Durability of Packaging Material in Globally Fielded PV Modules

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Dec 2019

DuPont global field reliability program

- Quantitative analysis: components, materials, age, failure modes
- Post-inspection analytical characterization
- Collaborative: field partners, developers, government labs, universities

Improved accelerated tests and informed materials selection

6.5 M
modules

355
Installations

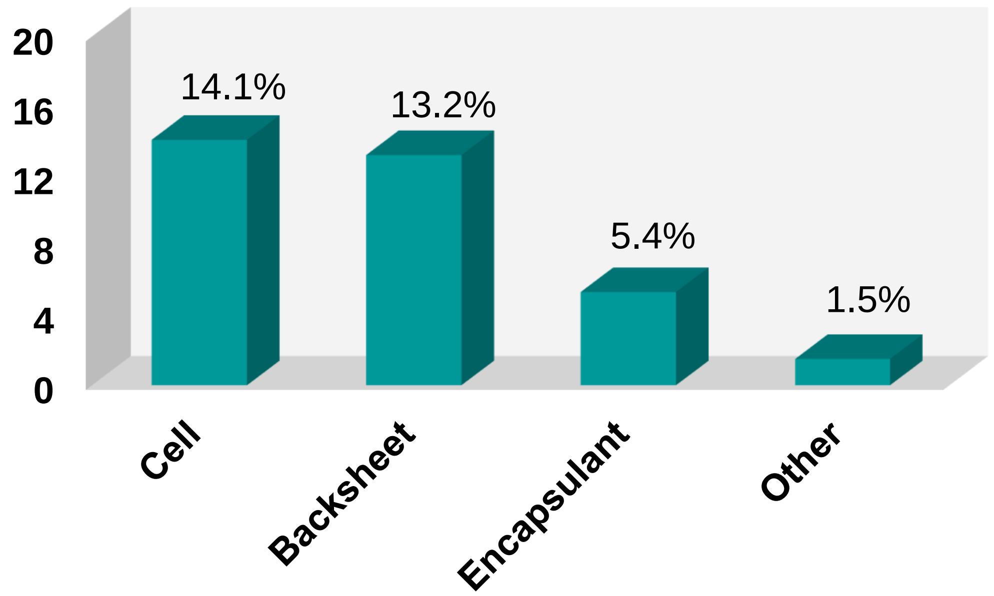
1.8 GW
modules

DUPONT

2019 tends in globally fielded PV modules

- Nearly **2 GW** of fields inspected
  - Total module defects observed: >25%
  - Total backsheet defects observed: 13%
  - ~50% year-over-year increase in BS defects
  - Cracking constitutes 66% of all backsheet defects

Module Defects



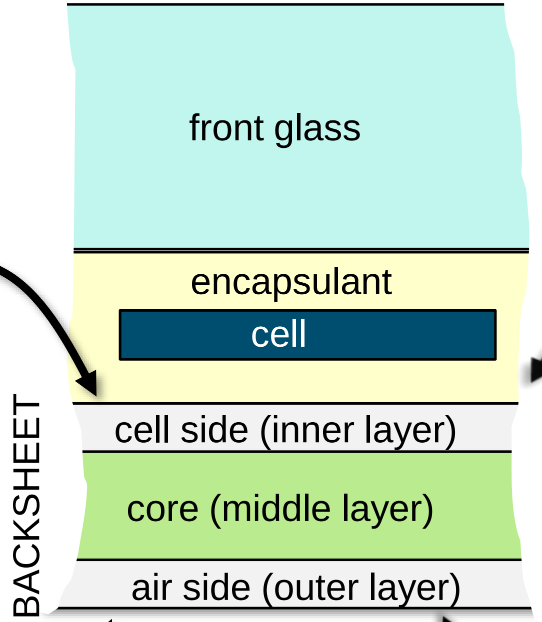
Cell / Interconnect: corrosion, hot spot, snail trails, broken interconnect, cracks, burn marks
Backsheet: outer layer (air side) and inner layer (cell side) cracking, delamination, yellowing
Encapsulant: discoloration, browning, delamination
Other: glass defects, loss of AR coating, junction box

Backsheet defects by degradation mode

Cell-side Yellowing (31%)

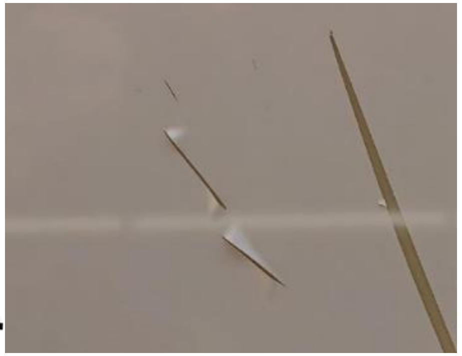
Air-side Yellowing (4%)

Module cross section



Cell-side Cracking (22%)

Air-side Cracking (41%)



Delamination (3%)

Cracking and delamination can compromise electrical insulation of the module

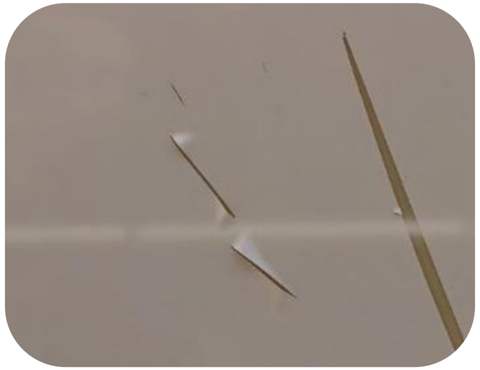
Yellowing can be a precursor to mechanical degradation and embrittlement of many backsheet polymers

Backsheet characterization tools

Air-side discoloration/gloss

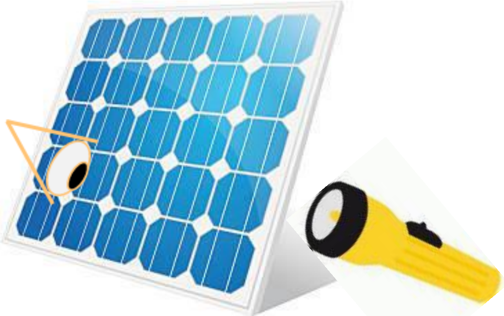
- Gloss meter (reflectance)
- Colorimeter (L a b*)
- Chalking strips (transmission)

Air-side Cracking



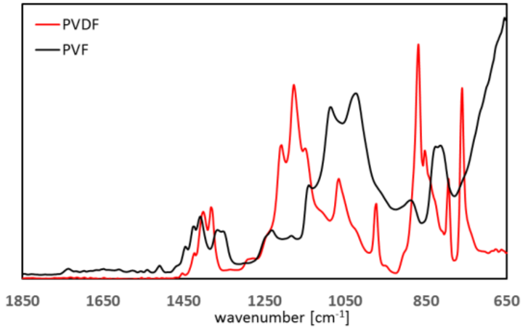
Visual inspection with direct and grazing angles
- Scratches
- Cracks/crazes
- Delamination
- Ripples

Cell-side Cracking



Illumination from front or rear
- Prominent near busbars
- Often coupled with corrosion of circuitry
- Implicated in shorts to ground

