NATIONAL RENEWABLE ENERGY LABORATORY

Technical Report
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November 2013

Photovoltaic Module Reliability Workshop 2012

February 28–March 1, 2012

Technical Monitor: Sarah Kurtz

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NREL's PHOTOVOLTAIC (PV) MODULE RELIABILITY WORKSHOP (PVMRW) brings together PV reliability experts to share information, leading to the improvement of PV module reliability. Such improvement reduces the cost of solar electricity and promotes investor confidence in the technology—both critical goals for moving PV technologies deeper into the electricity marketplace.

NREL's PVMRW is unique in its requirement that all participating companies share at least one presentation (either oral or poster). In most cases, participation from each company is limited to two people. These requirements greatly increase information sharing: If everyone shares a little information, everyone takes home a lot of information.

In 2012, the PVMRW included separate sessions for silicon, thin-film, and CPV in a format similar to previous workshops. The opening session highlighted the PVRessQ effort that has identified and helped to resolve many issues with older PV systems in Japan. The silicon sessions on the first day of the workshop focused on safety issues and on potential-induced degradation.

The distinguishing feature of the 2012 workshop was the addition of a day devoted to standards. This day reviewed recent work on standards development. The session "IEC 61215 on Steroids" described many new tests that test labs have developed to help differentiate the durability of PV modules. Updates were given on the status and plans for Task Groups 2–5 of the International PV Module Quality Assurance Task Force. The afternoon provided opportunity for input from all participants, creating many lively discussions and identifying many useful suggestions for the standards being developed.

On the final day of the workshop, the thin-film breakout focused on metastabilities, keeping the moisture out, and other thin-film module reliability issues. The CPV sessions highlighted accelerated testing and field experience, standards, and modeling of CPV reliability issues.

In addition to the oral sessions, the participants presented approximately 80 posters on PV reliability topics. Most of the participants shared their presentations for public posting; this document is a compilation of them. The success of the workshop is a direct result of the participants' willingness to share their results. We gratefully recognize the excellent contributions the community has made and thank all of the participants for the time and information they have shared.

The workshop was chaired by Sarah Kurtz with a lot of support from:

Ian Aeby	Ryan Gaston	Dirk Jordan	Govindasamy Tamizhmani
David DeGraaff	Jennifer Granata	Paul Lamarche	Kaitlyn VanSant
Neelkanth Dhere	Peter Hacke	Kenneth Leffew	Shuying Yang
Dan Doble	Pam Hajcak	Mark Roehrig	John Wohlgemuth
Lawrence Dunn	Peter Hebert	Kurt Scott	
Vivek Gade	Jason Hevelone	Samir Sharm	

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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PLENARY SESSION: STANDARDS

MATERIALS TESTING

QUALITY ASSURANCE OVERVIEWS OF PROPOSED TESTS

PROPOSED TEST PROTOCOL - IEC 61215 ON STEROIDS

POSTER SESSION: THIN-FILM MODULES

ORAL SESSION: CPV

CPV MODULE RELIABILITY — ACCELERATED TESTING AND FIELD EXPERIENCE

STANDARDS

MODELING OF CPV RELIABILITY ISSUES

POSTER SESSION: CPV

2012 PV Module Reliability Workshop
Feb 28 – March 1, 2012, Golden, CO

SunShot
U.S. Department of Energy

Overview

- The **SunShot** Initiative
- Systems Integration / Technology Validation Activities
- 2012 PV Module Reliability Workshop

SunShot Initiative

"The SunShot Initiative will spur American innovations to reduce life costs of solar energy and re-establish U.S. global leadership in this growing industry."

U.S. Energy Secretary Steven Chu

- DOE's **SunShot** Initiative aims to make solar electricity cost-competitive with conventional forms of energy before 2020.
- What is SunShot?
  - Subsidy-free solar electricity
  - 75% cost reduction by end of the decade
  - 5-6 cents/kWh at utility-scale
  - Global Competitiveness
- Coordination among DOE Solar Program, Office of Science, and ARPA-E.

SunShot
U.S. Department of Energy

Taking a Team Approach

R. Ramesh
SunShot Director

Minh Le
PV Module
EERE

Module Task Force (EERE)
GOAL: 0.50$/Watt

Power Electronics (ARPA-E)
GOAL: 0.10$/Watt

Rajeev Ram
Power Electronics
ARPA-E

Ranga Pitchumani
EERE

Kevin Lynn
Systems Integration
EERE

Ravi Prasher
ARPA-E
CSP

Fundamental Research (SC)
Foundational (EERE)

Balance of Systems (EERE)
GOAL: 0.40$/Watt

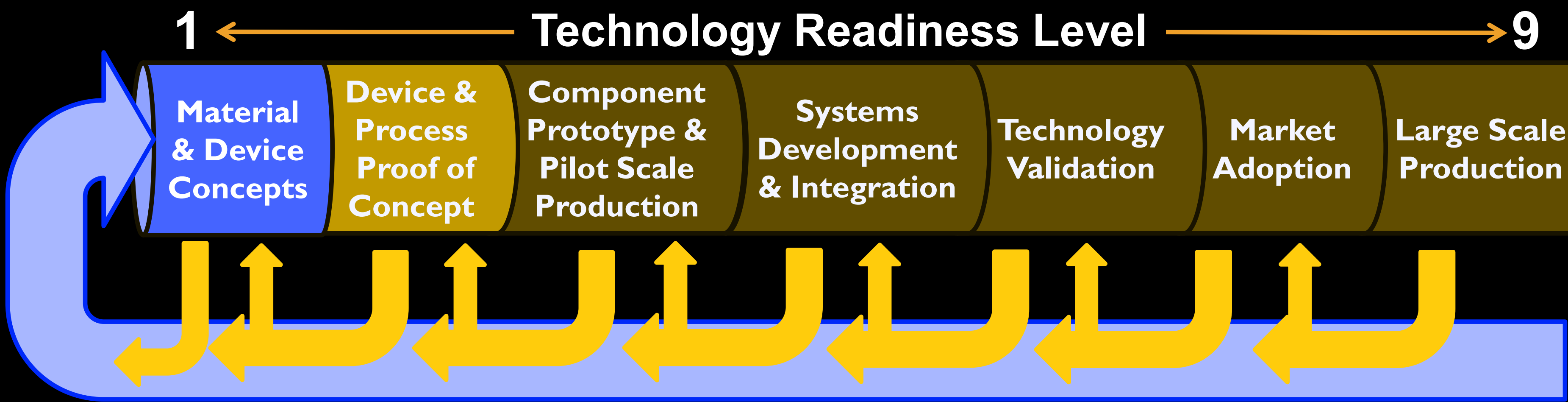
Jim Horwitz
Carol Bessel
Fundamental Science
SC

Rachel Tronstein
BOS-Soft
EERE

Craig Connelly
Financial Planning, EERE

Advisory Board: Bill Brinkman (SC); Arun Majumdar (ARPA-E); Henry Kelly(EERE)

SunShot Program Framework



- Basic Energy Sciences
- MURI
- Next Gen PV
- Program to Advance Cell Efficiency (PACE)
- SunShot Fellowships

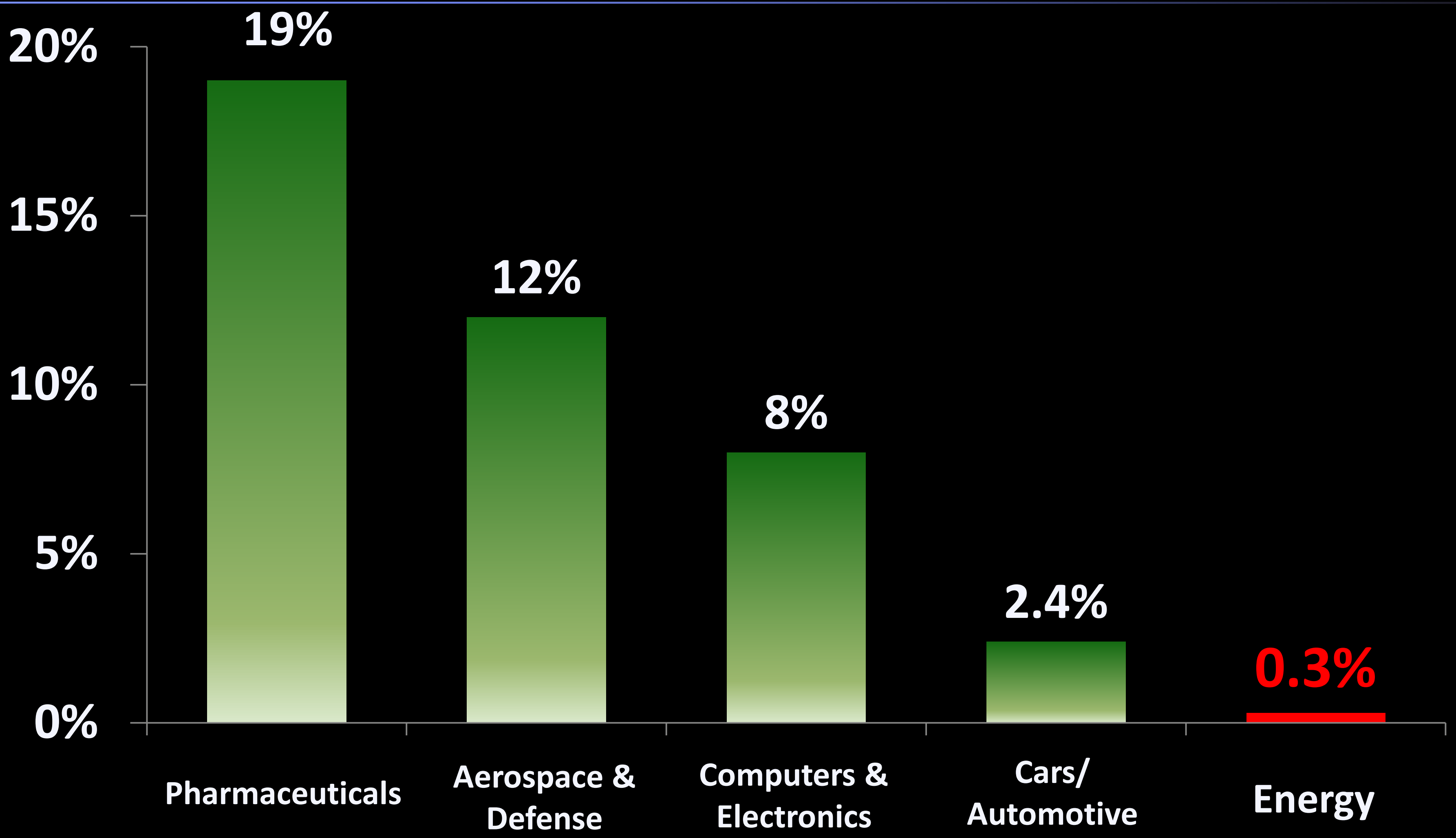
- SunShot Incubator
- PV Supply Chain
- Balance of Systems-Hardware
- PV Manufacturing Initiative I
- Solar ADEPT
- SEGIS
- CSP SunShot FOA
- Thermal Storage: HEATS

- High Penetration
- Incubator – Soft Costs
- PVMI II: SUNPATH

- Rooftop Solar Challenge
- Non-Hardware BOS

SunShot
U.S. Department of Energy

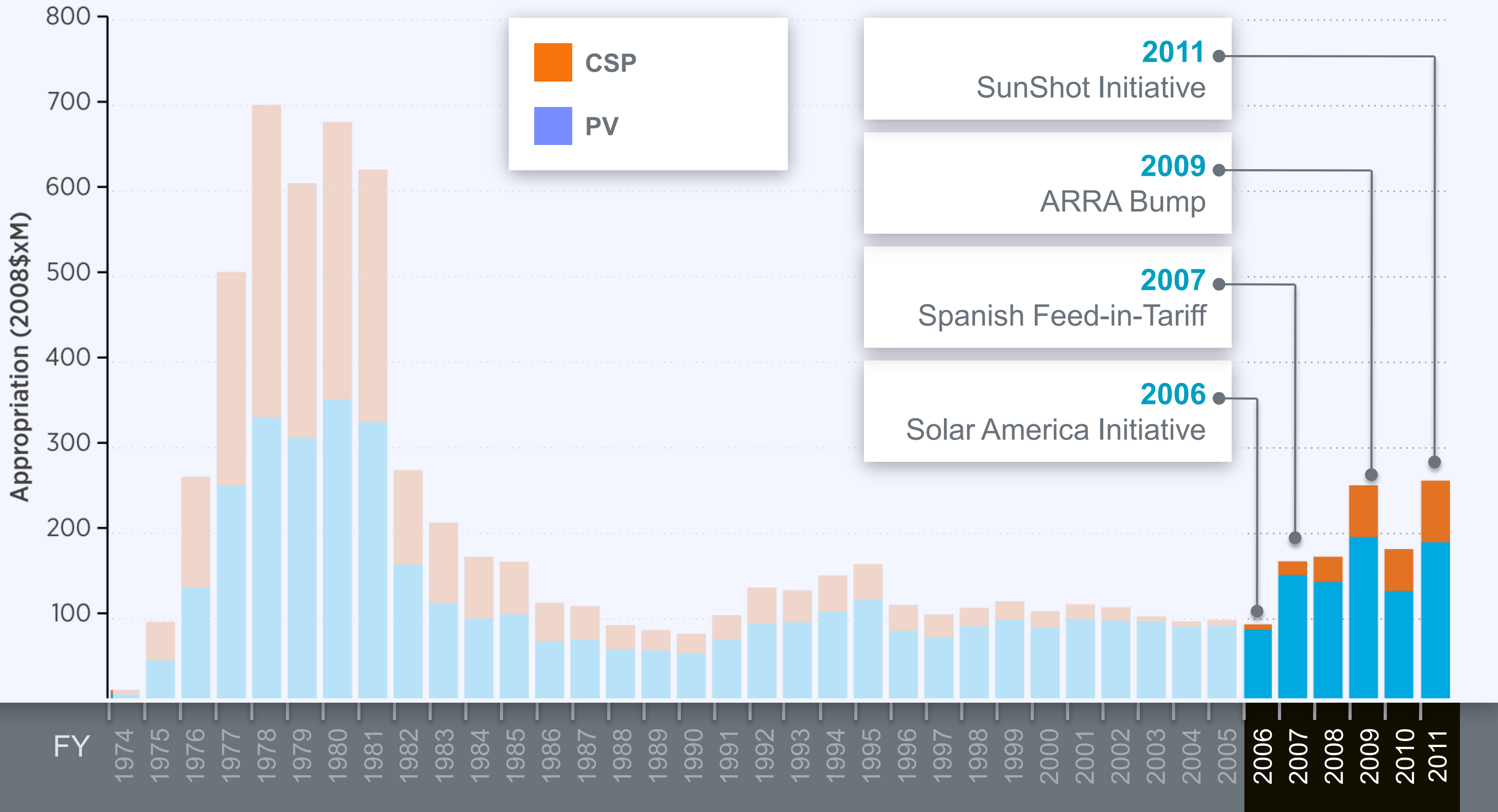
Percent Sales Invested in R&D



SunShot U.S. Department of Energy

Source: American Energy Innovation Council, *Business Plan for America's Energy Future*, 2010

History of Solar at DOE



SunShot
U.S. Department of Energy

SunShot - Systems Integration

Goals

- **BOS Costs:** Reducing the costs of power electronics and balance of system hardware
- **Bankability:** Reducing the risk associated with the use of new technologies
- **Grid Integration:** Establishing a timely process for integrating high penetrations of solar technologies into the grid in a safe, reliable, and cost-effective manner while providing value to the system owner and the utility grid.
- **Solar Resource:** Dramatically reduce the uncertainty in solar system performance due to solar radiation measurements, and provide grid operators and others the information necessary to cost-effectively and reliably integrate solar technologies into the grid.

SunShot – Technology Validation

Mission / Vision:

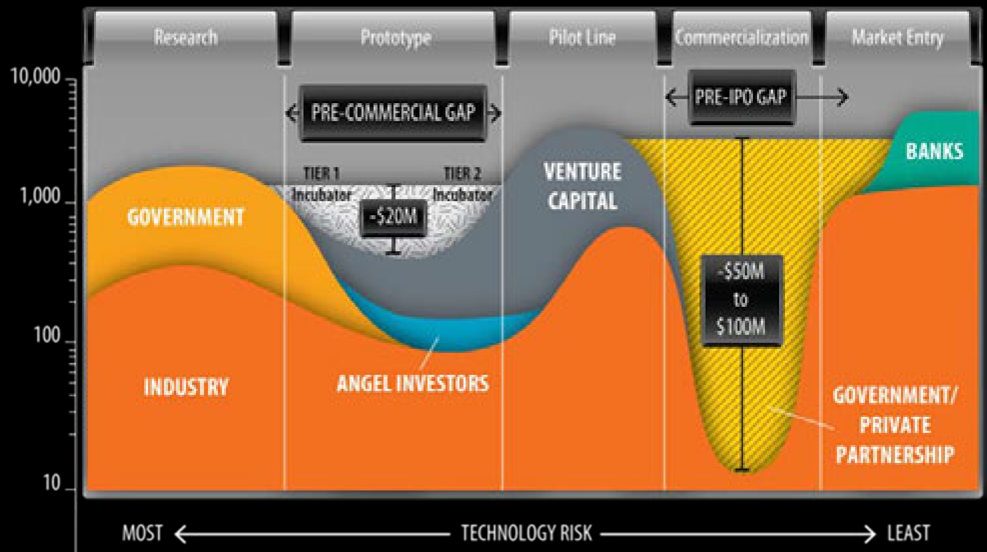
- To reduce the cost of PV by improving confidence in the expected performance, reliability, and safety of PV components and systems.
- Understanding of performance and reliability leads to reduction of risk and will lead to a greater investment in the technology.

Activities:

- Test & Evaluation
- Reliability & Safety
- Regional Test Centers (RTC's)
- Modeling & Analysis
- Codes & Standards

PV Regional Test Centers

- **Background / Vision:**
  - Accelerate adoption of renewable energy generation sources by helping U.S. PV manufacturers overcome the commercialization "Valley of Death"
  - Provide technical basis for bankability of PV systems
    - Test beds for large-scale systems in multiple climates, using a comprehensive validation approach to compare performance and initial reliability against predictions



- **Locations:**
  - Albuquerque (Sandia)
  - Denver (SolarTAC – NREL)
  - Orlando (UCF – FSEC)

2012 PV Module Reliability Workshop

- Objective: Share information among participants leading to the improvement of PV module reliability which:
  - Reduces the cost of solar electricity
  - Promotes investor confidence in the technology
  - Critical goals for moving PV technologies deeper into the electricity marketplace.
- Active participation provides benefit to all: everyone shares a little and takes home a lot.

2012 PVMRW Agenda

Sessions:

- **Silicon PV: Tues., Feb. 28, 2012**
- **PV Standards (Materials Testing / Quality Assurance Rating): Wed., Feb. 29, 2012**
- **Thin-Film Modules: Thurs., Mar. 1, 2012**
- **CPV: Thurs., Mar. 1, 2012**

Special Thanks to:

- Sarah Kurtz, *Chair*
- **Workshop Organizers:** Ian Aeby, Genmao Chen, David Degraaff, Neelkanth Dhere, Dan Doble, Ryan Gaston, Jennifer Granata, Peter Hacke, Pam Hajcak, Peter Hebert, Jason Hevelone, Dirk Jordan, Paul Lamarche, Kenneth Leffew, Michael Quintana, Mark Roehrig, Kurt Scott, Samir Sharma, Govindasamy Tamizhmani, Kaitlyn VanSant, Shuying Yang, John Wohlgemuth
- **Workshop Participants**

"PVRessQ!"
PV Module Failures Observed in the Field

Kazuhiko Kato
Research Center for Photovoltaic Technologies (RCPVT)
National Institute of Advanced Industrial Science and Technology (AIST)
JAPAN

Fukushima Nuclear Power Plant Accident and PV

Our government and
nuclear scientists had de
nuclear power plants were safe
and economical for long time.
But people have realized that
the story was a **"myth"**.

Now expectations for PV
have been drastically
increasing
after the accident of
Fukushima Nuclear Power Plant.

Are there any "myths" in PV market? How about "reliability" ?
In Japan, people religiously believe in reliability of PV.

General understandings of PV in Japan

The government and
many PV manufacturers/installers say…

"PV module has **over 20-year expected lifetime** in average."

"PV system is **easy-maintenance** or almost **no-maintenance**."

PV manufacturers and installers have **no legal obligation** to check PV systems with less than 50kW capacity.

They just **recommend** periodic inspection every four year to PV users.

They provide **10-year warranty** on **each PV module** for nominal power output.
(Some new comers do 25-year warranty.)

"PVRessQ!" activity

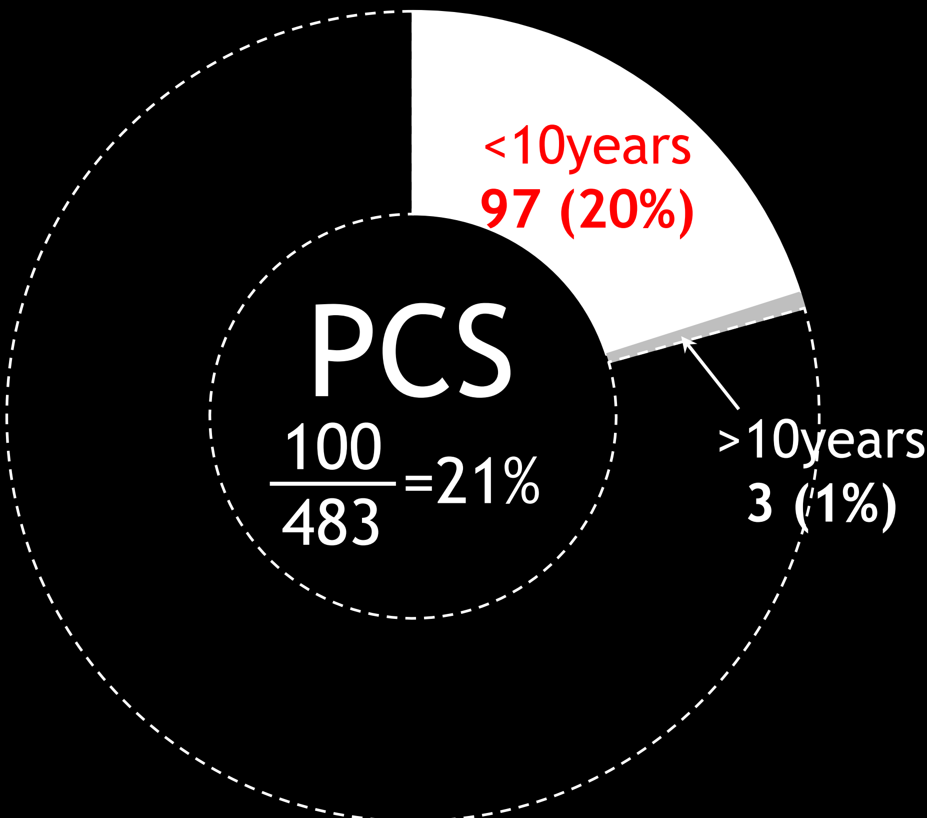
(**PV** – **Re**liable, **S**afe and **S**ustainable **Q**uality**!**)

- Started in 2006.
- One from AIST (Kato), others from local installer (not manufacturer)
- Independent research activity supported by donations from the people (always poor because no budget from METI nor AIST)
- Main task
  - Field survey on faults/failures of residential PV systems in operation
  - Statistical survey on PV system reliability
- Goal
  - Proposal of practical maintenance techniques to detect all PV system failures (technical issue)
  - Proposal of inspection system for PV system (social issue)

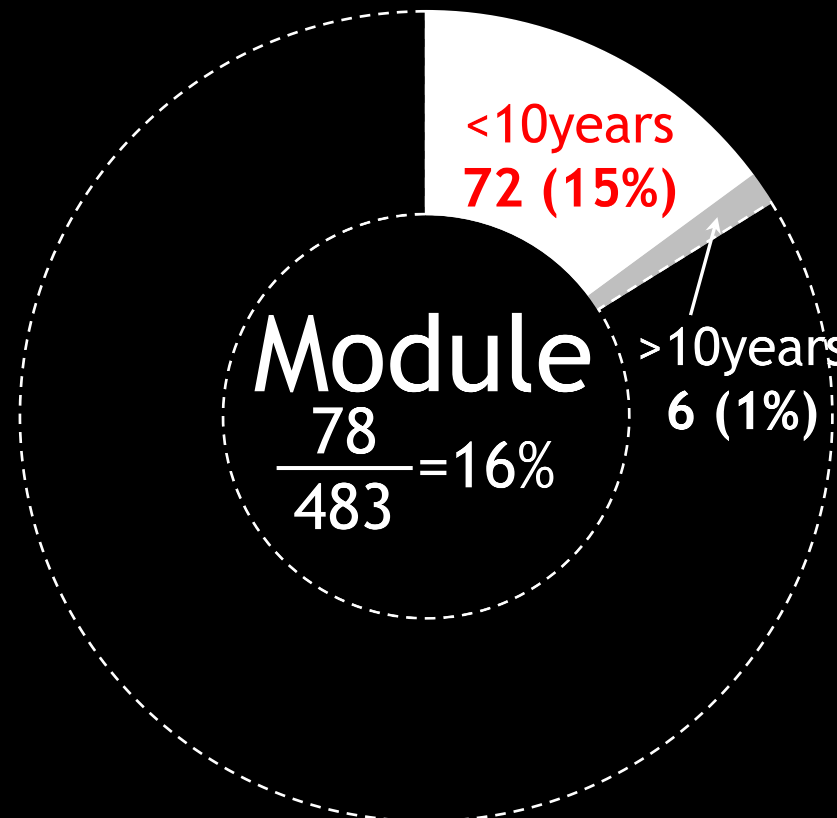
A statistical survey for PV-user records

483 residential PV systems installed in 1993-2006

Experienced repair/replacement of PCS

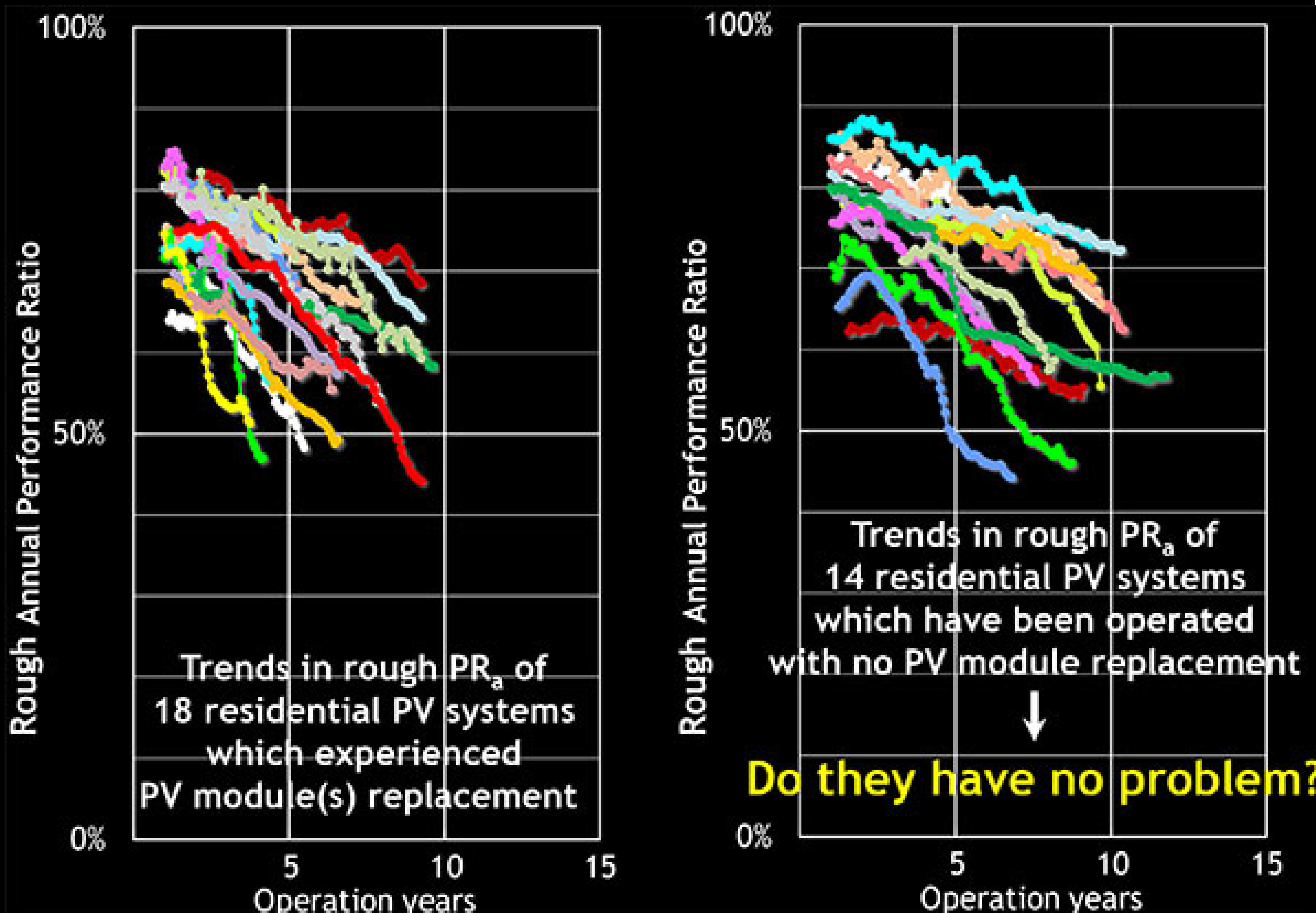


Experienced whole/partial replacement of PV modules



Is PV System Reliable for users ?

Trends in rough annual performance ratio(PR_a



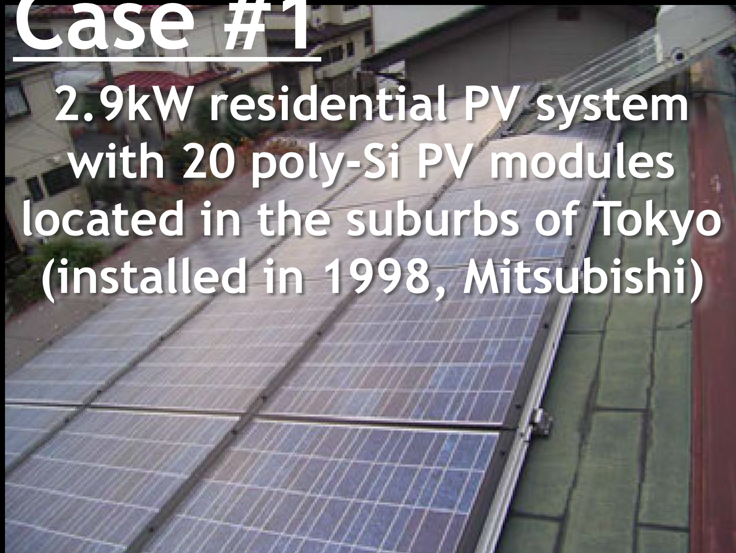
Field Survey for Residential PV Systems

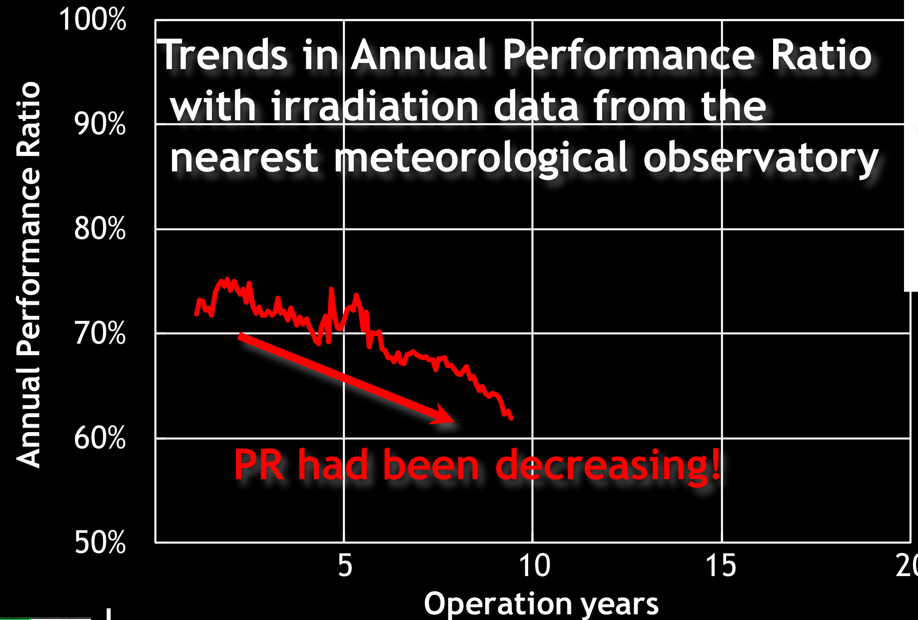
32 residential PV systems have been surveyed so far.

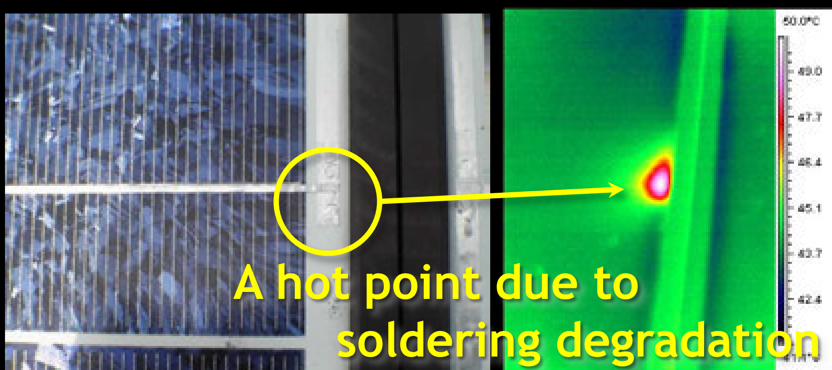
Many failures have been found in PV modules!

Case #1

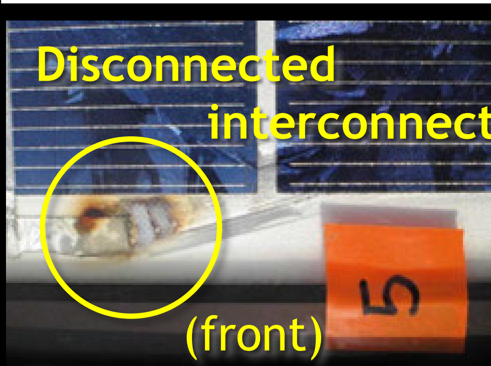
2.9kW residential PV system with 20 poly-Si PV modules located in the suburbs of Tokyo (installed in 1998, Mitsubishi)

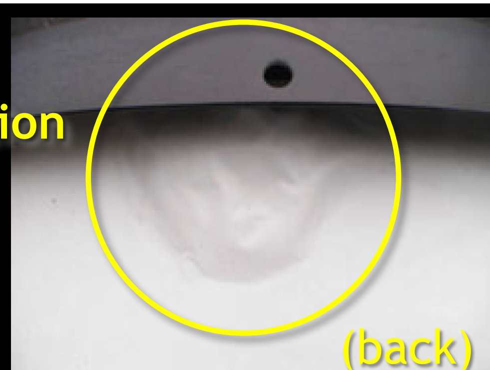


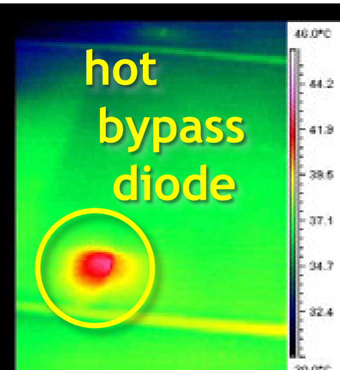


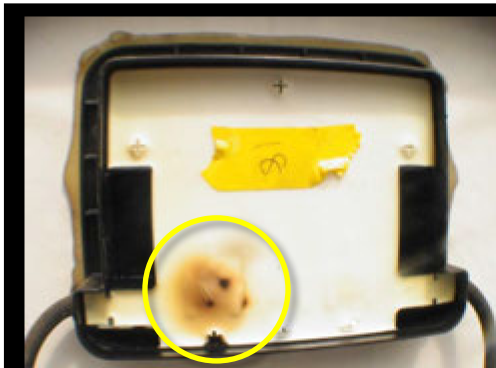


- Inspection by the installer reported "No roblem".
- The survey by PVRessQ! Judged that 10 of 20 PV modules had serious failures.
- The 10 modules were replaced by the manufacturer with no charge in the end.
- The others were not (the manufacturer said they would never have any problems.)



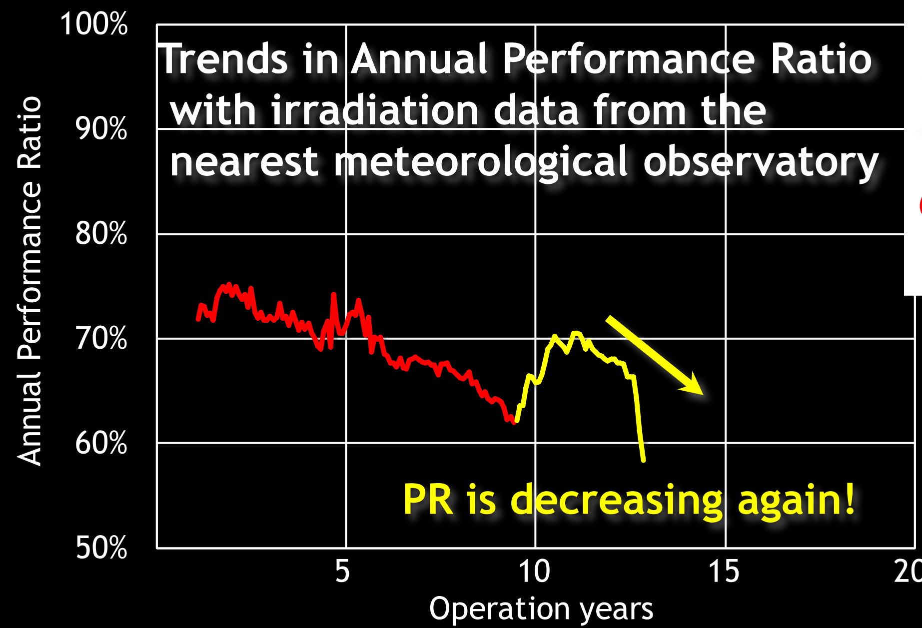


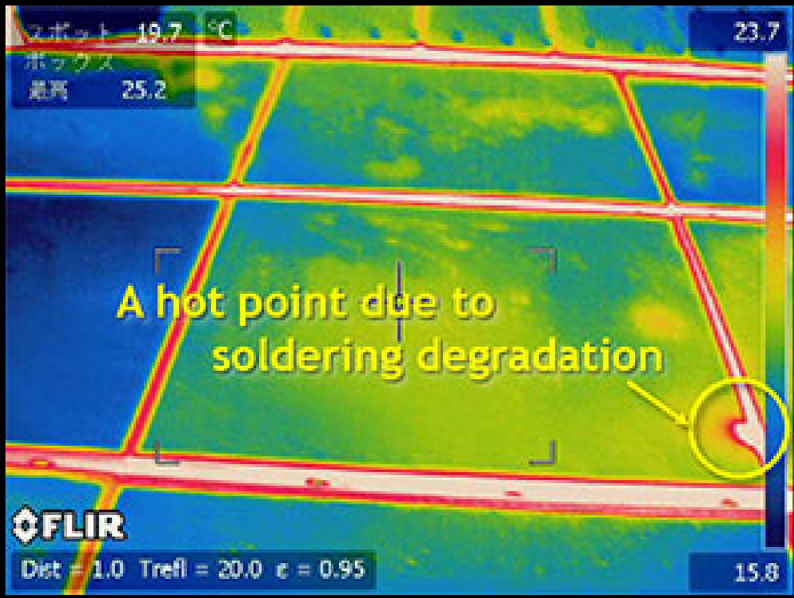


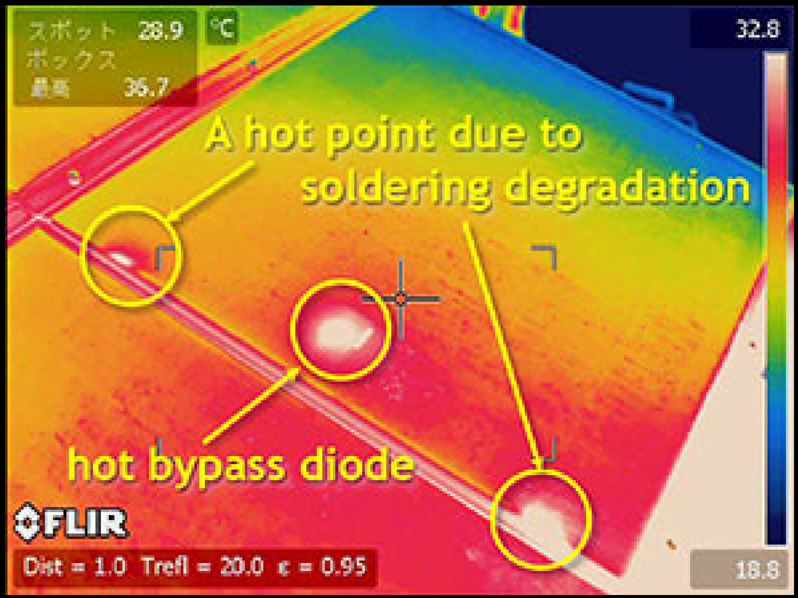


…and three years later

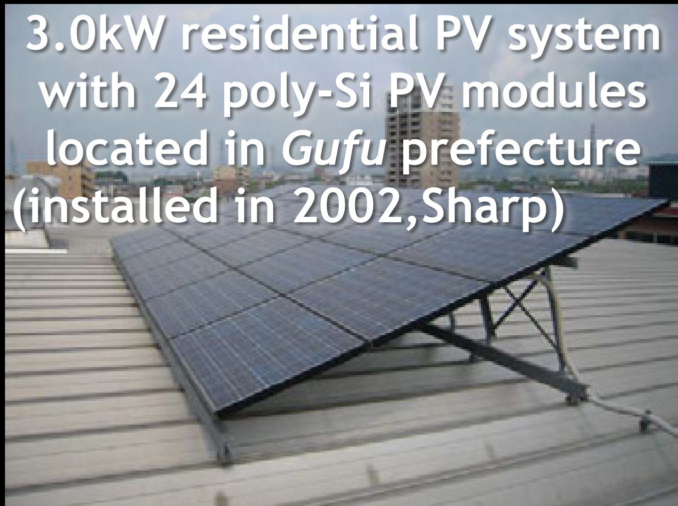
- The same kind of failure as before was found in old 5 modules.
- One of them could not generate voltage due to disconnection of internal circuit.
- The manufacturer replaced all the old modules with no charge, though their warranty period (10 years) was over

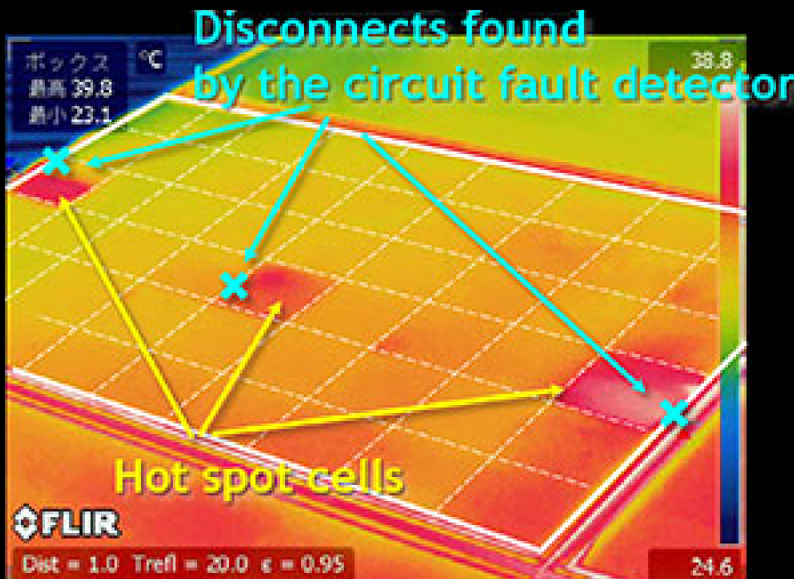


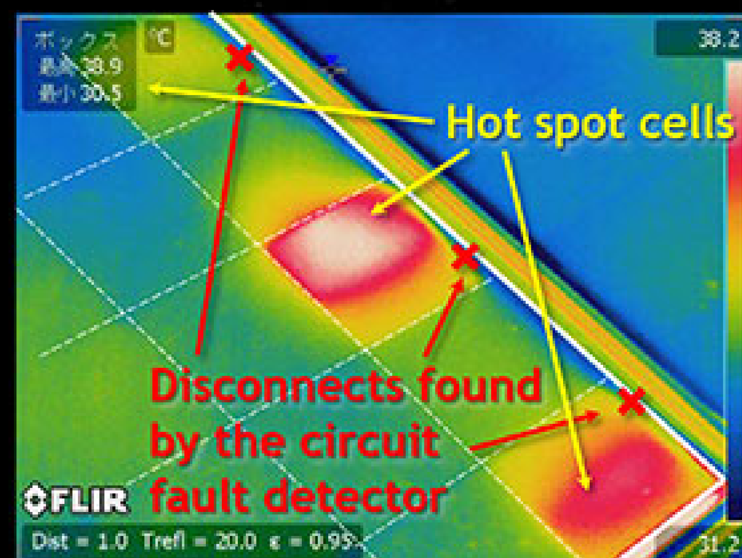




Case #2

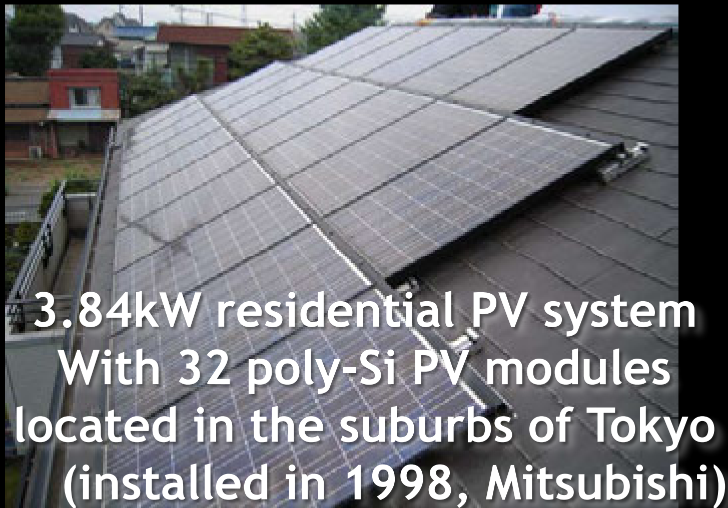


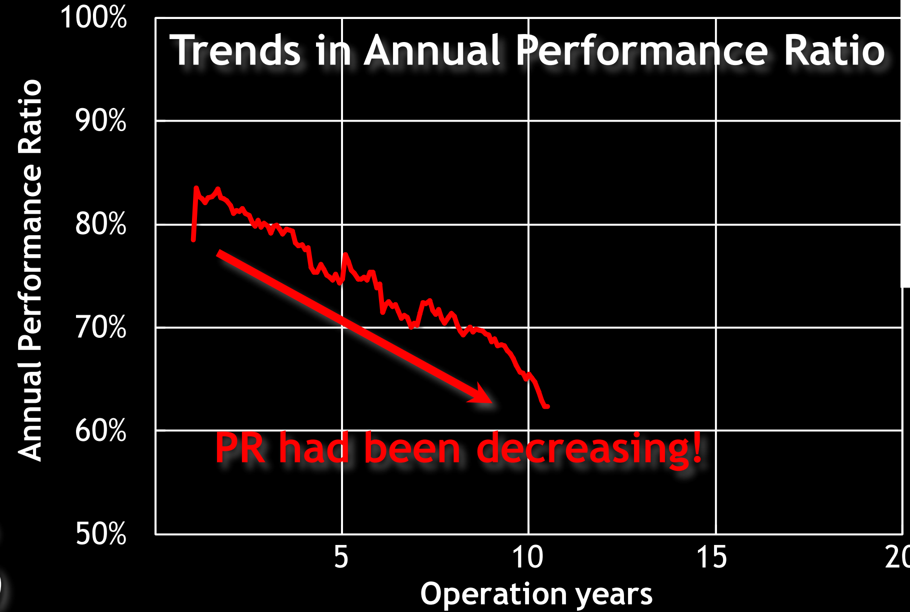




- PVRessQ! survey found failures in many PV modules.
- Discussion about module replacement is in preparation.

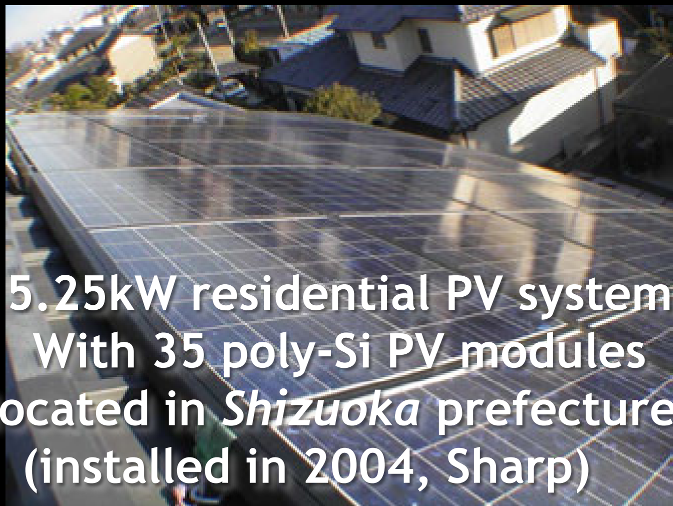
Case #3

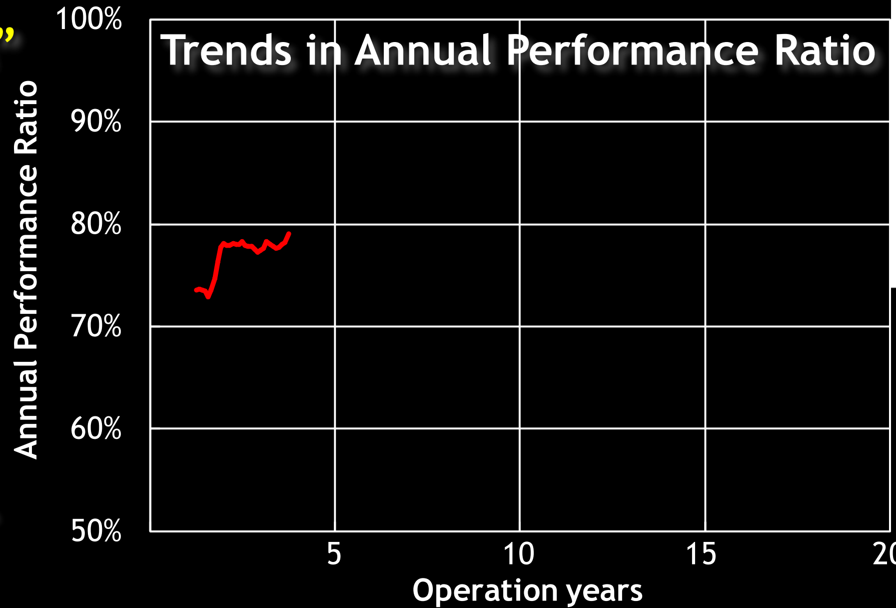


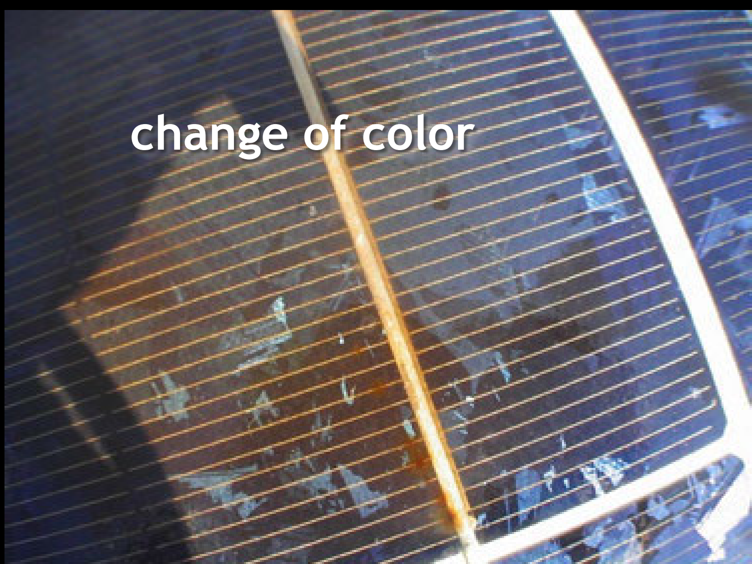


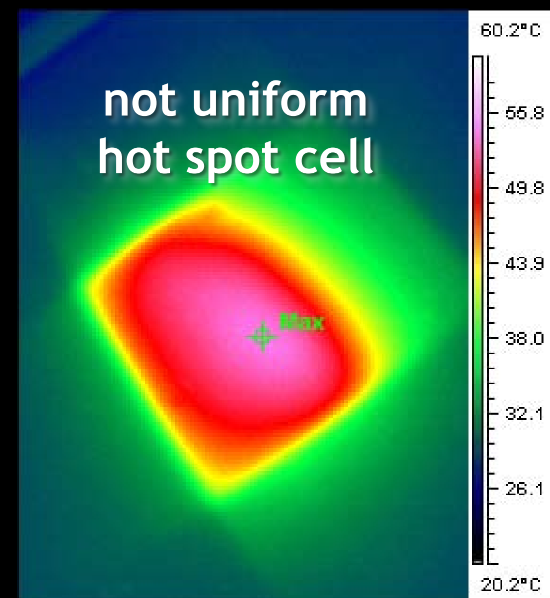
- PVRessQ! survey found 15 PV modules had serious failures.
- Though the warranty period (10 years) was over, all the PV modules were replaced with no charge.

Case #4 "Sharp ND-150AM"





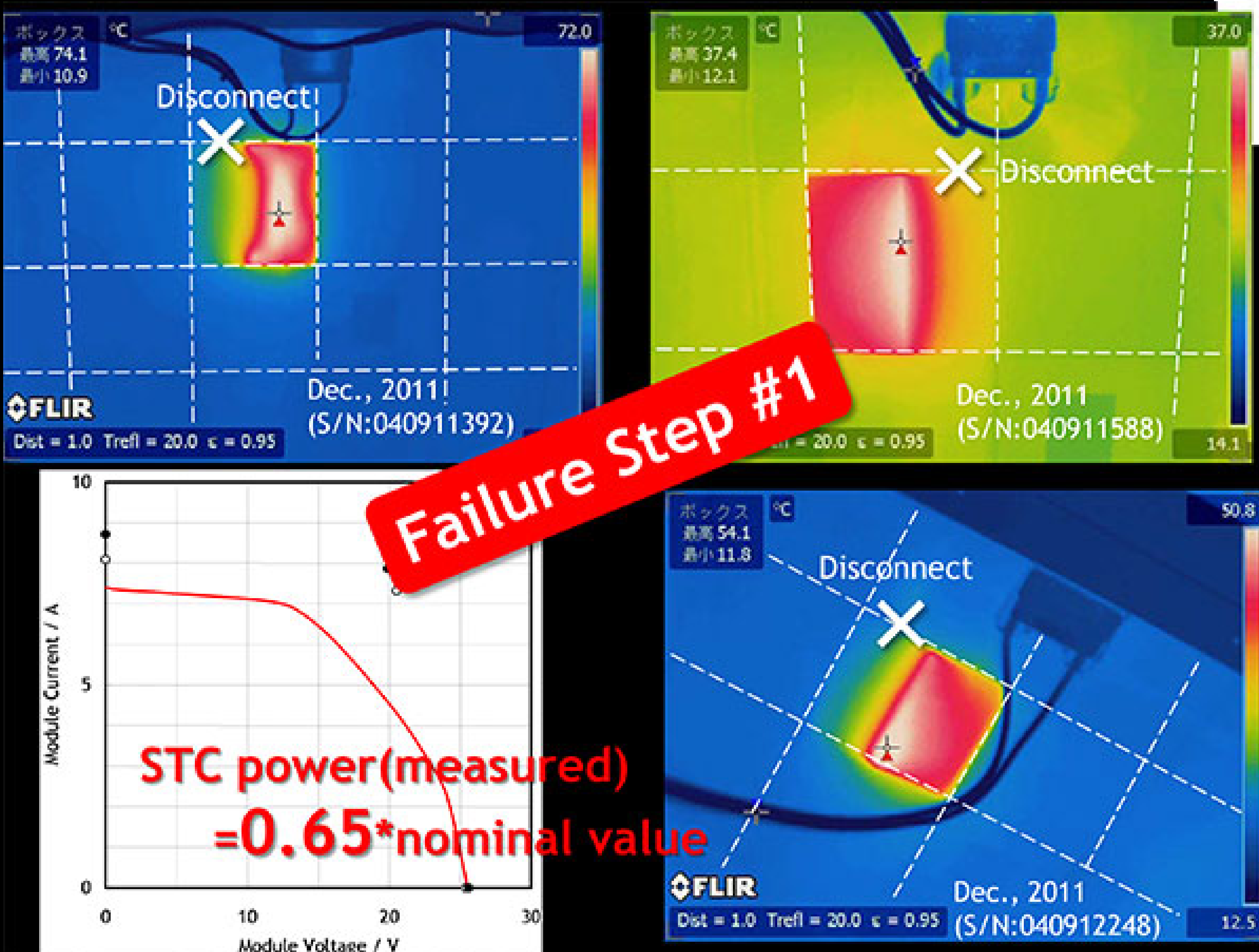




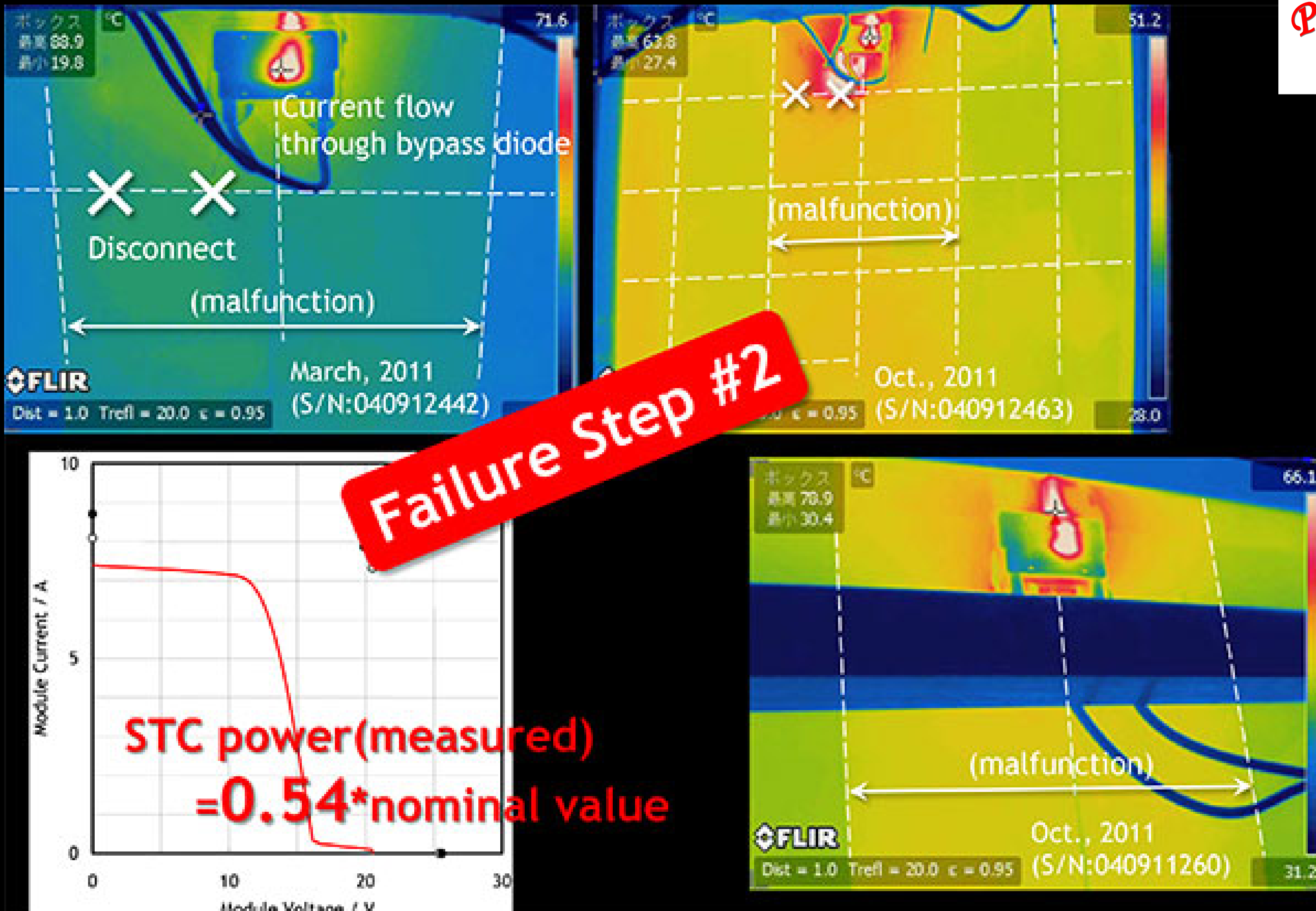
Four PV modules were replaced,
though high performance ratio and short operation years.

Part of PV installation in AIST

Part of PV installation in AIST

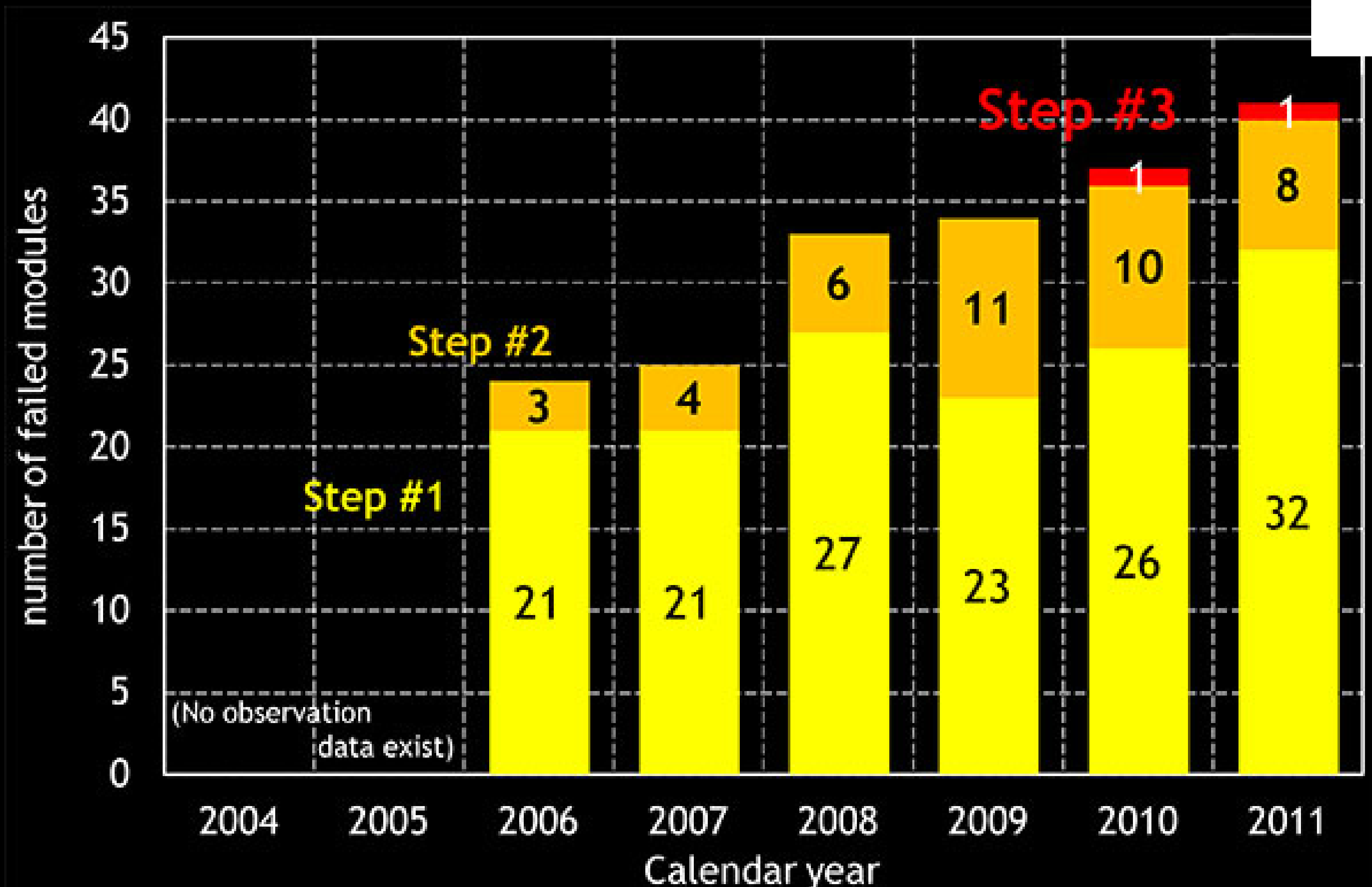


Part of PV installation in AIST

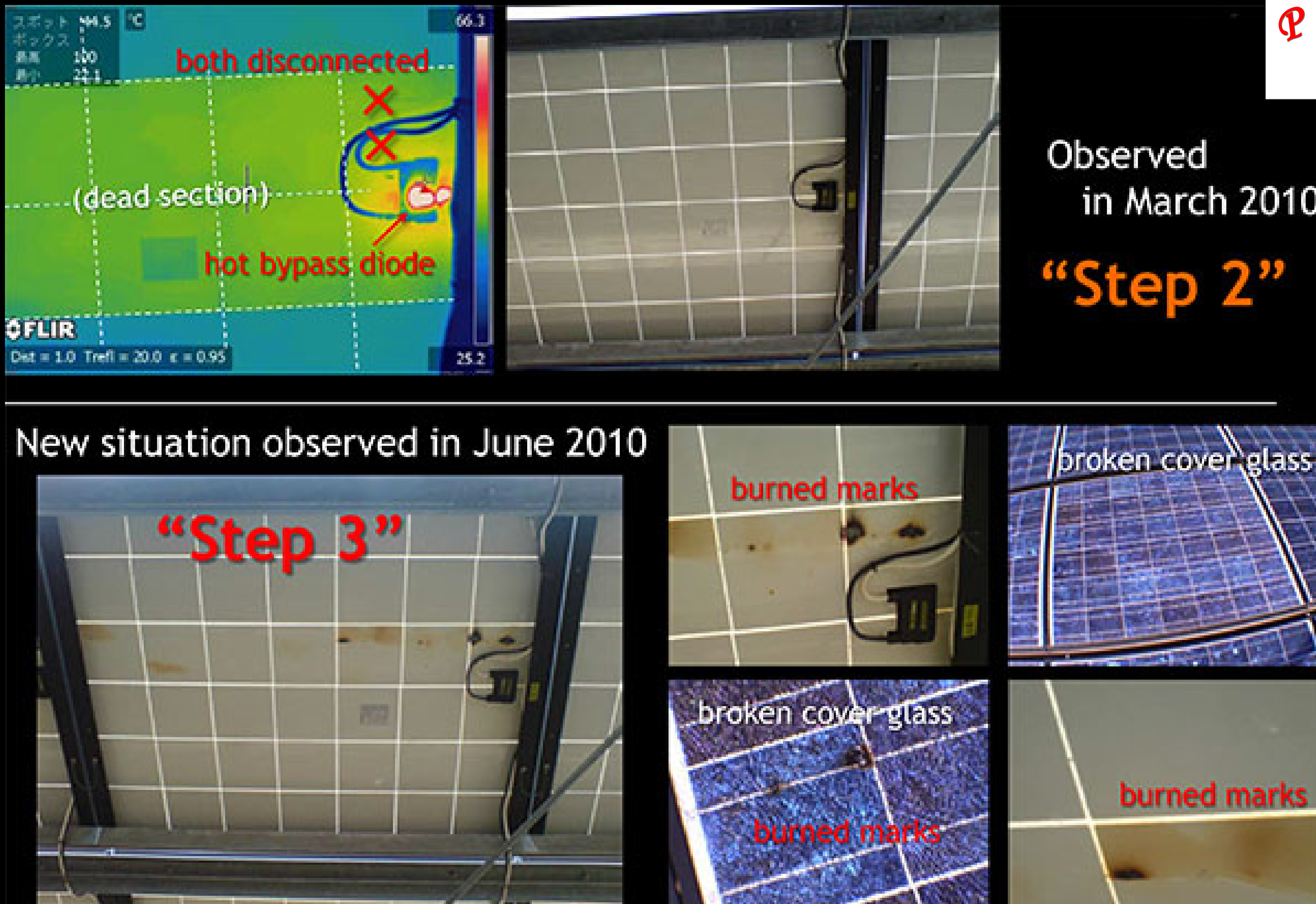


Part of PV installation in AIST

Trend in number of failed modules (out of 1,080 in total)

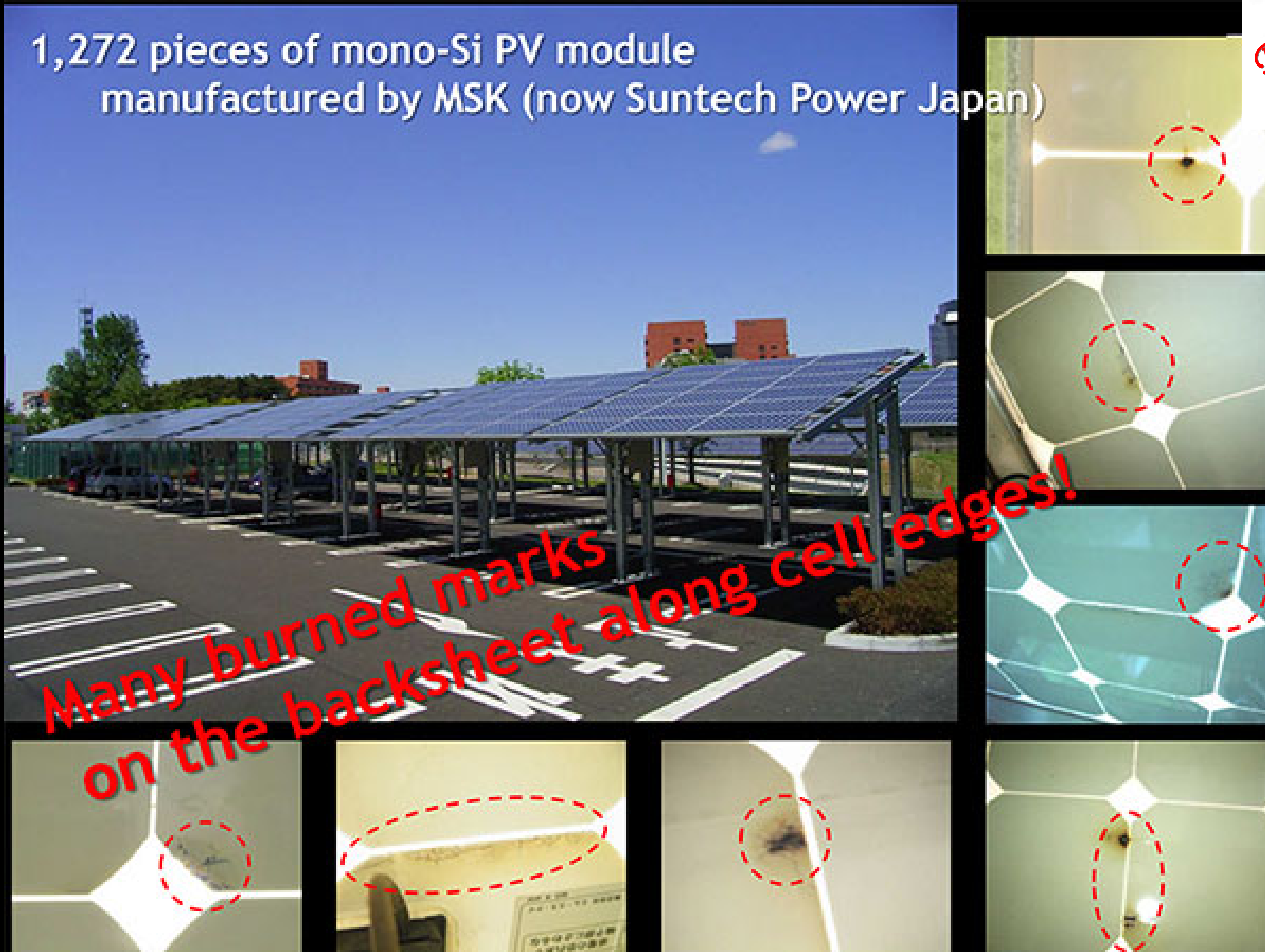


Part of PV installation in AIST

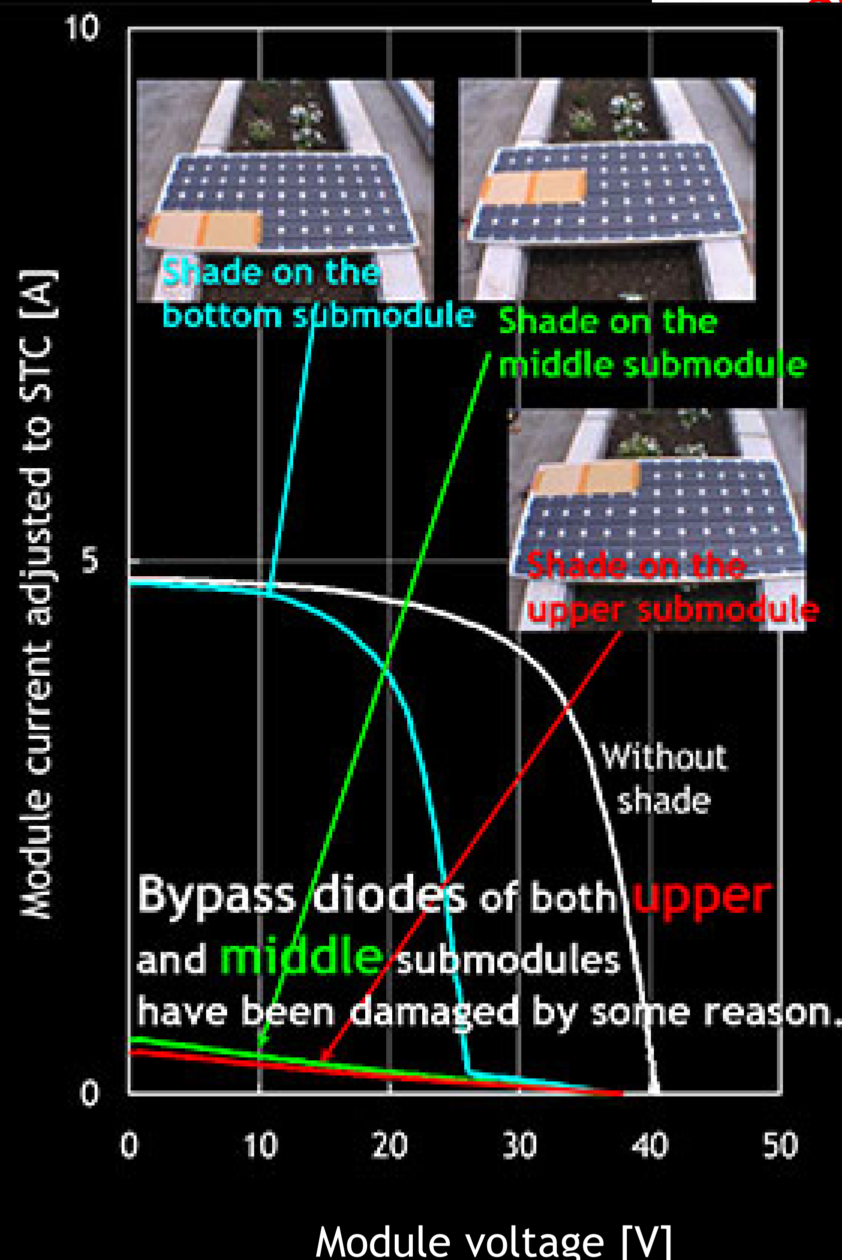


Part of PV installation in AIST

Another Module Failure occurring in AIST

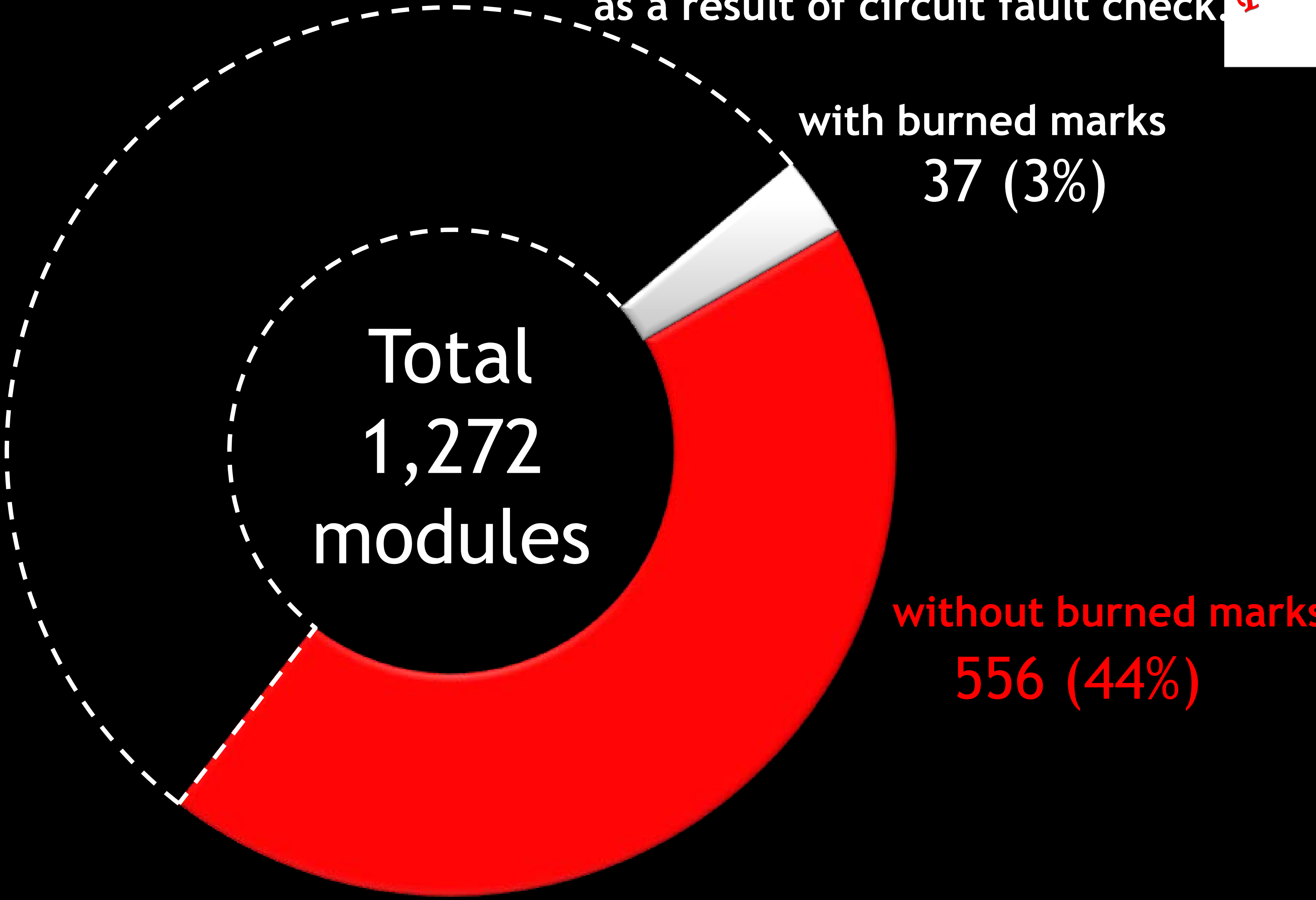


Another Module Failure occurring in AIST



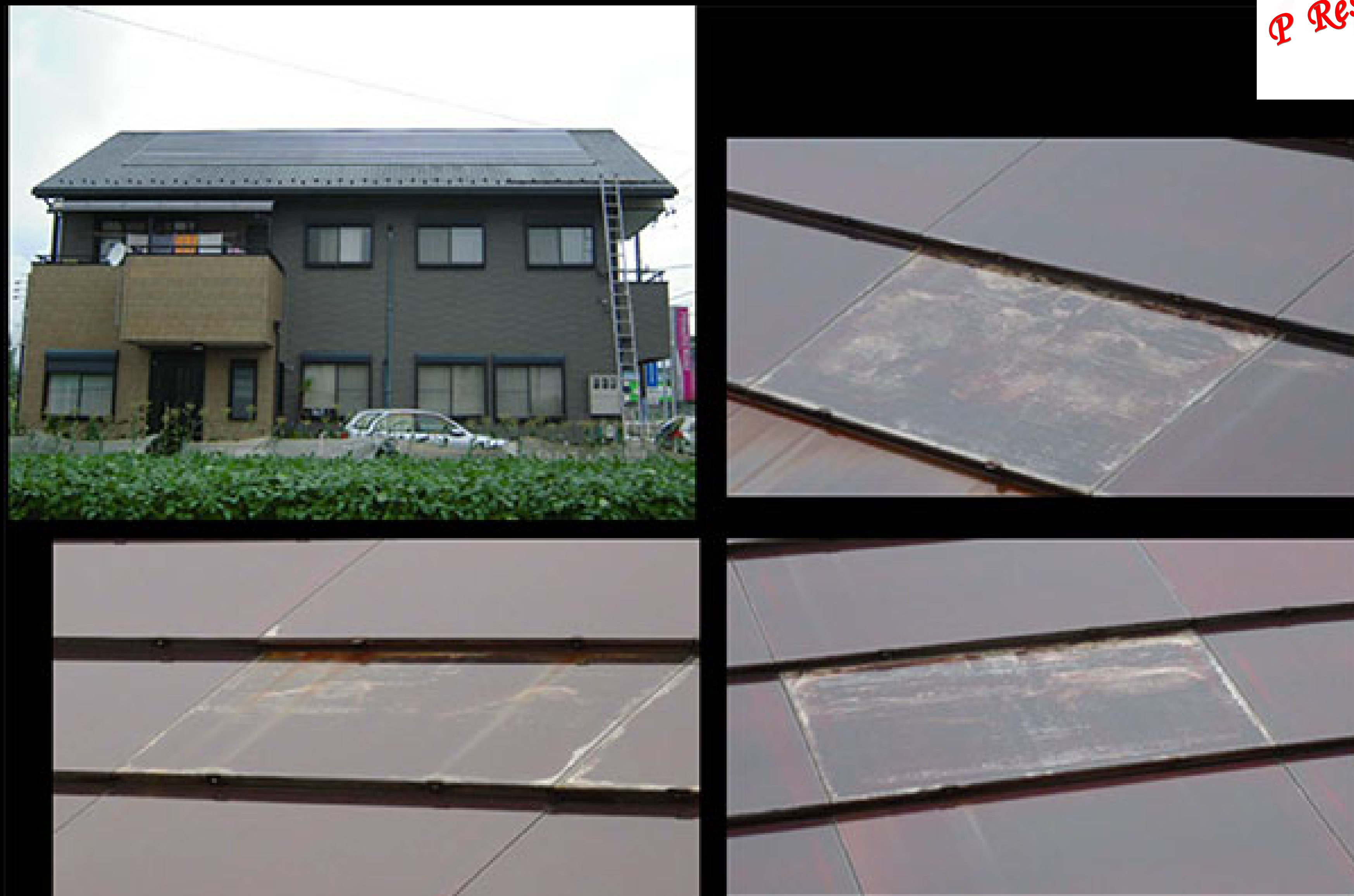
Another Module Failure occurring in AIST

Fraction of PV modules in which bypass diodes do not work as a result of circuit fault check.



PVRessQ! tackling thin-film PV modules now

No experience, no info, no instrument…no solution.



Some remarks from PVRessQ!

- PV module failures are often invisible.
  - -Visual inspection has less effect for casual field survey. Failures always hidden behind backdrop.
- What is “reliability” of PV module?
  - “Degradation” and “failure” must be discussed, respectively.
  - Harmless degradation damages nothing, but people might be injured with PV module failure.
  - long-term “Safety” is one important perspective of reliability, of course.
- What is “lifetime” of PV module?
  - A light bulb with 50% decrease in luminous flux may be not worth to use, but a harmless PV module with 50% drop in efficiency still can give you good-quality electricity.
  - Only power drop is not the indicator of lifetime of PV module.
- Higher quality must be required of PV module as an “industrial product”. But quality assurance without valid maintenance has less effect than your expectation.

We should pay attention to maintenance issue!

In conclusion…Back to Fukushima…

Some audience may think and laugh…

"You are only talking about PV modules with past and old-fashioned technologies."

But, remember…

Fukushima nuclear power plant started its operation 40 years ago! And nobody could make decision to stop it before this accident.

Another "China Syndrome" might be waiting for us…

Module Safety Issues

2012 PV Module Reliability Workshop

John Wohlgemuth

February 28, 2012

NREL/PR-5200-54715

How can Modules be Dangerous?

- Shock hazard
  - ❑ Touch hazard
- Mechanical
  - ❑ Parts can fall on somebody
  - ❑ Ice or snow can be dumped on someone
  - ❑ Dangerous particles (glass) can come off when modules are broken
- Fire
  - ❑ Can the module start a fire?
  - ❑ Can the module spread a fire?

Module Safety Testing

IEC 61730 and UL 1703

They have similar requirements

Both have a Design Criteria Section and a Testing Section

Both cover the following topics quite well:

- **Shock hazards – Although corrosion of ground terminals can impair the protection afforded by grounding the frames**
- **Spread of flame - Although as next talk indicates changes are coming**
- **Mechanical safety – Although paying attention to local building codes is also very important**

Neither covers the potential of the module itself to start fires.

Effort is underway to modify 61730 (edition 2) to improve how it addresses the potential for modules to cause fires.

Propose to adopt IEC 61730 edition 2 in US to replace UL 1703.

Corroded Ground Terminals

PV Grounding Problems

Corrosion in a harsh environment

This system is installed on an off-shore island of Taiwan for only 5 years

Pictures provided by Tim Zgonena of UL

Wind Damage

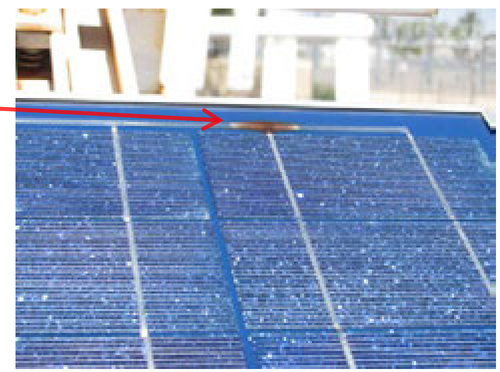
Hans Urban’s presentation at TUV Sponsored Module Workshop, 2006

PV Module Fire Hazards

What can cause a module to locally overheat and potentially cause a fire?

1. Hotspots

2. High Series Resistance

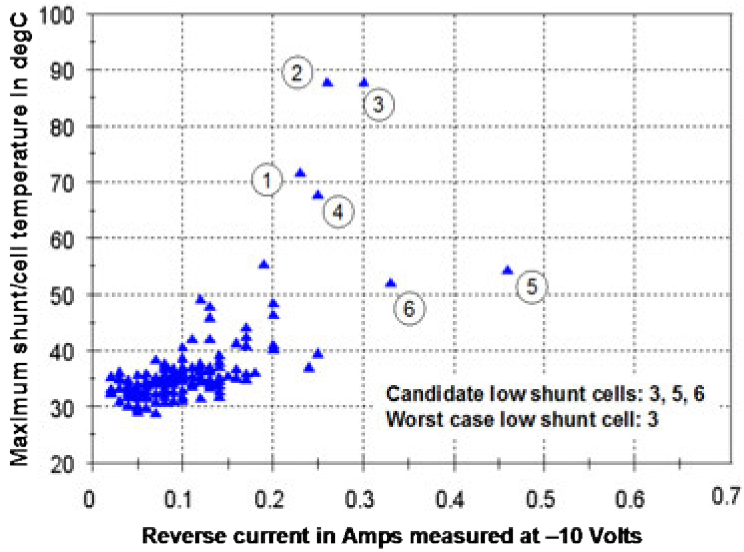


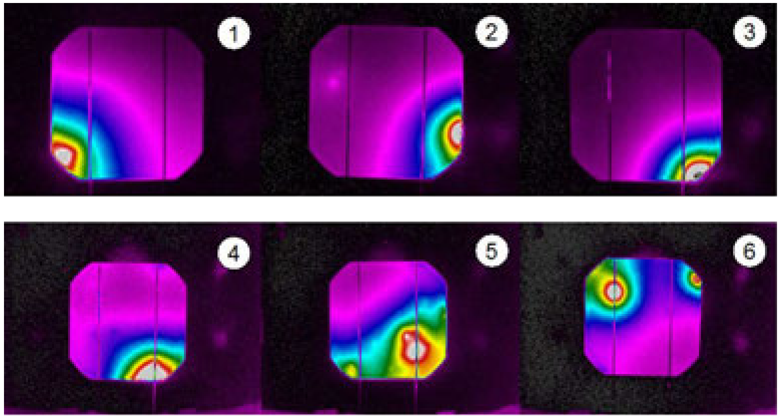
3. Arcing

Hot Spots

- When a cell (or cells) are forced into reverse bias because it (they) can not carry the peak power current being produced by the other cells.
- Can be caused by poor matching, cracks, localized soiling (bird droppings) or shadowing.
- Cells are suppose to be protected by the by-pass diodes that limit the reverse voltage across a cell to less than ~ 10 volts (20 cells per diode).
- Problems occur when the by-pass diodes fail or are never installed correctly or when the cells have low shunt resistances due to localized defects and therefore overheat at 10 volts reverse bias.

Hot Spots





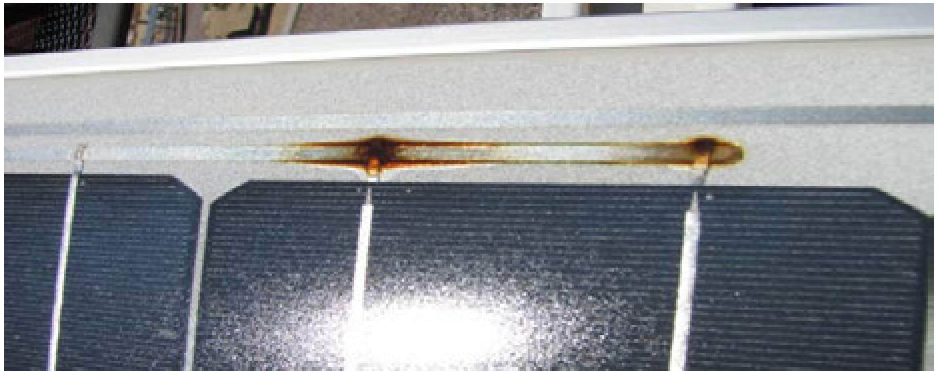
- Cells 2 and 3 have highest localized temperature although not the lowest shunt resistance.
- Cell 5 has the highest leakage current so lowest shunt resistance.
- For some cells 1 diode per 20 cells is not adequate.
- Either need fewer cells per diode or have to screen out cells with low shunt resistances or those with localized hot spots.
- This issue becomes more important with the use of larger cells when there is more power to cause overheating

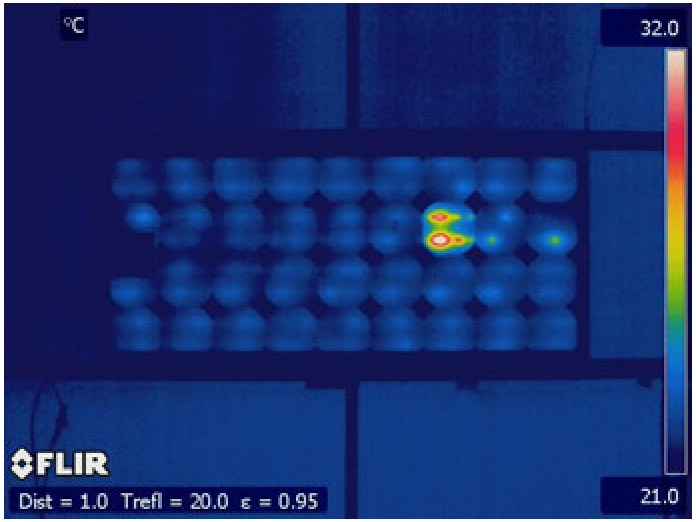
Hot Spots – Are they likely to cause a fire?

- The temperatures shown on the previous page topped out at around 90 C.
- On the other hand I have personally seen a hot spot melt silicon – but at much higher voltages such as might happen if the by-pass diode failed.
- When the hot spot melted silicon it was a localized event:
    - It did result in melting of the encapsulant and back sheet.
    - The melting silicon quickly shunted the cell so badly that it no longer produced a voltage or a hot spot.
    - The short duration of the localized heating did not result in a fire.
- I have never observed a "Hot Spot" causing a module to catch fire.
- See also "Analysis of Hot Spots in Crystalline Silicon Modules and their Impact on Roof Structures" by Cunningham, et. al. from 2011 NREL PVMRW showing that neither hot spots nor resistive heating causes fires.

High Series Resistance

- Failure of solder bonds within the module can lead to overheating at the solder bond that is failing and at the bonds that are left to carry the additional current.
- Such high resistance bonds do result in significant output power loss.
- However the temperatures reached at these poor solder bonds are typically not high enough to cause fires.
- The danger occurs when the resistive heating results in total failure of the bond – that is an open circuit which can lead to an arc.





Arcing in a PV Module

Two types of arcing

1. Series arc – caused by an open circuit in a high voltage dc array
2. Parallel arc – caused by close proximity between two different dc polarities.
   - In modules parallel arcs can occur due to ground faults.
   - Unlike an ac circuit, ground faults in a dc PV system usually do not trip the fuse or circuit breaker.

No material selection or module design is going to prevent a module from catching fire once an arc is sustained.

Series Arcs

- In modules a series arc can occur whenever the current path is disrupted.
- This is much worse for dc than ac as there is no zero cross-over every cycle to extinguish the arc.
- Once such a dc arc starts it will continue to arc until the current stops flowing by
  - Control system shuts it off
  - The sun goes down or
  - One of the connection points falls away.

Today UL 1703 says “Strain relief shall be provided so that stress on a lead intended for field connection, or otherwise likely to be handled in the field, including a flexible cord, is not transmitted to the connection inside the module or panel.

This has often been met by potting the output wires or running them through a compression fitting.

Either can hold the wire in place while it arcs.

Demonstration of Series Arc

Parallel Arcs

- In modules parallel arcs can occur due to ground faults.
- In US NEC calls for grounding one side of ac lines as well as the equipment itself.
- Because one side of the circuit and the equipment are both grounded, any ground faults to the active circuit usually trip the fuse or circuit breaker.
- Unlike an ac circuit, ground faults in a dc PV system usually do not trip the fuse or circuit breaker.
- In most cases it is not a good idea to ground one of the dc polarities.
  - Makes it more difficult to detect ground faults.
  - Makes it easier for ground loops to occur.
- Flow of current through components not designed to carry such currents means the potential for disruption of the current is high.
- Disruption of the current flow can result in arcing.

So how do we stop arcs from occurring in modules? {1}

Stopping open circuits from occurring

- **Design modules so that multiple failures are required in order for an open circuit to occur within the module. *For example use two or more tabbing ribbons per cell with multiple solder bonds on each ribbon.***
- **Protect module circuits with by-pass diodes and make sure the by-pass diodes are operational in the module before shipping.**
  - ❖ **This is even true for thin film modules that don't need by-pass diodes to protect cells from reverse bias {Hot Spot} damage. In thin film modules broken glass can result in arcing across the thin film cells. This will be prevented by the by-pass diode.**

So how do we stop arcs from occurring in modules?{2}

Stopping open circuits from occurring (2)

- All output leads (the most likely place to get an open circuit) should have redundant electrical connections.
  - Instead of a single solder bond use both a mechanical clip and a solder bond.
  - Instead of one weld use 2 independent welds.
  - Instead of one spring clip use a clip plus a second independent electrical connection (solder, screw, weld)
- Process Control
  - Train personnel performing any manual soldering.
  - Inspect and periodically test all solder bonds for quality – not just the ones on the cells.
  - Perform periodic accelerated stress testing (TC beyond 200) to validate all electrical bonds using IR to identify degradation before power loss occurs.

A redundant output connection is being discussed for the draft of IEC 61730-1 ed 2.

Examples of Arcs in Module

So how do we stop arcs from occurring in modules? {3}

Stopping ground faults from occurring

Many ground faults are installation related. Efforts to minimize their occurrence should include:

- **Better installer training**
- **Improved installation documentation**
- **Publication of installer safety design rules**

Module mounting systems should be designed to minimize the potential to contact active circuit area. This specifically means:

- **Do not attach mounting brackets or clips, etc to a polymer backsheet behind electrically active area.**
- **Module mounting like frames should attach outside the active area, meeting the creepage and clearance distance requirements for the rated systems voltage.**

So how do we stop arcs from occurring in modules? {4}

Stopping ground faults from occurring (cont)

- **Module manufacturers must pay particular attention to adhesion between encapsulant and glass.**
  - **Electrical leakage from active circuit to the ground plane along a delamination between encapsulant and glass is one of the failure modes observed in the field.**
  - **Such leakage is a shock hazard if the mounting system is not grounded and a ground fault hazard if it is.**
  - **The solution to this problem is a robust process with good process control.**
    - **Cleanliness of the glass**
    - **Use of a diffusion barrier on the inside of the glass to keep Na ions from diffusing to the surface and weakening the bond to the encapsulant material.**
    - **Control of the lamination cycle**
    - **Periodic accelerated stress testing of product, particularly damp heat**
    - **Continuous monitoring of the encapsulant cross-link density**

SUMMARY

Making modules inherently safer with minimum additional cost is the preferred approach for PV.

- ❑ **Safety starts with module design to ensure redundancy within the electrical circuitry to minimize open circuits and proper mounting instructions to prevent installation related ground faults.**
- ❑ **Module manufacturers must control the raw materials and processes to ensure that that every module is built like those qualified through the safety tests. This is the reason behind the QA task force effort to develop a "Guideline for PV Module Manufacturing QA".**
- ❑ **Periodic accelerated stress testing of production products is critical to validate the safety of the product.**

SUMMARY {2}

Combining safer PV modules with better systems designs is the ultimate goal.

This should be especially true for PV arrays on buildings.

❑ **Use of lower voltage dc circuits**

- **AC modules**
- **DC-DC converters**

❑ **Use of arc detectors and interrupters to detect arcs and open the circuits to extinguish the arcs.**

Thank you for your attention!

John.Wohlgemuth@nrel.gov

Fire Rating for PV Modules and Roofs

Larry Sherwood
Project Administrator
Solar America Board for Codes and Standards (Solar ABCs)

PV Module Reliability Workshop
February 28, 2012

Contains no confidential information

Solar ABCs

Solar ABCs is a collaborative effort among experts to provide coordinated recommendations to codes and standards making bodies for existing and new solar technologies.

Acknowledgement

This material is based upon work supported by the Department of Energy under Award Number DE-FC36-07GO17034.

Roof Fire Class Rating

- International Building Code requires that roofs have a fire classification rating (Class A, Class B, Class C)
- Different buildings have different fire classification rating requirements
- States or local jurisdictions may enforce stricter requirements than the IBC

Roof Fire Class Rating

- Roof fire classification rating determined by UL 790 or ASTM E108
  - Spread of Flame Test
  - Burning Brand Test
  - Intermittent Flame Test

Code Requirements are Different For:

BIPV

Rack Mounted

Building-Integrated PV

Must be tested and classified as a roof covering (using methods in UL 790 or ASTM E108)

Rack-Mounted PV

Currently, the PV module receives a fire classification rating during UL 1703 testing (utilizing a subset of the methods used in UL 790)

Issue

What is the impact of a PV array on the fire classification of a rated roof?

Solar ABCs Research Project

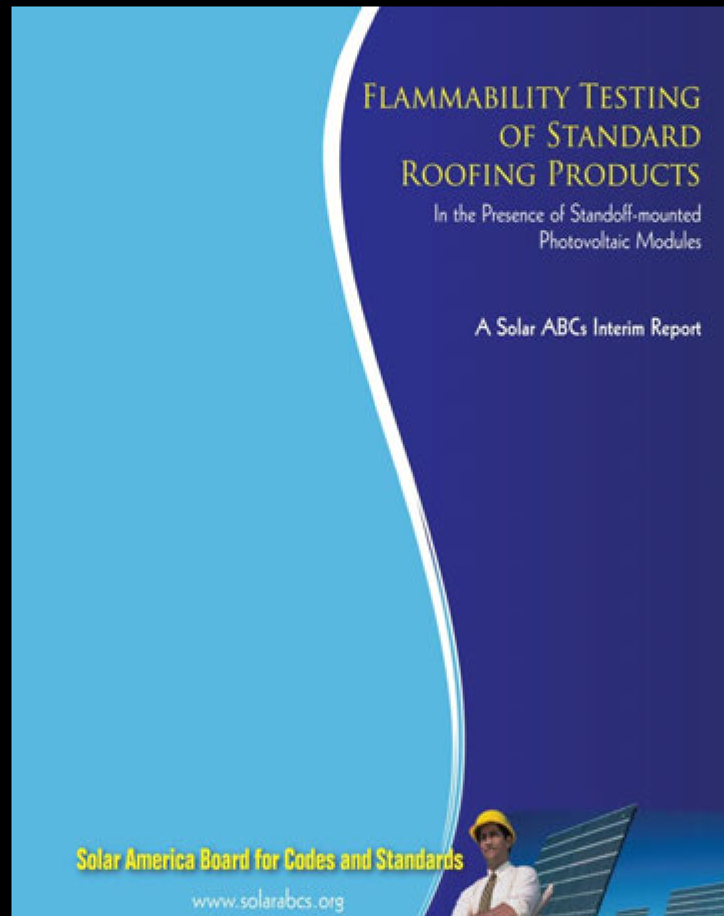
Investigate whether and how the presence of standoff-mounted PV arrays may affect the fire class rating of common roof covering materials.

Solar America Board for Codes and Standards

Results

The fire classification rating of the PV module is NOT a good predictor of the fire class rating of the PV module and roof as a system.

Summary and Results to date



Solar America Board for Codes and Standards

Current Work

- UL 1703 Standards Technical Panel is developing a system fire classification rating to replace the current module fire classification rating.

