# Advancing Reliability Assessments of Photovoltaic Modules and Materials through Combined-Accelerated Stress Testing

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# Content

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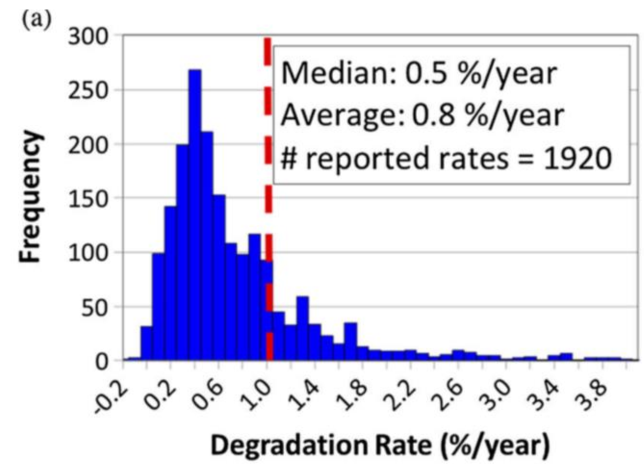
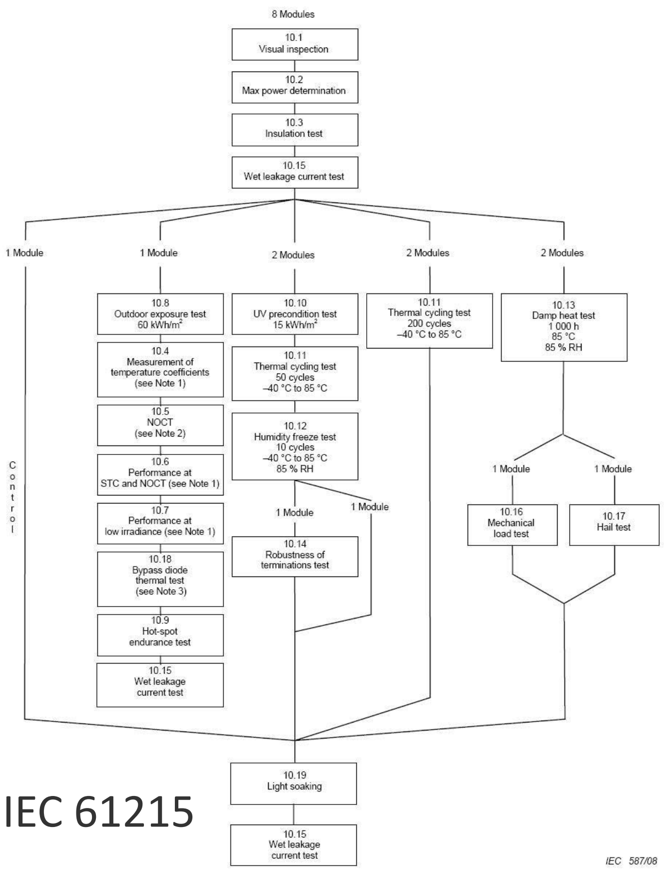
# Introduction

**Current state-of-the-art testing:**

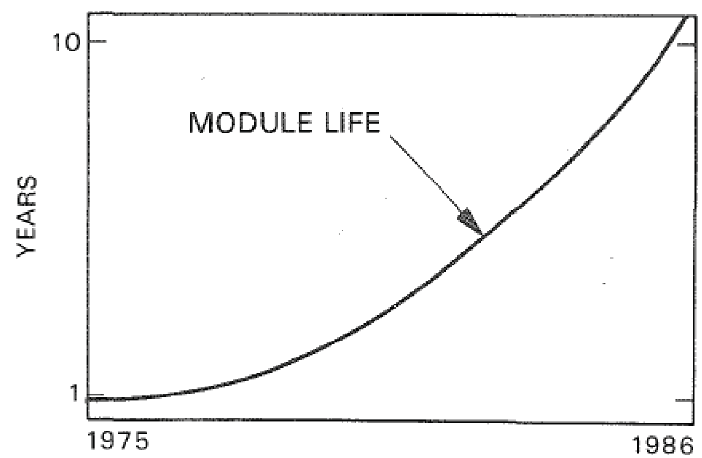
- Mechanism-specific tests
- Targets known failure mechanisms
- Applies, at most, two stress factors in combination
- Not always relevant to modern module architectures




Jordan et al, "*Photovoltaic Degradation Rates—an Analytical Review*", Prog. In Photovoltaics, 2013




IEC 61215




*Typical module lifetimes were less than 1 year but are now estimated to be greater than 10 years. (Ten-year warranties are now available.)*

# Introduction

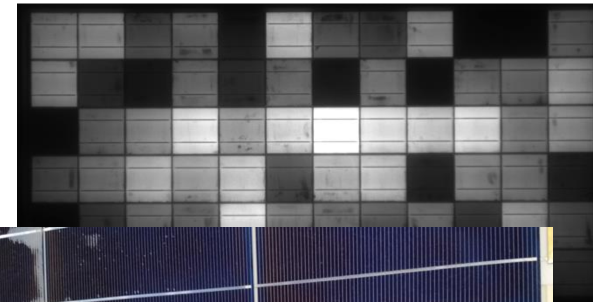
Field failures missed by conventional tests:

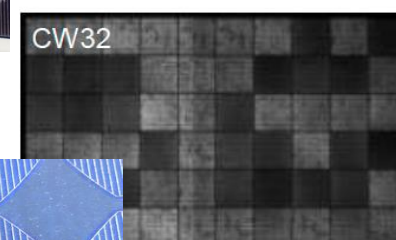
**Potential-Induced Degradation (PID):**
System voltage, humidity, temperature, light, soiling

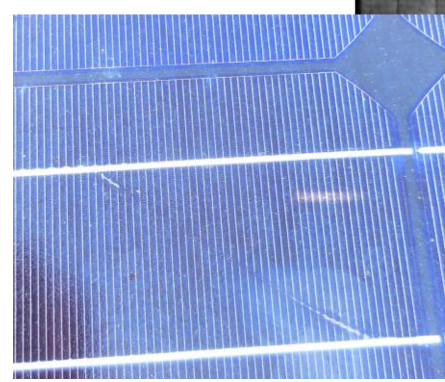
**Grid finger corrosion & delamination:**
System voltage, humidity, temperature, light, soiling

**Light and elevated temperature induced degradation (LeTID):**
Light, elevated temperature, current

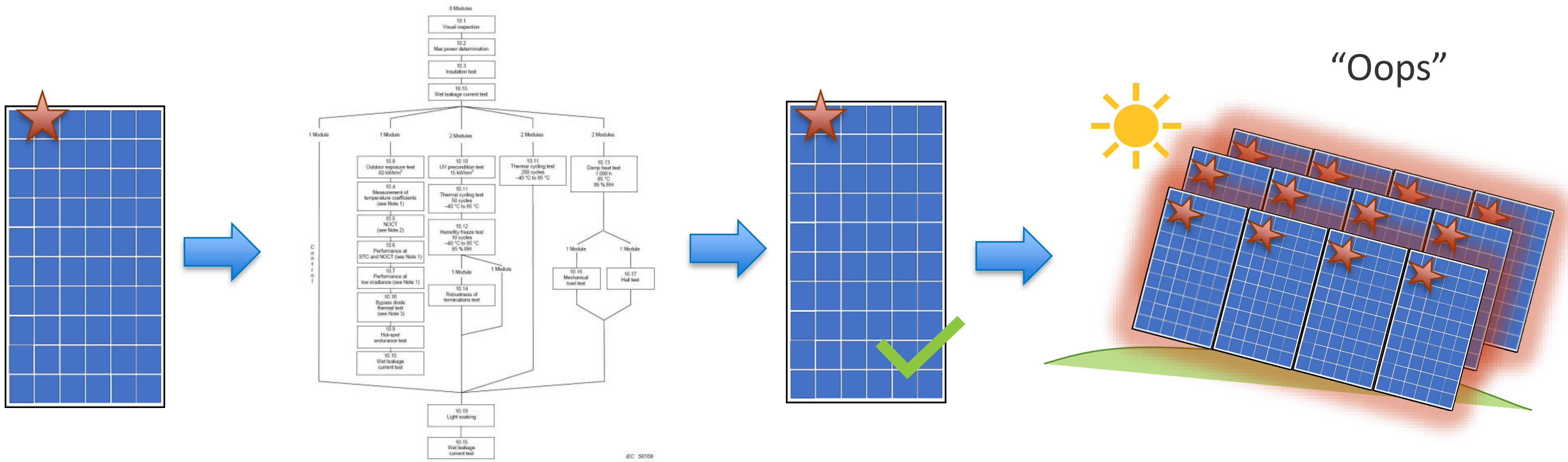
**Snail trails -> delamination:**
Mechanical loading, UV, electric field, moisture, impurities

