Weather durability testing and failures in terrestrial flat plate PV modules

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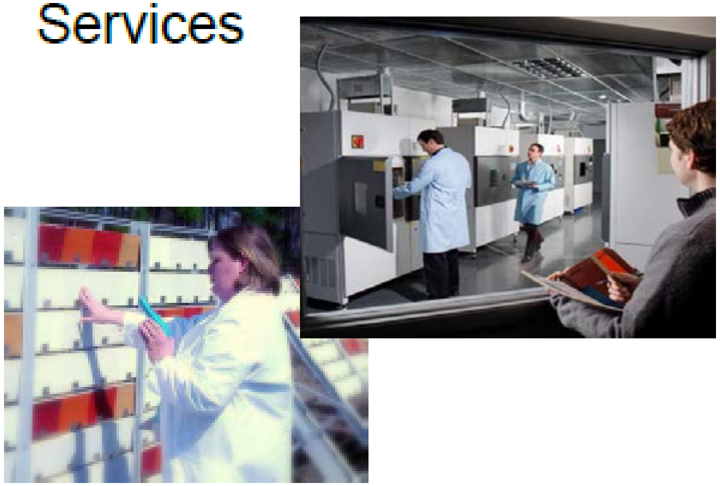
Atlas Material Testing Technology LLC

2nd Atlas/NIST Workshop on Photovoltaic Materials Durability
November 13-14, 2013, NIST, Gaithersburg, MD

About Atlas – 4 key weathering businesses

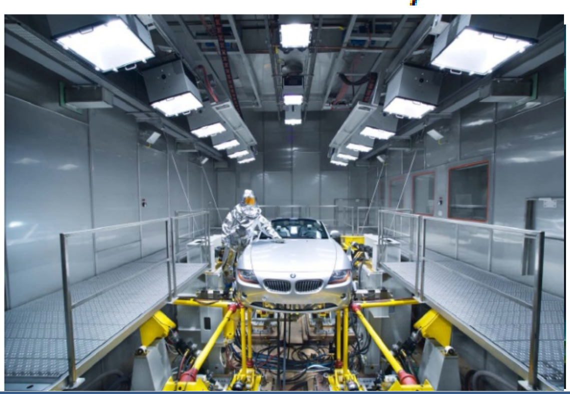
ATLAS
MATERIAL TESTING SOLUTIONS
AMETEK
MEASUREMENT & CALIBRATION TECHNOLOGIES

- Weathering Testing Services

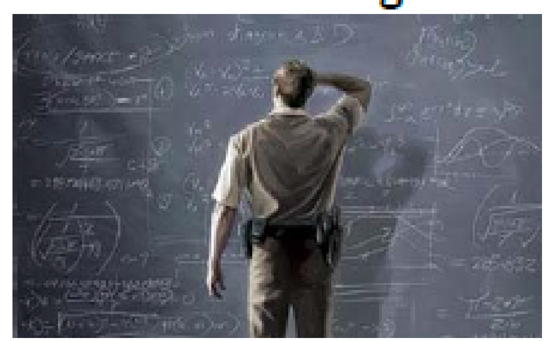


- Laboratory Weathering Instruments

- Custom Test Systems



- Global Consulting



Benchmark weathering exposure test sites

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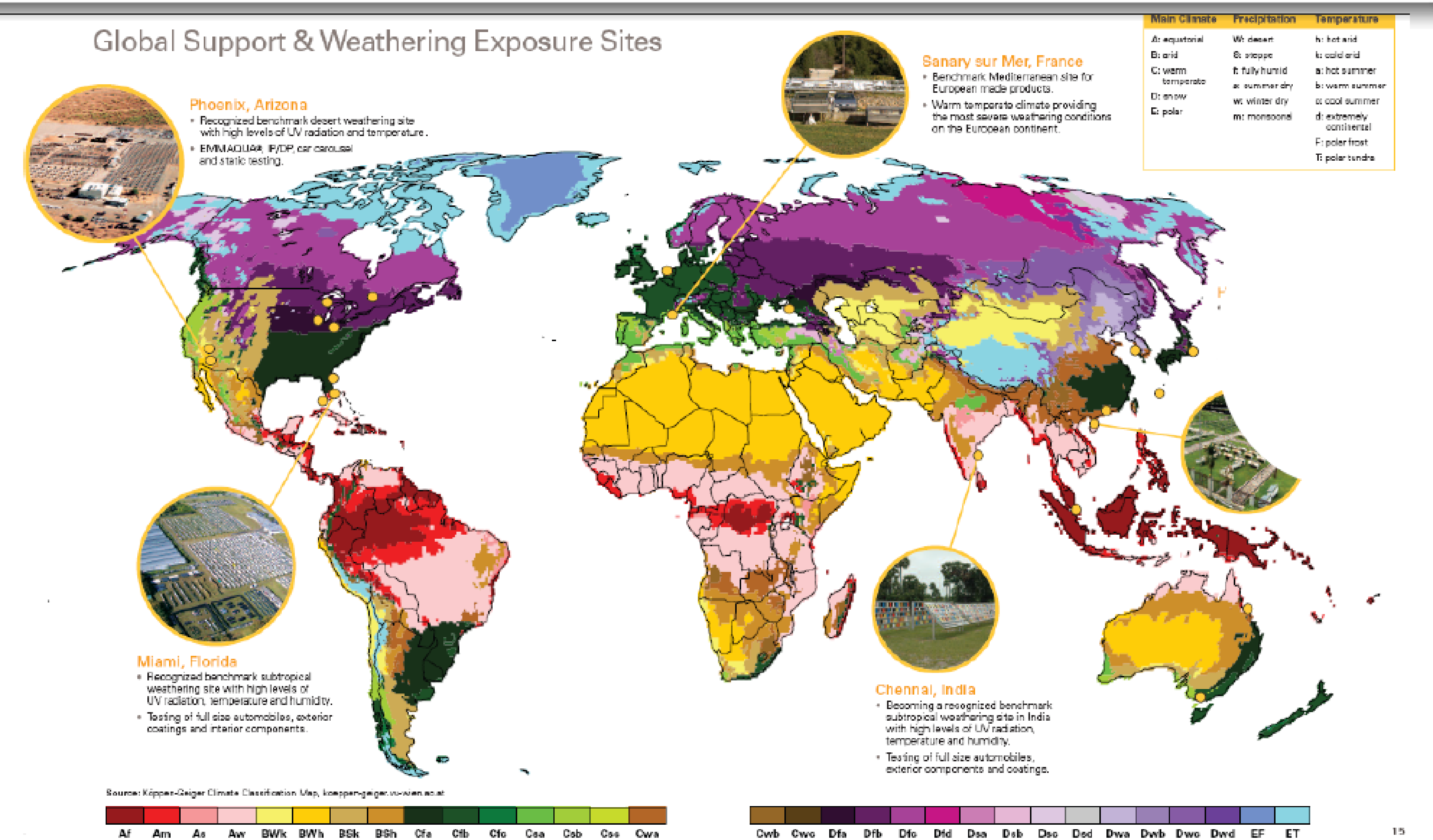

