Accelerated UV-Aging of EVA-based PV Encapsulants and Correlation with Outdoor Exposure of PV Modules

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“Rule of Thumb” for Xe Arc and PV

“1 Week in Xe Arc is Equivalent to 1 Year Field Exposure” [1]

When and How was this derived?

What are the assumptions behind this relationship?

Where is this valid?

[1] R. Tucker, “Results to Date: Development of a Low-Temperature, Super Fast-Cure Encapsulant”, Paper 5BV.4.8, 20th European Photovoltaic Solar Energy Conference, June **2005**, Barcelona, Spain

Origin: 1 yr Xe arc = 1 yr outdoor

The relationship was first published in 2005 by STR.

- Incorporated using information published in reports from the NREL administered PVMaT phase 3 project.
- Was very specific to a certain set of conditions and certain EVA grades.

Can the relationship be extrapolated to other conditions and materials?

- Use as a starting point for development of accelerated methods

Reference: PVMaT 3 project; US Dept. of Energy contract No. DE-AC36-83CH10093

"Advanced EVA-Based Encapsulants, Final Report January 1993-June 1997"
W.W. Holley and S.C. Argo, Specialized Technology Resources, Inc.
September **1998**, NREL/SR-520-25296

Background – early 1990's

Specialized Technology Resources, Inc.

Goals of PVMaT 3:

- Why did EVA-based encapsulants discolor?
- What was the mechanism?
- What test methods can be used to simulate this?

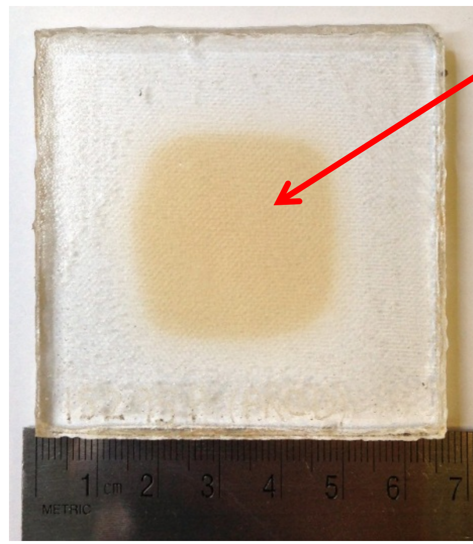
Key Conclusions (Holley/1998)

- Color formation: Chromophores created by polymer additives when exposed to Light, Heat and Humidity
- Glass type was a confounding factor
  - Less yellowing occurs with UV-blocking or cerium-containing glass
- Accelerated UV and Temperature tests replicated field browning for first-generation EVA of formulations

Test Coupons

PV Module, ~15 years Arizona. Encapsulant is PHOTOCAP 15295

Picture of Xe Arc Aged Coupon: Glass-EVA-Glass, ~65 x 65 mm



Yellowness Index ~ 35 (Measured in center)

Note: edges are unsealed

Yellowing in center of cell (or glass coupon) is the result of competing mechanisms- additive yellowing and oxidative bleaching.

Klemchuk, P., Ezrin, M., Lavigne, G., Holley, W., Galica, J. and Argo, S., “Investigation of the Degradation and Stabilization of EVA-Based Encapsulants in Field-Aged Solar Energy Modules,” Polymer Degradation and Stability, Vol 55, pp 347-365 (**1997**).

Materials:

Holley/1998 describes several EVA-based formulations; One encapsulant material was used for deriving the correlation:

