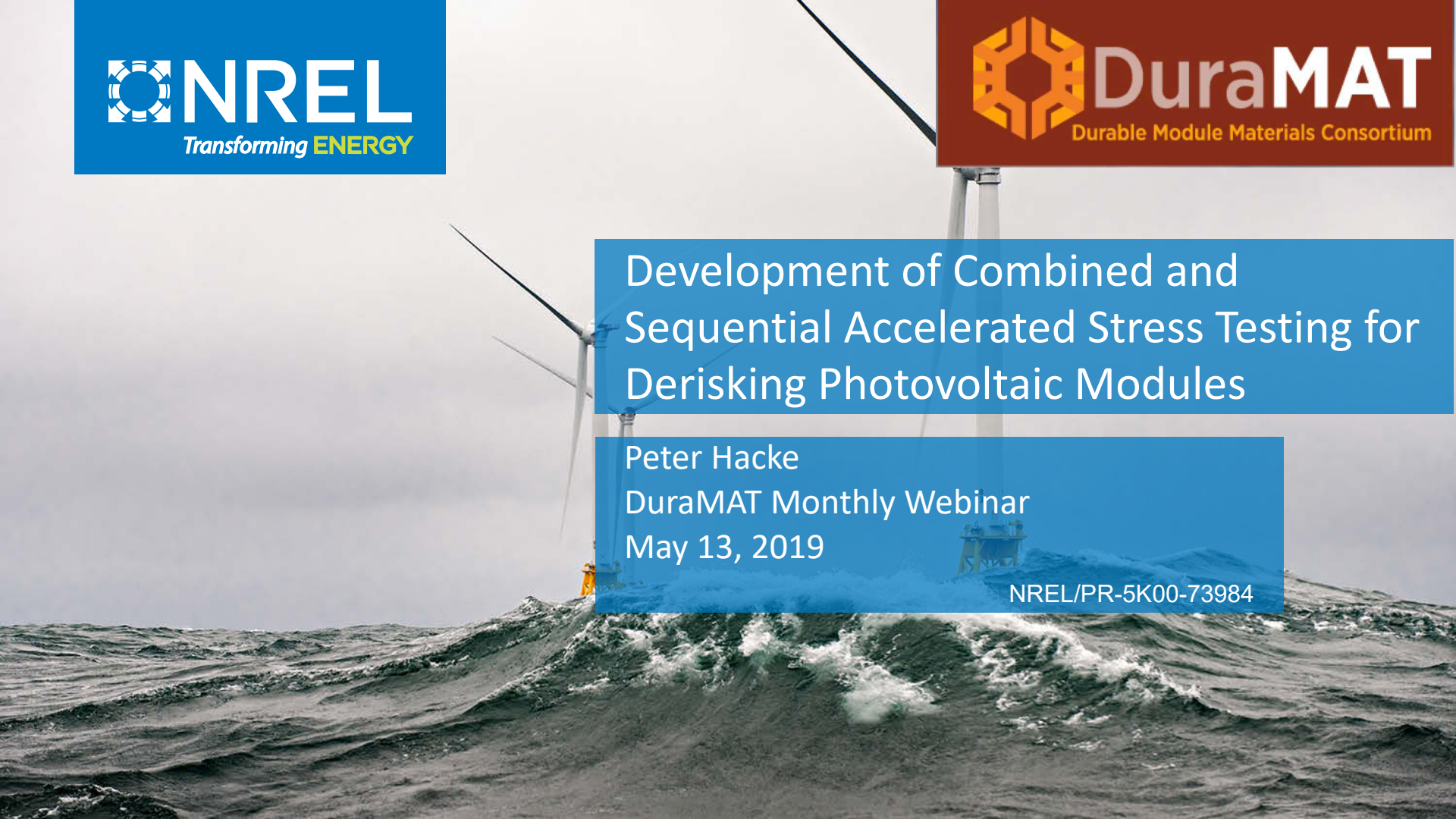


NREL Transforming ENERGY

DuraMAT Durable Module Materials Consortium

Development of Combined and Sequential Accelerated Stress Testing for Derisking Photovoltaic Modules

Peter Hacke

DuraMAT Monthly Webinar

May 13, 2019

NREL/PR-5K00-73984

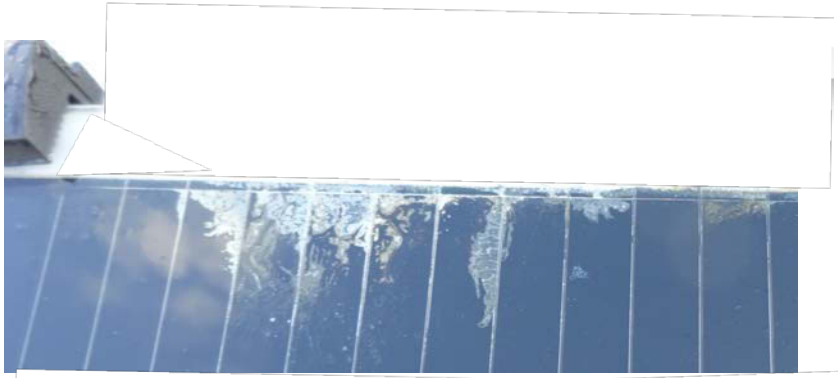
Contents

Contents

Corrosion

Electrochemical corrosion of metallization or cell, frame and grounding parts, where moisture ingress, system voltage, encapsulant (especially acidity), galvanic incompatibility, and temperature interact.

- **CdTe modules** Fielded, -1000 V_{sys} Florida 2 y



Delamination, can see through module

All-India Survey of Photovoltaic Module Reliability: 2014

Corrosion

Electrochemical corrosion of metallization or cell, frame and grounding parts, where moisture ingress, system voltage, encapsulant (especially acidity), galvanic incompatibility, and temperature interact.

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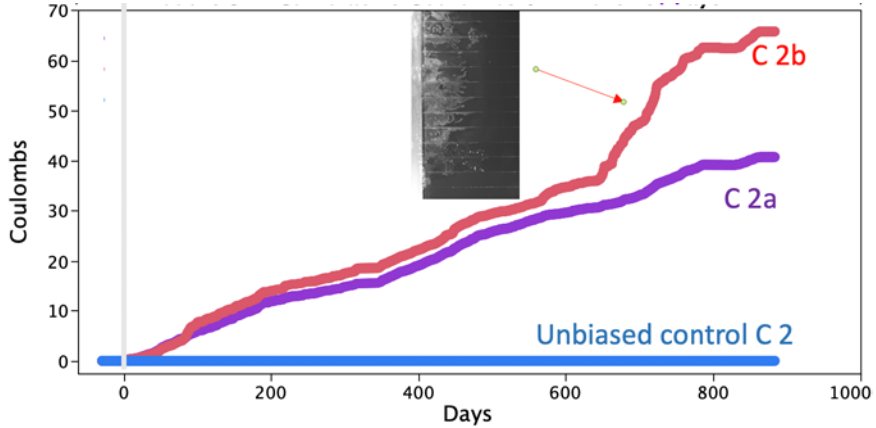


- System voltage (–), heat, humidity on surface of glass: *E* field drift of Na in glass to TCO
- Light, mechanical stress causes failure of edge seal, moisture ingress, current leakage increase

→ **Corrosion**

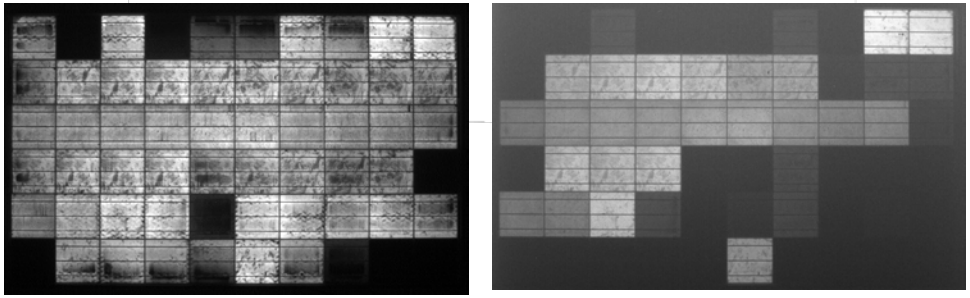
- (depends on TCO) Degradation of the SnO_2:F TCO suggested (possibly formation of NaF, Na_2SnO_3 and SnO)

Potential-induced degradation (PID)

Potential-induced degradation (shunting type), where Na drifts under an electric field and then diffuses into the p-n junction

- **C-Si module** Fielded, -600 V_{sys} Florida 4 y

Electroluminescence



1 Imp = 7.8 A

0.1 Imp = 0.78 A

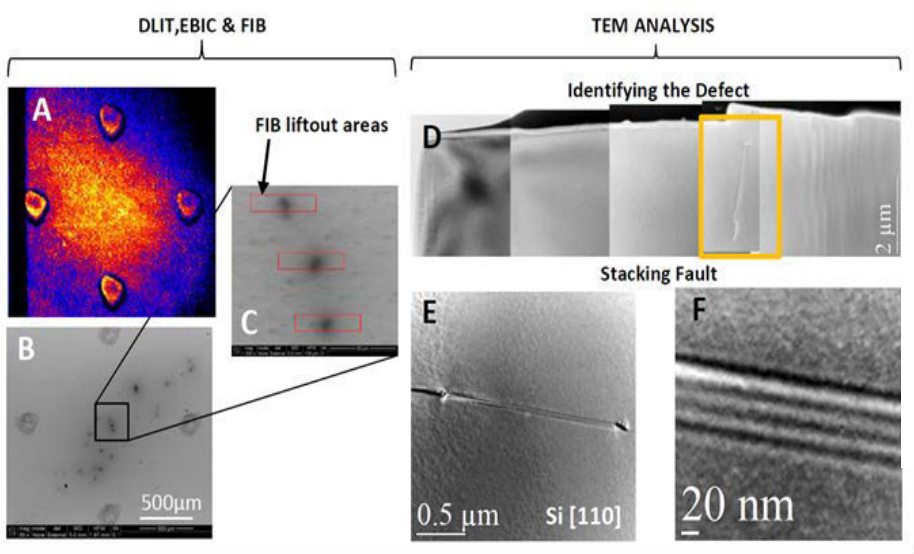
Potential-induced degradation (PID)

Potential-induced degradation (shunting type), where Na drifts under an electric field and then diffuses into the p-n junction

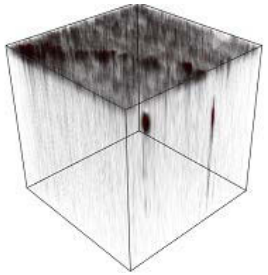
System voltage (–), heat, humidity on surface of glass: *E* field drift of Na

