-340 data parallel to the Xe data?



Degradation rate comparison, applied to compare UVA-340 and Xe sources . Data shown for the NREL aged τ coupons (center measurements).

- Arrhenius analysis used for different applied temperatures. ($E_a \propto m \cdot R$).
- EVA undergoes a melt transition at ~60°C.

UVA-340 vs. Xe: Insights From k_H Analysis

- 295≤λ≤360nm may be best criteria between Xe and UVA-340, because UVA-340 provides limited emission 360≤λ≤400 nm.

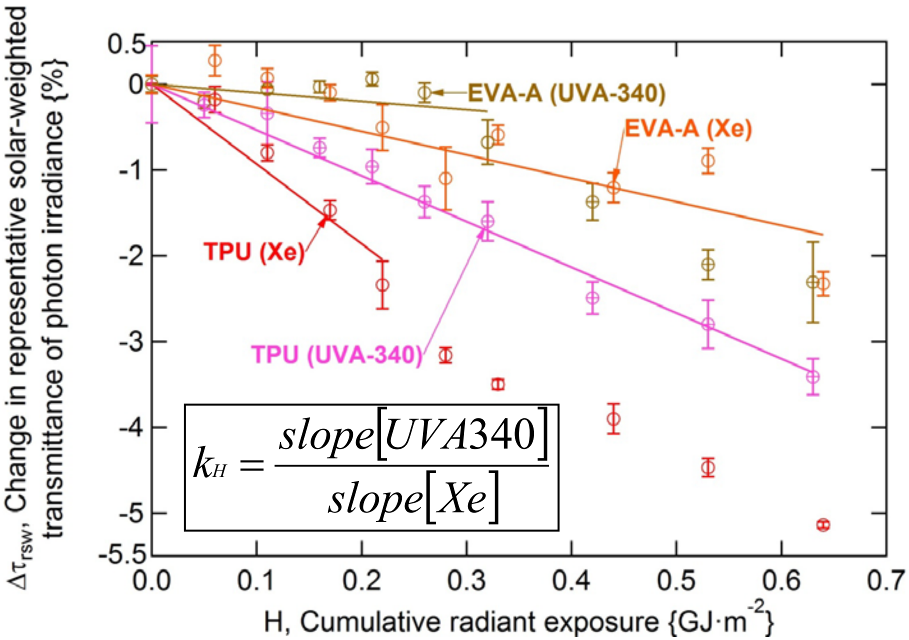
Fowler, "Developing Steady State Exposure Conditions in an ASTM G154 Fluorescent UV Test Chamber for Backsheet Materials", Proc. NREL PVMRW, 2014.

- k_H=0.6 for TPU (same order of magnitude).
- $T_{UVA\text{-}340}$ ~55°C; T_{Xe} ~63°C. ΔT~10°C $\Rightarrow$ 1.4^{-1} $\Rightarrow$ 0.7.

Pickett et. al., Polym. Deg. Stab., 93 684-691 (2008).

- k_H=0.08 for EVA-A.
- EVA-A not affected early for UVA-340.
- Different aging mechanisms initially dominate for UVA-340 or Xe.

- k_H=3.4, 1.1 for EVA-C, EVA-D.

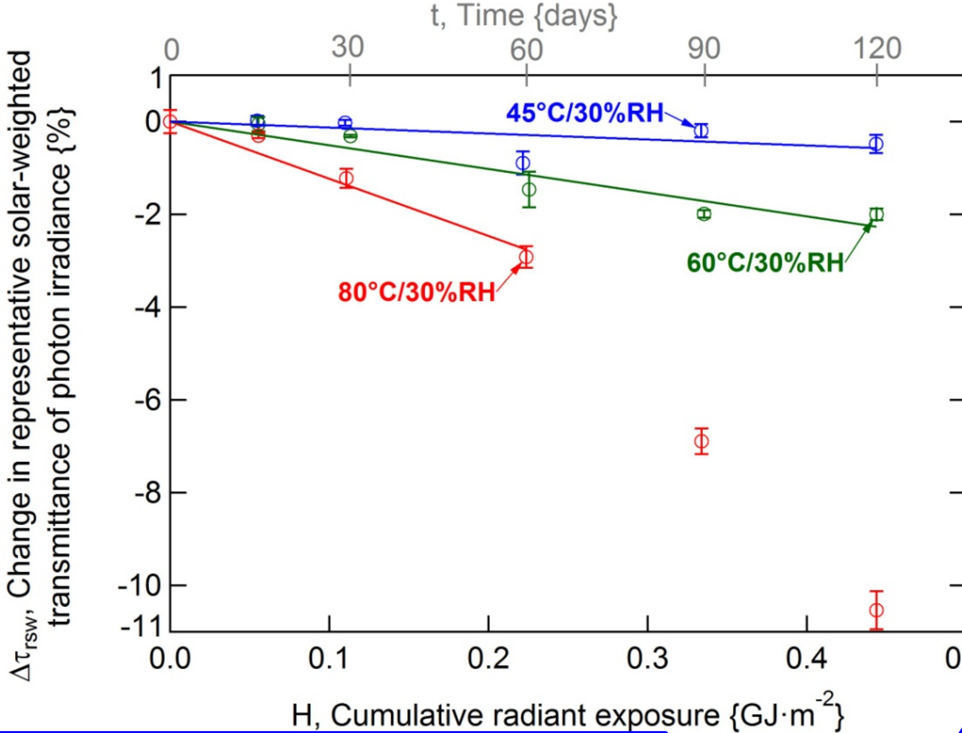


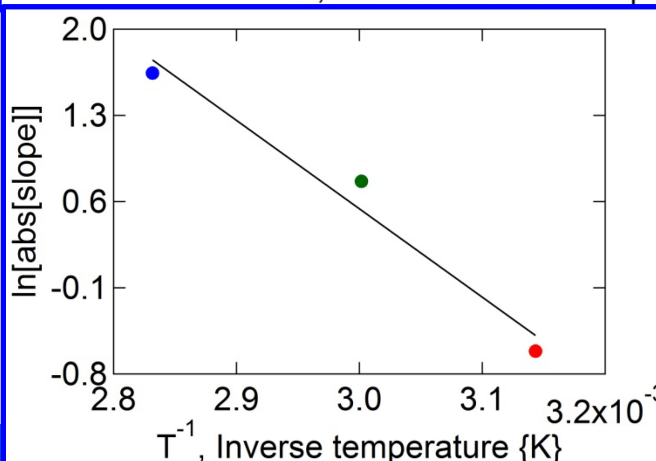
Data shown for NREL aged EVA-A and TPU coupons (center measurements).

Effect of Temperature Stands Out in Early Comparison

- Effect of *T* examined directly at 3M: same irradiance, *RH* applied using three similar chambers (Ci5000, Xe lamp with Right Light filter).

- Strong effect of aging as *T* is increased.
- Exception: EVA-E (no UV absorber). $\Delta\tau$~0.
- *T* coupling anticipated from field observation, *e.g.*, increased discoloration at local module hot spots.
- E_a on order of ~60 $kJ \cdot mol^{-1}$ (0.6 eV) estimated for EVA-A from interim experiment.





Summary

•"k_d" interlaboratory experiment presently being conducted to provide a quantitative basis for UV weathering tests.

Interim results:

•Material specific aging behavior $\Rightarrow$ discoloration follows foremost from the formulation additives (Lupersol 101, Naugard P, Tinuvin 770 or Tinuvin 123), rather than the base resin.