Approximately 22 global sites available for test exposures

Atlas Worldwide Exposure Network

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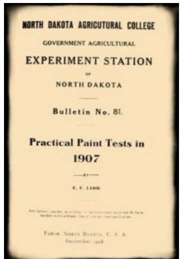
Location	Latitude	Longitude	Elevation (m)	Average Ambient Temperature (°C)	Average Ambient RH (%)	Rainfall (mm)	Total Radiant Energy (MJ/m²)
Miami, FL	**25° 56' N**	**80° 25' W**	**2**	**23**	**79**	**1686**	**6234**
Jacksonville, FL	**30° 29' N**	**81° 42' W**	**8**	**20**	**76**	**1303**	**5800**
New River, AZ	**33° 54' N**	**112° 08' W**	**610**	**22**	**33**	**338**	**7324**
Prescott, AZ	**34° 39' N**	**112° 26' W**	**1531**	**12**	**65**	**1093**	**7000**
Chicago, IL	**41° 47' N**	**87° 45' W**	**190**	**10**	**69**	**856**	**5100**
Louisville, KY	**38° 11' N**	**85° 44' W**	**149**	**13**	**67**	**1092**	**5100**
Sanary, France	**43° 08' N**	**5° 49' E**	**110**	**13**	**64**	**1200**	**5500**
Hoek van Holland, Netherlan	**51° 57' N**	**4° 10' E**	**6**	**10**	**87**	**800**	**3800**
Lochem, Netherlands	**52° 30' N**	**6° 30' E**	**35**	**9**	**83**	**715**	**3700**
Singapore (Changi Airport)	**1° 22' N**	**103° 59' E**	**15**	**27**	**84**	**2300**	**6030**
Melbourne, Australia	**37° 49' S**	**144° 58' E**	**35**	**16**	**62**	**650**	**5385**
Townsville, Australia	**19° 15' S**	**146° 46' E**	**15**	**25**	**70**	**937**	**7236**
Choshi, Japan	**35° 43' N**	**140° 45' E**	**53**	**14**	**78**	**1682**	**4659**
Miyakojima, Japan	**24° 44' N**	**125° 19' E**	**50**	**23**	**76**	**1741**	**4894**
Ottawa, Canada	**45° 20' N**	**75° 41' W**	**103**	**6**	**73**	**1910**	**4050**
Sochi, Russia	**43° 27' N**	**39° 57' E**	**30**	**14**	**77**	**1390**	**4980**
Dhahran, Saudi Arabia	**26° 32' N**	**50° 13' E**	**92**	**26**	**60**	**80**	**6946**

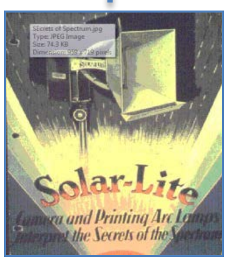
Weathering testing milestones

1906

Fargo ND test



1916



Lab Light-fastness

1918

Enclosed Carbon Arc

1927

Lab weathering

1931

South Florida site

1934

Sunshine Carbon Arc & DSET Arizona site

1954

Xenon Arc

1958

ASTM G90

1979

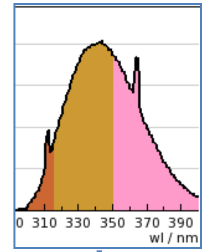
Controlled *E*

1984

FS-40 UVB lamps

1987

UVA-340 lamp

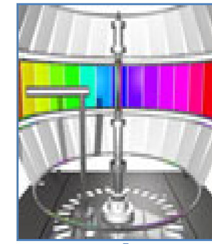


2009

Ultra Accelerated

2010-2011

Full Spectrum, S3T



100 year history

Brief Recap

- **1970** Atlas (DSET Laboratories) Atlas Super-MAQ™ durability exposure tests of original Skylab (SL-1) PV modules for NASA/JPL
- **1995** NREL installs first Atlas XR-260 large scale xenon weathering device specifically for PV testing (& standard Atlas xenon Weather-Ometers)
- **1996** NREL installs Atlas SolarClimatic 1600 metal-halide “global” solar environmental chamber
- **2008** Atlas attended NREL PV Reliability Workshop – no discussion of weathering
- **2009** Atlas Technical Conference on Accelerating Ageing and Evaluation (ATCAE-Solar) introduces Atlas 25+ PV module weathering test program
- **2010** Program cycle modifications for improved parameter control in larger solar/environmental chambers to accommodate larger module sizes
- **2011** Added more options/modifiers (such as coastal-marine, alpine) and evaluations (such as EL, wet-leakage current) to Atlas 25+
- **2012** Added Atlas 25+ Certification accreditation option
- **2013** Atlas 25+ 2013 edition implements additional climate options and test additions. Certified additional Atlas 25+ test partners in Taiwan, China, Korea.
- **2014** (Pending) Establish new climate parameters (China zones, etc.)

