NREL Transforming ENERGY

Combined stress testing simulating different climatic conditions

- how always testing at extremes may miss things -

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Photo by Dennis Schroeder, NREL 55200

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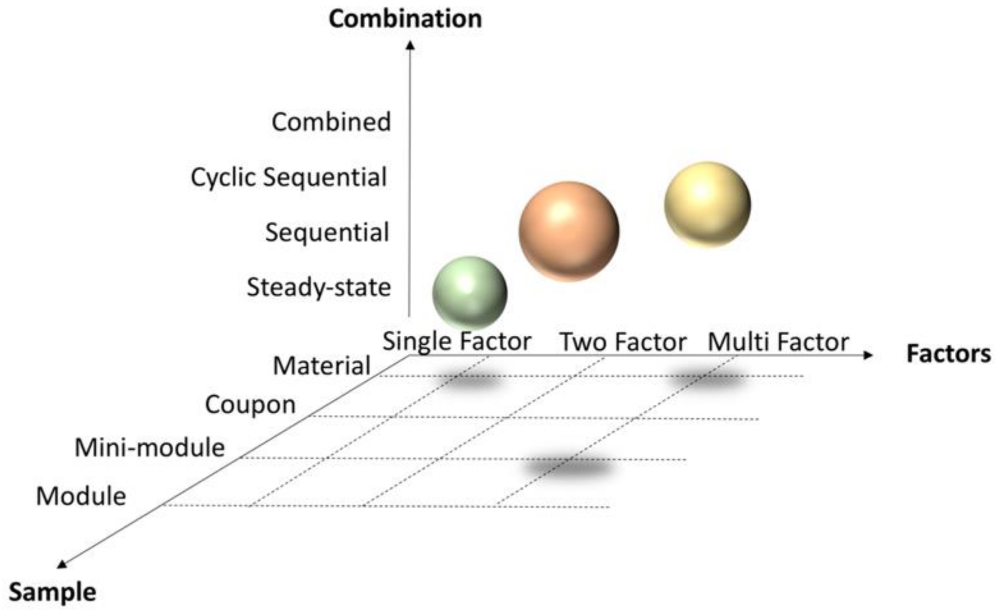
Combined-accelerated stress testing (CAST) Purpose for being

- **Numerous field failures seen in PV modules that pass qualification testing (IEC 61215)**
  - We create mechanism-specific tests only after the failure mode has been found in the field
- **Numerous parallel tests getting time consuming and expensive (PID, LETID, UVID…)**
- **Stakeholders considering buying into new technologies, materials, and designs incur residual risk, increasing LCOE**
  - Risk of new designs/materials (like new cell technologies)
  - Risk from incremental changes (like going to thinner PV cell)
  - Risks from failure of critical parts (like an edge seal for moisture-sensitive PV cells)
- **Reliability standards – more objectivity is sought**
  - Subject and limited to interest of those seeking to initiate the standards
  - Only move forward when all of industry understands and can solve the degradation mode
- **$US Billion industry. Risks as well as benefits of progress are substantial**
- **Testing apparatus is a challenge**
- **Addressing this, we developed combined-accelerated stress testing**

Comprehensiveness of representation in testing

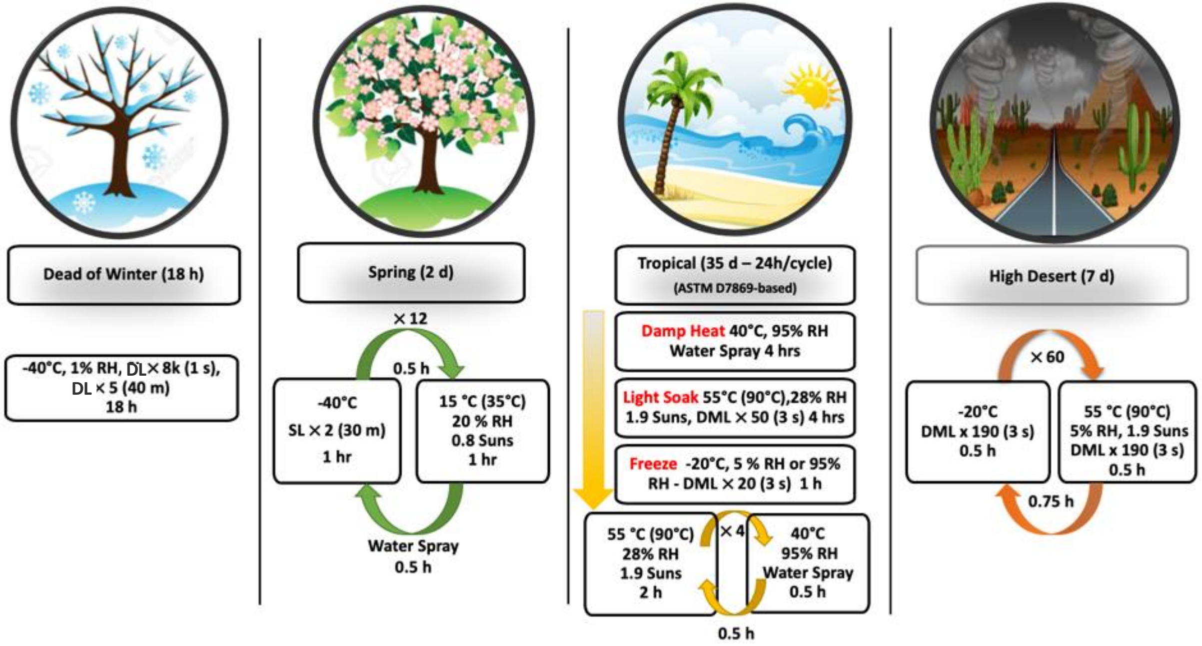


"Sample": representation of the materials interfaces, boundary conditions of the shipping module

