Accelerated Light Aging of PV Encapsulants: Correlation of Xenon Arc and Mirror Accelerated Outdoor Aging from 1993-1997

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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]

Is this valid?

Where did this come from?

What are the assumptions behind this relationship?

[1] Earliest printed citation is 2005

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

Introduction

This presentation describes the origin of this “rule of thumb”

This relationship was derived by STR.

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

The relationship may, or may not, be accurate when extrapolated to other conditions or other materials.

… but… This is a starting point for development of accelerated methods

Data Reference: (DOE PVMaT 3 project)
“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
(US Dept of Energy contract No. DE-AC36-83CH10093)

This reference will be called “**Holley/1998**” with in this document

Introduction

Goals of PVMaT 3:

- Why do encapsulants turn yellow or brown?
- What is the mechanism?
- What test methods can be used to simulate this?

Key Conclusions (Holley/1998)

- Color formation is due to creation of chromophores created by mixture of polymer additives exposed to UV and heat
- Glass type (cerium, non-cerium) was a complicating factor
- Accelerated UV and Temperature can replicate field observations for EVA browning of the older formulations

Materials:

Holley/1998 describes several different commercial and pre-commercial EVA based encapsulant products. Only one encapsulant material will be considered for the purpose of deriving the correlation between xenon arc and natural weathering:

EVA Encapsulant = STR PHOTOCAP® A9918P
(this product is the original standard cure EVA commercially introduced in 1979, and is still commercially available from STR Solar.)

Two different glass grades are used for this correlation work. Both grades are non-cerium, low iron glass intended for use in solar photovoltaic applications.

AFG Solite®
PPG Starphire®

AFG Solite is still commercially available from AGC and is in commercial use. PPG Starphire is also commercially in use for solar industry.

Test Coupons

The test coupons describe in Holley/1998 are as follows:

Glass-Encapsulant-Glass

Coupons have dimension of 68 x 70 mm (2.7 x 2.75 inch).
Coupons were vacuum/thermal laminated and cured.
Target gel content for these coupons was above 75% (toluene soak 60°C test method)

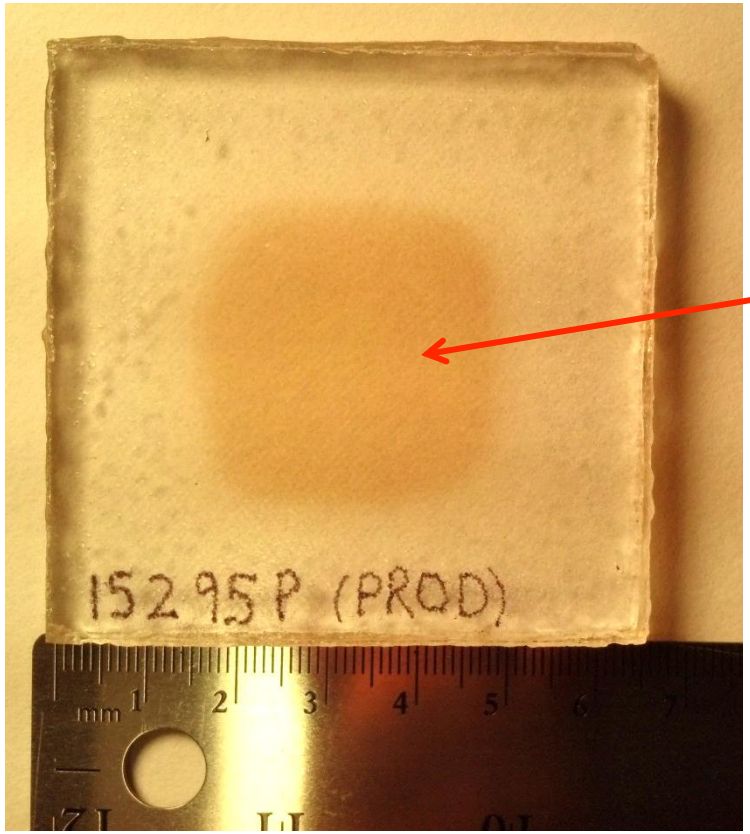
This coupon was selected in order to better simulate the encapsulant between the front face of the PV cell and the cover glass.