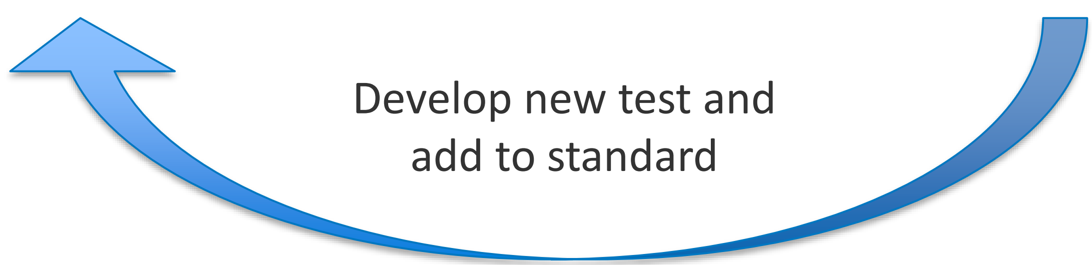






# Introduction




Losses have already been made

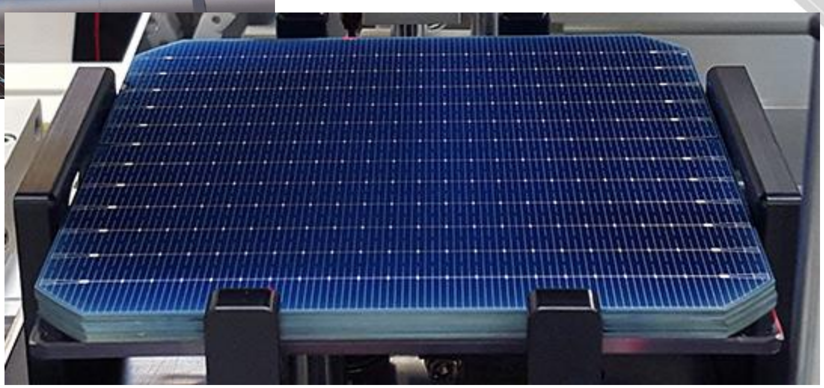
Slow process

# Introduction

The industry changes quickly…

Shingle cells with ECA

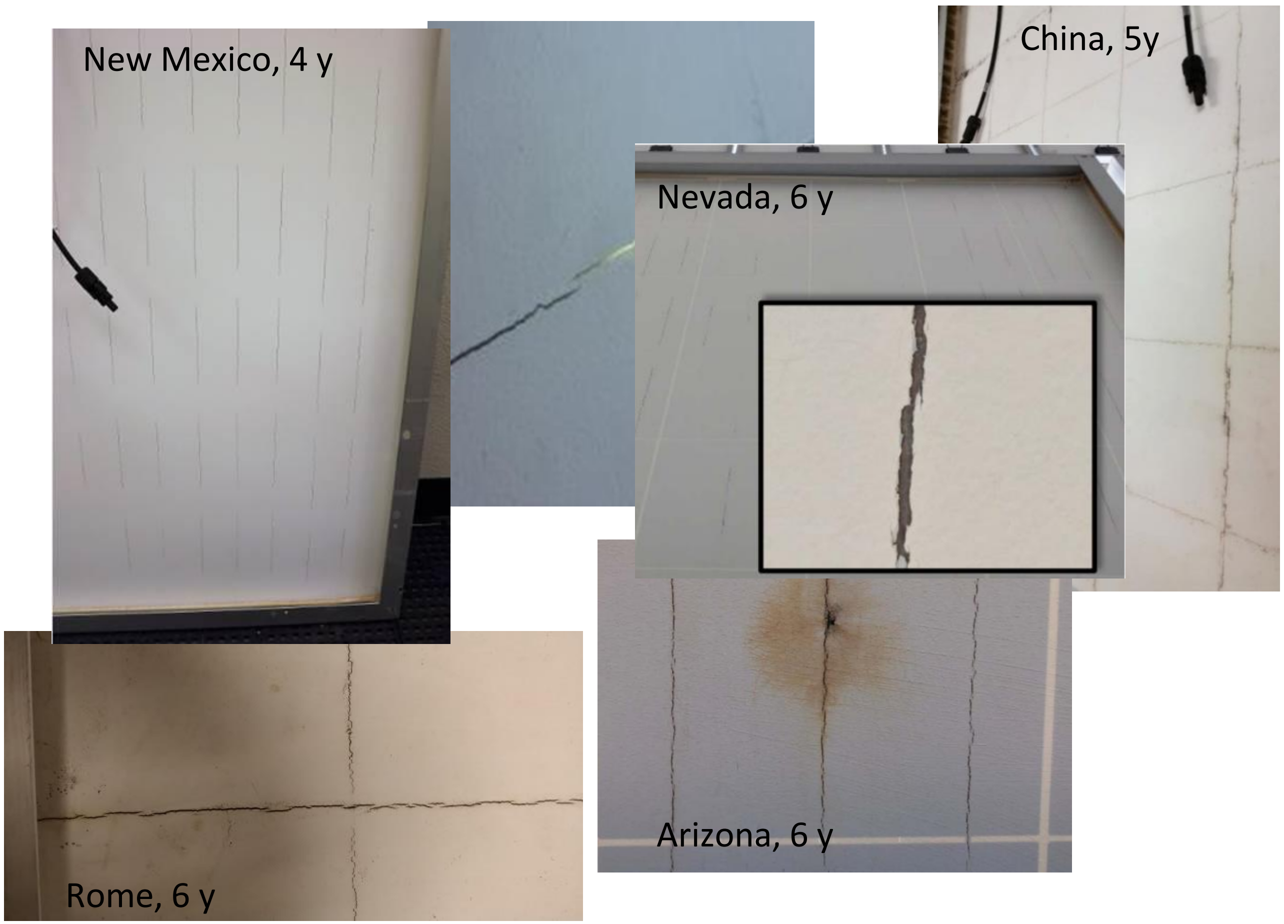
Bifacial modules with transparent backsheets



