An Overview of Backsheet Materials for Photovoltaic Modules

Michael Owen-Bellini – National Renewable Energy Laboratory

DuraMAT Webinar May 2020

Outline

- What and why?
- Types of Backsheets
- Recent issues
- Advances in Reliability Testing
- Emerging technologies
- Summary

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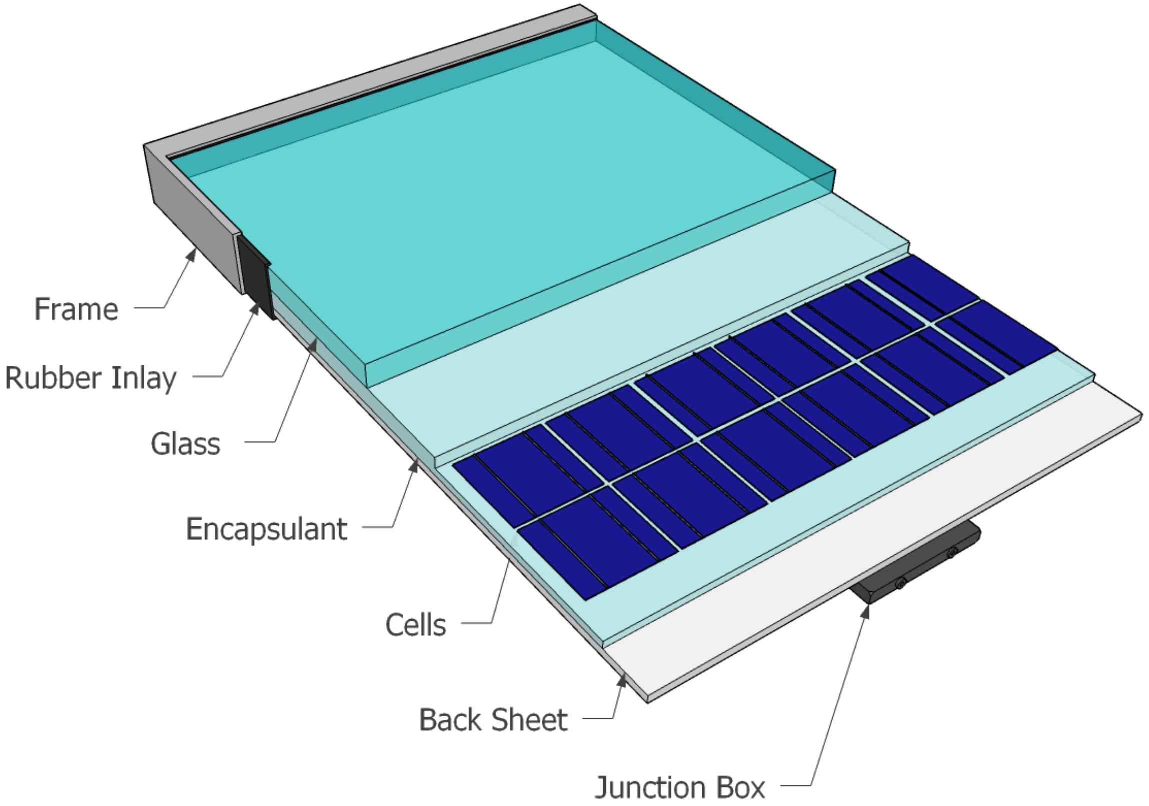
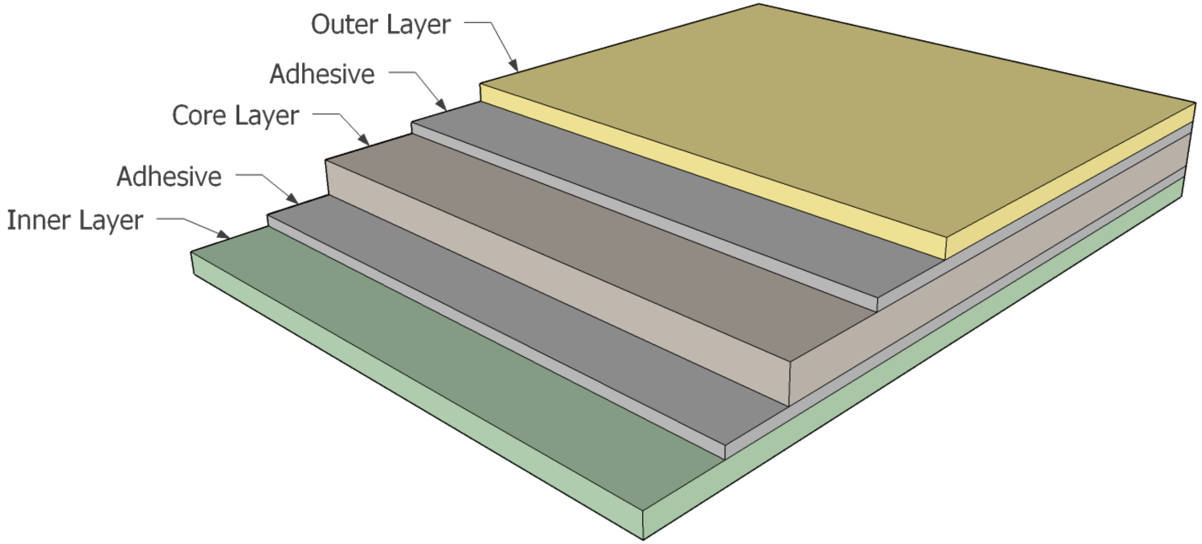
What and Why?

Typical PV Module Structure



Typical Multilayer Backsheet Structure

(Typically multi-layered systems, but monolayer backsheets do exist)



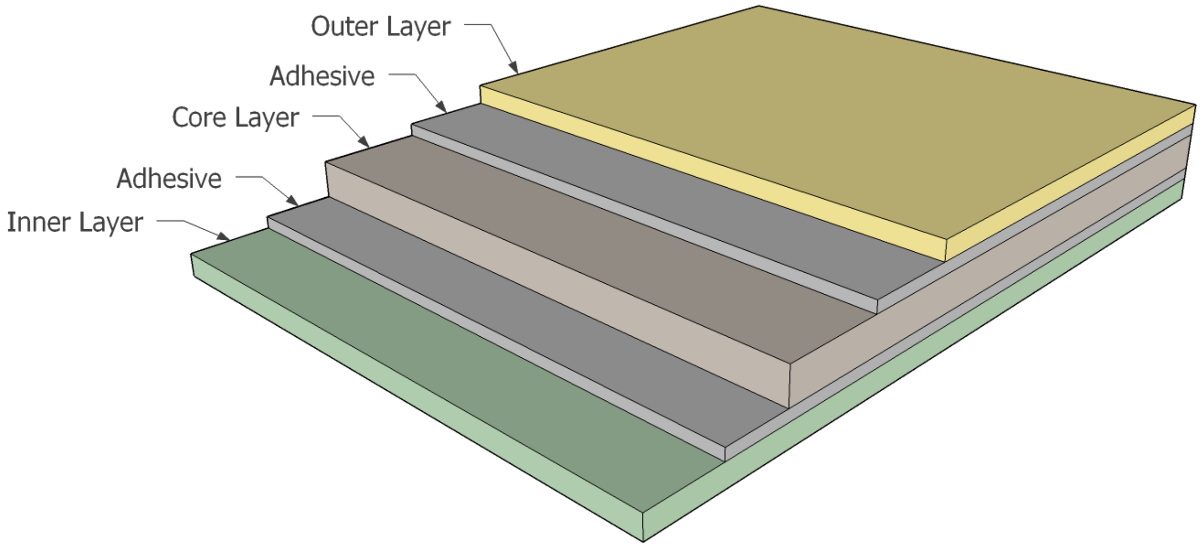
Primary function is to provide electrical isolation for safe operation

What and Why?: Key properties

Key Properties
Moisture Barrier
Heat Stability
UV Resistance
Erosion Resistance
Mechanical Stability
Dielectric Strength

Typical Multilayer Backsheet Structure

(Typically multi-layered systems, but monolayer backsheets do exist)



A compromised backsheet can present a serious safety hazard

Accelerates other degradation modes e.g. corrosion

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Types of backsheet

Fluoropolymers

Fluoropolymer-Free

Types of backsheet: Polyethylene terephthalate (PET)

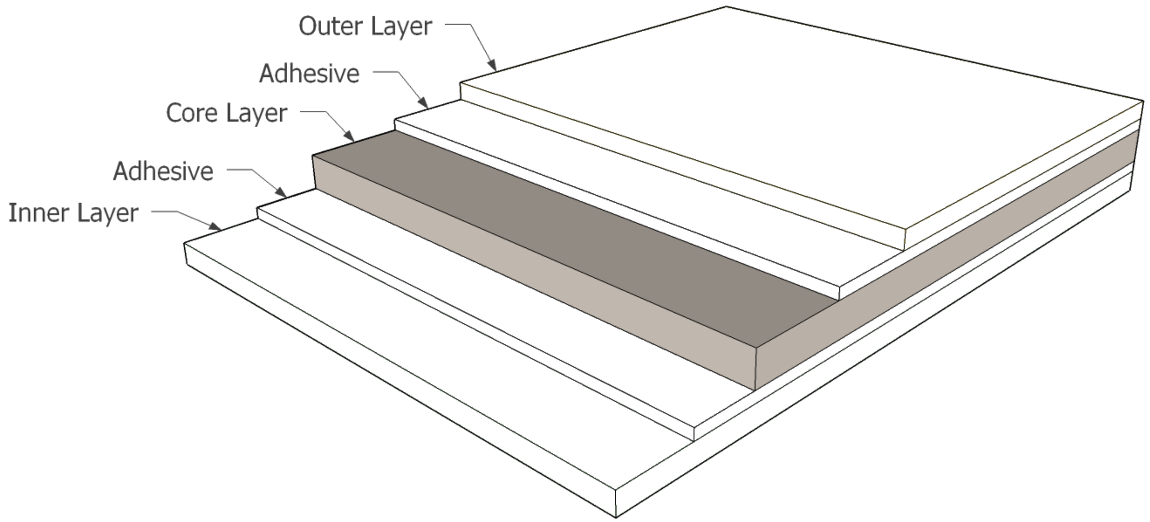
Polyethylene terephthalate (PET)

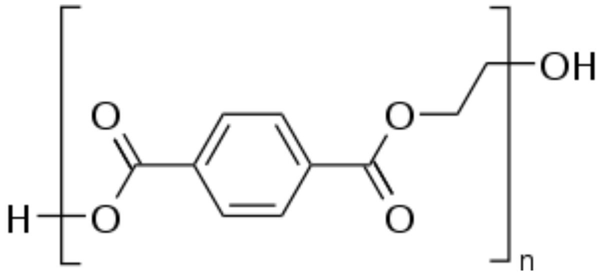
- Historically used as the core layer
- Provides mechanical integrity
- Dielectric strength
- Typical thickness range from 70 – 250µm*
- Make up the bulk of the backsheet

Susceptible to UV degradation and hydrolysis**

Core layer protected by an outer and inner layer

Typical Multilayer Backsheet Structure



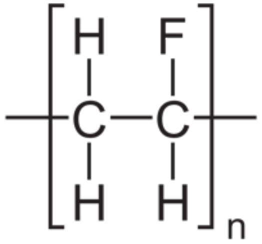


*Geretschlager et al, Sol. Mat., 2016
**Oreski et al, Solar Energy, 2005

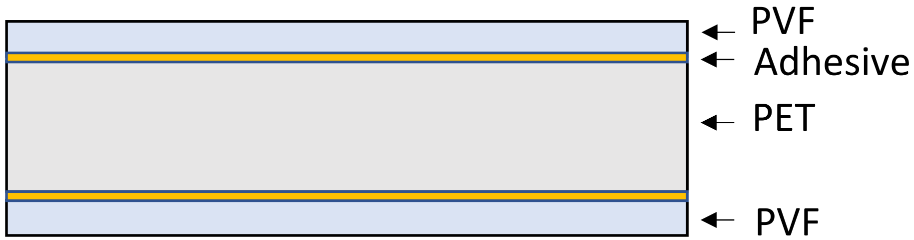
Types of backsheet: Polyvinyl fluoride (PVF)

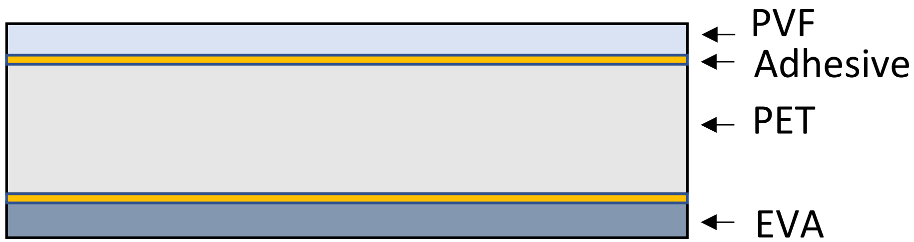
Polyvinyl fluoride (PVF)

- Typical thicknesses 30 – 50 µm
- Proven field history 25+ years*
- TiO_2 white pigment

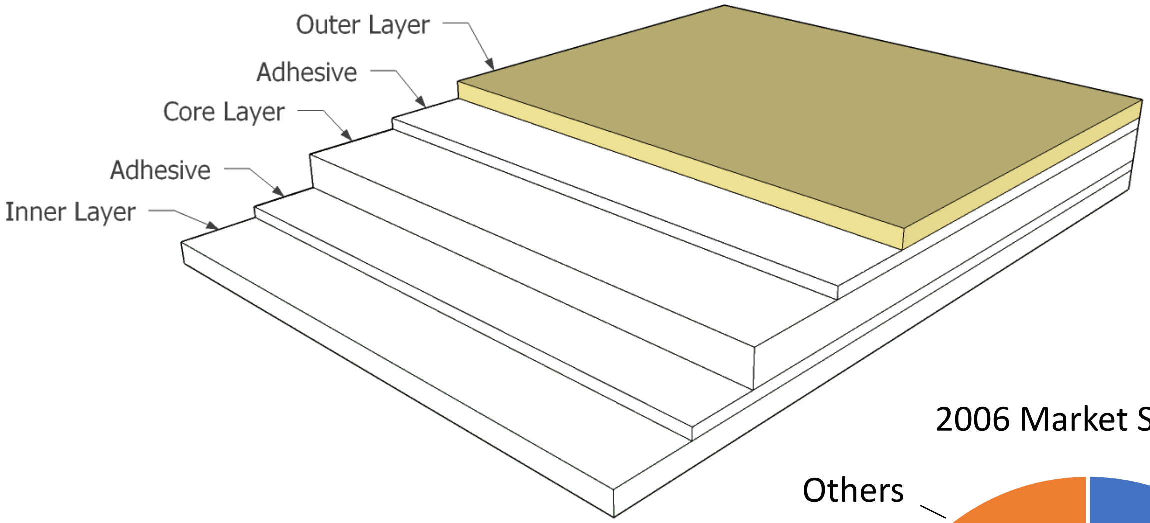


Example Configurations:

