NREL NATIONAL RENEWABLE ENERGY LABORATORY

Degradation in PV Encapsulant Transmittance: Results of the First PVQAT TG5 Study

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"Meeting Place" room (Hyatt Place Hotel, Boulder CO)

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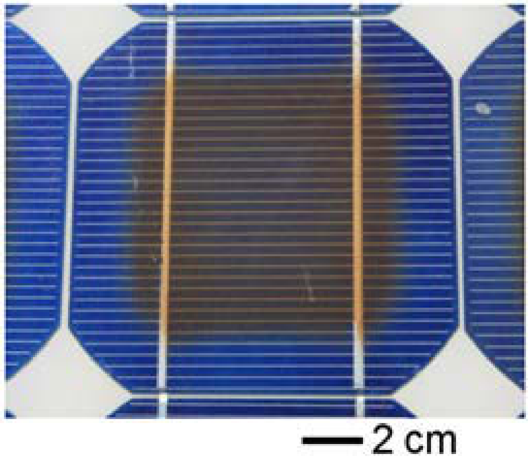
Slides updated in the process of publishing companion PIP journal paper

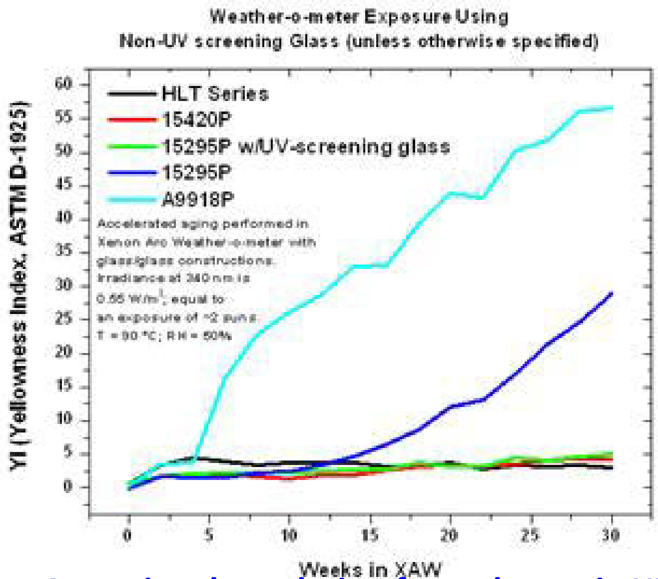
Background: The Discoloration of (EVA) Encapsulant

- Encapsulant discoloration gained significant attention from the 1980's Carizzo Plains CPV installation. Rosenthal et. al., Solar Cells, 30, 563-571, 1991.
- Measureable power loss is evident in the literature for early (pre 2000) & installations in hot climates. Jordan et. al., PIP, 24, 2016, 978-989. Dubey et. al., All India Survey, various.



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

- Literature correlates UV degradation with characteristics including: transmittance, YI, gel content, chemistry…



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

<u>Mechanisms identified:</u>

- Conjugated unsaturated sequences (polyenes).
- α- and β-unsaturated structures.
- **Incompatible formulation additives**.

Goal and Activities PVQAT Task Group 5 (UV, T, RH)

- IEC qualification tests (61215, 61646, 61730-2) presently prescribe up to 160 days field equivalent AM 1.5G TUV dose. This is << 25 years!
- **Goal**: develop UV test protocol(s) that may be used to compare:
  PV materials, components, and modules relative to a field deployment.

Core Activities:

1: Consider **weathering literature** and **climate meteorology** (*location-dependent information*).
e.g., known benchmark locations…Miami, FL; Phoenix, AZ

2: Leverage **existing standards**, including other industries.
√Summary exists from Kurt Scott *et. al.*

3: Improve understanding of existing PV UV tests.

4: Improve understanding of module durability.
4-1 Collect information about **field failure modes**.
e.g., the literature, site inspections, industry feedback
4-2 Confirm appropriate **UV weathering models**.

5: Consider suitable **artificial UV sources**.
√Summary of *module* capable equipment from David Burns *et. al.*

6: **Generate test procedure for accelerated UV weathering.**
Presently performing experiments to provide technical basis & confident decisions.

7: Perform **laboratory verification** of proposed test standard/failure mode.
- mini-module study (Japan), SoPhia round-robin (Europe), interlaboratory “study 1” (TG5 X)

Recent Activities for PVQAT TG5 (UV, T, RH)

- Encapsulant discoloration from UV degradation is a known degradation mode for PV modules. Jordan et. al., PIP, 24, 2016, 978-989.

- IEC 61215-2 qualification test prescribes 54 MJ·m^{-2} (~40 days equivalent*) IEC 60904-3 AM 1.5G UV radiation dose. IEC 61730-2 safety test: 4x.
  This is << 25 year warranty!

⇒International PV Quality Assurance Task Force (PVQAT)

- **TG5 Goal**: develop UV- and temperature-facilitated test protocol(s) that may be used to compare PV materials, components, and modules relative to long-term field service.

Applications:

- IEC 62788-7-2 (UV weathering of PV materials and components).
  Accelerated aging test(s) for encapsulation, backsheet, adhesives…
- IEC 62788-1-7 (optical durability of transparent PV materials).
  -Combines IEC 62788-1-4 (optical transmittance) and
  IEC 62788-7-2 (UV weathering).
  -To be required in IEC 62788-1-1 (encapsulant guiding standard).

*Assumes 1-axis tracking, 8 hour perfectly sunny days

Goals for the TG5 Transmittance Interlaboratory Study

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

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

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

- Knowing E_a is critical to prescribing & interpreting UV weathering.
- 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

The Materials Used in the TG5 Study

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

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
butylated hydroxytoluene	anti-oxidant (AO), heat stabilizer in EVA resin.	N/A	0.06	0.06	0.06	0.06	0.06	?
Z6030	siloxane 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	AO, phenolic phosphonite	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)

The Weathering Applied in the TG5 Study

- Only E_{340}, ChT, ChRH specified, e.g. no BPT specification.
- Lamps types: Xe-arc; HQI metal-halide; UVA-340 fluorescent; no light.
- Filter types: ASTM D7869 compliant; daylight; quartz; type S glass.
- Nominal condition: 1.0 W·m^{-2}·nm^{-1} (340 nm); ChT 60°C, and the ChRH 30%.

- Additional experiments:

-Arrhenius analysis (ChT 45, 60, & 80°C).

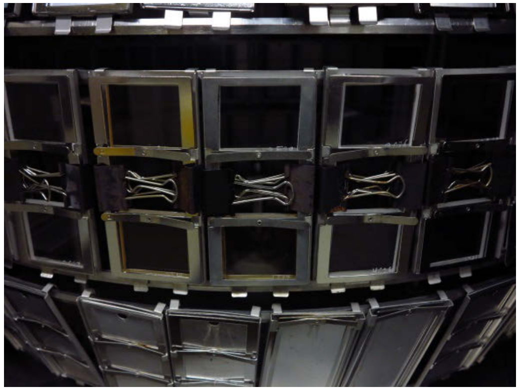
-Proposed 62788-7-2 (80°C/20%; 90°C/20%)

	ARTIFICIAL WEATHERING				
PARTICIPANT	IRRADIANCE SOURCE	IRRADIANCE FILTER (inner/outer)	E_{340}, IRRADIANCE AT 340 nm {W·m^{-2}·nm^{-1}}	ChT, CHAMBER TEMPERATURE {°C}	ChRH, CHAMBER RELATIVE HUMIDITY {%}
1	Xe	D7869/quartz	1.0	45	30
1	Xe	D7869/quartz	1.0	60	30
1	Xe	D7869/quartz	1.0	80	30
2	Xe	s-boro/quartz	0.80	80	20
3	HQI metal-halide	N/A	0.43	40	50
3	~UVA-340	N/A	2.17	60	50
3	~UVA-340	N/A	2.92	80	50
4	N/A	N/A	0	40	30
4	N/A	N/A	0	60	30
4	N/A	N/A	0	80	30
5	Xe	D7869/quartz	1.0	60	50
5	Xe	D7869/quartz	1.0	90	20
5	UVA-340	N/A	1.2	60	~7
6	UVA-340	N/A	1.0	60	~7
7	Xe	Daylight/quartz	1.0	60	30
7	UVA-340	N/A	1.0	60	~7

Summary of the weathering chambers and nominal chamber conditions (settings) in the study.

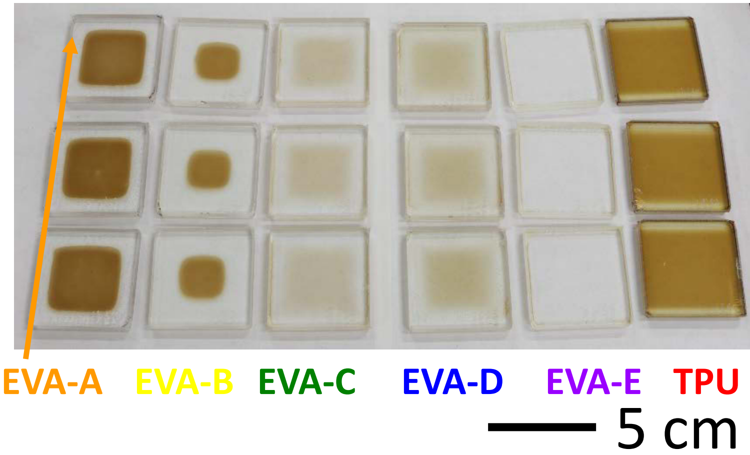
Details of the k_d Methods and Experiment: Encapsulation Transmittance Test

- 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.