Multi-busbars, smartwires

# Introduction

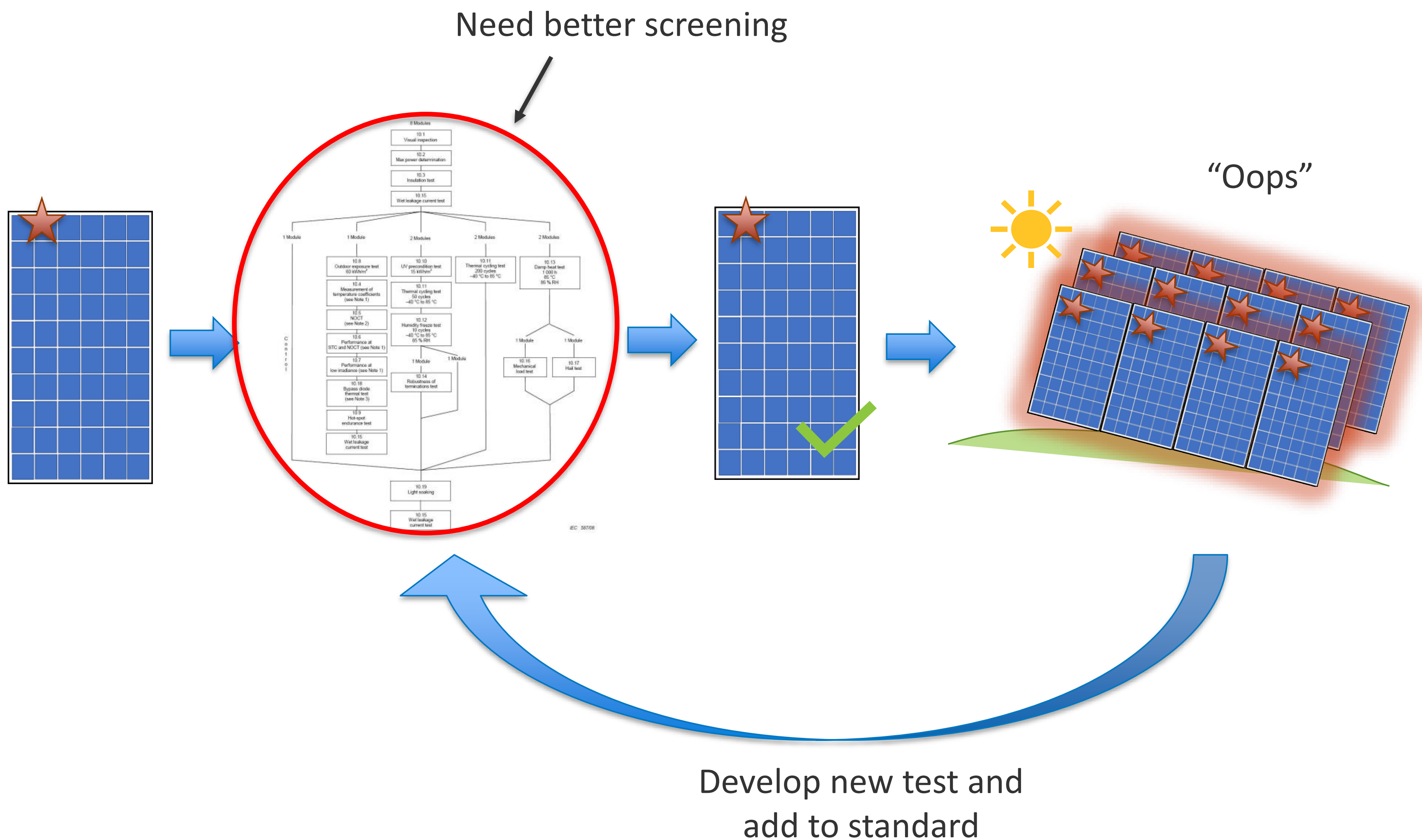
AAA backsheet disaster




- Upwards of 12GW deployed
- 90% failure rate in 6 years
- **Despite passing certification**
- **You cant always know what to test for**

Roy Choudhury et al "*Material Degradation Impacting performance of PV modules in the field*" NREL PV Reliability Workshop 2019

# Introduction



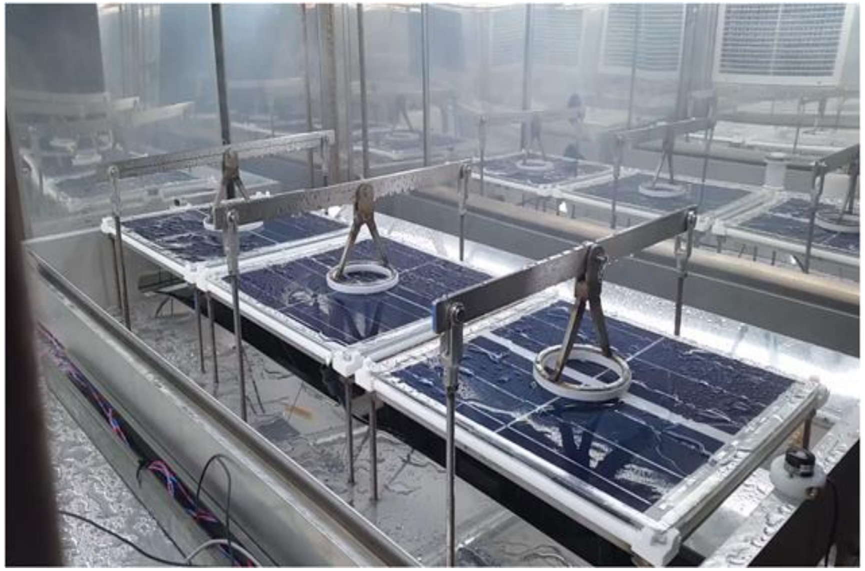
# Content

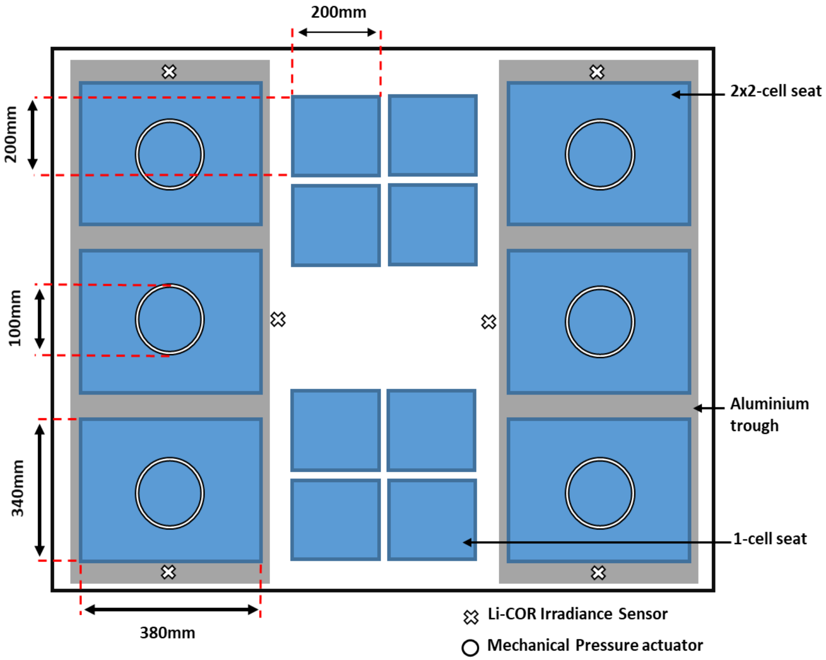
# Introduction

## Combined-accelerated stress testing (C-AST)

- **Combines multiple stress factors of the natural environment into a single test**
- **Agnostic testing philosophy – not targeting specific mechanisms**
- **Allows discovery of mechanisms in new module designs / materials *before deployment***
- **Improved risk assessment**

# Combined-Accelerated Stress Testing





Top-down view

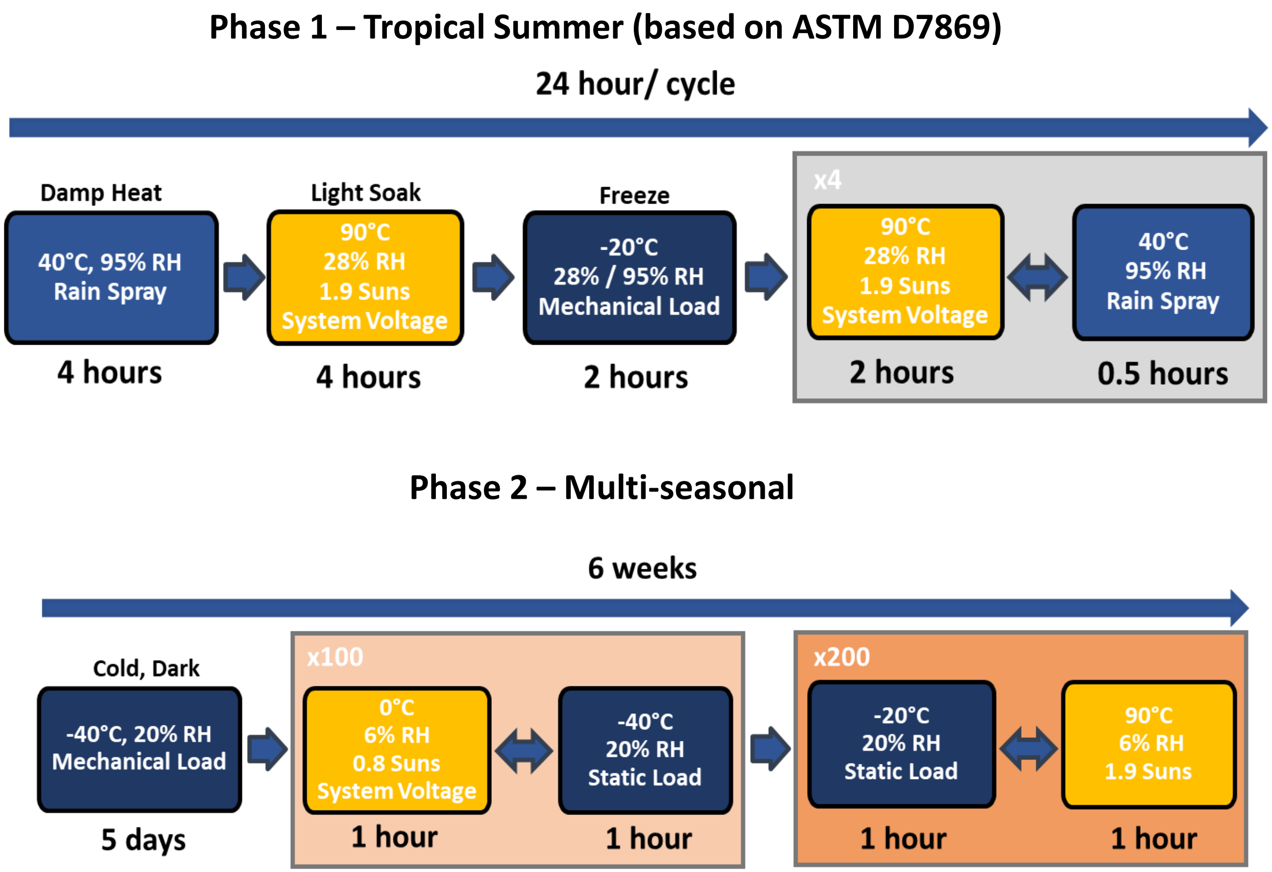
Modified Atlas XR-260 :

