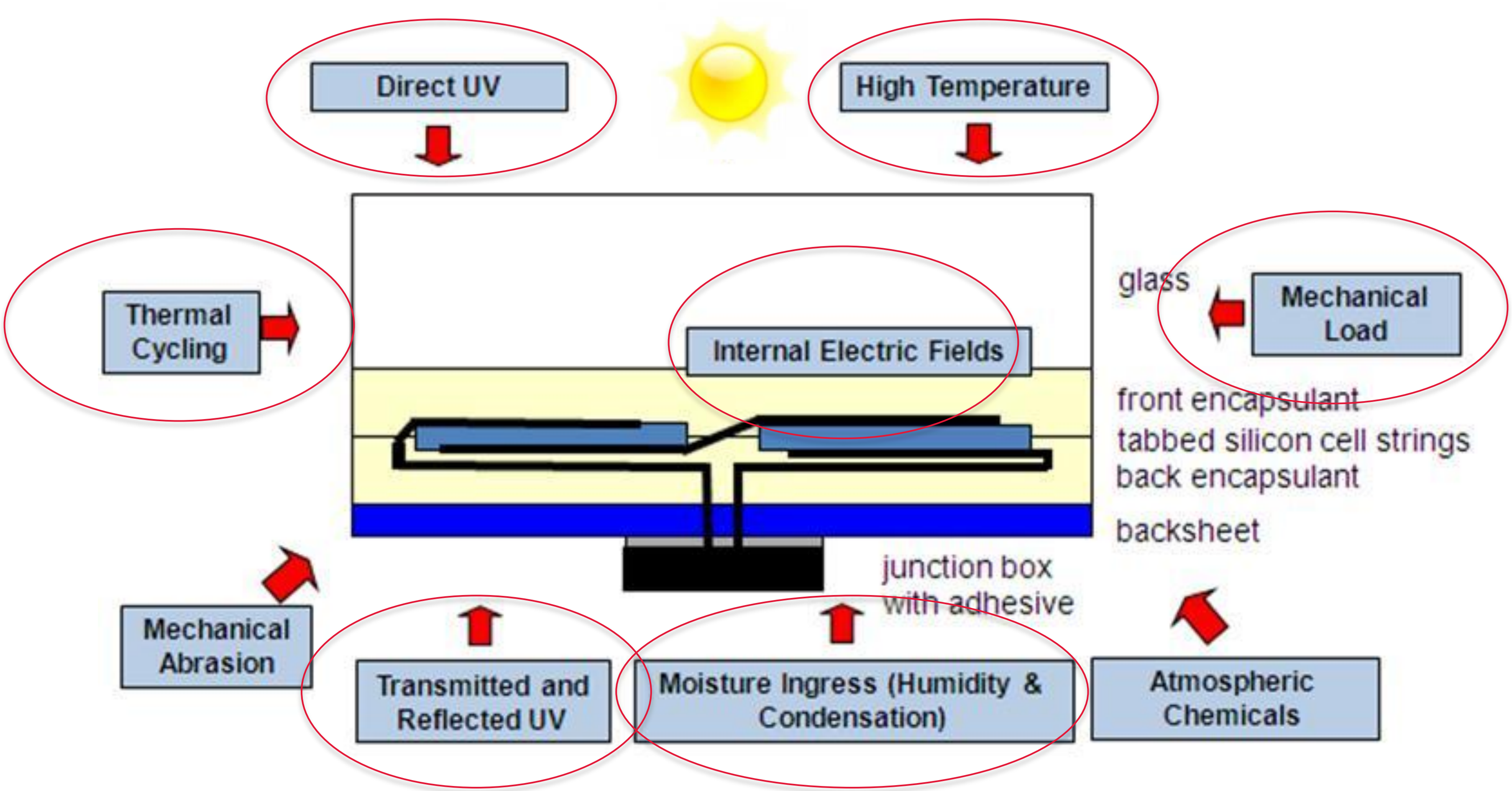
Sequential and Weathering Module Testing and Comparison to Fielded Modules

NREL PV Module Reliability Workshop 2015

W. Gambogi[1], J. Kopchick[1], T. Felder[1], S. MacMaster[1], A. Bradley[1], B. Hamzavytehrany[1], C.-F. Wang[2], H. Hu[2], Y. Heta[3], Lucie Garreau-Iles[4] and T. J. Trout[1]

(1) DuPont, Wilmington, DE, USA; (2) DuPont (China) Research& Development and Management Co., Ltd., Shanghai, P.R.C., (3) DuPont K.K., Utsunomiya, Japan; (4) Du Pont de Nemours International S.A., Geneva, Switzerland

Environmental Stresses in the Field



- Photovoltaic modules are exposed to a wide range of stress conditions
- Stresses operate on the module simultaneously and sequentially; synergistic effects are observed