Specimens in sample holders for indoor aging at NREL.

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



Visual appearance after 180 days of Xe weathering at 90 °C ChT, 20 % ChRH.

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.

The τ Measurements Used in the TG5 Study

Based on IEC 62788-1-4 ("optical τ encapsulants")

- Suggested settings (proven this study): $200 \leq \lambda \leq 2500$ nm. 1 nm increment.
  - $200 \leq \lambda \leq 400$ critical, including UV transparent encapsulants.

- Subsequent analysis:
  - τ_{sw} (general solar 280-2500 nm)
  - τ_{rsw} (1j PV, 300-1250 nm)
  - *YI* (acute indicator)
  - λ_{cUV} (UV absorber diagnosis)

- Some measurement discrepancies follow from equipment limitations.

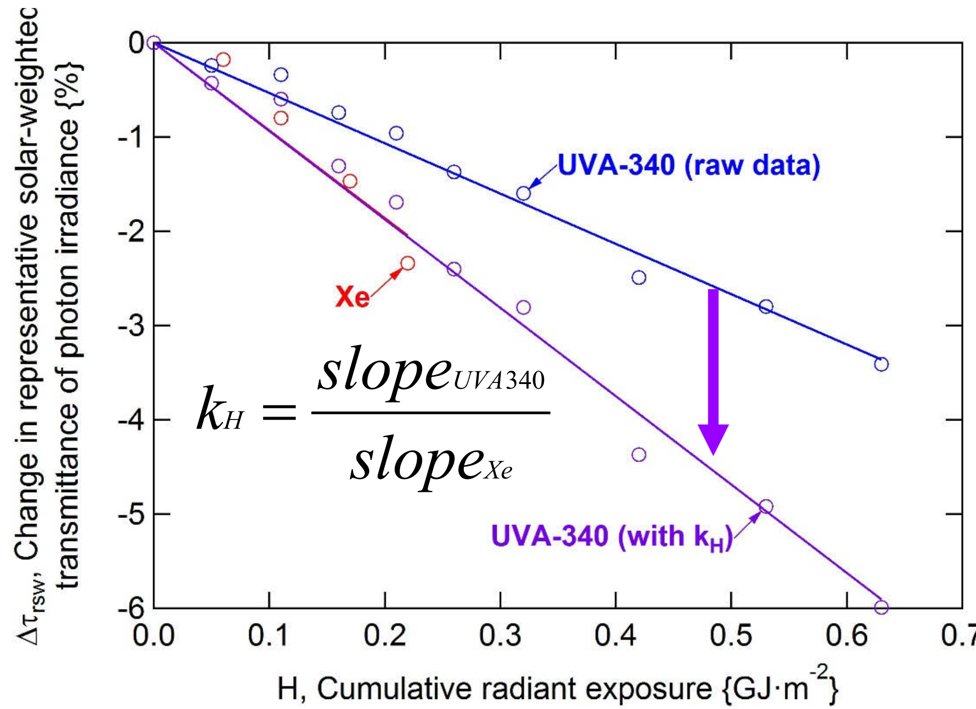
- Development of 62788-1-4: Miller et. al., Proc SPIE, 2013, 8825-8.

	OPTICAL CHARACTERIZATION		
PARTICIPANT	MAKE SPECTROPHOTOMETER	MODEL SPECTROPHOTOMETER	MEASUREMENT RANGE {nm}
1	Perkin Elmer	Lambda 1050	250-2500
1	Perkin Elmer	Lambda 1050	250-2500
1	Perkin Elmer	Lambda 1050	250-2500
2	Perkin Elmer	Lambda 950	200-2500
3	(a) Bruker & (b) custom	(a) Vertex 70 & (b) custom	320-2400
3	(a) Bruker & (b) custom	(a) Vertex 70 & (b) custom	320-2400
3	(a) Bruker & (b) custom	(a) Vertex 70 & (b) custom	320-2400
4	Perkin Elmer	Lambda 900	250-2500
4	Perkin Elmer	Lambda 900	250-2500
4	Perkin Elmer	Lambda 900	250-2500
5	Agilent	Cary 5000	200-2650
5	Perkin Elmer	Lambda 1050	200-2500
5	Agilent	Cary 5000	200-2650
6	Shimadzu	UV 2600	200-800
7	Otsuka Electronics	MCPD-7700	250-800
7	Otsuka Electronics	MCPD-7700	250-800

Summary of the optical characterization equipment and settings in the study.

The k_H Method of Data Analysis

- (Linear) degradation rate or (logarithmic) shift factor 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).

- Verify what data may be analyzed. *e.g.*, delayed loss of formulation additive.
- Here: H < inflections in $\Delta\tau_{rsw}$ or ΔYI data.

- Linear (e.g., not polynomial) fits here.
- Fits typically fixed to origin, i.e. $\Delta\tau_{rsw}$ and ΔYI were examined.

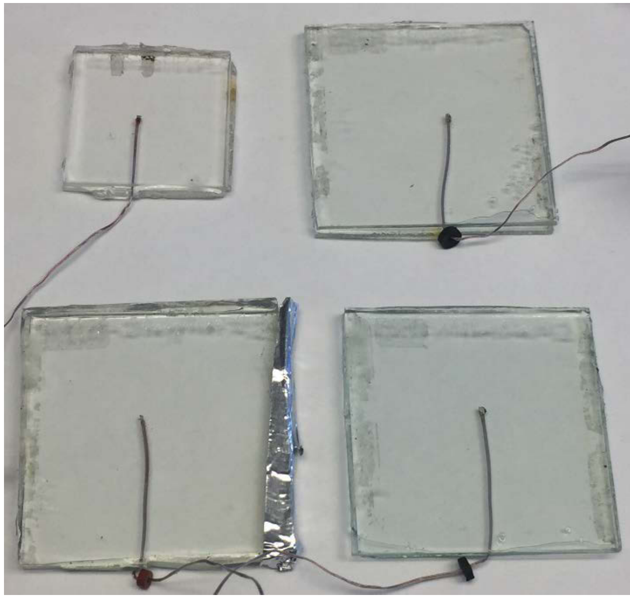
J.A. Simms, J. Coat. Technol., 59 (748), 1987, 45-53.
Gillen et. al., Polym. Deg. Stab., 24, 1989, 137-168.

Details of the Arrhenius Analysis

- Data analyzed for H for λ=340 nm for general comparison (commercial chambers control irradiation at 340 nm).

- Analysis performed at $T_{specimen}$, verified using coupons at weathering test conditions.
  - -Embedded T-type thermocouples.
  - -Concern over radiative heating… *T* may be high.

- Error analysis according to method of propagation of uncertainty.
  - -Rise in specimen temperature from discoloration was not considered in error analysis.
  - -Data analyzed typically limited to $\Delta\tau$<2%, e.g., inflection in data profile.

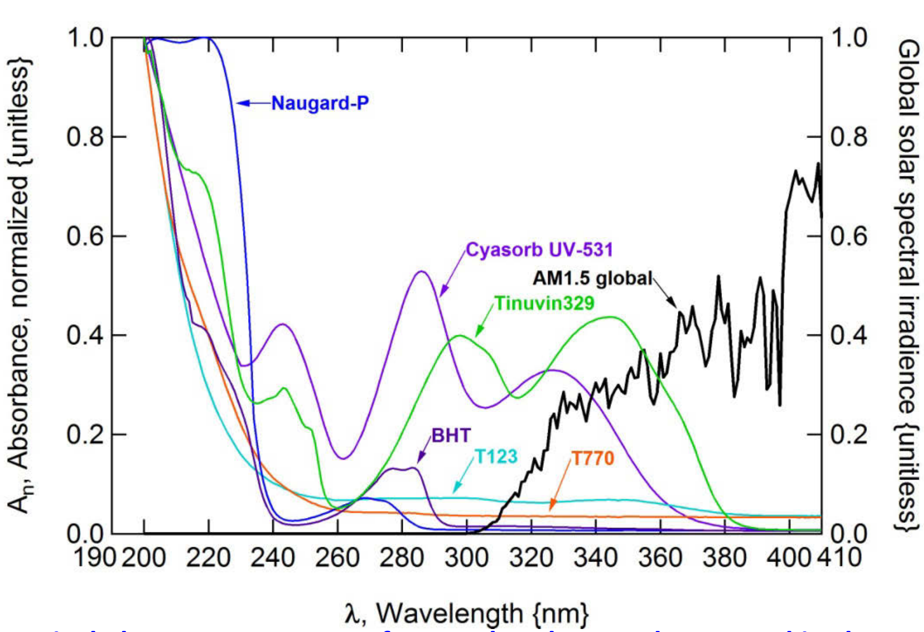


A set of 4 coupons (different representative makes of glass and encapsulant) were circulated in a separate round-robin experiment for temperature verification.

