Performance and durability of photovoltaic backsheets and comparison to outdoor performance

William Gambogi

DuPont Photovoltaic Solutions, Wilmington, DE, 19803

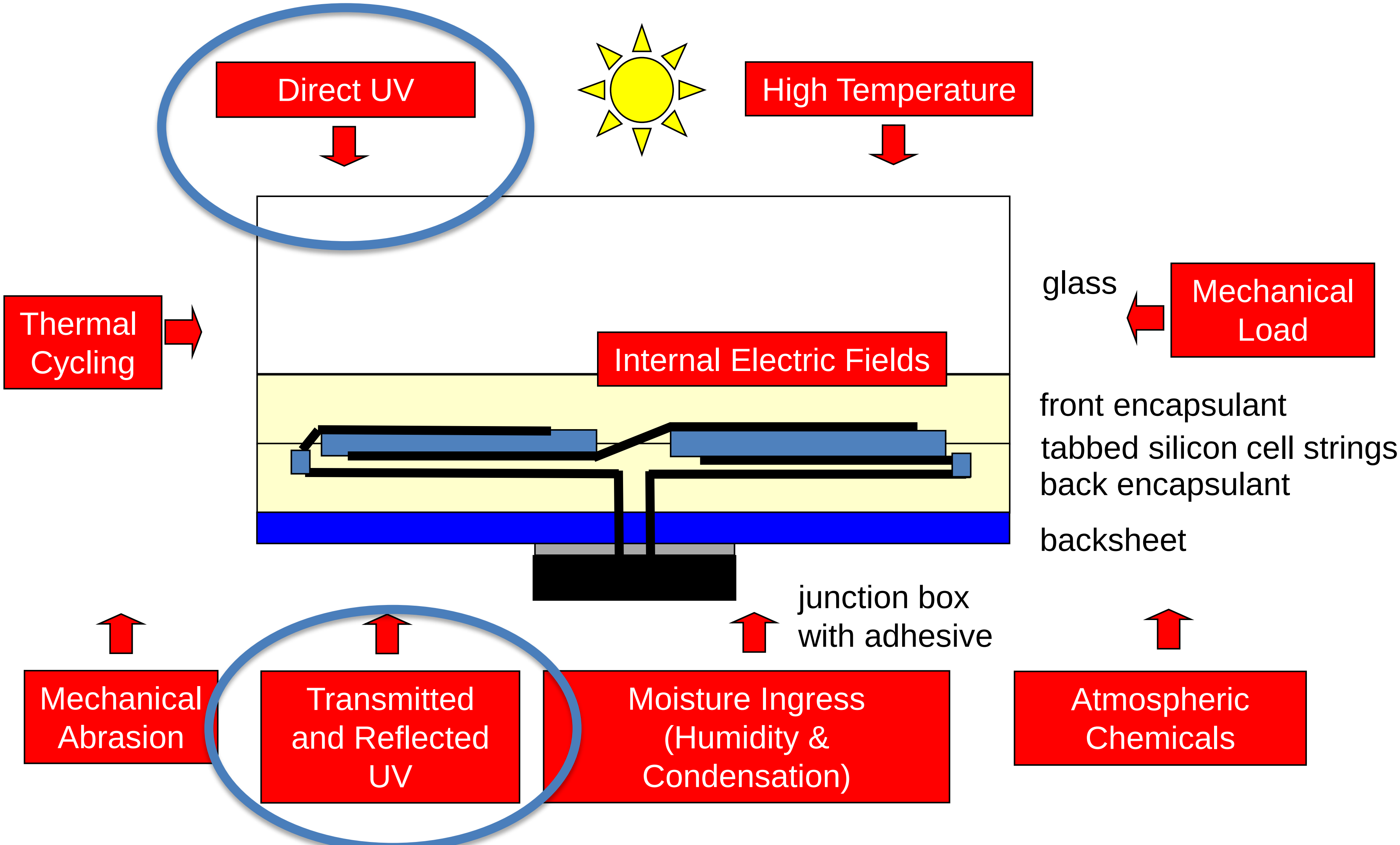
Atlas NIST Workshop on PV Materials Durability, Gaithersburg, MD

November 13, 2013

Outline

- Review Weathering Stresses
- Materials in Photovoltaic Module Constructions
- Fielded Module Studies
- Comparison of UV and DH Accelerated Results and Fielded Module Performance
- Accelerated Test Protocols
- UV Test Protocols for Backsheet to Address Qualification Shortcomings
- Conclusions

Stresses for PV Modules and Materials



- Combined stresses operate throughout greater than 25 year module lifetime
- Backsheet is the first line of defense in all geographic locations and installations
- **UV durability has been under-tested and its effects in the field under-estimated**