Regarding Xe and UVA-340 sources:

•Substantial $\Delta\lambda_{cUV}$, greater ΔYI for EVA-A aged with UVA-340. k_H of 0.08. k_H of 0.6 (0.7 ideal), 3.4, and 1.1 observed for TPU, EVA-C, and EVA-D.

•Δ slope (apparent degradation rate) observed for specific combinations of UV source and test materials.

$\Rightarrow$Xe and UVA-340 sources may not always be applied equally for accelerated aging of encapsulation.

•E_a on the order of ~60 $kJ \cdot mol^{-1}$ (0.6 eV) is estimated for EVA-A.

•Test *T, e.g.* 70, 80, or 90 °C, presently being evaluated for UV tests.

Acknowledgements

☞There has been fantastic participation in TG5.

Thank you to the many participants for your ongoing support!!!

- If interested in TG5 activites or the experiments, please contact the corresponding regional leader. (See title slide)
- Stay tuned for examination of encapsulant attachment strength.

(PVQAT TG5 k_d "part II").

Your questions and feedback are much appreciated! Please help me to cover the important details & perspectives.

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

NREL STM campus, Dennis Schroeder

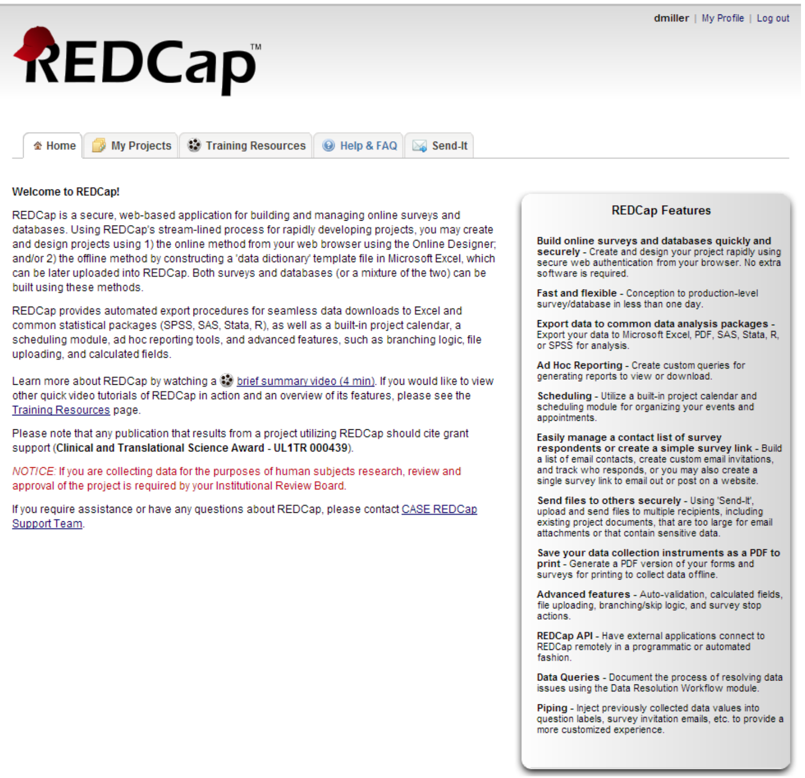
Extra Slides for Reference…

Use of REDCap Database for Transmittance Data

- -A LARGE QUANTITY- of transmittance data will be generated for experiment.
- Case Western Reserve University volunteered the REDcap database to TG5.
- REDCap comes from the medical research industry.

Benefits: Ensures designed experiments, high data capacity, simultaneous user access, automated data quality verification.

- REDCap allows users to view and analyze results in real-time.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Welcome to REDCap!

REDCap is a secure, web-based application for building and managing online surveys and databases. Using REDCap's stream-lined process for rapidly developing projects, you may create and design projects using 1) the online method from your web browser using the Online Designer; and/or 2) the offline method by constructing a 'data dictionary' template file in Microsoft Excel, which can be later uploaded into REDCap. Both surveys and databases (or a mixture of the two) can be built using these methods.

REDCap provides automated export procedures for seamless data downloads to Excel and common statistical packages (SPSS, SAS, Stata, R), as well as a built-in project calendar, a scheduling module, ad hoc reporting tools, and advanced features, such as branching logic, file uploading, and calculated fields.

Learn more about REDCap by watching a brief summary video (4 min). If you would like to view other quick video tutorials of REDCap in action and an overview of its features, please see the Training Resources page.

Please note that any publication that results from a project utilizing REDCap should cite grant support (**Clinical and Translational Science Award - UL1TR 000439**).

NOTICE: If you are collecting data for the purposes of human subjects research, review and approval of the project is required by your Institutional Review Board.

If you require assistance or have any questions about REDCap, please contact CASE REDCap Support Team.

REDCap Features

Build online surveys and databases quickly and securely - Create and design your project rapidly using secure web authentication from your browser. No extra software is required.

Fast and flexible - Conception to production-level survey/database in less than one day.

Export data to common data analysis packages - Export your data to Microsoft Excel, PDF, SAS, Stata, R, or SPSS for analysis.

Ad Hoc Reporting - Create custom queries for generating reports to view or download.

Scheduling - Utilize a built-in project calendar and scheduling module for organizing your events and appointments.

Easily manage a contact list of survey respondents or create a simple survey link - Build a list of email contacts, create custom email invitations, and track who responds, or you may also create a single survey link to email out or post on a website.

Send files to others securely - Using 'Send-It', upload and send files to multiple recipients, including existing project documents, that are too large for email attachments or that contain sensitive data.

Save your data collection instruments as a PDF to print - Generate a PDF version of your forms and surveys for printing to collect data offline.

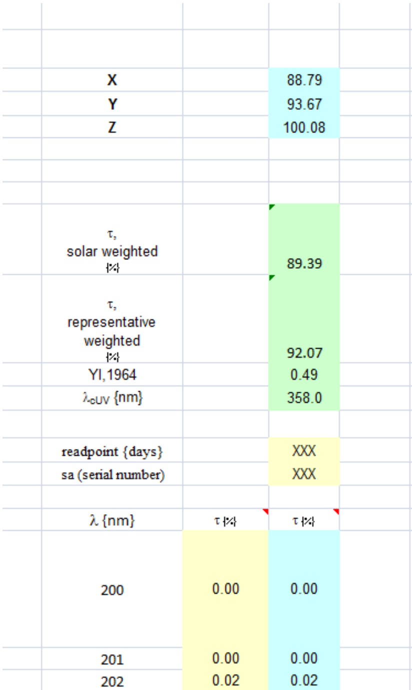
Advanced features - Auto-validation, calculated fields, file uploading, branching/skip logic, and survey stop actions.

REDCap API - Have external applications connect to REDCap remotely in a programmatic or automated fashion.

Data Queries - Document the process of resolving data issues using the Data Resolution Workflow module.

Piping - Inject previously collected data values into question labels, survey invitation emails, etc. to provide a more customized experience.