- -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)
- Reverse Bias
- Variable load resistors
- Reflective troughs (below sample plane)

Up to 6 4-cell mini-module + 8 single-cell modules + coupons

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

# Combined-Accelerated Stress Testing



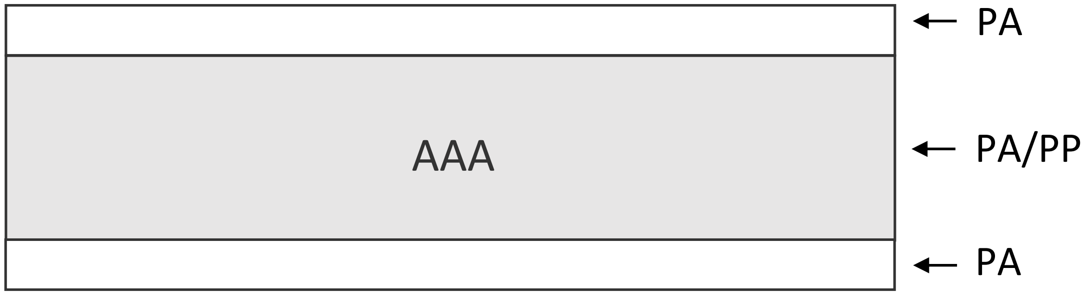

- Uses the upper statistical limits observed in the natural environment

- Does not subject samples to any conditions that could be deemed unrealistic

*"C-AST is like a bad day, everyday"*

# Content

# Backsheet Testing - AAA

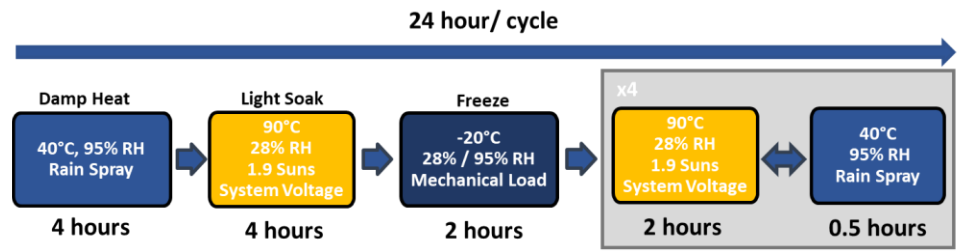



- Three-layer co-extruded backsheet
- Inner and outer layers composed of nylon-12 polyamide (PA) with $TiO_2$ white pigment
- Core layer PA and polypropylene (PP) blend with glass fibre filler
- Known bad material with widespread failures across multiple climates manifesting as overt cracking

# Backsheet Testing - AAA

25 mm

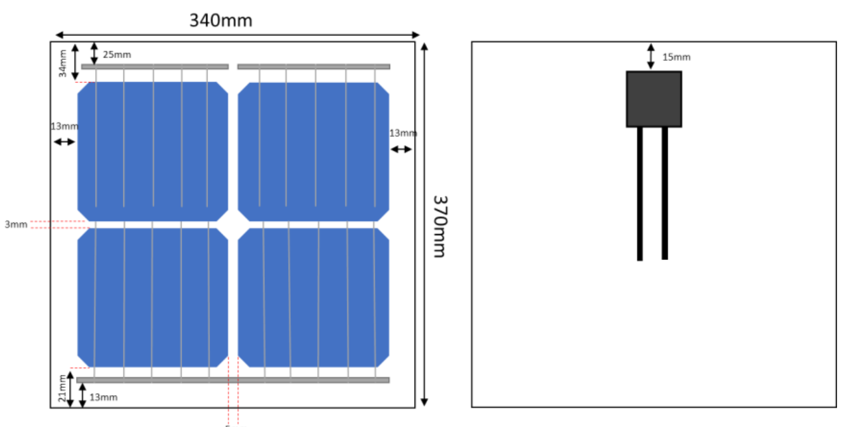
### Phase 1 – Tropical Summer (based on ASTM D7869)



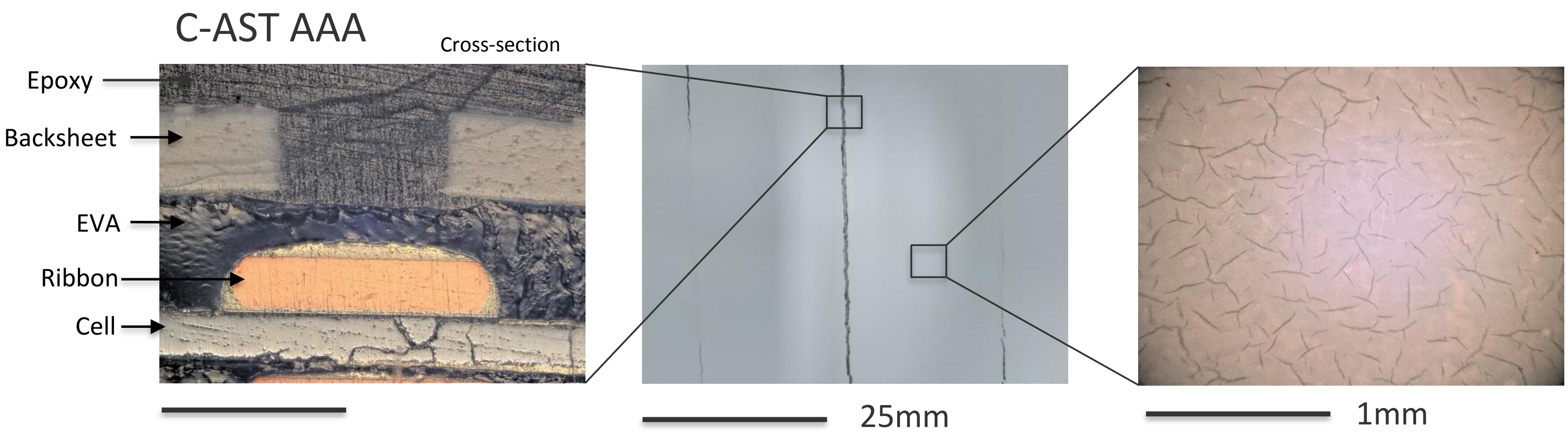

Macro cracking over underlying features (cell tabbing) following phase 1 (tropical) 4.5 months (cumulative)

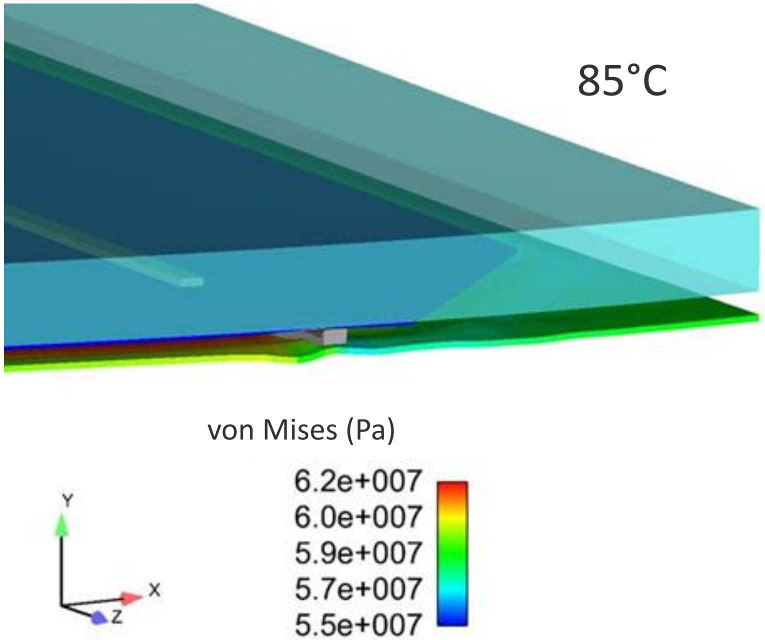
Important result since AAA cracking could not be reproduced in the standard stress tests