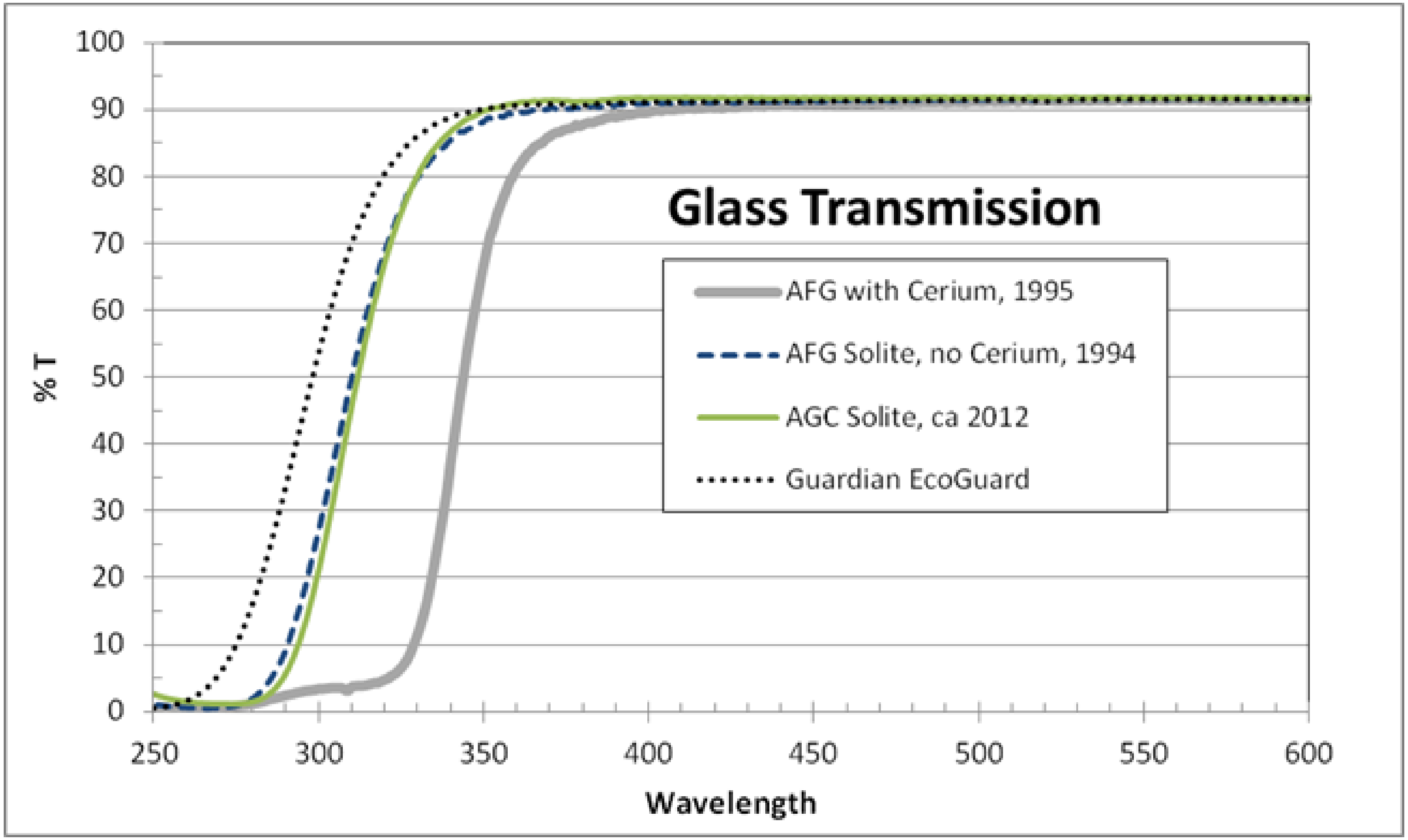
EVA Encapsulant = STR PHOTOCAP® A9918P (1st generation EVA for PV)

Two non-cerium, low iron glass were used for this correlation work.

AFG Solite®
PPG Starphire®

Both are still commercially available and in commercial use for solar industry.