Light, moisture ingress modulate rate

→ **PID** Drift of Na^+ by *E*-field through SiN_x Diffused at stacking faults



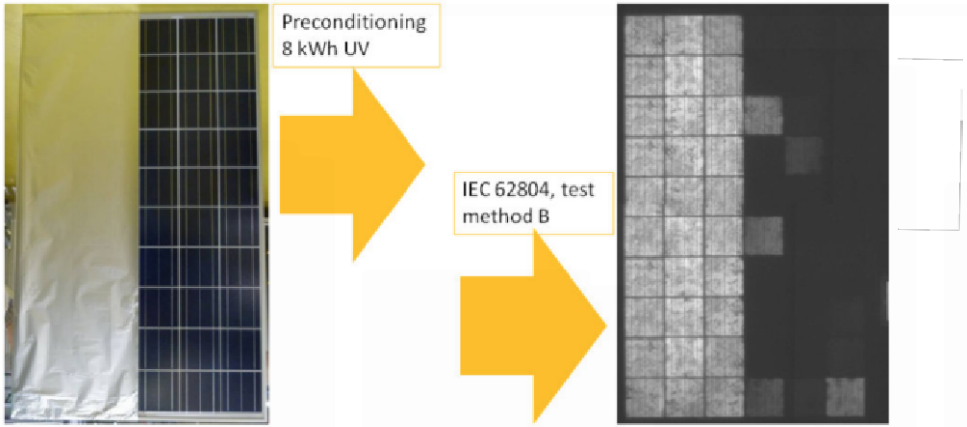
Naumann & coworkers (2012)
Harvey & coworkers (2016)



SIMS Map: Na in pockets below surface shunting junction

Potential-induced degradation (PID)

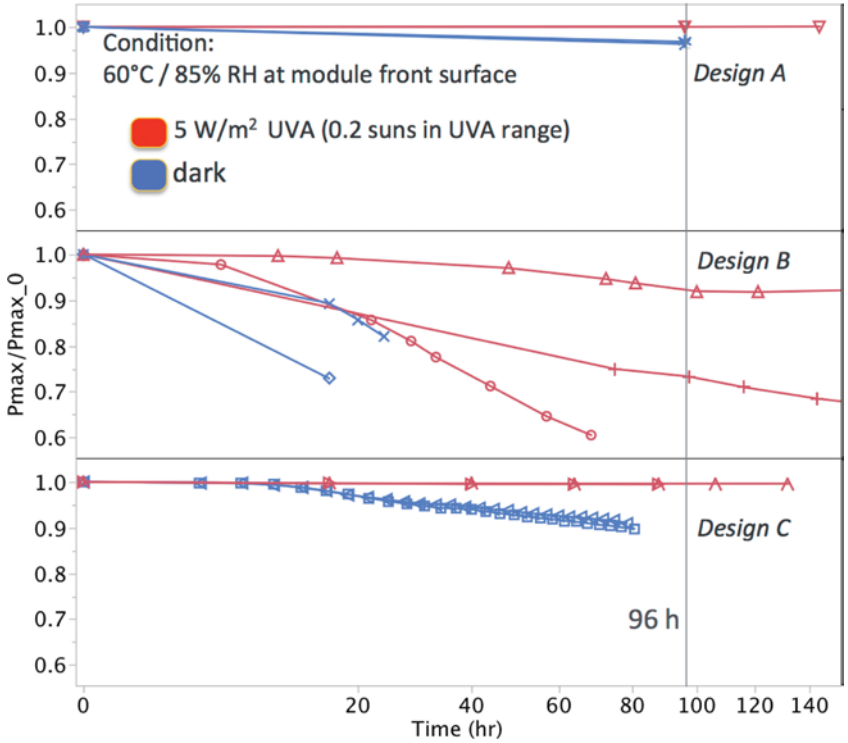
Potential-induced degradation (shunting type), where Na drifts under an electric field and then diffuses into the p-n junction



Preconditioning with light, followed by PID test:
Pre-exposure to light increases PID
-- mechanism not clear

Potential-induced degradation (PID)

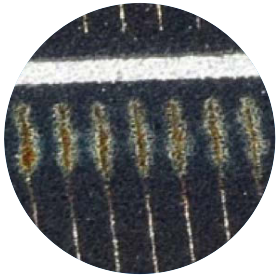
Potential-induced degradation (shunting type), where Na drifts under an electric field and then diffuses into the p-n junction



PID stress light mitigates PID

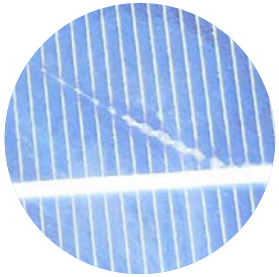
-SiN_x AR coating becomes photoconductive, arresting and neutralizing advancing Na^+ ions

Combined stress factors and resulting degradation modes



Corrosion

Voltage
Mechanical loading
Humidity
Light
High temperature
Temperature cycling

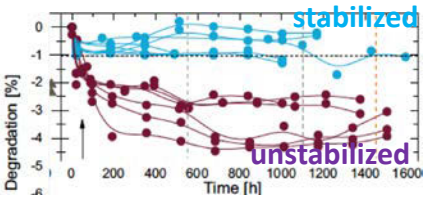


Delamination

Voltage
Mechanical loading
Humidity
Light
High temperature
Temperature cycling

Yellowing

Voltage
High temperature
Humidity
Light
High temperature
Acid/corrosive gasses



Power loss

Light
Voltage
Temperature
Temperature cycling
Mechanical loading

Polymer failure

High temperature
Light, mechanical loading
Humidity, dryness
Acid/corrosive gasses
Temperature cycling

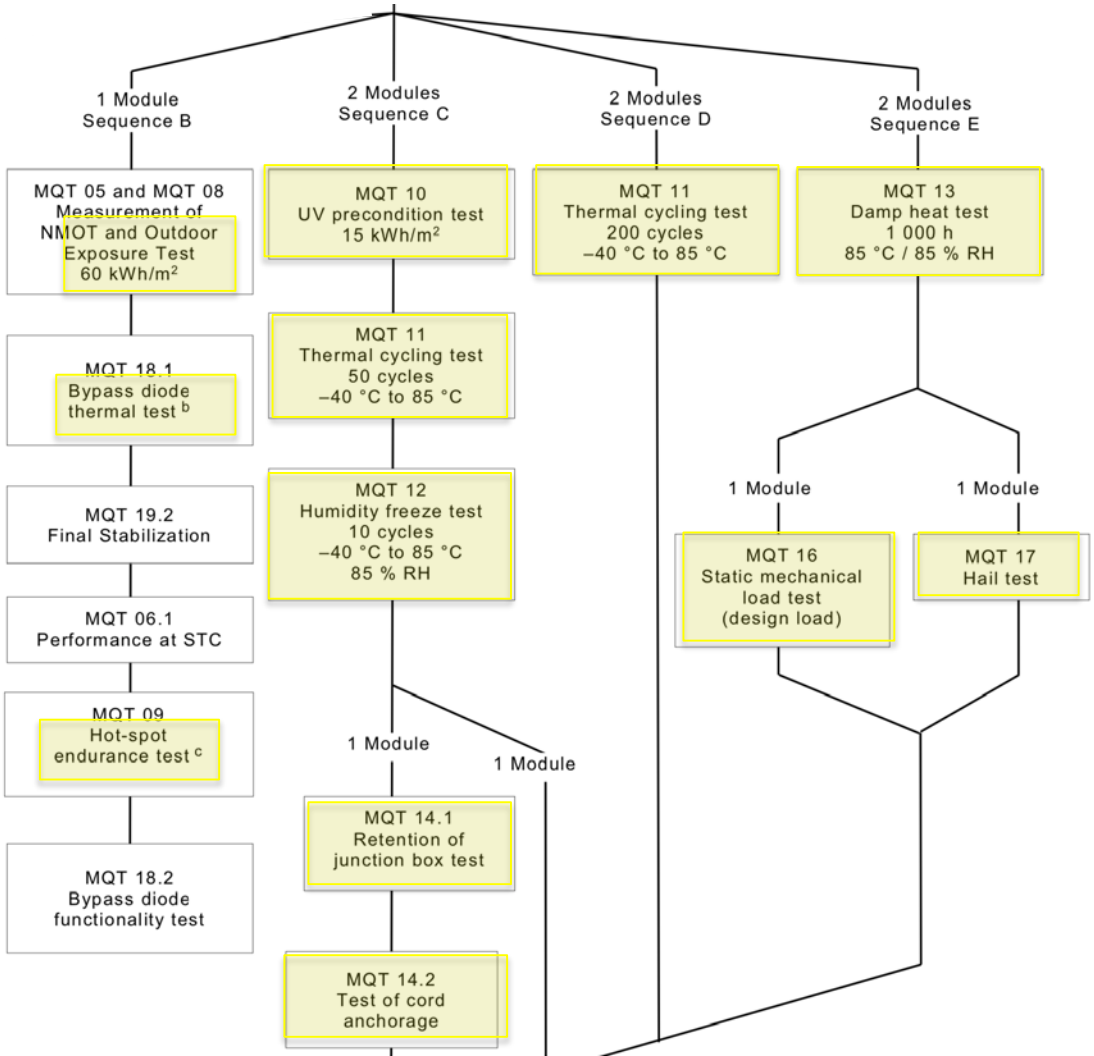
Contents

IEC 61215 ed. 3 Qualification test

…module is capable of withstanding prolonged exposure in use climates…

Minimal examination of combination of stresses

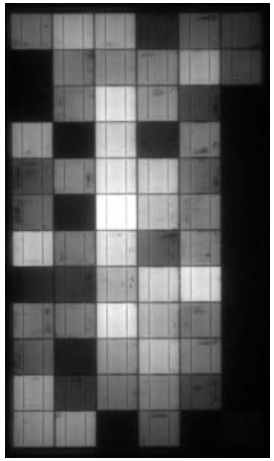
- Some sequencing of stresses



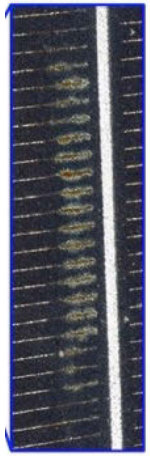
Contents

Field Fails

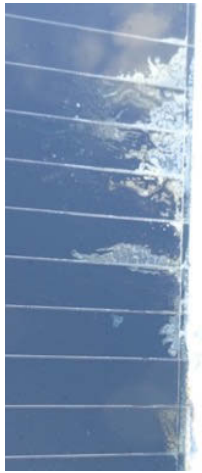
Polyamide backsheet



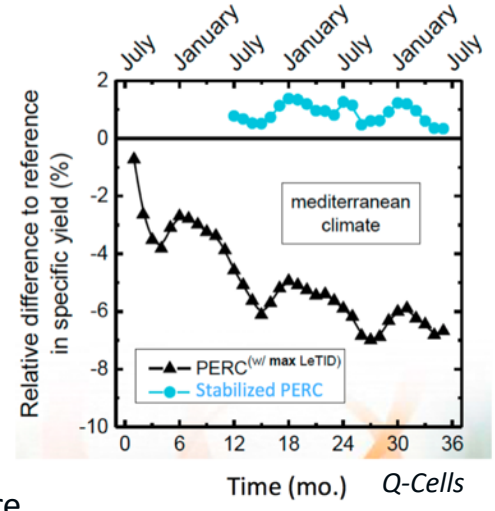
PID



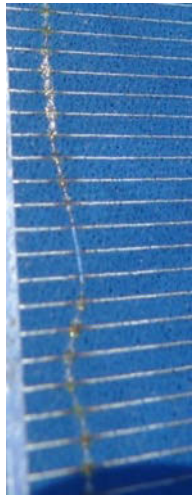
Corrosion



Edge seal failure



LeTID



Snail trails

Delamination

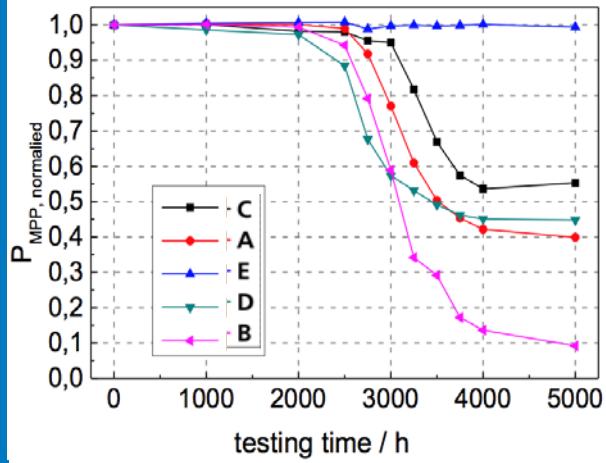
Issues manifesting in the field in modules that passed the standards
—Multiple factors working in combination leading to the degradation—