Materials Identification



Degradation modes of PV backsheets

Outer layer (air side) cracking

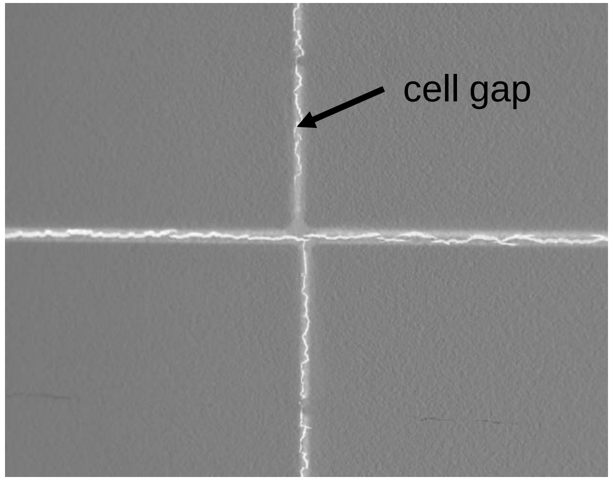
Cracks expose interior layers/encapsulant to moisture and UV light

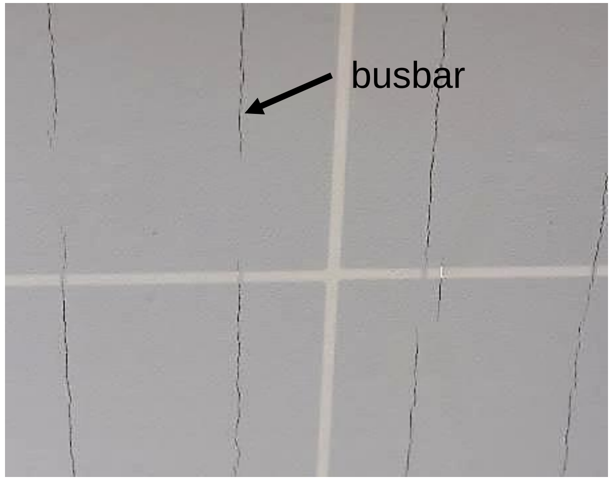
- PET core layer often not stabilized, may crack
- direct moisture pathway facilitates interface delamination

Observed over broad range of climates and materials

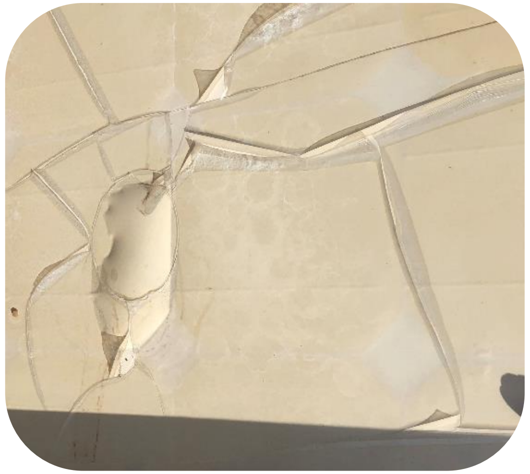
- Mediterranean, temperate, hot/cold deserts, hot/humid
- encountered in PET, polyamide-based, PVDF-based backsheets

Through-cracks along tabbing ribbons and cell gaps, 6 years, Sonoran Desert

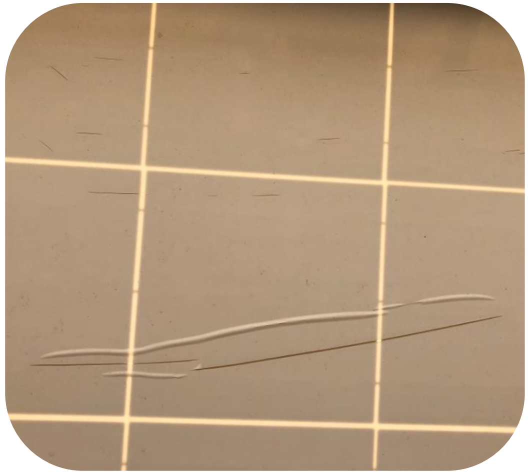




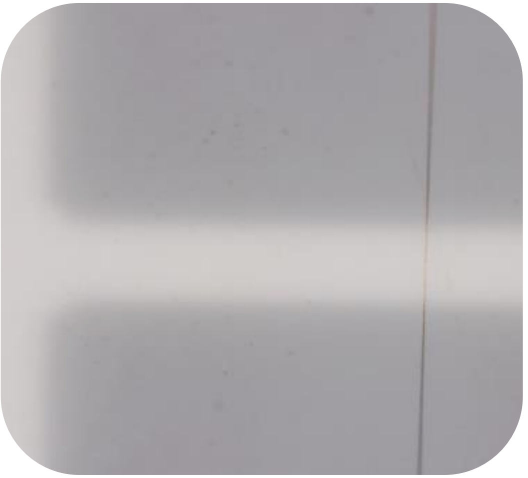
16 years, Arizona high desert



7.5 years, India



6 years, NW China desert

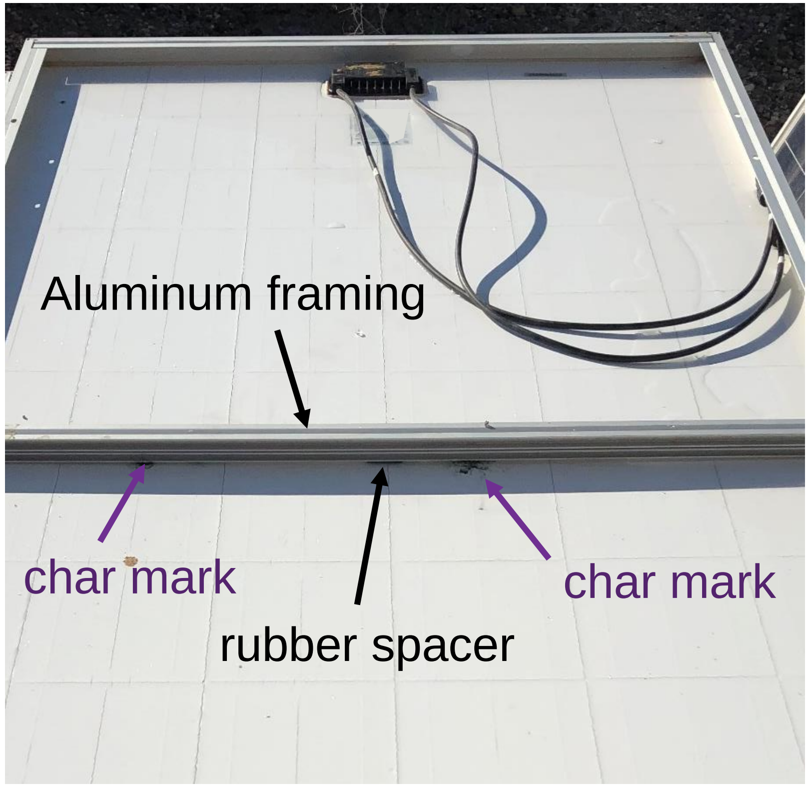


Implications of outer layer cracking

- prevalent along busbar ribbons, but extends to cell gaps and other regions with continued weathering
- corrosion, shorts, and arcing lead to localized melting/scorning and potentially full module fires
- reported inverter tripping and ground faults