Material Combinations Create Unique Interactions

B

Module Encapsulant Resins
Elvax®

A

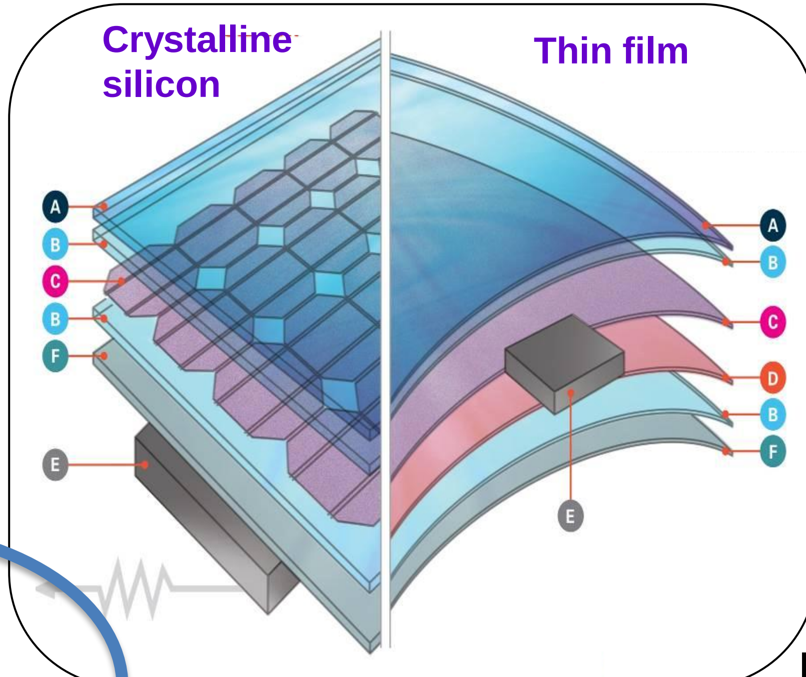
Front Sheet Materials
Teflon® films

B

Module Encapsulant Sheets
DuPont™ PV5200
DuPont™ PV5300

C

Cell metallization pastes
Solamet®



D

Thin Film Substrates
Kapton® polyimide films

F

Films for backsheets
Tedlar®

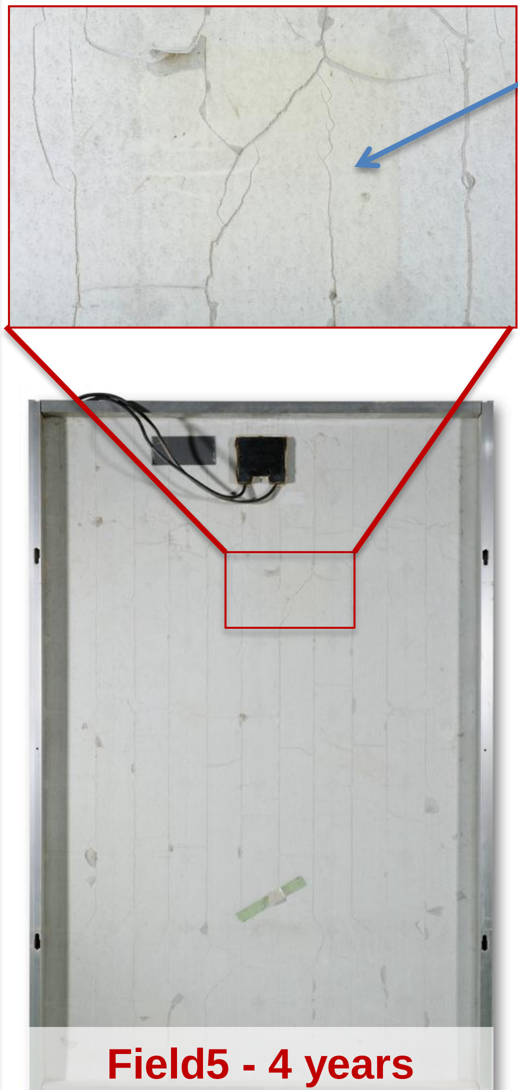
E

Engineering resins & components
Rynite®

Unique Opportunity for Deep Understanding of Performance

Module Failures due to UV Exposure: Polyester Yellowing and/or Cracking on Junction Box Side

