Development of Accelerated Tests Based On Analysis of Fielded Modules

Atlas/NIST Workshop on Photovoltaic Materials Durability

Gaithersburg, VA

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Outline

- Overview of Fielded Module Program
- Introduction to Backsheet Constructions
- Performance and Durability
  - Inner Layer
  - Core Layer
  - Outer Layer
- Conclusions

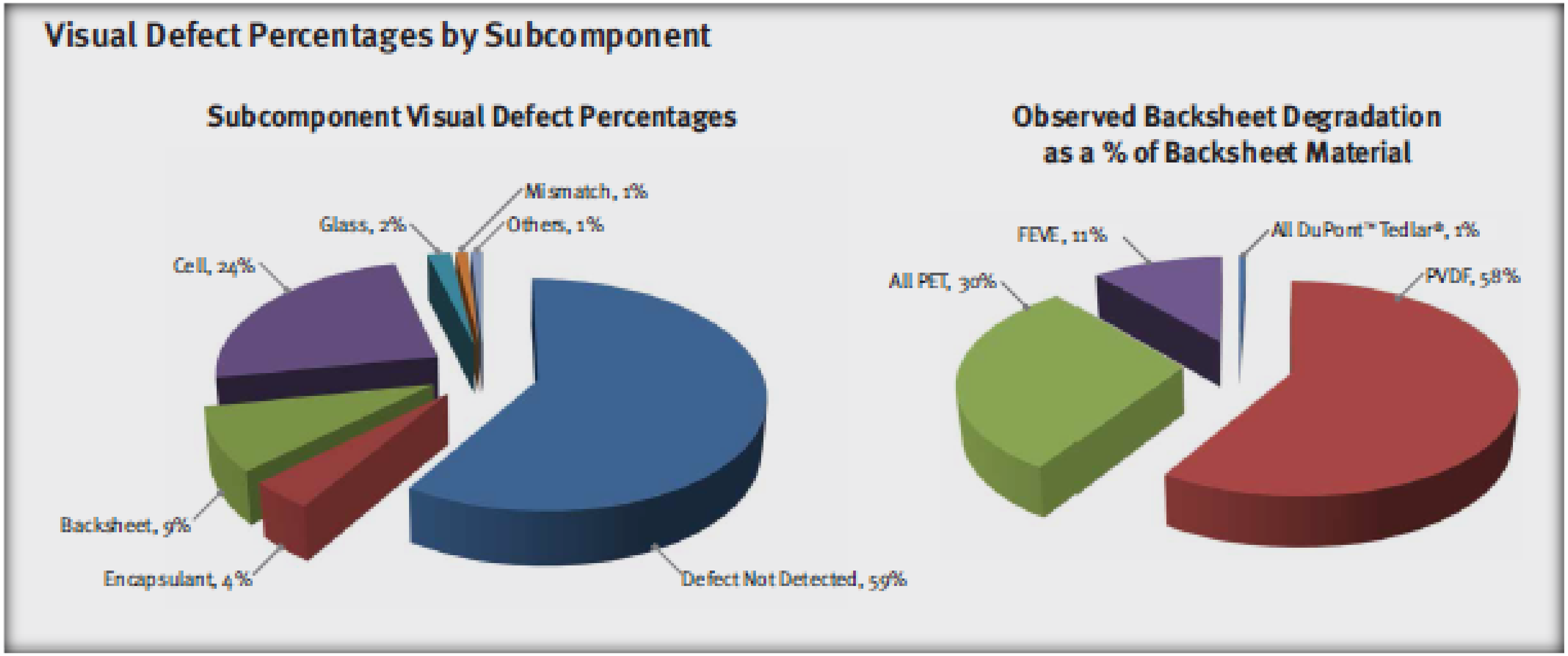
DuPont Field Module Program

Provides unique data driven insights on safety, defects and power degradation across a wide array of installations, environments and manufactures

- **> 70 global installations**
- **NA, EMEA & AP**
- **45 Module Manufacturers**
- **>1 Million Modules and 200 MW**
- **Newly installed to 30 years in the service**
- **Still expanding with additional testing and analysis commissioned**

Bringing real field data to the industry….provides supporting data for our industry

Quantifying Module Subcomponent Defects



Field Studies Reveal Quality Issues

41% of surveyed modules exhibited some visual defect

A. Bradley, et al. IEEE PVSC (New Orleans, 2015)

Backsheet Structure

PV backsheets are typically three-layer structures with the following functions:

	Functions	New Design and Material Changes
Inner Layer	adhesion to encapsulant	new material compositions
	UV protection core from "filtered" direct UV	thinner layer (<2 um)
	resistant to penetration during lamination	coated layers
	non-yellowing	
core layer	primary mechanical properties	new materials
	primary electrical insulation properties	thinner layers (~250 um to 75 um)
	water, oxygen and acetic acid barrier properties	
outer layer	weatherability	new materials
	UV protection of the core from indirect UV	thinner layer (<2 um)
	resistant to mechanical damage (handling, sand)	coated layers

Tedlar® PVF is Specified for PV Modules by Scientific Experts

NASA Jet Propulsion Laboratory Flat-Plate Solar Array Project

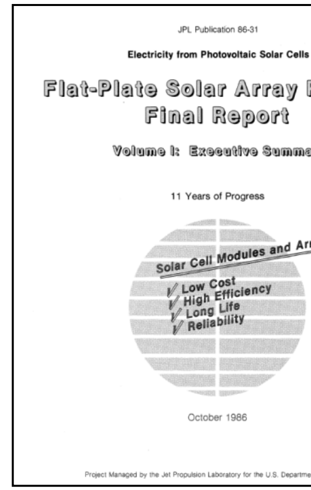
Most extensive study ever undertaken to improve PV module's efficiency, lifetime, reliability and quality

- Eleven years of designs & testing from 1975-1986
- Over $700 million spent (in 2013 dollars)
- Over 400 module designs tested
- **More than 22,000 modules purchased & fielded**
- Five rounds of design upgrades

"Module lifetimes increased from 1 or 2 years … to lifetimes of 20 to 30 years at the end of the project."

"The success of this approach is demonstrated by the fact that **most design details** of the Block V modules (final design) **have been adopted internationally**."