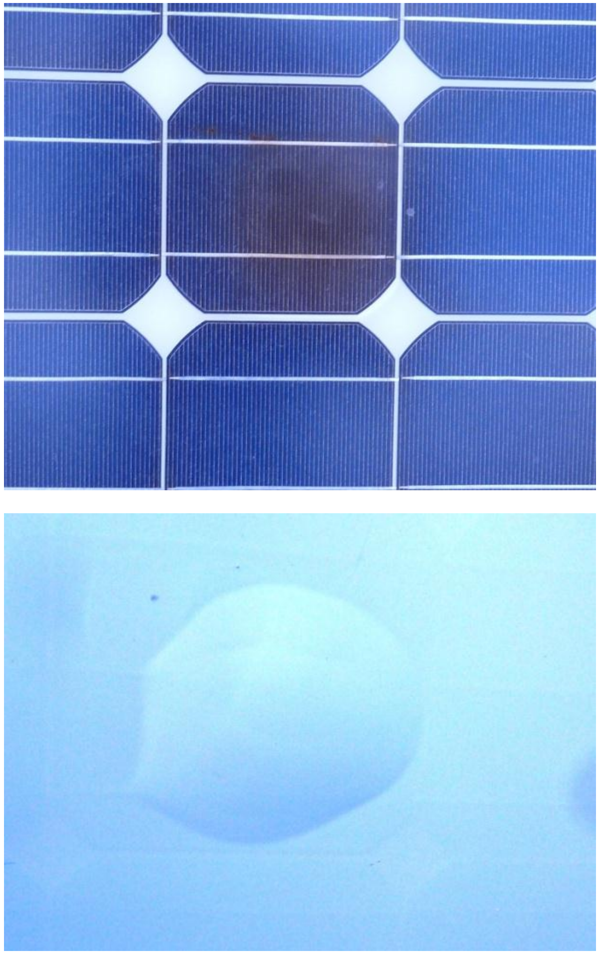
Fielded Module Studies

- Inspected modules in the field ranging from newly commissioned to 30 years installed
- Developed inspection protocols and analysis tools to assess composition and failure modes
- Developed module sampling and materials analysis methods
- Goal is to better understand the relationship of materials properties and field performance with accelerated testing

Summary of Observations from the Field

- Adhesion loss and delamination
- Outer layer backsheet cracking and yellowing
- Inner layer backsheet yellowing
- Hot spot cracking, yellowing and softening
- Outer layer yellowing on rooftop system

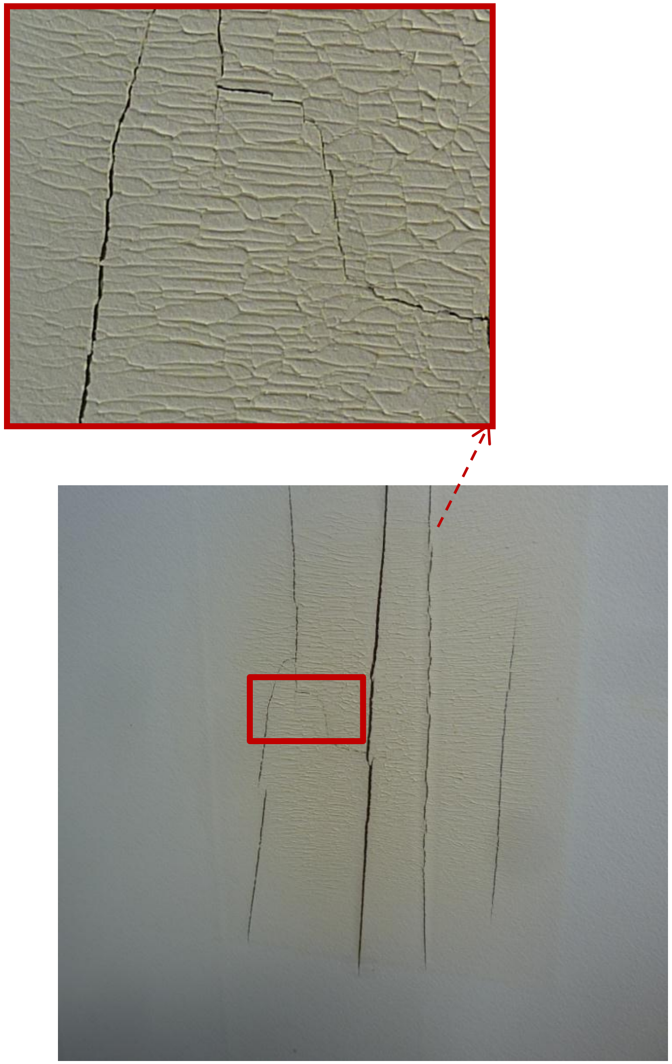
Field Studies: PVDF-Based Backsheets with Hot Spots & Delamination



Hot spot/cell causing delamination of PVDF-based backsheet on module in Spain

Additional examples of delamination on PVDF-based backsheet from hot spots in modules in Israel

