NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Extrapolating Accelerated UV Weathering Data: Perspective From PVQAT Task Group 5

David C. Miller[1], Eleonora Annigoni[2], Amal Ballion[3], Jayesh G. Bokria[4], Laura S. Bruckman[5], David M. Burns[6], Lamont Elliott[7], Roger H. French[5], Sean Fowler[8], Xiaohong Gu[9], Christian C. Honeker[10], Michael D. Kempe[1], Hussam Khonkar[11], Michael Köhl[3], Peter J. Krommenhoek[9], Laure-Emmanuelle Perret-Aebi[12], Nancy H. Phillips[6], Kurt P. Scott[7], Fanny Sculati-Meillaud[2], Tsuyoshi Shioda[13], Shigeo Suga[14], Shin Watanabe[14], and John H. Wohlgemuth[1]

[1]National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, CO 80401, USA
[2]École Polytechnique Fédérale de Lausanne (EPFL), Rue de la Maladière 71B, Ch 2002 Neuchâtel, Switzerland
[3]Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstrasse 2, 79110 Freiburg, Germany
[4]Specialized Technology Resources, Inc. (STR), 10 Water Street, Enfield, CT, USA 06082
[5]Case Western Reserve University (CWRU), White 538, 10900 Euclid Avenue, Cleveland, OH 44106, USA
[6]The 3M Company, 3M Center, Building 235 67 15, St. Paul, MN, 55144, USA
[7]Atlas Material Testing Technology LLC, 1500 Bishop Court, Mount Prospect, IL 60056, USA,
[8]Q Lab Corporation, 800 Canterbury Road, Cleveland, OH 44145 USA
[9]National Institute of Standards and Technology (NIST), 100 Bureau Dr., Gaithersburg, MD 20899 8615, USA
[10]Fraunhofer Center for Sustainable Energy Systems (CSE), 5 Channel Center, Boston, MA 02210, USA
[11]King Abdulaziz City for Science and Technology (KACST), 17 King Abdullah Road, Riyadh, 11442, Saudi Arabia
[12]Centre Suisse d'Electronique et Microtechnique SA. (CSEM), Rue Jaquet Droz 1, Ch 2002 Neuchâtel, Switzerland
[13]Mitsui Chemicals, Inc., 580 32 Nagaura cho, Sodegaura shi, Chiba, 299 0265, Japan
[14]Suga Test Instruments Co., Ltd., 5 4 14 Shinjuku, Shinjuku ku, 160 0022, Tokyo Japan

***Presenter & TG5 US: David.Miller@nrel.gov;**
TG5 China: fjt79@163.com (Leo Feng, CEI); TG5 Europe: michael.koehl@ise.fraunhofer.de; TG5 Japan: Tsuyoshi.Shioda@mitsui-chem.co.jp

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13:45-14:15 Tues, 2015/2/24

- This presentation contains no proprietary information -

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Overview

- Motivation and goals of TG5.
- E_a interlaboratory experiment for encapsulation (present US-led effort).

Encapsulation discoloration experiment:

- Test description
- Transmittance results (appearance, spectral τ, solar-weighted τ)
- Effect of specimen temperature (accelerated aging)
- Effect of light sources (Xe vs. UVA-340 fluorescent)

Encapsulation attachment strength (CST):

- Test description
- Early stress and resilience results

- Application and timeline of TG5 activities.

Not covered today:

- Edge seal attachment strength (part of E_a experiment)
- SoPhia round-robin for backsheet (present Europe effort)
- Other TG5 efforts (China and Japan)

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

- IEC qualification tests (61215, 61646, 61730-2) presently prescribe up to 137 days field equivalent (IEC 60904-3 AM 1.5) UV-B dose. This is << 25 years!
- **Goal**: develop UV- and temperature-facilitated 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
4-2 Confirm appropriate models for UV aging.

5: Consider suitable UV sources.
- summary of *module* capable equipment from David Burns *et. al.*

6: **Generate test procedure for accelerated UV aging.**

7: Perform laboratory verification of proposed test standard/failure mode.
- mini-module study (Japan), SoPhia round-robin (Europe), E_a interlaboratory study (US)

Motivation for the E_a Interlaboratory Experiment (TG5 US)

- Knowing E_a (for rate of change in a characteristic) is critical to prescribing and interpreting a *UV- and temperature*-mediated test.
- Unfortunately, E_a is not known for the UV degradation of common PV materials.

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

The modified Arrhenius equation

Critical unknowns
(Goals for the interlaboratory experiment):

1. Quantify E_a so that applied test conditions can be interpreted.
2. Provide a sense of the range of E_a that may be present by examining "known bad," "known good," and "intermediate" material formulations.
3. Determine if there is significant coupling between relevant aging factors, *i.e.,* UV, temperature, and humidity.
   What factors does TG5 need to consider?
4. Investigate the spectral requirements for light sources by comparing specimens aged by different sources, *i.e.*, Xe-arc, UVA-340, metal-halide.
   Is visible light required in addition to UV ?

The Materials Used in the E_a Experiment

- Discoloration of encapsulation has been studied in the literature:
  - We have a sense of the general rate of degradation.
  - We have a sense of the sorts of formulations used (historical and contemporary).
- 6 Materials examined in interlaboratory study:
  - Example: compare peroxide used for cross-linking.
  - Example: compare type or use of UVA.
  - A TPU formulation is chosen as a known bad 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, gama-methacroyloxy 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 (UVA), benzotriazole type	BASF Corp.	N/A	N/A	N/A	0.3	N/A	?
Cyasorb 531	UVA, benzophenone type	Cytech 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	EVA D (known good)	EVA E (modern, no UVA)	TPU (known bad)

Encapsulation materials being compared in the transmittance (discoloration) experiment.
The encapsulation adhesion experiment examines Material B only.

Interlaboratory Participation Enables a Wider Range of Study

- Indoor aging is expensive. No one institution has all the resources to apply the complete set of factors we would like to examine.
- Discoloration and adhesion will be studied at (12) -*volunteer*- institutions.
- Example: compare similar instrument makes and models (*e.g.*, Ci5000 & QSUN XE3).
- This overcomes the difficulty of limited availability of aging equipment.