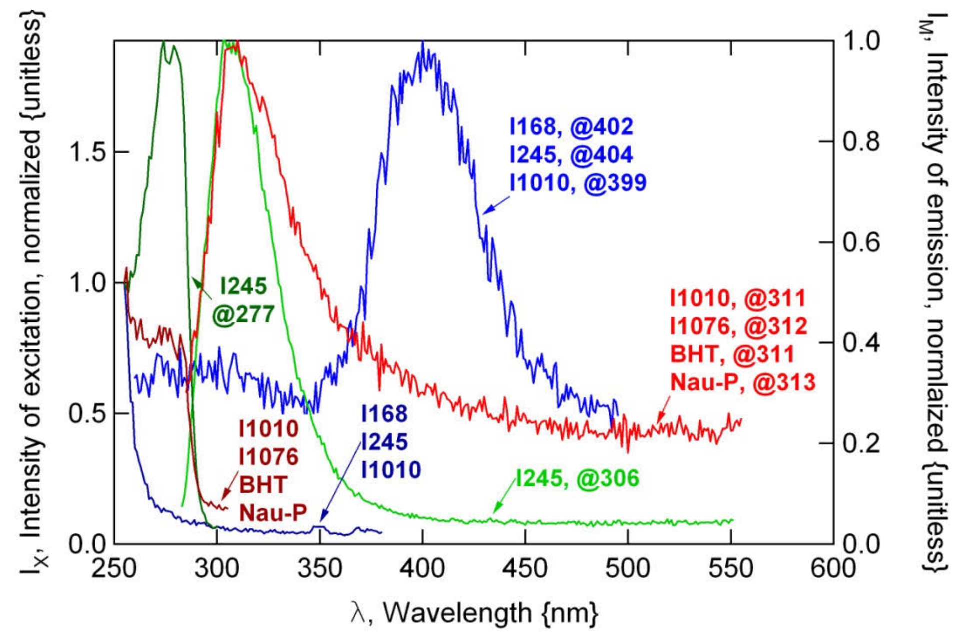
Effects of Additives in EVA and Polymers

- Representative (normalized) results shown for ~0.01% wt. concentration additive in hexane.
- UV absorbers (UV-531 & T329) feature double absorptance peaks and act 280≤λ≤380 nm.
- HALS and Anti-Oxidants typically characterized by strong absorptance at λ <240 nm.

- 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 different when multiples additives are present (and interacting).



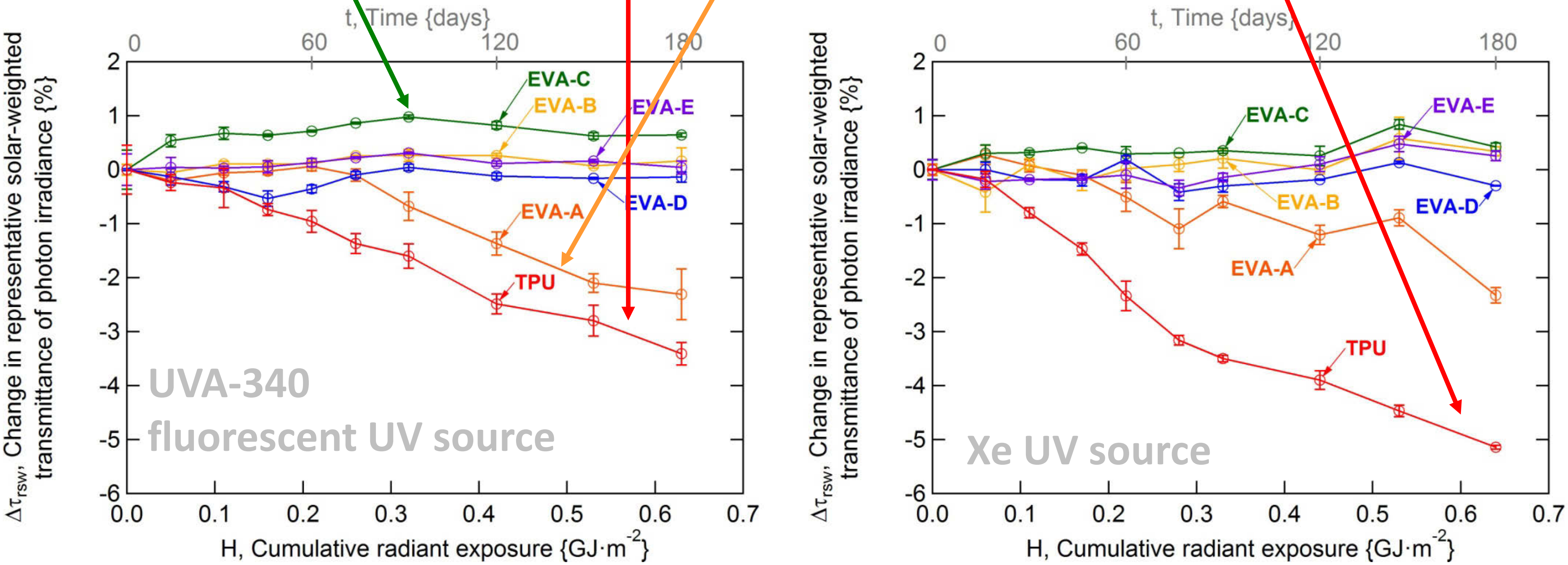
Optical absorptance spectra for UV absorbers and AOs used in the TG5 EVA formulations, including: Cyabsorb UV 531, Tinuvin 123, Tinuvin 328, Tinuvin 329, Tinuvin 770; butylated hydroxytoluene (BHT), and Naugard P.



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.

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

- 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)!



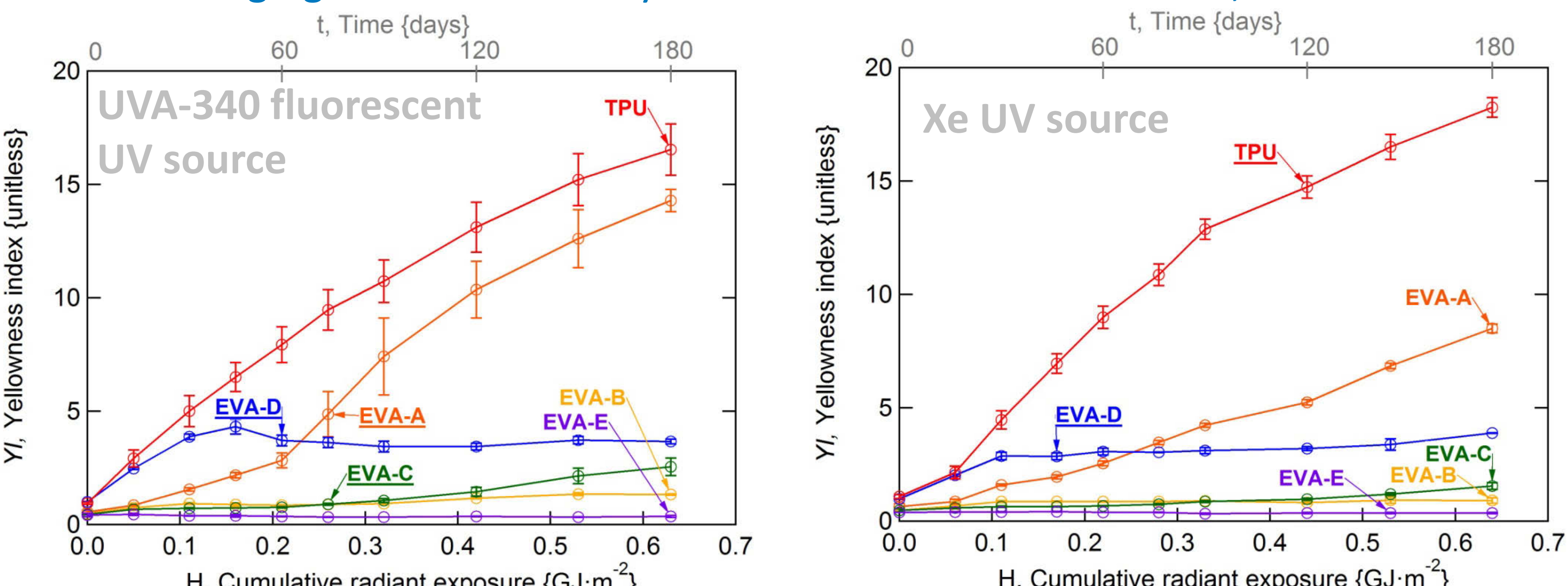
Change in τ_{rsw} with *H* for the NREL aged transmittance coupons (center measurements).
The data points have been connected to guide the eye.
***This presentation: H* shown for 295≤λ≤360 nm.**

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 irradiation.
- 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).