Weathering testing basic tenets (basic)

Based on over 100 years of weatherability testing across all industries:

- Material/product weathering is the result of:
  - Chemical and/or physical degradation processes which may occur simultaneously or sequentially
  - Multiple, simultaneous and continually varying extrinsic environmental stresses which often act synergistically; steady state conditions are rarely encountered in nature
  - Intrinsic material sensitivity (e.g., UV, thermal, etc.) to specific or combined stresses (interaction effects) or cycles

- Weathering tests (outdoor or laboratory)
  - Must reproduce the same physical and chemical degradation as the service exposure
  - Should reproduce and combine, at a minimum, the 3 primary stress factors of solar radiation, temperature and moisture, as well as their natural cycles, *unless demonstrated as not needed* (e.g., UV degradation not influenced by thermal effects)
  - Test Acceleration Factors are highly material and property specific; are often not linear with exposure; high acceleration factors often result in poor correlation
  - High irradiance has proven a valid technique for greater test acceleration, even in the absence of strict reciprocity. High overstress of other factors is usually problematic.
  - Materials/products should be tested in as close to an operational configuration as possible

"Weathering" & IPVQATF, IEC, etc.

IEC TC82 WG2

- **61730 – 2 Testing**
  - Awaiting weathering test - !SO 4892 -2 is being used as a place holder - high priority

Draft proposal to CEC

Photovoltaic Module "Qualification Plus" Testing

Sarah Kurtz, John Wohlgemuth, Michael Kempe, Nick Bosco, Peter Hacke, Dirk Jordan, David C. Miller, Timothy Silverman

National Renewable Energy Laboratory

Table 5. Accelerated tests proposed for "Qualification Plus"

Test	Associated failure	Origin or technical basis for test
1. System voltage (potential-induced degradation)	Power loss for modules operating at large (positive or negative) bias voltage	Test method: IEC 62804; Pass criteria: studies correlating test with field results
2. Thermal cycling	Solder bond or ribbon failure, usually associated with thermal fatigue	Extension of IEC 61215. Thermal cycling is known to identify this failure; field and modeling studies imply that longer testing may be beneficial.
3. Dynamic mechanical load (DML)	Cracked cells that cause hot spots and power loss	IEC 62782. Studies have shown that the combination of DML and thermal cycling can uncover this failure.
4. UV exposure for encapsulants	Discoloration and delamination of the encapsulant sometimes dominate the observed failures and cause power degradation	STR and other companies have successfully used this test to select EVA formulations for decades
5. UV exposure for connectors/cables	Cracked connectors or cables	EN 50521 and draft for IEC 62852
6. UV exposure for junction boxes	Loss of mechanical integrity for junction box	EN 50548 and draft for IEC 62790
7. UV exposure for backsheets	Cracked backsheets have been observed and can lead to safety issues	EN 50548 and draft for IEC 62790
8. Bypass diode thermal test	Failed bypass diodes and thermal degradation of junction box and/or potting	Logical extension of existing test to avoid junction box and diode failures that have been observed in the field
9. Enhanced hot spot test	Localized heating from partial shading conditions	ASTM E2481-06

"Weathering" & IPVQATF

Proposed rating system for climate and mounting

Proposal:

Increase UV exposure with appropriate temperature & humidity.

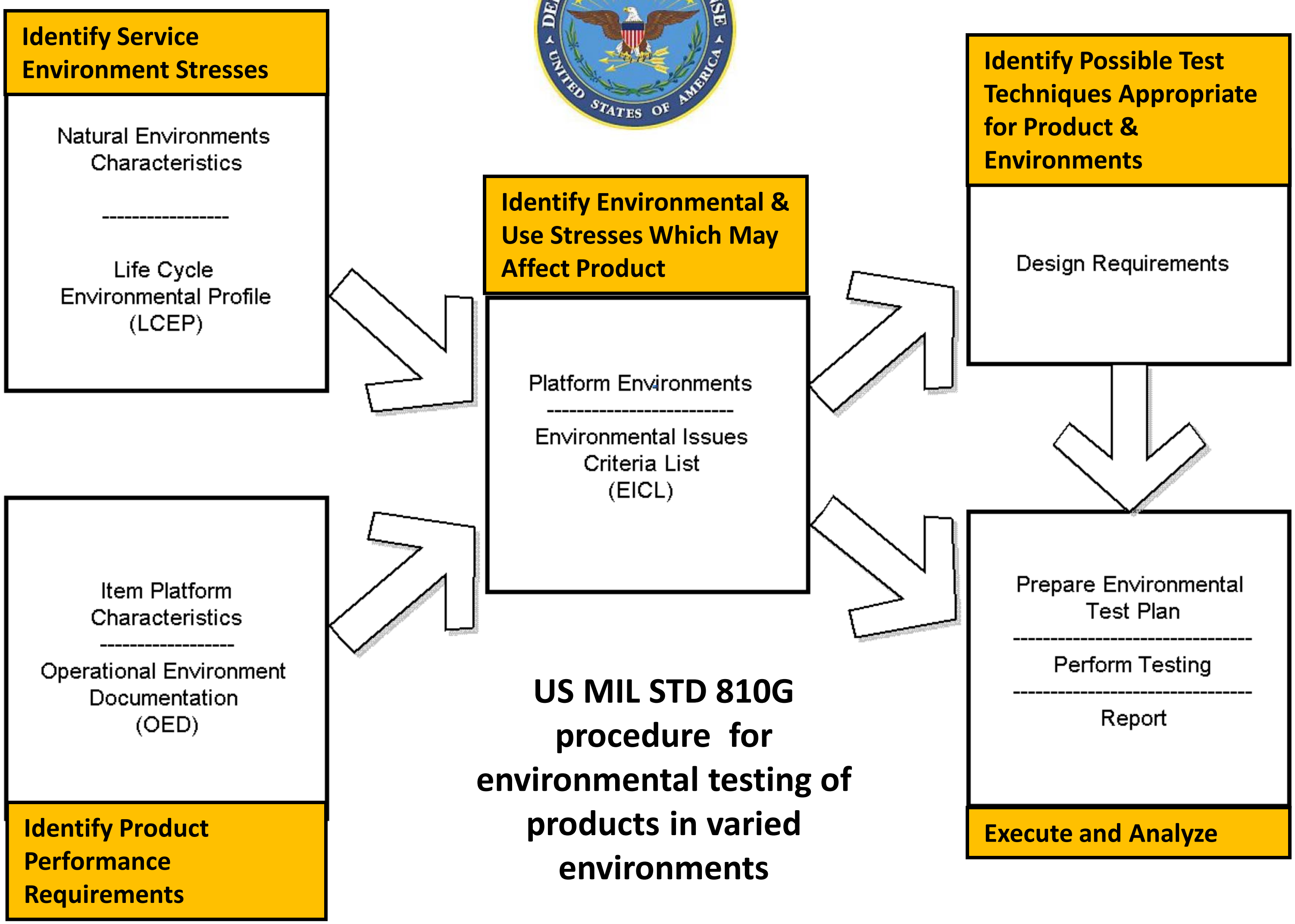
Use measurements and modeling to select temperatures.