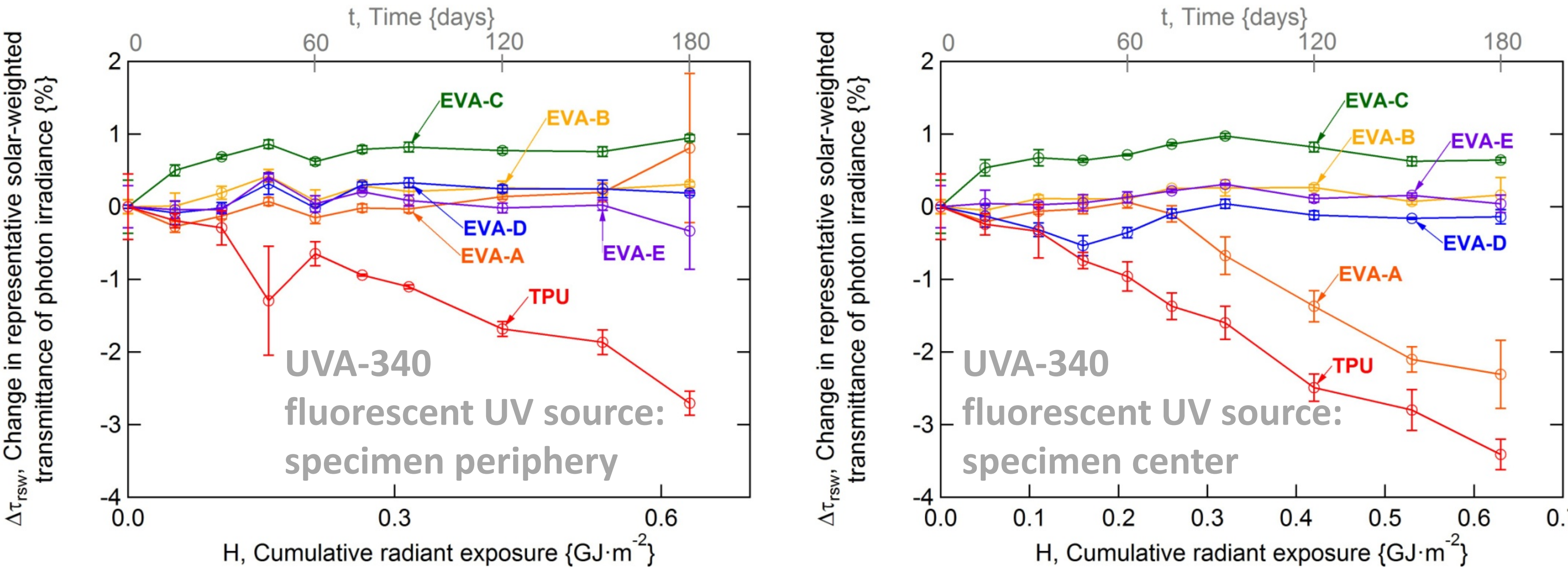
Home screen for https://dcru.case.edu/redcap



X		88.79
Y		93.67
Z		100.08
τ, solar weighted {%}		89.39
τ, representative weighted {%}		92.07
YI,1964		0.49
λ_{cUV} {nm}		358.0
readpoint {days}		XXX
sa (serial number)		XXX
λ {nm}	τ {%}	τ {%}
200	0.00	0.00
201	0.00	0.00
202	0.02	0.02

Transmittance results will be uploaded to REDCap using an Excel template file.

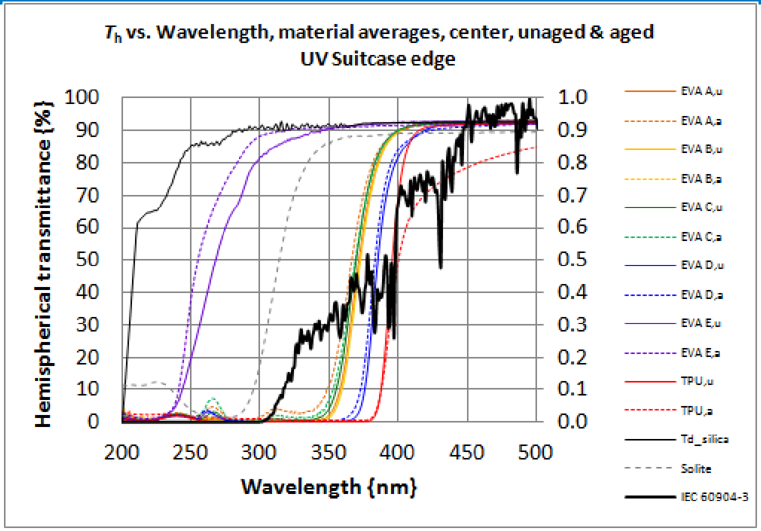
τ_{rsw}: Most Materials More Affected at Center in k_d Experiment

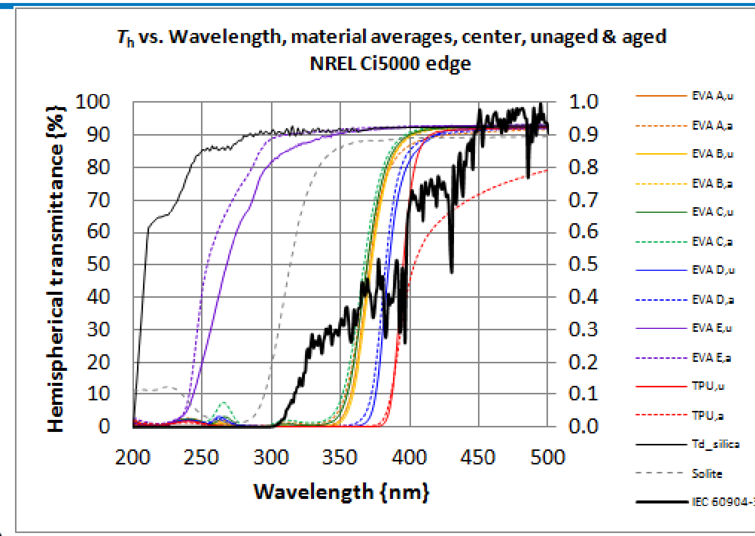


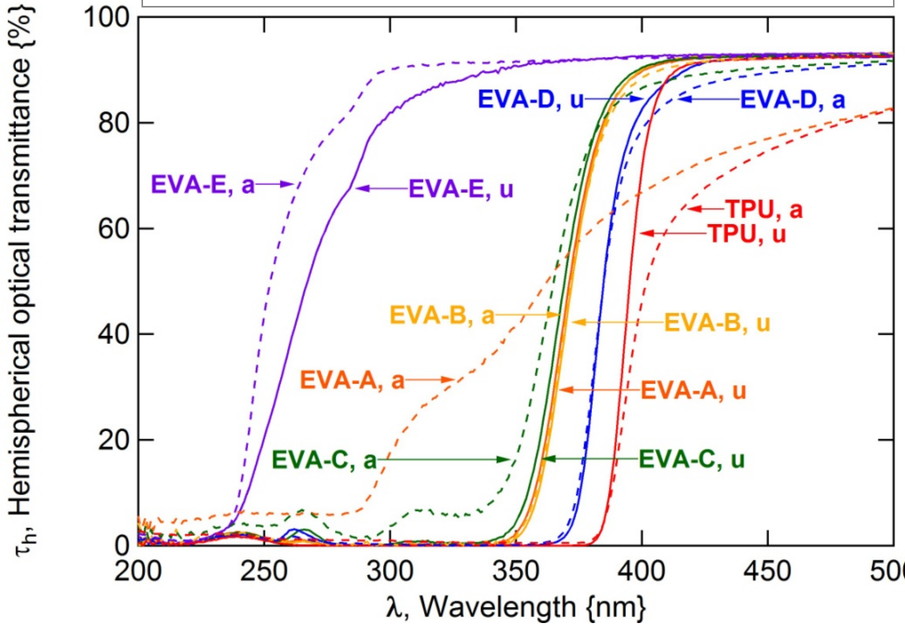
Change in transmittance for the NREL UV Suitcase aged specimens. Data points connected to guide the eye.