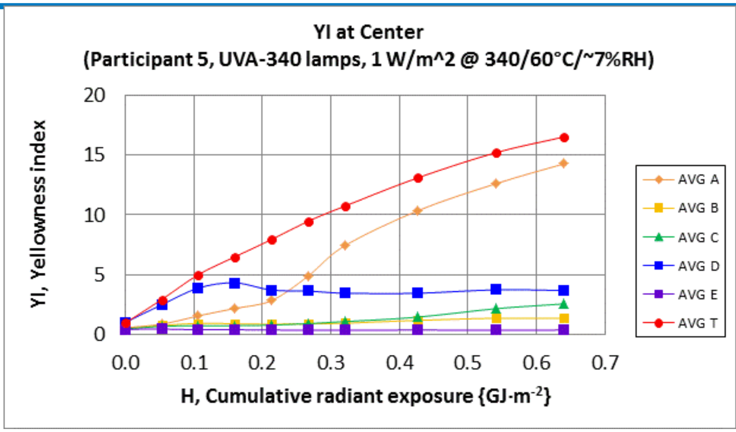
$\Rightarrow$Effects of aging are dominated by interactions between additives, not base material!

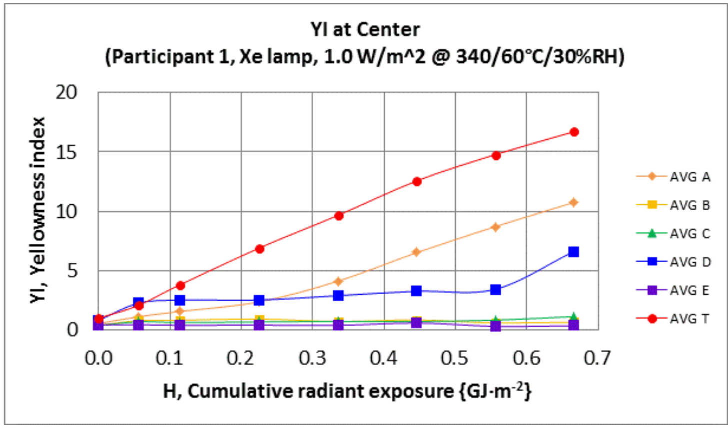


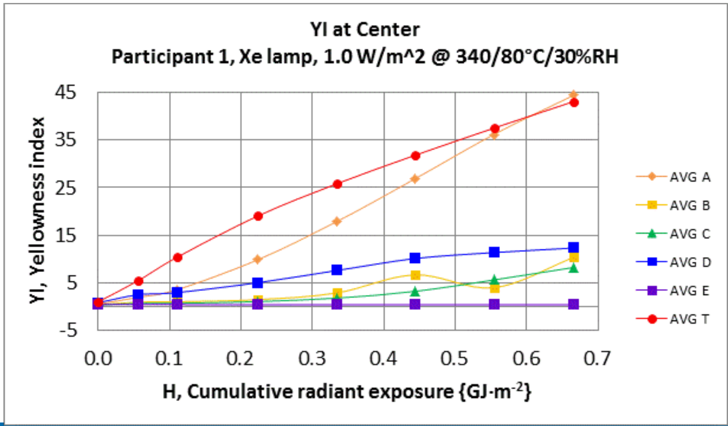
Change in YI with *H* for the NREL aged τ coupons (center measurements).
The data points have been connected to guide the eye.
This presentation: data shown for average of 3 replicates, with error bars for 1 S.D.

Formulation Specific Trends in the Study

- TPU demonstrated the greatest loss in τ_{rsw} with a corresponding increase in YI in 12/16 experiments.
- EVA-A was typically the second most affected material in the experiments.
- The occurrence and H duration for inflections for EVA-B, EVA-C, EVA-D, and TPU varied with the ChT used during weathering.
- EVA-E (no UV absorber) did not significantly change in τ_{rsw} or YI through the various experiments.
- Excluding Lupersol 101 peroxide (EVA-B) greatly reduces discoloration; excluding Naugard P AO (EVA-C) can modestly reduce discoloration.
- τ_{rsw} of EVA-C increased with weathering in several experiments - may follow from the evolution of crystallinity or loss of additives with weathering.
- EVA-E (no Cysorb UV-531) confirms that additive interactions with the UV absorber, are the primary source of discoloration in the EVA formulations here.





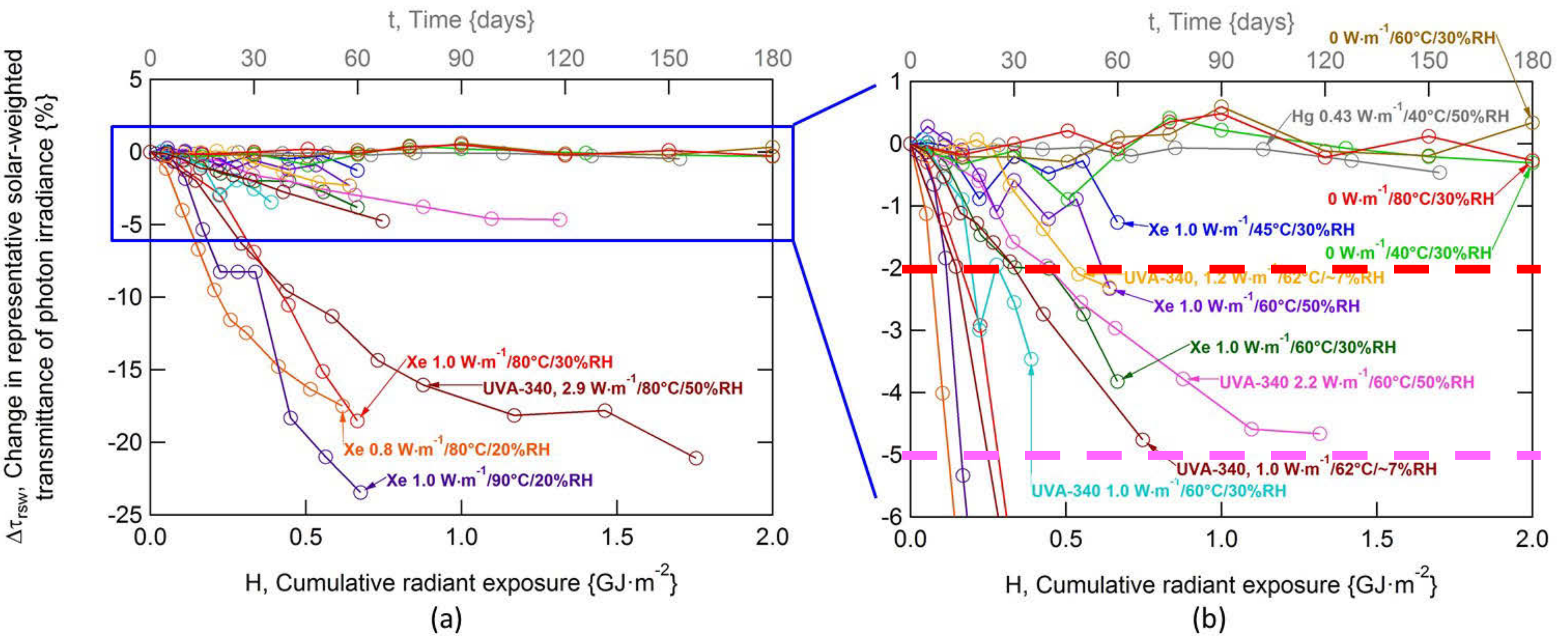


Change in YI with *H* for the NREL aged τ coupons (center measurements).
The data points have been connected to guide the eye.
This presentation: data shown for average of 3 replicates, with error bars for 1 S.D.

Comparing the Experiments: EVA-A

- Stable τ_{rsw} for E=0 identifies that degradation in other experiments follows from UV degradation. Thermal- and hydro-degradation are not significant without irradiation.

- The distinct separation between the experiments performed at the ChT of 80 °C or 90 °C suggests a different regime, e.g., where the kinetics has fundamentally changed by elevated temperature or loss of formulation additives.