IEC 60721-2-1 Climate Designation	Mounting classes	
	Rack mount	**Close-roof mount**
Moderate (Temperate)	500 thermal cycles or DML + 200 TC Increased UV exposure at 60°C*	500 thermal cycles or DML + 200 TC Increased UV exposure at 80°C*
Warm Damp, Equable (Tropical)	500 thermal cycles or DML + 200 TC Increased UV exposure at 80°C*	500 thermal cycles or DML + 200 TC Increased UV exposure at 100°C*
Extremely Warm Dry (Desert)	500 thermal cycles or DML + 200 TC Increased UV exposure at 80°C*	500 thermal cycles or DML + 200 TC Increased UV exposure at 100°C*

*Temperatures are estimates; final values TBD, but should vary with mounting/climate.

Proposal for Comparative PV Module Rating System, Sarah Kurtz, John Wohlgemuth, Tony Sample, Masaaki Yamamichi, Michio Kondo
4th International PV Module QA Forum, October 10, 2013

Environmental test tailoring in defense industry (US/NATO) - A model for Atlas 25+ development



Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests

Atlas 25+ weathering test tenets (basic)

Designed to weather stress modules to various climates

- Intended to complement, not duplicate or replace current or proposed extended IEC tests for evaluating longer term weathering effects (>10 yrs)
- Combines high cycle count of combined full-spectrum solar radiation with thermal/humidity day/night and seasonal cycling (Atlas large scale solar/environmental chamber)
- Test parameters are climate derived (Hot-Dry desert, Hot-Humid, Temperate, and “global composite”
- Sequences with extended UVA/UVB, salt fog, condensing humidity exposures and outdoor 2-axis solar tracking (Arizona including peak summer) not compatible with solar/environmental chamber testing
- Adds Arizona and South Florida 2-axis tracking outdoor exposures
- Optional add-ons for high-altitude (Prescott, AZ), coastal-marine atmosphere, etc.
- Modules are electrically operating whenever exposed to solar (sun or simulated)
- Multiple measurements: IR thermography, EL, IV, wet-leakage, visual, etc.
- Primarily “black box” approach to replicate weather, not specific failure modes

Atlas 25 + "global composite" environmental test cycle
(other climates available)

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	Atlas 25+ *Original* *Introduced October 2009*	**Atlas 25+ *Standard*** *Revised May 2011*
	1 module	1 module
UVA / UVB exposure	UV 30 kWh/m^2 (28 days)	→ Same
Salt spray corrision	400 hours	
Condensing humidity	125 hours	
Solar-Thernal-Humidity Cycle	7 days, 120 cycles	7 days, 96 cycles
	80 days, total 1,280	*100 days, total 1,290*
Solar-Thermal-Humidity/Freeze	3 days, 40 cycles	3 days, 33 cycles
AZ 10-wk Peak Summer tracking	10 weeks peak summer	→ Same
AZ balance of year solar tracking	~ 7 months	→ Same

Both include FL & AZ 2-axis Solar tracking modules for one year

ATLAS MATERIAL TESTING SOLUTIONS

Atlas 25 + "global composite" environmental test cycle (other climates available)

ATLAS MATERIAL TESTING SOLUTIONS
AMETEK MEASUREMENT & CALIBRATION TECHNOLOGIES

Atlas 25+ *Basic*
2012

1 module

UVA / UVB exposure — UV 30 kWh/m^2 (28 days)