Field Studies: PVDF-Based Backsheet with Yellowing and Cracking



PVDF-based backsheet from module in Spain

- Module removed from service
- Cracking & yellowing

Polyester-Based Backsheet Cracking After 4 years

Crack in backsheet exposing tabbing ribbon and potential electrical leakage path

Field Studies: Yellowing and Cracking of PET-Based Backsheets in Rooftop Application

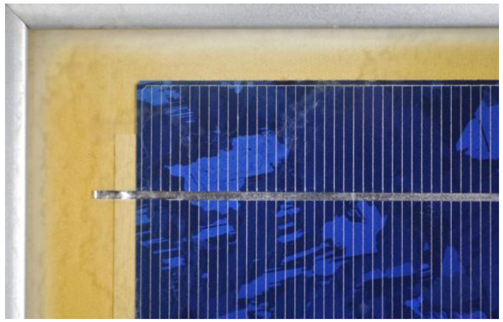
- PV array (12 modules) mounted on a metal corrugated rooftop of the commercial building for 15 years with ~150mm from corrugation to back of the solar panel
  - Outer PET layer cracking and brittle
  - High level of yellowing
  - Highest levels of yellowing near the edges of the array
- Other examples of PET-based backsheet yellowing, delamination and embrittlement have been previously described and examples from the field given

UP6						UP5						UP4					
27	26.1	25.9	26.4	25.8	25.5	24.9	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	24.8	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	24.1	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	21.9	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	19.5	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	16.7	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	18.4	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
Down6						Down5						Down4					

UP3						UP2						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
Down3						Down2						Down1					

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

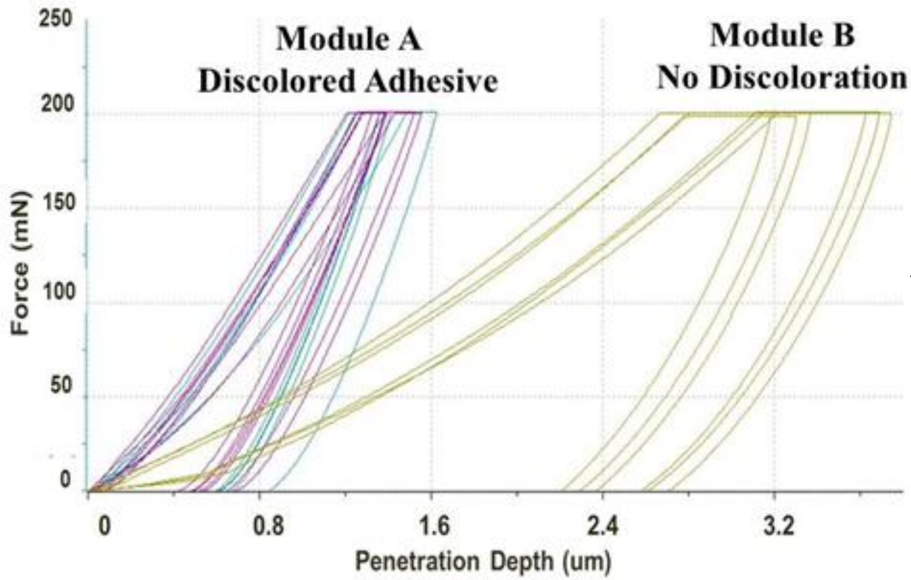
Field Studies: PVDF-Based Backsheet Frontside Yellowing



- Frontside yellowing observed in:
  - 5 different countries (Belgium, Spain, USA , Israel, and Germany)
  - Modules less than 5 years in the field
  - 5 different manufacturers

Gambogi et al., EUPVSEC 2013, Paris

Nano-indentation of inner layer of backsheet



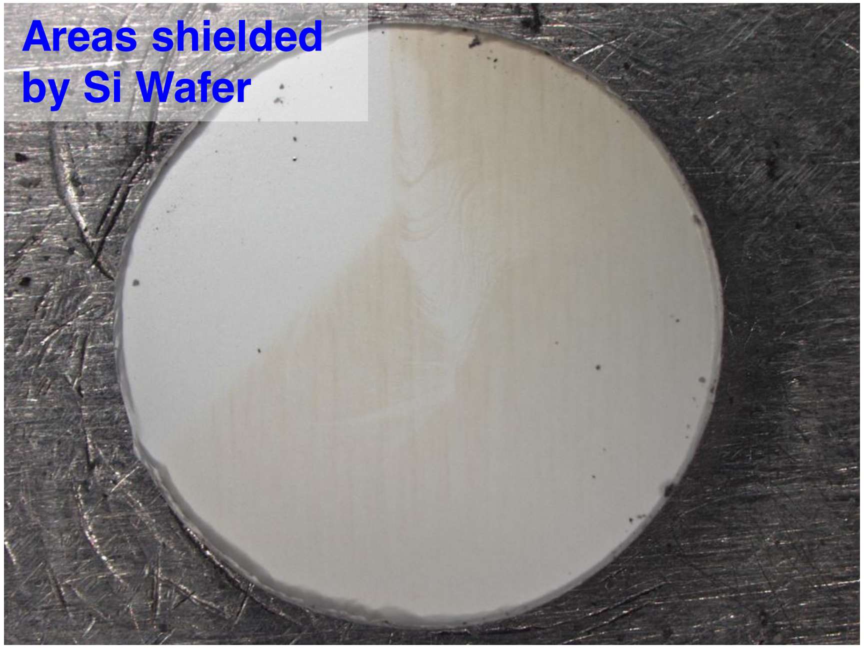
Embrittlement associated with yellowing of inner layer

