Sequential Testing that Better Predicts Field Performance

Atlas-NIST Workshop 2017 December 4-6, 2017

William Gambogi, Steven MacMaster, Bao-Ling Yu, Thomas Felder, Hongjie Hu, Kaushik Roy Choudhury, and T. John Trout

DuPont Photovoltaic Solutions

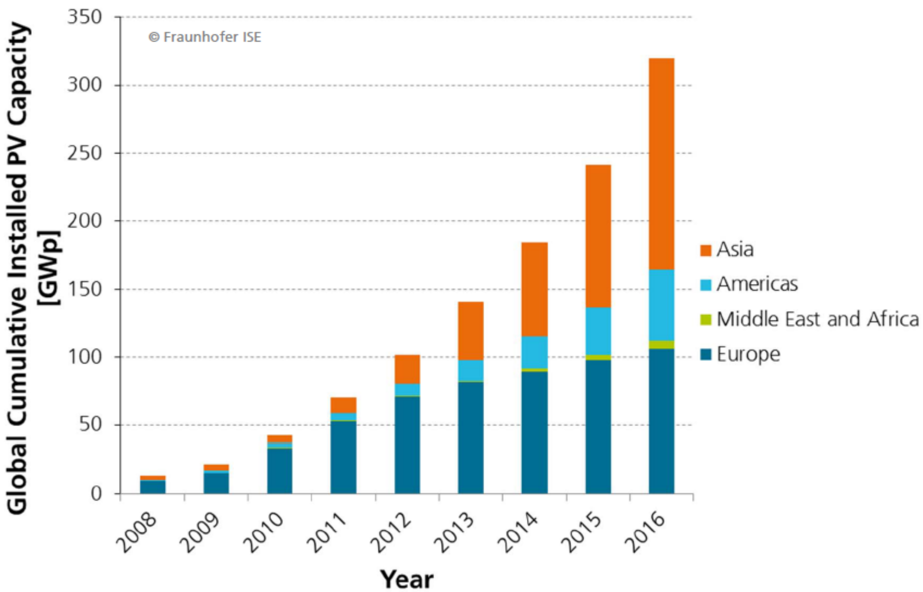
For over 40 years

our material innovations have led the photovoltaics industry forward, and helped our clients transform the power of the Sun into power for us all. Today we offer a portfolio of solutions that deliver proven power and lasting value over the long term. Whatever your material needs, you can count on quality DuPont Photovoltaic Solutions to deliver the performance, efficiency and value you require, day after day after day…

Outline

- PV Market
- Stresses in the PV Field
- Field Examples
- PV Module Qualification and Limitations of IEC Qualification
- Approaches to Assessing PV Module Durability
- Reducing the Duration of PV Module Assessment
- Conclusions

Global PV Installations and Largest PV Installations



Data: IHS. Graph: PSE AG 2017

Tengger Desert Solar Park, 1.5GW, China

Datong Solar Power Top Runner Base, 1.0 GW, China

Longyangxia Dam Solar Park, 850MW, China

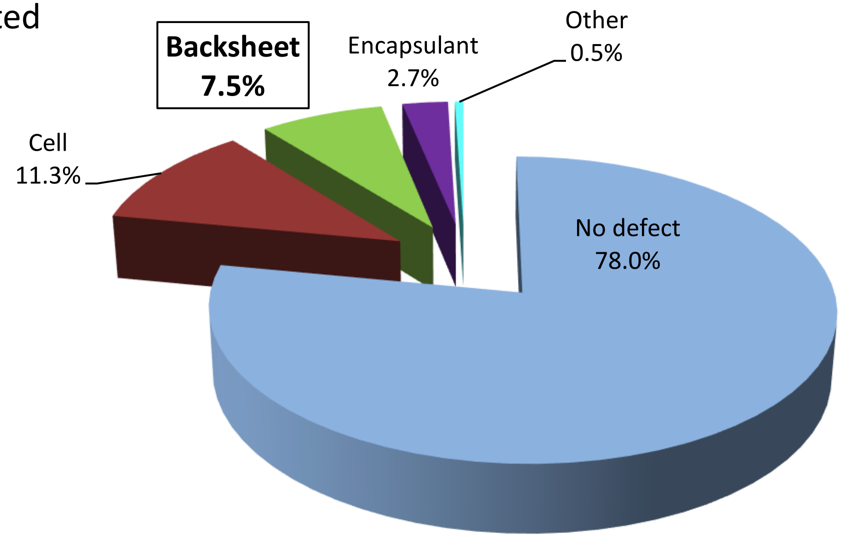
Kamuthi Solar Power Project, 648MW, India