Current Tests

- UL is presently conducting tests to determine values for the heat release rates and critical flux for ignition for representative PV modules, roof coverings, and other components.
- Base on these results, UL will determine the final values for all test parameters needed to conduct the new PV system fire classification rating test

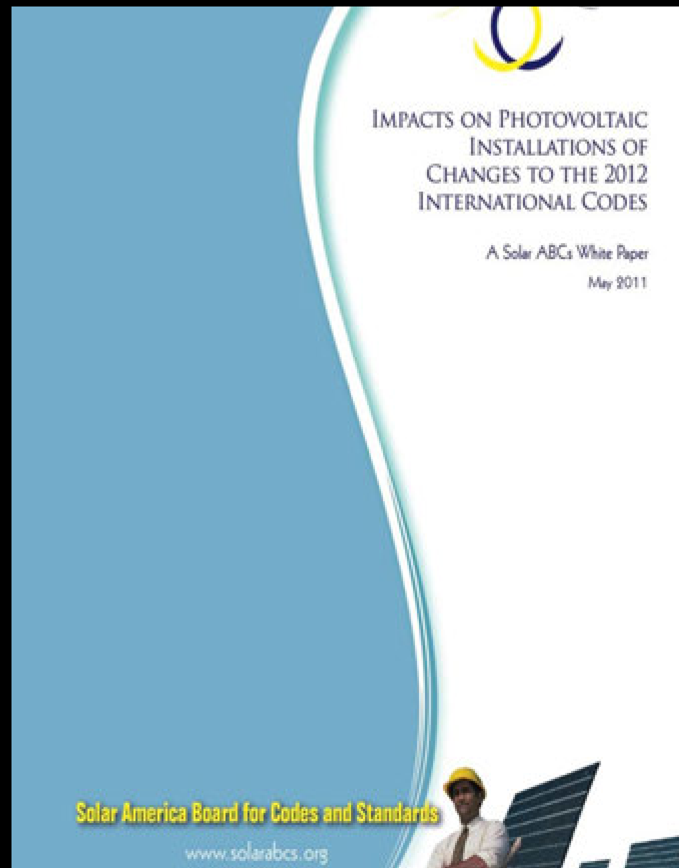
Overview of the New System Fire Classification Test

- Test is based on spread of flame and burning brand results for the module, rack and roof as a system
- Allows for substitution of similar module and roof covering materials
- Class A Rating will likely require barrier or baffle to prevent flame spread under the array
- New PV System test is a significant change from the module-only test currently in UL 1703

2012 International Building Code

- New language requires that fire classification of PV systems match the minimum fire classification of the roof assembly over which they are mounted.
- Straightforward implementation of this requirement is not possible at present.

2012 International Building Code


Impacts on Photovoltaic Installations of Changes to the 2012 International Codes

A Solar ABCs White Paper

May 2011

Solar America Board for Codes and Standards

www.solarabcs.org

2015 International Building Code

- Proposals due earlier in January

- Hearings in Dallas, April 29 – May 5

2015 International Building Code Proposals

- Rooftop mounted photovoltaic panel systems shall be listed and labeled in accordance with UL 1703 for fire classification.
- The minimum photovoltaic panel system fire classification listing shall be as required by the code.

2015 International Building Code Proposals

- Exceptions Proposed:
  - Direct contact with roof surface
  - At least 12 inches above the roof surface
  - Steel or equivalent barrier around the array

Current Tests

- Validate proposed exceptions

Updates on Results from New Fire Rating Research

http://www.solarabcs.org/current-issues/fire_class_rating.html

www.solarabcs.org

- Current Issues
- Fire and Flammability
- Fire Class Rating of PV Systems

For more information

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Module Lifetime Prediction through Integrated Modeling of Known Failure Modes

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This presentation contains no confidential information

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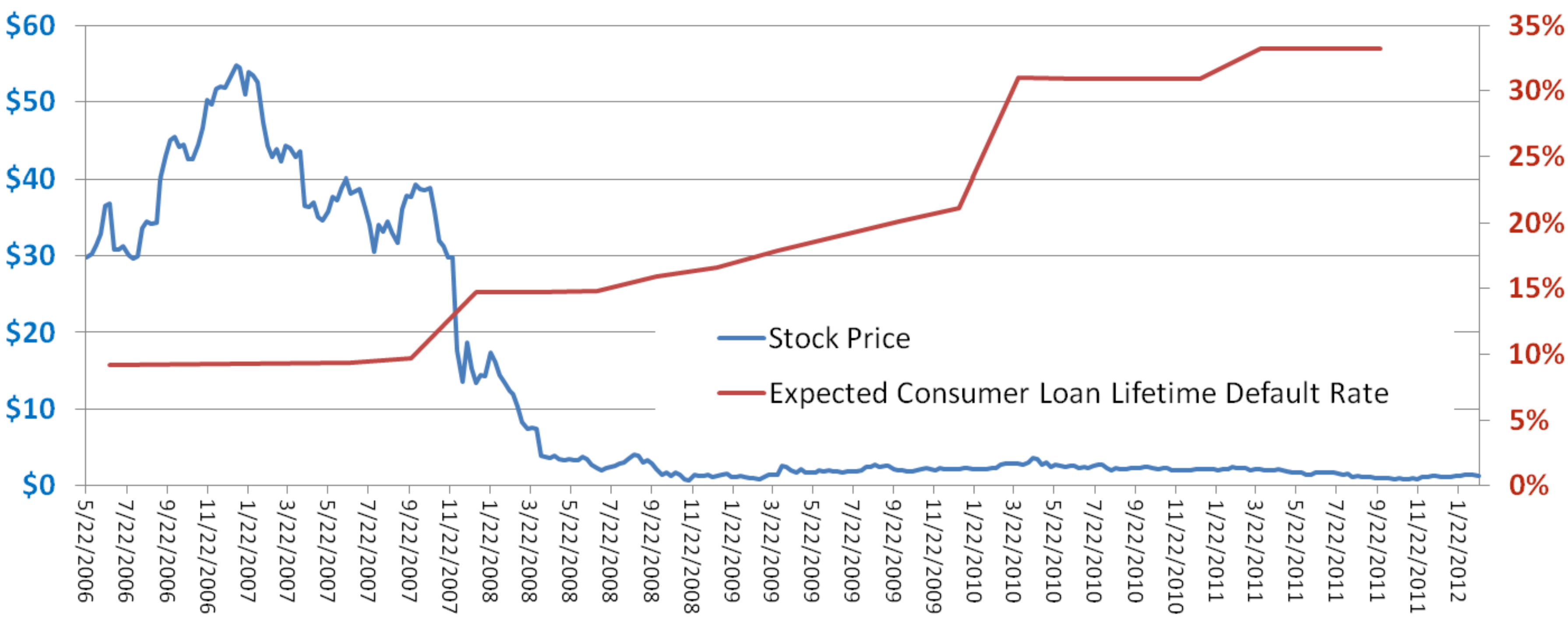
Motivation: analogy from the financial industry

- NYSE-traded **consumer loan** (not PV!) company, >$3B market cap at peak
- Balance sheet impact if defaults exceed expectations or default expectation increases
- Company used empirical data to infer future default behavior … not a behavioral model



What can PV companies do to be vigilant against "black swans"?

- Quality and Reliability Processes[1]
  - Reliability:
    - Failure Mode and Effects Analysis, Quality & Reliability Test Plans during product design / process development
  - Manufacturing Quality
    - Supplier quality control: Change notification, PSC (Prevention, Standardization/Simplification/Scalability, and Customer satisfaction) audits, STARS (Supplier Total Achievement Rating System) score
    - Statistical Process Control, Out-of-box audit, Reliability Monitoring Program
- Research into potential failure and degradation modes
  - Failure analysis on fielded modules to seek new possible modes
  - Physics of failure research into individual modes
  - Evaluate expected failure & degradation budgets/timing via physics-based modeling

[1] DeGraaff, "Case study: SunPower Manufacturing Quality Methods", NREL 2010 PVMRW; DeGraaff et al, "Qualification, manufacturing and reliability testing methodologies for deploying high-reliability solar modules", PVSEC Valencia, Spain, 2010.

PVLife

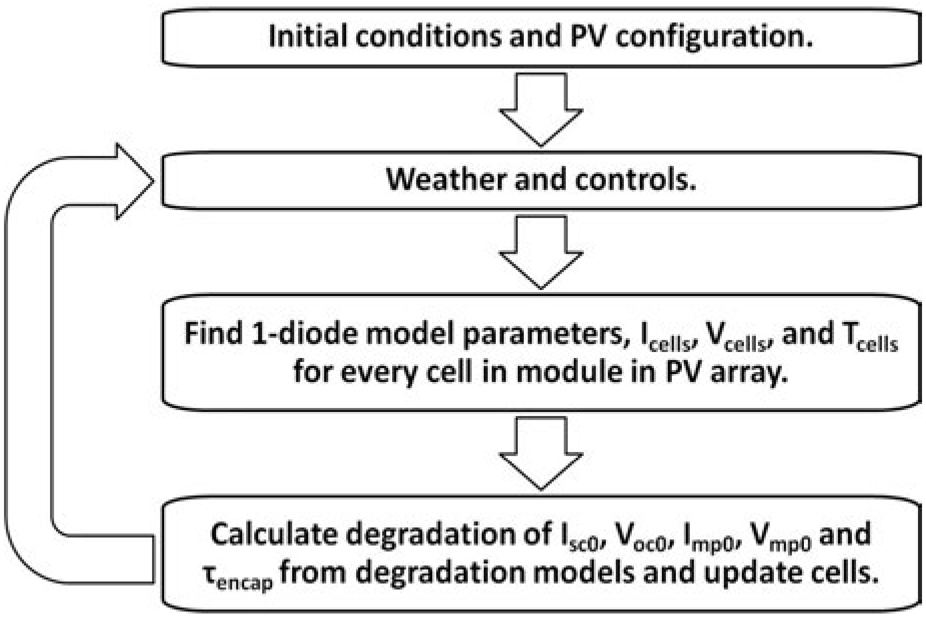
PVLife is:

- A behavioral model for PV modules, strings, eventually systems
- Attempts to capture as many known drivers as possible
- Includes key physics and chemistry models
  - Electrical/thermal behavior affects degradation and failure rates
  - Degradation affects electrical/thermal behavior

Why are we investing in this?

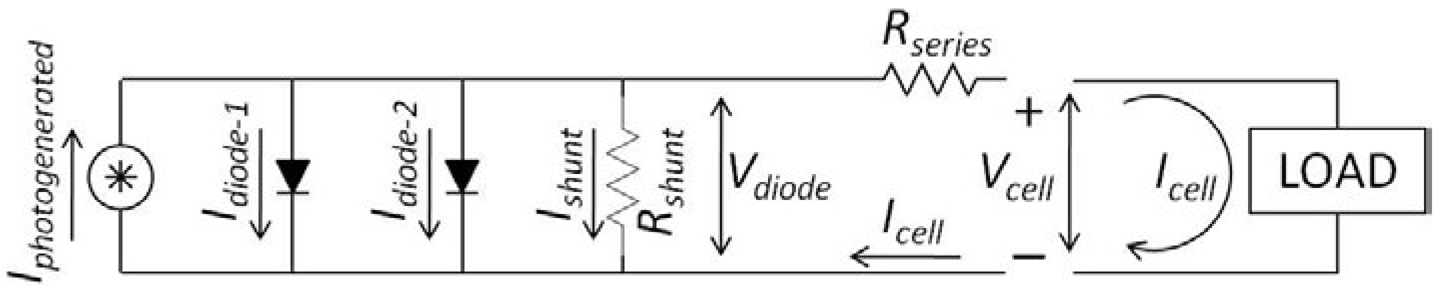
- Reduce uncertainties in our expectations, catch issues early
- Understand possible positive (bad) feedback loops that simple models cannot capture
- Rationalize and improve designs
- Quantify warranty expectations, degradation budget

Using array configuration & weather data, model computes performance for all cells in PV system



Electrical and thermal submodels

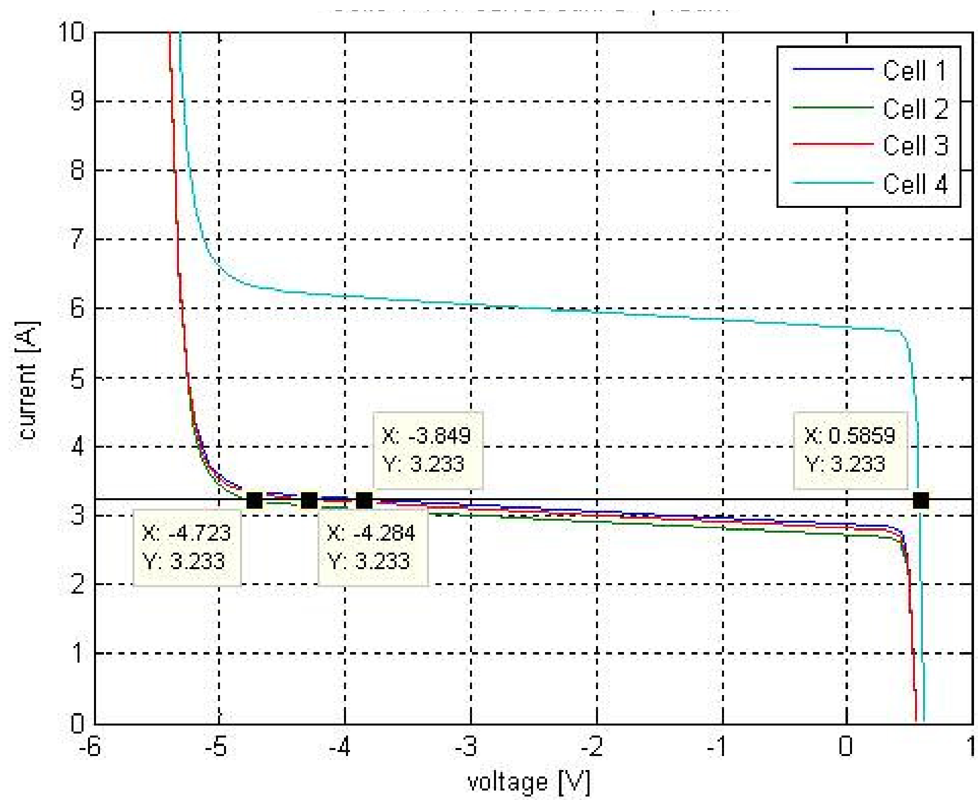
- 1- or 2-diode electrical model for each cell



- Thermal model for each cell
  – Resistance analogy w/quasi-steady state assumption
- Quasi-steady state assumptions
  – Electrical and thermal equilibrium established much faster than any form of degradation

Electrical characteristics obtained from data

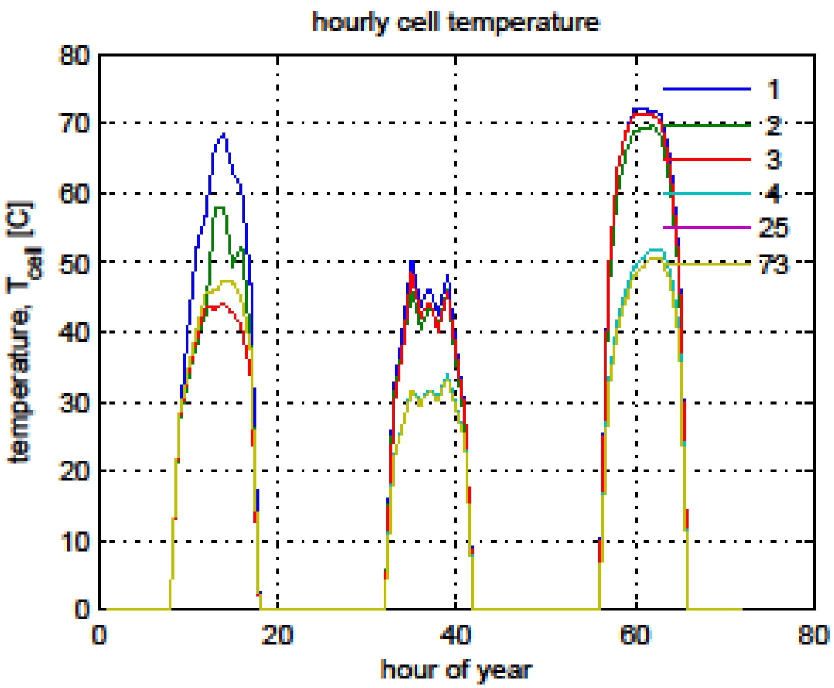
- I-V curves for cells obtained from real production data
  - Statistical or specific cases
- Sandia database for temperature coefficients
- Bypass diodes and other components also based on measured electrical characteristics

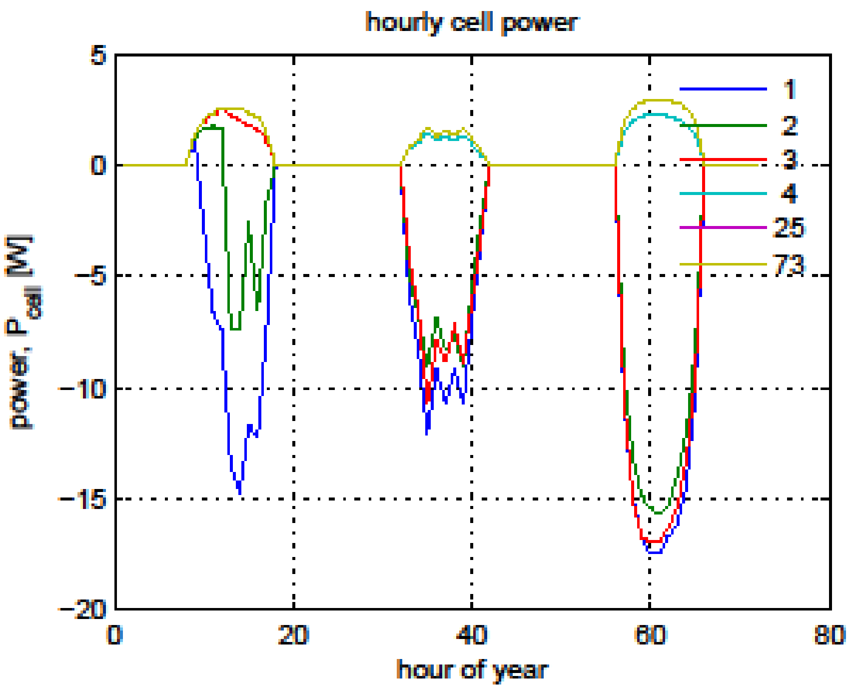


Example: I-V curves for 4 cells in series; Cells 1-3 are shaded

Cell-level model handles mismatch, shading

Example: a 72-cell module with 1st 3 cells progressively shaded, actual weather for Jan. 1-3, 2011



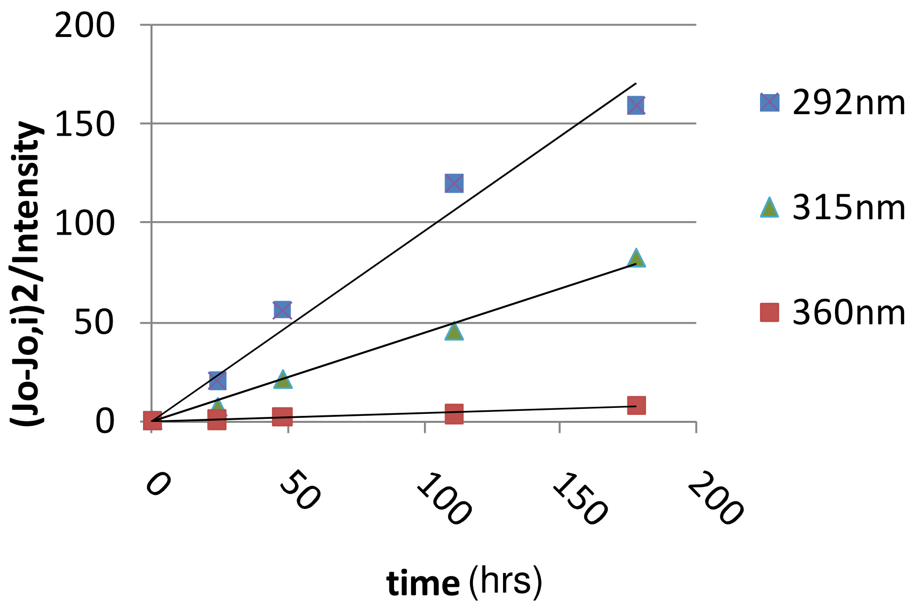


Potential Degradation and Failure Modes for PV Panels

- Continuous degradation modes
  - UV degradation
  - Encapsulant transmission
  - High voltage (potential-induced) degradation / polarization
  - Soiling
  - Reverse-bias cell degradation
  - Humidity-induced cell degradation
  - Cell cracks
  - Metal corrosion
  - Ion migration
- Binary failures
  - Solder joint failure
  - Bypass diode failure
  - Encapsulant adhesion failure
  - Backsheet cracking/delamination

Degradation mode example: UV degradation

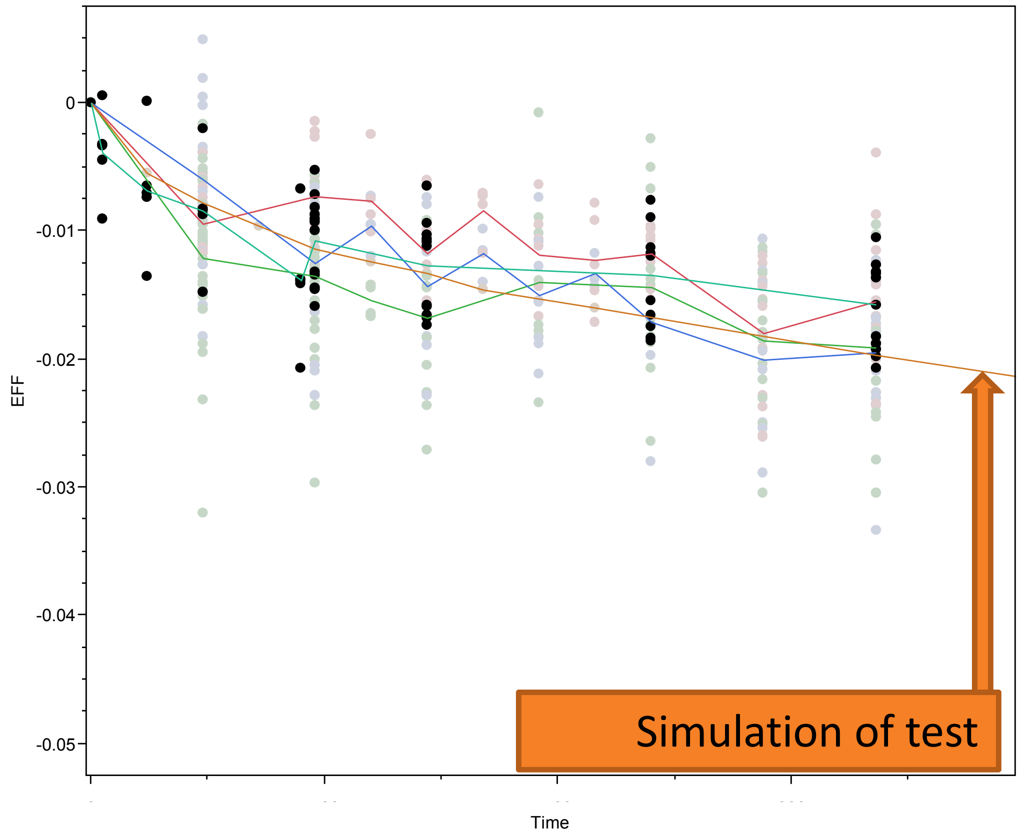
- Silicon subject to slight UV surface damage over time
  - Effect on recombination current, J_o
  - Initial rate consistent with MOSFET degradation literature
- Extensive modeling and laboratory observations of SunPower cells:
  - Scaling of initial rate
  - Strong wavelength dependence



$$J_0 = J_{0,i} + \sqrt{\int_{250nm}^{400nm} \left(\frac{m \cdot t}{I_{bandpass}} \right) \cdot I(\lambda, t)\, d\lambda}$$

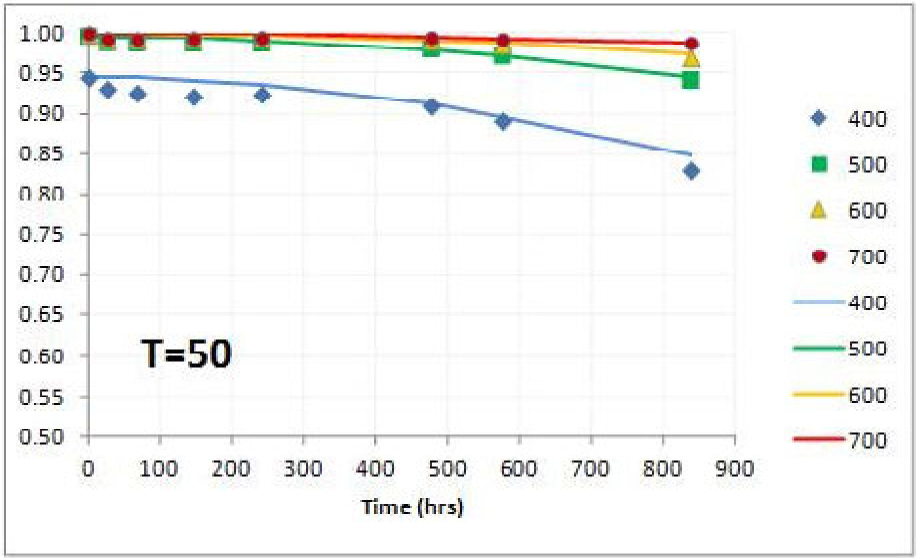
Cell UV degradation integration into PVLife

- Accelerated test data are obtained by exposing cells from multiple production lines to various UV intensities and temperatures
- Differential equations are constructed from fits of a physical or empirical model to lab data.
- Model is backtested by ensuring match to accelerated test data
  - Raw cells and EVA-encapsulated coupons
  - Temperature-dependent data
- Model is then validated against field exposure data

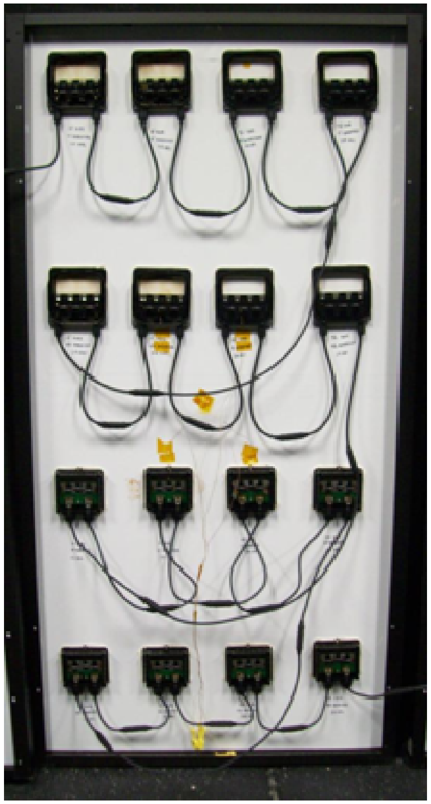


Photothermal Encapsulant Transmission Degradation

- UV & heat causes browning, decreasing transmission
- Approach:
  - Photothermal kinetics model, coupled with Beer's Law for absorption
  - Fit lab data to kinetics model, assess fit and reciprocity
  - Write as differential equations in time for absorber/chromophore concentration
  - Backtest against accelerated data, cored EVA samples from RMA modules

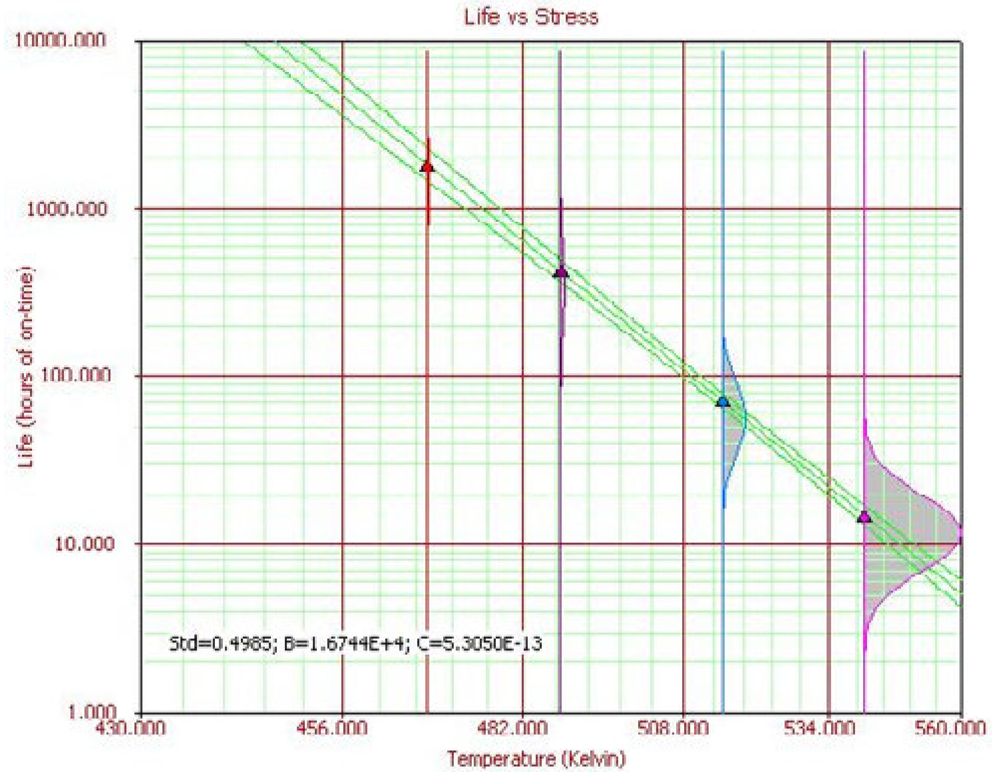


Failure mode example: Bypass diode failure



Dummy module,
DH 85, 6A current

Custom ceramic
diode fixture
Up to 16A current

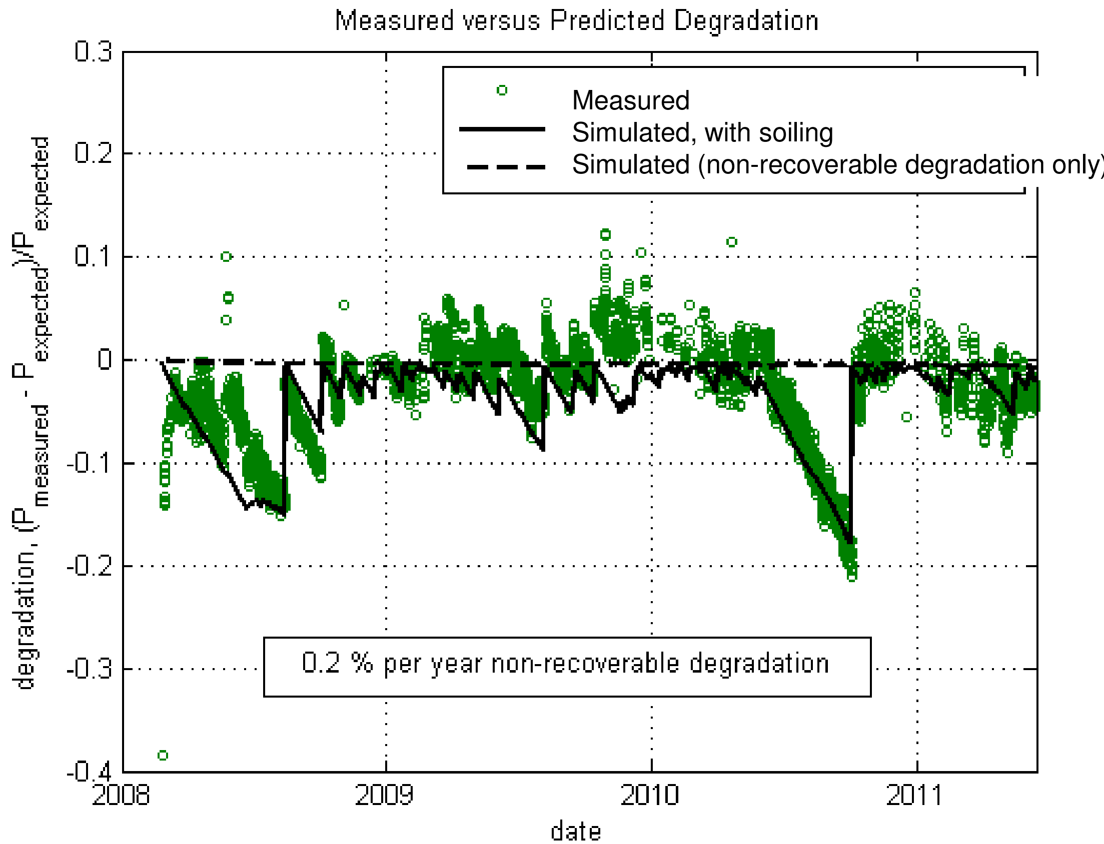


Results: *Lognormal Arrhenius*

Due to low reverse bias voltage, SunPower modules do not require bypass diodes for reliability, but we still care about diode failure to predict performance accurately

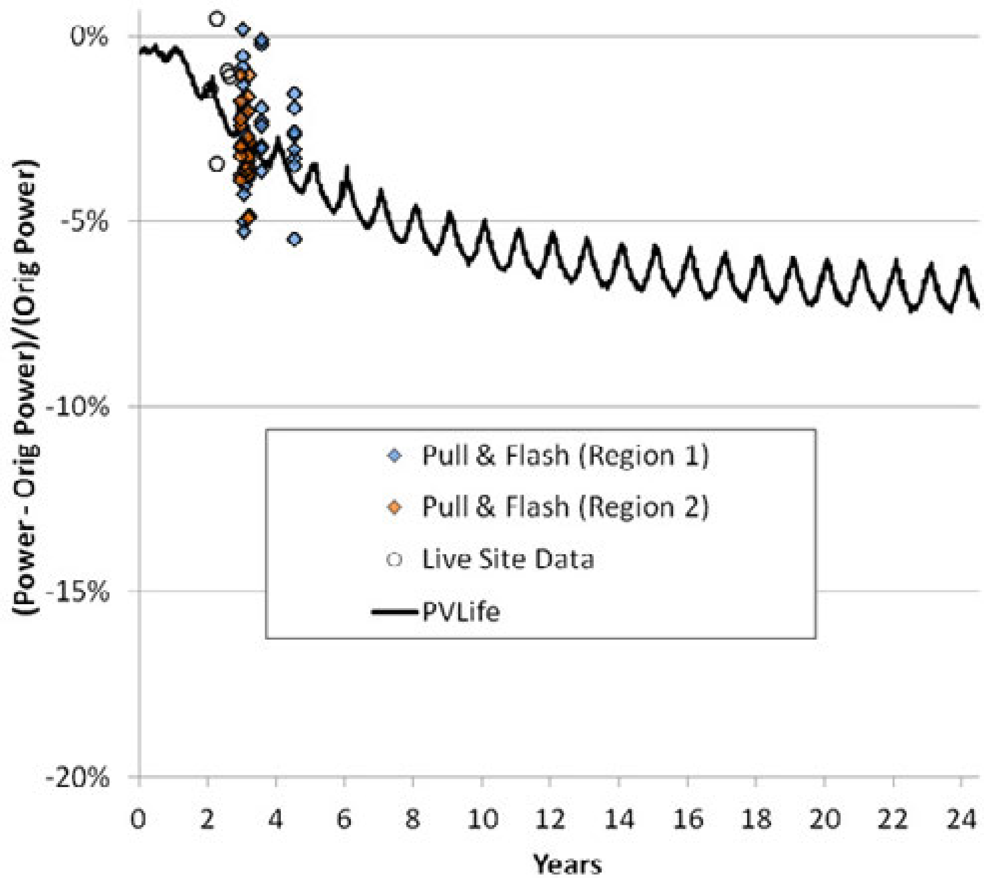
Results: Short-term

- Site in Manteca, CA, USA; rooftop system, SunPower modules. Weather data including rainfall from nearby meteorological stations
- Good agreement overall
- “Sawtooth” waveform due to soiling (and recovery with rainfall/washes) dominates, but is recoverable
- Simulation predicts initial NON-recoverable degradation = -0.2%/yr



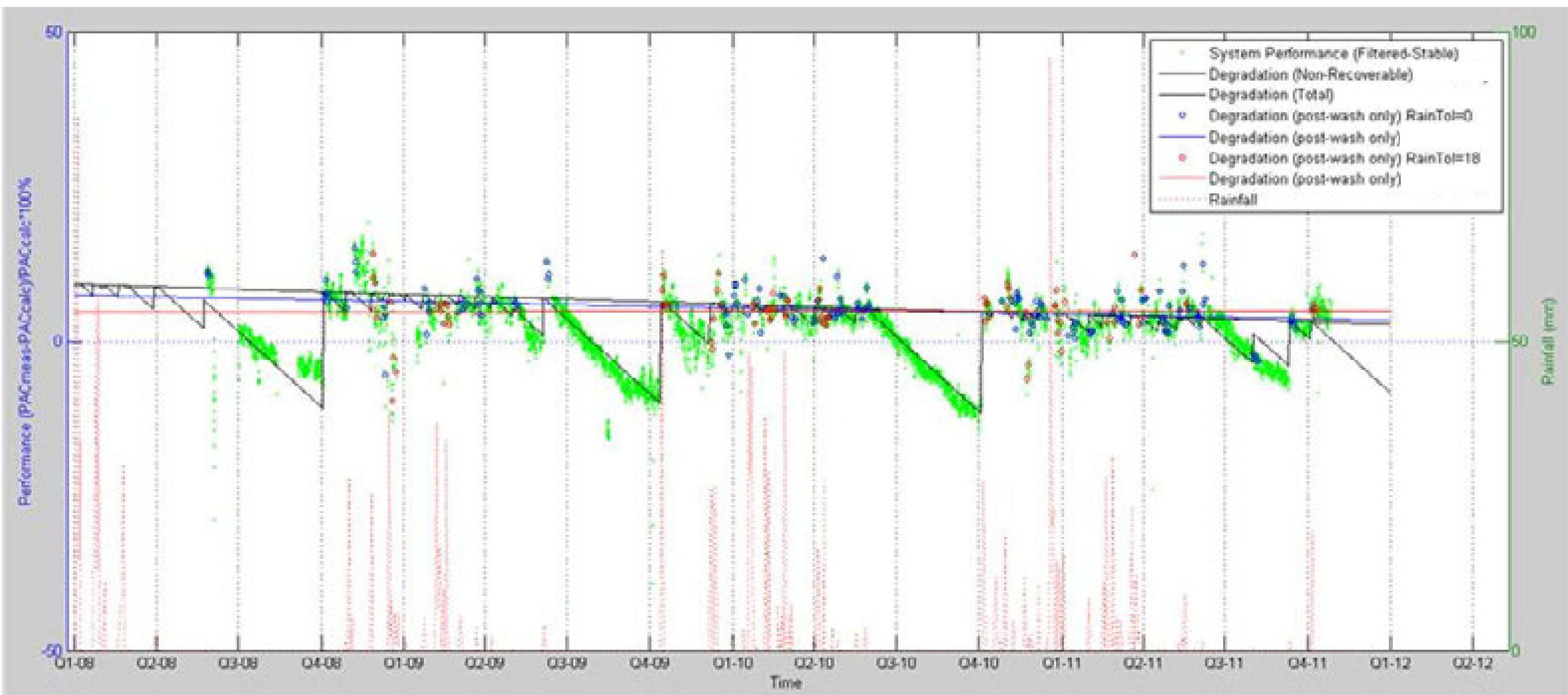
Results: Long-term simulations compared with field data

- Model within scatter; live-site data has significant uncertainty
- Data based on
  - Live site AC production data
  - Modules pulled from residential rooftops and re-flashed after time in the field.
- Prediction is well above SunPower warranty line
  - Rationalizes low RMA rates to date



Uncertainty in assessing degradation from site monitoring data can be substantial

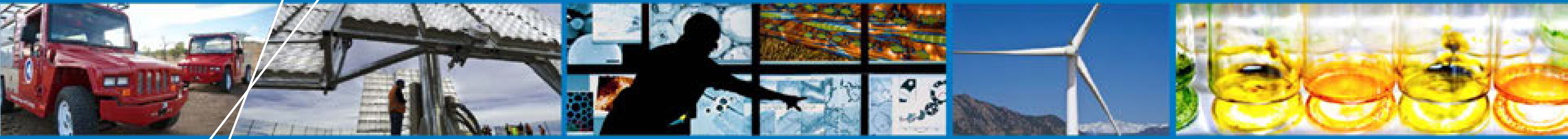
- Normalize actual output by model's expected (Similar approach to Jordan, Kurtz et al)
- Filter data to only look at clear, stable-irradiance days
- Two approaches to deal with soiling:
  - Filter data by post-rainfall (or wash) only … within *x* days of *y* mm of rainfall
  - Fit data using model with additional free parameters to account for soiling effects
- Results ±0.8% … prompting us to confirm with Pull/Flash program



Conclusions

- Physical model based on extensive lab and field research suggests low (and slowing) degradation of SunPower modules
- Creating this type of model requires a major investment …
  - Substantial investment in experimentation
  - Tens to hundreds of experiments per mode
  - Long timescales for experimentation
- … but it also yields major dividends
  - Major degradation modes are captured
  - We can observe coupling and non-linear effects
  - Able to prevent problems in the design phase, before they reach customers
  - High confidence warranty

Modeling Metal Fatigue As a Key Step in PV Module Life Time Prediction



NREL PVMRW

Nick Bosco

February 28 2012

NREL/PR-5200-54565

outline

- **Modeling metal fatigue**
  - Time independent (case studies):
    - Ribbon fatigue: wind loading
    - Ribbon fatigue: thermal loading
  - Time dependent, solder fatigue

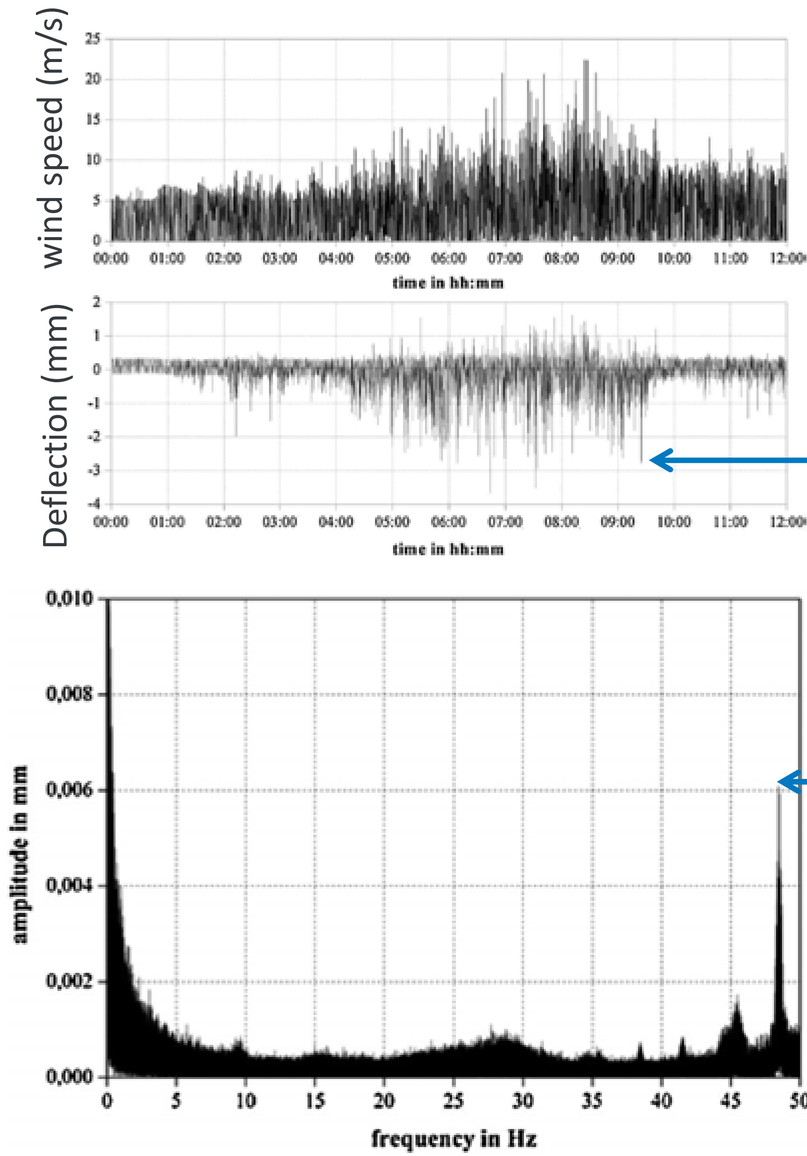
ribbon fatigue: wind loading

<table>
<tr><th>Mode</th><th>Mechanism</th><th>Driving Force</th></tr>
<tr><td rowspan="3">solder bond cracking</td><td rowspan="2">mechanical fatigue</td><td>wind</td></tr>
<tr><td>transportation</td></tr>
<tr><td rowspan="2">thermal fatigue</td><td rowspan="2">weather</td></tr>
<tr><td>ribbon cracking</td></tr>
</table>

← prediction

ribbon fatigue: wind loading

driving force



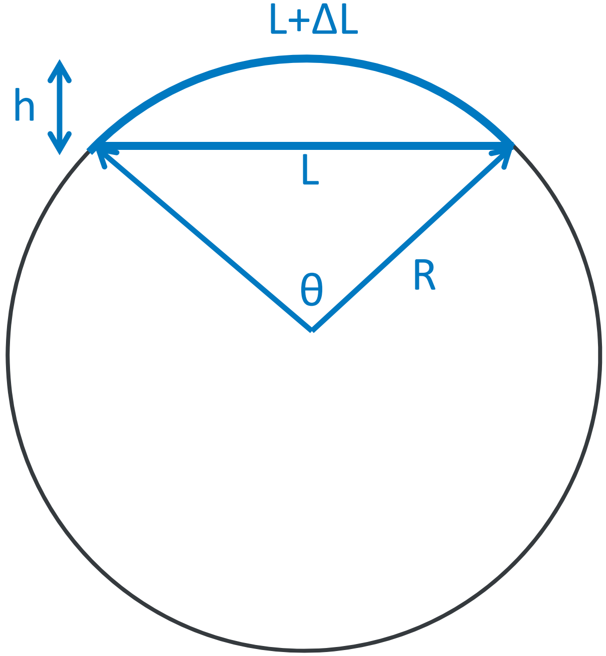
low freq:
3mm
200/day

high freq:
6 µm
50 Hz

Assmus, M., S. Jack, et al. (2011). "Measurement and simulation of vibrations of PV-modules induced by dynamic mechanical loads." Progress in Photovoltaics: Research and Applications **19**(6): 688-694.

ribbon fatigue: wind loading

driving force



$$R = \frac{h}{2} + \frac{L^2}{8h} = \frac{L}{2\sin\left(\frac{\theta}{2}\right)}$$

$$L + \Delta L = R\theta$$

$$\varepsilon = \frac{\Delta L}{L}$$

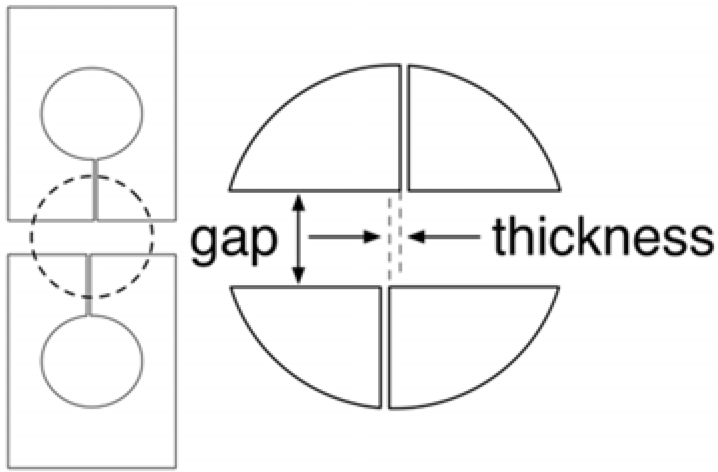
Assumptions:

- Pinned connections
- Semicircular bending
- Glass-Glass module
- No shear lag
- *1620*x810 mm

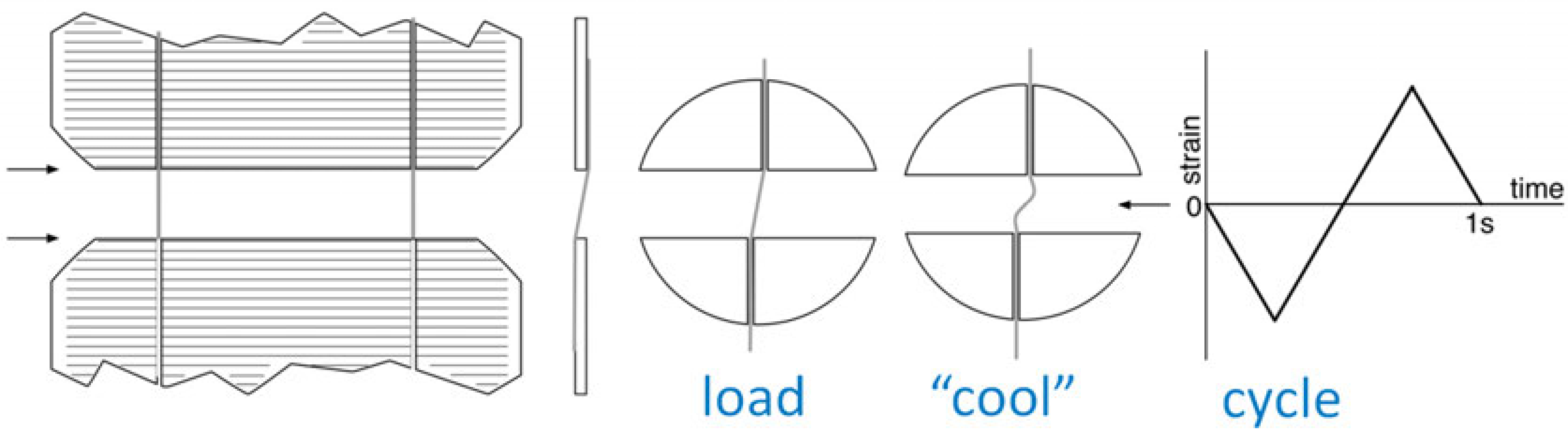
low freq:	3 mm =	0.00107 %
high freq:	6 µm =	4.27e-9 %

ribbon fatigue: wind loading

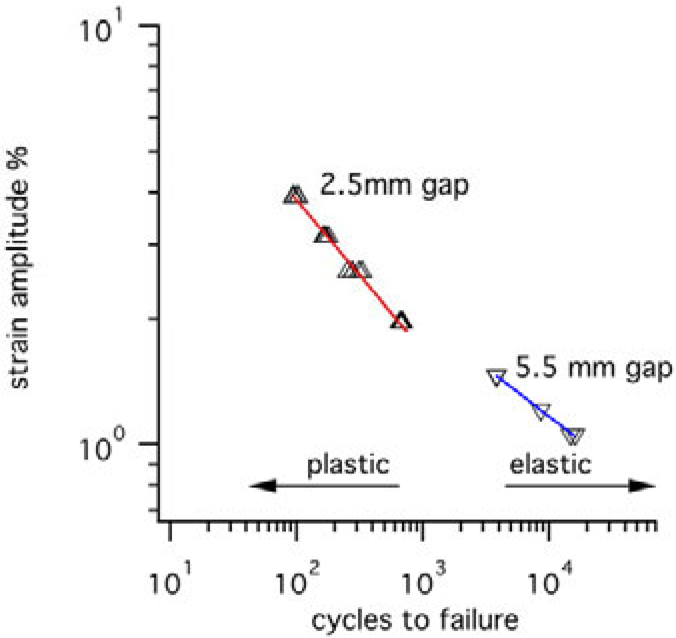
mechanism: fatigue experiment

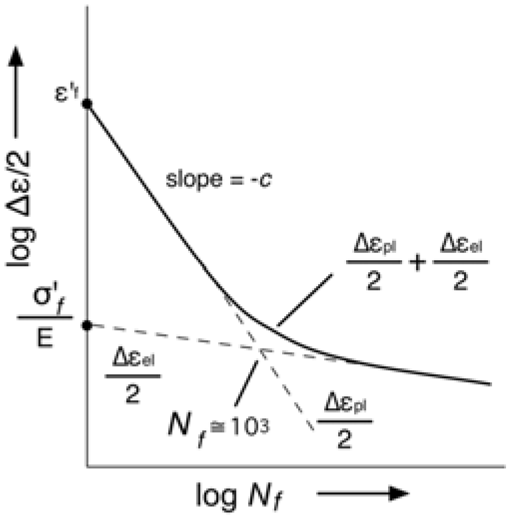


Grips fabricated to simulate ribbon attachment



ribbon fatigue: wind loading mode

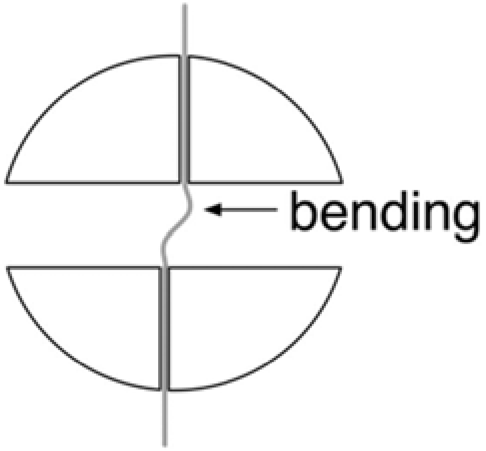




$$\frac{\Delta\varepsilon_{pl}}{2} = \varepsilon'_f \left(2N_f\right)^{-c}$$

$$\frac{\Delta\varepsilon_{el}}{2} = \frac{\sigma'_f}{E}\left(2N_f\right)^{-b}$$

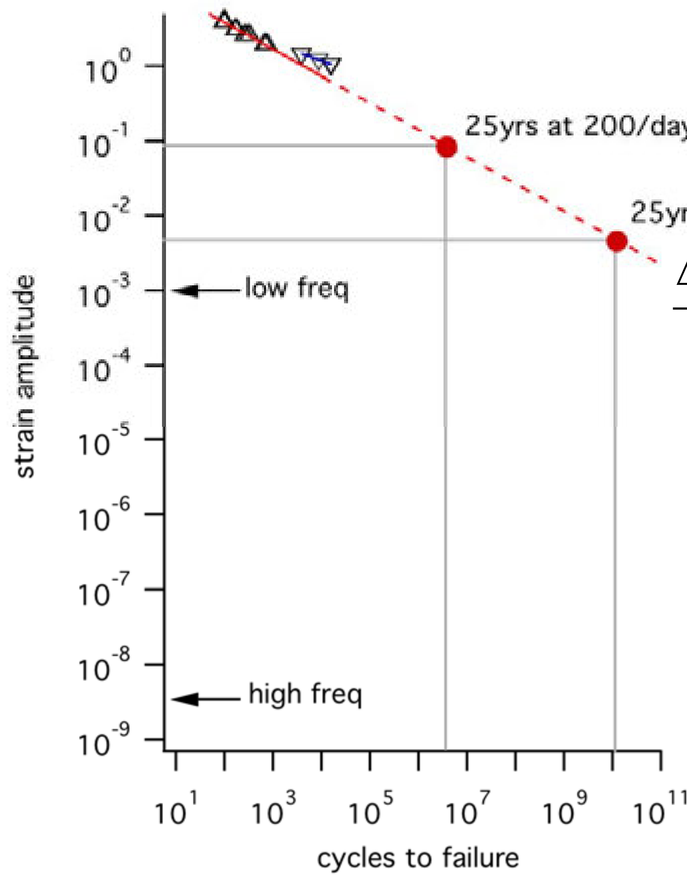
a longitudinal strain is imposed, but the ribbon is straining in bending



strain amplitudes evaluated likely have a large plastic component

ribbon fatigue: wind loading mode

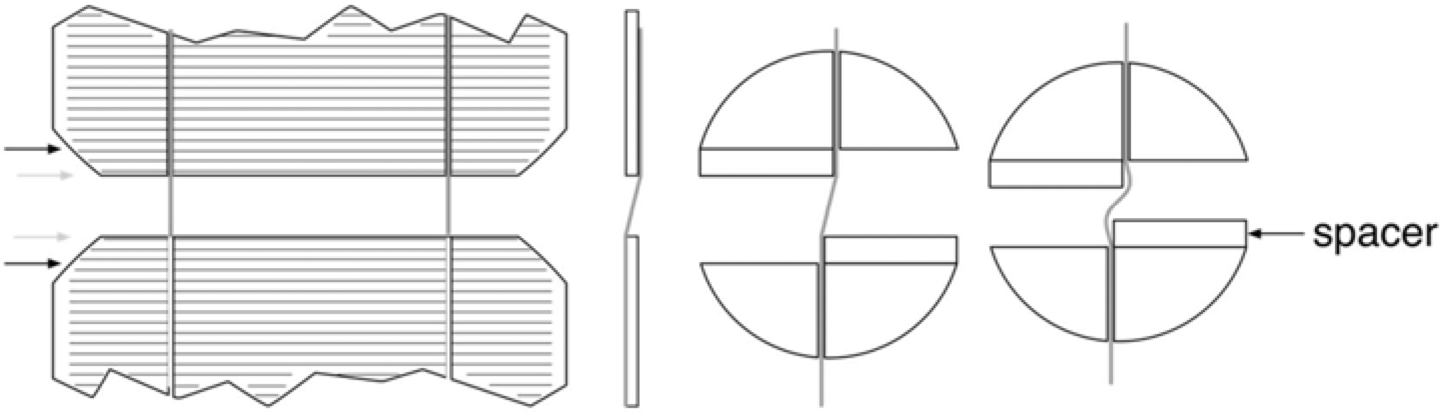
vibration due to wind loading will not result in ribbon fatigue within a module's lifetime.



$$\frac{\Delta \varepsilon_{pl}}{2} = \varepsilon'_f \left(2N_f\right)^{-c}$$

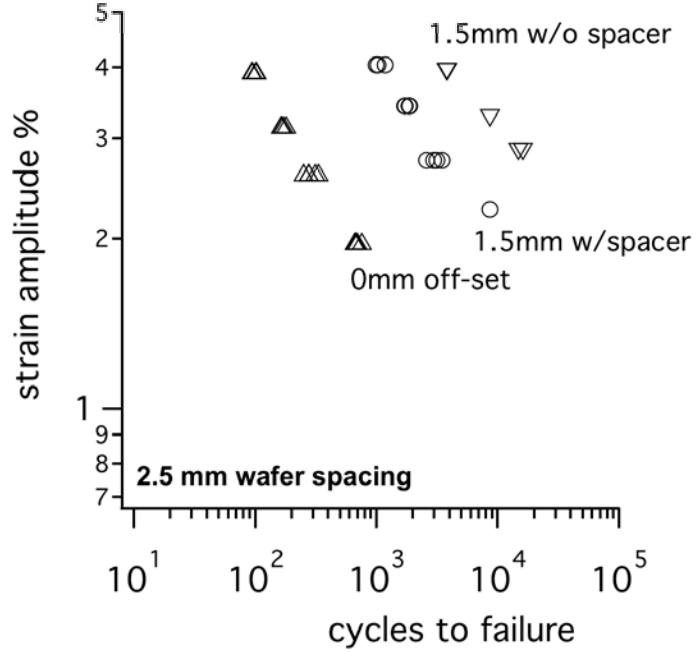
ribbon fatigue

fatigue experiment: off-set



incorporating an un-soldered length provides strain relief and longer lifetimes

ribbon constraint is a significant factor for these measurements



ribbon fatigue: thermal loading

Mode	Mechanism	Driving Force
solder bond cracking	mechanical fatigue	wind
		transportation
ribbon cracking	thermal fatigue	weather

← prediction

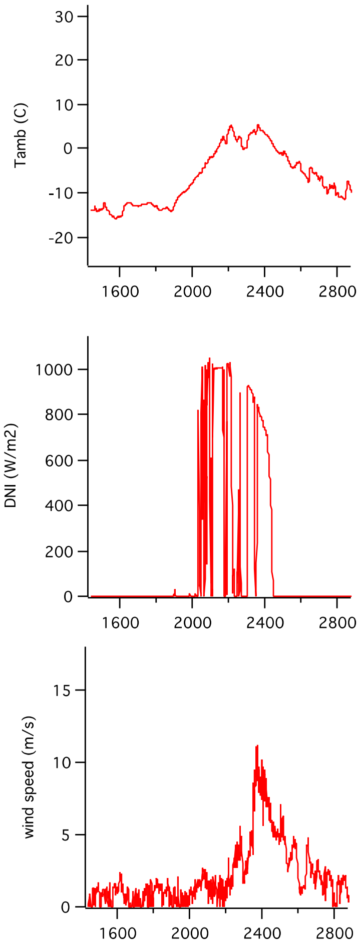
ribbon fatigue: thermal loading

Mode	Mechanism	Driving Force
solder bond cracking	mechanical fatigue	wind
		transportation
	thermal fatigue	weather
ribbon cracking		

← prediction

ribbon fatigue: thermal loading

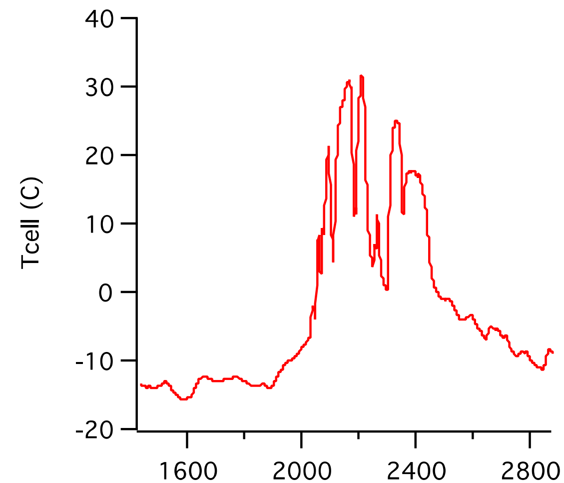
driving force



cell temperature is evaluated in one-minute intervals

$$T_{cell} = T_{amb} + E\exp\left(a + b\cdot WS\right) + E\frac{\Delta T}{1000}$$

$$T_{cell}\left(t+1\right) = T_{cell}\left(t\right)\alpha + T_{cell}\left(t+1\right)\left(1-\alpha\right)$$

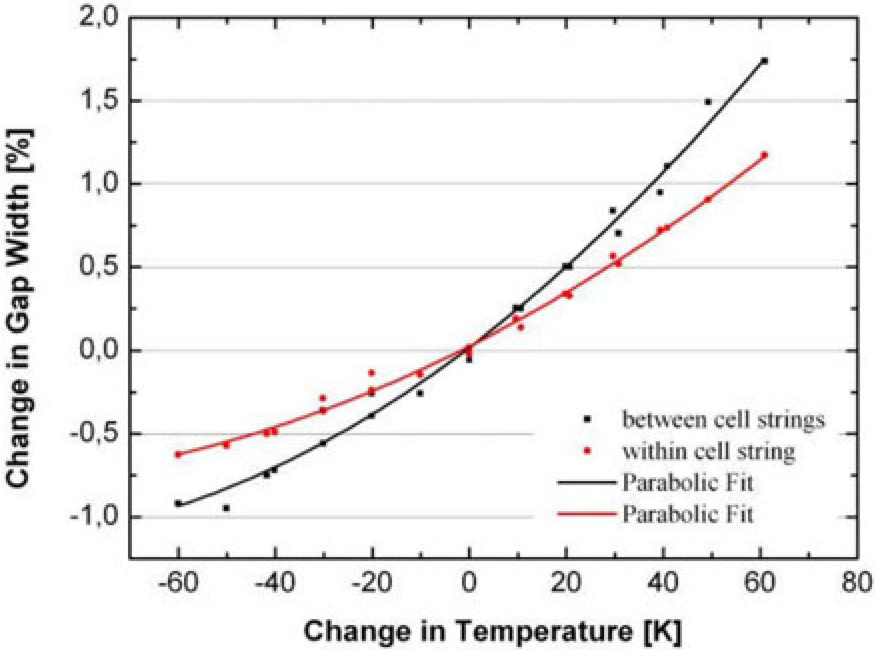


ribbon fatigue: thermal cycling

driving force

empirical relationship between temperature change and ribbon strain

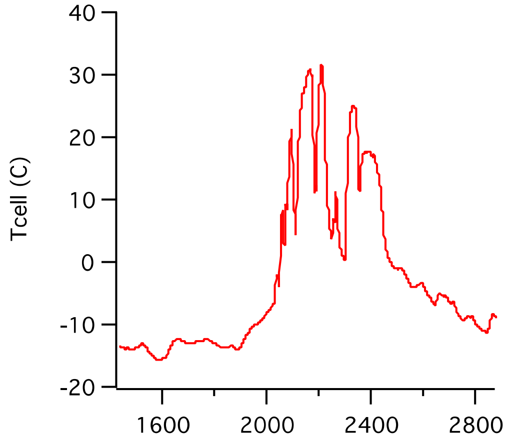
$$\Delta\varepsilon = A_1 + B_1\Delta T + B_2\Delta T^2$$



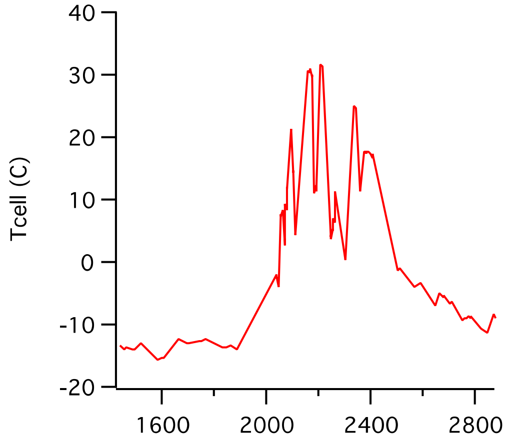
Meier, R., F. Kraemer, et al. (2010). Reliability of copper-ribbons in photovoltaic modules under thermo-mechanical loading. Photovoltaic Specialists Conference (PVSC), 2010 35th IEEE.

ribbon fatigue: thermal loading mechanism

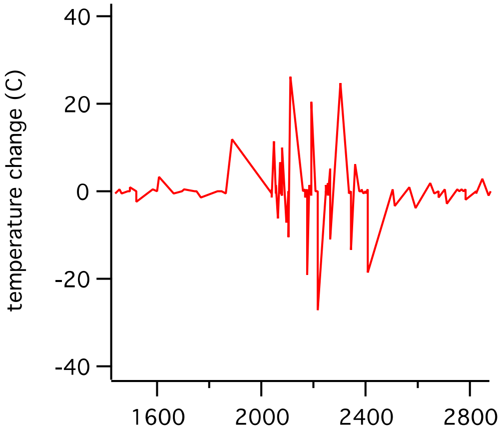
temperature history



identify peaks



extract ΔT



calculate strain

$$\Delta\varepsilon = A_1 + B_1\Delta T + B_2\Delta T^2$$

calculate cycles to failure

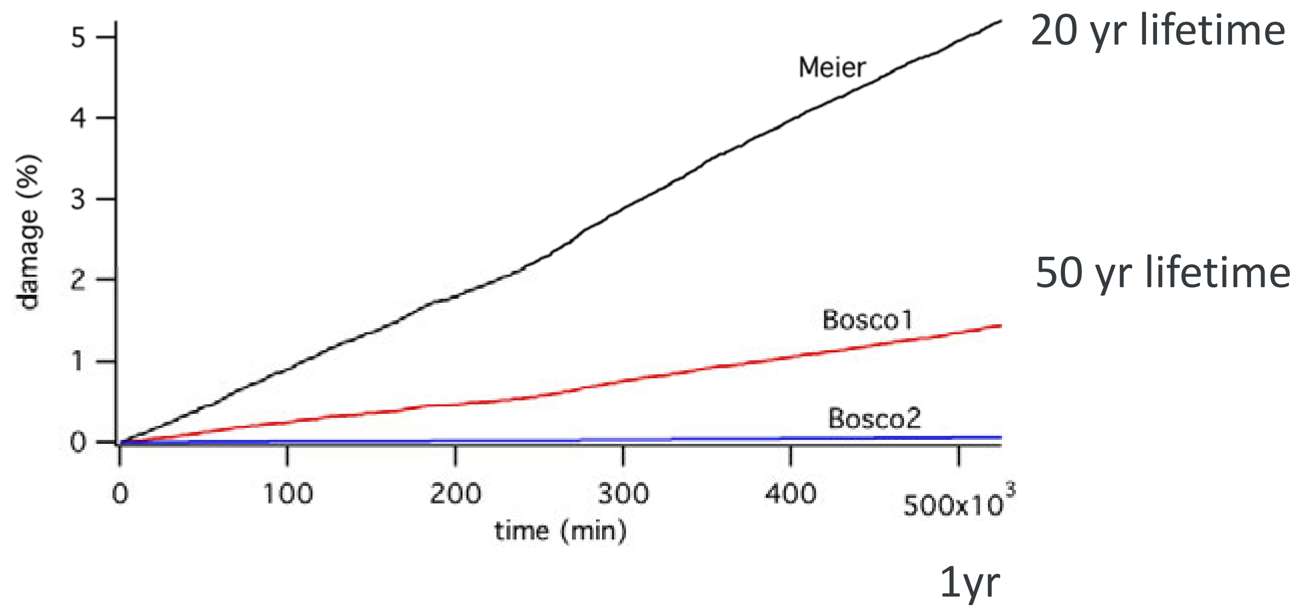
$$N_f = \left(\frac{\Delta\varepsilon}{a}\right)^{-1/c}$$

convert to damage

$$D = \sum_i^n \frac{1}{N_{f,i}}$$

ribbon fatigue: thermal loading mode

100% = failure

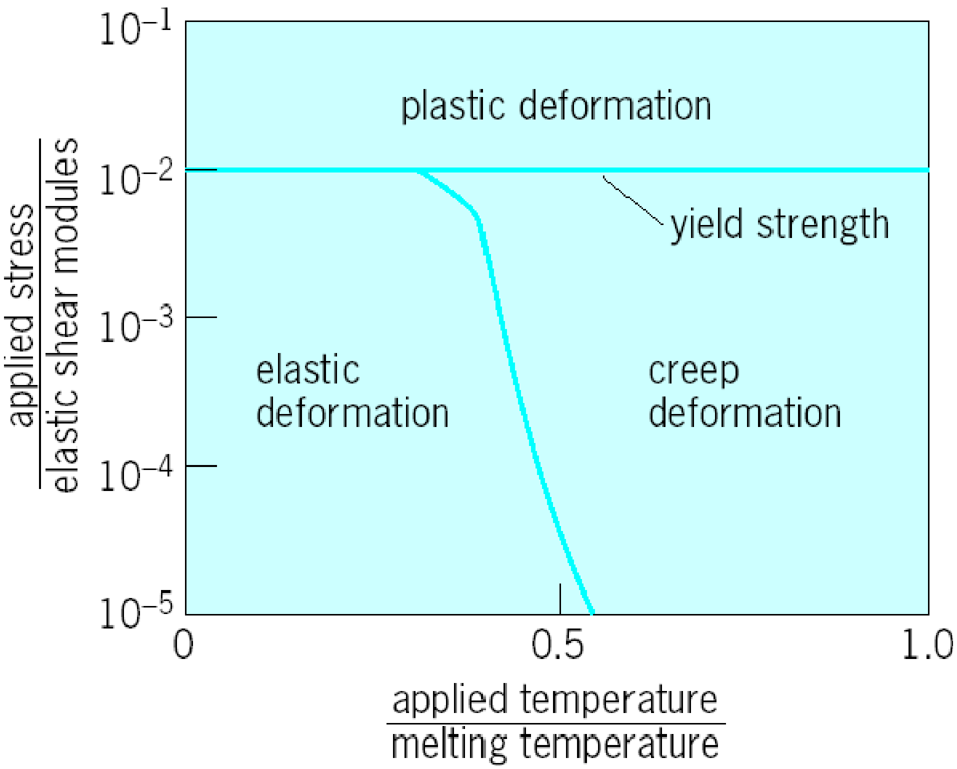


ribbon fatigue due to thermal loading may cause failure within a module’s lifetime.

leaving an unsoldered length will extend the ribbon’s lifetime.

<table>
<tr><th>Mode</th><th>Mechanism</th><th>Driving Force</th></tr>
<tr><td rowspan="3">solder bond cracking</td><td rowspan="2">mechanical fatigue</td><td>wind</td></tr>
<tr><td>transportation</td></tr>
<tr><td rowspan="2">thermal fatigue</td><td rowspan="2">weather</td></tr>
<tr><td>ribbon cracking</td></tr>
</table>

creep-fatigue



Deformation mechanism map. (After M. F. Ashby and D. R. H. Jones, Engineering Materials I: An Introduction to Their Properties and Applications, 2d ed., Butterworth- Heimann, 1996)

Time independent

$$\frac{\Delta\varepsilon_{pl}}{2} = \varepsilon'_f \left(2N_f\right)^{-c}$$

Time dependent

$$\frac{d\varepsilon_p}{dt} = A\exp\left(-\frac{Q}{RT}\right)\left[\sinh \xi \frac{\sigma^*}{s^*}\right]^{1/m}$$

$$\sigma^* = \frac{s_h}{\xi}\left(\frac{d\varepsilon_p}{Adt}\exp\left(\frac{Q}{RT}\right)\right)^n \sinh^{-1}\left[\left(\frac{d\varepsilon_p}{Adt}\exp\left(\frac{Q}{RT}\right)\right)^m\right]$$

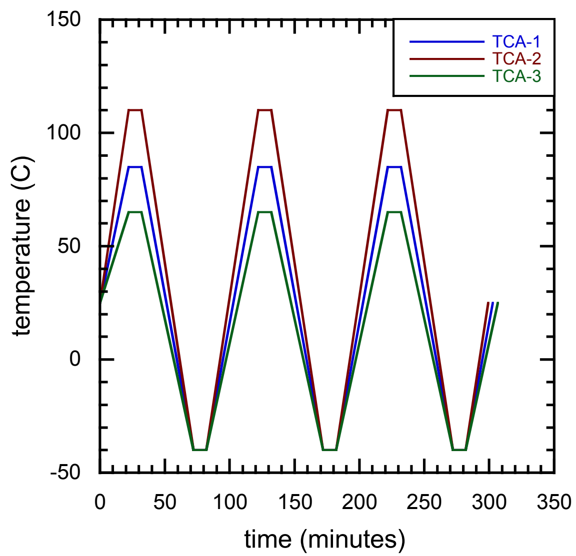
$$s^* = \hat{s}\left[\frac{\dot{\varepsilon}_{pl,eq}}{A}\exp\left(\frac{Q}{RT}\right)\right]^n$$

$$D \approx W_{pl} = \int |\sigma| d\varepsilon_{pl}$$

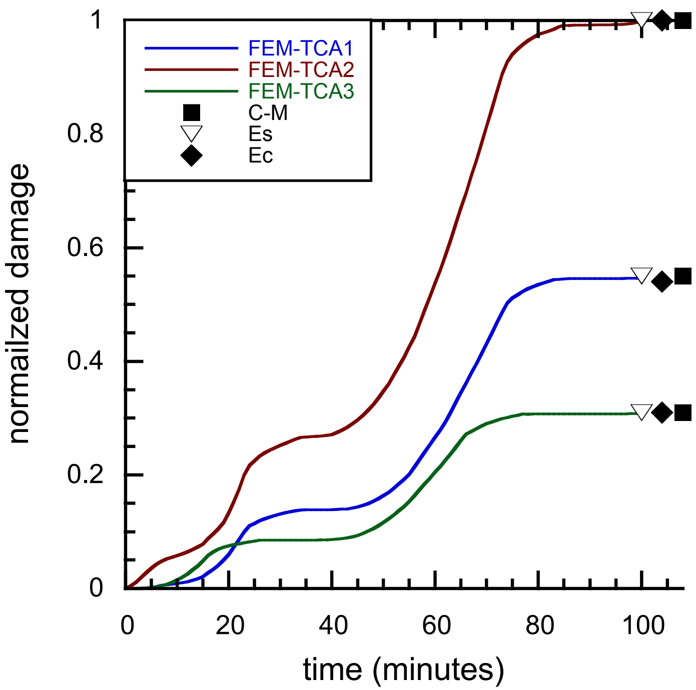
simulations and analysis

simulation

	TCA-1	TCA-2	TCA-3
T_{max} C	85	110	65
T_{min} C	-40	-40	-40
t_c (min)	100	100	100
t_d (min)	10	10	10



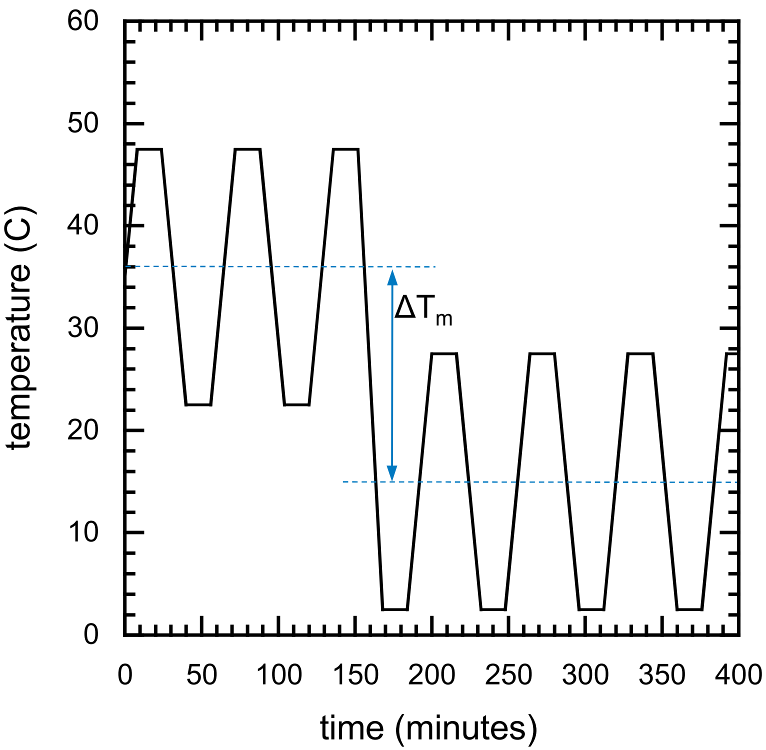
results FEM : empirical relationships



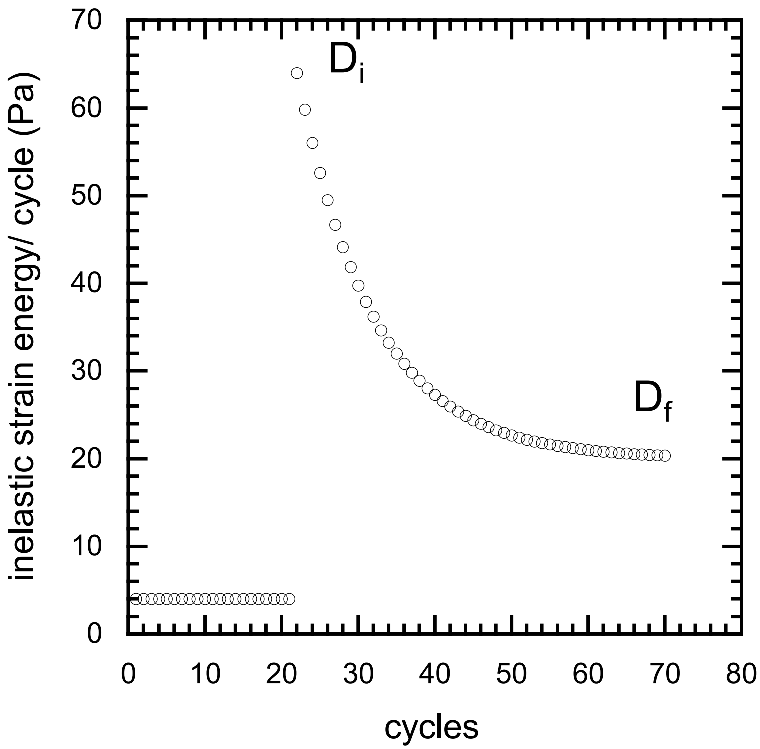
Empirical relationships may be effective for relating the damage done by various ALT

simulations and analysis

simulation

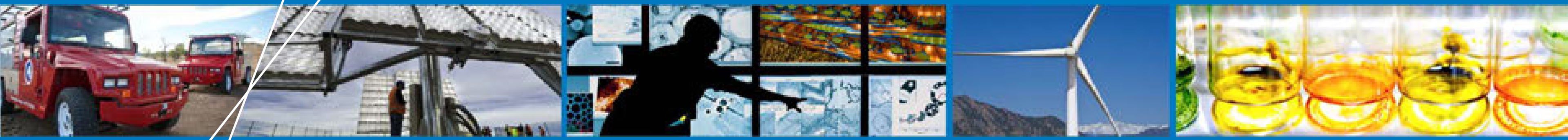


results



FEM is required to simulate temperature changes due to weather

Comparison of accelerated testing with modeling to predict lifetime of CPV solder layers



2012 PV Module Reliability Workshop

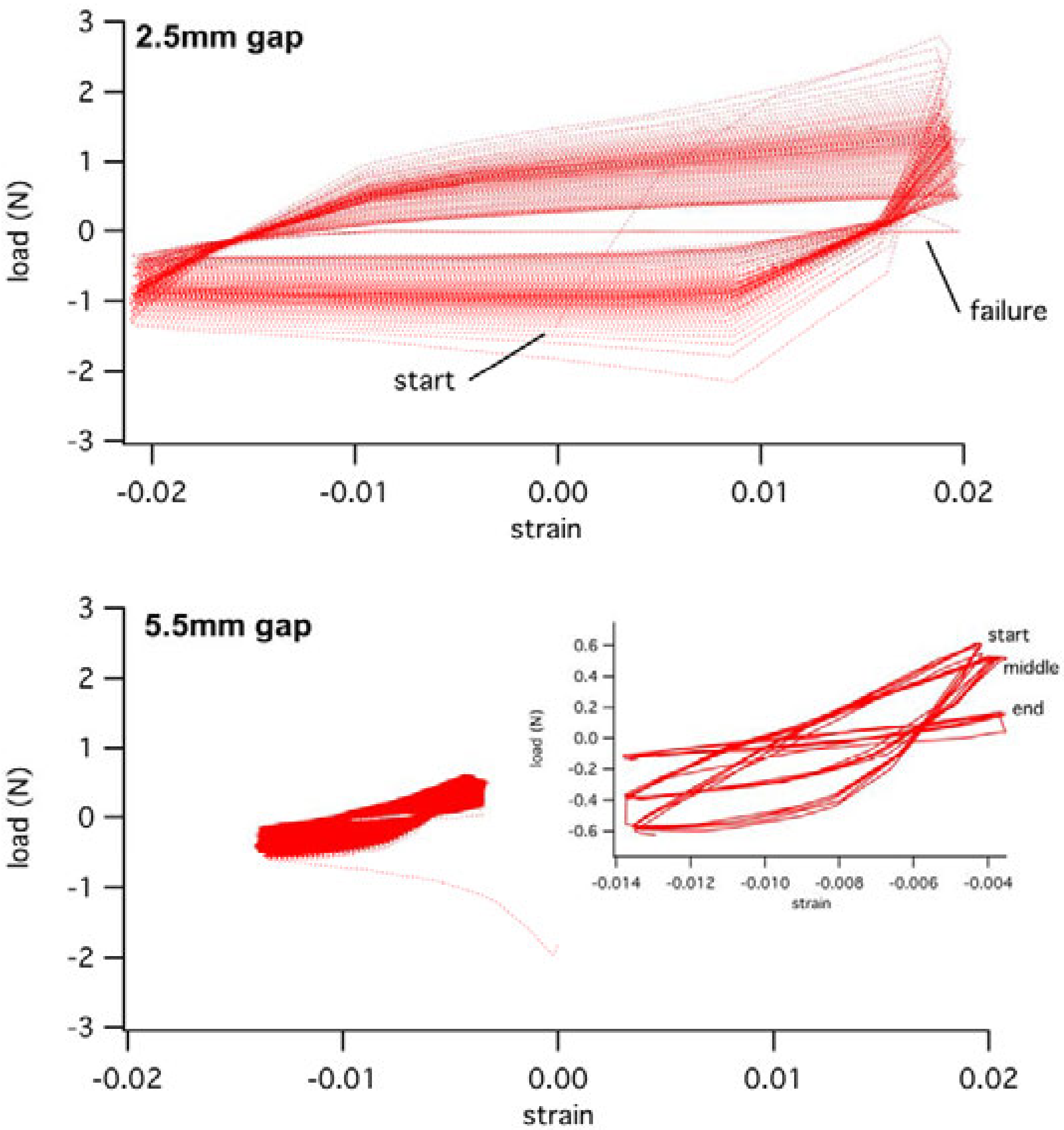
***Timothy J Silverman*, Nick Bosco, Sarah Kurtz**

Mar. 1 Afternoon II – Modeling of CPV Reliability Issues

conclusions

- **Modeling metal fatigue**
  – Consider driving force and mechanism
  – Testing must represent service
- **Cu ribbon fatigue**
  – Wind loading is likely inconsequential
  – Thermal loading *is* significant
    - May be mitigated by proper ribbon routing
    - Ribbon shape and constraints are important
- **Solder fatigue**
  – Time dependency complicates modeling
  – Empirical models may relate ALT, but not service

Sample Text and Object Slide with Bar



Modeling based on Damp Heat Testing

Kent Whitfield, Sr. Director, Quality and Reliability
Asher Salomon, Reliability Engineer

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Prologue

- Single stress testing *success*:
  - 1978 – 1986 – Large JPL body of work on specific PVB/EVA *Systems*.
- Damp Heat Manifestations
  - 169 hrs at 70C, 90%RH, Block I
  - 720hrs at 40C/93%RH, CEC 501
  - 480hrs at 90C, 95%RH, CEC 502
  - 1989→1000hrs 85/85, JIS C 8917
- Otth and Ross (1984)
  - "Rule-of-Thumb" 10° ~ 2x also
  - 1C≡1%RH
  - 1000-hour Damp Heat ~ 20 years in Miami, Florida (sort of…)
- New *Durability* offerings at 2x + the qualification standards.
- Question: How do we interpret this result in a reliability-relevant way.

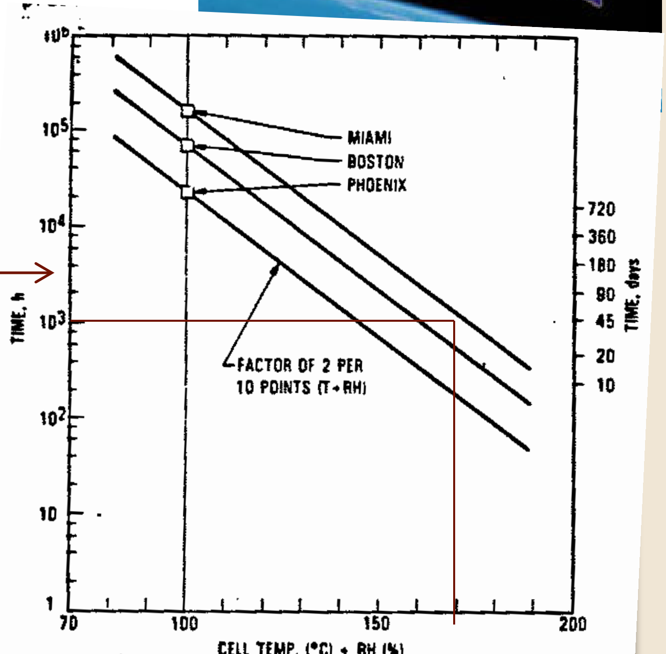
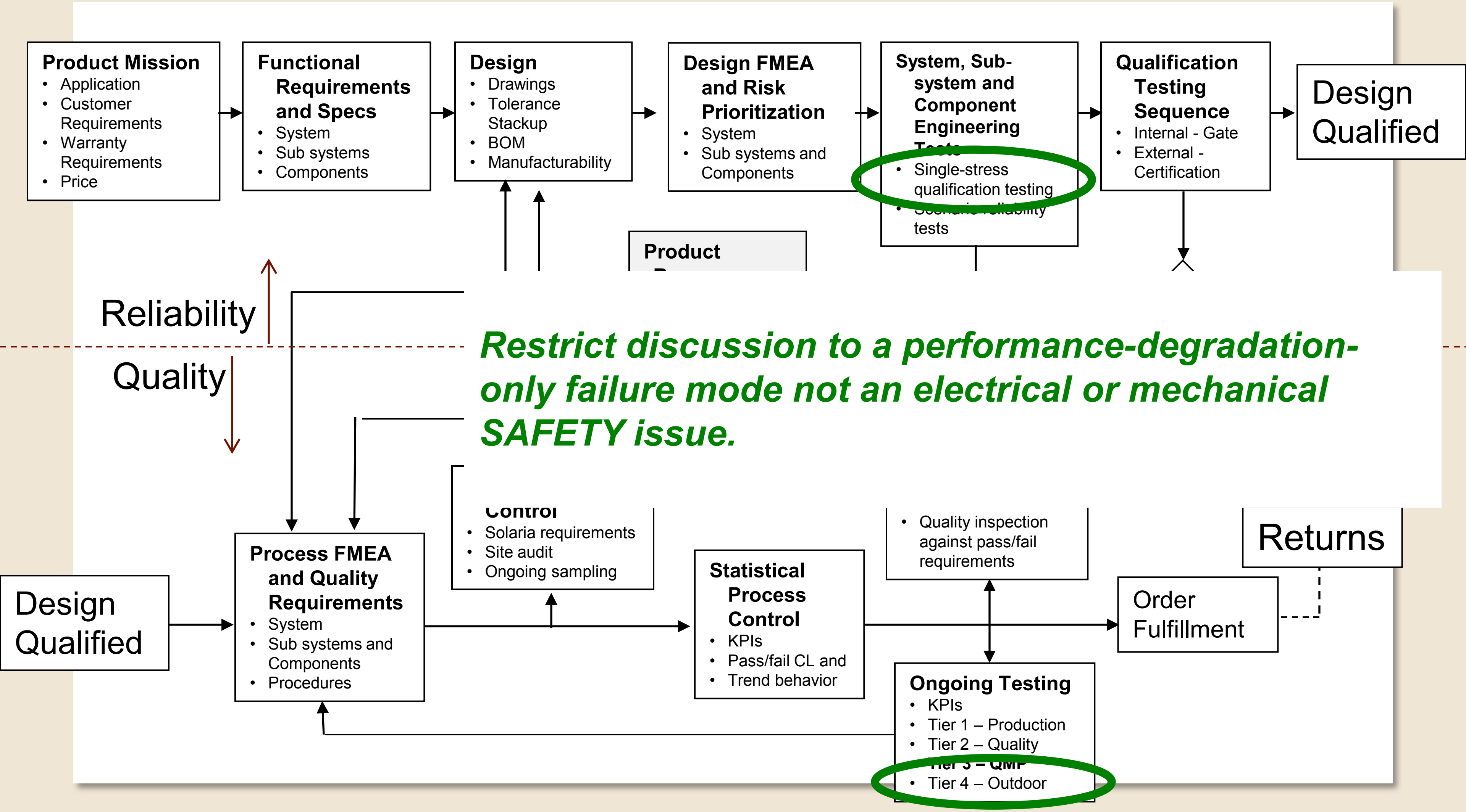


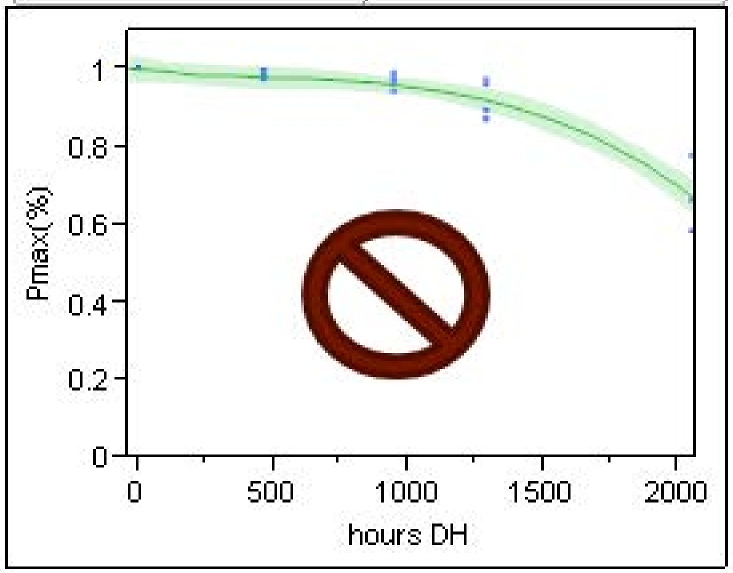
Figure 2. Temperature-humidity test duration equivalent to 20-year field exposure at indicated sites.

Context – When do we care?

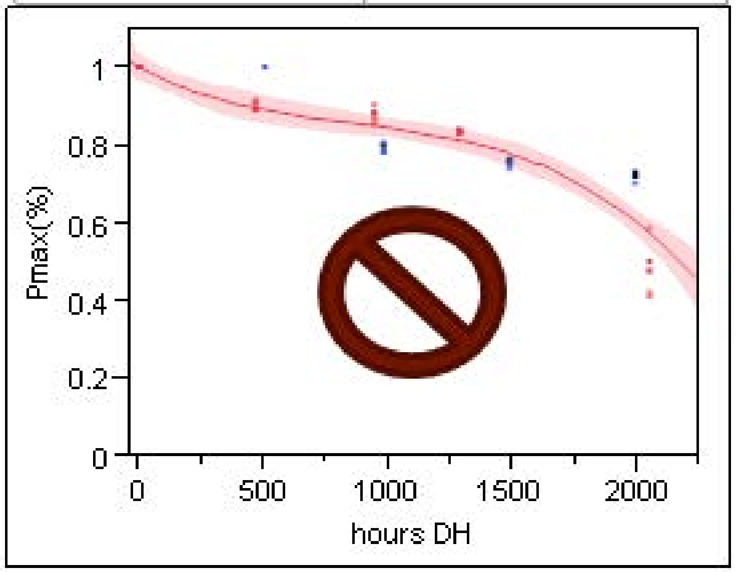


Restriction – Damp Heat Only

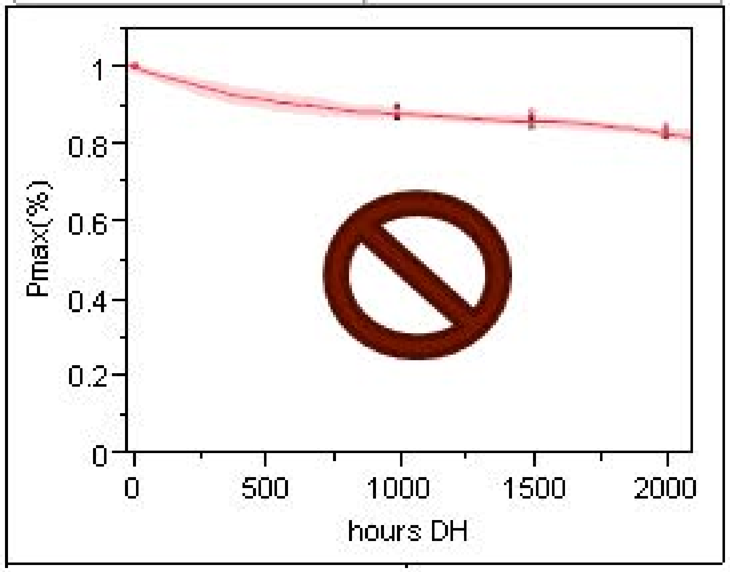
Bivariate Fit of Pmax(%) By hours DH Stress=DH,-1kVbias



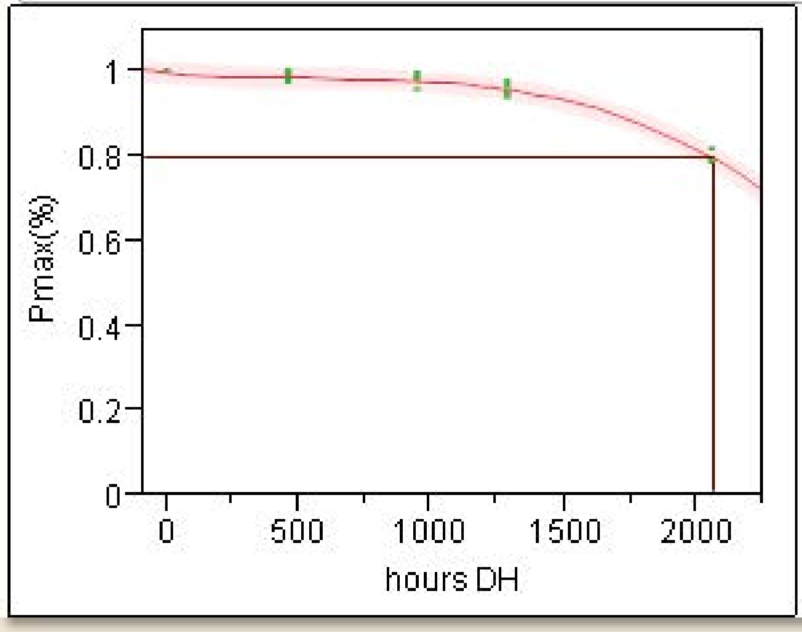
Bivariate Fit of Pmax(%) By hours DH Stress=DH,+1kVbias



Bivariate Fit of Pmax(%) By hours DH Stress=DH,+.6kVbias



Bivariate Fit of Pmax(%) By hours DH Stress=DH,0Vbias

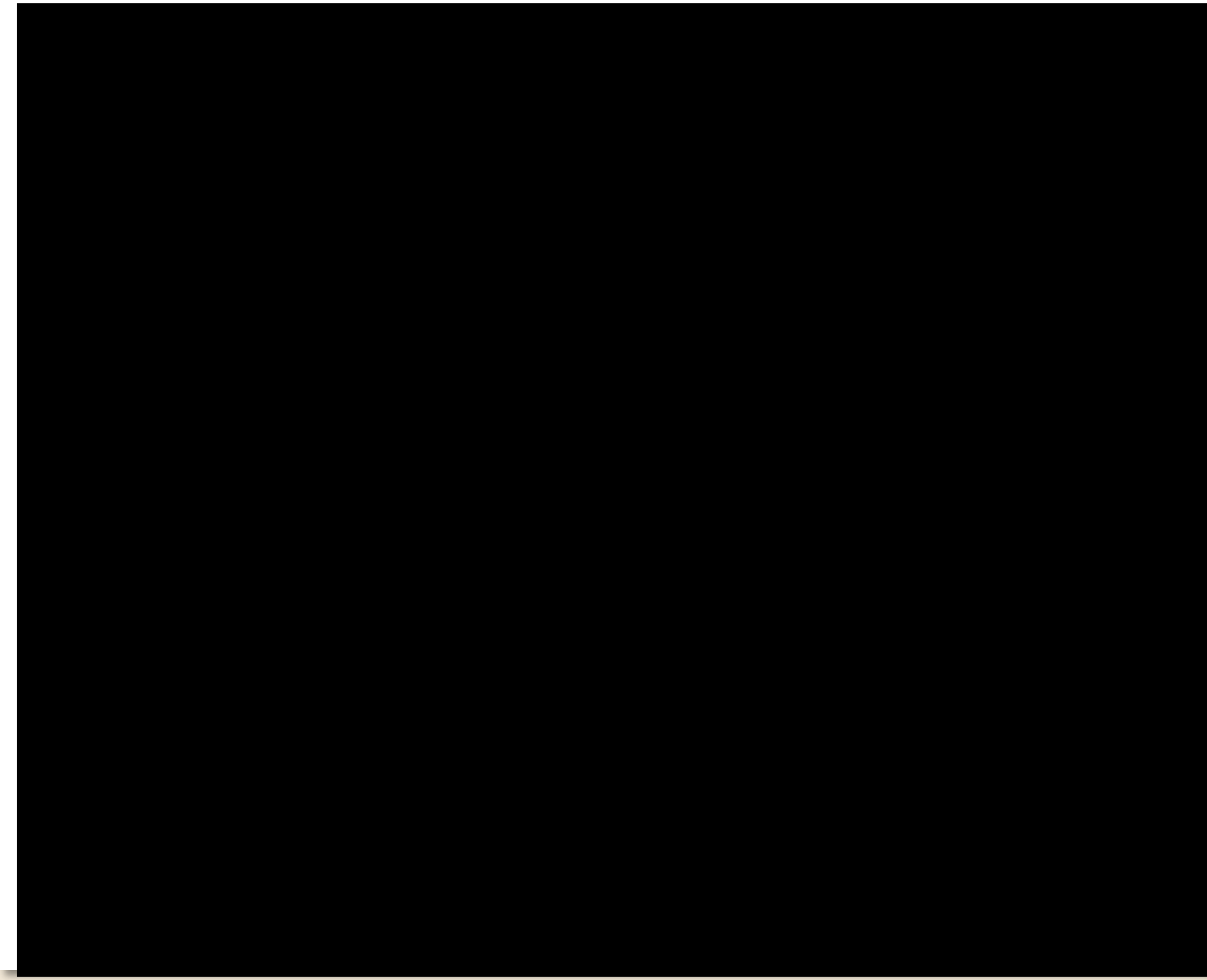


Do not perceive a significant risk of a PID failure (negative bias of p+ cells)

Positive bias work still underway.

HOWEVER – 2000 hours of DH produces ~20% Pmax degradation.

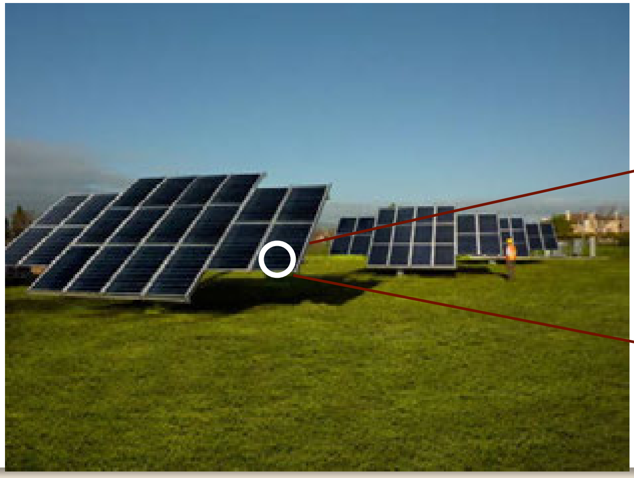
EL Observations

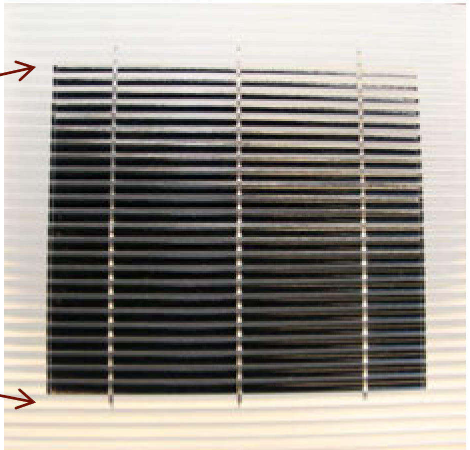


Primary impact ~ *series resistance*

Where to begin

- Must understand consequence of "shortened" time-to-failure in 0V Damp Heat.
  - Modeling
    - Accelerated Modeling – Peck/Power Law and Exponential Corrosion
    - Degradation Modeling – Extrapolation of reaction rates to field conditions
- Start with the Solaria product design…





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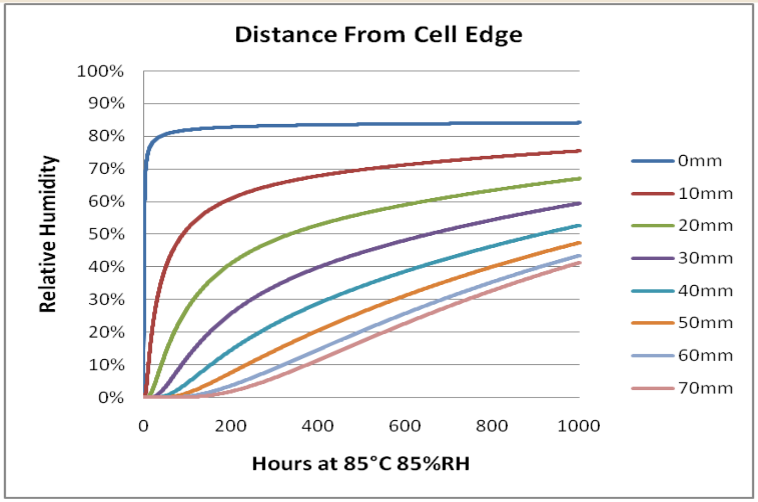
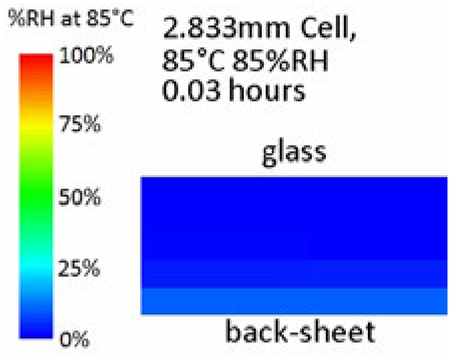
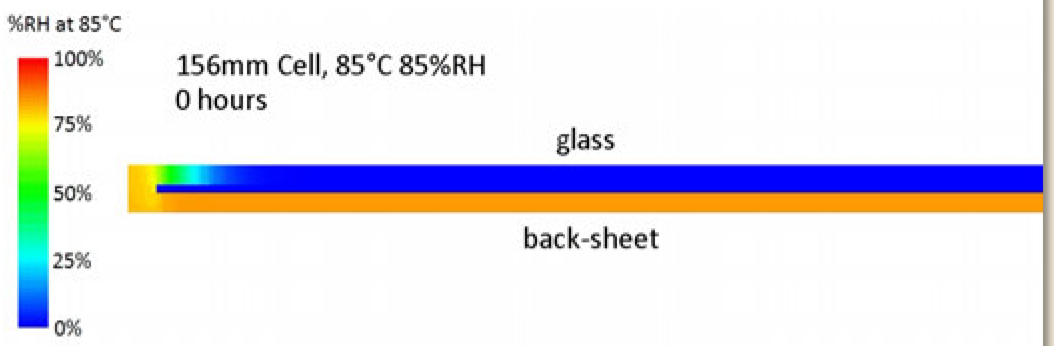
WVTR as a function of EVA transmission across sunny side of PV cell







Fick's Diffusion: $\vec{J} = -D\nabla C$

2006, Michael Kempe, *Modeling of Rates of Moisture Ingress into Photovoltaic Modules*, Solar Energy Materials & Solar Cells, Vol 90, 2006

Acceleration Model 1 – Peck/Power Law

- 1986, Stewart Peck
  - Survey of all available data on the corrosion of silicon-aluminum systems in plastic packages.
  - Goal was to identify a basic relationship that could be used to accelerate Damp Heat testing (85°C, 85%RH).