Resulted in TPT backsheet design



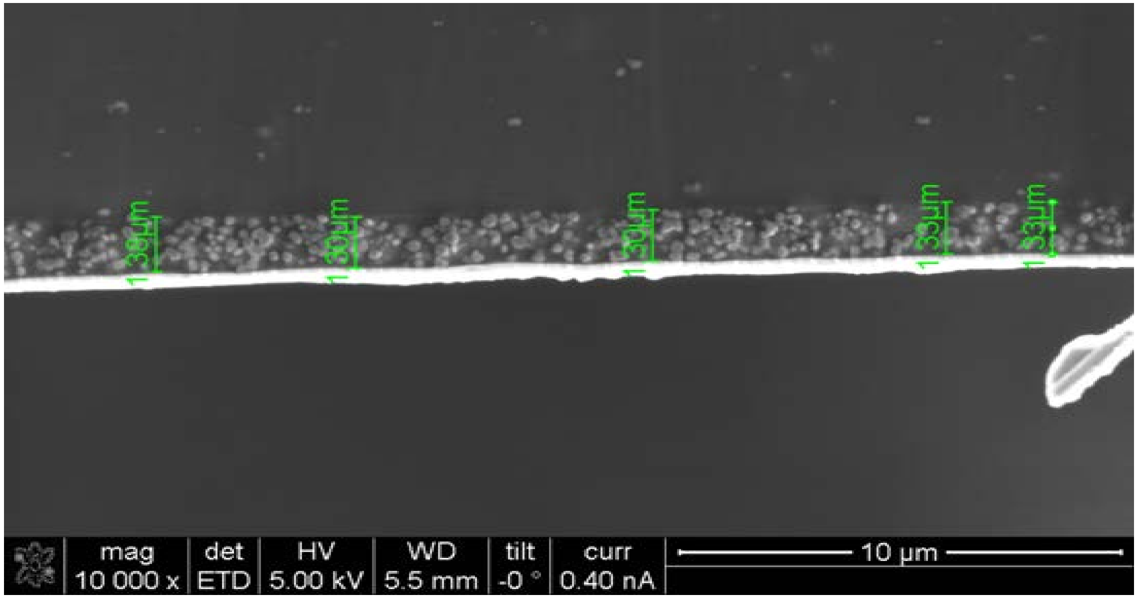
Block	Years	Manufacturer	Top Cover	Encapsulant	Backsheet	Number of Modules
I	1975-1976	Sensor Tech	RTV-615	RTV-615	Aluminum	6,750
		Solarex	Sylgard 184	Sylgard 184	NEMA-G10 Board	
		Solar Power	D.C. R4-3117	Sylgard 184	NEMA-G10 Board	
		Spectrolab	Glass	RTV-615	Aluminum	
II	1976-1977	Sensor Tech	RTV-615	RTV-615	Aluminum	5,291
		Solarex	Sylgard 184	Sylgard 184	NEMA-G10 Board	
		Solar Power	D.C. XL-2577	Sylgard 184	GFR Polyester Board	
		Spectrolab	Glass	PVB	Mylar®	
III	1978-1979	Arco Solar	Glass	PVB	Tedlar®	9,961
		Motorola	Glass	D.C 03-6527A	Stainless Steel	
		Sensor Tech	RTV-615	RTV-615	Aluminum	
		Solarex	Sylgard 184	Sylgard 184	NEMA-G10 Board	
		Solar Power	D.C. R4-3117	Sylgard 184	GFR Polyester Board	
IV	1980-1981	Arco Solar	Glass	PVB	Tedlar®/Stainless/Tedlar®	481
		ASEC		PVB	Tedlar®	
		GE Solar		GE SCS2402	MEAD PAN-L-Board	
		Motorola		PVB	Tedlar®/Al/Tedlar®	
		Photowatt		PVB	Tedlar®/Al/Tedlar®	
		Solarex		EVA	Tedlar®	
		Solarex		EVA	Tedlar®	
		Spire		EVA	[illegible]	
V	1981-1985	Arco Solar	Glass	EVA	Tedlar®/PET/Tedlar®	"10's" of Modules for evaluation
		GE Solar			Tedlar®/PET/Al/Tedlar®	
		MSEC			PET/Al/Tedlar®	
		Solarex			PET/PET/Tedlar®	
		Spire			Tedlar®	

Backsheet
Tedlar®/PET/Tedlar®
Tedlar®/PET/Al/Tedlar®
PET/Al/Tedlar®
PET/PET/Tedlar®
Tedlar®

Source:
Flat Plate Solar Array Project Final Report, Volumes I and VI, October 1986,JPL Publication 86-31.
"The block program approach to photovoltaic module development", Smokler, M. I.; Otth, D. H.; Ross, R. G., Jr., Photovoltaic Specialists Conference, 18th, Las Vegas, NV, October 21-25, 1985, Conference Record (A87-19826 07-44). New York, Institute of Electrical and Electronics Engineers, Inc., 1985, p. 1150-1158.

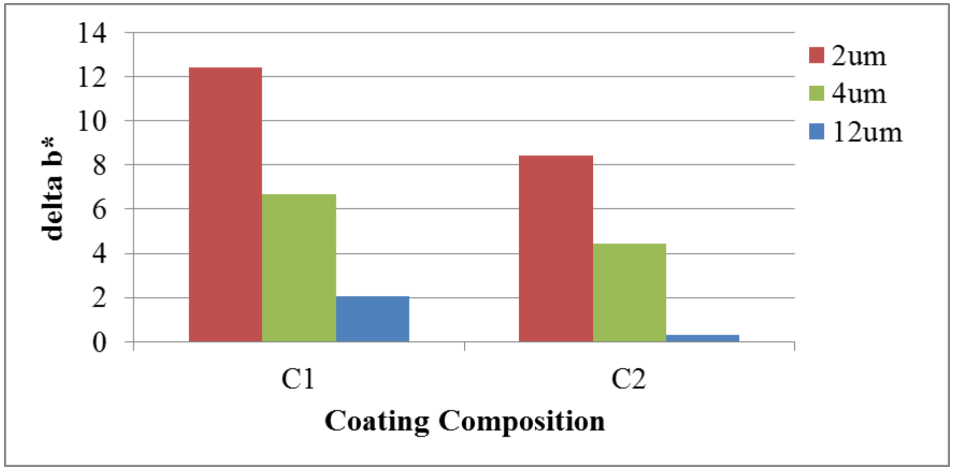
Inner Layers

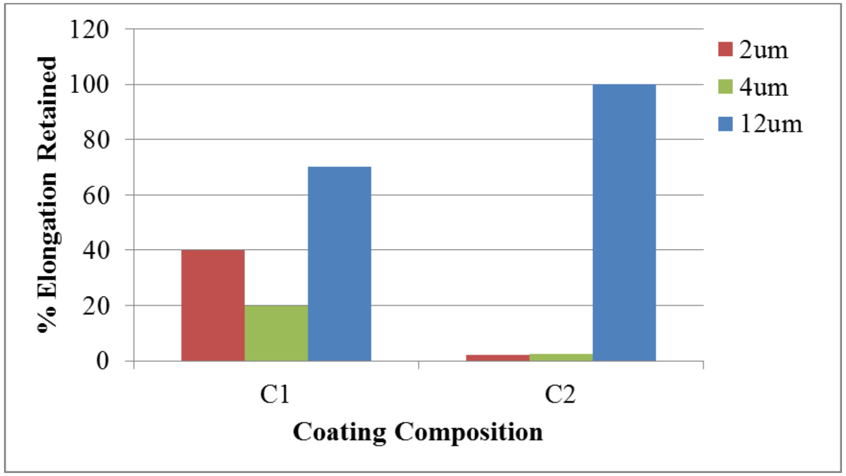
Example of Thin Inner Backsheet Layer



Thin (<2um) coated layer used in a commercial 1sPVDF backsheet on the **inner layer** of the backsheet to improve UV durability

Yellowing and Elongation Retention in Thin Coated Layers



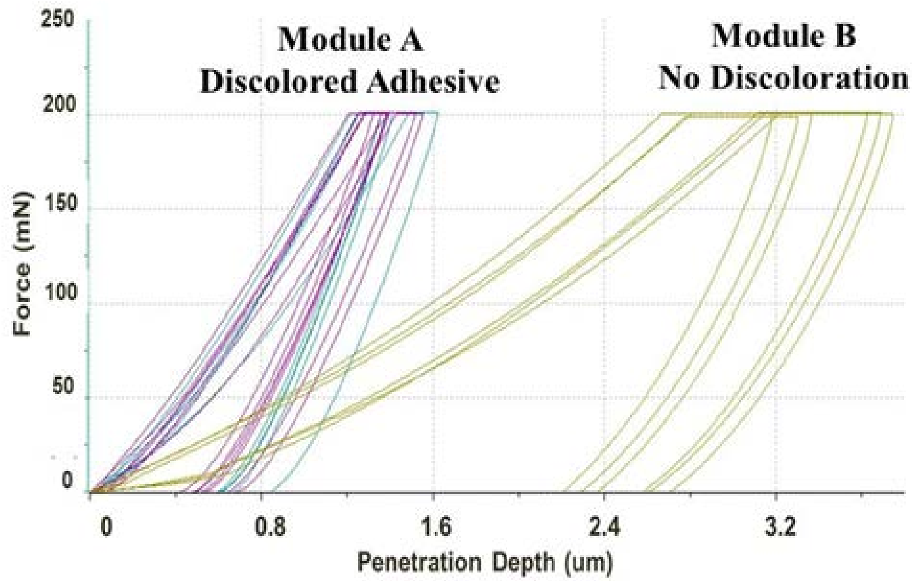


Yellowing vs protection layer thickness for two different compositions

Elongation Retained vs. protection layer thickness for two different compositions