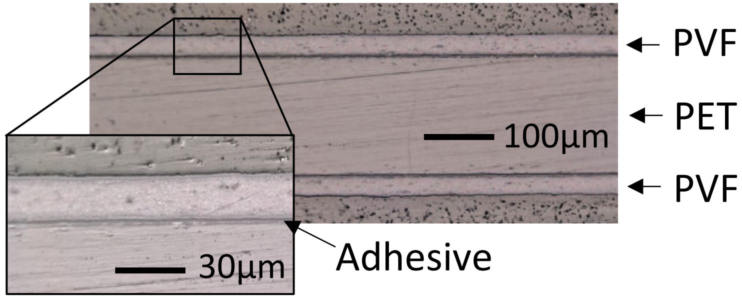




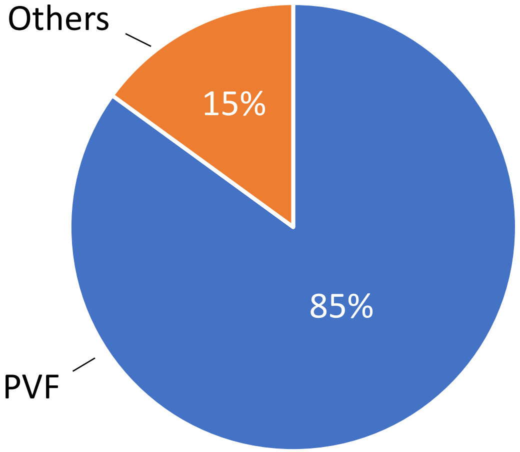
Typical Multilayer Backsheet Structure



Micrograph for PVF/PET/PVF



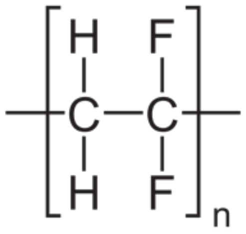
2006 Market Share*



*Maras, EUPVSEC, 2016

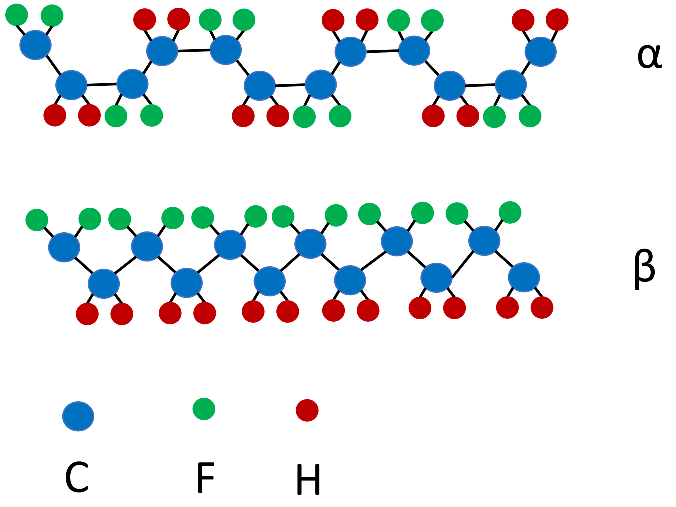
Types of backsheet: Polyvinylidene fluoride (PVDF)

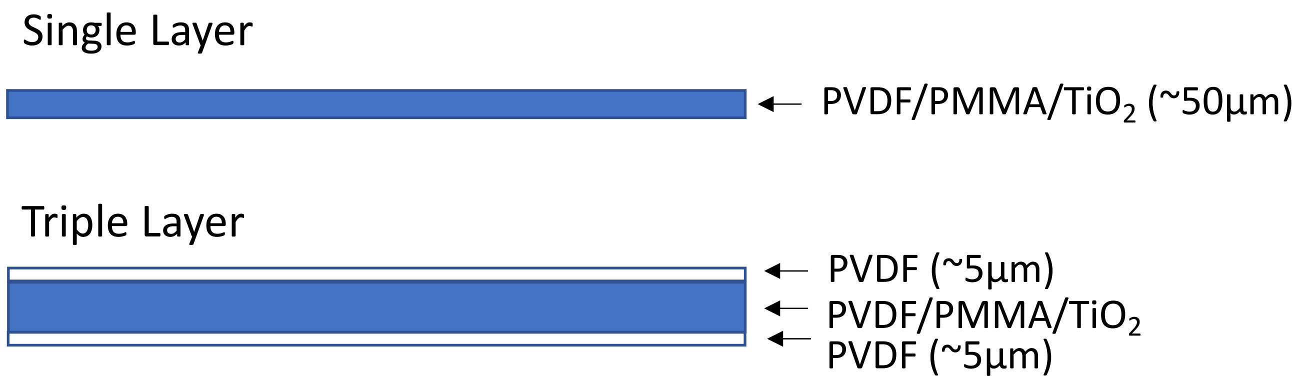
Polyvinylidene fluoride (PVDF)

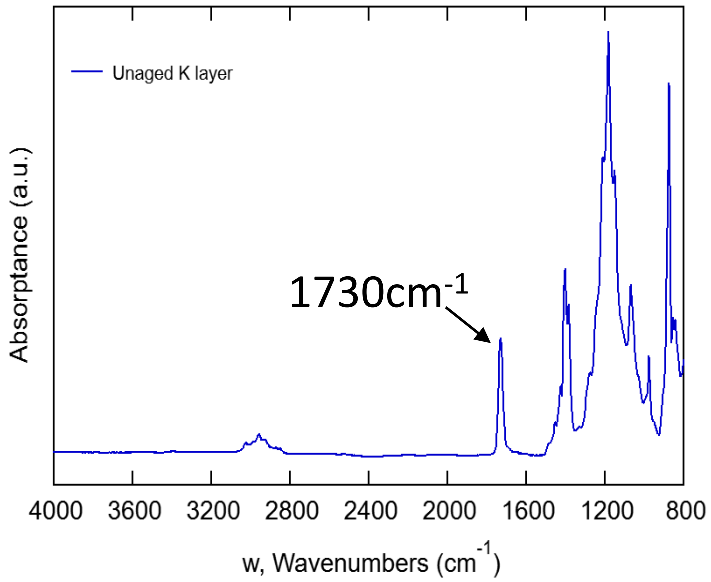


- Typical thicknesses 30 – 50 µm
- TiO_2 white pigment
- Typically blended with poly(methyl methacrylate) (PMMA)

- Semi-crystalline polymer with multiple crystal phases
- Crystal phase is governed by the orientation of the polymer chains
- Crystallinity and phase are critical to mechanical characteristics







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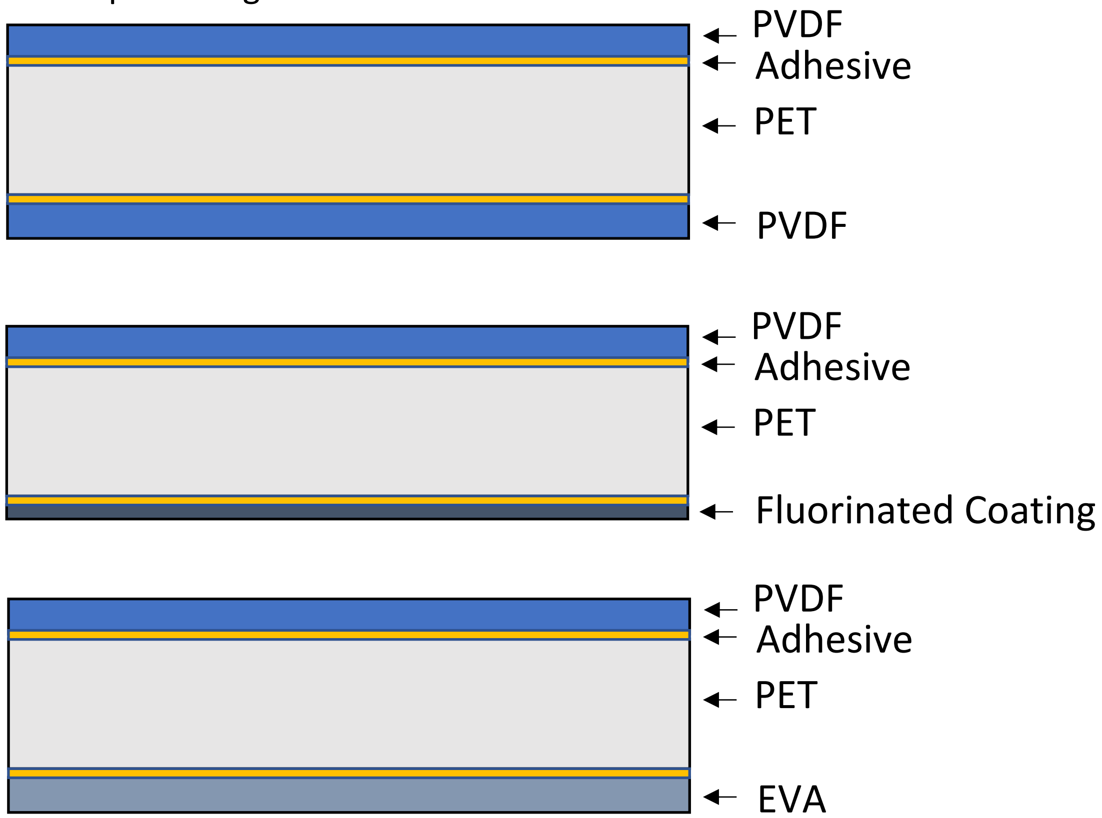
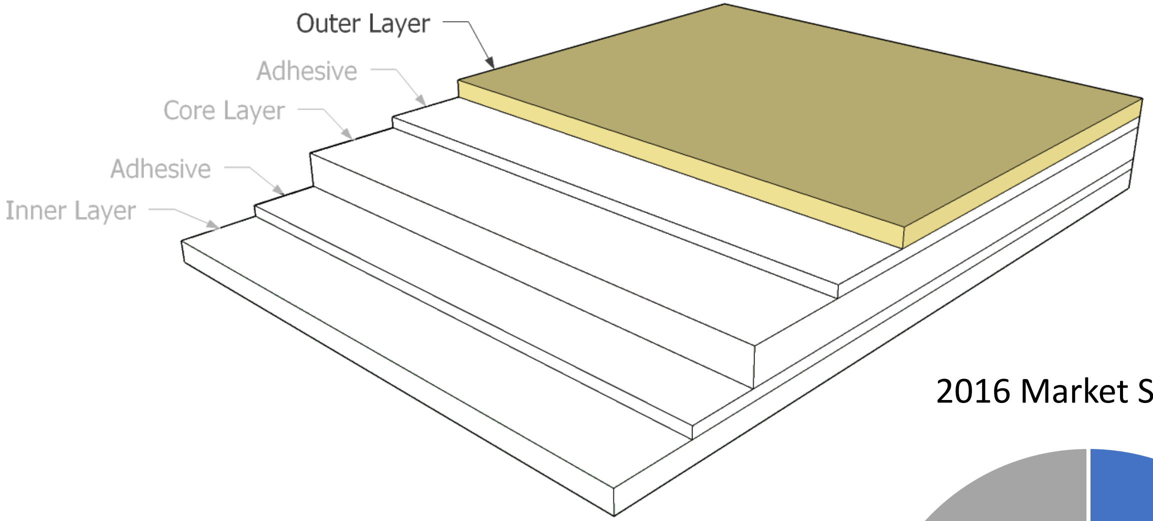
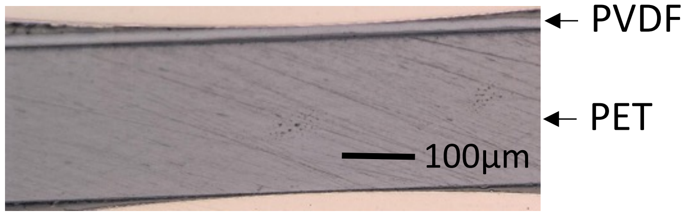


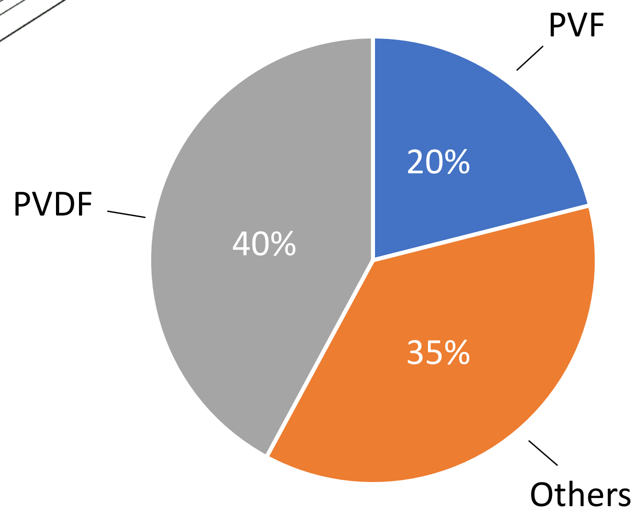
Typical Multilayer Backsheet Structure



Micrograph for PVDF/PET/Fluorine



2016 Market Share*



*Maras, EUPVSEC, 2016

Types of backsheet

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Fluoropolymer-Free

Types of backsheet: Polyamide (PA)

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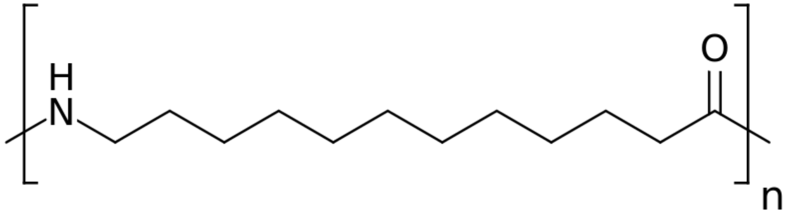
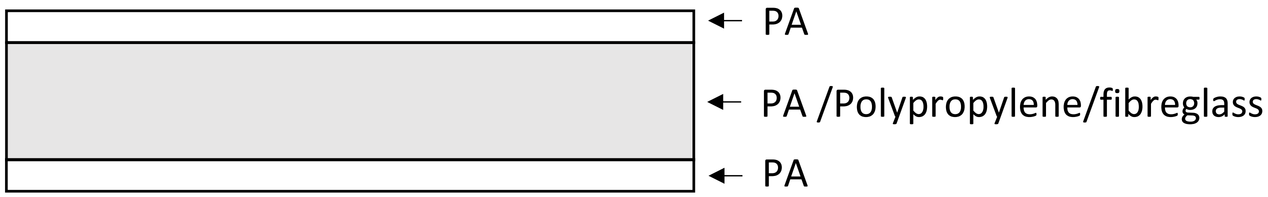
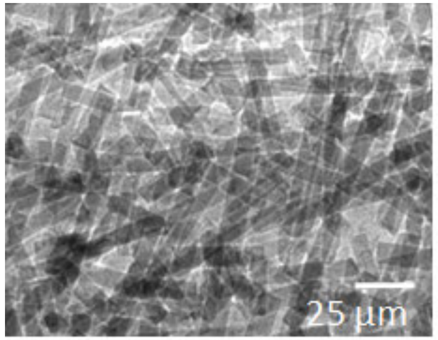


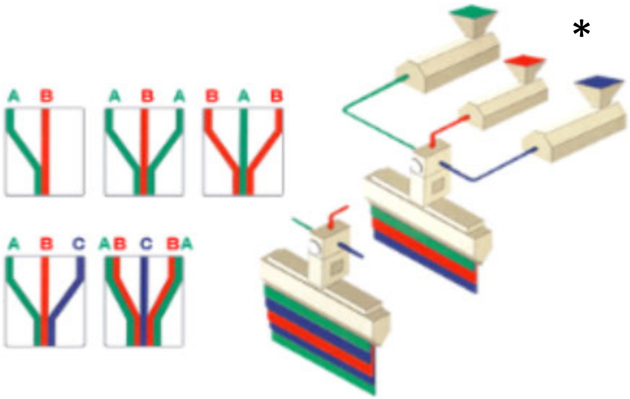
- Nylon-12 outer layers
- Core layer a blend of PA, polypropylene and fiber glass
- Outer layer thicknesses ~50µm, core layer ~250µm
- TiO_2 white pigment
- Co-extruded