Glass Transmission Spectra



Cerium containing glass blocks significant amount of UV light

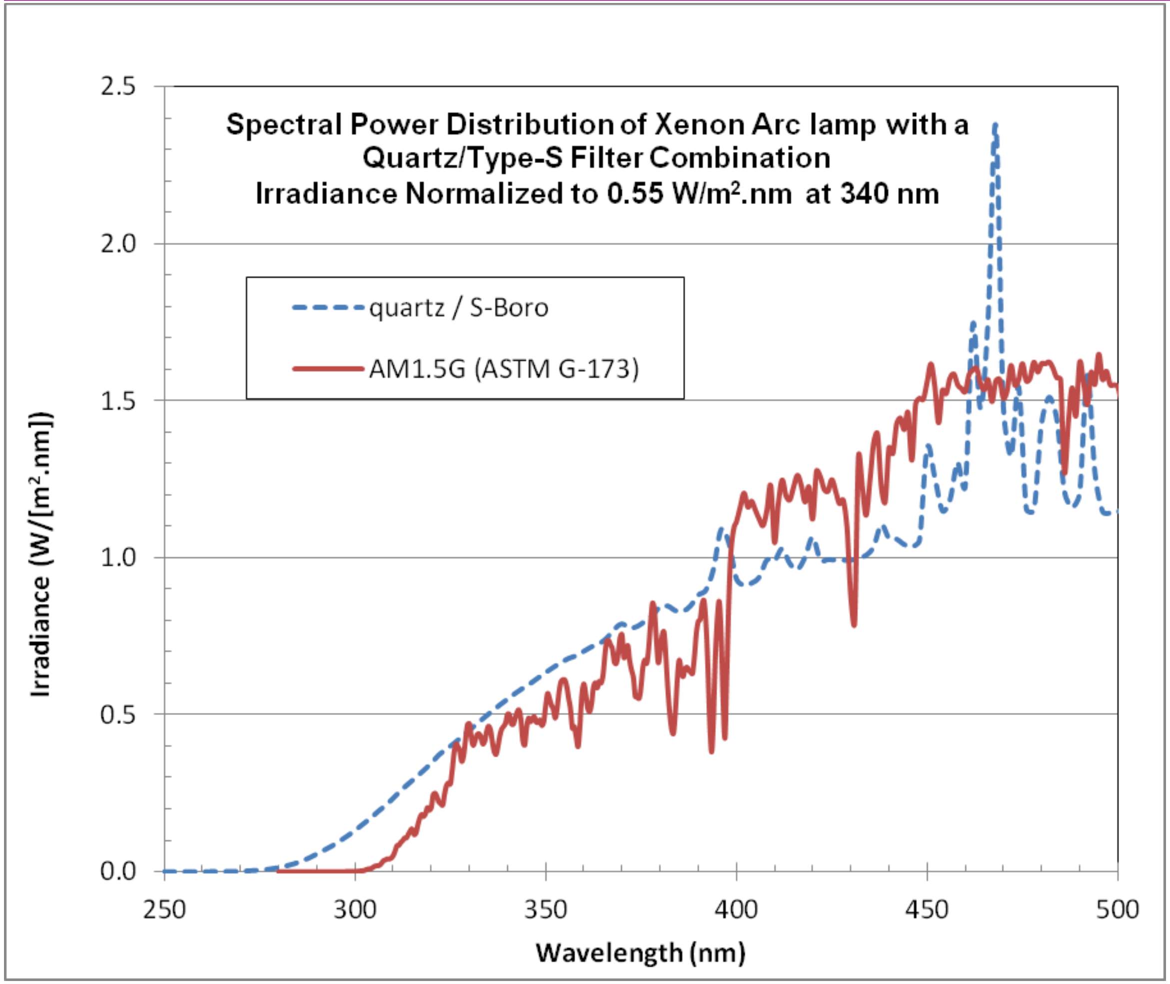
Xenon Arc Exposure

Test conditions were changed ca.1999 after the PVMaT-3 project was completed. These conditions yielded better instrument reliability.

	STR Test Conditions for 1993-1996	STR Test Conditions (1999 to Current)
Chamber	Atlas Ci35 Xe-Arc Weather-O-Meter	Atlas Ci35 or Ci5000 Xe-Arc Weather-O-Meter
Bulb	Xe arc, water cooled	Xe arc, water cooled
Bulb filters**	Quartz (inner) Borosilicate (outer)	Quartz (inner) Type S borosilicate (outer)
Irradiance	340 nm, fixed at 0.55 $W/m^2/nm$	340 nm, fixed at 0.55 $W/m^2/nm$
Light Cycle	Continuous. No dark cycle	Continuous. No dark cycle
Temperature	100 °C, black panel (uninsulated)	90 °C, black panel (uninsulated)
Air Temperature	Unknown	70 °C
Relative Humidity	> 95%, constant	50%, constant
Water Spray	Not used	Not used

** Spectral power distribution per SAE J2527, Table C1 (Extended UV Filters).

Xenon Arc Spectral Power Distribution



At 26 weeks of exposure, STR's Xe arc irradiance exposure is:

~3X IEC 61345 (280-320 nm)

~16X IEC 61345 (320-400 nm)

- Filters and SPD is per SAE J2527-C1 (former J1960)
- Used for automotive exterior components

Q/S filter combo: "Extra UV" is an additional accelerating factor (combined with T and %RH)

Outdoor Testing: EMMA

- Equatorial mount mirror acceleration (EMMA®) performed in Phoenix, Arizona, mid 1990's by DEST Labs (now owned by Atlas Material Testing Technology)

- EMMA is a ground mounted mirror and fresnel lens based accelerated aging protocol: 4-5X UV and 7-8X VIS light acceleration.
  (The method also holds the test specimens at a higher temperature.)