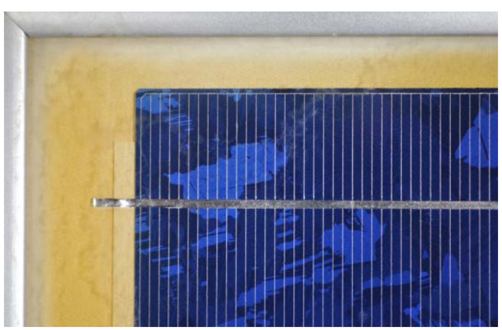
Inner Layer Backsheet Yellowing

Nano-Indentation of Inner Layer of Backsheet



Stika et al., IEEE PVSC 2014

Embrittlement seen with yellowing of inner layer

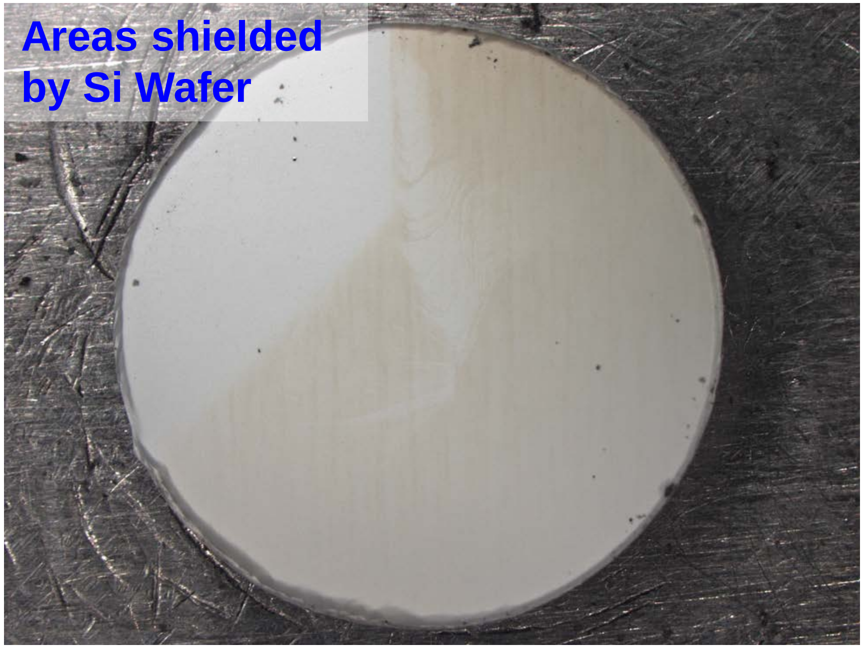


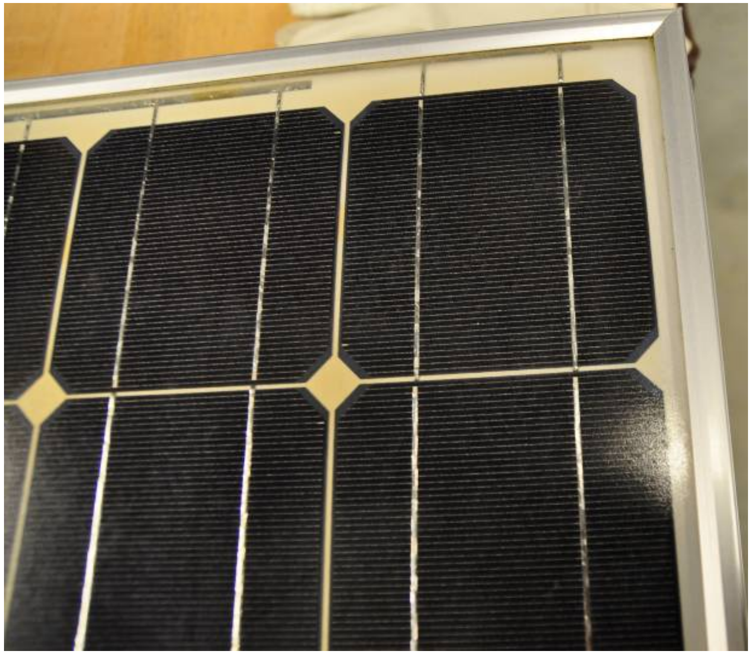
PVDF-based backsheet

- Years in service: < 5 years
- Location: 5 countries (Belgium, Spain, USA, Israel, Germany)
- Five different manufacturers

Gambogi et al., EUPVSEC 2013, Paris

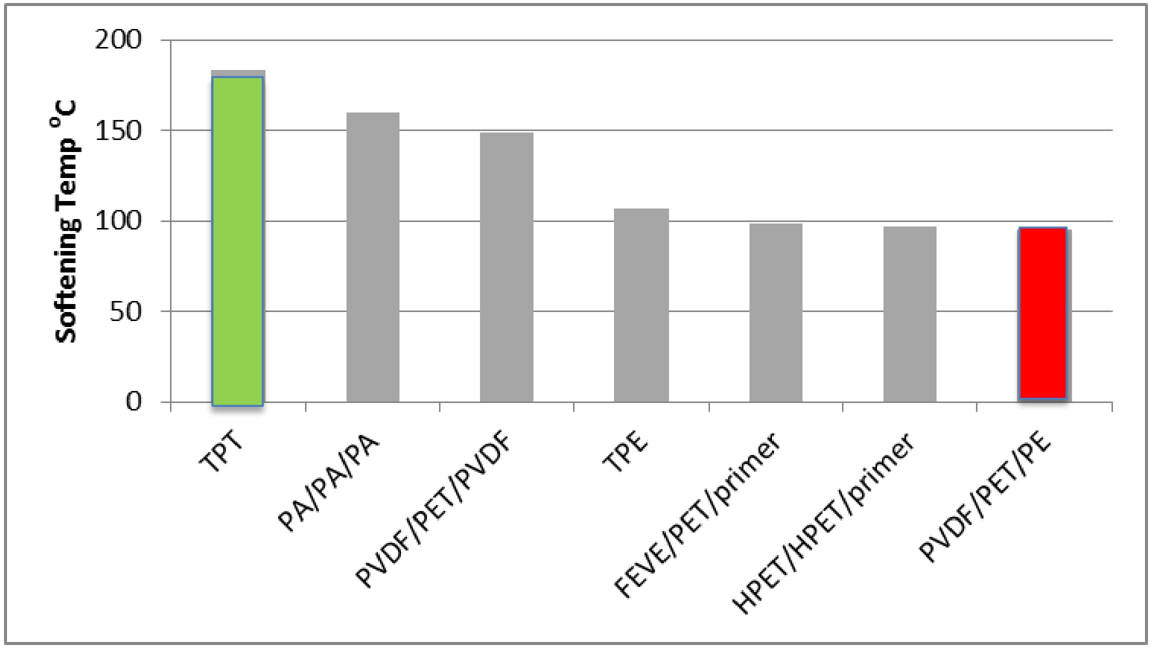
Inner Layer Backsheet Yellowing





PET-based backsheet
- Years in service: < 4 years
- Location: USA
- 100% field affected
- Rooftop and ground mount

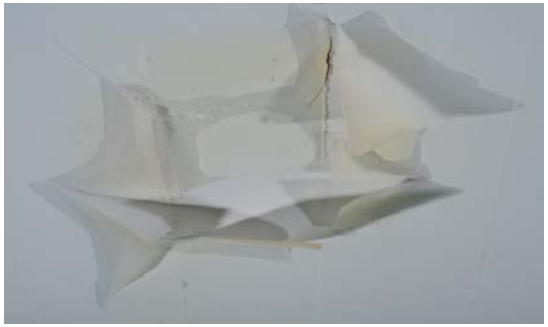
Inner Layer: Thermal Stability



JIS K7196 Heat Deformation Test- weighted stylus impinges on sample being heated, thermal transitions noted