Salt spray corrision — 400 hours

Condensing humidity — 125 hours

Solar-Thernal-Humidity Cycle — 7 days, 120 cycles

80 days, total 1,280

Solar-Thermal-Humidity/Freeze — 3 days, 40 cycles

AZ 10-wk Peak Summer tracking — 10 weeks peak summer

AZ balance of year solar tracking — *Eliminated in "Basic"*

Fewer measurement intervals and interim reports

Atlas 25+ *Enhanced*
2012

1 module - or 4 mini-modules

PID Potential Induced Degradation test

→ Same

7 days, 96 cycles

100 days, total 1,290

3 days, 33 cycles

In addition to included FL & AZ 2-axis Solar tracking modules

+ 1 module — High altitude Prescott AZ

+ 1 module — Florida Keys coastal marine

Continous Solar-Thermal-Humidity at elevated temperature

10 Days chamber

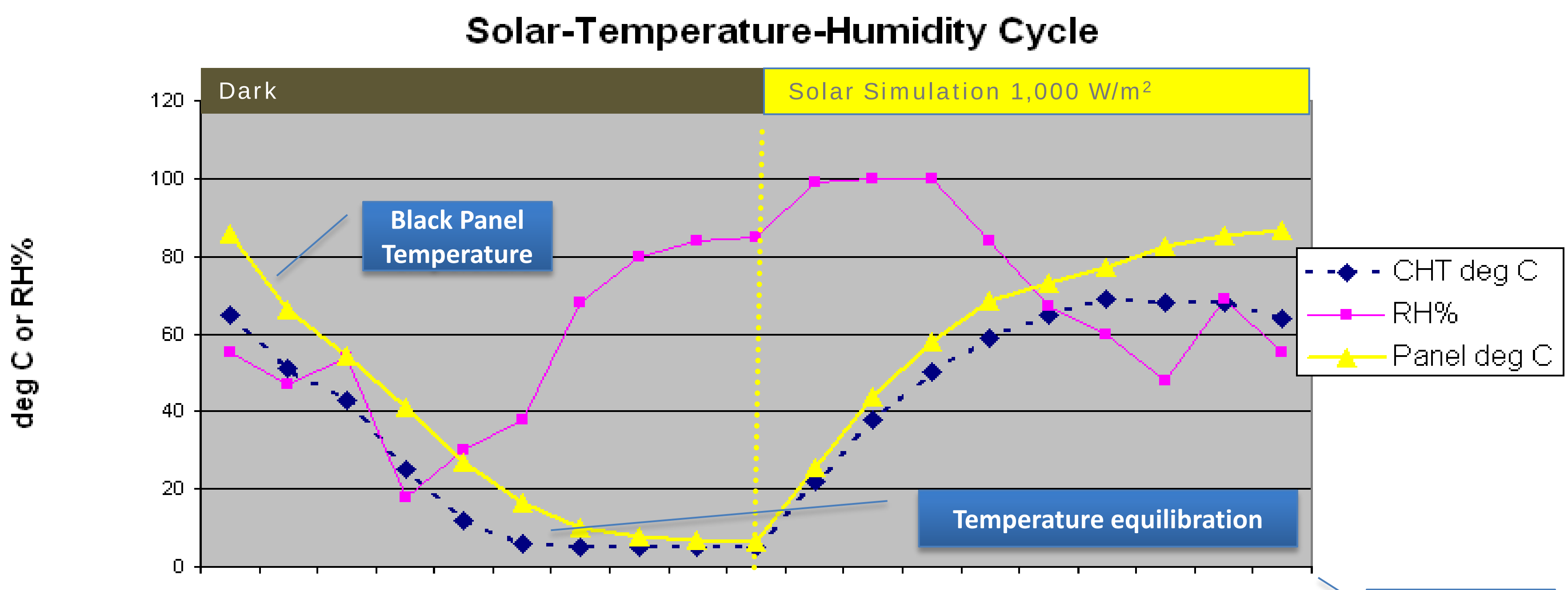
→ Same

~ 7 months

ATLAS MATERIAL TESTING SOLUTIONS

“Global Composite Climate” cycle STH

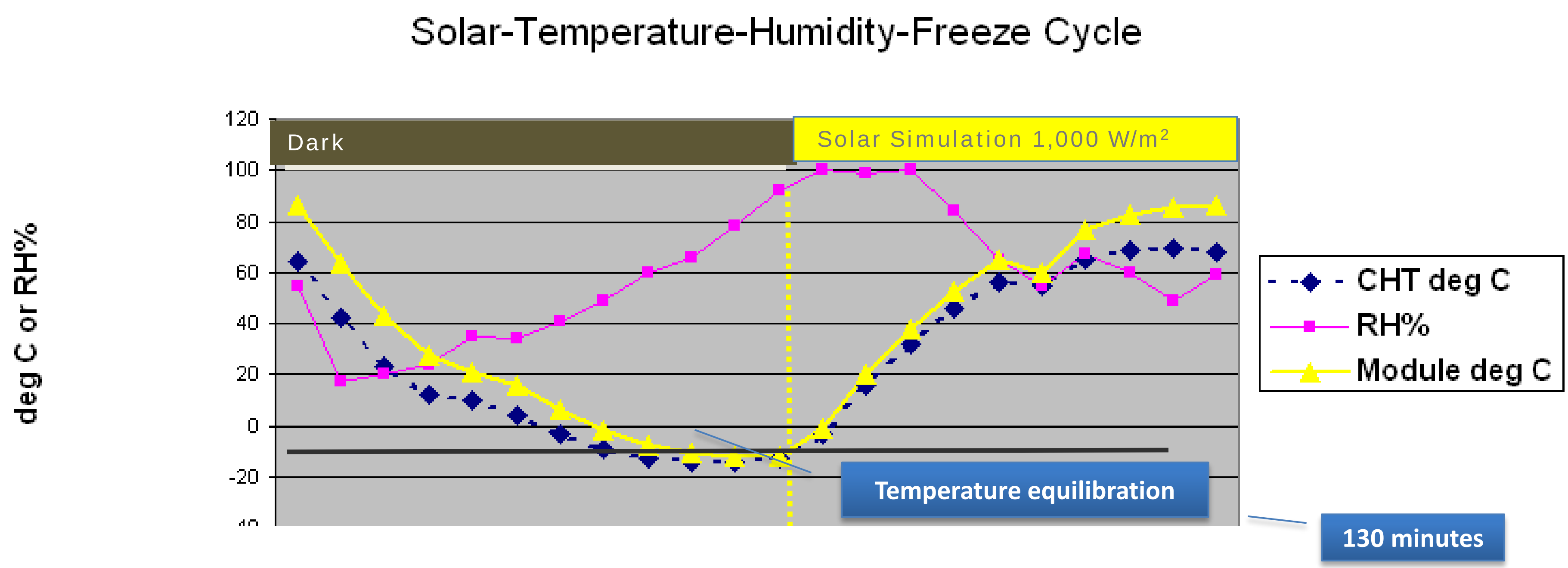
Simulates Spring-Summer-Autumn seasonal climate boundaries.



Module cycles between ca**. +85°C to -40°C** in dark cycle, then back in light.
Relative humidity cycles inversely with temperature between ca**. RH 100% and 18%**
Simulates range of thermal/humidity/solar radiation stresses in “Global Composite” environment boundary conditions.
Module is electrically operating with resistive load at Maximum Power Point.

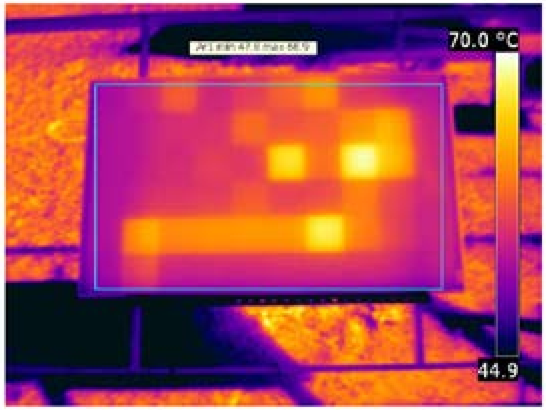
"Global Composite Climate" module cycle STH/F

Simulates high-latitude Winter seasonal climate.



Module cycles between ca**. +85°C to -12°C** in dark cycle, then back in solar load
Relative humidity cycles inversely with temperature between ca. 100% and 18%
Simulates range of thermal/humidity/solar radiation stresses in "Global Composite" environment boundary conditions.
Module is electrically operating under resistive load at Maximum Power Point.