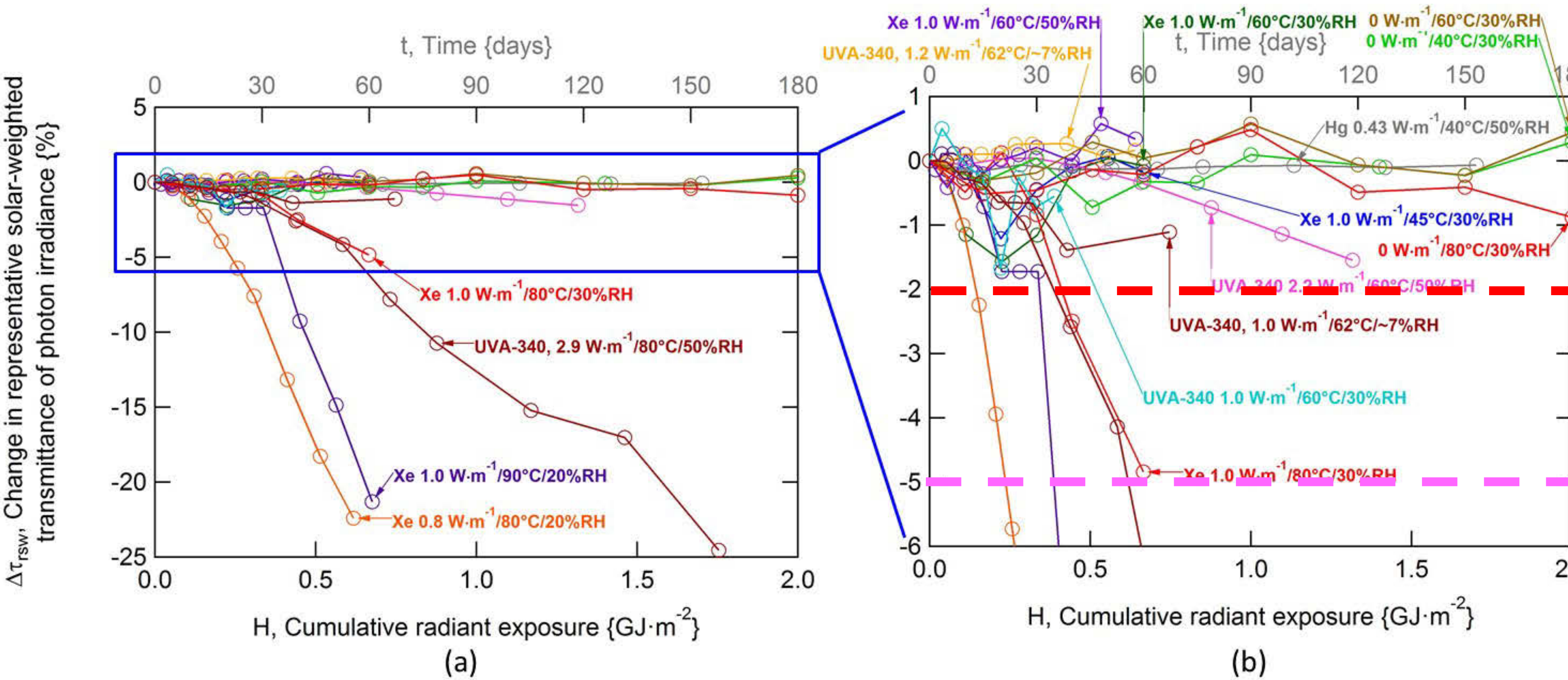


Overlay of all experiments for EVA-A. The details of the results at lower ChT are shown in the inset (b).

Comparing the Experiments: EVA-B

- Similar observations: minimal $\Delta\tau_{rsw}$ for E=0; elevated $\Delta\tau_{rsw}$ for ChT = 80 °C or 90 °C.

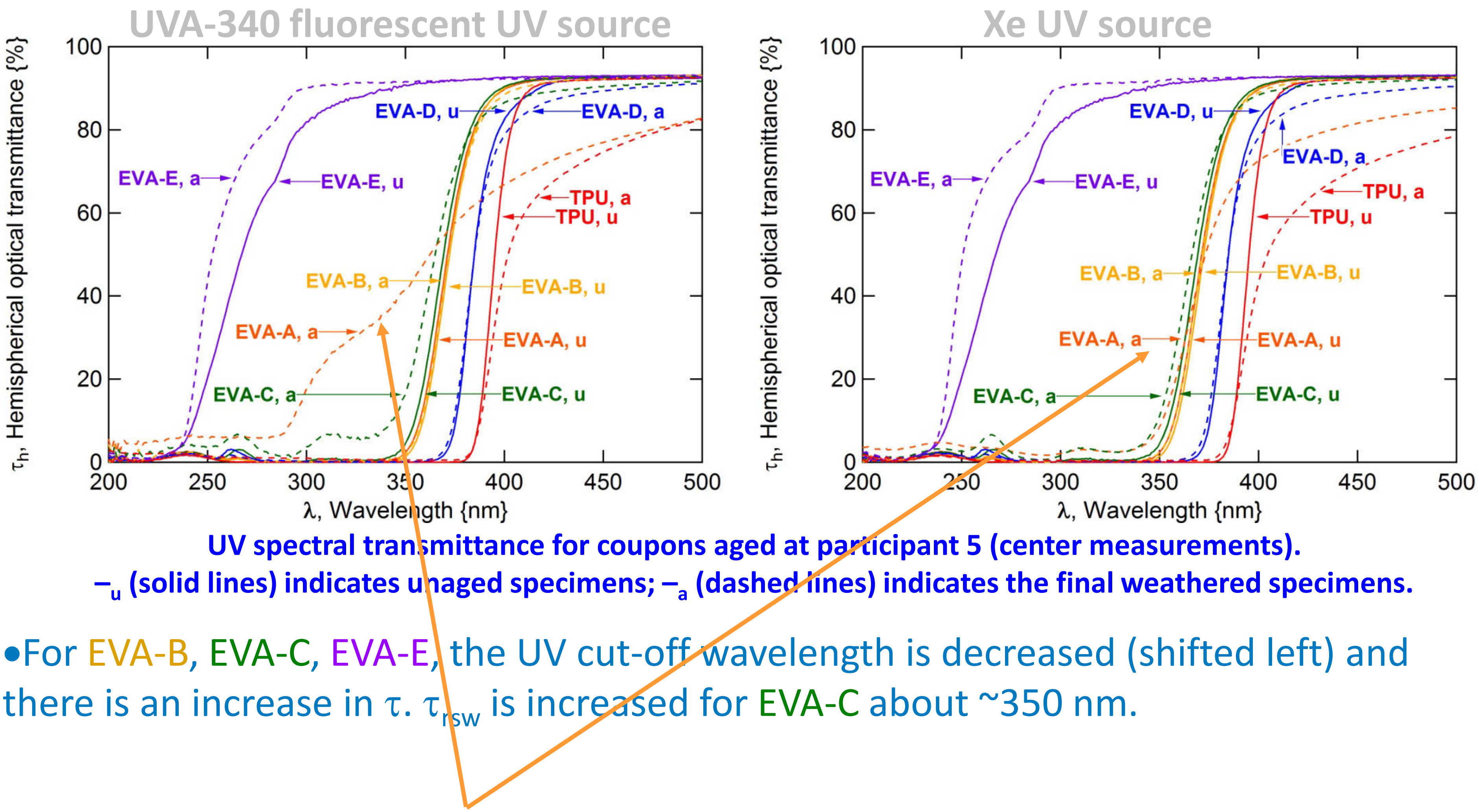
- Comparing EVA-A (known bad product) to EVA-B (improved product) suggests that the limit of 2% might be applied for τ_{rsw} as an acceptance limit for the ChT of ~60 °C.



Overlay of all experiments for EVA-B. The details of the results at lower ChT are shown in the inset (b).

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 UV absorber, peroxide, and AO).



UV spectral transmittance for coupons aged at participant 5 (center measurements).
$-_u$ (solid lines) indicates unaged specimens; $-_a$ (dashed lines) indicates the final weathered specimens.

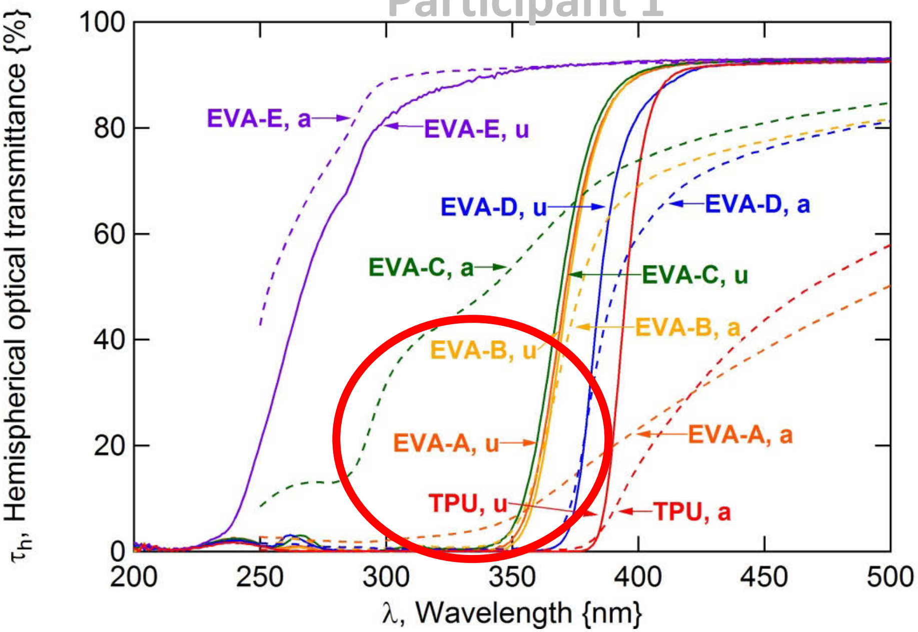
- For EVA-B, EVA-C, EVA-E, the UV cut-off wavelength is decreased (shifted left) and there is an increase in τ. τ_{rsw} is increased for EVA-C about ~350 nm.