High Intensity Hot Spot

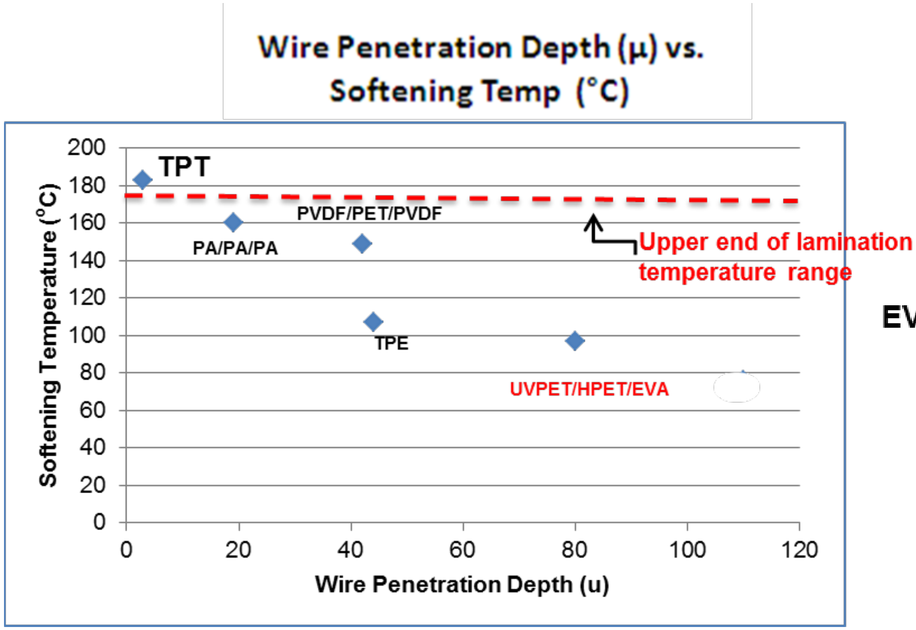
Diffuse Intensity Hot Spot



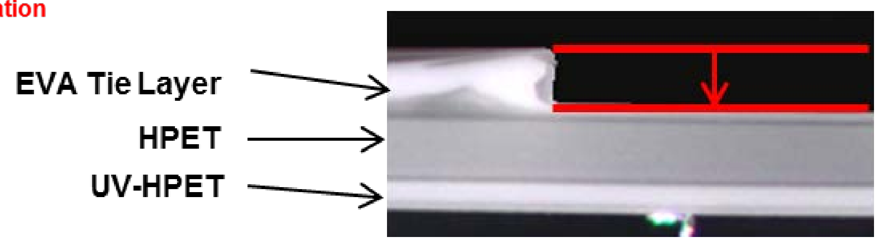
Low softening and melting temperatures can lead to backsheets melting or cracking in the field due to partial shading and hot spots

TPT: Tedlar® PVF/PET/Tedlar® PVF
TPE: Tedlar® PVF/PET/primer

Comparison of Wire Penetration Depth



UVPET/HPET/EVA



Penetration of tabbing ribbon into the inner layer of commercial backsheets under standard EVA lamination conditions

Penetration of tabbing wires evaluated by optical micrograph of a cross-sectioned backsheet with a soft inner layer

(TPT: Tedlar(R) PVF/PET/Tedlar(R) PVF

Outer Layers

Outer Layer Backsheet Cracking and Yellowing

Polyester-based backsheet
- Years in service: 4 years
- Location: Spain
- 5,000 modules affected

- Crack in polyester-based backsheet
- Exposes tabbing ribbon and potential electrical leakage path

Outer Layer Backsheet Yellowing on Rooftop System

- Yellowness measurements (b*) taken on 12 of 14 modules in the array
- Each module tested for yellowness in 53 locations
- Overall yellowing of backsheets due to UV or combination of stresses (thermal, UV, etc.)
  - High level of yellowing even on the interior of array (b* of 13-20)
  - Highest yellowing is along edges with highest UV exposure (b* up to 27)

Yellowness (b*) measurements of 12 modules

A-Up6						A-Up5						A-Up4					
27	26.1	25.9	26.4	25.8	25.5	4.9	25.6	26.4	26	26.2	26.8	24.8	25.2	25.8	25.4	25.8	26.3
26.5	25.8	25.7	26.2	25.5	25.1	4.8	25.2	25.9	25.5	25.7	26.5	23.9	24	25.1	24.3	23.9	25
26	24.8	24.7		24.9	24.8	4.1	24.5	25.2		24.7	26.2	22.9	23.4	24.1		22.8	24.5
26.1	24.9	24.5	24.8	24.4	24.4	24	24.3	25.1	24.9	24.7	25.9	22.5	22.7	23.7	22.8	23	24.2
24.2	22.7	22.5	22.9	22.4	22.4	1.9	22.4	23.4	22.4	22.6	23.6	19.9	19.9	21.2	20	19.6	21.4
23.4	20.9	19.8	20.3	19.7	21.1	20.3	19.7	20.8	19.6	20.9	23.1	18.6	16.4	17.8	16.8	17.6	20.8
23.1	20.4	18.6	19.2	18.4	20.6	9.5	18.5	19.4	18.6	20.1	21.9	18.3	14.8	16	14.6	16.6	20.2
21.3	19.2	17.6	18.9	17.5	18.8	6.7	16.6	18	16.7	17.8	19.3	15.9	13.7	15	13.4	14.4	17.7
23.3	20.9	19.2	19.7	19	20.9	8.4	18.4	19.4	18.4	19.2	21	17.3	13.9	15.4	13.8	15.2	19.2
21	20	20.3	17	18.1	19.9	18.1	18.3	19.1	17.3	19.5	21.1	18.5	15.9	17.1	15.5	16.6	20.3
18.7	18.3	18.5	16.1	15.5	17.4	15.9	16.4	17.8	16	16.1	18.4	17.3	14.6	17	15	14.5	17.4
20.4	19.2	18.8		16.5	19.7	18.4	17.4	18.5		19	21.4	18.7	15.6	17.4		16.7	20.6
20.9	20.2	20.2	18.8	18.5	20.6	19.4	19.3	20	19.2	20.2	22.2	19.7	18	19.2	18.5	18.3	21.4
21.1	21.5	21.7	21.2	20.4	21.5	21.1	21.6	22.1	21.3	21.4	22.4	20.7	20.9	21.9	21.1	20.6	21.9
23.5	23.6	24.3	23.6	23.1	24.4	23.3	23.5	24.4	23.6	23.6	24.6	23.2	23.3	24.1	23.6	23.1	24.5
24.4	24.5	25.4	24.8	24.7	25.4	24	24.3	25.5	24.8	24.9	25.5	24.3	24.7	25.5	25.1	24.6	25.4
24.7	24.9	25.8	25.5	25.3	25.7	24.6	24.9	25.6	25.6	25.4	26	24.8	25.2	26.2	25.8	25.7	26.1
25	25.7	26.5	26.7	26.3	26.5	25.4	25.6	26.3	26.3	26.2	26.6	25.1	25.7	26.3	26.3	26.5	26.8
A-Down6						A-Down5						A-Down4					