- Loss in τ_{rsw} less significant at the specimen periphery.
  Example: EVA-A. Significant heterogeneity.
  Exceptions: EVA-C, TPU. Affected relatively uniformly throughout specimen.
- In EVA, a photobleaching effect typically occurs at periphery, but is limited by rate of O_2 diffusion to interior.

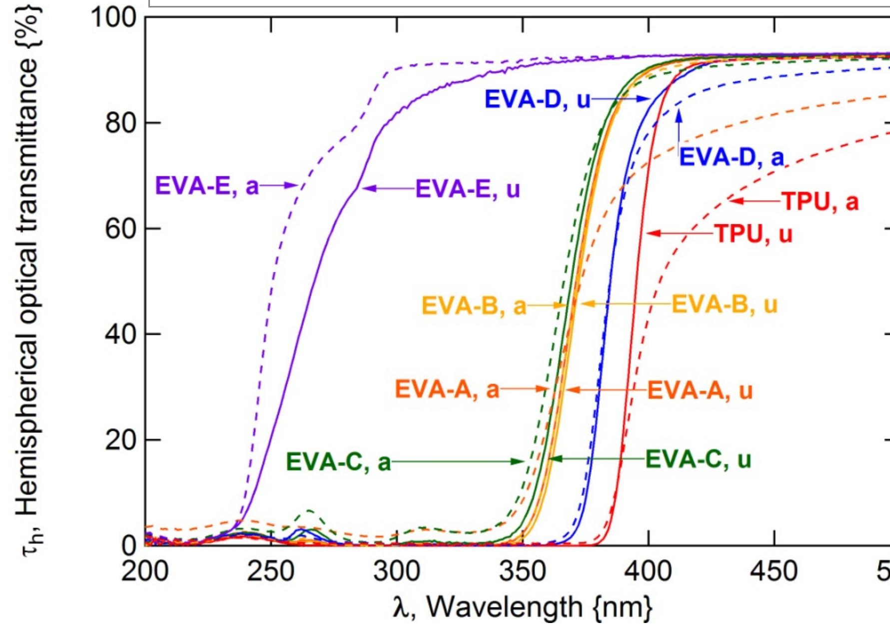
Comparing UVA-340 and Xe sources







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 (60°C/~7%RH). Results for specimen-periphery (top) and -center (bottom).



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 Ci5000 (60 °C/50%RH).

Comparing UVA-340 and Xe sources

Major changes: (most overt to least affecting differences between weathered samples)

•The spectral bandwidth was greatly increased ($\Delta\lambda_{cUV}$=-64 nm) for EVA-A for the UVA-340 light source but not for Xe ($\Delta\lambda_{cUV}$=-6 nm). This implies the UV absorber was uniquely degraded or depleted for the fluorescent light source. The result is consistent with the UV-VIS fluorescence spectra observed for EVA-A, which could be distinguished between the different weathering chambers.

•A more severe rounding of the cut-on profile was observed for EVA-A aged usingUVA-340 (ΔYI=13.7) then for Xe (ΔYI=7.9). A more severe rounding of the cut-on profile was observed for TPU aged using Xe (ΔYI=17.2) then for UVA-340 (ΔYI=15.6). Increased yellowness implies the formation of optically absorbing chromophore species. These results suggest the action spectrum for TPU includes the full range of UV wavelengths (*i.e.*, $300\leq\lambda\leq400$ nm as supplied by a Xe source). The difference for EVA-A may result from a photobleaching process, enabled by the longer wavelengths of UV light present in Xe.

•EVA-C was more affected by UVA-340 ($\Delta\lambda_{cUV}$=-11 nm for UV Suitcase) than Xe ($\Delta\lambda_{cUV}$=-5 nm for Ci5000) spectrum. Transmittance reduction from discoloration (ΔYI=2.1 and ΔYI=1.1) was outweighed by the increased spectral bandwidth, increasing transmittance (τ_{rsw} 0.6% and τ_{rsw} 0.4%) for EVA-C in UVA-340 and Xe, respectively.

Lesser changes:

•The spectral bandwidth was slightly more increased for EVA-D at its periphery ($\Delta\lambda_{cUV}$=-3 nm) than at its center ($\Delta\lambda_{cUV}$=-1 nm). EVA-D, however, was more discolored at its center (ΔYI=2.7 and ΔYI=2.9) than at its periphery (ΔYI=0.8 and ΔYI=0.8) , for UVA-340 and Xe, respectively.

Comparing UVA-340 and Xe sources

UV Suitcase (60 °C/~7%RH) center measurements

CUMULATIVE WEATHERING {days}		0	15	30	45	60	75	90	120	150	180	Δ (final-initial)	>2 s,?
RADIANT EXPOSURE, $300 \le \lambda \le 400$ nm {GJ·m^{-2}}		0	0.13	0.26	0.40	0.53	0.66	0.79	1.06	1.32	1.59		
RADIANT EXPOSURE, 340 nm {MJ·m^{-2}}		0	1.28	2.55	3.83	5.11	6.38	7.66	10.21	11.70	14.04		
RADIANT EXPOSURE, $295 \le \lambda \le 360$ nm {GJ·m^{-2}}		0	0.06	0.11	0.17	0.22	0.28	0.33	0.44	0.53	0.64		
RADIANT EXPOSURE, $360 \le \lambda \le 400$ nm {GJ·m^{-2}}		0	0.08	0.16	0.24	0.31	0.39	0.47	0.63	0.78	0.94		
τ_{sw}, (solar weighted) {%}	EVA-A	88.6	88.4	88.5	88.5	88.6	88.5	88.1	87.7	87.2	87.1	-1.4	
	EVA-B	88.2	88.2	88.3	88.4	88.3	88.4	88.5	88.5	88.3	88.5	0.2	
	EVA-C	88.2	88.5	88.6	88.5	88.6	88.7	88.8	88.7	88.6	88.6	0.4	
	EVA-D	87.9	87.8	87.7	87.5	87.6	87.9	88.0	87.9	87.8	87.8	0.0	
	EVA-E	89.5	89.5	89.5	89.5	89.6	89.6	89.7	89.6	89.6	89.5	0.0	
	TPU	88.3	87.0	87.0	86.8	86.6	86.4	86.2	85.6	85.4	84.9	-3.3	YES
τ_{rsw}, (representative solar weighted) {%}	EVA-A	91.2	91.0	91.2	91.2	91.3	91.1	90.6	90.0	89.3	89.1	-2.1	YES
	EVA-B	91.0	90.9	91.1	91.1	91.1	91.2	91.2	91.2	91.0	91.1	0.1	
	EVA-C	90.7	91.2	91.3	91.3	91.3	91.5	91.6	91.4	91.3	91.3	0.6	
	EVA-D	90.4	90.3	90.1	89.9	90.1	90.3	90.4	90.3	90.2	90.3	-0.1	
	EVA-E	92.6	92.6	92.6	92.6	92.7	92.8	92.9	92.7	92.7	92.6	0.0	
	TPU	90.0	89.8	89.7	89.3	89.1	88.8	88.6	87.8	87.5	86.9	-3.1	YES
YI, (yellowness index) {unitless}	EVA-A	0.6	0.9	1.5	2.2	2.8	4.9	7.4	10.4	12.6	14.3	13.7	YES
	EVA-B	0.5	0.7	0.9	0.9	0.8	0.9	0.9	1.2	1.3	1.3	0.9	YES
	EVA-C	0.4	0.7	0.7	0.7	0.8	0.9	1.1	1.4	2.1	2.5	2.1	YES
	EVA-D	1.0	2.5	3.9	4.3	3.7	3.6	3.4	3.4	3.7	3.7	2.7	YES
	EVA-E	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.4	0.3	0.4	-0.1	
	TPU	0.9	2.9	5.0	6.5	7.9	9.5	10.7	13.1	15.2	16.5	15.6	YES
λ_{cUV}, (UV cut-off wavelngth) {nm}	EVA-A	356	355	351	341	299	296	293	293	292	292	-64.3	YES
	EVA-B	359	359	359	358	358	358	358	358	358	358	-1.0	
	EVA-C	354	353	352	351	350	348	346	346	345	343	-11.0	YES
	EVA-D	375	374	374	374	374	374	374	374	374	374	-1.0	
	EVA-E	241	241	241	241	240	240	240	240	240	240	-0.7	
	TPU	386	387	387	387	387	387	387	387	387	366	-20.0	YES