Kurnool Ultra Mega Solar Park, 900 MW, India

DuPont 2016 Field Analysis and Database - Overview

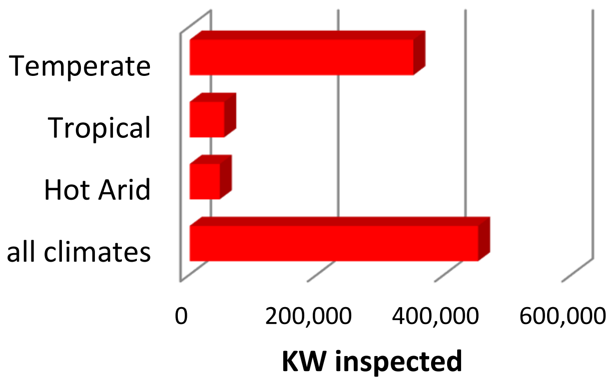
2016 Analysis

453MW inspected



	2016
Installations	197
Number of panels	1,919,000
Average age (years)	3.4
MW	453

Climate sample sizes 2016



Data size more than doubled from 2015 to 453 MW

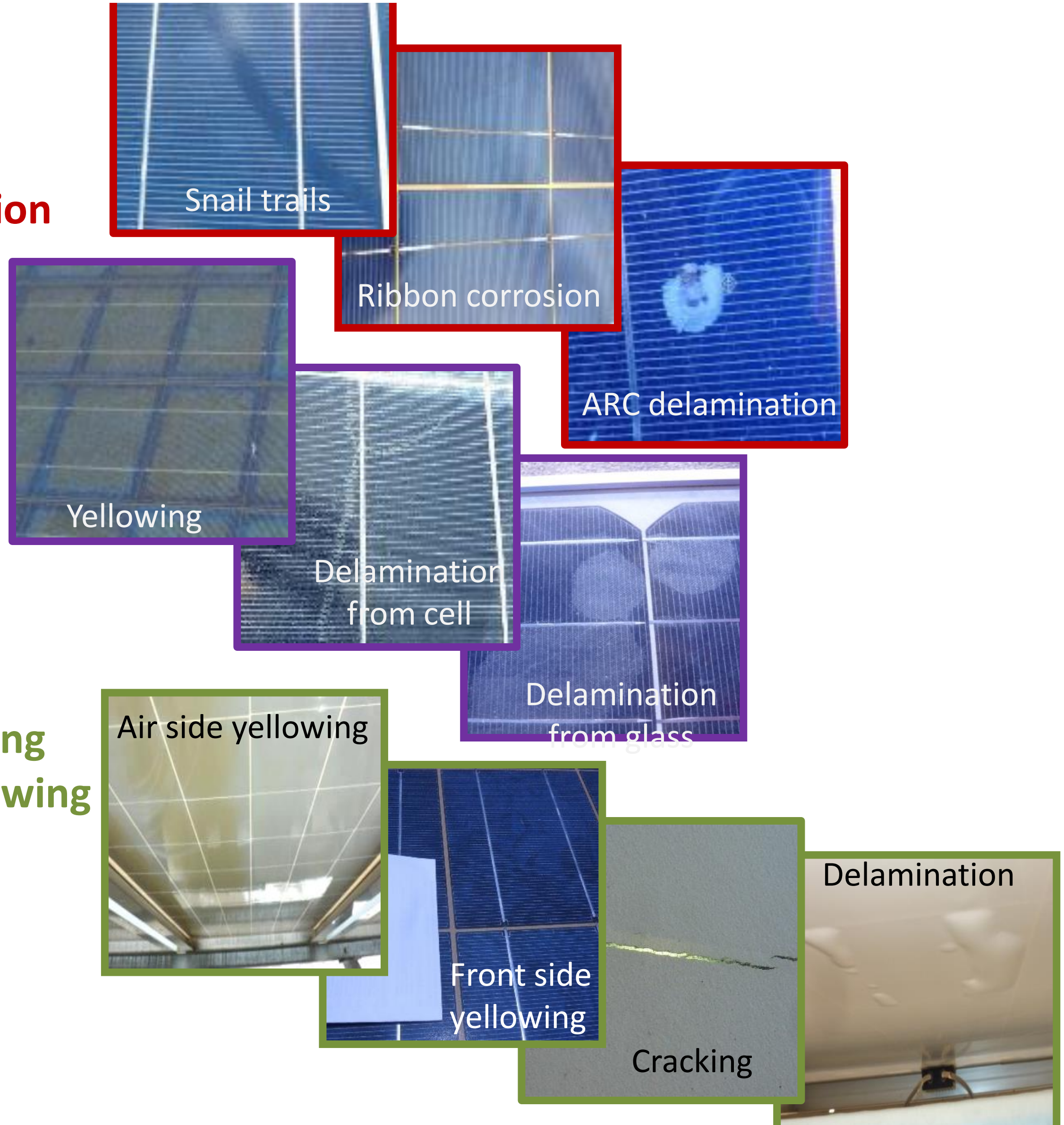
- All defects 22%
- Cell related defects 11.3%
- Backsheet defects 7.5%

Field Degradation and Defect Categories

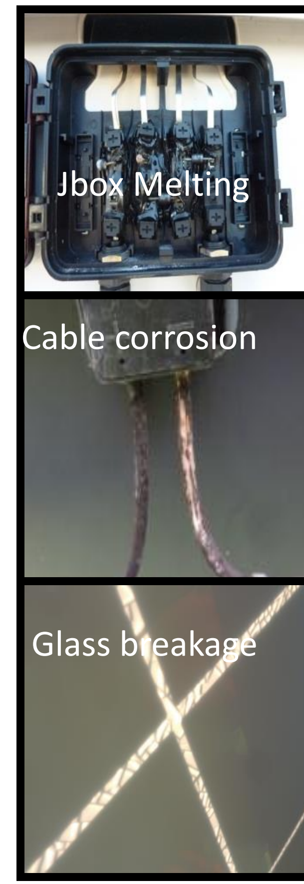
Cell defects
- Snail Trails
- Corrosion
- ARC Delamination

EVA defects
- Yellowing
- Delamination

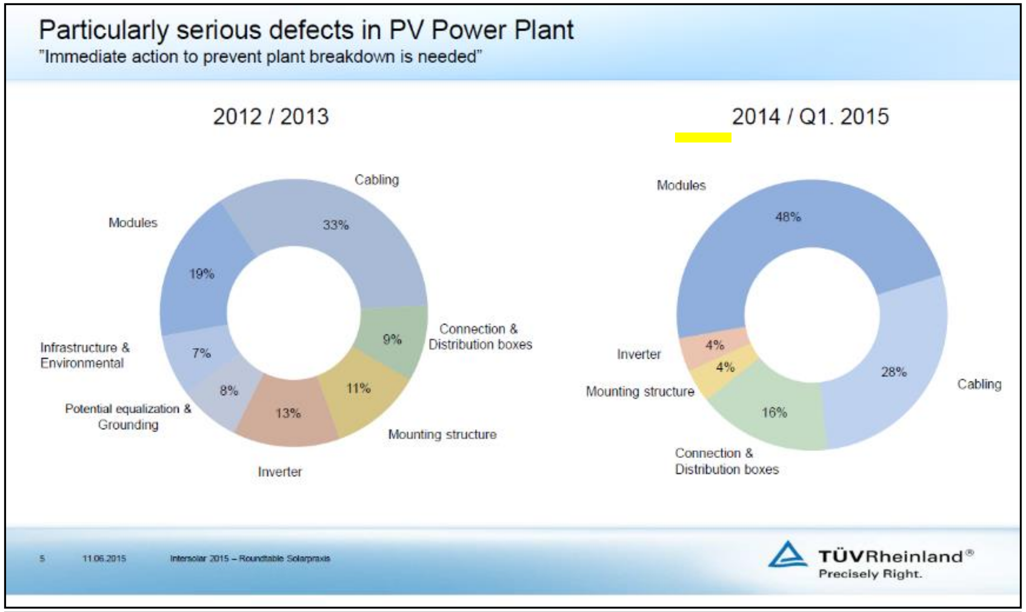
Backsheet defects
- Air Side Yellowing
- Front Side Yellowing
- Cracking
- Delamination
- Bubbling
- Other