"Factors": extent of inclusion of the stress factors of the natural environment

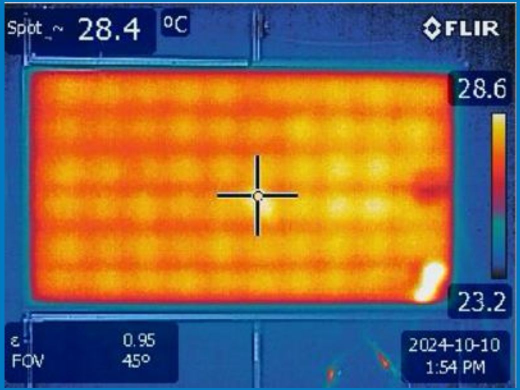
"Combination": representation of the actual combination and sequences of stress factors as in the natural environment and their balance (exceeding vs not exceeding real-world stress levels)

Combined-accelerated stress testing (CAST)



- Five stress factors of the natural environment
  - Temperature
  - Humidity
  - System voltage
  - UV/Full spectrum light
  - Mechanical loading
- Stress levels at extremes (not exceeding) natural environment
- Representative testing

Degradation examples in CAST - depending on climate



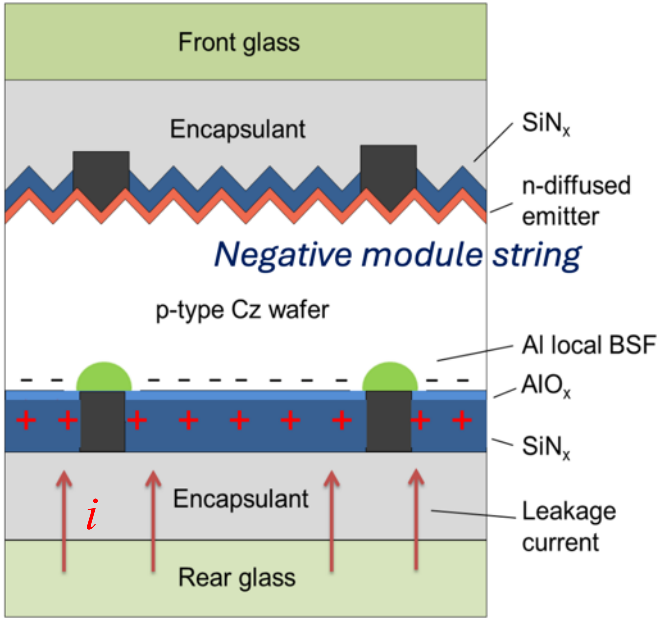
- **Potential-induced degradation bifacial PERC**
- PVDF backsheet cracking
- Cell grid finger failure

Potential-induced degradation bifacial PERC in CAST

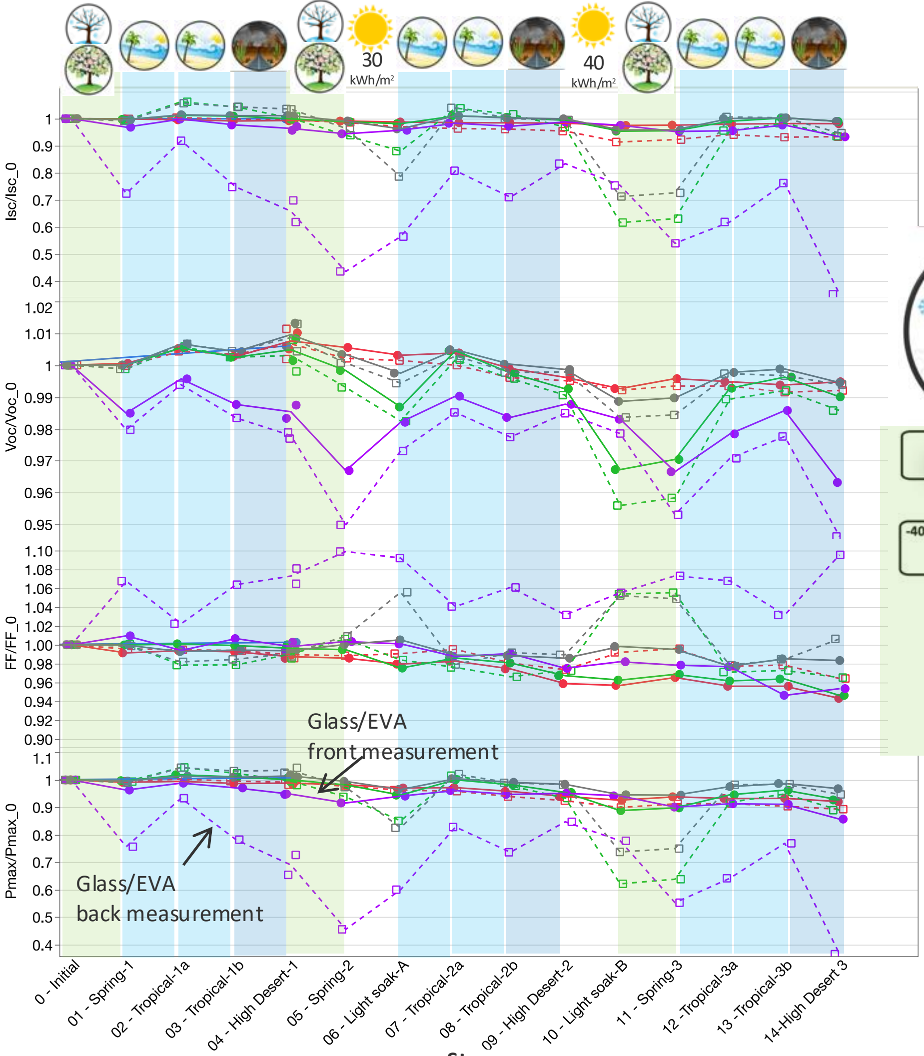
Overview of potential-induced degradation polarization (PID-p) on rear of bifacial PERC