A-Up3						A-Up2						A-Up1					
25.6	25.5	25.6	25.8	25.5	25.7	24.5	25.3	26.1	24.9	25.2	25.8	26.3	25.6	25.2	25.7	25.1	24.6
25.6	25.1	25.8	26.2	25.7	25.3	23.9	24.9	25.8	20.2	23	25.3	26.2	25.3	25	25.6	24.5	24.3
26	25.3	26.1		25.3	25.3	23.3	23.1	24		20.6	23	25.2	24.4	24.3		24.8	24.3
25.7	25.2	26	25.5	25.5	25.2	23.9	23.9	24.7	23.5	22.9	24.2	24.6	24.2	24.3	25.8	25	24.6
24.3	23.8	24.2	23.6	24	23.5	21.9	22	23.2	22	21.1	22.5	22.8	22.6	23.1	24.9	24.7	24.2
23.4	20.7	20.4	19.7	20.1	21.2	21.8	20.7	21	20.1	19.4	22	21.9	20.3	21.7	24.7	24.7	24.3
22.9	19.7	18.6	17.9	18.4	20.3	21.6	20.1	20	18.1	18.6	21.3	21.4	19.6	20.8	24.8	24.6	24.3
20.7	18.3	17.7	17.3	17.7	18.6	18.9	18.6	19	17.2	17.3	19.7	19.8	18.5	19.7	23.6	24.3	24.2
21.9	19.2	18.2	18	17.9	20.3	20.6	19.5	19.3	17.6	18.1	20.9	20.7	19.1	20.2	24	24.5	24.6
18.4	16.7	17.6	14.5	15.1	18.3	22	19.7	18.3	17.9	18.8	20.1	20	18.6	17.4	25	24.9	24.9
16.6	15.4	17.1	14.2	13.1	15.2	20.3	18.4	16.8	17.2	17.4	17.2	19.1	17.8	19.4	23.5	24.1	24.3
18.5	16.3	17.7		14.2	18.1	22.2	19.6	17.8		18.6	20.8	20.4	18.8	20.6		24.7	25
19.3	18.5	19.5	17.5	17.3	19.6	22.8	21.1	19.7	20.2	20.5	21.6	21.2	20	21.2	24.6	24.8	24.6
20.3	20.9	21.9	20.8	19.8	21.1	22.8	22.6	22.2	22.5	22.6	22.4	22.2	22	22.7	24.3	24.4	24.7
23.1	23.1	24.2	23.4	22.9	23.9	24.7	23.9	24.5	24.7	24.5	24.3	24.2	23.8	24	25.2	24.6	24.4
24	24.3	25.4	24.5	24.4	25.1	25	23.7	24.6	24.9	24.8	24.6	25.2	24.7	24.4	25.4	24.4	24.4
24.6	25.1	26	25.4	25.4	26	24.7	24	24.3	24.5	24.6	24	26	25.3	25.1	25.3	24.6	24.1
25.6	25.9	27	26.5	26.7	26.9	26	25.4	25.9	26	25.6	24.9	26.6	26.1	25.7	26.1	25.3	25.2
A-Down3						A-Down2						A-Down1					

b* value	
Max	High
27.0	
24.2	
21.4	
18.7	
15.9	
13.1	
Min	Low

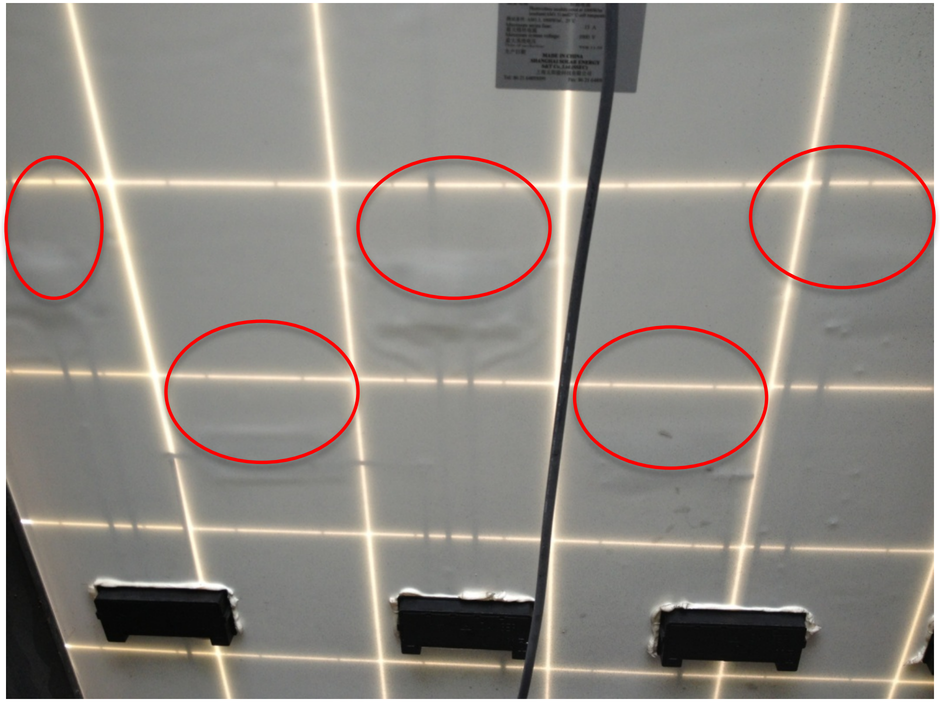
PET-based backsheet

- Years in service: 15 years
- Location: Japan

Source: Modules provided by AIST; DuPont analysis

Adhesion Loss and Delamination

Large Amount of Delamination

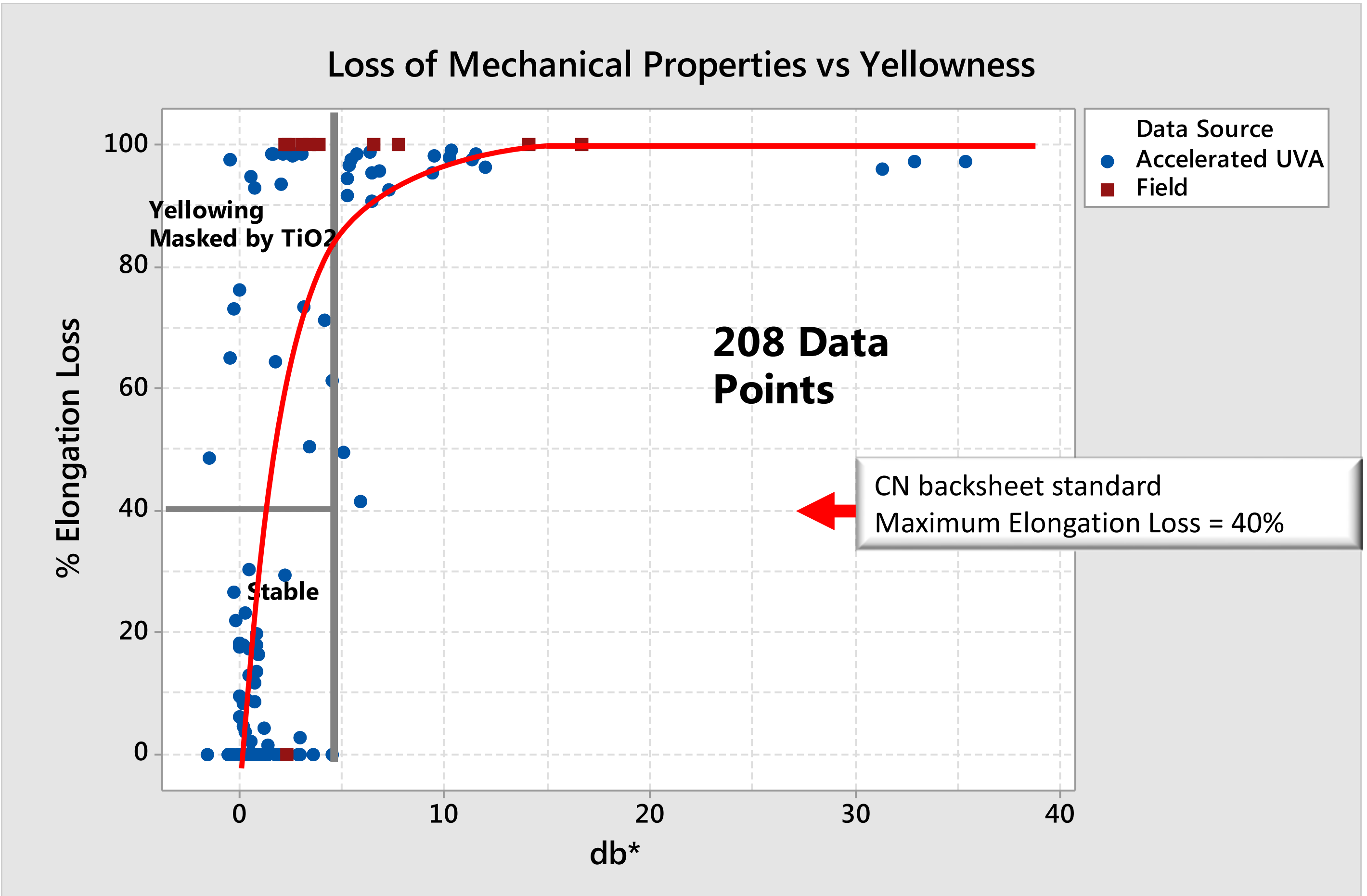


Bubbling and Yellowing

FEVE-based backsheet

- Years in service: 5 years
- Location: Shanghai, China
- Installation: Rooftop
- 30% of array affected