Other defects



TÜV Rheinland Data Shows Causes of Defects



Examples for Particularly Serious Defects (PSD), Serious Defects (SD) and Less Serious Defects (LSD)

Components	Category	Defects	Example
Modules	PSD	PID – Potential Induced Degradation Undervalued power, glass breakage, delamination Burned junction box Defective backsheet	 Delamination
	SD	Browning, serious micro cracks	
	LSD	Module frame damaged Snail tracks	
Inverter	PSD	Out of operation	
	SD	Insulation faults Not suitable for local environmental conditions	
	LSD	Inverter door without filter	
Connection & Distribution boxes	PSD	Missing Cover	 Burned Connection
	SD	Burned connection, surge protector out of operation Water in distribution box Wrong fuse rating Missing labels	
	LSD	Dirt inside	

11.06.2015 Intersolar 2015 – Roundtable Solarpraxis

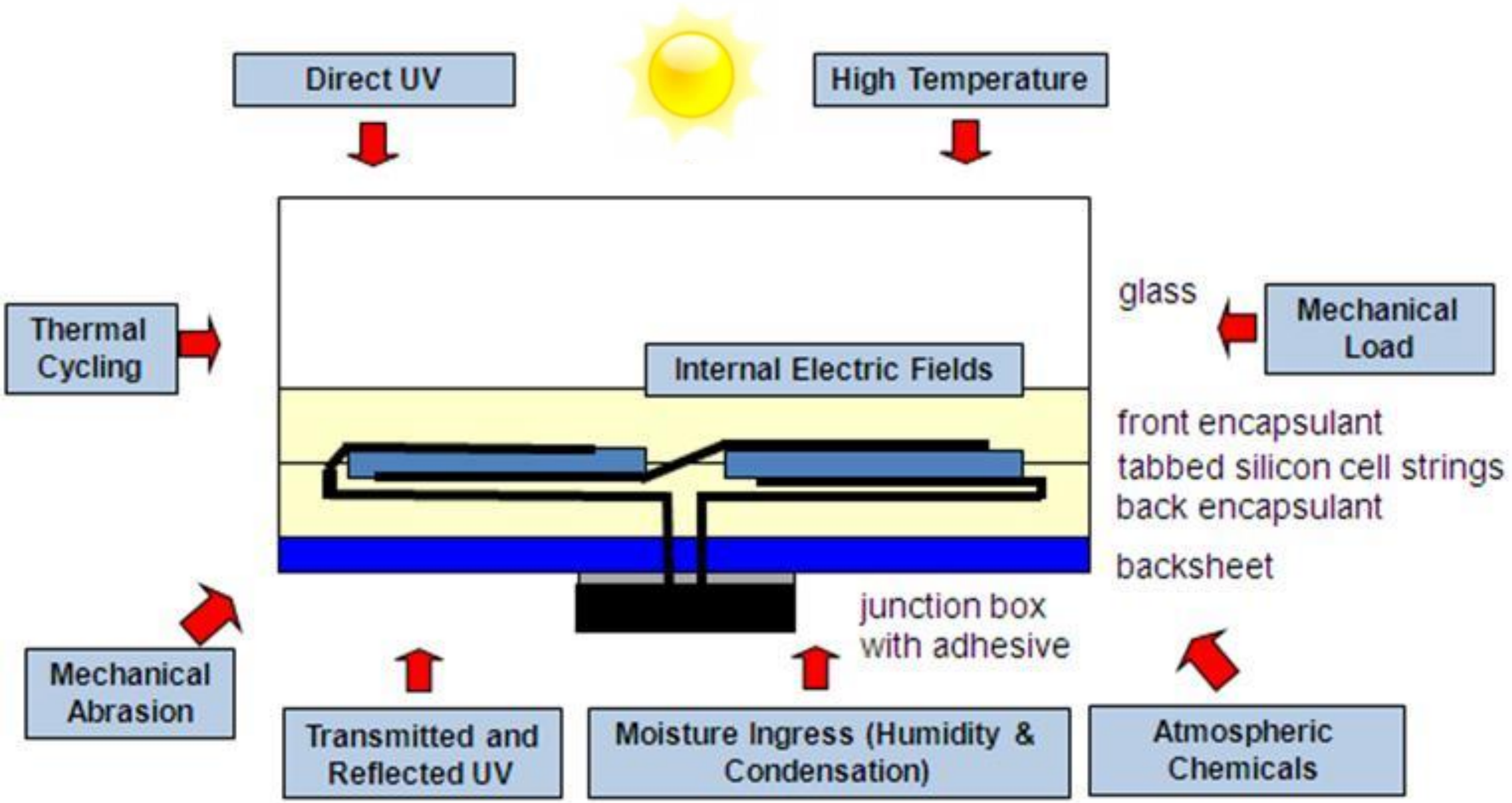
TÜVRheinland®
Precisely Right.

Increasing trend of module related issues reported (19% to 48%)

Defective backsheet and delamination termed "Particularly Serious Defects".