When and where does it happen

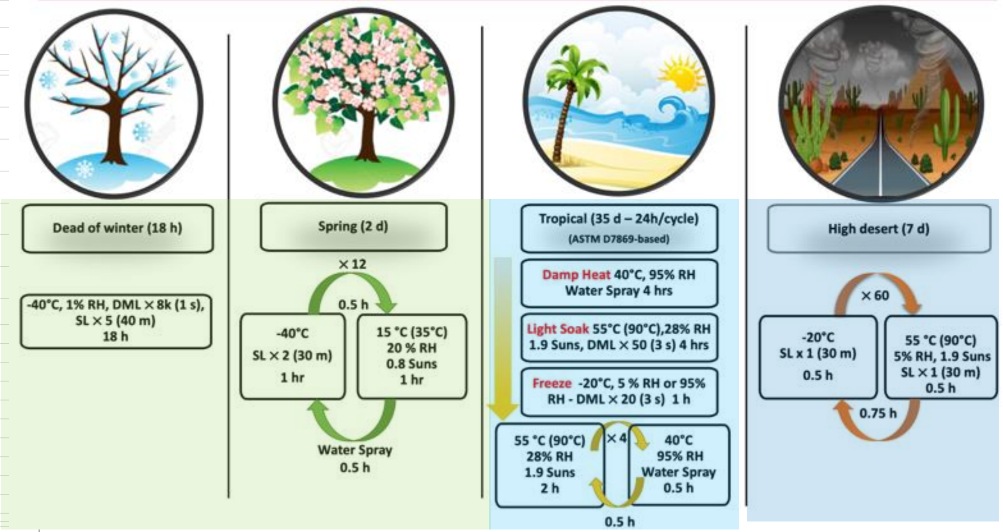
- Rear of bifacial PERC (undoped, sensitive to dielectric charge state) [1]
- Occurs most in EVA-glass back modules[1]
- Negative system voltage (builds up + charge in dielectric)[2]
- Generally correlated to high leakage current[1]
- Degradation greater under low light or dark[3]
- Recovery under light soak because of SiNx photoconductivity and annihilation of charge[2-4]
- Recovery under opposite system voltage polarity[5]



1 *Luo, W and coworkers, Progress in Photovoltaics: Research and Applications 2018, 26 (10), 859-867.*
2 *Luo, W and coworkers, IEEE Journal of Photovoltaics 2018, 8 (5), 1168-1173.*
3 *Habersberger, B. M.; Hacke Progress in Photovoltaics: Research and Applications 2022, 30 (5), 455-463.*
4 *Hacke, P. and coworkers, IEEE Journal of Photovoltaics, vol. 5, no. 1, pp. 94-101, Jan. 2015*
5 *Swanson and coworkers, proceedings 15th International PVSEC, 2005.*