X-ray transmission image of core layer

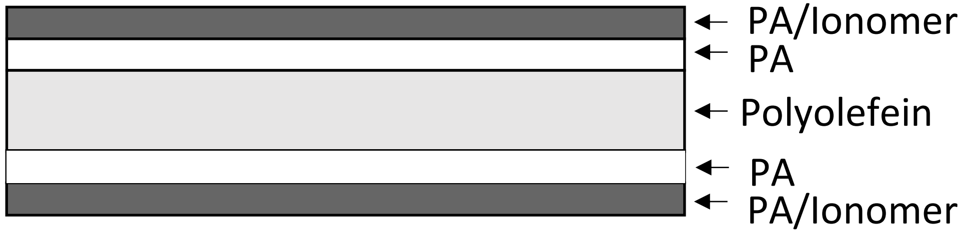


SLAC NATIONAL ACCELERATOR LABORATORY



*

- PA/Ionomer blended outer layers
- PA intermediate layers
- Polyolfein Core layer
- TiO_2 white pigment or carbon black pigment
- Talc filler for dimensional stability
- Co-extruded



Benefits of co-extrusion:

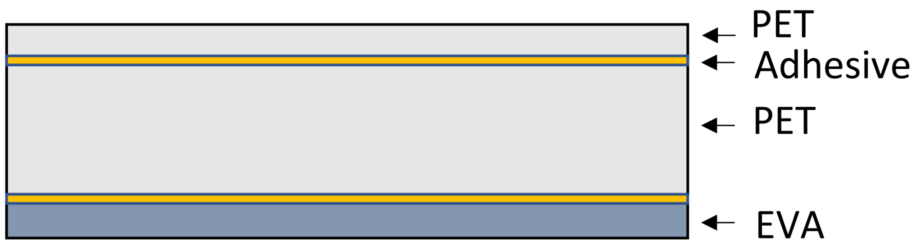
- Eliminates lamination step
- Eliminates need for adhesive
- Reduces delamination between layers
- Easier material modification (additives. fillers etc)

*Thellen et al, EUPVSEC, 2016

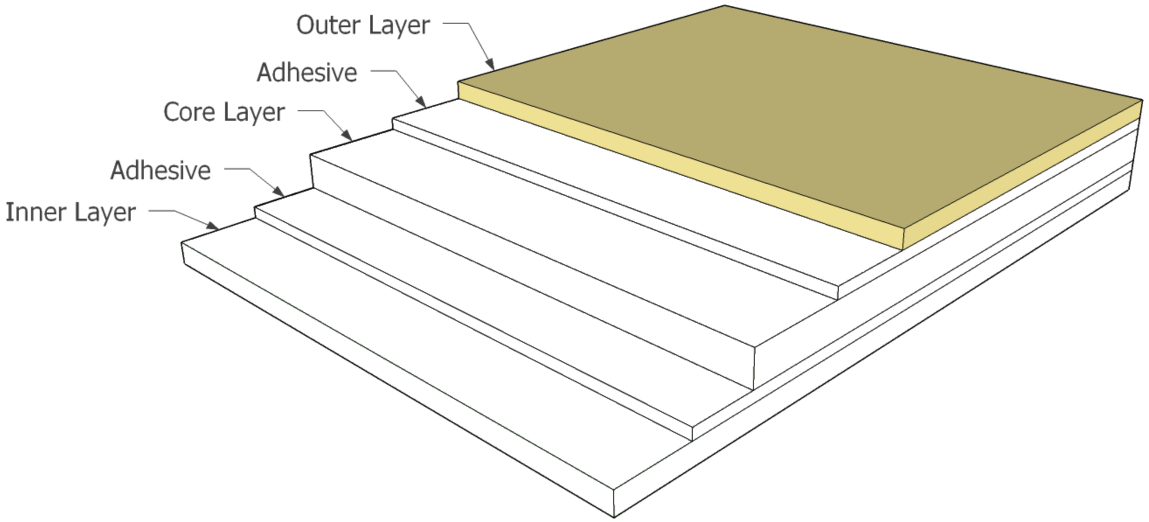
Types of backsheet: Polyethylene terephthalate (PET)

Polyethylene terephthalate (PET)

- Typical thicknesses 30 – 50 µm
- TiO_2 white pigment
- Outer PET layer stabilized using additives



Typical Multilayer Backsheet Structure



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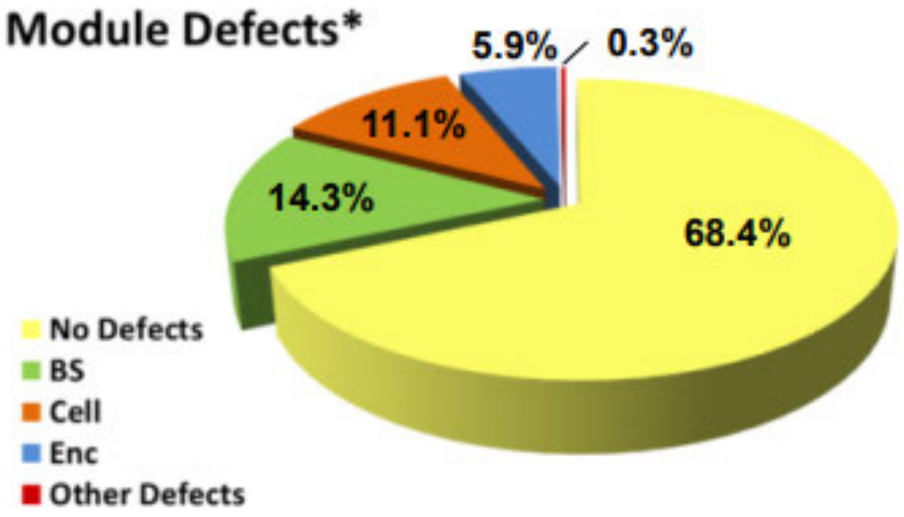
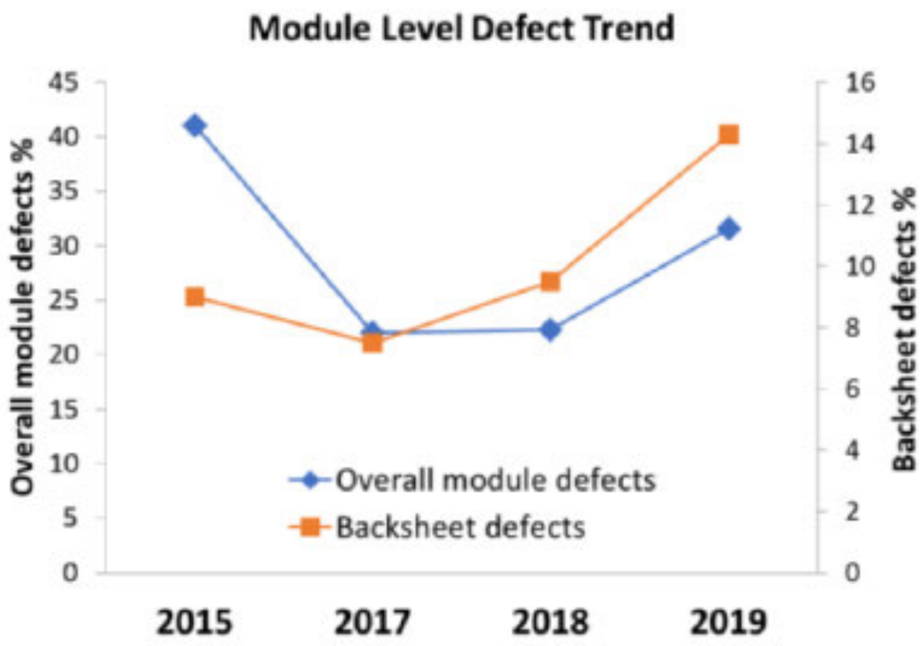
Recent Issues: Backsheet Defect Increases





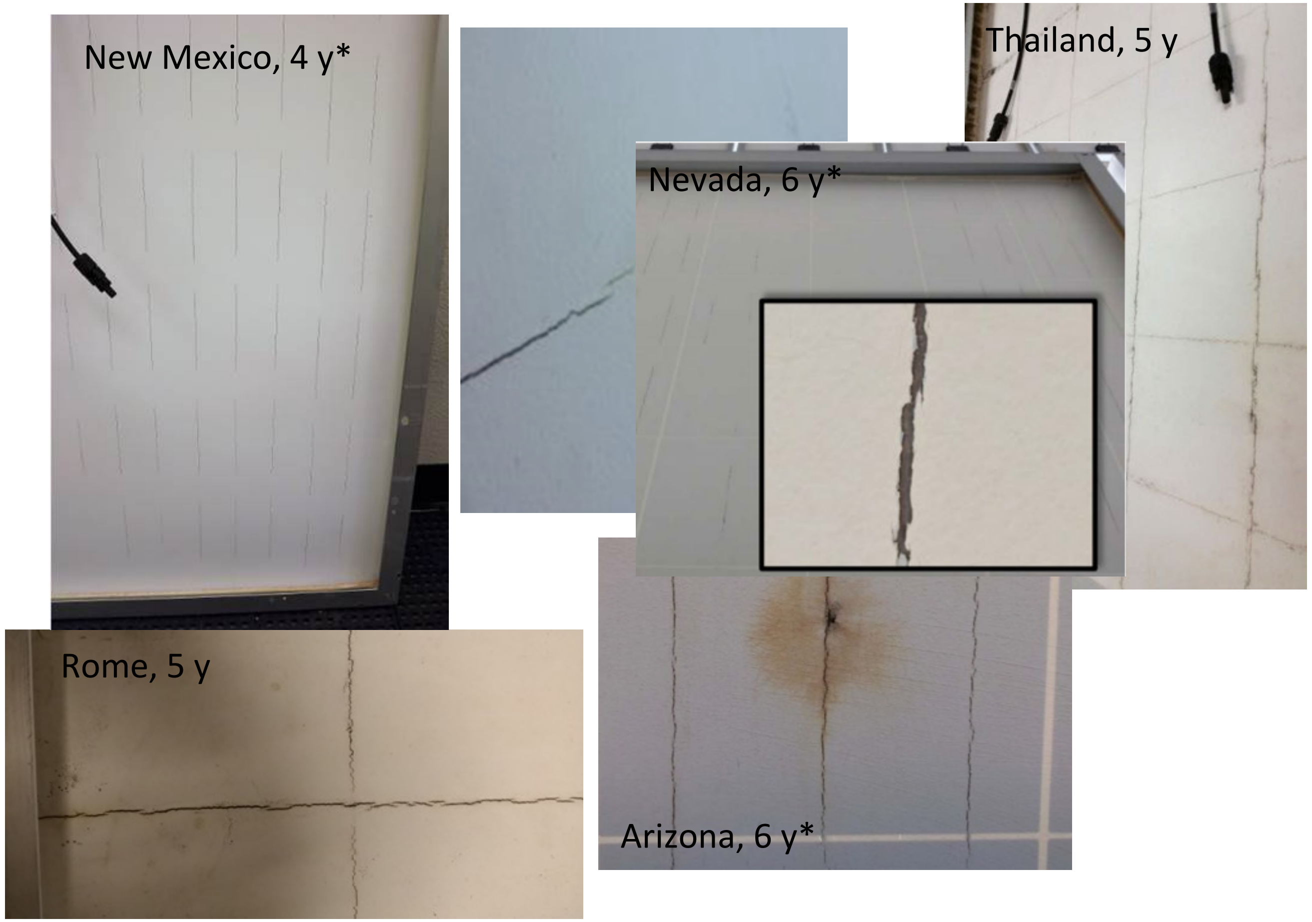
Highlights	2019
North America, Europe, Middle East, Asia/Pacific	
Installations	322
# of panels (million)	6.1
# of module makers	102
Age range (yrs)	1 to 33
Average age (yrs)	3.7
GW	1.8

- Total module defects 32%; backsheet defects 14%*
- YOY: Backsheet defects increased by 48%
- Polymer defects: hot > tropical > temperate climate

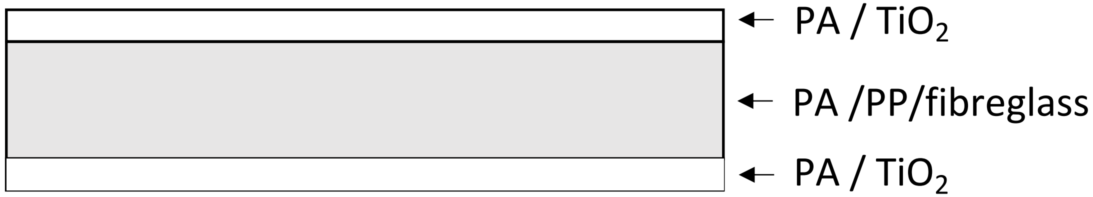
*Choudhury et al, PVRW, 2019

Recent Issues: PA field-failures

PA Field-failures



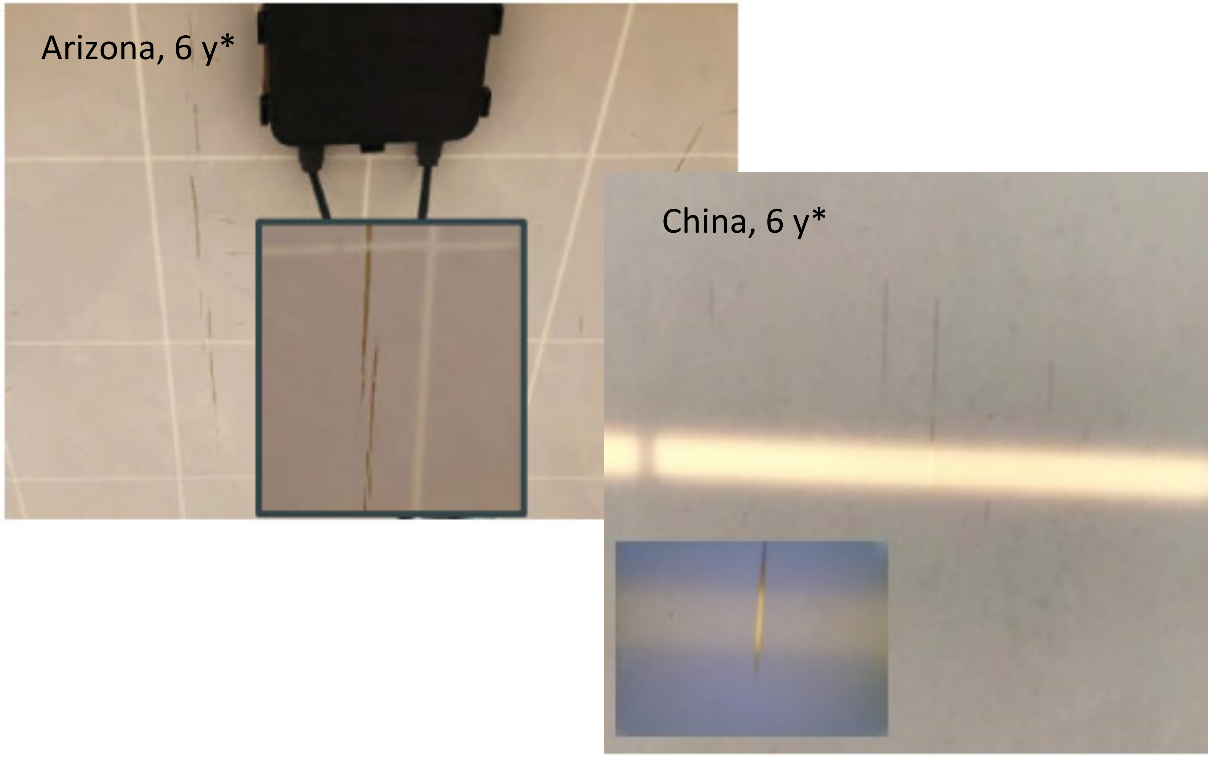
- Upwards of 12GW deployed globally
- >95% failure rate in 6 years
- **Despite passing certification**