In all cases, some bleaching occurred around the perimeter of the coupon. This is due to oxidative bleaching of the EVA yellowing/browning, a mechanism that is well understood and described in other papers.

Yellowness index was measured in the center of the coupon to minimize the influence of oxidative bleaching.

Test Coupons

Picture of Xe Arc Aged Coupon: Glass-EVA-Glass, 70 x 70 mm



Yellowness Index ~ 35
Measurement made in center

Background is white.
Color correction issues with camera

Note – edges are not sealed.

Xenon Arc Exposure

Instrument used: Atlas Ci35A, installed circa 1992-1993
Test conditions:
- Bulb filters = quartz inner / Type S-glass borosilicate outer
- Irradiance controlled at 340 nm, to 0.55 W/m^2
- Temperature = 100°C
- Humidity >95%

Holley/1998 report does not state if the temperature is black body panel or air temperature. It is reasonable to presume that this is the black body panel temperature

Holley/1998 report does not provide details about the humidity control.

This same instrument is still in use at STR Inc in East Windsor, Connecticut, USA.
Atlas Ci5000 also in use

Test conditions used today by STR for this and other xenon arc instruments are:
- 0.55 W/m^2 at 340 nm (quartz / type S boro filters)
- 90°C black body panel,
- 70°C air temperature, and
- 50% relative humidity.

Outdoor Testing: Equatorial Mount Mirror Acceleration

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

EMMA is a ground mounted mirror and fresnel lens based accelerated aging protocol. EMMA is designed to achieve about 4X UV acceleration and 7-8X visible light acceleration. The method also accelerates temperature and holds the test specimens at a higher temperature than ambient conditions.

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

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 data reported in Holley/1998 are from dry aged, accelerated irradiance and elevated temperature.

Results: Xenon Arc Exposure

XAW exposed yellowness index data for EVA encapsulant coupons are shown in Table 7 of **Holley/ 1998**
(image at right).

Total exposure time 24 weeks
Tests performed ~1993-1994

Use the values reported for "A9918/Starphire (Control)"

Table 7 - Average Change in Yellowness Index of Cured Glass/EVA/Glass Laminates With Weather-O-Meter Aging (1)

Sample Construction (2)	Change in Yellowness Index 4 weeks	8 weeks	12 weeks	24 weeks
"Standard Cure" Encapsulants				
X9903P/Starphire	2.4	2.1	1.6	2.0
X9933P/Starphire	2.8	4.3	5.3	4.3
X9923P/Starphire	1.8	2.0	--	1.0
A9918P/Starphire (Control)	6.3	16.0	29.9	58.8 (4)
A9918P/Solatex II or Airphire	5.6	6.8	8.0	12.6
"Fast Cure" Encapsulants				
X15303P/Starphire	2.1	1.9	0.9 (3)	2.0
15295P/Starphire (Control)	0.8	2.6	6.1	48.9
15295/Solite (Control)	1.7	2.7	5.8	31.2
15295P/Solatex II	1.3	1.8	2.2	4.8