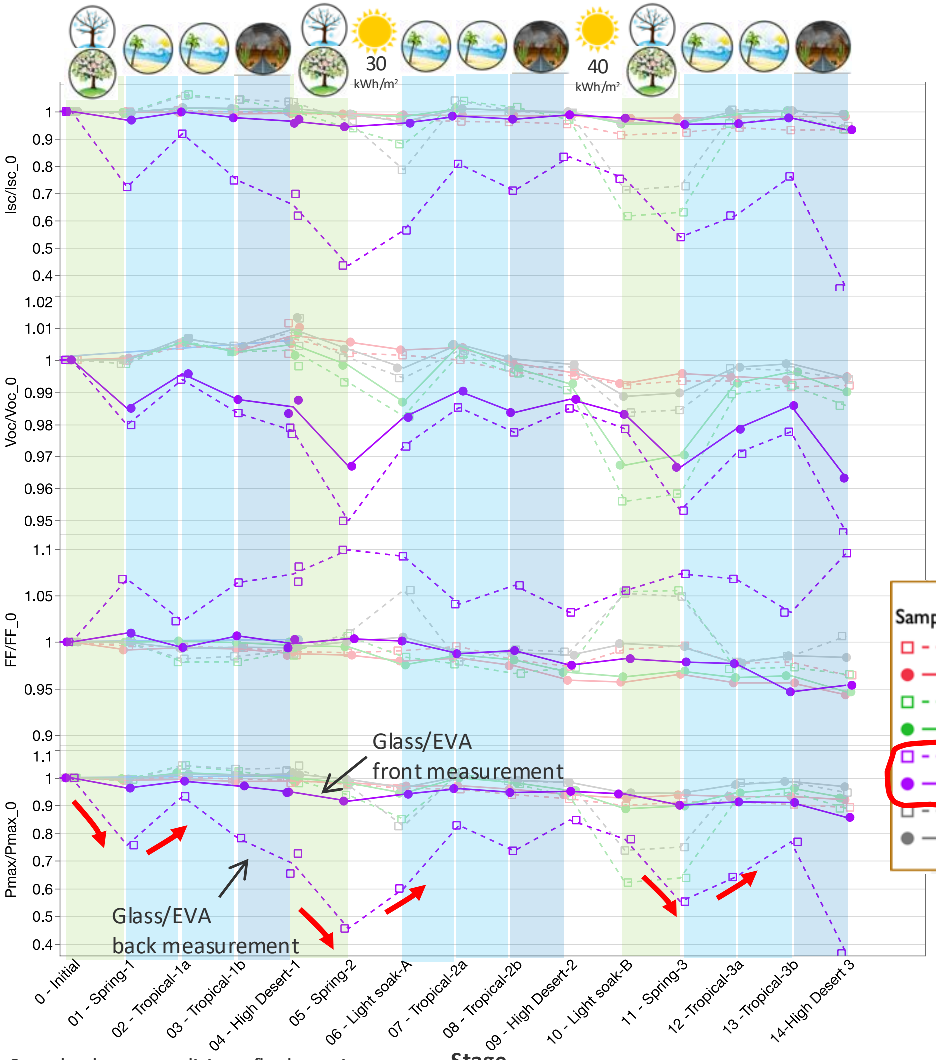


Standard test conditions flash testing

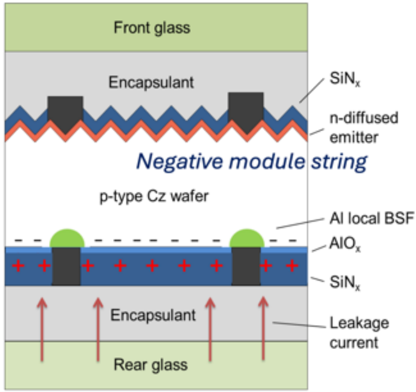


PID results

Glass back with EVA encapsulant sample shows most significant loss in I_{sc} and V_{oc} from the rear in bifacial PERC

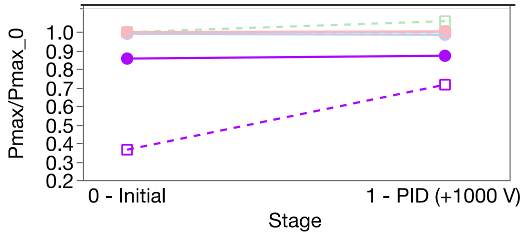


- ✓ Glass/EVA module construction
- ✓ -1200 V system voltage applied
- ✓ Seen with highest leakage current
- ✓ Degradation under low light condition (Spring: 800 W/m² 35 °C)
- ✓ Recovery with elevated irradiation
- ✓ Recovery under opposite polarity