*Choudhury et al, PVRW, 2019

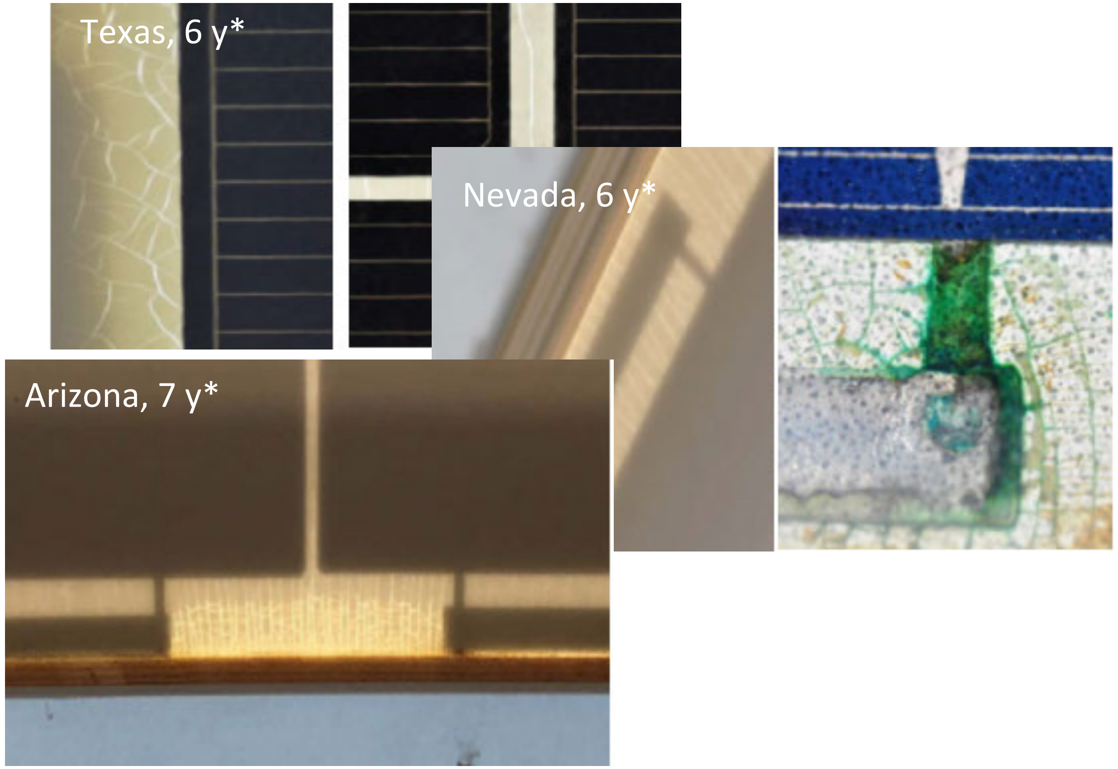
Recent Issues: PVDF and PET field-failures

PVDF Field-failure



- Cracking of the outer, PVDF layer

PET/PET/EVA Field-failure

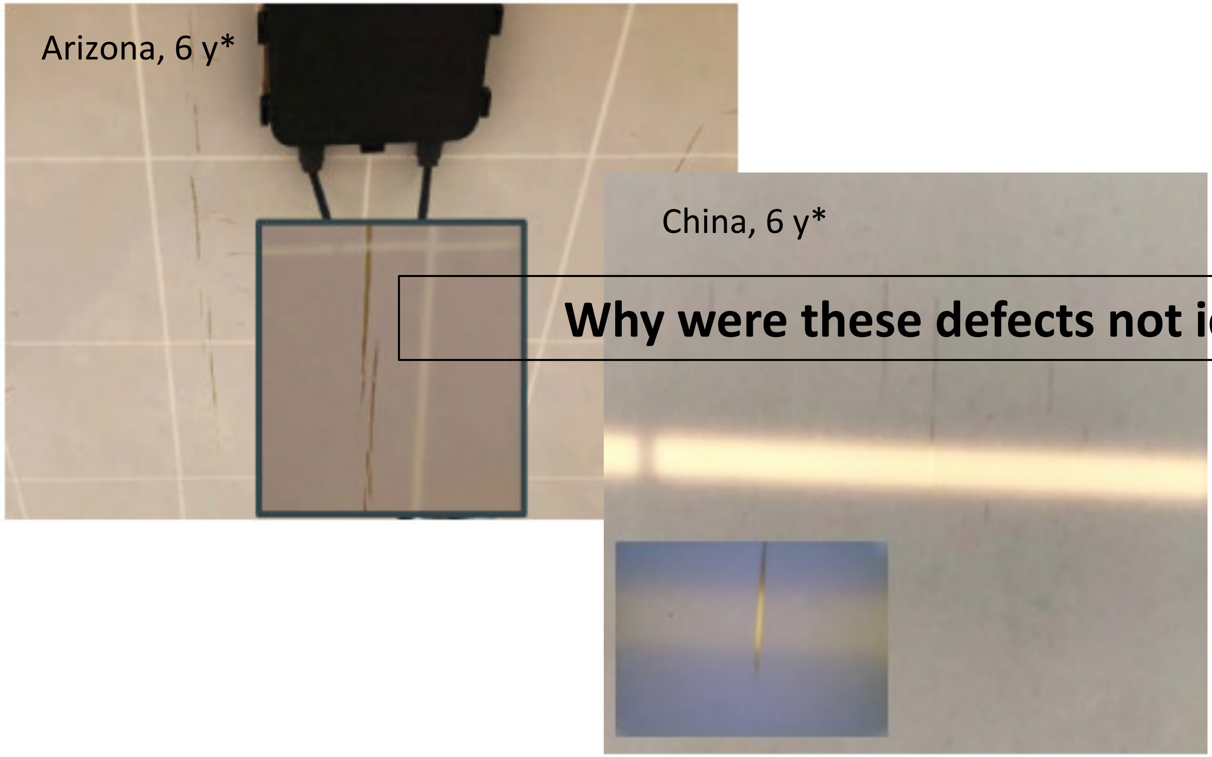


- Cracking of an inner layer
- Accelerates corrosion
- Leads to shorting and suspected inverter tripping

*Choudhury et al, PVRW, 2019

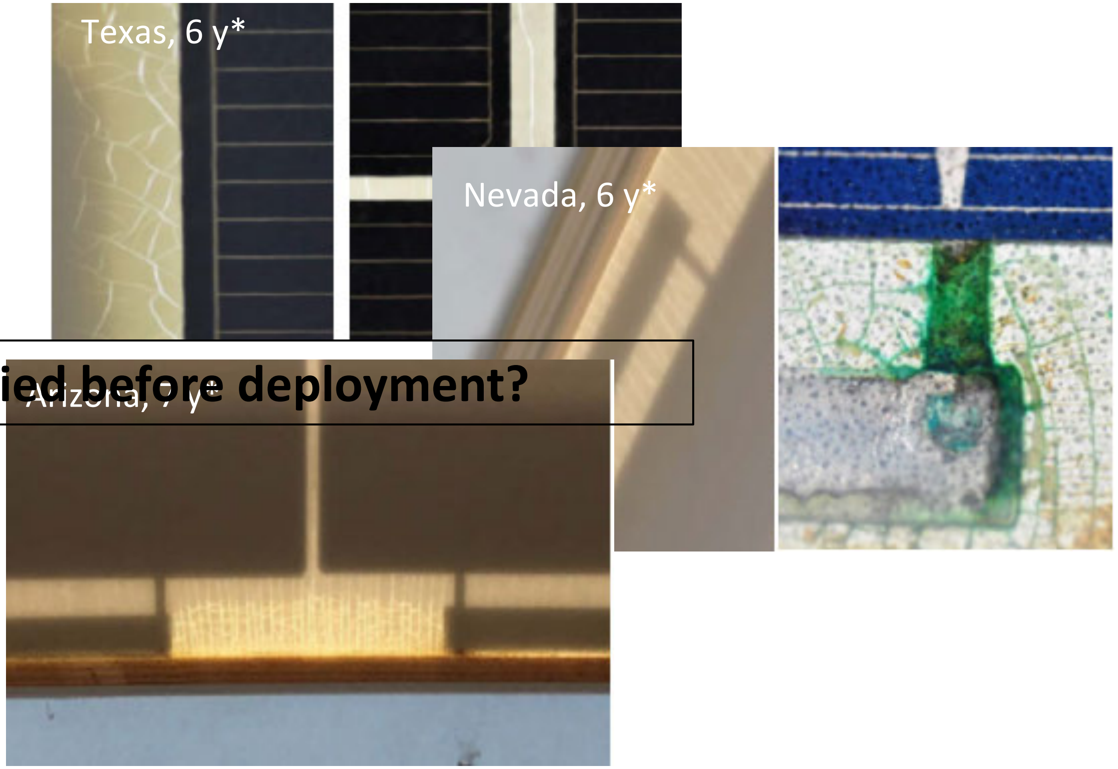
Recent Issues: PVDF and PET field-failures

PVDF Field-failure



- Cracking of the outer, PVDF layer

PPE Field-failure



Why were these defects not identified before deployment?

- Cracking of an inner layer
- Accelerates corrosion
- Leads to shorting and suspected inverter tripping

*Choudhury et al, PVRW, 2019

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Advances in Reliability Testing: Current Standards

IEC 61215

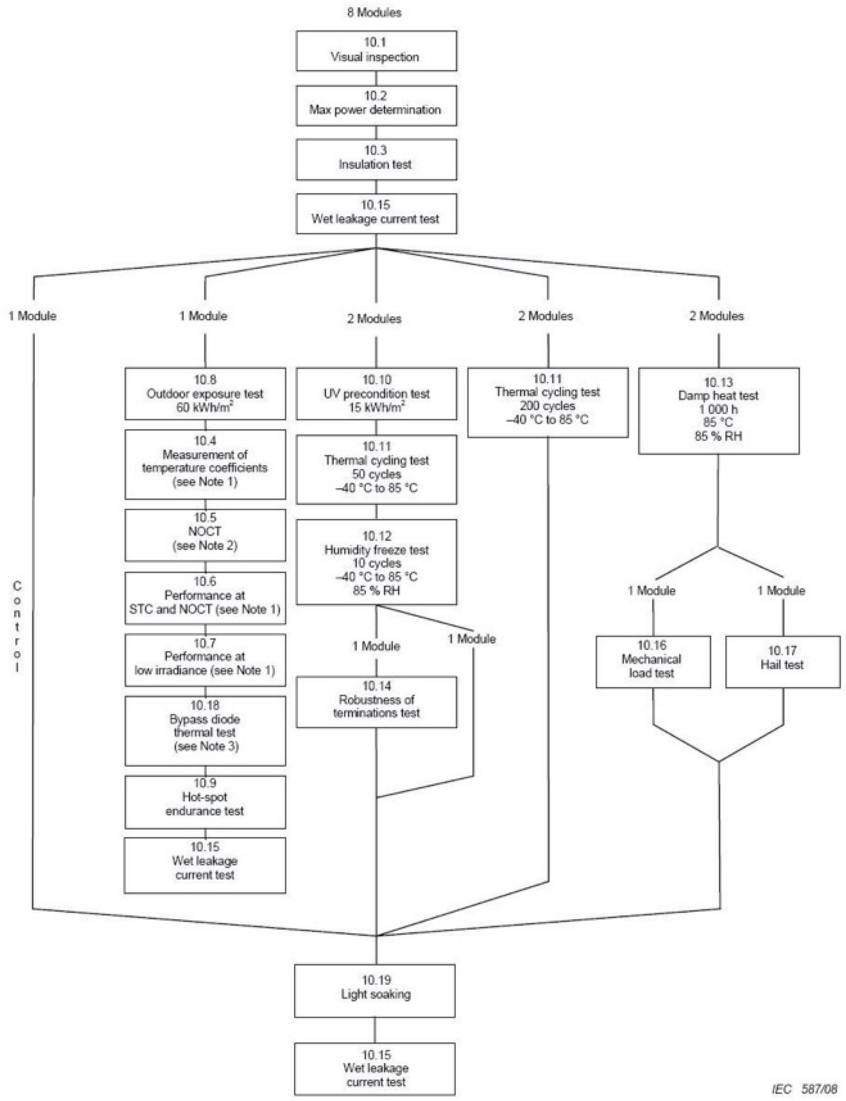
Module Level Tests

Mostly 1-2 stress factor combinations

Minimal evaluation of interdependent stressors

Not reliability tests

It's a certification against infant failure



IEC TS 62788-7-2 A Conditions

Component level test for backsheets

90°C BPT, 0.8Wm^{-2} UV, 20% *RH*

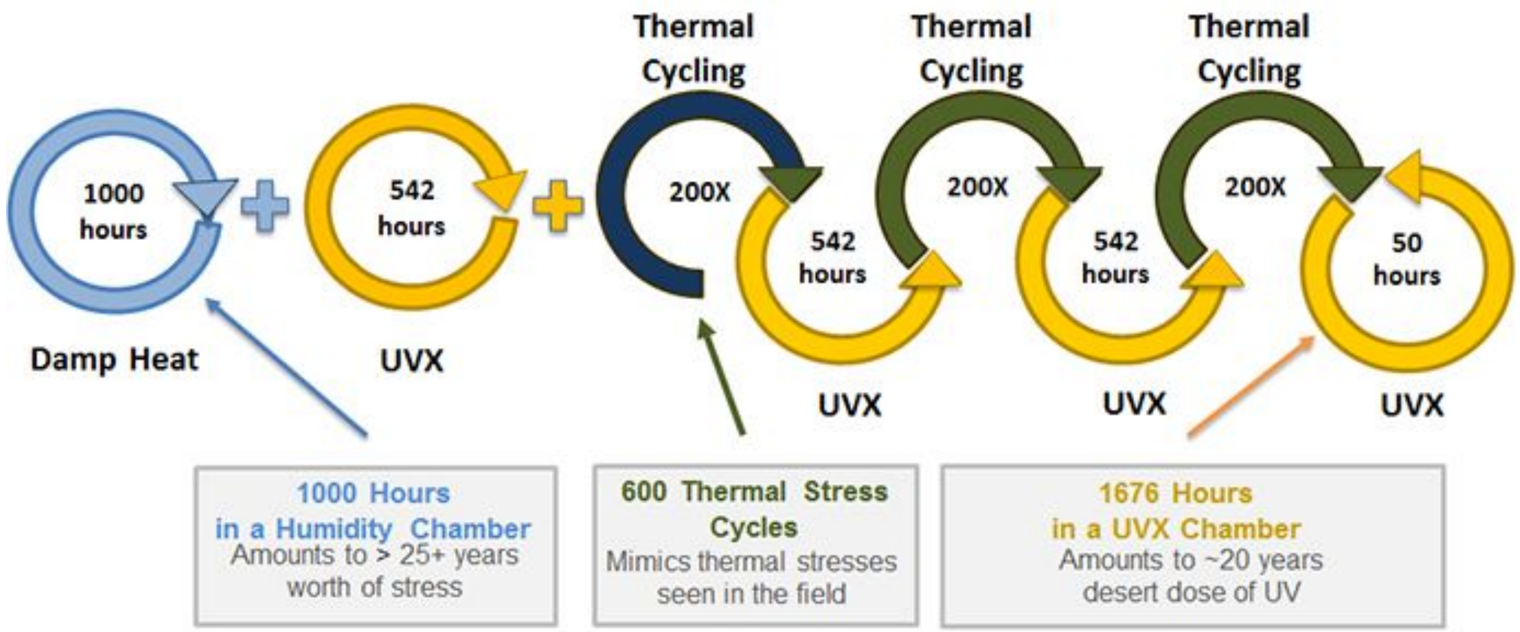
Combines some stressors together, but not all

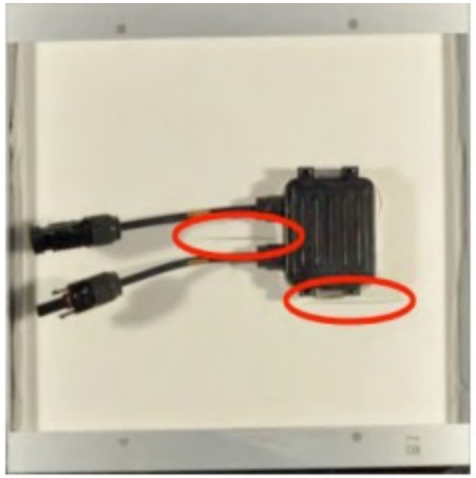
Backsheets failing in the field passed these certifications