Spain

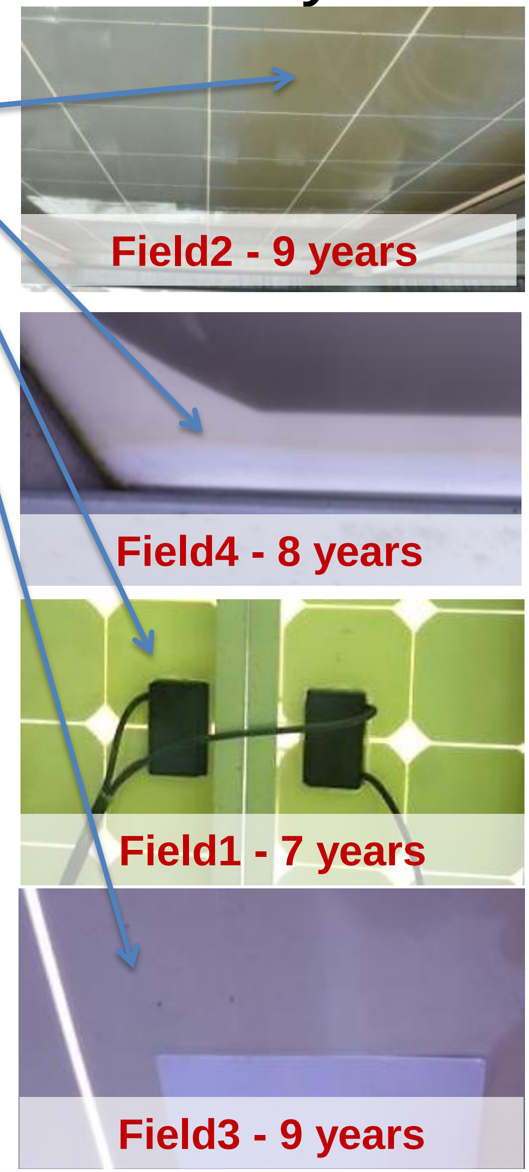


Cracking & Yellowing

Yellowing

Arizona, USA

Italy

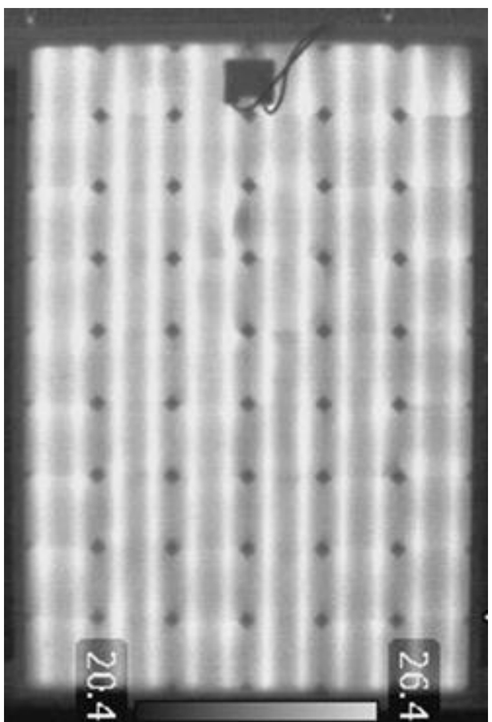


Failures from UV damage observed in the field early in expected module lifetime

Fielded Module Example

Cracking on the outer polyester layer of backsheet

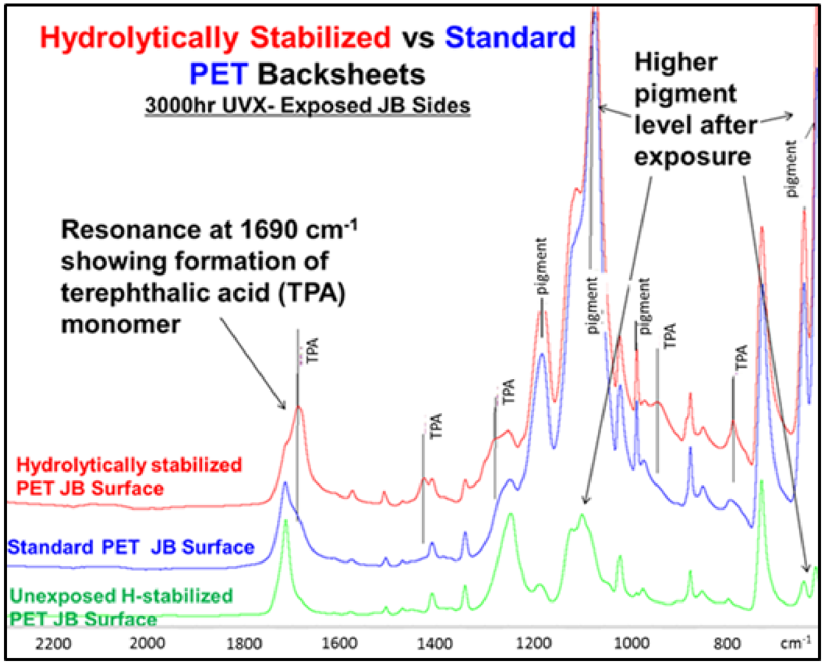
- Modules were removed from a commercial MW plant after 5 years for cracking and delamination on the backsheet along the rear tabbing ribbons and 9% loss of power.
- The IR analysis identified outer layer as polyester.
- Thermal image shows localized heating at cell contacts.



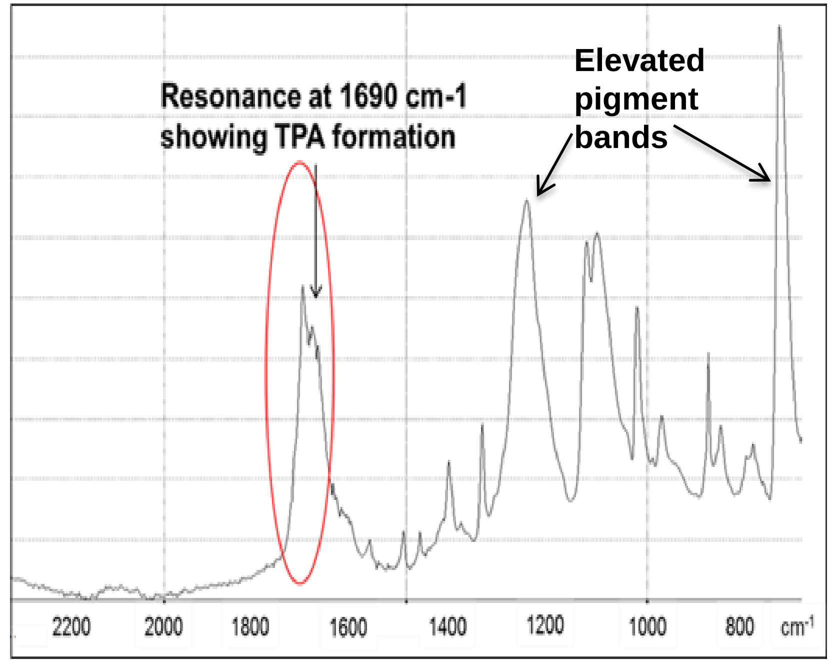
Cracking of the backsheet is likely due to indirect UV exposure. Backsheet testing to reflected light from albedo can identify instability in the outdoor environment.

FTIR Analysis of Accelerated Weathering and Fielded Module

Hydrolytically-stabilized PET-based backsheet, standard PET-based backsheet JB side exposed for 360 kWhr/m^2 TUV in Atlas Weather-o-meter*, compared to PET-based backsheet from fielded module 6 years in AZ



Atlas Weather-o-Meter exposure



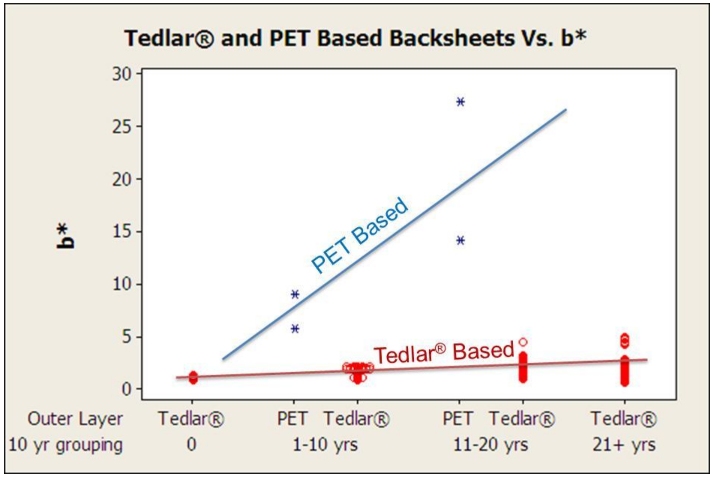
Fielded module 6 years an AZ

PET before exposure shows resonance at 1710 cm-1.
Both Weather-o-Meter exposed and fielded sample show 1690 cm-1 resonance, evidence of degradation of PET to TPA monomer

* ASTM G155 cycle9 (modified), xenon lamp with daylight filter, 120W/m2 (300-400nm), 65° C BPT, 102min. radiation, 18min. radiation + water spray