Examples



Florida (August) @ 6-month 2-axis tracker

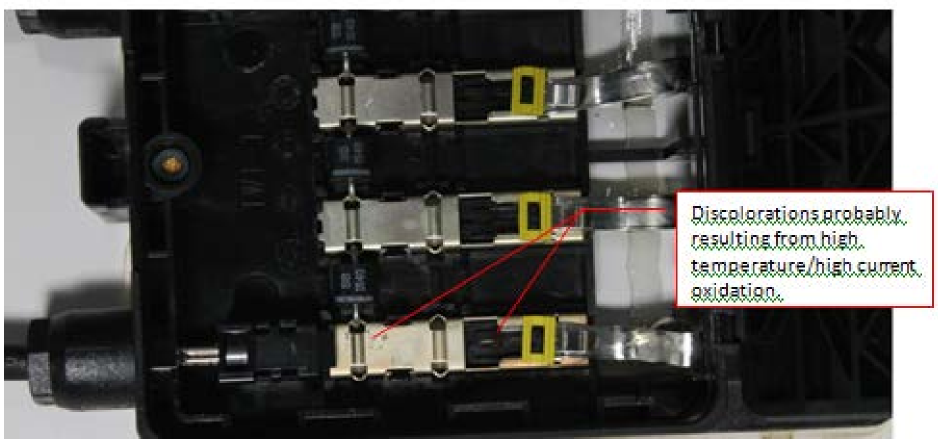
Power loss mean 4.2% at end of test

Evolution of “spots” during chamber tests

Note all data shown is proprietary and may not be of commercial products

Examples

10.3 IV Report - Post Solar Thermal-Humidity & Solar Thermal-Humidity/Freeze cycles Primary Lab Module 139 Digital Images (2 of 5)



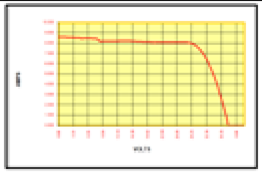
Examples

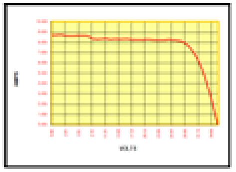
Frame Corrosion

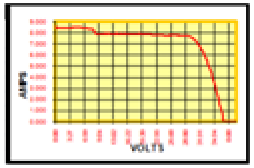
12.1 Arizona Solar Tracking Module – 6 month Evaluation – Digital Image 5 of 5

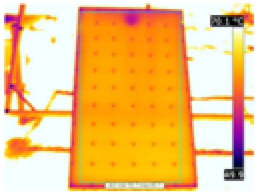
Examples

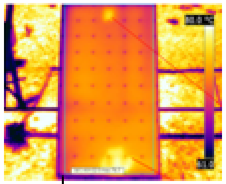
Stage	Post Salt Fog/Condensation	Post 50% Pk Summer Track	Post STH - STH/F Chamber
Fill Factor	74.27%	73.28%	73.25%
Imax	7.89 Amp	7.86 Amp	7.67 Amp
Isc	8.59 Amp	8.68 Amp	8.44 Amp
Panel Temperature	25.0°C	24.9°C	25.0°C
Vmax	29.6 Volt	29.0 Volt	29.7 Volt
Voc	36.5 Volt	35.9 Volt	36.8 Volt
Peak Power	233.1 Watt	228.1 Watt	227.9 Watt

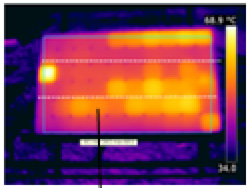








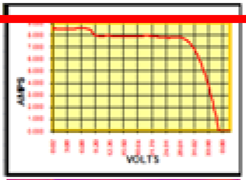


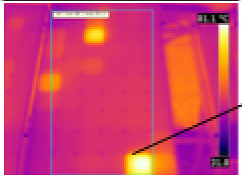


Lower cells are approx. NOCT +40°C. Cell over J-box NOCT +35°C.

Bright cells are approx. NOCT + 25°C. Cell over J-box NOCT +30°C.

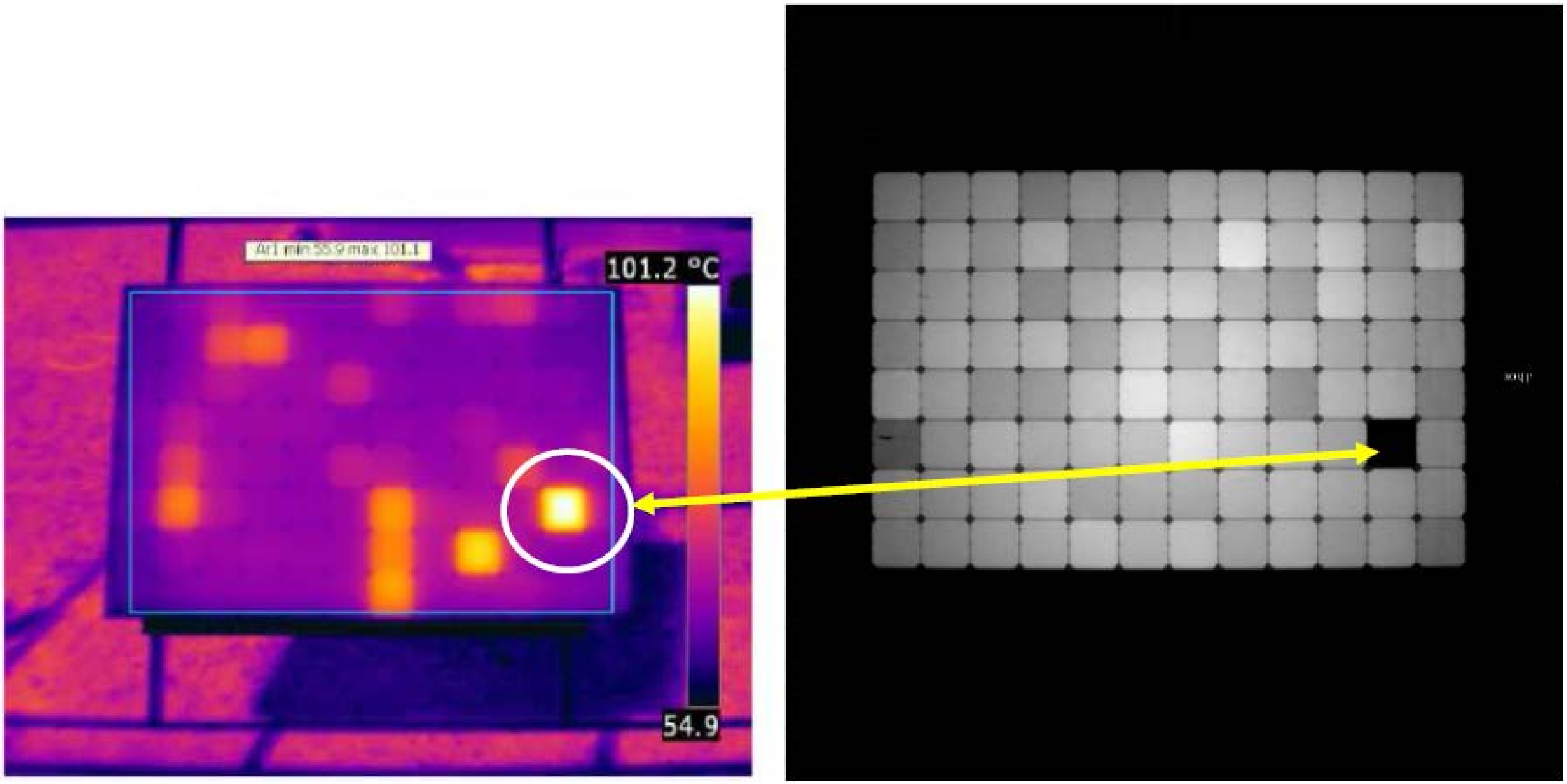
Stage	Final		Δ Final: post light soak values
Fill Factor	72.32%		Decrease 4.84%
Imax	7.68 Amp, 5.0%		Decrease 0.46 Amp
Isc	8.49 Amp		Decrease 0.06 Amp
Panel Temperature	25.0°C		Decrease 0.1° C
Vmax	28.8 Volt		Increase 0.9 Volt
Voc	[illegible]		[illegible]
Peak Power	221		Decrease 8.5%