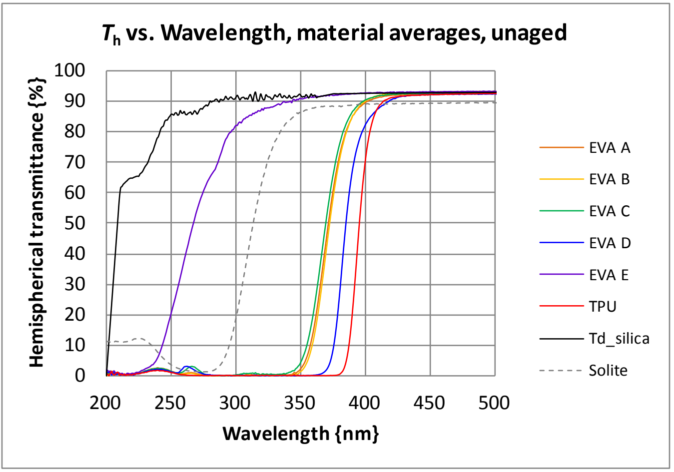
LIGHT SOURCE, FILTER	Xe Arc (right-light/cira filter) or (Suga-Q/#295/Ircut)					Xe Arc (right-light/cira filter)	UVA 340 fluorescent (no filter)		UVA 340 fluorescent (no filter)	Metal-Halide	No light			field deployment (outdoors)
UV LIGHT INTENSITY	NOMINAL (102 W•m^{-2} for 300≤λ≤400)					STANDARD (0.8 W•m-2@ 340 nm)	NOMINAL (1.0 W•m^{-2}@ 340 nm)		NOMINAL (~150 W•m^{-2} for 300≤λ≤400)		0 W•m^{-2}			
CHAMBER RELATIVE HUMIDITY {%}	30 ("low")			50 ("high")		20 ("low")	~7% ("very low")		60 ("high")	30 ("low")	30 ("low")			ambient
CHAMBER TEMEPRATURE {°C}	40	60	80	40	60	80	40	60	60→80→40	60	40	60	80	ambient
PARTICIPANT (INSTRUMENT MODEL)	3M (Ci5000)	3M (Ci5000)	3M (Ci5000)	Mitsui (SX120)	NREL (Ci5000)	Fraunhofer CSE (Ci4000)	QLAB (QUV)	QLAB (QUV)	Fraunhofer ISE (custom)	EPFL	NIST (custom)	NIST (custom)	NIST (custom)	ATLAS (EMMA in Phoenix)
		QLAB (QSUN XE3)			QLAB (QSUN XE3)		ATLAS (UVTEST)	NREL (custom UV suitcase)						CWRU (5x in Cleveland)
		ATLAS (SunTest XXL)						Fraunhofer ISE (custom)						ATLAS (rack in Phoenix)
		Suga (SX75)						Suga (FDP)						ATLAS (rack in Miami
								CWRU (QUV)@1.55 W·m-2 @ 340 nm						NREL (rack in Golden)
														KACST (rack in Riyadh)

Summary of participating laboratories and test conditions

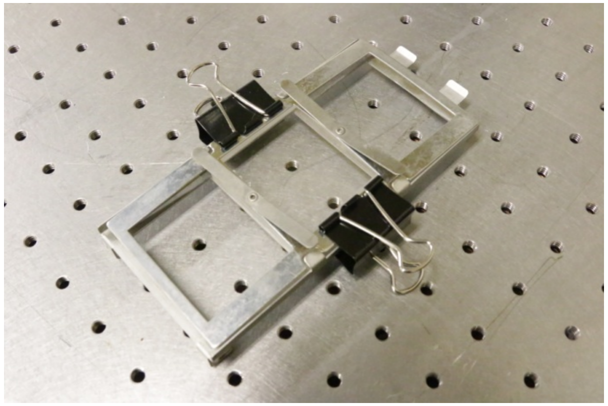
- A standard condition (60°C chamber ambient) allows a broad variety of light sources to be compared.
- Rate of degradation will be compared against field data to allow site-specific acceleration factors to be determined.
- Outdoor data will verify the validity of the indoor test.
- Separate experiment at NIST (EVA-A & EVA-B) will examine action spectrum.

Details of the E_a Methods and Experiment: Encapsulation Transmittance Test

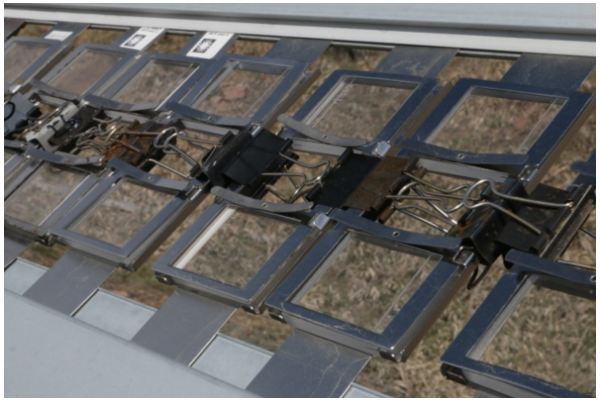
- Glass/polymer/glass coupon specimens measured using a spectrophotometer (with integrating sphere)
- Measure at specimen center (anaerobic, no O_2) and edge (aerobic)
- Analyze: solar-weighted transmittance, yellowness index, and UV cut-off wavelength.



Transmittance will be examined using silica/polymer/silica samples.



Specimen in sample holder for indoor aging at NREL.

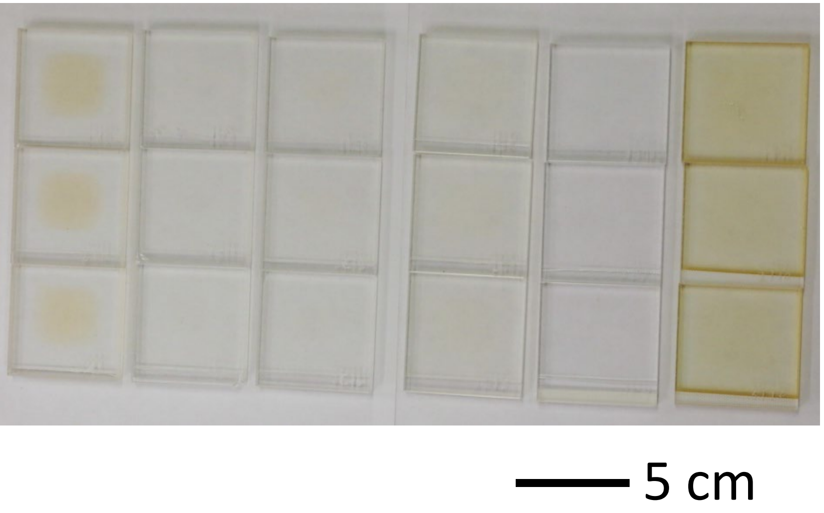


Specimens on outdoor rack, aging in Golden, CO at NREL.

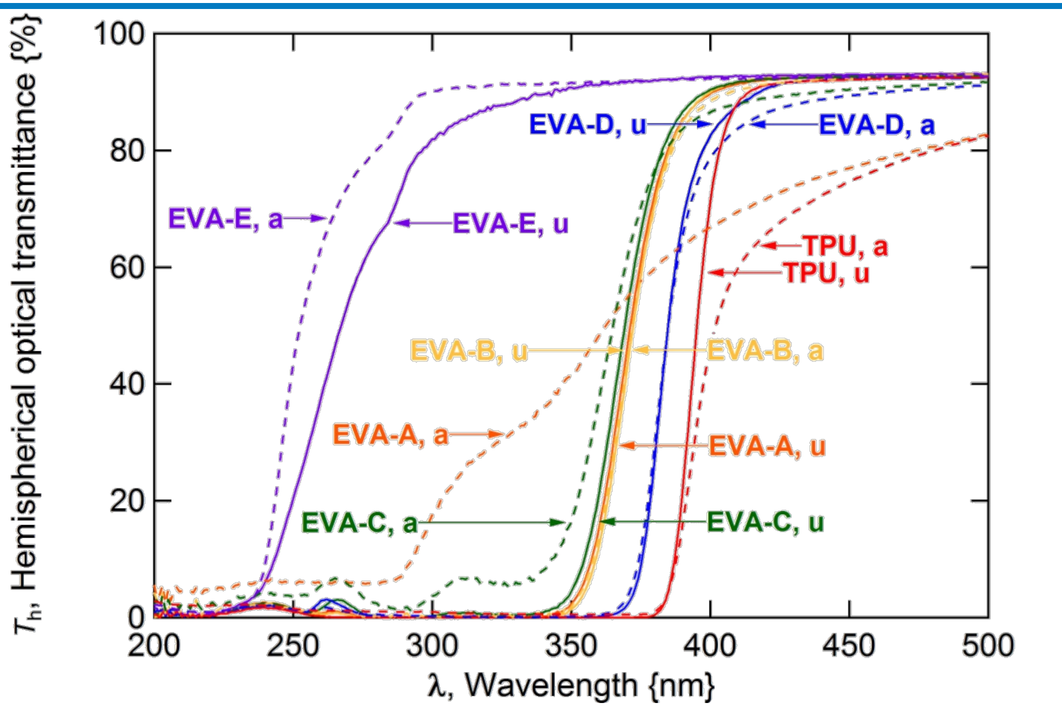
User summary:

- Geometry: glass/polymer/glass (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

Formulation Specific Results Emerging From the E_a Experiment



Visual appearance of the UV Suitcase aged specimens at NREL at 180 days. Specimens arranged in columns for EVA-A, EVA-B, EVA-C, EVA-D, EVA-E, and TPU.