NREL Ci5000 (60 °C/50%RH) center measurements

CUMULATIVE WEATHERING {days}		0	15	30	45	60	75	90	120	150	180	Δ (final-initial)	>2 s,?
RADIANT EXPOSURE, $300 \le \lambda \le 400$ nm {GJ·m^{-2}}		0	0.13	0.26	0.40	0.53	0.66	0.79	1.06	1.32	1.59		
RADIANT EXPOSURE, 340 nm {MJ·m^{-2}}		0	1.28	2.55	3.83	5.11	6.38	7.66	10.21	11.70	14.04		
RADIANT EXPOSURE, $295 \le \lambda \le 360$ nm {GJ·m^{-2}}		0	0.06	0.11	0.17	0.22	0.28	0.33	0.44	0.53	0.64		
RADIANT EXPOSURE, $360 \le \lambda \le 400$ nm {GJ·m^{-2}}		0	0.08	0.16	0.24	0.31	0.39	0.47	0.63	0.78	0.94		
τ_{sw}, (solar weighted) {%}	EVA-A	88.4	87.1	88.2	88.2	87.9	87.5	87.9	87.4	87.9	86.8	-1.6	YES
	EVA-B	88.9	88.1	88.6	88.3	88.5	88.6	88.7	88.5	89.0	88.8	0.0	
	EVA-C	88.4	88.7	88.7	88.7	88.6	88.7	88.7	88.6	89.2	88.9	0.5	
	EVA-D	89.4	88.0	88.0	88.0	88.3	87.8	87.9	88.0	88.3	88.0	-1.4	
	EVA-E	89.8	89.4	89.5	89.5	89.6	89.4	89.5	89.7	90.1	89.9	0.2	
	TPU	87.3	87.0	86.6	86.2	85.6	85.1	84.9	84.7	84.3	83.9	-3.4	YES
τ_{rsw}, (representative solar weighted) {%}	EVA-A	91.0	91.2	91.0	90.9	90.5	90.0	90.4	89.9	90.2	88.8	-2.1	YES
	EVA-B	91.4	90.7	91.1	90.9	91.1	91.1	91.2	91.1	91.6	91.4	0.0	
	EVA-C	91.1	91.4	91.4	91.4	91.3	91.4	91.4	91.3	91.8	91.5	0.4	
	EVA-D	90.5	90.5	90.3	90.3	90.6	90.1	90.2	90.3	90.6	90.2	-0.3	
	EVA-E	92.8	92.6	92.6	92.7	92.7	92.5	92.7	92.9	93.3	93.1	0.2	
	TPU	87.3	87.0	86.6	86.2	85.6	85.1	84.9	84.7	84.3	83.9	-3.4	YES
YI, (yellowness index) {unitless}	EVA-A	0.6	0.9	1.6	2.0	2.5	3.5	4.2	5.2	6.8	8.5	7.9	YES
	EVA-B	0.5	0.7	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.4	
	EVA-C	0.5	0.6	0.6	0.6	0.7	0.7	0.9	1.0	1.2	1.5	1.1	YES
	EVA-D	1.0	2.0	2.9	2.9	3.1	3.0	3.1	3.2	3.4	3.9	2.9	YES
	EVA-E	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.0	
	TPU	1.1	2.1	4.5	6.9	9.0	10.9	12.9	14.7	16.5	18.2	17.2	YES
λ_{cUV}, (UV cut-off wavelngth) {nm}	EVA-A	357	356	356	353	352	352	352	352	351	351	-6.0	YES
	EVA-B	358	358	358	357	357	357	357	357	357	357	-1.0	
	EVA-C	353	353	353	352	351	351	350	350	349	349	-4.7	
	EVA-D	375	373	373	373	373	373	374	374	374	374	-1.0	
	EVA-E	242	241	240	240	240	240	239	240	239	239	-3.0	
	TPU	387	387	387	387	387	387	387	387	386	386	-0.7	

UV Suitcase (60 °C/~7%RH) edger measurements

CUMULATIVE WEATHERING {days}		0	15	30	45	60	75	90	120	150	180	Δ (final-initial)	>2 s,?
RADIANT EXPOSURE, $300 \le \lambda \le 400$ nm {GJ·m^{-2}}		0	0.13	0.26	0.40	0.53	0.66	0.79	1.06	1.32	1.59		
RADIANT EXPOSURE, 340 nm {MJ·m^{-2}}		0	1.28	2.55	3.83	5.11	6.38	7.66	10.21	11.70	14.04		
RADIANT EXPOSURE, $295 \le \lambda \le 360$ nm {GJ·m^{-2}}		0	0.06	0.11	0.17	0.22	0.28	0.33	0.44	0.53	0.64		
RADIANT EXPOSURE, $360 \le \lambda \le 400$ nm {GJ·m^{-2}}		0	0.08	0.16	0.24	0.31	0.39	0.47	0.63	0.78	0.94		
τ_{sw}, (solar weighted) {%}	EVA-A	88.6	88.3	88.4	88.6	88.4	88.5	88.5	88.7	88.7	89.2	0.7	
	EVA-B	88.2	88.3	88.5	88.7	88.4	88.6	88.5	88.6	88.6	88.6	0.4	
	EVA-C	88.2	88.5	88.6	88.8	88.5	88.7	88.7	88.7	88.7	88.8	0.6	
	EVA-D	87.9	87.9	87.9	88.2	87.9	88.2	88.2	88.1	88.1	88.1	0.2	
	EVA-E	89.5	89.5	89.5	89.9	89.5	89.7	89.6	89.5	89.5	89.2	-0.3	
	TPU	88.3	87.0	87.0	86.2	86.8	86.6	86.5	86.0	86.0	85.3	-2.9	YES
τ_{rsw}, (representative solar weighted) {%}	EVA-A	91.2	91.0	91.1	91.3	91.1	91.2	91.2	91.4	91.4	92.0	0.7	
	EVA-B	91.0	91.0	91.2	91.4	91.1	91.2	91.2	91.2	91.2	91.3	0.3	
	EVA-C	90.7	91.1	91.3	91.5	91.3	91.4	91.4	91.4	91.4	91.6	0.9	
	EVA-D	90.4	90.3	90.4	90.7	90.4	90.7	90.7	90.6	90.6	90.6	0.2	
	EVA-E	92.6	92.5	92.5	93.0	92.6	92.8	92.7	92.6	92.6	92.3	-0.3	
	TPU	90.0	89.8	89.7	88.8	89.4	89.2	89.0	88.5	88.3	87.6	-2.4	YES
YI, (yellowness index) {unitless}	EVA-A	0.6	0.8	1.2	1.3	1.6	2.0	1.1	0.9	1.0	1.1	0.6	YES
	EVA-B	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.2	
	EVA-C	0.4	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.3	
	EVA-D	1.0	2.1	2.3	2.3	2.3	2.1	1.9	1.8	1.8	1.8	0.8	YES
	EVA-E	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.5	0.1	
	TPU	0.9	2.6	4.1	5.2	6.5	7.4	7.6	8.8	10.7	12.9	12.0	YES
λ_{cUV}, (UV cut-off wavelngth) {nm}	EVA-A	356	356	355	354	352	351	352	352	350	348	-8.7	YES
	EVA-B	359	358	358	358	358	358	358	358	358	357	-1.3	
	EVA-C	354	354	353	353	353	352	353	352	352	352	-2.0	
	EVA-D	375	374	374	374	374	373	373	373	372	372	-3.3	
	EVA-E	241	241	240	240	240	240	240	240	240	240	-0.7	
	TPU	386	387	387	387	387	387	387	387	387	387	0.7	