Loss of Mechanical Properties vs Yellowness

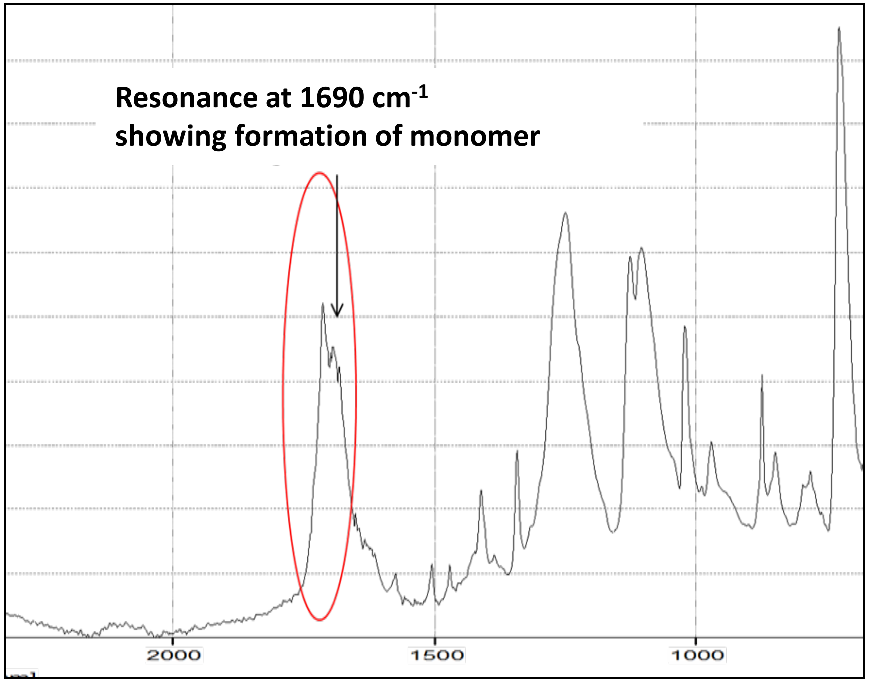


- Note significant loss of elongation when db*>4
- Field and UVA Accelerated Exposure Data Correlate % Elongation Loss with Yellowing

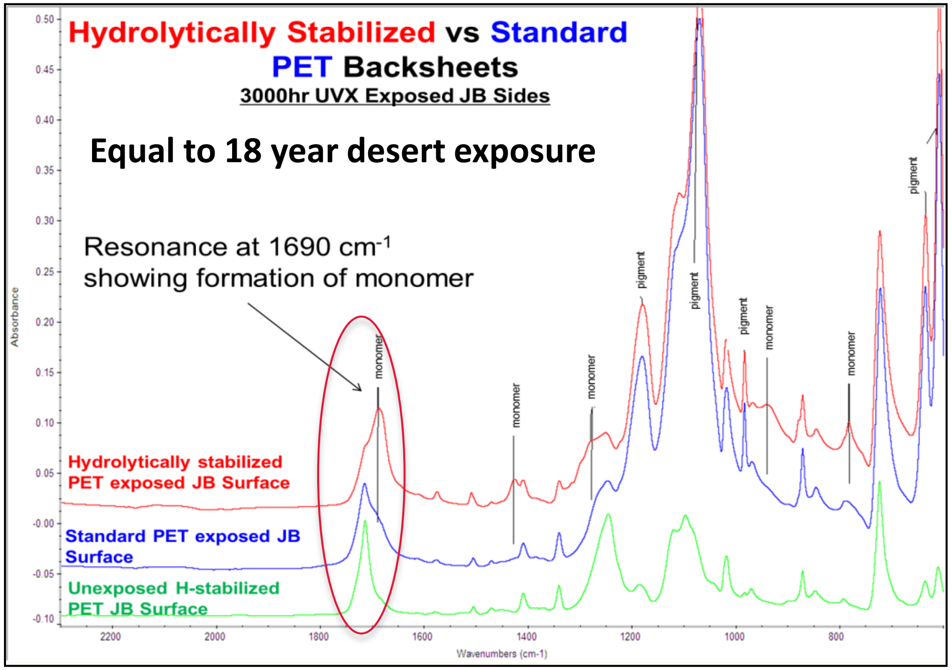
UVA, 65W/sqm, 70°C BPT, 3000 hours = 195kWhr/sqm, 18 year desert equivalent
Field exposures ranged from 4 to 14 years

PET-Based Backsheets Show Polymer Degradation to Monomers

FTIR of 6 year-old fielded module in Arizona



FTIR of hydrolytically stabilized PET backsheet and standard PET backsheet given accelerated UV-water spray exposure*, compare with unexposed PET backsheet,



Same degradation observed in fielded module and accelerated UV weathering test.
Polymer degradation can lead to cracking, module failure, and a safety hazard.

* ASTM G155 cycle9 (modified), xenon lamp with daylight filter, 120W/m^2 (250-400nm), 65^{o}C BPT, 102min. UVX, 18min. UVX + water spray, 3000 hours total is equivalent to 34 years desert exposure

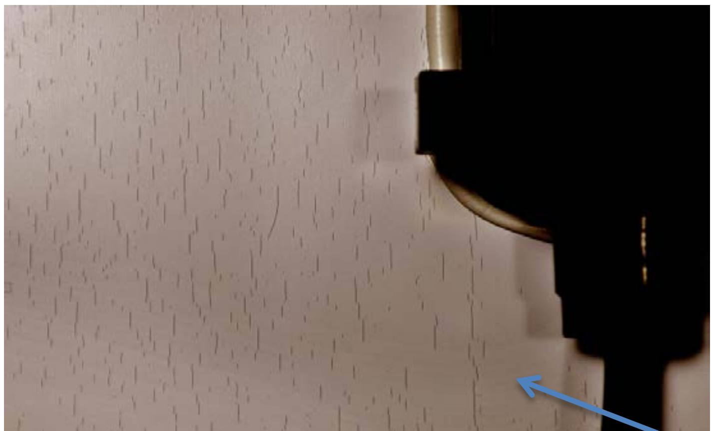
Sequential Stress Testing of Modules

Damp Heat → UVA → Thermal Cycling

DH1000/UVA1000/TC200

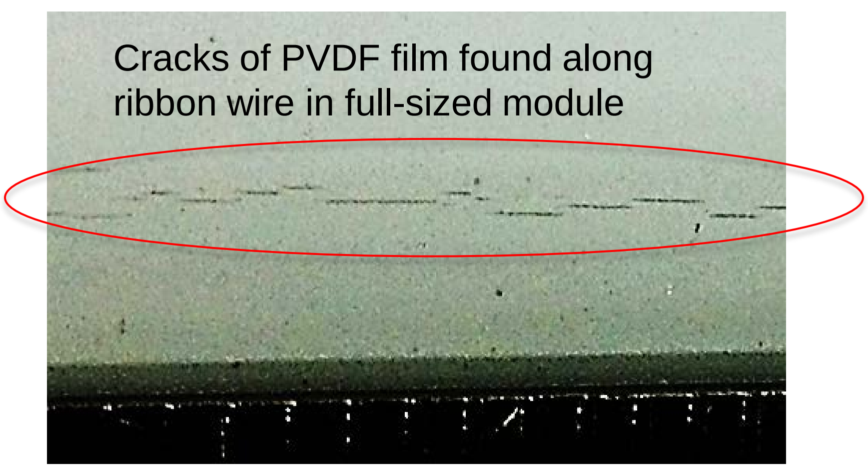
Damp Heat → Thermal Cycling → Damp Heat → Thermal Cycling