Comparison UV and Damp Heat to Fielded Performance

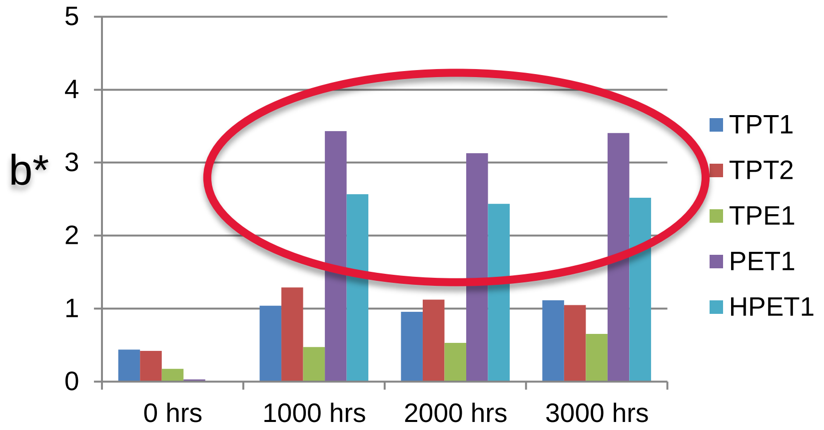
Fielded Tedlar® and PET Modules



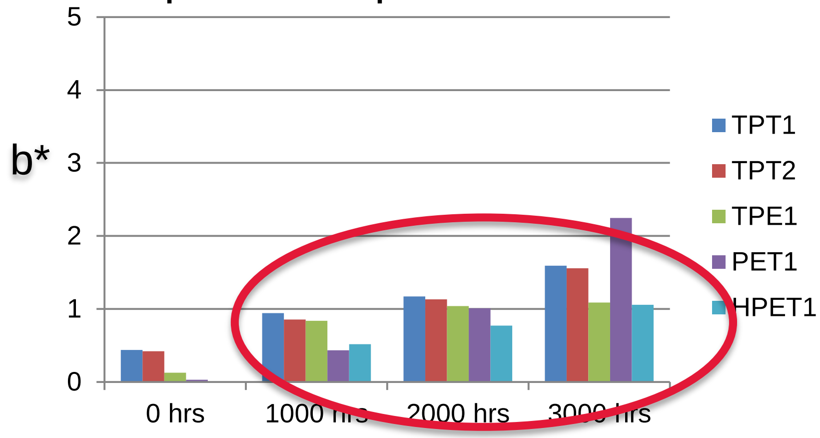
227 Tedlar® and 4 PET based backsheet modules from various locations and manufacturers

- Small color change consistent with changes seen in damp heat and UVA exposure for Tedlar® -based backsheets
- Significantly larger changes in b* (9~27) for PET-based backsheets indicating polymer damage and degradation

UVA Exposure of Modules



Damp Heat Exposure of Modules

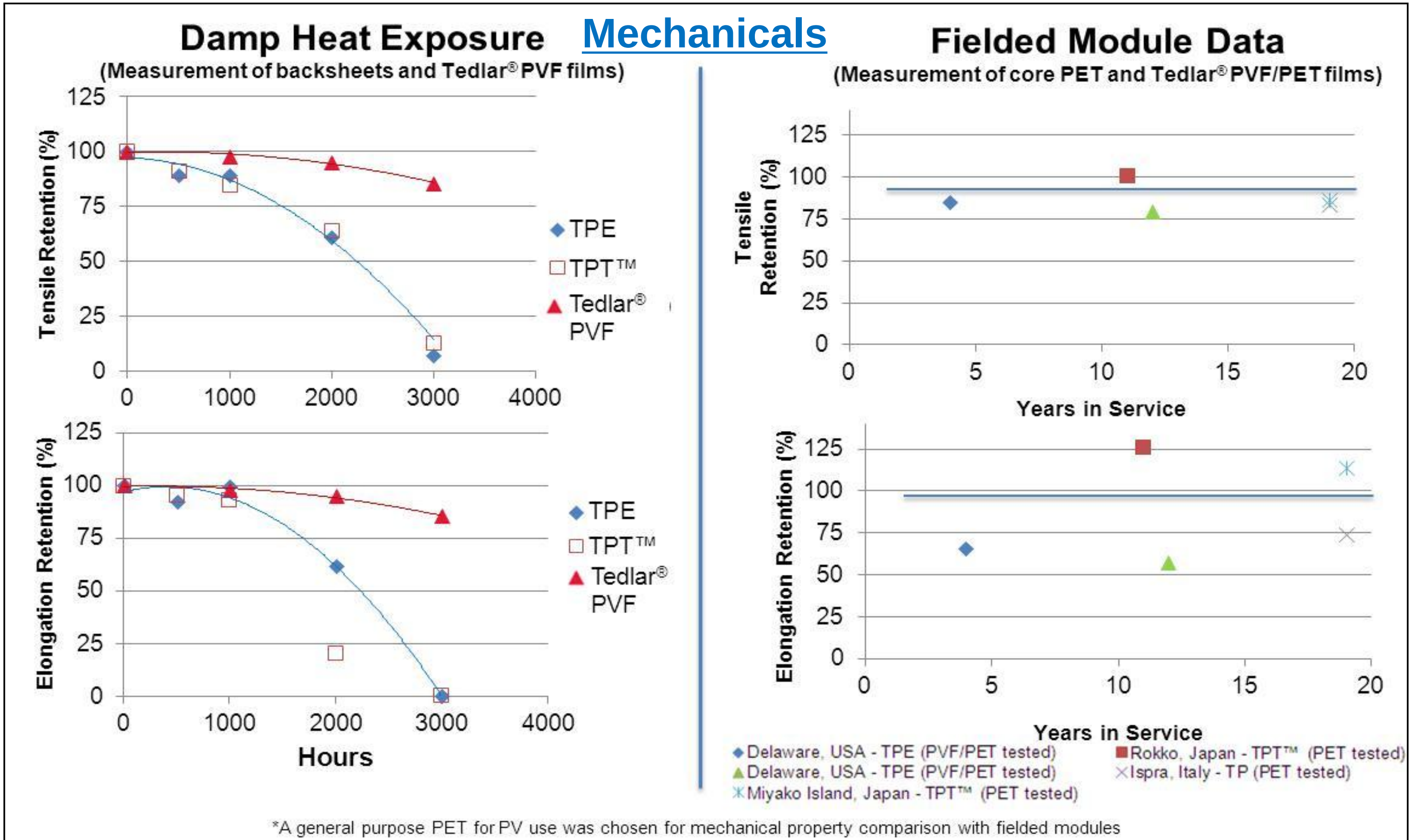


UV exposure of PET-based backsheets more damaging and likely responsible for much higher yellowing observed in the field

- Level of yellowing in damp heat not changing appreciably from 1000 to 3000h
- Level of yellowing for PET modules in damp heat not consistent with yellowing in the field

Damp Heat : 85°C, 85%RH
UVA: 70°C BPT, 65W/m² (250 - 400nm), no water

Comparison of Properties - Damp Heat and Fielded Exposure

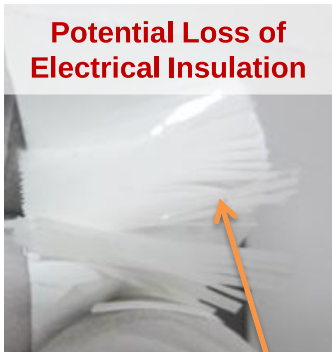


- Loss in mechanical properties in damp heat (>1000h) due to hydrolysis of PET core layers (not Tedlar®)
  No loss in mechanical properties for humid environment – Miyako Island, Japan
- Mechanical loss at 2000h and 3000h much greater than observed in the field
- Fielded modules from different environments obtained from DuPont (USA), AIST (Japan) and JRC (Italy)