Comparison of the spectral transmittance at 180 days (dashed lines) relative to unaged specimens (solid) for the UV Suitcase (UVA-340 fluorescent) aged specimens at NREL.

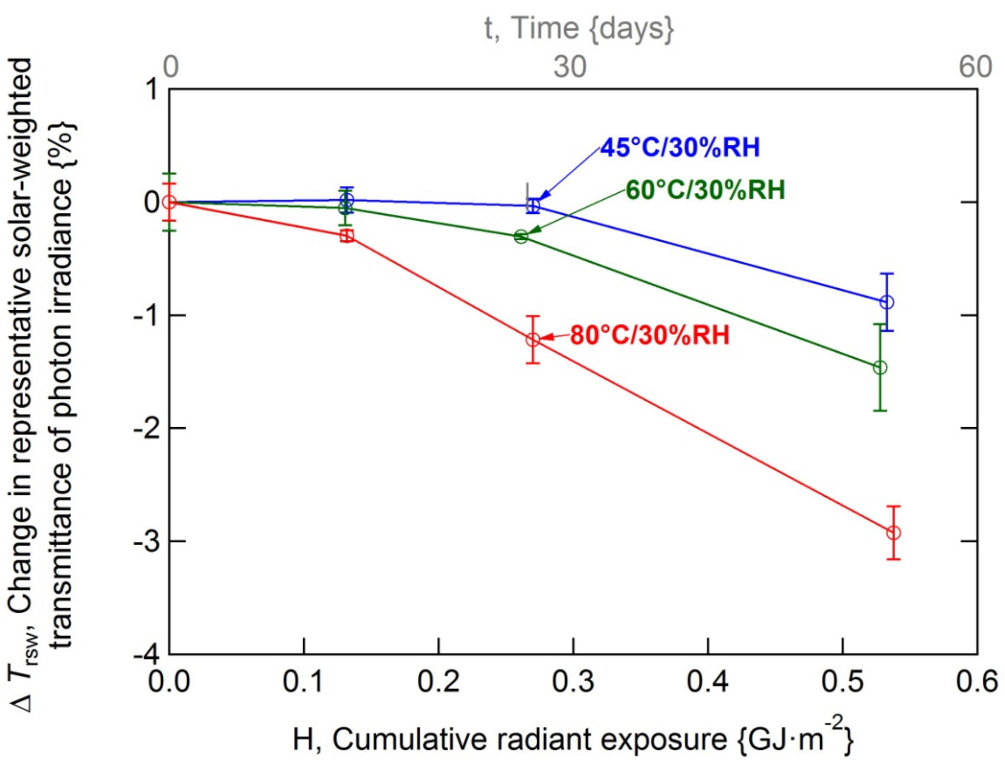
- For EVA-A, EVA-D, and TPU, a significant discoloration is observed that may be correlated to a rounding of the UV cut-off and increased yellowness.
- Result corresponds to the formation of chromophore species.

- For EVA-B, EVA-C, EVA-E, the UV cut-off wavelength is instead decreased and there is an increase in the transmittance. The transmittance is increased broadly for EVA-C.
- Result may be explained by the loss of additive(s) with age.

Effect of Temperature Stands Out in Early Comparison

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

- Effect of aging is increased with temperature.
- Same trend observed for EVA-A and TPU (not shown).
- Coupling anticipated from field observation, *e.g.*, increased discoloration at local hot spots in modules.
- E_a can be determined from experiment.

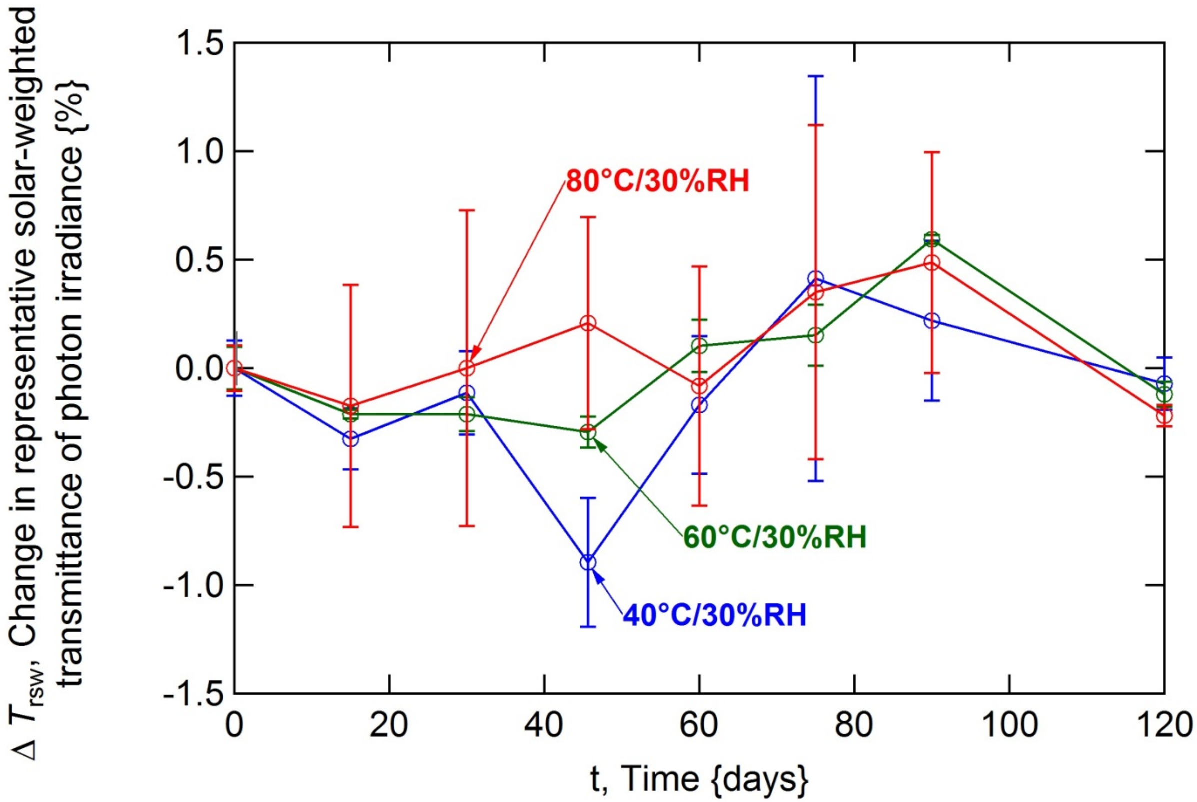


EVA-A: comparison of change in transmittance with aging temperature (aged at 3M, with Xe lamp). The default temperature and humidity conditions were applied in separate chambers.