7 years, Sonoran Desert, USA

6 years, Sonoran Desert, USA



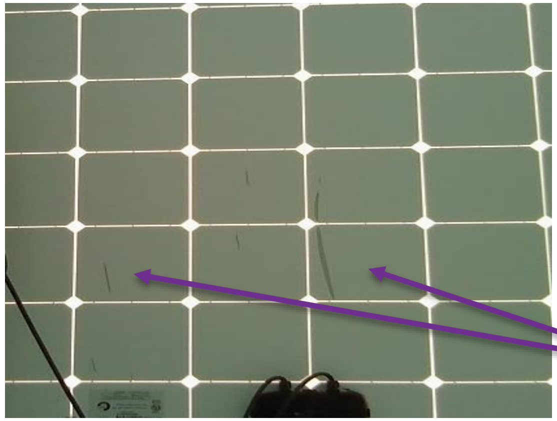
Rapid damage progression of outer layer

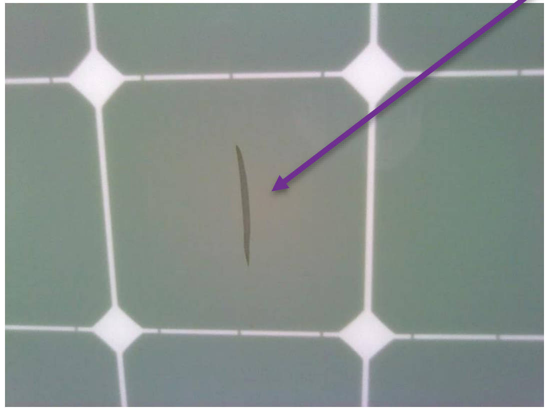
Initial inspection: 4 yrs, Canada

- 10% of modules exhibit cracking

Reinspection: 6 years, Canada

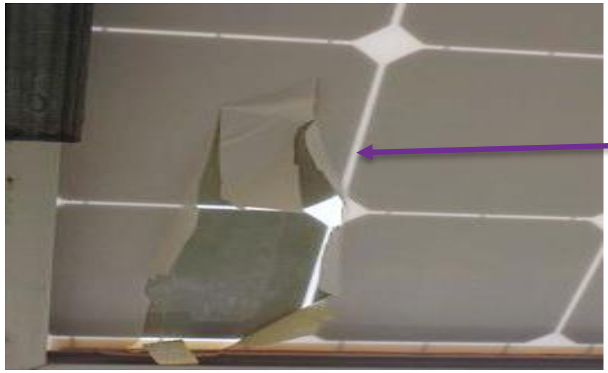
- 40% of modules exhibits widespread cracking, delamination



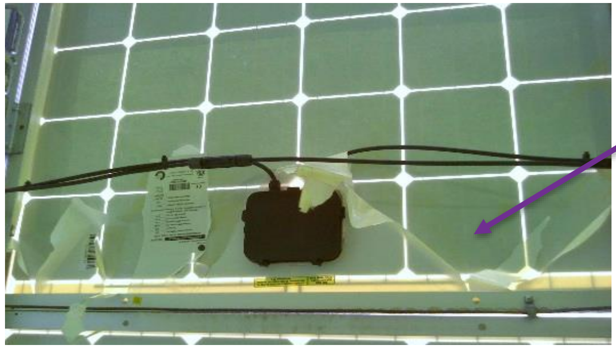


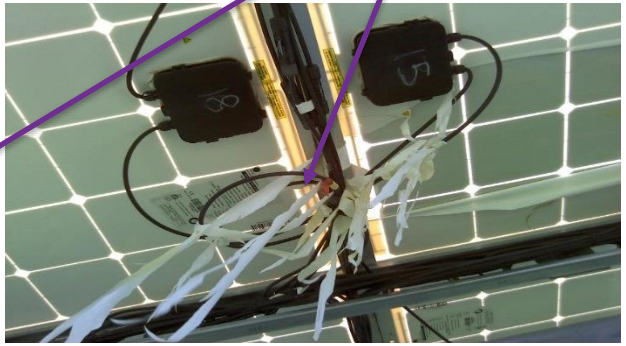
Cracked outer layer

2 yrs



Cracks evolving into delamination



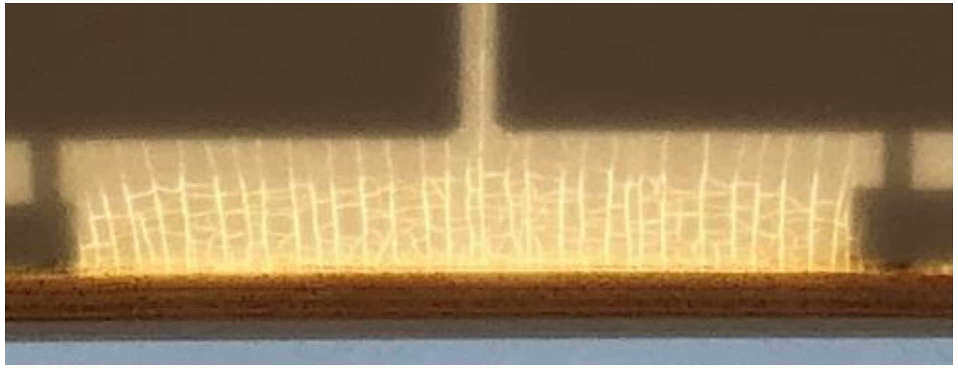


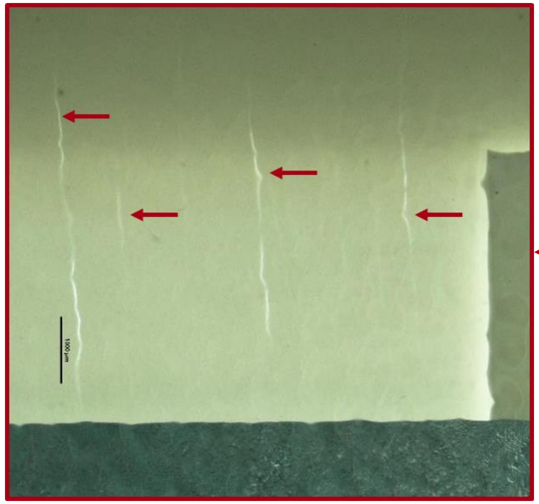
Remains of backsheet outer layer

Inner layer (cell side) cracking

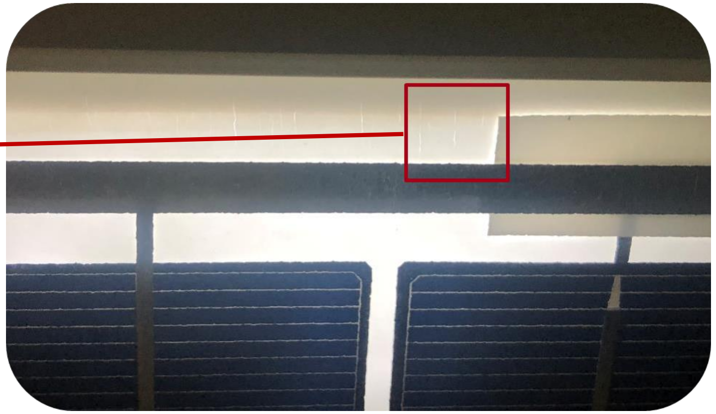
- Inner (tie) ayer often an EVA (low VA content)/polyolefin material
    - usually encountered in backsheets composed of FEVE or PET-based outer layers
- Not always readily visible by eye; may require backlit illumination
- Often originate at/near busbar: corrosion can be visual cue