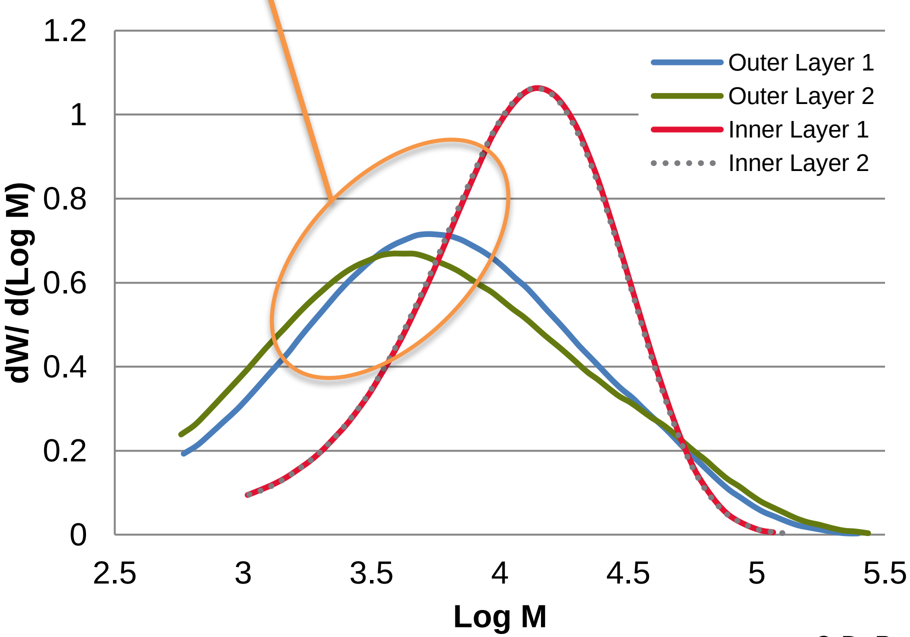
Analysis of Fielded PET Module

	Field Location	Time in service	Backsheet Construction (thickness/µm color)	Mount Type	b*
Module 6	Japan	9 yrs	PET(12µm, Clear?) / PET(50µm, White)	Open Rack	5.77

**Modules 4, 5 and 6 are all from the same manufacturer.



PET Layer Tested	Mn	Mw	Mw/Mn
Outer Layer 1	3,340	13,000	3.90
Outer Layer 2	3,000	13,700	4.56
Inner Layer 1	7,400	15,800	2.14
Inner Layer 2	7,300	15,600	2.15



Analyses of PET Layers

Molecular Weight Analysis

- Outer PET layer shows likely drop and broadening of Mw
- Inner PET layer no changes were observed
- These changes are most likely due to stresses during service (UV, moisture, etc.)

Mechanical Properties

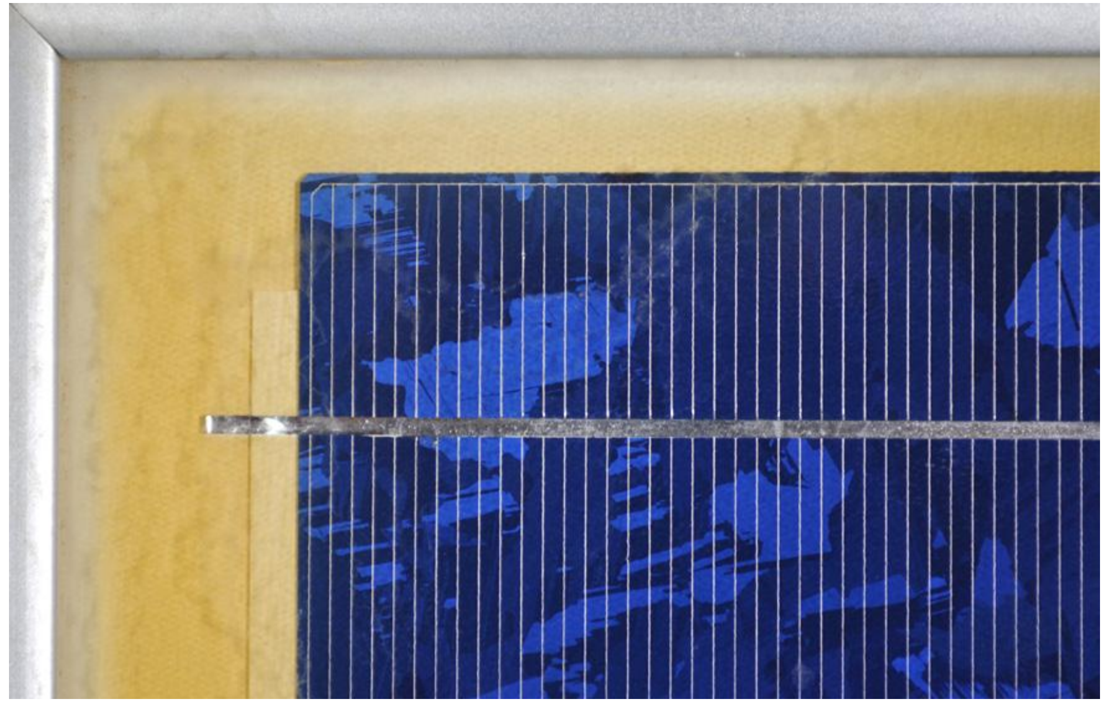
- Compared to a standard PET, the inner layer of PET dropped 60% in tensile (MD) and 40% in elongation properties
- Outer layer lost all mechanical properties

Outer PET degraded – Mw changes and loss of mechanical properties
Inner PET degraded – loss of mechanical properties with no Mw changes

	Inner PET Layer	Control PET	% Retention
Tensile (Mpa)	127.50	207.00	61.59
Elongation (%)	71.14	150.00	47.43

**Could not measure air side - no mechanical integrity

Module Failures due to UV Exposure: 1s PVDF Front Side Yellowing



Front side yellowing observed in:

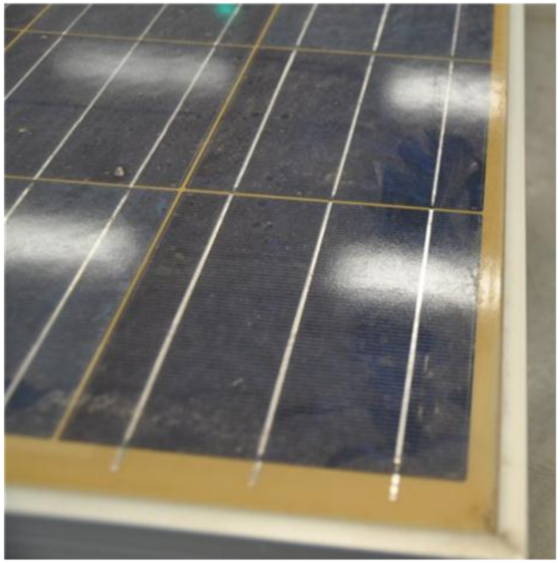
- 5 different countries (Belgium, Spain, USA, Israel and Germany)
- 5 different module manufacturers
- **Modules less than 5 years in the field**