If we had this test in the past, 12 GW of AAA would probably have never made it to the field



# Backsheet Testing - AAA



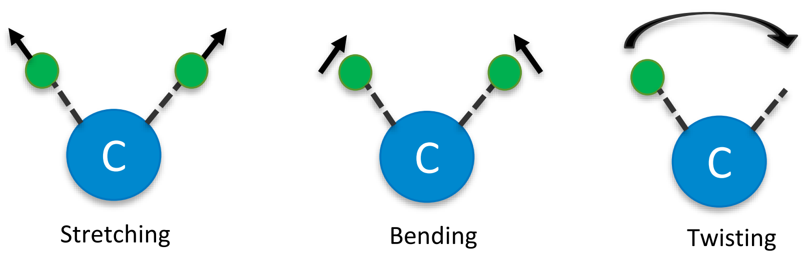




- Micro-cracks developed on the surface develop into macro-cracks at local stress concentrations
- Cell tabbing causes these stress concentrations on the backsheet

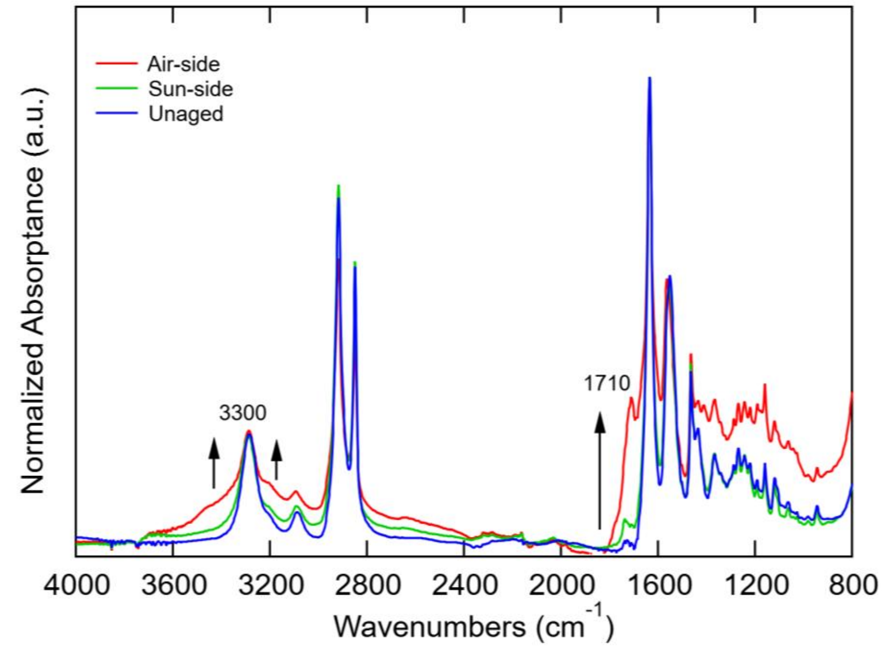
# Backsheet Testing - AAA

Fourier transform infrared spectroscopy (FTIR)

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



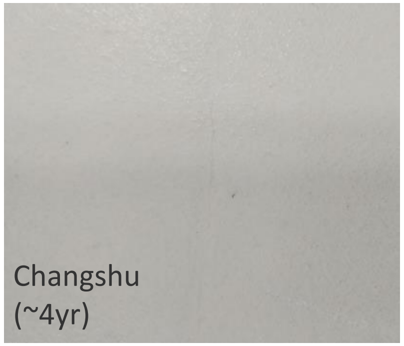

Air-side exposed to UV
Sun side shaded from UV




- Broadening of bands between 3200 and 3400 cm$^{-1}$ suggests the formation of hydroxylated products and primary amines
- Increase in the peak at 1710 cm$^{-1}$ suggests formation of carboxylic groups and C=C bonds which are associated with photo-oxidation*

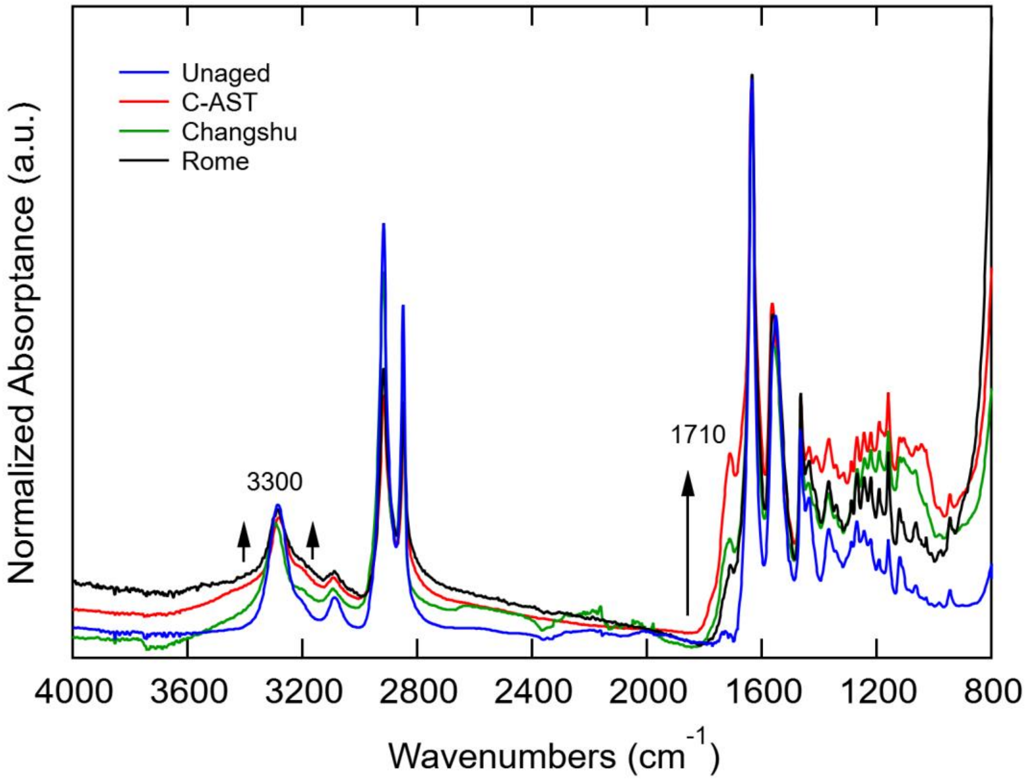
*Lyu et al "*Degradation and Cracking Behavior of Polyamide-Based Backsheet Subjected to Sequential Fragmentation Test*", IEEE JPV, 2018

# Backsheet Testing - AAA



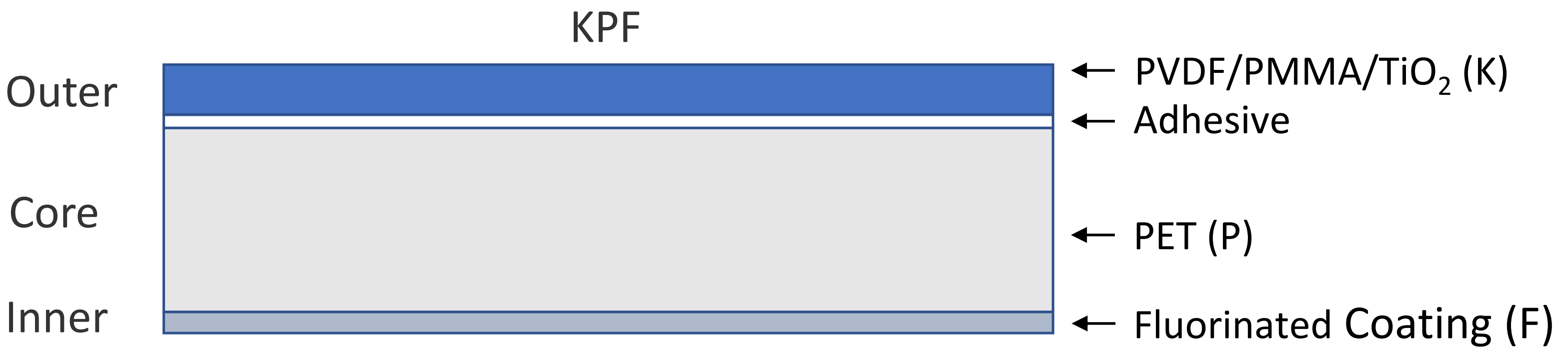
FTIR-ATR for AAA outer surface: unaged, C-AST aged and field aged samples




- Similar changes in FTIR-ATR spectra observed in fielded modules.