Image from Atlas Material Testing Technology

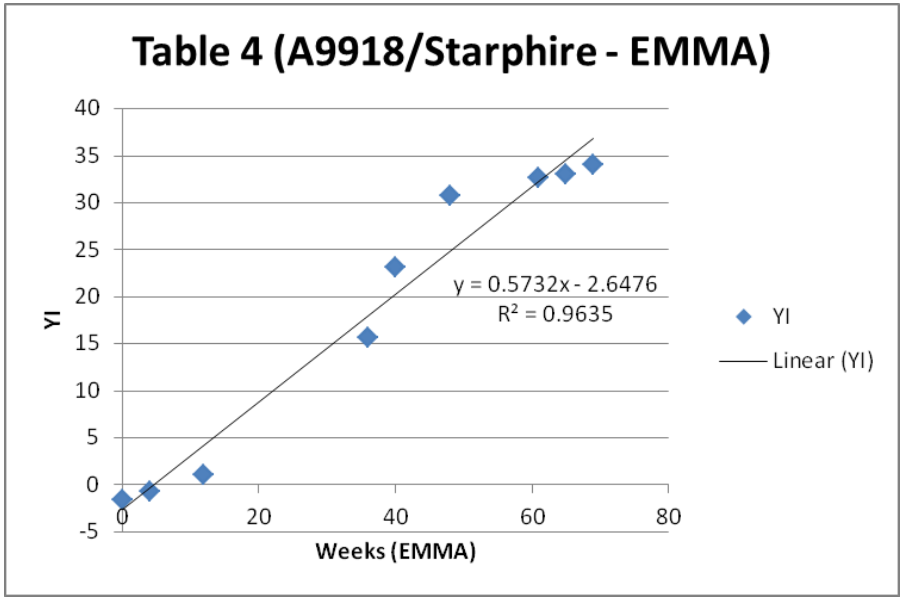
The EMMA used in mid 1990's did not have temperature control and humidity/water spray was not used.

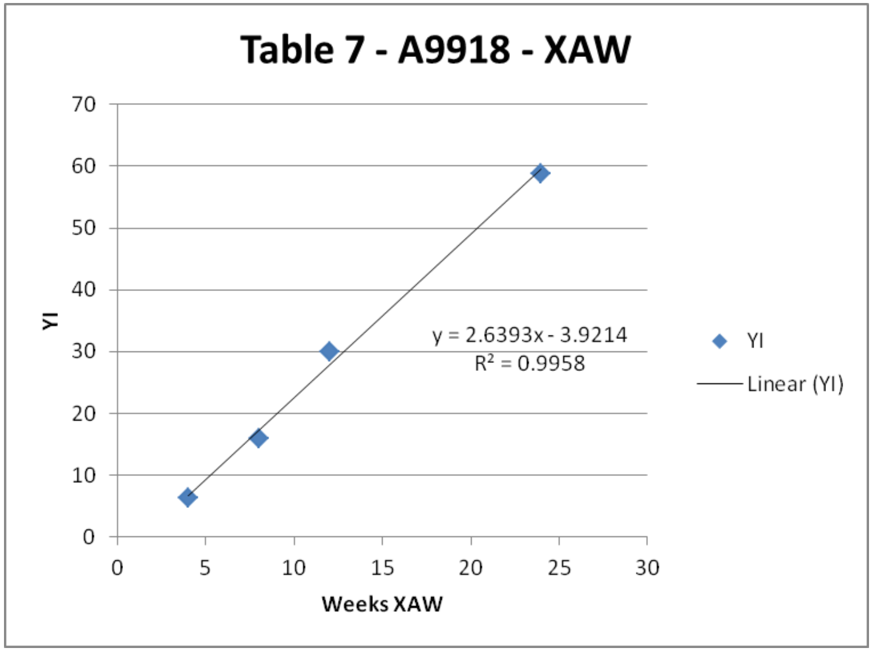
The aging reported in Holley/1998 is for: Dry aged, Elevated temperature, and Accelerated irradiance.