Dark Chamber Aging: UV Facilitated Degradation

- Control experiment in environmental chambers at NIST.
- Apply default *T* and *RH*, with no UV present.

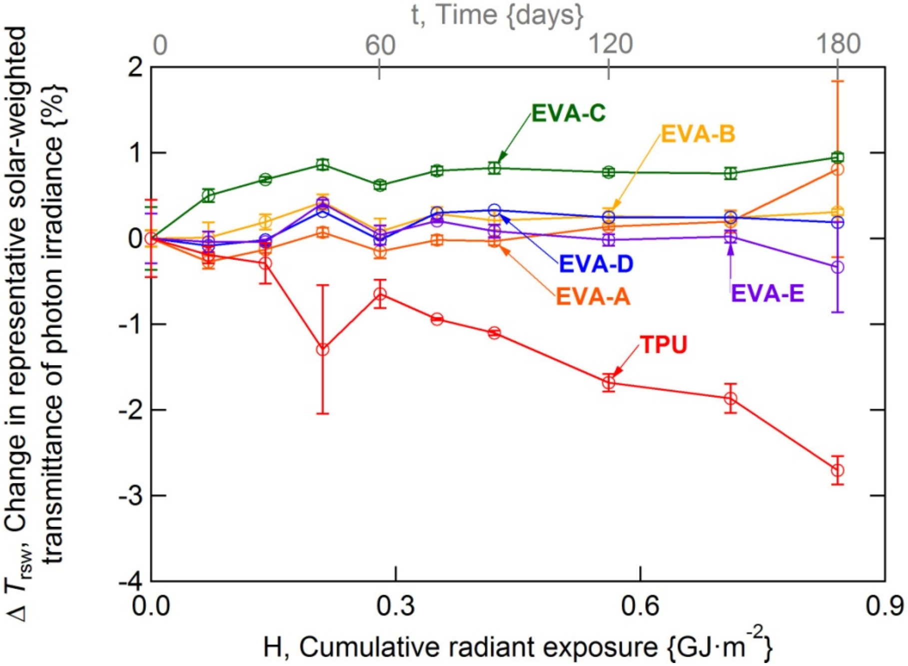
- No discoloration visually observed to date for EVA formulations.
- Some rounding of UV cut-off for EVA-E (no UVA).
- Slight discoloration observed with time for TPU at 80°C, both center and edge. (Δ*YI*~2).
- Implication: Δτ results from UV degradation.



EVA-A: comparison of change in transmittance in dark chambers (aged at NIST, with no UV) for the default temperature and humidity conditions.

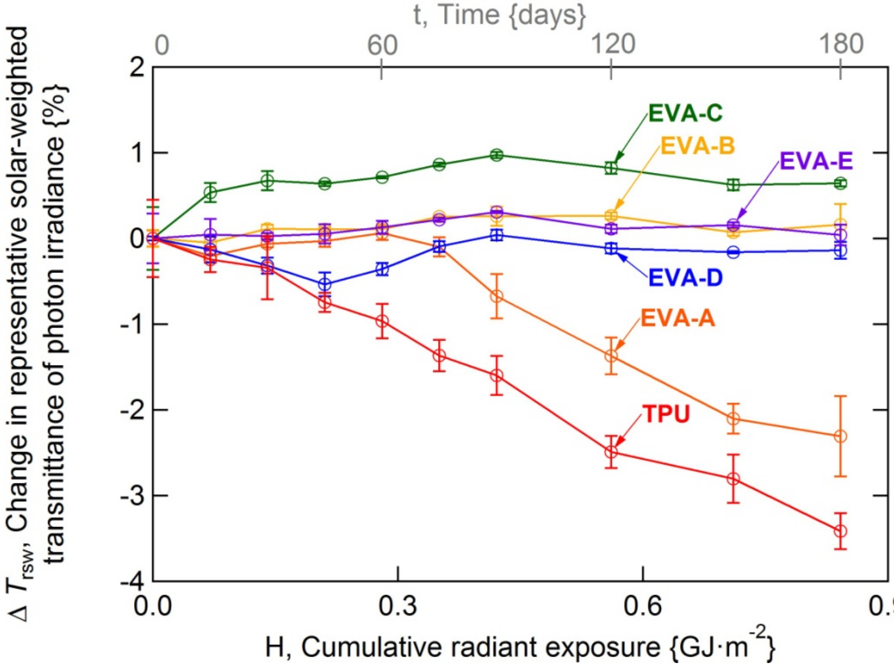
Formulation Specific Results Emerging From the E_a Experiment

Specimen Edge



Change in representative solar weighted transmittance (300≤λ≤1250 nm) for the encapsulation specimens at their center. Results shown for UV Suitcase (fluorescent) at NREL.

Specimen Center



Change in representative solar weighted transmittance (300≤λ≤1250 nm) for the encapsulation specimens at their edge. Results shown for UV Suitcase (fluorescent) at NREL.

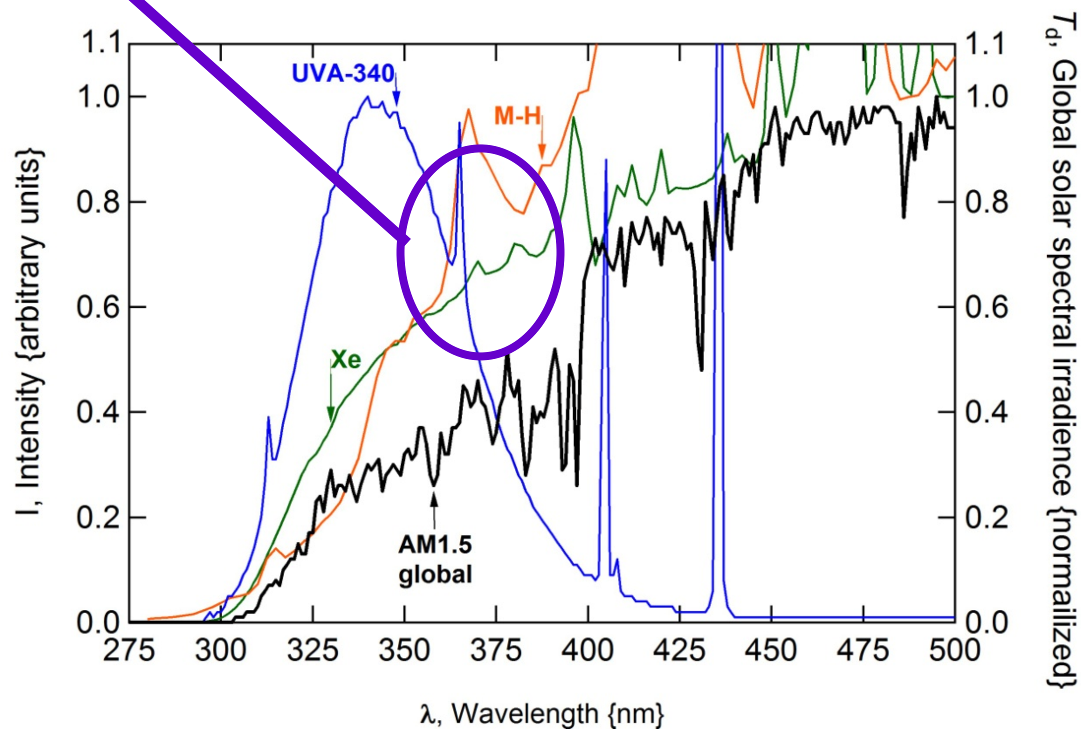
- The effects of aging are less significant at the specimen periphery (except TPU).
- In EVA, a photobleaching effect occurs at edges, but is limited by rate of O_2 diffusion.