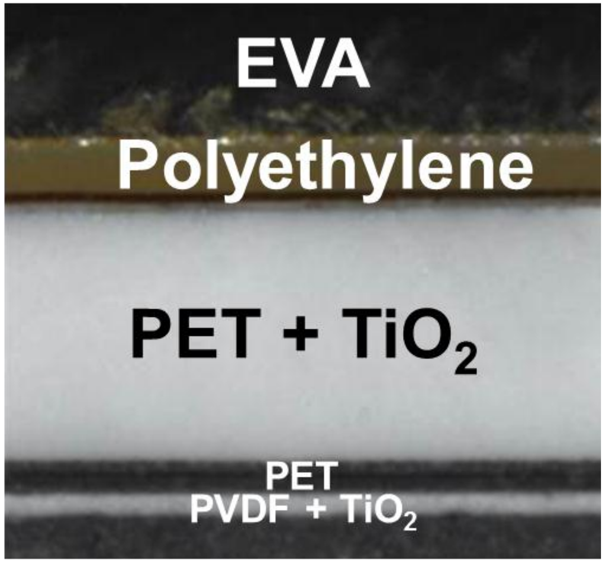
Failures from UV damage observed in the field early in expected module lifetime

Fielded Module Example

Discoloration in the inner layer of a PV module backsheet

- Modules removed from a commercial MW power plant after 2 years for severe yellowing and loss of ~4% power.
- Destructive analysis determined yellowing of inner polyethylene layer and associated adhesive layers in the PVDF/PET/PET/PE backsheet structure.
- UV absorbance of the EVA lower than expected resulting in higher UV exposure of the inner layer of the backsheet





Testing of the stability of the inner layer to UV exposure would have identified the instability and avoided damage

DuPont Testing Protocols

Test	Exposure Condition	Evaluation	Technical Reason
Damp Heat	85°C, 85%RH	1000h	adequate for PET hydrolysis damage
		2000h	assess materials stability
		>3000h	test-to-failure
UV (Junction Box Side)	UV, 70°C BPT, 0.55 W/m^2-nm at 340nm, ~60 W/m^2 (300-400nm)	275 kWh/m^2 (4230 h)	desert climate(25 year equivalent)
		235 kWh/m^2 (3630 h)	tropical climate (25 year equivalent)
		171 kWh/m^2 (2630 h)	temperate climate (25 year equivalent)
UV (Encapsulant Side)	UV, 70°C BPT, 1.1W/m^2-nm at 340nm, ~120 W/m^2 (300-400nm), glass/EVA/EVA filter, std. EVA and UV transmissive EVA	550kWh/m^2 (4600 h)	desert condition (6 - 16 year equivalent)
		550 kWh/m^2 (4600 h)	tropical condition (7 - 19 year equivalent)
		550 kWh/m^2 (4600 h)	temperate condition (10 - 26 year equivalent)
Thermal Cycling	-40°C, 85°C, 200cyc	1x, 2x, 3x	assess durability
Thermal Cycling Humidity Freeze	-40°C, 85°C (50cyc); -40°C, 85°C 85%RH (10cyc)	1x, 2x, 3x	assess durability

* IEC 61215 UV pre-conditioning, 15 kWh/m^2 (280-385nm), **front exposure only, ~70 days outdoors**

- UV testing needs to be extended to adequately address backsheet performance in the outdoor environment
- Dosage for UV testing should match 25 year outdoor exposure to insure durability.
- Damp heat testing to 1000 hours is more than sufficient for PET hydrolysis damage of backsheets over 25 years of outdoor exposure

Need for Backsheet UV Testing

- Durability issues related to the backsheet are observed and documented in fielded modules (cracking, yellowing, delamination)
- We propose to add backsheet UV exposure to current industry standard (currently little or no UV exposure in qualification standards) consistent with the service environment
- Polymeric component testing of UV stability established in ASTM standards and used in other industries
  - ➢ Testing designed for easy adoption and implementation using existing equipment, methodology, and duration less than six months
  - ➢ Key properties and acceptance criteria consistent with industry protocols and field experience
  - ➢ Module testing limited by equipment, exposure time and established test methodology

UV Durability Test Conditions for PV Backsheet

1. **UV Junction Box side exposure:** Xenon (daylight) or UVA fluorescent exposure, 70C BPT, 275 kWh/m2 TUV, ~25y desert exposure**)
    1. Test free-standing backsheet

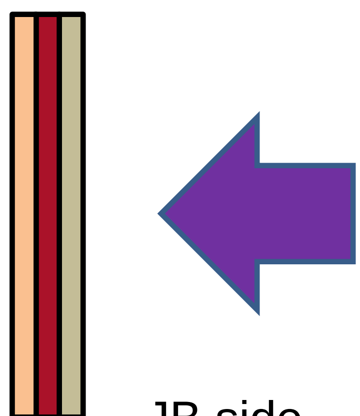
2. **UV Encapsulant side exposure:** Xenon (daylight) exposure, 70C BPT, 550 kWh/m2 TUV, ~6y desert exposure)
    1. Test laminate and free-standing backsheet
    2. UV exposure through glass/2EVA/FEP filter
    3. Test using standard and UV transmissive EVA

	Desert	Tropical	Temperate
Annual UV Exposure (kWh/m2)*	**92**	**79**	**57**
25 year UV Exposure (kWh/m2)	2300	1975	1425
25 year JB-side Exposure (kWh/m2)**	**276**	**237**	**171**
Equivalent JB-side exposure @275 kWh/m2 (years)	25	29	40
Equivalent E-side exposure @550 kWh/m2 (years)	6	7	10
Equivalent UVT E-side exposure @550 kWh/m2 (years)	16	19	26
* Total UV exposure (300-400 nm), reference: Atlas			
** Assumes 12% albedo			