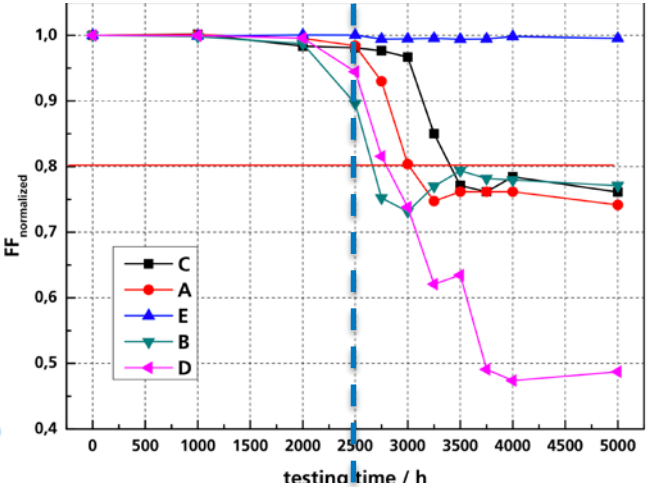
Contents

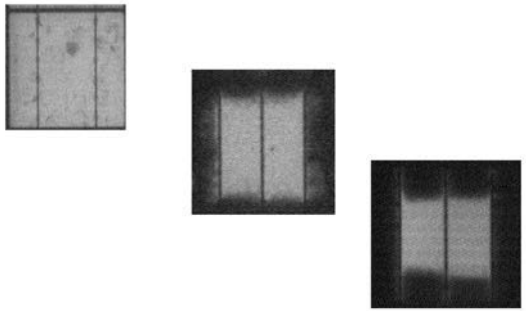
Fraunhofer ISE 2017

Fill factor primarily degrading, associated with failing Ag-Si contacts

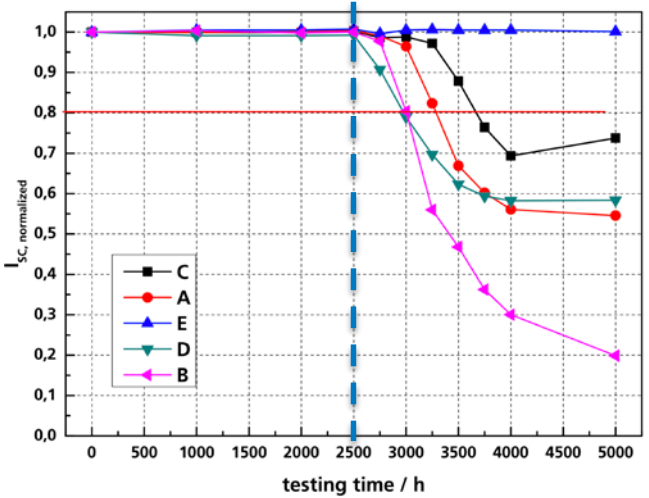
Damp Heat, 85°C, 85% RH







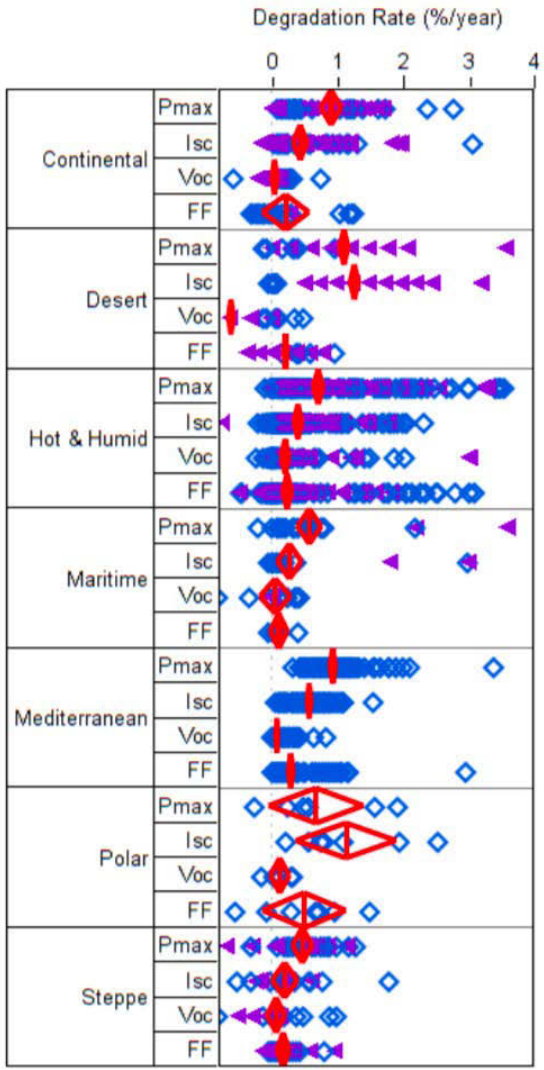
Electroluminescence



Koehl and coworkers

NREL 2012

In field results, I_{sc} is the primary loss factor leading to power degradation



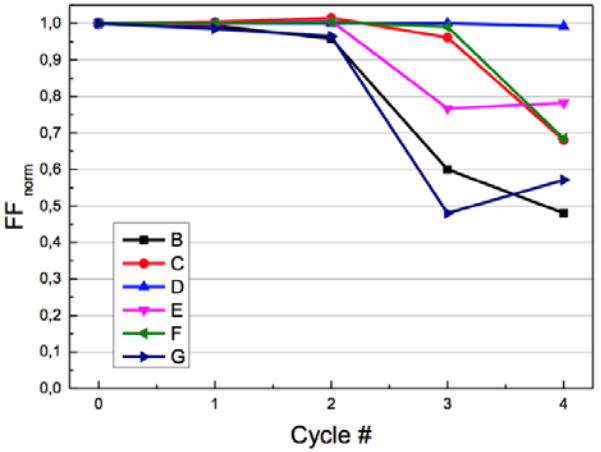
Jordan and coworkers

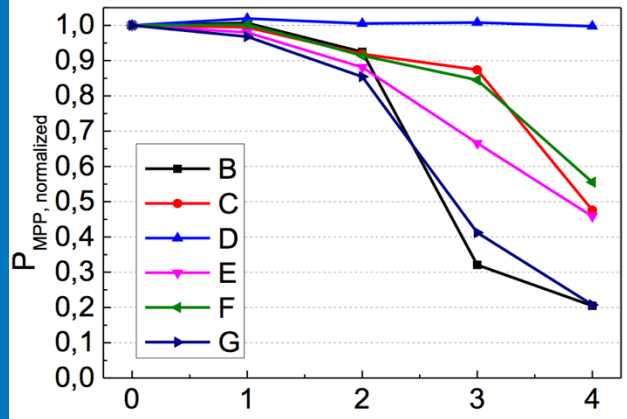
Fraunhofer ISE, 2014

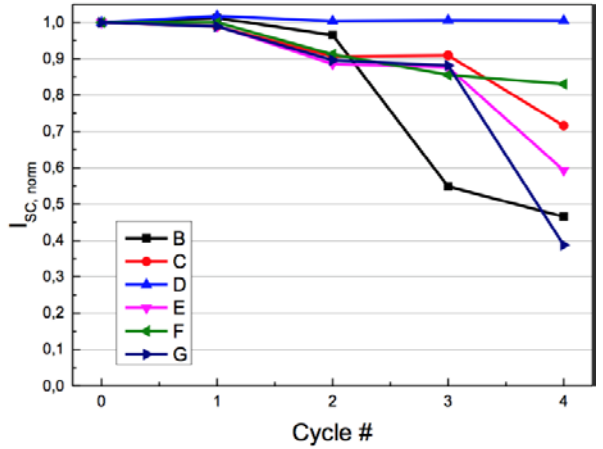
Sequential tests to better replicate losses of I_{sc} & FF as they appear in the field

- More representative levels of humidity in the module

Test	Duration	
Damp Heat 85°C / 85% rh	1000 h	initial
Temperature Cycle -40°C / +85°C	100 cycles	initial
Damp Heat – UV @ 85°C module temperature	500 h	initial
Damp Heat 85°C / 85% rh	500 h	repeating
Temperature Cycle -40°C / +85°C	100 cycles	repeating
Damp Heat – UV @ 85°C module temperature	500h	repeating





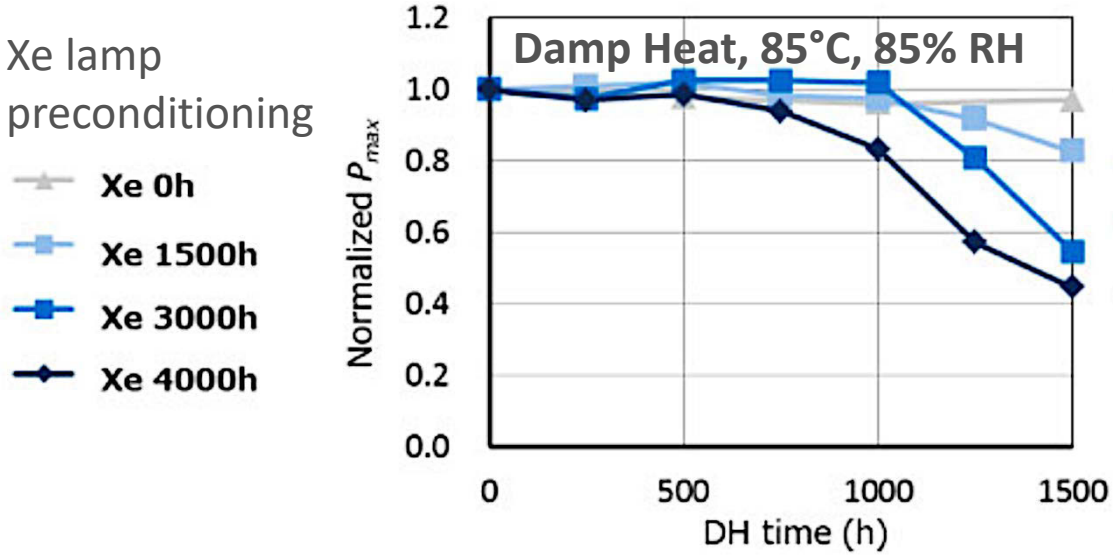


Koehl and coworkers

AIST 2015

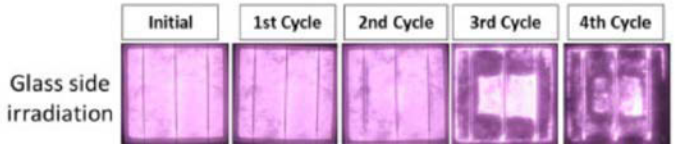
Light preconditioning followed by damp heat → Increased degradation