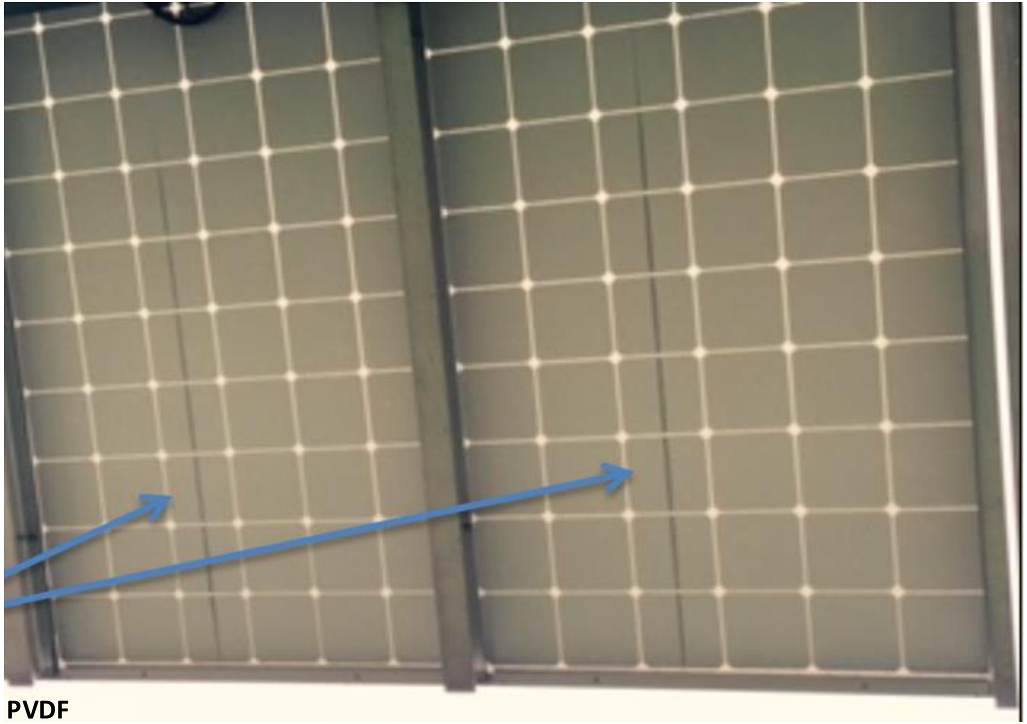
Sample	Substrate	Encapsulant	Coulombs cycle
39B	T-PVF	EVA	1.37
39F	T-PVF	EVA	
40B	T-PVF	POE	0.35
40F	T-PVF	POE	
41B	Glass	EVA	2.15
41F	Glass	EVA	
42B	Glass	POE	0.19
42F	Glass	POE	

+1000 V 60°C 96 h (faces grounded)
→PID recovery



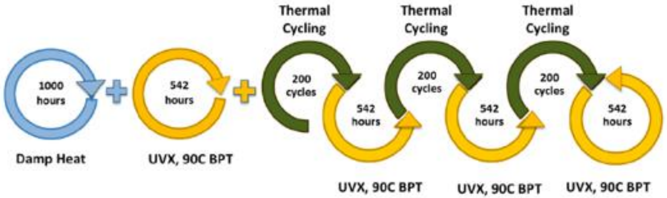
PVDF backsheeet cracking in CAST

PVDF cracking



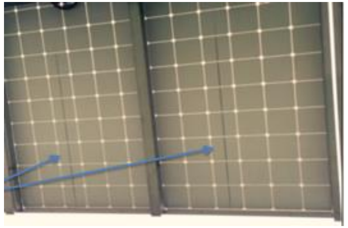
PVDF
Saskatchewan Canada, 5 y
(photo credit: DuPont)

Manifests in
- DuPont MAST 1



PVDF cracking

Tropical
ASTM D7869-based
Tropical RH levels



PVDF
Saskatchewan Canada, 5 y
(photo credit: DuPont)

-20°C / 90°C:84 cycles
40°C / 90°C: 196 cycles

$Wh/m^2/nm$ at 340 nm: 137.8

12 weeks

PVDF

OK !

PVDF

168 cycles
392 cycles

275.52

24 weeks OK !

Winter (dark/cold mechanical loading)
Spring (0.8 Suns/low temperature cycling/mechanical loading)

OK !

OK !

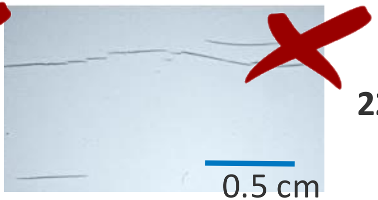
Desert
(~5% RH)

-20°C / 90°C: **60 cycles**
Wh/m^2 at 340 nm: 12.0

60 cycles
12.0

Loss of humidity
-loss of plasticizing effect
-shrinkage

-20°C / 90°C: 144 cycles



228 cycles

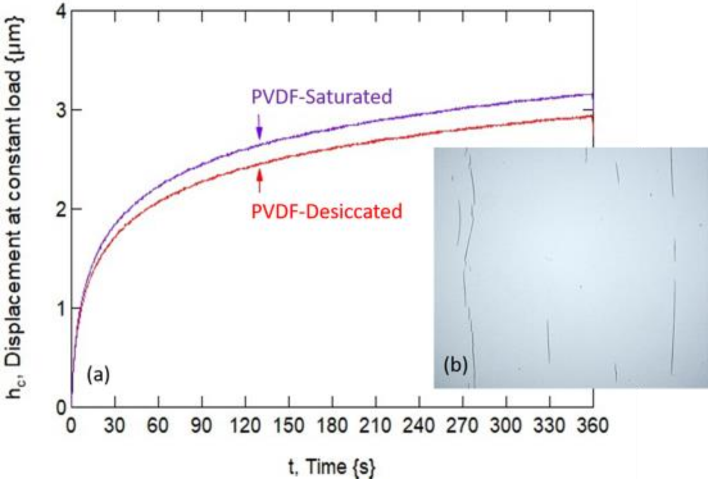
Analysis: cause of the PVDF cracking

Indentation testing

Displacement/time data for creep–hold indentation tests for a PVDF backsheet type following 24-weeks in C-AST Tropical followed by the following courses for 14 days:

(1) desiccation (20 °C, <5% RH)

(2) moisture saturation (40 °C / 96% *RH*)