- Basic form

$$TF = A_o \cdot RH^{-n} \cdot e^{\frac{Ea}{kT}}$$

Expanded form

$$TF = A_o \cdot RH^{-n} \cdot f(V) \cdot e^{\frac{Ea}{kT}}$$

According to the present model, acceleration factors over 85/85 results include the following:

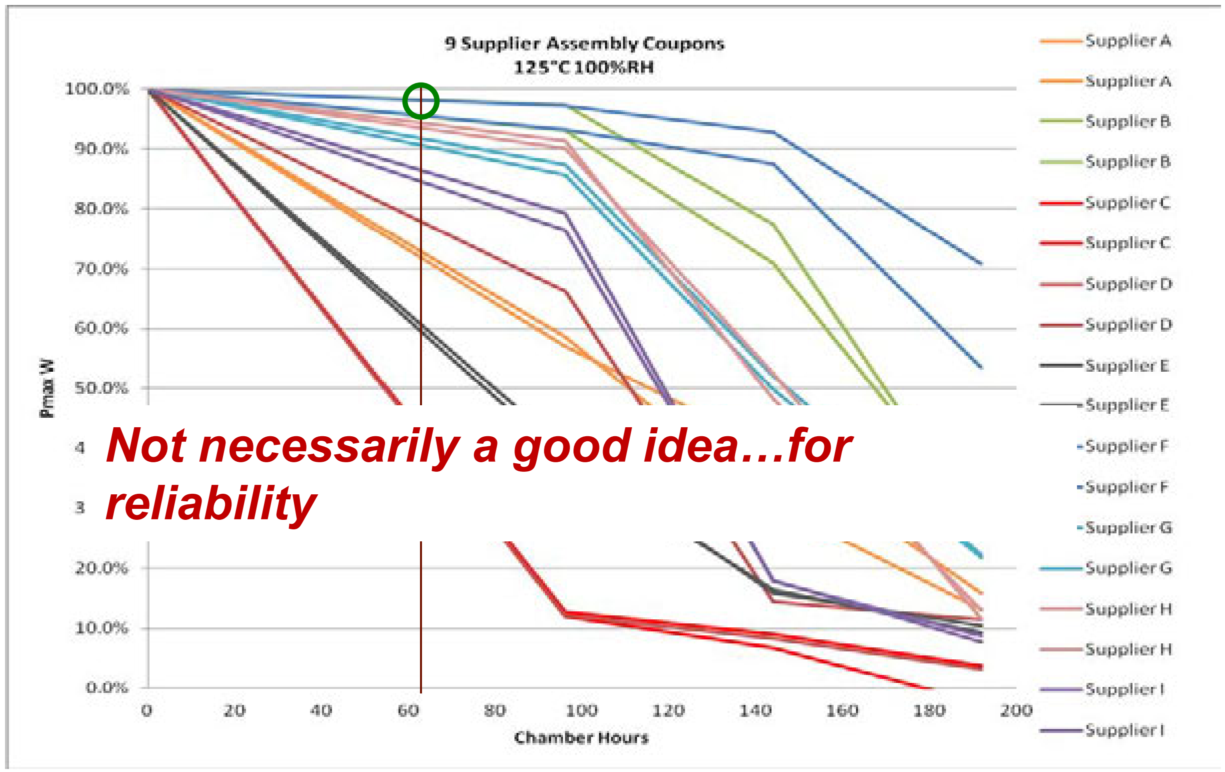
Condition	Acceleration
121/100	16
135/94	30
140/94	40
140/100	50
150/100	77

Jedec Test Method A110-B

~62.5 hours→1k hrs Damp Heat
121 C and 100%RH

Durability Cell Comparison

- Same construction coupons varying only the cell supplier.
- Primary objective, corrosion tolerance in the Damp Heat test.



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Design of Experiments

Power-law humidity model [42]:

$$\mathrm{TF} = A_0(\mathrm{RH})^{-n}\exp\left(\frac{Q}{K_B T}\right)$$

Exponential humidity model [37–44]:

$$\mathrm{TF} = A_0\exp(-a\cdot\mathrm{RH})\exp\left(\frac{Q}{K_B T}\right)$$

Semiconductor corrosion failure models

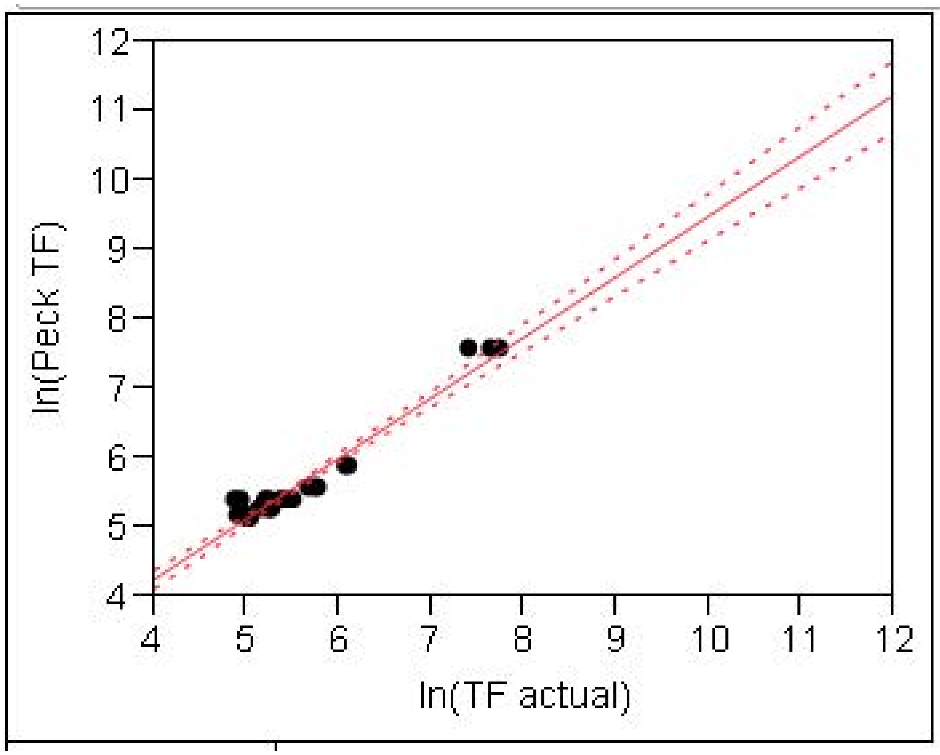
Handbook of Semiconductor Manufacturing Technology, edited by Robert Doering, Yoshio Nishi, CRC Press, 2007.

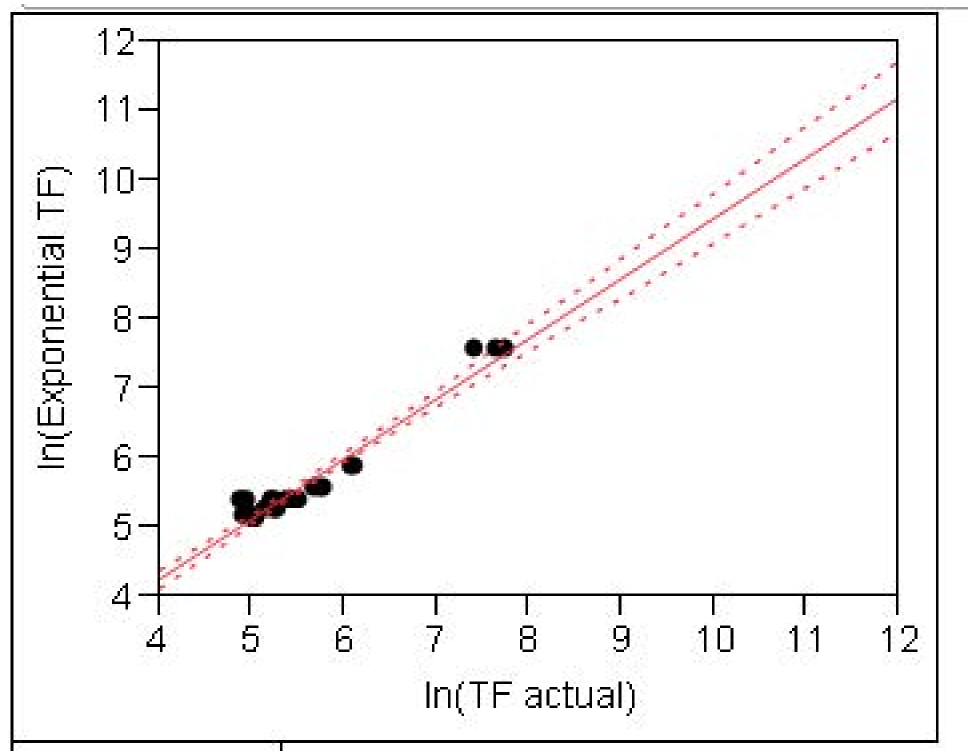
To solve these equations – several factors + time + money!

Cell	Temperature	Humidity
A/B/C	85°C	85%
A/B/C	110°C	100%
A/B/C	120°C	100%
A/B/C	125°C	100%
A/B/C	130°C	80%
A/B/C	130°C	90%
A/B/C	130°C	95%

Initial DOE

Cell Type A– 25 year window at 5% significance





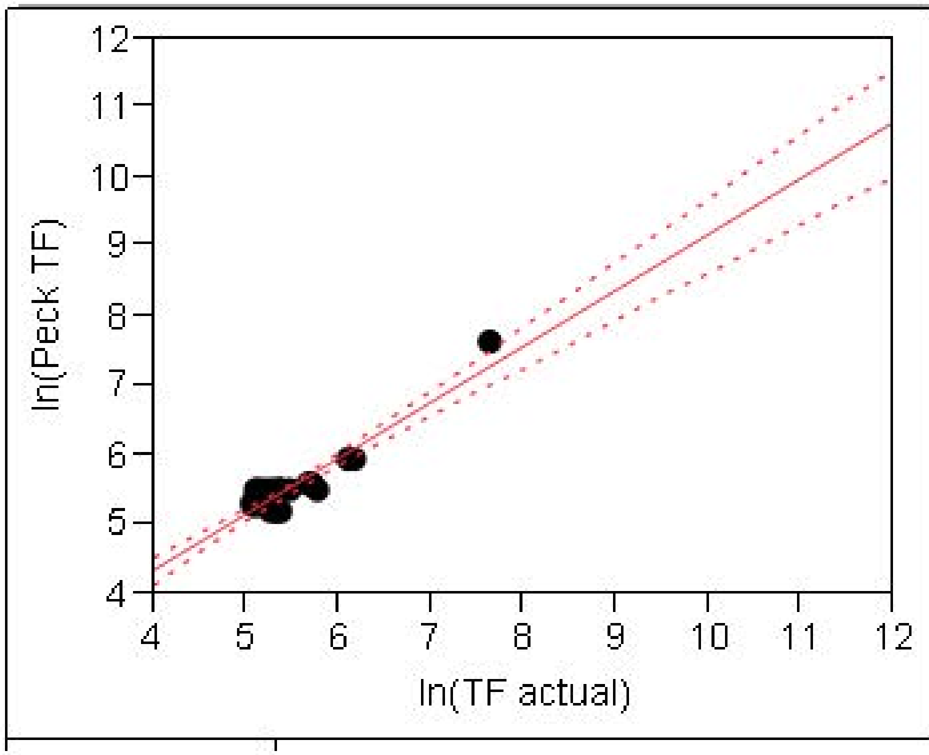
Parameter

$$\left[\begin{array}{l}\text{Prefactor} = 1.82363387862689, \\ \text{exponent} = -2.7712835232765, \\ \text{Ea} = 0.59604040742163\end{array}\right],\ \text{Prefactor} * \left[\text{RH}(\%) * 100\right]^{\text{exponent}} * \text{Exp}\left[\frac{\text{Ea}}{\left[\text{T}(\text{K}) * 0.000086173324\right]}\right]$$

Parameter

$$\left[\begin{array}{l}\text{a} = -3.0328211358062, \\ \text{Ea} = 0.59459080681632, \\ \text{Prefactor} = 0.00011322609919\end{array}\right],\ \text{Prefactor} * \text{Exp}\left[\text{RH}(\%) * \text{a}\right] * \text{Exp}\left[\frac{\text{Ea}}{\left[\text{T}(\text{K}) * 0.000086173324\right]}\right]$$

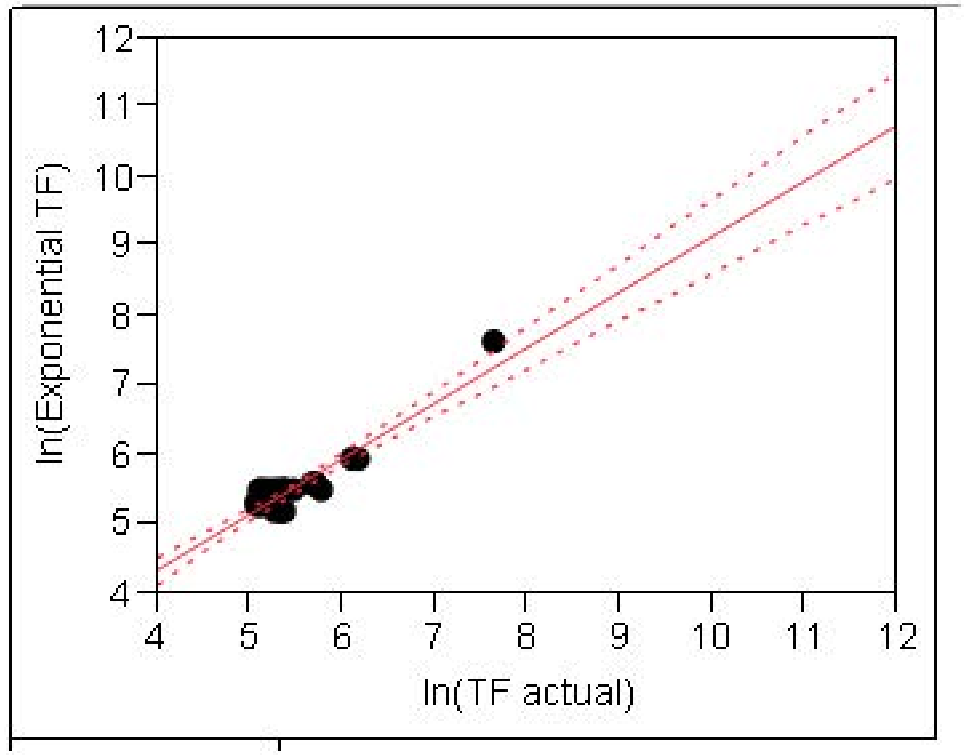
Cell Type B – 25 year window at 5% significance



Parameter

[Prefactor = 0.31971158461547, exponent = -2.3936668295299, Ea = 0.59867721086698],

$$Prefactor \cdot \left[RH(\%) \cdot 100\right]^{exponent} \cdot Exp\left[\frac{Ea}{\left[T(K) \cdot 0.000086173324\right]}\right]$$



Parameter

[a = -2.6227004052091, Ea = 0.59733301018947, Prefactor = 0.00007473022573],

$$Prefactor \cdot Exp\left[RH(\%) \cdot a\right] \cdot Exp\left[\frac{Ea}{\left[T(K) \cdot 0.000086173324\right]}\right]$$

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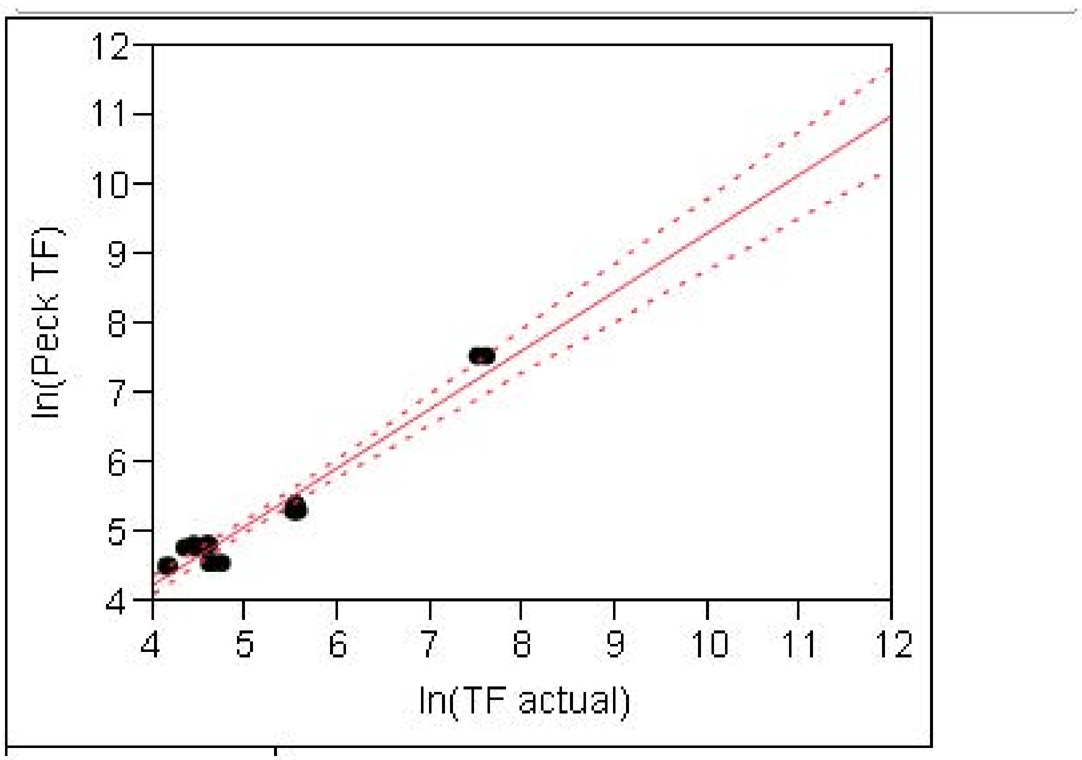
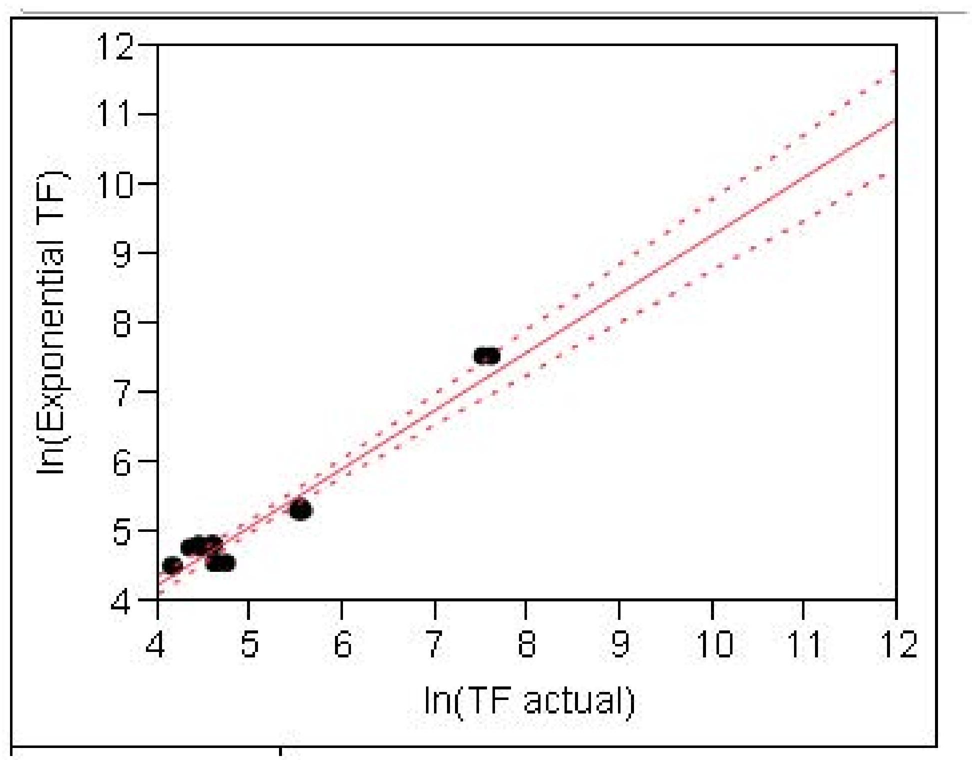
Cell Type C – 25 year window at 5% significance





Parameter

$$\left[\left[\begin{array}{l}\text{Prefactor} = 1883.99097582613,\\ \text{exponent} = -4.9493019117116,\\ \text{Ea} = 0.67930186944304\end{array}\right], \text{Prefactor} * \left(\text{RH }(\%) * 100\right)^{\text{exponent}} * \text{Exp}\left[\frac{\text{Ea}}{\left(\text{T (K)} * 0.000086173324\right)}\right]\right]$$

Parameter

$$\left[\left[\begin{array}{l}\text{a} = -5.4225725571623,\\ \text{Ea} = 0.67691355080915,\\ \text{Prefactor} = 0.00005769905167\end{array}\right], \text{Prefactor} * \text{Exp}\left(\text{RH }(\%) * \text{a}\right) * \text{Exp}\left[\frac{\text{Ea}}{\left(\text{T (K)} * 0.000086173324\right)}\right]\right]$$

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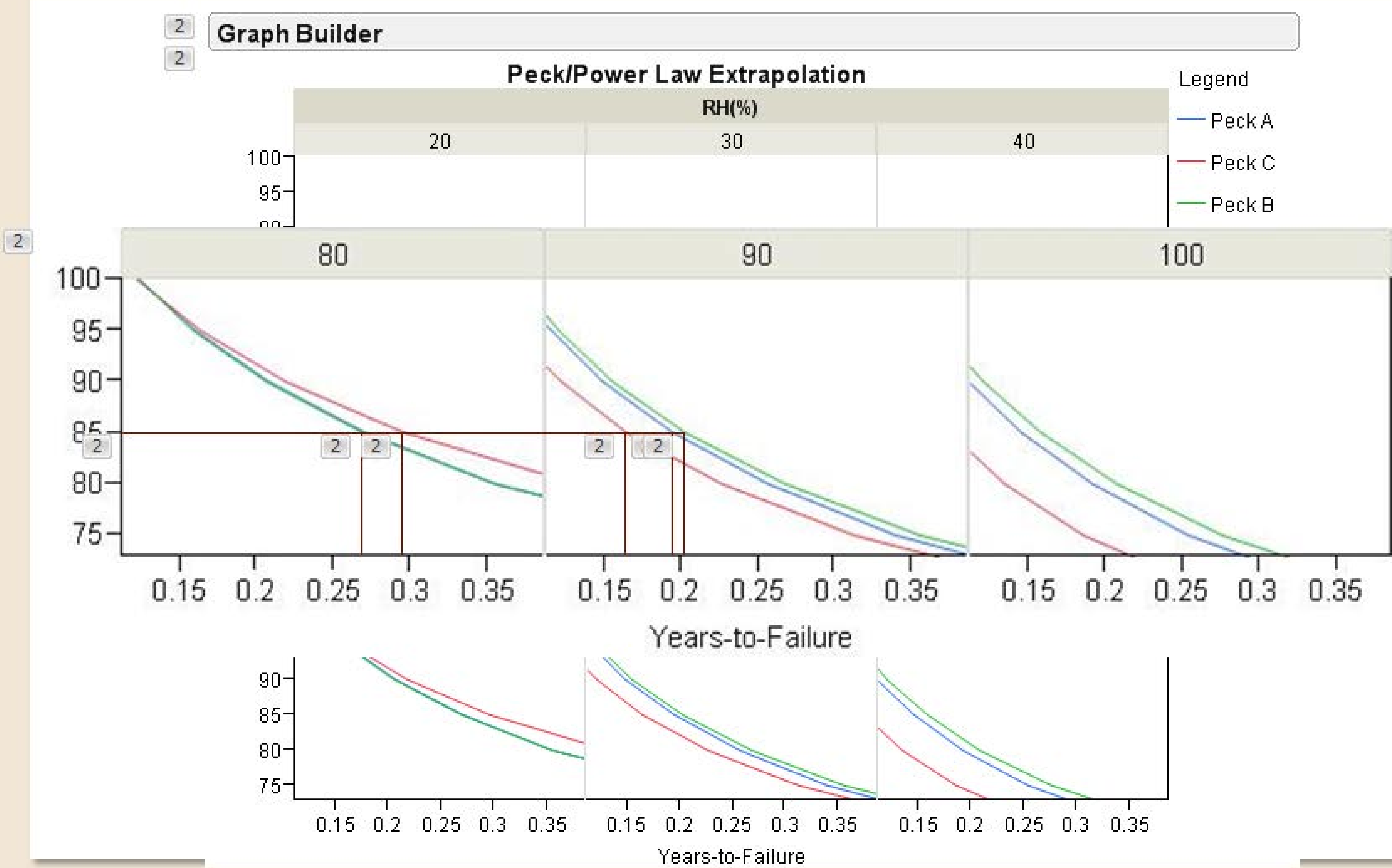
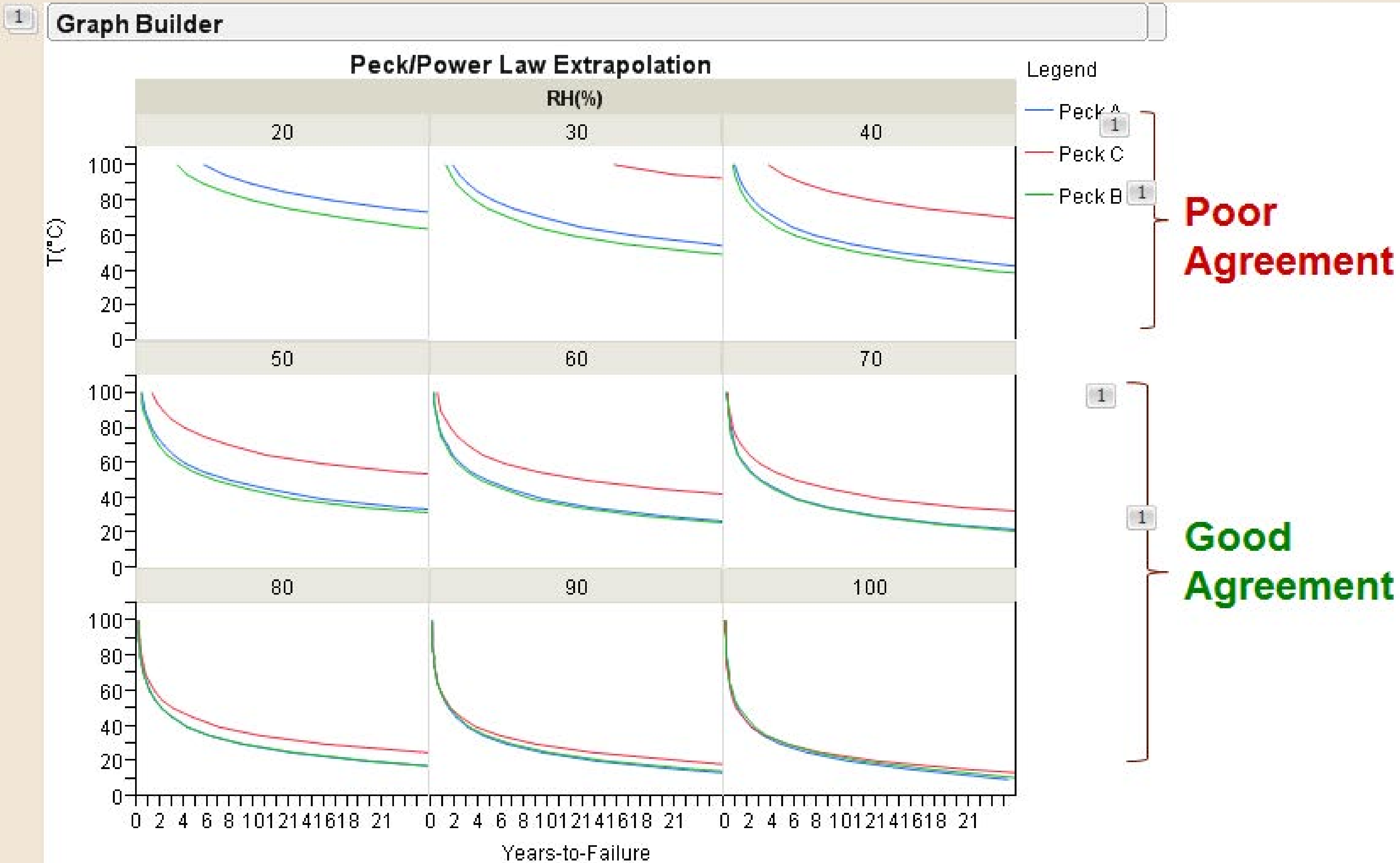
Acceleration Model Significance



Divergence at Low Humidity - Expected



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How to Reconcile?

Fill in the Blanks!!

Data are being collected at 120°C and 9%RH

- Prediction Peck A = 20.6 years
- Prediction Exponential A = 3600 hrs

- Prediction Peck B = 8.96 years
- Prediction Exponential B = 2700 hrs

- C-type cells are predicted to last over 1-year with the Exponential model…

Also gathering data at 95°C and 80%RH to Refine Crossover Behavior

Modeling Product Temperature in the Field

Methodology and approach from:

+

SNL Coefficients for Solaria (2June2011):
$a=-3.53$, $b=-0.077$, $\Delta T=3$

Comparison to New Mexico Test Site

Conclusion: Method provides an ability to predict Tm to ±5°C at 95%confidence

Could also use David Faiman's approach

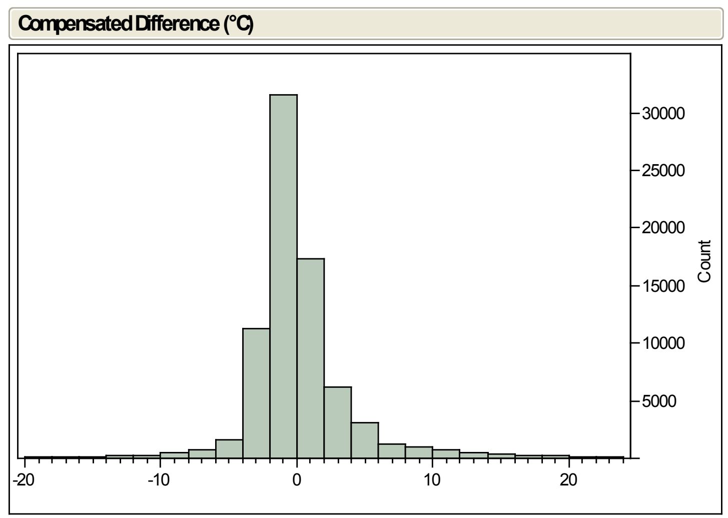
PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2011)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.1103

RESEARCH ARTICLE

Evaluation of high-temperature exposure of photovoltaic modules

Sarah Kurtz[1*], Kent Whitfield[2], G. TamizhMani[3], Michael Koehl[4], David Miller[1], James Joyce[5], John Wohlgemuth[1], Nick Bosco[1], Michael Kempe[1] and Timothy Zgonena[5]

[1] National Renewable Energy Laboratory, Golden, CO, USA
[2] Solaria, Fremont, CA, USA
[3] TUV Rheinland PTL, Tempe, AZ, USA
[4] Fraunhofer ISE, Freiburg, Germany
[5] Underwriters Laboratories Inc., Northbrook, IL, USA

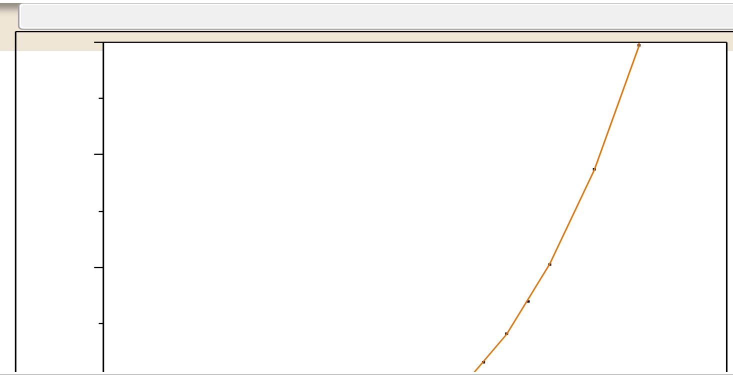


Tolerance Intervals

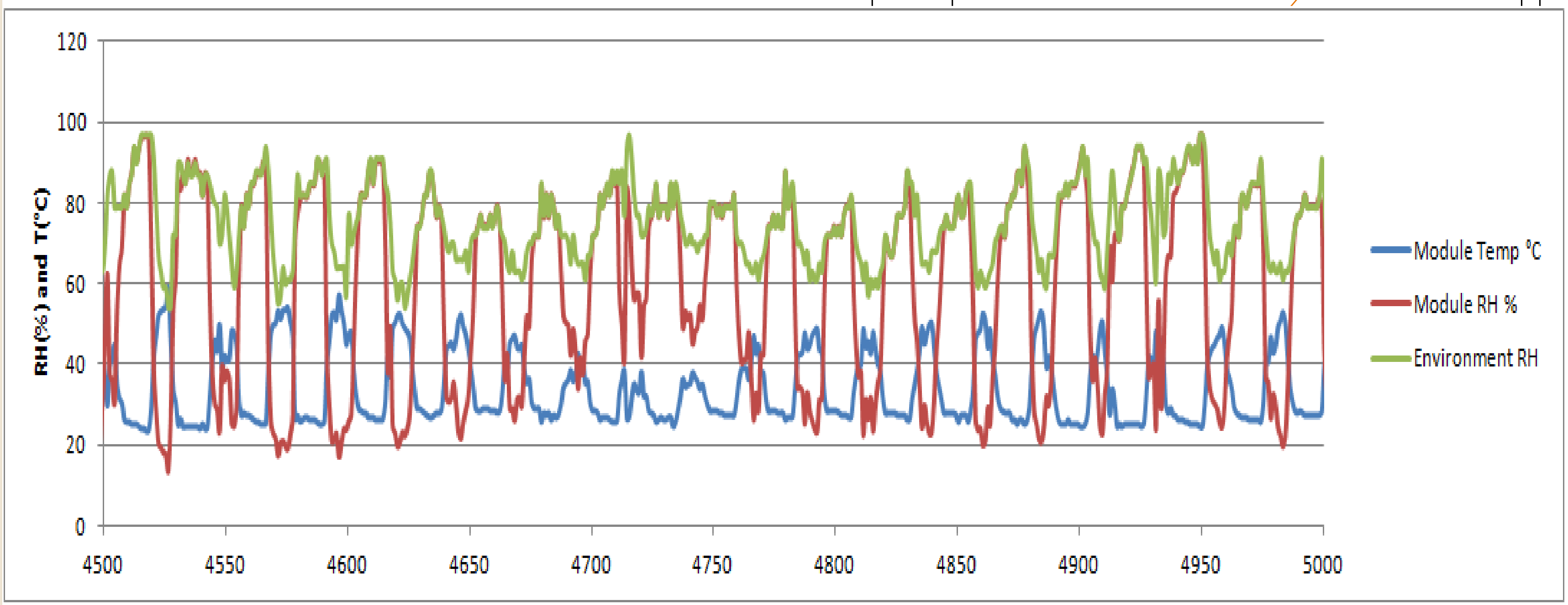
Proportion	Lower TI	Upper TI	1-Alpha
0.900	-5.27479	5.314319	0.950

SOLARIA

Isobaric Heating – Module RH from Ambient



During the day, module is typically 20 to 30 C above ambient. At night, re-radiation may make module slightly cooler than ambient.



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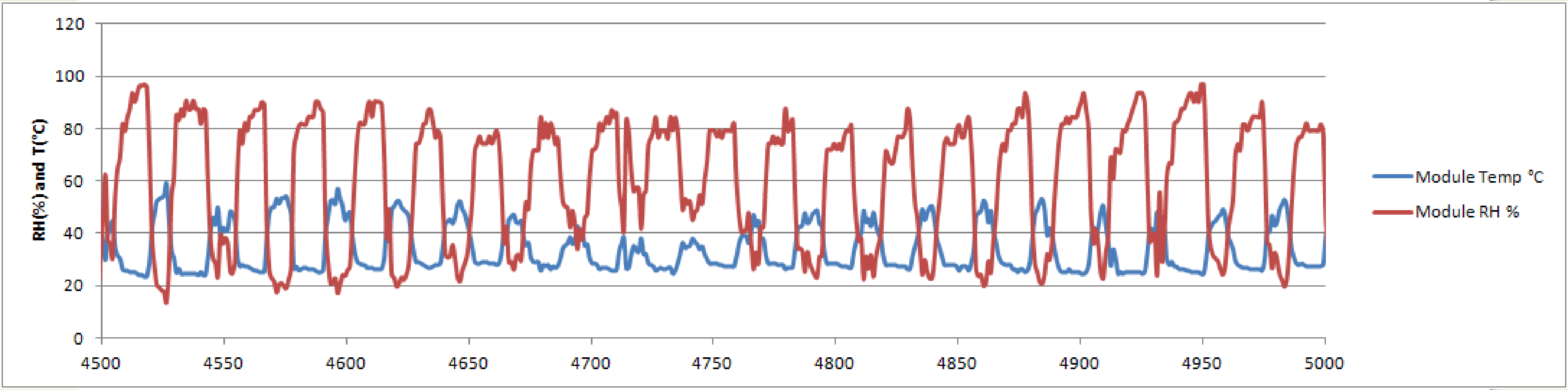
Module Temperature and Humidity



Miami, FL TMY3 Simulation

- Would not properly account for the out-of-phase nature of the relationship between the two.
- Recall that design does not have significant phase-lag, so we are assuming that it is irrelevant for now.
- Need a numerical integration method.

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Degradation Model

- Assume a power law <u>or</u> an exponential corrosion model *will* enable us to predict a time-to-failure, TF, based on varying module temperature $T_m(t)$ and effective module humidity $RH_m(t)$.
- Furthermore, define a extent-of-reaction variable X, such that

$$X = \begin{matrix} 0: P\max = 100\%, t = 0 \\ 1: P\max = 80\%, t = TF \end{matrix}$$

- Where $TF=TF(RH_m,T_m)$ from the earlier acceleration models.
- If we define X=t/TF (or R*t) we also see that

$$\int_0^{X'} dX = \int_0^{t'} \frac{1}{TF(RH_m(t),T_m(t))} dt$$

SOLARIA

Making a Field Connection

- We consider, one *typical* year, where, using the exponential corrosion accelerated model,

$$TF(Tm_t, RHm_t) = A * e^{-b \cdot RHm(t)} * e^{Ea/k \cdot Tm(t)}$$

$$X' = \int_0^{t'} \frac{1}{A * e^{-b \cdot RHm(t)} * e^{Ea/k \cdot Tm(t)}} dt = \int_0^{1\,year} \frac{1}{A} * e^{b \cdot RHm(t)} * e^{-Ea/k \cdot Tm(t)} dt$$

- As all *typical* years are the same, the integrand becomes a constant reaction rate such that

$$X' = R * (1\,year)$$

and at failure, $1 = R * TF(years)$

or $TF = \frac{1}{R} = \frac{1}{X'}$

SOLARIA

Finally

- Numerical integration method over a one-year weather file and presume that this weather pattern repeats itself indefinitely.

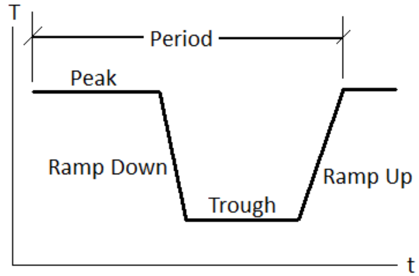
12839 Miami, FL -5	A-Power	B-Power	C-Power	A-Exponential	B-Exponential	C-Exponential
Reaction Extent after One Year	4.69%	4.88%	2.22%	6.26%	6.61%	2.70%
Time to Failure (Years)	21	20	45	16	15	37

725090 Boston, MA -5	A-Power	B-Power	C-Power	A-Exponential	B-Exponential	C-Exponential
Reaction Extent after One Year	1.78%	1.83%	0.82%	2.46%	2.60%	0.99%
Time to Failure (Years)	56	55	122	41	38	101

722780 Phoenix, AZ -7	A-Power	B-Power	C-Power	A-Exponential	B-Exponential	C-Exponential
Reaction Extent after One Year	0.64%	0.78%	0.16%	3.50%	4.45%	0.59%
Time to Failure (Years)	156	127	622	29	22	169

- Divergence between Power Law and Exponential Models extreme for dry climates!

More Work Needed

- Longer duration data at lower stress levels mandatory because at highly accelerated conditions:
  - Effect of measurement uncertainty exaggerated
  - Effect of testing perturbations exaggerated.
- Real effort – Validation
  - Must corroborate predictions against a test!
  - 

- Starting with 125°C, 100%RH to a 85°C, 85%RH trough

Conclusions

- Damp Heat has been the standard corrosion test for well over 30 years.
  - Remains an important milestone for certification and will always have a place in my heart.
  - Cannot alone enable reliability prediction.
    - Must perform multiple-stress tests to understand risk.
    - Interpretation requires a modeling approach. Shown here:
      - Acceleration Models (Peck/Power Law or Exponential Corrosion)
      - Degradation Modeling (Linear extrapolation based on a constant reaction rate calculated over a typical meteorological year)
        - » Presumes knowledge of module temperature and "module" humidity
        - » Shown here was an isobaric approximation for "module" humidity based on an assumption of infinitely fast mass transfer ~clear approximation
- Running a 2000-3000 hour Damp Heat test will not guarantee a 25-year life!

Select References

Hoffman, A., Ross., R., "Environmental Qualification Testing of Terrestrial Solar Cell Modules," *Proceedings of the 13th IEEE PV Specialists Conference*, Washington, DC, USA, 1978.

Otth , D., Ross, R., "Assessing Photovoltaic Module Degradation and Lifetime from Long-Term Environmental Tests." Proceedings of the 30th Institute of Environmental Sciences Technical Meetings, Los Angeles, CA, 1984.

Cuddihy, E., "The Aging Correlation (RH+t):Relative Humdity (%) + Temperature (°C)," JPL Publication 86-7, DOE/JPL-1012-121, January, 1986.

Osterwald, C. "History of Accelerated and Qualification Testing of Terrestrial Photovoltaic Modules: A Literature Review." Progress in Photovoltaics: Research and Applications, Vol. 17, pp. 11-33, 2009.

Tobias, P. and Trindade, D., *Applied Reliability*, Chapter 7 Physical Acceleration Models, Van Nostrand Reinhold Company, 1986.
Peck, D., "Comprehensive Module for Humidity Testing Correlation", Proceedings of the 24th Reliability Physics Symposium, Anaheim, California, USA, 1986.

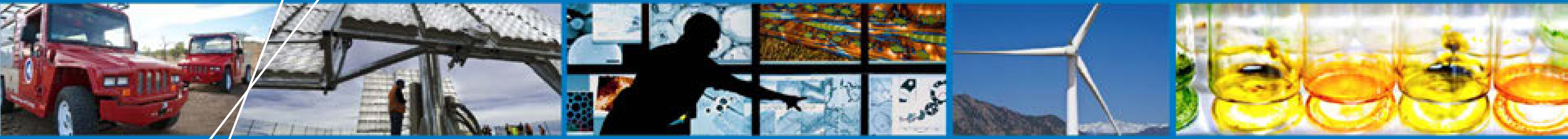
Mon, G., Wen, L., Meyer, J., Ross, R., and Nelson, A., "Electrochemical and Galvanic Corrosion Effects in Thin-Film Photovoltaic Modules," Proceedings of the 20th Photovoltaic Specialists Conference, Las Vegas, Nevada, USA, 1988.

Blish,R., Durrant N., *Semiconductor Device Reliability Failure Models*, International SEMATECH Technology Transfer # 00053955A-XFR, May, 2000.

Kempe, M., "Modeling of Rates of Moisture Ingress into Photovoltaic Modules," Solar Energy Materials & Solar Cells, Vol. 90, pp.2720-2738, 2006.

Reisner, E., Sotllwerck, G., Peerlings, H., and Shafiq, F., "Humidity in a Solar Modules – Horror Vision or Negligible," Proceedings of the 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 2006.

Considerations for a Standardized Test for Potential-Induced Degradation of Crystalline Silicon PV Modules



2012 PVMRW

Peter Hacke

February 29, 2012

NREL/PR-5200-54581

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Major contributions from:

Steve Glick
Ryan Smith
Mike Kempe
Steve Johnston
Joel Pankow
Sarah Kurtz
Kent Terwilliger
Dirk Jordan
Steve Rummel
Alan Anderberg
Bill Sekulic

Motivation

"Oh no! our modules are down 40%,
we think it is potential–induced degradation"

-anonymous module manufacturer, 2010

- **Over the past decade, there have been observations of module degradation and power loss because of the stress that system voltage bias exerts.**
  - More sensitive modules
  - Higher system voltage
- **This results in part from qualification tests and standards not adequately evaluating for the durability of modules to the long-term effects of high voltage bias that they experience in fielded arrays.**
- **This talk deals with factors for consideration, progress, and information still needed for a standardized test for degradation due to system voltage stress.**

Timeline for system voltage durability

- Need for a better standard for system voltage durability brought up several times in the last decades, but did not get traction. Lack of field data, proposed tests overly harsh.
- I brought this up again in the Fall 2010 Working Group 2 (WG 2) meeting (Köln) and got a small working together, but most people were in the process of getting experience about system voltage effects.
- Spring 2011 WG 2 meeting (Shanghai), indications of increased urgency for a standard, assembled more people for this task team.
- Fall 2011 WG 2 meeting (Montreal), presented an initial draft for comments.
- Present day…

Goals for a standard – two steps

1. **Stand-alone test (new standard):**

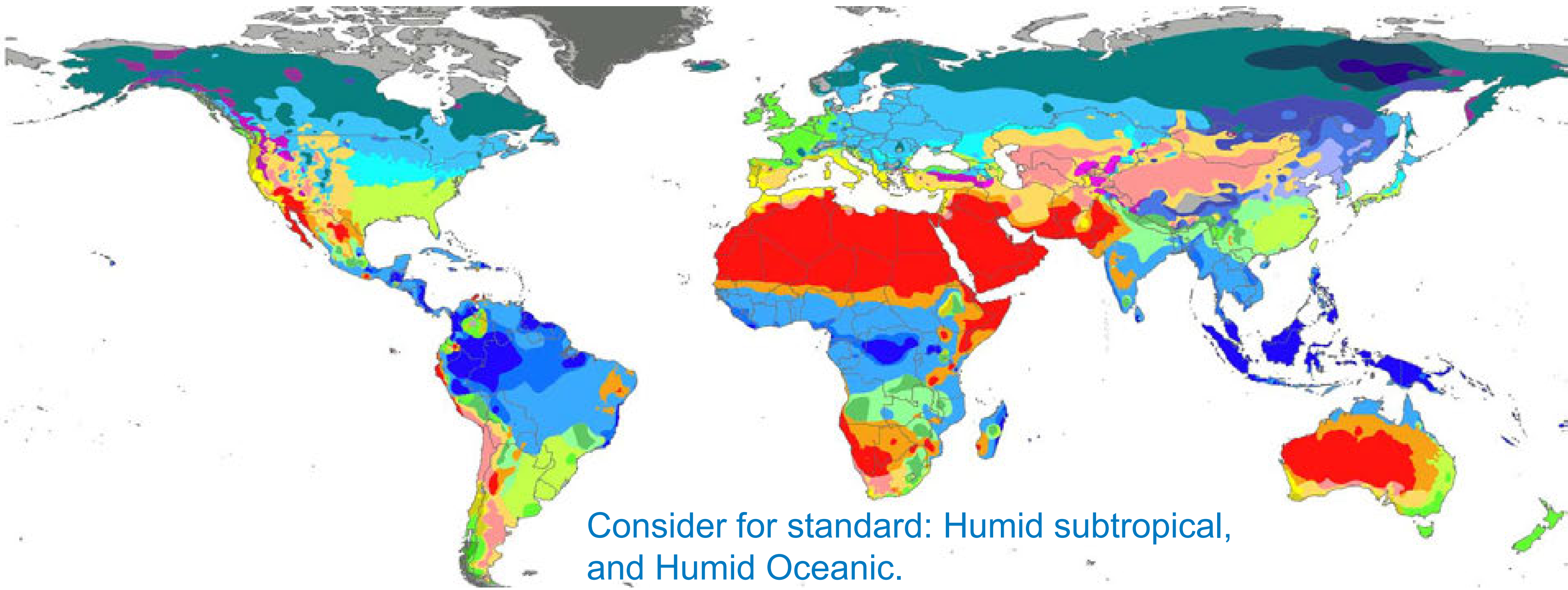
   System voltage durability test for crystalline silicon modules – design qualification and type approval, submitted as a New Work Item Proposal to IEC, Dec. 2011.

2. **Incorporate test into IEC 61215**

   Seek to incorporate above stand-alone test with any necessary supplements within IEC 61215

   – add test after clause 10.13, Damp Heat Test 1000 h under consideration.

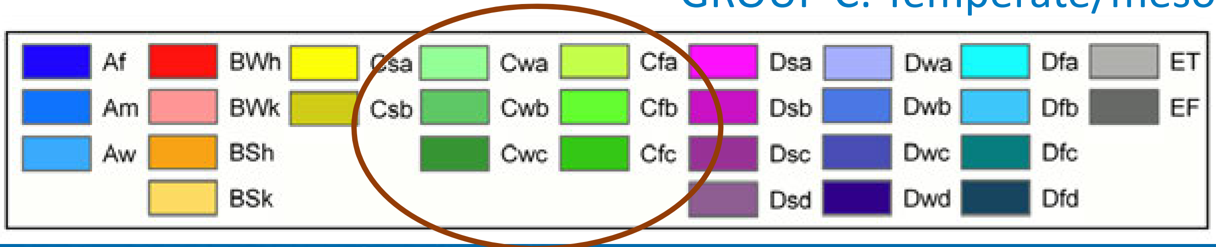
Design standard for a climate: Köppen climate classification



Consider for standard: Humid subtropical, and Humid Oceanic.

Need to design for the market. More stressful environments exist, and that should be noted in the eventual standard.

GROUP C: Temperate/mesothermal climates



Maritime/oceanic climates: (Cfb, Cwb, Cfc)

Humid subtropical climates (Cfa, Cwa)

Experimental Overview

1) HV Test bed in Florida USA

- 2 module types fielded in February 2011

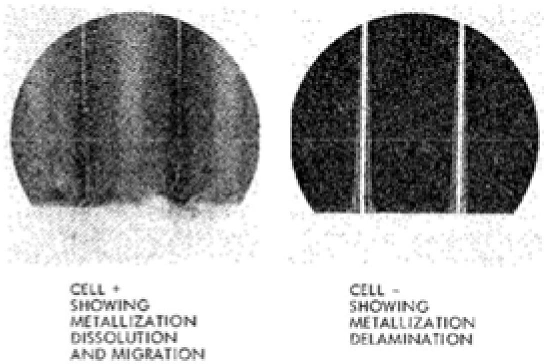
2) Chamber testing of the same 2 module designs tested in Florida

- 85% RH; 85°C, 60°C, 50°C

  P_{max} vs *t*

3) Comparison of failure rates for determination of acceleration factors and failure mechanisms for input into standardized test

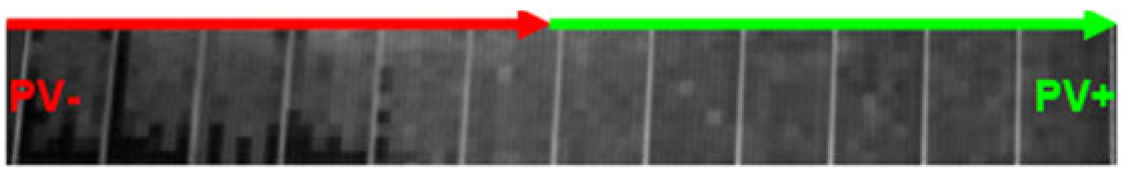
Definitions



← Electrochemical corrosion
c-Si
Mon & Ross
JPL, 1985

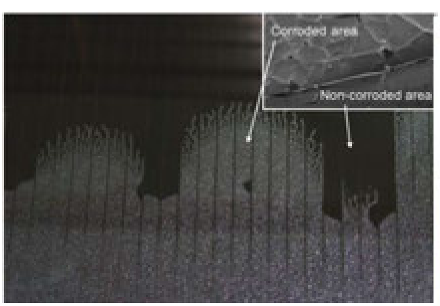
Polarization →
c-Si
Swanson
SunPower, 2005

Potential-Induced Degradation



Electroluminescence of mc-Si module strings indicating shunting in the negative portion of a center mounted or floating string

S. Pingel et al., "**Potential Induced Degradation of Solar Cells and Panels**," 35th IEEE PVSC, Honolulu, 2010, pp. 2817–2822.



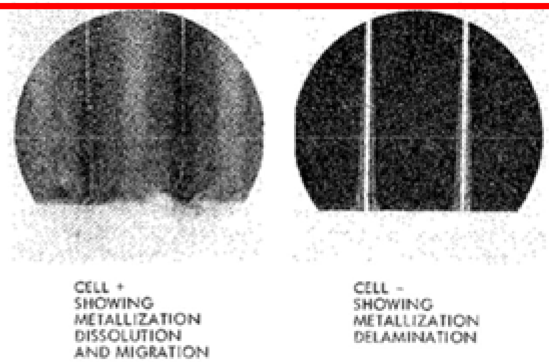
← Delamination, corrosion
a-Si
Wohlgemuth
BP Solar, 2000

Other power loss →
thin-films
unpublished

?

Definitions

Potential-Induced Degradation



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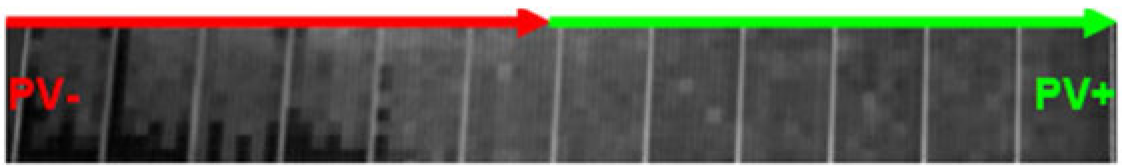
Polarization →
c-Si
Swanson
SunPower, 2005

Needs an unambiguous name →



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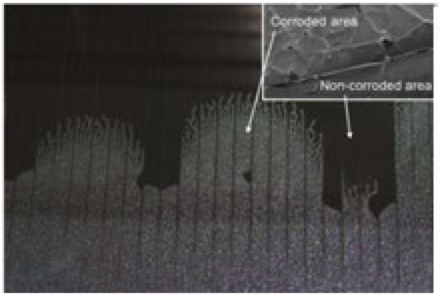
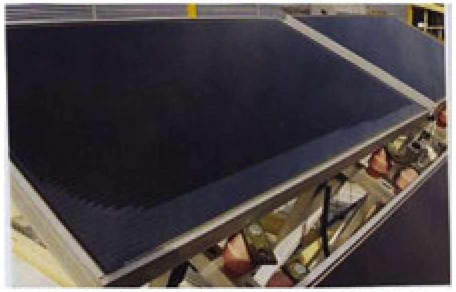


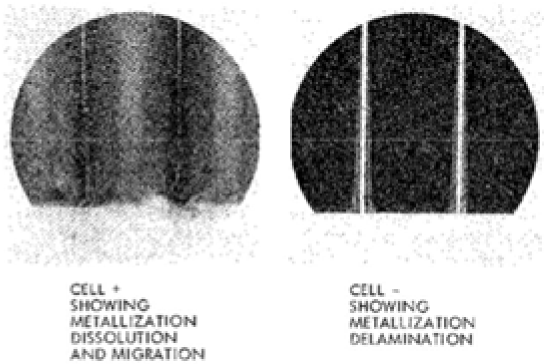


← Delamination, corrosion
a-Si
Wohlgemuth
BP Solar, 2000

Other power loss →
thin-films
unpublished

?

Definitions – this standard will cover



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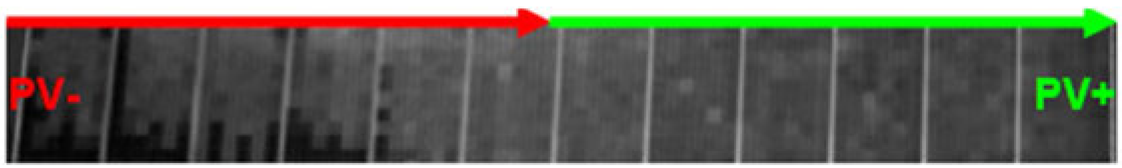

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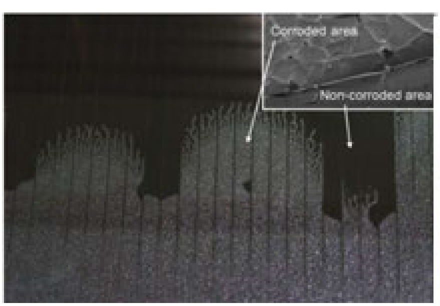

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Polarization ➔
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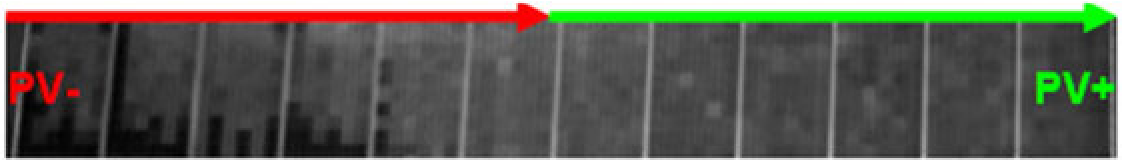

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System voltage durability

- Designed to cover c-Si

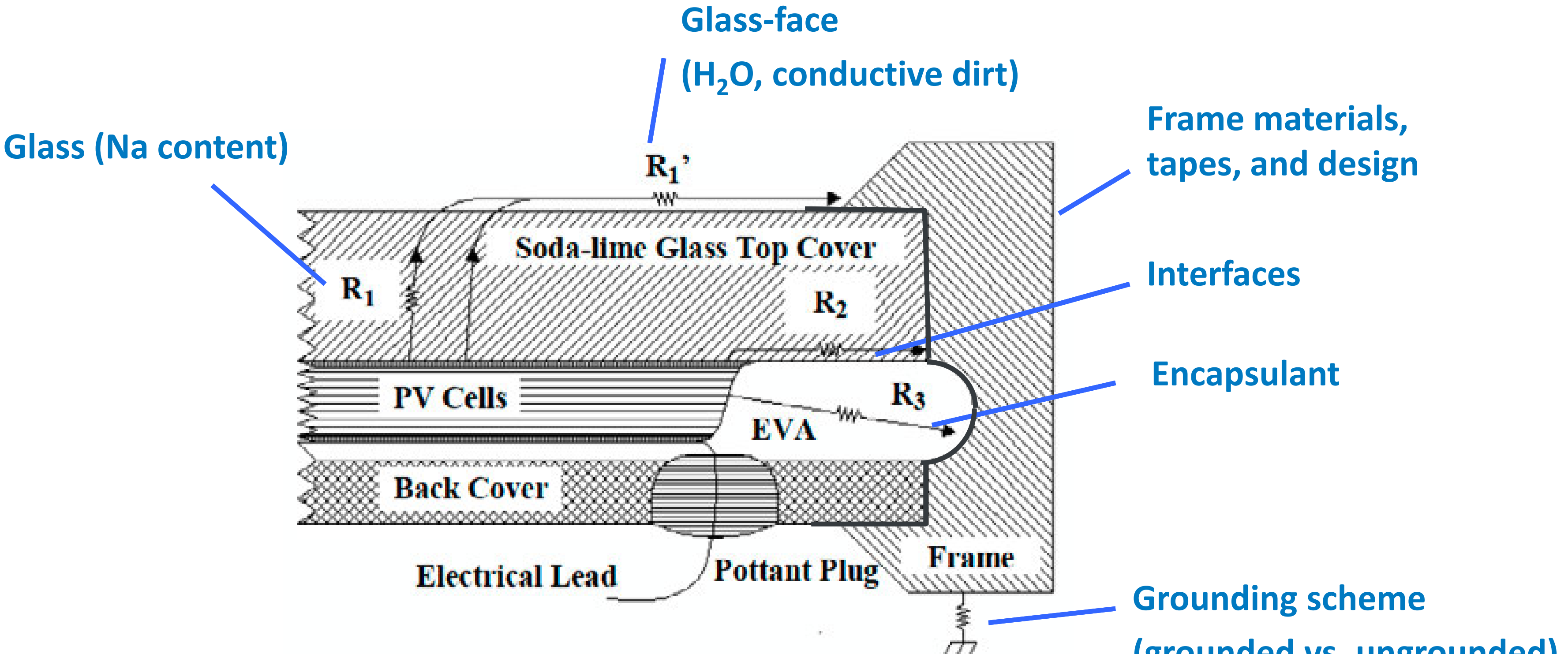
- More than just PID of conventional cells/modules
- Polarization (like SunPower)
- Non-reversible elements of PID
- Rear junction bifacial cells. ECN bifacial/Yingli 'Panda'
- HIT cells
- Framed/unframed modules of various types

- Long term view for harmonization with thin film system voltage durability

Factors for test – leakage current

Voltage potential of active layer, and leakage from that voltage to ground govern degradation in susceptible modules

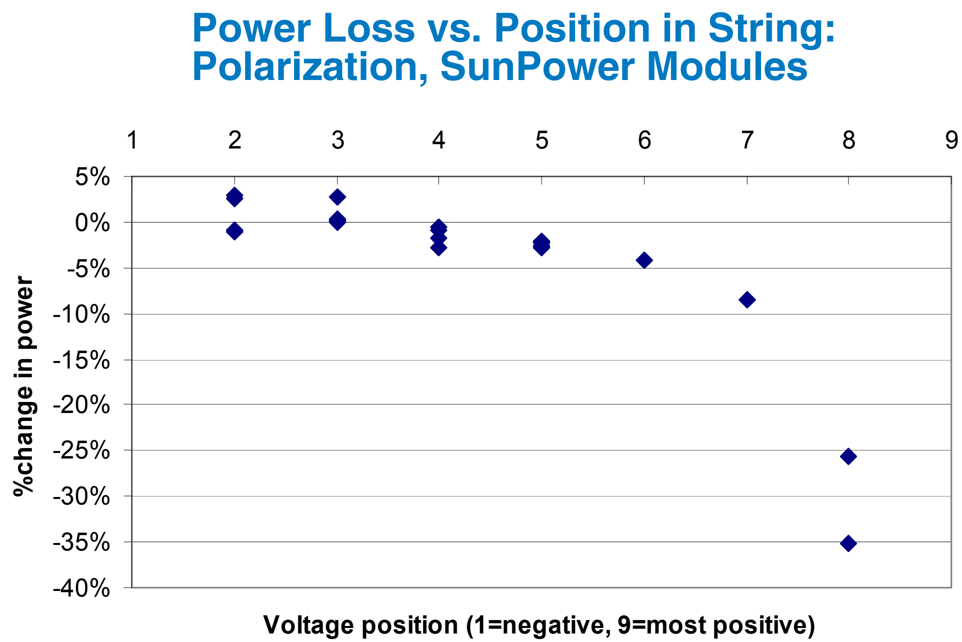
Circuit resistance factors – cutting relevant series R cuts degradation



T. J. McMahone, Prog. Photovolt: Res. Appl. 2004; 12:235–248

Test factors

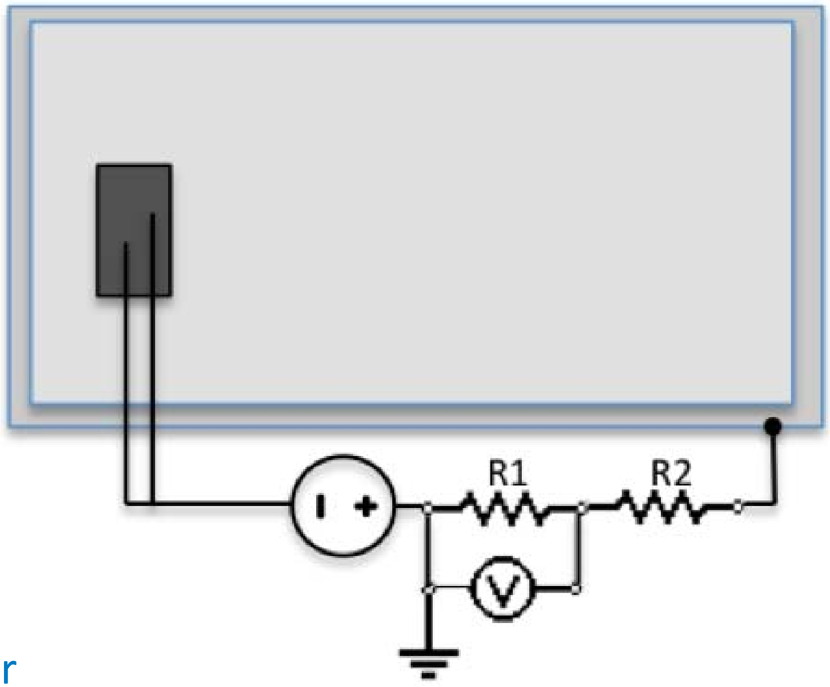
- **Voltage**
- Mounting/grounding
- Humidity, surface conductivity
- Temperature



R . M. Swanson, The surface polarization effect in high-efficiency solar cells, PVSEC-15, Shanghai

Test factors

- Voltage
- **Mounting/grounding**
- Humidity, surface conductivity
- Temperature



Completing the circuit to ground in a manner representative of mfg. module mounting scheme

Leakage current may be measured as in indicator of module package resistance

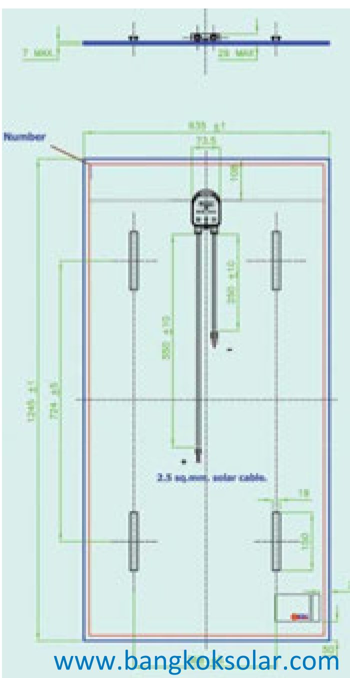
Test factors

- Voltage
- Mounting/grounding
- **Humidity, surface conductivity**
- Temperature

Photo: Erik Eikelboom 2011:10:17

Al foil, carbon film, etc, for surface conductivity

+ Quick/cheap
+ Good screening test
– Won't differentiate humidity effects
  (water leaches Na-lime glass)
– unclear how it connects to textured glass
– bypasses frame or laminate mount's ability to reduce degradation, limiting fixes to PID



From: C. R. Osterwald, Solar Energy Materials & Solar Cells 79 (2003) 21–33

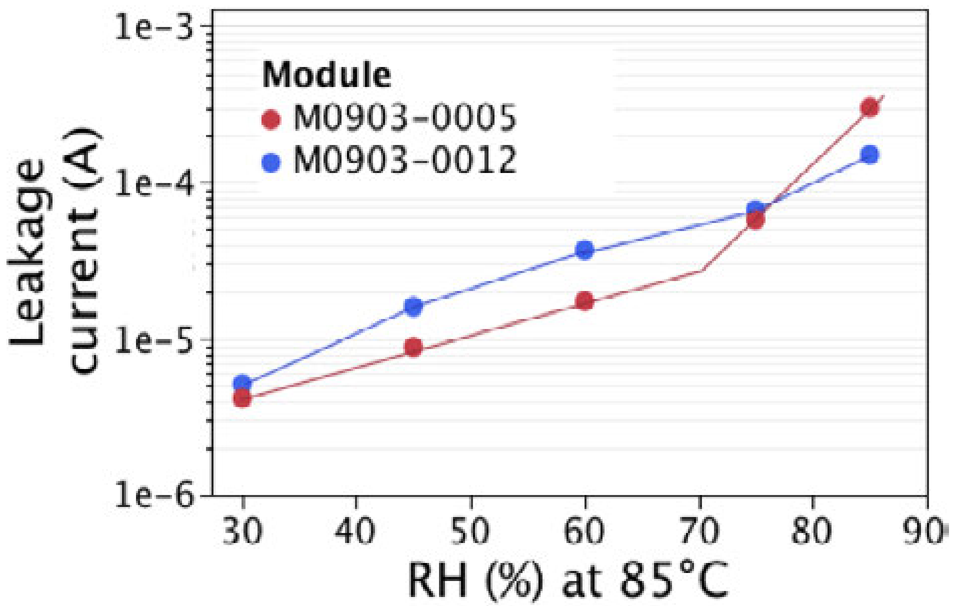
*** Modules that lack a frame and use mounting points bonded to the backsheet glass show no damage [to the extent tested].**

*** Damage rates can be slowed if leakage currents that are caused by voltage potentials between the frame and the internal circuitry are reduced.**

Test factors

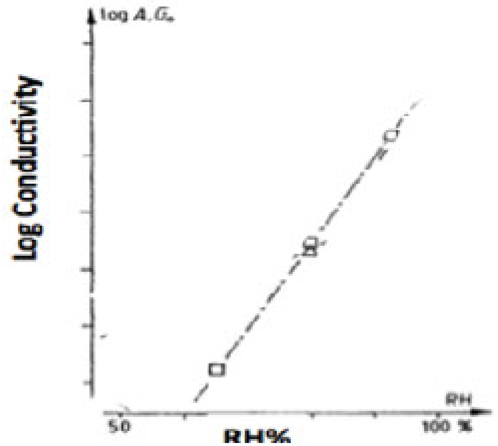
- Voltage
- Mounting/grounding
- **Humidity, surface conductivity**
- Temperature

Module leakage vs. humidity



P. Hacke *et. al.*, *25th EPVSEC*, 6-10 September 2010, Valencia, Spain

Surface conductivity of soda-lime glass vs. humidity

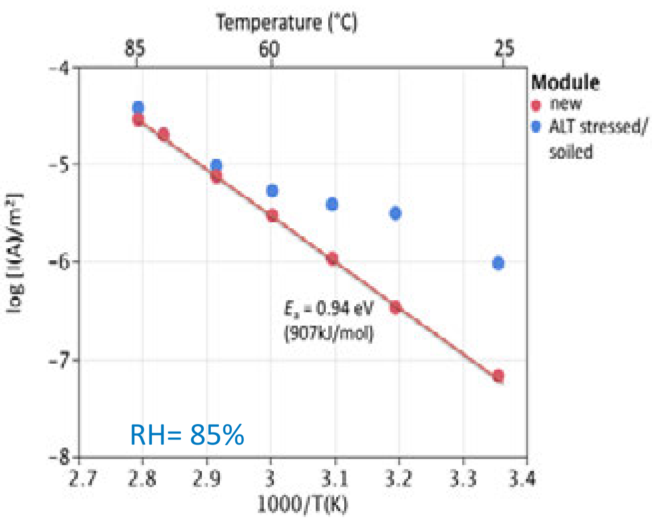


IEEE Transactions on Electrical Insulation *Vol. 23 No. 3, June 1988*

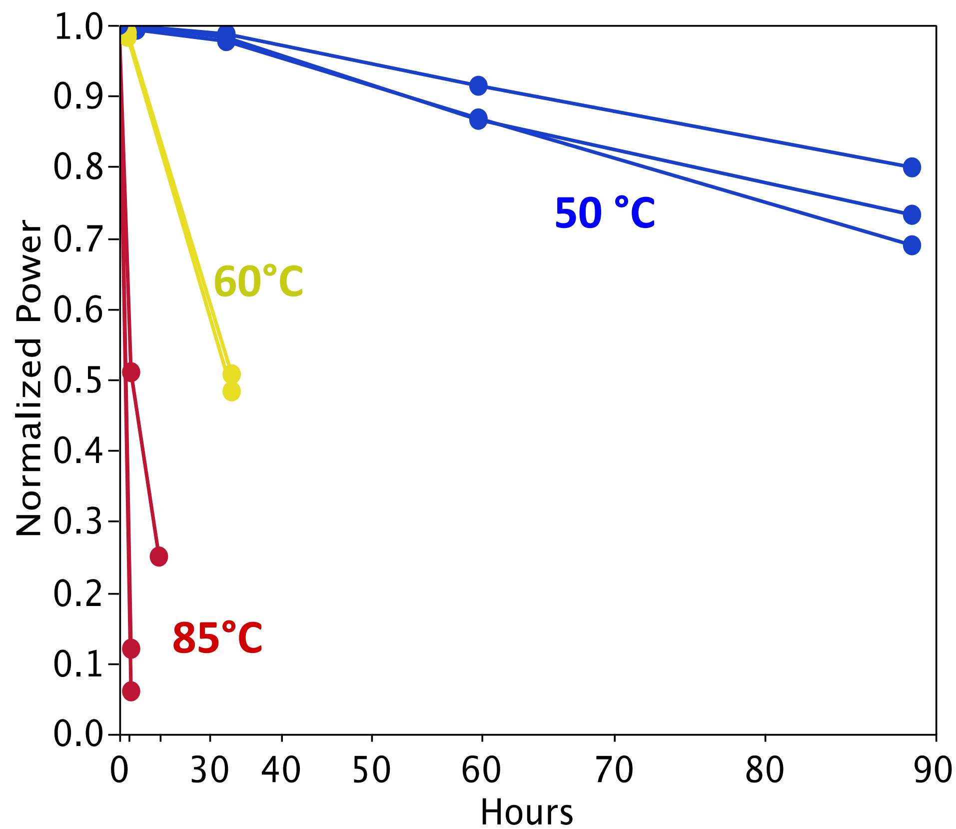
Because we need to measure the performance of not only the module laminate, but the frame or mounts, the standard as written uses humidity for the circuit to ground.

Test factors

- Voltage
- Mounting/grounding
- Humidity, surface conductivity
- **Temperature**



Degradation vs. time of mc-Si modules, -600 V, 85% RH

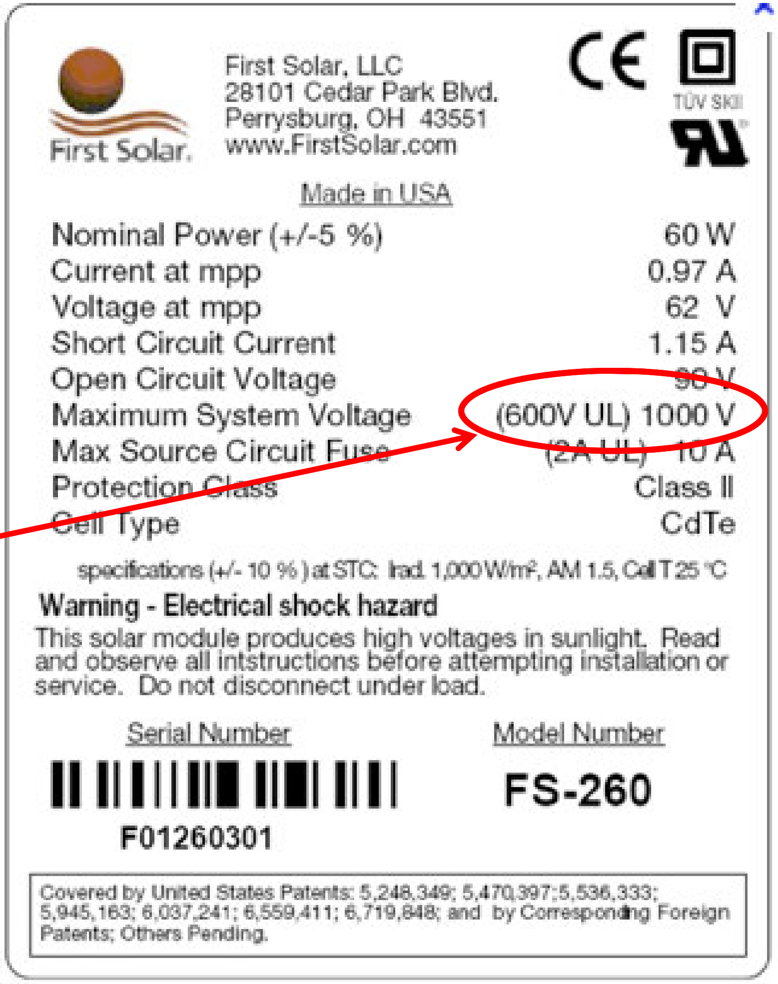


P. Hacke *et al*., Testing and Analysis for Lifetime Prediction of Crystalline Silicon PV Modules Undergoing Degradation by System Voltage Stress, 38th IEEE PVSC, Austin, 2012

- **Temperature dependence, repeatable**
- **Arrhenius behavior over temperature range, unless alternate conduction paths exist**

Test levels

- **Voltage**
- Mounting/grounding
- Humidity, surface conductivity
- Temperature
- System voltage, now effectively governed by IEC 61730-2's partial discharge test, not PID, generally
- Test at rated system voltage
  - Maximum nameplate value (behind-the-fence/utilities don't run to UL code)
  - Both polarities (if not polarity is specified)
  - Slight acceleration since actual operating V lower



D. Buemi, *Thin-Film PV Powers the Number 1 Global Solar Integrator,* davebuemi.com, accessed Feb 22, 2012

Test levels

- Voltage
- **Mounting/grounding**
- Humidity, surface conductivity
- Temperature

Draft standard:

"For continuous metallic frames encasing the perimeter of the module, the ground terminal of the high voltage power supply shall be connected … to a module grounding point of the module. "

"If (1) the PV module is provided or is specified for use with means for mounting and (2) the module is designed and specified not to be connected to ground, then such method of mounting the module shall be implemented to the extent possible."

http://www.solarframeworks.com
SolarFrameWorks Co, BIPV Cool Ply
Accessed Feb 22, 2012

Test levels

- Voltage
- Mounting/grounding
- **Humidity, surface conductivity**
- Temperature

  - **85% RH damp heat chamber, a level that chambers are capable of holding, uniformly**

Test levels

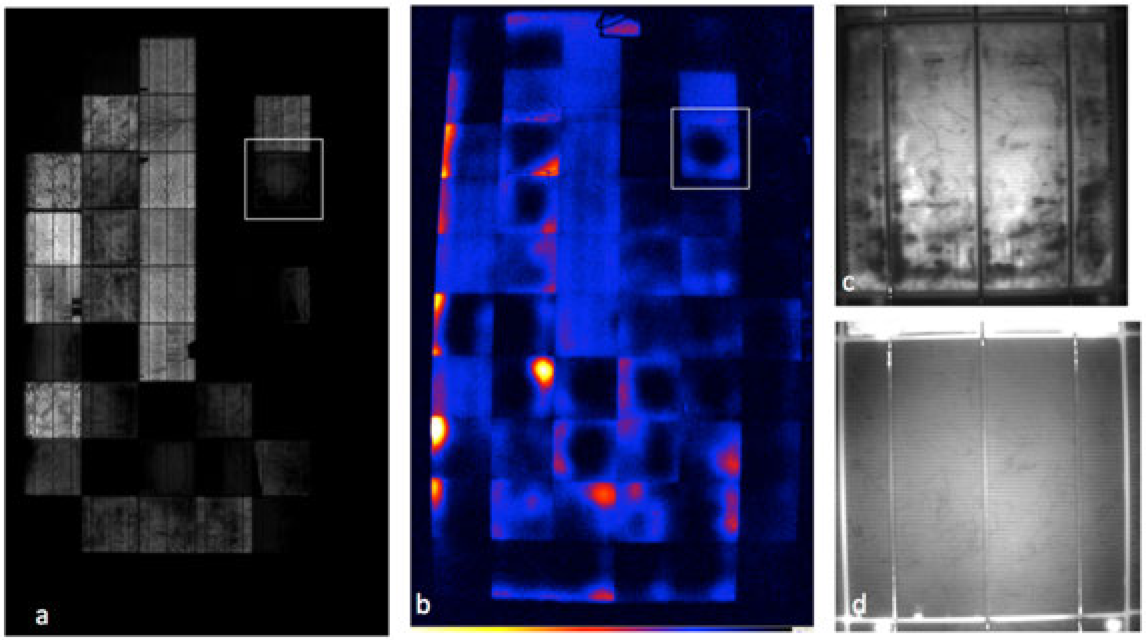
- Voltage
- Mounting/grounding
- Humidity, surface conductivity
- **Temperature**

What level of stress in an accelerated tests reproduces well the failure modes we seek to test for ?

How long should it be stressed at that temperature?
What is the acceleration factor?

Failure mode in fielded module

Module mounted in Florida, USA after ten months with the active layer biased at -1500 V during the day degraded to 0.35 P_{max_0}



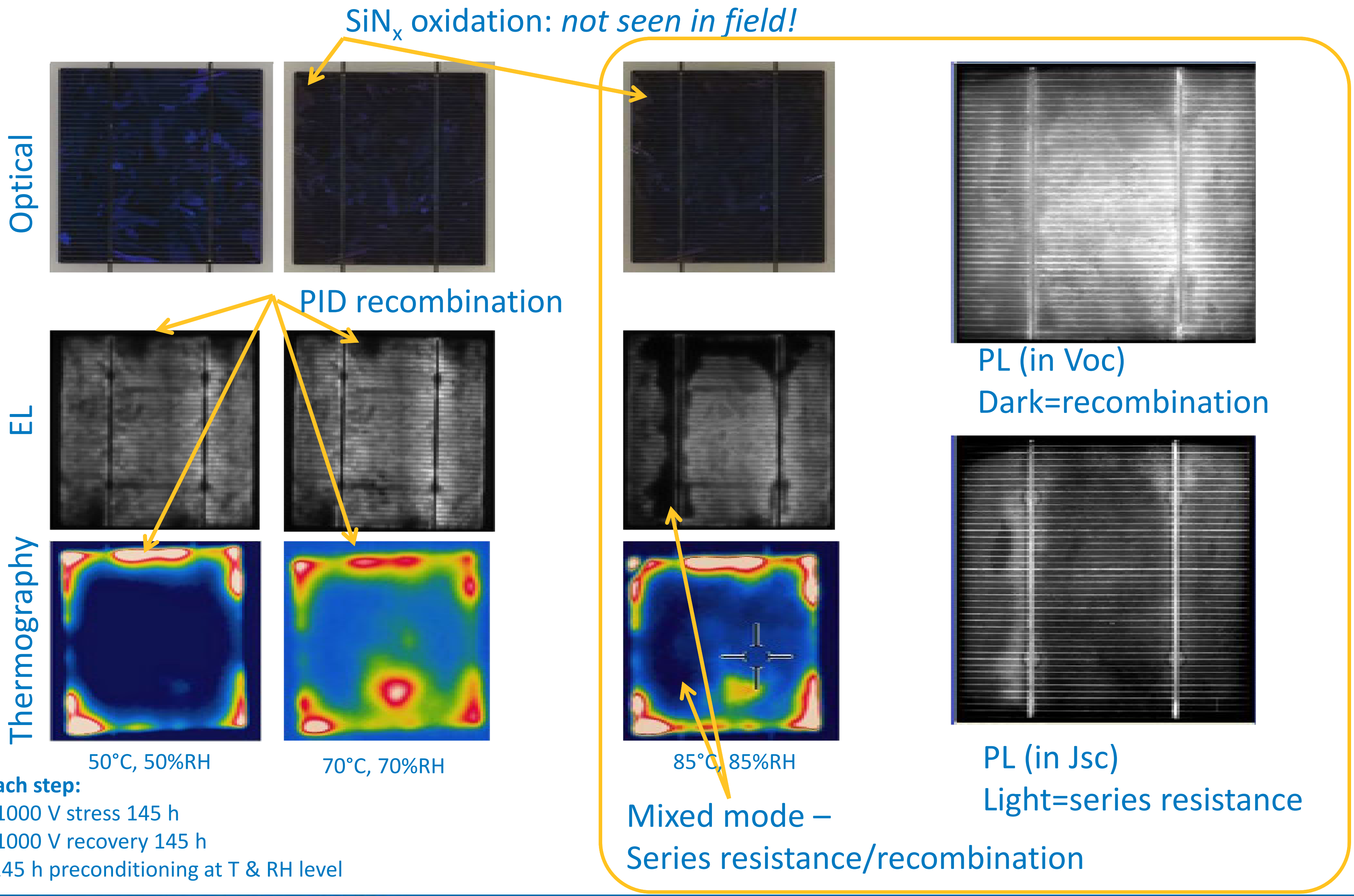
PL (in Voc)
Dark=recombination

PL (in Jsc)
Light=series resistance

EL   Thermography

Series resistance losses, as seen in chamber tests, are not yet observed in the field

Step-stress for determination of failure mode

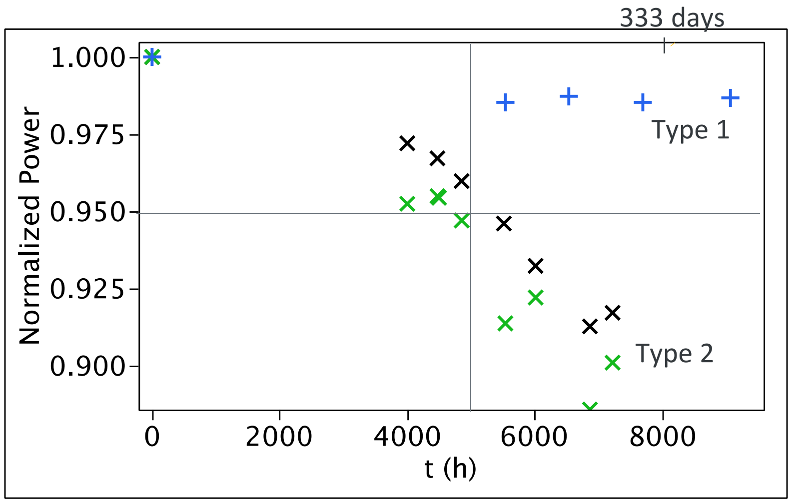


Each step:
–1000 V stress 145 h
+1000 V recovery 145 h
(145 h preconditioning at T & RH level

Performance of two module types

In Florida, USA

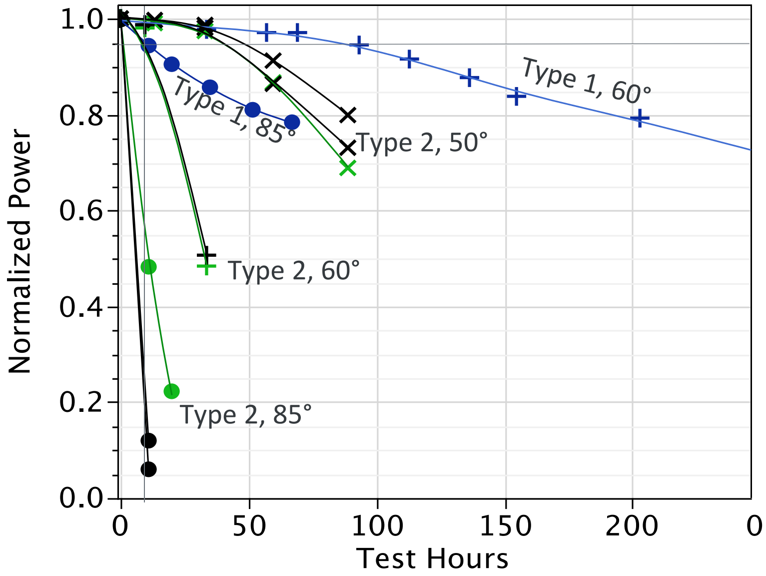
–600 V applied logarithmically with irradiance



In chamber

85% RH

–600 V

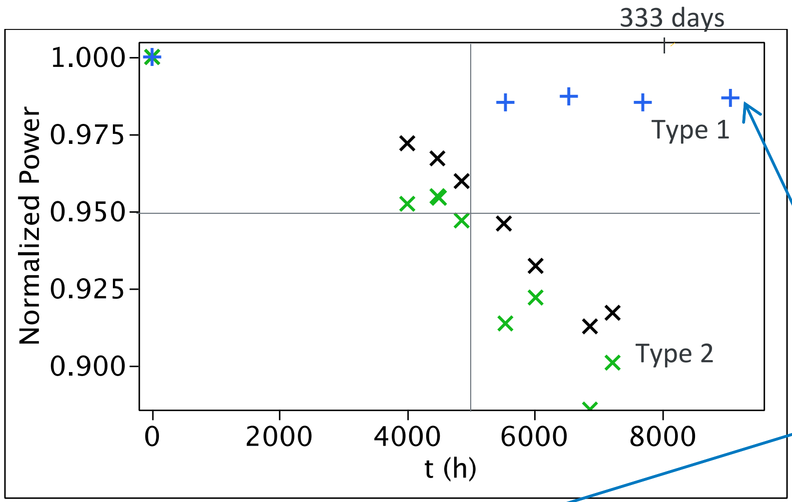


More details at 2012 IEEE PVSC

Performance of two module types

In Florida, USA

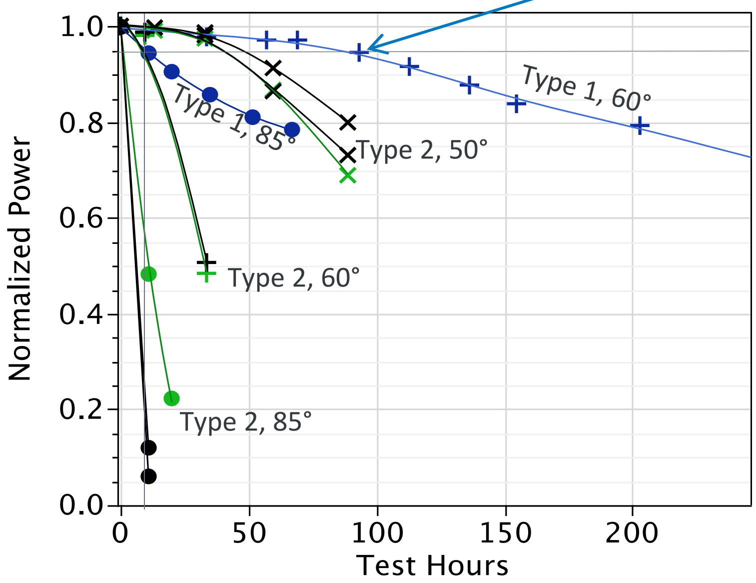
–600 V applied logarithmically with irradiance



In chamber

85% RH

–600 V

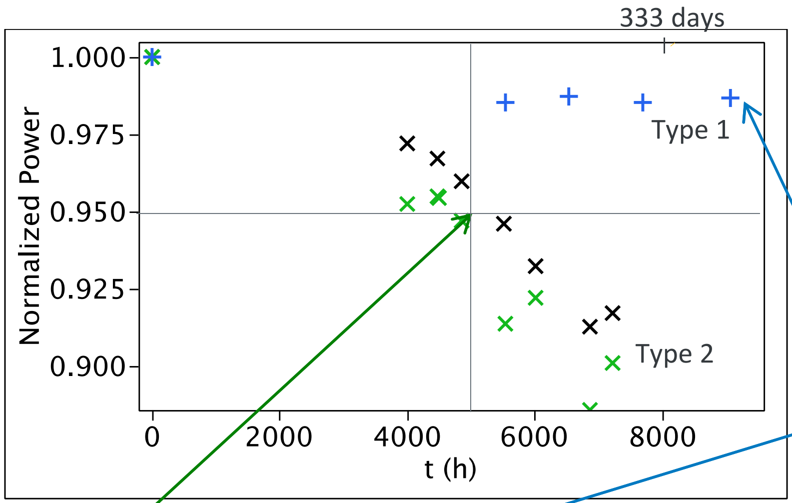


Module Type 1: Acceptable performance in the field survives with less than 5% power drop in chamber with 85% RH, 60°C, rated system voltage, for 96 h

Performance of two module types

In Florida, USA

–600 V applied logarithmically with irradiance

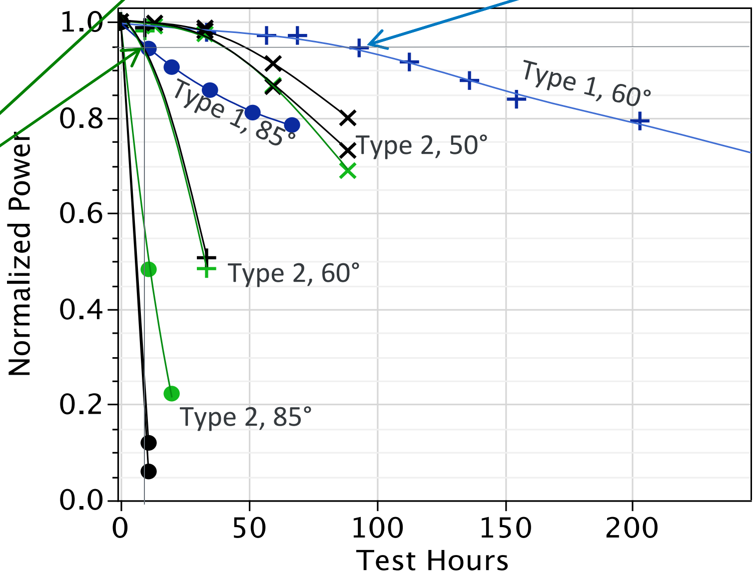


Module Type 1: Acceptable performance in the field survives with less than 5% power drop in chamber with 85% RH, 60°C, rated system voltage, for 96 h

In chamber

85% RH

–600 V

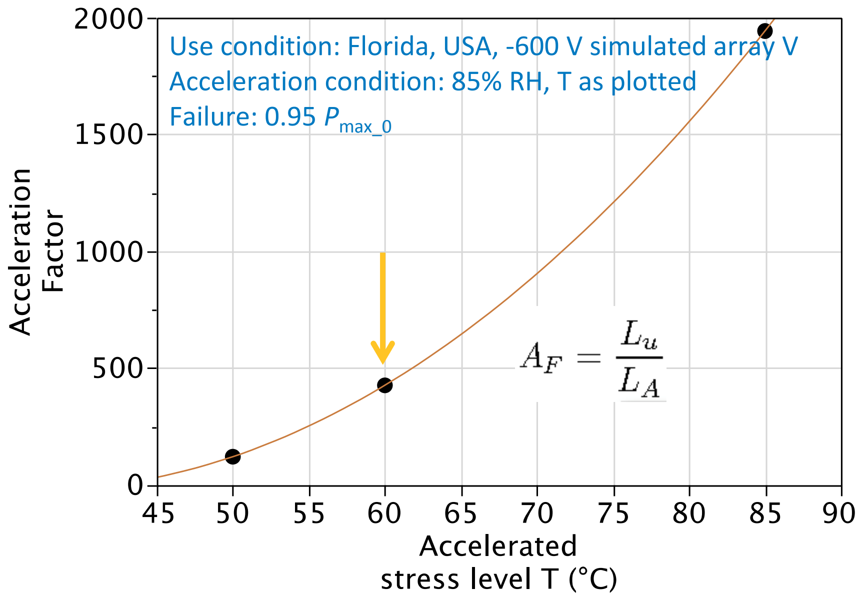


Module Type 2: 5% power drop in 4934 h in Florida and 12 h in chamber at 60° C, (considered a failing module)

More details at 2012 IEEE PVSC

Test levels

- Voltage
- Mounting/grounding
- Humidity, surface conductivity
- **Temperature**



Draft standard:

"The following conditions shall be applied:

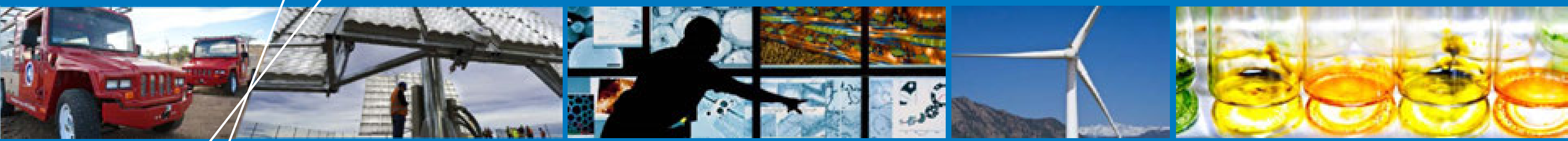
- Chamber air temperature 60 °C ± 2°C
- Chamber relative humidity 85 % ± 5 % RH
- Test duration 96 h
- Voltage: module rated system voltage and polarities" (one module per polarity)"

AF = 427 at 60°C, 85% RH
Test duration, 96 h
Field equivalent: 4.7 y

Next steps: Testing at multiple labs

Determine reproducibility

- **2-3 samples per condition**
  - Presumably 85% RH-60°C, but consider alternates for post IEC-61215 tests
- **5 labs**
  - NREL
  - ASU
  - …let us know if you are interested!
- **Samples from 3 manufacturers**



Thank you

Mechanical Load Test / PI Berlin AG

Potential Induced Degradation Effects and Tests for Crystalline Silicon Cells

<u>Simon Koch</u>

J. Berghold, D. Nieschalk, C. Seidel, O. Okoroafor, S. Lehmann, S. Wendlandt

PI Photovoltaik Institut Berlin AG

Photovoltaik-Modultechnologie

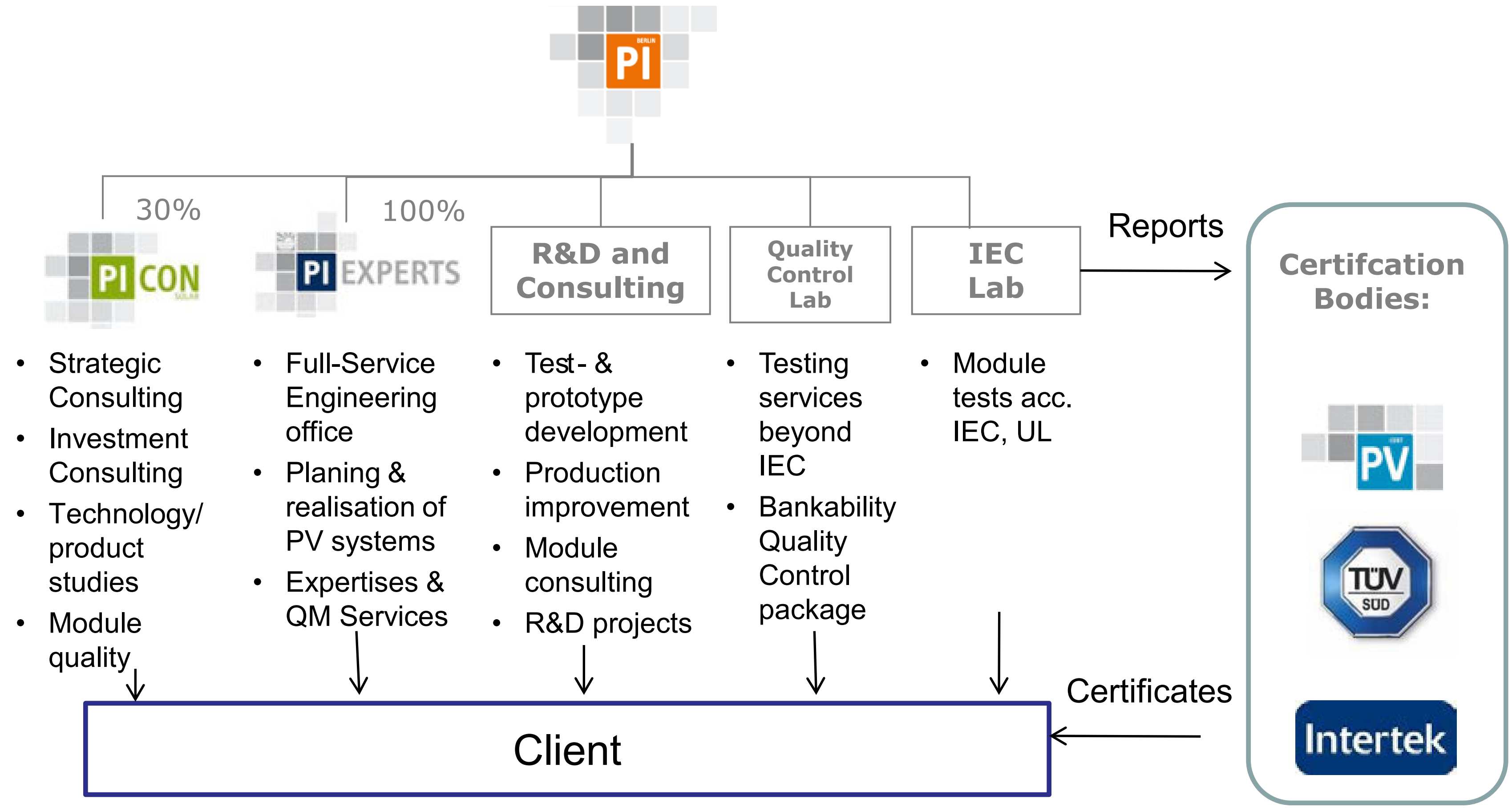
Testing | Consulting | Development | Research

Wrangelstr.100, 10997 Berlin, Germany

Overview

1. PI-Berlin AG
2. Introduction Potential induced degradation
3. PID influencing test parameters
4. The influence of the anti reflective coating
5. The influence of the encapsulant
6. Outlook
7. Summary

PI Berlin Business Units



PI Berlin Business Units

Clients	Service
• Manufacturers	Certificates, Re-Testing, Pre-testing, bench-marking, Test-to-Failure tests
• Turn-key Suppliers	see above
• Component Suppliers	Lamination service, screening, extended IEC tests (double, triple)
• Wholesalers, OEM-Clients	Factory Inspection, Bench Marking, Quality Control, Certification, Analysis of Field returns
• System developers, Owners	Incoming Module Quality Control, Systems engineering
• Banks, Investors	Expertise in module failure probability
• Assurances	Failure analysis, Module repair
• Universities, Institutes, Industrial R&D teams	Project partnering in industrial R&D projects

Introduction

1978, Hoffman and Ross (JPL), "Environmental Qualification Testing of Terrestrial Solar Cell Modules"

Polarization (Sunpower 2005)

	N-type silicon	P-type silicon	Amorphus/micro morphus Silicon	CIGS	CdTe
+ potential	x				
- potential		x	x		

PID (SOLON 2009)

TCO Corrossion (Mon 1985)

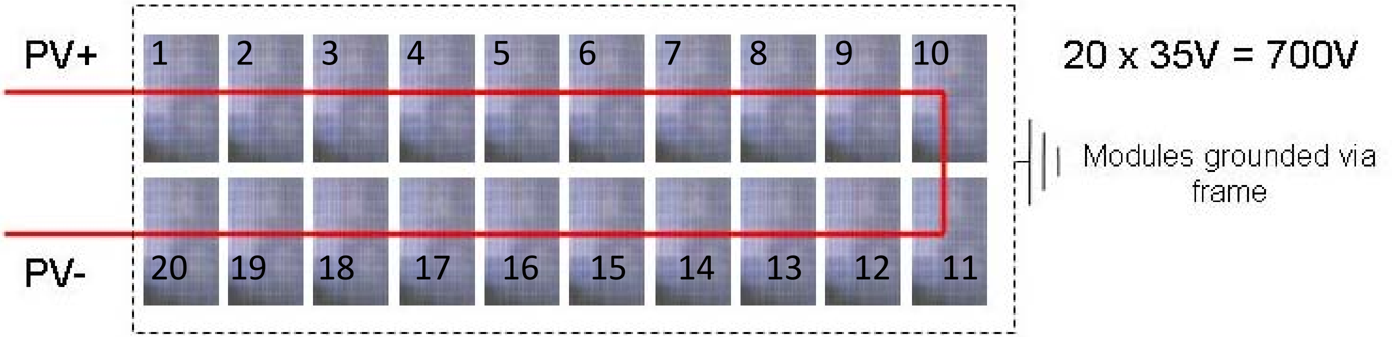
Potential induced degradation subsumption and definition

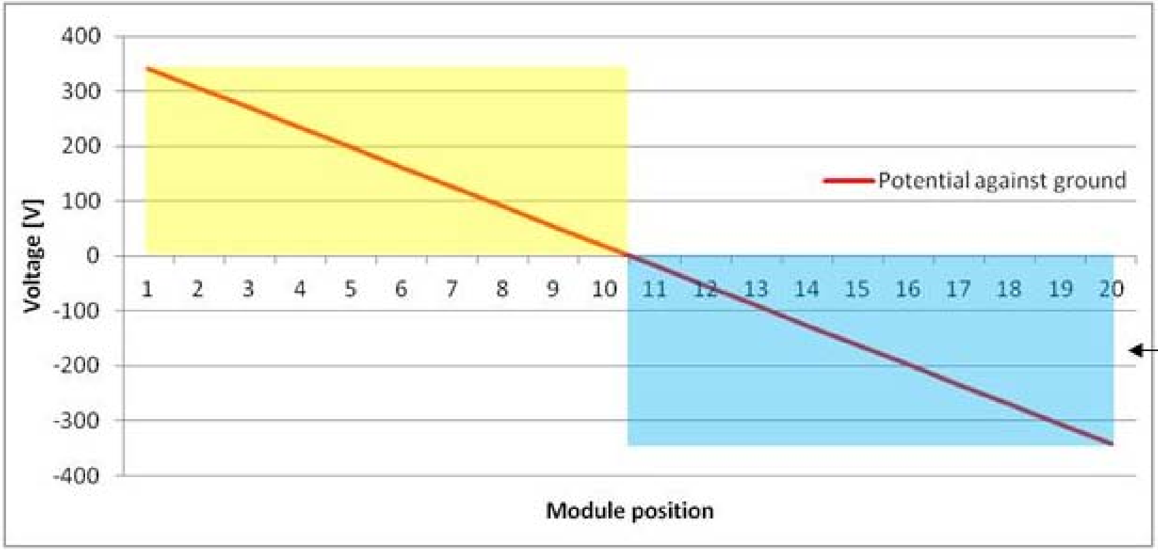
	N-type silicon	P-type silicon	Amorphus/micro morphus Silicon	CIGS	CdTe
+ potential	R&D	R&D	R&D	R&D	R&D
- potential	R&D	R&D	R&D	R&D	R&D

Potential induced degradation ≠ Module behaviour induced by voltage stress

- Used cell technology (p-type, n-type, thin film, etc.)
- Positive or negative potential relative to ground

Which modules have a risk of PID in the field?