7 years, Sonoran Desert, Arizona

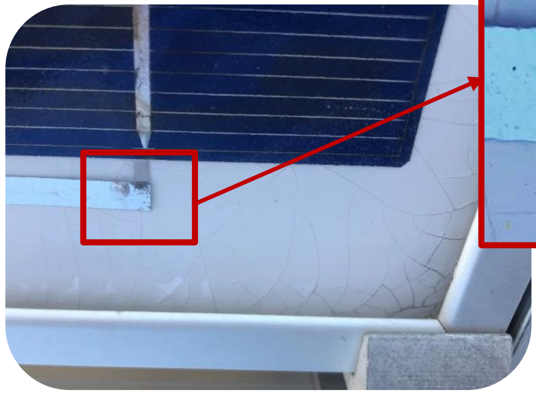




Cracking under backlit illumination,
7 years, Arizona high-desert



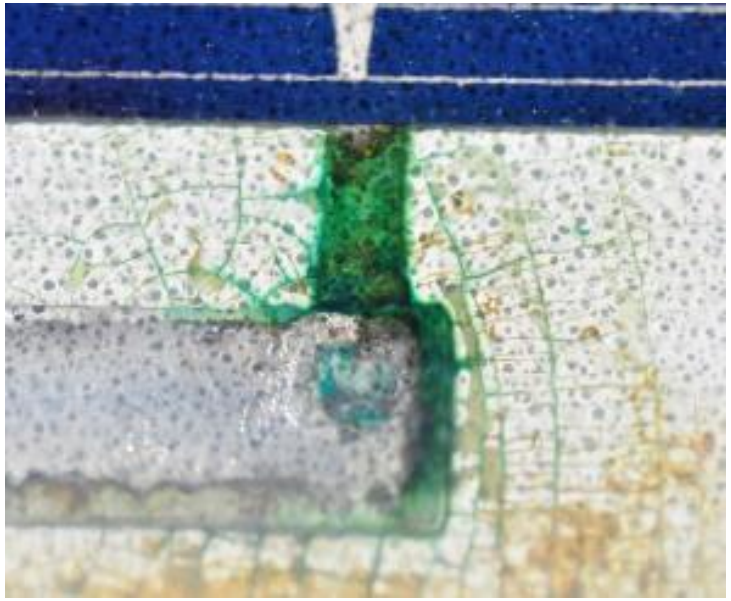
8 years, rooftop,
Phoenix, Arizona

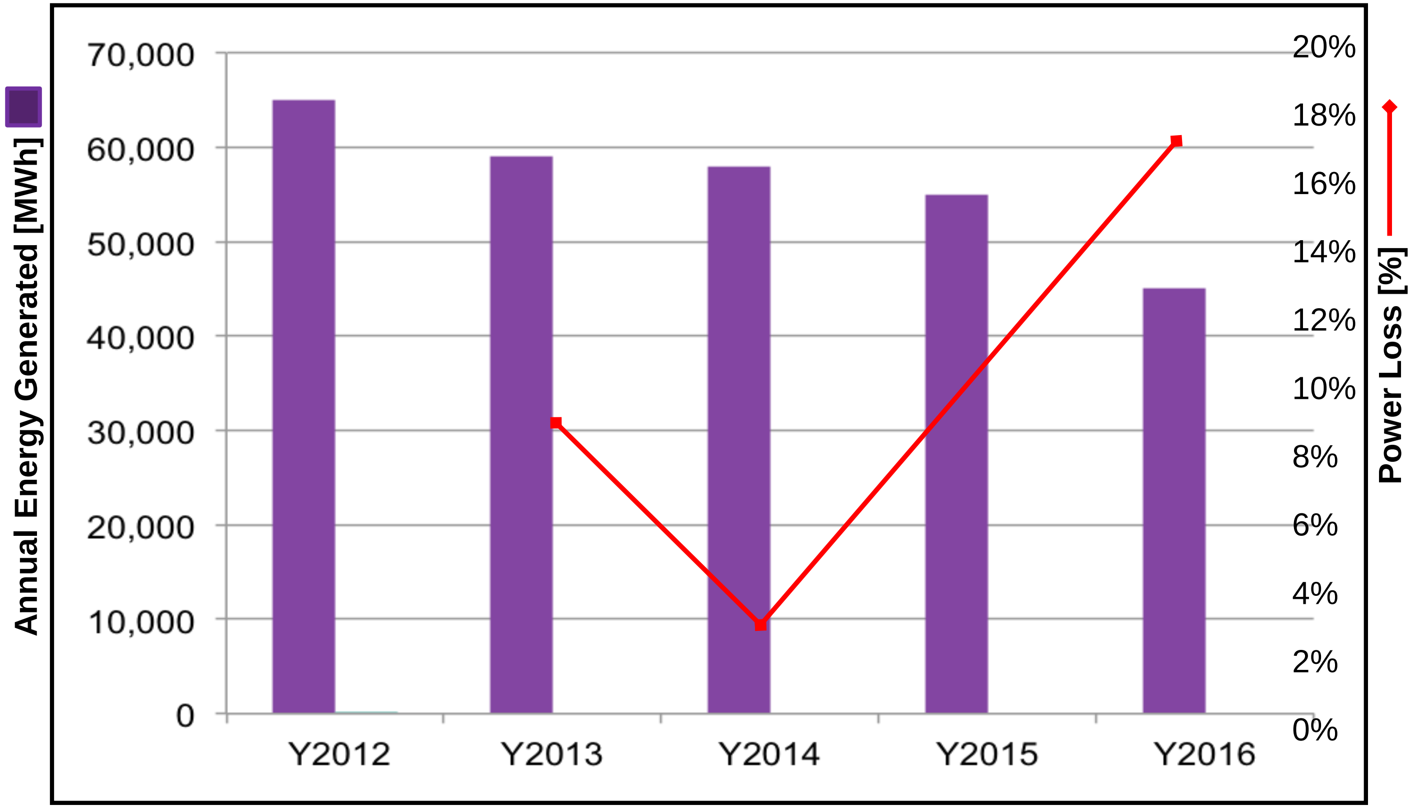


Implications of inner layer cracking

- facilitate moisture ingress, often leading to busbar corrosion
- exposure of module interiors to moisture may lead to shorting, inverter trips, power loss, module fires
- correlation between power loss and inner layer cracking

Corrosion of busbar/tabbing ribbon





Backsheet discoloration

- Generally observed in outer layer, inner tie layer, and/or interface adhesives of various backsheets
- Implications: yellowing may be an early indicator of material degradation and embrittlement
- Observed in diverse climates