(1) Ci35A xenon-arc Weather-O-Meter, 100° C, 0.55 watts/square meter at 340 nm

(2) Glass/EVA/Glass laminates with Starphire on the back side

(3) Data taken by different technician

(4) Solite glass superstrate

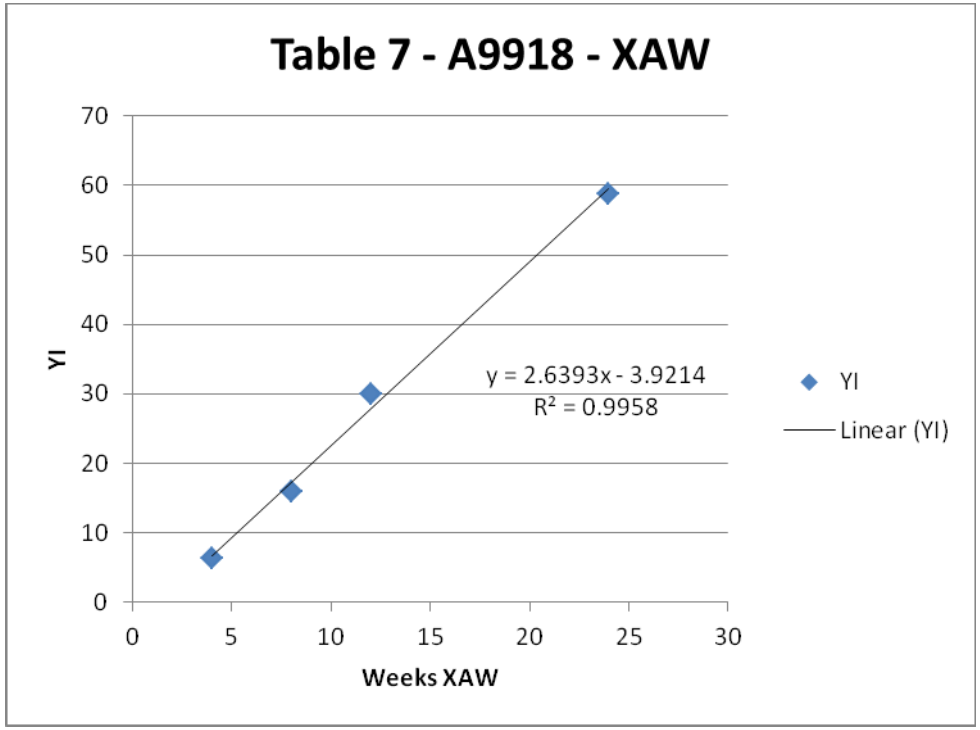
Results: Xenon Arc Exposure

Sample:
EVA = STR A9918P
Glass = PPG Starphire

Yellowness index increases monotonically with increased xenon arc exposure. Rate of increase is approximately:

2.6 YI / week-XAW

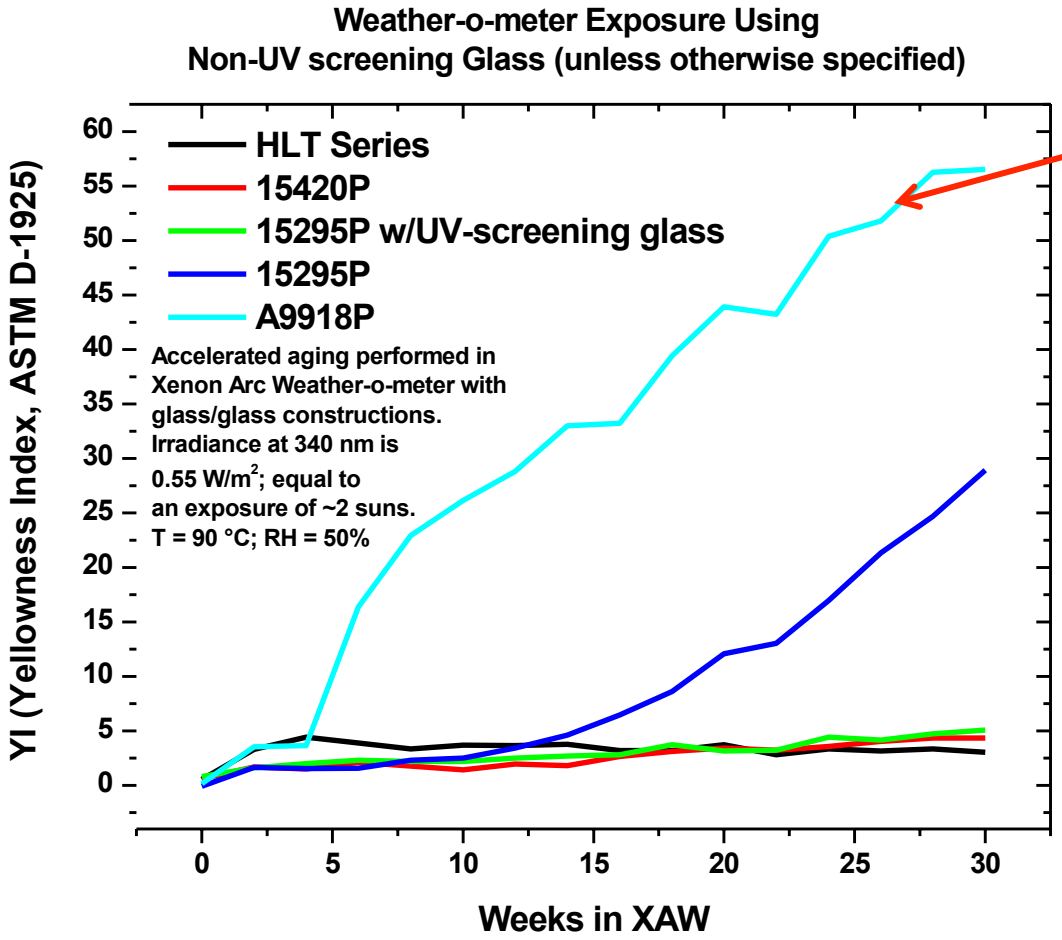
Holley/1998



Xenon Arc Exposure – 2010 Results

Xenon arc is used as a screening tool for new compositions.

A9918 is used as the "control" for new studies.



A9918P
25 weeks
YI ~ 50

XAW Test Conditions:

- 0.55 W/m2 at 340 nm.
- 24 hr light, no dark cycle
- Black panel T= 90°C
- Dry bulb T = 70°C
- Humidity = 50%

- *"HLT Series" are new High Light Transmission grades that are transparent over 300-360 nm range.*

Results: Outdoor EMMA exposure

EMMA exposed yellowness index data for EVA encapsulant coupons are shown in Table 4 of **Holley/1998** (image at right).

Total exposure time = 60 weeks.

Total irradiance = 78 GJ/m^2

Use the values reported for “Starphire/A9918”

Table 4: Average Yellowness Index (2) of Cured Laminates After EMMA(1)

Samples	Construction of Lam	week 0	week 4	week 12	week 36	week 40	week 48	week 61	week 65	week 69	difference 0 to 69 W
1, 2	Solite/A9918P	-1.3	0.5	1.6	13.8	21.1	30.3	34.1	34.5	34.7	36
3, 4	Solatex II/A9918P	-1.2	0.0	-0.0	1.0	1.3	1.3	0.6	0.6	0.8	2.0
5, 6	Starphire/A9918P	-1.6	-0.7	1.1	15.7	23.2	30.7	32.7	33.1	34.0	35.6
7, 8	Tefzel/A9918P	-0.1	-0.6	-0.9	-0.9	-0.9	-0.9	-1.1	-1.3	-1.1	--
9, 10	Solite/15295P	-2.6	-1.4	-1.0	-0.7	-0.0	2.3	3.9	4.2	4.8	7.4
11, 12	Solatex II/15295P	-2.3	-1.9	-2.0	-1.5	-2.1	-1.5	-1.8	-2.0	-1.8	0.5
							Difference 0 to 40				
new	Starphire/X9903P	-1.4	-1.7	-1.7	-	-1.5	--				