Florian Reil Intersolar EU, 2015

Stresses in the PV Field



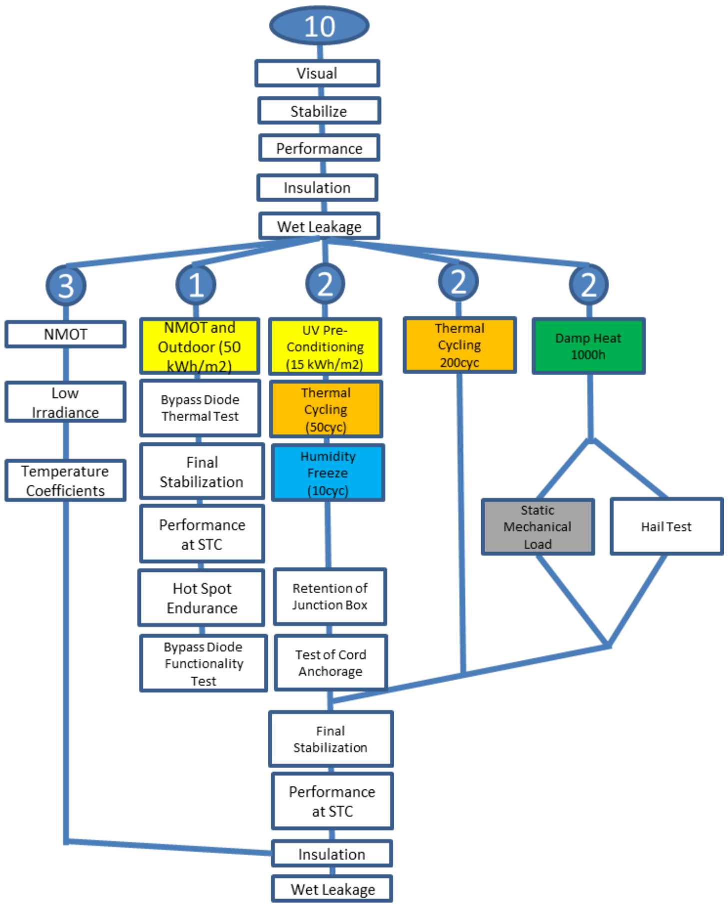
- Photovoltaic modules are exposed to a wide range of stress conditions
- Stresses operate on the module simultaneously and sequentially, synergistic effects are observed

Shortcomings of Current Qualification Tests

Current IEC qualification standards

- were designed to identify early failures due to module design, not predict long term durability
- do not address synergistic effects of multiple stresses in the field
- do not adequately address durability of materials to UV exposure and weathering

- UV and weathering tests are typically not applied to modules due to the equipment challenges associated with large area UV and weathering exposure
- Only 10 modules used to establish PV module qualification
- Relatively low durability stress conditions



DuPont Single Exposure Testing Protocols

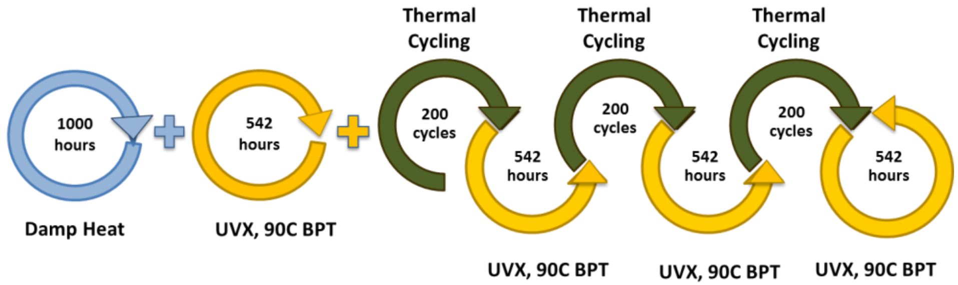
Test	Exposure Condition	Evaluation	Technical Reason
Damp Heat	85°C, 85%RH	1000h	adequate for PET hydrolysis damage
		2000h	test-to-failure
		>3000h	test-to-failure
UV (Junction Box Side)	UV, 70°C BPT 0.55 W/m²-nm at 340nm, ~60 W/m² (300-400nm)	275 kWh/m² (4230 h)	desert climate (25 year equivalent)
		235 kWh/m² (3630 h)	tropical climate (25 year equivalent)
		171 kWh/m² (2630 h)	temperate climate (25 year equivalent)
UV (Encapsulant Side)	UV, 70°C BPT 1.1W/m²-nm at 340nm, ~120 W/m² (300-400nm), glass/EVA/EVA filter, Standard and UV transmissive EVA	550 kWh/m² (4600 h)	desert condition (6 - 16 year equivalent)
			tropical condition (7 - 19 year equivalent)
			temperate condition (10 - 26 year equivalent)
Thermal Cycling	-40°C, 85°C, 200cyc	1x, 2x, 3x	3 x IEC requirement
Thermal Cycling / Humidity Freeze	-40°C, 85°C (50cyc); -40°C, 85°C 85%RH (10cyc)	1x, 2x, 3x	3 x IEC requirement

- **Damp heat testing to 1000 hours is more than sufficient for PET hydrolysis over 25 years of outdoor exposure**
- **UV testing needs to be extended to 25 years to adequately address backsheet performance in the outdoor environment**
- **Dosage for UV testing should match 25 year outdoor exposure to insure durability**

DuPont Recommended Sequential Tests

Rationale

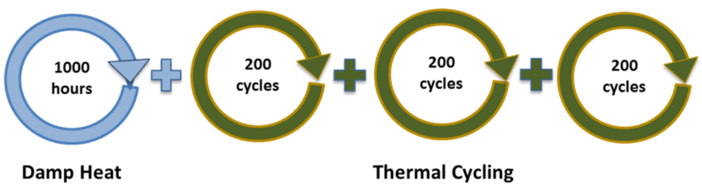
Test 1



Backsheet, minimodule, or full-size module

Combines the most important stress factors in the field, appropriate for component, minimodule, or full-size module testing, our best recommendation