**Suggests mechanisms are the same and thus C-AST is representative**

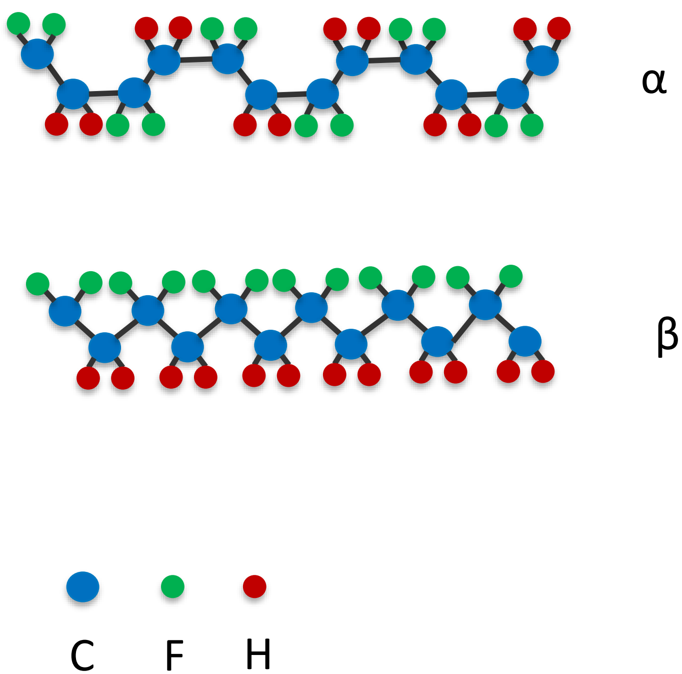
# Backsheet Testing - KPF



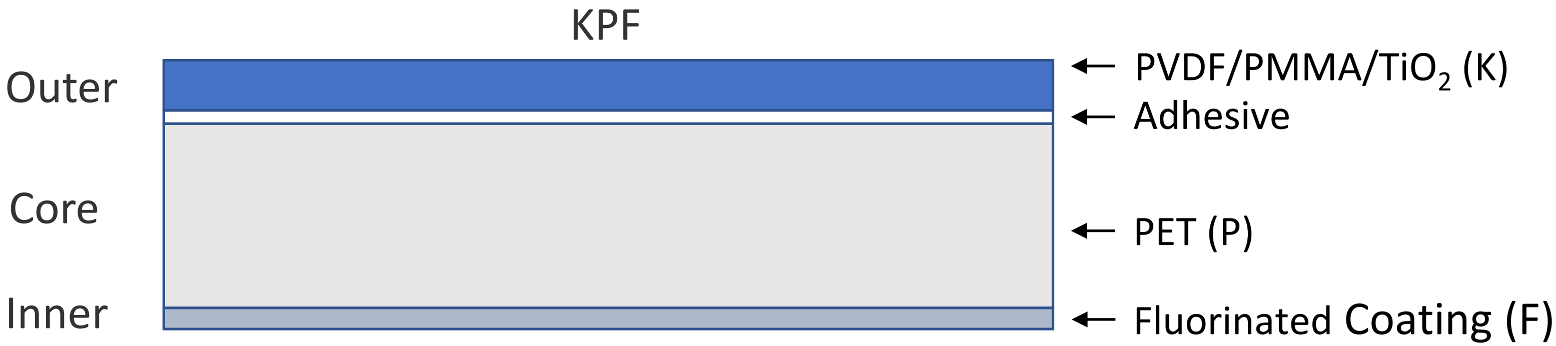

- Poly(vinylidene fluoride) (PVDF) is a semi-crystalline polymer (anywhere between 30-70%)

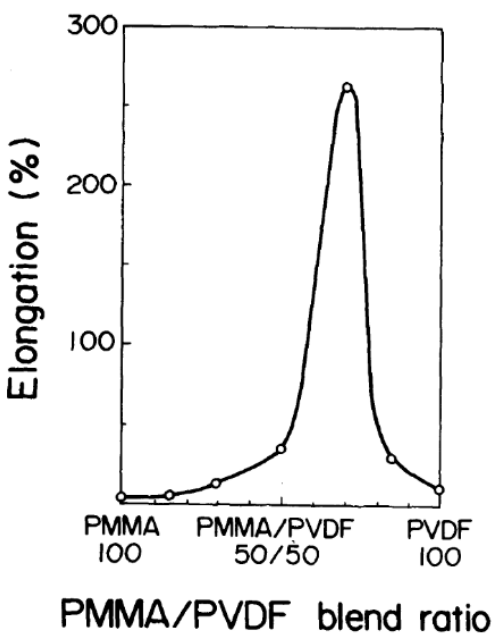
- Multiple crystal phases α, β, γ, δ, ε. Governed by polymer chain arrangement

- Crystallinity and phase are critical to mechanical properties



# Backsheet Testing - KPF



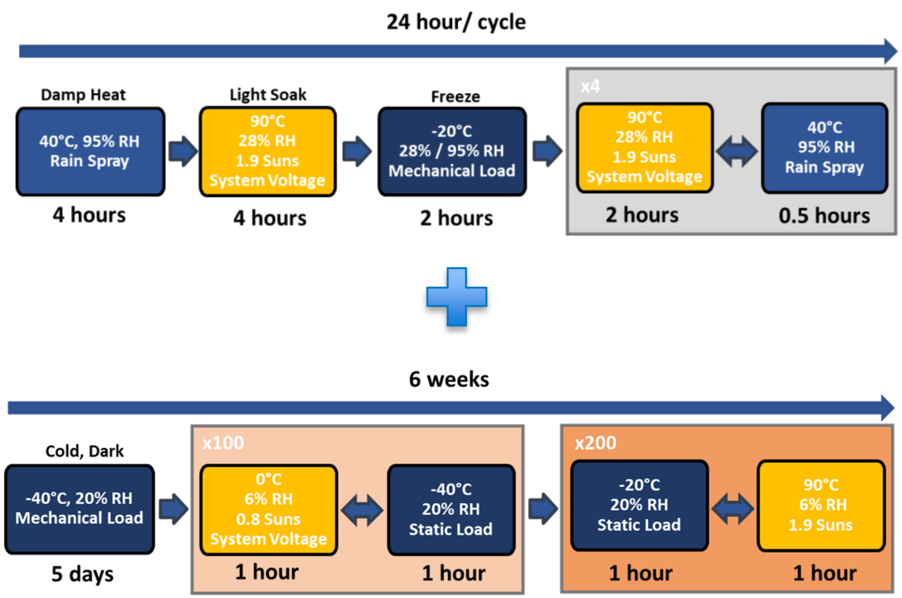



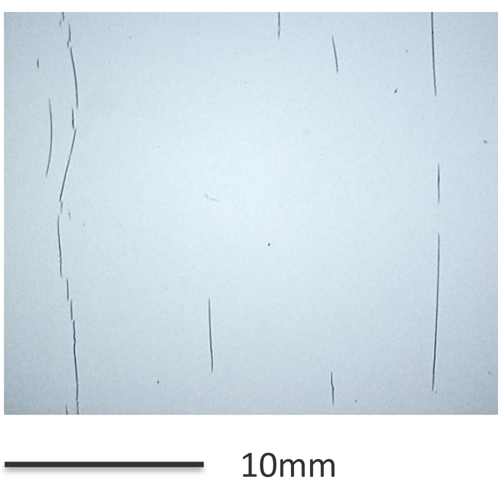

- Poly(methyl methacrylate) (PMMA) is sometimes blended with PVDF to improve properties such as adhesion, heat resistance and pigmentation distribution
- Blend ratio has a strong influence on elongation-to-break properties
- PMMA is vulnerable to UV degradation which can manifest as a crystal phase change, discoloration and chalking in PVDF/PMMA blends

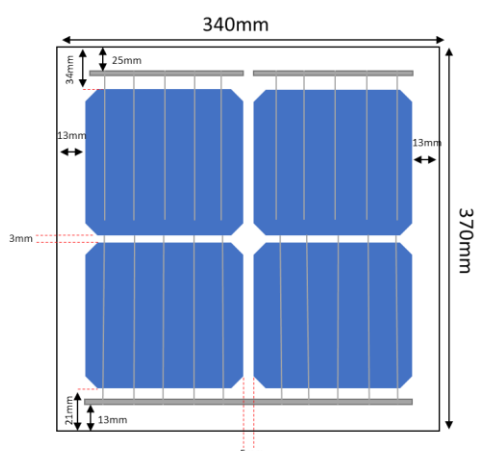

A. Tanaka, H. Sawada, and Y. Kojima, "*Application of Poly(vinylidene fluoride) and Poly(methyl methacrylate) Blends to Optical Material*," Polym. J., vol. 22, no. 6, pp. 463–467, 1990.