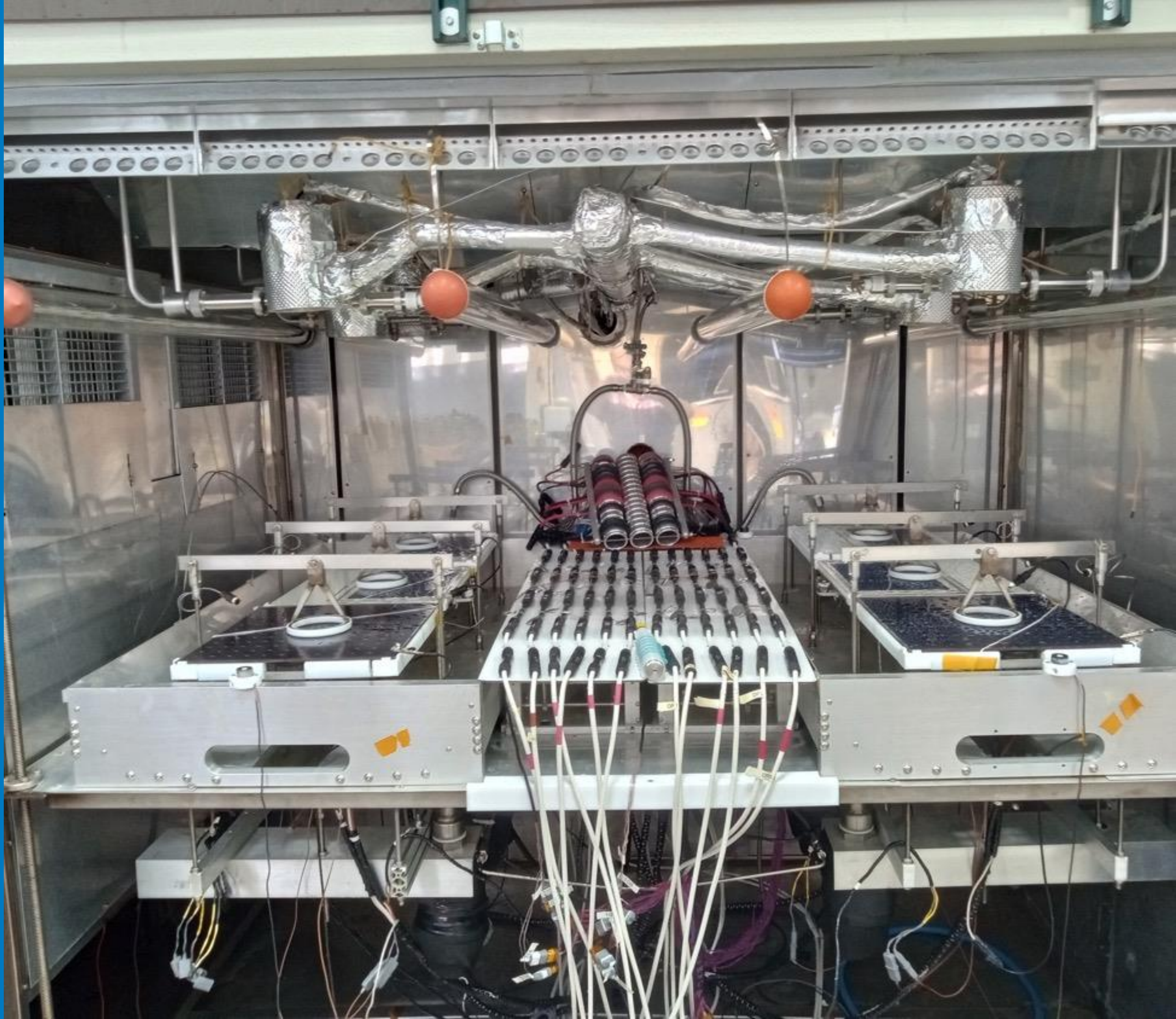


CONDITION	BERKOVICH HARDNESS		VICKERS HARDNESS		ELASTIC MODULUS (INDENTATION)	
	AVG H_B, {MPa}	2 STD H_B, {MPa}	AVG H_V, {MPa}	2 STD H_V, {MPa}	AVG E_i, {GPa}	2 STD E_i, {GPa}
DESSICATED	85.9	22.8	8.0	2.1	1.60	0.14
SATURATED	76.0	18.0	7.0	1.7	1.27	0.08