Test 2



DH/TC exposure to evaluate full size modules

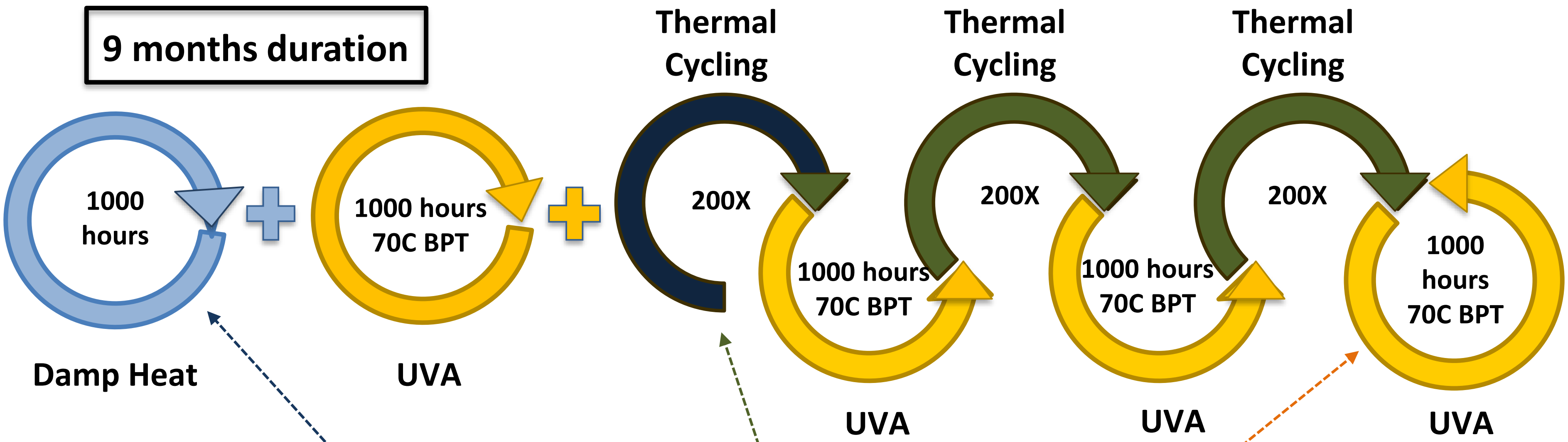
Combines two important stress factors in a shorter test not requiring expensive UV equipment. Appropriate for full-size module testing

Test 3

ASTM or SAE weathrting protocols
Xenon Weatherometer
Backsheet coupon or Minimodule

Combines UV and rainfall simulation, common weathering test conditions in commercially available weatheromter

Module Accelerated Sequential Test (MAST1)



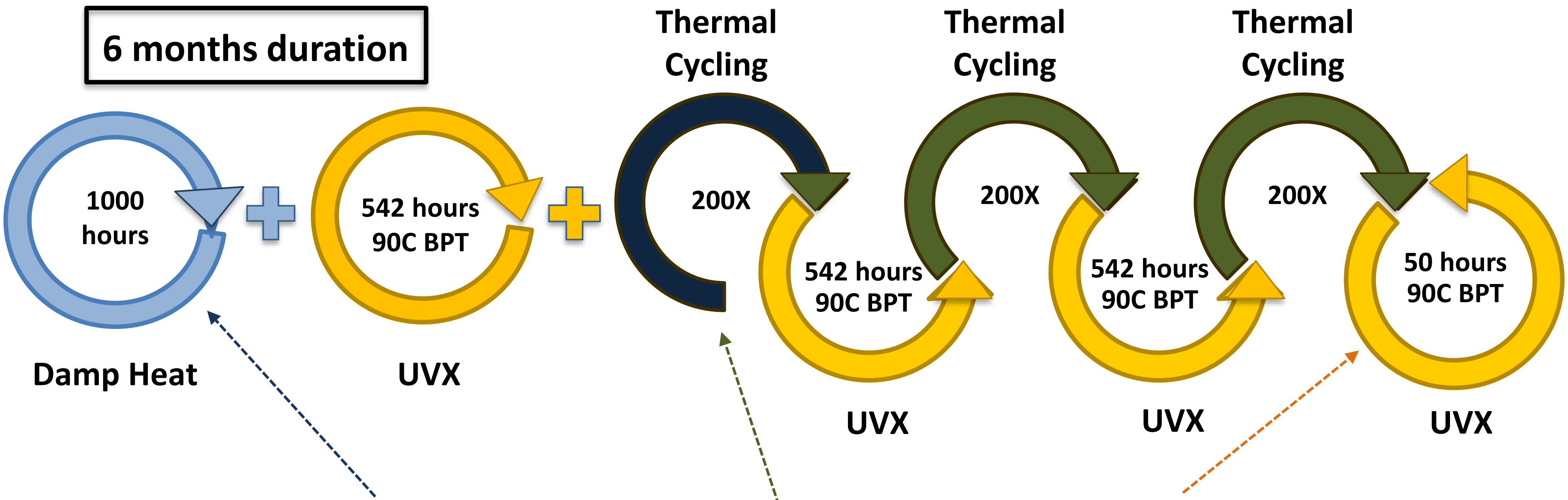
1000 Hours in a Humidity Chamber
Amounts to > 25+ years worth of stress

600 Thermal Stress Cycles
Mimics thermal stresses seen in the field

4000 Hours in a UVA Chamber
Amounts to ~24 years worth of UV desert stress

Most predictive test for backsheet field performance. Appropriate for component, minimodule, or full size module testing

Module Accelerated Sequential Test (MAST2)



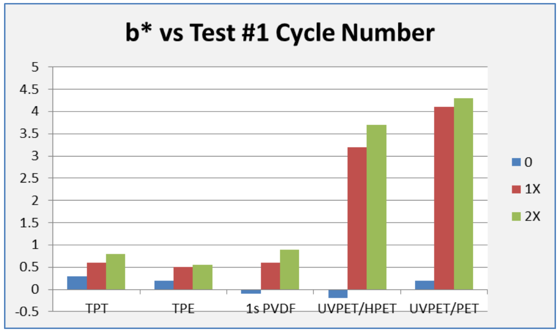
1000 Hours in a Humidity Chamber
Amounts to > 25+ years worth of stress

600 Thermal Stress Cycles
Mimics thermal stresses seen in the field

1676 Hours in a UVX Chamber
Amounts to ~20 years desert dose of UVA

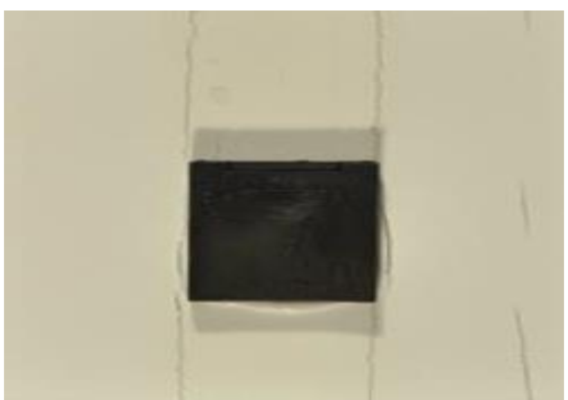
Shortened MAST by using higher intensity UV Xenon exposure for shorter time at higher 90°C BPT. Results are equivalent to original MAST.