Lacking the appropriate combinations that mimics real environments

Advances in Reliability Testing: M-AST

Module Accelerated Stress Test (M-AST)





PA Cracking

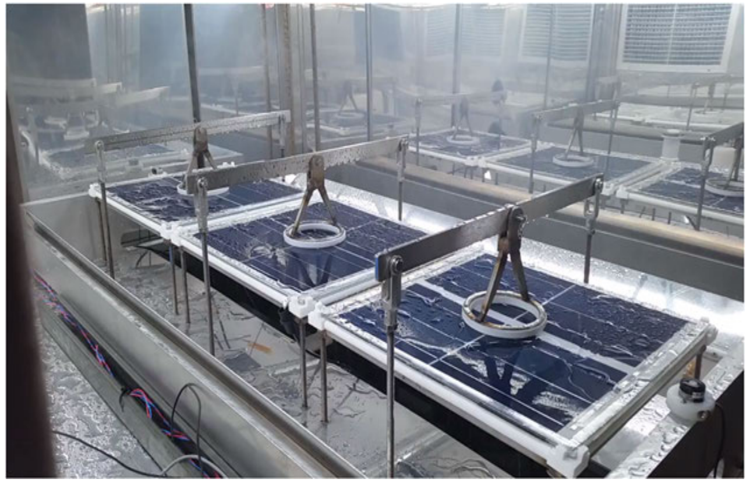
PVDF Cracking

DUPONT™

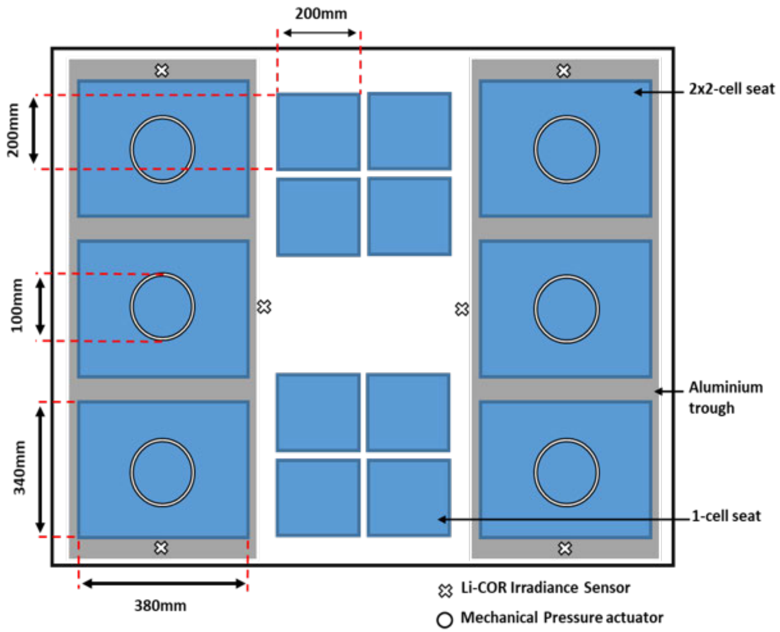
*Gambogi et al, IEEE WCPEC, 2018

Advances in Reliability Testing: C-AST

Combined-Accelerated Stress Testing (C-AST)



Internal view of C-AST chamber*



6x 4-cell mini-module
8x single-cell modules
Multiple coupons

- Rear surface module temperatures
- LI-COR Irradiance sensors
- Humidity monitoring
- Leakage current monitoring
- Module power monitoring
- IV Curve tracing
- *In situ* EL**

Modified Atlas XR-260 :

- -40°C to 90°C temperature control
- 5% to >95% relative humidity
- 2-sun Xenon-arc light exposure

- Water spray (front and back)
- Mechanical loading
- System voltage bias (±1500 V)
- Variable load resistors
- Reflective troughs (below sample plane)

Hacke, DuraMat Webinar, May 2019
Woodhouse/Hacke, DuraMat, March 2020

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

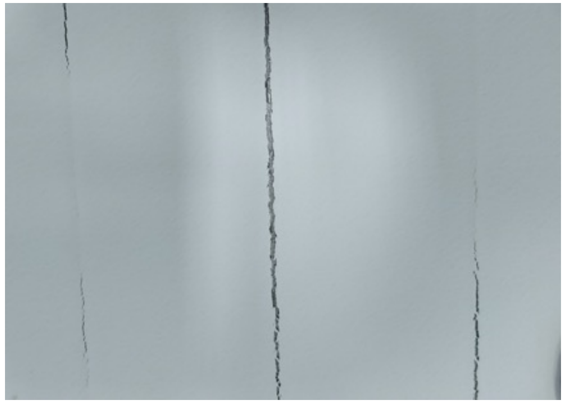
*Spataru et al, IEEE WCPEC, 2018
**Owen-Bellini et al, IEEE JPV, 2020

Advances in Reliability Testing: C-AST

Phase 1 – Tropical Summer (based on ASTM D7869)

24 hour/ cycle

- **Damp Heat**: 40°C, 95% RH, Rain Spray — **4 hours**
- **Light Soak**: 90°C, 28% RH, 1.9 Suns, System Voltage — **4 hours**
- **Freeze**: -20°C, 28% / 95% RH, Mechanical Load — **2 hours**
- **x4**:
  - 90°C, 28% RH, 1.9 Suns, System Voltage — **2 hours**
  - 40°C, 95% RH, Rain Spray — **0.5 hours**



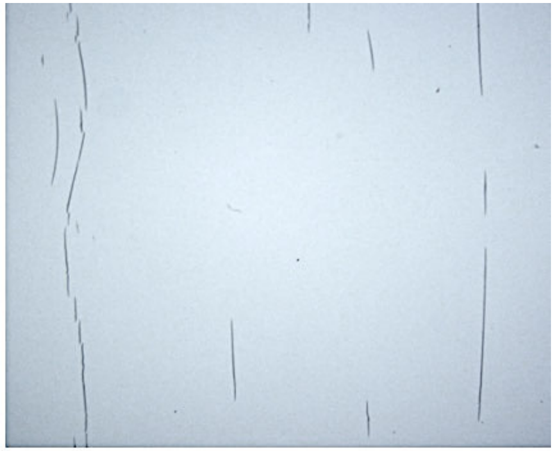
25 mm

PA Cracking after 120 days in Phase 1

Phase 2 – Multi-seasonal

6 weeks

- **Cold, Dark**: -40°C, 20% RH, Mechanical Load — **5 days**
- **x100**:
  - 0°C, 6% RH, 0.8 Suns, System Voltage — **1 hour**
  - -40°C, 20% RH, Static Load — **1 hour**
- **x200**:
  - -20°C, 20% RH, Static Load — **1 hour**
  - 90°C, 6% RH, 1.9 Suns — **1 hour**

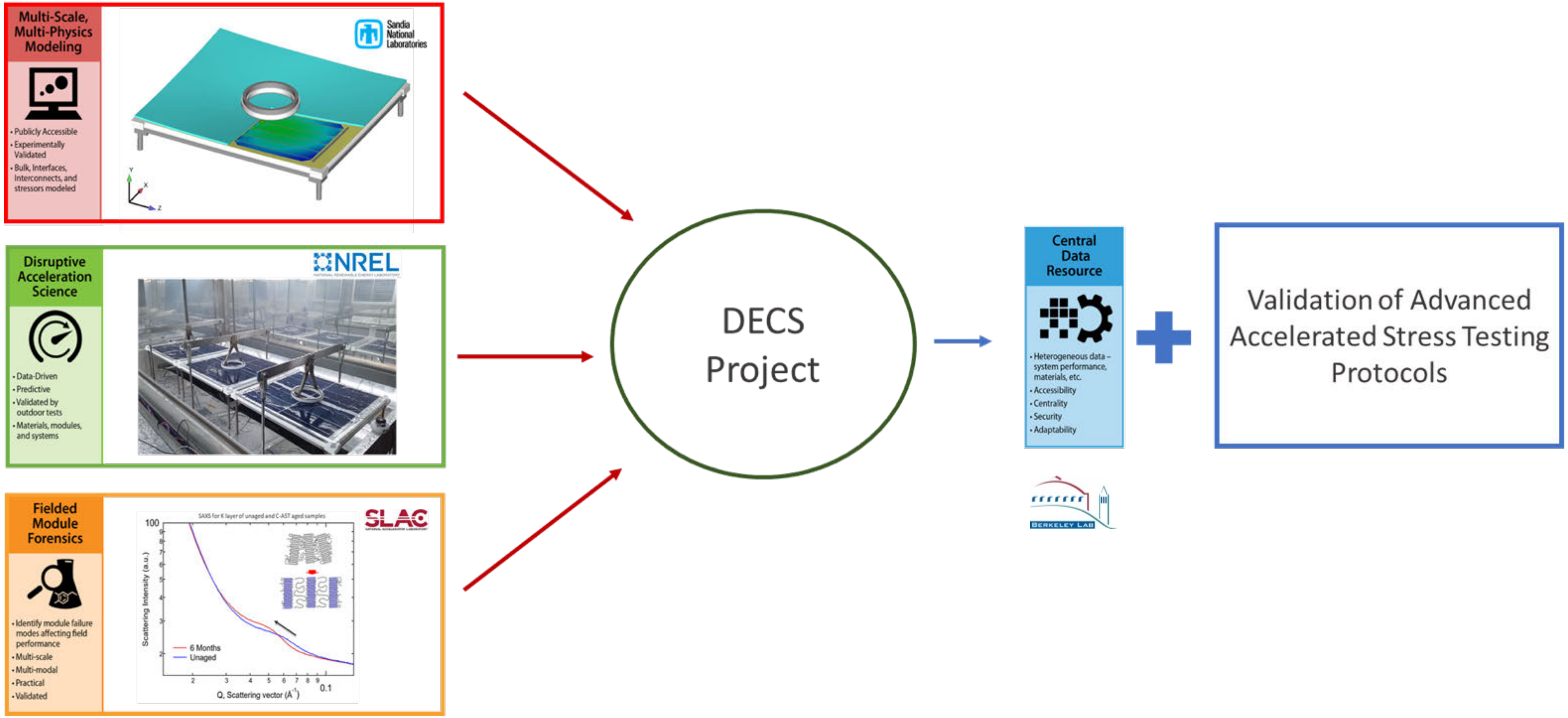


10mm

PVDF Cracking after 84 days phase 1 + 42 days phase 2

Advances in Reliability Testing: DECS Project

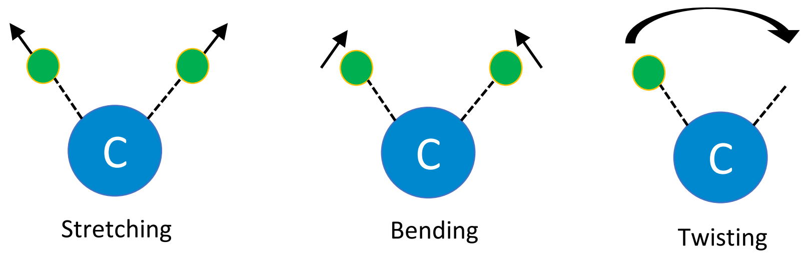
DuraMAT Early Career Scientists (DECS) Project

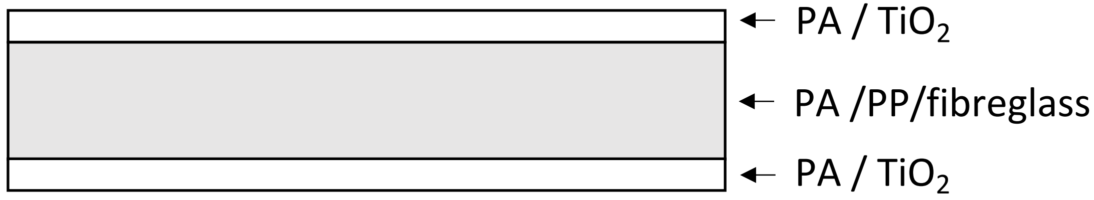


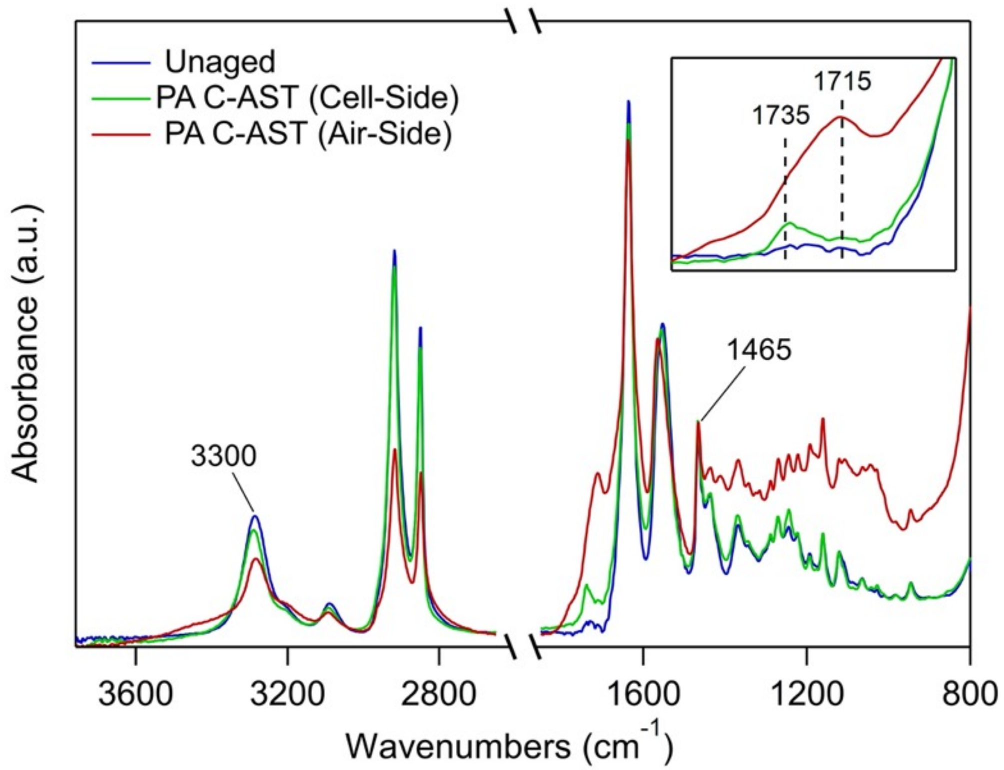
Advances in Reliability Testing: PA failure analysis

Fourier transform infrared spectroscopy (FTIR)

Uses infrared light to probe the stretching and deformation modes that are **unique** to different chemical bonds







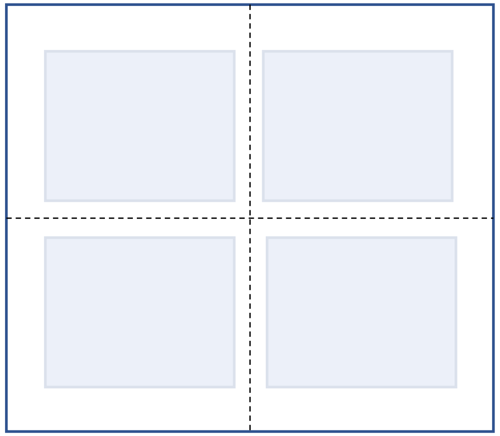
- Broadening of bands between 3200 and 3400 cm^{-1} suggests the formation of hydroxylated products and primary amines
- Increase in the peak at 1715 cm^{-1} suggests formation of carboxylic acids associated with photo-oxidation