Xe lamp preconditioning



Working model: light activates decomposition and formation of acetic acid in EVA

- Weakens Ag/Si contacts



Ngo and coworkers

Electroluminescence

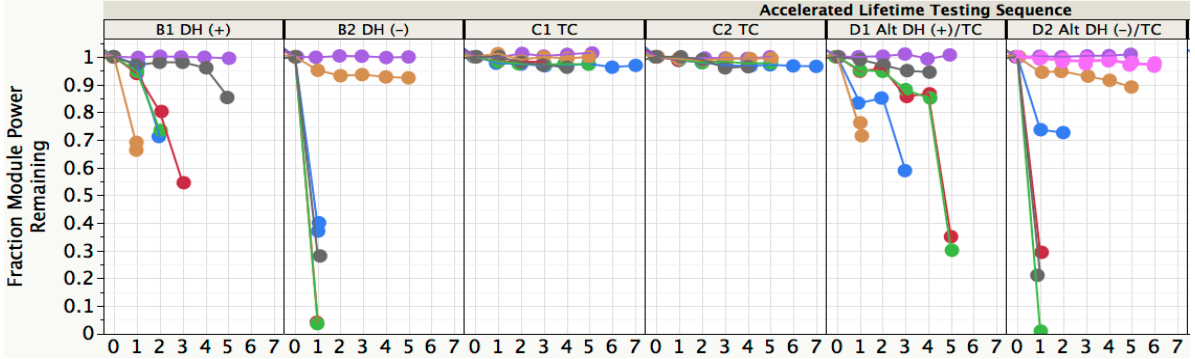
NREL Test-to-Failure 2010

Combined:

System voltage + Damp heat & alternatively sequenced with thermal cycling

Sequence	A. Control		B. Damp Heat with Bias 85°C/85%RH		C. Thermal Cycling with load -40°C/85°C		D. Alternating Seq. B/C DH/TC	
	5 kW hrs/m^2 light soak							
Round 1			DH+	DH-	TC	TC	DH+	DH -
Round 2			DH+	DH-	TC	TC	TC	TC
Round 3			DH+	DH-	TC	TC	DH+	DH -
Round 4			DH+	DH-	TC	TC	TC	TC
Round 5			DH+	DH-	TC	TC	DH+	DH -

- DH refers to 1000 hrs 85°C 85% relative humidity, IEC 61215 Ed. 2 sec. 10.13
- DH+(-) indicates +(-) voltage bias of 600 V or module's rated system voltage (whichever is greater) on shorted module leads with respect to grounded frame
- TC refers to 200 cycles between -40°C and 85°C, IEC 61215 Sec. 10.11 (I_{mp} applied when T> 25°C)
- Alt. DH/TC refers to a sequence of alternating 1000 Hrs. DH and TC 200 stress cycles described above



- Damp heat with bias → potential induced degradation
- Alternating DH with bias/TC → backsheet cracks
  - Hydrolytic degradation, desiccation, loss of plasticity, shrinkage, stress

NREL Test-to-Failure 2010

Combined:

System voltage + Damp heat & alternatively sequenced with thermal cycling

Sequence	A. Control		B. Damp Heat with Bias 85°C/85%RH		C. Thermal Cycling with load -40°C/85°C		D. Alternating Seq. B/C DH/TC	
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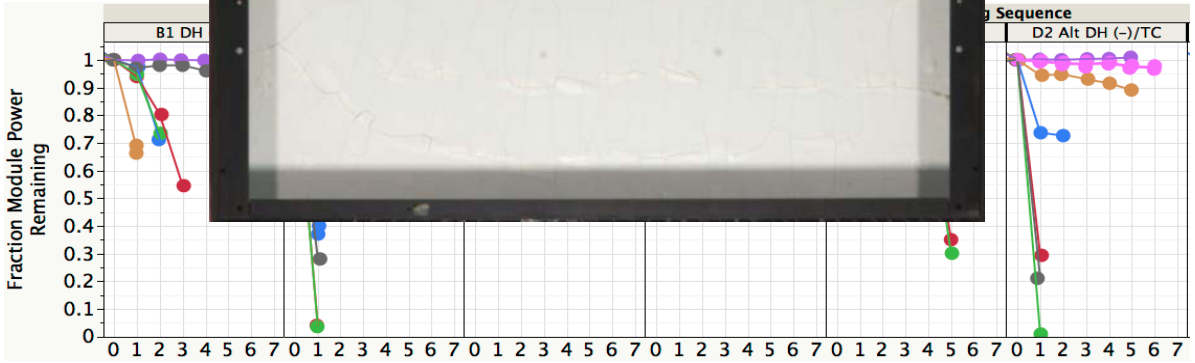
Round 3			DH+	DH-	TC	TC	DH+	DH -
Round 4			DH+	DH-	TC	TC	TC	TC
Round 5			DH+	DH-	TC	TC	DH+	DH -

- DH refers to 1
- DH+(-) indicat … on shorted mo
- TC refers to 20
- Alt. DH/TC refe

…chever is greater)

…d when T> 25°C)

…es described above



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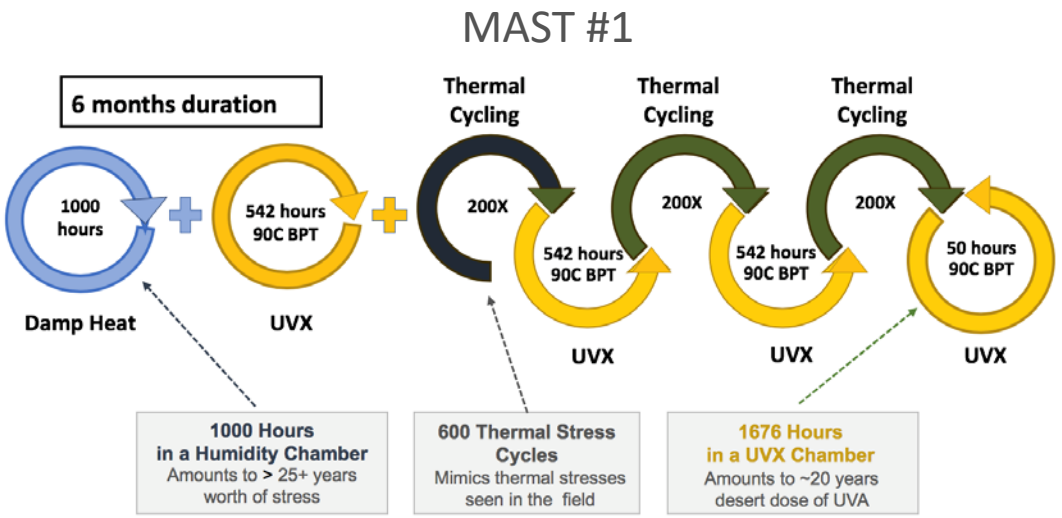
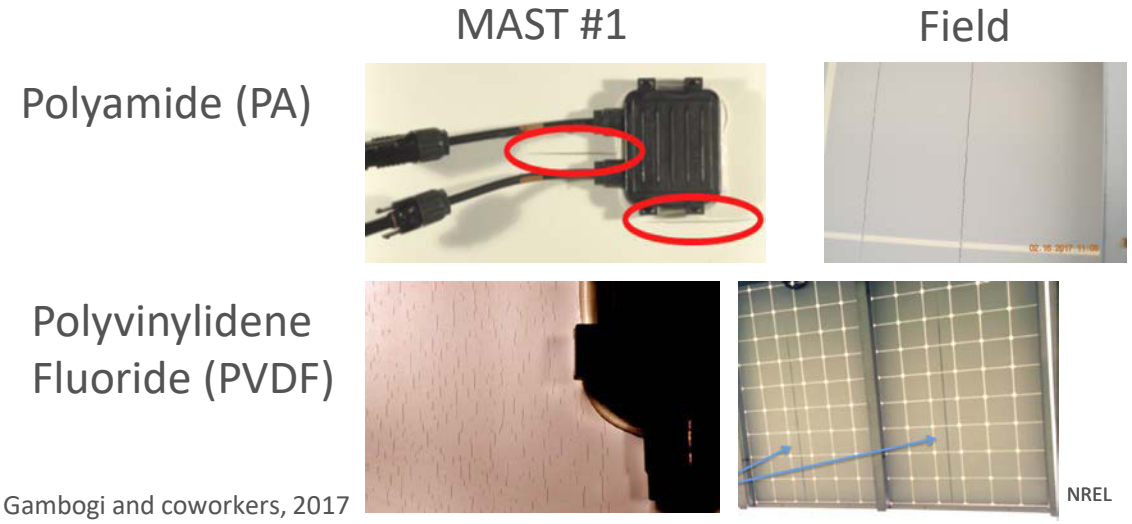
DuPont 2017

Module accelerated stress tests (MAST)

Sequences of DH, UV, and TC to replicate backsheet field failures





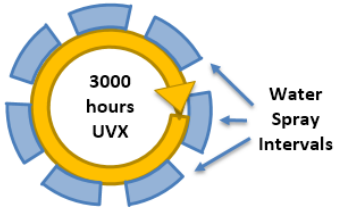
Gambogi and coworkers, 2017

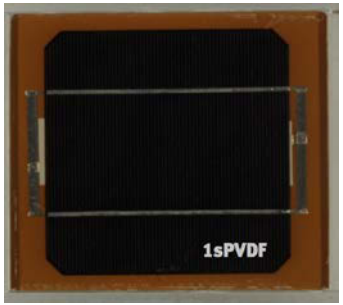
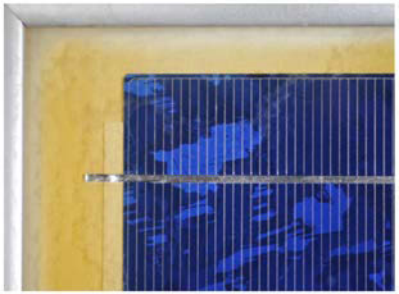
DuPont 2017

Module accelerated stress tests (MAST)

Sequences of UV + heat, intermittent water spray to replicate backsheet field failures

MAST #3



	MAST #3	Field
Polyvinylidene Fluoride (PVDF)		
Polyethylene terephthalate (PET)		

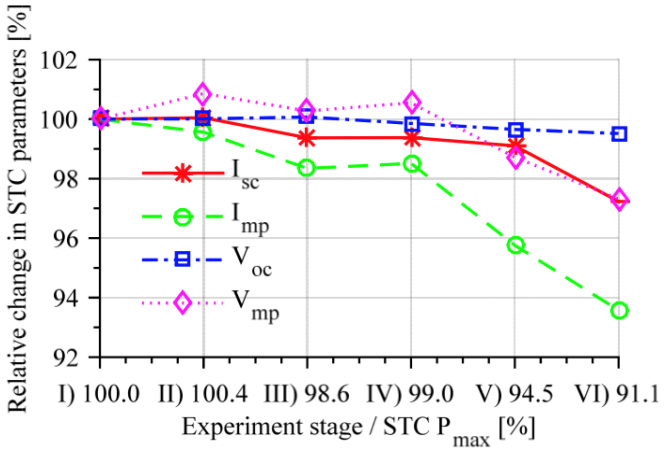
Gambogi and coworkers, 2017

Shown with Back-lighting

NREL/U. Aalborg 2017

Mechanical loading sequenced with thermal cycling, humidity freeze

Stage	Description
I	Four new mc-Si modules characterized at STC
II	Static mechanical loading with 2400 Pa (IEC 61215)
III	29 cycles of TC and 4 cycles of HF (IEC 61215)
IV	18 cycles of HF (IEC 61215)
V	Static mechanical loading with 2400 Pa (IEC 61215)
VI	13 cycles of HF (IEC 61215)