MAST Test Results



Yellowing in PET Backsheets in Test #1

Cracking in 1s PVDF Backsheet



Cracking in PA Backsheet

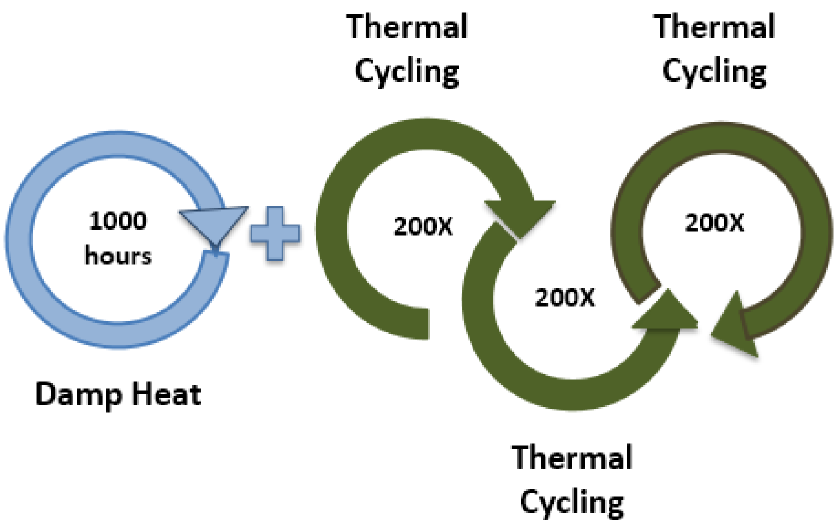
Fielded Module Examples

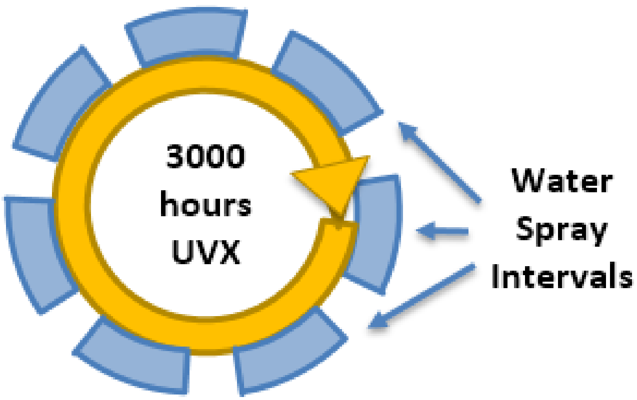
Yellowing in PET Backsheets observed in the field

Cracking and delamination in 1s PVDF Backsheet

Cracking in PA Backsheet

MAST Alternative Testing Sequences





Damp Heat & Thermal Cycling
Combines two important stress factors in a shorter test not requiring full size, expensive UV equipment.

UVA & Water Simulation
Combines UV and rainfall simulation, common weathering test conditions using commercially available weatherometer.

Test Conditions
DH 85C/85%RH
Thermal Cycling 85^{o}C <=> -40^{o}C

Test Conditions: ASTM G155 or SAE J1960 protocols in a weatherometer for backsheet coupon or minimodule. BPT = 90 C.

Summary of Sequential Tests Results

MAST Test Summary					Double Sided Fluoro			Single-Sided Fluoro			Non-Fluoro		
Test	Sequence	Measurement	Format	Unit	Tedlar® PVF TPT	PVDF	FEVE	Tedlar® PVF TPE	PVDF	FEVE	Nylon	UVPET / HPET (Hydrolytically-stabilized)	UVPET / PET (Standard)
1	DH1000-UVA1000-3x(TC200-UVA1000)	Yellowing	Full size module, Minimodule or backsheet samples	b*	0.8	OK	not available	0.6	0.2	0.6	3.1	3.7	4.1
1	DH1000-UVA1000-3x(TC200-UVA1000)	Mechanical Loss-Cracking	Full size module, Minimodule or backsheet samples	Observe or % Elongation loss	OK	Micro Cracking	not available	OK	Cracking	45	Cracking	50-100	100
2	DH1000-3x(TC200)	Mechanical Loss-Cracking	Minimodule	Observe	OK	OK	not available	OK	Cracking	not available	Cracking	OK	OK
3	Weatherometer UVX-water spray-3000 hours	Yellowing	Minimodule or backsheet samples	b*	0.1	not available	not available	0.2	0	not available	4.7	0.8	6.4
3	Weatherometer UVX-water spray-3000 hours	Mechanical Loss-Cracking	Minimodule or backsheet samples	% Elongation loss	0	not available	not available	0	0	not available	50	10-100	80-100
Outdoor Performance		Years in Field		Years	34	4	4	26	7	9	7	9	19
Field		Yellowing	Modules	b*	OK			OK	OK			3-10	3-20
Field		Cracking	Modules	Observe	OK			OK	Cracking	Cracking	Cracking	Cracking	Cracking

Extensive Testing – both test methods and different backsheets
Sequential Tests shows best correlation to field results