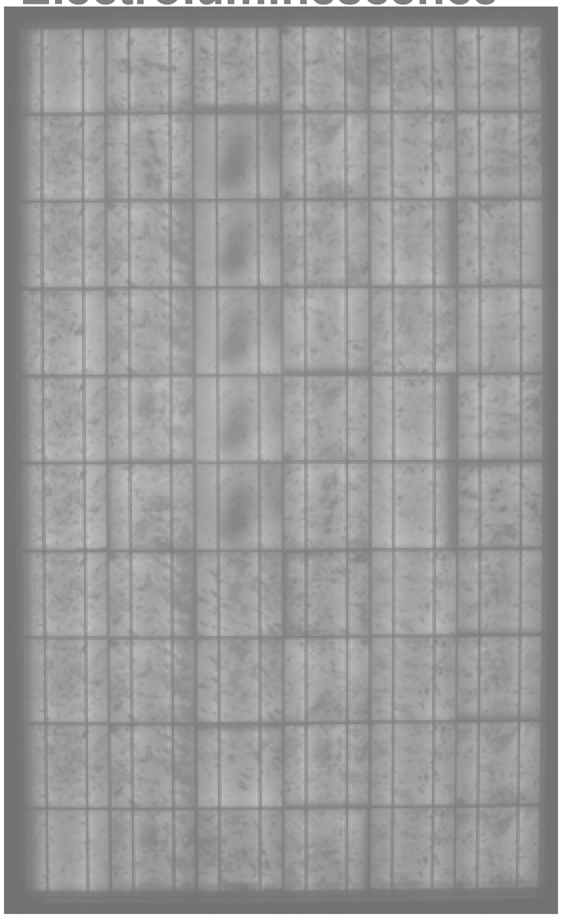


PID effect for p-type silicon cell technologies

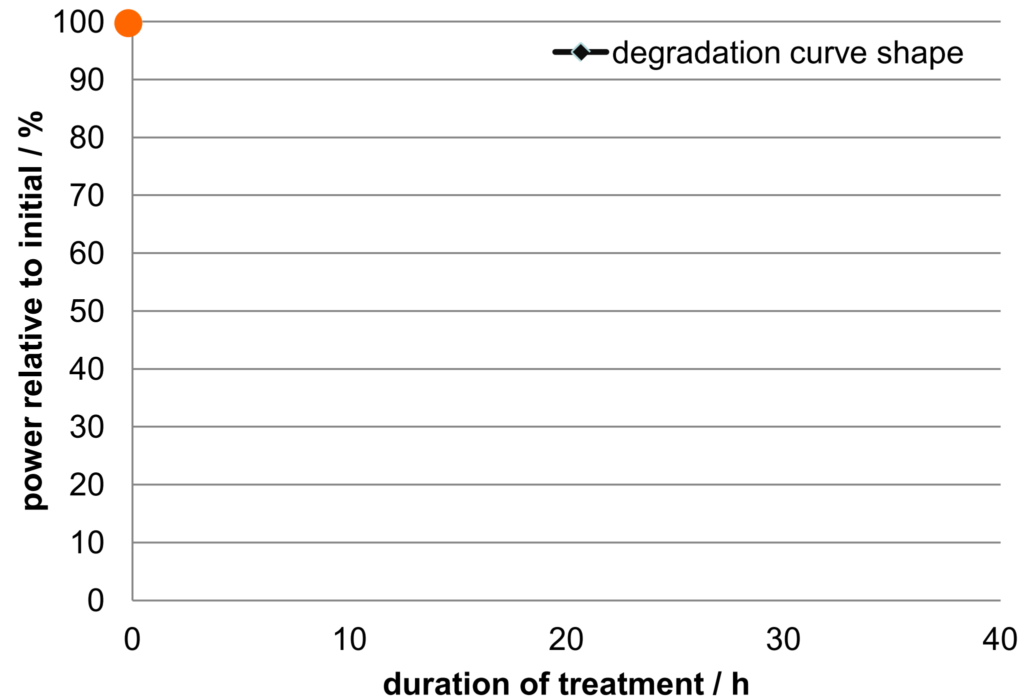
Fig. 1: Potential against ground module string with floating potential

Damp heat 85 C/85% r.H. -1000V (PID Test)

Electroluminescence

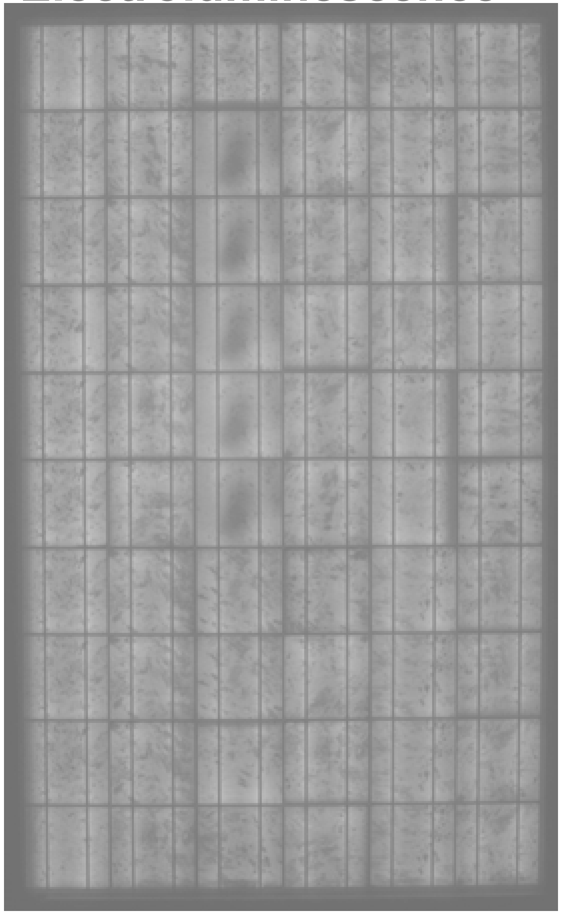


STC Power

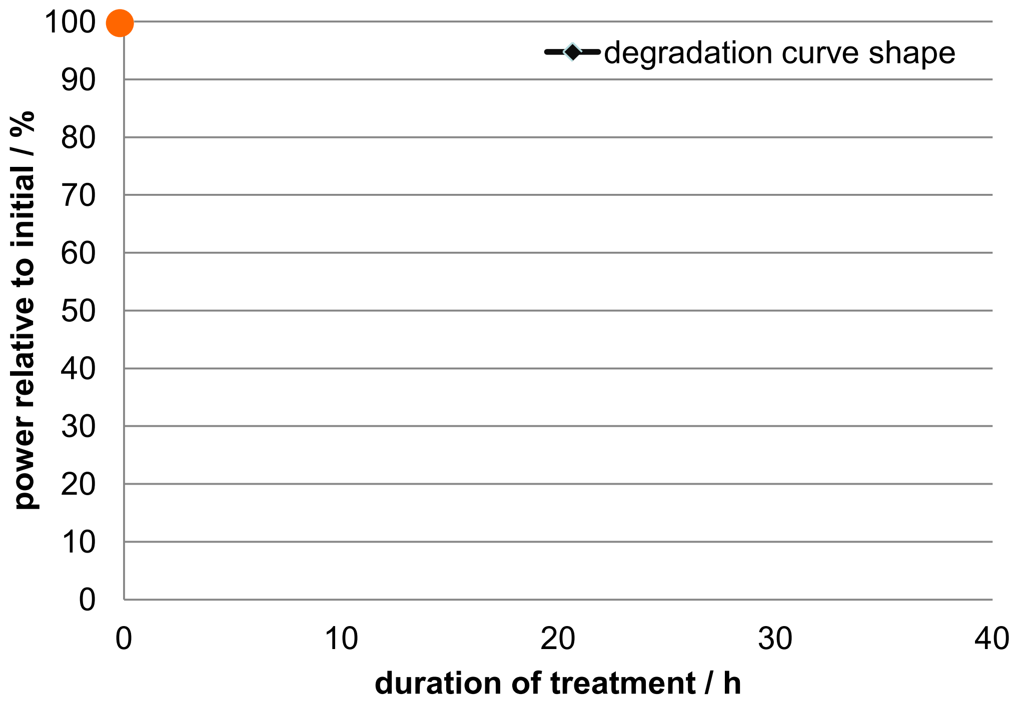


Damp heat 85 C/85% r.H. -1000V (PID Test)

Electroluminescence

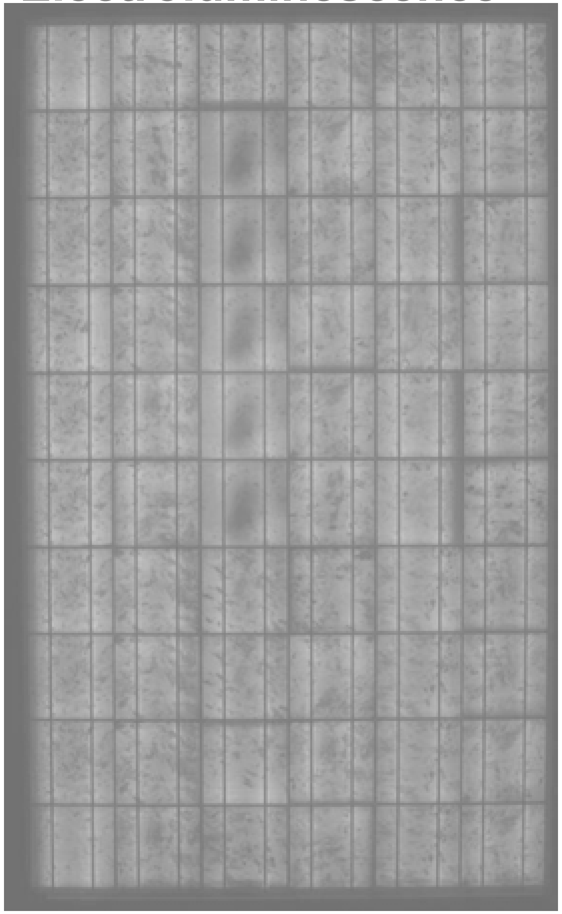


STC Power



Damp heat 85 C/85% r.H. -1000V (PID Test)

Electroluminescence



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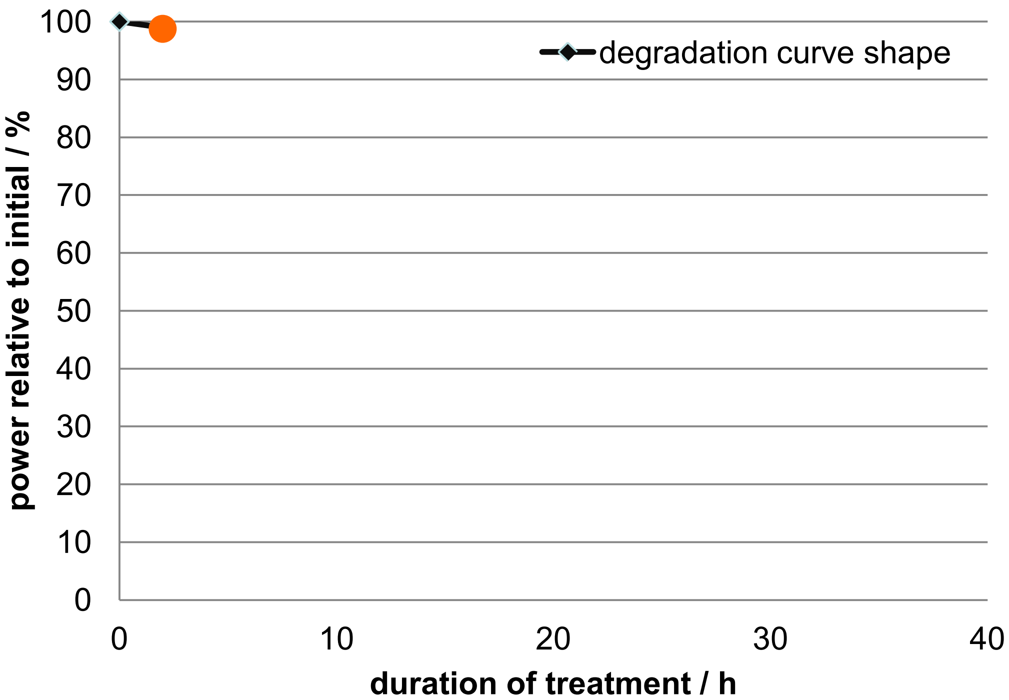
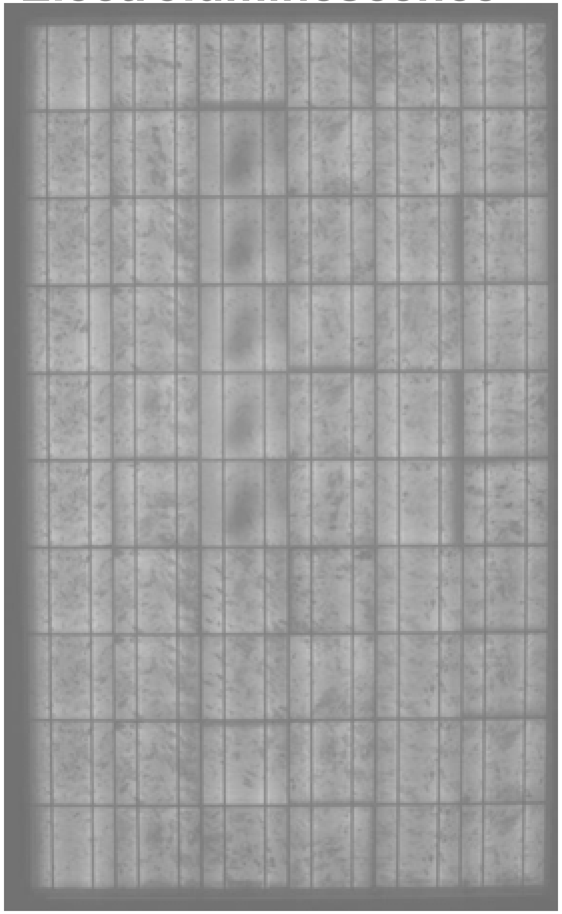


Damp heat 85 C/85% r.H. -1000V (PID Test)

Electroluminescence



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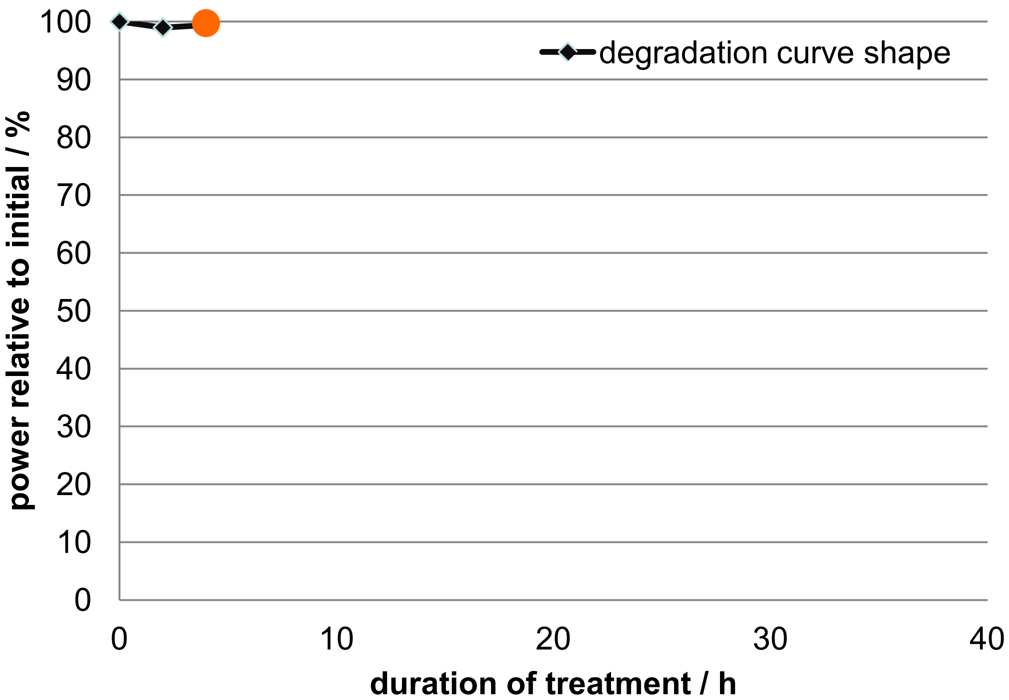

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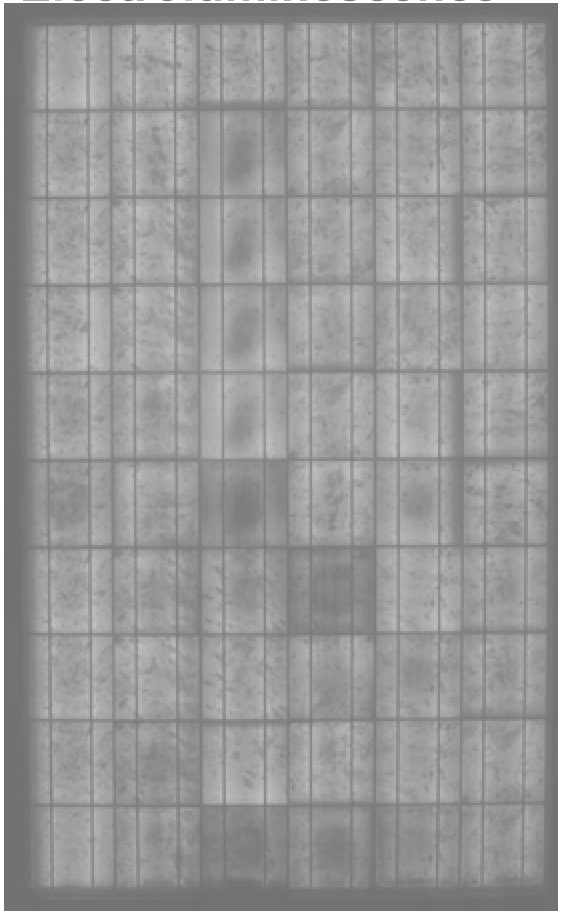
Electroluminescence



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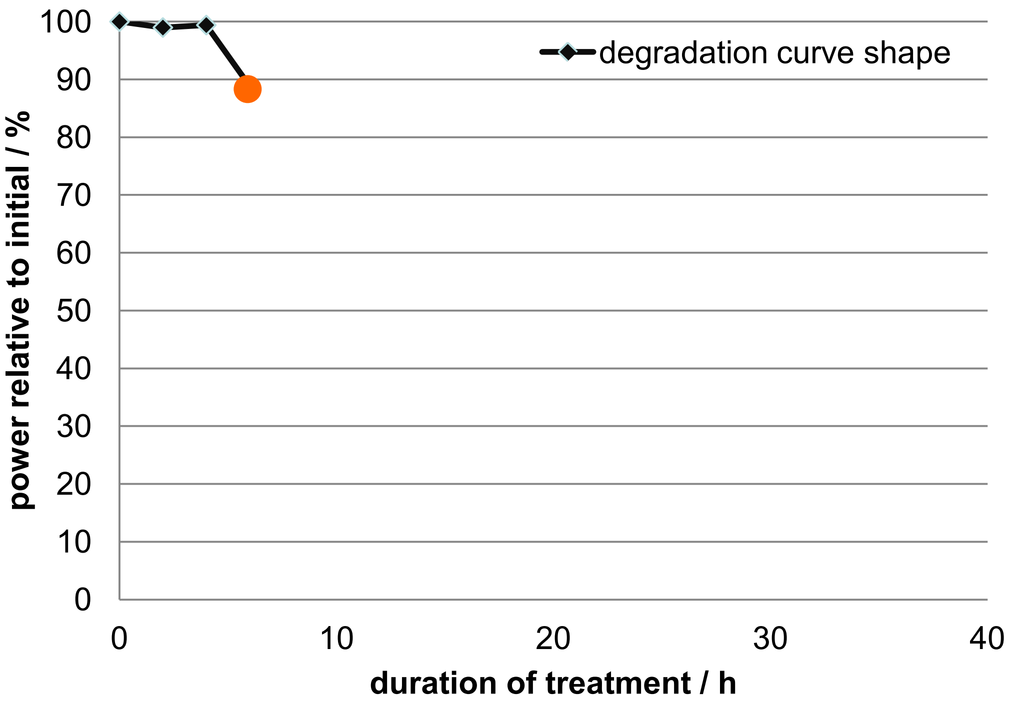

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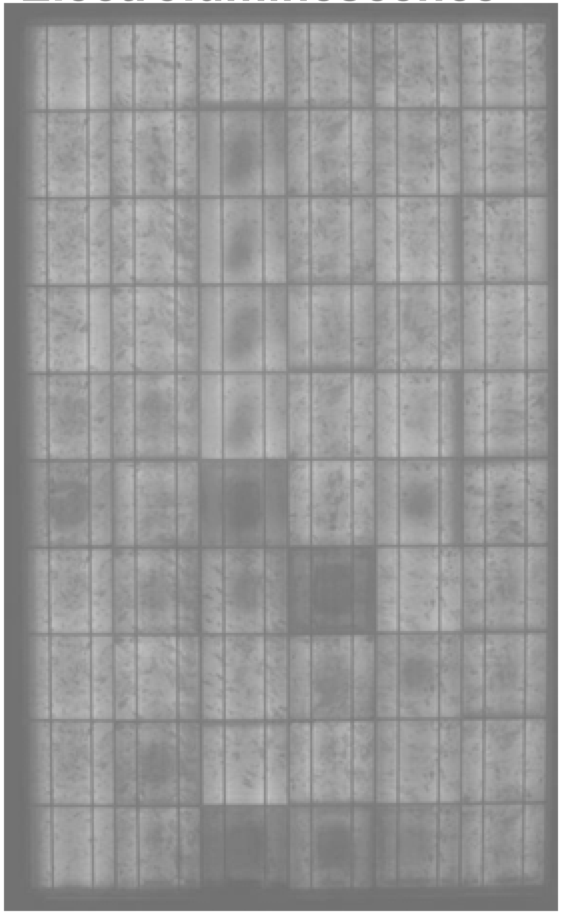
Electroluminescence



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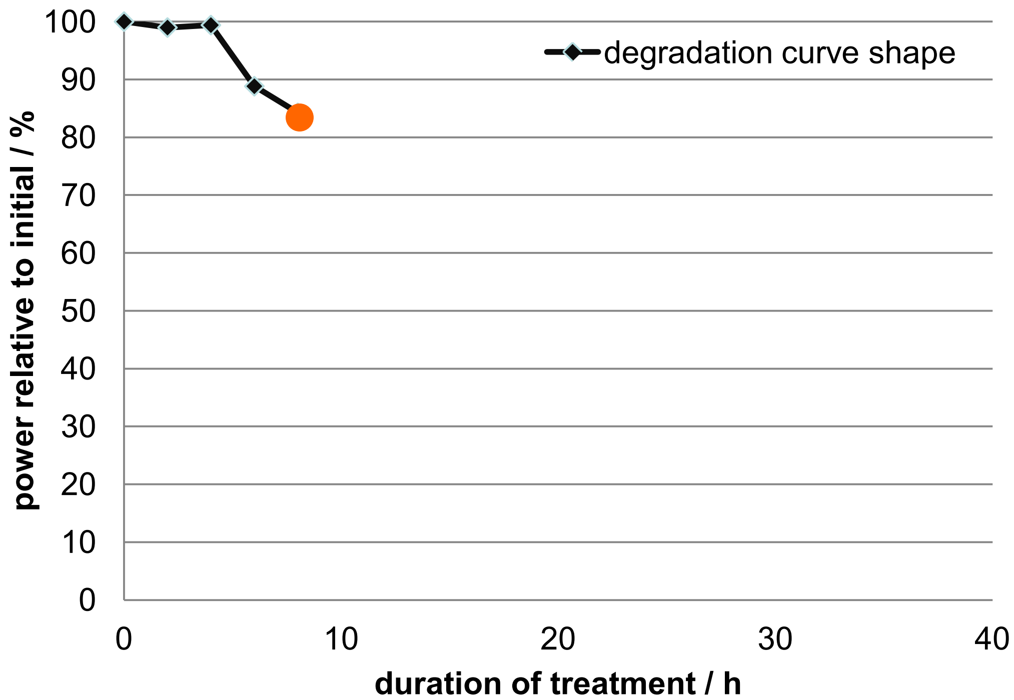
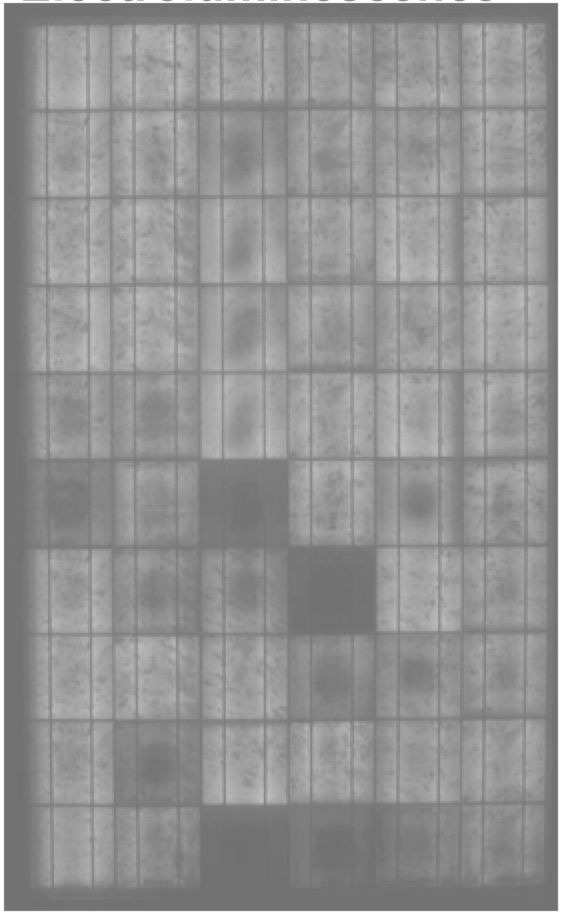


Damp heat 85 C/85% r.H. -1000V (PID Test)

Electroluminescence



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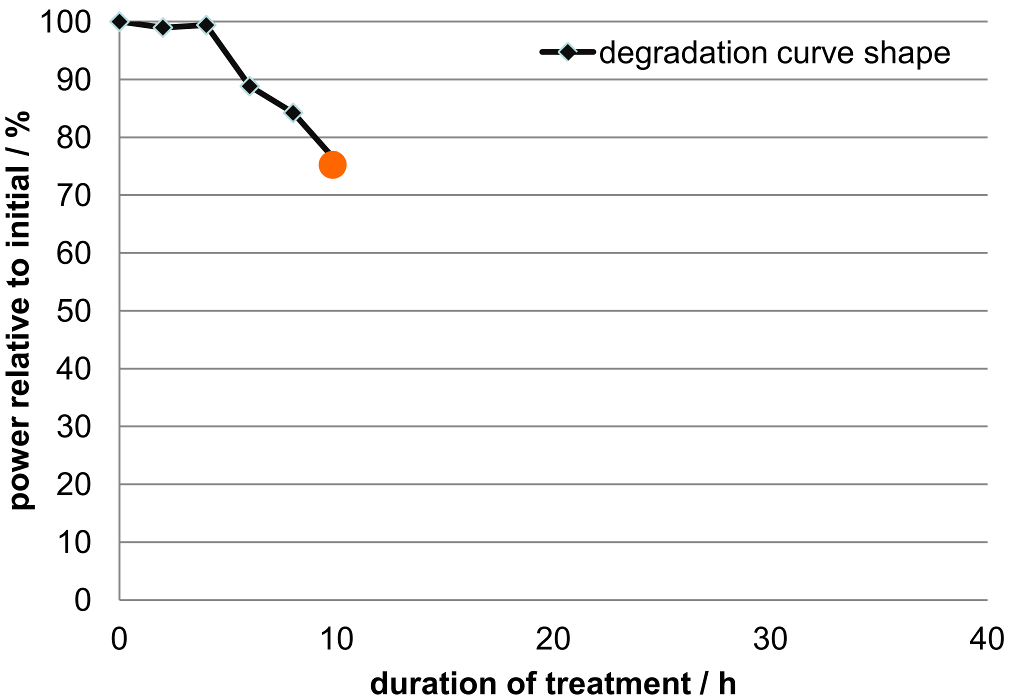

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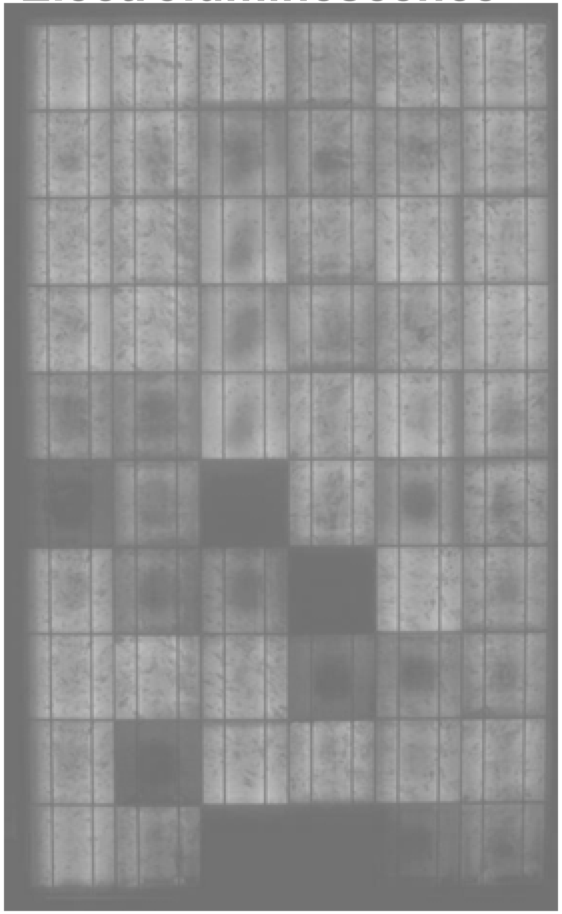
Electroluminescence



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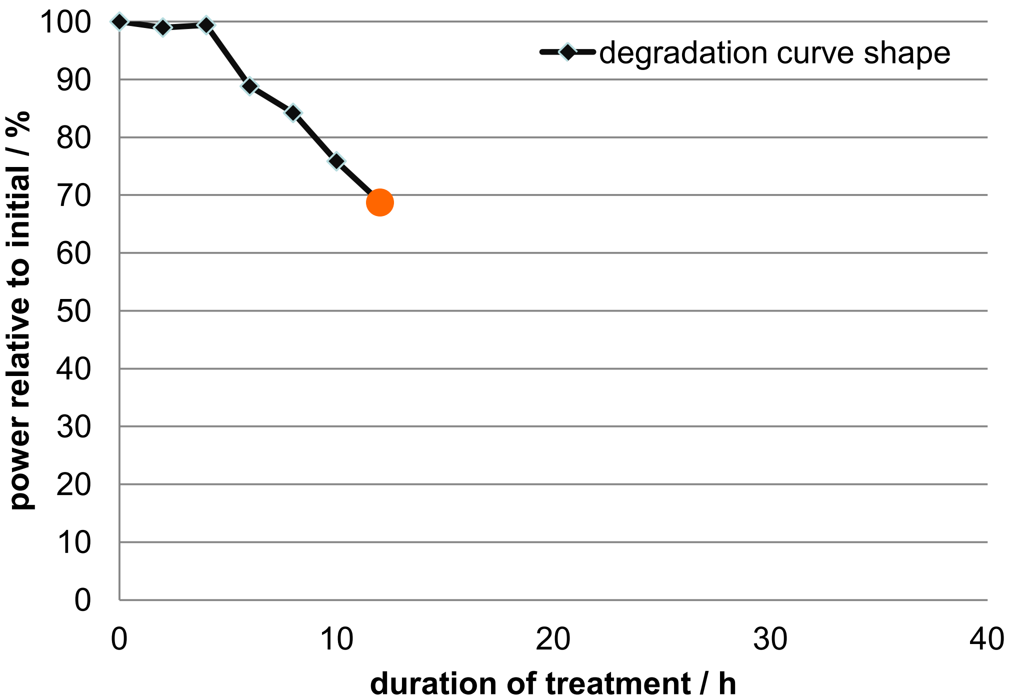

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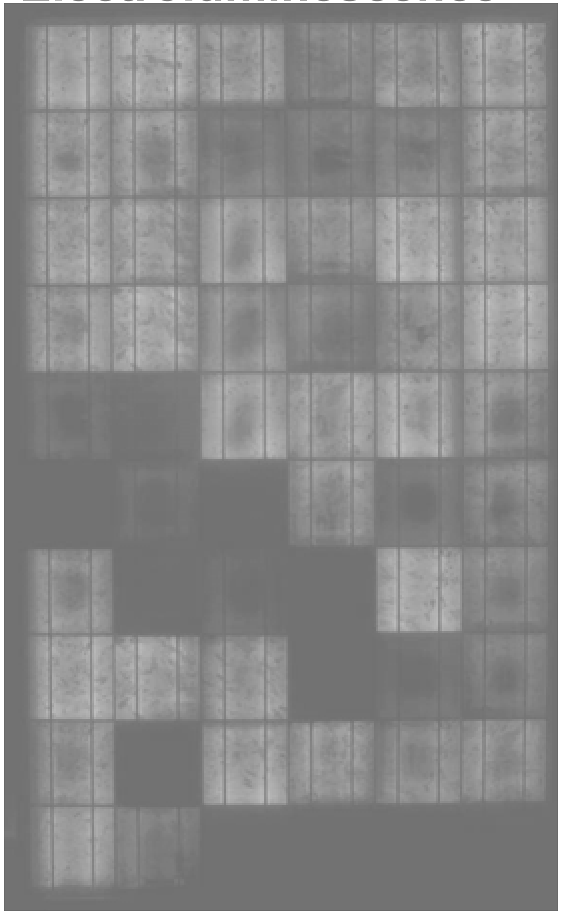

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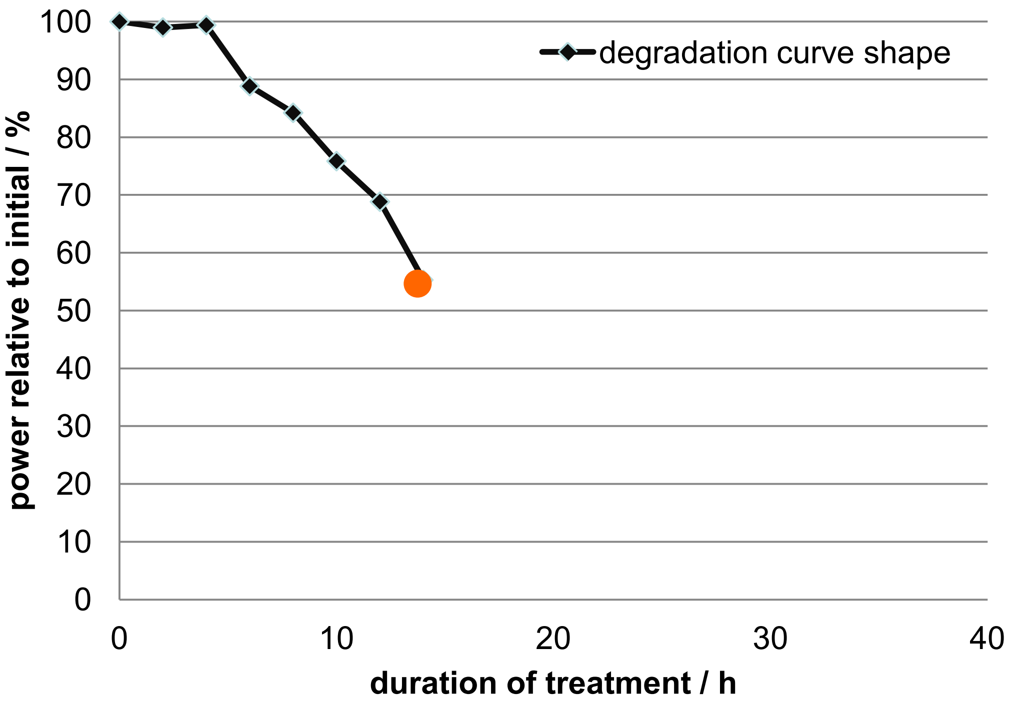

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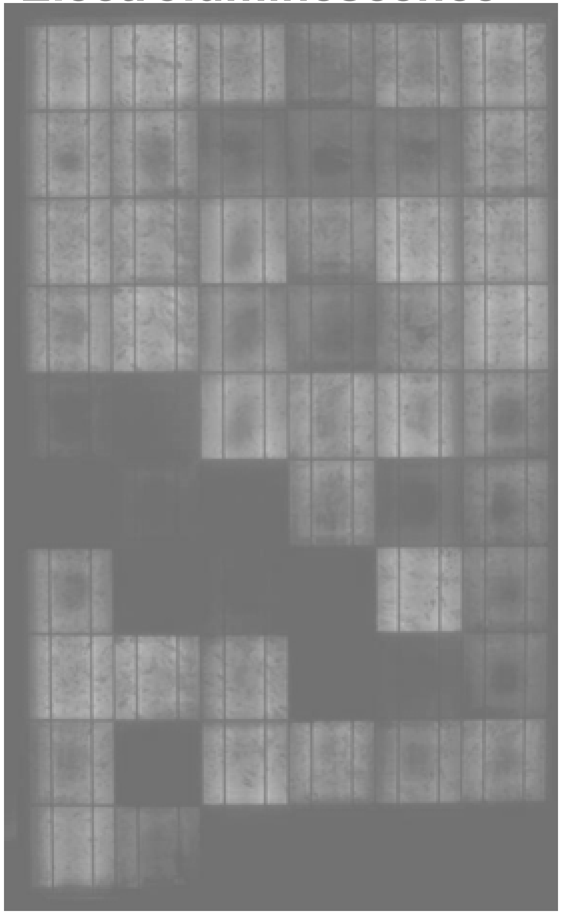

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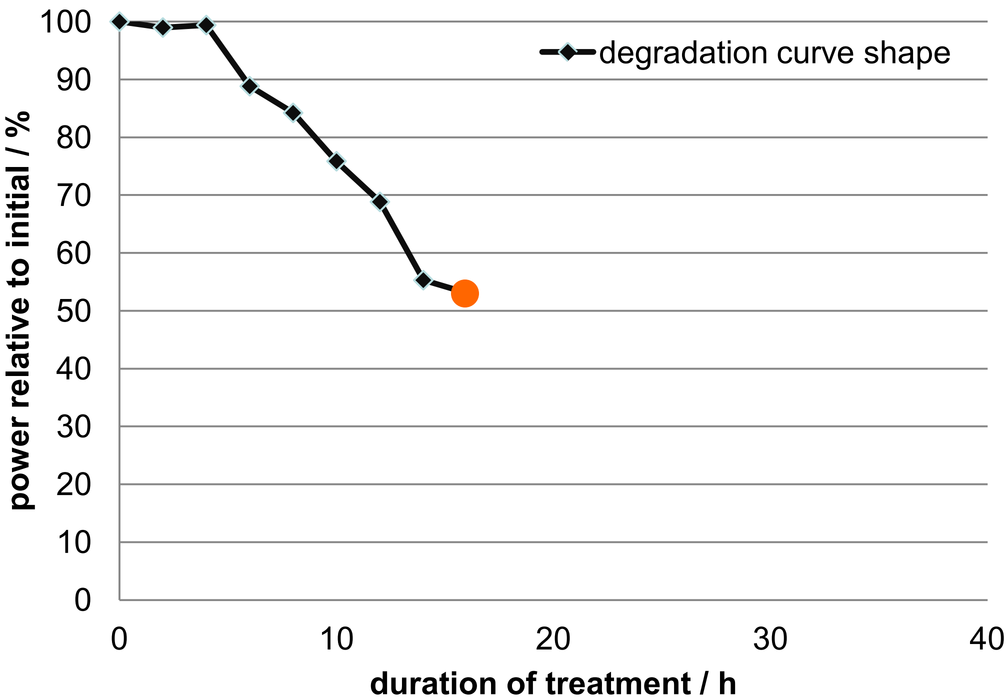

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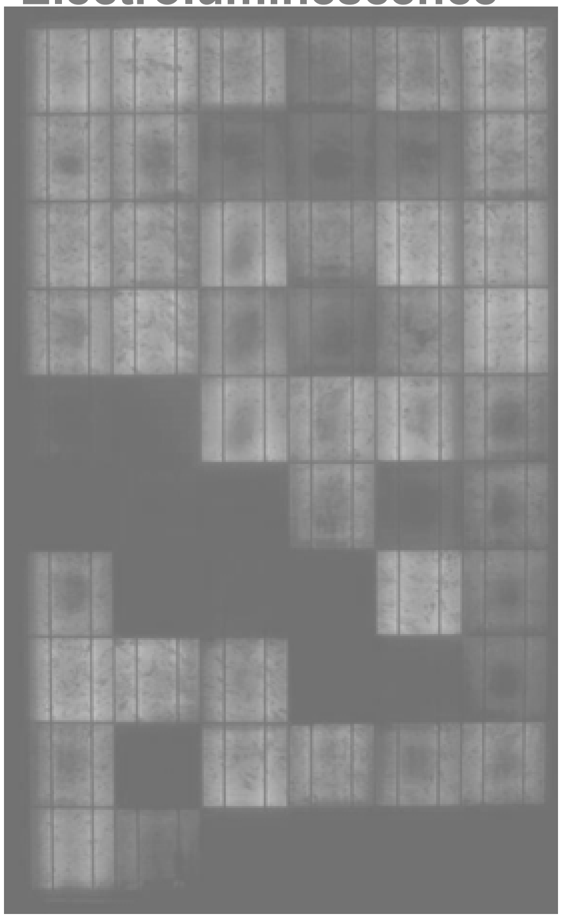

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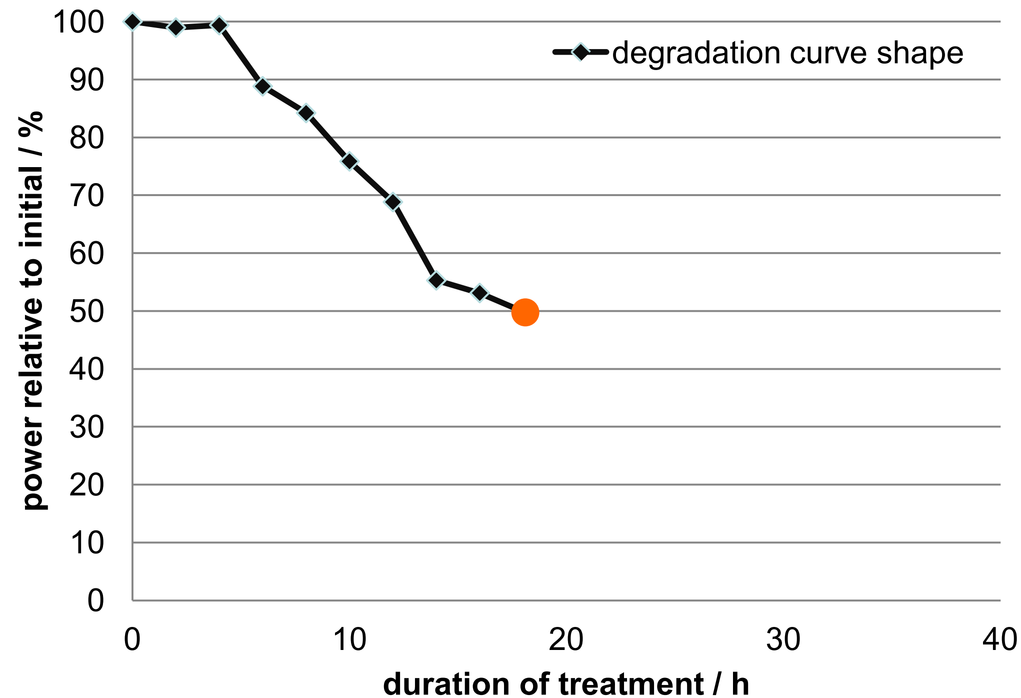

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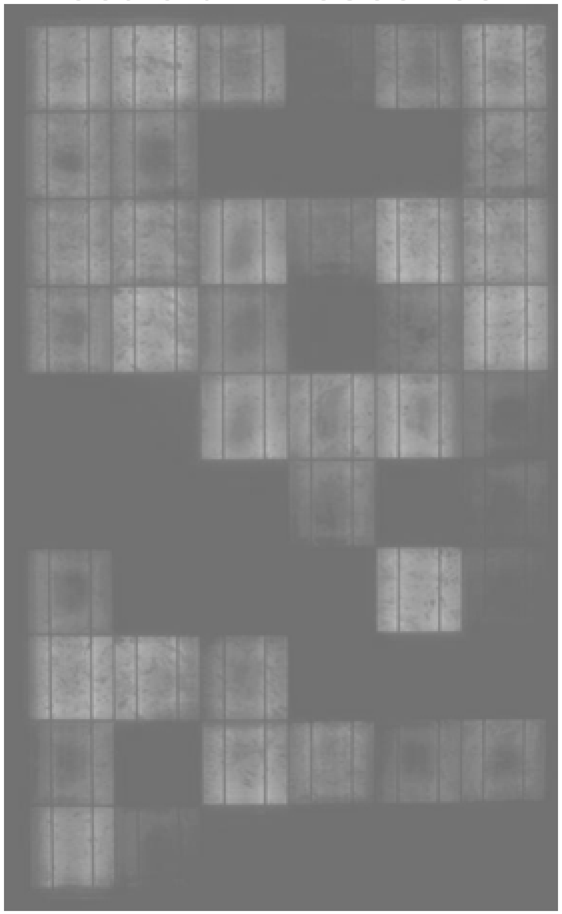

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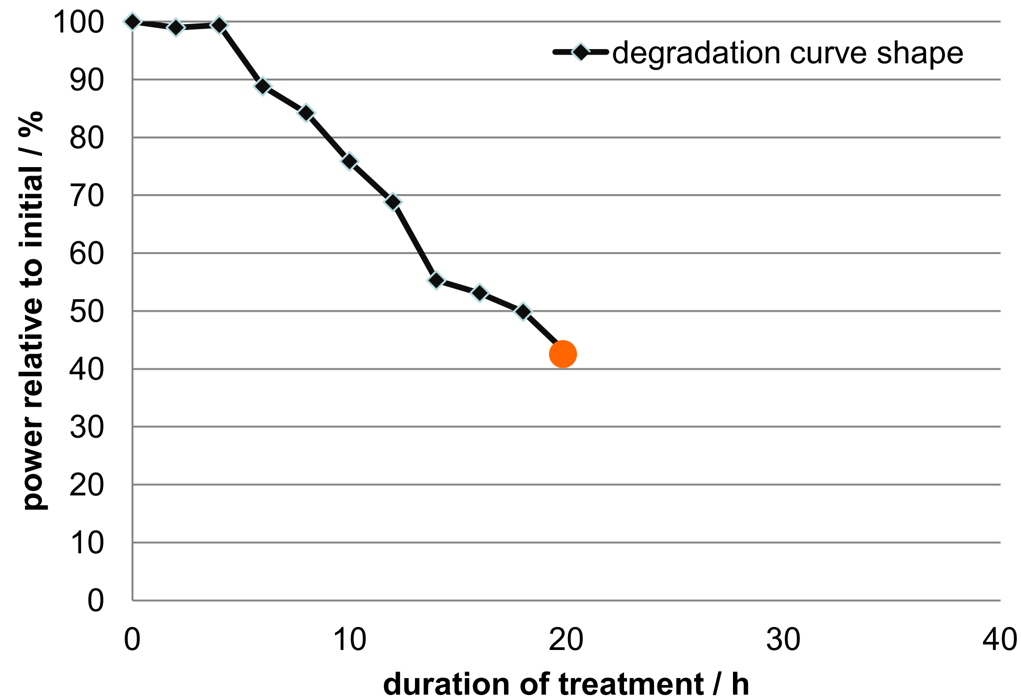

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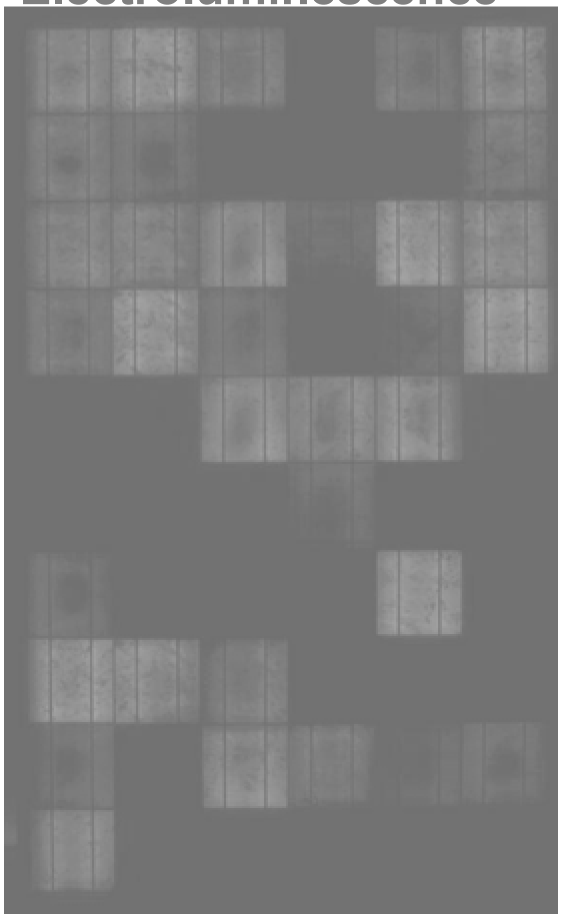

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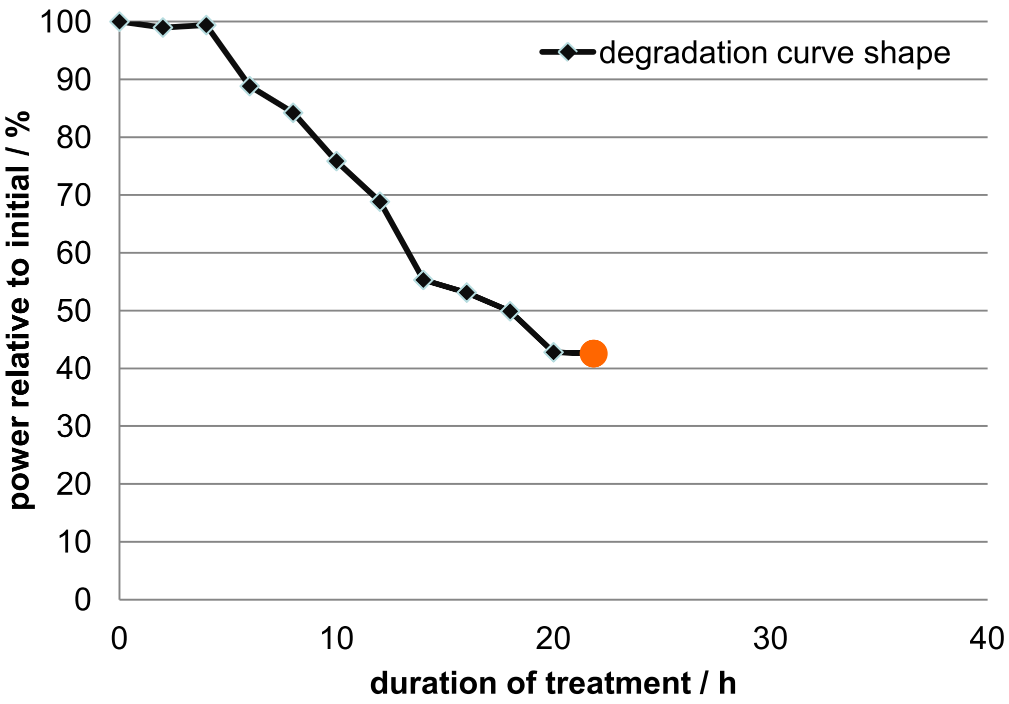

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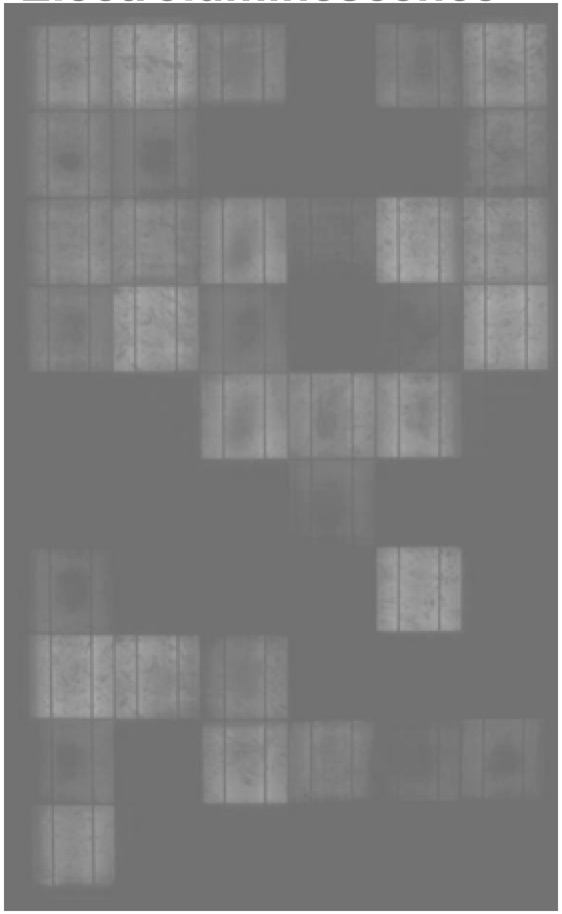

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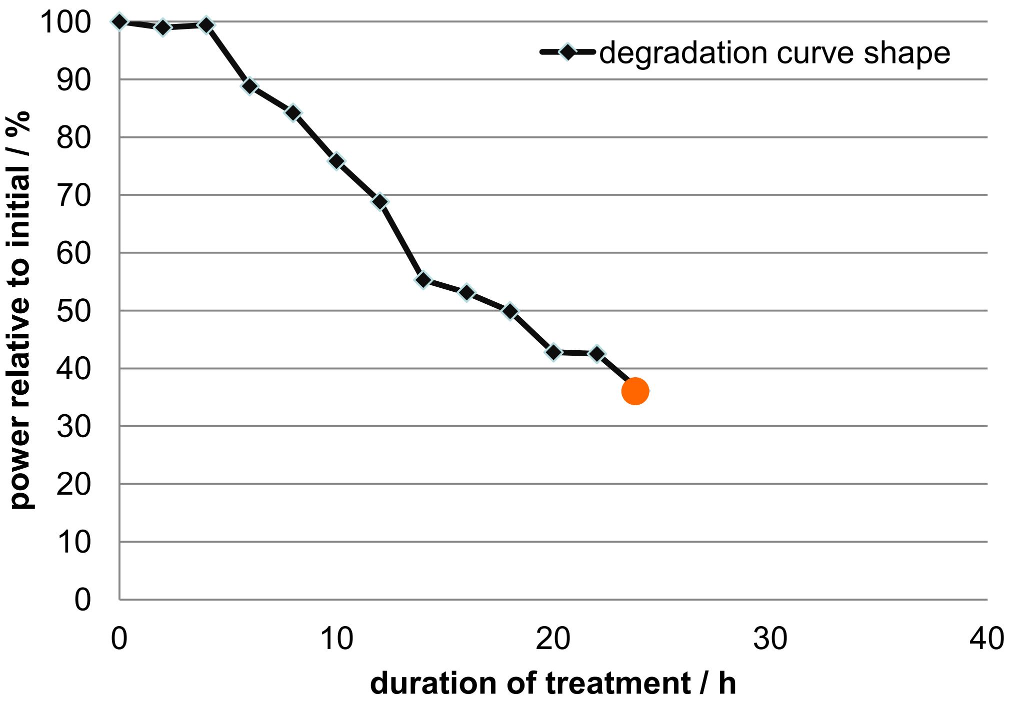

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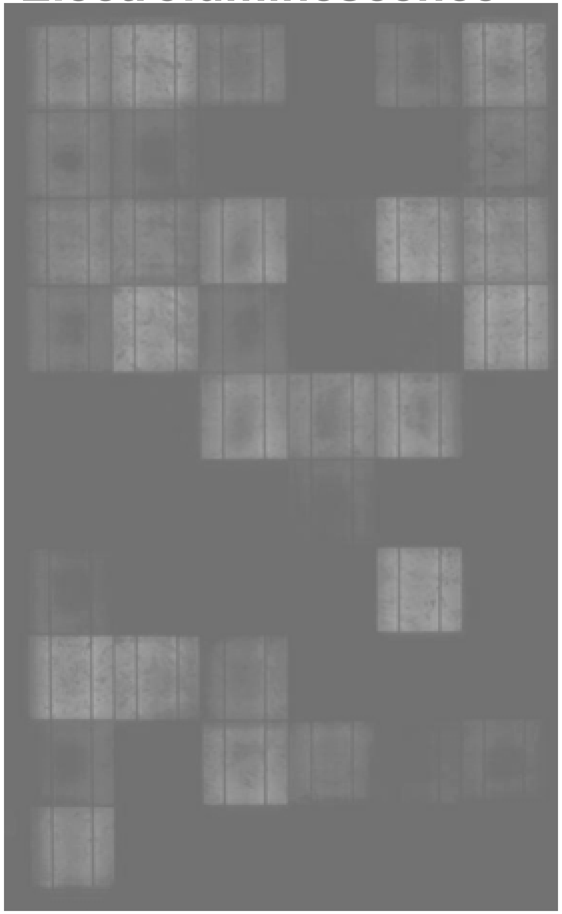

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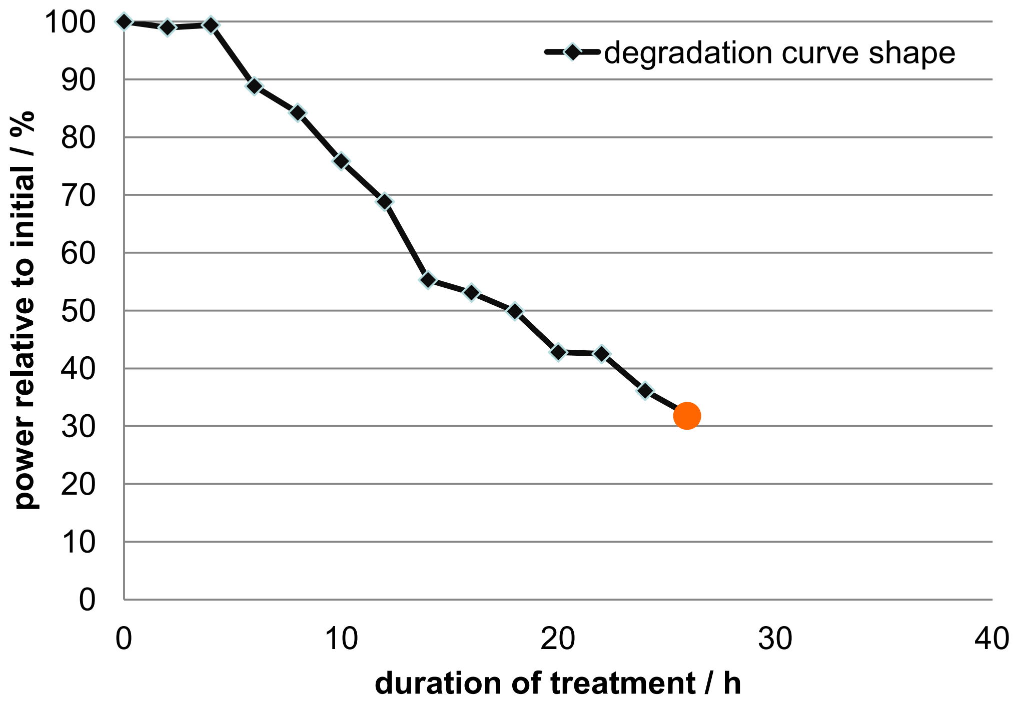

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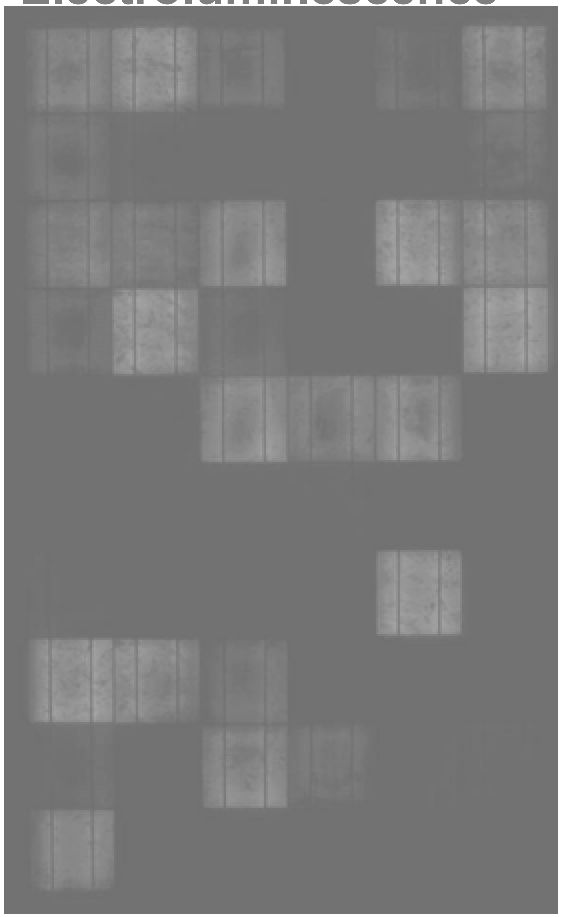

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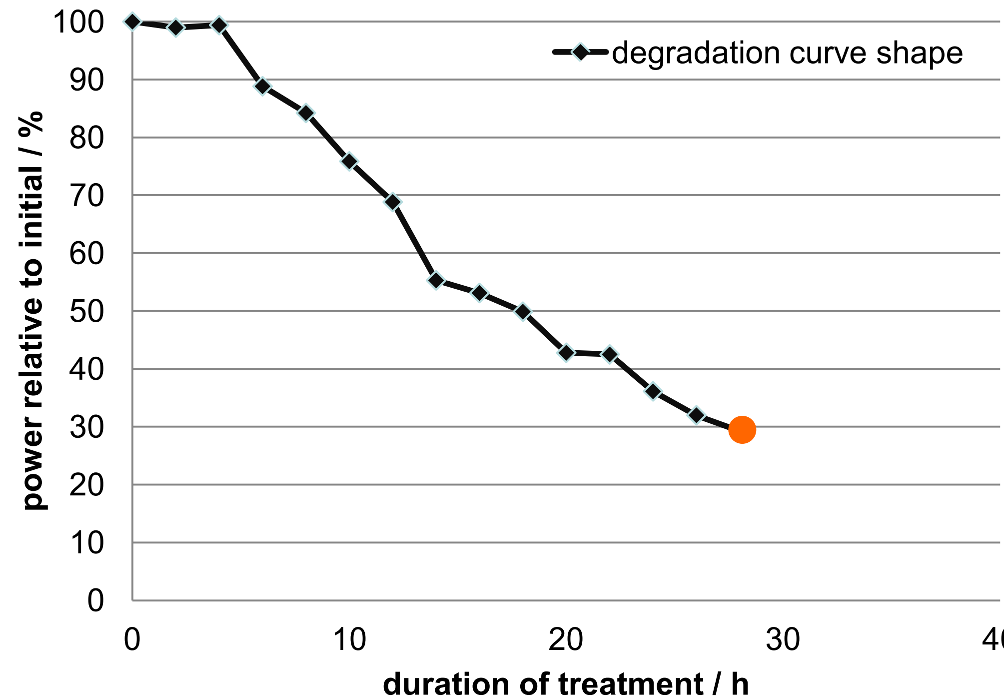

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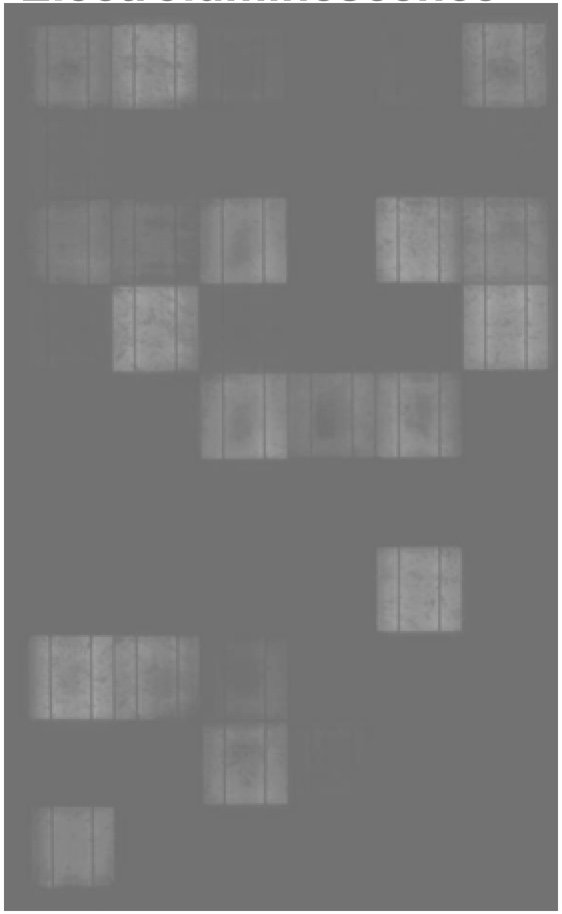
Electroluminescence



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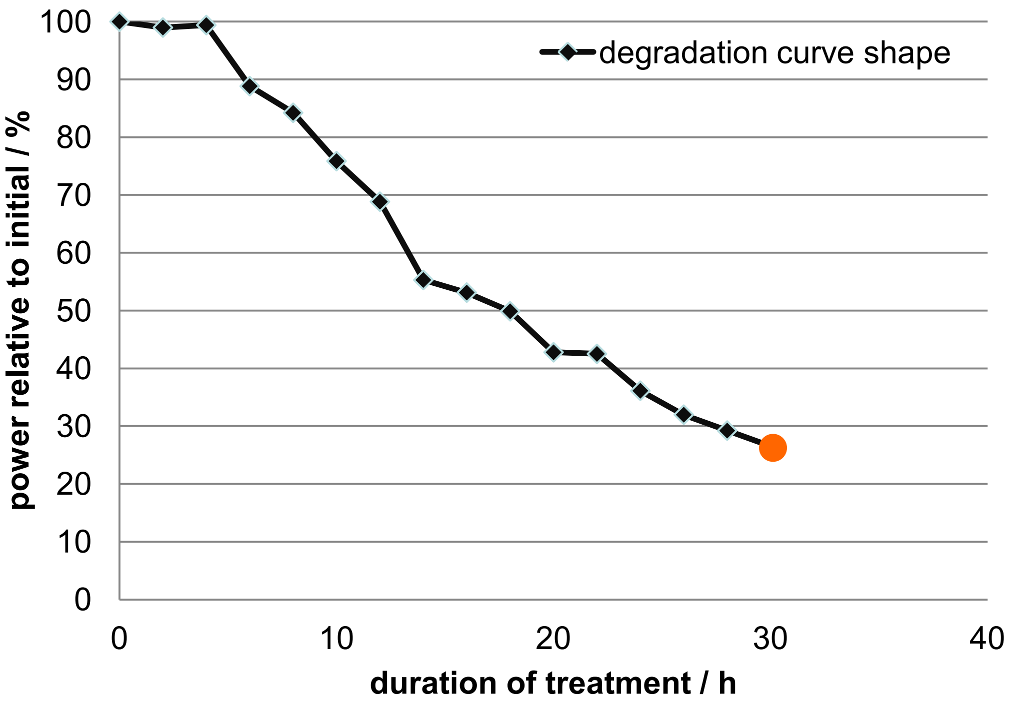

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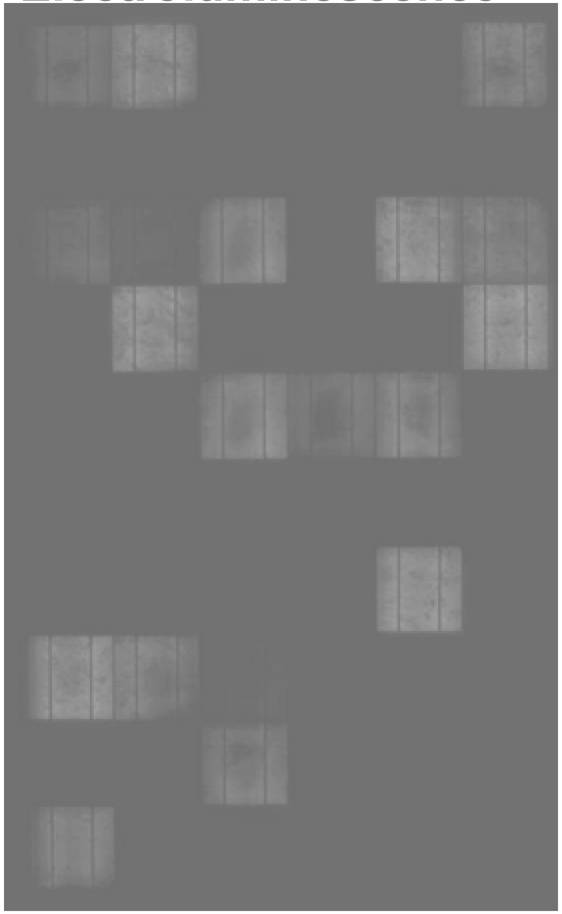
Electroluminescence



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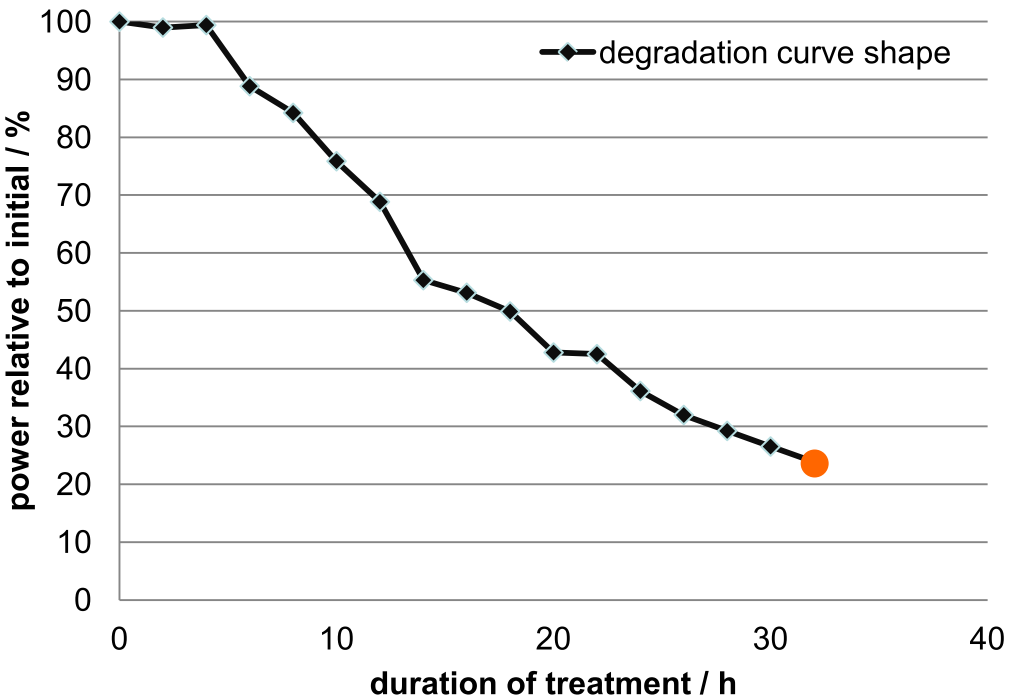

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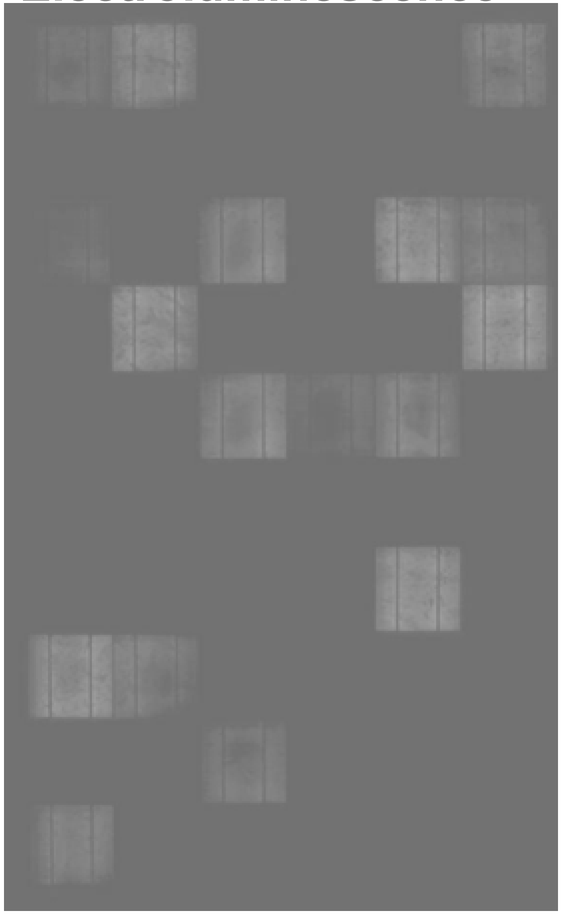
Electroluminescence



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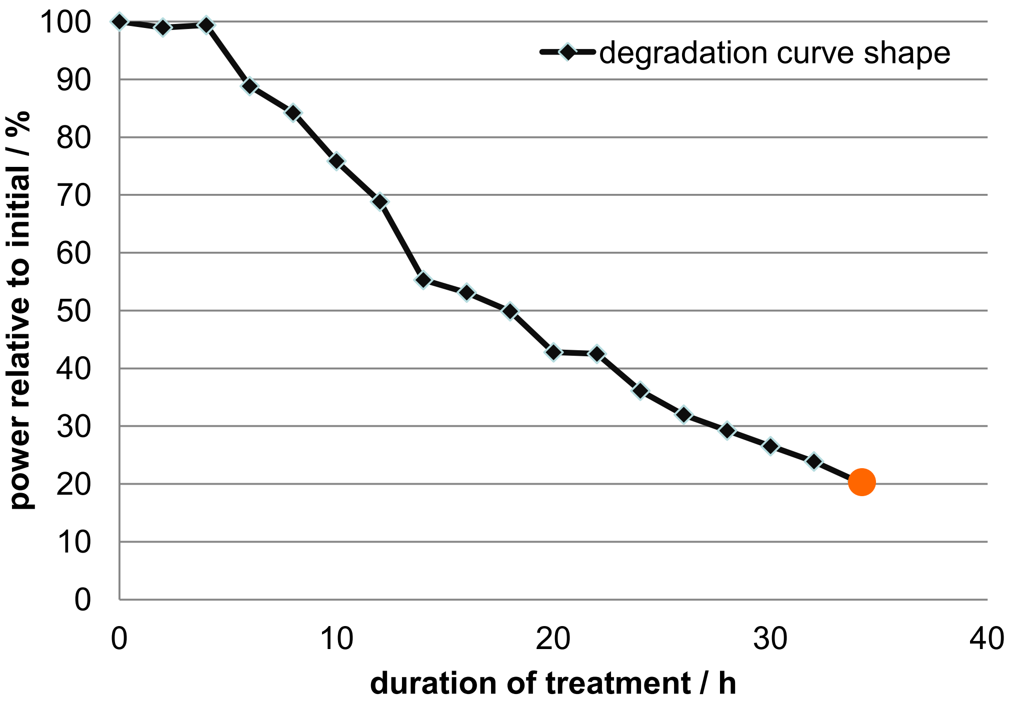
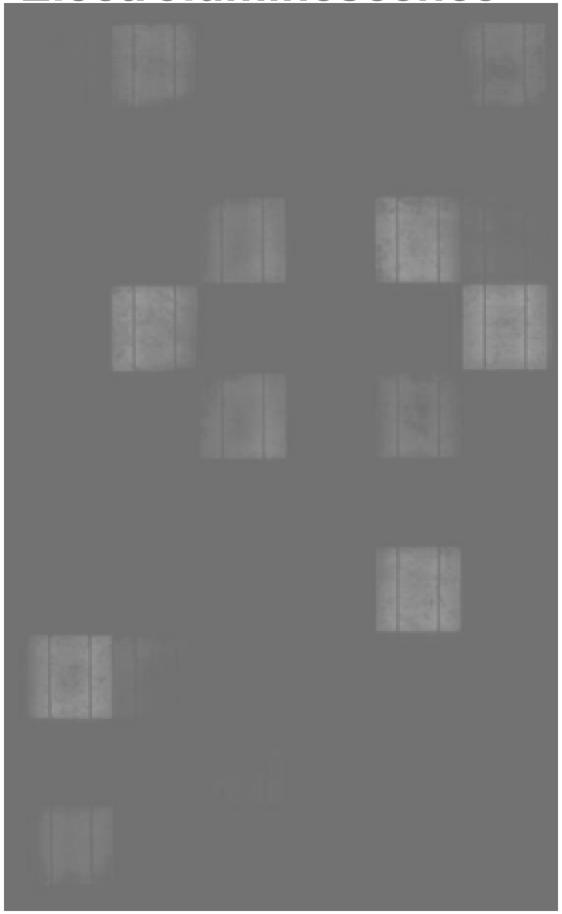


Damp heat 85 C/85% r.H. -1000V (PID Test)

Electroluminescence



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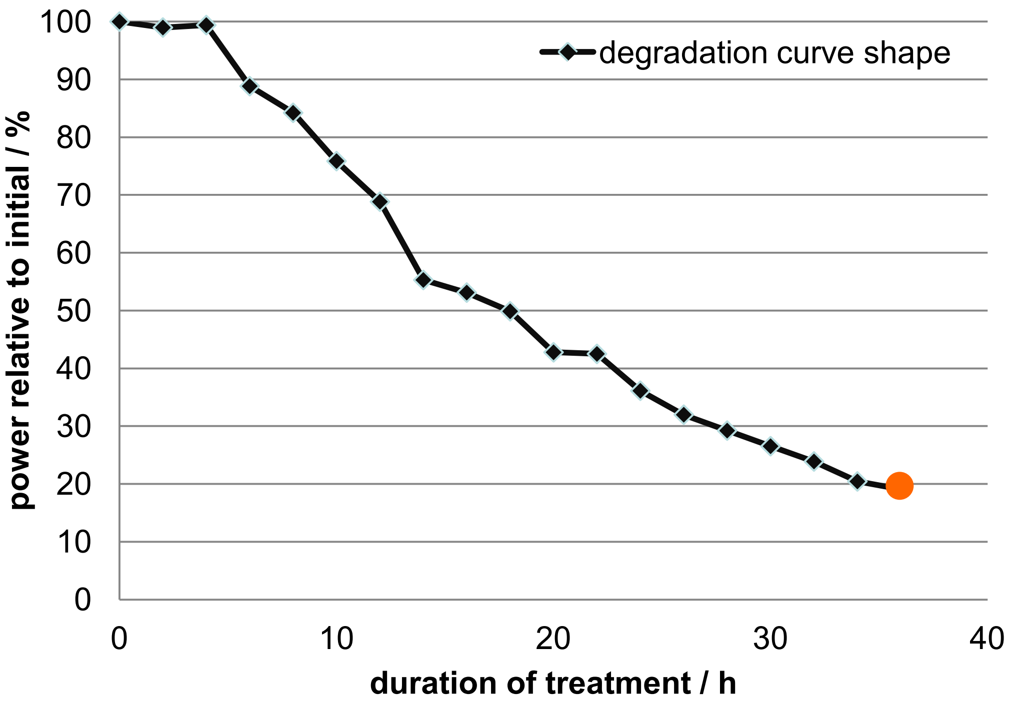


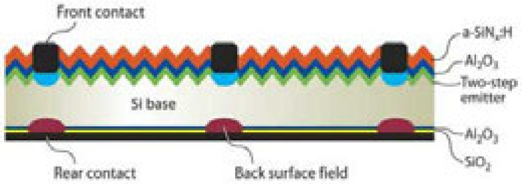
PID influencing parameters

PID influencing test parameters :

- Voltage
- Humidity
- Temperature
- Grounding

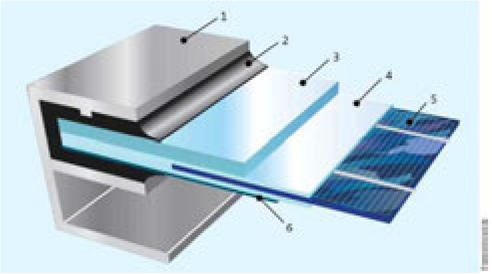
Influencing parameters on cell level:

- Anti reflective coating
- Emitter depth
- Type of base doping



Influencing parameters on module level:

- Front sheet
- Encapsulant material
- Back sheet
- Module design (frame, mounting, isolation)



PID influencing parameters

- **Applied voltage**

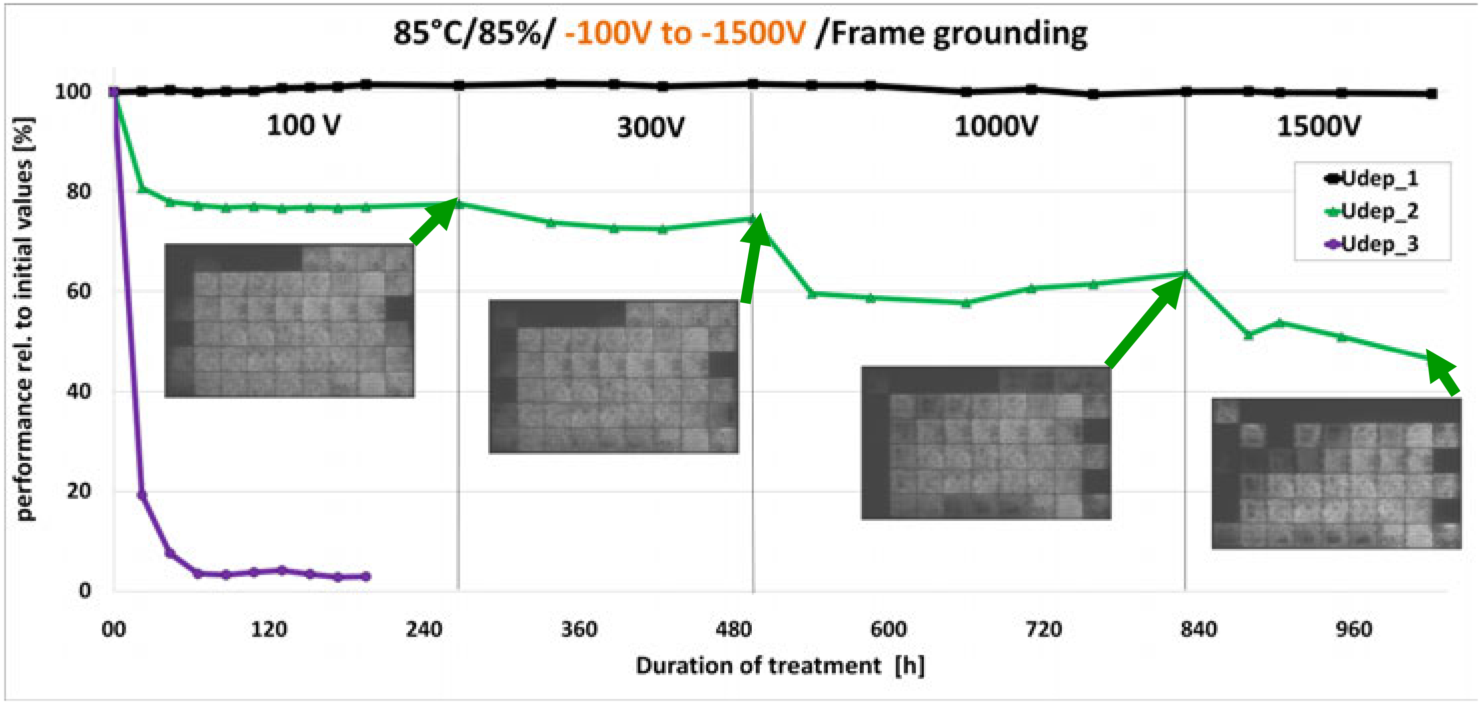
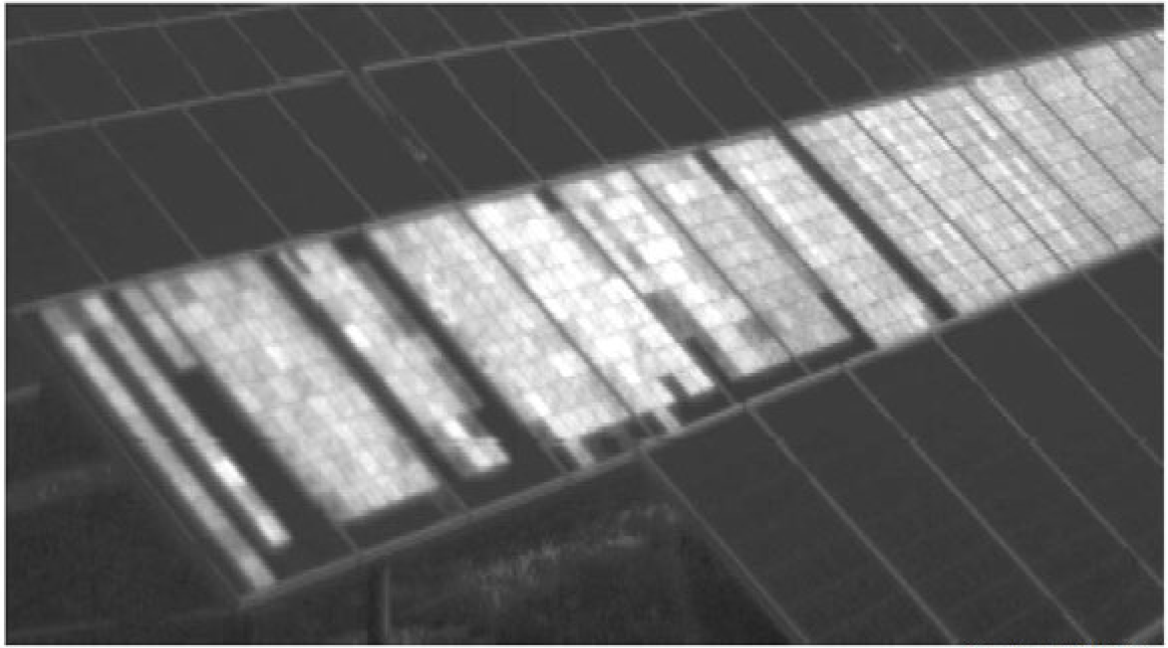


Fig. 2: Modules tested with increasing voltage

PID influencing parameters

- **Applied voltage**



(Quelle: SOLON)

- *Applied voltage is influencing the degradation level*

PID influencing parameters

- **Temperature**

48h / 25 C / 85% RH / Frame grounding **48h / 85 C / 85% RH / Frame grounding**

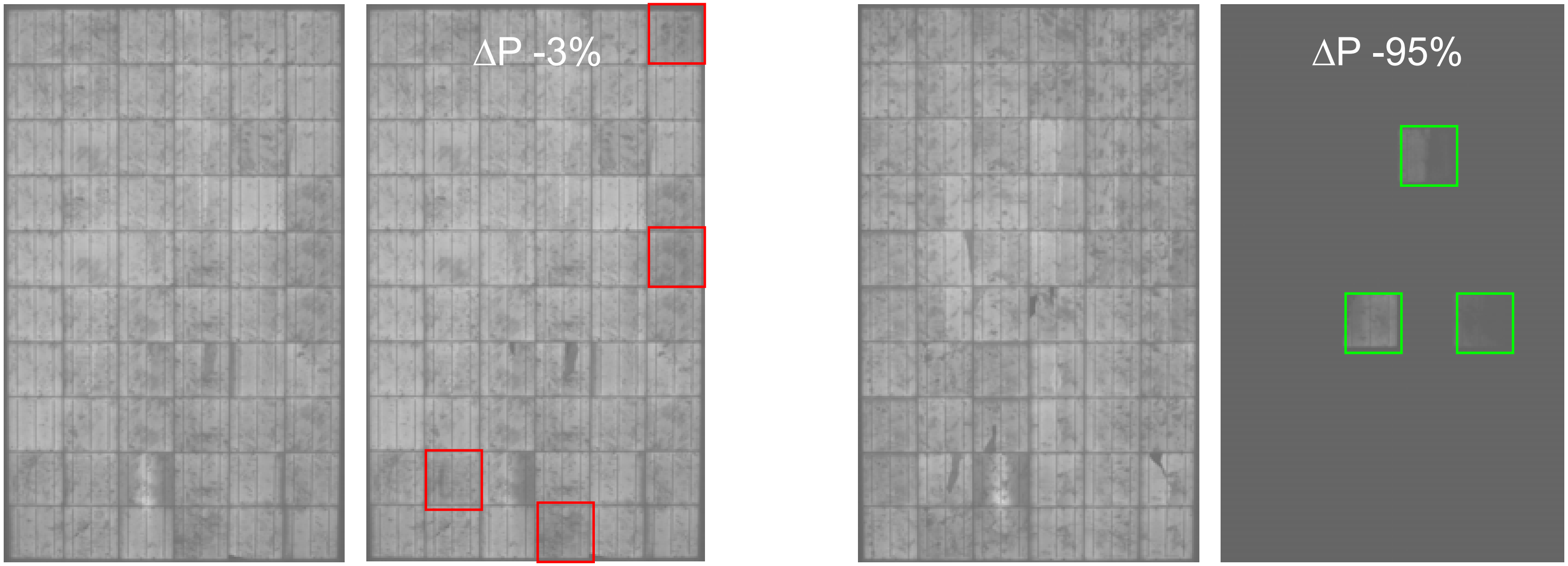


Fig. 3: Modules tested at different temperatures

- *Temperature is increasing the degradation rate*

• **Humidity**

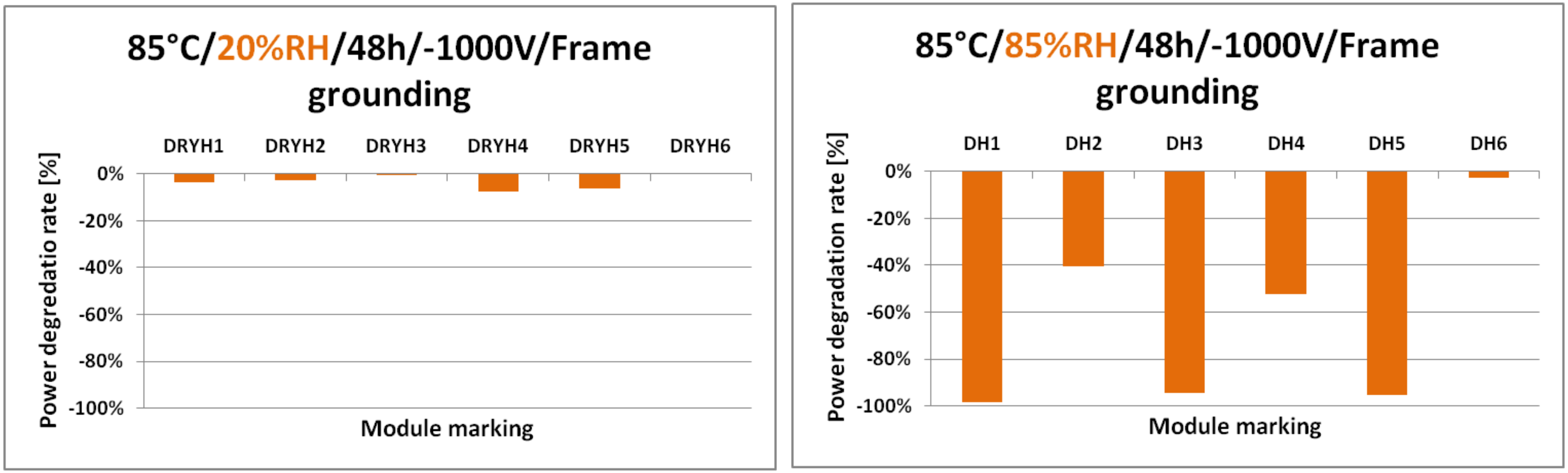


Fig. 4: PID treatment with different humidity conditions

• *Humidity is influencing the degradation rate*

PID influencing parameters

- **Contact situation**

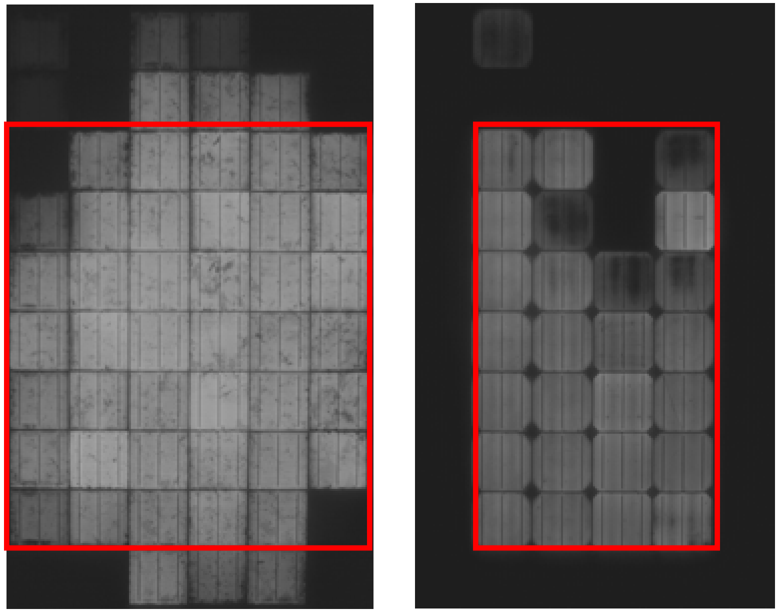


Fig. 5: Lab tested modules – frame grounded

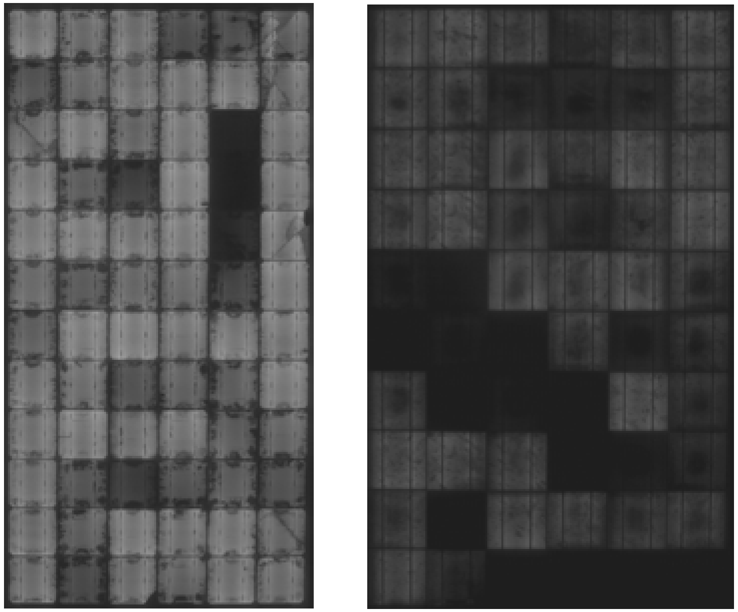
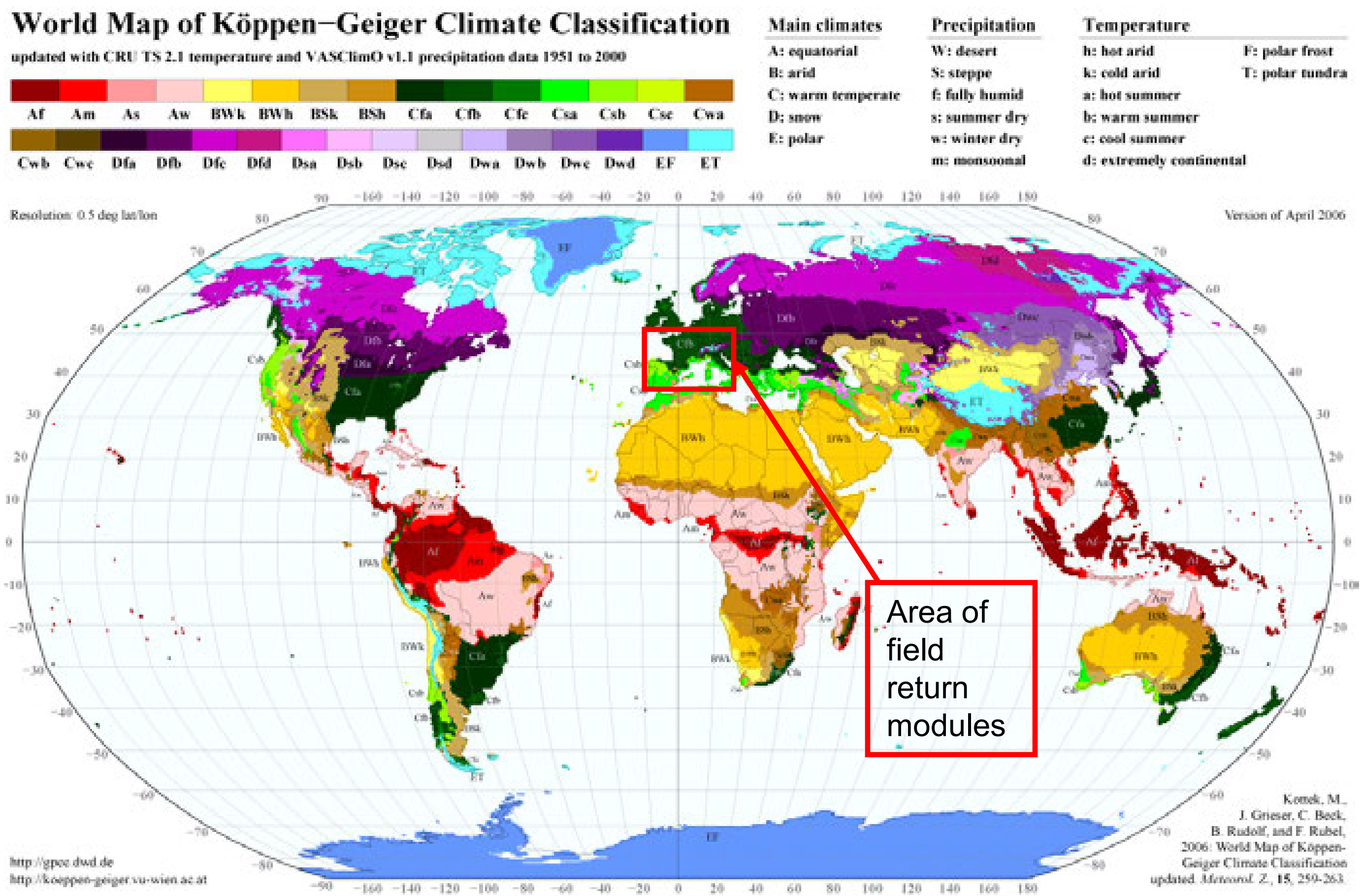


Fig. 6: Lab tested modules – surface grounded

- <u>*Grounding is influencing the degradation pattern*</u>

Comparison between field returns and laboratory tests



Comparison between field returns and laboratory tests

- **Contact situation**

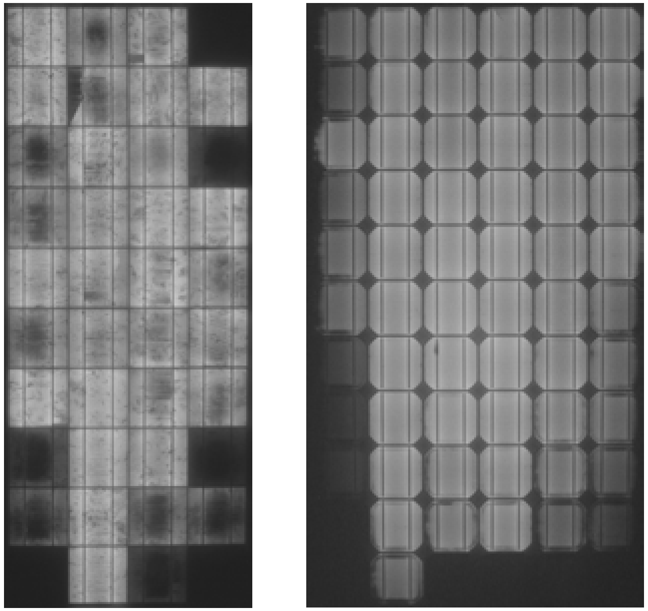


Fig. 7: Field return modules from different suppliers and power plants

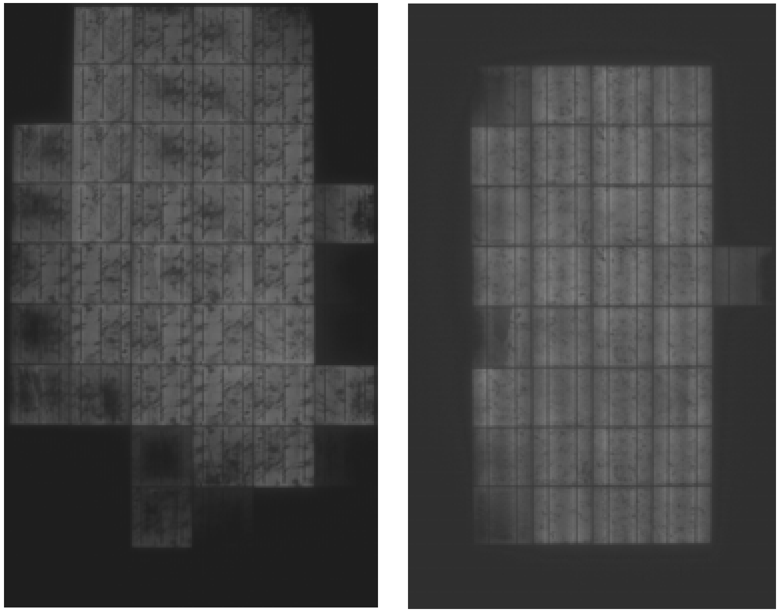


Fig. 8: Modules which were grounded via the frame

- *<u>Field return modules show similar pattern like modules grounded via the frame</u>*