Sequence of stresses yield power loss

NREL/U. Aalborg 2017

Mechanical loading sequenced with thermal cycling, humidity freeze

Losses from J_o, n, and importantly R_s in later stages

Stage	Description
I	Four new mc-Si modules characterized at STC
II	Static mechanical loading with 2400 Pa (IEC 61215)
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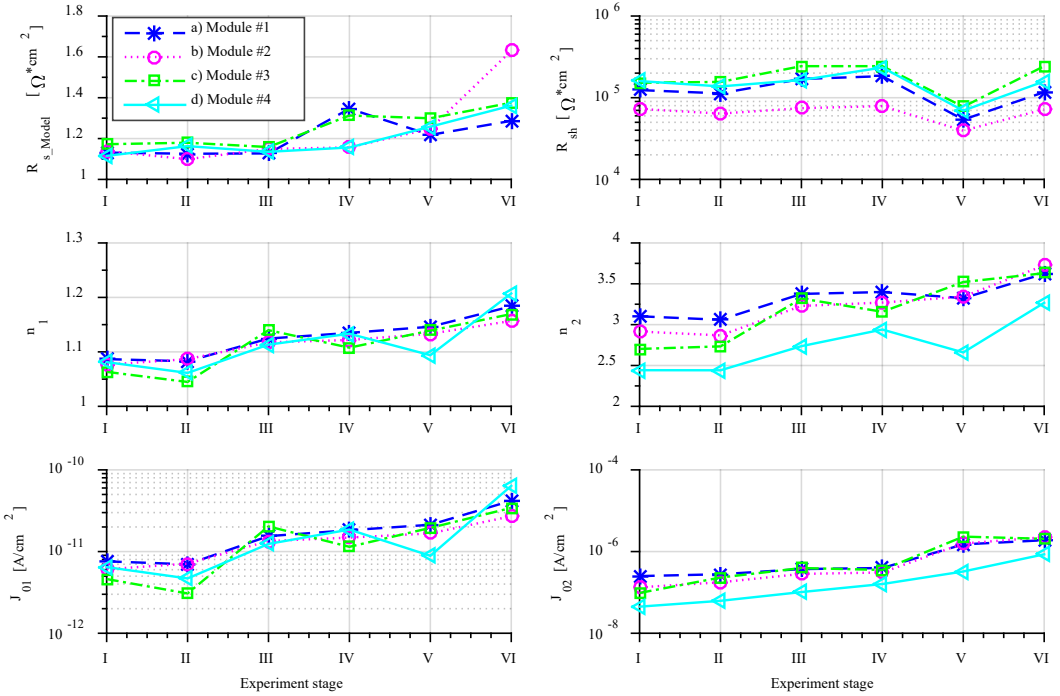
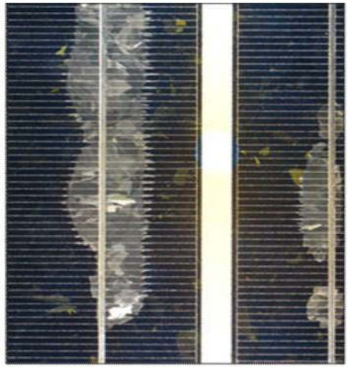


AIST 2009

UV light + high temperature leads to delamination

some AR coating

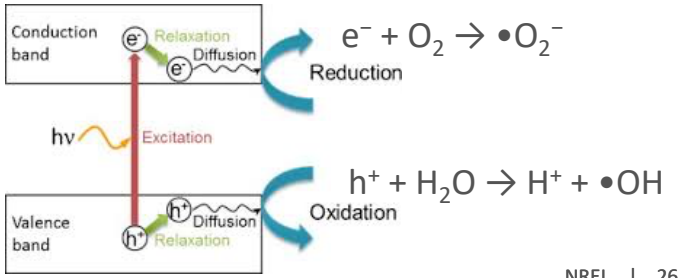


65°C + UV :180 W/m^2 900 h

75°C without UV light, 1000 h

Field example, NM

Photocatalytic reactions at TiOx ARC leading to delamination

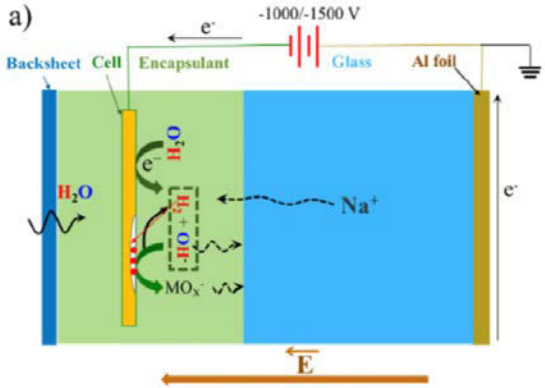


JPL
1980s

NREL/SunPower
2016

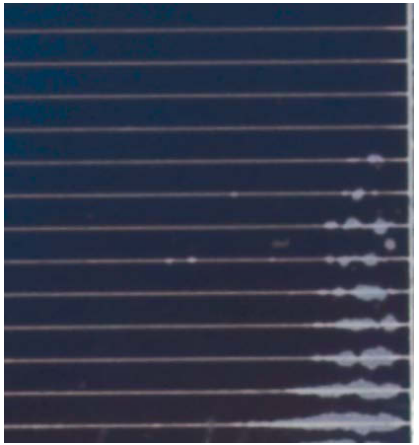
System voltage bias & damp heat leads to corrosion, delamination

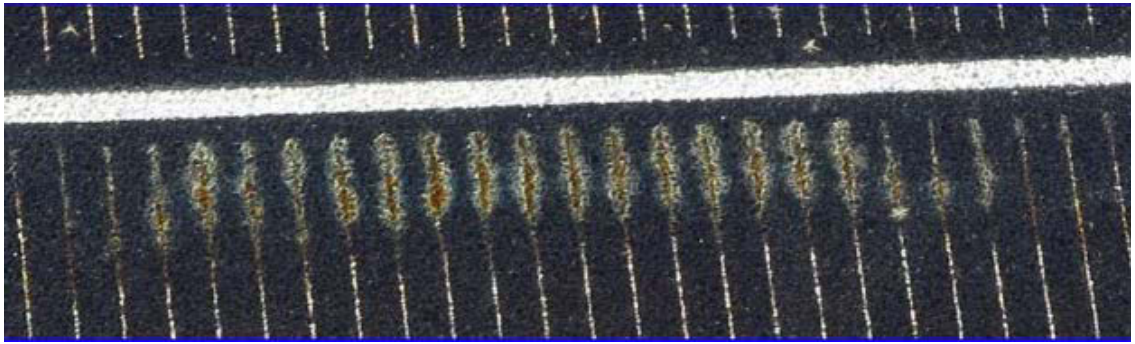
Damp heat &
(–) system voltage bias



Chamber

85°C, 85% RH 1000h → 72°C 95% RH, -1000 V



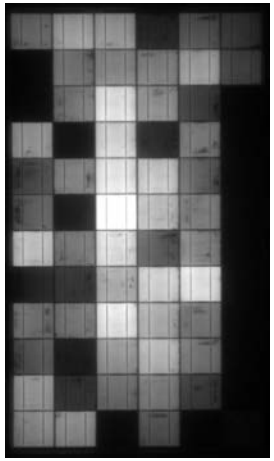


Field example, NM

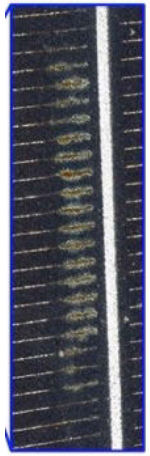
Contents

Field Fails

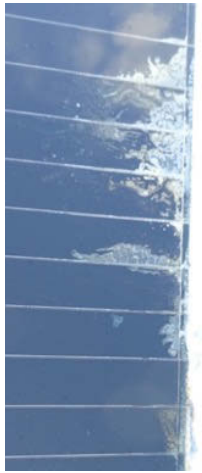
Polyamide backsheet



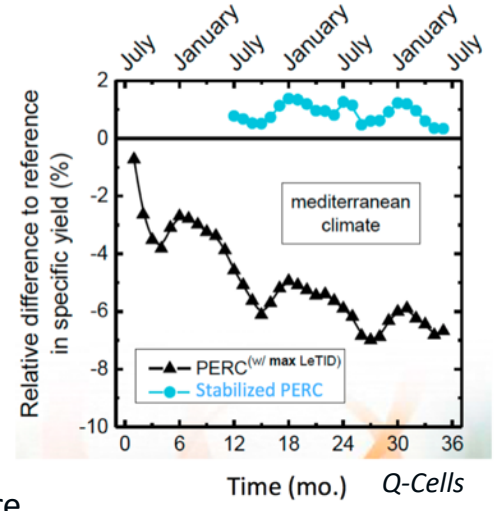
PID



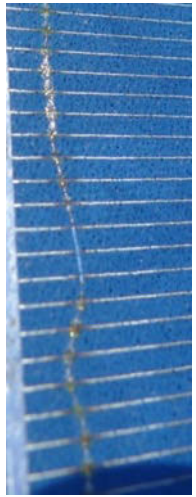
Corrosion



Edge seal failure



LeTID



Snail trails

Delamination

Issues manifesting in the field in modules that passed the standards
—Multiple factors working in combination leading to the degradation—

Combined-accelerated stress testing

Combining stress factors

- Heat
- Light
- Humidity
  - Condensing
  - Non-condensing
- Mechanical pressure
- System voltage
- Reverse bias *(in progress)*

Mini-module platform

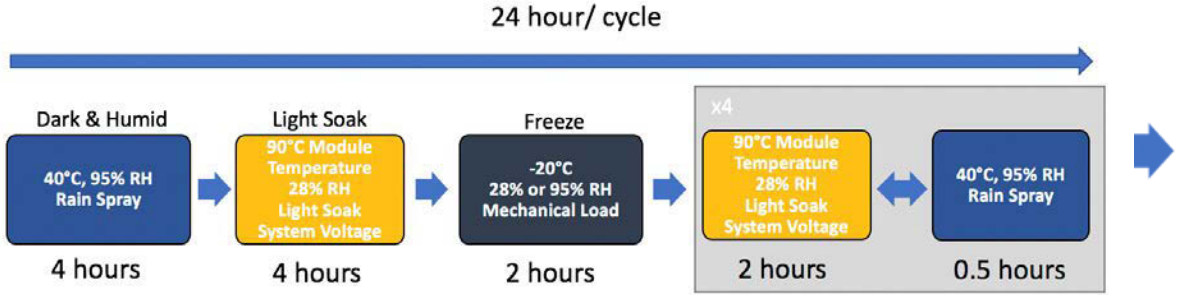
In-situ Metrology

- RH, T_{module}, *I-V*, EL

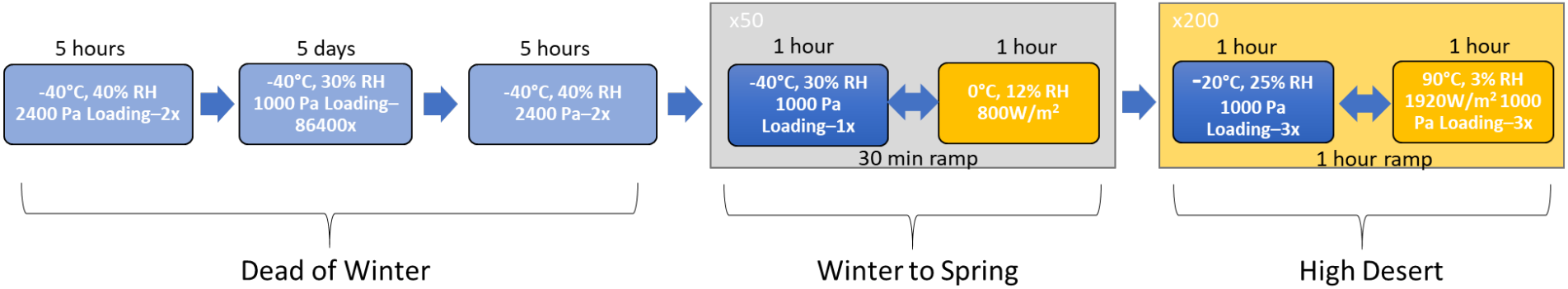
Discover potential weaknesses in module designs, both known and not *a-priori* recognized, reduce risk, accelerate time to market, bankability and reduce costly overdesign, to lower the levelized cost of electricity.