Additional information: http://atlas-mts.com/services/natural-weathering-testing/accelerated-weathering/emmaqua

Results: XAW & EMMA – 1990's

Data published in Table 4 & 7 of **Holley/1998**





<u>Sample Info:</u>

EVA = STR A9918P (first generation EVA encapsulant, commericalized 1979)
Glass = PPG Starphire (non Cerium)
Yellowness index increases with increased UV exposure with both methods.

1990's XAW vs EMMA Correlation

EMMA: 5X acceleration of UV exposure
1 week EMMA = 5 weeks Arizona

$$\frac{10.4\text{ week EMMA}}{1\text{ year Arizona}} \bullet \frac{0.57\text{ YI Units}}{1\text{ week EMMA}} \bullet \frac{1\text{ week XAW}}{2.6\text{ YI Units}} \cong \frac{2.3\text{ week XAW}}{1\text{ year Arizona}}$$

Further Simplification:

Solar irradiance in Arizona is about 2X that of Northern industrialized climates, such as Germany and North East USA. Thus, the relationship has been extrapolated to be :

1 week XAW ~ 1 year Outdoor exposure

CAVEATS:
Relationship is based upon yellowing of STR PHOTOCAP A9918 with Glass-EVA-Glass coupons.
Interaction effects between encapsulant and PV cells are neglected.
The relationship uses both EMMA and Xenon arc, both of which have accelerated irradiance and elevated temperatures.

A9918 Modules from 1997

Modules added by STR to the PVMaT-3 module study as controls.

12 modules that differ only by the type of glass used:

- Cerium containing versus Non-Cerium glass were used
- Encapsulant was PHOTOCAP A9918 in all 12 modules

Power tests from 1997:

Encap.	Glass		**Isc (A)**	**Voc (V)**	**FF%**	**Pmax (W)**
A9918	**Cerium**	Avg of 6	3.27	21.7	73%	50.0
		Stdev	0.03	0.2	2%	1.2
A9918	**Starphie (non cerium)**	Avg of 6	3.33	21.6	73%	50.9
		Stdev	0.02	0.1	2%	1.5
	Non-Cerium vs. Cerium	Difference	1.8%	-0.2%	-0.1%	1.6%

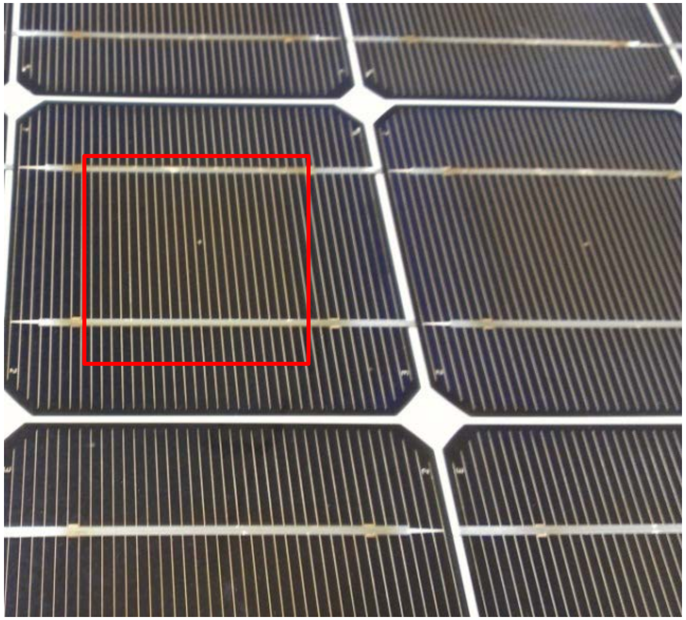
Non-cerium glass yielded ~1.6% power increase due to more photons striking the surface of the PV cells.