Reasearch on cell level

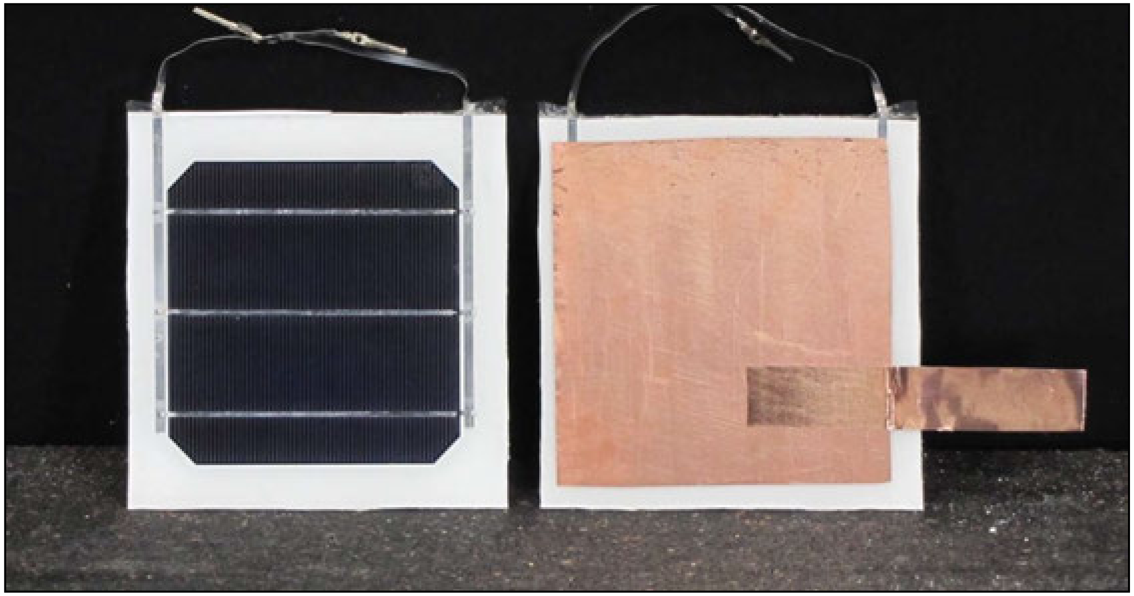
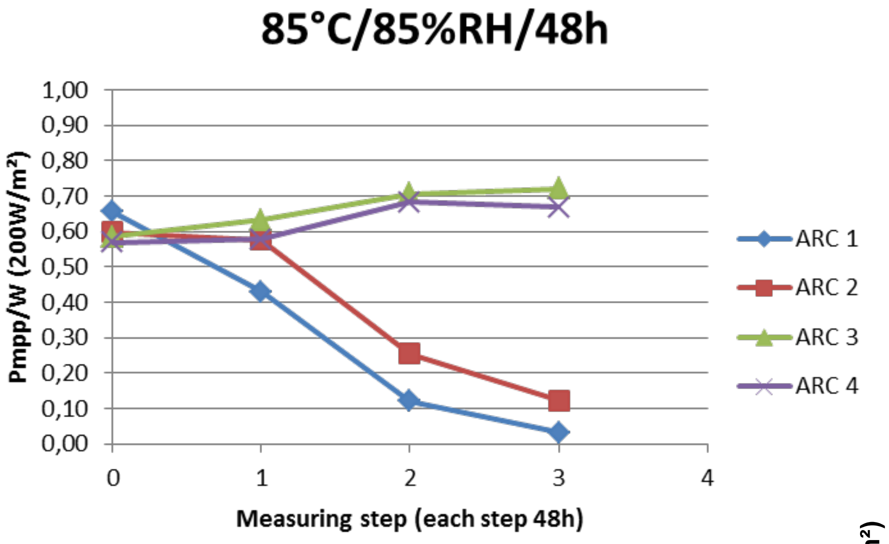


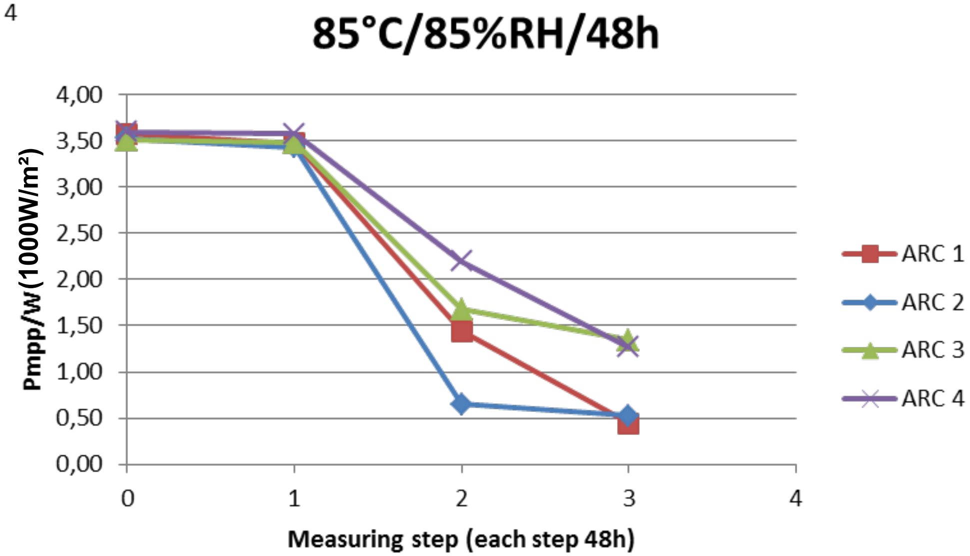
Fig. 9: Typical one cell module

- Investigations on different anti reflective coatings and their optimation against PID
- Research on small one cell modules with 200 x 200 mm
- Contact via copper foil on the whole front side
- Apllied voltage between 50 and 200 V

Anti reflective coating

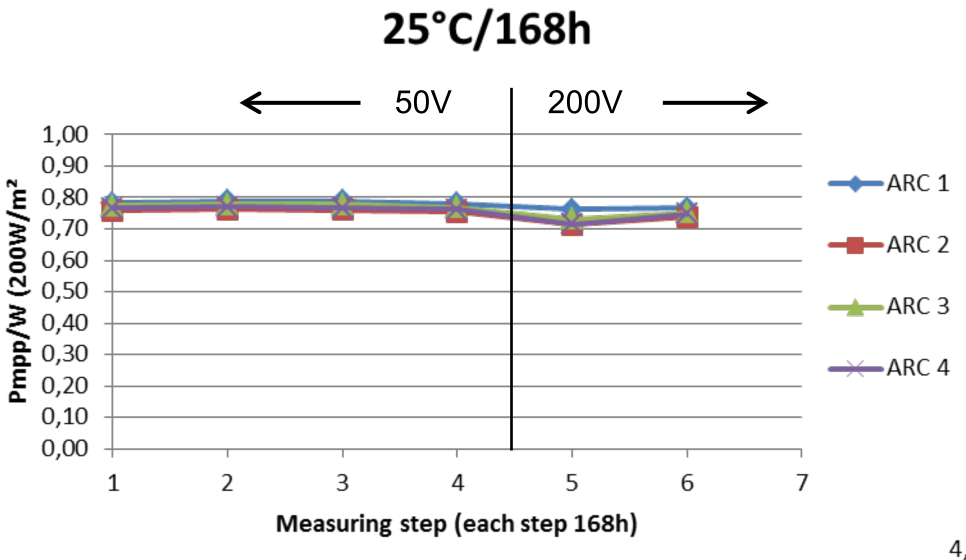


- Equal wafer material
- Four different anti reflective coatings
- Two different Encapsulate materials



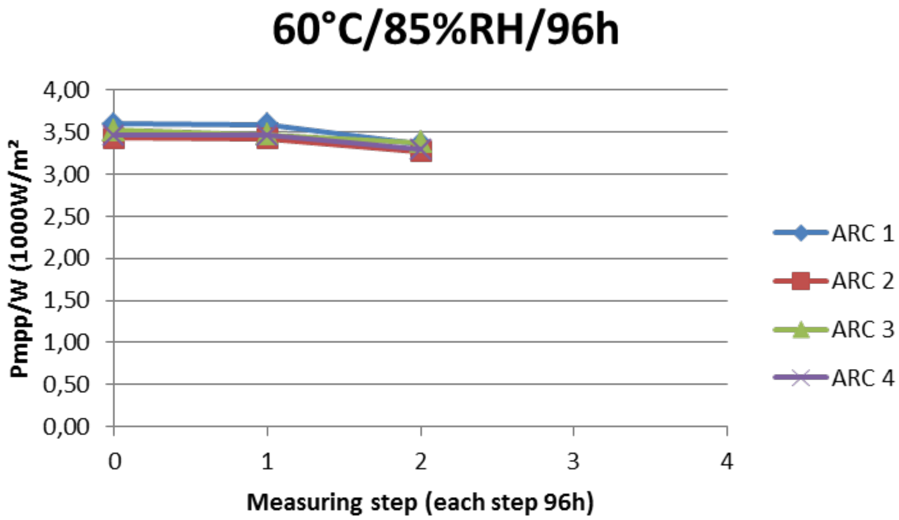
- Segnificant spread between ARC 2 and ARC 3 for both materials
- The influence between encapsulant and anti reflective coating havn‘t been clearifite yet

Anti reflective coating



Three different test methods:

1. 85 C/85%RH/48h
2. 25 C/168h
3. 60 C/85%RH/96h



- No segnificant difference during 25 C test
- Small power drop after increasing the voltage to 200V
- No significant power drop after two cycles for the 60 C test

Encapsulant materials

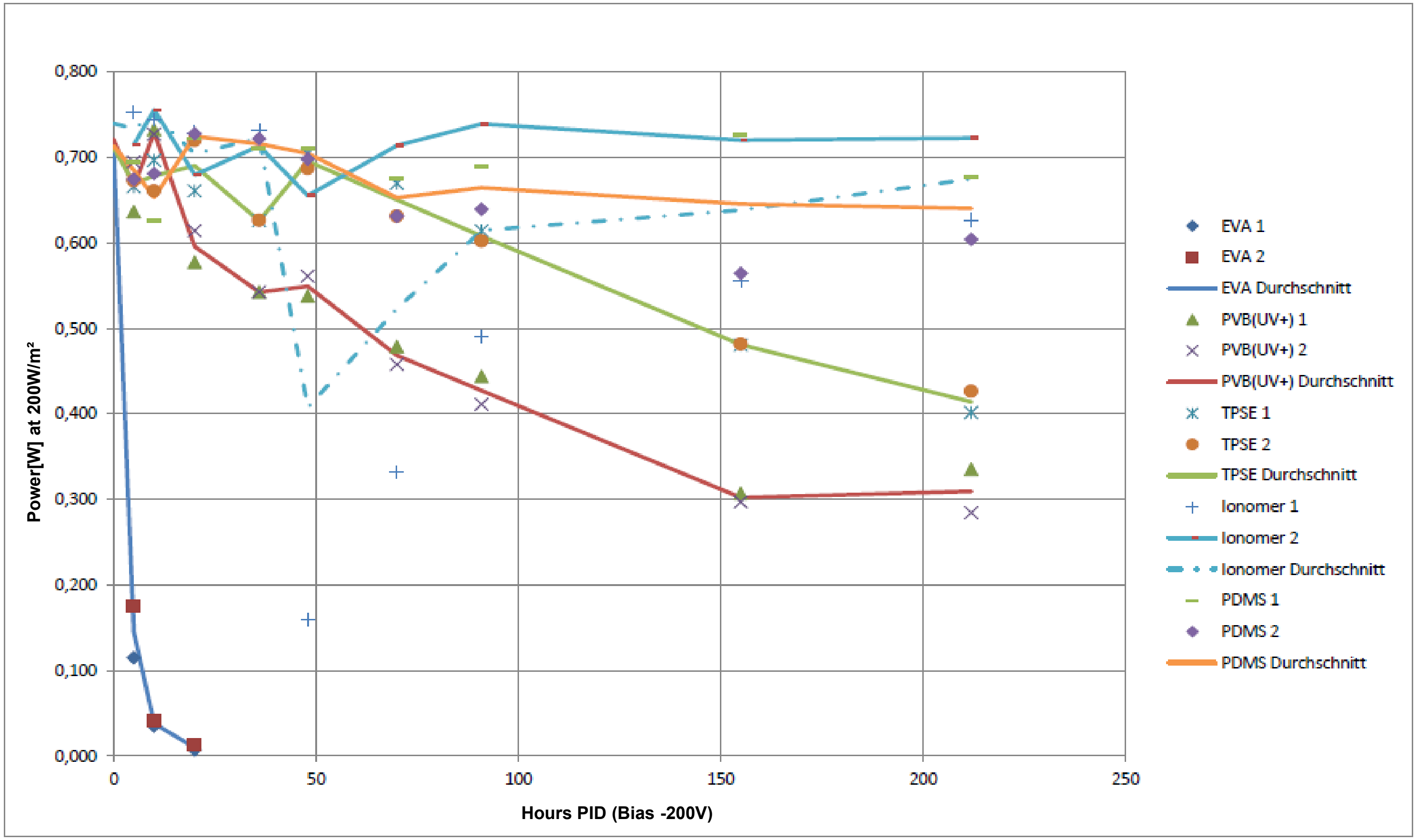


Fig. 10: Investigation on different encapsulant materials

Outlook

- **PID in the field – Procedure from PI/PIExpert**

1. Analysis of modules in the PI Berlin laboratory

•Degradation

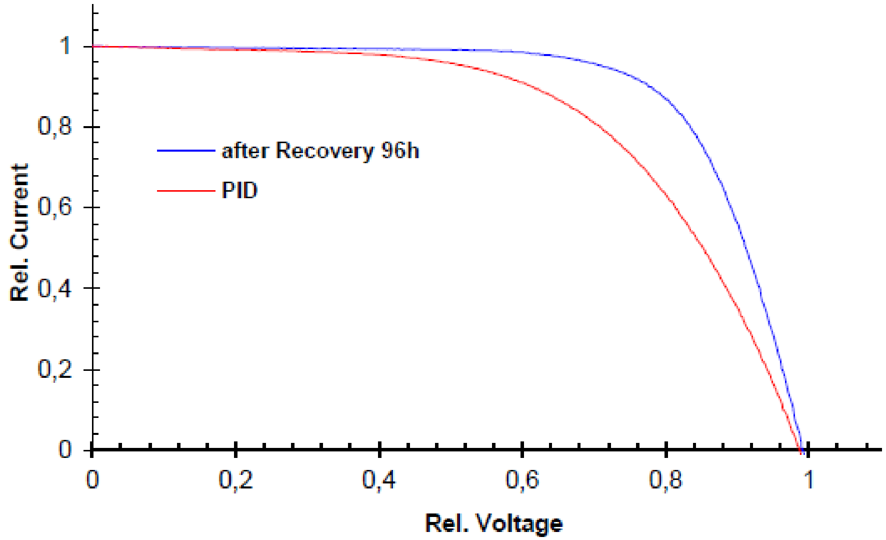
•Recovery

2. Field analysis + action monitoring

Outlook

1. Analysis of modules in the PI Berlin laboratory

- PID testing
- Recovery testing
- Analysis methods: IV, EL, IR



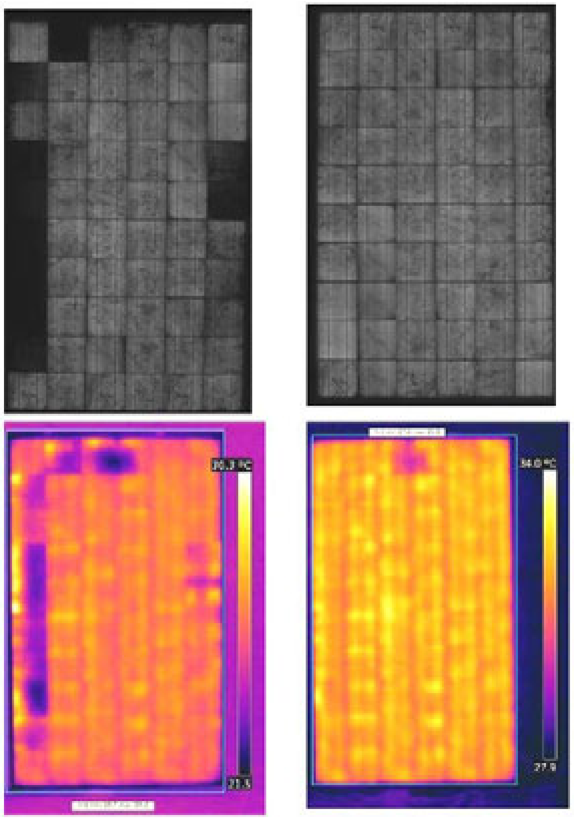
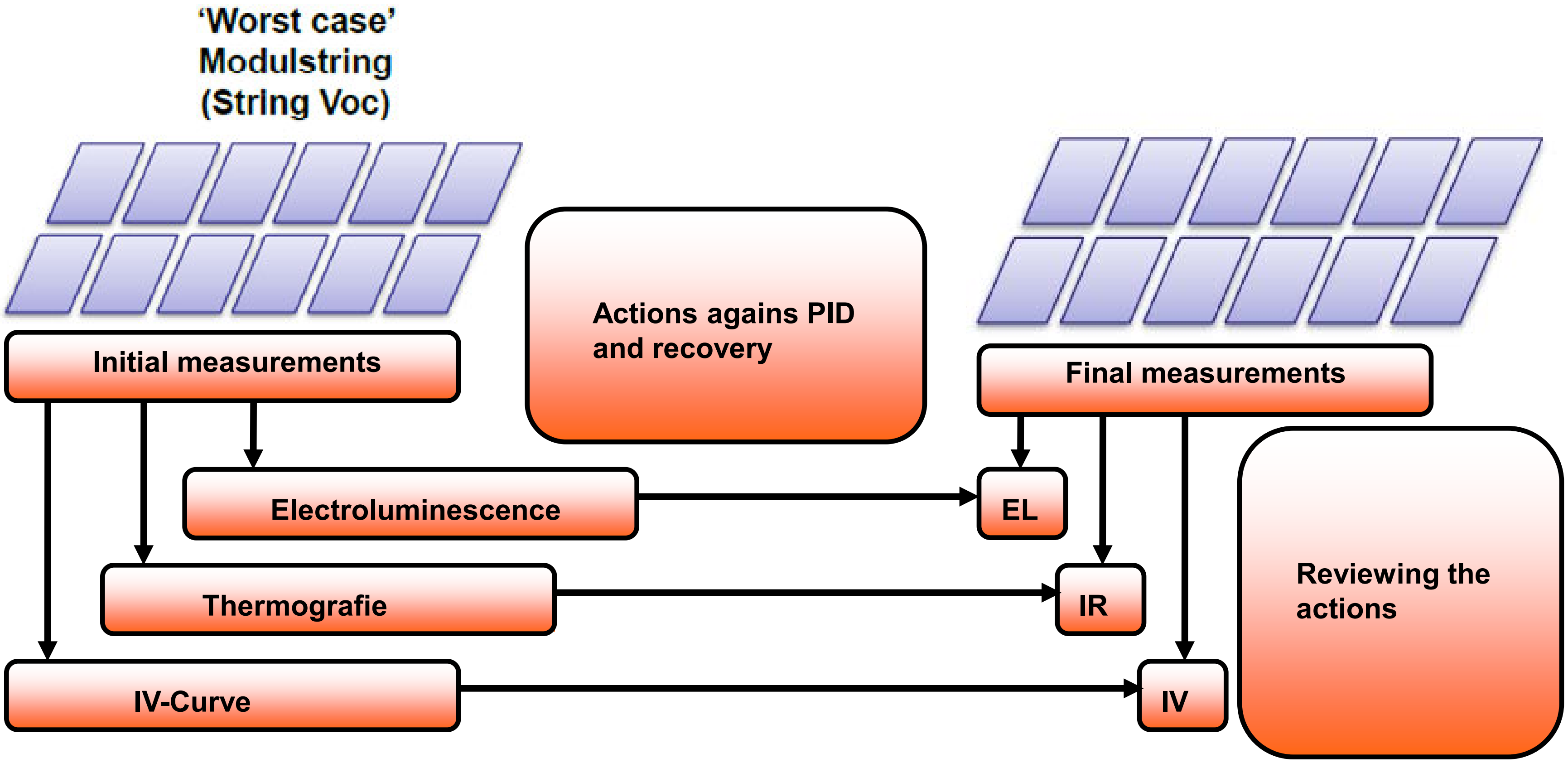


Fig. 11: EL/IR of field modules (left)
EL/IR after recovery (right)

Outlook

1. Field analysis + action monitoring



Summary

- PID is just one of many effects which are caused by high system voltage
- PID rate is influenced by:
  - System voltage
  - Humidity
  - Temperature
  - Contact situation
  - Cells
  - Module materials
- PI-Berlin/PI-Experts: Pakage for analysis of PID in the field + action monitoring
- The PID test can just show if a module is susceptible to PID or not. Till now there are no simulation programms available which allow a forecast for module behaviour in the field. PI-Berlin is working on different R&D projects about indoor/outdoor corolations at the moment.

Thank you for your attention!

koch@pi-berlin.com

This work was supported by the German Federal Ministry of Education and Research (BMBF) under Contract number 13N10445.

PID test according to PI-Berlin standard

2 Modules

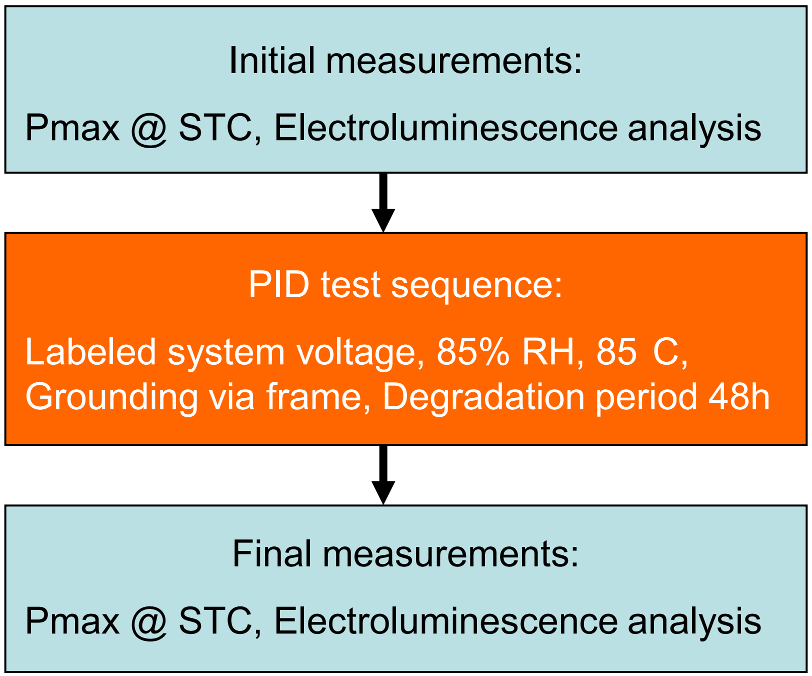


Fig.10: PID standard test sequence

<u>PID quality categories:</u>

Class A → ΔP < 5%

Class B → 5% < ΔP < 30%

Class C → ΔP > 30%

PID test according to PI-Berlin standard

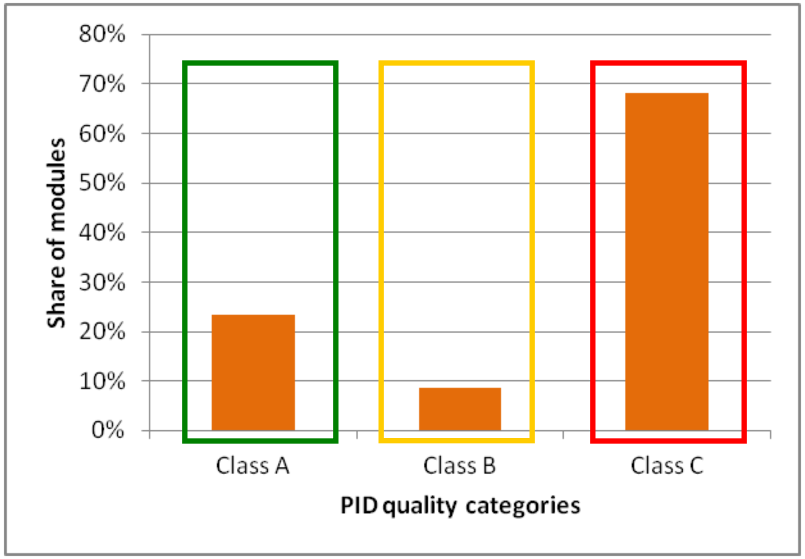


Fig.8: Summary of ~50 modules tested with PID standard test sequence

PID quality categories:

Class A → $\Delta P < 5\%$

Class B → $5\% < \Delta P < 30\%$

Class C → $\Delta P > 30\%$

12–18 Year-Old PV Power Plants in Arizona:

Potential Induced Degradation Analysis of 1900 Individual Modules

ASU PRL

Mani G. Tamizh-Mani

PV Reliability Laboratory (PRL)
Arizona State University

manit@asu.edu

ASU
Arizona State University

Dedicated To

John Wiedner

Manager *(former)* , APS-STAR

Arizona State University

Outline

PID

- **Evaluated Systems: An overview**
- **Question:** ***Is the PID mechanism responsible for PV module degradation in hot-dry climatic conditions?***

- **Fielded Systems Test Data**
  - *1900 modules tested individually*
  - *3-23 modules per string*
  - *Six different models/manufacturers*
  - *12-18 years old*

- **Accelerated Indoor Test Data**
  - *Three different models/manufacturers*
  - *+ Bias (fresh, TC200 and DH1000 stressed samples)*
  - *- Bias (fresh, TC200 and DH1000 stressed samples)*
  - *+ Regeneration Bias (fresh, TC200 and DH1000 samples)*
- **Conclusions**

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Evaluated Systems

Fielded Systems: Location (Tempe, Arizona)

Hot-Dry Climate, + Biased Systems

Fielded Systems: Module Designation

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Fielded Systems: Details

Model Designation and Module Count								
Array	Model A18	Model A13	Model B	Model C12	Model C4	Model D	Model E	Model F
Size	9 kW	11.6 kW	81.9 kW	51.3 kW	51.3 kW	12 kW	8.8 kW	14.4 kW
#Modules (1-axis)	168		1155	176	40	48	50	120
#Modules (33°Lat.Tilt)		216	-		-	-	-	-
#Modules (String)	3	21	21	8	8	8	12	23
String Voltage (Voc)	65	455	455	505	505	485	532	483
Years Fielded	18	13.3	13.3	11.7	3-4	11.7	11.7	11.7

Replaced Modules

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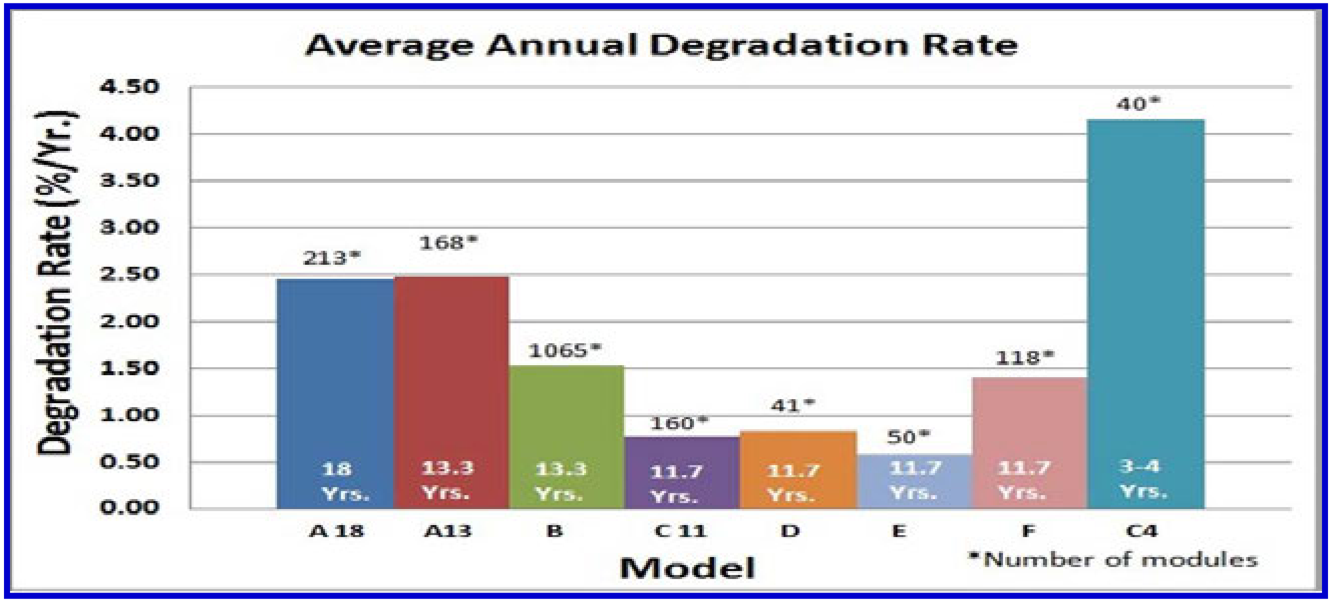
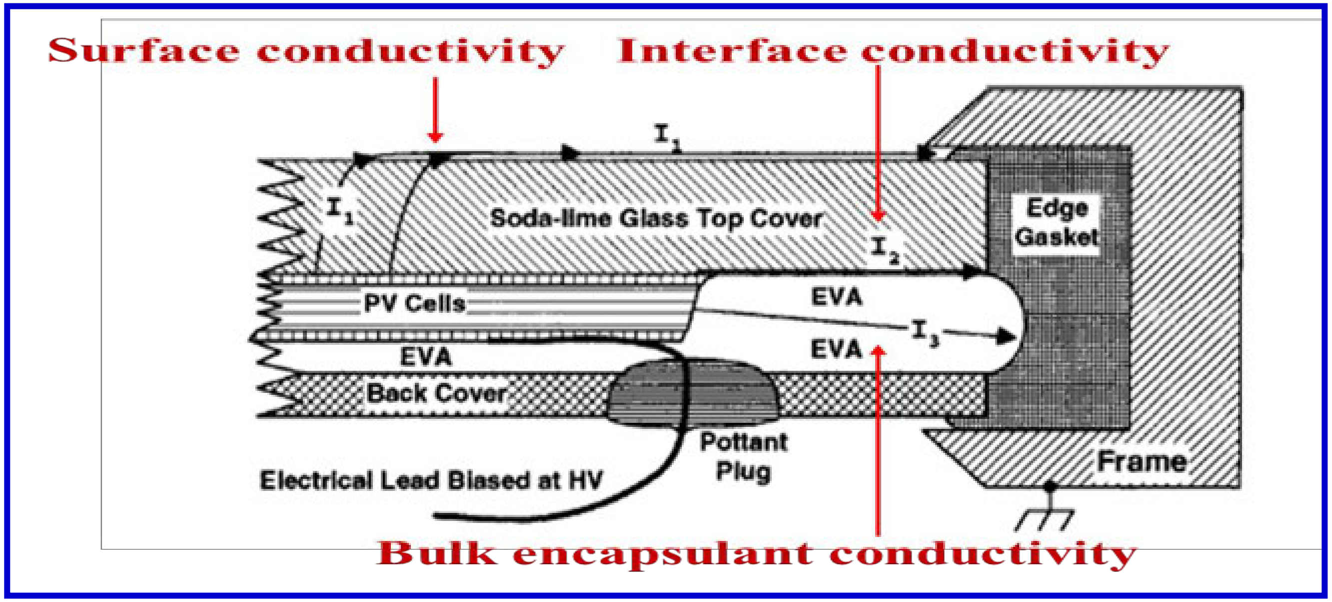
Question

Question



Hot-Dry Climate

Is PID mechanism responsible for the degradation in hot-dry climates?



PID

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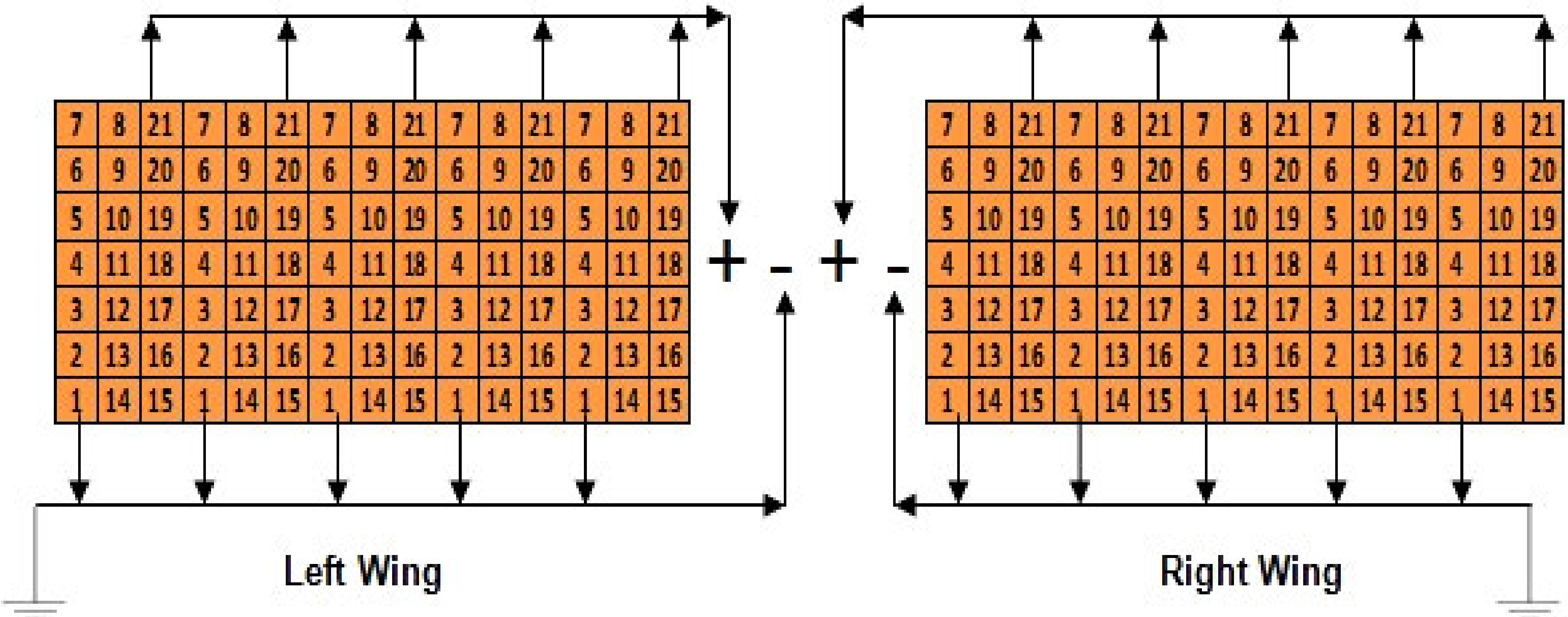
Fielded Systems Test Data

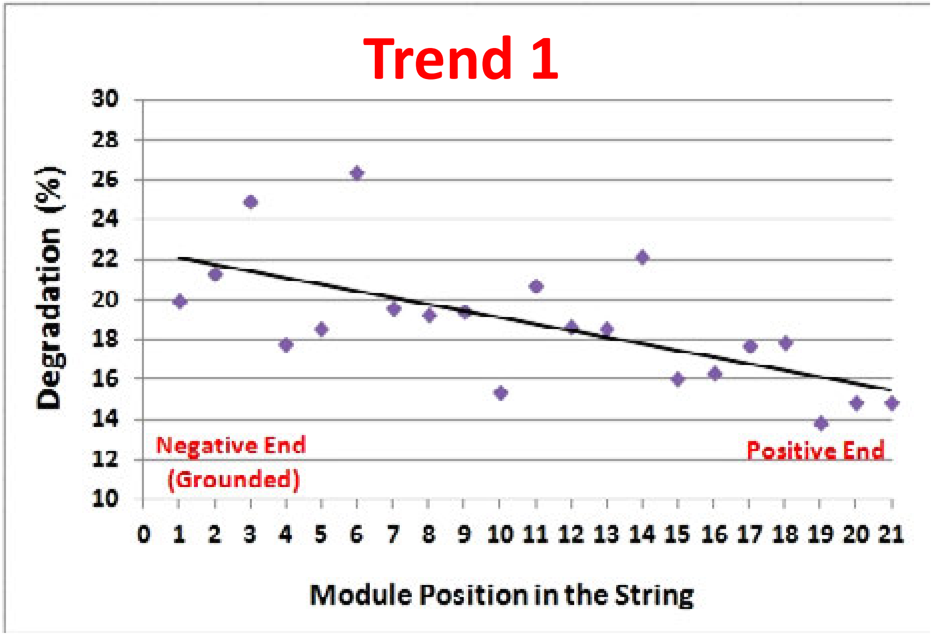
Model B

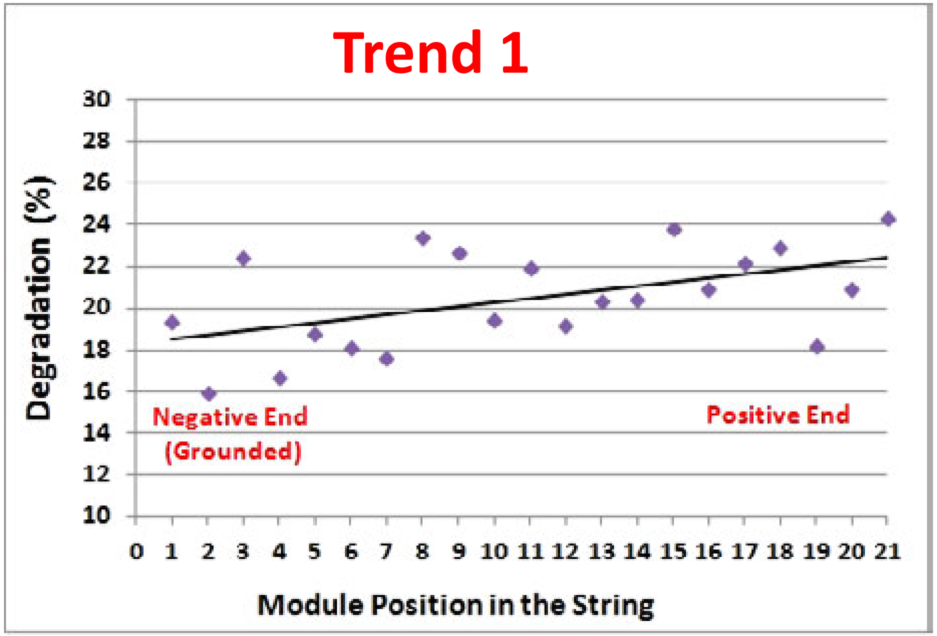
1-Axis Tracker

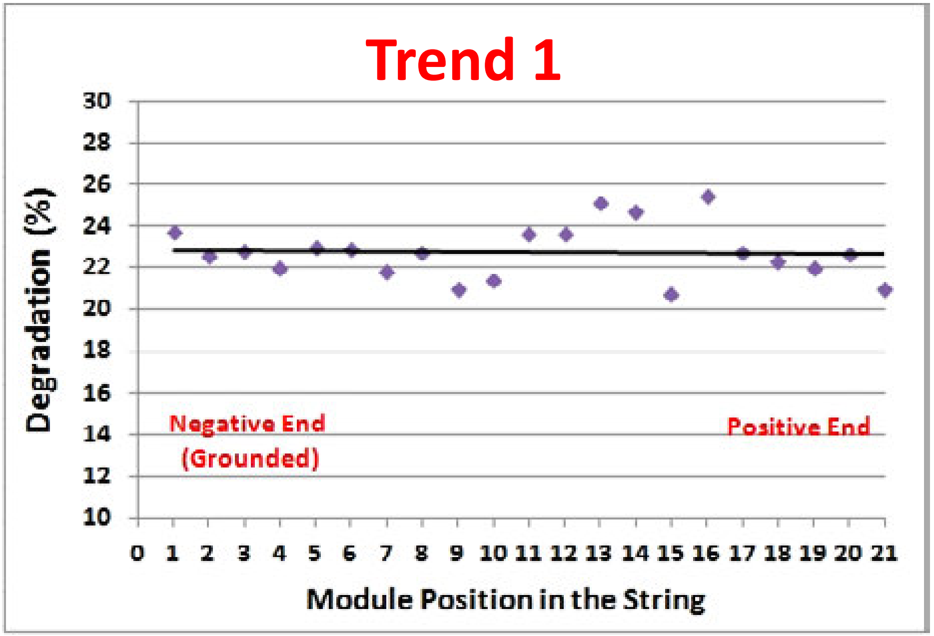


- 21 modules in a series string
- 55 strings total

Model B







Overall: No Specific Trend

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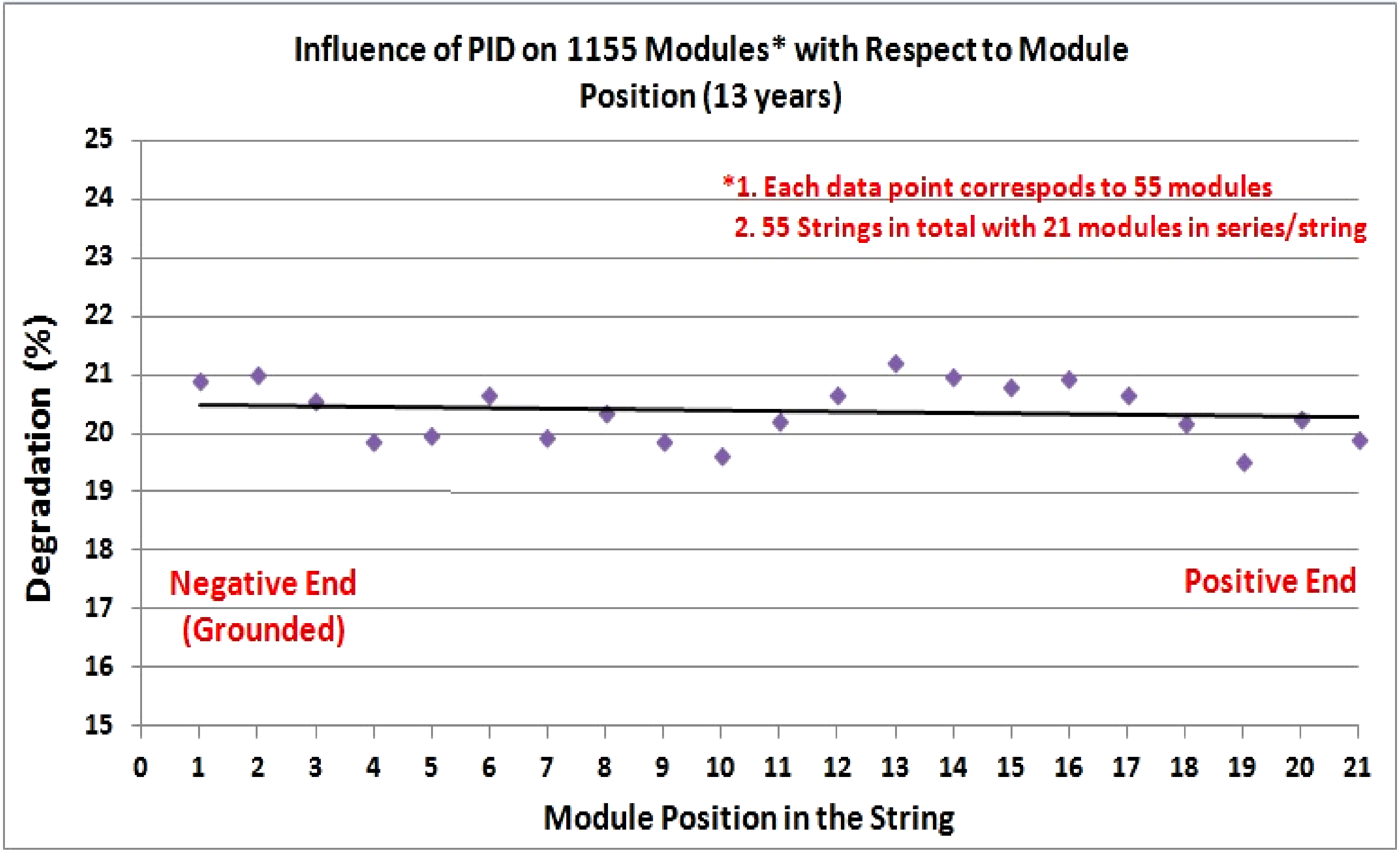
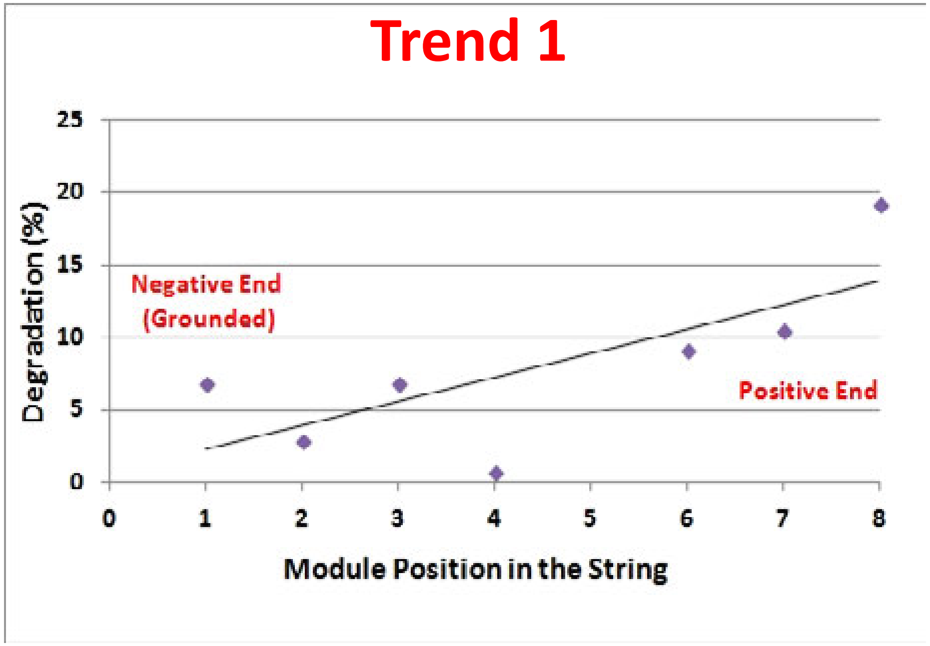
Model B

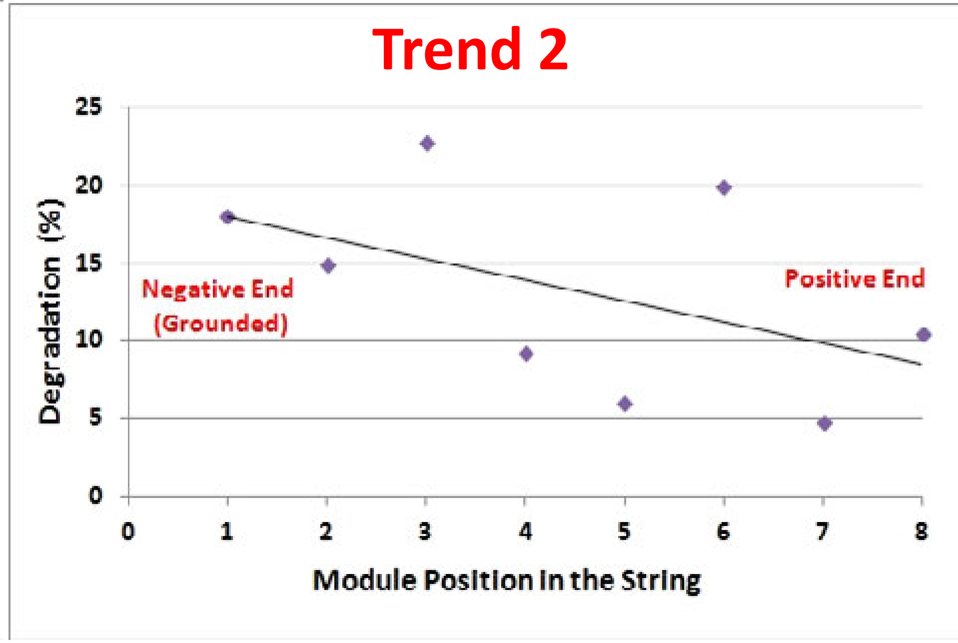
Overall: No Specific Trend

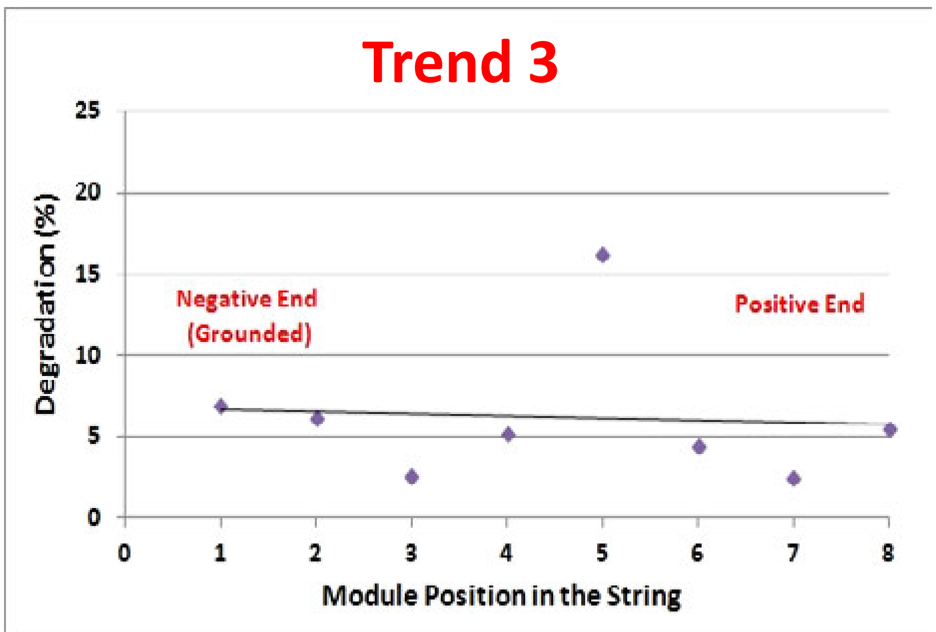
PID Mechanism Does not Seem to Be Responsible for Degradation



Model C





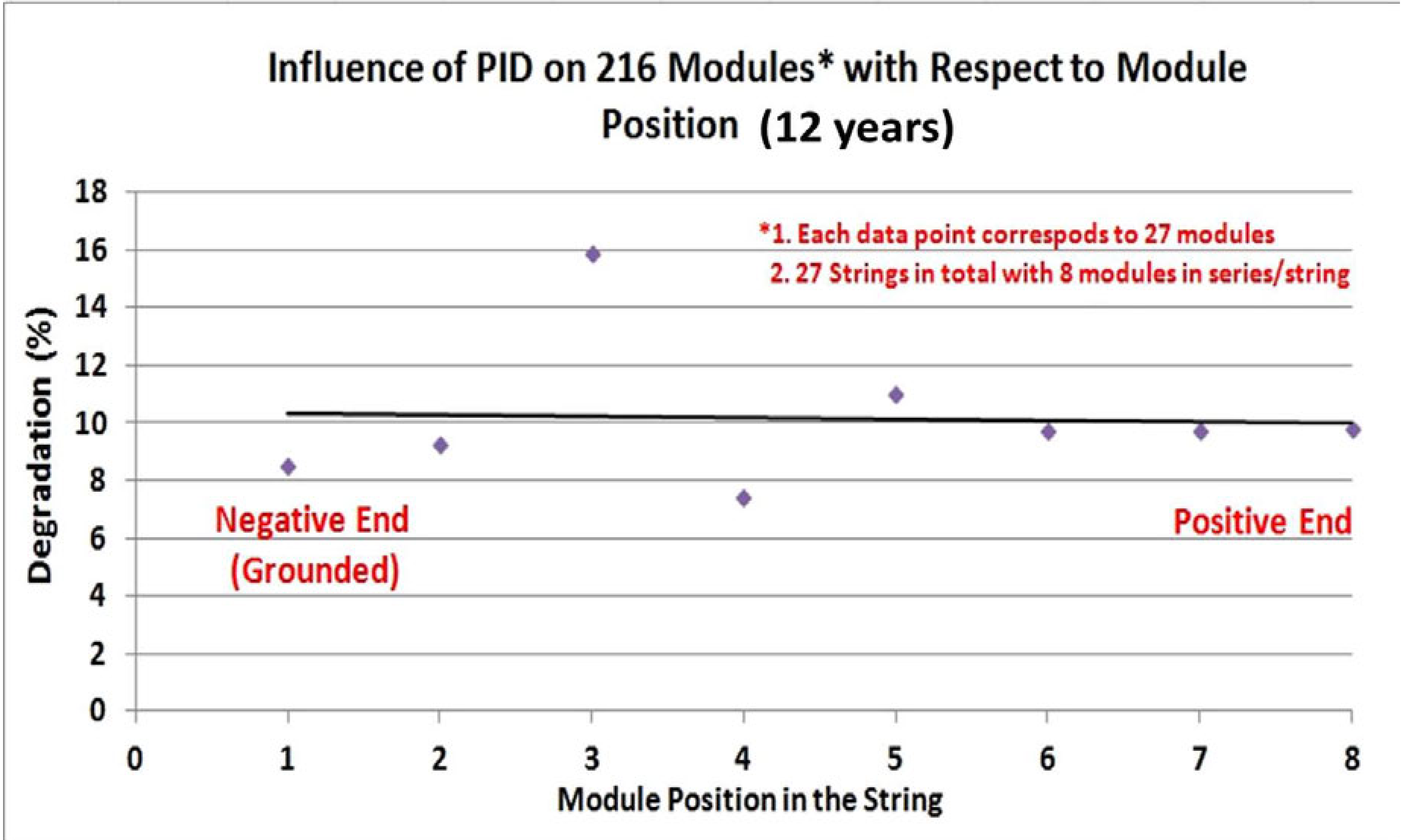


Overall: No Specific Trend

Model C

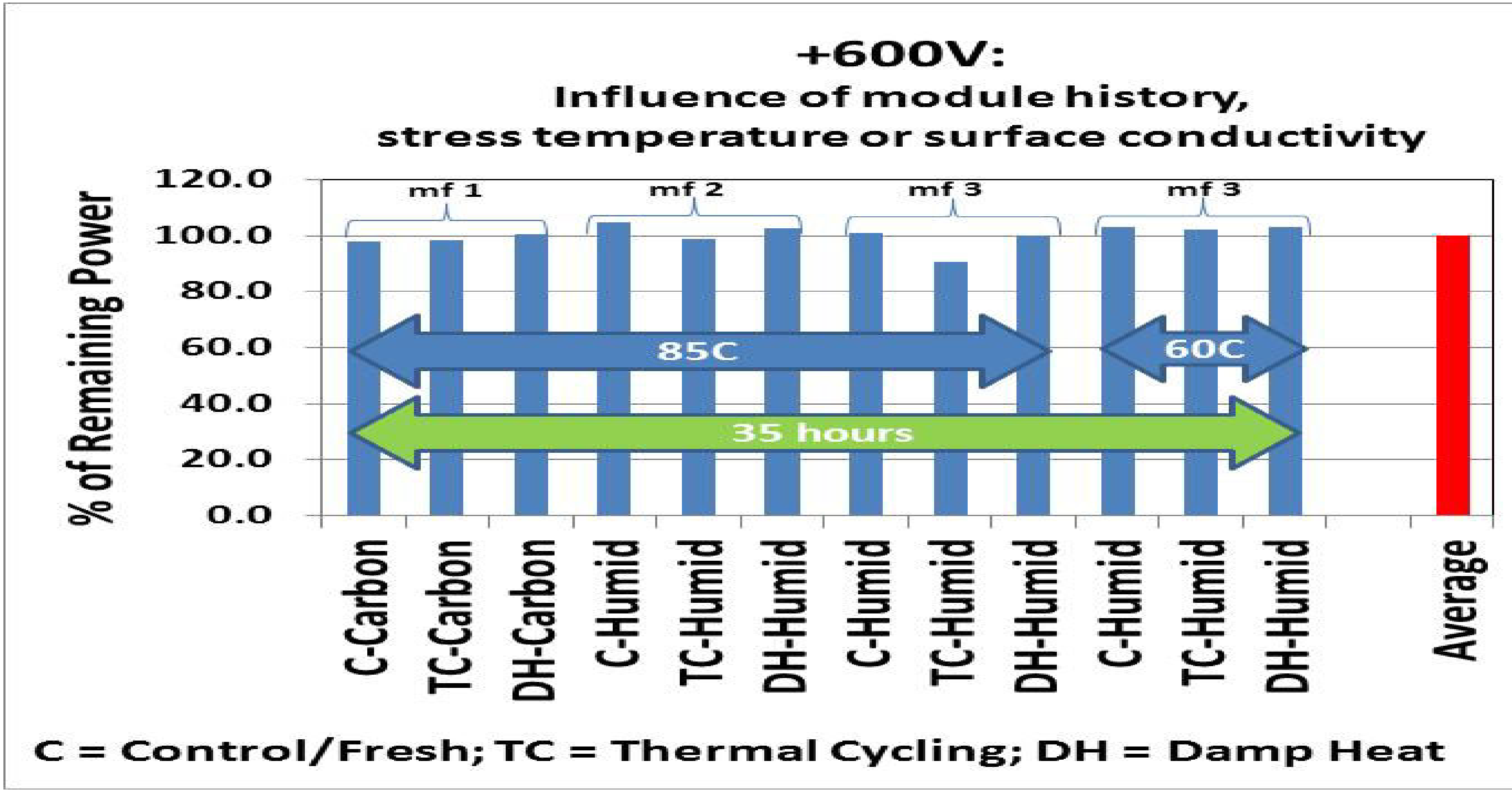
Overall: No Specific Trend

PID Mechanism Does not Seem to Be Responsible for Degradation



Accelerated Indoor Test Data

Bias: + 600V



+ Bias: Does not seem to affect the performance irrespective of pre-history (fresh, TC or DH) and surface conductivity (conductive carbon or humidity) of the modules. It is consistent with fielded systems test data.

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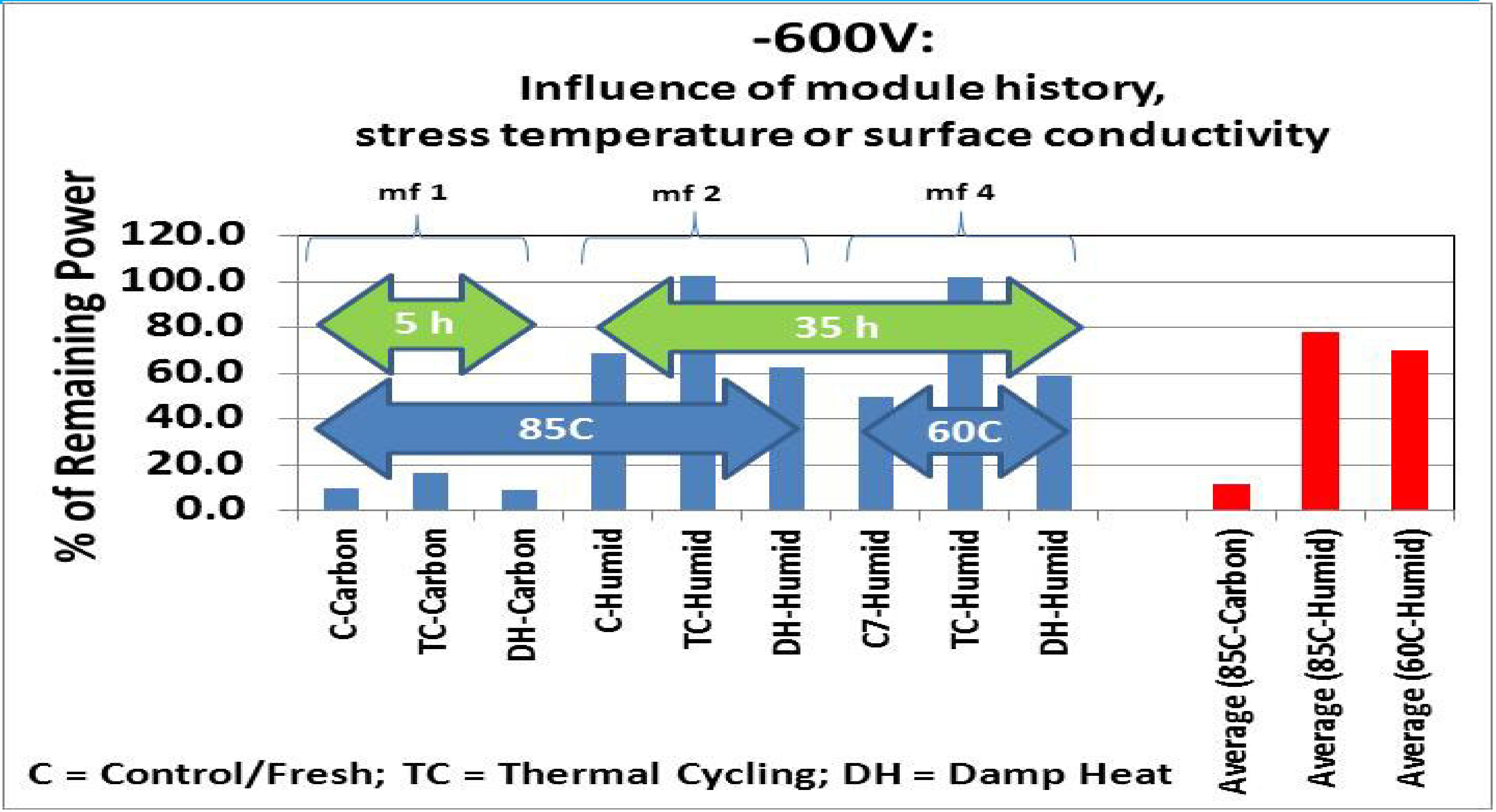
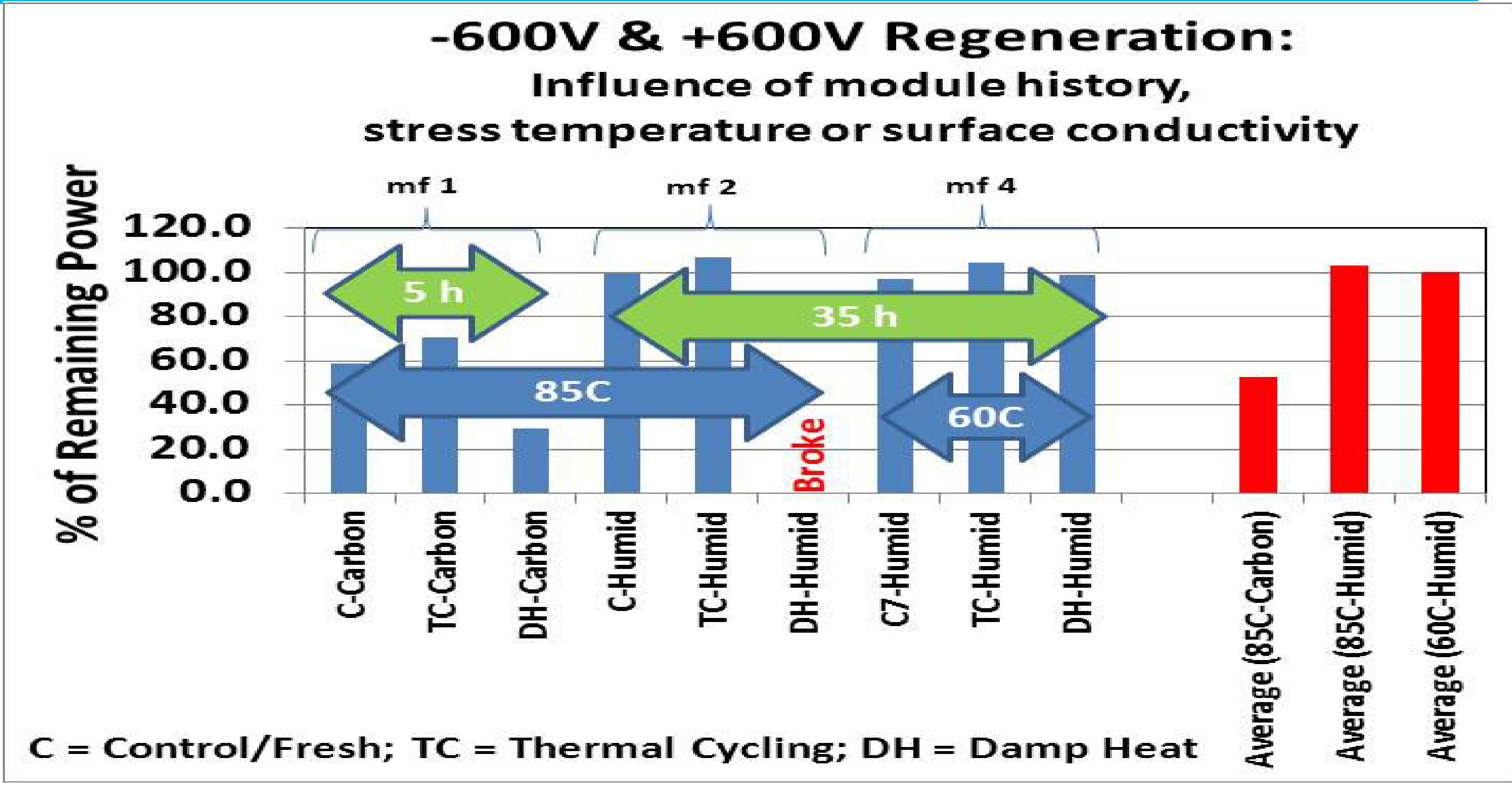
Bias: -600V



- **Bias:** Seems the performance degradation depends on the pre-history (fresh, TC or DH) and surface conductivity (conductive carbon or humidity) of the modules. The TC stressed module does not degrade under low surface conductivity (TC-Humid) as compared to fresh and DH stressed modules (similar to hot-dry climatic conditions of Phoenix, AZ?).

Bias: -600V & +600V Regeneration



+ Regeneration Bias: Original power is fully (if humidity) or partly (if conductive carbon) recovered depending the surface conductivity. The DH stressed module with conductive carbon film recovered only very little as compared to fresh and TC stressed modules.

Conclusions

Conclusions

- **Fielded Systems Test Data**
  - **+ Bias:** Modules degrade at 0.6-2.5% per year but the **PID does not seem** to be responsible for the degradation of negative grounded systems in the hot-dry climatic condition of Phoenix, Arizona

- **Accelerated Indoor Test Data**
  - **+ Bias:** Does **not** seem to affect the performance irrespective of pre-history (fresh, TC or DH) and surface conductivity (conductive carbon or humidity) of the modules. It is consistent with fielded systems test data.
  - **- Bias:** Seems the performance degradation **depends** on the pre-history (fresh, TC or DH) and surface conductivity (conductive carbon or humidity) of the modules.
  - **+ Regeneration Bias:** Original power is **fully** (if humidity) or **partly** (if conductive carbon) recovered depending the surface conductivity.

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Funding Support:

- **Science Foundation Arizona (SFAz)**
- **NREL**
- **Arizona Public Service (APS)**
- **DOE**

Thankfully Acknowledged!

PV QA Task Force 1

"Guideline for Integration of QA practices in the manufacturing process of PV Modules"

NREL 2/28/12

Observation

- The act of certifying a module or a module family is not meaningful unless it relates to the "Quality Systems requirements" and its ability to control the processes under which it is made so it is representative of the routine output.

Background

(the progress of “PV QA Guideline for Manufacturing Consistency”)

- In the “beginning” (after San Francisco)
  - “We stumbled in the wilderness for a while”
  - We accumulated samples and many suggestions of approaches to Quality systems, best practices, check lists, etc
  - PV QA Guideline for Manufacturing Consistency — (leader Ivan Sinicco) held on line meetings and created the four regions
- The Issue & the Survey
  - Issue = how to create Quality Systems / methods criteria that we all can ***harmoniously*** support
  - Ivan established a survey to gather opinions to determine how closely aligned the “group of *enthusiastic* volunteers” were.
  - Results showed that the key “ISO elements” were strongly supported.

The Issue & the Survey continued

- The clarity of the survey provided the direction to establish the "scope" of what we determined we would now focus on. The scales were "very important, neutral, not important, don't know" only the % of very important is shown here.
  - 1.42 Document Control 85.7%
  - 2.4.2.2 Quality Manual 85.7%
  - 3.4.2.3 Control of Documents 85.7%
  - 4.4.2.4 Control of Records 92.9%
  - 5.1.1 Management Commitment 84.6%
  - 2.5.2 Customer Focus 84.6%
  - 3.5.3 Quality Policy 84.6%
  - 4.5.4 Planning 69.1%
  - 5.5.5 Responsibility Authority & communication. 84.6%
  - 6.5.6 Management review 61.5%
  - 1.6.1 Provision of resources 30.8%
  - 2.6.2 Human Resources 14.3%
  - 4.7.3 Design & Development 83.3%
  - 5.7.4 Purchasing 50.0%
  - 6.7.5 Production & Service Provision 66.7%
  - 7.0 Control of monitoring 100.0%
  - 1.8.2 Monitoring & Measurement 100.0%
  - 2.8.3 Control of Nonconforming Product 92.9%
  - 3.8.4 Analysis of Data 85.7%

The Scope!

- *Design a guideline that could be used as base document for a new IEC standard or as a new ISO standard for PV. The guideline is focused on PV manufacturing processes and procedures aiming to insure manufacturing quality and the consistency of the produced photovoltaic modules to the warranties given by the producer. The ISO 9001-2008 standard is considered as starting point for drafting the guideline and an ISO-like structure must be reflected in the guideline.*
- *Each regional task group will focus initially on chapters 7 & 8 of the ISO9001-2008 standard.*

Where we are or “Progress to date”?

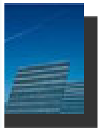
- Now that we have something “solid” to work on or from, we have begun to examine specific chapters that deal with the process of manufacturing in the ISO standard. Primarily chapters 6 & 7.
- In the following slides are our attempts at tracking and examples of the proposed changes to the standard that would primarily affect the Solar manufacturing activities.

ISO 9001:2000	PV Proposal	TS 16949:2000	DIS 13485	AS9100 Rev A
7.3.7 – Control of Design & Development Changes	Linda Merritt	Same as ISO	Same as ISO	• Adds customer and/or regulatory approval on changes
7.4 – Purchasing				
7.4.1 – Purchasing Process	**Paul Robusto**	**• Adds regulatory conformity** **•Adds Supplier Quality Management System development**	**• Requires a documented process**	**• Approved Supplier Control**
~~7.4.2 – Purchasing Information~~	~~Paul Robusto~~	~~Same as ISO~~	~~• Adds traceability requirement~~	~~• Adds more specific requirements including supplier notification of changes~~
7.4.3 – Verification of Purchased Product	Lisa Dwornik	• Specifies incoming product quality control and supplier monitoring	• Records of verification are required	• More stringent requirements for incoming quality control
7.5 – Production & Service Provision				
~~7.5.1 – Control of Production & Service Provision~~	~~Robin Kobren~~	~~• Requires control plans for all parts~~ ~~• Control plans are updated when changes occur~~ ~~•Adds PM & predictive maintenance~~	~~• Adds records keeping, sterile devices, cleanliness, installation & servicing~~	~~• Adds process control plans with in-process verification points~~ ~~• Control of production process changes & tools~~

* Summarized from Elsmar Cove Forum poster "howste" - posted on June 19, 2003

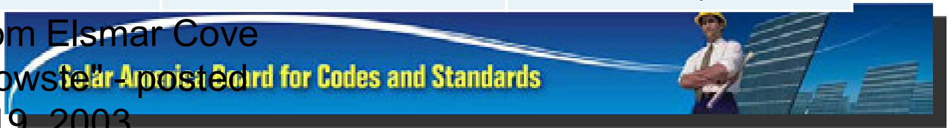
ISO 9001:2000	PV Proposal	TS 16949:2000	DIS 13485	AS9100 Rev A
~~7.2 – Customer-related Processes~~	~~Linda & Stacey – 1st Draft~~	_	_	
~~7.2.1 – Determination of requirements related to the product~~	~~Linda & Stacey – 1st Draft~~	~~• Adds notes for post-delivery, activities & compliance to environmental requirements~~ ~~• Customer-designed special characteristics~~	~~Same as ISO~~	~~Same as ISO~~
~~7.2.2 – Review of requirements related to the product~~	~~Linda & Stacey – 1st Draft~~	~~• Adds requirement of customer review to waive a formal review~~ ~~•Requires documentation of manufacturing feasibility in contract review~~	~~• Requires documentation~~	~~• Risks have to be evaluated~~
~~7.2.3 – Customer Communication~~	~~Linda & Stacey – 1st Draft~~	~~• Adds more specifics for ability to communicate via CAD & electronic data exchange~~	~~• Adds advisory notice~~	~~Same as ISO~~
7.3 – Design & Development		• Adds a note that it includes manufacturing process design & focuses on prevention rather than detection		
7.3.1 – Design & Development Planning	**Paul Norum**	**• Adds a multi-disciplinary approach**	**• Planning must be documented and updated**	**• Splits design into tasks and requires responsible people identified**

* Summarized from Elsmar Cove Forum poster "howste" – posted on June 19, 2003



ISO 9001:2000	PV Proposal	TS 16949:2000	DIS 13485	AS9100 Rev A
~~7.3.2 – Design & Development Inputs~~	~~Paul Robusto~~	~~• Adds more specific design inputs including knowledge gained from previous design~~ ~~• Adds design of manufacturing process~~ ~~• Adds special characteristics~~	~~• Adds requirement for approval~~	~~Same as ISO~~
7.3.3 – Design & Development Outputs	Lisa Dwornik	• Adds design FMEA • Adds process FMEA for manufacturing process	• Requires records	• Requires Design Package
~~7.3.4 – Design & Development Review~~	~~Robin Kobren~~	~~• Requires monitoring with measurements at design stages~~	~~Same as ISO~~	~~• Introduces authorization to progress to the next stage~~
~~7.3.5 – Design & Development Verification~~	~~Paul Norum~~	~~Same as ISO~~	~~Same as ISO~~	~~• Adds note to specify possible methods of verification~~
7.3.6 – Design & Development Validation	Stacey Rassas	• Adds specifics of prototype program and approval process	• Validation must be completed before delivering product • Adds clinical evaluations	• Adds notes defining validation • Adds documentation requirement •Defines test plan

* Summarized from Elsmar Cove Forum poster" howste" posted on June 19, 2003



ISO 9001:2000	PV Proposal	TS 16949:2000	DIS 13485	AS9100 Rev A
~~7.2 – Customer-related Processes~~	~~Linda & Stacey – 1st Draft~~	–	–	
~~7.2.1 – Determination of requirements related to the product~~	~~Linda & Stacey – 1st Draft~~	~~• Adds notes for post-delivery, activities & compliance to environmental requirements~~ ~~• Customer-designed special characteristics~~	~~Same as ISO~~	~~Same as ISO~~
~~7.2.2 – Review of requirements related to the product~~	~~Linda & Stacey – 1st Draft~~	~~• Adds requirement of customer review to waive a formal review~~ ~~•Requires documentation of manufacturing feasibility in contract review~~	~~• Requires documentation~~	~~• Risks have to be evaluated~~
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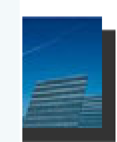

ISO 9001:2000	PV Proposal	TS 16949:2000	DIS 13485	AS9100 Rev A
8.3 – Control of Nonconforming Product	Stacey Rassas	• Adds reworked product • Customer waiver	• Only allows release of nonconforming product that meet regulatory requirements • Document rework procedure	• Customers must approve use-as-is or repair • Notification of nonconforming product
8.4 – Analysis of Data	Linda Merritt	• Trends in quality compared against goals	• Requires documented procedures and records	Same as ISO
8.5 – Improvement				
8.5.1 – Continual Improvement	**Robin Kobren**	• **Continual improvement of the organization** • **Reduction of manufacturing variation**	• **Advisory notes for medical devices** • **Records of customer complaints**	**Same as ISO**
~~8.5.2 – Corrective Action~~	~~Paul Robusto~~	~~• Requires process for problem solving~~ ~~• Error proofing~~ ~~• Rejects product test/analyzed~~	~~• Records~~	~~• Flow down corrective action to suppliers~~
8.5.3 – Preventive Action	Lisa Dwornik	Same as ISO	• Records • Review preventive action and it effectiveness	Same as ISO

* Summarized from Elsmar Cove Forum poster" howste" posted on June 19, 2003

ISO 9001:2000	PV Proposal	TS 16949:2000	DIS 13485	AS9100 Rev A
8 – Measuring, Analysis & Improvement				
8.1 – General	**Paul Norum**	**• Identification of statistical tools • Knowledge of basic statistical concepts**	**• Exchanges "maintain" for continually improvement**	**• Adds note on where statistics can be used.**
8.2 – Monitoring and Measurement				
8.2.1 – Customer Satisfaction	Paul Robusto	• Specifies measures for customer satisfaction	• Requires documentation of customer feedback system	Same as ISO
8.2.2 – Internal Audit	Lisa Dwornik	• Adds QMS, manufacturing process and product audits • Adds requirement for Internal Auditor qualification	Same as ISO	• Requires appropriate tools and techniques be developed for Internal Audits • Adds contract and/or regulatory audits
8.2.3 – Monitoring & Measurement of Processes	Robin Kobren	• Requires process capability studies • More detail on control plans • Requires out of control action plans	Same as ISO	• Specifies process for nonconformities
8.2.4 – Monitoring & Measurement of Product	Paul Norum	• Requires input inspection and functional testing • Adds requirements for appearance items	• Documentation required • Implantable devices	• Requires statistically valid sampling plans • Positive recall system • Inspection documents •First Article required

* Summarized from Elsmar Cove Forum poster" howste" posted on June 19, 2003

Example of “Solar required updates”

- **7.4 Purchasing**
- **7.4.1 Purchasing process**
- The organization shall ensure that purchased product conforms to specified purchase requirements. The type and extent of control applied to the supplier and the purchased product shall be dependent upon the effect of the purchased product on subsequent product realization or the final product.
- Materials, components, and sub-assemblies which have a safety implication on the finished product and which are purchased from or prepared by an outside supplier, require higher levels of control and shall be verified as complying with designated specifications.
- The organization shall evaluate and select suppliers based on their ability to supply product in accordance with the organization’s requirements. Organizations. which must comply with technical specification, drawings, etc. Criteria for selection, evaluation and re-evaluation shall be established. Records of the results of evaluations and any necessary actions arising from the evaluation shall be maintained (see 4.2.4).
- *Note: It is the responsibility of the organization to ensure that sub-assemblies and assemblies completed by subcontractors meet the quality plans and relevant safety requirements. To ensure this, subcontracted assembly and production services must meet all requirements of paragraph 7.4 purchasing and the subparagraphs that comprise it.*

The issues

- Who wants what?
- Who will pay?
- Who will warrant the value, the performance

Highly Accelerated UV Aging of Organic Luminescent Materials

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*Contact: galers@ucsc.edu

Abstract

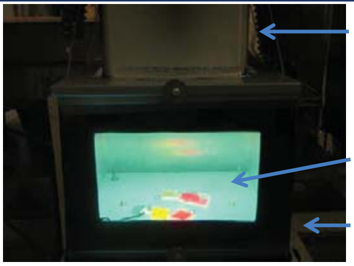
Organic luminescent materials are being developed for application to solar modules but have a history of degradation under full sun illumination. A highly accelerated UV test has been developed to screen luminescent materials and determine accleration parameters. Active water cooling is used to control temperature under exposure to high intensity UV light. Samples are encapsulated in a glass/organic/glass packaged and then submerged in a water bath with temperature controlled between 20 – 60ºC. The improved cooling allows up to 50 suns of equivalent UVA radiation be applied to the samples with no heating and a linear dependence of degradation rate on intensity. Some luminescent materials show no degradation after the equivalent of 20 years of UV light.

Application of Luminescent Materials for Solar

1) Downconversion of blue light to region of high EQE
- CdS layer in CIGS and CdTe absorbs photons with λ<500nm
- Luminescent materials: Absorb <500nm → Emit >600nm
- Up to 10% improvement in efficiency demonstrated in CdTe

2) Luminescent Solar Concentrators
- Absorb → emit into waveguide for collection in PV cell

Test Chamber



High intensity UV lamp
Metal Halide D: Broad UV spectrum
250 mW/cm^2 of UVA
(Sun ~ 5mW/cm2)

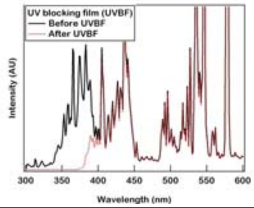
Water Bath
Samples submerged

Circulator (20-60ºC)

Water is transparent to UV and maintains accurate temperature

Test Methodology

Control Spectrum: UV blocking films
Replace UV blocking film daily

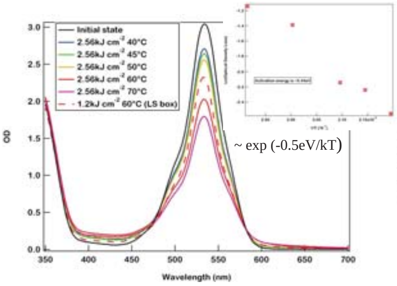


Controlled degradation

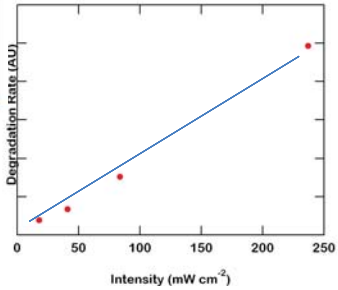
Measure Degradation vs. UV cutoff and Temperature

Select Results on Old Generation Dyes

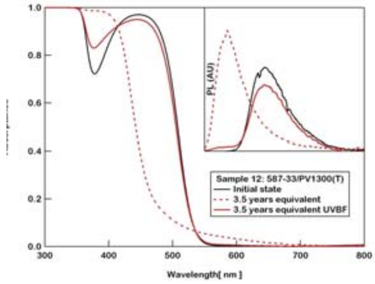
Temperature Dependence Arrhenius



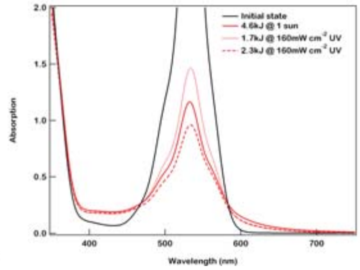
Degradation rate: linear with intensity



Absorption and photoluminescence degradation can be different



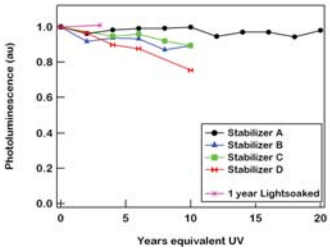
Reasonable correlation to lifetime under 1 sun

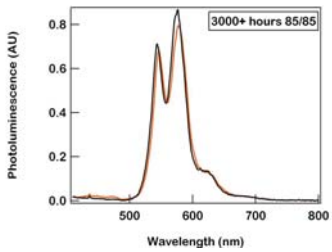


Accurate temperature control + UV cutoff control + high intensity = Quantitative acceleration parameters

Example of Stable Luminescent Material

Stable Dyes: 20 years equivalent of UV with no degradation
1) Dye with high intrinsic stability
2) Proper host (PMMA vs. PVB vs. EVA)
3) Proper stabilization of host





Stability of Current Generation Luminescent Materials

1) Luminescent materials can withstand >10 years equivalent UV

Differences in testing of Luminescent materials vs. polymers
1) Luminescent materials are very dilute (<1%) in host matrix
→ low capture cross section
2) Luminescent materials have short excited state lifetime
→ Short time for photo-oxidation to occur

New methodology: water cooling + very high intensity UV light
Avoid excessive heating of samples from high intensity light
Improved temperature control → improved extrapolations

Used for testing sealed PV encapsulants (CIGS and CdTe)

Water cooling can be applied to cooling front face glass

Photovoltaic Module Outdoor Analysis and Power Estimation

Dohyun Baek*, Jaehoon Lee, Jeongho Son, Jongchul Lee, Yongmo Choi, Sundong Choi, Seonghyeon Cheon, Yongdeuk Kim, and Dongseop Kim

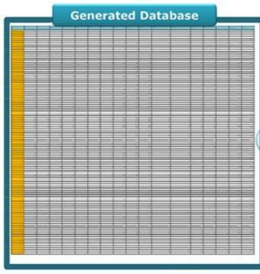
Solar Energy Business Division, Samsung SKI, South Korea
Email: dohyun.baek@samsung.com

Motivation & Initiation

PV Outdoor Test Site

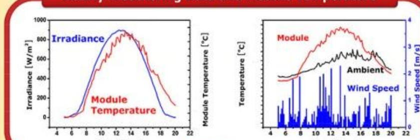
When power is maximum?
How high module temperature?

Generated Database



Wow!! What are these?
A whole lot of data...

Hourly Weathering Data and Module Temperature



Module Temperature Equation

- Module Temperature Parameters
  - T_{module}: Module Temperature [°C]
  - $T_{ambient}$: Ambient Temperature [°C]
  - $I_{irradiance}$: Solar Irradiance [W/m²]
  - a: Slope parameter @ Wind speed items
  - b: Intercept parameter @ Wind speed items
  - X_{ws}: Wind Speed [m/s]

$$T_{module} = T_{ambient} + I_{irradinace} \times \exp(aX_{ws} + b)$$

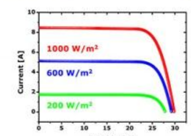
Equation??
Looks complicated!!
What does that mean?

Irradiance, Ambient Temperature, Windspeed Summary

Mon	Solar [KWh/m²]			UV [KWh/m²]		UV [%]		T_{amb} [°C]			RH [%]		WS [m/s]		
	AZ	FL	KOR	AZ	FL	AZ	FL	AZ	FL	KOR	AZ	FL	AZ	FL	KOR
1	6861.1	7194.4	5249.4	241.67	297.22	3.52	4.13	19	22	7.5	57	92	3.3	2.3	0.6
2	7638.9	7666.7	6089.7	294.44	350.00	3.85	4.57	19	23	10.5	74	96	2.8	2.3	0.9
3	8055.6	7722.2	6731.5	358.33	383.33	4.45	4.96	21	24	19.5	67	97	2.9	2.6	1.0
4	8194.4	7416.7	6785.4	377.78	397.22	4.61	5.36	26	28	21.9	44	90	3.0	2.6	1.0
5	7833.3	6444.4	7329.1	391.67	388.89	5.00	6.03	31	32	26.1	59	90	2.9	2.3	0.9
6	7388.9	6194.4	6794.7	388.89	383.33	5.26	6.19	38	35	29.4	63	94	2.5	2.1	0.9
7	7166.7	6277.8	6554.3	383.33	380.56	5.35	6.06	40	34	29.6	70	96	2.7	2.1	1.0
8	7305.6	6583.3	6915.4	377.78	380.56	5.17	5.78	38	34	33.2	59	99	2.7	1.6	0.9
9	7777.8	6944.4	7044.4	372.22	372.22	4.79	5.36	39	32	28.1	33	98	2.8	2.0	0.7
10	7527.8	7111.1	6292.8	327.78	358.33	4.35	5.04	30	31	30.9	56	96	2.9	1.9	0.7
11	6944.4	7111.1	5649.9	272.22	302.78	3.92	4.26	23	28	20.1	42	98	3.2	1.8	0.8
12	6416.7	6888.9	5141.6	216.67	266.67	3.38	3.87	21	22	8.9	58	91	2.7	2.2	0.7
AVG	7425.9	6962.9	4000.5	333.56	355.09	4.47	5.13	28.75	28.75	22.14	56.83	94.75	2.87	2.15	0.84

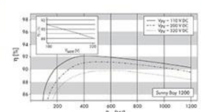
PV I-V Characteristics

Items	Values
I_{sc} [A]	8.5
V_{oc} [V]	30
P_{max} [W]	195
I_{pm} [A]	8
V_{pm} [V]	24.3
Reference Temp. [°C]	25



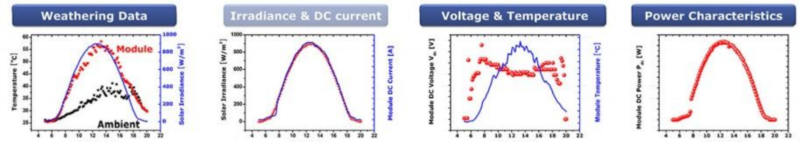
Inverter Characteristics

Items	Param	Values
Maximum DC power at cos ϕ = 1	P_{DC}	1320W
Maximum DC voltage	V_{DCmax}	400V
MPP voltage range at 230 V AC	V_{PV}	100V ~ 320V
DC nominal voltage	V_{DCnom}	120V
Minimum DC voltage at 230 V AC	V_{DCmin}	100V
Start voltage, adjustable	$V_{PVStart}$	120V
Maximum input current	I_{PVmax}	12.6A
Number of MPP trackers		1
Maximum number of parallel strings		2
Voltage ripple of input voltage	V_{pp}	< 10%
Internal consumption during operation		< 4W



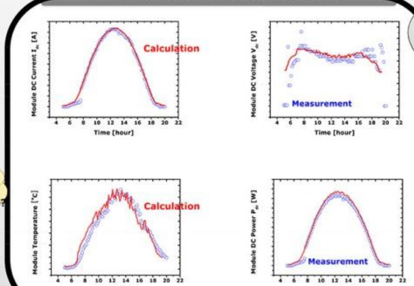
Hourly PV Module and Weathering Characteristics

Weathering Data | Irradiance & DC current | Voltage & Temperature | Power Characteristics



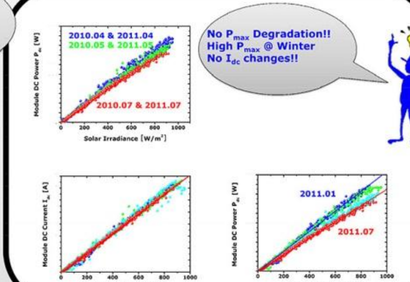
They are NOT linear...
How to fit them???

Measurement and Calculation Correlation



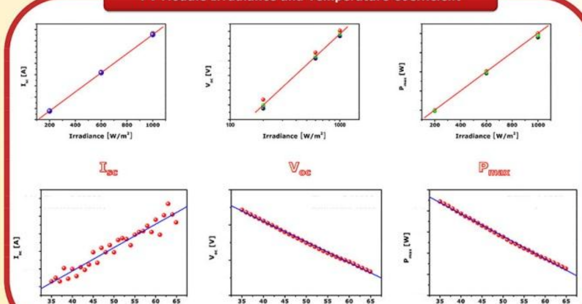
Looks well matched!!
Do you agree??

Yearly and Monthly PV Characteristics Comparison



No P_{max} Degradation!!
High P_{max} @ Winter
No I_{dc} changes!!

PV Module Irradiance and Temperature Coefficient



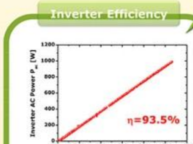
PV module irradiance and temperature coefficients are extracted at various irradiance intensities and temperature

Power Estimation Fomular

$$P_{dc}(I_{irr}, T_{amb}, WS) = I_{dc}(I_{irr}, T_{amb}, WS) \times V_{dc}(I_{irr}, T_{amb}, WS)$$
$$P_{ac}(I_{irr}, T_{amb}, WS) = \eta_{inv} \times P_{dc}(I_{irr}, T_{amb}, WS)$$

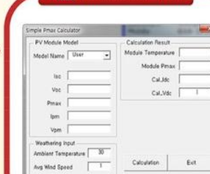
No More Equations

Inverter Efficiency



We're able to estimate the P_{max} and module temperature at different weather conditions!!

P_{max} Calculation Tool



Power Estimation

I_{irr}	T_{amb}	WS	T_m	I_{dc}	V_{dc}	P_{dc}	P_{ac}	Remarks
1000	-10	2	7.19	7.91	26.17	207.0	192.6	Maximum Power
1000	7	2	25.0	8.00	24.3	194.7	181.1	STC
1000	40	2	27.9	8.19	20.7	169.6	157.7	How Weather
800	7	1	23.1	6.41	24.3	155.8	144.9	KOR(Winter)
800	35	1	51.1	6.54	21.2	139.0	129.3	KOR(Summer)

SAMSUNG SDI SAMSUNG

Sunset Technology, Inc.

PV Standards.
What new things does the IEC have for you?

By Howard O. Barikmo, Sunset Technology, Inc.
hbarikmo@aol.com

February 28, 2012

Technical Committee 82 and its Working Groups

• **WG1: Glossary**	Task: To prepare a glossary.
• **WG2: Modules, non-concentrating**	Task: To develop international standards for non-concentrating, terrestrial photovoltaic modules--crystalline & thin-film
• **WG3: Systems**	Task: To give general instructions for the photovoltaic system design, and maintenance.
• **WG6: Balance-of-system components**	Task: To develop international standards for balance-of-system components for PV systems.
• **WG 7: Concentrator modules**	Task: To develop international standards for photovoltaic concentrators and receivers.
• **JWG 21/TC 82 Batteries**	Task: To draw up standard require-ments for battery storage systems intended for use in photovoltaic systems.
• **JWG 1--TC 82/TC 88/TC21/SC21A**	Task: To prepare guidelines for Decentralized Rural Electrification (DRE) projects which are now being implemented in developing countries.

TC 82 WG2

- Standards published by TC 82 can be found on the internet at:

http://www.iec.ch/dyn/www/f?p=103:23:0::::FSP_ORG_ID,FSP_LANG_ID:1276,25

Or simply go to www.iec.ch and search for TC 82 dashboard finder. Select IEC - **TC 82 Dashboard** > Scope and click on Projects/Publications. The TC 82 Work Programmed will be listed. Click on Publications to view all standards that have been published to date.

This report will focus on and list New Work Item Proposals and maintenance work that is underway.

Figures in red indicate expected completion dates, or other status on project.

TC 82
WG1 and WG2

- **Working Group 1**
- **IEC/TS 61836 Ed. 3.0** Solar photovoltaic energy systems - Terms, definitions and symbols 2012

- **Working Group 2**
- **IEC 61215 Ed. 3.0** Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval 2013
- **EC 61730-1 am2 Ed. 1.0** Amendment 2 to IEC 61730-1 Ed.1: Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction 2013
- **IEC 61730-2 Ed. 2.0** Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing 2014
- **IEC 61853-2 Ed. 1.0** Photovoltaic (PV) module performance testing and energy rating - Part 2: Spectral response, incidence angle and module operating temperature measurements 2012
- **IEC 62716 Ed. 1.0** Ammonia corrosion testing of photovoltaic (PV) modules 2012
- **IEC 62759-1 Ed. 1.0** Transportation testing of photovoltaic (PV) modules - Part 1: Transportation and shipping of PV module stacks 2013
- **IEC 62775 Ed. 1.0** Cross-linking degree test method for Ethylene-Vinyl Acetate applied in photovoltaic modules - Differential Scanning Calorimetry (DSC) 2014

TC 82
WG2

- **IEC 62782 Ed. 1.0** Dynamic mechanical load testing for photovoltaic (PV) modules
- **IEC 62788-1-2 Ed.1** Measurement procedures for materials used in photovoltaic modules - Part 1-2: Encapsulants - Measurement of resistivity of photovoltaic encapsulation and backsheet materials 2015
- **IEC 62788-1-4 Ed.1** Measurement procedures for materials used in Photovoltaic Modules - Part 1-4: Encapsulants - Measurement of optical transmittance and calculation of the solar-weighted photon transmittance, yellowness index, and UV cut-off frequency 2015
- **PNW 82-654 Ed. 1.0** Photovoltaic devices - Part11: Measurement of initial light-induced degradation of crystalline silicon solar cells and photovoltaic modules 2014
- 2015
- **PNW 82-668 Ed. 1.0** Future IEC 6XXXX-1-3 Ed.1: Measurement procedures for materials used in photovoltaic modules - Part 1-3: Encapsulants - Measurement of dielectric strength 2015
- **PNW 82-669 Ed. 1.0** Future IEC 6XXXX-1-5 Ed.1: Measurement procedures for materials used in photovoltaic modules - Part 1-5: Encapsulants - Measurement of change in linear dimensions of sheet encapsulation material under thermal conditions On hold
- **PNW 82-674 Ed. 1.0** Junction boxes for photovoltaic modules - Safety requirements and tests 2015
- **PNW 82-675 Ed. 1.0** Connectors for DC-application in photovoltaic systems - Safety requirements and tests On hold

TC 82
WG2 and WG3

- **PNW 82-685 Ed. 1.0** System voltage durability test for crystalline silicon modules - Qualification and type approval Closes Apr 14 2012
- **PNW 82-689 Ed. 1.0** Test method for total haze and spectral distribution of haze of transparent conductive coated glass for solar cells Closes Apr 27 2012
- **PNW 82-690 Ed. 1.0** Edge protecting materials for laminated solar glass modules
- Closes April 27 2012
- **PNW 82-691 Ed. 1.0** Test method for transmittance and reflectance of transparent conductive coated glass for solar cells Closes April 27 2012
- **Working Group 3**
- **EC 61829 Ed. 2.0** Crystalline silicon photovoltaic (PV) array - On-site measurement of I-V characteristics 2013
- **IEC 62548 Ed. 1.0** Design requirements for photovoltaic (PV) arrays 2013
- **IEC/TS 62738 Ed. 1.0** Design guidelines and recommendations for photovoltaic power plants 2012
- **IEC/TS 62748 Ed. 1.0** PV systems on buildings 2012

TC 82
WG6 and WG7

- **Working Group 6**
- **IEC 62109-4 Ed. 1.0** Safety of power converters for use in photovoltaic power systems - Part 4: Particular requirements for combiner box On hold
- **PNW 82-696 Ed. 1.0** Safety of power converters for use in photovoltaic power systems - Part 3: Particular requirements for PV modules with integrated electronics Closes May 18, 2012

- **Working Group 7**
- **IEC 62670-1 Ed. 1.0** Concentrator photovoltaic (CPV) module and assembly performance testing and energy rating - Part 1: Performance measurements and power rating - Irradiance and temperature 2013
- **IEC 62688 Ed. 1.0** Concentrator photovoltaic (CPV) module and assembly safety qualification 2013
- **IEC 62787 Ed. 1.0** Concentrator photovoltaic (CPV) solar cells and cell-on-carrier (COC) assemblies - Reliability qualification 2014
- **IEC/TS 62727 Ed. 1.0** Specification for solar trackers used for photovoltaic systems 2012
- **PNW/TS 82-652 Ed. 1.0** Specification for concentrator cell description On hold

TC 82
JWG 21/TC 82 and JWG 1

- **JWG 21/TC 82 Batteries**
- IEC 61427-2 Secondary cells and batteries for renewable energy storage Part 2: On-grid applications 2014

- **JWG 1--TC 82/TC 88/TC21/SC21A**
- IEC/TS 62257-9-6 Ed. 2 Recommendations for small renewable energy and hybrid systems for rural electrification – Part 9-6 : Selection of Photovoltaic Individual Electrification Systems (PV-IES) [to include selection of PV powered LED lanterns] 2012

Exploring highly accelerated aging on c-Si modules

EDF R&D : Mike Van Iseghem, Antoine Plotton, Didier Binesti - Moret-sur-Loing (France)
EDF Energies Nouvelles : Khalid Radouane, Pierre-Guy Therond - Paris La Défense (France)

As a PV power plant operator and investor we are interested in rapid quality control of modules.

Today, it seems that the typical accelerated aging tests are not very representative of outdoor failures, and they are also particularly long and therefore expensive to use, especially for quality control. The results presented here shows attempts to thermally accelerate the damp heat test of crystalline silicon modules.

For this study we applied 2 different damp heat conditions :

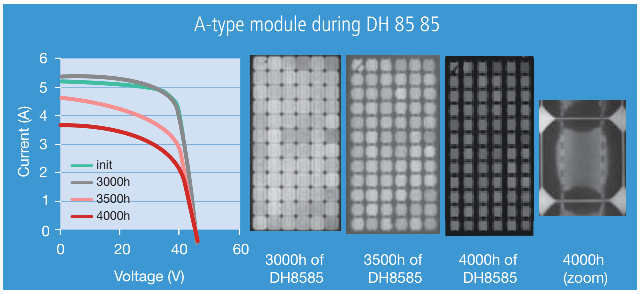
- DH 85°C 85% RH, as required by the IEC 61215 standard,
- DH 95°C 85% RH.

2 different types of commercially available modules have been tested:

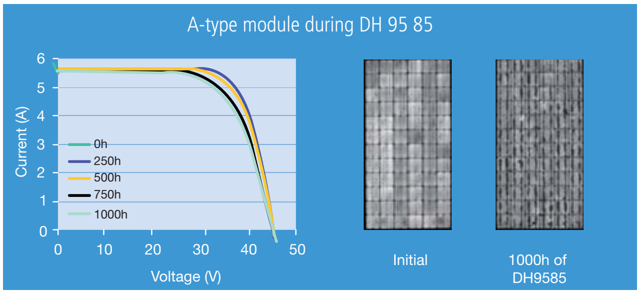
- A-type modules are mono-crystalline,
- B-type modules are poly-crystalline from a different supplier.

At each test, 3 modules per type have been aged, while one extra module is kept for reference. For each test, the 3 modules showed about the same behaviour. Some tests have been completed until failure of the module, while others are still on-going, in order to reach a significant power loss.

In the following, we show I-V curves measured at STC (25°C, 1000W/m², AM1.5) with a PASAN flasher of AAA quality, and electro-luminescence images obtained with a basic setup, which allows to get complementary information not accessible by visual inspection.

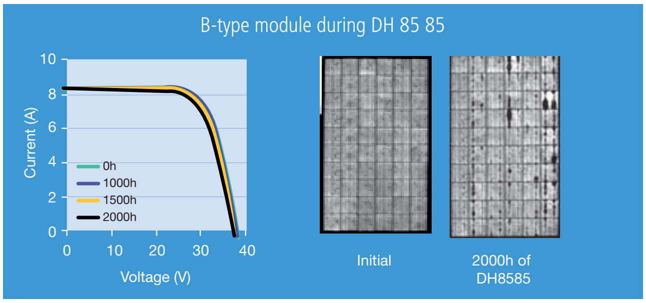


This module resisted to more than 3000 hours of DH8585, which is 3 times longer than the time required by the IEC standard. After that, we observed that the front side of the cells became inactive from their edges. We suspect that humidity entered homogeneously through the Tedlar back-sheet and further on between the cells towards the front. We suspect that the EVA encapsulation released acetic acid which is corrosive for the front contacts.