Protocol

Phase 1 – Based on ASTM D7869 for tropical conditions



Phase 2 – Multi-season

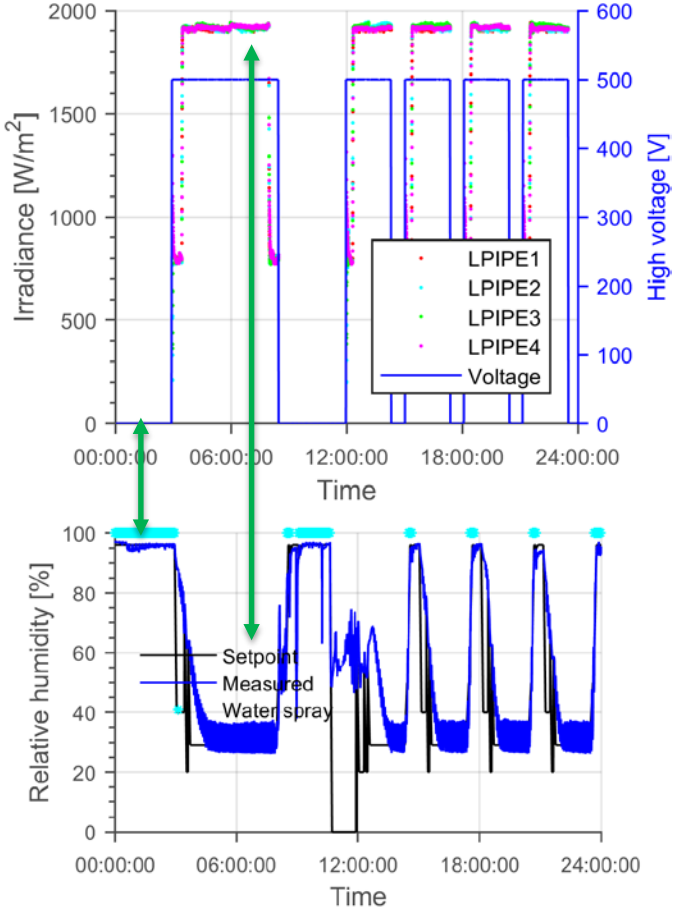


- Field relevant levels
- Acceleration factor 8 × - 16 ×
- No light + rain combination (wet during transitions)
- PID voltage bias with light only

Stress cycle (phase 1)

Xe lights on, system voltage bias on -

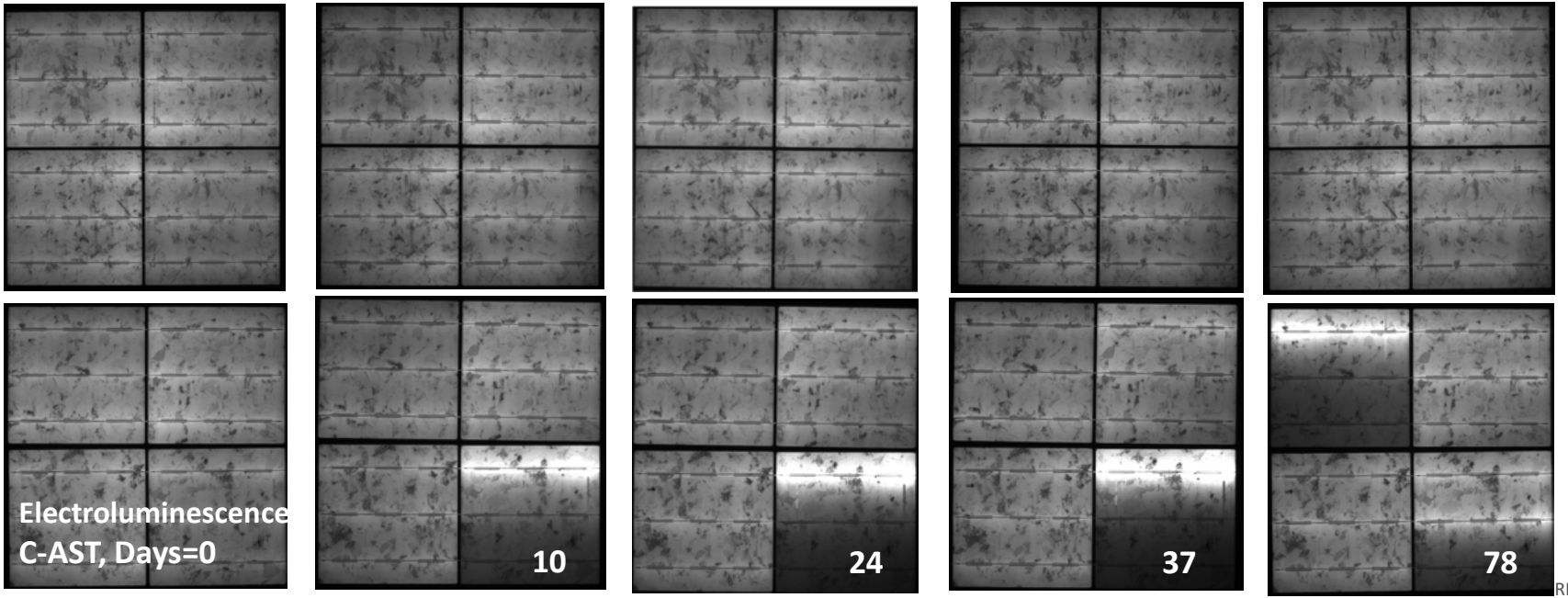
Lights on: humidity lower -
Lights off: modules wet



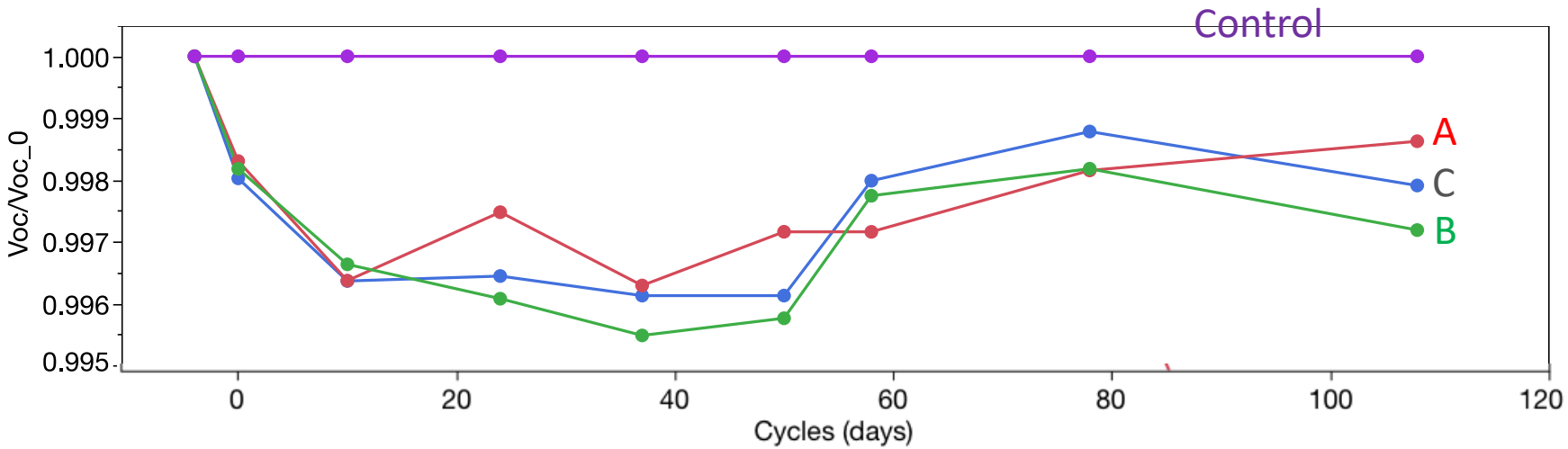
Modes	Types/issues	Stress factors	IEC	C-AST
Fatigue, breakage (→burns)	Cell spacing, cell thickness/nature, ribbon dimensions/bends, non-solder distance, solder/ECA quality	Mechanical and thermomechanical stress on conductors. Current leading to joule heating in the conductors	IEC 61215 MQT 11 TC IEC 62782 – DML + IEC 62759 (transp.): 50 TC, 20 HF, ML 2400 Pa)	✓

A

B



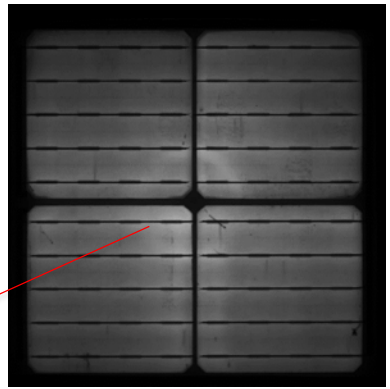
Modes	Types/issues	Stress factors	IEC	C-AST
Light-induced degradation	B-O, Fe-B, sponge LID	Sunlight + temperature	IEC 61215 MQT 19 Stabilization c-Si / Thin Film IEC 61345 module UV test (withdrawn)	✓
	Light & elevated temperature degradation 1) c:Si 2) Thin Film			
	UV LID (H, charges)			



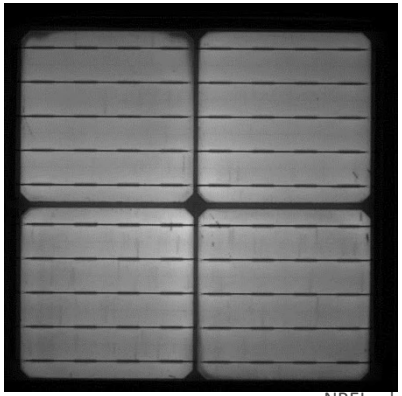
Modes	Types/issues	Stress factors	IEC	C-AST
Light-induced degradation	B-O, Fe-B, sponge LID Light & elevated temperature degradation 1) c:Si 2) Thin Film UV LID (H, charges)	Sunlight + temperature	IEC 61215 MQT 19 Stabilization c-Si / Thin Film IEC 61345 module UV test (withdrawn)	✓