Here and previous slides:

EVA's ⇒ effects of aging are dominated by interactions between additives.

E_a 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), UV source (*e.g.*, 360-400) could render different results.
- Aged EVA's have not yet varied significantly between sources.
- Other base materials or components (backsheet) may have stronger spectral dependence.
- NIST SPHERE experiment (passband filters) will provide additional insight.
- Also method: ASTM G178.



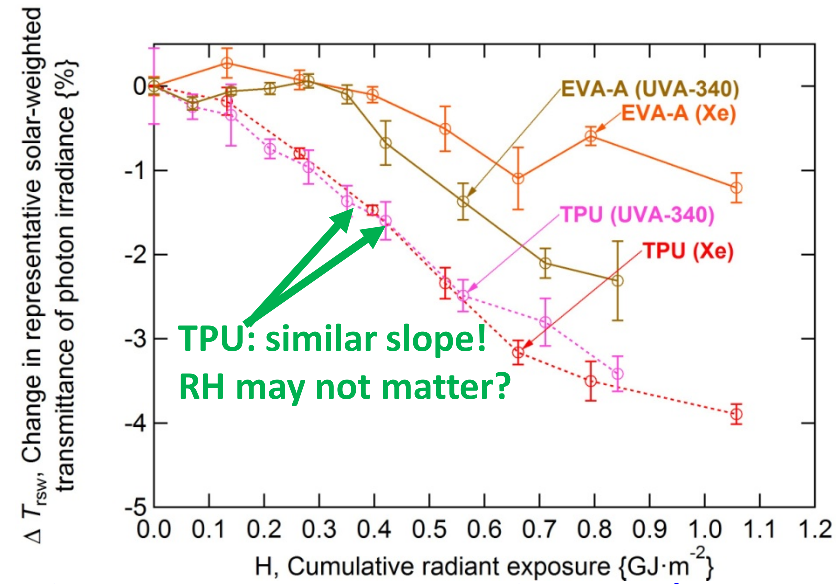
Overlay of representative common artificial UV sources, relative to the AM1.5 global spectrum.

Beginning to Compare Between Artificial Light Sources

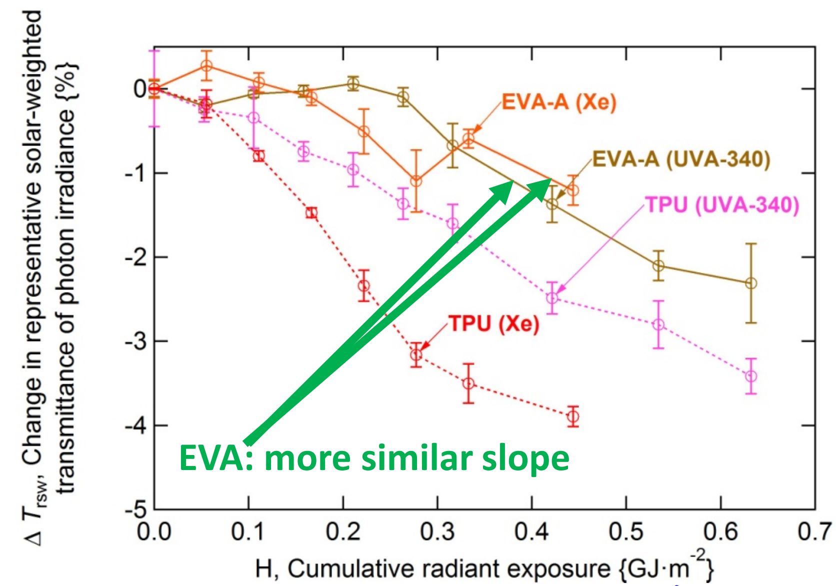
- A common metric for *H* must be agreed upon when comparing Xe-arc and UVA-340 fluorescent sources.
- One might think to overlay data (τ of EVA-A and TPU) at a similar aging condition (chamber 60 °C) for the total UV, $300 \leq \lambda \leq 400$ nm.
- But: UVA-340 lacks emission from $360 \leq \lambda \leq 400$nm.

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

- $295 \leq \lambda \leq 360$nm: may be best criteria between Xe and UVA-340 fluorescent.
- Comparing figures implies different action spectrum.
- Quantitative analysis (*e.g.*, E_a) will provide greatest insight.



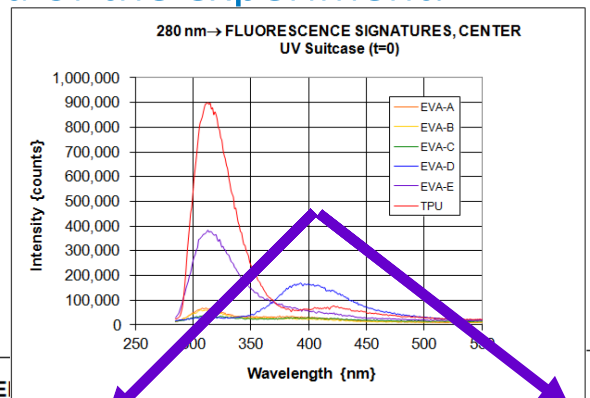
$\Delta\tau$: Shown for Ci5000 and UV Suitcase, *H* from $300 \leq \lambda \leq 400$ nm.



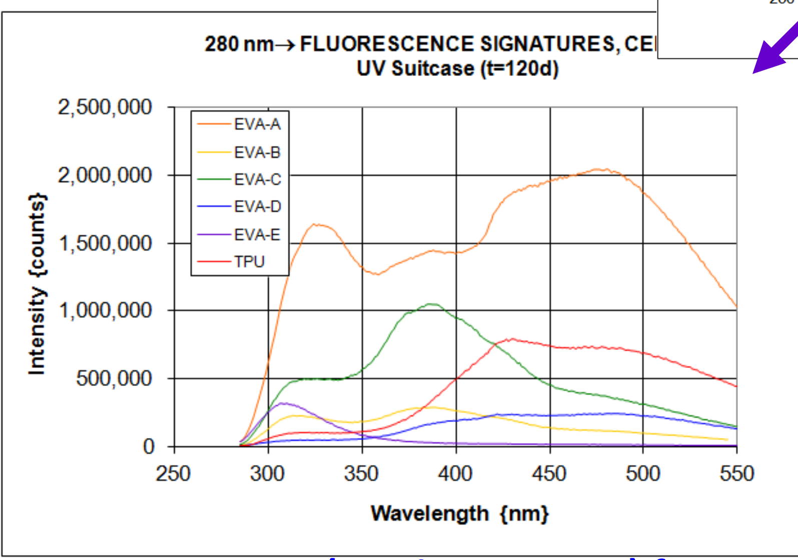
$\Delta\tau$: Shown for Ci5000 and UV Suitcase, *H* from $295 \leq \lambda \leq 360$ nm.