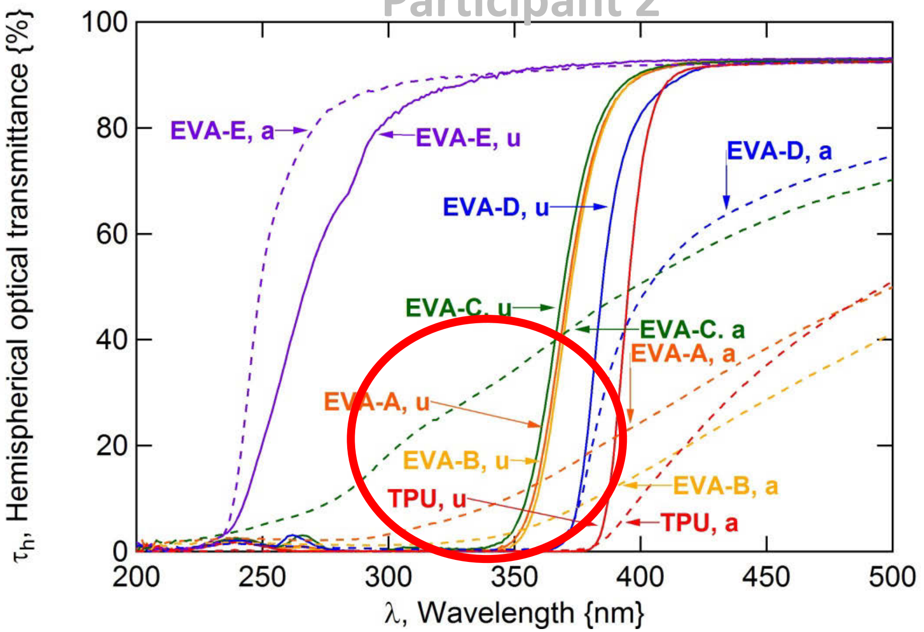
- EVA-A: is UV absorber lost for UVA-340 source? VIS required (photobleaching for Xe)?

Insights From the τ Spectra for Hot Experiments

Participant 1 (E_{340} of **1.0** $W \cdot m^{-2} \cdot nm^{-1}$, ChT of 80 °C, ChRH 30%) is compared to Participant 2 (E_{340} of **0.8** $W \cdot m^{-2} \cdot nm^{-1}$, ChT of 80 °C, ChRH 20%).

- Both labs: Loss of UV absorber implied from τ_h for EVA-A and EVA-C.
  UV absorber only active additive from 280<λ<380nm.
  Participant 2: UV absorber for EVA-B depleting enough to affect λ_{cUV}. More damage.
- Greater degradation (despite lesser E and ChRH follows from s-boro/quartz filters at participant 2. Short λ radiation exceeding terrestrial spectrum.



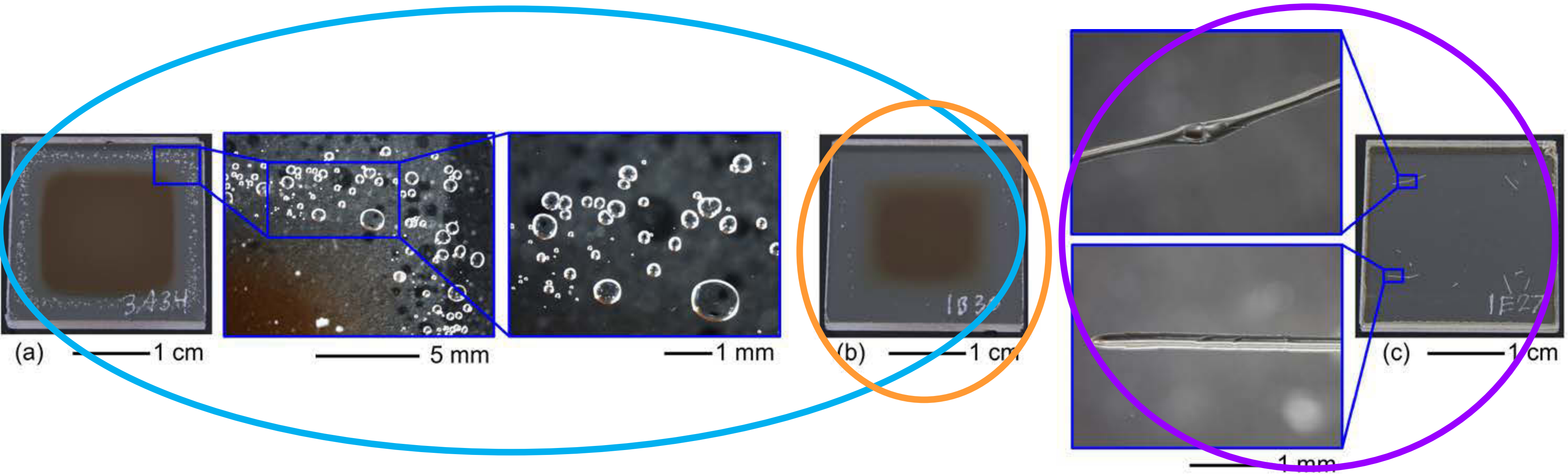


UV spectral transmittance for the Xe chamber experiments.
(center measurements , participant 1 on left; participant 2 on right).
$-_u$ (solid lines) indicates unaged specimens; $-_a$ (dashed lines) indicates the final weathered specimens.

Unique Damage Was Observed in the Hottest Experiments

For ChT 80 or 90 °C (4 experiments):

- **Rounded voids** observed, e.g. EVA-A, with a lesser frequency for EVA-B, -C and –D.
  - -Located at periphery.
  - -Not observed in traditional PV modules (rack mounted glass/backsheet).
  - -Voids/delamination observed in CPV encapsulation study (glass/glass coupons). Miller et. al., PIP, 24, 1385-1409, 2016.
- **Heterogeneous discoloration** was observed for the EVA-A, -B, -C, -D.
- **Linear voids** observed specifically for EVA-E (no UV absorber).
  - -The key factors contributing to the unique geometry here are not clear.

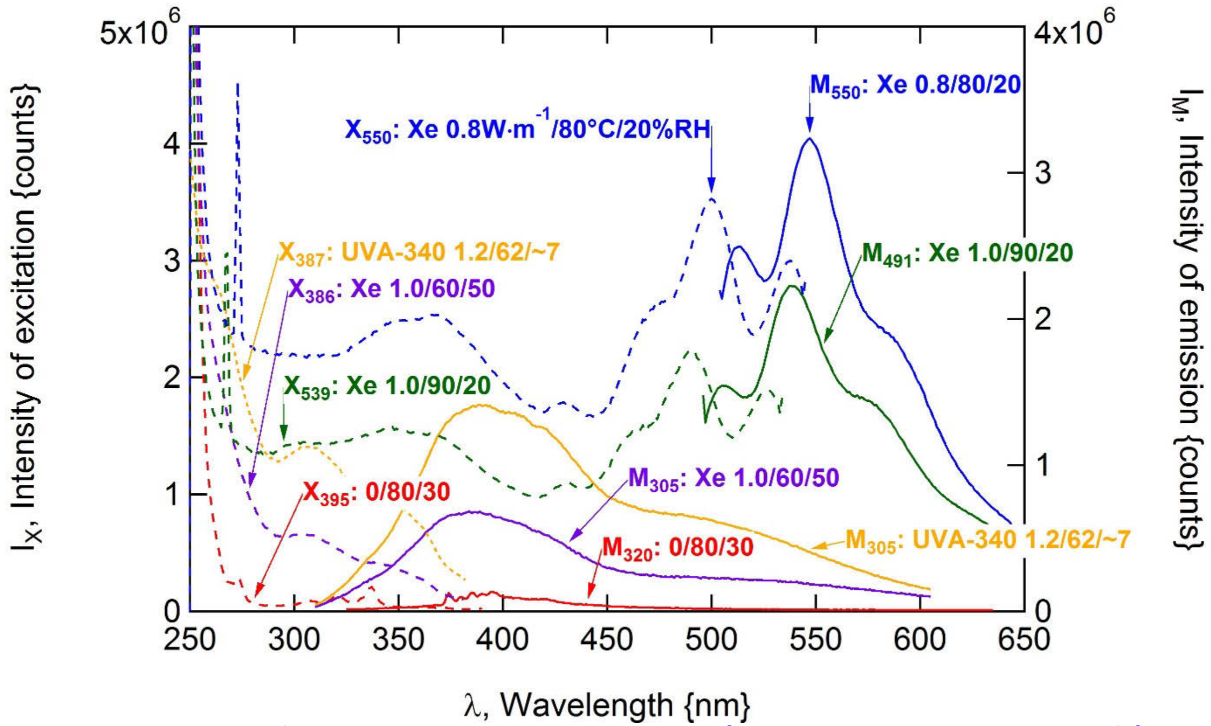


Visual appearance of specimens from the hottest experiments, including: (a) round voids at the periphery of the coupon for participant 2 [Xe lamp, with the chamber controlled at 80°C and 20%RH]; (b) round voids and heterogeneous discoloration in EVA-B for participant 2 [Xe lamp, with the chamber controlled at 80°C and 20%RH]; and (c) linear voids in EVA-E for participant 1 [~UVA-340 lamp, with the chamber controlled at 80°C and 50%RH].