Shadowed region showing higher minority carrier lifetime

TPT UV Pass EVA

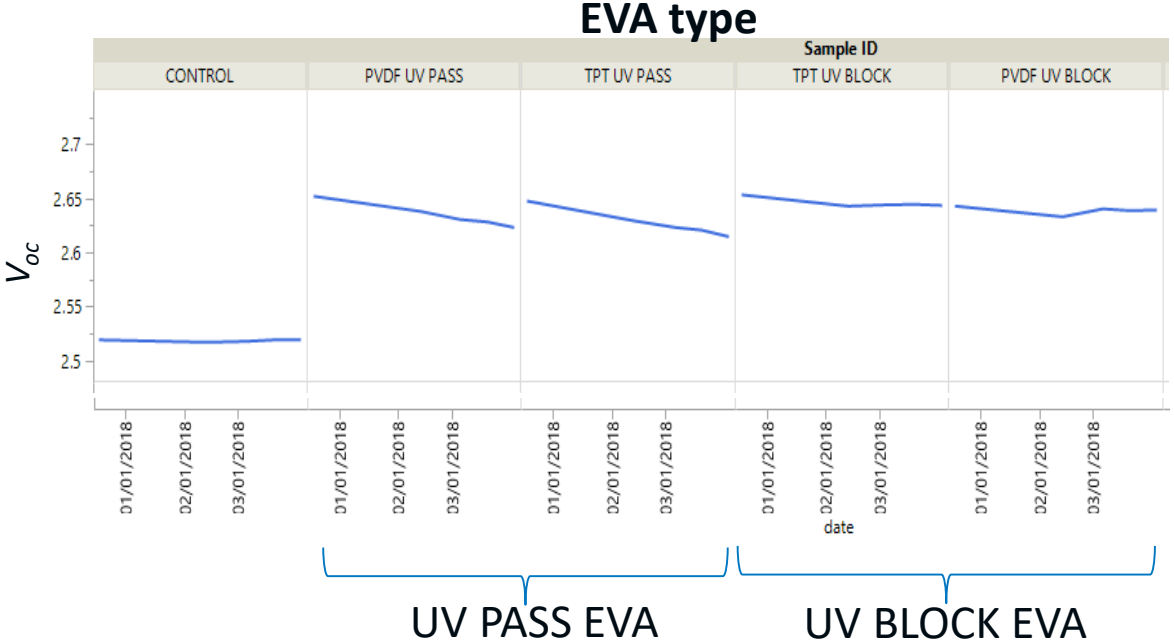


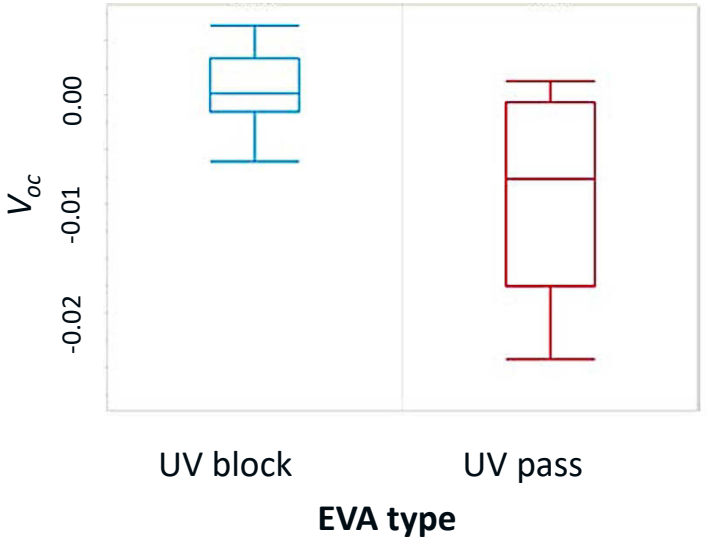
TPT UV Block EVA



Electroluminescence

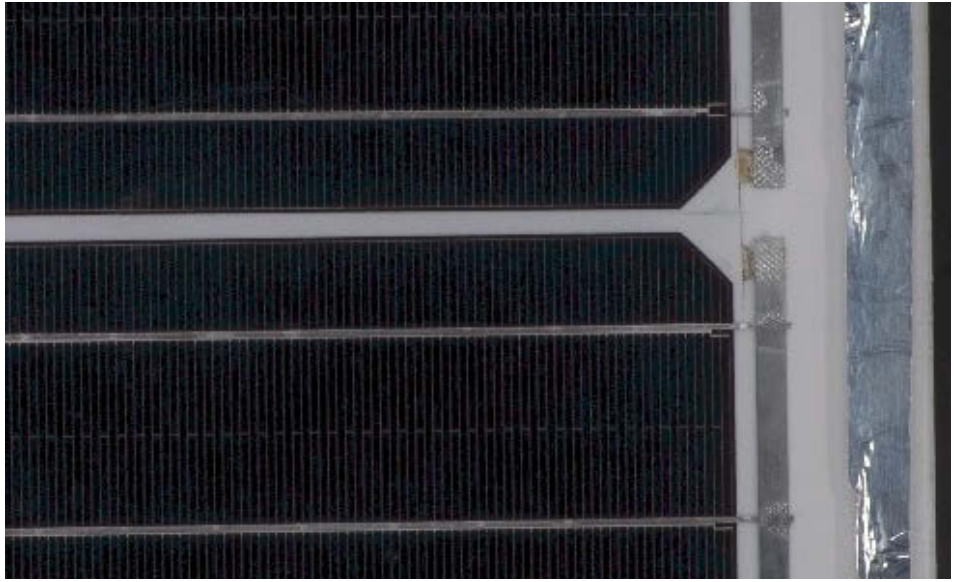
Modes	Types/issues	Stress factors	IEC	C-AST
Light-induced degradation	B-O, FeB, Sponge LID	Sunlight + temperature	IEC 61215 MQT 19 Stabilization	✓
	Light & elevated temperature degradation 1) c:Si 2) Thin Film		c-Si / thin film	
	UV LID (H, charges)		IEC 61345 module UV test (withdrawn)	

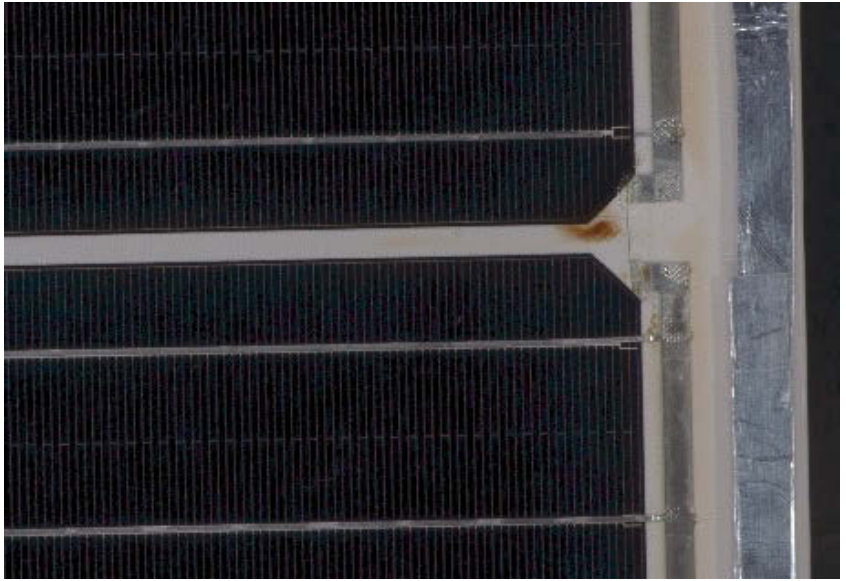




Modes	Types/issues	Stress factors	IEC	C-AST
Yellowing & module packaging optical losses	Photochemical degradation of polymers, ion migration	Sunlight, temperature, humidity, electrical-bias	IEC 62788-7-2 (coupon testing, coupon not precisely defined, does not include electrical bias)	✓

2 module types through C-AST:





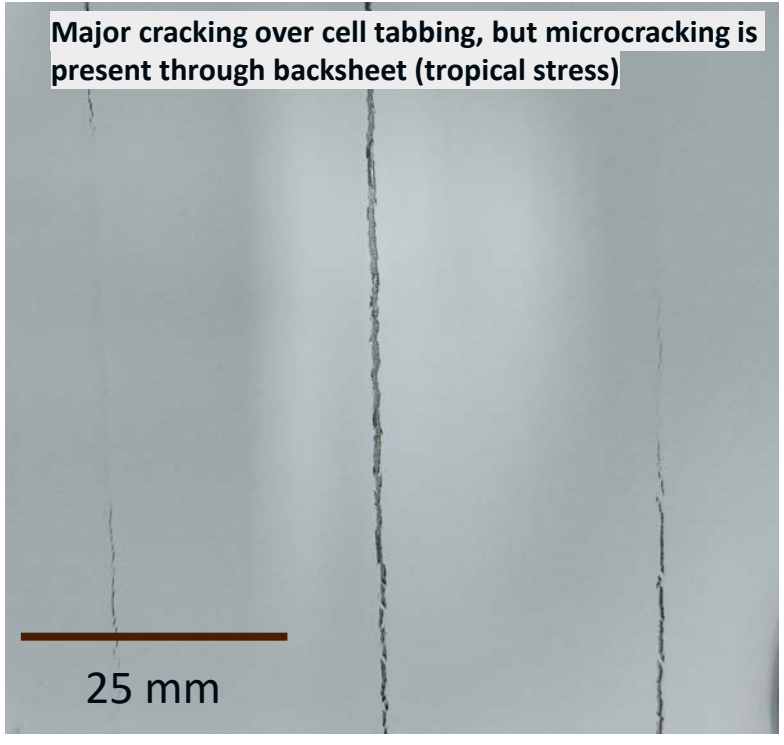
Apply C-AST to identify weaknesses in backsheets

Encapsulant	*Backsheet* PVF	PA	PVDF
UV Pass EVA	✓	✓	✓
UV Block EVA	✓	✓	✓

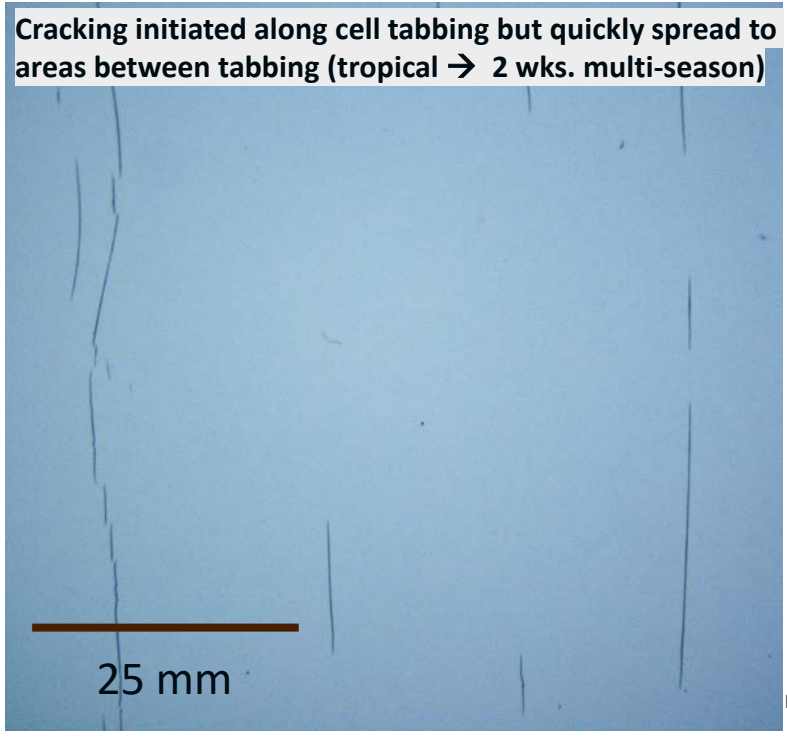
→ Apply C-AST to identify failures in backsheets failed in field but failures not detected in conventional testing