Inner layer yellowing

6 years, SW USA

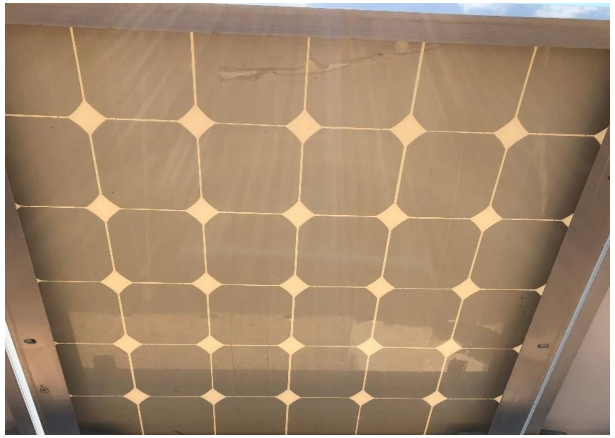
6 years, NW China

7.5 years, Italy

5 years, India

Outer layer yellowing

PET, 16 years, Arizona high desert



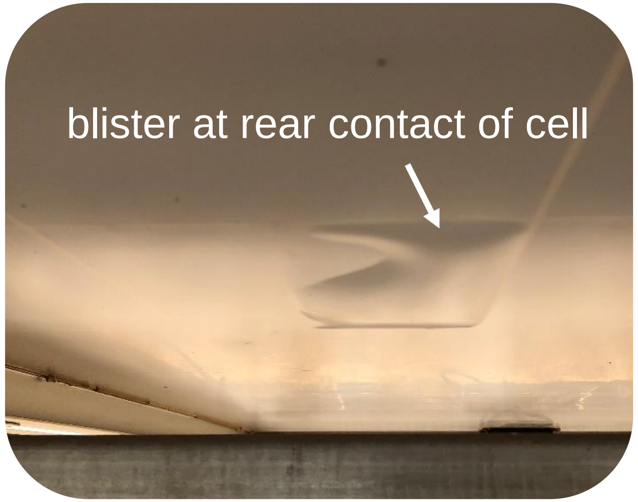
PVDF, 6 years, Sonoran Desert

DUPONT

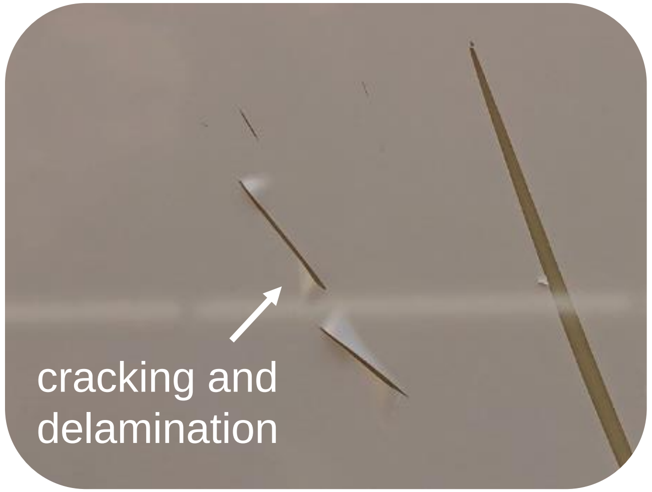
Interface delamination/blistering

- Observed at interfaces within backsheet laminates or at encapsulant interface
- If accompanying cracking, delamination will expose PET core to environmental stressors
- Can provide pathway for shorts to ground, potential module fires

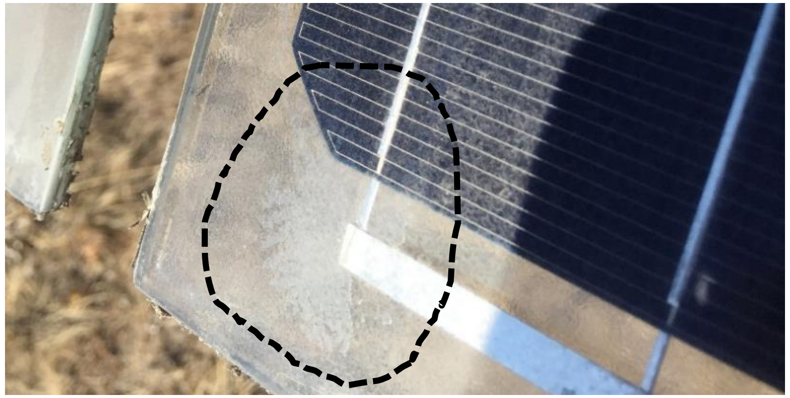
6 years, Sonoran Desert, Arizona



7 years, Arizona high desert



Dual glass module, 1.5 years, NW China



Dual glass module, 10 years, Arizona

Case study: backsheet failures in mixed BoM installation

Multiple Bill Of Materials (backsheets, possibly other components) mixed in the same model number with mixed serial numbers from a single module maker

12 MW field in Arizona, USA, 7 years old

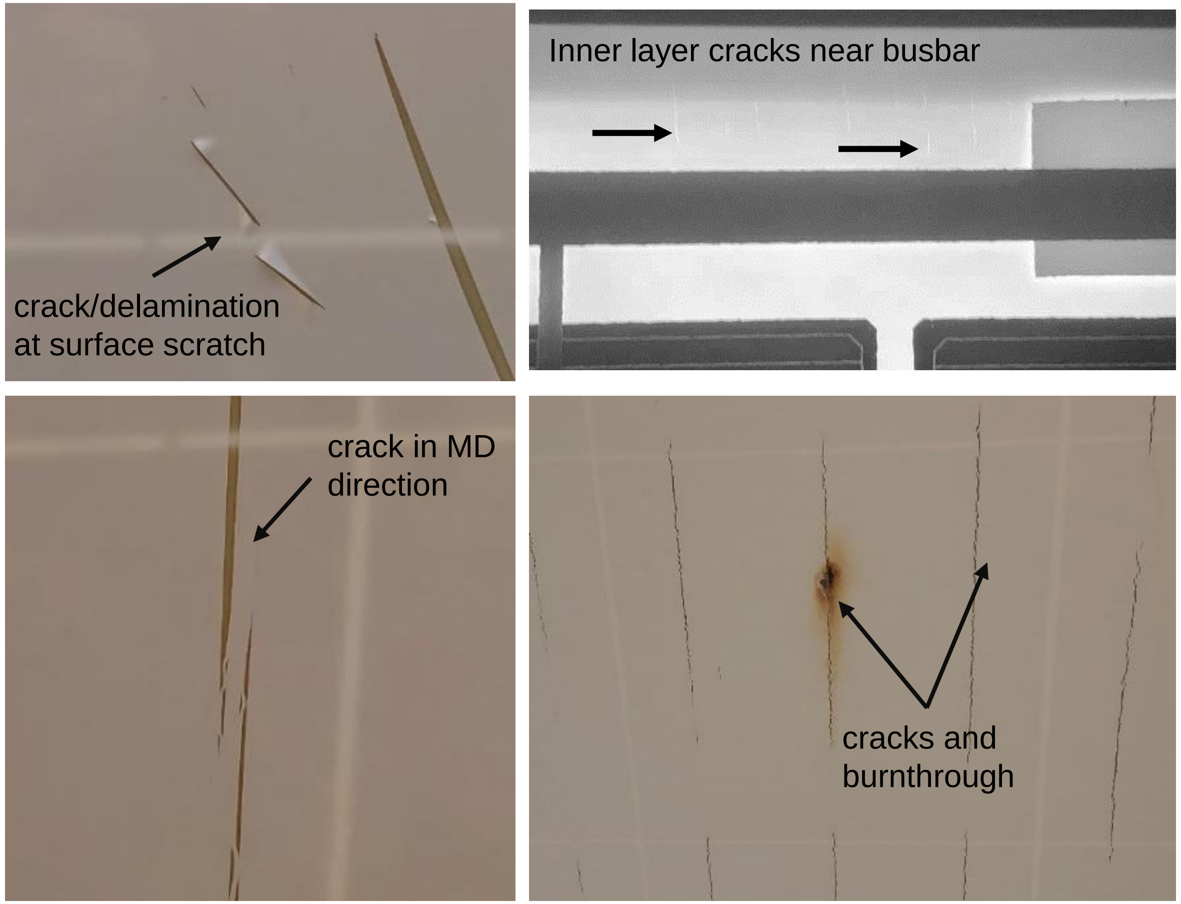
All modules from same manufacturer, but mixed backsheet Bill of Materials:

PA (6 MW), PET (3 MW), PVDF (1.5 MW), PVF (1.5 MW)

Significant defects observed in PA, PET, and PVDF

- 100% of PA backsheet exhibited cracking along busbar ribbons, with several instances of burn-through
- 100% of PVDF backsheet exhibited outer layer cracking, leading to outer layer delamination
- Inner layer cracking in 100% PET-based backsheets, with ~5% severe busbar corrosion
- No defects in PVF