Comparison of Stress Tests to Field Results for Backsheet Degradation

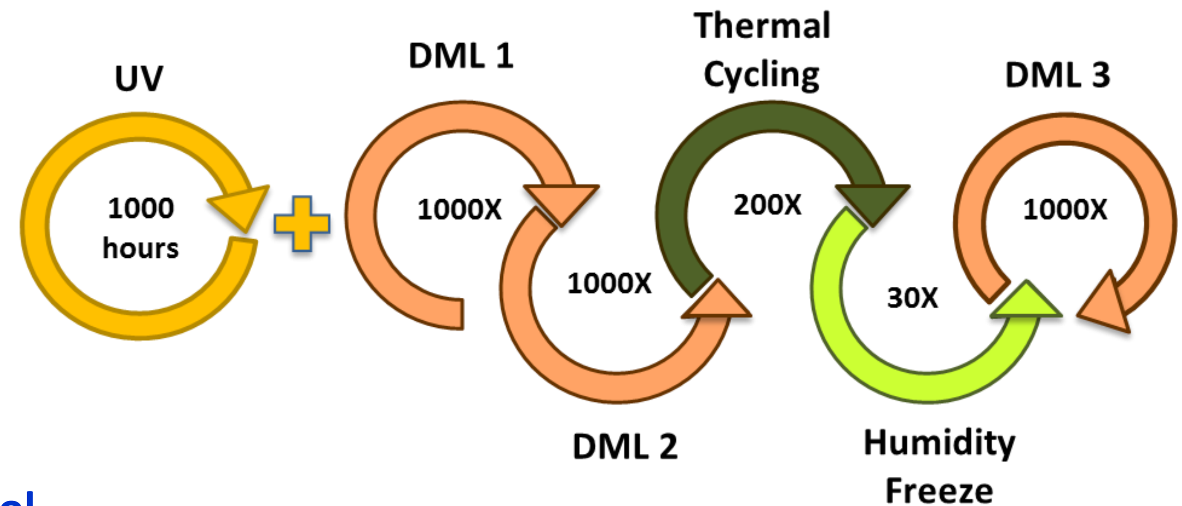
Stress	PPE	KPE	PolyAmide	TPT/TPE	Comment
Field	Yellowing Mech Prop Loss Cracking	Cracking Front Side Yellowing	Yellowing Mech Prop Loss Cracking	Low defects	Effects of simultaneous and sequential stresses
Damp Heat (1000 hrs)	Slight Yellowing	No Change	Mech Prop Loss	No Change	Misses UV degradation
UV (4000 hrs)	Yellowing Mech Prop Loss	No Change	Mech Prop Loss	No Change	Misses hydrolysis and moisture
DH/UV/TC (MAST Sequential Test)	Yellowing Mech Prop Loss Cracking	Cracking Front Side Yellowing	Yellowing Mech Prop Loss Cracking	No Change	Combines key stresses Gives best correlation

Sequential Tests correlate better with degradation seen in the field

- Combine most important stress factors
- Use Stress levels / dosages that match field exposures
- Accelerate with highest temperature but
- Do NOT produce degradation not found in the field

New Accelerated Sequential Dynamic Mechanical Load Test

- Designed to better simulate the Field by combining Sequential Testing and with Dynamic Loading
  - In field environments mechanical loads are dynamic
- Current IEC 61215 only uses Static Mechanical Load



Protocol

- **UV exposure**: 65kWh/m^2 on the front
- **DML 1**: 1000 cycles of ±1500 Pa of loading @ 1/6 Hz
- **DML 2**: 1000 cycles of ±1500 Pa of loading @ 1 Hz
- **TC200** = Thermal Cycling, -40°C ⟷ 85°C, ramp and hold *per IEC62782*, 200 cycles
- **HF30** = Humidity Freeze, 30 cycles

Optional

- **DML 3**: 1000 cycles of ±1000 Pa of loading @ 4 Hz

Tests designed by DuPont, conducted on full-size modules by independent 3rd party testing lab DNV-GL, USA

Results

	G/G modules	G/Backsheet modules
UVA	No change	No change
DML 1	No change	No change
DML 2	Slight delamination on front	No change
TC 200	Delamination on front, encapsulant voids on back	No change
HF 30	**Severe delamination** on front, **multiple encapsulant voids** on the back	Slight yellowing along the edge, no delamination

DML 3 not performed

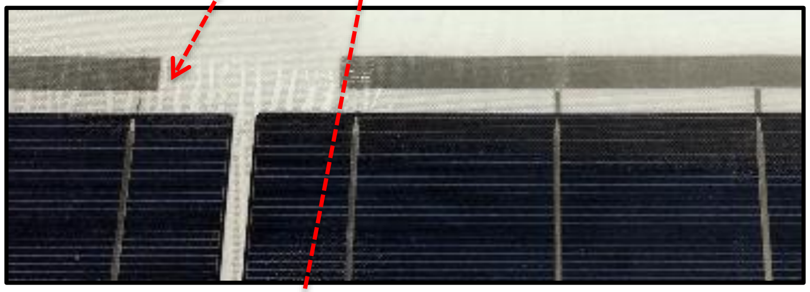
EL: Some cracked cells in both G/G and G/Backsheet modules
Wet-leakage: Both G/G and G/Backsheet modules passed test

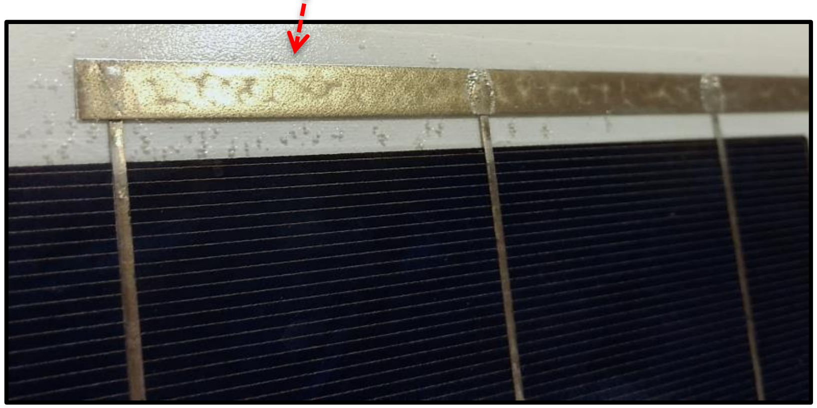
Glass-Glass modules are more prone to delamination induced by mechanical load combined with UV exposure, thermal cycling and humidity

- **Glass / Glass structures are more rigid and cannot dissipate stresses**
- **Glass/ Glass structures are not breathable and trap EVA degradation products**