Modes	Types/issues	Stress factors	IEC	
Backsheet cracking and delamination	Oxidative, photo, hydrolytic reactions, localized stress	Heat, sunlight, voltage moisture and mechanical stress	IEC 61730-2 Seq B: DH 200/UV 60/ HF 10/UV 60/HF 10	✓

PA Backsheet cracking

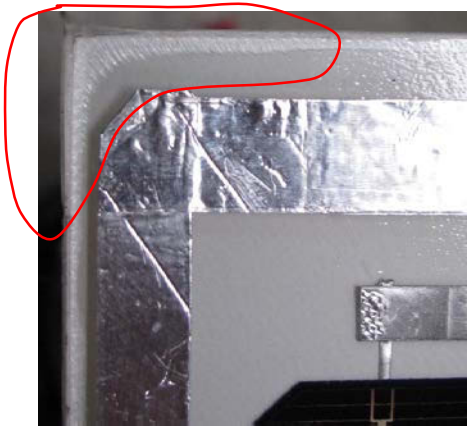


PVDF Backsheet cracking

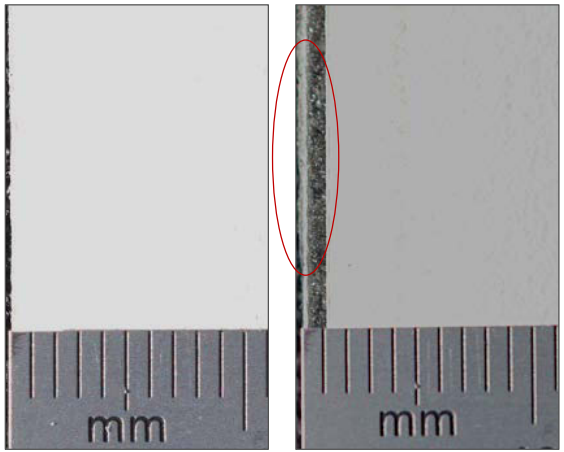


Representation: the sample

Delamination of PA backsheet edge seen at week 8 of C-AST



Associated with shrinkage of backsheet offset from glass edge of about 1 mm shown at week 22 on the right



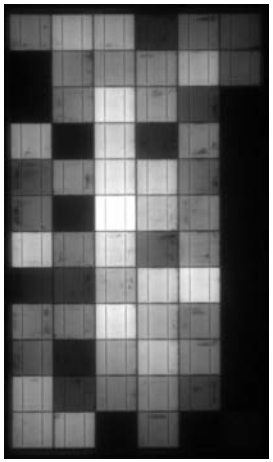
If you have a free-standing coupon, or too small a sample, you might not have the critical dimensions to see the shrinkage and cracking: Sample representation critical

The tally

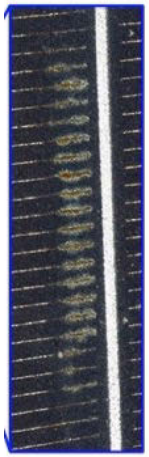
IEC protocol tests, existing or missing vs C-AST

13 + 7 Missing = 20

Polyamide backsheet

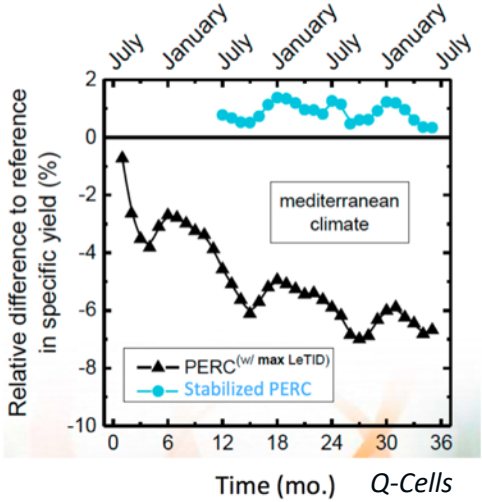


PID

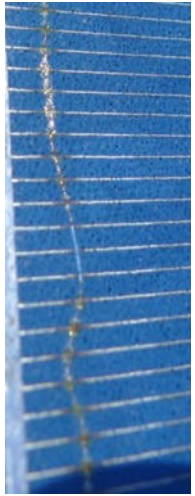


Corrosion

Edge seal failure



LeTID



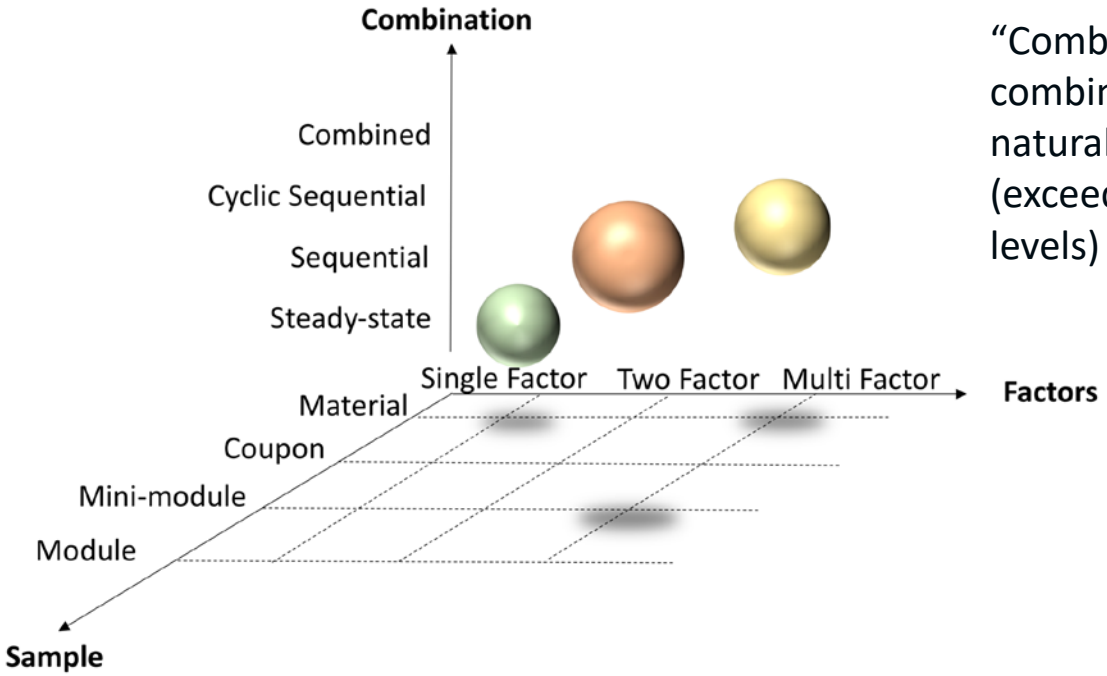
Snail trails

Delam.

Multiple factors working in combination leading to the degradation

Contents

Representation

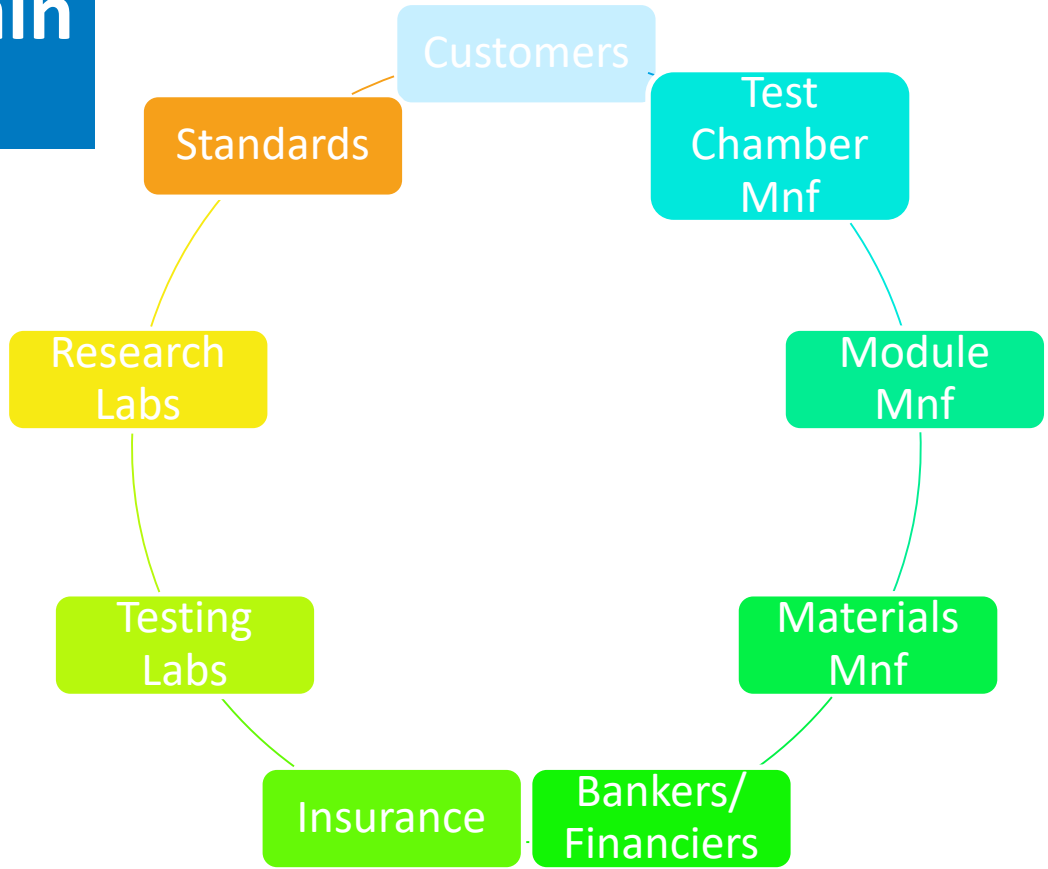


"Sample": representation of the materials interfaces, boundary conditions of the shipping module

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

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

C-AST – the value chain



Contents

Summary & next steps

- *To de-risk modules, we must represent:*
  - The sample
  - Stress factors of the natural environment
  - Their combination

    → success at reproducing field failures
- *Future work, especially in C-AST:*
  - Further show field-failure mechanisms
  - Engagement of all segments of the value chain
  - Further develop value proposition
  - Acceleration factor studies
  - Migration to full size modules
  - Better simulate wind load with dual side pressure
- *Join our discussions:*
  - PV Quality Assurance Taskforce (PVQAT- Task Group 3)
  - IEC Technical Committee 82 Working group 2: two IEC Technical Reports in progress

Thank you

NREL Team: Michael Owen Bellini, David Miller, Dana Sulas, Hannah North, Michael Kempe, Greg Perrin, and Kent Terwilliger
AIST Team: Tadanori Tanahashi and Keiichiro Sakurai **Aalborg U**: Sergiu Spataru
Dupont Team: Bill Gambogi **Mitsui Chemical**: Tsuyoshi Shioda **Tessolar Inc**: Katy Hartman
Itek Energy **PVQAT TG3** members, **DuraMAT team**