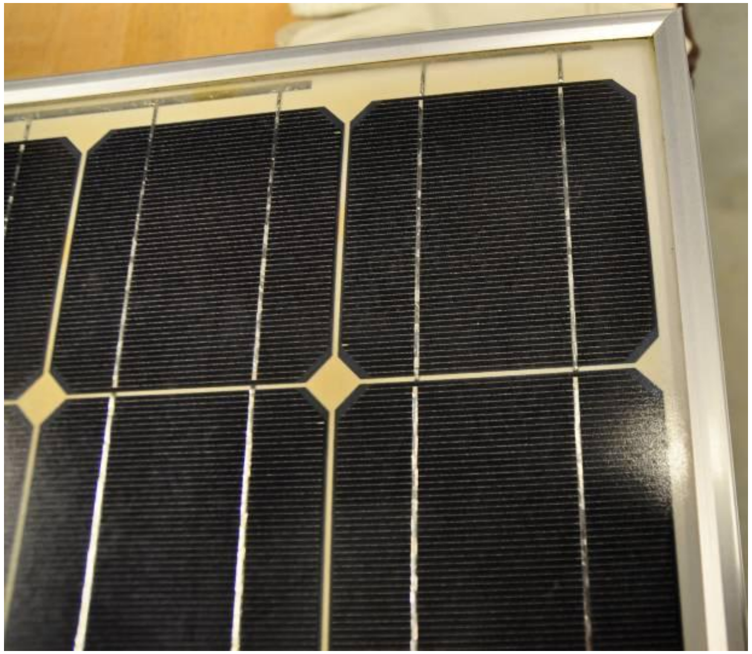
Stika et al., IEEE PVSC 2014

PET Inner Layer Discoloration

Area below cell has not discolored, indicating UV contributed to inner layer PET yellowing

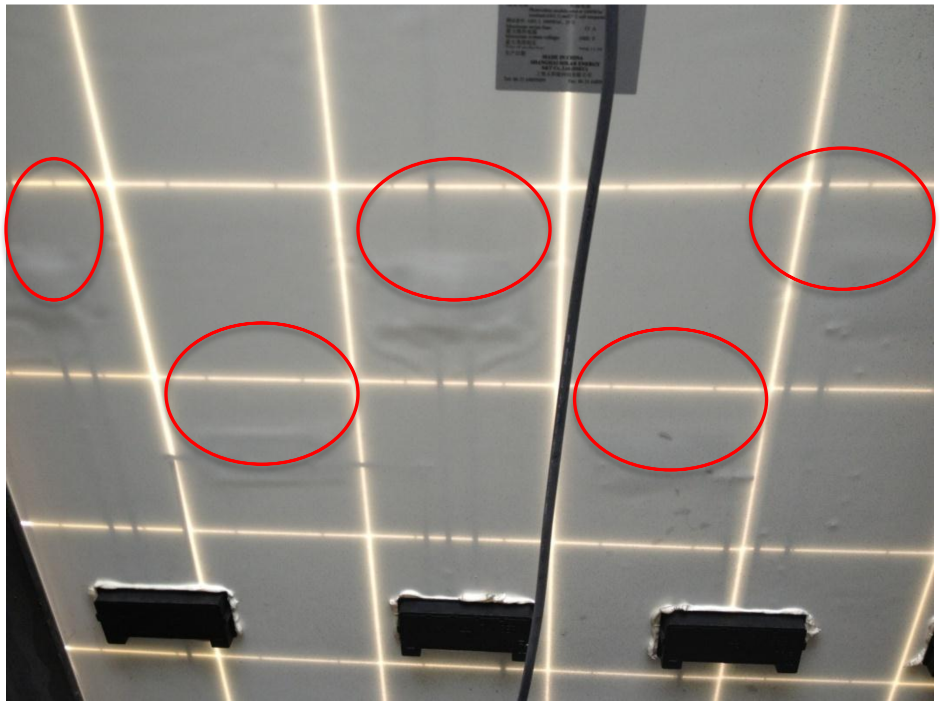
4 years in field, 100% discoloration found in typical commercial/industrial systems (250-750 kW) both rooftop and ground mount, USA