X. Gu, C. A. Michaels, D. Nguyen, Y. C. Jean, J. W. Martin, and T. Nguyen, "*Surface and interfacial properties of PVDF/acrylic copolymer blends before and after UV exposure*," Applied Surface Science, vol. 252, no. 14, pp. 5168–5181, May 2006.

# Backsheet Testing - KPF




2x KPF samples.

One with **3 months** exposure to tropical and one with **6 months** exposure to tropical. ***Without failure***.

Both cracked **simultaneously** after one round of phase 2. Though the 6 month module saw a higher crack density

Phase 1 is predominantly **wet** while phase 2 is predominantly **dry**. Failure to induce cracking in phase 1 suggests some kind of plasticization.

**Highlights need for testing across multiple conditions / climates / seasons**

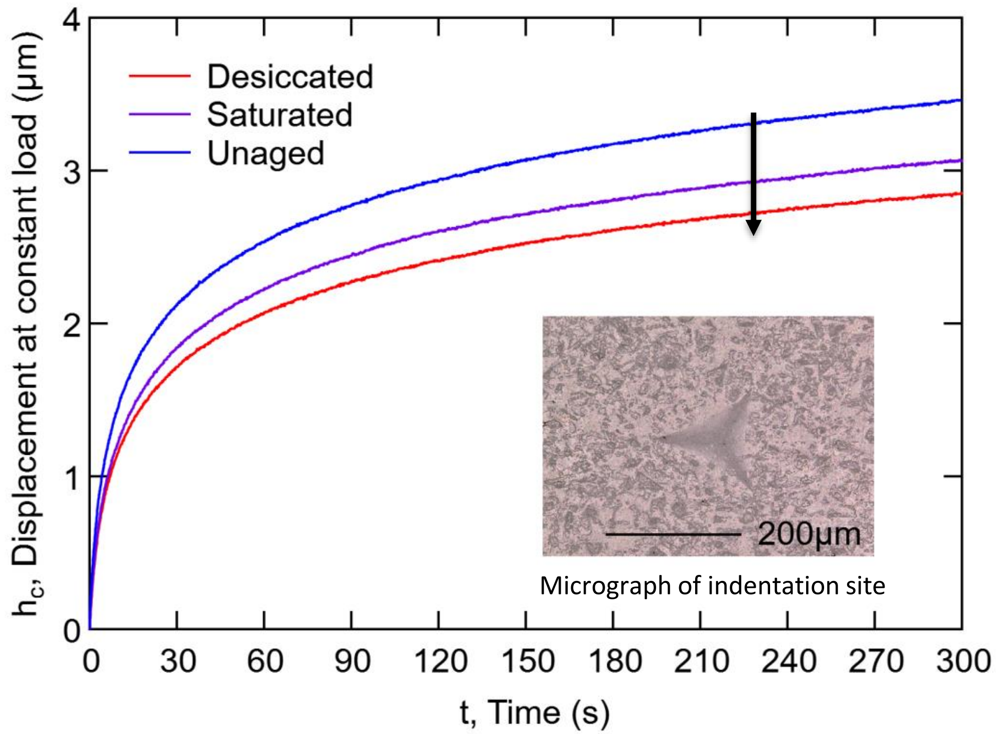
# Backsheet Testing - KPF

Indentation Hardness

Used to quantify fracture toughness (embrittlement) of a material

- Two KPF samples underwent **6 months of tropical**
- One was saturated at 96% RH/40°C
- One desiccated at 5% RH/40°C,
- Reduced creep displacement in aged materials
- Desiccated sample has greater resistance to creep deformation

Displacement/time data profile for creep hold of each sample

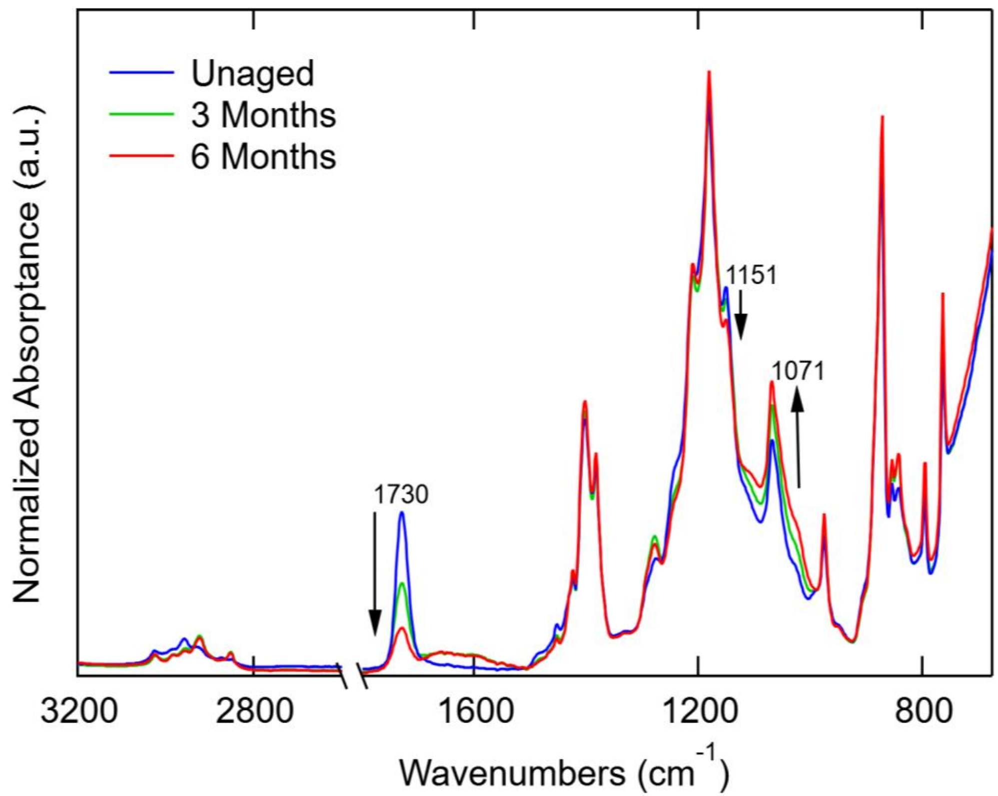



D. C. Miller, M. Owen-Bellini, P. L. Hacke, "*Use of indentation to study the degradation of photovoltaic backsheets*", Sol. Mat, 2019

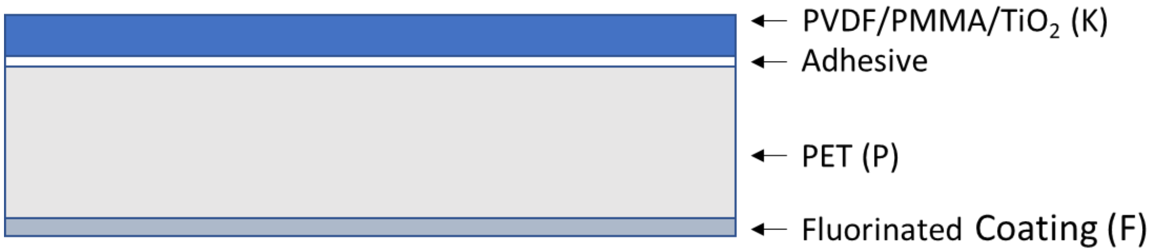
# Backsheet Testing - KPF

- 1730cm$^{-1}$ carbonyl group and 1151cm$^{-1}$ ester are associated with PMMA
- Decreasing 1730cm$^{-1}$ and 1151cm$^{-1}$ suggests depletion 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