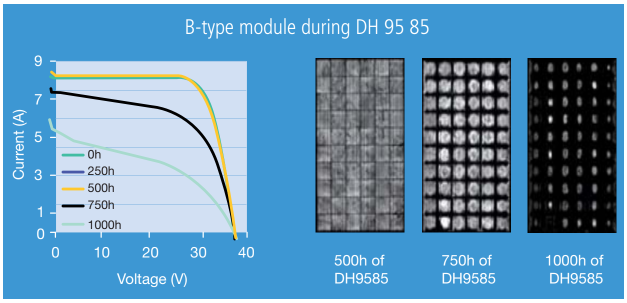


Although this module comes from the same supplier A, it's design is slightly different from the one tested at CH8585.

At the current stage (1000h of DH9585) this module has lost 13% of it's power, mainly due to series resistance increase. Soldering of the front contacts seems to be degraded. Further DH is on-going.



At this stage (2000h of DH8585) the module shown has lost 7% of it's power, mainly due to series resistance increase. Soldering of the front contacts seems to be degraded. Further DH is on-going.



This module has failed by Isc, Rs and Rsh degradation after more than 500 hours of DH9585. We suspect that humidity went through the back-sheet, came between the cells and attacked their front side from the edges.

DISCUSSION

We have tested 2 different commercially available c-Si module types A and B at 2 different damp heat temperatures : 85°C and 95°C, both at 85% relative humidity.

For both module types, increasing test temperature accelerates power degradation by a factor of 2 or 3.

However, at higher test temperatures, the failure modes changed. The observed failure modes are:

- homogeneous humidity penetration from the back-sheet, between the cells and further on towards their front surface. The cells degrade individually from their edges.
- soldering failures at the front side of the cells, which leads to increased series resistance

We suspect that the tested modules come from different production batches and therefore behave differently.

This poster does not contain any proprietary or confidential information

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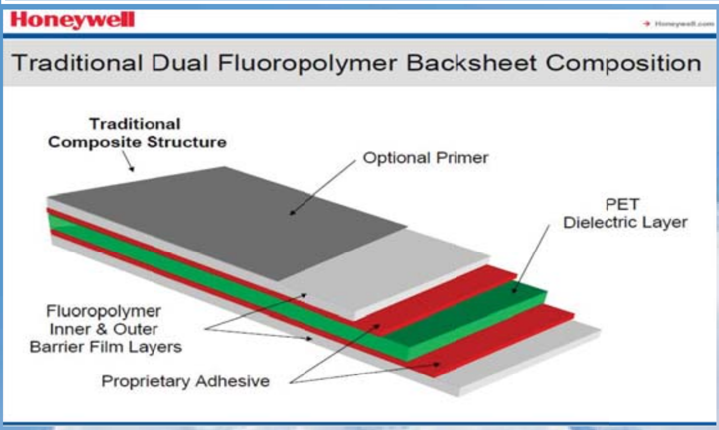
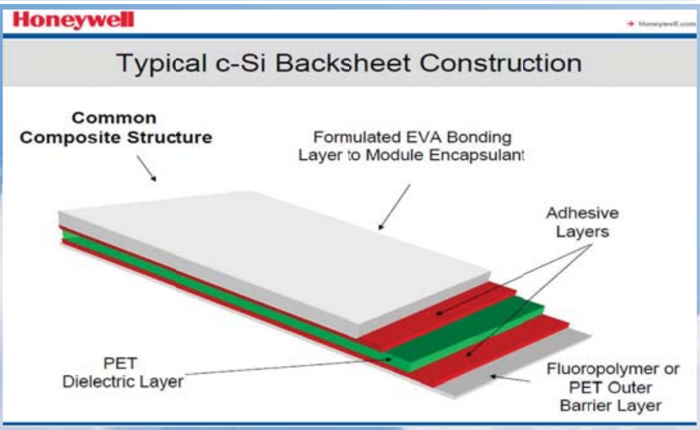
Title: Evaluating Backsheets without Fluoropolymer Sun-Facing Layers

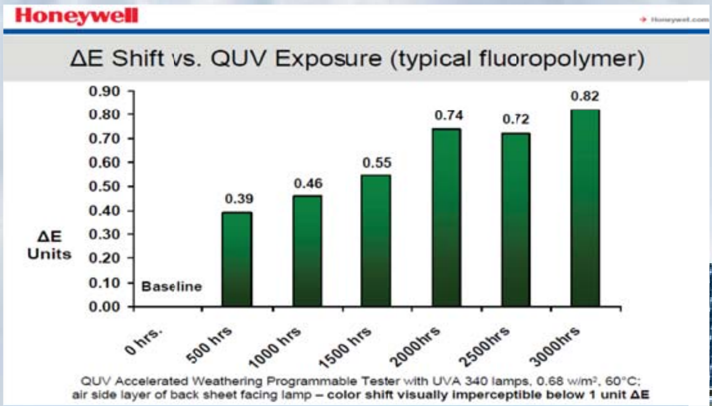
Abstract: Over the last 5 years, almost 60% of the c-Si modules used globally have shifted to no longer utilizing a high-opacity and highly-stable fluoropolymer layer on the sun-facing side of their backsheet constructions, generally due to the contribution of the fluoropolymer material to the backsheet cost. While not necessarily a major detriment to module reliability, it does raise the importance that the alternative constructions be well-chosen and tested adequately on the sun-facing side rather than assumed to be equivalent to the fluoropolymer layer which they replace. Common replacement layers, such as those based on modified polyethylenes or EVA's, are often much more susceptible to UV and damp heat yellowing, which in turn can imply premature loss of esthetics, reduction of reflectivity, and perhaps early degradation of dielectric or structural performance. The impact may be more of a concern with encapsulants having lower degrees of UV screening to improve light transmission to the cell surface.



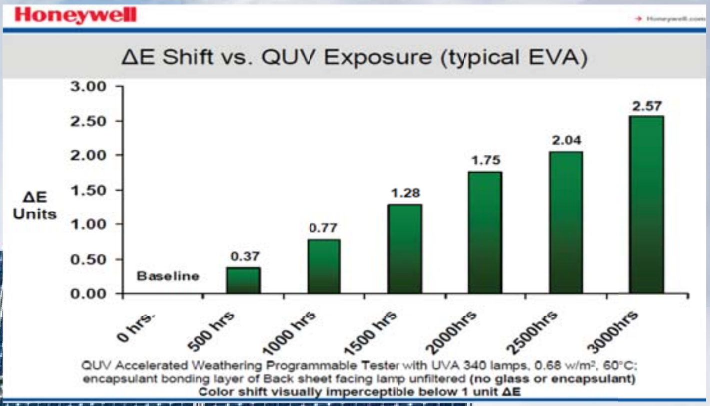
Traditional backsheets generally have had durable pigmented fluoropolymer film layers on both the sun-facing side as well as the weather barrier side. The sun-facing fluoropolymer layer is immune to UV damage and attenuates any UV light passing through the glass and encapsulant layers to minimize UV exposure to the PET dielectric layer.



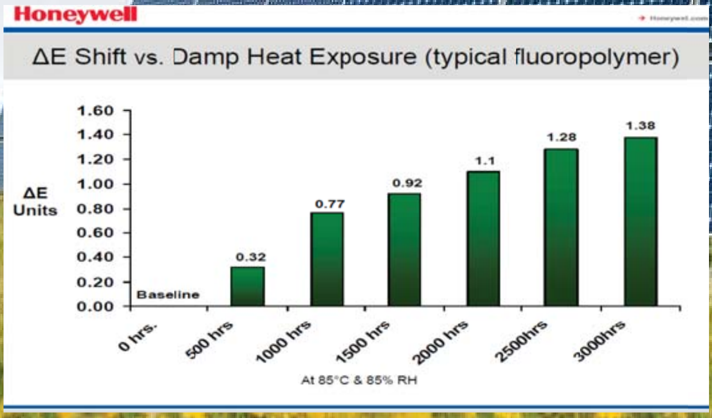
Today's typical backsheets constructions often substitute modified polyethylene (EVA) layers on the sun-facing side while leaving a fluoropolymer layer on the weather barrier side. The sun-facing polyethylene layer must then be both resistant to UV exposure as well as adequately block UV from degrading the PET dielectric layer.



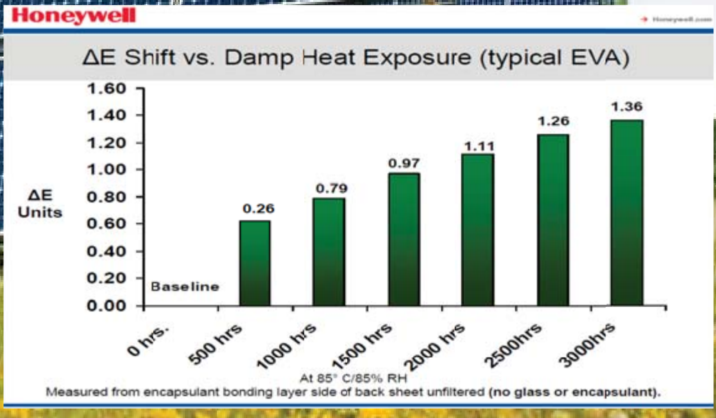
Fluoropolymer films properly designed as sun-facing backsheet layers generally show almost imperceptible color shift, even after extended UV exposure. Reflectivity and esthetics changes are minimized.



Newer backsheets employing even well-made PE (EVA) sun-facing layers still can shift color nearly 3X faster than fluoropolymer-types, generally darker and yellower from the original "clear" or "white" color.



Fluoropolymer films properly designed as sun-facing backsheet layers generally show almost imperceptible color shift, even after extended damp heat exposure .



Newer backsheets employing well-made PE (EVA) sun-facing layers can be formulated to resist damp heat color shift (generally, yellowing) from the original "clear" or "white" color.

Conclusions: When substituting materials for fluoropolymer PV backsheet sun-facing layers, proper design and appropriate testing should be performed to assure that the replacement material has adequate environmental stability to resist light, humidity and temperature-induced degradation which may influence module appearance and perhaps optimum module function over time.

OUTDOOR HIGH-VOLTAGE BIAS TESTING OF PV MODULES

Neelkanth G. Dhere, Ashwani Kaul

Florida Solar Energy Center, 1679 Clearlake Road, Cocoa, FL 32922-5703 USA

1. Introduction

• PV modules studies have shown that most of the degradation mechanism and reliability issues in PV cells have been determined by the tests carried out on field-deployed modules.

• Essential to understand the failure modes and mechanisms in PV modules and recommend improvements in the manufacturing technology so as to assure 25-30 year useful lifetime of field-deployed modules.

2. Degradation studies of PV Modules

• In late 80's and early 90's, array of 640 first-generation, framed, a-Si:H PV Modules were installed with a tilt of ~25º towards the south by the Florida Power Corp at Orlando, FL in collaboration with researchers of the Florida Solar Energy Center. The array operational voltage was 300 V DC.

• a-Si:H thin-film PV modules were fabricated with SnO_2:F TCO layers on superstrate glass. Ground fault was created within the PV circuit of the module. Considerable degradation was observed in negatively-biased, modules (Fig. 1 showing arcing and molten glass as a result of corrosion reaching the junction box that created ~7" long gaping hole.

• Cause of degradation was thin-film circuit reaching all the way to the edge of the frame

FIGURE 1

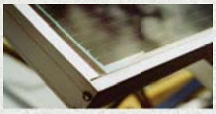
FIGURE 2

FIGURE 3

• Study of BP Solar a-Si:H (Fig. 4) PV module installed at latitude tilt at various bias voltages during 2001-2004.

• Corrosion initiated near the southern edges of individual cell strips and moved inwards (Fig. 5).

FIGURE 4



-600 V Module – After 8 months

FIGURE 5

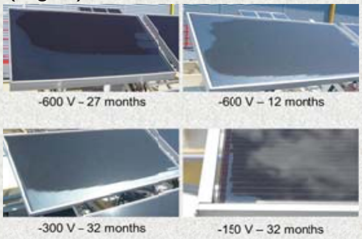


FIGURE 6

•Sodium diffusion seems to have resulted in severe delamination of SnO2:F layer from glass surface.

• Cells were fully destroyed due to electro-corrosion (Fig.6). Despite edge delete these modules encountered problems.

• Since PV modules are mostly mounted at latitude tilt, the role of latitude tilt is very important during the high-voltage testing at noted above the degradation begins from the bottom edges where most of the moisture and dirt accumulation takes places in actual outdoor conditions.

FIGURE 7

• Side by side testing of thin-film PV modules with maximum system voltage of ±600 V from all US manufacturers was carried out with a project from NREL (Fig. 7).

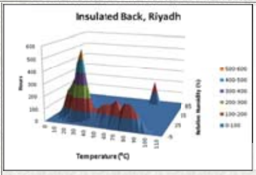


FIG. 8 (Courtesy M. Kempe)

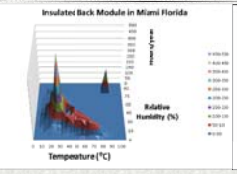


FIG. 9 (Courtesy M. Kempe)

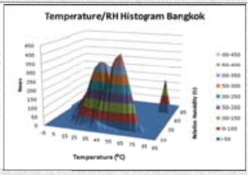


FIG. 10 (Courtesy M. Kempe)

• Typically 85°C-85%RH damp heat testing is used as the qualification test for PV modules. However, modules never see these conditions in the field (Fig 8,9,10).

•Testing PV modules outdoors with an external bias voltage is a more realistic test since it gives an opportunity to test them in nature's own laboratory where they are subjected to the actual conditions of solar irradiance, diurnal temperature variations, relative humidity.

•The acceleration factor comes from (1) higher voltage and (2) the additional biasing at night

3. CURRENT METHODS

FIGURE 11

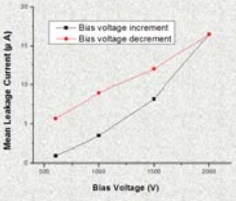


FIGURE 12

• Very high-voltage test bed was designed with the participation of graduate students. Design was approved by structural engineering firm and the entire arrangement complies with the electrical (NEC) and safety codes (OSHA).
• High-voltage bias testing (±1500 V) of c-Si PV modules, specially designed for HV applications was carried out (Fig. 11).
• Negatively biased modules showed degradation within an year.
• A new test was designed. A new module of the same type was biased at voltages up to -2000 V. The test was initiated with bias voltage at -600 V and the bias voltage was increased in steps of -600, -1000, -1500 and -2000 V with the module maintained for one week at each bias.
•Bias voltage was then decreased in same steps, again maintaining the module at each bias voltage step for one week in order to verify hysteresis.
• Figure 12 shows magnitude of mean value of leakage current at different biasing voltages for the abovementioned relative humidity and temperature range. It can be clearly seen in figure 8 that there exists a hysteresis.

4. New Plans

• To build the second high-voltage platform with improved methodology and hardware to avoid problems encountered in the past.

• PV modules from various technologies will be deployed for testing at very high voltage. Special care will be taken during the testing to avoid instantaneous irreversible degradation.

5. CONCLUSIONS

• From the studied undertaken, it is clear that high-voltage bias testing is the proper realistic test for acceleration testing of PV modules as compared to 85°C-85%RH damp heat testing.

• Therefore, outdoor high-voltage bias testing should be made an essential test for acceleration testing of PV modules.

• The chosen voltages and the latitude tilt are very important aspects of this test.

Performance and Reliability Test Methodology

Thai Phuong Do, Anders Søreng _ Technology, REC Solar, Singapore

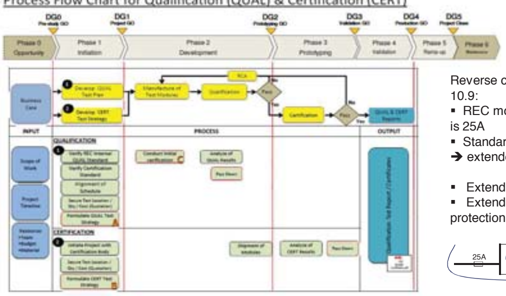
➔ *Abstract*

Product Quality Assurance is one of the main focuses of REC Solar aimed to ensure solar modules quality and safety over 25 years of lifetime. In this work, good understanding of modules performance and materials degradation is very important. Therefore, internal REC test methodology has been developed based on existing test from standards (IEC, UL) with further investigation on system functioning, material characterization, etc. Example of reverse current load test will be shown to illustrate our way of working in Product Development and Quality Assurance

Standard tests

Highly Accelerated Life Testing (HALT)

- Active in short notice failure modes and predict module 's capacity to withstand stress
- Provide baseline of degradation rate for module design/ quality benchmark
- REC's Qualification/ Certification Process ensure Product quality meeting and beyond standard requirement with high product design margin

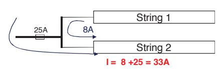


Reverse current overload Test, IEC61730-2, 10.9:

- REC module Maximum Reverse Current rate is 25A
- Standard 25A x 1.35 = 33.8A, duration of 2h

➔ extended to

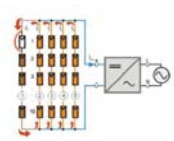
- Extend of test duration until 20h
- Extend current to worst case in double string protection fuse design: I = 33 A x 1.35 = 44.6A

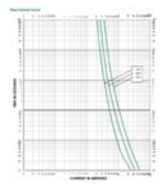


Field risk analysis

Investigation of failure probability caused by system and environment factors => FMEA establishment

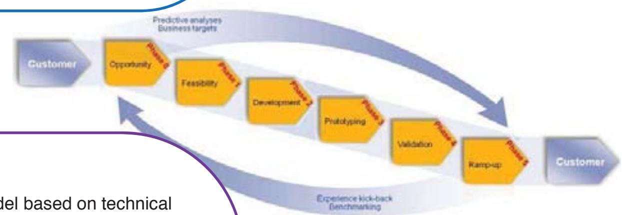
- Use external partner and customer feedback
- Use REC monitoring systems data
- Outputs will be used for building test plan





High reverse current failure:

- Survey of possible failure modes causing in sites: ground fault, shading, inverter fault, wrong polarity
- Function analysis of system components function: inverter, fuse in each case
- Building hypothesis of most severe case for testing



Modeling

1. Statistical model describing failure rate based on customer feedback and monitoring data to predict future failure rate

2. Physical model based on technical understanding of failure mechanism to predict effects on modules

Simulation of shading scenario

↓

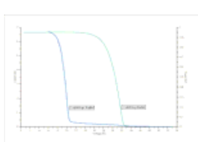
Calculate of possible reverse current

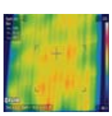
↓

Calculate of maximum temperature

↓

Comparison of simulation with testing





3. System modeling

- Predict system performance
- Compare with monitoring data ➔ analysis of possible degradation causes

Component material test

Testing data for material characterizing from provided by:

- Component test data by suppliers according to REC's material specification
- In-house test on component material and final product
- As solar integrated manufacture, REC is able to control wafers and cells quality

Discussion

REC test methodology has been developed in order to ensure product quality over 25 year. This long term work needs to be enriched continuously with our growing knowledge in PV technology, process improvement and field data.

About REC

REC is a leading vertically integrated player in the solar energy industry. Ranked among the world's largest producers of polysilicon and wafers for solar applications and a rapidly growing manufacturer of solar cells and modules, REC also engages in project development activities in selected PV segments.

Founded in Norway in 1996, REC is an international solar company, employing about 3,700 people worldwide with revenues of more than NOK 13 billion in 2011. Please visit www.recgroup.com to learn more about REC.

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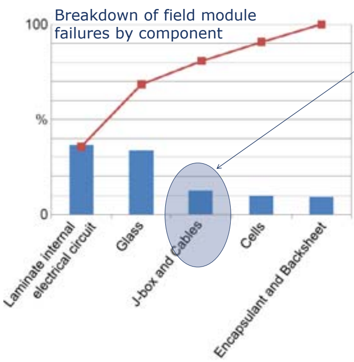
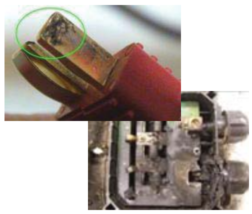
Improved Plastic Materials for Application in PV Modules

Reliability of J-Box and Connector Materials

Importance of Connectors and Junction Boxes in PV Module Reliability



Junction boxes, cables and connectors are the source of 12% of module failures



Data shows % failure of non-SunPower modules over 7 year timescale. From David DeGraaff, Ryan Lacerda, Zach Campeau (SunPower Corp), NREL 2011 PV Module Reliability Workshop, Golden, CO

Stressors on Plastic Materials in PV

Operational stresses
- Impact during installation and maintenance
- High voltage

Environmental stresses
- Moisture
- Temperature
- UV

Failure-induced stresses
- Flames
- Electrical arcs

Critical Properties for Plastics in PV

- Impervious to environmental stresses
- Impact resistance at range of temperatures
- Flame and arc resistance
- No creep or embrittlement with aging

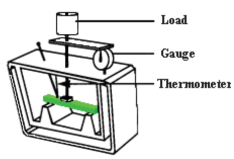
Experimental Methodology: Tests Performed on Material Samples

Impact resistance / embrittlement with aging

- Izod notched impact (INI) test (ISO 180) at -30 °C
- Ductility multi axial impact test (ISO 6603) at 0, 1000, 2000 and 3500 h of 85 °C 85 % RH

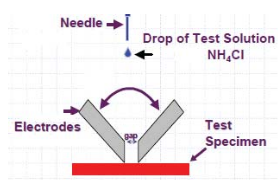
Thermal distortion

- Heat distortion temperature (HDT) test (ISO 75)
- Relative thermal index (RTI) impact test (UL 746)



Arc resistance and formation of carbonized track

- Comparative tracking index (CTI, ASTM D3638)



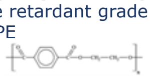
Flammability:

- V-rating (for 0.8mm specimen, UL 94)
- Minimum thickness for V0 rating
- Minimum thickness for VA rating

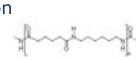
Materials Tested

The six most promising plastic materials were tested:

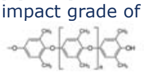
PET (polyethylene terephthalate)
- A flame retardant grade of glass filled PPE



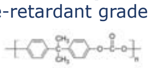
PA (polyamide)
- A flame retardant, glass filled grade of nylon



PPE (poly phenylene ether)
- A high impact grade of PPE

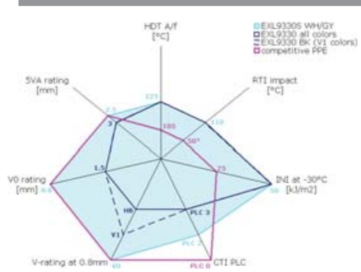


PC (polycarbonate)
- A flame-retardant grade of PC

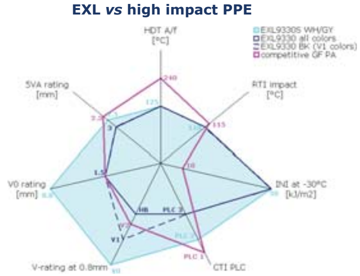


PC / silicone copolymer
- Lexan* EXL9330
- Lexan* EXL9330S

Results

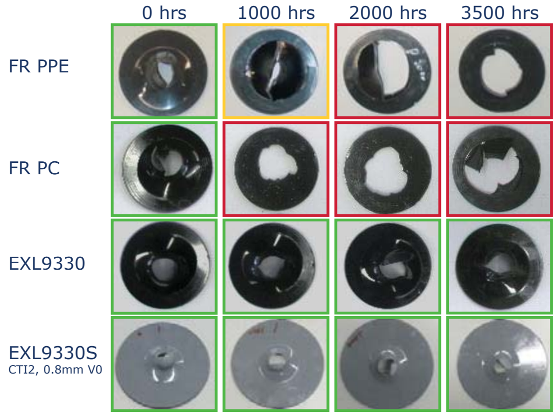


EXL *vs* high impact PPE



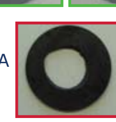
EXL *vs* GF PA

Damp Heat testing at 85°C and 85% rel humidity



GF FR PET (unaged)

GF FR PA (unaged)



Polycarbonate/silicone copolymers provided the best overall reliability

* Trademark of SABIC Innovative Plastics IP BV

Karin van de Wetering, Robert van de Grampel, Richard Lucas, Jaykisor Pal, Anil Ks, Dan M.J. Doble, Andrew Kodis, Bala Ambravan, Rob deJong, Dirk Noordegraaf

CHEMISTRY THAT MATTERS™

Spectral Effects in Performance Ratio Measurement: Comparing PV Reference Devices and Pyranometers

Lawrence Dunn[1], Michael Gostein

Atonometrics, Inc.

Non-Confidential Information

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Background

- PV Array Performance Ratio (PR) measurements depend critically on insolation measurements.
- Pyranometers historically described as near-ideal insolation meters due to flat spectral response.
- Large body of historical data from Pyranometer measurements exists.
- Pyranometer response can differ significantly from PV technologies primarily due to long-wavelength response (*i.e.*, >1200 nm).
- Our thinking: the measurement important to PV operation is perceived (*i.e.,* spectrally matched) insolation specific to that PV device.

Summary of Findings

- Pyranometers deviate from PV module perceived irradiances due to spectral effects.
  - Monthly deviations can be > 3%.
  - Annual deviations can be > 1.5%.
- Atmospheric conditions matter
  - Houston: high water vapor→larger Pyranometer deviation from PV measurement
  - Phoenix: less water vapor→smaller (but still significant) Pyranometer deviation from PV measurement
- C-Si reference devices also show significant mismatch errors with thin film modules.

Reference Devices

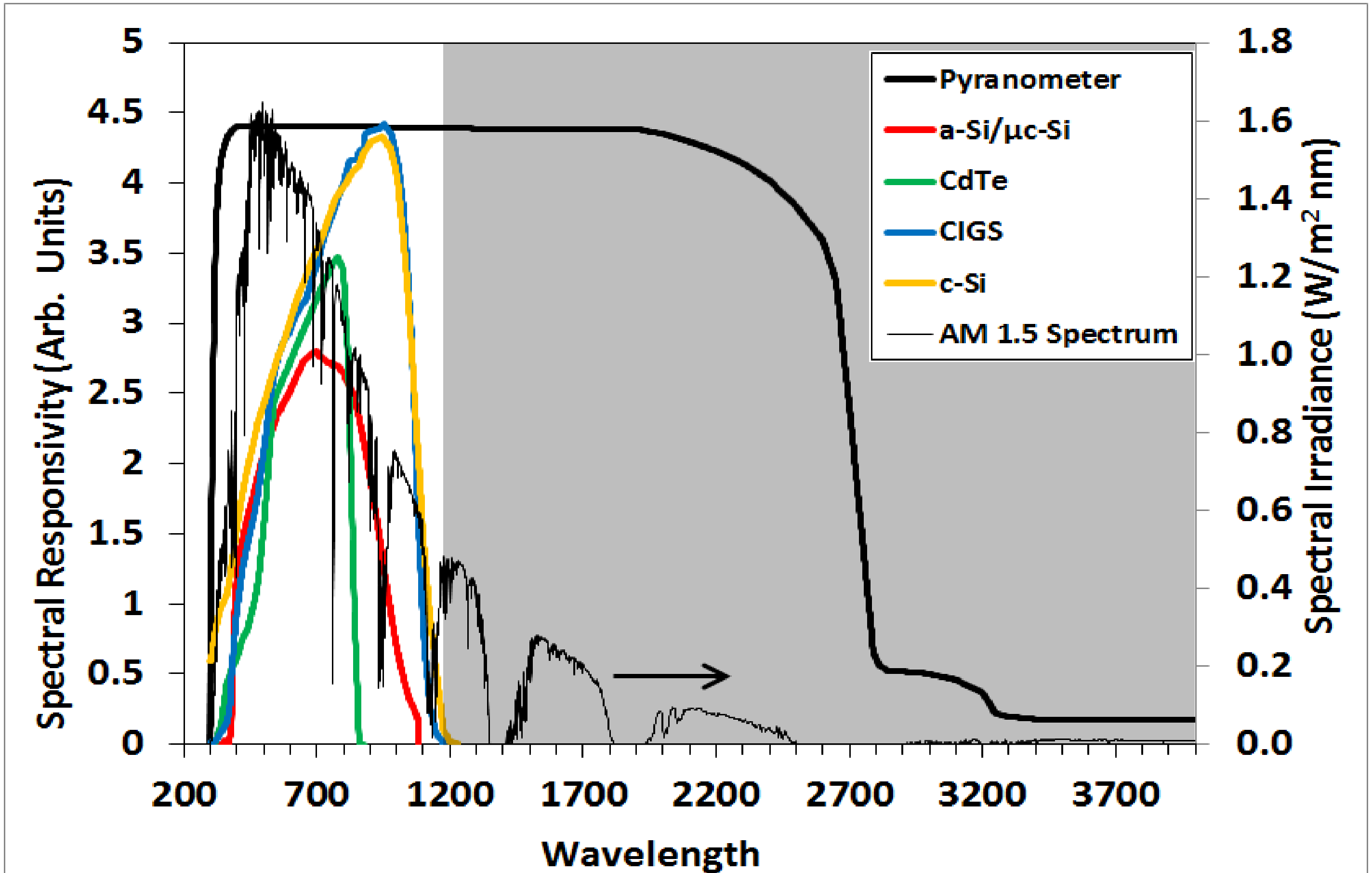
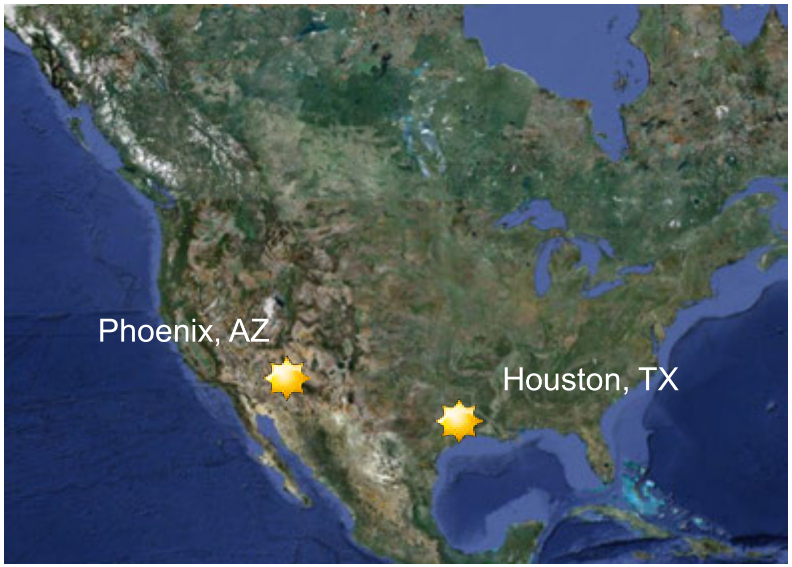


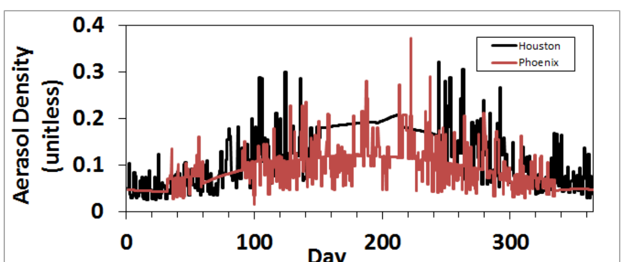
Figure 1: Spectral Response of Pyranometer and PV devices of various technologies, shown with the AM 1.5 Reference Spectrum. Shaded area represents spectral region of Pyranometer response and no PV response. Pyranometer Spectral Response taken from data published by a Pyranometer manufacturer. a-Si/µc-Si, c-Si, CdTe, and CIGS spectral responses taken from NREL calibration reports or from literature. Note Spectral Response is shown on the left y-axis.

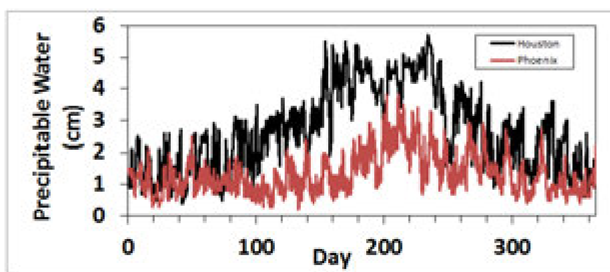
Simulating Solar Spectra

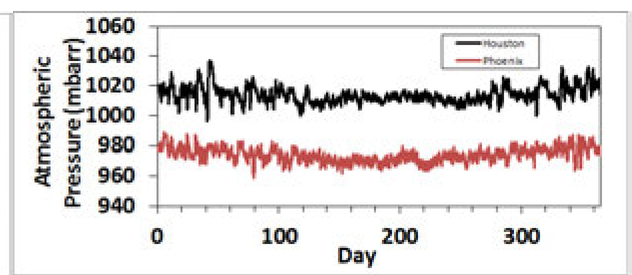


- NREL SPECTRL2 worksheet based on Bird's Simple Spectral Model used to generate solar spectra at 5 minute increments.
- Aerosol density (AOD), atmospheric pressure, and precipitable water inputs to spectral model taken from Typical Meteorological Year 3 (TMY3) database hosted by NREL
- Simulations done for clear-sky conditions only
- Houston, TX (sunny, humid) and Phoenix, AZ (sunny, dry) chosen as simulated locations.

TMY3 Weather Data







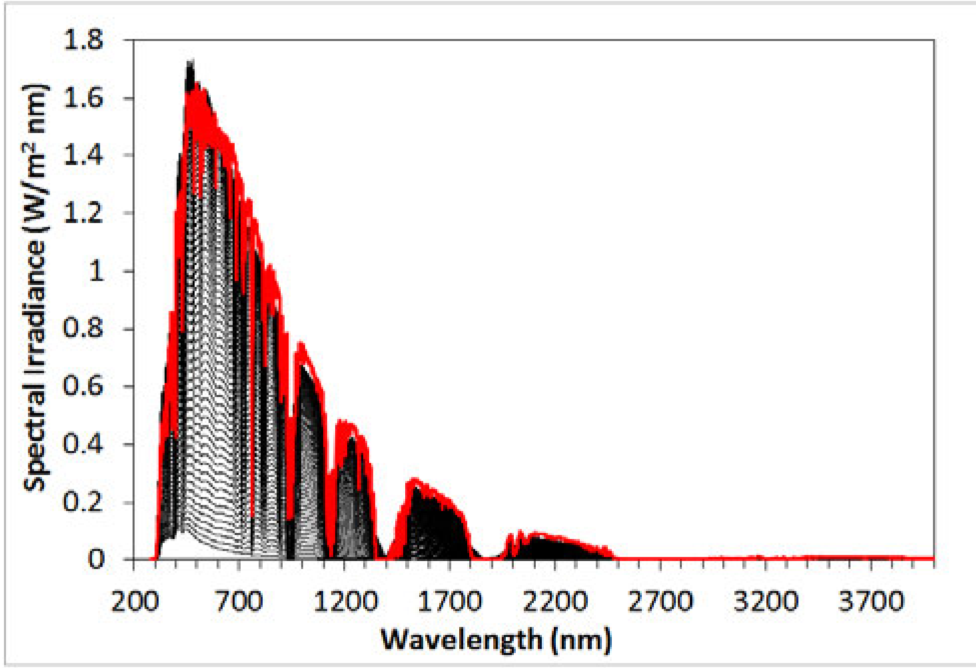


Figure 2: Example simulated spectra at 5 minute increments from 6:30 a.m. to 12:30 p.m. in Phoenix, Arizona on the 152nd day of the year (June 1). The thick red curve is the AM 1.5 reference spectrum.

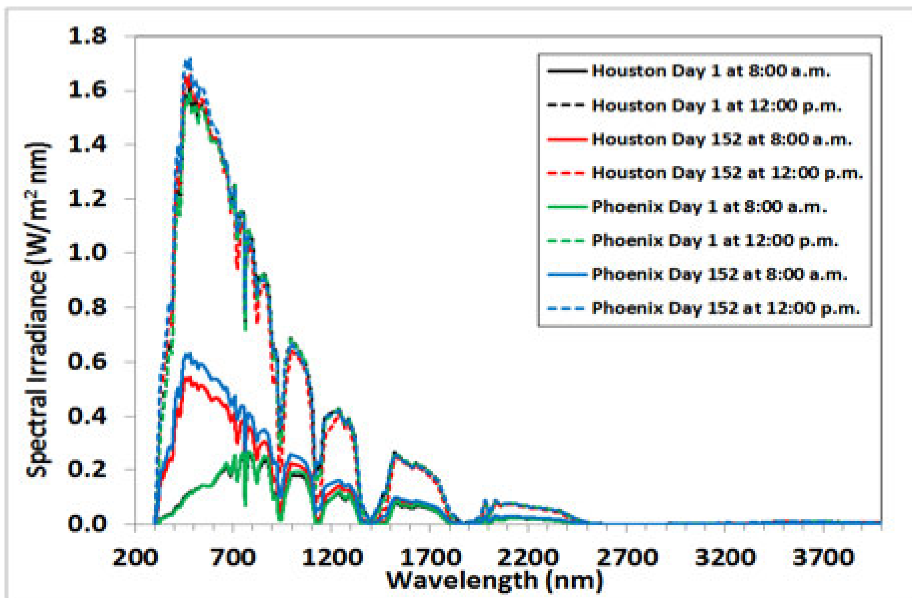
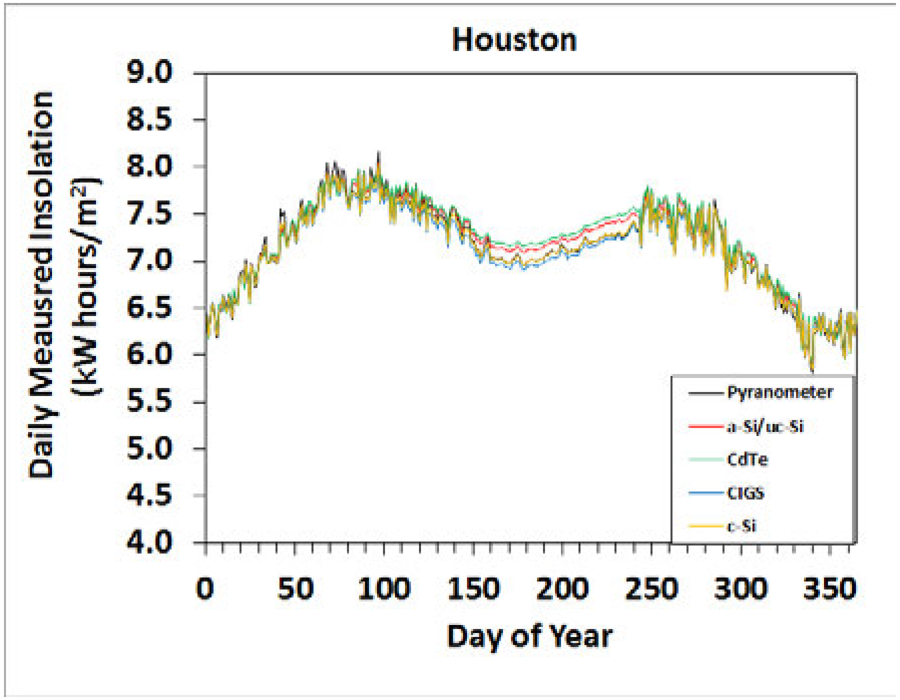


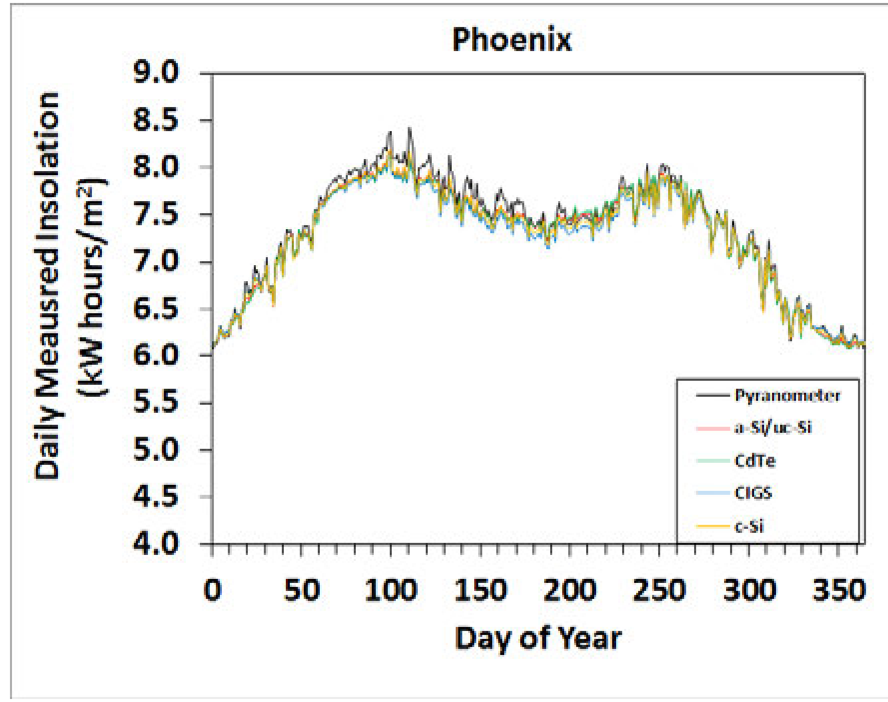
Figure 3: Example simulated spectra in Houston, TX and Phoenix, AZ on the first (January 1) and 152nd (June 1) days of the year at 8:00 a.m. and noon.

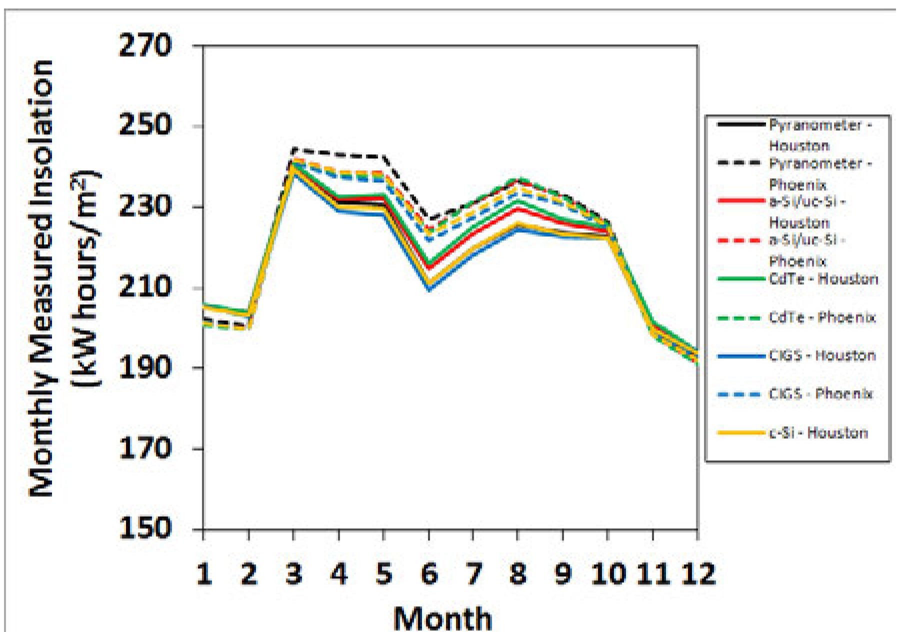
Methodology

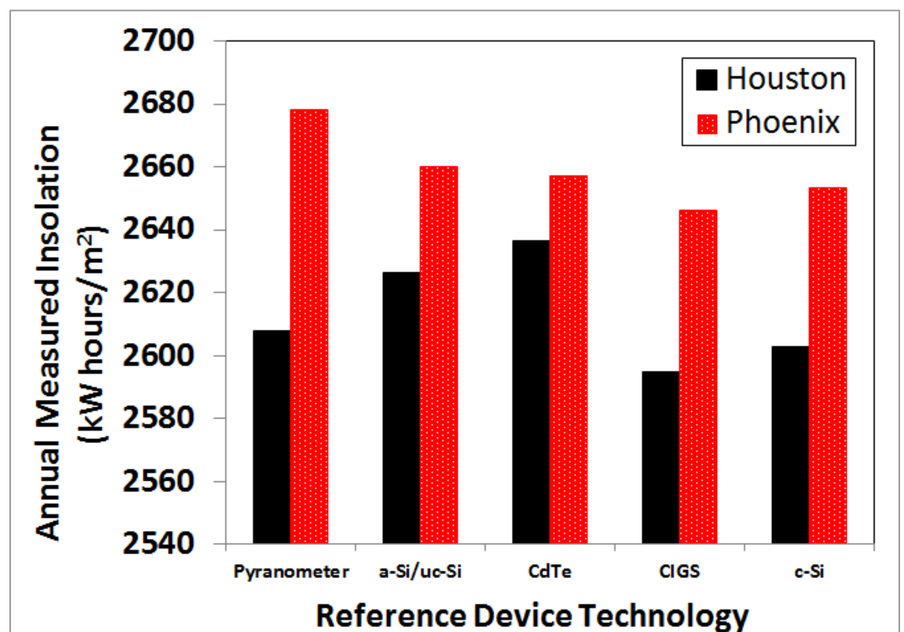
- Response of each reference device under AM 1.5 Spectrum calculated to perform a simulated calibration.
  - Thermopile Pyranometer
  - a-Si/μc-Si
  - CdTe
  - CIGS
  - Crystalline Si
- Thousands of simulated spectra generated from TMY3 data using the SPECTRAL2 model for each location.
- Each device's calibrated response calculated for all spectra and compiled.
- Simulated daily, monthly, and annual insolation measurements for each technology were calculated.
  - Errors between perceived irradiances by power generating PV modules and reference devices calculated.

Daily, Monthly, and Annually Simulated Insolation Values

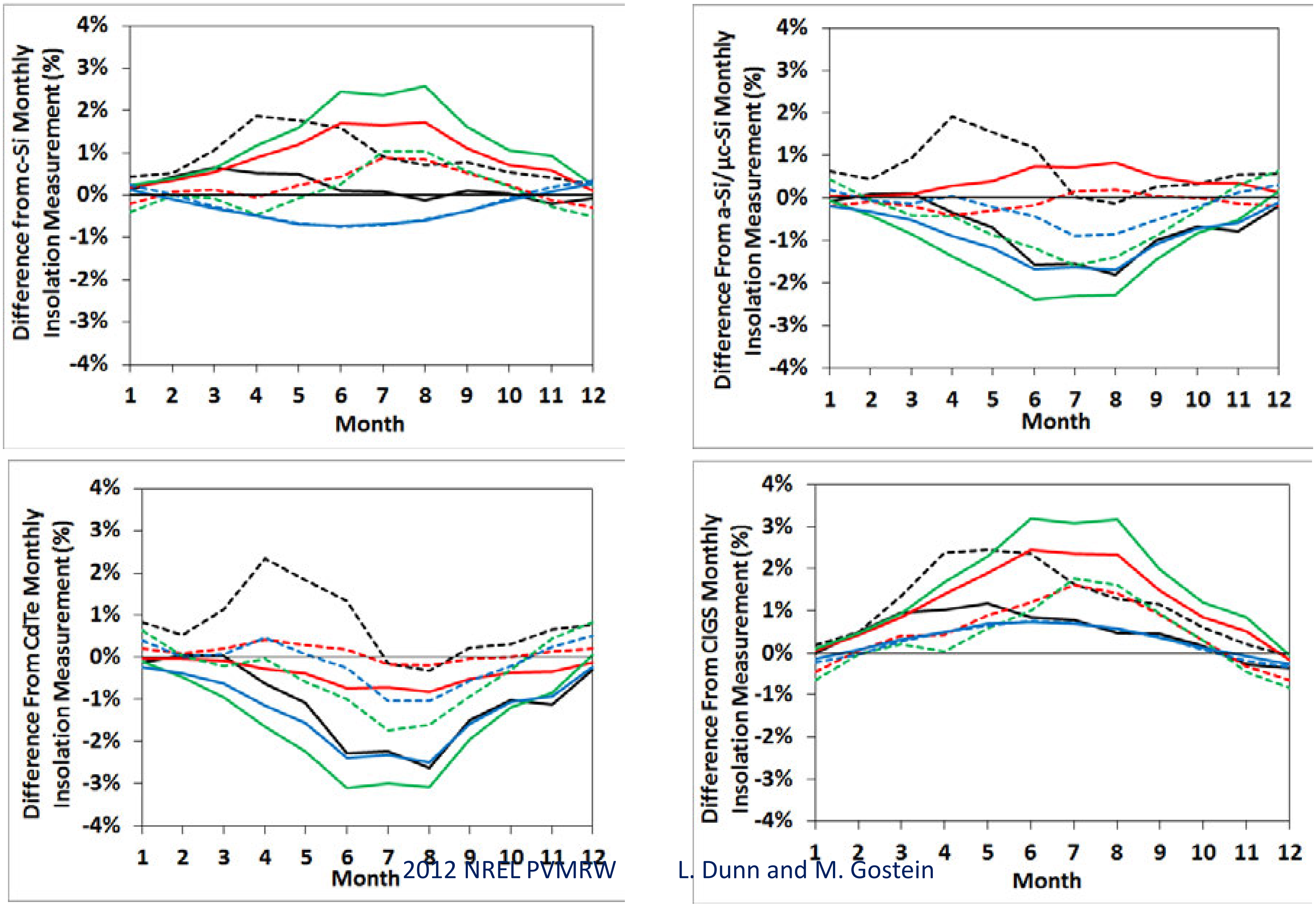




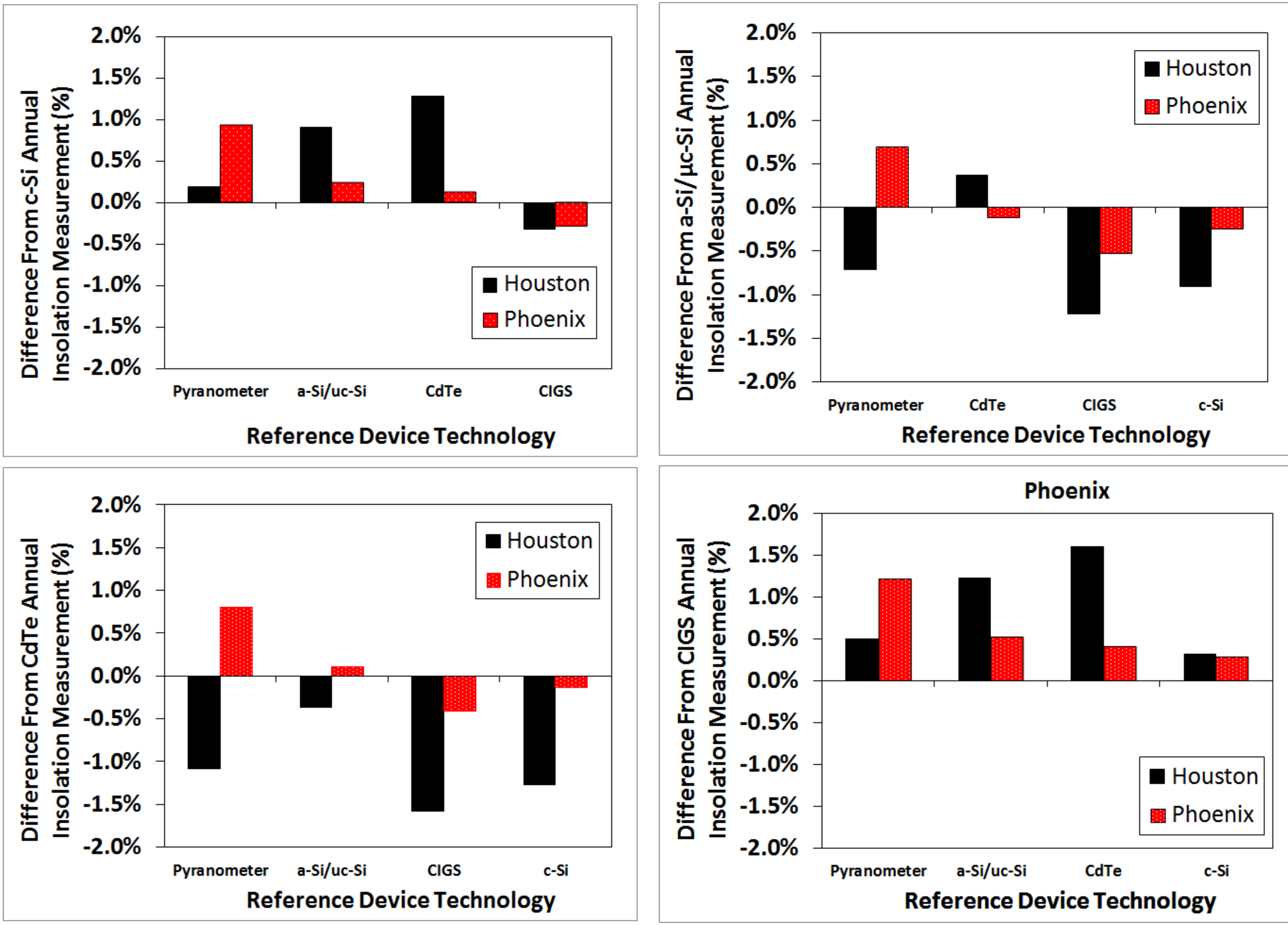




Discrepancies in Monthly Insolation Measurements for Various PV Technologies



Discrepancies in Annual Insolation Measurements



Results Summary Table

Annual Data		Reference Device Technology									
		Pyranometer		c-Si		a-Si/μc-Si		CdTe		CIGS	
		Houston	Phoenix	Houston	Phoenix	Houston	Phoenix	Houston	Phoenix	Houston	Phoenix
PV Module Technology	c-Si	0.2%	0.9%	0.0%	0.0%	0.9%	0.2%	1.3%	0.1%	-0.3%	-0.3%
	a-Si/μc-Si	-0.7%	0.7%	-0.9%	-0.2%	0.0%	0.0%	0.4%	-0.1%	-1.2%	-0.5%
	CdTe	-1.1%	0.8%	-1.3%	-0.1%	-0.4%	0.1%	0.0%	0.0%	-1.6%	-0.4%
	CIGS	0.5%	1.2%	0.3%	0.3%	1.2%	0.5%	1.6%	0.4%	0.0%	0.0%

Legend

Error = 0.0%

0% <|Error|≤ 0.5%

0.5% ≤|Error|≤ 1.5%

1.5% ≤|Error|≤ 2.5%

|Error|< 2.5%

	Difference from c-Si Monthly Measured Insolation									
	Reference Device Technology									
	Pyranometer		c-Si		a-Si/μc-Si		CdTe		CIGS	
	Houston	Phoenix	Phoenix	Houston	Phoenix	Houston	Phoenix	Houston	Phoenix	Houston
Jan	0.1%	0.4%	0.0%	0.0%	0.2%	-0.2%	0.2%	-0.4%	0.1%	0.2%
Feb	0.4%	0.5%	0.0%	0.0%	0.3%	0.1%	0.4%	0.0%	-0.1%	0.0%
March	0.6%	1.1%	0.0%	0.0%	0.5%	0.1%	0.6%	-0.1%	-0.3%	-0.3%
April	0.5%	1.9%	0.0%	0.0%	0.9%	0.0%	1.2%	-0.5%	-0.5%	-0.5%
May	0.5%	1.8%	0.0%	0.0%	1.2%	0.2%	1.6%	-0.1%	-0.7%	-0.7%
June	0.1%	1.6%	0.0%	0.0%	1.7%	0.4%	2.4%	0.3%	-0.7%	-0.7%
July	0.1%	0.9%	0.0%	0.0%	1.6%	0.9%	2.4%	1.0%	-0.7%	-0.7%
August	-0.1%	0.7%	0.0%	0.0%	1.7%	0.8%	2.6%	1.0%	-0.6%	-0.6%
Sept	0.1%	0.8%	0.0%	0.0%	1.1%	0.5%	1.6%	0.6%	-0.4%	-0.4%
Oct	0.0%	0.5%	0.0%	0.0%	0.7%	0.2%	1.1%	0.2%	-0.1%	-0.1%
Nov	-0.2%	0.4%	0.0%	0.0%	0.6%	-0.1%	0.9%	-0.3%	0.1%	0.2%
Dec	-0.1%	0.3%	0.0%	0.0%	0.1%	-0.3%	0.2%	-0.5%	0.3%	0.3%

Monthly Results for a-Si/μc-Si Modules

	Difference from a-Si/μc-Si Monthly Measured Insolation									
	Reference Device Technology									
	Pyranometer		c-Si		a-Si/μc-Si		CdTe		CIGS	
	Houston	Phoenix	Phoenix	Houston	Phoenix	Houston	Phoenix	Houston	Phoenix	Houston
Jan	-0.1%	0.6%	-0.2%	0.2%	0.0%	0.0%	0.0%	-0.2%	-0.1%	0.4%
Feb	0.1%	0.4%	-0.3%	-0.1%	0.0%	0.0%	0.0%	-0.1%	-0.4%	-0.1%
March	0.1%	0.9%	-0.5%	-0.1%	0.0%	0.0%	0.1%	-0.2%	-0.9%	-0.4%
April	-0.4%	1.9%	-0.9%	0.0%	0.0%	0.0%	0.3%	-0.4%	-1.4%	-0.4%
May	-0.7%	1.5%	-1.2%	-0.2%	0.0%	0.0%	0.4%	-0.3%	-1.9%	-0.9%
June	-1.6%	1.2%	-1.7%	-0.4%	0.0%	0.0%	0.7%	-0.2%	-2.4%	-1.2%
July	-1.5%	0.0%	-1.6%	-0.9%	0.0%	0.0%	0.7%	0.2%	-2.3%	-1.6%
August	-1.8%	-0.1%	-1.7%	-0.8%	0.0%	0.0%	0.8%	0.2%	-2.3%	-1.4%
Sept	-1.0%	0.3%	-1.1%	-0.5%	0.0%	0.0%	0.5%	0.0%	-1.5%	-0.9%
Oct	-0.7%	0.3%	-0.7%	-0.2%	0.0%	0.0%	0.4%	0.0%	-0.8%	-0.3%
Nov	-0.8%	0.5%	-0.6%	0.1%	0.0%	0.0%	0.3%	-0.1%	-0.5%	0.3%
Dec	-0.2%	0.6%	-0.1%	0.3%	0.0%	0.0%	0.1%	-0.2%	0.2%	0.6%

Monthly Results for CdTe Modules

	Difference from CdTe Monthly Measured Insolation									
	Reference Device Technology									
	Pyranometer		c-Si		a-Si/µc-Si		CdTe		CIGS	
	Houston	Phoenix	Phoenix	Houston	Phoenix	Houston	Phoenix	Houston	Phoenix	Houston
Jan	-0.1%	0.8%	-0.2%	0.4%	0.0%	0.2%	0.0%	0.0%	-0.1%	0.6%
Feb	0.0%	0.5%	-0.4%	0.0%	0.0%	0.1%	0.0%	0.0%	-0.5%	0.0%
March	0.0%	1.1%	-0.6%	0.1%	-0.1%	0.2%	0.0%	0.0%	-0.9%	-0.2%
April	-0.6%	2.3%	-1.2%	0.5%	-0.3%	0.4%	0.0%	0.0%	-1.6%	0.0%
May	-1.1%	1.8%	-1.6%	0.1%	-0.4%	0.3%	0.0%	0.0%	-2.2%	-0.6%
June	-2.3%	1.3%	-2.4%	-0.3%	-0.7%	0.2%	0.0%	0.0%	-3.1%	-1.0%
July	-2.2%	-0.1%	-2.3%	-1.0%	-0.7%	-0.2%	0.0%	0.0%	-3.0%	-1.7%
August	-2.6%	-0.3%	-2.5%	-1.0%	-0.8%	-0.2%	0.0%	0.0%	-3.1%	-1.6%
Sept	-1.5%	0.2%	-1.6%	-0.5%	-0.5%	0.0%	0.0%	0.0%	-1.9%	-0.9%
Oct	-1.0%	0.3%	-1.1%	-0.2%	-0.4%	0.0%	0.0%	0.0%	-1.2%	-0.3%
Nov	-1.1%	0.7%	-0.9%	0.3%	-0.3%	0.1%	0.0%	0.0%	-0.8%	0.4%
Dec	-0.3%	0.8%	-0.2%	0.5%	-0.1%	0.2%	0.0%	0.0%	0.0%	0.8%

Monthly Results for CIGS Modules

	Difference from CIGS Monthly Measured Insolation									
	Reference Device Technology									
	Pyranometer		c-Si		a-Si/µc-Si		CdTe		CIGS	
	Houston	Phoenix	Phoenix	Houston	Phoenix	Houston	Phoenix	Houston	Phoenix	Houston
Jan	0.0%	0.2%	-0.1%	-0.2%	0.1%	-0.4%	0.1%	-0.6%	0.0%	0.0%
Feb	0.5%	0.5%	0.1%	0.0%	0.4%	0.1%	0.5%	0.0%	0.0%	0.0%
March	1.0%	1.3%	0.3%	0.3%	0.9%	0.4%	0.9%	0.2%	0.0%	0.0%
April	1.0%	2.4%	0.5%	0.5%	1.4%	0.4%	1.7%	0.0%	0.0%	0.0%
May	1.2%	2.4%	0.7%	0.7%	1.9%	0.9%	2.3%	0.6%	0.0%	0.0%
June	0.8%	2.4%	0.7%	0.8%	2.5%	1.2%	3.2%	1.0%	0.0%	0.0%
July	0.8%	1.6%	0.7%	0.7%	2.4%	1.6%	3.1%	1.8%	0.0%	0.0%
August	0.5%	1.3%	0.6%	0.6%	2.3%	1.4%	3.2%	1.6%	0.0%	0.0%
Sept	0.5%	1.2%	0.4%	0.4%	1.5%	0.9%	2.0%	0.9%	0.0%	0.0%
Oct	0.2%	0.6%	0.1%	0.1%	0.8%	0.3%	1.2%	0.3%	0.0%	0.0%
Nov	-0.3%	0.2%	-0.1%	-0.2%	0.5%	-0.3%	0.9%	-0.4%	0.0%	0.0%
Dec	-0.3%	-0.1%	-0.3%	-0.3%	-0.2%	-0.6%	0.0%	-0.8%	0.0%	0.0%

Requirement for PV reliability assurance system

(design, production and product warranty)

NREL PV reliability workshop

Denver, USA

THE JAPAN ELECTRICAL MANUFACTURERS' ASSOCIATION

Presenter: Yoshihito Eguchi, SHARP CORPORATION

February 28th, 2012

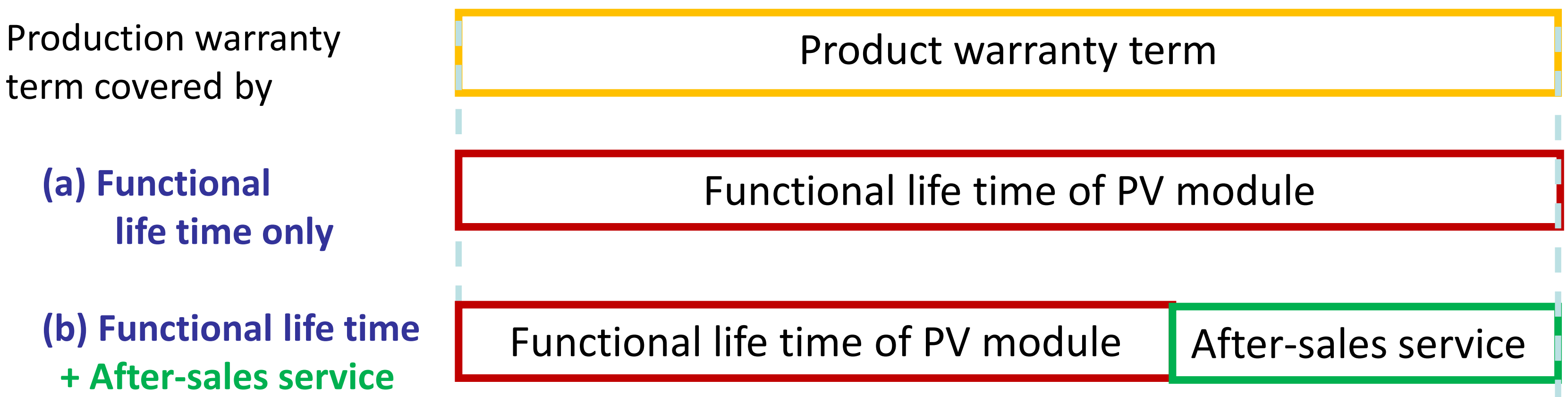
Content

1. Introduction
2. Secured the PV module
3. Definition of Functional lifetime
4. Definition of Product Manager
5. Requirements for PV module design
6. Requirements for After-sales service
7. Conclusion

Secured the PV module reliability

□PV module reliability to be secured by combination of the functioning lifetime design of PV module and product warranty.

- If the functioning life time is shorter than product warranty term, the product warranty shall be ensured by the control system of after-sales service.
- Rules and systems to assess harmonization between functioning lifetime and warranty to be established and maintained.



Definition of Functional lifetime

Functioning lifetime: a key parameter in PV module design

- "Functioning lifetime" is a design parameter to define a period of PV module functioning its designed performance under specified conditions.
- Functioning lifetime is to be well technically supported and validated by feedback from user/market, supplier, manufacturing, and R&D.
- Rules and systems to assess validity of defining function lifetime to be established and maintained.

Functioning lifetime to navigate all aspects of module design and manufacturing including inline inspection.

- Rules and systems to assess reliability of produced PV module to be established and maintained to make sure functioning life time is secured.

Definition of Product Manager

- Product manager: an organization who takes primary responsibilities for production, quality assurance and warranty of PV module.
  - A single entity needed to take primary responsibilities in case more than one players exist in business flow between manufactures and customers.
  - Product manager can entrust other(s) with some parts of responsibilities in design and/or manufacturing of PV module
  - Product manager to take responsibilities for development and implementation of harmonized QMS in design, manufacturing, and after-sales service to ensure quality assurance and warranty of PV module.

Requirements for PV module design

1. To define Functioning lifetime of the module
   - The functioning lifetime is to be defined based on characteristics of the cell/module design type and climate and other relevant conditions around expected use.
   - PV module design to be implemented in such a manner to secure its defined functioning lifetime.

2. To define rules and/or management systems for PV module design review to check if functioning lifetime is secured in the module design.
   - Appropriate examination items and test methods to asses functioning lifetime of PV module well prescribed in design and secured in the products.

3. To provide user/installer with information about use and/or installation of the PV module if any specific attention needed for them to secure functioning lifetime of the module.

Requirements for After-sales service

1. To keep good alignment between contents of product warranty certificate and internal rules and/or customer support systems to implement warranty.

2. To provide user with accurate written information in document about the contents and conditions of product warranty.

3. To prepare effective after-sales service system to secure implementation of warranty.

Conclusion

To secure the PV module liability for end users, qualification tests and quality assurance program already exist.

But, it is difficult to define the evaluation method of PV module life time 25 years and it take a long time.

□**To secure the PV module liability for end users ;**

(1) Make the new regional **quality assurance standard** and establish national **certification scheme**

(2) **Propose** it to National standardization Committee through QA forum activity.

Material Characterization in PV Modules

William Gambogi, Katherine Stika, Alex Bradley,
Babak Hamzavy, Rebecca Smith and Michael DeBergalis, DuPont Photovoltaic Solutions

2012 NREL PV Module Reliability Workshop, Golden, CO

Goals: Performance, Durability & Safety Testing

- Identify the critical material properties needed for long term durability, reliability and safety in a photovoltaic module.
- Establish testing protocols to address the stability of these critical properties under accelerated and use conditions.
- Produce and test modules for performance, durability and safety.
- Develop materials and module analysis diagnostics tools to provide insight into degradation mechanisms.
- Apply analysis methods to modules exposed under accelerated durability test conditions and modules from the field and compare their performance
- Relate changes in material properties to module performance.

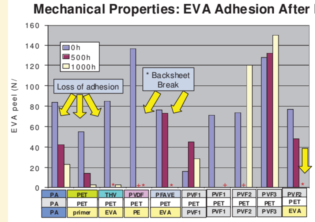
1

Durability Test Conditions

- Typical durability test conditions are based on the performance and safety qualification test conditions (IEC61215, UL1703) including damp heat, UV, thermal cycling and humidity freeze.
- Module manufacturers typically test from 1.25 to >3x qualification exposure times.
- Several reliability groups are advocating combination tests which test backsheets, laminates and/or modules under combined conditions either simultaneously or in sequence.
- Test-to-failure methods are being studied.
- Comparison to outdoor testing is needed to validate acceleration conditions or test to failure protocol.
- DuPont is testing beyond qualification exposure, investigating combined stress exposure and using extended UV exposure to better understand long term durability.

2

Mechanical Properties: EVA Adhesion After Damp Heat

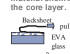


Issues with Accelerated Exposure

You not only test the integrity of interfaces, you test the integrity of the base materials as well.

For most backsheets, damp heat is particularly damaging to core layer.

At some point, the limit of performance is not adhesion chemistry, but the material chemistry of the core layer.

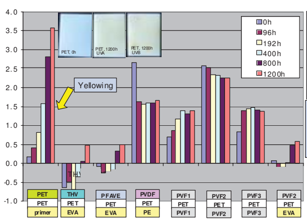


+ EVA peel from glass indicating strong EVA/backsheet adhesion
* Backsheet break during test

PFV1=PV2000 series
PVF2=PV2100 series
PVF3=PV2400 series

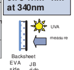
3

Optical Properties: Color Changes with UVA Exposure



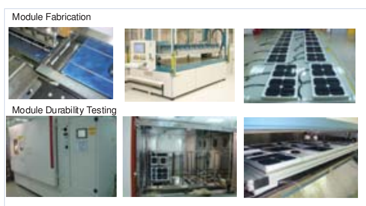
Three PET backsheets tested showed same or greater yellowing as the one shown

Backsheet exposure: 70°C, 0.78 W/m²*nm at 340nm



4

Module Fabrication and Durability Testing



5

Module Durability after Damp Heat

- EL image of modules showing cell degradation after 3000h damp heat for modules using TPT™ and PPX backsheets. Modules with TPT™ lost 15% power, modules with PPX lost 50% power.
- Cracking, delamination and failure at junction box in PET/PET backsheet
- Cracking near frame edge for FPX backsheet
- Yellowing of FPX backsheet
- Cracking of the underlying PET layer in TPT™ observed without delamination.

- Differences in module performance with different backsheet materials
- Visual changes consistent with materials test results in damp heat

6

Module Durability after UV Exposure

PPX1 PPX2 TPT™

Yellowing in modules with PET/PET backsheets after 5x IEC UV pre-conditioning exposure from back side of module

- Differences in module performance based on backsheet material
- Visual changes consistent with materials test results after UVA exposure

7

Analysis of Commercial Modules from the Field

- Program to evaluate modules from the field for their performance, durability and safety
- Apply non-destructive analysis to identify localized degradation and failure sites
- Apply destructive analysis methods to better understand degradation mechanisms
- Compare performance to degradation and failure mechanisms observed under accelerated durability test conditions
- Understand the relationship between materials, design, process, installation and environment

8

Materials and Module Analysis Methods

Module ⟷ **Material Analysis**

- Metals Analysis
- Mass Spectrometry
- Microscopy
- Molecular Weight
- NMR
- Physical Measurements
- Separations
- Spectroscopy
- Surface and Particle Science
- Thermal Analysis
- Wet Chemistry
- X-Ray

Stage One – Non Destructive Analysis

1. Visual Inspection and Documentation
2. Power Output Measurement (IV Curve)
3. Electroluminescence (EL) Imaging
4. Thermal Imaging under forward bias
5. Wet Leakage Current or Dry Insulation Test

Stage Two – Destructive Analysis

1. Sample extraction via back side core
2. Physical layer profile (SEM)
3. Chemical layer profile (IR/SEM)
4. Defect pathways (X-Ray)

Photovoltaic Module Performance and Durability Following Long-term Field Exposure D.L. King,* M. A. Quintana, J. A. Kratochvil, D. E. Ellibee and B. R. Hansen. Prog. Photovolt. Res. Appl. 2000; 8: 241±256

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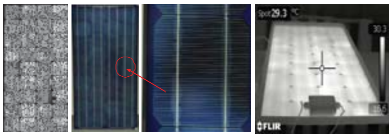
Example #1: Fielded Module



- **Module construction and exposure:** glass/EVA/Si/EVA/TPT™, residential rooftop array.
- **Visual inspection:** some localized frontside encapsulant delamination at tabbing wires.
- **EL imaging:** fine line interruptions and a few cells not operating at optimum efficiency, contributing to the small amount of power loss.
- **Wet leakage current testing:** good electrical insulation.
- **Thermal imaging:** no hot spots.

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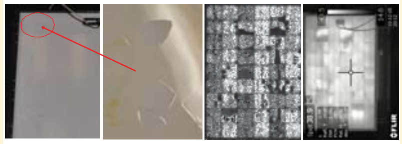
Example #2: Fielded Module



- **Module construction and exposure:** glass/EVA/Si/EVA/PPX, residential rooftop array
- **Visual inspection:** localized delamination between PET-PET backsheet interlayers
- **EL imaging:** fine line interruptions and many cracked cells.
- **Wet leakage current measurement:** resistance of <1MOhm/m²
- **Thermal imaging:** temperature non-uniformities but no excessive hot spots.

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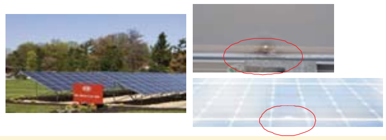
Example #3 : Installation Damage in PV Array

40kW ground mounted system

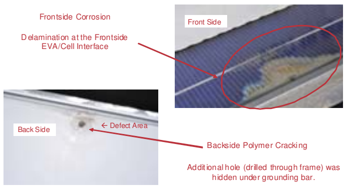
173 W c-Si Module – **Damage during installation** initiated corrosion and delamination

Locus of Failure – Characterization & Analysis

- Depth profile, chemical analysis, and X-Ray tomography to understand compromised module

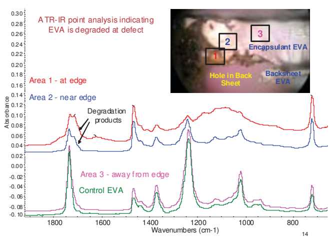


Visual Identification of Module Defect



13

Encapsulant EVA Oxidation at the Defect



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Summary

- The performance and durability of a PV module is determined by a combination of materials, process and design
- Understanding material durability and interactions can provide insights into module durability
- Comparison of accelerated durability testing to fielded module performance is important to understanding relevant degradation mechanisms and validating and quantifying acceleration factors
- Fundamental understanding of materials changes under use conditions over the expected service life of the PV module is key to understanding and improving durability
- Analytical methods are being effectively applied to provide insights into chemical and physical materials changes and module performance issues

15

Effects of Simultaneous UV Radiation, Temperature and Moisture on Degradation of PV Polymers

Polymeric Materials Group
Engineering Laboratory

Xiaohong Gu, Yongyan Pang, Debbie Stanley, Tinh Nguyen, and Joannie W. Chin*

INTRODUCTION

A fundamental understanding of degradation mechanism of photovoltaics (PV) materials under simultaneous multiple stresses (temperature, moisture, UV radiation) is important to the development of reliable accelerated laboratory test methods that correlate to field performance.

In this study, the laboratory accelerated tests of several PV polymers, such as ethylene vinyl acetate (EVA), poly (methyl methacrylate) (PMMA), and ionomers were conducted on the well-controlled NIST SPHERE environmental chamber. A factorial experiment was designed to evaluate the effects of temperature, relative humidity, and spectral ultraviolet (UV) irradiance, either applied individually or in combination on the main degradation mechanisms of these materials. The outdoor exposure was carried out in Gaithersburg, MD. Multiscale chemical, optical, mechanical and morphological measurements were performed to follow changes during accelerated and outdoor exposures. The degradation mechanism and failure mode of PV materials and components were studied.

Linking Laboratory and Outdoor Exposures

Reliability-based Methodology

- **Accelerated Laboratory Exposure** (to study effects of critical environmental factors on degradation mechanism of PV materials/modules)
- **Outdoor Exposure** (with monitored weather parameters)
- Cumulative Damage Prediction Model
- Failure Mode Analysis

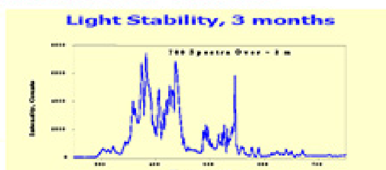
➢ To develop reliable accelerated laboratory test methods that correlate to field performance.

ACCELERATED LABORATORY EXPOSURE DEVICE

NIST Integrating Sphere-based UV Chamber

NIST-Patented 2-meter SPHERE

(Simulated Photodegradation via High Energy Radiant Exposure)



- High UV Radiant Exposure (8400 W UV)
- 95% exposure uniformity
- Visible and infrared radiation mostly removed
- Temperature and relative humidity around specimens precisely controlled (25-75 °C; 0-95 % RH)
- Capability for mechanical and electrical loadings
- Exposure conditions of 32 chambers can be individually controlled (UV, RH,T)

• *Chin et al, Review of Scientific Instruments (2004), 75, 4951; Martin and Chin, U.S. Patent 6626053*

EXPERIMENTAL

Materials

(A) EVA

3 Types of Sample Designs

- EVA
- Crosslinked EVA
- Laminated EVA

CaF_2 Substrate *(for FTIR UV-visible and AFM)*

(B) PMMA

(C) Ionomer

SPHERE Exposure

UV/T/RH, individually or in combination, under

- Different Spectral UV Intensities *(25-200 W/m², 295-480 nm)*
- Different Temperatures *(25-85 °C)*
- Different RHs *(0-75%)*

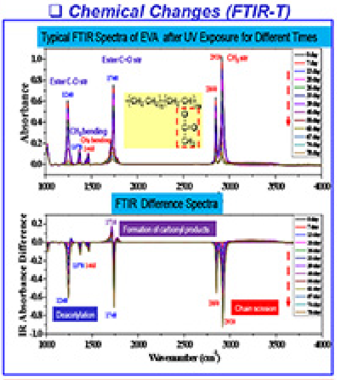
Outdoor Exposure

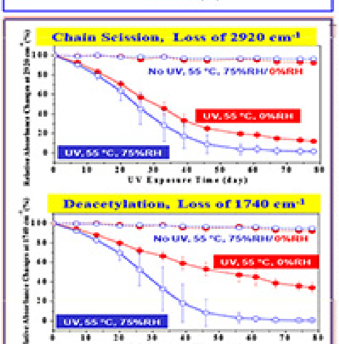
Gaithersburg, MD

RESULTS FROM LABORATORY EXPOSURE

Effect of Simultaneous UV/RH/T on Degradation of EVA

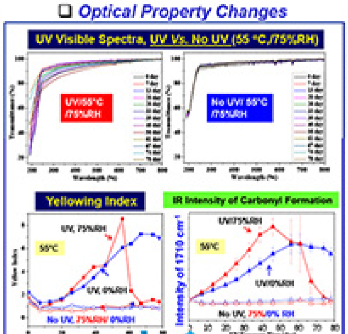
❑ *Chemical Changes (FTIR-T)*





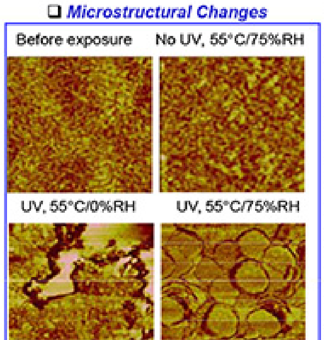
• Both UV and RH are important factors.
• Synergistic effect between UV and RH.

❑ *Optical Property Changes*



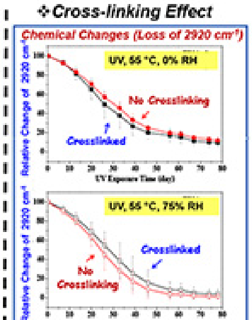
• Carbonyl formation may contribute to yellowing.

❑ *Microstructural Changes*



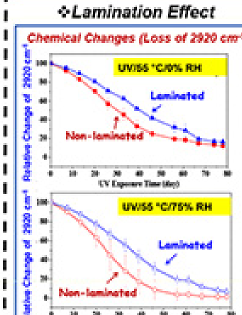
*78 days exposure

❖ *Cross-linking Effect*



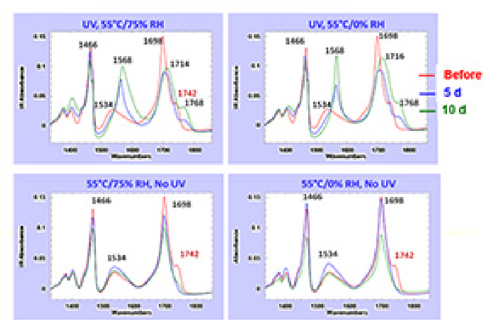
• Essentially no effect on chemical changes observed from crosslinking.

❖ *Lamination Effect*



• Lamination reduced EVA degradation rate.

UV Effect on PV Ionomers

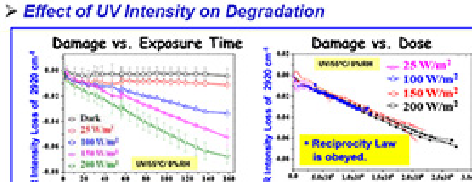


1466 cm⁻¹: -CH₂
1534 -1568 cm⁻¹: C=O, carboxylate ions
1698 cm⁻¹: C=O, carboxylic acids (H-bond)
1768 cm⁻¹: C=O, anhydrides or lactones

❖ UV radiation has a strong effect on chemical changes of PV ionomers, but humidity does not.

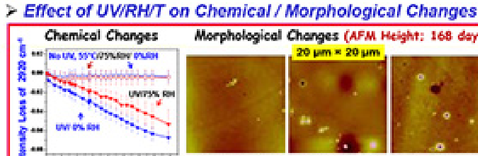
Photodegradation of PMMA (4UVs/55°C/2RHs)

➢ *Effect of UV Intensity on Degradation*



• Degradation rates increase with higher UV intensities, but the degradation mechanism of PMMA remains same at 4 UV intensities.

➢ *Effect of UV/RH/T on Chemical / Morphological Changes*



• UV has strong effect on PMMA degradation, but humidity does not.

SUMMARY

➢ UV radiation was the most important factor for degradation of all studied materials. A RH/UV synergistic effect was observed for EVA, but not for PMMA and PV ionomer.

➢ A higher UV intensity led to a higher degradation rate, but there was no change in degradation mechanism for PMMA exposed to T/RH/UV with different UV intensities.

Lifetime Prediction of Silicon PV Module Ribbon Wire in Three Local Weathers

Feb. 28. 2012

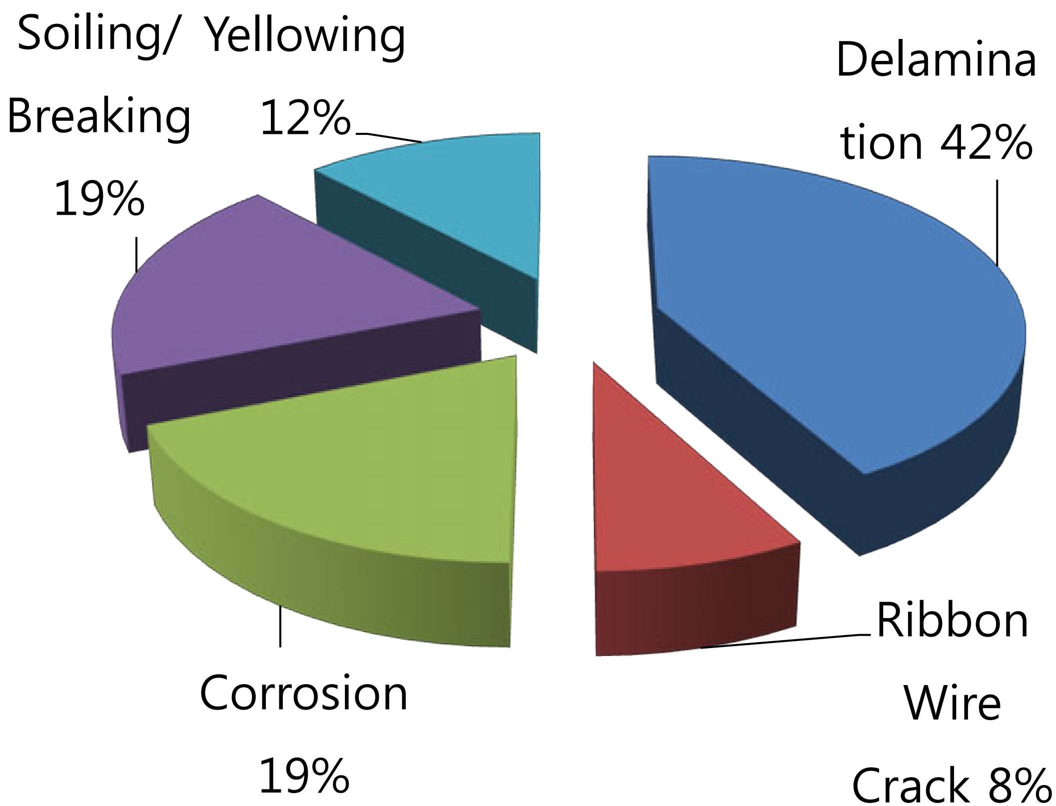
Changwoon Han, Nochang Park, and Jaeseong Jeong

Korea Electronics Technology Institute

Who are we?

Located at South Korea, More than 600 Research Engineers
Research Areas : Component & Material, Energy & Display, System IC

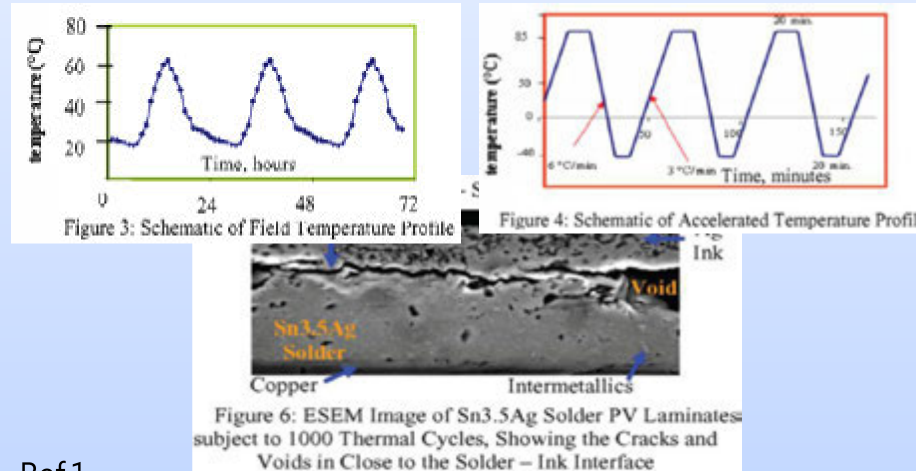
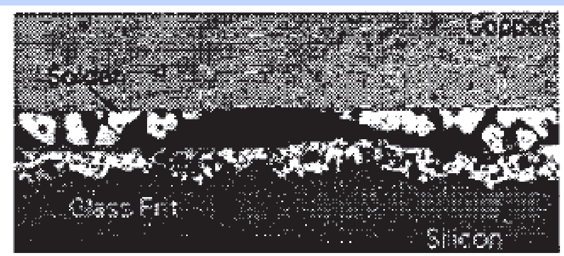
Silicon PV Module : Failure Modes



References

1. K.Morita et al., Degradation factor analysis of crystalline-si PV modules through long-term field exposure test, 3rd World conference on photovoltaic energy conversion, 2003.
2. A.R. Gxasheka et al., Evaluation of performance parameters of PV modules deployed outdoors Renewable Energy 30, 2005.
3. E. D. Dunlop et al., 20 Years of Life and More : Where it the end of life of a PV Module Photovoltaic Specialists Conference, 2005.
4. Y. Hishikawa et al., Field Test results on the stability of 2400 PV modules manufactured in 1900's, 3rd World conference on photovoltaic energy conversion, 2002.
5. M.A. Quintana et al., Diagnostic analysis of Silicon PV Module 20 Years field exposure, Photovoltaic Specialists Conference, 2000.
6. K. Otani et al., Performance and reliability of MW PV Power facilities in AIST," Photovoltaic Energy Conversion Conference, 2006
7. E. D. Dunlop, Lifetime performance of crystalline silicon PV Module, 3rd World conference on photovoltaic energy conversion, 2003.
8. E.E. van Dyk et al., Investigation of Delamination in an edge-defined film-fed growth PV module, Solar Energy Materials & Solarcell 88, 2005.
9. A.Realini et al, Mean time before failure of PV, Active solar energy PV Program in Swiss, 2002.
10. J. H. Wohlgemuth, Long term Reliability of PV module, NCPV and Solar Program review meeting, 2003.

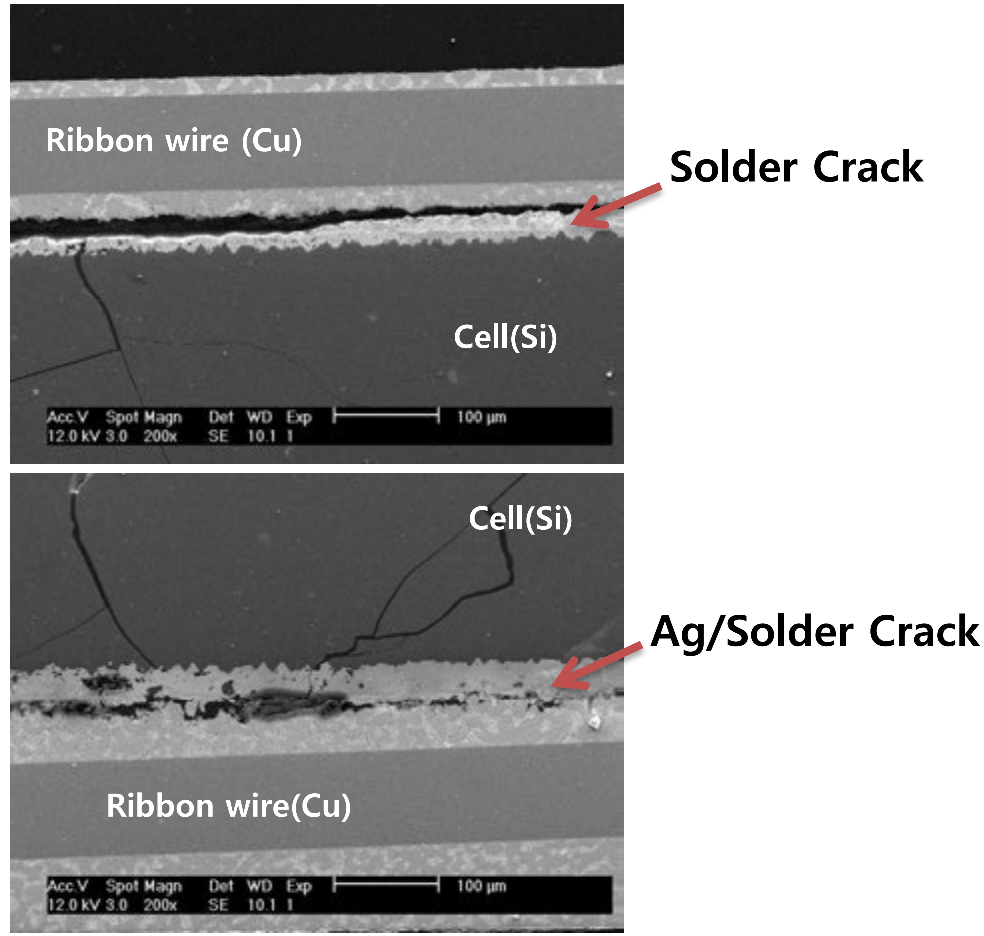
R/W Failure Reported in Literatures

Failure Location	Failure Mode	Failure Stress	Failure Mechanism	Figures
Solder–Ag Ink Interface	Crack, Voids	Thermal Cycling 1000cycle (-40℃ ~ 80℃)	Thermo-mechanical Fatigue	Figure 3: Schematic of Field Temperature Profile Figure 4: Schematic of Accelerated Temperature Profile Figure 6: ESEM Image of Sn3.5Ag Solder PV Laminates subject to 1000 Thermal Cycles, Showing the Cracks and Voids in Close to the Solder – Ink Interface Ref.1
Solder–Ag Ink Interface	Crack	Field Failure	Thermo-mechanical Fatigue	Fig. 3. Solder-joints from two field-aged modules show some coarsening. The 20-year-old joint (top) was more robust while the bottom joint showed voids and dewetting. Ref.2

1. G. Cuddalorepatta et al., "Durability of Pb-Free Solder Connection between Copper Interconnect Wire and Crystalline Silicon Solar Cells - Experimental Approach," 2006
2. M.A. Quintana et al., "Commonly Observed Degradation in Field-aged Photovoltaic Modules," 2002

Failure Analysis : 25 year-old PV

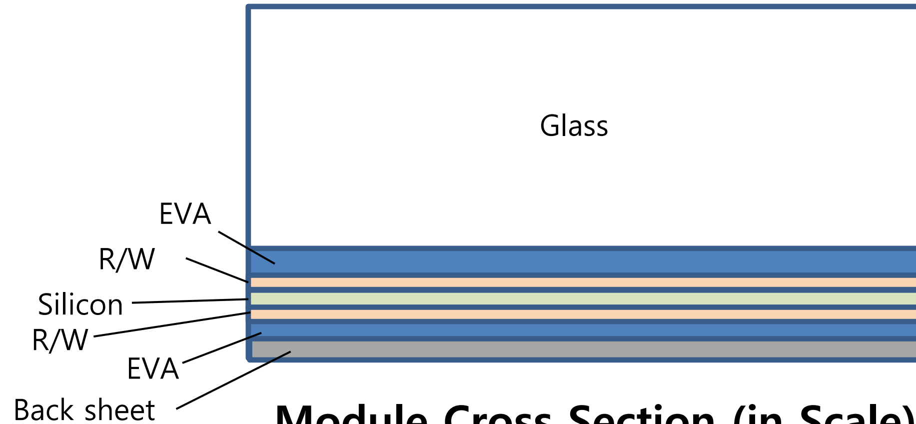
25 year-old PV Module



Failure Analysis Conducted.