ALL MODULES REPLACED

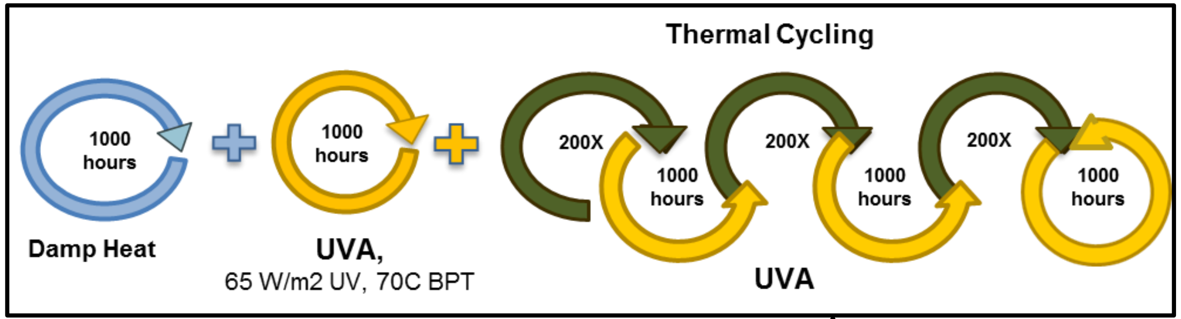


Connecting accelerated testing to the field

Replicating field degradation with sequential testing

PVDF outer layer cracks observed in globally fielded modules

- single layer and tri-layer PVDF films
- multiple climates
- originate at:
  - tabbing ribbons in MD direction (single layer and tri-layer)
  - surface scratches, any orientation (tri-layer only)
- accelerated sequential testing replicates cracking

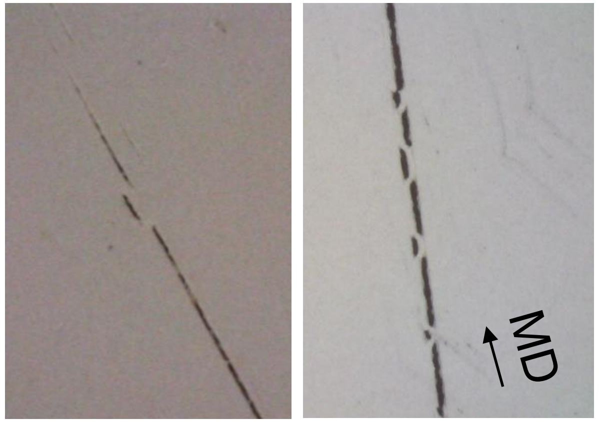


Lab

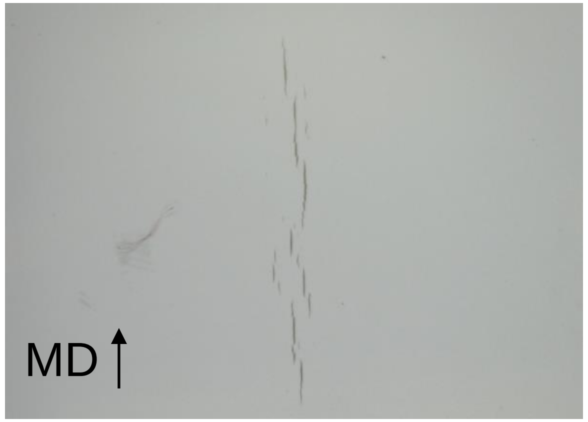
Location	Highest Monthly Mean Temp (°C)	Lowest Monthly Mean Temp (°C)	Highest Monthly Max Temp (°C)	Lowest Monthly Min Temp (°C)
China (high desert)	27	-11	34	-17
North America (temperate)	22	-4	27	-7
North America (high desert)	24	7	32	-5
Mediterranean	21	7	25	4
India	34	19	42	10

Field

6 yrs China



1st cycle sequential testing



cracking along tabbing ribbon of single layer PVDF

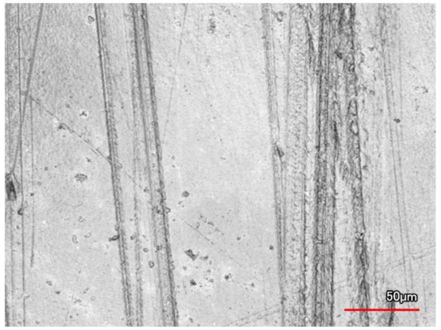
DUPONT

Replicating field degradation with sequential testing

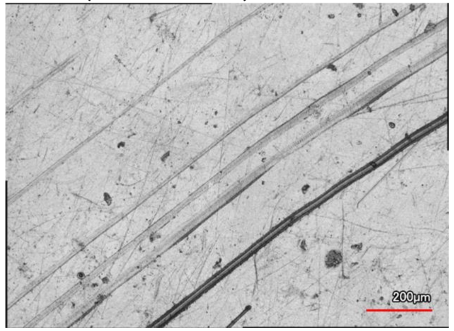
Cracking in tri-layer PVDF

- generally propagate in MD direction or along surface scratches/scuffs
- nucleation and extension observed when thermally cycled
- outermost neat layer exhibits brittle morphology

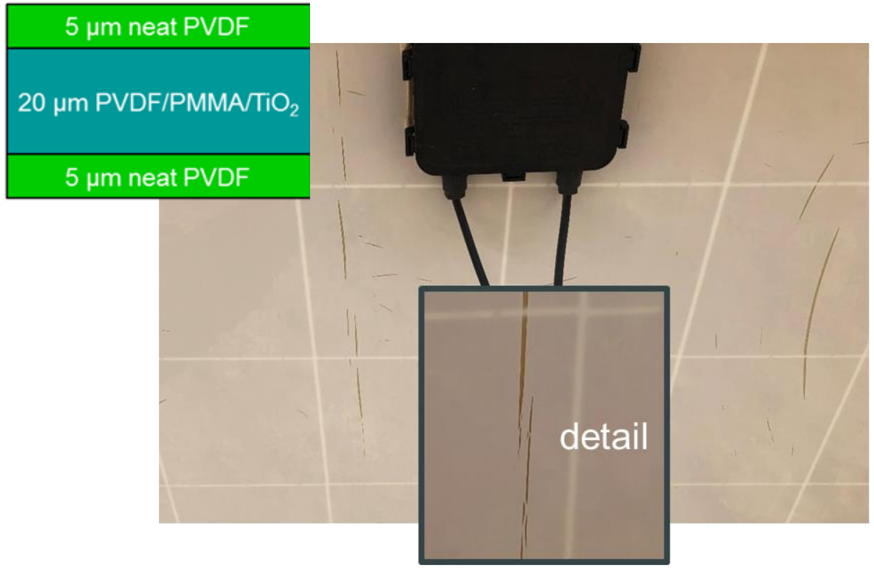
Arizona (laser confocal)



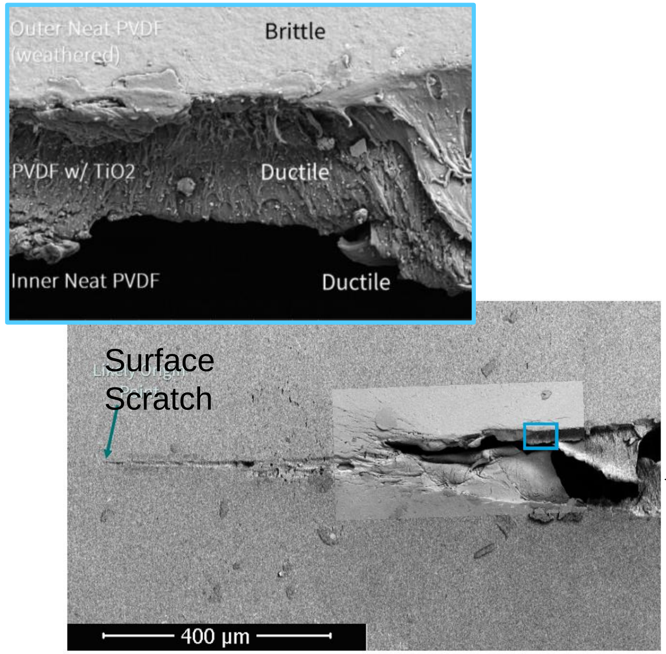
India (laser confocal)