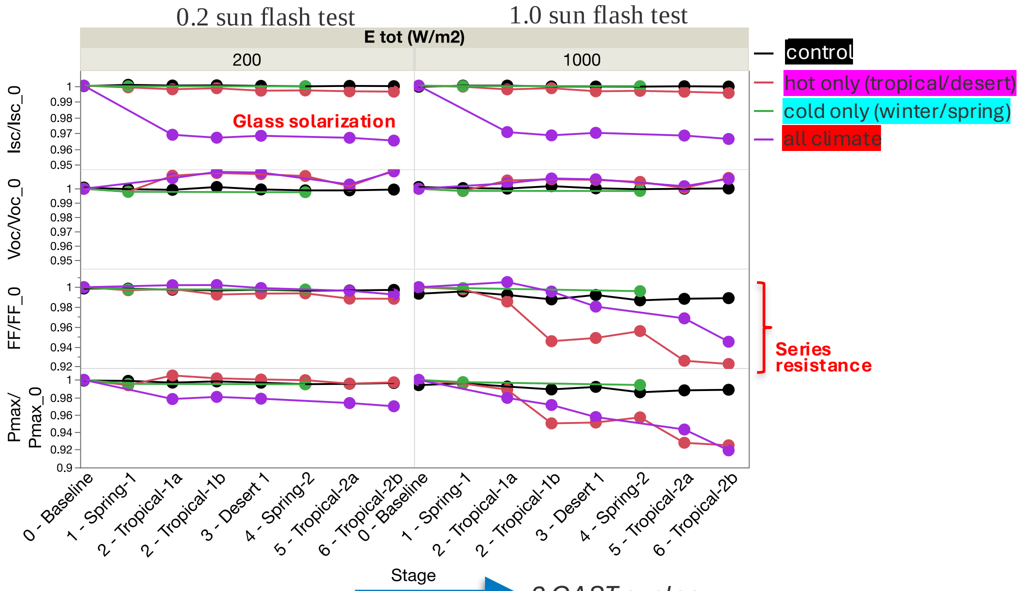
Moisture leads to plasticization of the backsheet – whereas the desiccated PVDF is harder, more rigid, less prone to creep. Dry conditions on the weathered material finally produce the cracking.

Cracking is believe associated with phase changes in the PVDF in weathering and poly(methyl methacrylate) PMMA additive used for adhesion, processing, and cost

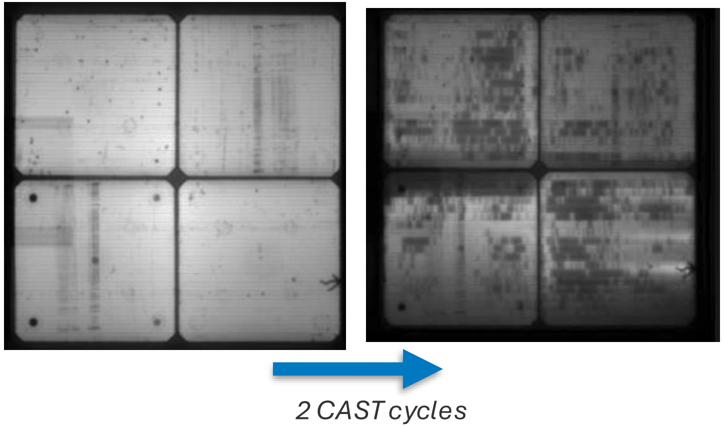
Cell grid finger failure observations in CAST