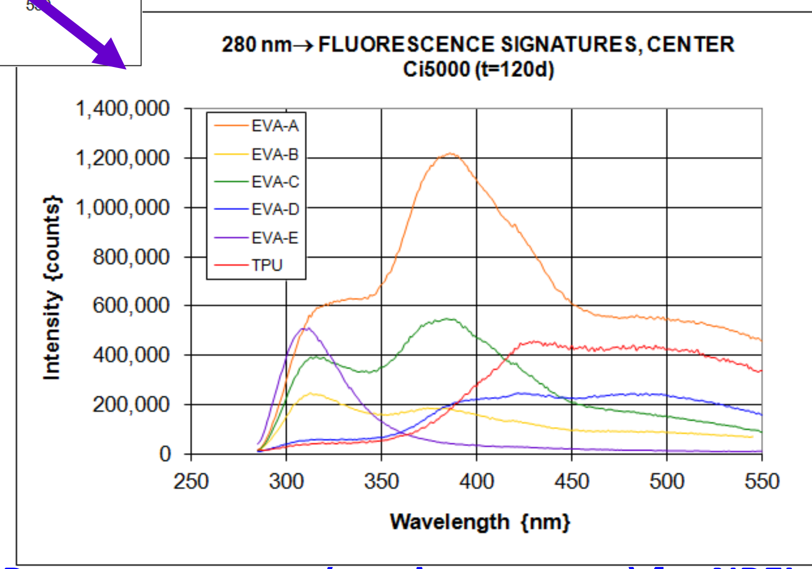
Fluorescence Spectroscopy: Xe and UVA-340 Affect Similarly

- Photoactive electronic structure evolves significantly with age at the specimen center. (less profound changes seen at periphery).
- Distinct signatures between EVA's suggests interaction between formulation additives.
- Similar profiles suggest specimen chemistry affected similarly for UVA-340 & Ci5000.
- EVA-A: Verify signature at end of the experiment.



Base scan spectra for NREL unaged specimens.





Base scan spectra (specimen center) for NREL UV Suitcase (UVA-340 @2x, 60°C) at 120 days.

Base scan spectra (specimen center) for NREL Ci5000 (Xe @2x, 60°C, 50%RH) at 120 days.

Transmittance: Comparison to Historic & Outdoor Data

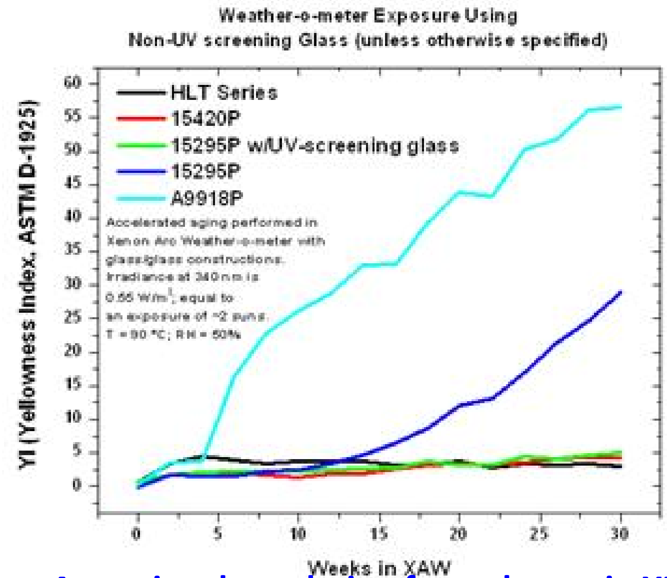
- Historically, yellowness index has been used to compare between indoor- and field-aged encapsulation.
- We examine 2 of the classic formulations, using a modern version of the same glass.
- ΔYI, EVA-A: ~8 (Xe, 60°C) vs. ~55 (Xe, 70°C).
- Contiued verification & analysis to follow.

- Same & similar formulations deployed at APS in 1996.

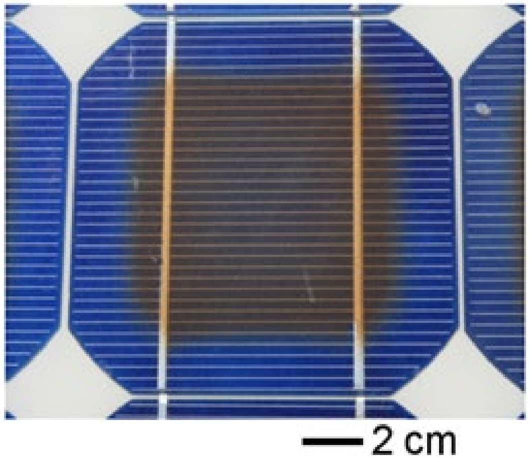
⇒Conclusion: discoloration resulted from additive interactions (as in E_a experiment).

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

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



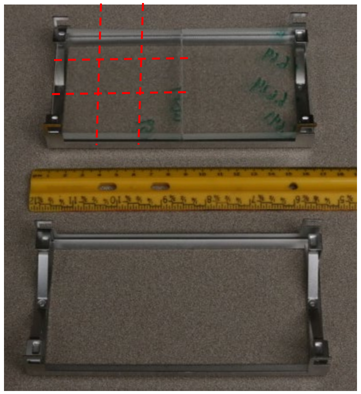
Assessing degradation from change in YI.
Reid et. al., Proc SPIE, 2013, 8825-7.



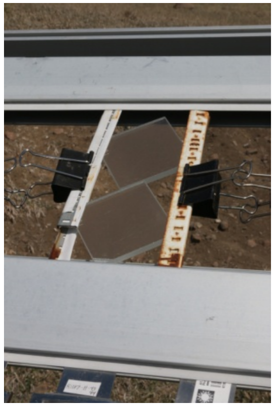
Localized discoloration of EVA (known formulation in module) at the APS site.
Wohlgemuth et. al., Proc IEEE PVSC, 2013, 3260-3265.

Details of the E_a Methods and Experiment: Encapsulation CST Adhesion Test

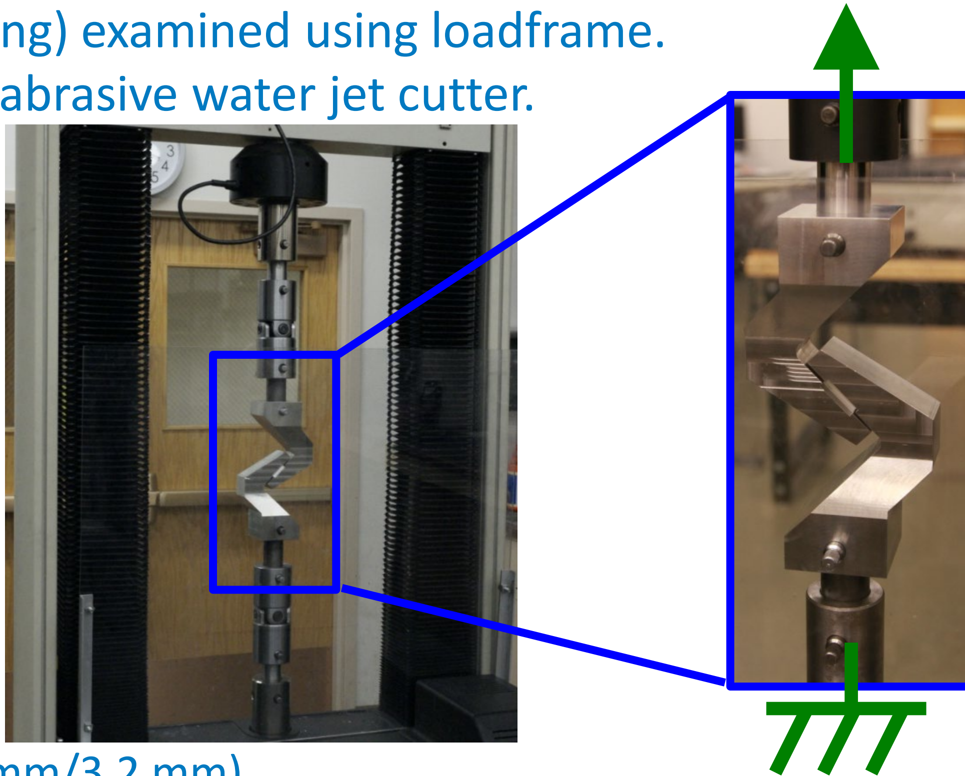
- Better physics-based methods being developed as IEC standard.
- 25 mm square specimens (diced, after aging) examined using loadframe.
- Pristine edge quality is critical. Dice using abrasive water jet cutter.