NREL Ci5000 (60 °C/50%RH) edge measurements

CUMULATIVE WEATHERING {days}		0	15	30	45	60	75	90	120	150	180	Δ (final-initial)	>2 s,?
RADIANT EXPOSURE, $300 \le \lambda \le 400$ nm {GJ·m^{-2}}		0	0.13	0.26	0.40	0.53	0.66	0.79	1.06	1.32	1.59		
RADIANT EXPOSURE, 340 nm {MJ·m^{-2}}		0	1.28	2.55	3.83	5.11	6.38	7.66	10.21	11.70	14.04		
RADIANT EXPOSURE, $295 \le \lambda \le 360$ nm {GJ·m^{-2}}		0	0.06	0.11	0.17	0.22	0.28	0.33	0.44	0.53	0.64		
RADIANT EXPOSURE, $360 \le \lambda \le 400$ nm {GJ·m^{-2}}		0	0.08	0.16	0.24	0.31	0.39	0.47	0.63	0.78	0.94		
τ_{sw}, (solar weighted) {%}	EVA-A	88.4	87.8	88.3	88.3	88.2	87.6	88.6	88.3	89.2	88.4	0.0	
	EVA-B	88.9	88.3	88.7	88.3	88.5	88.6	88.8	88.5	89.0	88.9	0.0	
	EVA-C	88.4	88.6	88.8	88.8	88.7	88.7	88.8	88.8	89.3	89.1	0.7	
	EVA-D	89.4	88.2	88.3	88.4	88.8	88.2	88.5	88.5	88.9	88.6	-0.8	
	EVA-E	89.8	89.4	89.5	89.5	89.5	89.2	89.4	89.6	89.9	89.9	0.1	
	TPU	87.3	87.1	86.7	86.4	85.9	85.3	85.1	85.0	84.6	84.1	-3.2	YES
τ_{rsw}, (representative solar weighted) {%}	EVA-A	91.0	90.5	91.1	91.1	90.9	90.3	91.3	91.0	92.0	91.1	0.1	
	EVA-B	91.4	90.4	91.3	90.9	91.1	91.2	91.4	91.1	91.6	91.4	0.1	
	EVA-C	91.1	91.3	91.4	91.5	91.3	91.3	91.4	91.4	92.0	91.7	0.7	
	EVA-D	91.8	90.5	90.6	90.8	91.2	90.6	90.8	90.9	91.4	90.9	-0.9	
	EVA-E	92.8	92.6	92.6	92.7	92.7	92.3	92.5	92.8	93.1	93.0	0.2	
	TPU	90.1	89.9	89.4	89.0	88.3	87.6	87.3	87.1	86.4	85.7	-4.4	YES
YI, (yellowness index) {unitless}	EVA-A	0.6	0.8	1.3	1.0	0.8	0.9	0.7	0.9	0.8	1.8	1.2	YES
	EVA-B	0.5	0.6	0.5	0.5	0.5	0.6	0.5	0.6	0.6	0.6	0.1	
	EVA-C	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1	
	EVA-D	1.0	1.6	1.7	1.2	1.2	1.0	1.0	1.2	1.0	1.8	0.8	YES
	EVA-E	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.0	
	TPU	1.1	2.1	4.1	5.9	7.5	9.0	11.0	12.6	14.8	17.2	16.1	YES
λ_{cUV}, (UV cut-off wavelngth) {nm}	EVA-A	357	356	357	356	356	355	355	354	354	353	-4.3	
	EVA-B	358	358	358	358	358	357	357	357	357	357	-1.0	
	EVA-C	353	353	353	353	353	352	352	352	351	351	-2.3	
	EVA-D	375	373	374	373	373	371	372	372	371	372	-2.5	
	EVA-E	242	240	240	240	240	240	239	240	240	240	-2.3	
	TPU	387	387	387	387	387	386	386	386	386	386	-1.0	

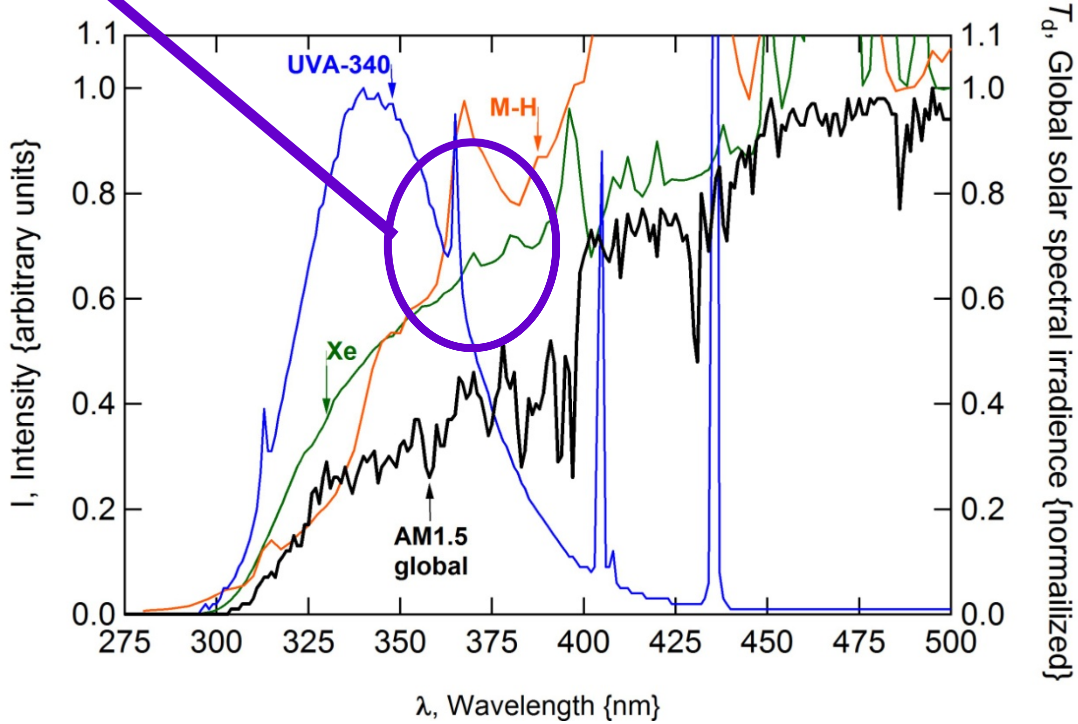
Summary of the results for samples weathered in the NREL UV Suitcase (UVA-340) and NREL Ci5000 (Xe) chambers.