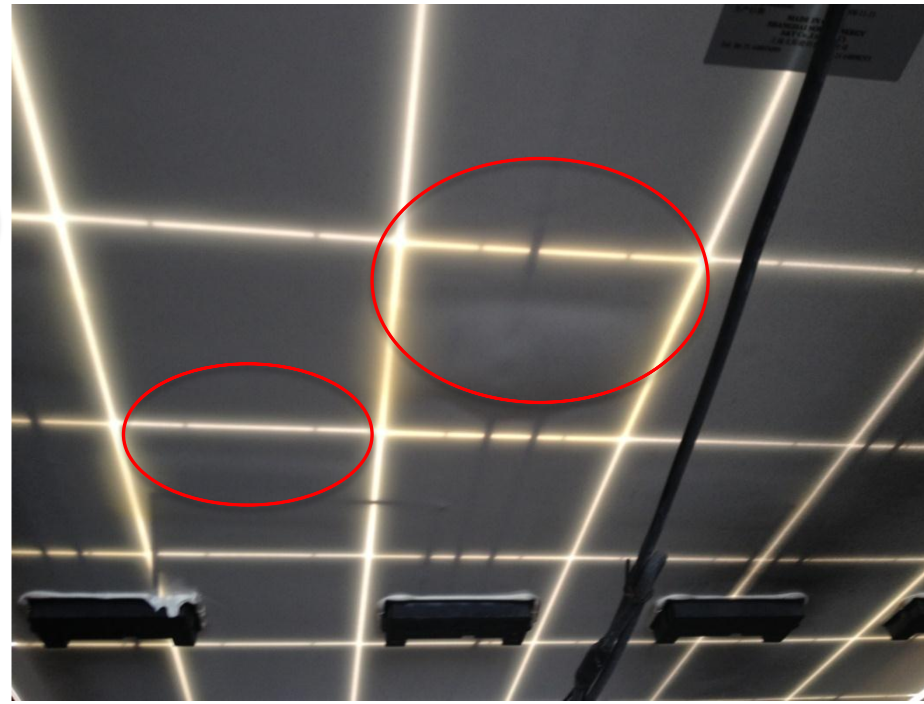


Rooftop Array, FEVE (5 years, Shanghai), >30% modules

Large amount of delamination



Bubbling and yellowing



	Control FEVE-based coated backsheet, no field exposure	FEVE backsheet samples with 5 years field exposure in Shanghai	Change
b* value (color)	0.04	2.57	**2.53**
60^{O} Gloss change	70.2	44.9	**25.3**

Shortcomings of Current Qualification Tests

- Current IEC qualification standards were designed to identify early failures due to module design; does not predict long-term durability
- IEC qualification standards do not adequately address durability of materials to UV exposure and weathering
- UV and weathering tests are not applied to modules due to the equipment challenges associated with large area UV and weathering exposure
- IEC qualification conditions do not address synergistic effects of multiple stresses in the field
- We propose sequential testing using damp heat (DH), thermal cycling (TC) and UV exposure (UVA) to better predict long term outdoor performance

DuPont Accelerated 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/m²-nm at 340nm, ~60 W/m² (300-400nm)	275 kWh/m² (4230 h)	desert climate (25 year equivalent)
		235 kWh/m² (3630 h)	tropical climate (25 year equivalent)
		171 kWh/m² (2630 h)	temperate climate (25 year equivalent)
UV (Encapsulant Side)	UV, 70°C BPT, 1.1W/m²-nm at 340nm, ~120 W/m² (300-400nm), glass/EVA/EVA filter, std. EVA and UV transmissive EVA	550kWh/m² (4600 h)	desert condition (6 - 16 year equivalent)
		550 kWh/m² (4600 h)	tropical condition (7 - 19 year equivalent)
		550 kWh/m² (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/m² (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; assumes a 12% albedo exposure on junction box side
- Damp heat testing to 1000 hours is more than sufficient for PET hydrolysis damage of backsheets over 25 years of outdoor exposure

Basis for Sequential Exposure

- Outdoor environment has multiple stresses operating throughout PV module service life
- DH1000 (85C, 85%RH, 1000h) is considered to be >25 years equivalent in the harshest climate, based on NREL model
- UVA1000 (UVA, 65W/m2, 300-400nm, 1000h) is estimated to be ~ 6 years equivalent exposure on the backsheet side of a module
- TC200 (-40C, 85C, 200 cycles) is a standard thermal stress condition in qualification and recent recommended changes propose extension to multiple exposures
- Sequential DH and UVA exposure results in materials degradation similar to the field; thermal cycling creates mechanical stresses similar to those experienced by modules in the field

Recommended Sequential Tests

Damp Heat → UVA → nX (Thermal Cycling → UVA)

Backsheet or Modules

Backsheet Yellowing, Cracking

Damp Heat → nX (Thermal Cycling)

Full-size Laminates or Module

Backsheet Cracking

UVX → Water Spray

Backsheets: weathering (Xe), 102m light, 18m light + water spray
Module: resistive loading, weathering exposure (above)