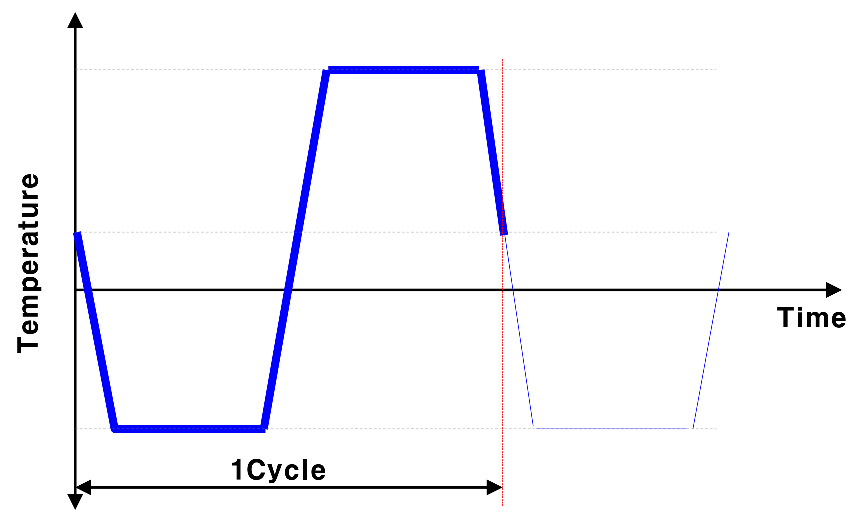
Failure Mechanism Validation

Silicon PV Module



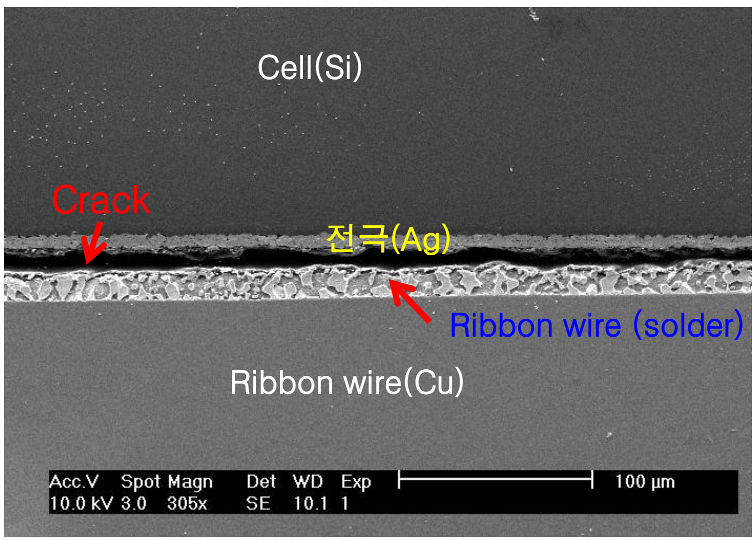
Module Cross Section (in Scale)

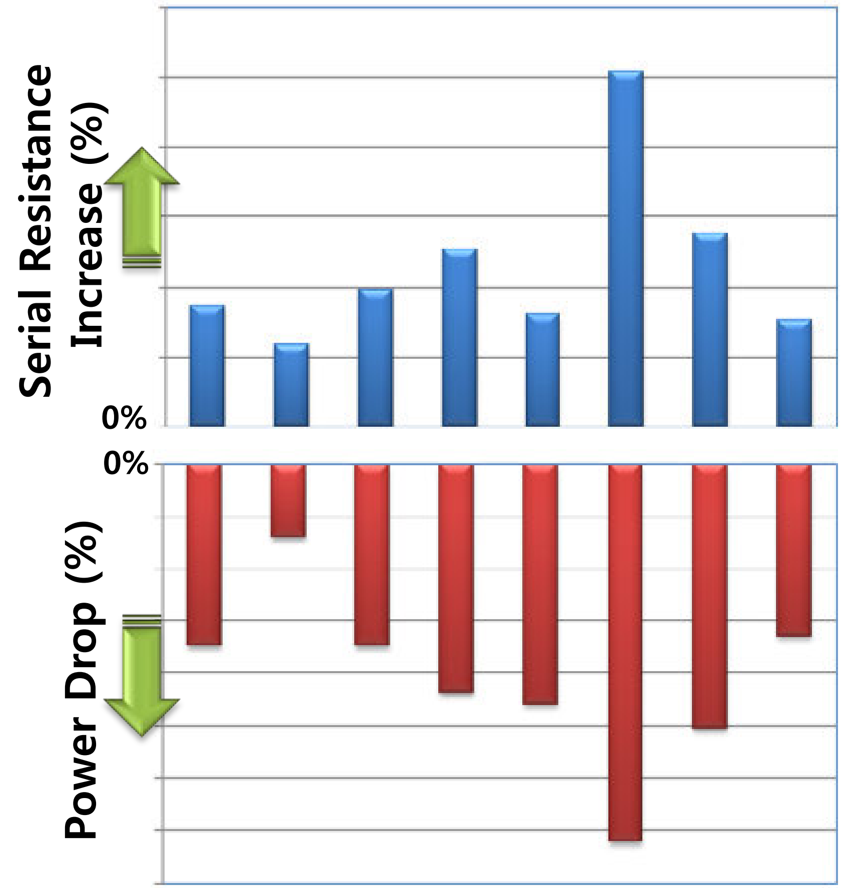
Thermal Cycling Chamber



Thermal Cycling Profile (1,000 Cycling)

Failure Mechanism Validation

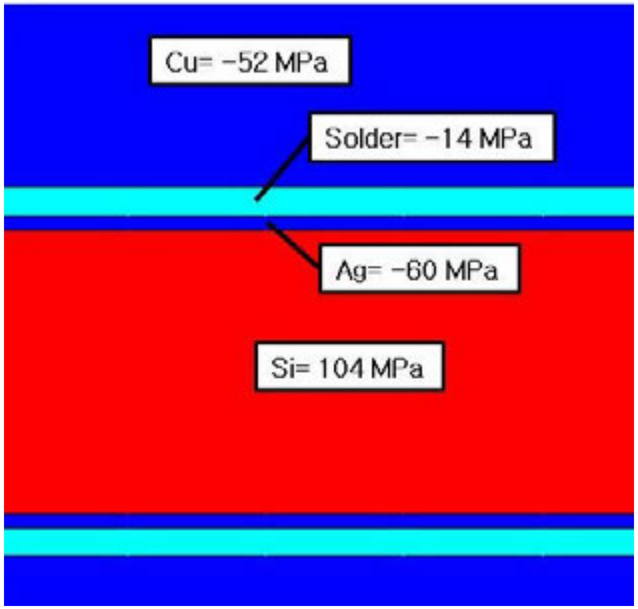


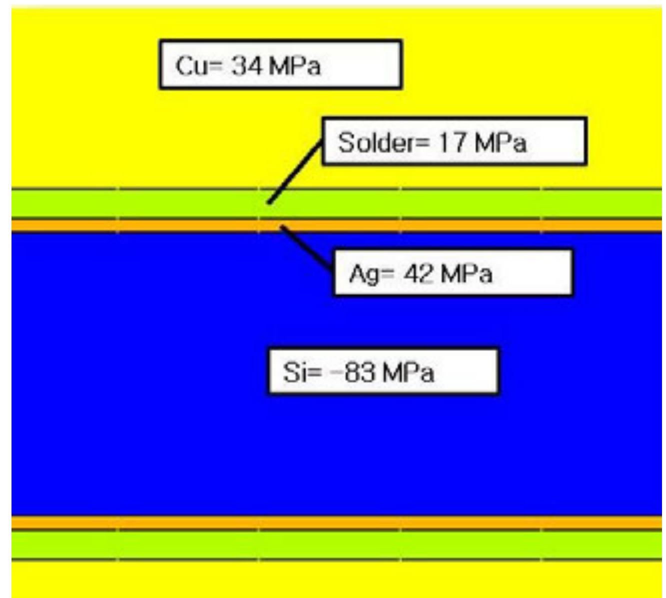


Failure Mechanism Validation

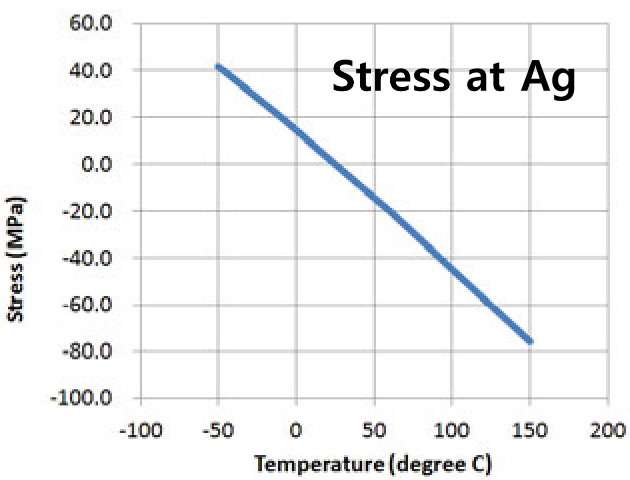
Finite Element Analysis

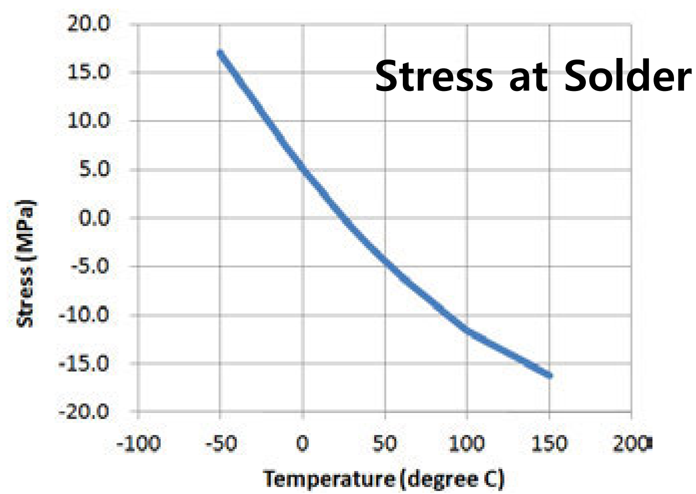
At High Temperature





At Low Temperature





Accelerated Life Test Design

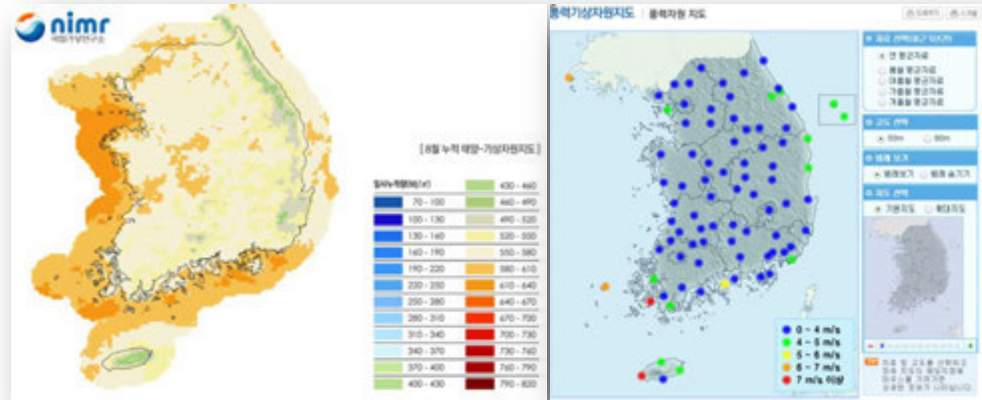
1

Weather data : Temp,

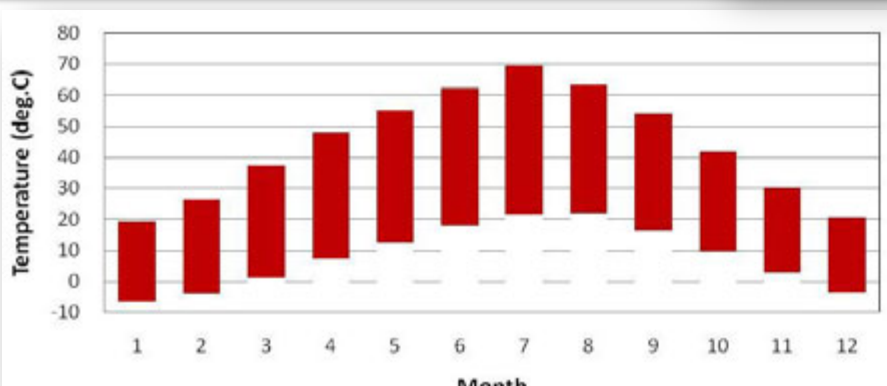
Irradiance,

Wind Speed

$T_m - T_{amb} = Irradiance * \exp(-2.98 - 0.0471 * WS)$



2



Module Temperature Variation (Seoul)

T_mean = 7 ~ 46 ℃

Delta _T = 24 ~ 48 ℃

3

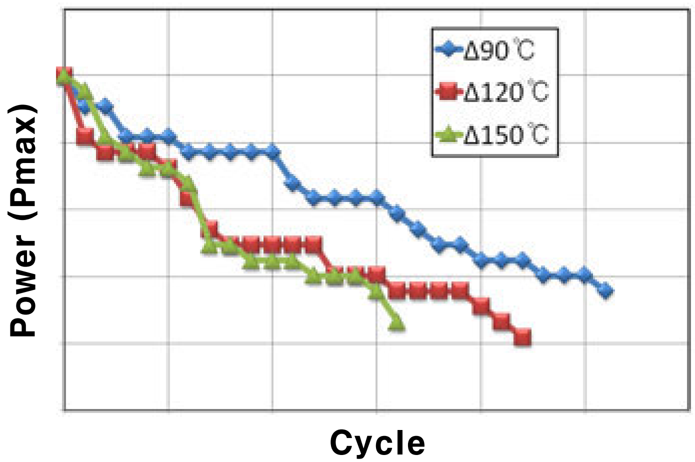
Three accelerated test conditions design

No.	T_low (℃)	T_high (℃)	△T (℃)
1	−20	70	90
2	−35	85	120
3	−50	100	150

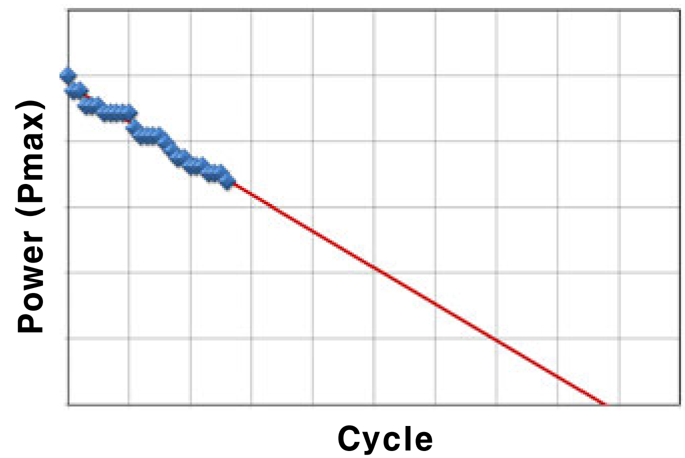
Life Prediction Model Development

1

Test Data

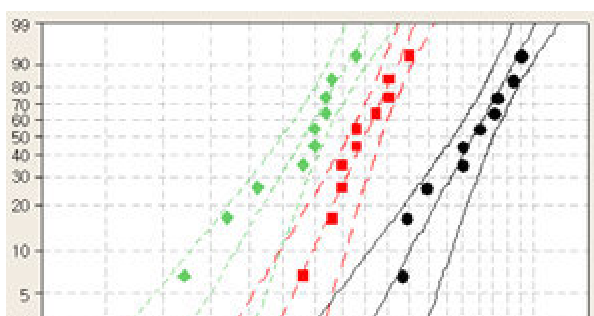


Linear Extrapolation



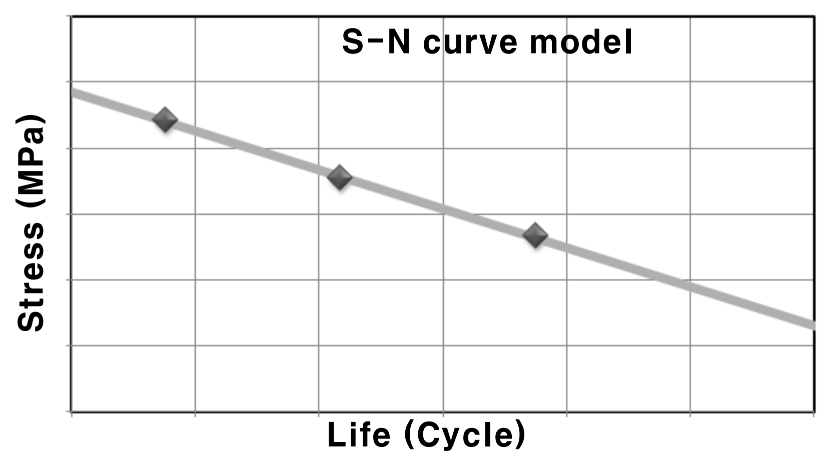
2

Lifetime Calculation

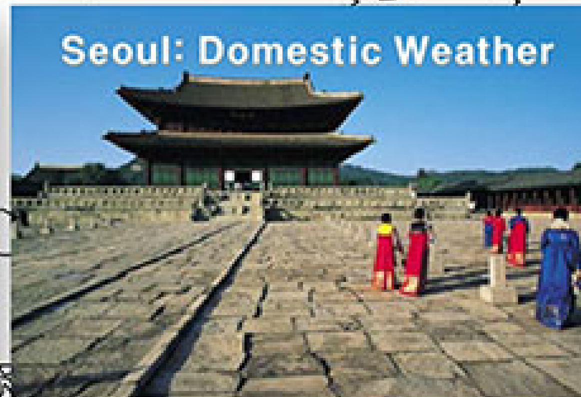


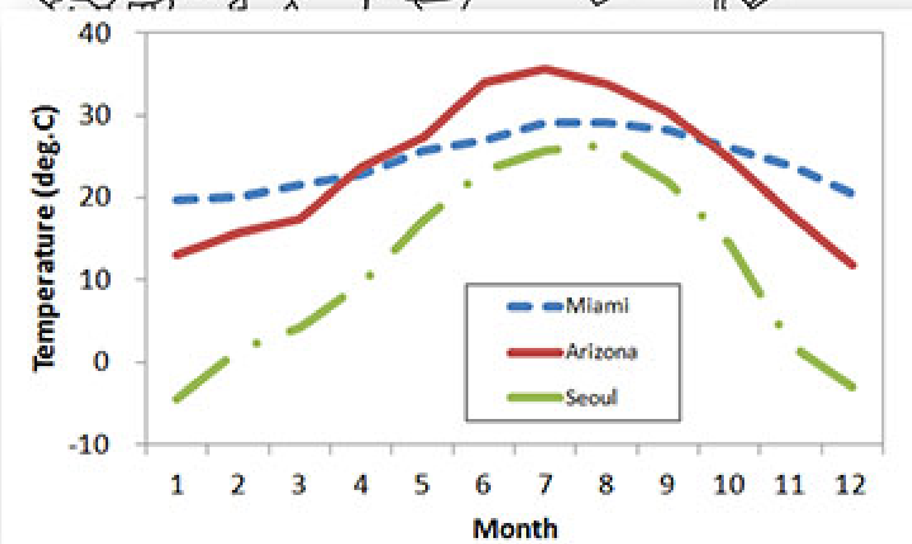
Test condition	△T : 90	△T : 120	△T : 150
Lifetime (cycles)			

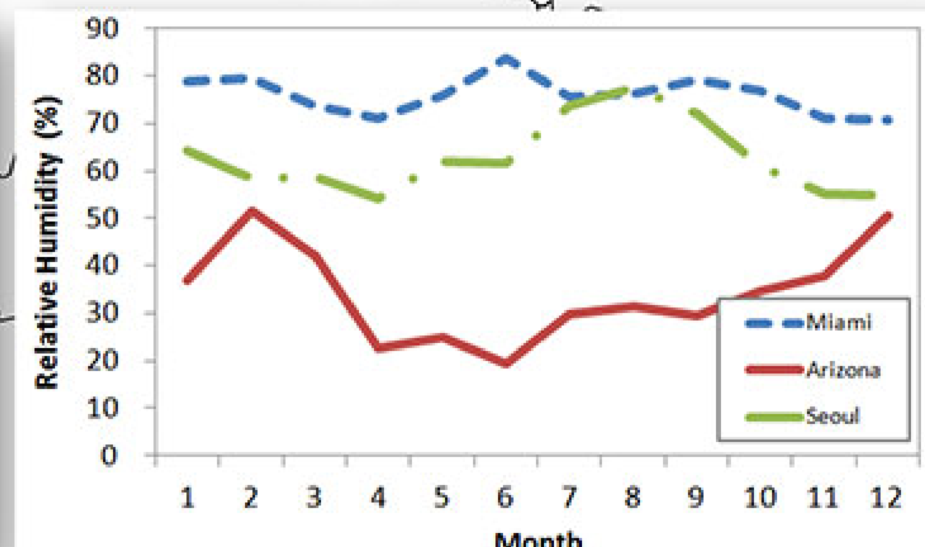
Life Prediction Model Development



Weather Data : Three Cities







Lifetime Prediction at Local Cities

1

$$D = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdot \cdot \cdot + \frac{n_2}{N_2}$$

Miner's linear damage rule

Month	Day	Minimum Module Temp.(℃)	Maximum Module Temp.(℃)	Module Temp . Change △T	Stress at Min. Temp. (MPa)	Stress at Max. Temp. (MPa)	Stress Change (MPa)	Expected Life (N)	Damage on Life
1	1	-13	7	20	21.6	9.9	11.7	13223	7.56258E-05
1	2	-7	7	14	18.5	10.2	8.3	14128	7.07818E-05
1	3	-11	9	20	20.3	8.5	11.8	13209	7.57038E-05
1	4	-8	2	10	18.8	13.0	5.8	14837	6.7398E-05
1	5	-12	5	17	21.4	11.1	10.2	13611	7.34675E-05
1	6	-13	4	17	21.9	11.7	10.2	13630	7.33697E-05
1	7	-14	6	20	22.1	10.4	11.7	13226	7.56083E-05
…	…				..				
12	30								

Module Temperature

Module Stress

Expected Life

Damage = 1/Life

2 Lifetime Prediction

City	Miami	Arizona	Seoul
Lifetime	34 years	31 years	36 years

Thank you!

Email : cw_han@keti.re.kr

Feb. 28. 2012

Changwoon Han, Nochang Park, and Jaesung Jeong

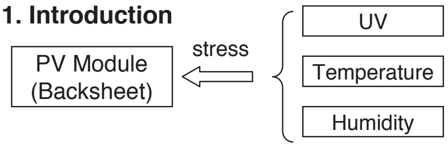
Korea Electronics Technology Institute

Observing Mini PV Module Degradation Through Successive Damp Heat Testing and Thermal Cycle Testing Procedure

‘TORAY’ Innovation by Chemistry

Takashi Arai, Ryuhei Metabi, Michiko Tanaka, Takao Amioka, Miki Terada, Kusato Hirota

1. Introduction



Backsheets have degraded by environmental stresses such as UV, temperature, thermal cycling, and humidity, etc. However, the degradation effects due to these factors during PV module’s lifetime are not clear. We have studied reliability of the modules that have a backsheet using a <u>high durability (anti-hydrolysis) PET film</u>, and a common backsheet "TPT".(PVF/PET/PVF)

2. Experiment

Table.1 Backsheets of testing modules

	Module “A” Backsheet ”A”	Module “B” Backsheet ”B”	Module “C” Backsheet ”C”
EVA side→	PVF 38μm	Olefin 150μm	Olefin 150μm
Cross-sectional View of BS	PET 250μm	Anti hydrolysis PET 125μm	White Anti hydrolysis PET 125μm
Outer side→	PVF 38μm	Protective coating	

Fig.1 Mini PV module
400mm x 400mm, 6” p-Si 4 cells

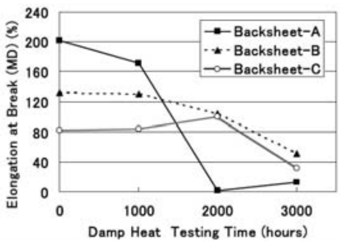


Fig.2 DHT degradation of backsheets’ elongation

The elongation at break of backsheet "A" decreased significantly after Dump Heat Test of 2000 hours. This result shows that the 250-micron standard PET film in backsheet "A" has degraded and became brittle.
On the other hand, backsheet "B" and "C" have maintained over 100% elongation in value. This results show that those backsheets have enough flexibility, and suggest that the high durability PET ("Lumirror" X10S or MX11) has not degraded significantrly.

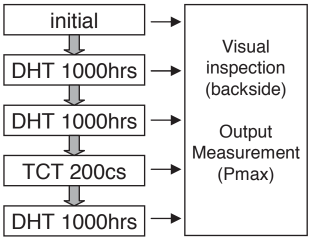
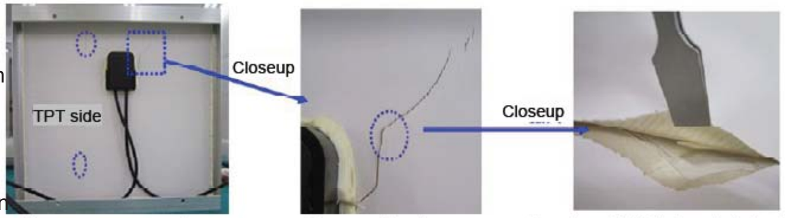


Fig.3 Test Method for modules
DHT : 85℃85%RH, TCT : -40~85℃

3.Result and Conclusion

3.1 Visual inspection

After DHT2000hrs+TCT200c, visual inspection from the backside of module "A" showed cracking in the common grade PET film of the core layer. This result can be attributed that standard PET film has degraded and became brittle after DHT 2000 hours ,and it has broken under the stress of TCT.
Contrary Module “B” and “C” did not changed in visual.



There are many cracks at core layer PET film. Some cracks also occur on outer PVF film. Core layer PET film breaks into pieces. Yellow discoloration at adhesion layer.

Fig. 4 Visual Inspection from the backside of **module ”A”** after DHT 2000hrs and TCT 200cycles

3.2 Output characteristics

After DHT 2000 hrs, Pmax of all modules did not degrade. But after TCT200c, module "A" has more degraded than that of module "B“&"C". The degrading ΔPmax value is 5.3%.
After additional DHT of 1000hrs, Pmax of module "A" has further degraded to 90% of initial Pmax value. On the other hand, Pmax of module "B“& "C" after additional DHT 1000h (total DHT 3000hr) have maintained more than 95% of initial Pmax Value. The difference between module"A" and "B“(or "C")is more expanding than that before additional DHT1000hrs.The modules with a backsheet using high durability PET film have higher Pmax retention of initial Pmax value than a backsheet used PVF/common grade PET/PVF.

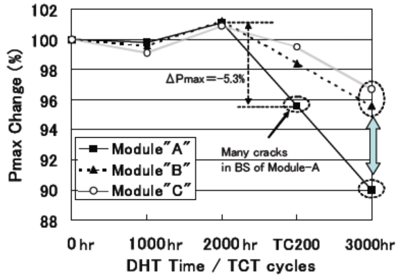


Fig. 5 Pmax Changes after DHT／TCT

3.3 Conclusion

For longer module's lifetime, high durability PET film is better solution for backsheet design. Furthermore, cracking of backsheet is a potentially serious to electric safety. High durability PET film is the one of the key factor to improve PV module life.

Acknowledgment : This study is supported by “Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability carried out at National Institute of Advanced Industrial Science and Technology (AIST)”.

Hotspot Detection for Cell Production Lines

G.S. Horner, J.E. Hudson, J. Schmidt, L.A. Vasilyev, K. Lu,
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Abstract

Since the 1970's manufacturers of both thin-film and conventional c-Si modules have known of the reliability problems associated with hotspot defects. The recent multi-GW ramp of PV manufacturing has occurred without industry-standardized inline hotspot tests, and some fraction of today's field failures may be attributed to this class of defect. We describe several of the root causes and outline a measurement technique that has been developed and deployed for use in both R&D labs and manufacturing lines.

Background

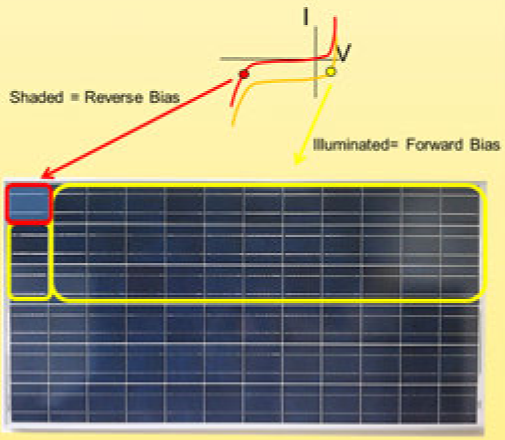
Hotspots are, in general, most noticeable when a cell is placed in reverse bias. As an example, consider the c-Si module shown below.

Assume that one cell (outlined in red) is shaded while all other cells are fully illuminated.

Causes of shading might include:
- Bird or Leaf
- Building Shadow… etc.

A shaded cell with minor defects will readily withstand the high reverse bias (~10-12Volts, typical) that persists until the shadow is removed, but a cell with significant shunts will leak reverse current and exhibit extremely localized heating at each defect.

The temperature rise near a defect can vary from mild (1-80C) to extreme (>200C), but equilibrium is reached within 10's of seconds.



Hotspots: Common Causes

x-Si
- Incomplete edge isolation
- Crystalline defects intersecting junction
- Metal-decorated cracks
- Overfiring: pn junction "punchthrough"

Modules
- High resistance or "cold" solder points

Thin Film
- Scribeline shunts- incomplete removal or redeposition

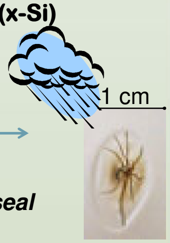
Back Contact & Emitter Wrap-through
- Metal particles & bridges on backside
- Print alignment errors

Typical Damage (x-Si)

Mild (<80C rise)
- Low damage probability

Moderate (~80-200C rise)
- Backsheet bubbles
- Coverglass cracking
- ***loss of quasi-hermetic seal***

Extreme (>200C rise)
- Cell damage



Long term effect

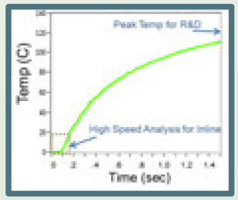
Moisture Intrusion
→ Corrosion & Power Loss
→ Warranty failure.

Manufacturing Requirement

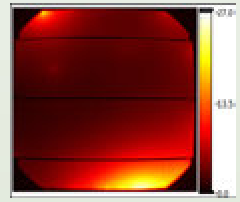
- Reduce Warranty Exposure by removing hotspot cells prior to lamination with high speed (~100-400ms), high reliability (>99.9% accurate) inspection.

Measurement Method

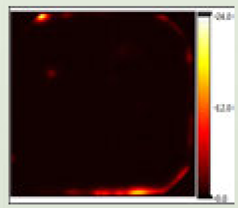
Method: Time-resolved Thermography^Patents Pending
Camera: LWIR (8-12 micron)
Speed: a) Inline: 30-400ms / cell
b) R&D: 30ms- 5 min.
Simultaneous capture of time-resolved I-V
a) breakdown events
b) busted shunts



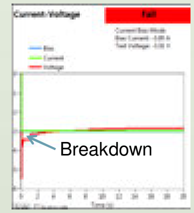
Individual pixel Analysis



Peak Temp @ 20s



Severity @ 400ms



Time-resolved I-V

Inline Inspection Points

Cell Line- Hotspot Detection

Module Line- Hotspot Detection

Summary

Field failures caused by hotspots may be addressed with modern cell or module-level hotspot inspection machines capable of >3000 WPH.

Tau Science
Process Control for PV

Thermoanalytical Characterization of Ethylene Vinyl Acetate Copolymer (EVA) for Lamination Process Simulation and Gel Content Determination in Photovoltaic Modules

2012 PV Module Reliability Workshop
Golden, Colorado, February 28–March 1, 2012, Denver Marriott West, NREL, USA

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Introduction

A photovoltaic module consists of many jointly-connected solar cells. These solar cells are packaged between a polymeric backsheet on the bottom and a tempered-glass window on the top, and are typically encapsulated in a cross-linked polymer matrix. The encapsulant serves many functions – it provides mechanical support, electrical isolation, and protection against outdoor environmental elements of moisture, UV radiation and temperature stress. Many different materials can be used for encapsulation, but one commonly used is ethylene-vinyl acetate (EVA) copolymer.

As the encapusalant properties and performance are largely dependent on the degree of crosslinking of the EVA, it is important to accurately know the curing state of the thermoset matrix. Currently, the most popular method to determine the curing state of EVA is the xylene extraction gelcontent analysis. However, Differential Scanning Calorimetry (DSC) is an alternative, more efficient and convenient way to determine the curing degree of EVA.

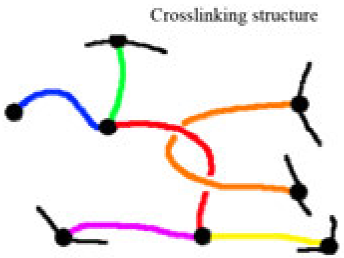
Normally a peroxide or peroxide mixture is the key component to initiate the curing reaction of the EVA encapsulant. As such, it is very important to know the dispensability of the peroxide in whole EVA film scroll. In this study, a sample of fresh EVA film (105cm wide, 165cm length, the same size of a real PV module), was evenly divided into 10cm x 10cm sections. A specimen from each section was analyzed by DSC (TA Instruments, model Q2000 with 50 position autosampler) from -90°C to 250°C at 10°C/min under N2 purge. From this experiment, the curing enthalpy of the peroxide (which relates directly to the initial degree of EVA cure) can be determined automatically by the analysis software. Finally, a color map of the corresponding curing enthalpy for the fresh EVA film has been established that reflect the homogeneity of the peroxides that will have the influence on curing rate of EVA.

Alternate methods of determining the degree of curing were then compared. Each cured EVA sample with different crosslinking density was tested using the following three analytical techniques: (1) gel-content by xylene extraction; (2) curing degree by DSC and (3) viscoelastic properties by rheometer (TA Instruments, model AR-G2) or DMA (Dynamic Mechanical Analysis, TA Instruments, model Q800). The correlation between the xylene gel-content and DSC curing degree for cured EVA was built on the first step. Then the relationship between the xylene gel-content and tan delta (loss factor, the viscous modulus divided by the elastic modulus) will be established. DSC also can play a role as a mini-laminator to simulate the field laminator's actual temperature profile. The DSC could be operating according to the real laminator's measured temperature profiles following the control cooling for crystallization and control heating for melting and finally continue go on the full curing temperature on a DSC experiment run.

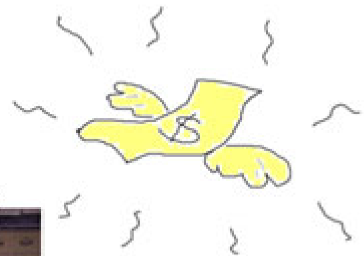
Finally, the EVA crosslinking properties could be developed to relating the viscoelastics behavior, ie., complex viscosity and tan delta value by means of DMA and Rheometer. The optimum curing degree of EVA also determined through the low temperature damping and high temperature creep properties. The Gel content by DSC (curing degree, crystallization, melting) was comparable with DMA and Rheometer results.

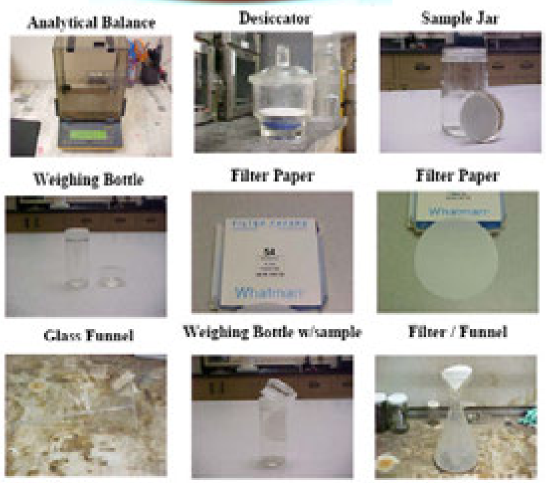
Gel Content Test of Cured EVA

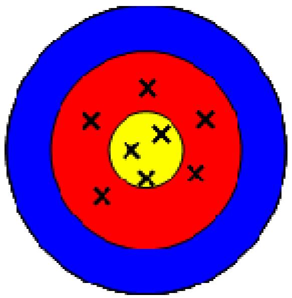
Gel content is very important parameter for setting up the condition of the lamination process – including heating temperature and time.

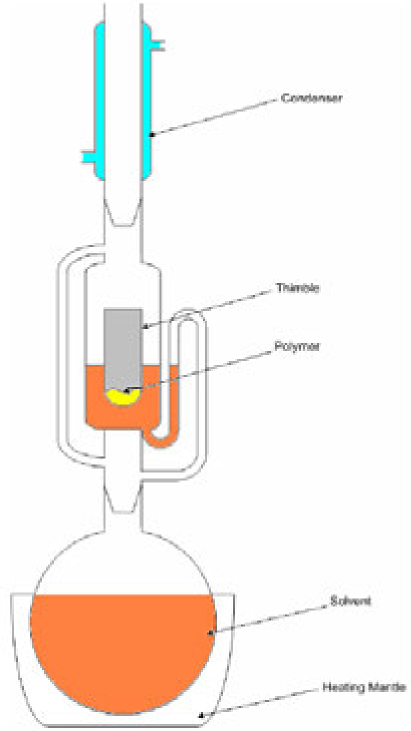


$$\text{Gel content}(\%) = \frac{\text{residual weight}}{\text{initial weight}} \times 100$$



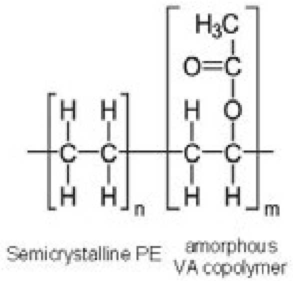


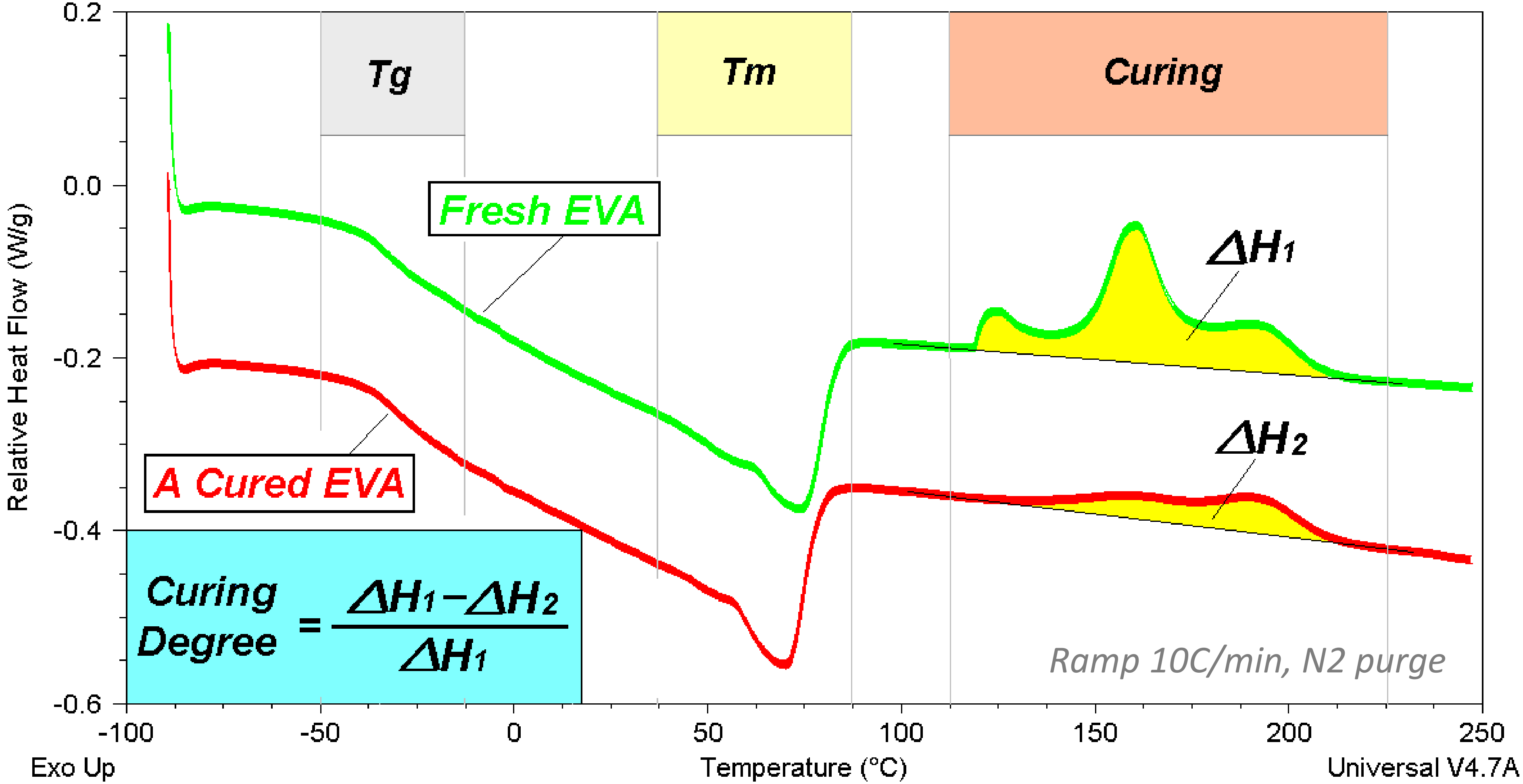




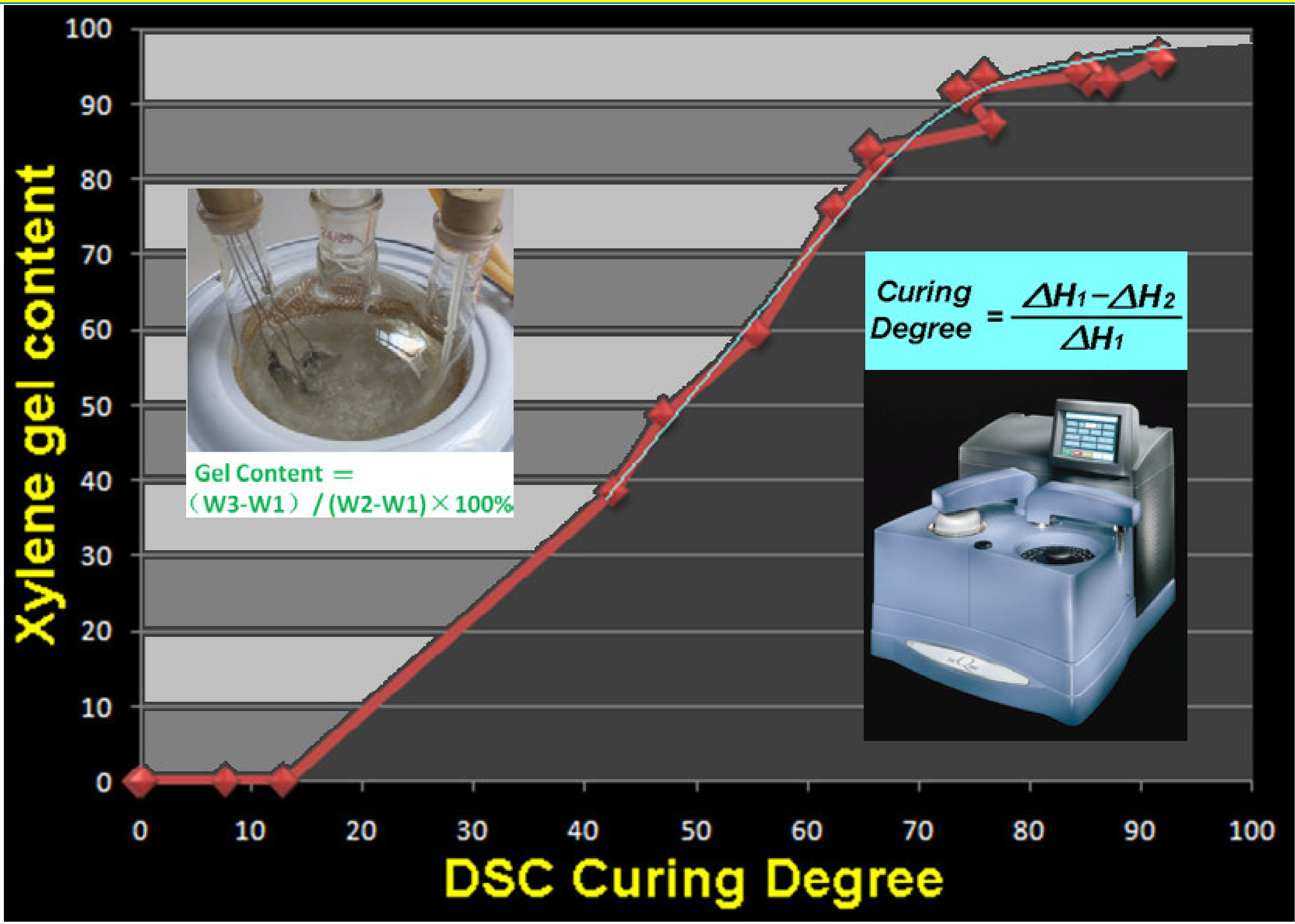
Soxhlet extraction apparatus

Determining EVA Curing Degree by DSC Method

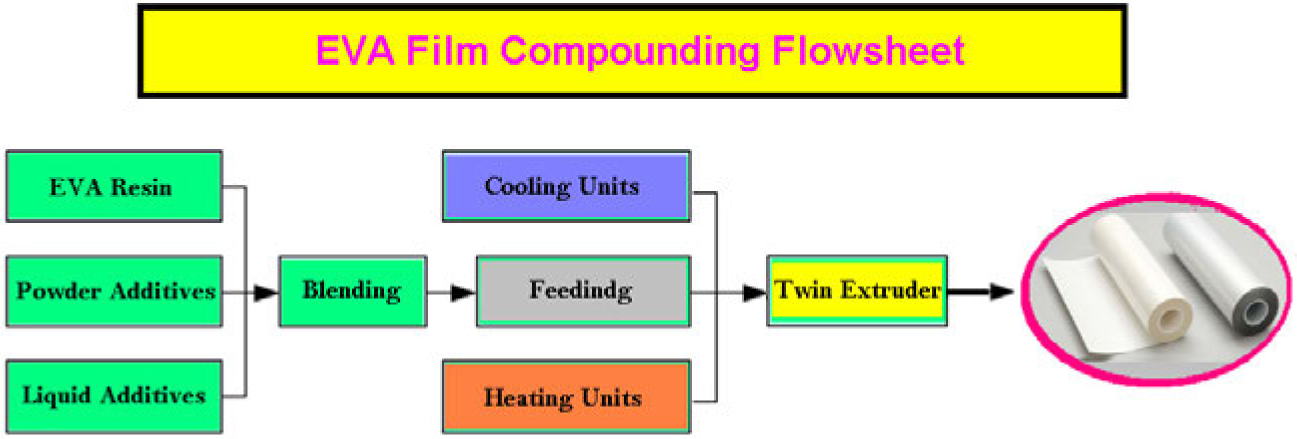


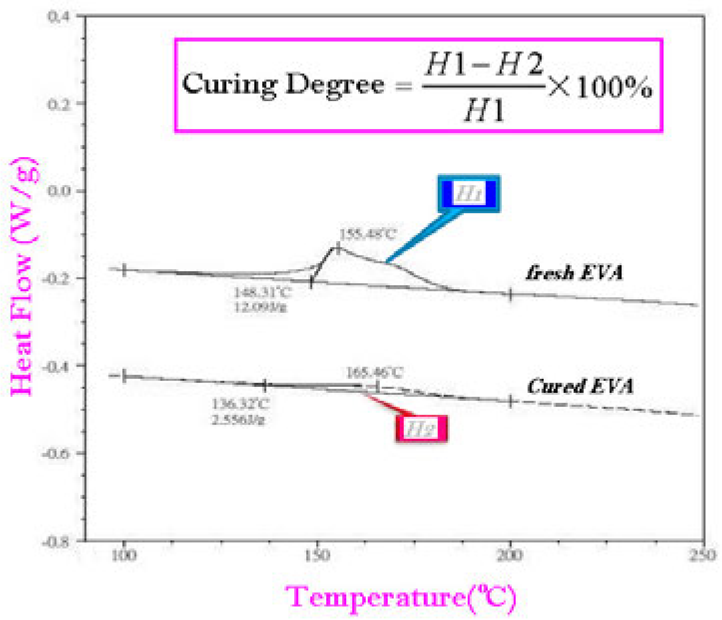


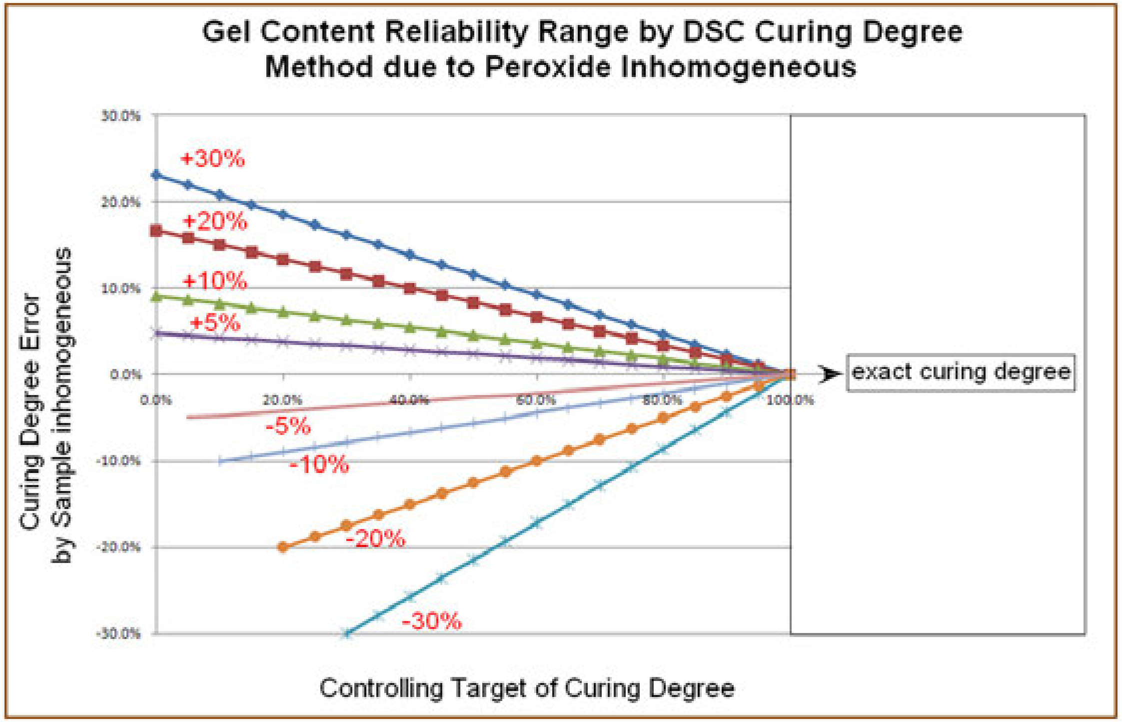
The Relationship between Gel Content and Curing Degree Should be Established for Every Type EVA



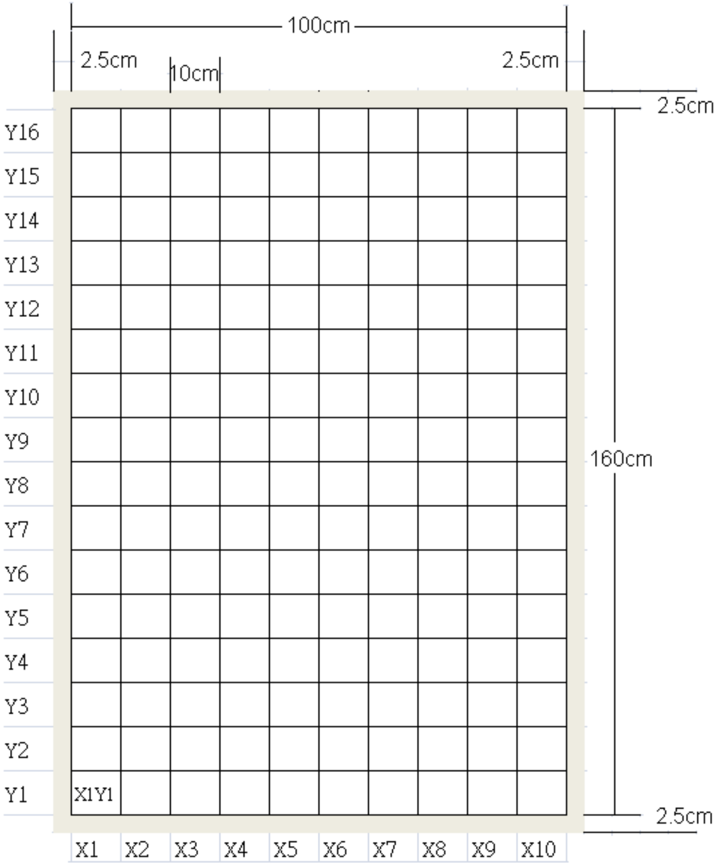
The uncertainty of EVA Curing Degree Calculation

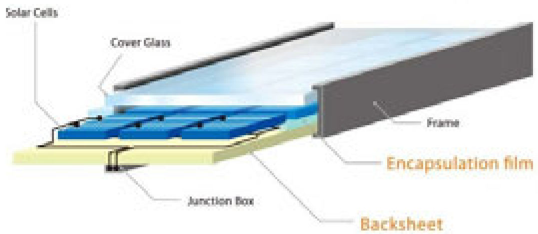






Mapping Study of EVA ΔH_1 Curing Heat Deviation on Real PV Module Scale



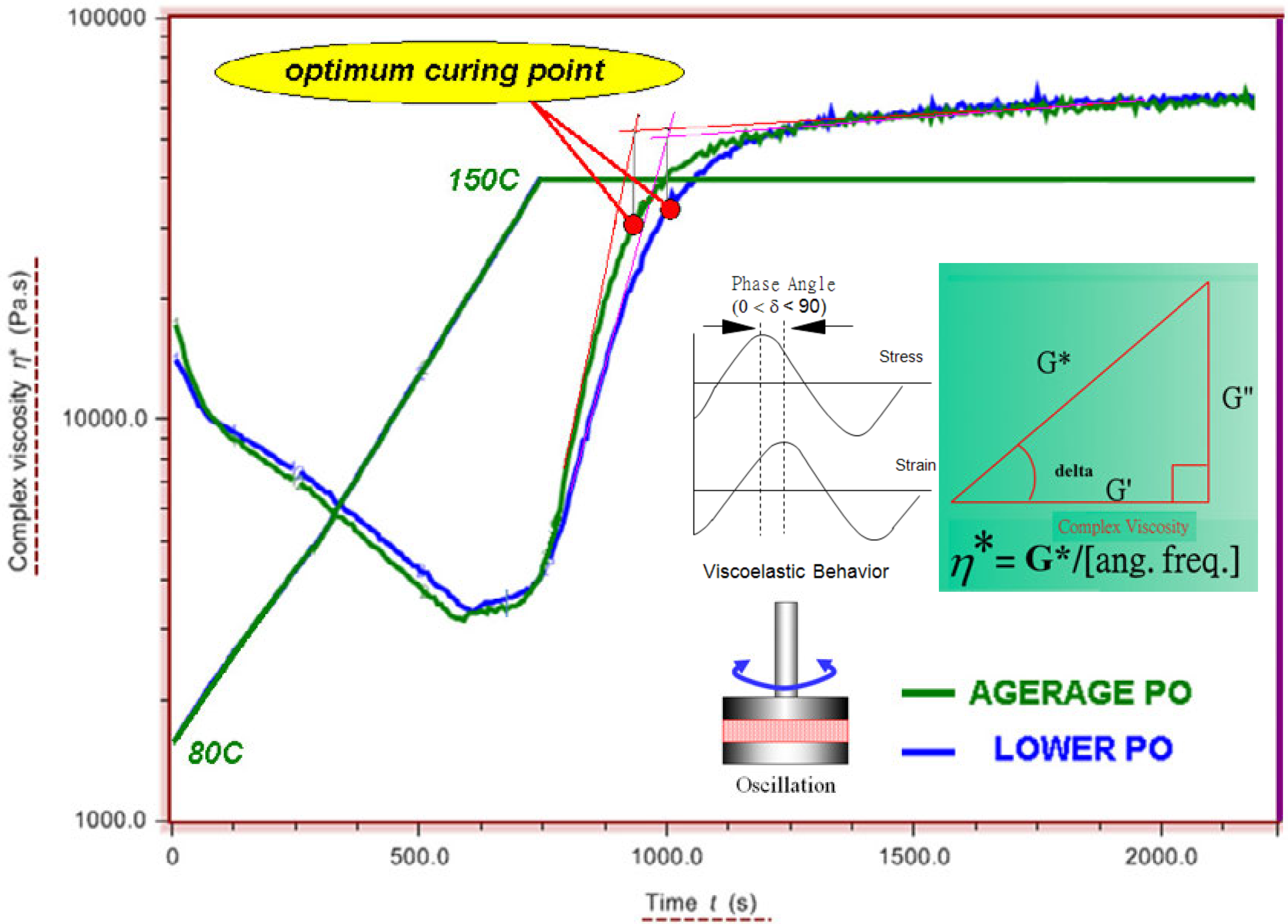


	26.7	29.2	29.6	30.0	30.1	30.5	29.9	30.4	29.9	29.2	29.55
Y16	27.9	30.5	32.0	30.9	28.3	31.7	30.7	31.1	30.8	32.5	30.64
Y15	27.9	29.5	30.3	31.0	30.1	29.2	27.8	30.1	29.0	27.3	29.22
Y14	27.1	29.8	30.4	30.6	31.6	31.5	29.8	30.7	29.4	28.3	29.91
Y13	26.5	30.1	30.6	29.7	32.4	30.6	29.9	29.6	29.6	27.2	29.60
Y12	29.1	31.0	30.4	30.8	31.3	30.7	30.1	32.7	28.0	28.7	30.27
Y11	26.5	29.1	30.1	30.4	30.4	31.0	30.2	30.5	29.4	29.4	29.72
Y10	29.0	30.2	29.4	30.0	27.0	31.2	30.6	30.5	29.5	28.5	29.60
Y9	29.6	31.7	28.4	29.7	32.2	31.0	31.0	30.0	29.6	30.0	30.31
Y8	27.6	28.6	30.6	31.8	30.4	31.5	31.7	31.0	30.8	30.9	30.49
Y7	25.4	28.0	28.2	29.3	29.1	29.9	29.5	28.9	29.6	27.8	28.57
Y6	26.5	29.0	28.8	30.6	31.5	32.0	31.0	30.9	31.3	30.5	30.21
Y5	25.5	28.3	29.0	28.9	30.6	31.0	29.5	30.5	29.8	30.0	29.30
Y4	24.3	28.7	28.2	29.4	30.8	28.2	29.9	30.4	31.0	30.1	29.09
Y3	27.4	29.1	30.1	32.2	31.3	31.2	30.8	32.3	30.6	30.8	30.58
Y2	23.6	28.1	29.2	26.7	27.5	30.1	29.8	30.1	30.0	29.5	28.44
Y1	23.9	26.1	28.5	27.4	27.4	27.3	26.4	26.5	29.3	26.3	26.89
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	

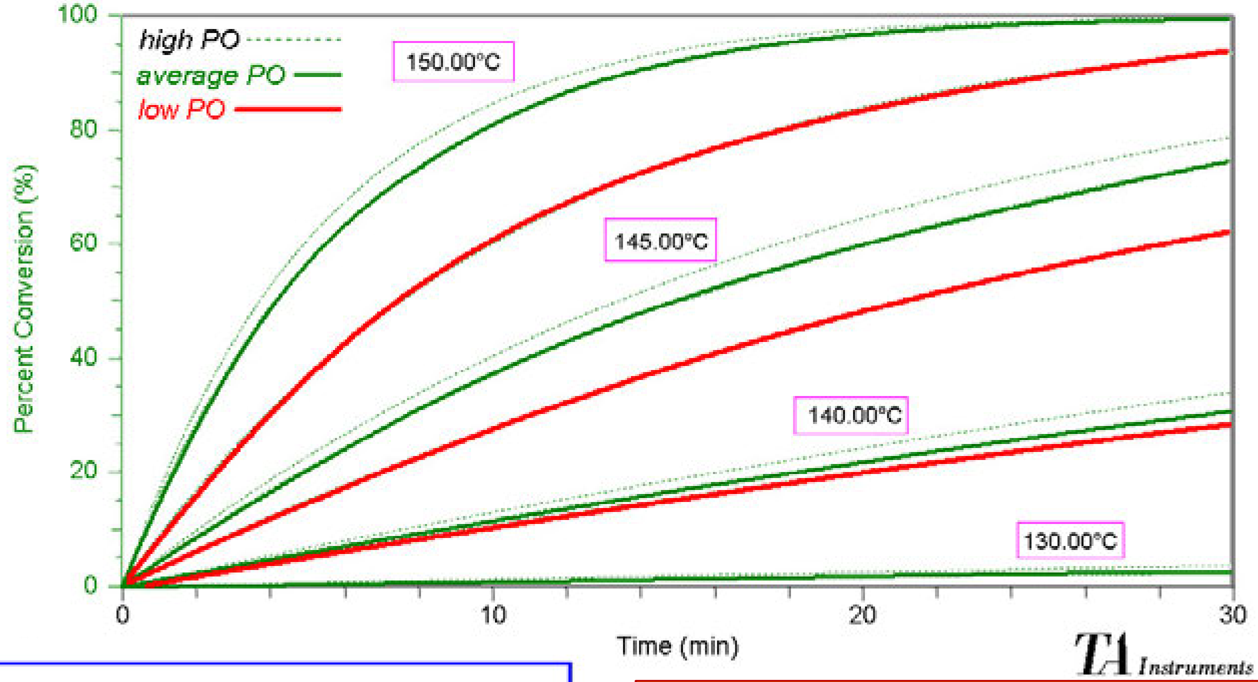
legend

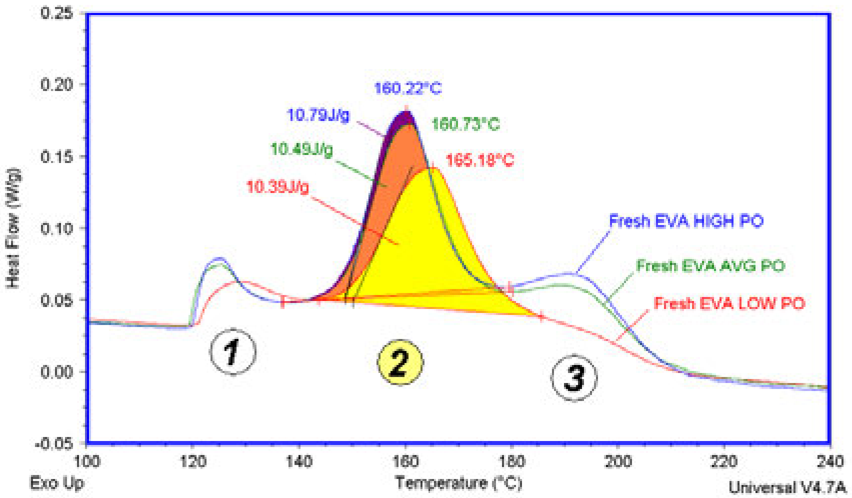
ΔH_1	+/-%
>33	>+12.0%
32.1~33.0	+8.6~11.9%
31.1~32.0	+5.0~8.5%
30.1~31.0	+1.8~5.0%
29.1~30.0	+/-1.7%
28.1~29.0	-1.8~5.0%
27.1~28.0	-5.1~8.1%
26.1~27.0	-8.2~11.5%
25.1~26.0	-11.6~14.9%
<25	<15.0%

Identify the Peroxide Enthalpy will Impact the EVA Curing Rate by Rheology



Identify the Peroxide Enthalpy will Impact the EVA Curing Rate by DSC Kinetics Software





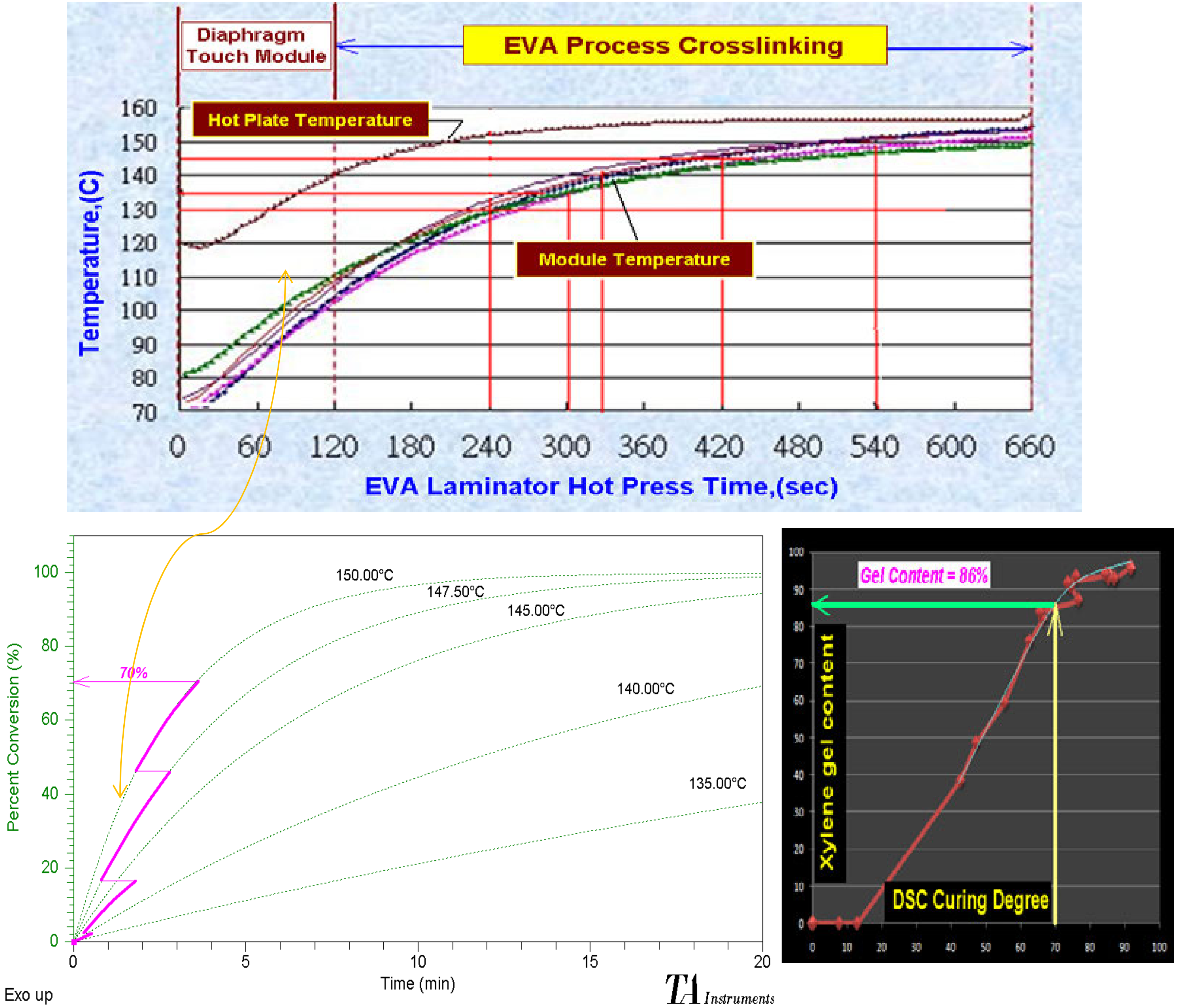
Borchardt and Daniels (B/D) kinetics

$$k(T) = Z\, e^{-Ea/RT}$$

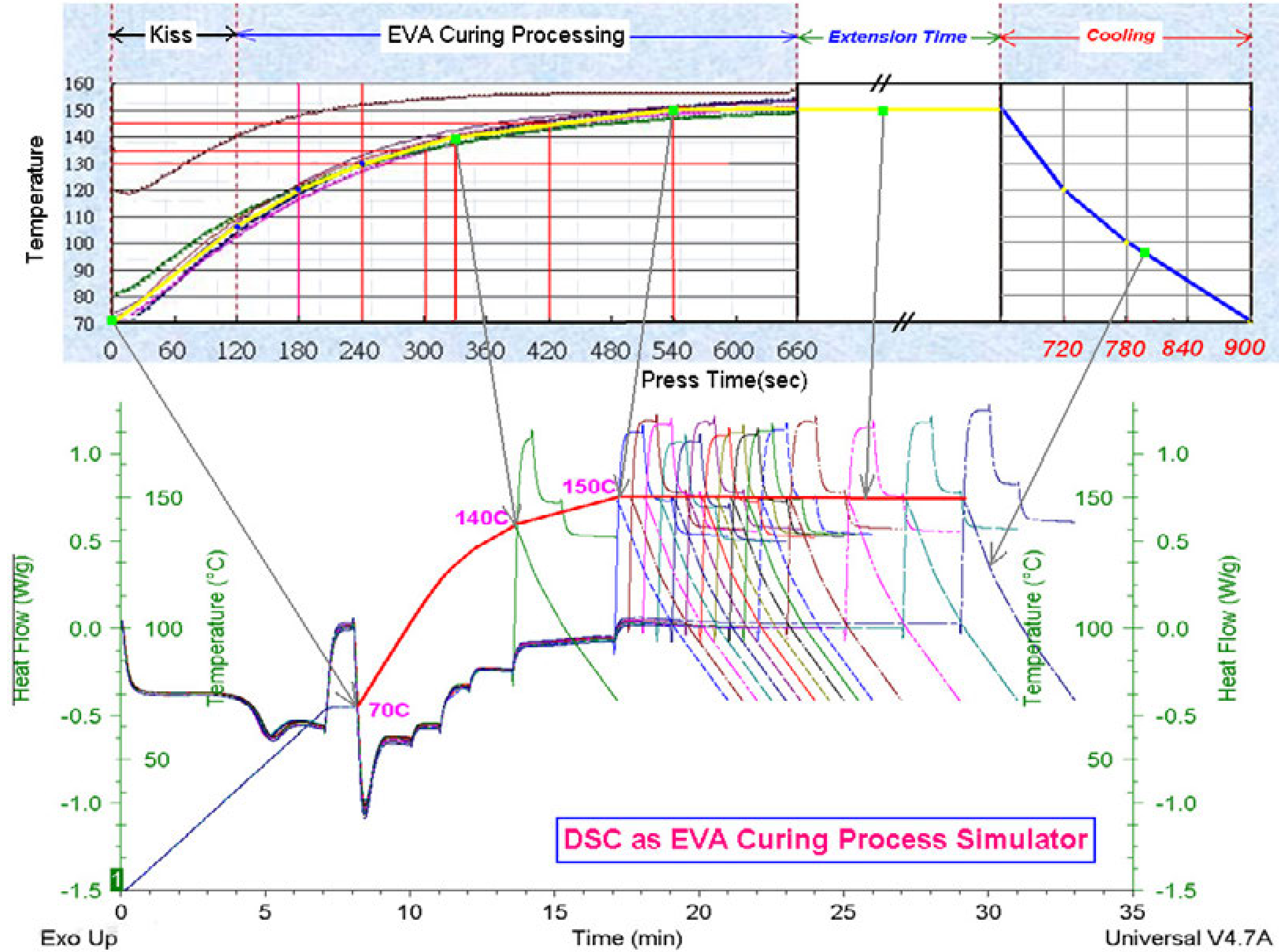
$$d\alpha/dt = Z\, e^{-Ea/RT}\, [1-\alpha]^{n}$$

$$\ln (d\alpha/dt) = \ln (Z) - Ea/RT + n \ln [1 - \alpha]$$

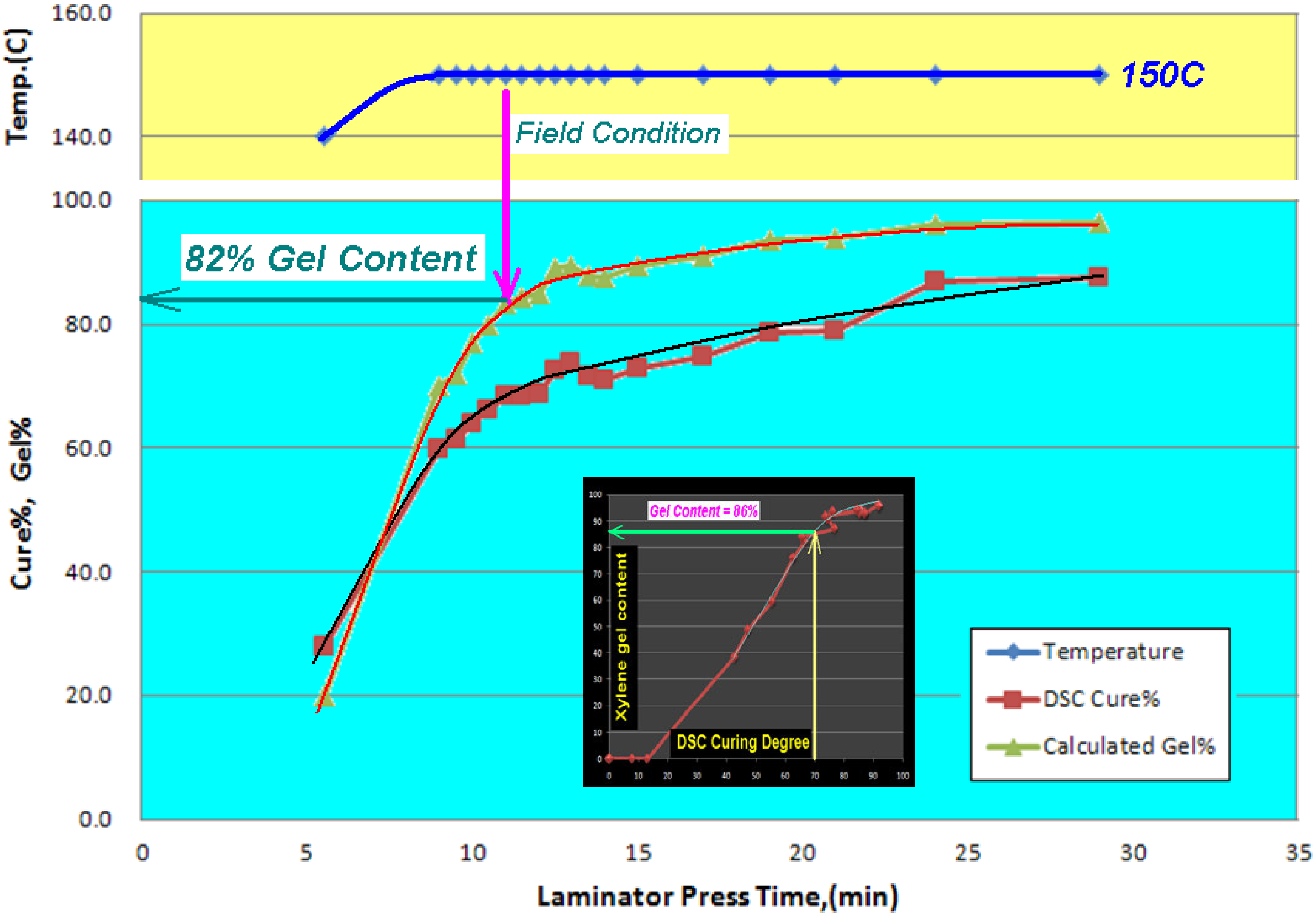
Simulation the Curing Degree of the Real EVA Lamination Process by DSC Kinetics Software



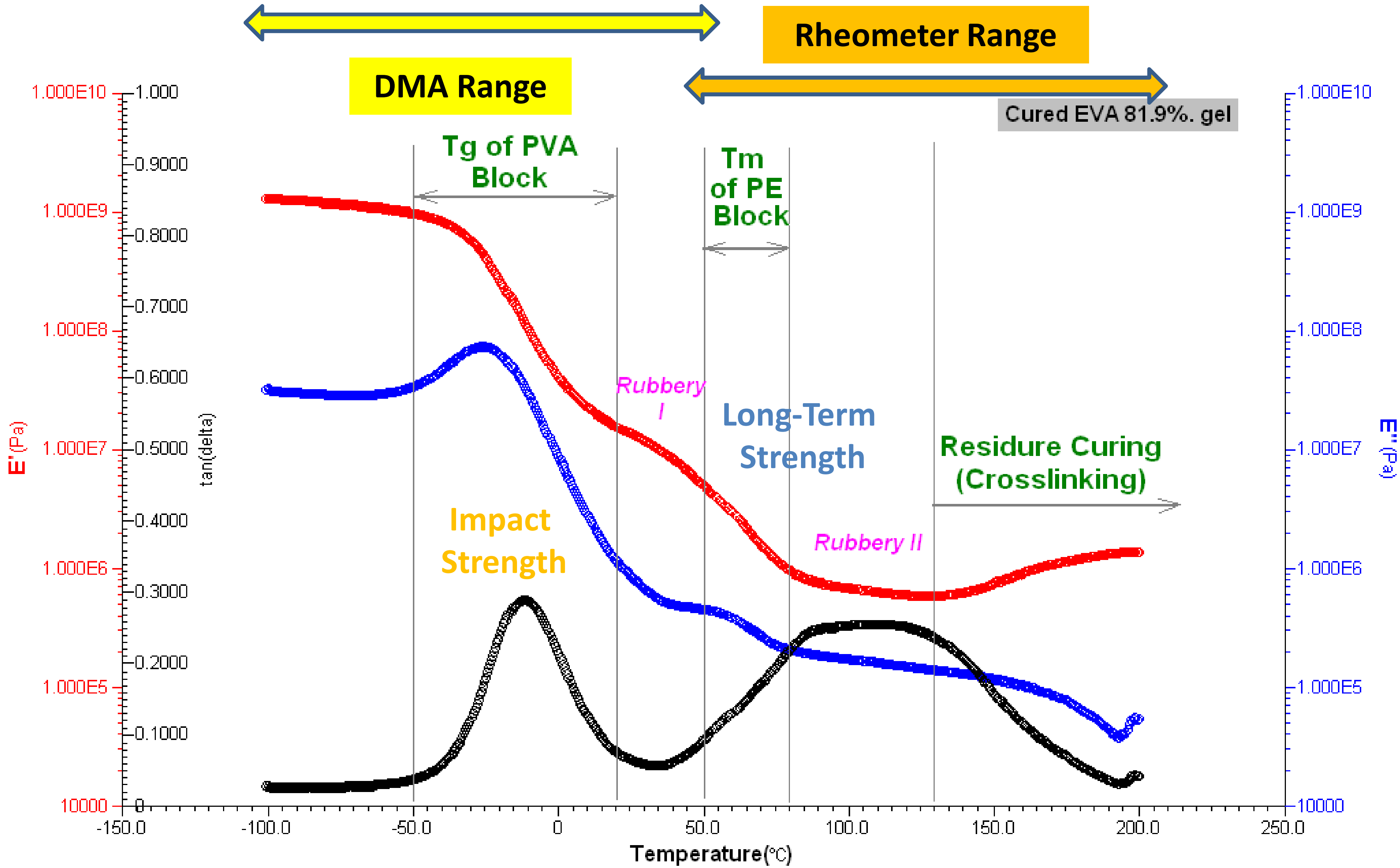
Simulation the Curing Degree of the Real EVA Lamination Process by Direct DSC Furnace Heat Treatment



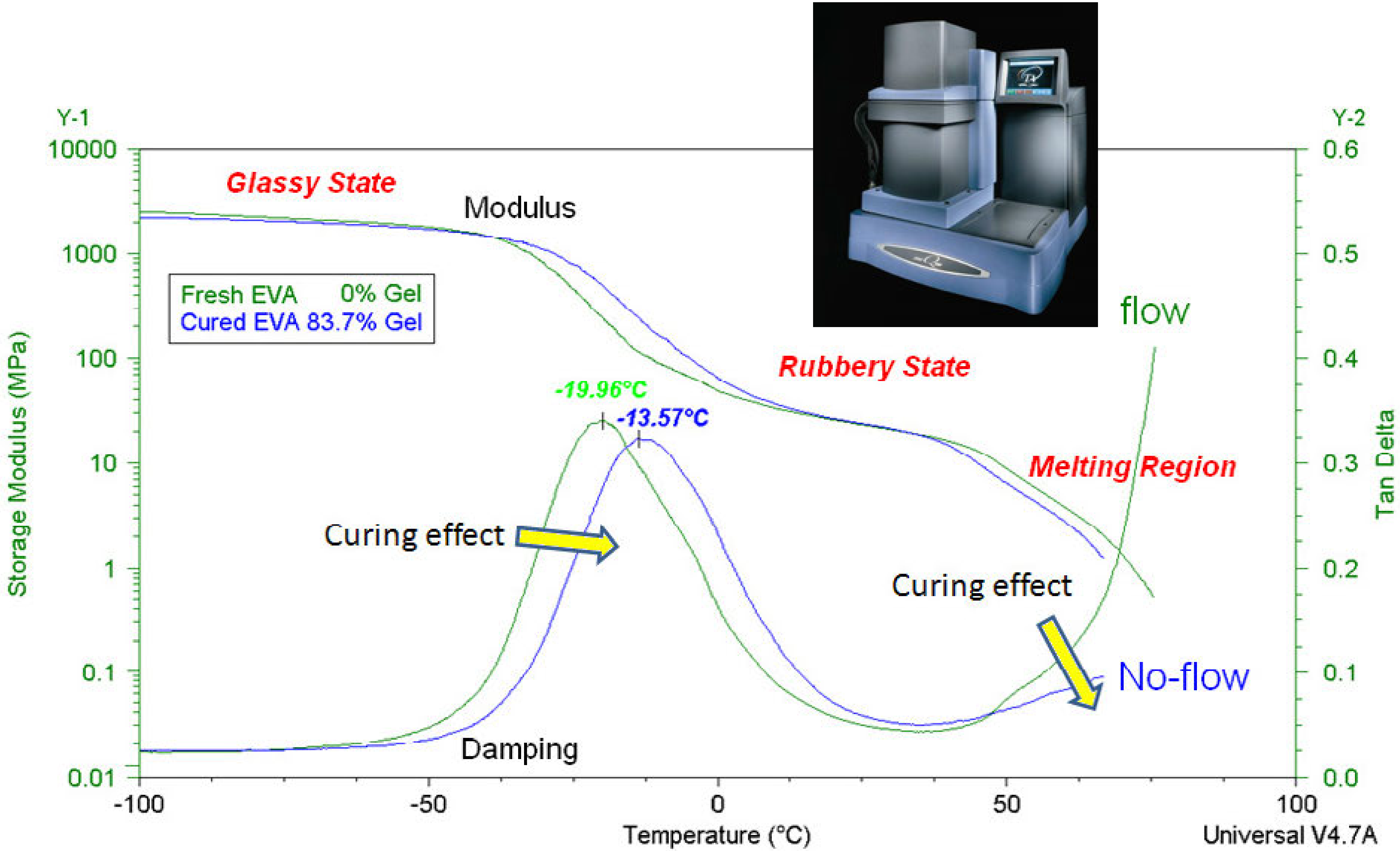
Simulation the Curing Degree of the Real EVA Lamination Process by Direct DSC Furnace Heat Treatment (Cont.)



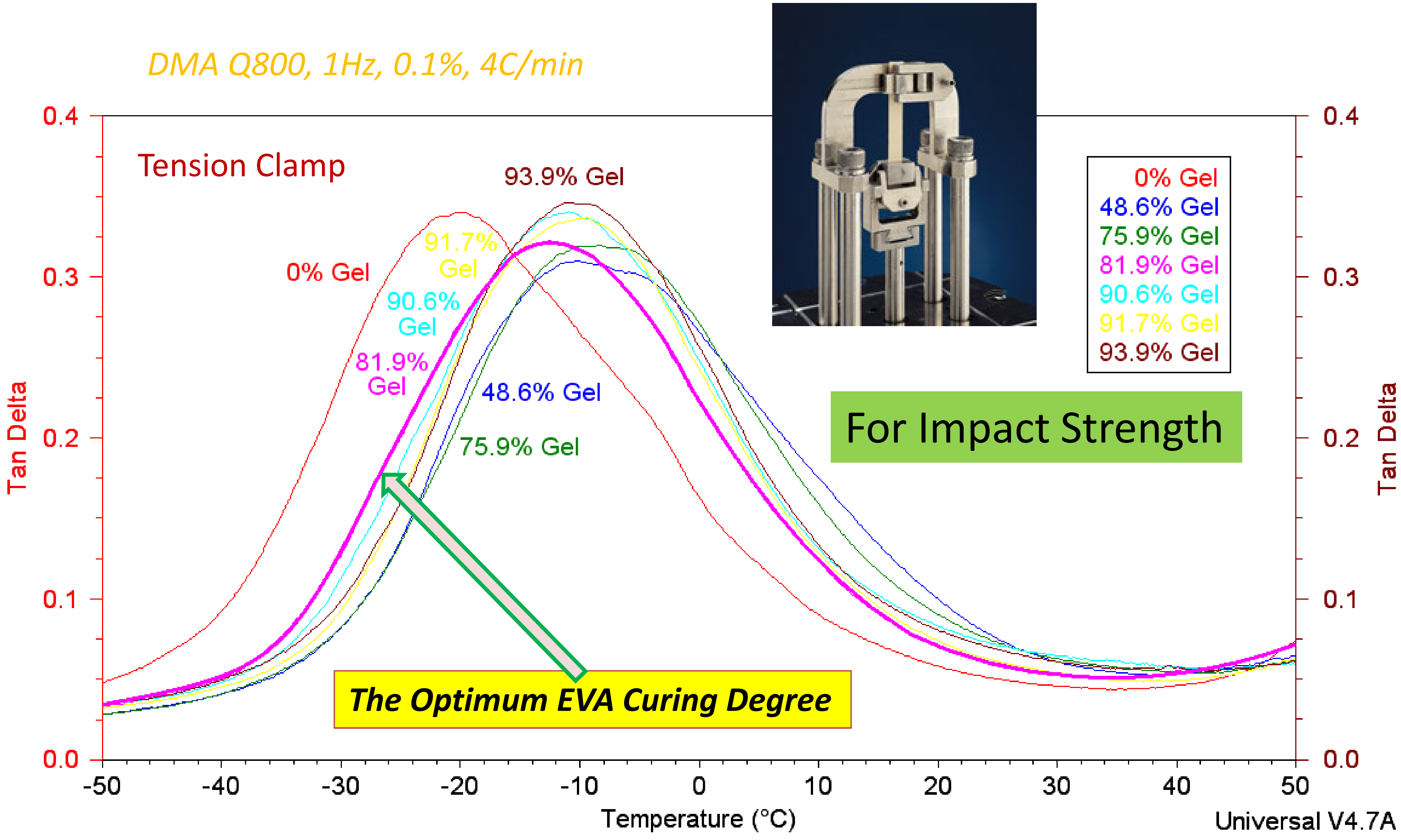
Use the Viscoelastic Properties to Evaluate What's the Optimum EVA Gel Content ?



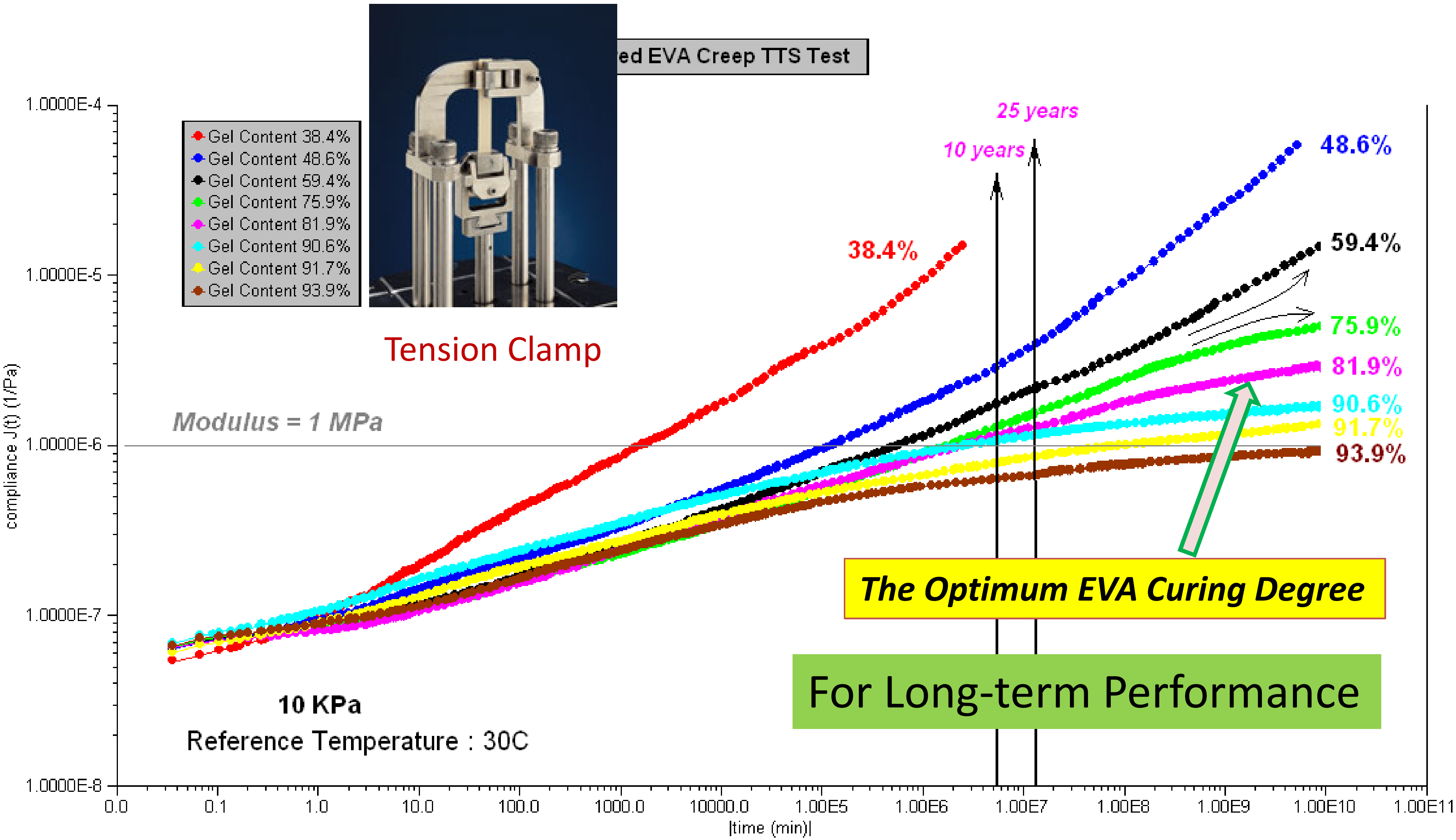
DMA Test to Get the Viscoelastic Properties Response for Fresh and Cured EVA Laminated



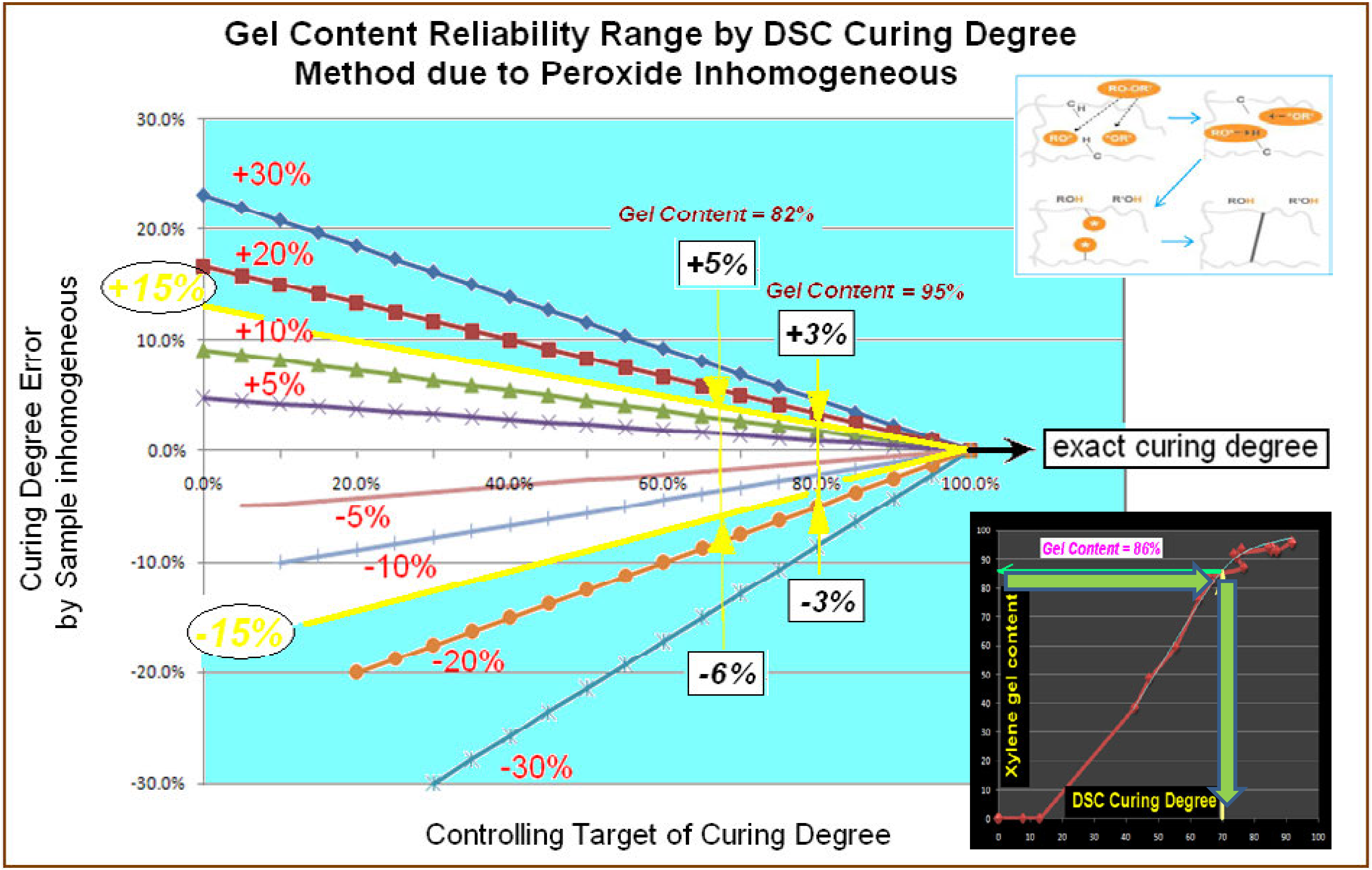
DMA Test : From the Tan Delta Low Temperature Damping Behavior to Get the Optimum EVA Curing Degree



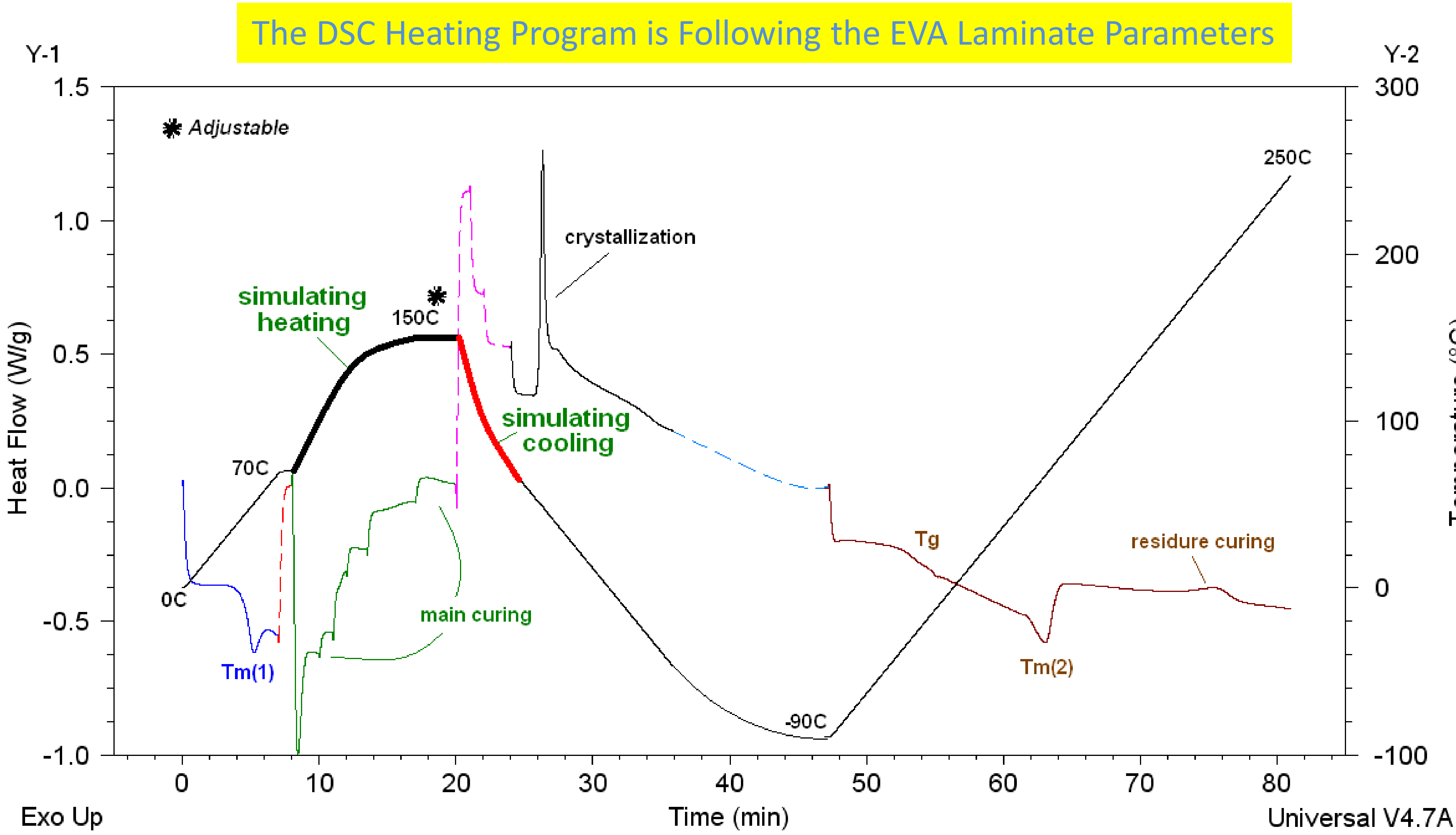
DMA Test : From the Creep Time-Temperature-Superposition Method to Get the Optimum EVA Curing Degree



To Estimate the Possible Deviation For the EVA Gel Content Transformation From the DSC Curing Degree Method on the Optimum Control Position

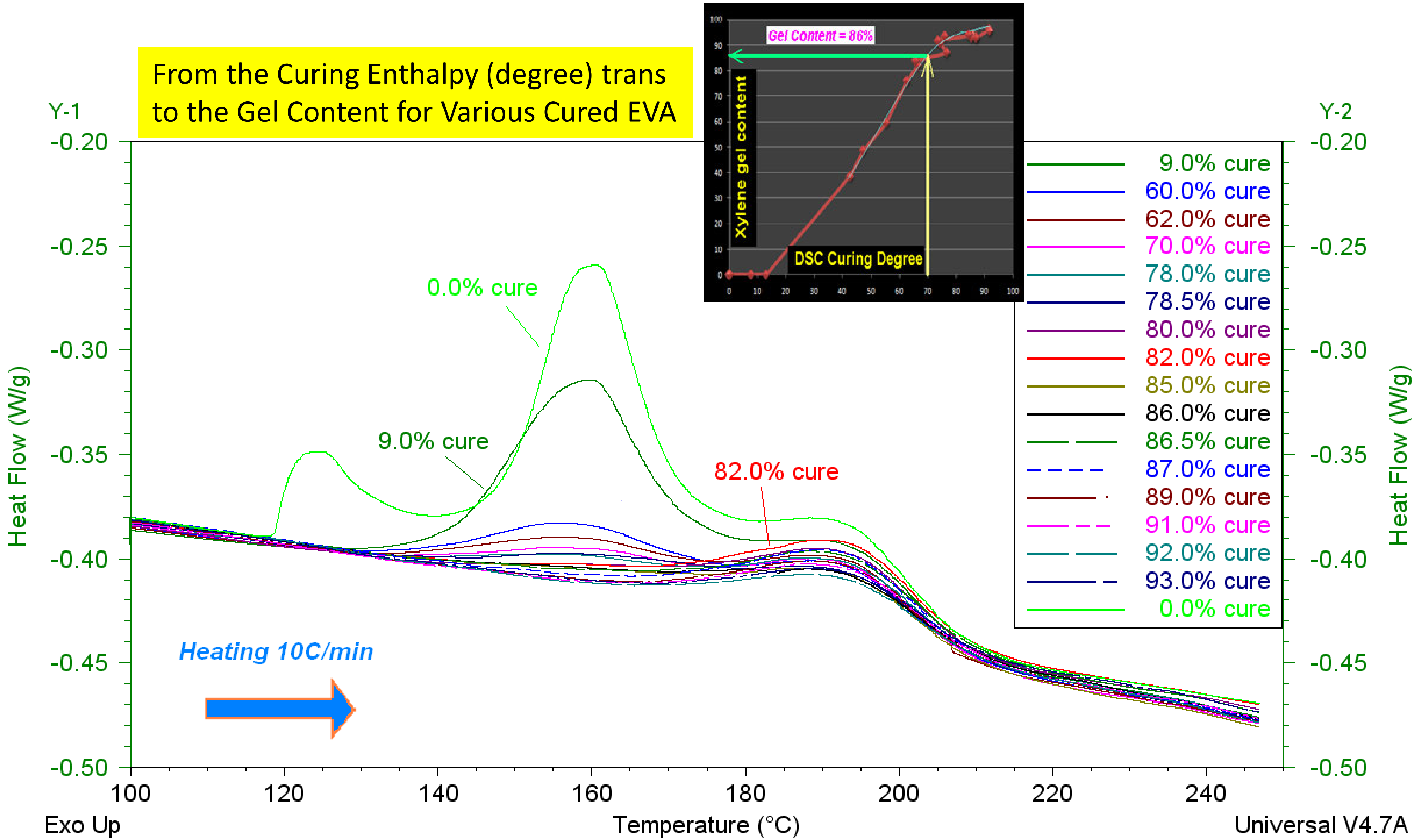


Double Check To Confirm the DSC Curing Degree Method through the Cooling Crystallization Way for Cured EVA



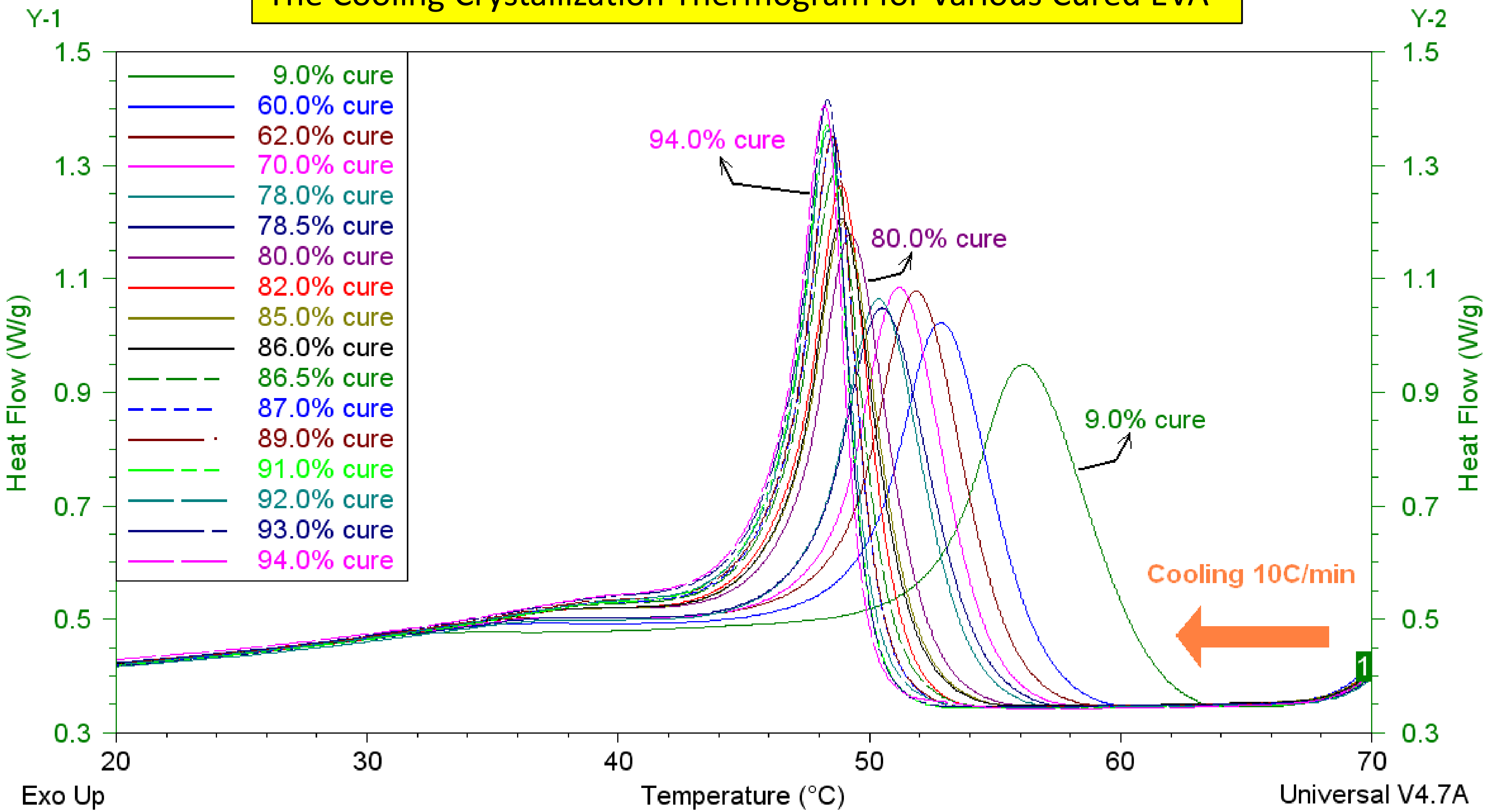
Double Check To Confirm the DSC Curing Degree Method through the Cooling Crystallization Way for Cured EVA (Cont.)

From the Curing Enthalpy (degree) trans to the Gel Content for Various Cured EVA



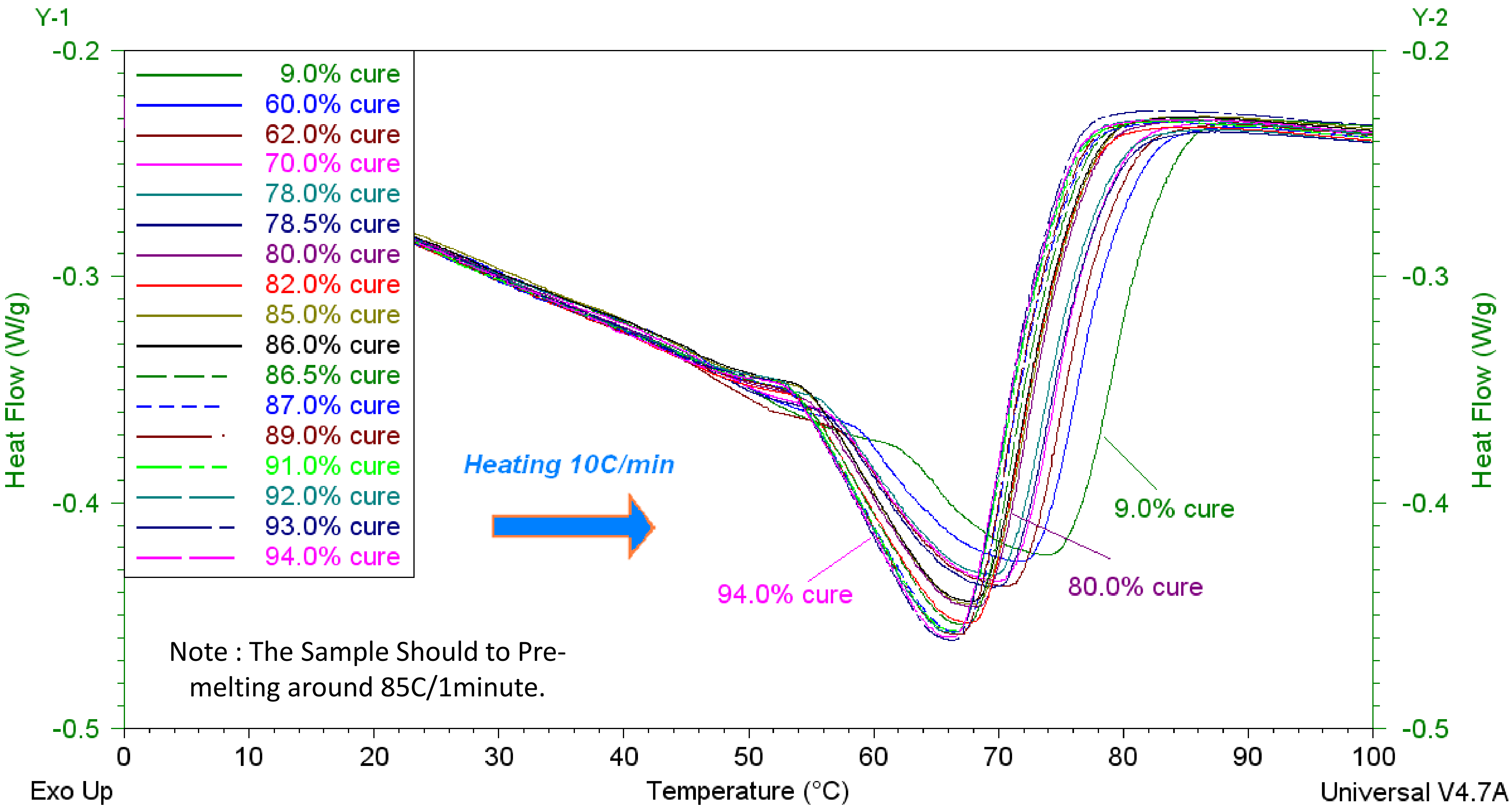
Double Check To Confirm the DSC Curing Degree Method through the Cooling Crystallization Way for Cured EVA (Cont.)

The Cooling Crystallization Thermogram for Various Cured EVA

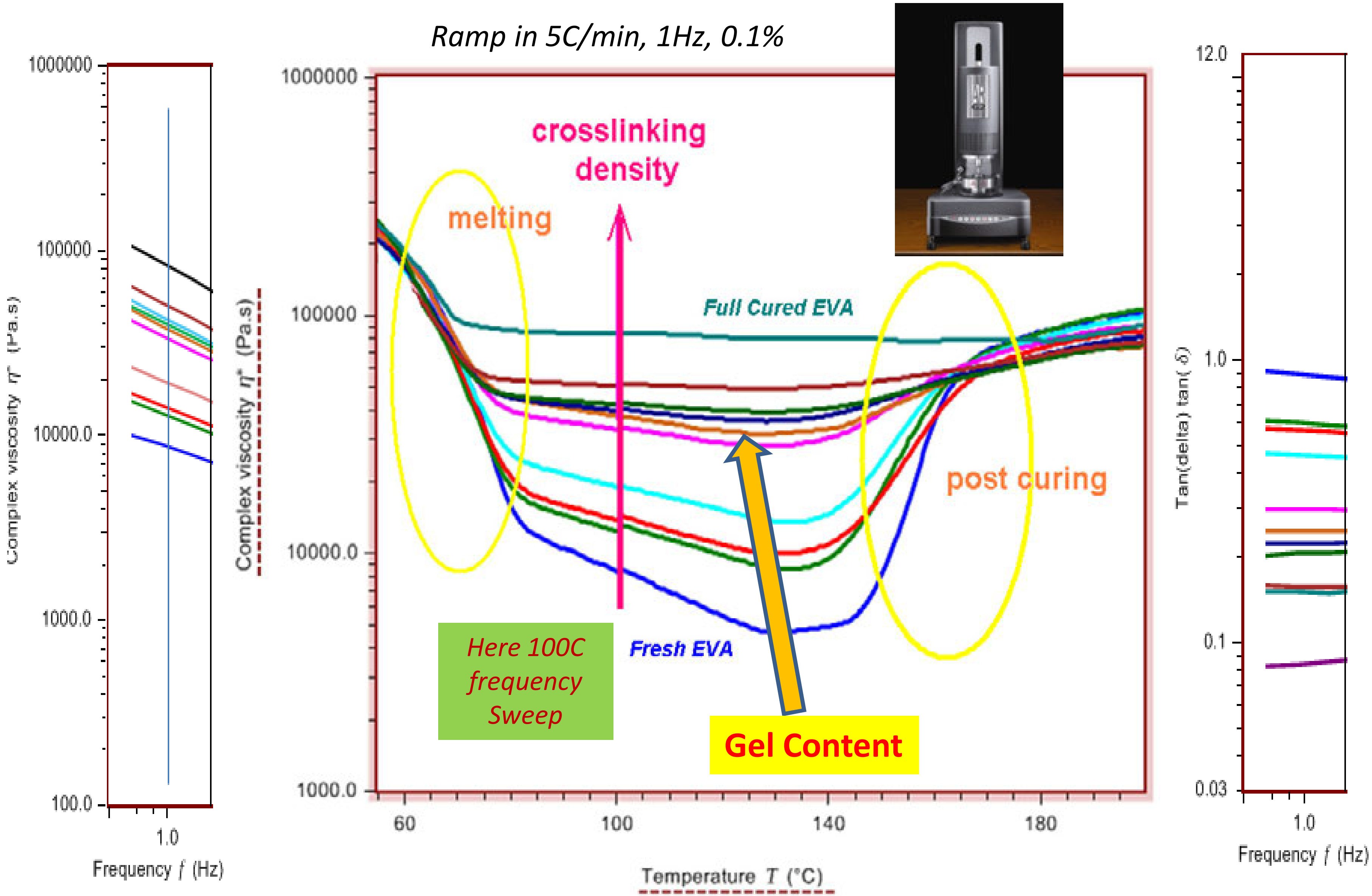


Triple Check To Confirm the DSC Curing Degree Method through the Heating Melting Way for Cured EVA

The Heating Melting Thermogram for Various Cured EVA



Rheology Method To Confirm the Gel Content for Cured EVA



Discussion

1. The DSC Curing Degree could trans to the Xylene Gel Content for Cured EVA in PV module.
2. The Materials Income Properties Stability of EVA for PV Module Purpose could be Studied by DSC Method.
3. The Cooling Crystallization and Re-heating Melting Behavior can ensure the Gel Content Calculation Results.
4. The Viscoelastic Properties of Cured EVA could Direct Related to its Gel Content or Crosslinking Structure better than DSC's Indirect Relationship.
5. DMA (Dynamic Mechanical Analyzer) and Rheology should be the More Important Measurement Tools for EVA Materials in the Future.