k_d Experiment Examines Relevant Source Spectra

- Will compare Xe, UVA-340, M-H, and terrestrial light sources for all formulations examined.
- Depending on specimen's action spectrum (damage susceptibility), the UV source *(e.g.,* 360-400) could render different results.

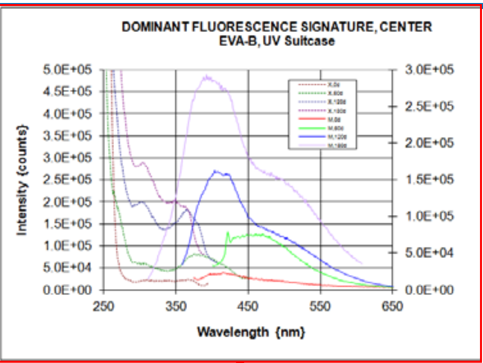
- Other base materials or components (backsheet) may have even stronger spectral dependence than encapsulation.

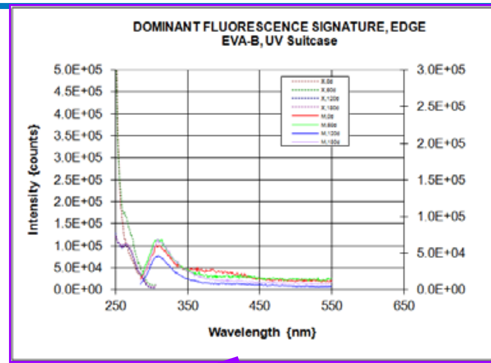
- NIST SPHERE experiment (passband filters) will provide additional insight.
- Also method: ASTM G178.



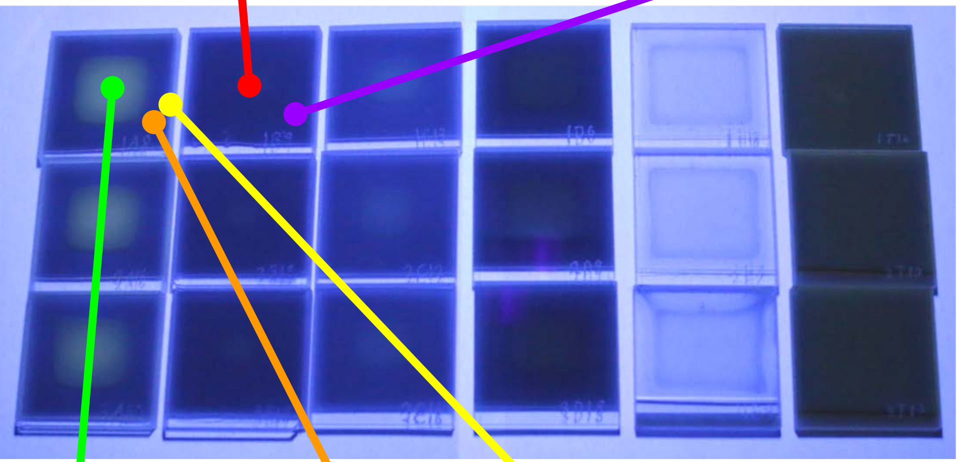
Overlay of representative common artificial UV sources, relative to the AM1.5 global spectrum.

Fluorescence Spectroscopy: Additional Insights

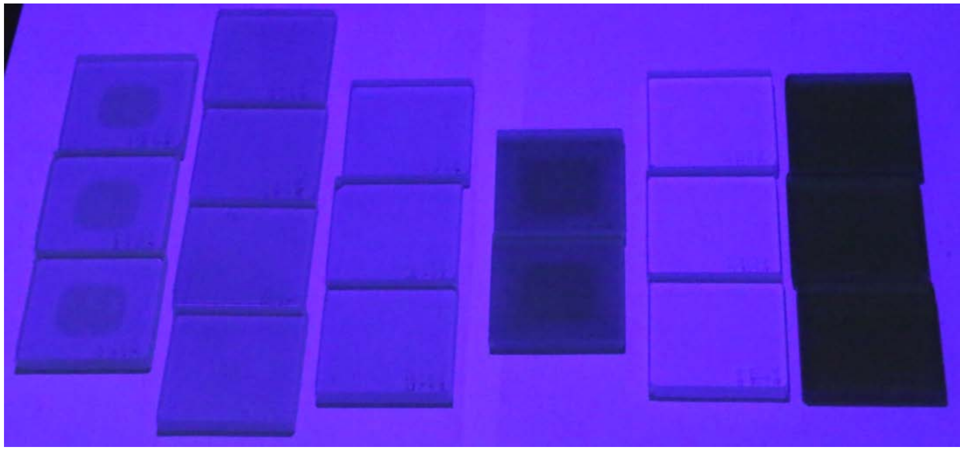




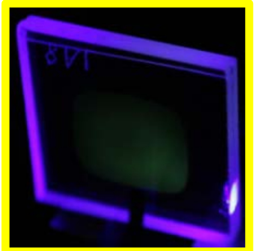
- Anaerobic center and aerobic periphery are readily distinguished with a black light.
- Different extent of regions observed on EVA's. TPU is homogenous.
- Minimal UV-VIS fluorescence observed at periphery relative to specimen interior.



Blacklight image (for *E* @ 254 nm) for specimens aged for 180 days in NREL UV Suitcase (UVA-340 source).



Blacklight image (for *E* @ 365 nm) for specimens aged for 180 days in NREL Ci5000 (Xe lamp). Samples are arranged in columns: EVA-A, -B, -C, -D, -E, and TPU.