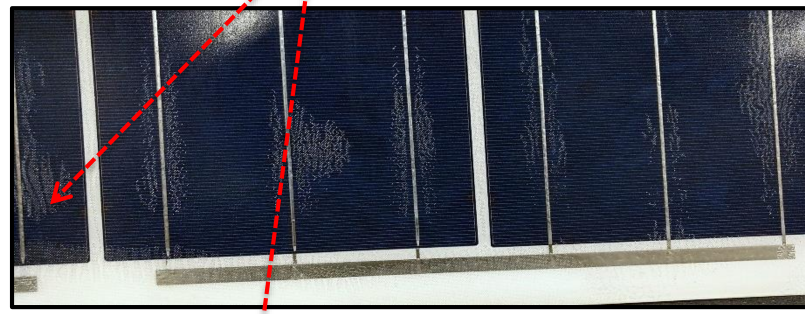
G-G modules: Front-side delamination in DML test and seen in field

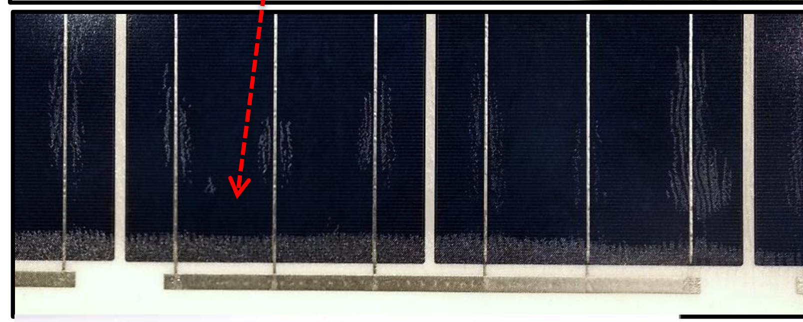
Initial delamination around the edges and tabbing ribbon



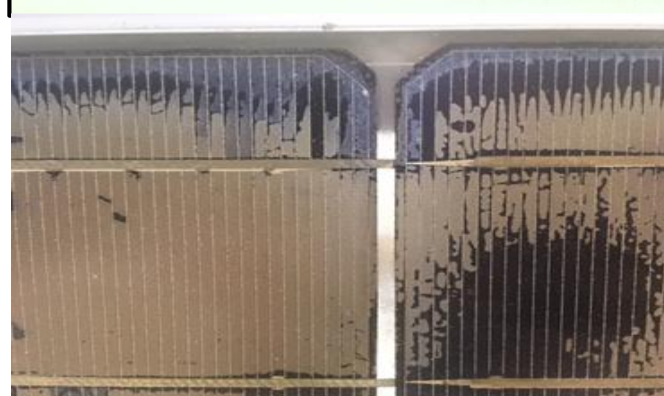


Final delamination extending inward from the edges





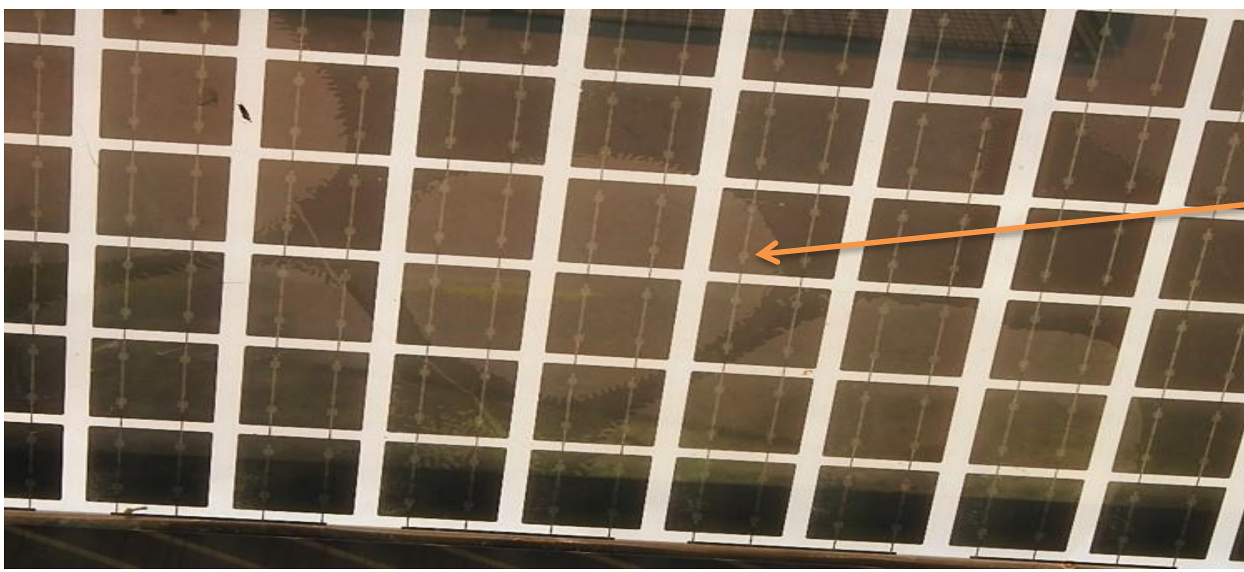
Delamination and corrosion from fielded G/G module in JRC field study[1]



[1]A. Skoczek, et. al., Prog. Photovolt: Res. Appl. (2008)
(JRC) Institute for Energy, Renewable Energy unit, Italy,

G-G modules: Back-side delamination from DML test and seen in field

Encapsulant voids from DML test



Fielded G/G module shows large encapsulant voids

Future Directions

- Higher irradiance
  - new equipment with higher intensity and full size module capability
- Higher temperature
  - Extend work with xenon exposure to higher temperature (from 90C to 100C BPT)
- New stress conditions
  - Static mechanical load, dynamic mechanical load, humidity freeze (-40C, 85C/85%RH), damp heat with bias, weathering (UV + water spray)

Improved durability test methods are the most effective way to prevent large scale field failures

Conclusions

- Sequential testing protocols introduced as an approach to assess synergistic stresses in the field
- Timing reduced from 9 months to 6 months for MAST test protocol
- Sequential testing shown to be a good predictor of backsheet defects observed in the field
- Major stresses are included at doses adequate for lifetime assessment
- New sequential test protocols offer an opportunity to assess new module structures and materials

Improved durability test methods are the most effective way to prevent large scale field failures

photovoltaics.dupont.com

The miracles of science™