*** Assumes UVT EVA transmits >320nm and std EVA transmits at >370nm

Criteria for Junction Box Side Exposure

	Impact on Power	*Impact on Safety*	*Acceptance Criteria*	*Justification*
Mechanical				
Visual Appearance	Indicates materials degradation and associated loss in key protective properties	Indicates materials degradation and associated loss in key properties	no cracking, flaking, bubbling or failure of adhesive bonds	consistent with IEC61215
Tensile Strength	brittleness/cracking of the backsheet leads to accelerated corrosion of the electrical contacts	lower force needed to cracking of the backsheet and compromises the electrical insulation	>70% retention	consistent with UL 746C criteria and referenced in UL1703
Elongation	brittleness/cracking of the backsheet leads to accelerated corrosion of the electrical contacts	lower elongation results in cracking of the backsheet and compromises the electrical insulation	>70% retention	consistent with UL 746C criteria and referenced in UL1703
Optical				
Color Change (b*)	Yellowing indicates materials changes that could translate to reduced physical properties tensile, elongation, adhesion/delamination)	Yellowing indicates materials changes that could translate to reduced physical properties tensile, elongation, adhesion)	change in b* <2.0	consistent with comparison of accelerated test and outdoor performance



UVA or UVX (daylight), 65W/m2 UV, BPT 70C, 275 kWh/m2, 4200h

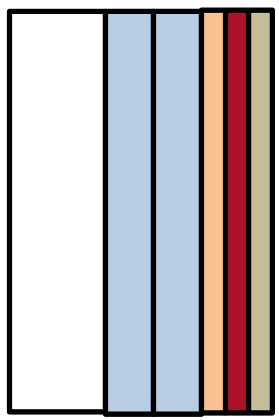
JB side

Criteria for Encapsulant Side Exposure

	Impact on Power	***Impact on Safety***	***Acceptance Criteria***	***Justification***
Mechanical				
Visual Appearance	Indicates materials degradation and associated loss in key protective properties	Indicates materials degradation and associated loss in key properties	no cracking, flaking, bubbling or failure of adhesive bonds	consistent with IEC61215
Optical				
Reflectance	Lower reflectance reduces recaptured light from interstitial spaces at edge and between cells		change < 20% absolute	consistent with estimated 1% change in power
Color Change (b*)	Yellowing indicates materials changes that could translate to reduced physical properties tensile, elongation, adhesion/delamination)	Yellowing indicates materials changes that could translate to reduced physical properties tensile, elongation, adhesion)	change in b* < 2.0	consistent with comparison of accelerated testing and outdoor performance

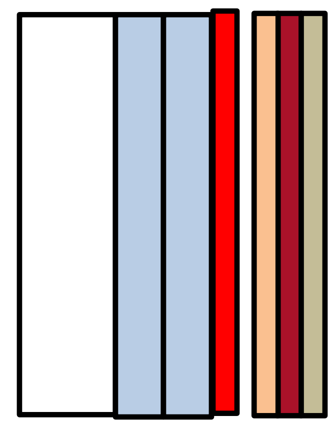
UVX (daylight), 120 W/m2, BPT 70° C, 550 kWh/m2, 4200h

UVT and std EVA



Laminate test

UVT and std EVA



Backsheet test

Using UV transmissive EVA to get higher acceleration, wavelength sensitivity and test range of commercial constructions. Mechanical retention criteria TBD.

Test for inner layer backsheet stability

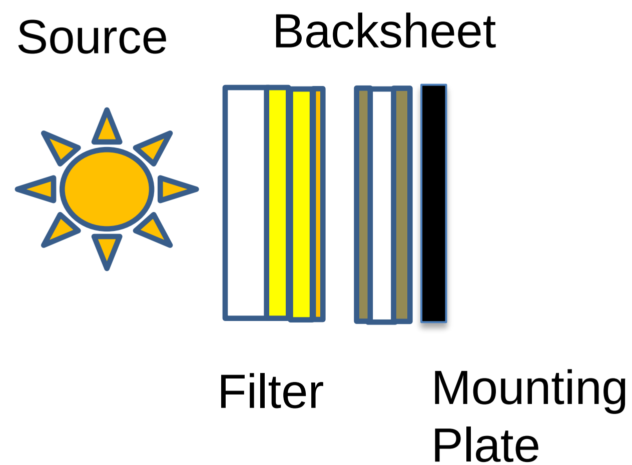
Simulates long term solar exposure from the glass side of a PV module with short wavelength (<360nm) light removed by glass/2xEVA filter.

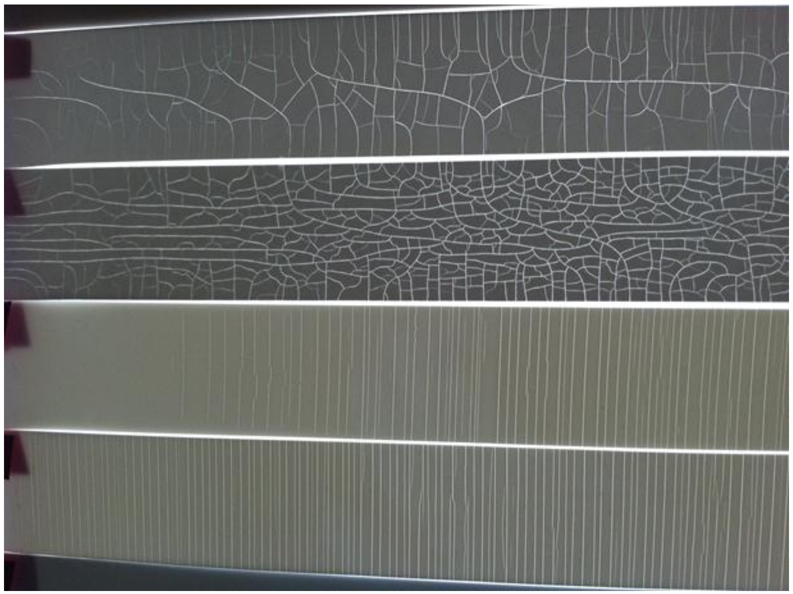
Source: 1500 W/m2 MH lamp
Filter: glass/EVA/EVA/FEP
Backsheets: various structures

After 540kWh/m2 at 70C:
Some single-sided backsheet showing instability of the inner layer

High intensity metal halide "filtered" exposures are showing changes to the inner layer of some backsheets

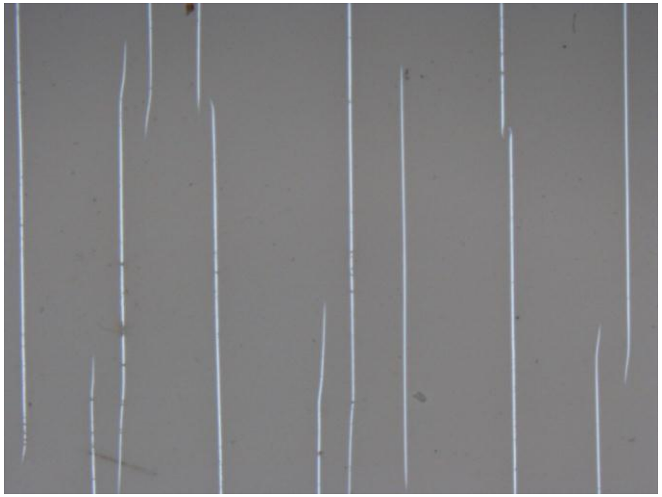
Exposure Geometry





Combinations of UV/visible radiation, temperature, moisture (water spray, condensation and/or chamber relative humidity) and thermal cycling are more relevant to the outdoor environment