A9918 Modules from 1997

Pictures from 2012

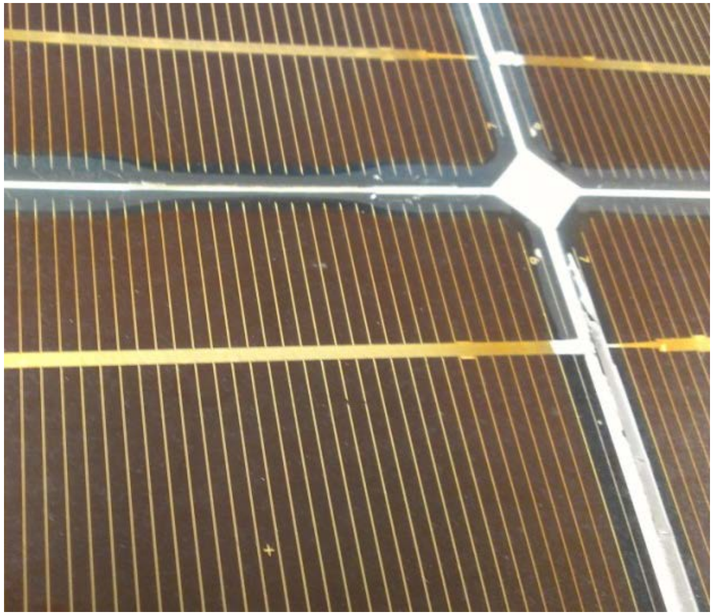
Modules Exposed for 15 Years, 2-axis Tracker, Phoenix, Arizona

Encapsulant = PHOTOCAP A9918, same manufacturer



Glass with cerium

Yellowing only in center of cell



Glass without cerium (PPG Starphire)

Yellowing over entire cell.

A9918 Modules from 1997

Power Tests: 2012 relative to 1997:
Exposure = 15 years, two-axis tracker, or “effective” 24 years fixed axis

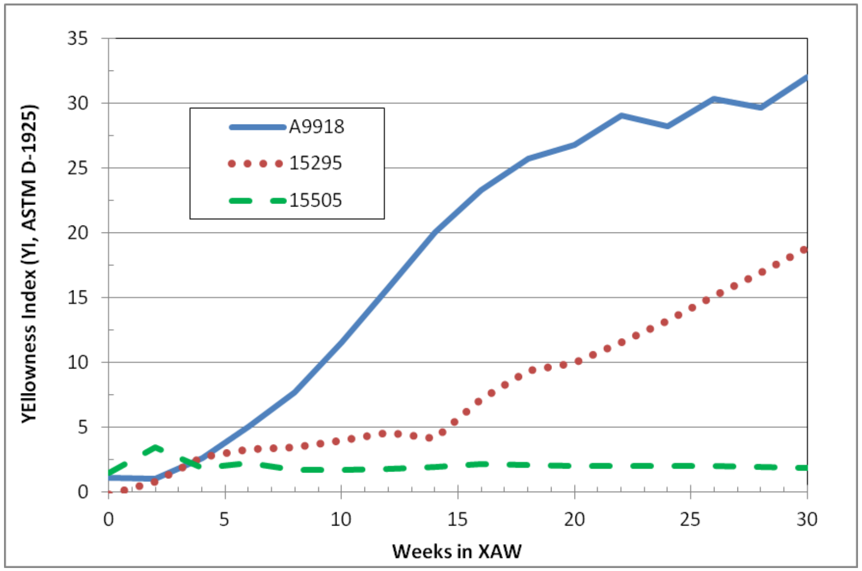
Encap.	Glass		Isc (A)	Voc (V)	FF%	Pmax (W)
A9918	**Cerium**	Retention	100% (!!!)	98%	74%	75%
A9918	**Starphire (non cerium)**	Retention	89%	98%	77%	69%

Conclusions:

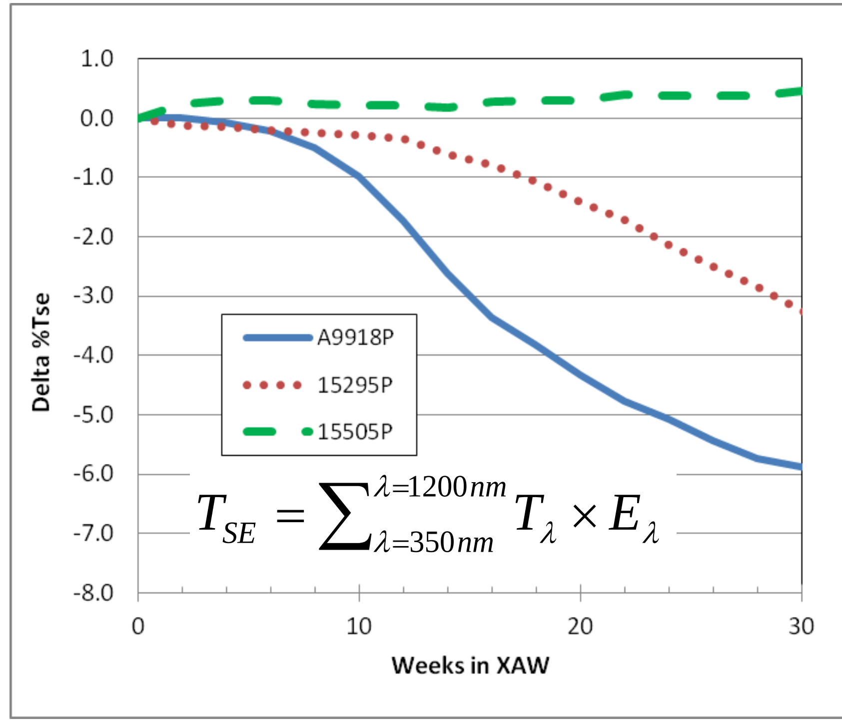
- UV-Filtering by Ce-Glass protects the module
  - Virtually ZERO loss of Isc
  - ~25% FF loss is due to factors other than encapsulant browning
- UV-Transmissive Non-Ce glass
  - 11% loss of Isc and 6% loss of power due to EVA browning

Xenon Arc Aging: 2010-2012 Tests

Xenon arc aging using current conditions.
Non cerium glass



Yellowness index



$\%T_{SE}$: solar energy weighted %Transmission

(Reference: ASTM E424-07)

Decrease in $\%T_{SE}$ is approximately equal to expected power loss

“New” Xe-Arc and Outdoor Aging Correlation

Outdoor aging for 1st generation Photocap® A9918:

- Isc decreases by 11% in 24 yrs fixed-mount Arizona exposure (Use 10% as conservative metric)

Xenon arc aging (STR conditions)

- $\%T_{SE}$ decreases by 6% in 30 weeks of aging

Assume $\%T_{SE}$ causes equivalent decrease of Isc:

$$\frac{\text{30 week XAW}}{\text{6\% loss } T_{SE}} \bullet \frac{\text{10\% loss Isc}}{\text{24 years Arizona}} \cong \frac{\text{2.1 week XAW}}{\text{1 year Arizona}}$$