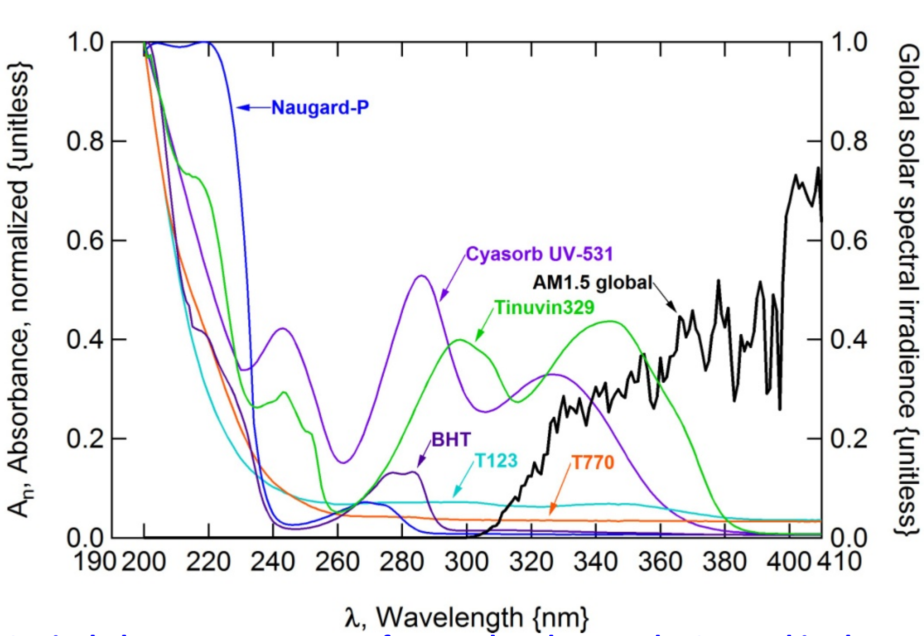


- The geometry and effect in the specimens can be confirmed during the use of the fluorescence spectrometer.

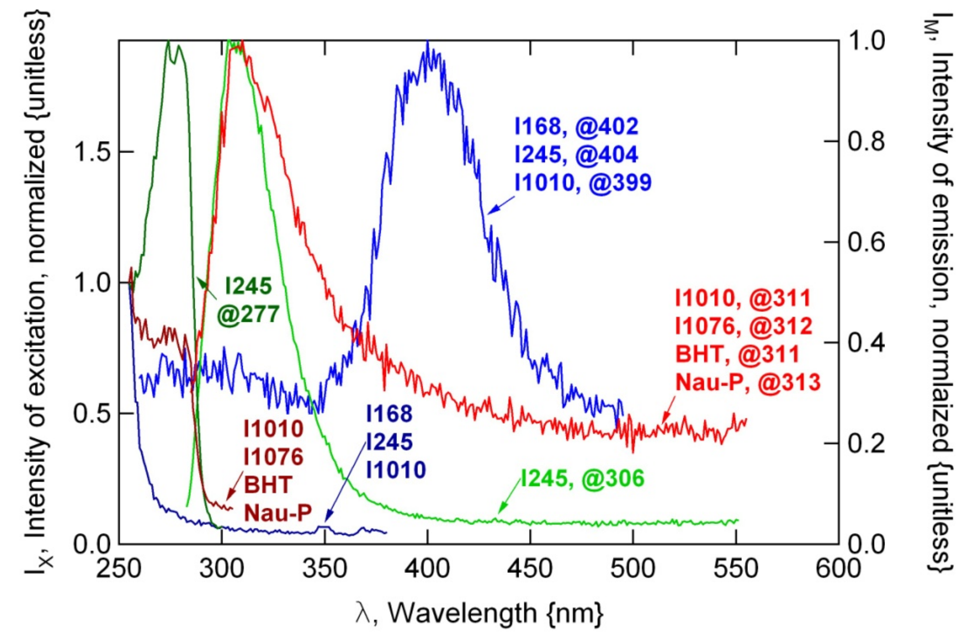
Examples of the test configurations for the UV-VIS fluorescence spectrophotometer. The examination region can be confirmed from the spot, which appears different (based on its fluorescence) at the center or periphery of the specimen. The size and shape of the discolored anaerobic region can be confirmed when the excitation beam is placed at the edge of the silica superstrate.

Effects of Additives in EVA and Polymers

- Representative (normalized) results shown for ~0.01% wt. concentration additive in hexane.
- UV absorbers often feature double absorptance peaks; Anti-Oxidants often characterized by absorptance at even shorter wavelengths.
- UV absorbers often characterized by single thermalization emission peak at ~400 nm, *e.g.*, I168.
- AOs may characterized by more specific excitation & emission peaks, although a few common peak sets were observed here.
- Fluorescence signature may be very different when multiples additives are present (and interacting).



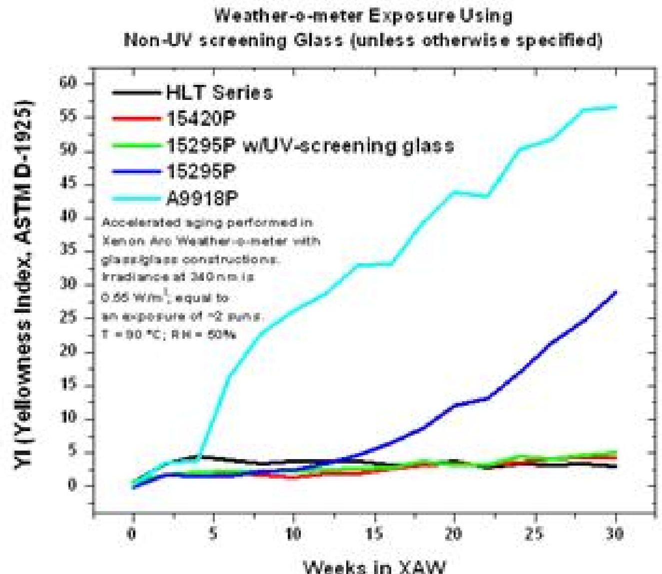
Optical absorptance spectra for UV absorbers and AOs used in the TG5 EVA formulations, including: Cyabsorb UV 531, Tinuvin 123, Tinuvin 328, Tinuvin 329, Tinuvin 770; butylated hydroxytoluene (BHT), and Naugard P.



Representative fluorescence spectra (excitation on left; emission on right) for AOs often used in contemporary polymers, including butylated hydroxytoluene (BHT), Irgafos 168, Irganox 245, Irganox 1010, Irganox 1076, and Naugard P. Some additives have multiple fluorescence peaks.

Transmittance: Comparison to Historic & Outdoor Data

- Historically, yellowness index has been used to compare between indoor- and field-aged encapsulation.
- We examine 2 of the classic formulations, using a modern version of the same glass.
- ΔYI, EVA-A: ~8 (Xe, 60°C) vs. ~55 (Xe, 70°C).



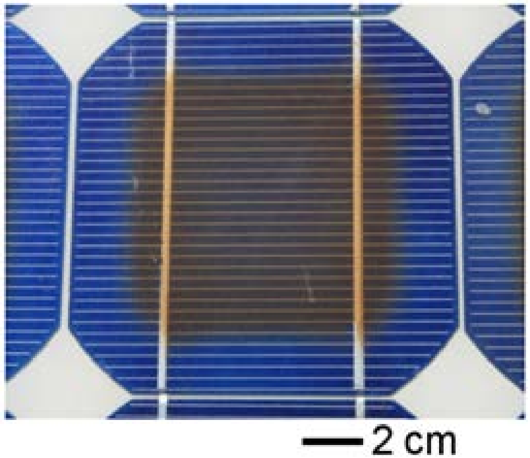
Assessing degradation from change in YI.
Reid et. al., Proc SPIE, 2013, 8825-7.

- Same & similar formulations in k_d experiment deployed at APS in 1996.

⇒Conclusion: discoloration resulted from additive interactions (as in k_d experiment).

- Location specific results (center vs. periphery) as in k_d experiment.

- TG5 will determine location specific acceleration factor for Cleveland, Golden, Miami, Phoenix, & Riyadh.



Localized discoloration of EVA
(known formulation in module) at the APS site.
Wohlgemuth et. al., Proc IEEE PVSC, 2013, 3260-3265.