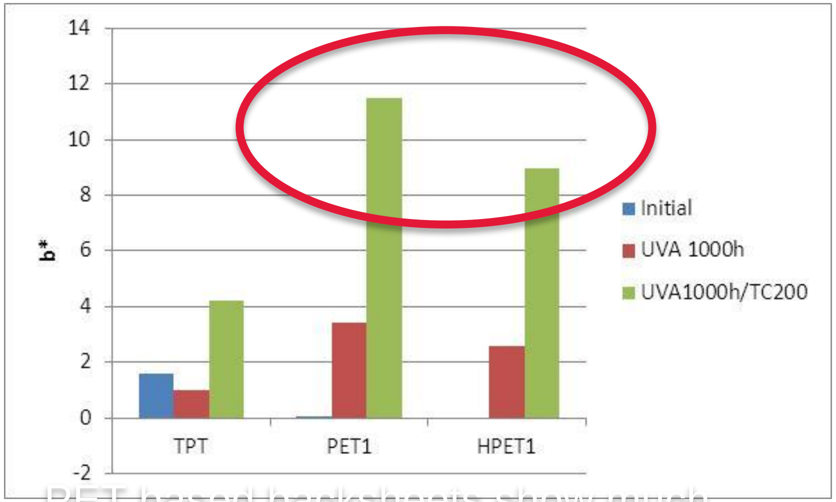
Xenon-Water Spray Weathering of Backsheets*



Cracking of inner tie layer in PET backsheet after 1500h outer layer exposure. Xenon exposure only, cracking seen at 5000 hours

* ASTM G155 cycle9 (modified), xenon lamp with daylight filter, 120W/m2 (300-400nm), 65˚ C BPT, 102min. radiation, 18min. radiation + water spray

Sequential Stress (UVA vs. UVA+TC)**



PET-based backsheets show much greater color change after UVA/TC indicating polymer degradation and damage

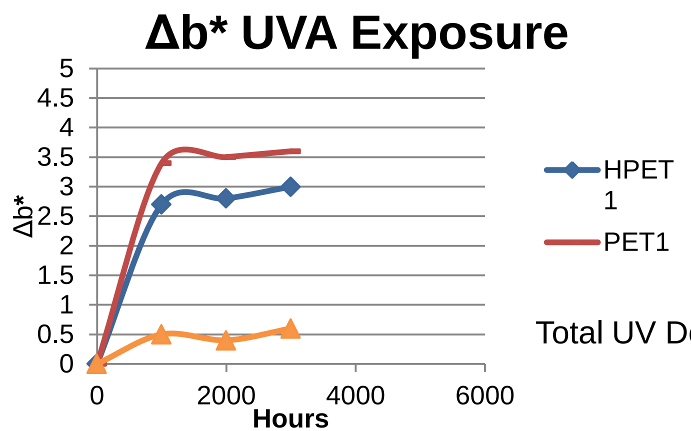
- Greater than UVA alone
- Similar to levels seen in fielded modules

** Backsheet side of module measured
UVA: 70°C BPT, 65W/m^2 (250 - 400nm), no water
TC: -40°C, 85°C, 200 cycles per IEC 61215

TPT™ vs PET : QUVA and Xenon Exposures of Backsheets

Exposure of Air Side of Backsheet

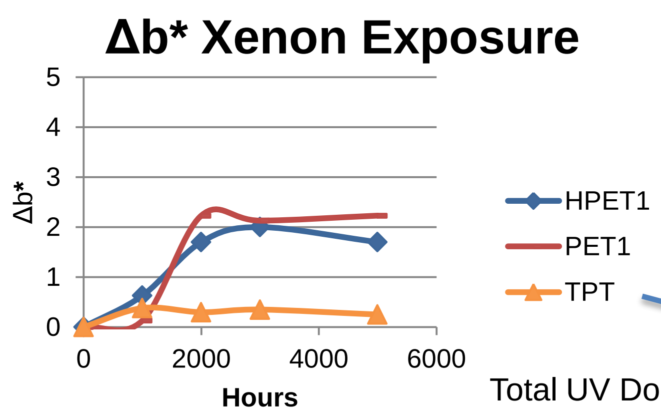
UVA



Total UV Dose: 195 kWh/m²

HPET1 inner tie layer cracking after 5000 hour air side xenon exposure

Xenon



Total UV Dose: 300 kWh/m²

TPT™- E side - no cracking after 5000 hour air side xenon exposure

Yellowing of PET-based backsheets using recommended UVA and UVX exposure and tie layer cracking with UVX

UVX: 65°C BPT, 60W/m² (300 - 400nm), 50%RH, no water
UVA: 70°C BPT, 65W/m² (250 - 400nm), ambient humidity, no water

Sequential Stress Testing

Four cell mini-modules exposed to sequential stress testing to assess impact of multiple stresses on performance and durability vs. a single stress exposure. Loss of properties in single stress (damp heat) is observed after applying additional stresses.

Sequential Stress #1: DH1000/UVA1000/TC200

Cracking of a single-sided PVDF backsheet after sequential exposure to damp heat, UV and thermal cycling (contrast increased to highlight cracking)

Sequential Stress #2: 2x(DH1000/TC200)

Cracking of a single-sided PVDF backsheet after sequential exposure to damp heat and thermal cycling

Conclusions

- Current UV testing in qualification is not addressing UV stress in backsheets. Improved UV testing is needed to better predict durability of PV modules to stresses in the service environment

- UV test protocol developed to address encapsulant side and junction box side exposure based on outdoor environment

- Damp heat exposure of 1000 hours is sufficient to match fielded module degradation in even the harshest humid conditions, longer damp heat exposure leads to degradation mechanisms not observed in the field.

- Accelerated aging tests using combinations of UV, temperature cycling and moisture are more predictive of fielded module degradation than any single stress test alone.

- Accelerated tests correlating to observed degradation in fielded modules are a critical tool needed to understand and improve module durability.

Acknowledgements

A Global Effort with Many Contributors. Thank you!