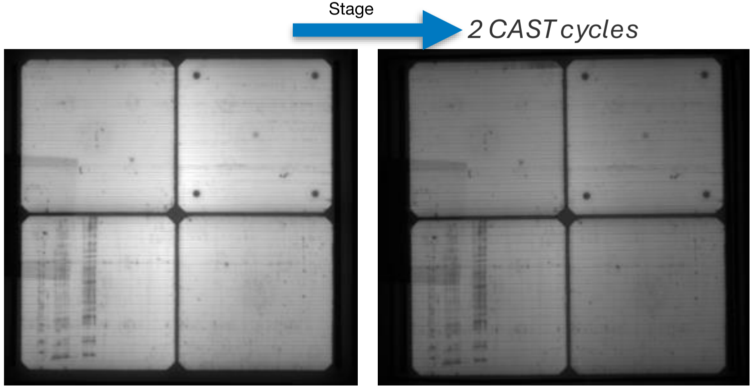


Low temperature solder interconnect through CAST

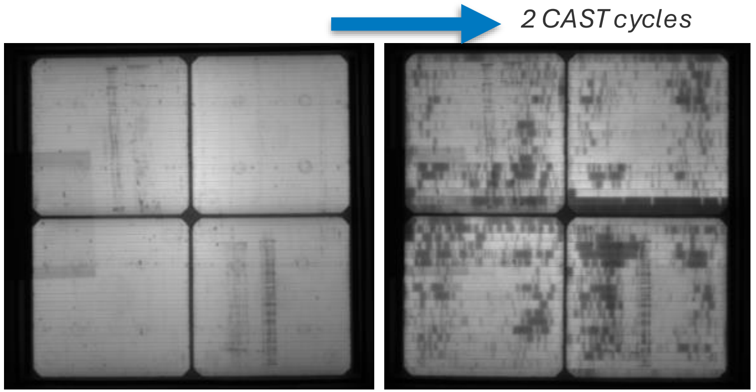


All climate





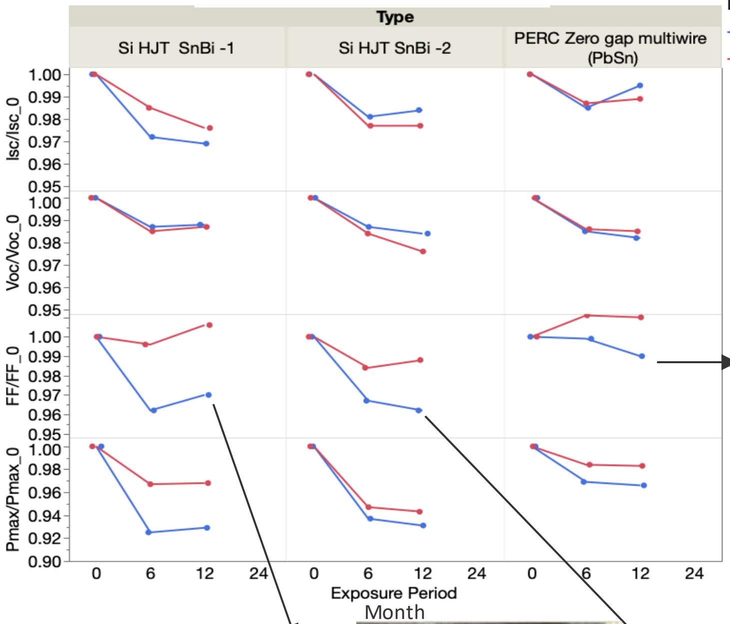
Cold only

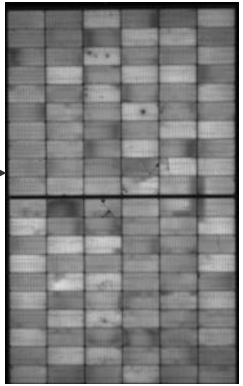


Hot only

Elevated temperature in AZ leads to more degradation

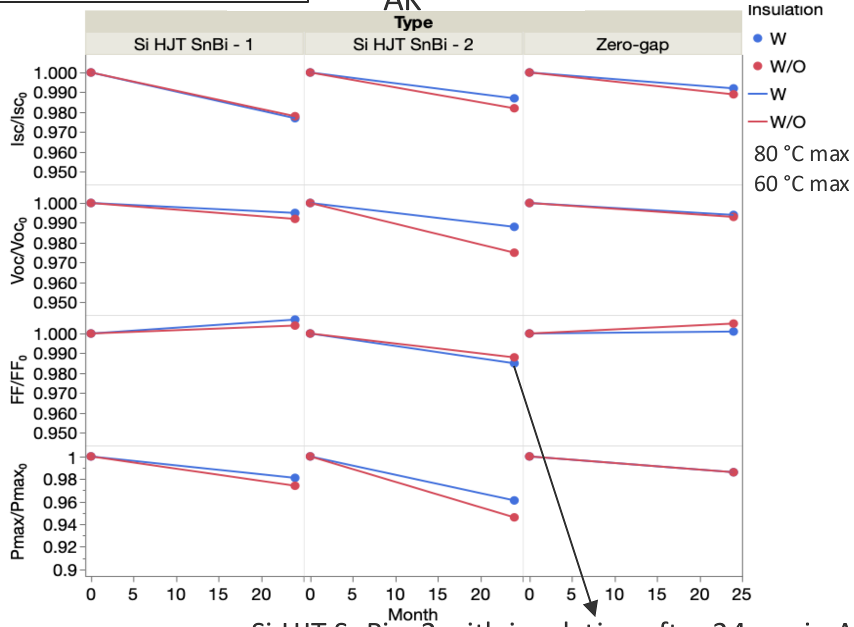
AZ



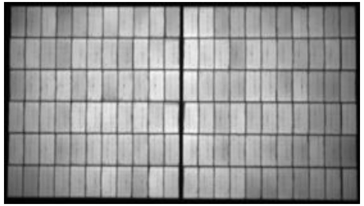


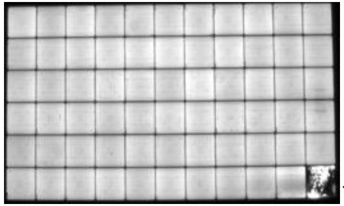
PERC Zero gap ribbon with rear insulation 24 months

AK

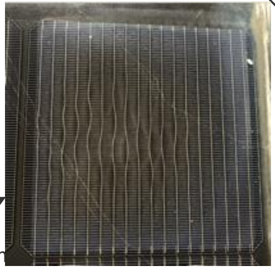


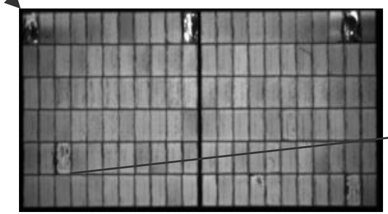
Si HJT SnBi – 2 with insulation after 24 mo in AK





Si HJT SnBi -1 with rear insulation 24 month





Si HJT SnBi -2 with rear insulation 24 months

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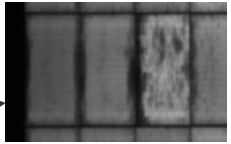

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Summary

- Multi-season/climate CAST well suited for understanding behavior in various climate conditions
  - PID-polarization on rear of bifacial PERC most consistently apparent in *spring* climate (modest illumination)
  - PVDF cracking seen after various CAST weathering in the *high desert* climate (desiccation)
  - Cell grid finger failures apparent at higher temperature stress tests (*tropical, high desert*)

Thank you

Q&A?

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