Fluorescence Spectroscopy Reveals Changes in Chemistry With Test Conditions

- Strongest emission and corresponding excitation spectra are self-similar for Xe & UVA-340 experiments for ChT ≤ 60°C.
  - -Similar profile, greater intensity for UVA-340 1.2/62/~7 and Xe 0.8/60/50.
  - -Weak spectra observed for dark experiment for ChT of 80°C.
- Different spectra profiles observed for Xe chambers, ChT of 80 and 90°C.

- Photodegradation is again implied vs. dark experiments.
- Different product species and corresponding enabling chemistry is implied for the hottest experiments.
- The UV source spectra can be disproportionately damaging.



Comparison of fluorescence spectra for EVA-C. Excitation spectra (X, dashed lines on the left) and corresponding emission spectra (M, solid lines on the right) are shown for a representative experiments. The nomenclature in the figure identifies the wavelength of greatest emission (for M) or wavelength monitored during excitation (X) as well as the source type, chamber temperature, and chamber relative humidity.

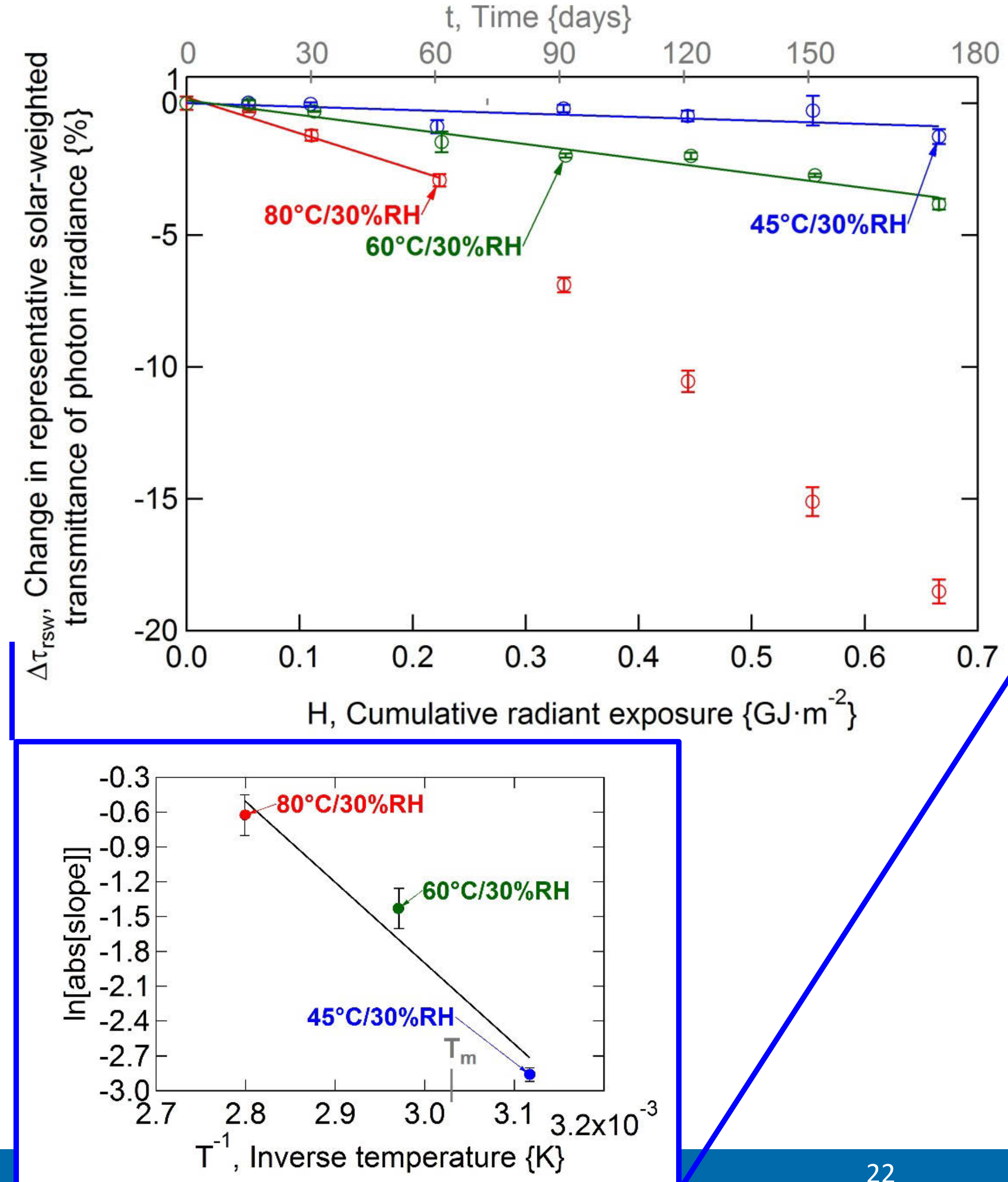
Thermal Activation Was Quantified in Study 1

•Effect of *T* examined directly at lab 1: same irradiance, *RH* applied using three similar chambers (Ci5000, Xe lamp with Right Light filter).

•Analysis (linear fit) was performed up to an inflection (shown as data points only).

•EVA-D uniquely analyzed after initial stabilization.

•T_m of 56.4 °C (average measured for the EVAs) indicated in inset.



Comparison of change in transmittance with ChT for EVA-A. The same default irradiance and RH conditions were used at in separate Xe chambers, set at 45, 60, or 80 °C. *H* is shown for 295≤λ≤360 nm. The slope from linear trendline fits (through the origin, prior to an inflection in the data profile) was examined using an Arrhenius analysis.

Results of the Arrhenius Analysis in Study 1

- EVA's and TPU effected, E_a ~30-60 kJ·mol^{-1}.
- Exception: EVA-E (no UV absorber). $\Delta\tau$~0. E_a could not be determined.
- τ nd YI (analyzed separately) gave similar (order of magnitude) results.
- Low E_a's consistent with defect mediated degradation.
  (additive interactions or impurities).

Summary of the Arrhenius analysis at λ=340 for the six materials in the study. Results were separately analyzed for transmittance and yellowness index.

	τ_{rsw}		YI	
MATERIAL	c_1, FREQUENCY FACTOR {s^{-1}}	E_a {kJ·mol^{-1}}	c_1, FREQUENCY FACTOR {s^{-1}}	E_a {kJ·mol^{-1}}
EVA-A	1.8E+08	58±8	3.5E+09	49±5
EVA-B	2.7E+06	50±8	2.9E+10	59±9
EVA-C	8.4E+03	36±8	1.7E+06	32±8
EVA-D	2.8E+06	47±8	1.9E+09	50±8
EVA-E	N/A	N/A	N/A	N/A
TPU	8.3E+07	53±8	7.9E+09	50±4

Moisture Reduced the Affect of UV Degradation for EVA

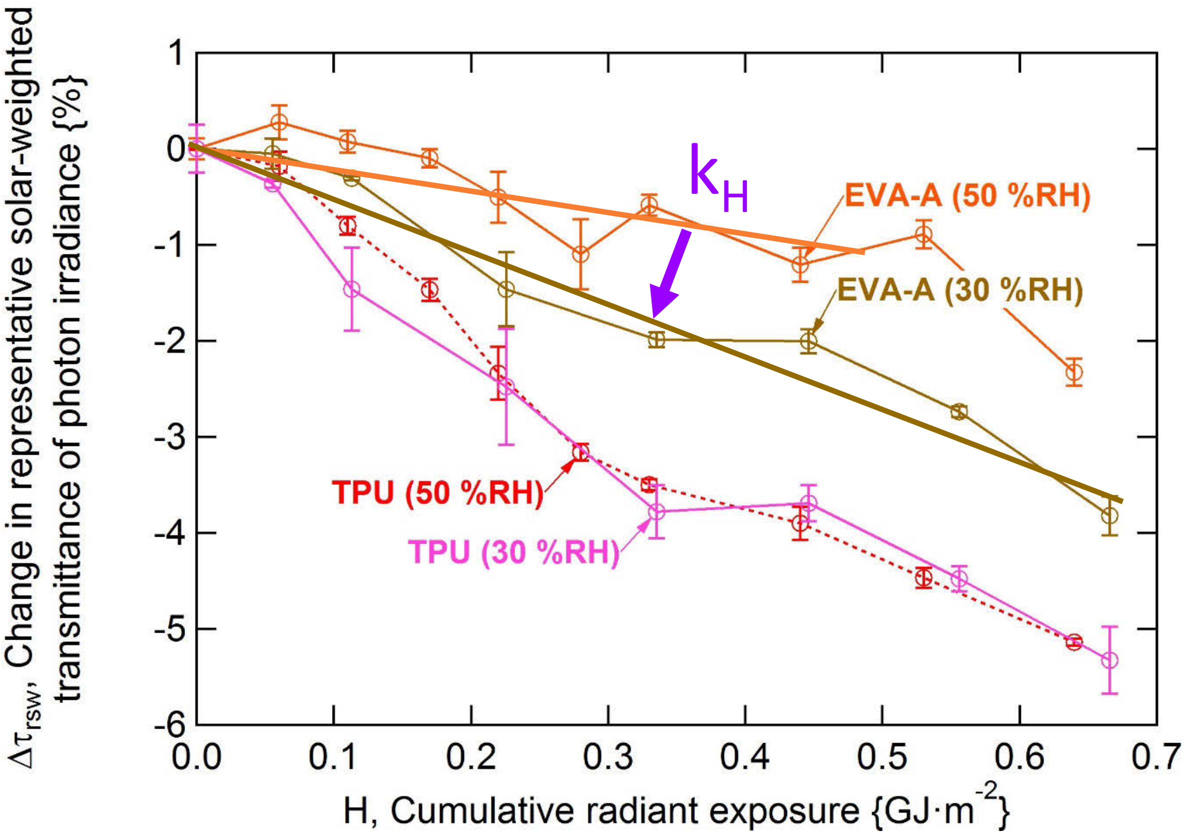
- Degradation rate compared for Xe chamber: 30% or 50% RH.