(1) EMMA Aging by DSET Laboratories, Phoenix, nominal 5 suns in U.V. region

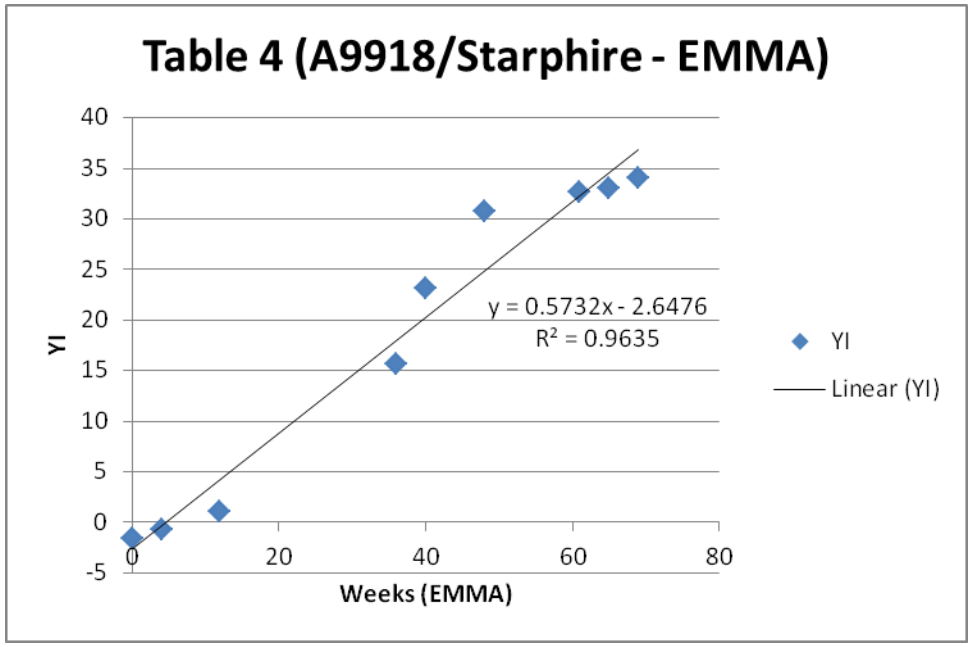
Results: EMMA exposure

Sample:
EVA = STR A9918P
Glass = PPG Starphire

Yellowness index increases monotonically with increased xenon arc exposure. Rate of increase is approximately:

0.57 YI / week-EMMA

Holley/1998



XAW vs EMMA Correlation

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

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

Further Simplification:

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

1 week XAW ~ 1 year Outdoor exposure.

CAVEATS:
Relationship is based upon yellowing of STR PHOTOCAP A9918P 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.

XAW vs EMMA Correlation

"2 week Xenon Arc ~ 1 year Outdoor AZ exposure"

This is a simple correlation based on EVA browning phenomenon of 1st Generation EVA encapsulants.

Xenon arc is a key test to ensure new encapsulant products do not exhibit this type of browning.

How is Xe Arc Used Today?

Encapsulation Formulation Development

- This is a routine component test, Glass-Encapsulant-Glass
- Different polymers
- Different additives
- Process changes, etc.