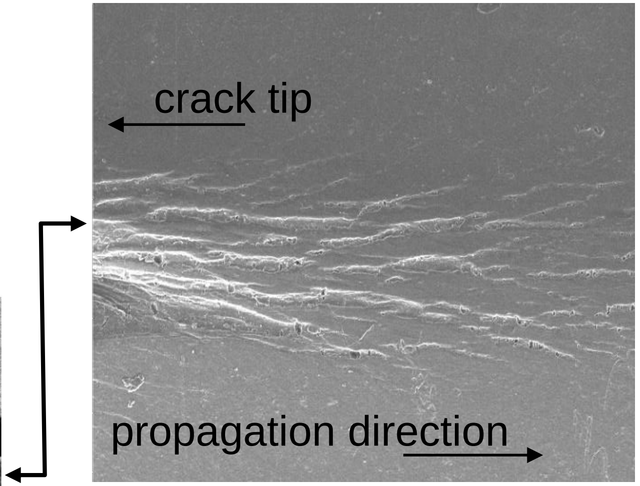


Scratches in neat PVDF layer of globally fielded modules



Outer layer crack in tri-layer PVDF after 7 yrs in Arizona



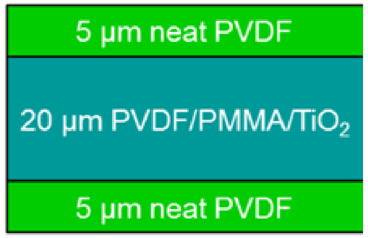


Crack bifurcation of neat outer layer in plastic zone of crack (7 yrs Arizona)

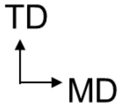
Replicating field degradation with sequential testing

Further degradation driven through thermal cycling

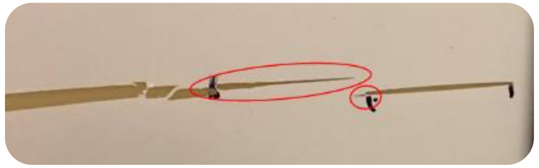
- observed where max temp exceeds secondary transition
- extension not sensitive to min temps below ambient
- widespread delamination and blistering after 100 cumulative thermal cycles



15 cycles (-40°C to 85°C)

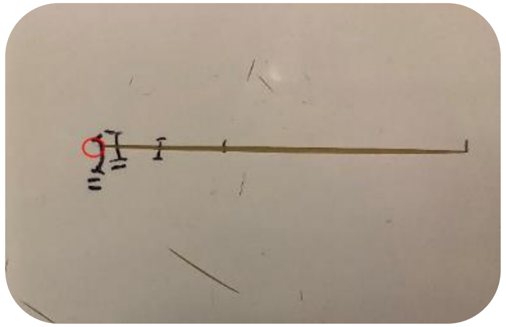


new cracks and delamination



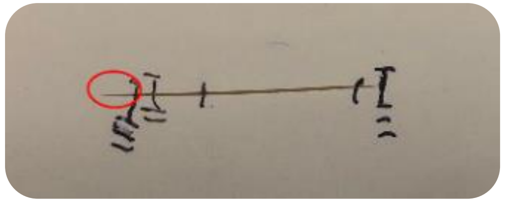
30% crack extension

15 cycles (-40°C to 20°C)



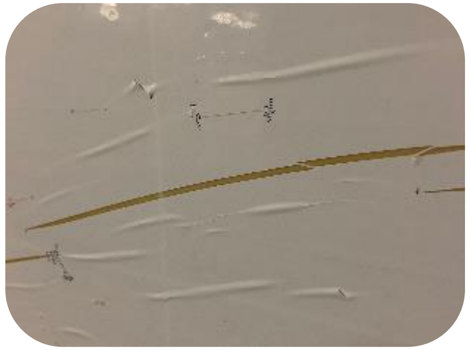
no new cracks or significant crack extension

15 cycles (20°C to 85°C)



crack extension and new cracks

100 total thermal cycles

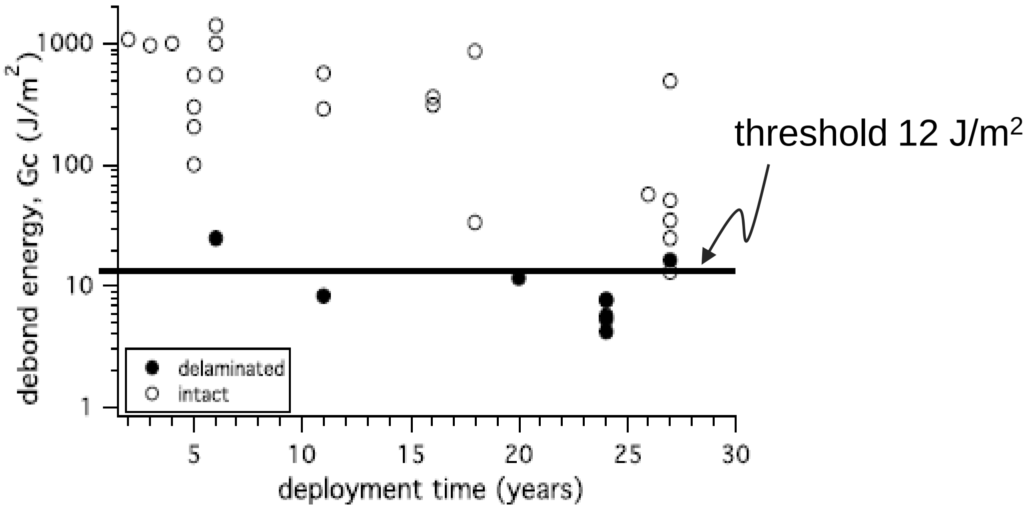


new cracks, severe delamination and blistering

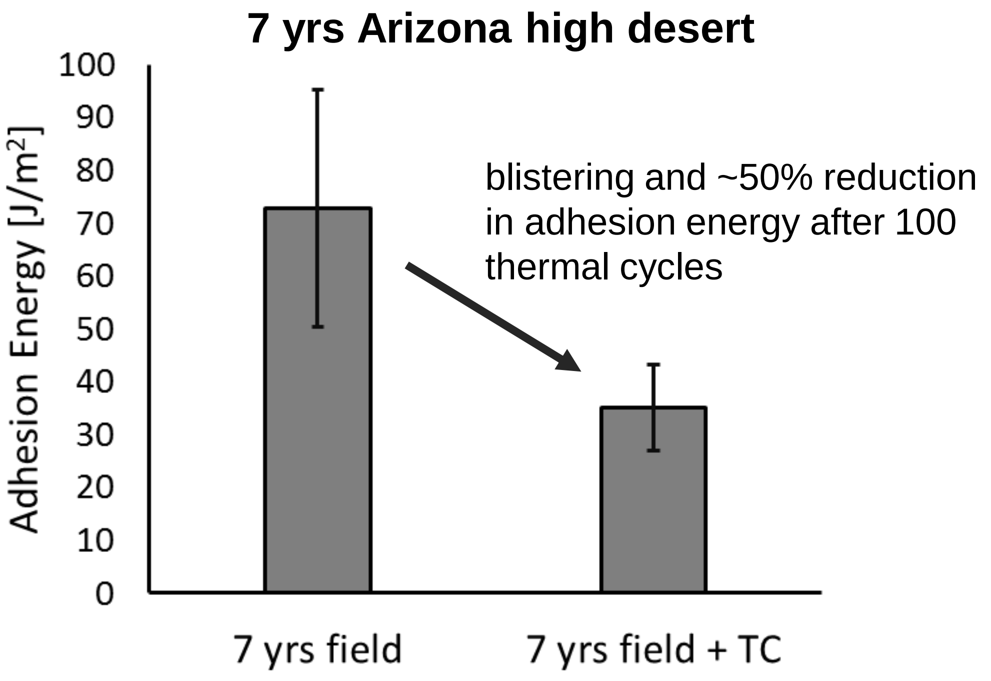
Replicating field degradation with sequential testing