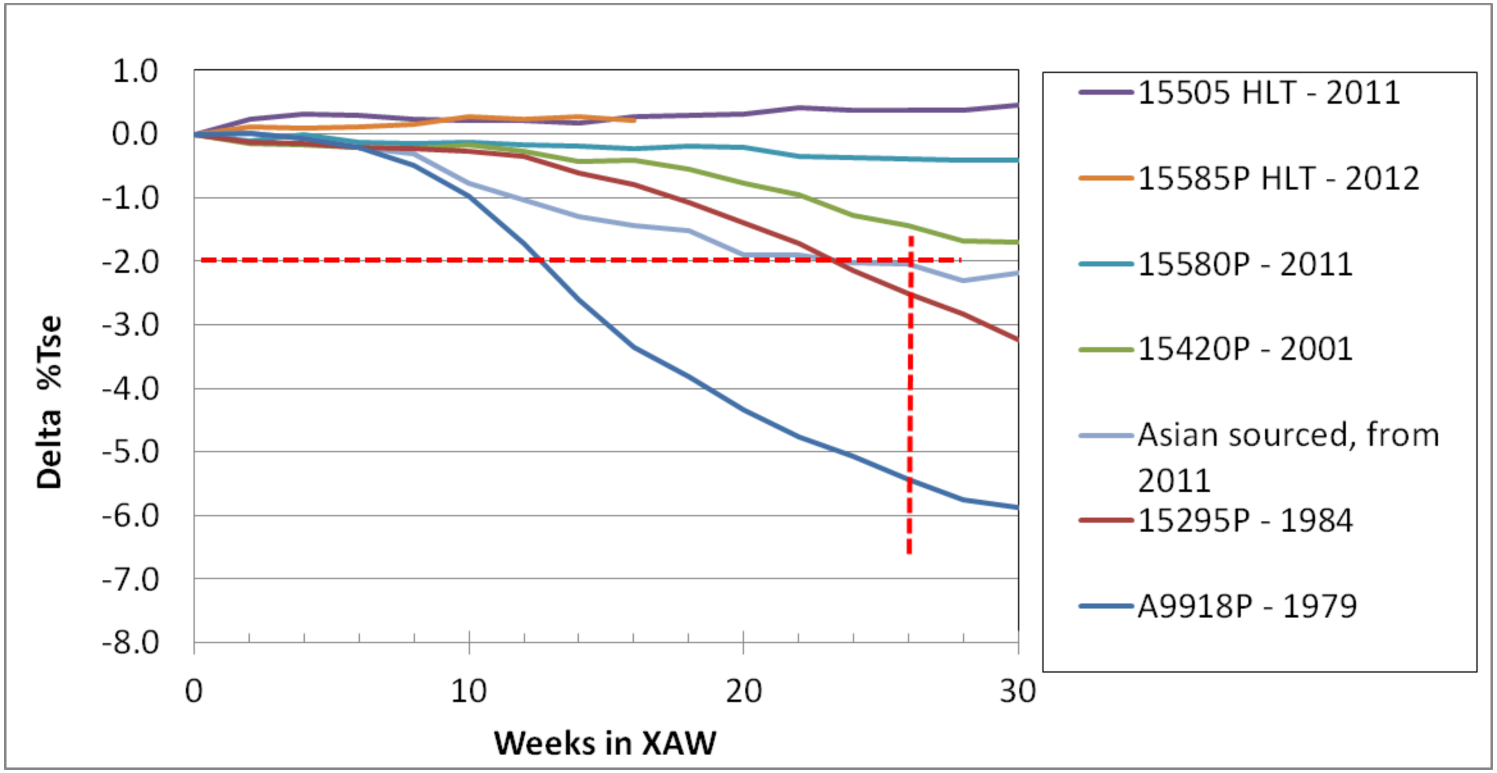
Surprisingly, the acceleration factor from Xe arc to outdoor Arizona fixed axis exposure is the same as derived from 1994-1997 tests.

Xe Arc – Modern Encapsulants

2% Loss of T_{SE} at 26 weeks XAW

- Reasonable Expectation for High Performing Encapsulating Materials

Modern Products Show Significantly Less Change in %T during UV Exposure



Commercial introduction dates of grade shown

Is EVA-Browning Fully Understood?

For EVA alone – Yes:

- Component test of encapsulant and glass is well studied and understood.
- Tests described here are used for development of new encapsulant formulations

For EVA in Contact with Other Components – Yes & No

- Encapsulant and backsheet interactions
- Interaction of encapsulant with metals on surface of cell
  - Conductive fingers
  - Anti Reflection coatings
  - Soldering components
- Electric field aging mechanisms (eg, electrophoresis)

Conclusions

Xenon Arc Tests Strongly Correlated with Field Aging:

- Yellowing of first-generation EVA-based PV encapsulants (PHOTOCAP® A9918, phased out of production)
- Outdoor tests:
  - Mirror accelerated aging, 1995-1996
  - 2-axis tracker aging, 1997-2012

Xenon Arc Methods is Recommended as Acceptance Criterion for New PV Encapsulants:

- STR test conditions: 0.55 $W/m^2/nm$, 90°C Black Panel, SAE J2527 Table C1 spectra (Extended UV filters)
- Test for >26 weeks (4,368 h) continuous light
- Suggest ≤ 2% loss of T_{SE} as criterion at 26 weeks

International PV-QA, Group 5, Studying Effects of UV on PV Modules

- Multi-Laboratory study of A9918, 15295, and other EVA samples
- Xenon arc, fluorescent UV lamps (UVA, UVB), and Hg lamps, to be studied
- Planned for 2013-2014

Specialized Technology Resources, Inc.

THANK YOU

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