Properties Tested with Xenon Arc Coupons

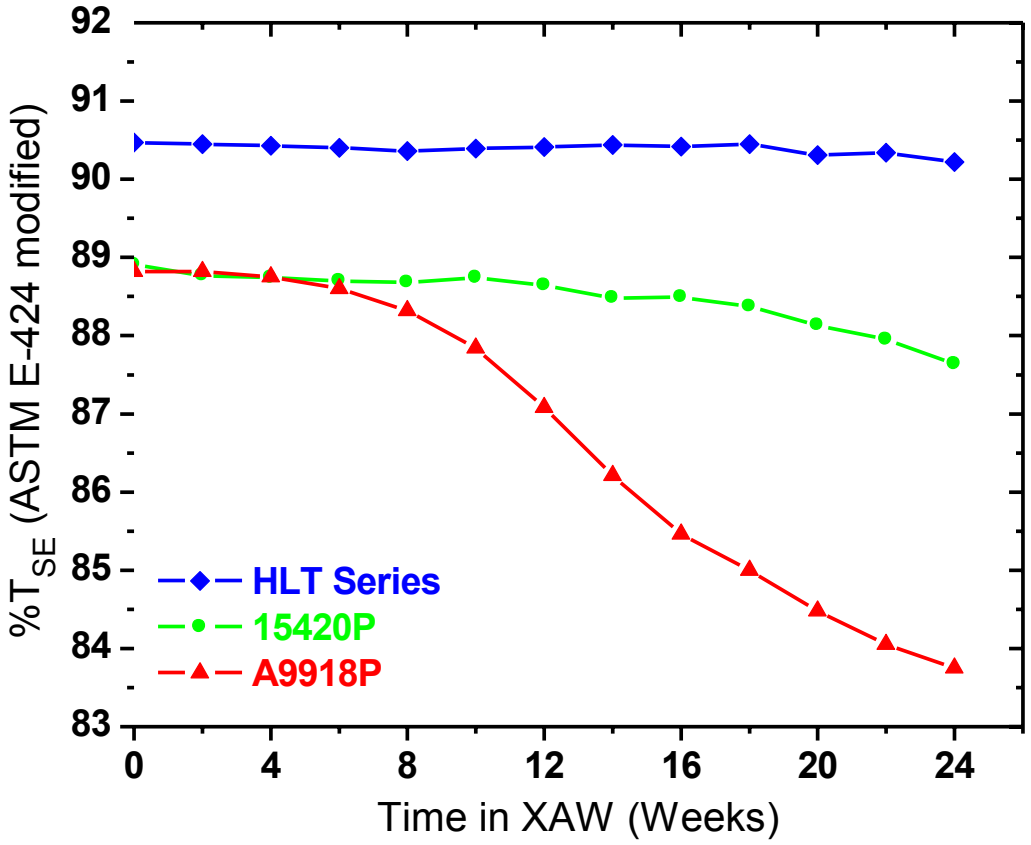
- Color formation
- %Transmission and shifts in UV absorbance
- Glass adhesion stability
- I-V curves for PV cells
- Component corrosion

Interaction Effects:

- Encapsulant interacts with all other components in a PV module

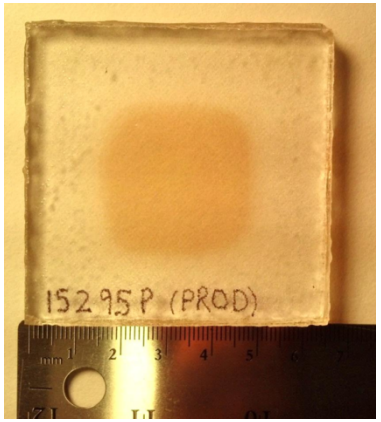
Xenon Arc and %T Measurements

- Solar-energy Weighted %T ($\%T_{SE}$)
  - Practical characterization of %T with UV-Vis Spectrometer
  - %T value integrated over a specific wavelength range (350-1200 nm)
  - Method modified from ASTM E-424 (2007)



3.2 mm Solite glass only = 90.8 %Tse

Is EVA-Browning Understood?



For EVA Alone as a Component – Yes:

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

For EVA in Contact with Other Components – Yes & No

- Color formation can vary depending upon the PV cell
- Encapsulant and backsheet interactions can cause color
- PID: ion migration through encapsulant to the PV device
- Snail Trails: appears to be silver migration from the fingers into the encapsulant, which interacts with the additive system

Xenon Arc Method Can Be Used to Study Interactions of PV Components for Degradation by UV, T, and humidity

Conclusions

"2 week Xenon Arc ~ 1 year Outdoor AZ exposure"

- This statement is derived from coupon testing done during PVMaT-3 in mid 1990's
- It is reasonably accurate for EVA-browning/yellowing accelerated by UV and Temperature
- This statement cannot be extrapolated to other PV module components or interaction between components

The Xenon Arc Method Can Be Used To Study Combined Stress Acceleration of Components and Interactions