Sample holder configuration for indoor aging at NREL. Samples are diced after aging.



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



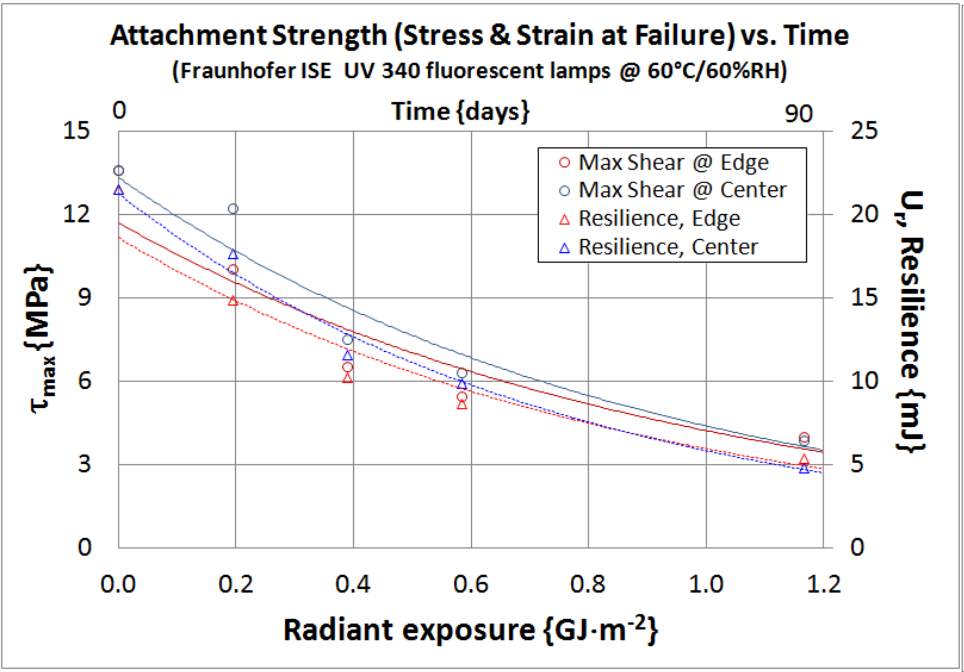
The CST will be used to examine the attachment of EVA. Method from: Chapuis et al., PIP, 22 (4), 2014, pp.405–41. (EPFL)

User summary:

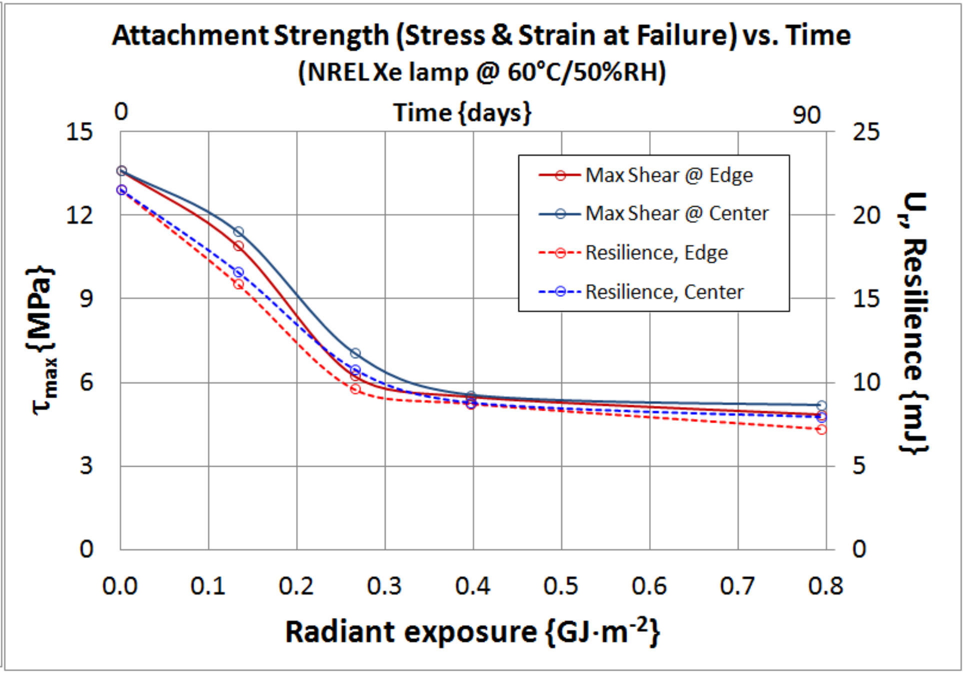
- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm)
- Size: 3” x 3”
- Quantity: 10 replicates of 1 material (pre-conditioned), plus 5 extras (not pre-conditioned)
- Aging: 15, 30, 45, 90, and 180 cumulative days (indoors), or 1, 2, 3, 4, 5 years (outdoors)
- Remove 2 coupons at each increment
- Measurements(destructive): age at each laboratory/test site, then sent to NREL for measurement

Profound Reduction in Attachment Strength Initially Observed

- Examining EVA-B (STR 15295 P/UF), found in many veteran PV installations.
- Strength and resilience were seen to decrease significantly (by 66%) in the first 90 days aging at Fraunhofer ISE.
- Similar magnitude of effect observed for specimens aged at NREL.
- This change exceeds the rule of 50% for pass/fail, typically applied in relative thermal index (RTI) tests.
- Experiment will verify if the strength is maintained after prolonged aging, *e.g.*, as in an absolute minimum requirement.



Change in strength of attachment and resilience for fluorescent UV Custom Chamber at Fraunhofer ISE.



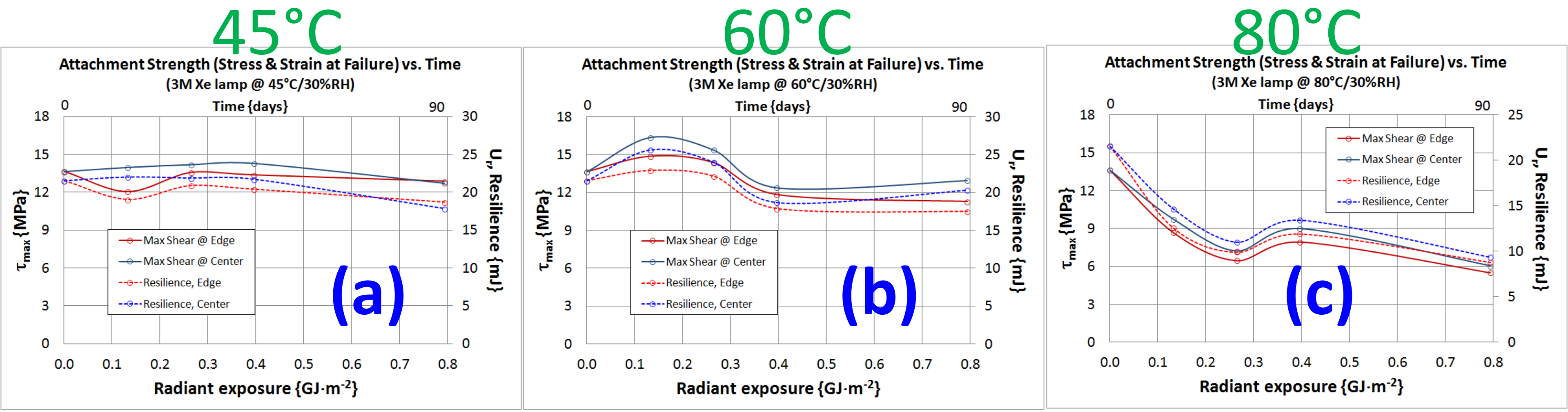
Change in maximum strength of attachment and resilience for Xe Chamber at NREL.