FTIR-ATR for KPF unaged and C-AST aged samples



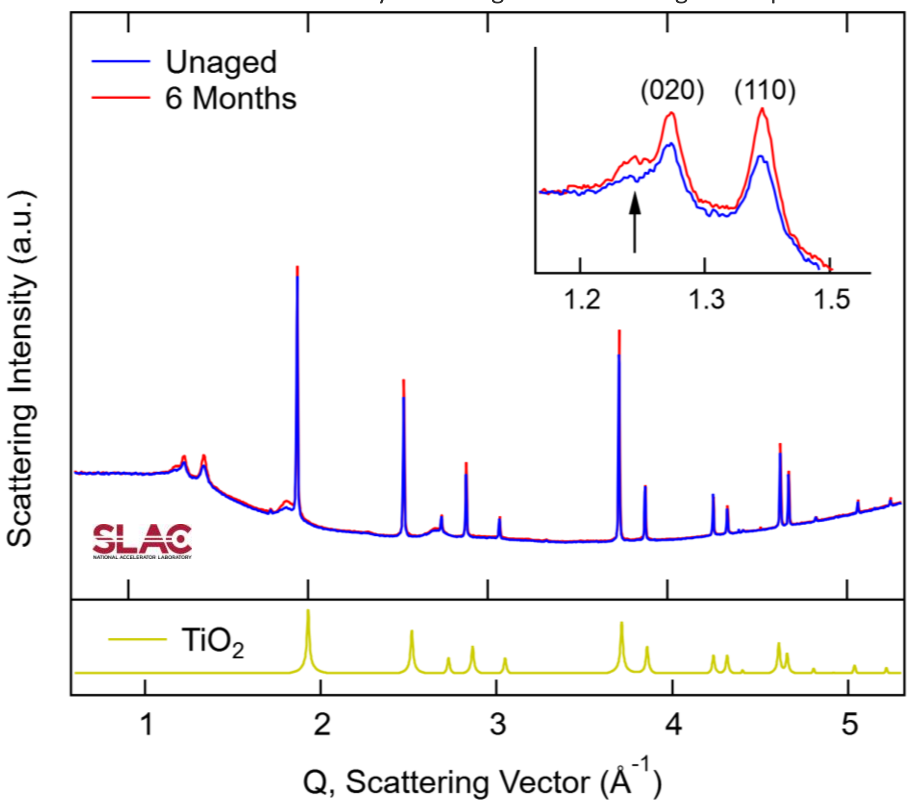

KPF




X. Cai, T. Lei, D. Sun, and L. Lin, "*A critical analysis of the α, β and γ phases in poly(vinylidene fluoride) using FTIR*," *RSC Adv.*, vol. 7, no. 25, pp. 15382–15389, 2017

# Backsheet Testing - KPF

WAXS for K layer of unaged and C-AST aged samples

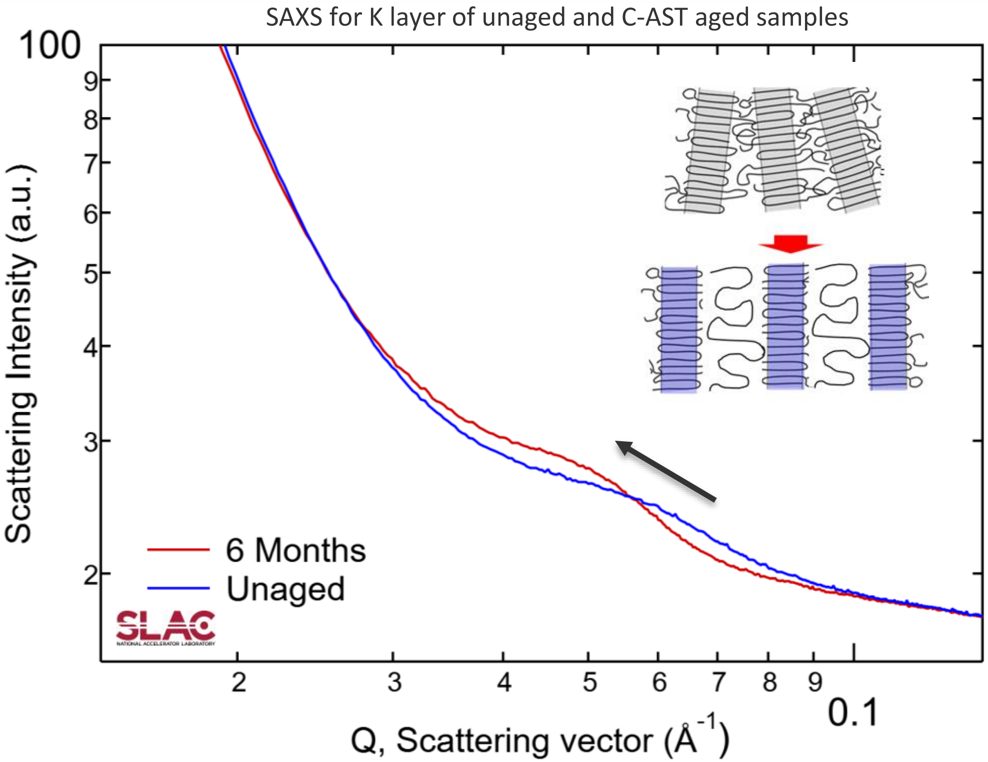



PVDF/PMMA/$TiO_2$ (K) layer separated from rest of the backsheet

- 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


W. H. Baur and A. A. Khan, "*Rutile-type compounds. IV. $SiO_2$, $GeO_2$ and a comparison with other rutile-type structures*," *Acta Crystallogr. Sect. B*, vol. 27, no. 11, pp. 2133–2139, Nov. 1971.

# Backsheet Testing - KPF




PVDF/PMMA/$TiO_2$ (K) layer separated from rest of the backsheet

- 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

P.Y.Yuen, S.L. Moffitt, F. D. Novoa, L.T.Schelhas, R. Dauskardt, "*Tearing and reliability of photovoltaic module backsheets*", Prog. In. Photovoltaics, 2019

# Content

# Additional Failure Mechanisms

<table>
<tr><th>Modes</th><th>Types/issues</th><th>Stress factors</th><th>C-AST</th></tr>
<tr><td>Fatigue, breakage</td><td>Cell spacing, cell thickness/nature, ribbon dimensions/bends, non-solder distance, solder/ECA quality</td><td>Mechanical and thermomechanical stress on conductors. Current leading to joule heating in the conductors</td><td rowspan="8">1</td></tr>
<tr><td rowspan="3">Light-induced Degradation</td><td>B-O, Fe-B, sponge LID</td><td rowspan="3">Light + temperature</td></tr>
<tr><td>LeTID</td></tr>
<tr><td>UV LID</td></tr>
<tr><td>Yellowing & optical losses</td><td>Photochemical degradation of polymers, ion migration</td><td>Light, temperature, humidity, electrical-bias</td></tr>
<tr><td>Backsheet cracking & delamination</td><td>Oxidative, photo, hydrolytic reactions, localized stress</td><td>Heat, light, voltage, moisture and mechanical stress</td></tr>
<tr><td>Corrosion, cell-front delamination</td><td>Oxidative, hydrolytic; electro & photo-catalytic reactions</td><td>Heat, humidity, light, system voltage bias, mechanical stress</td></tr>
<tr><td>Potential-Induced Degradation</td><td>Polarization, shunting, ion migration, insufficient isolation</td><td>Heat, humidity and system voltage bias, modulated by sunlight</td></tr>
</table>

Could be possible to reduce number of IEC tests used for screening into a single test

# Content

# Conclusions

- Detection of new failure mechanisms can be achieved **before** deployment through combined-accelerated stress testing

- It's important that stress combinations from different environments are covered, as evidenced by requirement of both tropical and dry conditions for PVDF failure

- Degradation mechanisms observed in fielded AAA backsheets also reproduced in C-AST. C-AST is representative of field conditions

- Failures in KPF could stem from degradation of PMMA in the outer layer PVDF/PMMA blend and an increase in crystallinity leading to embrittlement

Combining advanced stress tests with appropriate materials analysis can help to develop more robust materials with longer service lives and avoid another AAA disaster

Durable Module Materials Consortium

# Thank You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