Advances in Reliability Testing: Field-aged PA

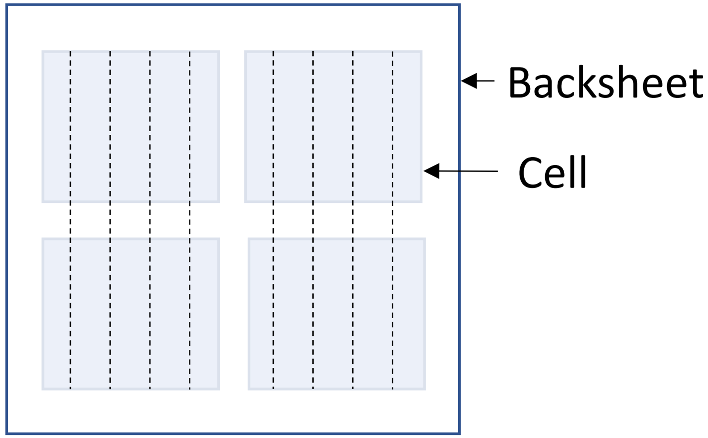
60-cell modules from the field with PA backsheet

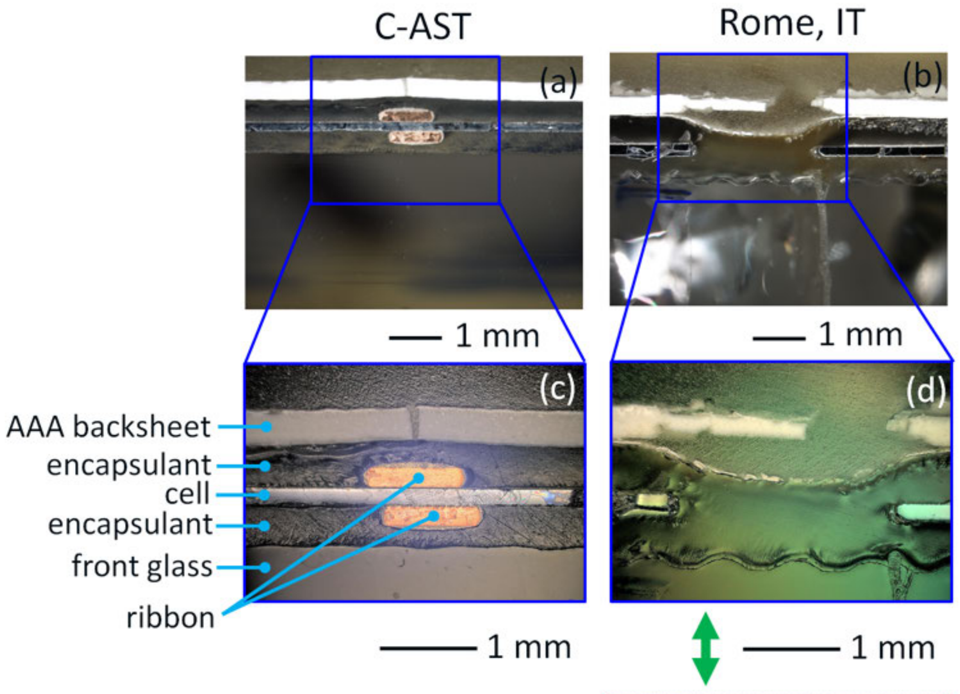
Location	Deployment Time	Features
Tonopah, USA	3	Cracking over cell tabs
Changshu, China	4	Cracking over cell tabs
Rome, Italy	5	Cracking between cells
Bergamo, Italy	6	Cracking between cells

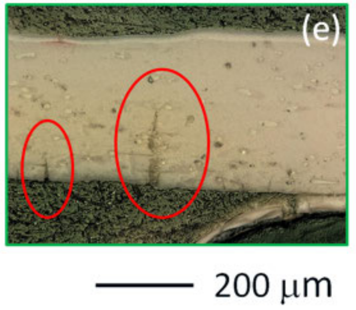
Cracking between cells



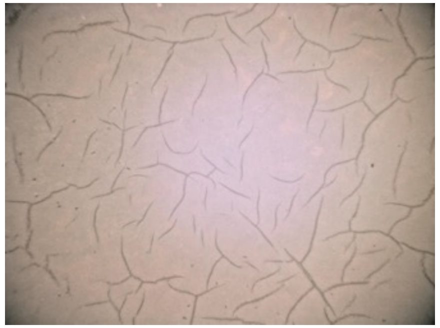
Cracking over cell tabs







Outer layer microcracking of PA



Advances in Reliability Testing: Field-aged PA

Polyamide

Location	Deployment Time	Features
Tonopah, USA	3	Cracking over cell tabs
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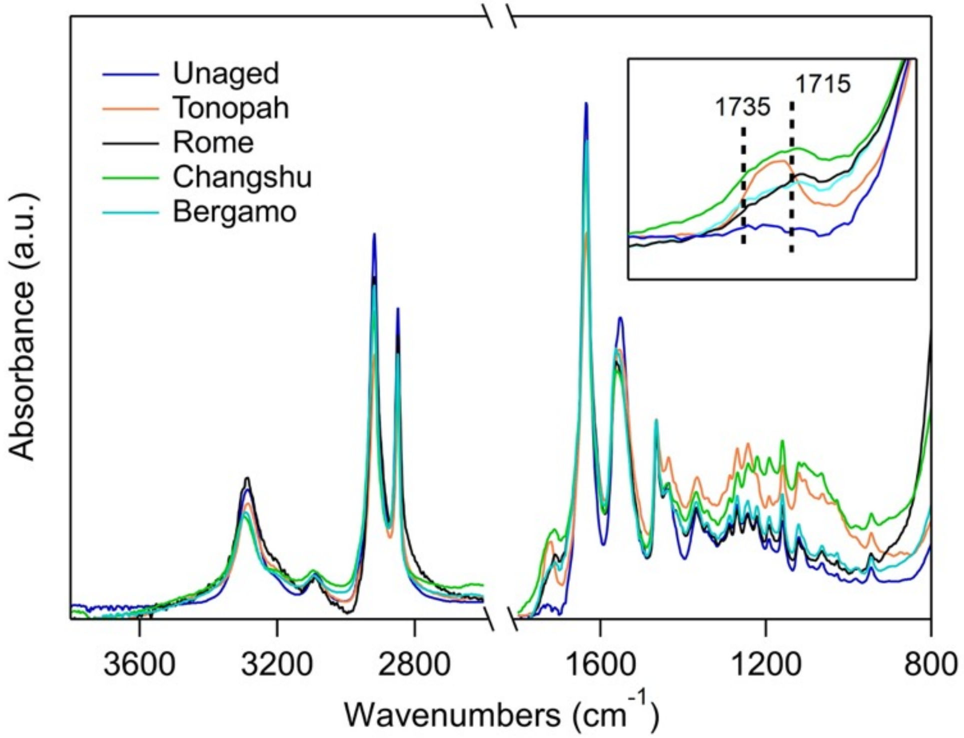
FTIR Measured from Outer layers

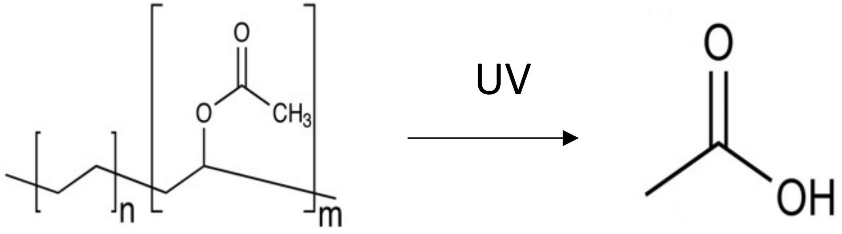


Fielded modules had UV blocking EVA

Suggests inner layer cracking could be a different mechanism

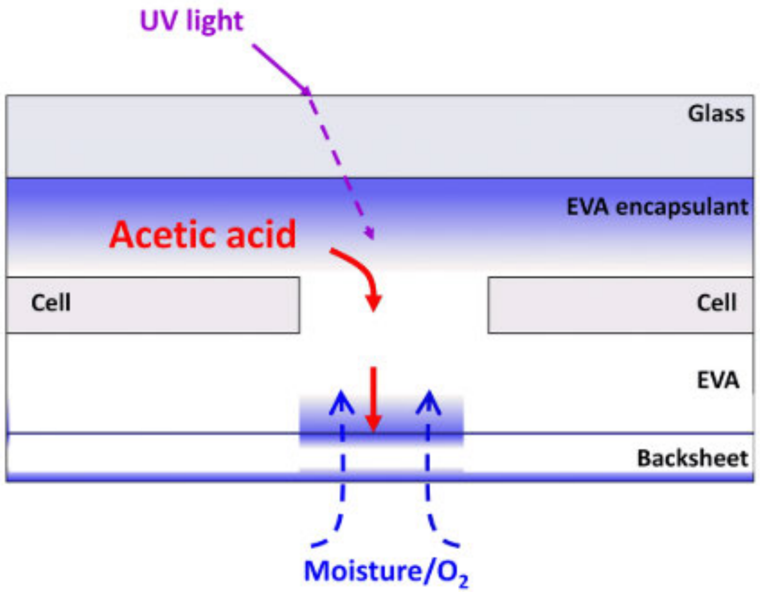
- See similar increases in peak intensity at 1715cm, suggesting that the same photo-oxidation mechanism is happening

Advances in Reliability Testing: Acetic Acid interaction

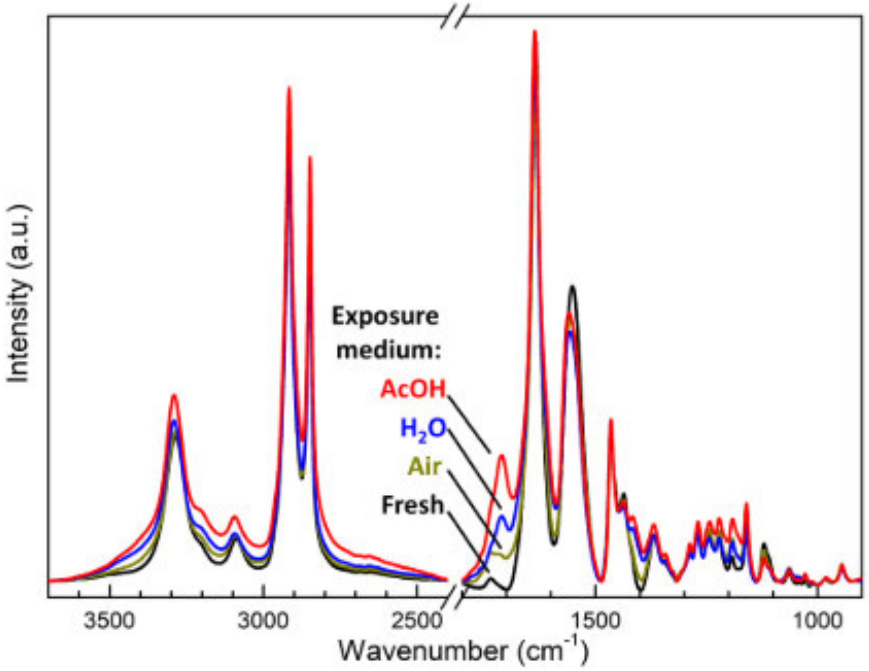


EVA

Acetic Acid*



**



C-AST samples had known good EVA

Field modules cracking from inner side likely had a lower quality EVA with higher acetic acid generation

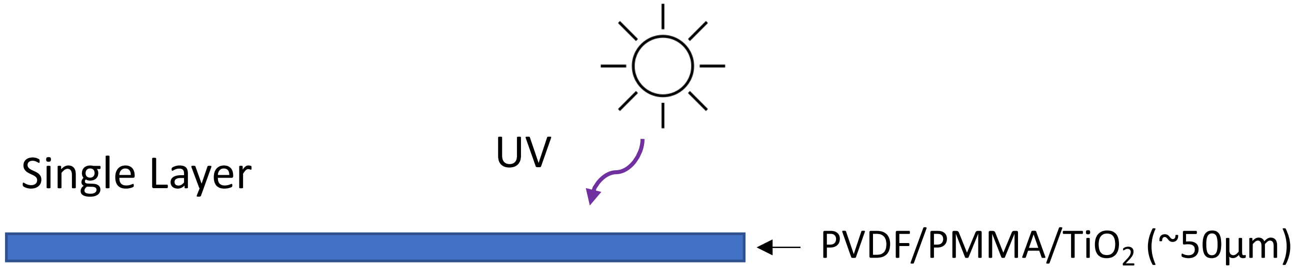
Material combinations matter

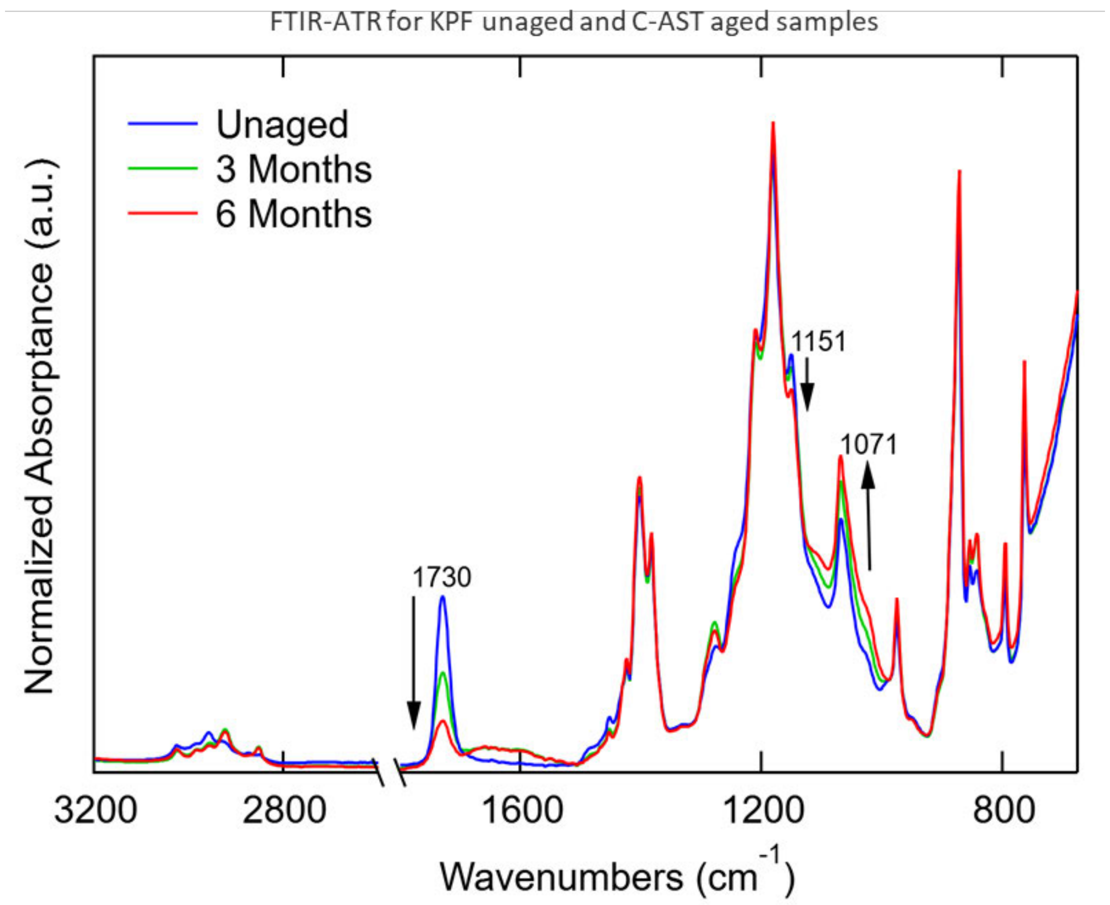
*Kempe, Sol. Mat., 2007
**Lyu et al, Prog. in PV, 2020