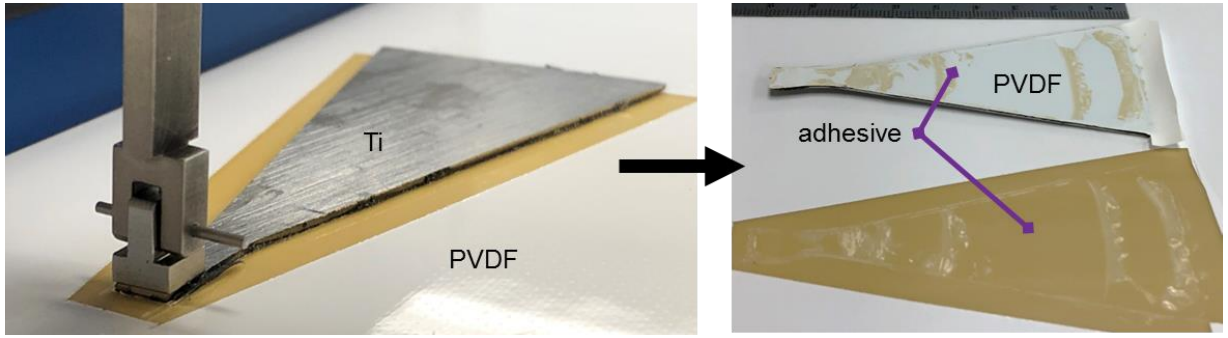
Modules exhibiting backsheet outer layer delamination exhibit low interface adhesion energy, G_c [J/m^2]

- PVDF, 7 yrs, Arizona: 70 J/m^2
- further reduction following 100 thermal cycles



N. Bosco, J. Tracy, S. Kurtz, R. H. Dauskardt, "Defining threshold values of encapsulant and backsheet adhesion for PV module reliability", *IEEE J. Photovolt.*, vol. 7, no. 6, pp. 1536-1540, Nov. 2017



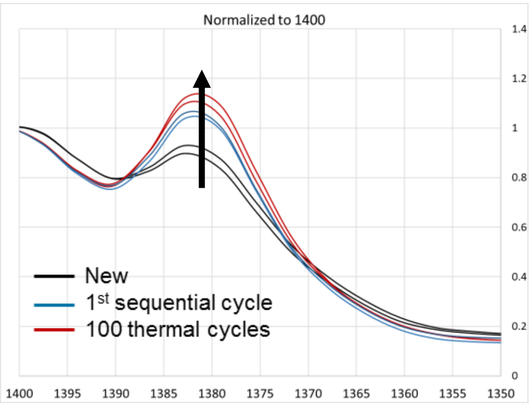


delamination at PVDF/adhesive (polyester isophtalate) interface

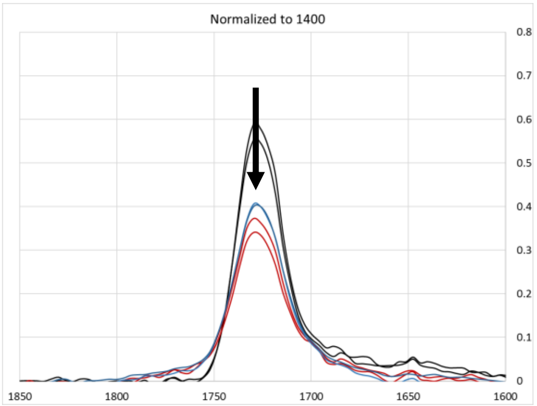
Replicating field degradation with sequential testing

Cracking exacerbated through thermal cycling

- isolated tabbing ribbon cracks detected in single layer PVDF films after first sequential weathering cycle: 1000 hrs DH + TC50/HF10 + 1000 hrs UVA
- subsequent crack extension and nucleation beyond tabbing ribbon driven solely by thermal cycling
- ATR of surface indicates increase alpha crystalline phase and reduction in carbonyl (PMMA) peak heights



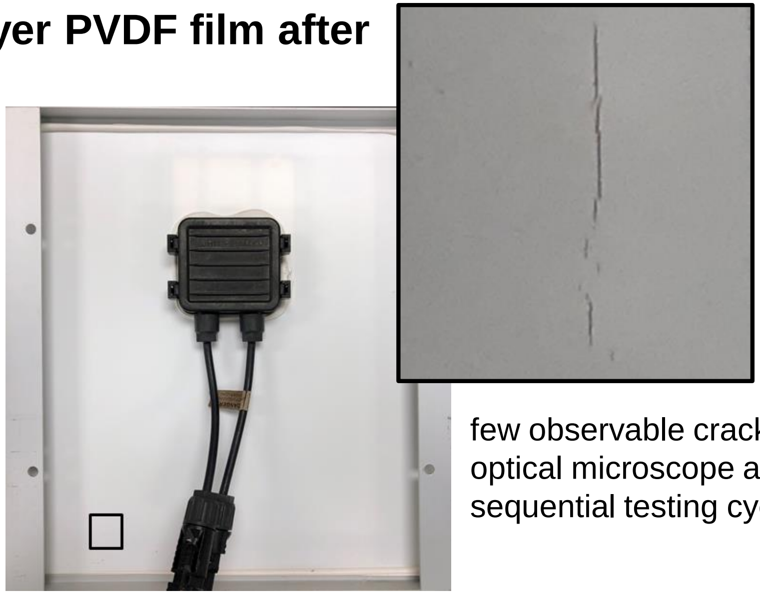
increase in alpha phase



decrease in carbonyl

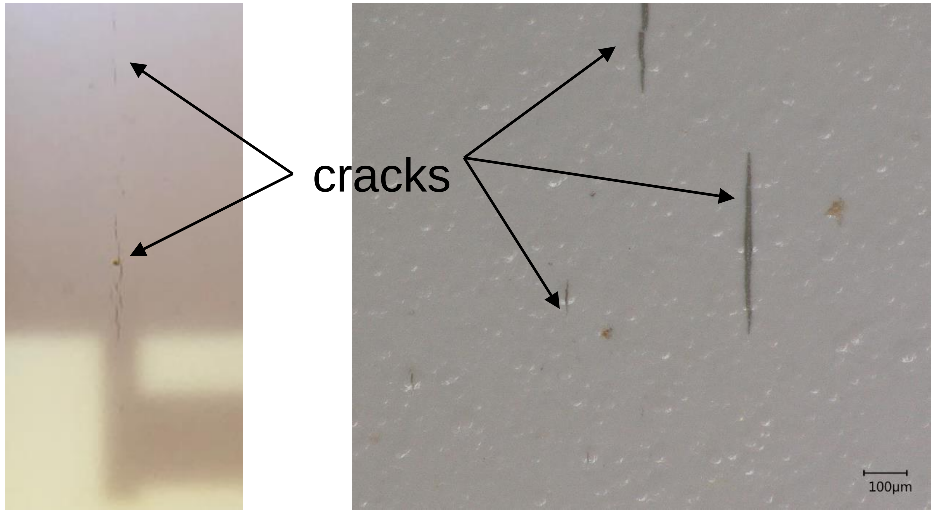
Cracked single layer PVDF film after sequential test

20-30 µm PVDF/PMMA/TiO_2



few observable cracks by optical microscope after single sequential testing cycle

TC 100



cracks form and extend along and beyond tabbing ribbons with additional thermal cycling

Summary

- Backsheet and cell defects are most prominent failure modes (~14% each)
- Cracking and delamination 66% of observed backsheet defects
  - Severe degradation can manifest after just several years in the field

Coupling field observations with failure analysis and characterization techniques improves accelerated testing and predictive modeling