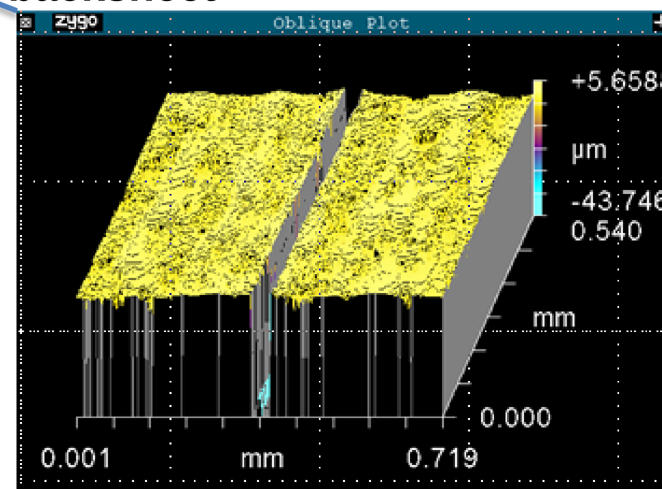
2x(DH1000/TC200)



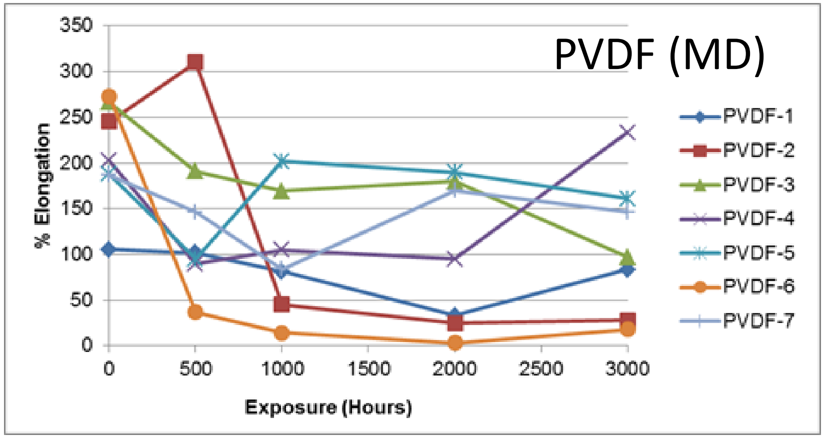
Fine cracking of PVDF layer in PVDF/PET/FEVE backsheet

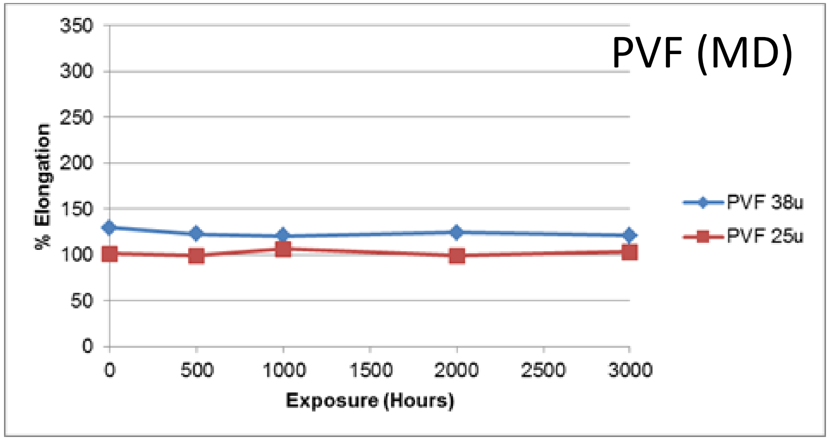
Large cracks in PVDF/PET/FEVE backsheet

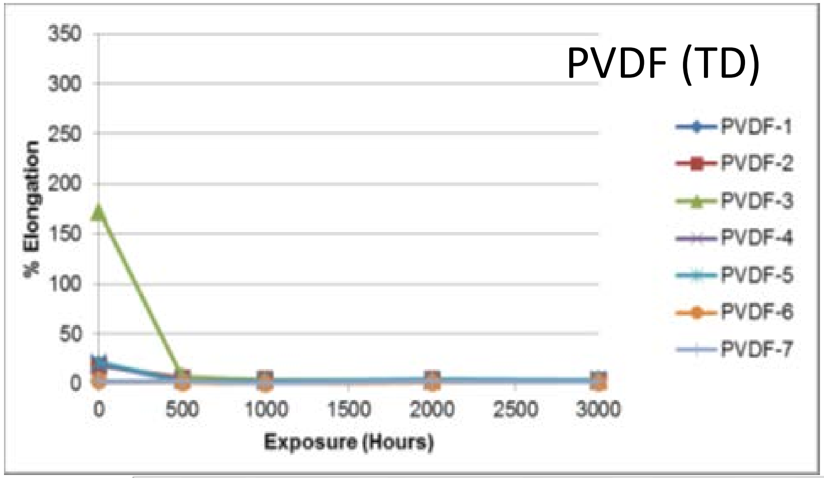


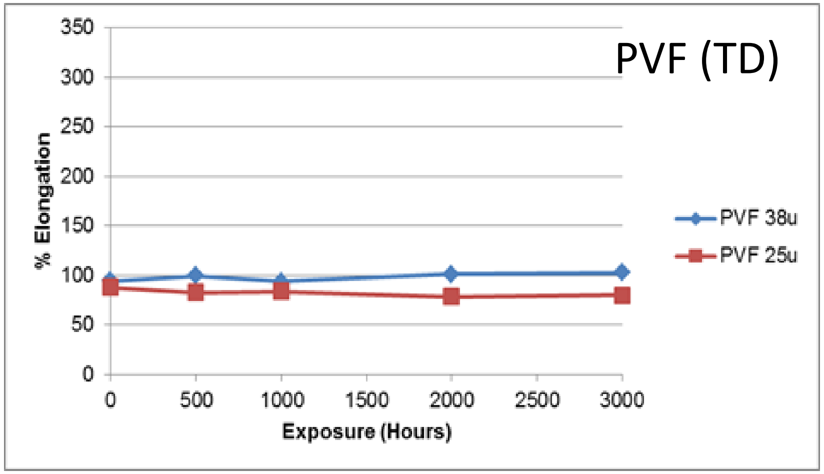


Mechanical Durability of Outer Backsheet Layer May Impact Susceptibility to Cracking