Advances in Reliability Testing: PVDF Failure Analysis

Polyvinylidene fluoride (PVDF)

- 1730cm^{-1} carbonyl group and 1151cm^{-1} ester are associated with PMMA
- Decreasing 1730cm^{-1} and 1151cm^{-1} suggests depletion of UV-induced degradation of PMMA*
- Increasing 1071cm^{-1} symmetric stretching of CF_2 and suggests a crystalline phase change is occurring, however, this could be either α, β or γ phase**

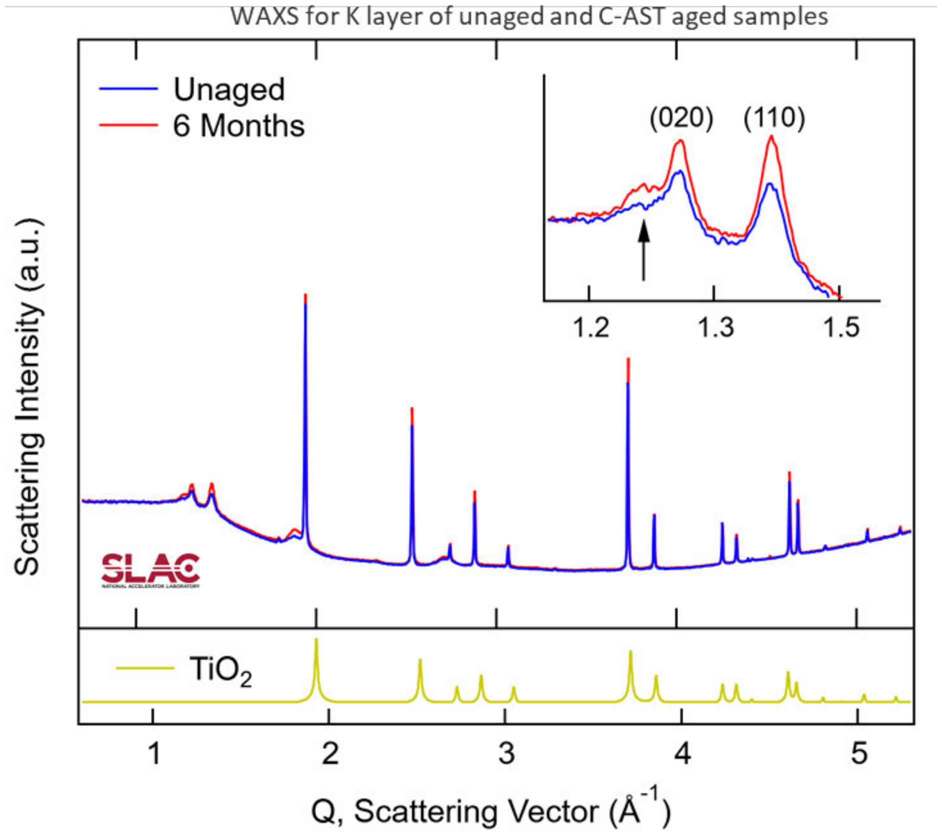




*Miller, Sol. Mat., 2011
**Cai et al, RSC Adv., 2017

Advances in Reliability Testing: Wide-angle X-ray Scattering

Polyvinylidene fluoride (PVDF)

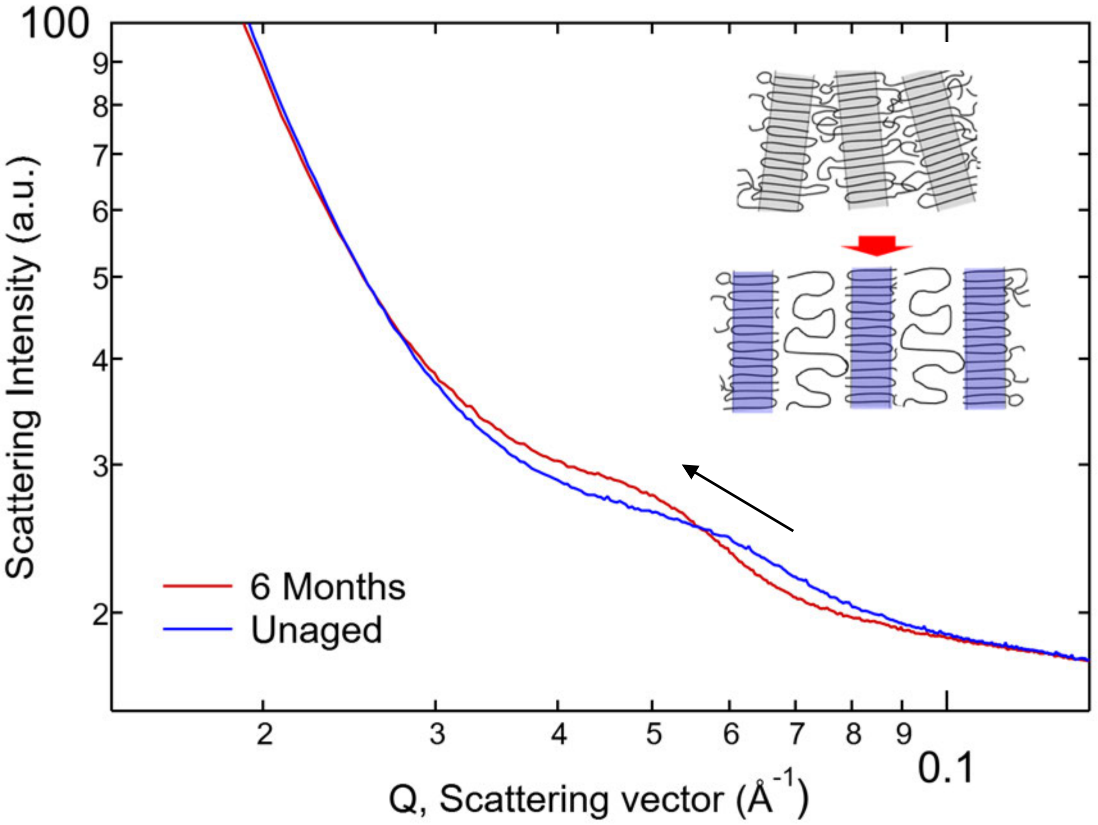


PVDF/PMMA/TiO_2 layer separated from rest of the backsheet

- Wide-angle X-ray scattering (WAXS) collected at Stanford Synchrotron Radiation Lightsource (SSRL) at SLAC
- Allows determination of the crystalline structure of polymer samples through analysis of diffraction of X-rays caused by the crystal structures
- Inset compares aged PVDF to unaged PVDF at peaks (020) and (110), shoulder associated with α-phase crystal structure
- Suggests increase in α-phase content and an overall increase in crystallinity

Advances in Reliability Testing: Small-angle X-ray Scattering

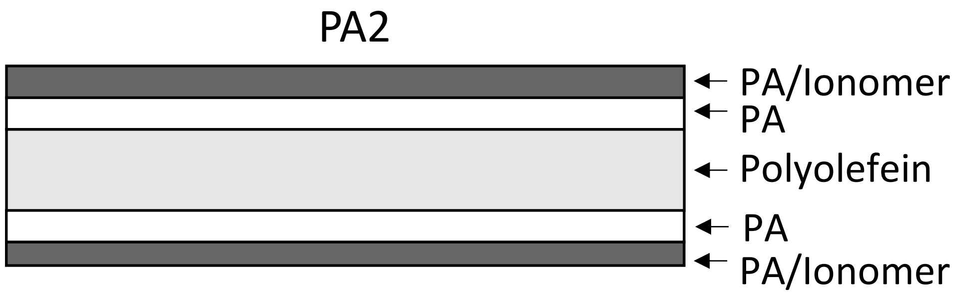
Polyvinylidene fluoride (PVDF)

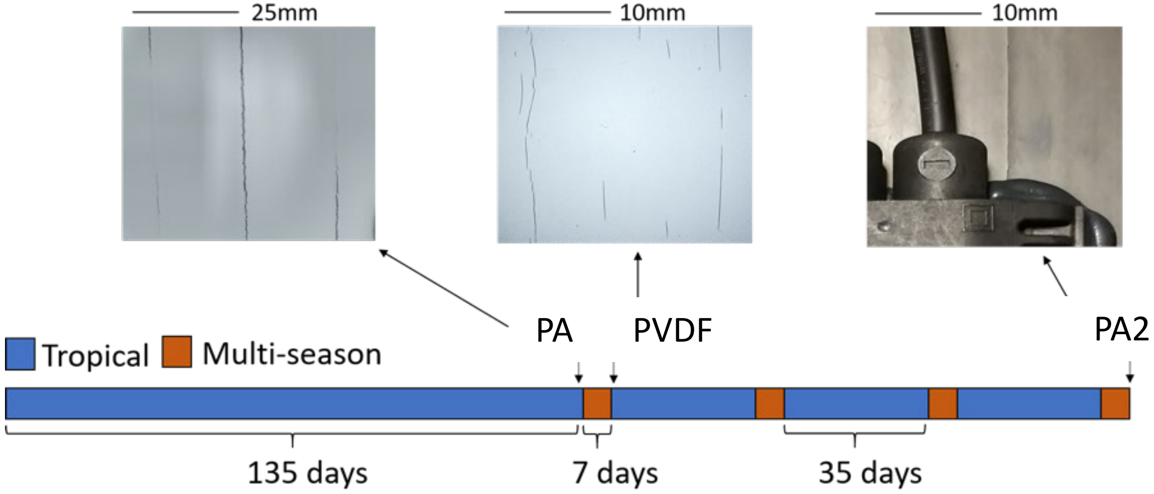


- Small-angle X-ray scattering (SAXS) collected at Stanford Synchrotron Radiative Lightsource (SSRL) at SLAC
- SAXS probes the lamellar packing distance between the crystalline and amorphous domains of the polymer
- The lamellar feature of PVDF shifts towards smaller *Q* values and becomes slightly more pronounced after aging
- This suggests that the lamellar packing distance becomes larger and more well-defined, consistent with the increased crystallinity observed in WAXS

Yuen et al, Prog. In. PV, 2019

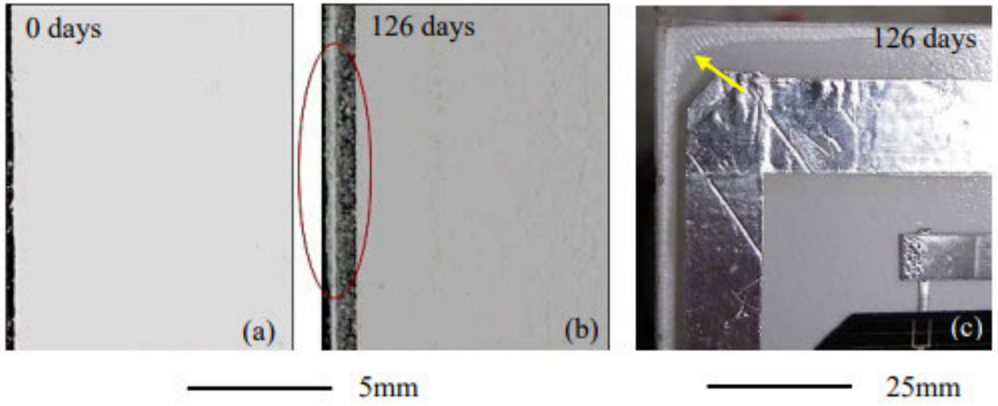
Advances in Reliability Testing: Backsheet design





C-AST testing

PA/PA/PA backsheet shrinkage



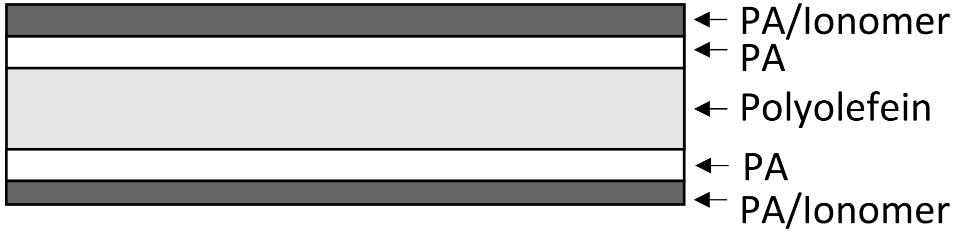
Talc was used for dimensional stability in PA2 backsheet

No shrinkage was observed

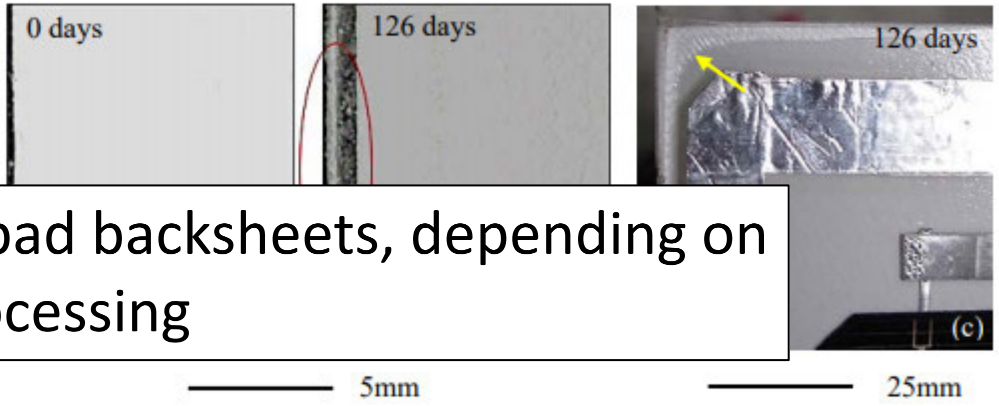
*Owen-Bellini, IEEE PVSC, 2020

Advances in Reliability Testing: Backsheet design

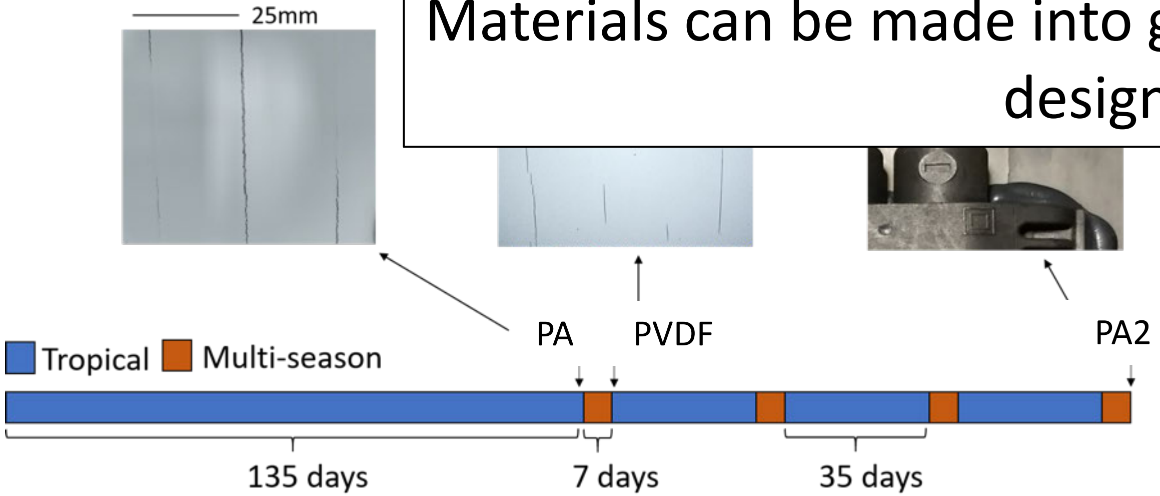
PA2



PA/PA/PA backsheet shrinkage



Materials can be made into good or bad backsheets, depending on design and processing