$$k_H = \frac{m_{50\%}}{m_{30\%}}$$

- 0.4< k_H EVA <1; 1.1 < k_H TPU <1.2.

- Suggests increased degradation for EVA in drier environments.

- Rate of production and/or neutralization of chromophores could be affected by water.



Comparison of change in transmittance for EVA-A and TPU with chamber relative humidity (30 %RH or 50 %RH). The default irradiance of 1.0 W·m^{-2}·nm^{-1} at 340 nm and temperature of 60°C was applied in each Xe chamber.

Use of UV Weathering to Screen Through Early Life

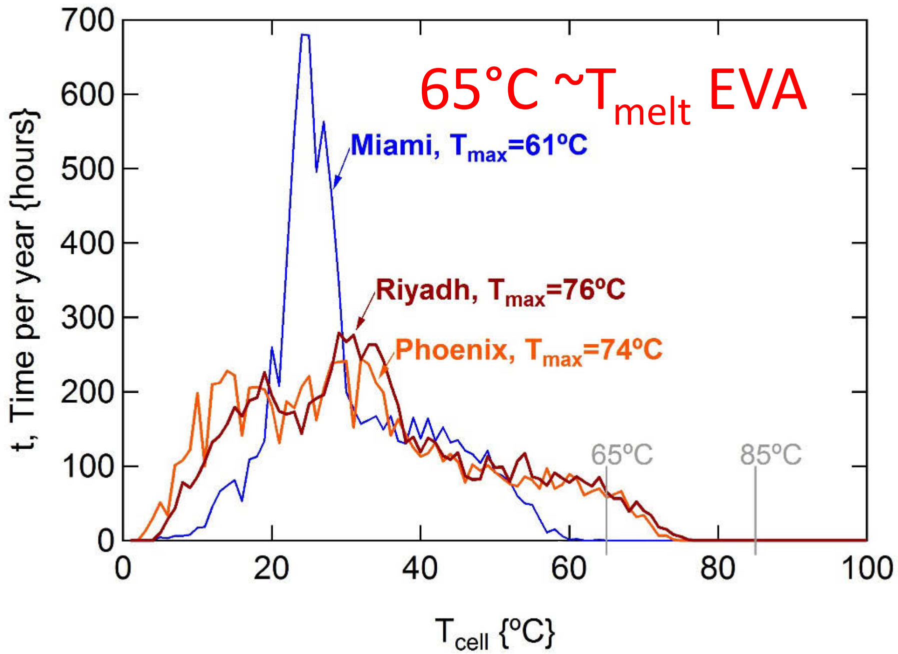
- The hottest experiments suggest an alternate weathering regime, based on large $\Delta\tau$, loss of UV absorber (from spectra), void formation, and disparate lumophore product species.
- Unclear if melt transition, out-diffusion/breakdown of additives, or competing kinetics dominates results in hottest experiments.
- Relative to hottest experiments, the ChT of ~60°C is recommended for typical PV products (rack mounted).

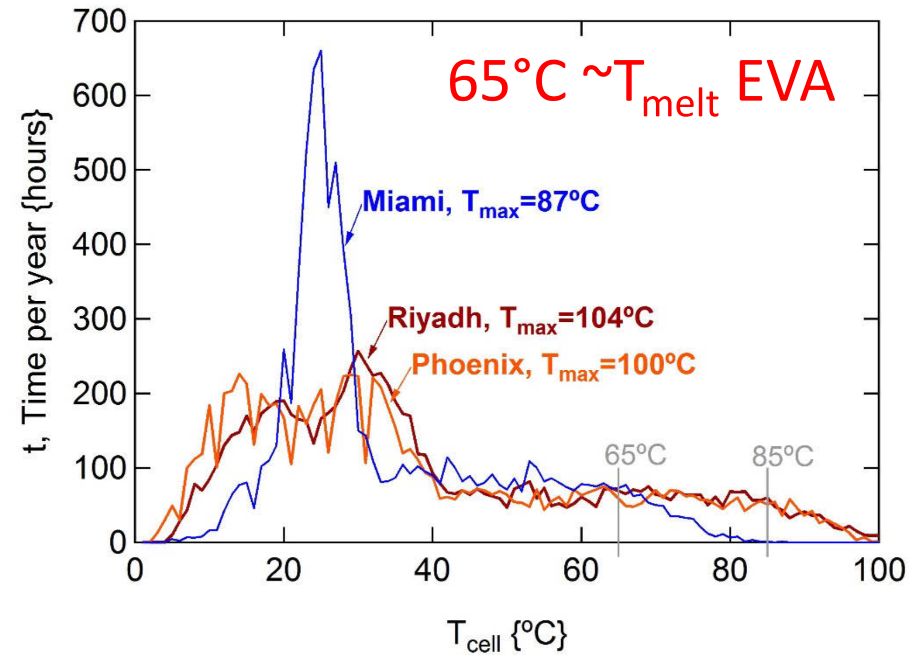
- TG5 study 1: H ~ 3.5y equivalent dose AM1.5G TUV in Phoenix, AZ.
- Literature: I_{sc} degradation rate of ~0.25-0.33 $\%\cdot y^{-1}$ from discoloration is estimated for Si PV.
  - Loss in performance on the order of 2% might be expected after 6-8 years of field use.
- Compared to EVA-B, 2%$\Delta\tau$ acceptance limit, would apply to the early life of a PV module constructed using improved EVA, weathered similar to nominal test conditions of:
  1.0 $W\cdot m^{-2}\cdot nm^{-1}$ at 340 nm, ChT of 60°C, ChRH of 30% RH.

Weathering ChT and Application (Module) T

How much time do PV modules spend at the ChT in the experiments?

- Hottest modules found in hot-dry locations, e.g., Riyadh or Phoenix.
- Rack mounted glass/glass modules ~200 hours ≥65°C·TMY3^{-1}.
- Insulated-back glass/backsheet modules ~200 hours ≥85°C·TMY3^{-1}.





Time-temperature histograms (King model, with 1°C binning) of the cell in rack-mounted glass/glass (left) and insulated-back glass/backsheet (right) modules. T_{max} values are given in the figures for each location.

- Both ~96% percentile temperatures in hot-dry locations, respectively.
- 4000h weathering cumulative of ~25y at highest temperatures.
- Also: hot spot (reverse bias) T >100°C.

Summary

•Xe/s-boro/quartz filter and UVA-340 fluorescent sources, confirm the importance of the source spectrum. Match the terrestrial spectrum.
•Additive specific durability of the materials $\Rightarrow$ degradation is specific to the formulation (i.e. UV absorber), not the base resin material (EVA).
•2% $\Delta\tau$ is suggested here to screen for acceptable encapsulant materials, in artificial weathering when simulating the early years of module life.

•An alternate weathering regime was identified for the hottest experiments in this study, i.e. chamber temperature at or above 80 °C.
•Enabling factor(s) could include: out-diffusion and/or breakdown of formulation additives; T_m of EVA; competing kinetics of the enabling chemistry.
•Chamber temperature on the order of 60 °C should be used for artificial weathering of transparent coupon specimens for typical (rack) PV products.

•E_a of ~50 $kJ \cdot mol^{-1}$ determined here, consistent with defect mediated degradation, facilitated by additive interactions and impurities.
•Rate factor analysis suggests moisture reduces discoloration during aging.

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☞There has been fantastic participation in TG5.

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- If interested in TG5 activities or the experiments, please contact David.Miller@nrel.gov

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NREL STM campus, Dennis Schroeder

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