Backsheet Yellowing, Mechanical Loss
Module: Power Loss

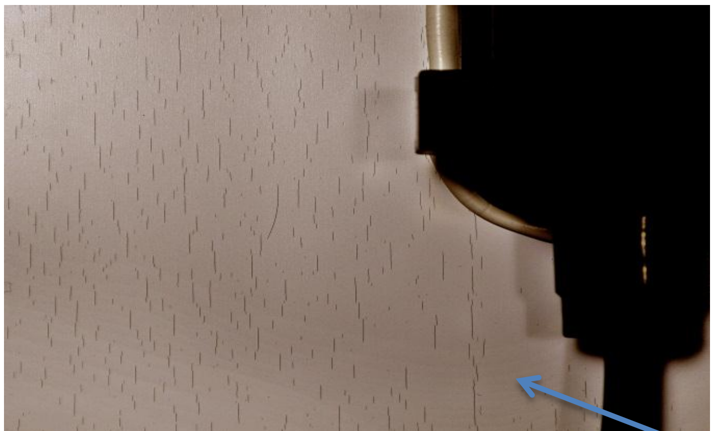
Sequential Stress Testing of PVDF/PET/FEVE

Damp Heat → UV → Thermal Cycling

DH1000/UVA1000/TC200

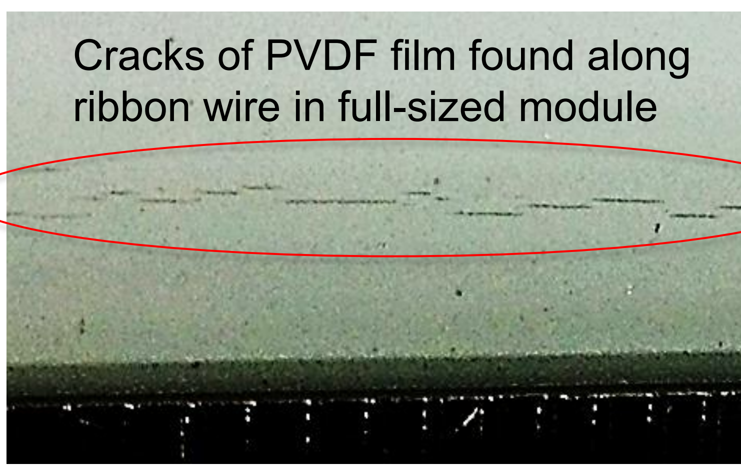
Damp Heat → Thermal Cycling → Damp Heat → Thermal Cycling

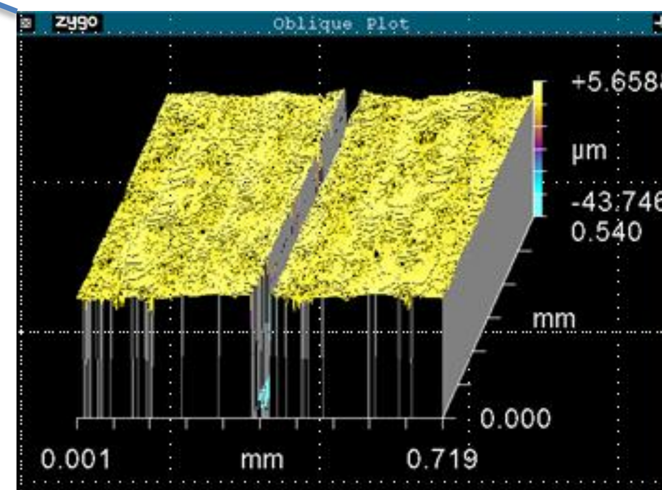
2x(DH1000/TC200)



Fine cracking of PVDF layer of 1s PVDF-based backsheet

Large cracks in 1s PVDF-based backsheet





Sequential Testing of Full-Size Module Format

Full-Size Framed Laminate (glass/EVA/EVA/backsheet)

Backsheet	***DH1000***	***TC200***	***TC400***
1s PVDF1	OK	cracks	more cracks
1s PVDF2	OK	OK	minor cracks
1sPVDF3	OK	OK	many cracks
TPT	OK	OK	OK
TPE	OK	OK	OK

Backsheet	***DH1000***	***TC50HF10***	***2x(TC50HF10)***
1s PVDF1	OK	OK	cracks
1s PVDF2	OK	minor cracks	minor cracks
1sPVDF3	OK	OK	few cracks
TPT	OK	OK	OK
TPE	OK	OK	OK