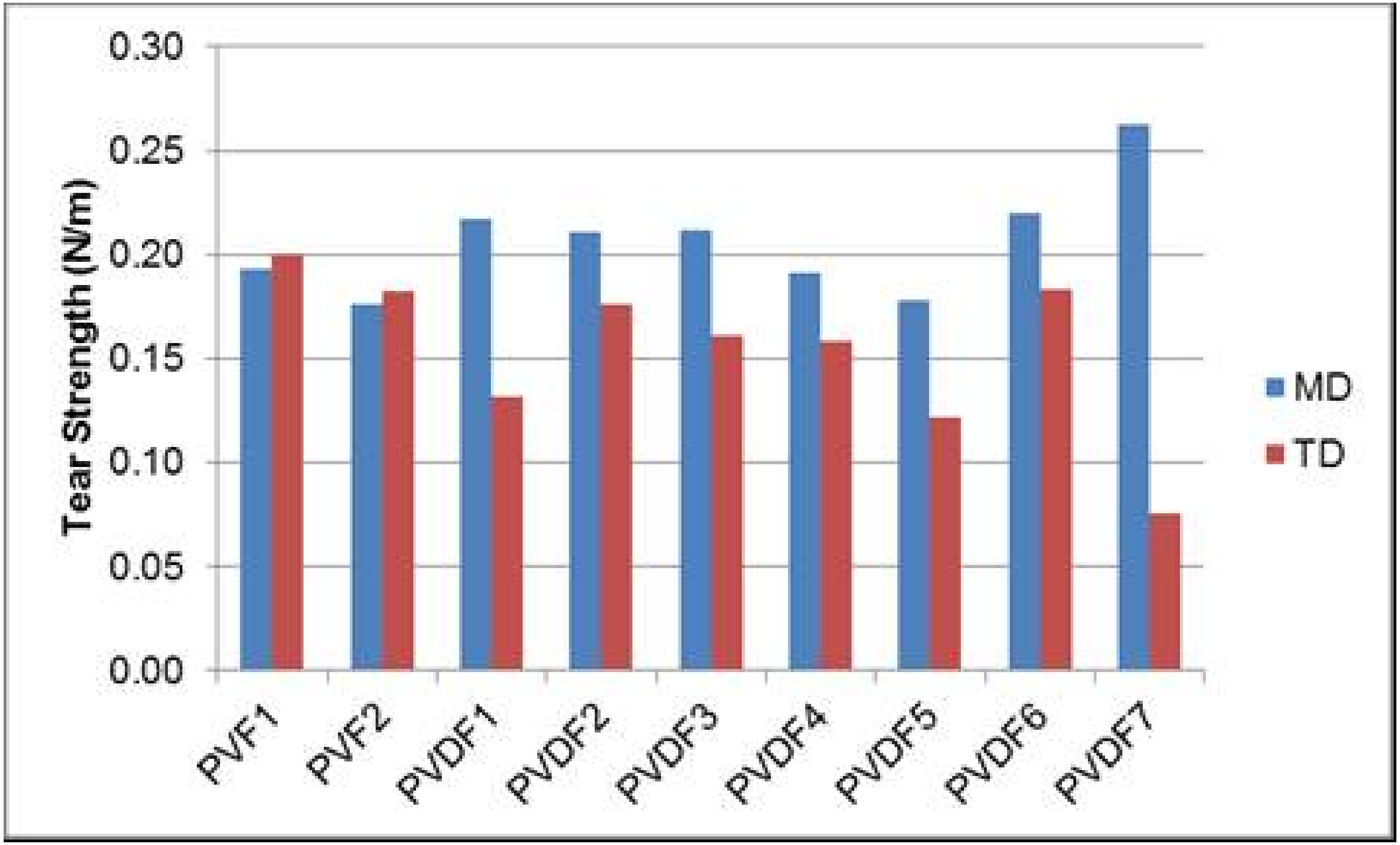




Lower elongation in the TD direction may make PVDF film more vulnerable to cracking and may be responsible for cracking in sequential testing

Test Conditions: DH (85°C, 85%RH)

Tear Strength of Outer Backsheet Layer May Impact Susceptibility to Tear



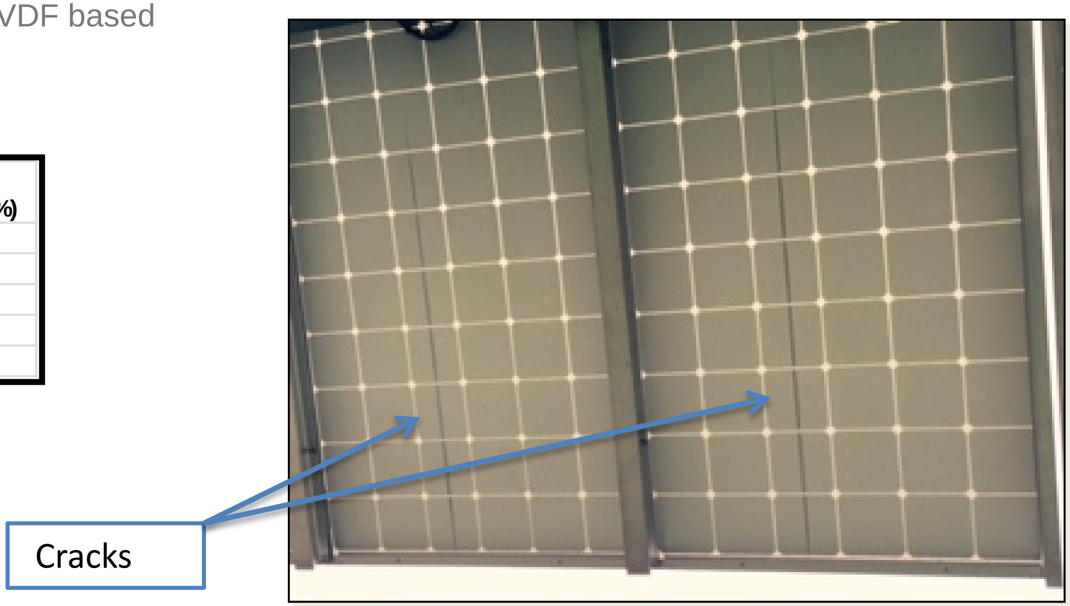
PVDF Field Survey Overview

Initial year of operation	2011
• Service Time	4 years
• Location	North America
• # of modules	48 x 4
• System size	4 x 10 kW
• Mounting configuration	Ground mounted
• Date of inspection	May 15, 2015
• Fixed tilt or tracking	2 axis
• Backsheet:	single sided PVDF based
• Technology	mono

4 Identical 10 kW Installations	Backsheet/Cracking Delamination Percentage (%)
System 1	85.4
System 2	41.7
System 3	20.8
System 4	33.3
Average	**57.2**

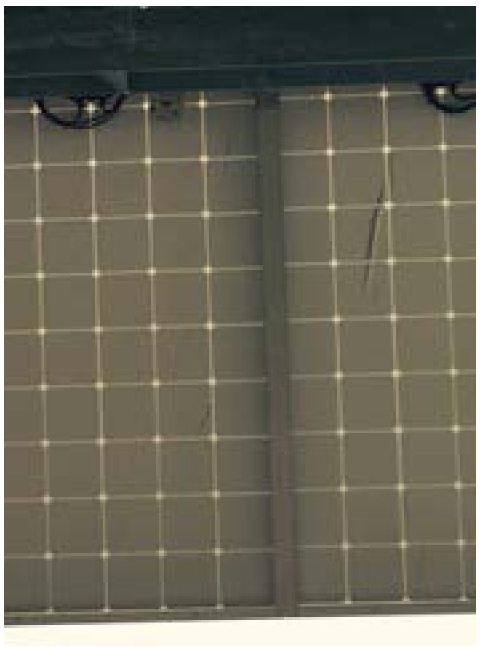
Summary

- Four 10 kW installations surveyed
- Backsheet cracking & delamination ranged from 21% to 85% (avg 57%)
- PVDF outer layer backsheet
- Cracking appears to be uniform and consistent in the vertical or longitudinal direction of the module
- Machine direction of backsheets is typically aligned in the vertical direction of a module



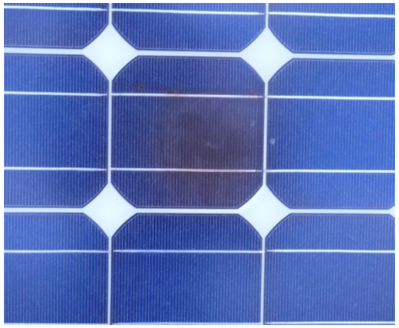
PVDF-Based Backsheet Degradation Sequence

- Initial crack formation followed by tear propagation and subsequent delamination
- Occurs consistently in the vertical direction – machine direction of backsheet



Initial Crack → **Propagation Tear** → **Final Delamination**

Hot Spot Cracking, Yellowing and Softening



PVDF-based backsheet

- Years in service: 5 years
- Location: Spain

PVDF-based backsheet

- Years in service: 7 years
- Location: Israel

Conclusions

- Changes to backsheet materials and construction can have an impact on module durability in the field

- Recommended accelerated test methods including sequential stress testing have been developed to better predict outdoor performance.

- Evaluating modules in the field is an effective approach to better understand degradation methods and to validate new test methods.

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