C-AST testing

Talc was used for dimensional stability in PA2 backsheet

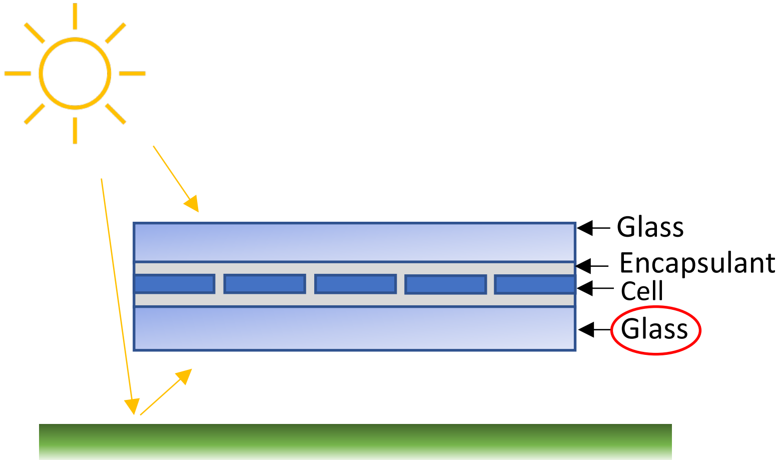
No shrinkage was observed

*Owen-Bellini, IEEE PVSC, 2020

Outline

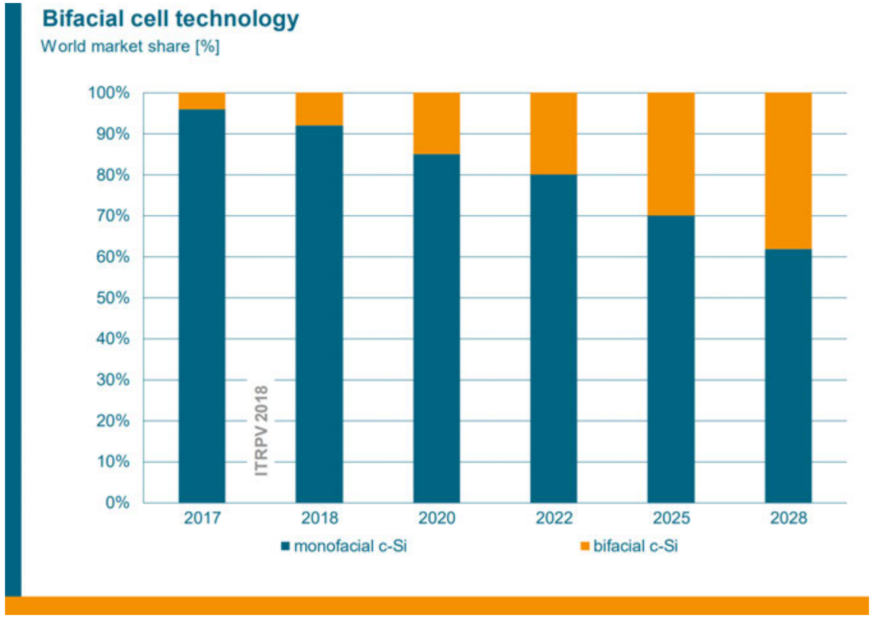
- What and why?
- Types of Backsheets
- Recent issues
- Advances in Reliability Testing
- Emerging technologies
- Summary

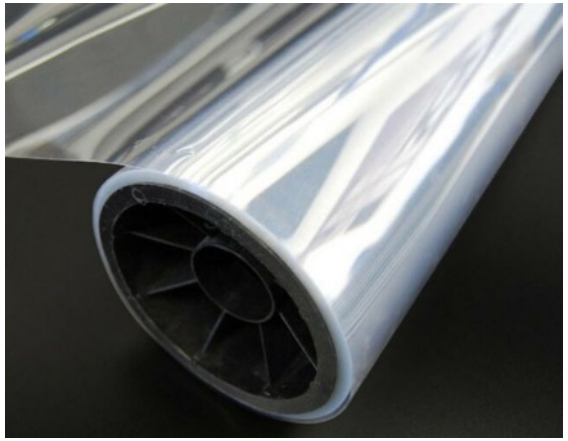
Emerging Technologies: Bifacial PV



Potential Issues

- **Loss of optical transmission?**
- **Unforeseen material interactions?**
- **Cracking?**





Transparent backsheets

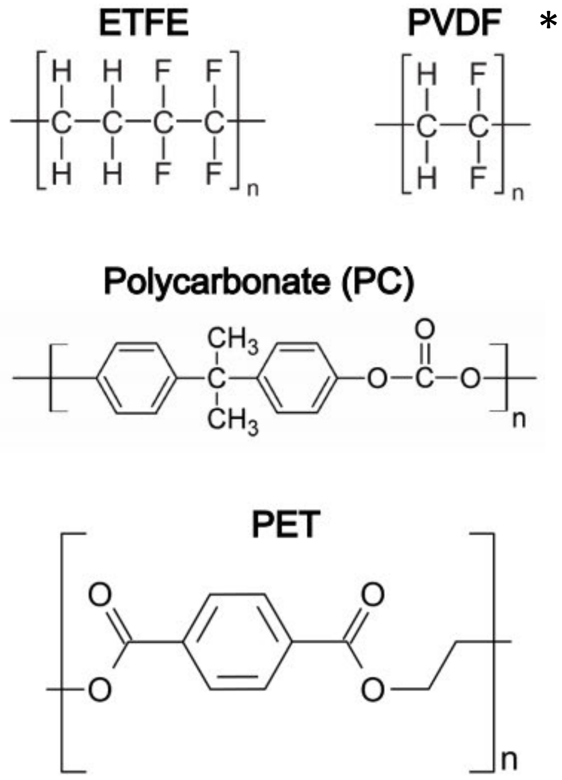
- Reduced weight
- Lower installation costs
- Breathability
- Reduced potential-induced degradation (PID)?

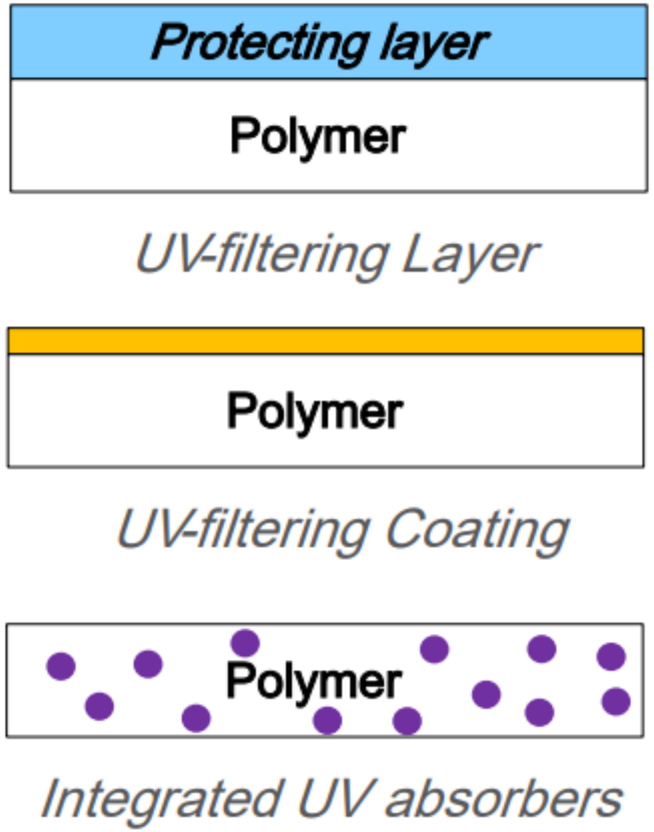
Emerging Technologies: Frontsheets

- Light-weight, flexible modules
- Reduce installation costs

ETFE (Positive control) →
Non -PET options
PET w/ UV filtering layer →
PET w/ UV filtering coating
PET w/ integrated UV absorbers
Non -stabilized PET (Negative control)

#	Material	Cost
1	ETFE	High
14	PVDF	High-Med
15	Acrylic-coated PC	High-Med
3	Fluoropolymer-laminated PET	Medium
13	Fluoropolymer-coated 2 PET	Medium
4	Acrylic-coated 3 PET	Med-Low
9	Acrylic-coated 1 PET	Med-Low
11	Acrylic-coated 2 PET	Med-Low
12	Fluoropolymer-coated 1 PET	Med-Low
6	UV-blocker 1 (High) PET	Med-Low
8	UV-blocker 2 (High) PET	Med-Low
5	UV-blocker 1 (Med) PET	Low
7	UV-blocker 2 (Med) PET	Low
2	Untreated PET 1	Lowest
10	Untreated PET 2	Lowest





*Ng et al, PVRW, 2020
**Kempe, PVSC, 2020

Outline

- What and why?
- Types of Backsheets
- Recent issues
- Advances in Reliability Testing
- Emerging technologies
- Summary

Summary

- Weaknesses in backsheets can be identified prior to deployment with the right testing
- It is important to test material combinations – *not just components*!
- Appropriate materials characterization can help to inform how to address weaknesses in backsheet designs
- Polymers can be used to make good or bad backsheets depending on design and processing

Combining advanced stress tests with appropriate materials analysis can help to develop more robust materials with longer service lives

Upcoming DuraMAT Webinars

June 2020 – **A Pathway To Reduce Operations and Maintenance Expenses by Mitigating Cracked Solar Cells and Hot Spot Formation**

- Presented by Sang Han, Osazda and University of New Mexico & Mike Woodhouse, NREL

July 2020 – **Multi-Scale Modeling of PV Module Electrically Conductive Adhesive Interconnects for Reliability Testing**

- Presented by Nick Bosco, NREL

Register at duramat.org/webinars.html

Acknowledgments

Thank You

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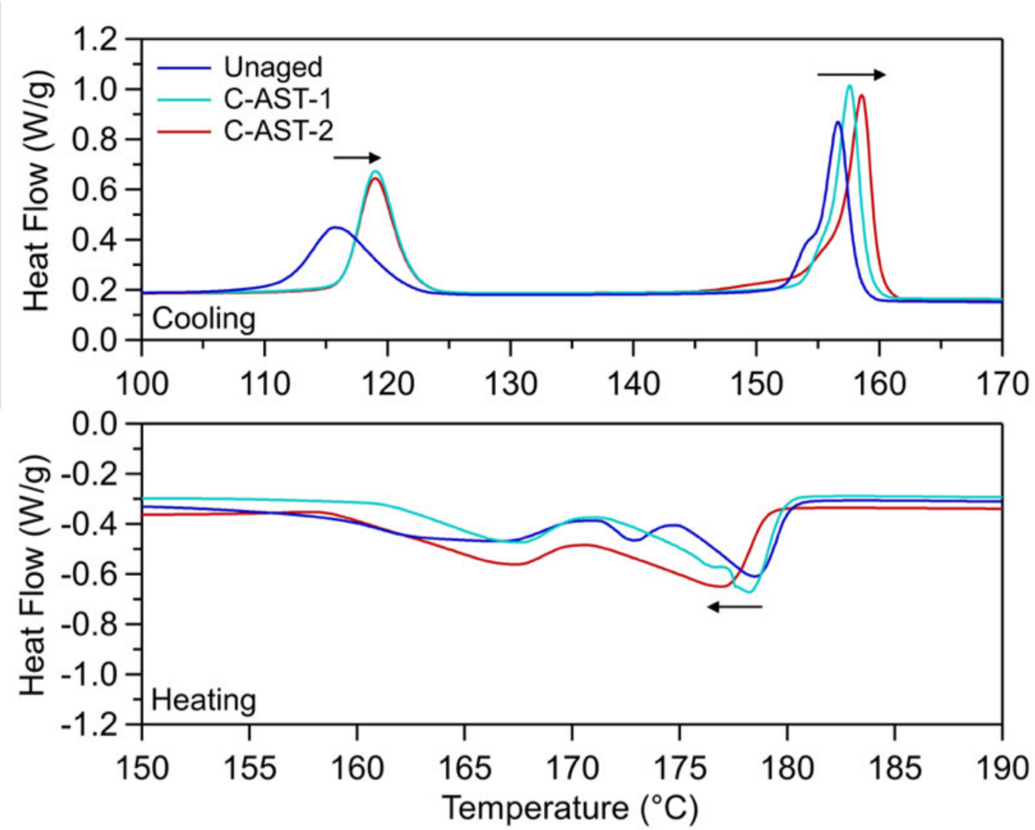
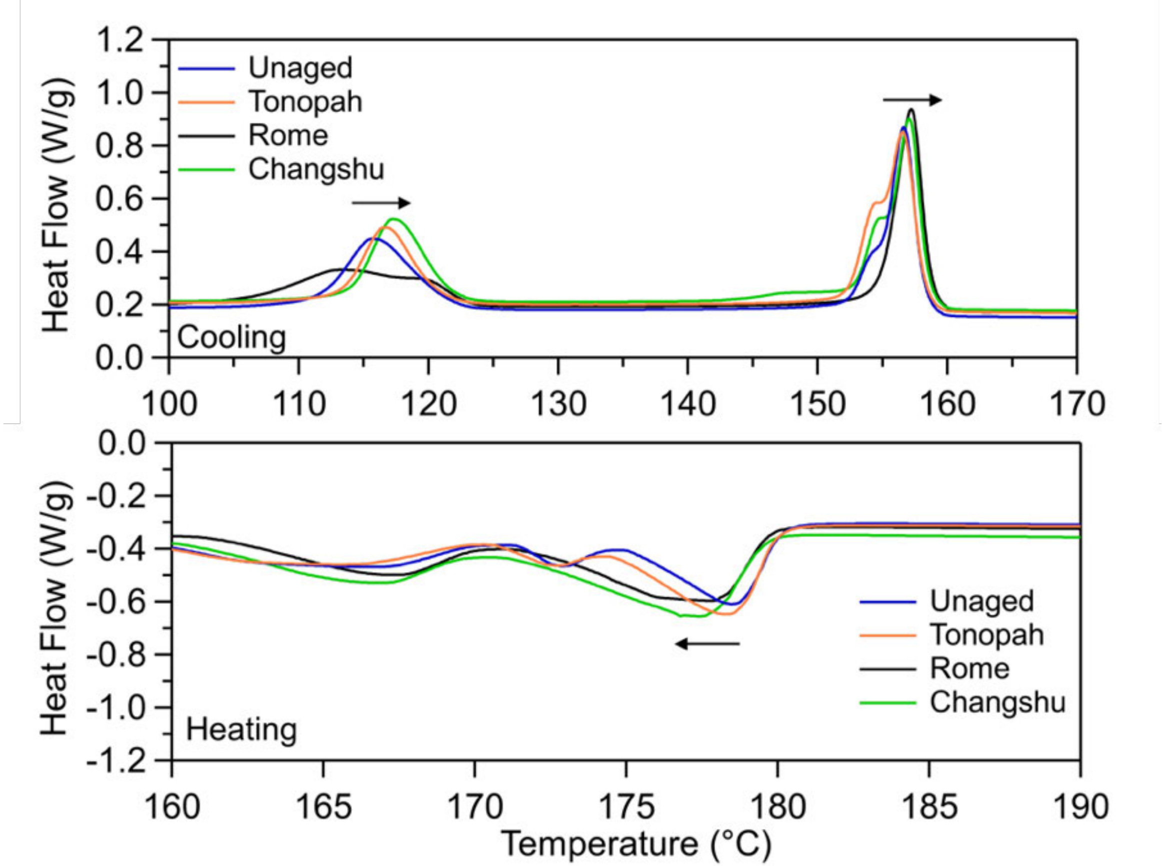
Chris Thellen, Andreas Rothacker
Tomark-Worthen

PVQAT TG3/5 Members

AAA DSC



Unaged
C-AST-1
C-AST-2
Cooling
Heating
Heat Flow (W/g)
Temperature (°C)



Unaged
Tonopah
Rome
Changshu
Cooling
Heating
Heat Flow (W/g)
Temperature (°C)