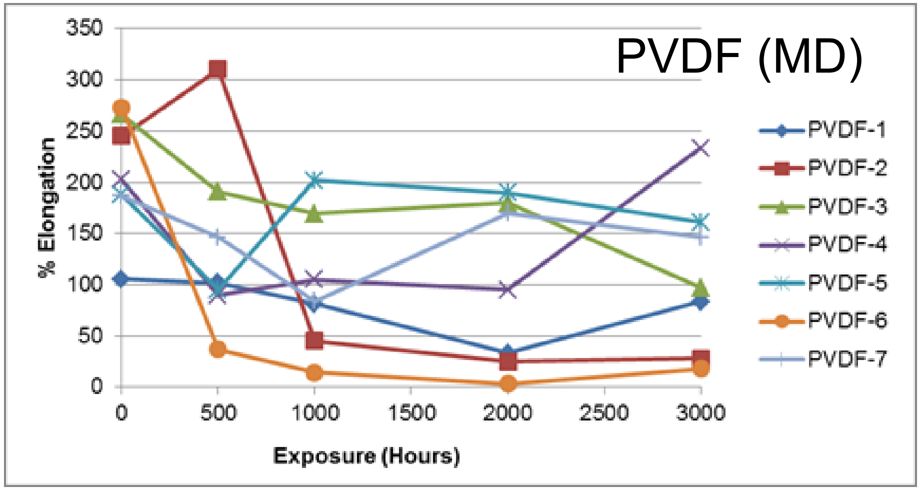
Full-Size Module (DH1000/UVA1000/TC200)

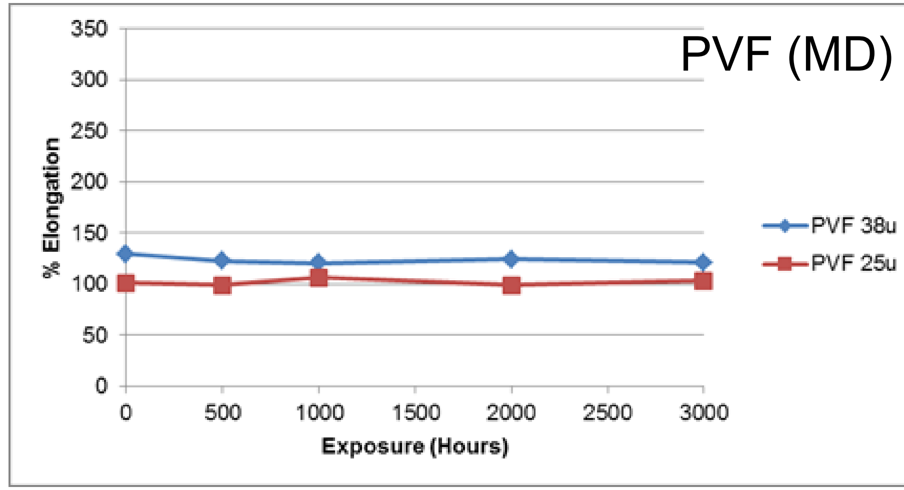
Backsheet	***DH1000***	***UVA1000***	***TC200***
1s PVDF	OK	OK	cracks*
1s PVF	OK	OK	OK

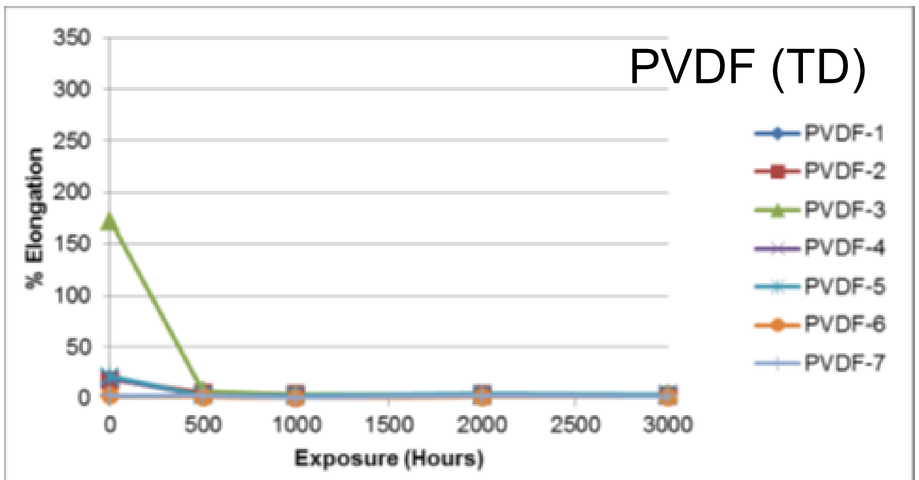
TPT: Tedlar® PVF/PET/Tedlar® PVF
TPE: Tedlar® PVF/PET/primer

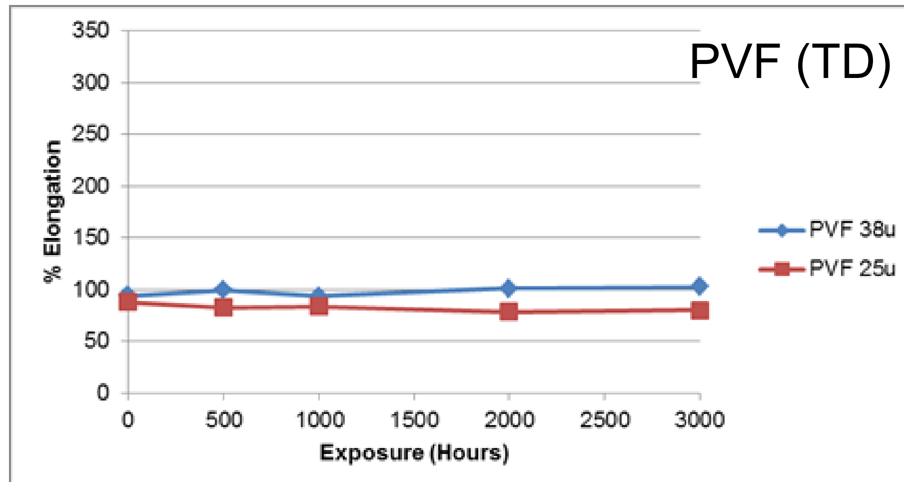
* Cracks were along all back busbar ribbons on the module using 1s PVDF-based backsheet