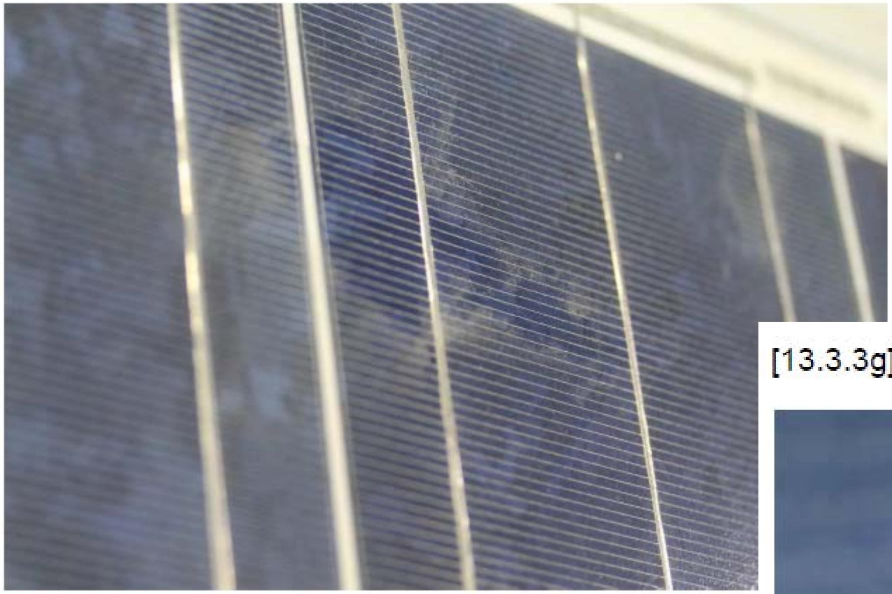
Bright cell is approx. NOCT + 40°C. Cell over J-box +35°C. Cells in Column 1 (left) NOCT ~+30°C.

Examples



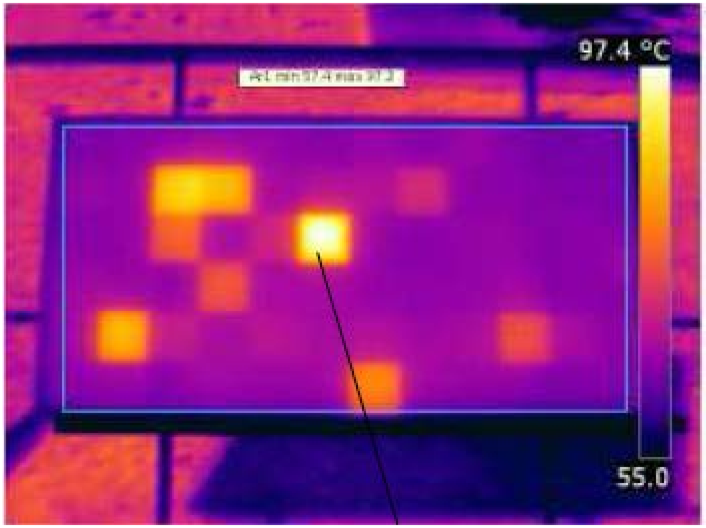
Examples

[13.2.2e] Mildew retention on face of glass (not easily seen on photos).

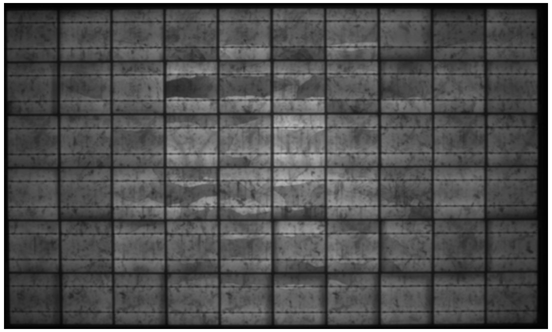


[13.3.3g]Some mildew formation on side of frame and between frame and glass.