Additional Aging Conditions Suggest More Complicated Story

- 3M samples aged with Xe at 2x UV and 30% RH, T = 45, 60, or 80 °C.
- 3M: little or no effect seen at 45 & 60 °C.
- Fraunhofer ISE & EPFL: minimal effect seen at 40°C (3x) or 60°C (1x).

Explanations:

- Threshold of UV, T, or RH required to invoke substantial damage?
- Effect is due only to absorbed moisture (polymer plasticization)?
- Comment: T_m~60°C for EVA.
- Additional results (at 80 °C or in dark) should elucidate.



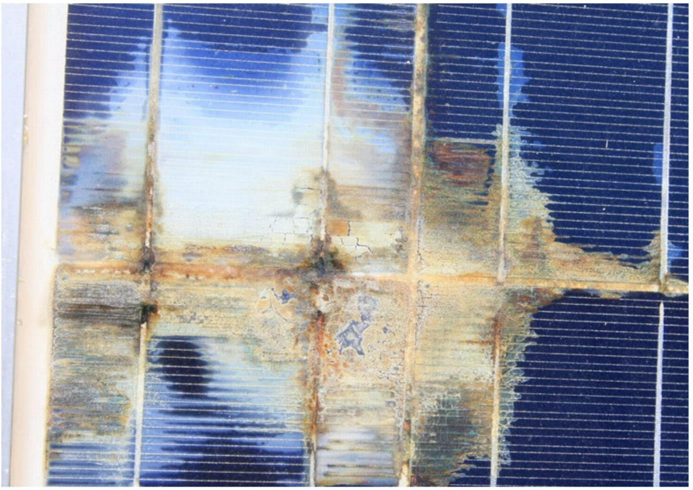
CST results for 3M Ci5000 chambers, Xe @ 2x and 30%RH: (a) 45 °C; (b) 60 °C; and (c) 80 °C.

Adhesion: Comparison to Historic and Outdoor Data

- No good systematic quantitative study of adhesion in the PV literature.
- e.g., accelerated conditions and duration to examine delamination not established.

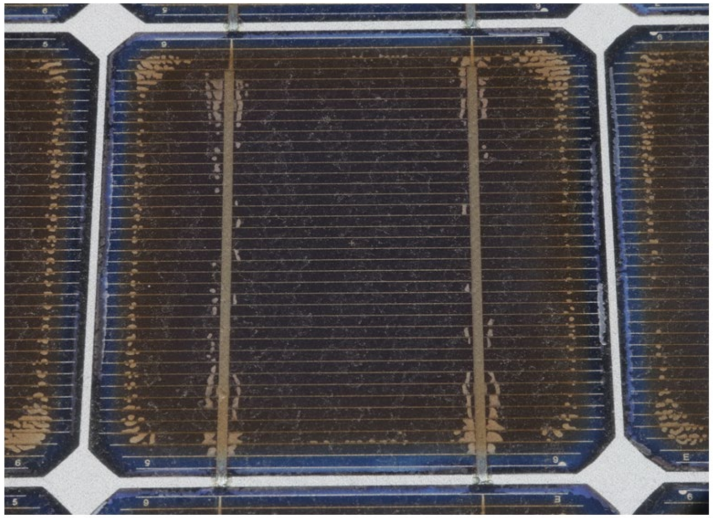
Anecdotally then:

- Encapsulation/cell interface often weakest.
- Delamination often precedes corrosion.
- May not be tightly correlated with encapsulation discoloration.



9.5 cm

Delmaination and subsequent corrosion in EFG-Si cell module at TEP Springerville facility.



5 cm

Delamination at cell-corners and -interconnect ribbons in mono-Si module at SMUD Hedges facility.

Refer also to:

- Adhesion test method: refer to Bosco *et. al.*, "A Fracture Mechanics Based Approach to Adhesion Testing in the PV Module", Proc. PVMRW 2015.
- Site data: refer to Silverman *et. al.*, "Review of observed degradation modes and mechanisms from fielded modules", Proc. PVMRW 2015.

Application of the UV Test

Direct application:

- IEC 62792 (climate- & configuration-specific aging sequences)

  This is the primary application forTG5 effort.

- IEC 62788 (PV module materials and components)

  -1 = Encapsulation; -2 = Backsheets; -... (tests of characteristics)

  -7 =Weathering

  (may draw directly upon the TG5 results in a UV test)

Indirect or perhaps future influence:

- IEC 61730-1 (module materials & components safety tests)
- IEC 61730-2 (PV module safety tests)
- IEC 61215 (PV module qualification tests)

Timeline of Activities for TG5

- NREL specimens are presently at 150 days (Ci5000) and 180 days (UV suitcase).
- Results will be used to assign t, T, %RH for a climate- & configuration-specific UV test.

	Qualification	QMS	Climate- & Configuration-Specific Test	Service Life Prediction
Current status	Issued as standards	Revised NWIP submitted	Proposed as concepts	Concepts
2014 goal	Submit 61215 (Ed 3) 61730 (Ed 2)	Publish new TS	Initiate E_a test. Create strawman UV standard.	Develop criteria to evaluate QMS related to service life; NWIP
2015 goal	Publish new editions	Start use of the TS in factory inspection	Submit UV standard NWIP. Create strawman test sequence standard. Complete indoor E_a test.	
2016 goal		Revise QMS document to reflect feedback	Publish E_a results. Submit CD of UV standard.	
Chamber test times	Modules: ~ 6 weeks	TBD	~6 months	~18 months

Summary

- "E_a" interlaboratory experiment being conducted to provide a quantitative basis for climate- and configuration-specific UV weathering test.
- Preliminary (qualitative) observations presented.

Encapsulation transmittance:

- Have replicated behaviors of fielded materials (specimen location- and formulation additive-specific discoloration).
- *T* coupling observed for UV aging.
- $\Delta\tau$ degradation in EVA results from **UV** aging.
- Good qualitative comparison between Xe and UVA-340 sources for EVA.

Encapsulation adhesion:

- Attachment strength can decrease drastically (>50%) with age.
- Early results suggest significant factor (UV, *T*, *RH*) dependence.
- Much to be learned about adhesion.

- We look forward to the quantitative values from the experiment.

Acknowledgements

☞ There has been fantastic participation in TG5.

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

- If interested in TG5 or the experiments, please contact the corresponding regional TG5 leader. (See title slide)
- Future publication, "Degradation in PV Encapsulation Transmittance: An Interlaboratory Study Towards a Climate-Specific Test", *submitted Proc. IEEE PVSC*.

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

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NREL STM campus, Dennis Schroeder