Mechanical Stress: PVDF Films Have Low TD Elongation and Get Brittle after Damp Heat Aging







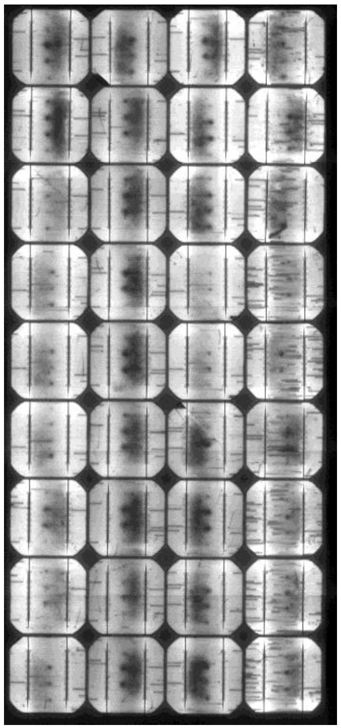


Lower elongation may make PVDF film more vulnerable to cracking

Test Conditions: DH (85°C, 85%RH)

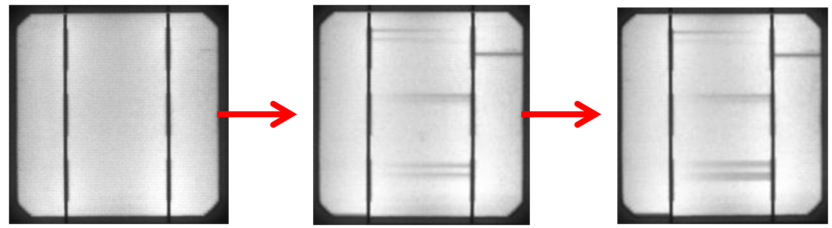
Loaded Module Weathering Compared to Field and Other Tests

Field



- Age: 15 years ,ΔP: -1.2%/yr

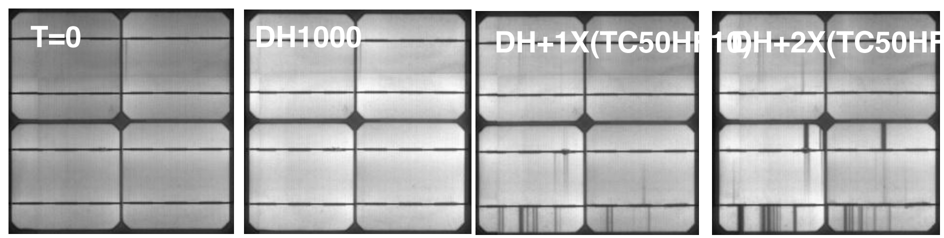
Load Module Weathering (DH500, WOM)



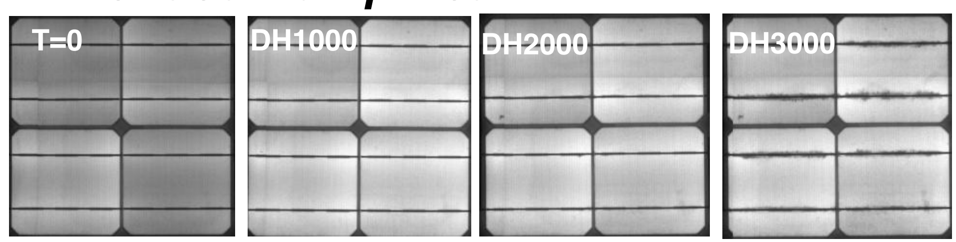
DH500 | 150 kWh/m2 UV | 180 kWh/m2 UV

- 25y desert exposure ~2290 kWh/m2 UV

Sequential (DH1000, TC/HF)



Extended Damp Heat



- Fine line degradation seen in fielded modules
- Similar to what is observed in loaded module weathering and sequential tests
- Not observed in extended damp heat

Conclusions

- Field inspections and fielded module analysis are key to fundamentally understand of PV component performance and durability

- Multiple stress testing is critical to understanding the interaction and synergistic effects of outdoor exposure

- Testing of full-size modules and laminates provides new insights into the performance and durability of component materials in the PV module

- Future directions include assessment of unaddressed stresses in the field, shortening accelerated test protocols and improved correlation photovoltaics.dupont.com

DUPONT®

The miracles of science™