Gen-1 EVA Encapsulants are Good "Standards" for New Method Developemnt to Ensure Browning is Observed

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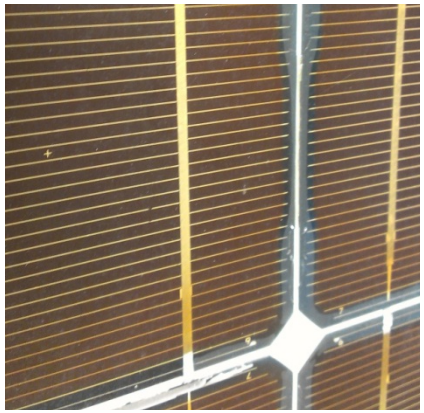
Extra Slides – Modules from the PVMat-3 Project

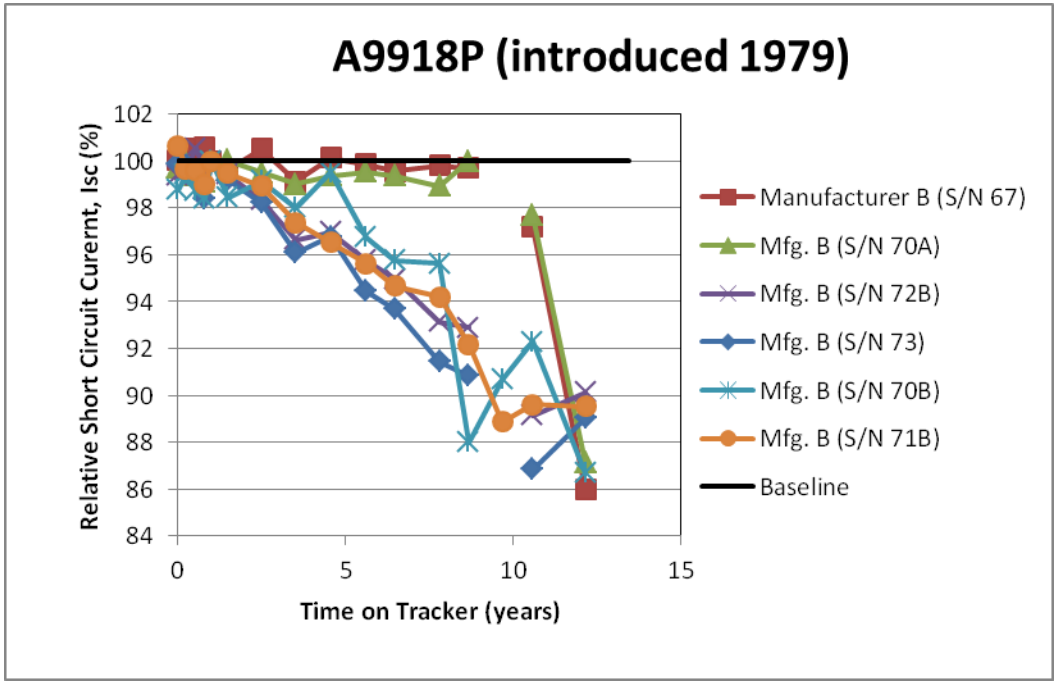
PVMaT-3 Project Modules
Encapsulant A9918P (browning/yellowing)

Slight browning
(panels w/ cerium-based glass)



Cell browning &
cell edge delam to EVA
(panels w/ starphire glass)

Non-Cerium glass:
Isc has dropped ~15%.
Pmax has dropped ~ 50% (interconnect issues)



PVMaT-3 Project Modules Encapsulant X15303 (15420P)

Modules made in 1996-97, fielded until 2012, tested by ASU-PRL in situ. Modules are now at STR for diagnostic testing.

Relative Maximum Power (Pmax)

- **Mfg-E = 99.4%**
- **Mfg-F = 100.1%**
- **Mfg-B = 58.8%**

Mfg B modules have corrosion on solder junctions at end of strings. Isc is 95% of original value.