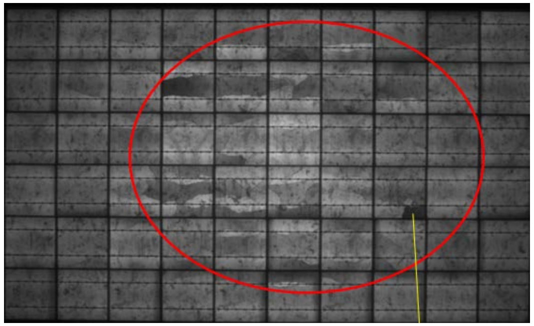
Examples



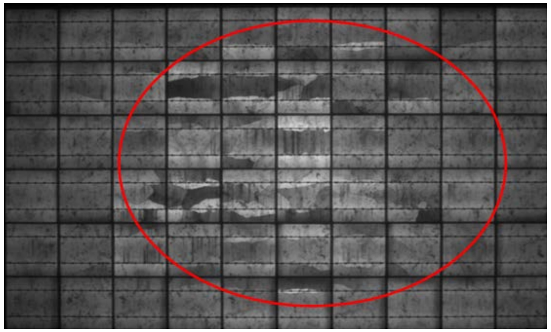
Examples



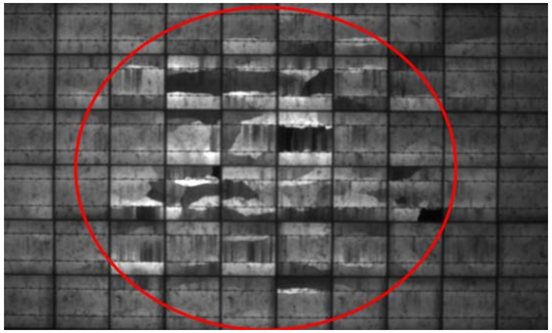
Initial



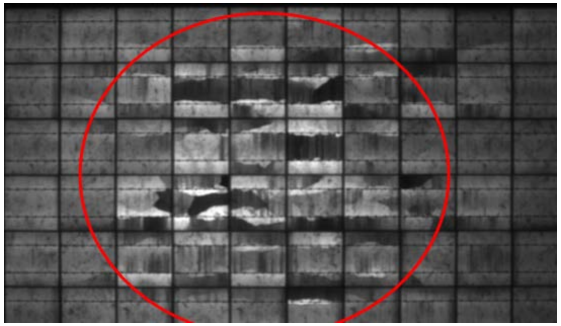
Post UVA/UVB



Post Salt Fog/Condensation

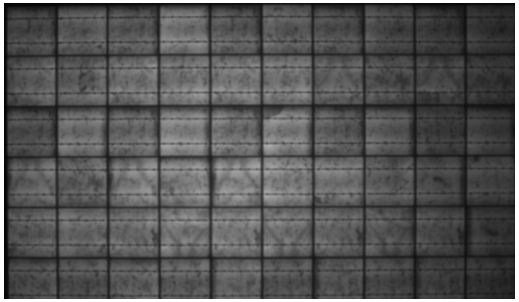


Post Chamber

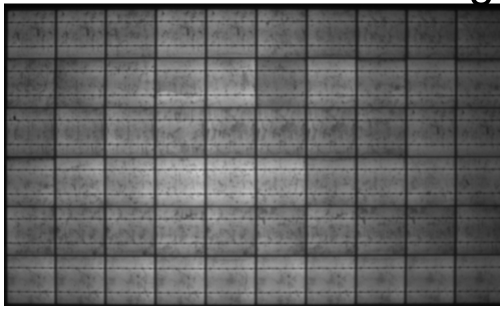


10-week AZ Pk. Summer Tracking (-12.9)

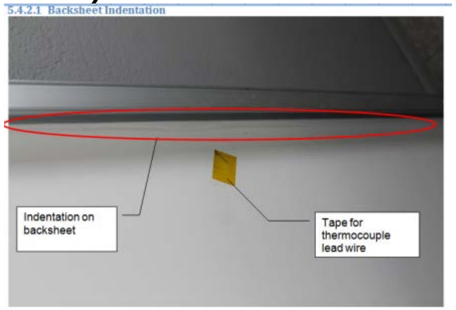
Note: This series is known to be an experimental backsheet, other series did not experience problems.



1-yr FL Tracking (-5.7%)



1Yr AZ Tracking (-4.5%)



BS defect

Example

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	Florida Tracking Module 2	*Arizona Tracking Module 2*	*Lab Module 2*
Date	April 10, 2013	January 28, 2013	February 8, 2013
Stage	Final (Washed)	Final	Final post STH – STH/F Chamber
Fill Factor (%)	72.5 [Δ +0.3]	72.1 [Δ +0.1%]	66.0 [Δ -6.7%]
Imax (Amp)	7.77 [Δ -0.18 (Δ -2.3%)]	7.80 [Δ -0.21 (Δ -2.6%)]	7.56[Δ -0.55 (Δ -6.8%)]
Isc (Amp)	8.52 [Δ -0.41 (Δ -4.6%)]	8.57 [Δ -0.31 (Δ -3.5%)]	8.51 [Δ -0.28 (Δ -3.2%)]
Panel Temp. (°C.)	24.9	25.0	25.1
Vmax (Volt)	28.13 [Δ +1.00 (Δ +3.6%)]	28.04 [Δ -0.53 (Δ -1.9%)]	25.5 [Δ -1.88 (Δ -6.6%)]
Voc (Volt)	35.37 [Δ -0.58 (Δ -1.6%)]	35.39 [Δ -0.42 (Δ -1.2%)]	35.70 [Δ -0.3 (Δ -0.8%)]
Peak Power (Watt)	218.6 [Δ 0-13.3 (Δ -5.7%)]	218.6 [Δ -10.2 (Δ -4.5%)]	200.4 [Δ -29.7 (Δ -12.9%)]

Note: Control Module 2 Peak Power [Δ -4.9 Watts (Δ -2.1%)]

Observations and summary

ATLAS MATERIAL TESTING SOLUTIONS
AMETEK MEASUREMENT & CALIBRATION TECHNOLOGIES

- Modeling and client field data (available and provided for some but not all modules) for power loss was generally consistent with ~ 5-10+ years field experience for multiple technologies (AF's are mode & property dependent)
- Modules types tested had all already met current IEC qualification tests
- Some modules had 2X extended chamber tests (global-composite cycle)
- Diode failures (one module series) were consistent with reported field failures
- Some front glass and backsheet types were particularly subject to dirt and/or mildew pickup and retention in Florida
- May provide additional information on longer term weather & climate-related durability/performance for module types as a complement to IEC-type qualification and material-level weathering tests.

Thank you

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