Introduction to the SunFarm Outdoor Test Facilities at the Solar Durability and Lifetime Extension Center in Case Western Reserve University

Yang Hu[1]*, Joseph Karas[1], Roger H. French[1], David A. Hollingshead[2], Scott A. Brown[2], Mark A. Schuetz[2]
[1]CWRU, Cleveland, OH, United States, [2]Replex, Mount Vernon, OH, United States

Introduction to the SDLE SunFarm

SunFarm outdoor test facility
- Highly instrumented
  - Not commonly seen in academic research
- 14 dual axis trackers
- 60 meters adjustable tilt fixed rack

Ability of SunFarm
- 148 full size PV modules
  - With/ without mirror augmentation
- 10,000 samples
  - 2X 3X 4X 5X accelerated exposure
- Metrology platforms for logging
  - Environmental conditions
  - System performance

PV lifetime and degradation science
- Determine degradation rates & lifetimes
  - In outdoor and indoor exposures
- Using a stress-response framework
- Determine degradation mechanisms & rates
- For efficacy and lifetime prediction

We establish SDLE SunFarm
- For outdoor testing of long lived
- Materials, components and systems

SunFarm on CWRU Campus: Part of SDLE Center

Layout of the S-DLE SunFarm Outdoor Test Facility

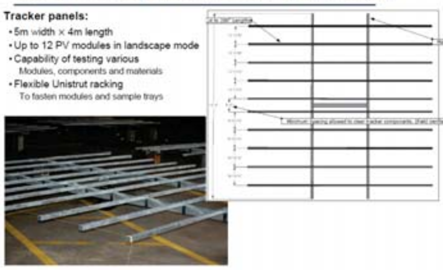
16 electrical sites including
- About 1 acre in size

Fixed and 2-axis tracked sites
- 2 Sites adjustable tile racking
- 14 high precision dual axis trackers

Opel Solar SF-20 trackers
- Manufactured by Feina (Spain)

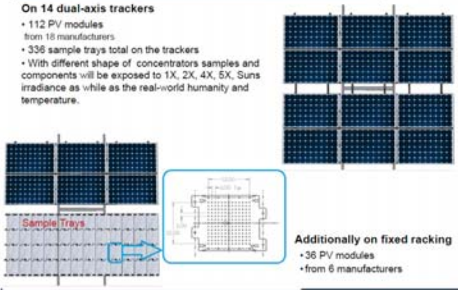
Modular Mounting for Modules on the SF-20 Trackers

Tracker panels:
- 5m width × 4m length
- Up to 12 PV modules in landscape mode
- Capability of testing various
  - Modules, components and materials
- Flexible Unistrut racking
  - To fasten modules and sample trays



Trackers Layout

On 14 dual-axis trackers
- 112 PV modules
  - from 18 manufacturers
- 336 sample trays total on the trackers
- With different shape of concentrators samples and components will be exposed to 1X, 2X, 4X, 5X, Suns irradiance as while as the real-world humanity and temperature.



Additionally on fixed racking
- 36 PV modules
- from 6 manufacturers

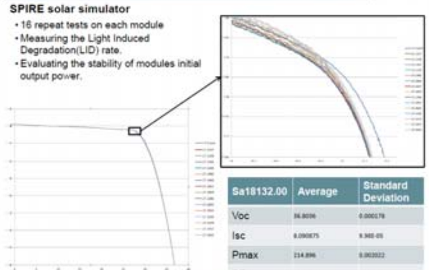
PV modules

- 148 PV modules from 24 manufacturers all over the world
- Monocrystalline Silicon Modules
- Polycrystalline Silicon Modules

Manufactor	Modle	Description	total number
CSI	CS6P	220watt	6
Hyundai	HiS-M230MG	230 watt	6
Perlight	PLM-250M 60 Mono	240 watt	6
AUO	240-P Silver Frame	240 watt	6
REC	REC230PEBLK	230 watt	6
MX Solar	MX60 230	230 watt	6
Sanyo	HIT-N220A01	220 watt	6
Schott	POLY230	230 watt	6
Schuco	MPE240-PS-09	240 watt	6
Sharp	ND-U235Q1	235 watt	6
Solar World	SW230Poly 2.0 Frame	230 watt	6
ET Solar	ET-P660235BZ Zero Rack BLK	235 watt	6
Bosch	c-si M60-225-16	225 watt	6
Trina	TSM-230-PA05	230 watt	6
Conergy	PowerPlus 220W	220 watt	8
Silken	SLK60P6L SLV/WHT 220W	220 watt	8
LG	LG220M1C	220 watt	6
Astronergy	CHSM 6610P 235 watt	235 watt	6
Yingli	YL230P-29b	230 watt	6
Mage	Powertec Plus 230/PH	230 watt	6
Kyocera	KD240GX-LPB	240 watt	6
Helios	6T240	240 watt	6
UpSolar	UP-M240P	240 watt	6
EcoSolargy	EC 02305156P-60	230 watt	6

Modules Baseline

SPIRE solar simulator
- 16 repeat tests on each module
- Measuring the Light Induced Degradation(LID) rate.
- Evaluating the stability of modules initial output power.



Sa18132.00	Average	Standard Deviation
Voc	36.8036	0.000176
Isc	8.090875	8.34E-05
Pmax	214.896	0.002022
FF	0.721673	0.000217

Inverters

Microinverter reliability testing platform
- 120 microinverters from two manufacturers
  - Evaluate microinverter life time & durability

Evaluate power degradation rate
- Power output
- I-V curves
- Environmental conditions

Microinverters
- For each solar module
  - Converts DC power to grid-compliant AC power
- Use power line communications

Also 2 String Inverters
- Solectria PVI 18000

Enphase M215

Electrical design

Grid-tied through reversing relay

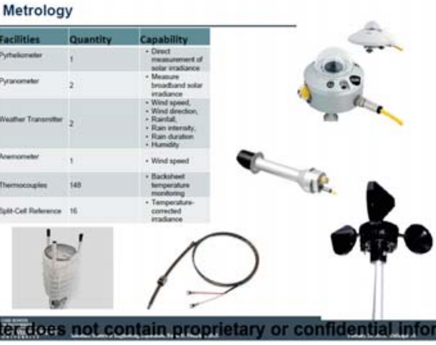
Input power to trackers
- 120V to power tracker motors, data loggers, etc.

Output power
- Inverters output 240V split-phase
- Enphase inverters get dedicated power panel with line filter
- e-QED and Solectria inverters on remaining two panels

Panels at sites
- Input panel contains data logger, Ethernet, and 120V outlet
- Output panel contains 240V connection with external disconnect and lockout-tagout

Metrology

Facilities	Quantity	Capability
Pyrheliometer	1	• Direct measurement of solar irradiance
Pyranometer	2	• Measure broadband solar irradiance
Weather Transmitter	2	• Wind speed, • Wind direction, • Rainfall, • Rain intensity, • Rain duration • Humidity
Anemometer	1	• Wind speed
Thermocouples	148	• Backsheet temperature monitoring
Split-Cell Reference	16	• Temperature-corrected irradiance



Data logging

Network
- SunFarm office connected to CWRU fiber-optic network
- 24 port switch connects each tracker by Ethernet

Daystar Multi-tracer load unit

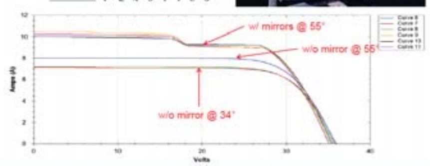
Module power monitoring
- Solectria inverters connected by Ethernet
- Enphase uses data-over-power with network-connected Envoy
- e-QED uses data-over-power also

Environmental metrology
- Campbell CR1000 data logger
  - 16 analog channels
  - 8 digital I/O
  - Communicate by Ethernet
- Weather sensors, irradiance sensors, thermocouples

Campbell CR 1000

Mirror Augmented PV: Replex, Mount Vernon OH

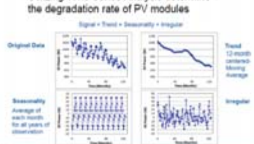
I-V curve tracing by Daystar Multi-Tracer
- 3 mirror augmented 55° tile modules
- 1 without mirror 55° tile modules
- 2 without mirror 34° tile modules



Mirror Augmented PV: CWRU SDLE SunFarm

Mirror Augmented PV (MAPV)
- 1.0X 1.5X 2.0X Suns low concentrated mirror

Daystar multi-tracer
- Acquire power, IV, environmental conditions
- Correct for daily and seasonal variations
- Determine Rd parameters
- Map to Module performance at STC
- Utilizing Time Series Analysis determine the degradation rate of PV modules

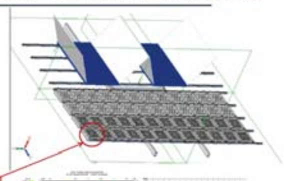


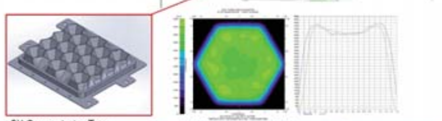
Daystar control unit

Daystar load unit

Outdoor Exposures At Multiple Irradiances: 1X, 2X, 4X, 5X

Samples and components
- Cut into 1.96cm*1.46cm
- Concentrated solar irradiance
- Illuminated in the center
- Illumination is uniform
- Concentration alternated with the shape





5X Concentrator Tray

MATLAB simulation of 5X concentrator

Acknowledgements

Conclusion:
- Outdoor test facilities for power degradation rate of component, modules, PV systems
- For outdoor exposure of materials under real-world environment

SDLE Collaborating Partners
- UL, DuPont, eQED, Q-Lab, Xunlight26

SDLE Partners
- Replex, Evonik, Greenfield Solar,
- Xunlight, Energizer, Borrego Solar

Funding from Ohio Third Frontier Tech 11-060 and Tech 12-004

This poster does not contain proprietary or confidential information.

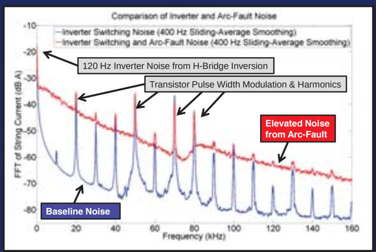
Arc-Fault Detection and Mitigation in PV Systems
Industry Progress and Future Needs

Jay Johnson - Sandia National Laboratories

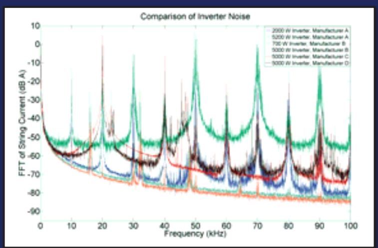
Series arc-fault detectors (AFDs) are being developed to meet National Electrical Code 690.11. These devices de-energize the photovoltaic system when an arc-fault occurs in order to prevent electrical fires. Many AFDs use AC noise on the DC side of the PV system to detect arcing conditions. This methodology accurately detects arc-faults, but leaves the PV system vulnerable to nuisance tripping from noise sources and fails to differentiate parallel and series arc-faults. A need remains for AFDs which safely handle series and parallel arc-faults, passive and prognostic arc-fault mitigation tools, and instruments for locating arc-faults after the AFD has tripped.

Arc-Fault Detection Basics

Many arc-fault detectors use the AC noise on the DC subsystem to determine when there is an arc. Unfortunately, inverter switching noise varies greatly between manufacturers, so it is difficult to perform arc-fault detection using a single frequency.



Mean of 10 Fast Fourier Transforms (FFTs) of normal PV string operation and AC string noise with an arc-fault.



Mean of 10 Fast Fourier Transforms (FFTs) of different inverter noise signatures normalized to 0 dB at the 120 Hz inversion frequency.

Industry Progress

Many companies have publicly announced they are developing PV arc-fault protection devices. A few companies designing arc-fault detection products include:

SMA inverters SB5000-US-12, SB6000-US-12, SB7000-US-12, and SB8000-US-12 include the first arc-fault detection devices listed to series arc-fault protection standard UL 1699B.

On Sept. 1, 2011, Tigo Energy was awarded $3M in DOE SunShot Incubator funding to produce new, low-cost, arc-fault detectors.

Eaton Corporation has performed extensive arc-fault detection studies for residential and commercial-scale installations and is currently listing their device to UL 1699B.

MidNite Solar's line of Classic MPPT Charge Controllers includes arc-fault detection.

SolarBOS has an Arc-Fault Detection and Interruption combiner box which extinguishes series arc-faults by disconnecting the ungrounded conductor.

In Sept. 2011, Texas Instruments acquired National Semiconductor and their SolarMagic DC Arc Detection Reference Design Package. The evaluation board is currently available for purchase and testing.

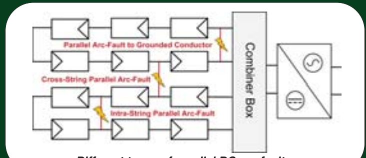
Fronius has developed an arc-detection plug-in card that can be inserted into their inverters. Production is planned for 2012.

SolarEdge power optimizers have module-level arc-fault detection and mitigation algorithms.

Industry Needs for Arc-Fault Safety

Parallel Arc-Fault Detection and Mitigation

In order to insure there are no electrical fires in PV systems, series and parallel arc-faults must be quickly and appropriately de-energized. Therefore, arc-fault detectors need to differentiate series and parallel arcing types because the corrective responses are different.



Different types of parallel DC arc-faults.

Monitoring and Prognostics of PV Systems

The best arc-fault is one that never happens. With known arc-fault failure precursors, PV systems can be monitored for signs of future arc-fault failures and prognostic maintenance could be prescribed.

Arc-Fault Locating Tools

Many series arc-fault interruption approaches detect and de-energize the arc-fault at the inverter or string level. In some PV installations this leaves a large area to search for the faulty component. Further, if the component is not readily identified, the arc-fault indication may incorrectly be assumed to be a false trip.

Acknowledgements

The author would like to thank Sigifredo Gonzalez, Armando Fresquez, and Michael Montoya for their assistance in the Distributed Energy Technologies Laboratory collecting inverter and arc-fault signatures.

National Nuclear Security Administration

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This poster does not contain any proprietary or confidential information.

Lockheed Martin

Sandia National Laboratories

tenKsolar®

fundamentally better solar

tenKsolar’s Cell-to-Grid Redundant PV System delivers High System Availability

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tenKsolar generates 40% more energy per Watt with standard PV materials

- More Energy Per Sq. Ft.
- More Energy per Installed KW
- Faster, More Flexible Installs
- Very Light Weight
- High System Availability
- Built In Safety

Performance of typical 250 KW Solar PV system in New Jersey

	tenKsolar	Conventional
Lifetime Energy Generated	10,400,000 kwh	7,800,000 kwh
Typical Weight	<4.5 lbs / ft^2	<6.4 lbs / ft^2
Roof Penetrations	None	Typical
Arc Fault / Fire Risk	None	Yes

tenKsolar® fundamentally better solar

Cell to Grid Redundant PV Array Delivers High System Availability

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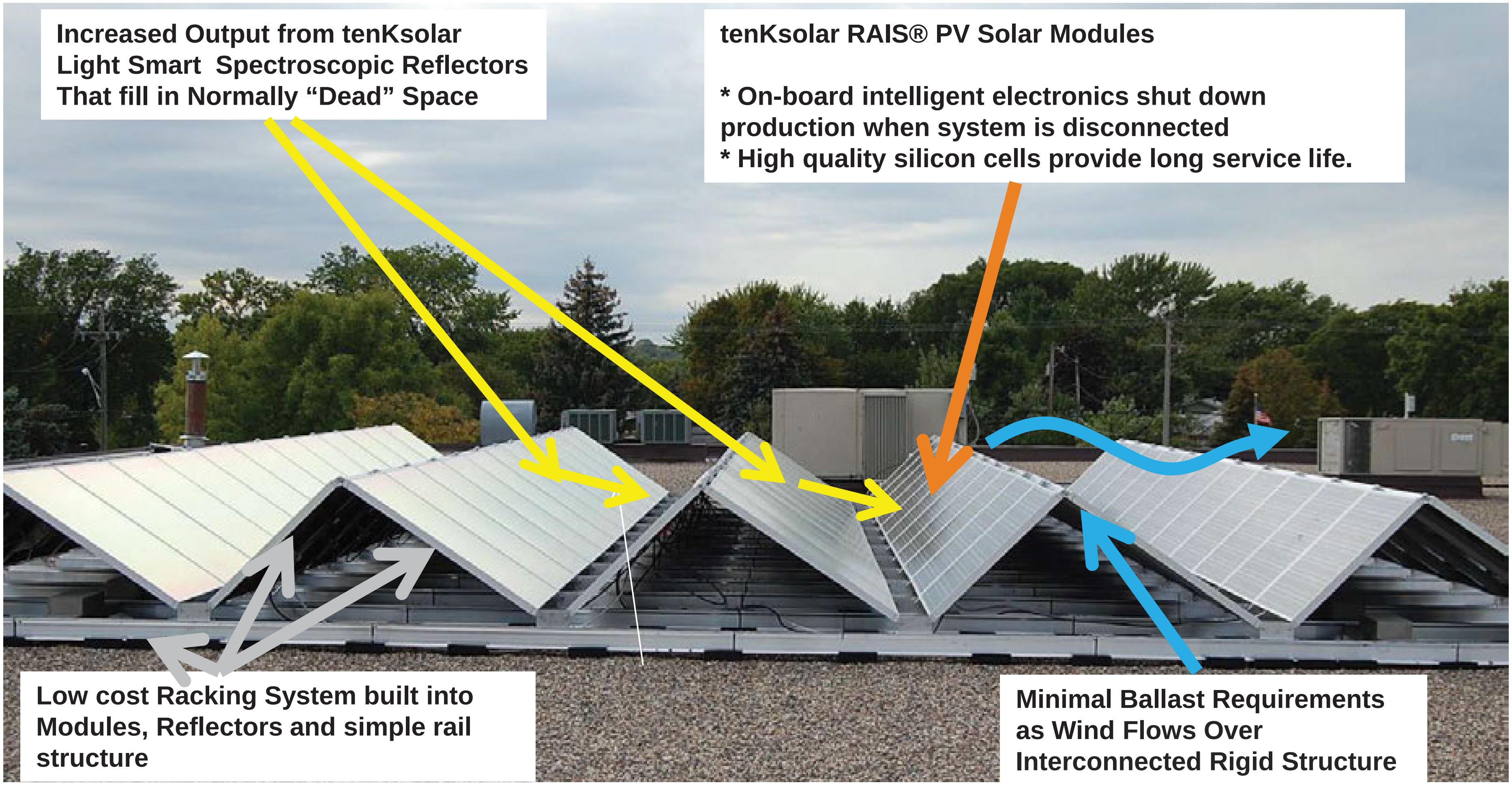
The RAIS® WAVE was designed as a complete system.



Design Challenge

- The availability of today's communications infrastructure were made possible by redundant systems
  - Data Processing
  - Information Storage
  - Aircraft, Automobiles
  - Telecommunications

- So Why Are Current Solar Systems Designed With So Many Single Points of Failure?

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RAIS Design Concept – Eliminate All Single Points of Failure

RAIS = **R**edundant **A**rray of **I**ntegrated **S**olar

Technology Generations

	Gen 1	Gen 2	Gen 2	Gen 3
	Conventional Strings	Micro-Inverter	String Optimizer	RAIS - Highly Fault Tolerant
Cell-Cell Interconnects	Single Point of Failure	Single Point of Failure	Single Point of Failure	Interconnected - Redundant (6:4)
Within Module Connects	Single Point of Failure	Single Point of Failure	Single Point of Failure	Interconnected - Redundant (6:4)
J-Box Connects	Single Point of Failure	Single Point of Failure	Single Point of Failure	Interconnected - Redundant (10:2)
Electronic Connects	None Used	Single Point of Failure	Single Point of Failure	Interconnected - Redundant (10:2)
Module Electronics	None Used	Single Point of Failure	Single Point of Failure	Fully Redundant (Fault Tolerant) (6:4)
Master Balancing System	None Used	None Used	Single Point of Failure	None Used
Module Connections	Single Point of Failure	Single Point of Failure	Single Point of Failure	Bus - All Modules Independent
Module AC Connects	None Used	Single Point of Failure	None Used	None Used
Combiner Box Connects	Single Point of Failure	Single Point of Failure	Single Point of Failure	Line Redundancy (2:1)
AFCI	Single Point of Failure	Not Required	Single Point of Failure	Not Required
OCP (Fuse)	Single Point of Failure	Single Point of Failure	Single Point of Failure	Line Redundancy (2:1)
DC Run	Single Point of Failure	Not Required	Single Point of Failure	Not Required
Inverter	Single Point of Failure	Single Point of Failure	Single Point of Failure	Redundant (5:4 or 4:3)

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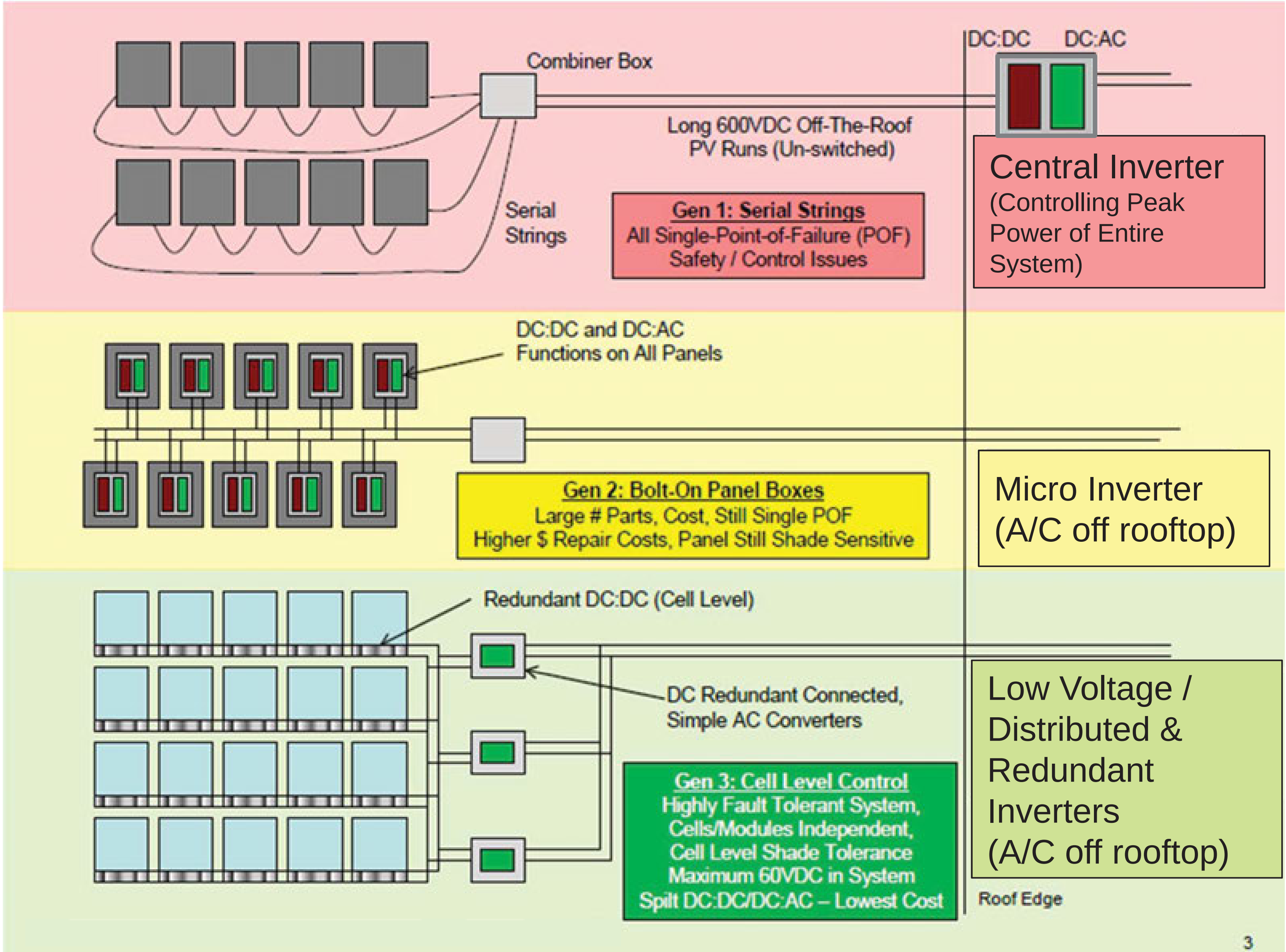
System Topologies



Why Throw Away Power With an On/Off Switch (i.e., a Diode)?

Conventional – Portrait Mode

90% of Area With
100% Illumination

10% of Area With
90% Illumination

Condition 1:
Diodes Open
Power: 90%
(Soiled Area Limiting)

Condition 2:
Diodes Shunting
Power: 0-67%
(1, 2, 3 Shunting)

Many Diodes– Portrait Mode

90% of Area With
100% Illumination

10% of Area With
90% Illumination

Condition 1:
Base Diode Open
Power: 90%
(Soiled Area Limiting)

Condition 2:
Base Diode Shunting
Power: 90%
(10% Eliminated by Diode)

Conventional – Landscape Mode

90% of Area With
100% Illumination

10% of Area With
90% Illumination

Condition 1:
Base Diode Open
Power: 90%
(Soiled Area Limiting)

Condition 2:
Base Diode Shunting
Power: 67%
(33% Eliminated by Diode)

tenKsolar RAIS

90% of Area With
100% Illumination

10% of Area With
90% Illumination

Single State Operation
(No Diodes)

Power:
Top Area: 90%*100% = 90%
Soiled Area: 10%*90% = 9%
Total Power: 99%

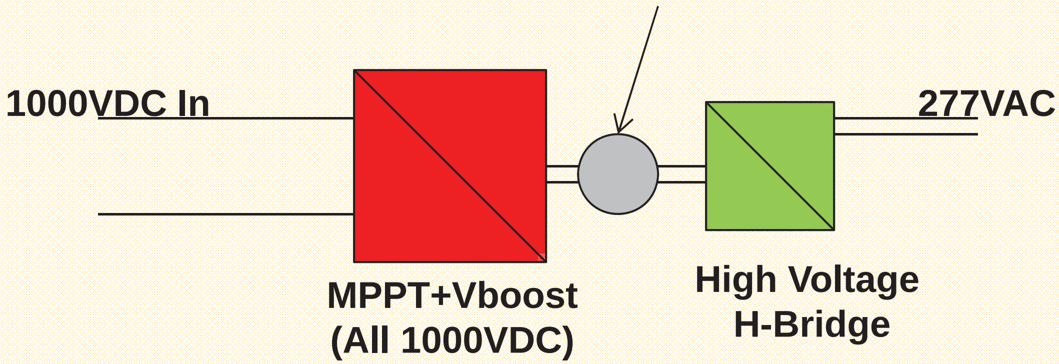
In All Condition 1 States – The Soiled Area Limits Entire Array to 90%
(Not Just the Soiled Module)

DC:AC Conversion Topology – Not Just A Scaled Down Central Inverter!

Primary Failure Mode of Active Components (FETs, Diodes, Caps, …)

Power Leakage: $V_{op}^2 / R_{leakage}$

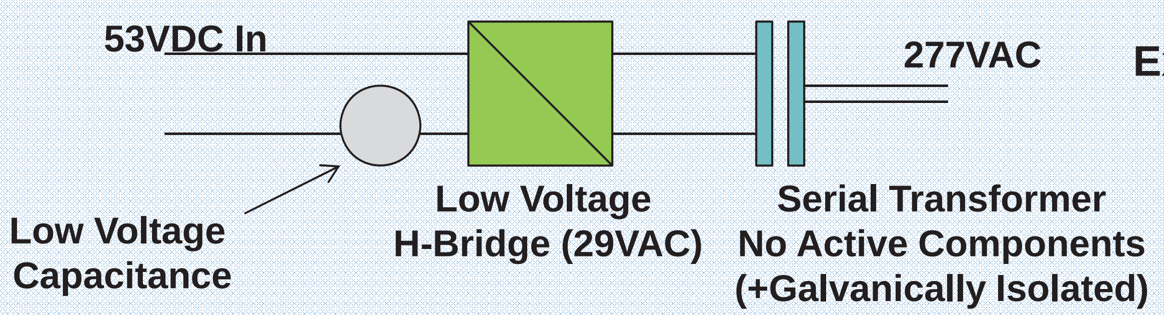
Conventional:



All Actives Exposed To 400-1000V_{peak} Voltage Stress

$P_{leakage}$= 1,000,000 / $R_{leakage}$

RAIS Wave Topology:



Active Components Exposed To <60V_{peak} Voltage Stress

$P_{leakage}$ = 2,700 / $R_{leakage}$

(Automotive Levels)

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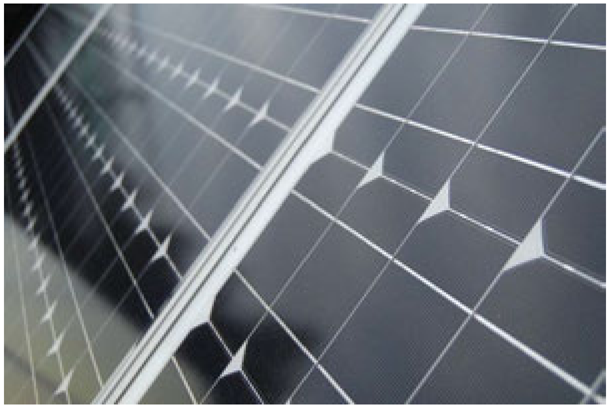
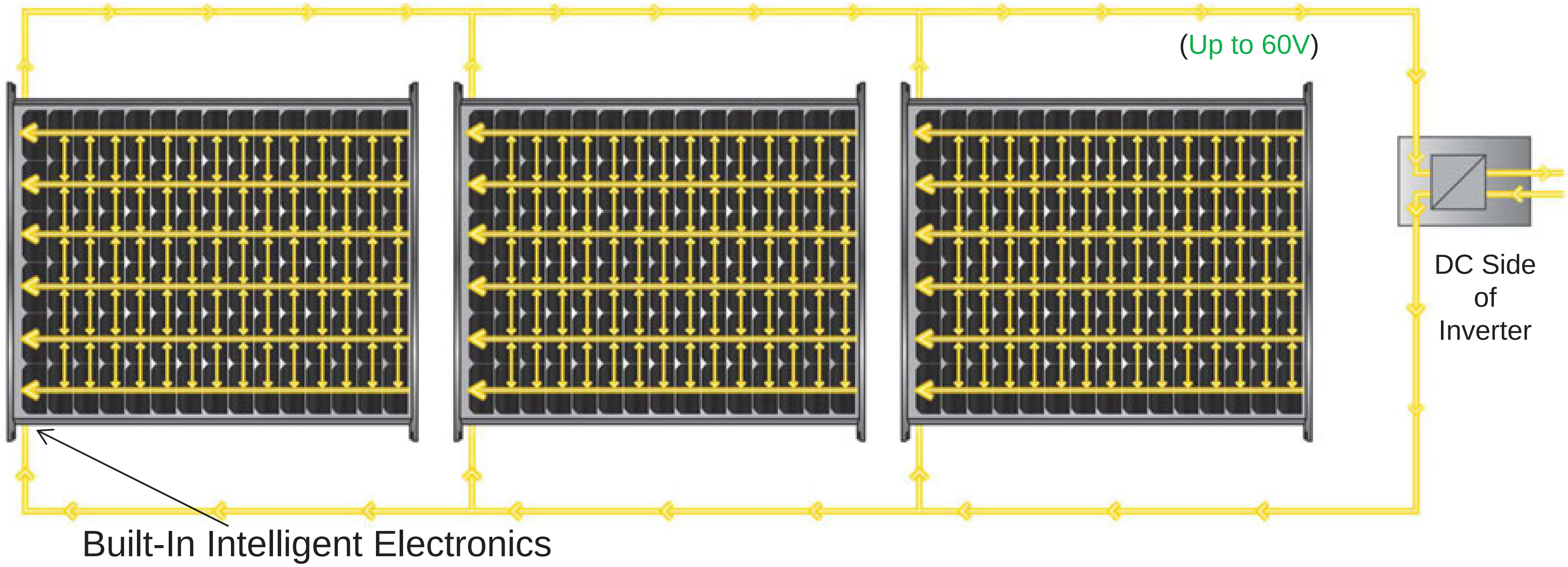
tenKsolar RAIS Module: Mesh Grid Architecture

- Soiling/Shade/Snow Tolerant
- Maximum Production with Minimal Cleaning
- Cell Level Power Optimization through Embedded Intelligent Electronics





Definitions:

<u>Degradation</u> refers to a gradual degradation of power over time, usually related to changes in specific cells gradually dragging down the system output due to the serial interdependencies in the system (the Christmas tree light architecture within a traditional solar panel).

<u>Failure</u> refers to a more sudden drop in power due to a failure of an individual component, such as a cracked cell, broken interconnect, inverter failure, etc. A trip to the site for corrective action, even if it is just a simple reset required, a quick repair, etc., still constitutes a failure due to the cost of the technician + truck-roll.

<u>Conventional module</u> is any solar panel except a tenKsolar module.

<u>tenKsolar module</u> is a module designed to eliminate all single point of failure points and serial interdependencies across the entire system. A problem with any individual cell, interconnect, panel leads, MC connectors or even the inverters do not lead to significant losses of power, creating an unprecedented level of reliability. The module is called a RAIS module (Redundant Array of Integrated Solar).

Comparison of System Response to Component Failure Modes

Failure mode	In conventional modules	In tenKsolar modules
Failed Cell Interconnections (interconnections between cells fail, due to latent defects or hot/cold stress over time)	Power drops entire string output by 30-100%, fails other interconnects over time.	No cell-cell interdependency, many current paths through module, output drop is negligible. No long-term stress issues.
Cracked Cell Within Single Panel (cell develops crack due to latent defects, wind buffeting, hot/cold stress over time)	Power drops entire string output by 10-100%, depending on shape and location in cell. Added degradation long-term.	No cell-cell interdependency, output drop negligible. No long-term stress issues.

Comparison of System Response to Component Failure Modes

Failure mode	In conventional modules	In tenKsolar modules
Cell Cracking Within Panel Due to Wind Buffeting or Snow Deflections (initial micro-cracks within cells extend and run across the cell resulting in a full crack)	Each deflection from the face (wind or snow) flexes the cell, eventually leading to fatigue failure in the cell (crack advances).	Material stack used creates an in-plane compressive stress across the cells, avoiding formation of tensile stresses in the cells from wind or snow.
Cell Shading Due to Snow or Soiling (partial coverage of the module with snow or non-uniform soiling creates mis-matches within the array)	Localized snow on a single panel, or preferential soiling along the lowest cells, reduces production in the entire string.	The cells are not dependent upon each other, therefore non-uniform soiling or snow partial coverage only impact the covered areas, not the unaffected cells or array.

Comparison of System Response to Component Failure Modes

Failure mode	In conventional modules	In tenKsolar modules
Solar Cell Degradation (light induced degradation, increased internal shunting losses due to poor edge trimming, water ingress creating added shunting shorts, lifted screen printed collectors, or other loss of current production within one cell)	Entire string drops with single cell, bypass diodes are of no help because it is only a partial loss of production.	No cell-cell interdependency, output drop negligible. No long-term stress issues from cell-cell imbalance.
Hot Spot Failures (mismatched, cracked or shaded cells lead to hot spot failures over time)	Affects module or possibly entire string depending on severity.	Cell-cell independence and low voltage operation eliminates possibility of hot spots.
Failed Internal Panel Interconnection (failures of the internal panel leads connecting the Jbox)	Power drops entire string output by 100%.	There is no panel routing leads, all connections are highly redundant.

Comparison of System Response to Component Failure Modes

Failure mode	In conventional modules	In tenKsolar modules
Module-Module Connection Degradation (MC connectors degrade due to field workmanship, moisture ingress, rubber cord cracking / degradation, excessive stress where leads are pulled, pinched leads, etc.)	Entire string power degrades due to added resistance within string.	Modules are connected in parallel, utility style connectors, utility grade wire, and no module-module interdependency.
Module Delamination (material stack of the module separates, due to workmanship, poor materials, or moisture ingress due to temperature/humidity exposure)	Individual cells affected due to air gaps (optical loss), corroded contacts, etc. – often power loss on a string of 100%.	Modules use best-in-class material suppliers and a metal backsheet and metal-glass edge seal to avoid moisture ingress.

Comparison of System Response to Component Failure Modes

Failure mode	In conventional modules	In tenKsolar modules
Moisture Ingress Into the Module (conventional panels use plastic backsheets that allow moisture to pass into the panel over time, degrading the adhesives, corroding the contacts, shunting the cells, etc.)	Degradation occurs over time due to impact on encapsulants, cell shunt growth due to ionic contaminants, electrochemical corrosion of interconnections.	Modules use metal backsheet and metal-glass edge seal to avoid moisture ingress, irrespective of installation conditions.
Temperature Related Degradation (cells, conductors and and encapsulants are all very sensitive to temperature, and conventional panels have NOCT values of >45ºC, when installed in closed racks operate at temperatures and even higher when installed adjacent to the roof)	Higher temperatures result in power loss, and accelerated degradation of the panel.	Modules have a very low NOCT of 41ºC, and are installed open and roof temperatures are reduced by the reflectors.
Ground Fault Fuse Failures (ground fault fuses within inverter fail due to leakage currents, require technician service to replace)	Complete system failure, no output until serviced.	Low voltage operation, negligible leakage currents.

Comparison of System Response to Component Failure Modes

Failure mode	In conventional modules	In tenKsolar modules
System Fuse Failures (fuses fail due to current spikes from weather (cloud edges), component issues, etc.)	Entire loss of string production with single fuse failure.	Each module is internally current limited, parallel fuse rating of up to 80A.
Bypass Diode Failure (bypass diodes degrade due to undersizing and/or overheating and low quality manufacturing, when failing open they present a very significant fire hazard to the entire array)	When failing short, loss of panel power and large temperature rise in Jbox, when failing open no longer prevents reverse biasing of cells (fire hazard).	No bypass diodes are used. Cells are never exposed to large reverse bias voltages.
Jbox Failure or Attachment Failure (failure of the Jbox when attached to the panel, or failure within the Jbox often resulting in melting / deformations)	Jbox falls off presenting hazard to all, melting / deformation results in loss of power for full string.	Electronics integrated into module, entire back of module is metal (not plastic), connectors attached using metal-metal connections.

Comparison of System Response to Component Failure Modes

Failure mode	In conventional modules	In tenKsolar modules
Bypass Triggers Due to Shading, etc. in One String (with many strings in parallel through a combiner box)	Entire string drops in power due to operating at non-peak power conditions (voltage offset from other strings, voltage set at central inverter)	Cell-cell power optimization completed internal to module, no dependencies outside the module.
Inverter Failures (inverter fails for ground fault, internal faults, component failure, etc.)	All interconnected strings are affected.	Current flows to other inverters. Given profile of typical solar day – minimal impact to power production.
Module Glass Breakage (Shattering of the top glass surface can occur due to vandalism, thermal stress, handling, wind or hail.)	Affects entire string of modules, significant current leakage, significant safety and fire hazard.	No affect on other modules – no safety risk, module cannot arc (low voltage) and will stop making power if a fault occurs.

Comparison of System Response to Component Failure Modes

Failure mode	In conventional modules	In tenKsolar modules
Confirmation of Degradation or Failure (diagnosing a conventional module failure is difficult – trial and error to isolate a defective panel)	Technician spends time jumpering high voltage modules and repeated covering / cycling the system to find defective components. Warranty disputes typical after identified as it may not repeat outside of the string.	Digital diagnostics, communication system and front side visible LED allow rapid detection and corrective actions. No warranty disputes.

Conclusion:
By thinking about reliability as a system requirement, and re-architecting the system accordingly, tenKsolar has designed out all of the major failure modes found in conventional solar systems today. As a result, tenKsolar delivers the most reliable solar array found on the market today.

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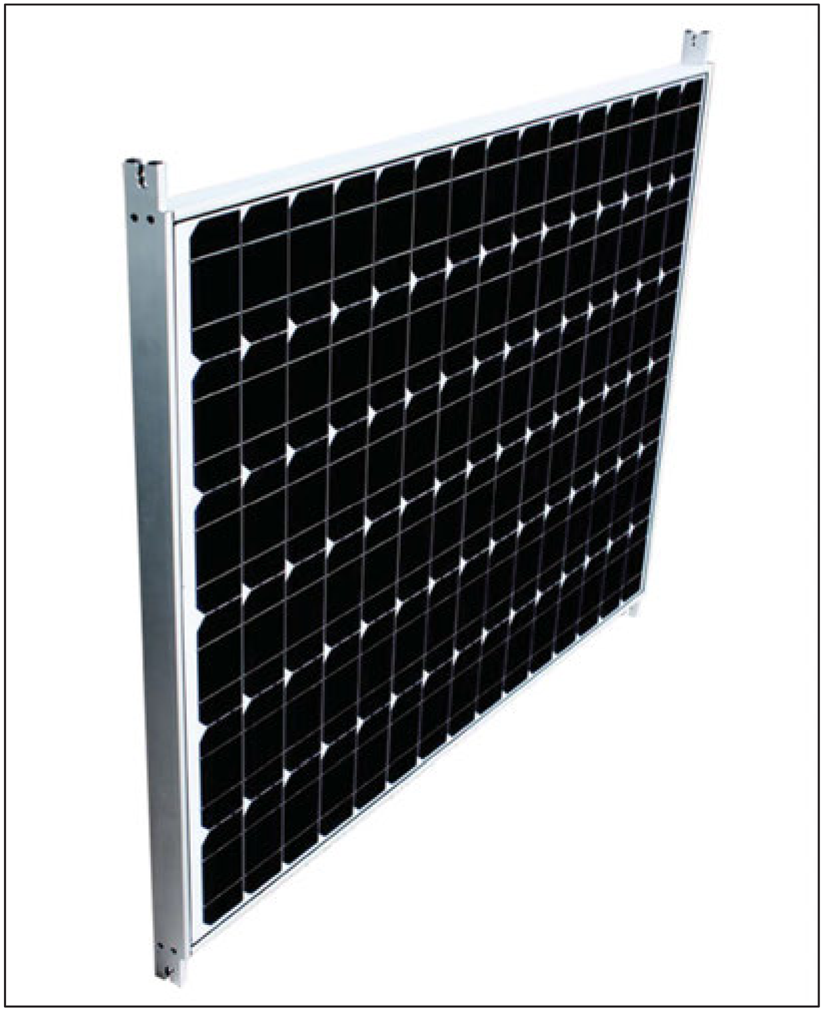
Oh..BTW…RAIS Sets the PV Safety Standard!

- Modules < 10V – no arc risk in panel
- RAIS Modules provided continuous monitoring
  - Check if Live Circuit?
  - If Not – Module remains isolated
  - Uses Analog device
- Autonomous, Integrated GFDI
  - Limits risk of double ground fault in conjunction with inverter ground fault detection
  - Limits time duration of any possible system arc



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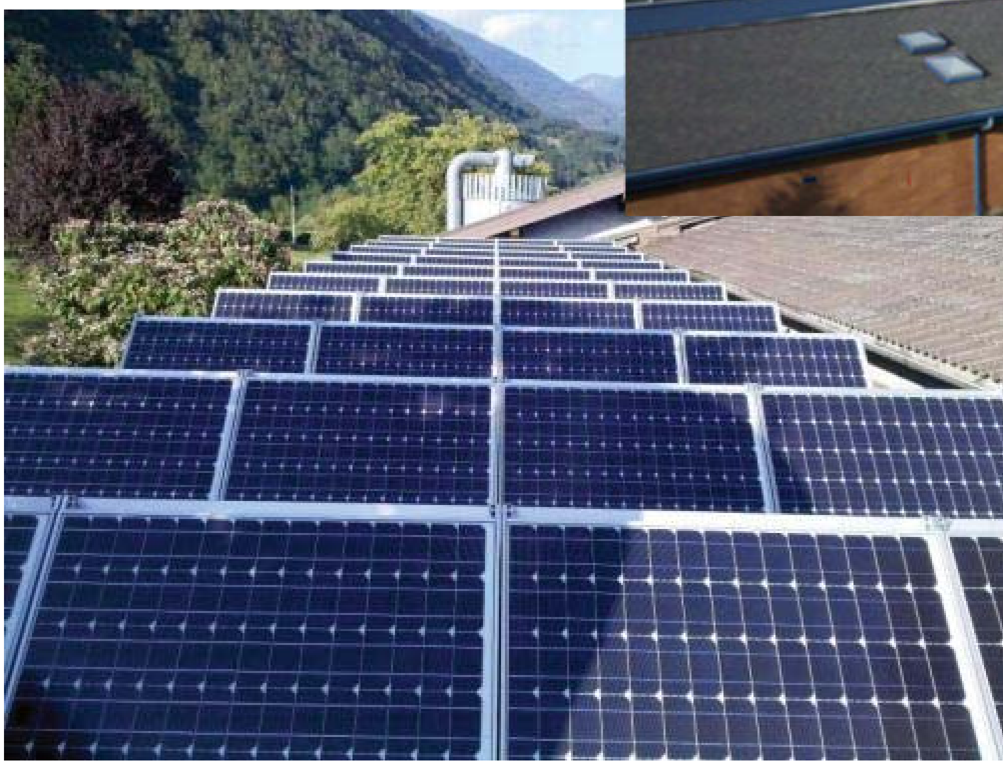

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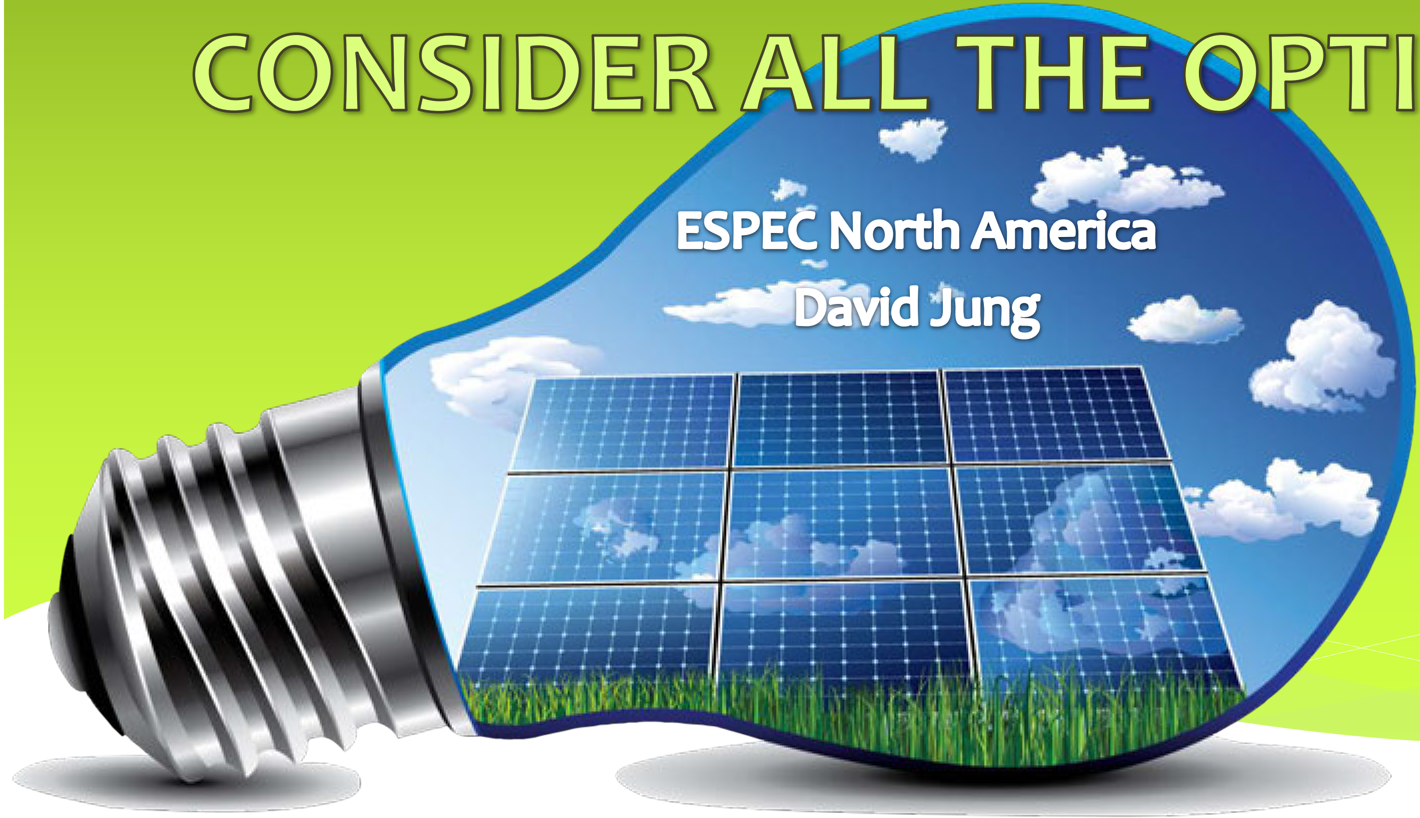
ESPEC

Test Chamber Brainstorming

CONSIDER ALL THE OPTIONS



ESPEC North America
David Jung

VOTE FOR YOUR FAVORITES

- Which test expansions are most worth consideration?
- And/or which test "issues" are most worth addressing?
- **Why? What benefits?**
- Have more details, add a Post-it!

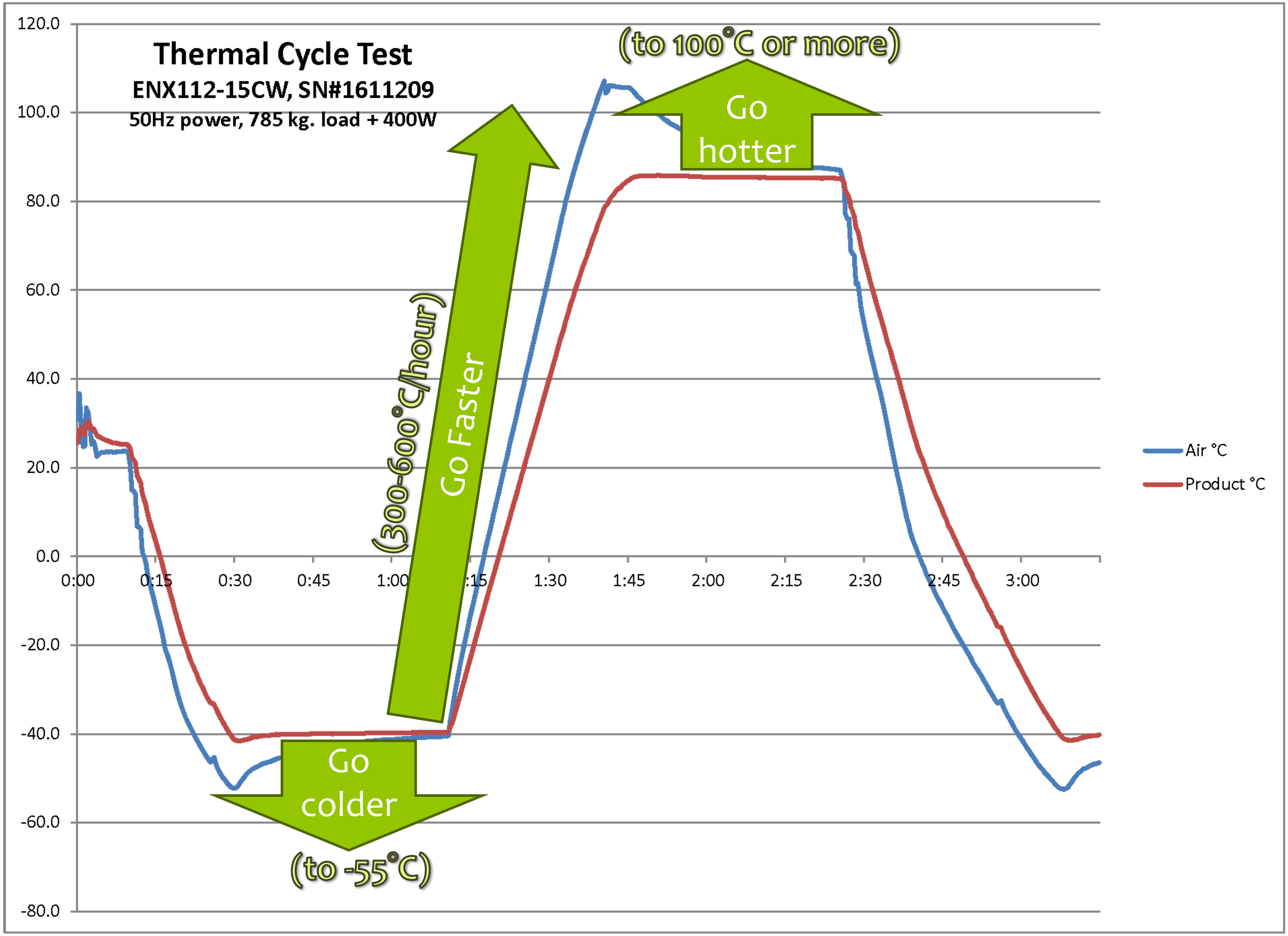
Why brainstorming?

* As a chamber manufacturer, we want you to explore the possibilities and limitations of what our chambers can do for PV testing.
* The existing tests have problems that may be impeding success.
* Many of these items may have been addressed in individual R&D or situations, but should also be considered for reliability benefits.

David Jung, djung@espec.com
ESPEC NORTH AMERICA

Temperature Cycling

* Current: Testing to -40 to 85°C, ramping at 44-100°C/hr
* EASY: Wider temp range = more stress
* MEDIUM: Faster ramping = more stress, time savings
  * Most modern chambers can go faster than 100C/hr
  * Faster rate is inversely proportional to # panels tested
* **PROBLEM: How is "max" ramping defined and controlled?**



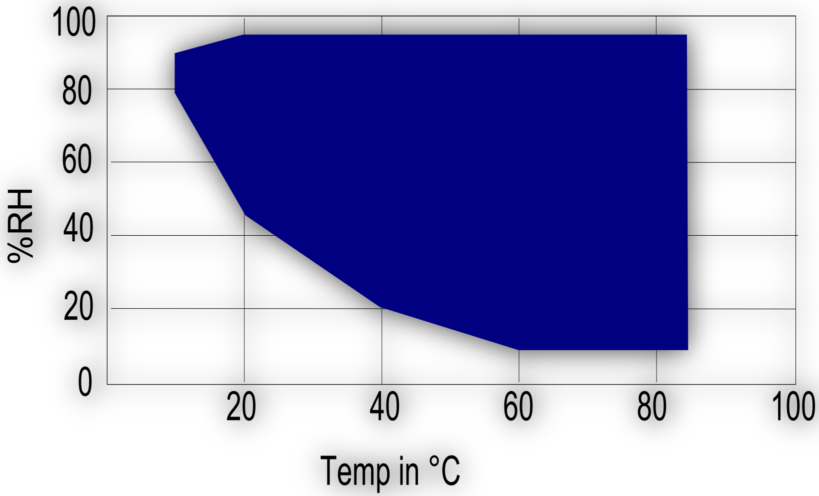
Thermal Cycle Test
ENX112-15CW, SN#1611209
50Hz power, 785 kg. load + 400W
(to 100°C or more)
Go hotter
Go Faster
(300-600°C/hour)
Go colder
(to -55°C)
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
2:30
2:45
3:00
Air °C
Product °C

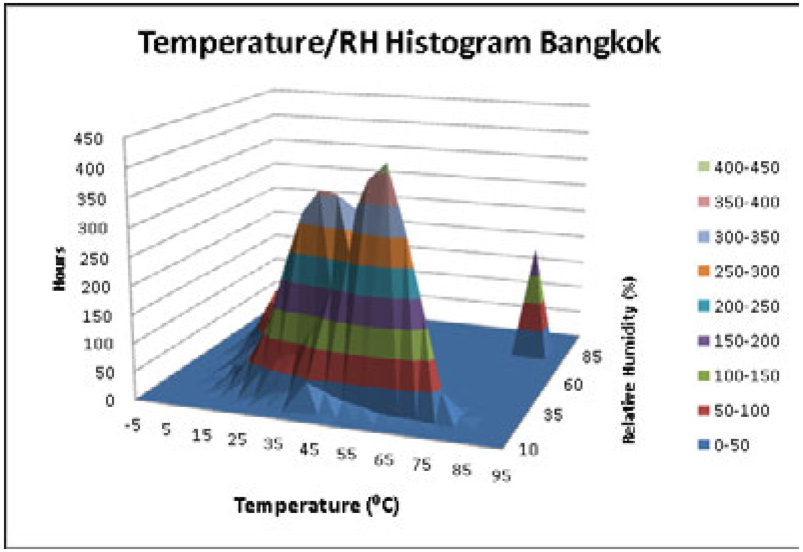
Damp Heat

* Current: Damp heat 85°C/85%

* EASY: 85°C/95% with existing chambers
* HARD: Higher than 85°C with humidity
* NEW:
  * Lower humidity? Or dry?
  * HAST: 120°C / 85-100%
  * Drop in favor of HF (like UL 1701)

Humidity Options



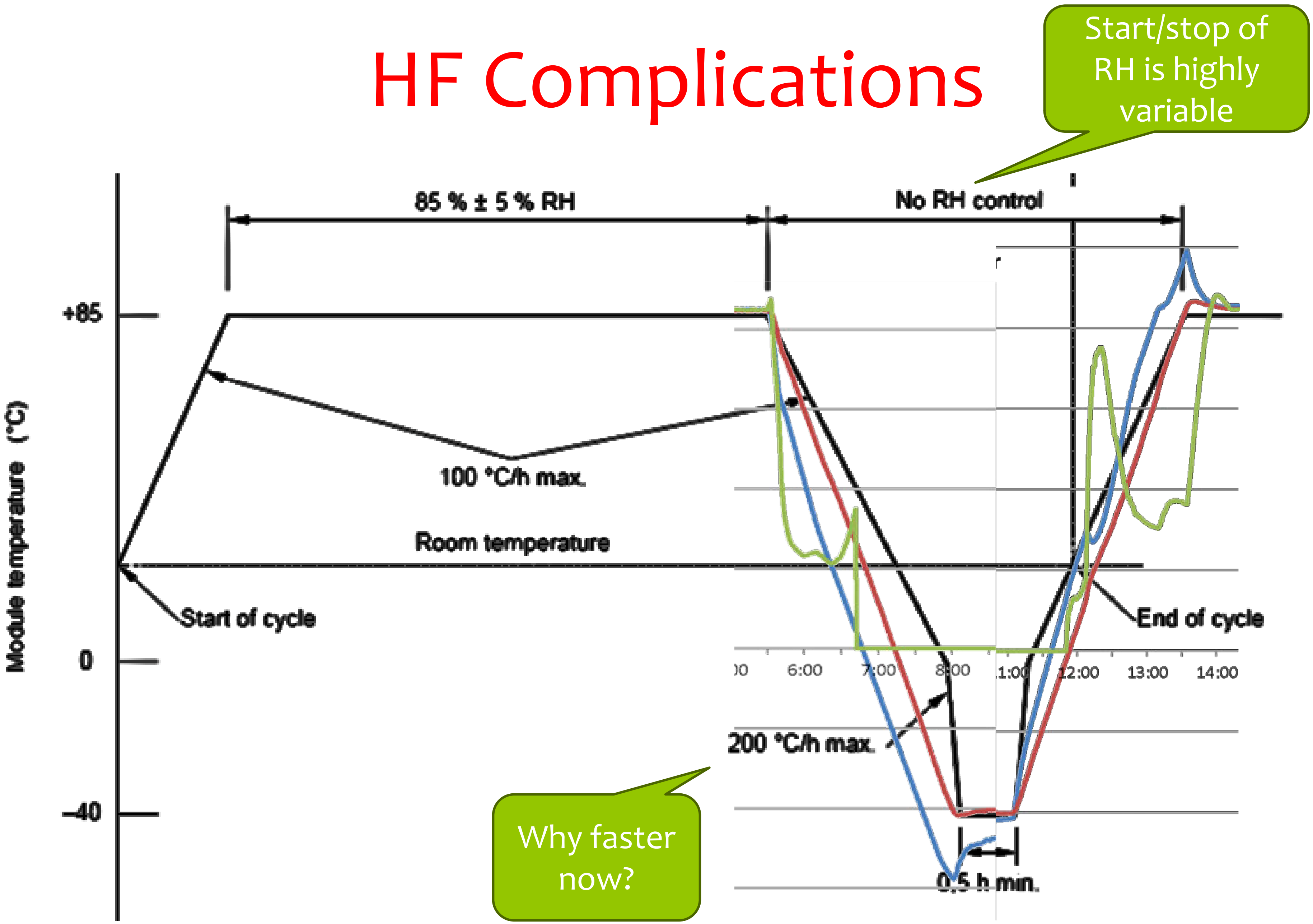


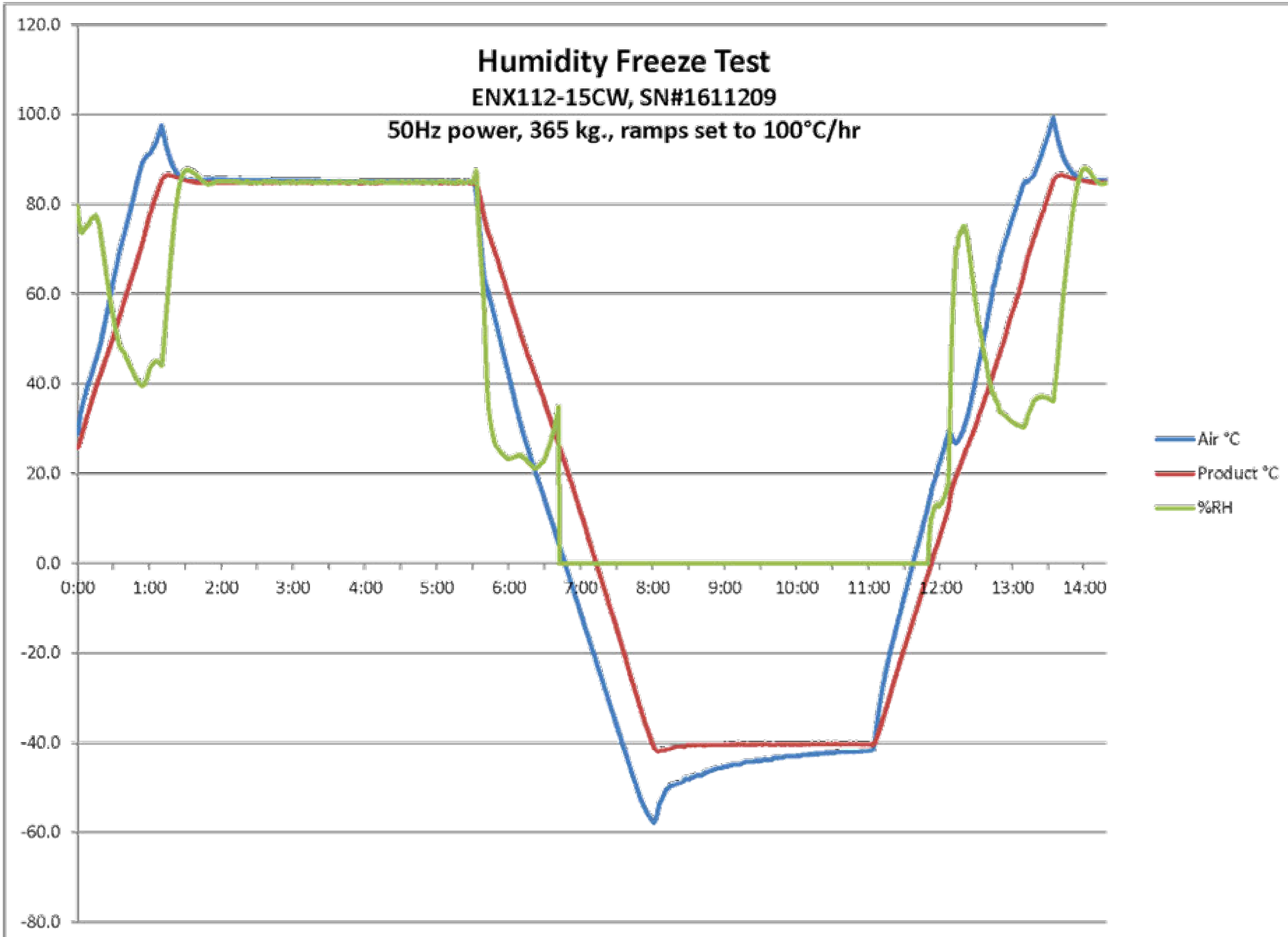
- Typical test chamber capability
- Real-world humidity exposure

Humidity Freeze

- CURRENT: Cycle between -40 and 85/85, then soak for 20 hours
  - Any real ways to improve this test?
  - Is sequential DH and TC tests better?
- ISSUES:
  - Start/stop of humidity is highly variable by chamber and operator, not defined in IEC.
  - 61646 & 61215 define RH start/stop differently
  - Ramp rate restricted to 100, then 200°C/hr. Why?
  - Definition of ‘max’ ramp rate needed: linear or average?
  - Should moisture condense (or not) during ramping?

HF Complications





Humidity Freeze Test
ENX112-15CW, SN#1611209
50Hz power, 365 kg., ramps set to 100°C/hr
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
0:00
1:00
2:00
3:00
4:00
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
Air °C
Product °C
%RH

Dew/Condensation

A REAL-LIFE STRESS

* PROBLEM: Humidity-freeze not designed to create dew

* MEDIUM (modification or new chamber):
  * Slower airflow to ensure dew creation
  * Faster heat-up to ensure greater air/module temp delta
    * Make heat-up NOT panel-temperature controlled
* HARD (test definition change):
  * Find best timing and settings to create dew and standardize
  * See GR-CORE 326 method 4.4.2.4

* Benefit: Up to 50% of real-world exposure involves dew/moisture

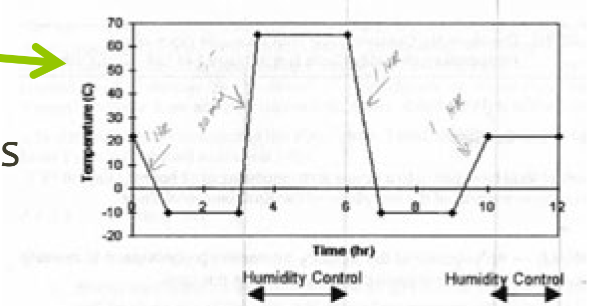


Figure 4-4. Temperature/Humidity Profile for Humidity/Condensation Test

Rain
EASY TO ADD SPRAY. ANY VALUE?

* Current: None
* MEDIUM (Special chamber feature):
  * Atomizing spray for near 100% humidity
  * Misting spray on panels
  * Water and chamber can be at different temps.
* Benefits: Simulate real-world; create dew during high humidity; overcome radiant UV heating to maintain humidity

Lighting (UV/Sun/IR)
CAN THIS BE MADE REASONABLE?

* Current: UV as preconditioning (sequential test)

* MEDIUM (Specialized equipment):
  * Combined UV with temp/humidity chamber

* Benefits: UV increases stress with humidity
* Issues: Large, expensive chamber, low thru-put, lamp heat

Radiant Radiation

HOW ABOUT A PANEL TOASTER?

- Current: None
- PROBLEM: Chambers are designed with convection heat/cool (blowing air), but PV experience radiant heat

- HARD (New test & chamber type)
  - Imagine a ‘solar panel toaster’
  - Can wire heaters stand-in for solar radiation?

- Benefit: Simulate real-world stress; skip complexity of UV
- Risk: Unproven shortcut

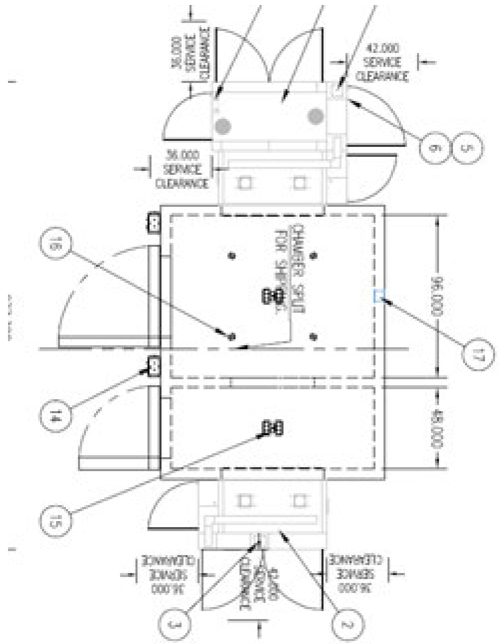
Front/back Dissimilarities
TESTING VERSUS REAL-WORLD

* Current: None

* MEDIUM:
  * Two section chamber, with different temperatures on each side

  * T/H/UV chambers do this intrinsically

* BENEFIT: Real-world thermal stress because of dissimilar temperatures



Added variables
Can be added to chambers

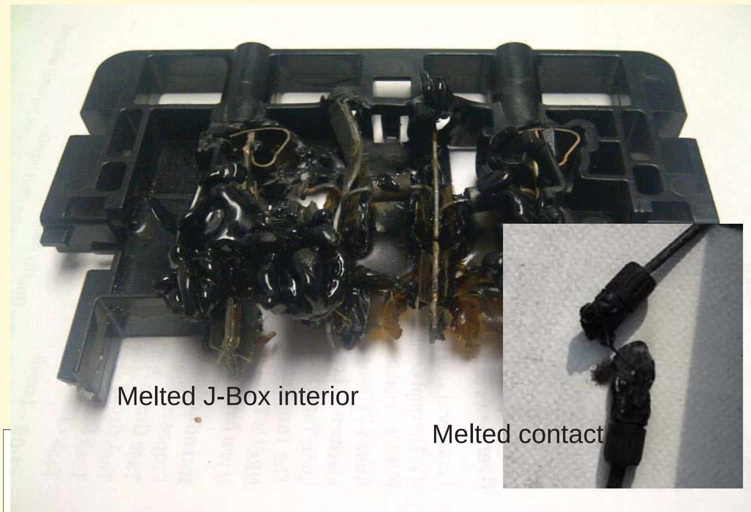
* Ammonia
* Salt
* Vibration
* Vacuum or Pressure
* Electrical loading stress to panels

Junction Box and Wiring Issues in Reliability*

Juris Kalejs, American Capital Energy, North Chelmsford, MA 01863

Abstract: Junction box design sometimes may be part art as well as part engineering, but it is always cost driven. Cost cutting has the potential to drive J-box configurations in directions compromising safety and durability. J-box and wiring deficiencies are being reported in our PV field installations after relatively short outdoor exposure of a few years. Some failures are traceable to lack of quality control in manufacturing or installation, but a commonality in failures appears to be designs allowing the onset of arcing. Standards in place (at IEC) or being written now (at UL) may not be adequate to identify the observed field J-Box and wiring failures. We examine what kind of testing beyond these certifications could be useful in anticipating the infant mortality field failures being observed and for guiding development of O&M programs.

Example of J-Box and wiring failures from overheating within 2-3 years in the field



Statement of Problem:

IEC and UL certification play central roles in eliminating deficient materials, validating mechanical and electrical designs, and establishing manufacturing guidelines/standards

IEC and UL certification cannot protect the customer against:

- **Manufacturing or installation errors**
- **Deficiencies in module material properties**
- **Failures caused by field conditions which combine extreme variable excursions:**
  - **mechanical, temperature and applied voltage stresses**

Certification is not sufficient to provide guidance for structuring of O&M

Studies are needed to evaluate what testing beyond certification can identify deleterious impacts of observed short term component failures on long term PV plant performance

Standards applicable to J-Boxes and wiring

- European Standard EN 50548:
  (Reviewed by Guido Volberg of TUV Rheinland, in *Photovoltaics International,* November, 2011, pp. 114-121)
  - Nine tests (A-I) specified
  - Only one "I" (Reverse current test) relates to electrical performance
  - Corrosion tests subject metal parts to ammonium chloride solution
  - Mechanical test protocols are very precise on stress application limits
  - Protocols leave a lot to subjectivity for training of installers
  - Soldered and non-soldered not called out in standards
- UL 1703 and 2703 - J-Box standards currently under development

Experience in early mortality (2-4 years) field failures

- Melting of J-Boxes with non-soldered wiring contacts
- Plastic cracking of interconnect wiring sleeves in products made with materials which have passed UL certification testing
- Melted connectors likely due to poor installation practices

Field failures have not been studied systematically for a number of reasons**:** proprietary designs, inadequate post-mortem examinations, multiple failure mode possibilities

Cannot expect tests can be devised to identify all factors, particularly manufacturing errors, BUT:

- What systematic studies on early field failure modes are needed to cull out bad designs in J-Boxes and wiring?
- What new tests are needed to address quality control in manufacturing and installation?

Case studies, extended testing are needed. Example:

Suspect arcing may be common fault in wiring and J-Box press fit contacts which may be less robust than soldered ones. Tests can be performed while under electrical load to determine rate of corrosion, deterioration during:

- Mechanical tests (shifting of contacts, fatigue)
- Electrical tests (corrosive effects, impact of humidity)
- Use of different pottant compounds (flammability)
- Elevated temperatures (simulating overheated diode)

* Contains no confidential information

Validation of Real Life Silicone Array Efficiency Gains

Anna Keeley, Barry Ketola, and David Armstrong, USA

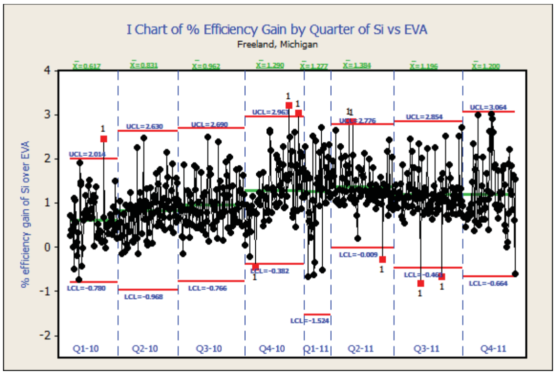
Dow Corning Corporation Installed Array Field Studies

Dow Corning SSAC in Freeland, Michigan

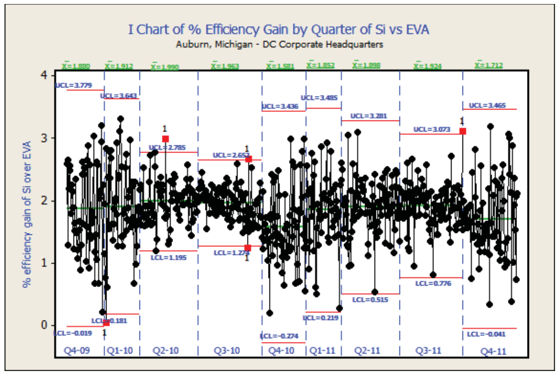
10 kWp - Multi-crystalline (5 kWp Si & 5kWp EVA)

Dow Corning in Auburn, Michigan

30 kWp - Mono-crystalline (15 kWp Si & 15kWp EVA)



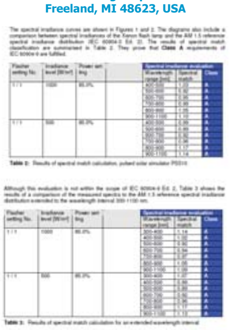
1.1% average efficiency gain since Q4-2009



1.9% average efficiency gain since Q4-2009

Field study results are able to be validated in the lab utilizing a sun simulator certified below 400nm, previously not possible due to instrumentation that filtered out the UV spectrum. The inherent properties of silicone allow the cells to utilize light below 400nm independent of cell type or size.

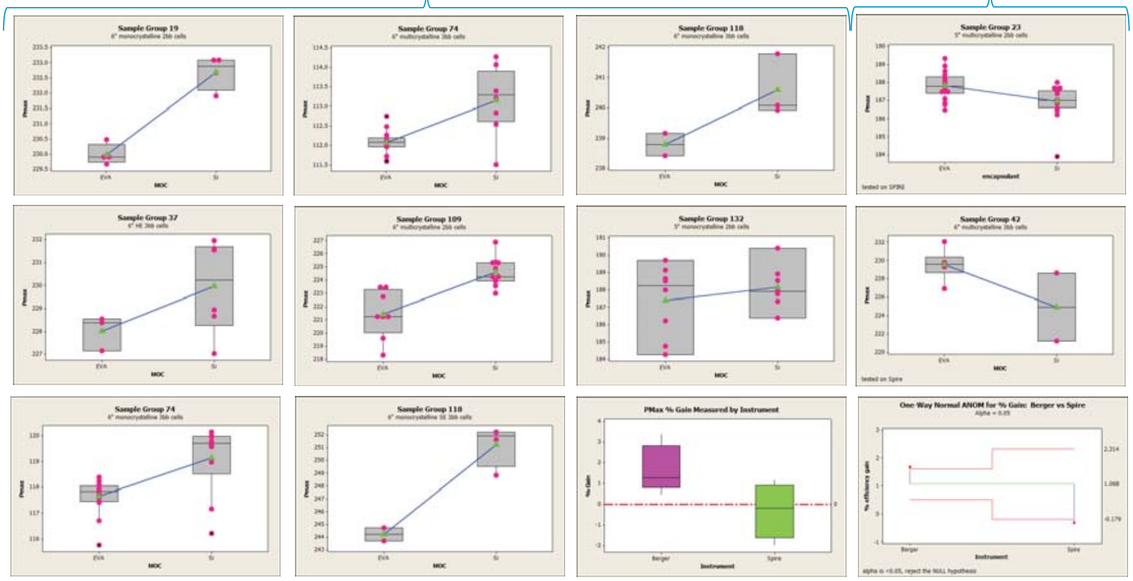
TÜVRheinland®
Precisely Right.



Report-No.: 21213889b
on
Solar Simulator Performance Measurement
Dow Corning Corporation
Freeland, MI 48623, USA

Panels Tested Between 300-1100 nm

Panels Tested Between 400-1100 nm



DOW CORNING Solar Solutions

www.dowcorning.com/solar

Quality control during the manufacturing of PV back-sheets:

A fundamental key component to the long term performance of PV modules

Robin Kobren – Research Manager at DUNMORE Corporation

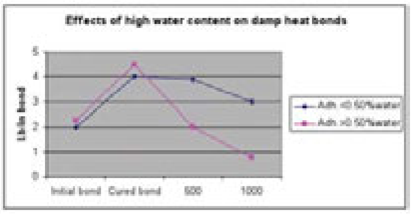
DUNMORE

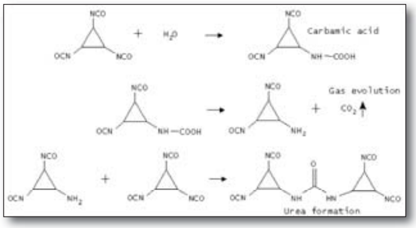
TÜV SÜD ISO 9001: 2008 Certified

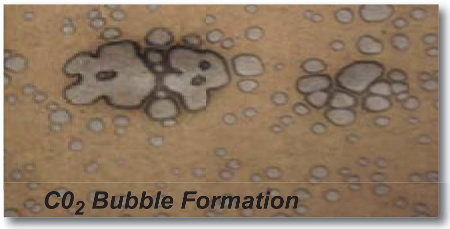
Incoming Raw Components

Chemicals - %H_20

When polyisocyanates come in contact with water, they react to form a unstable carbamic acid. The carbamic acid immediately decomposes to carbon dioxide and amine. The carbon dioxide can form bubbles in the film and the amine, once formed, reacts rapidly with others to form polyureas. If reaction with water predominated, the polyol would not be fully crosslinked and resulting films would have very poor properties.







$C0_2$ Bubble Formation

%NCO and OH # *(ASTM D2572-97 and 1899-02)*

Confirmation of stoichiometric NCO:OH ratios are necessary to ensure that they are correctly balanced. If the NCO to OH ratio is less than 1.0/1.0, the adhesive will be “undercrosslinked” and it becomes a less durable outdoor coating. A NCO to OH ratio higher than 1.0/1.0 results in “overcrosslinking” that could lead to harder and a more brittle cured adhesive.

Chemicals: Color

Signals M.W. distribution out of spec or high water content.

Same polyol different batches

Films: FTIR Analysis and Surface Energy

Low dynes will reduce bonds and junction box adhesion.

In Process

Coat Weights

Direct correlation to all bond values

Solvent Retention

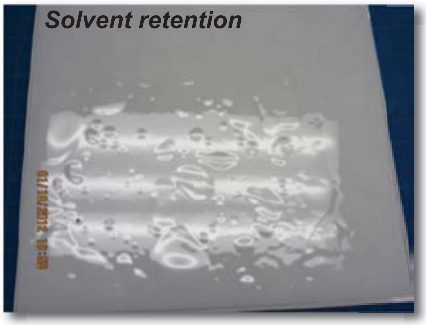
High % SR will result in bubbles during vacuum lamination

%H_20

Nitrogen filters should be used to minimize water absorption of polyol

180/T Peel Bonds (green)

Signals coat wt. and mix shelf life



Solvent retention

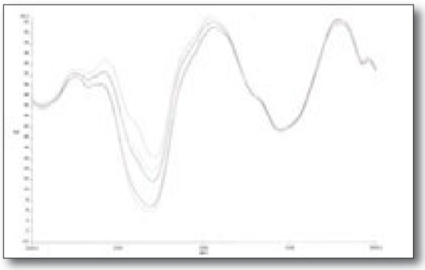
180/T peel bonds

Finishing

180/T Peel Bonds (cured)

%NCO conversion

Inadequate cure will result in bubbles and delamination after vacuum lamination.



Abstract

Quality control is critical in the manufacture of PV back-sheets because process and raw component variability can adversely affect the reliability of installed PV modules. This poster will state the reasons why it is necessary to carry out a quality control program during PV back-sheet manufacturing to ensure that safety and reliability standards are met. Moreover, this work marks the guidelines to following for the basic quality control testing procedures that must be present throughout the manufacturing lifecycle as well as demonstrates the affects on the PV modules if critical parameters are not met.

The challenges of testing the UV-impact on PV-modules

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Email: Michael.Koehl@ise.fraunhofer.de

Abstract

Accelerated testing of the durability of materials exposed to natural weathering requires testing of the UV-stability, especially for polymeric materials. The type approval testing of PV-modules according to the standards IEC 61215 and IEC 61646 includes a so-called UV-preconditioning test with a total UV-dose of 15 kWh/m². Measurements of the natural UV-stress indicate a yearly total UV-dose of more than 100 kWh/m². Accelerated life testing requires higher UV-power than provided by natural sun-light und additional acceleration by enhanced temperatures and the neglecting of dark periods. The combination with humidity as a potential reaction partner for degradation processes becomes an even bigger challenge under such circumstances. Results from PV-module testing will be presented and a work plan for evaluation of accelerated life testing procedures will be outlined.

Challenge 1: Spectral Sensitivity of Materials

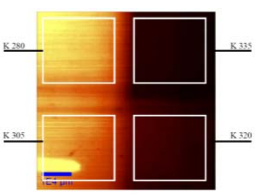
Glass-EVA-TPT

UV-weathering:

45 kWh @ 60 °C

Critical wavelengths:

l < 320 nm



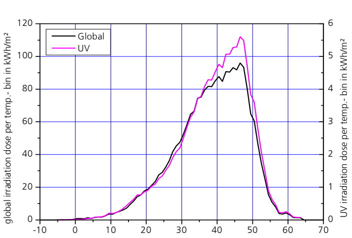
Raman Analysis after UV weathering of Glass-EVA-TPT test modules behind different edge filters.

<u>IEC 61215/61646:</u>
UV-testing of PV-modules and components is of minor importance

UV pre-conditioning testing according to IEC 61215/61646 10.10:

- No specification of the spectrum of the light-source
- No specification of the UV – detectors
- No correlation with real loads under operation

Challenge 2: UV Stress in Operation

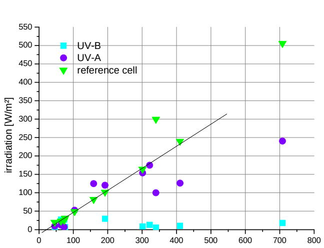


Histogram of global and UV-radiation at different sample temperatures for 1 year in the Negev, Israel.

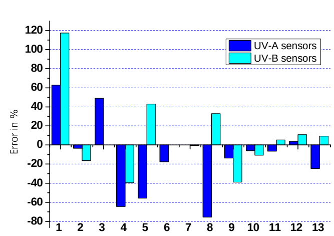
- Measured yearly UV-dose in the desert Negev: 120 kWh/(m²a)

  Therefore 2-4 months real operation is simulated (IEC 61646)
- Monitoring of UV radiation or global solar radiation at typical PV locations needed
- Evaluation of the specific UV stresses for module components
- Rough estimate: UV-dose = 5% of global solar irradiation

Challenge 3: Integral UV-Sensors

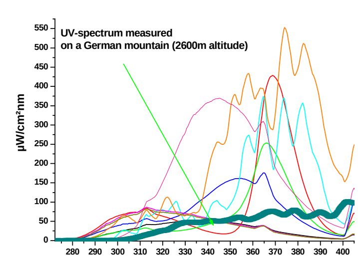


Integral sensors compared to pyranometer: Reference cell readings are proportional to the pyranometer (except of two metal-halide lamps). Correlation with UV-A integral Lab-sensors is acceptable, except for the relatively low values for metal-halide.

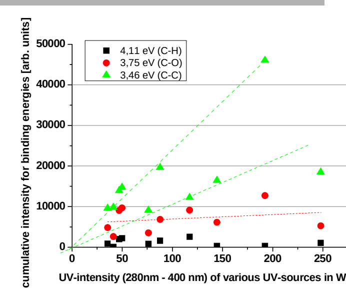


Relative error of the integral UV-sensors compared to integrated spectro-radiometric measurements .

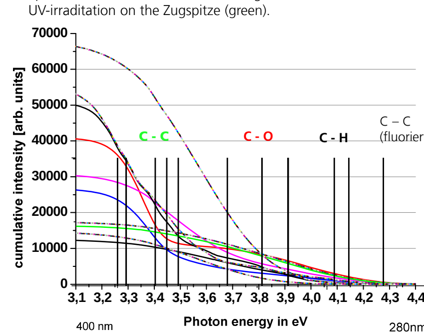
Challenge 4: Different UV-Sources



Spectral irradiation of different UV-light sources and natural UV-irraditation on the Zugspitze (green).

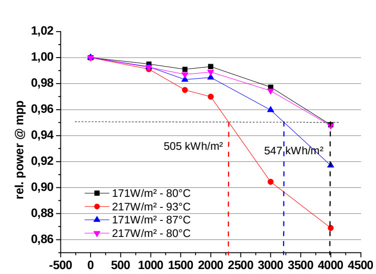


Photon-power with energies higher than required for destruction of molecular bonds in different UV-sources.

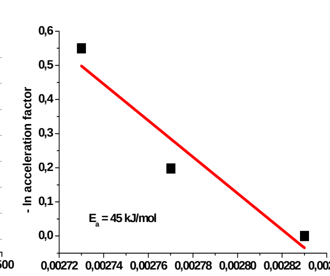


Energetic scale for the spectra-cumulation of photons with higher energies.

Challenge 5: UV, Temperature and Humidity



Simultaneous testing of four identical commercial modules in a climatic cabinet at 60°C, 85% rel.h and UV irradiation.



Arrhenius plot of the test results.

Summary

- The total UV-dose in a desert was found to be about 120 kWh/(m² a), roughly about 5,5% of the total solar irradiation. A service life of 25 a sums up to 3000 kWh/m².
- Accelerated life tests are needed.
- Artificial UV-sources differ strongly from the solar UV-spectrum, therefore different ageing behavior of samples with a wavelength-dependent spectral sensitivity in UV-tests with different lamps have to be expected.
- Integral UV-sensors for artificial UV-sources can be used for rough estimates, especially when they are calibrated with the same kind of radiation source.
- In-expensive spectro-radiometers can be suitable for the measurement of the UV-radiation when they are well calibrated.

Acknowledgements

- The authors would like to thank the colleagues of the laboratories involved in the interlaboratory comparison
- German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU FKz 0329978)

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

ENHANCED PROTECTION OF PHOTOVOLTAIC SYSTEMS

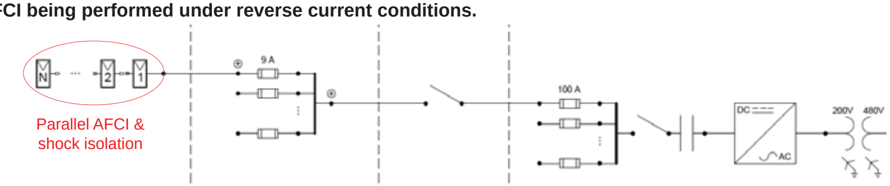
Charles Luebke[1], Birger Pahl[1], Thomas Schoepf[1]
Jerome Hastings[2]
[1]Eaton Corporation, Milwaukee, WI, USA
[2]Electrical Power Management Consulting, Sussex, WI, USA

Abstract

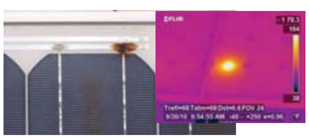
Photovoltaic (PV) systems have distributed DC power generation that requires multiple forms of fault protection to reduce the risk for PV related fires and shock hazard. Today, overcurrent protection (fuses) on strings provide protection only for reverse currents into a shorted string from parallel strings. Other electrical faults in distributed PV power systems include series and parallel arcing faults, ground faults, and shock hazards. Enhanced protection for each type of fault requires different detection and mitigation methods. We identify current mitigation practices, present test results that define enhanced protection and system requirements, and propose solutions for increased electrical safety.

Conclusions

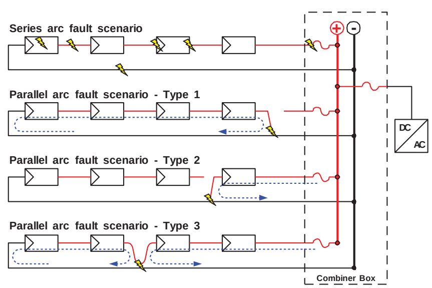
- The 2011 National Electric Code® added requirement 690.11 for series DC arc fault circuit protection. Arc faults have been known to cause PV fires.
- Additional testing is being performed to assess ignition/burn thru times for In-module arcing with the close proximity to encapsulant and backsheet materials.
- PV on Fire testing at UL demonstrated the need for module level shutdown due to residual shock hazard and parallel arcing from compromised wiring and modules.
- NFPA Task Group on Firefighter Safety recommended and submitted 2014 NEC proposal: 690.12 PV Array Response to Emergency [Module] Shutdown for residential and commercial PV source circuits.
- A requirement for parallel DC arc fault protection has been proposed for 2014 NEC. Testing is being performed at higher arc wattages to determine ignition/burn through times, and for consideration of extending the trip time curve of UL1699B above 900 W.
- A requirement for AC Arc Fault Circuit Interrupters has been proposed for 2014 NEC to protect wire harness and exposed cable for PV systems with AC Modules and PV microinverters. Testing of AC AFCI being performed under reverse current conditions.



PV system with distributed DC power generation

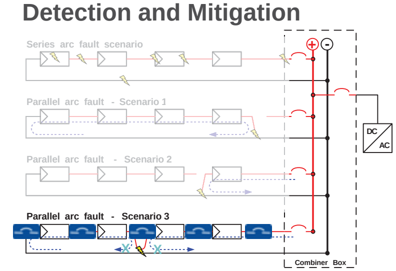


PV Module Failures

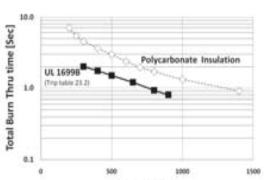


Arc Fault Detection and Mitigation

Shock Hazard (Ground Fault) Detection and Mitigation



Sleeve of PV cable type “USE2” during burn-through test at 7 A



UL1699B trip curve established with safety margin below ignition/burn through times of PV insulation materials

Arc Fault Detector

Single Module Arc Test

Single Module Arc test demonstrated sufficient power to generate sustained arc fault and fire, and that **module shutdown must be an open DC switch** (to mitigate internal arc faults), not a shorting FET (as some have proposed to just reduce shock hazard).

Module Level Shutdown

Powering Business Worldwide

PV EVOLUTION LABS
ADVANCING SOLAR

Increasing Investor Confidence in PV Power Plants through Latent Defect Screening (LDS)

A.C. Mayer and Jenya Meydbray, PV Evolution Labs

OVERVIEW

Solar power plant investors expect photovoltaic (PV) modules to safely and efficiently produce electricity for 25 years. International certification standards such as IEC are designed to evaluate new module designs for material and design flaws that contribute to product safety or performance issues. This initial certification testing is performed on ~10 panels and does not insure against defects caused by deviations in the manufacturing process. These defects affect between 0.1 and 10% of all installed panels and lead to increased performance degradation. Moreover, these defects are known as latent in that they typically manifest several years after installation. There is currently no certification analogous to IEC that insures against these latent defects. Knowledge of the exact quality of the PV panels installed at a given power plant provides opportunity for improved output predictability and investor confidence. In this poster we introduce the concept of latent defect screening (LDS) for PV modules. LDS involves the random sampling and accelerated life-testing of the PV panels to be used at the construction site. We find that for an additional testing cost of 1 penny per watt, we can be 85% sure that there are fewer than 2% defects at a 20 MW installation.

Latent Defects in the Field

A latent defect in a panel is unobservable at the factory gate but manifests in the field before the expiration of the warranty. These defects can cause a reduction in the power conversion efficiency beyond the manufacturer's spec, or can lead to a safety issues such as electric shocks or electrical fires.

There are many ways in which a panel can cease to function properly. Examples include solder-joint and junction-box degradation.

Latent defects lead to lost revenue:

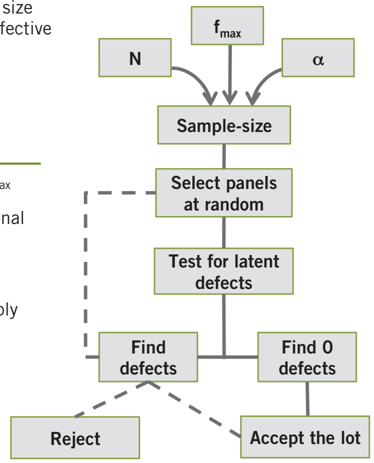
» Reduced power production; it can take several months to detect the defect, verity the defect, and enact the warranty.
» The costs associated with replacing the defective panel, including logistics, labor, and powering down a string of modules to make the replacement.
» Increased O&M costs associated with panel inspections to find other defective units.

Production period	% Affected	Notes
1994-2002	0.13% annually	2 million modules in the field
2008	100% recall	All of 2008 production
2008-2009	4%	Loss of performance
early 2000's	10%	Junction box fires
early 2000's	~3.5%	Severe cell cracks
early 2000's	2.9%	Local heating from solder joint failure

Latent Defect Screening (LDS)

Test	Qualification	Timing	Volume
IEC/UL	Design/Materials	Prototypes	8 – 12 panels
LDS	Process	Lot-by-Lot	Statistically Significant

N = Installation size
f_{max} = Max % defective
= Confidence



FINDING A DEFECT

» Calculate new f_{max}

» Calculate additional sample-size for preferred f_{max}

» Renegotiate supply agreements

TESTING

Thermal Cycling
Damp Heat
Humidity Freeze
UV
Dynamic Mechanical Testing
DH under bias

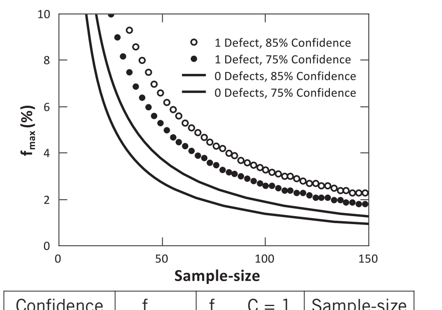
Statistics of f_{max} and Confidence

» The confidence (α) around the max percent defective (f_{max}) is dependent on the installation-size (N) and the sample-size (n).
» If no defects are encountered in testing, the relationship can be calculated using the hypergeometric distribution:

$$P(c = 0 \mid n, f_{max}) = 1 - \alpha = \frac{\binom{N(1-f_{max})}{n}\cdot\binom{Nf_{max}}{0}}{\binom{N}{n}}$$

» If a defect is encountered, the numerator is modified

Dependence of f_{max} on sample-size for a 20 MW plant

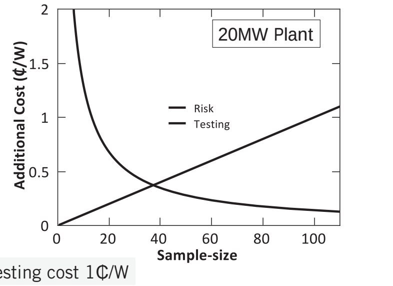


Confidence	f_{max}	f_{max}, C = 1	Sample-size
75%	1.5%	2.9%	90
75%	2.9%	5.5%	47
85%	2%	3.7%	90
85%	4%	6.9%	47

Financial Implications

» The best way to judge the value of testing is to compare the testing cost versus the risk associated with f_{max} and confidence as a function of sample-size.
» For simplicity, the cost of testing can be estimated at $2000/panel.
» An accurate financial calculation is complicated and depends on replacement costs, insurance premiums, interest rates, etc. However, a simplified calculation based on avoided risk cost, $\$_{risk}$, can be estimated assuming a replacement cost , $\$_{repl}$ = $0.5/W as: $\$_{risk} = \$_{repl}\cdot f_{max}\cdot(1-\alpha)$

Comparing testing cost and avoided risk



Fixed testing cost 1₵/W

Confidence	Project Size	f_{max}	Sample-size,
75 %	1 MW	24 %	5
85 %	1 MW	31 %	5
75 %	20 MW	1.4 %	100
85 %	20 MW	1.8 %	100

Summary and Outlook

» Certifications such as IEC and UL insure product design and materials, but do not guarantee against deviations in the manufacturing process that can lead to defects in the field. These defects can lead to reduced performance or safety risks.
» Third party LDS increases the confidence in the quality of panels for a given installation to help maximize the return on investment through reduced risk.
» Testing costs can be below 1₵/W for a financial risk below 0.2₵/W; actual benefits will be much higher.
» This is becoming increasingly important as the market penetration of PV increases; especially considering the large number of module suppliers.

Questions for Discussion

» How does prior knowledge of a manufacturer's quality affect the statistics? Is this valuable?
» How will increasing the confidence affect insurance premiums, interest rates, debt-service coverage ratios, etc?
» How will this affect approved vendor lists?

References

1. G. TamizhMani, "Testing the reliability and safety of photovoltaic modules: failure rates and temperature effects", PV-Tech (2010).
2. D. DeGraaf, R. Lacerda, Z. Campeau, "Degradation Mechanisms in Si Module Technologies Observed in the Field; Their Analysis and Statistics", presented at NREL 2001 Photovoltaic Module Reliability Workshop (2011).
3. "Utilizing Panel-Level Monitoring to Improve Project ROI", Alternative Energy Magazine (2012)

SALVAGE OPERATION DETERMINES VALUE OF USED PHOTOVOLTAICS

Joseph McCabe, P.E.

ABSTRACT

As photovoltaic (PV) system prices become less expensive, the salvage value can be increasingly important in life cycle economic calculations. This presentation examines data from historic utility salvage sales and reliability perspectives, and an actual 2011 salvage operation. From 2005 to 2010, large volume PV modules sold at salvage for a variety of pricing dependent upon strength of glass, amount of easily recycled aluminum, industry reduced average selling price (ASP) of new modules and expectations for future energy production. Reliability of product, both real and perceived, are important factors in resale valuations.

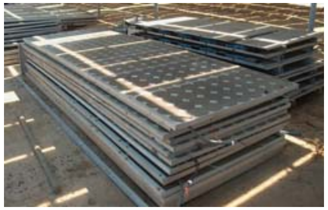


Photo 1: 2006 Stacked single crystal silicon salvage sales PV panels.

LARGE SCALE SALVAGE SALES

The Sacramento Municipal Utility District (SMUD) has been re-selling salvaged PV equipment since 2005. The table presented includes the technology based dollar per nameplate watt prices. Over 0.9 megawatts of nameplate modules were sold during this period.

Winning bids ranged from $0.04 to $1.26 / watt. The table shows minimum, maximum, average $/watt winning price for individual lots and approximate nameplate wattage sold that year. Modules sold included tandem amorphous silicon (a-Si), single crystal (Single) and polycrystal (Poly) PV. Model numbers included: Solarex MST 43 and MSX 60, Shell SQ 75/80, Solec SP-102 and SQ-80, and Siemens M55's. Some modules had been panelized, as shown in Photo 1.

Winning Bids from 6 Years of Surplus Photovoltaic Sales at SMUD												
	2005		2006		2007		2008		2009		2010	
Bid Lot	Type	Price Per watt	Type	Price Per watt	Type	Price Per watt	Type	Price Per watt	Type	Price Per watt	Type	Price Per watt
1	a-Si	$0.46	a-Si	$0.46	Single	$0.78	a-Si	$0.53	a-Si	$0.07	a-Si	$0.09
2	a-Si	$0.46	a-Si	$0.31	Single	$0.66	a-Si	$0.50	a-Si	$0.06	a-Si	$0.13
3	a-Si	$0.46	a-Si	$0.20	Single	$0.77	a-Si	$0.97	a-Si	$0.04	a-Si	$0.07
4	Poly	$0.98	a-Si	$0.22	Single	$0.82	Poly	$0.44	a-Si	$0.06	Poly	$0.23
5	Poly	$0.75	a-Si	$0.24	Single	$0.73	Poly	$1.15	a-Si	$0.04	Single	$0.13
6	Single	$0.51	Single	$0.66	Single	$0.82	Single	$0.54	a-Si	$0.04	Single	$0.13
7	Single	$0.51	Single	$1.04	Single	$0.72	Single	$0.83	Poly	$0.17	Single	$0.18
8	Single	$0.61	Single	$1.26	Single	$0.48	Single	$0.88	Poly	$0.48	Single	$0.19
9	Single	$0.61	Single	$0.77	Single	$0.66	Single	$0.76	Poly	$0.24	Single	$0.33
10	Single	$0.61	Single	$0.77	Single	$0.82	Single	$0.88	Poly	$0.29	Single	$0.04
11			Single	$0.92	Single	$0.78	Single	$0.91	Poly	$0.21	Single	$0.24
12					Single	$0.82	Single	$0.72	Poly	$0.17		
13					Single	$0.52	Single	$0.56	Poly	$0.23		
14							Single	$0.72	Single	$0.25		
15							Single	$0.65	Single	$0.24		
16									Single	$0.17		
17									Single	$0.30		
18									Single	$0.16		
Min		$0.46		$0.20		$0.48		$0.44		$0.04		$0.04
Max		$0.98		$1.26		$0.82		$1.15		$0.48		$0.33
Total kW	150		69		177		136		212		160	

Table 1: 2005 – 2010 Salvage Values for various technologies; 0.9 MW total original capacity. .

RESALE MARKETS

Used or salvaged modules are bought and sold in a number of ways. In some cases, they can be installed into non-incentivized systems like off grid markets. Or they might be showing up in resale channels like on E-Bay, Craigslist or classified section of Home Power Magazine.

It is possible individual modules are being sold into existing systems where a component has broken. All modules in a system should perform at exactly the same level, thus avoiding miss match conditions that reduce overall system performance. Similar to a fine china dinner set that has a broken plate; specific modules have a high replacement value, even if they are a used module. If an existing PV system has a problem with an individual module, replacing that module could have a very high system level value.

Used modules could be sold into a wholesale green power generator; however a tax credit for the installation would not be allowable because the PV materials are not new.

Scrap markets can utilize crystalline cells, as well as the aluminum frames, thus non-working crystalline modules can have an attractive scrap value. Various PV recycling programs have begun around the world including PV ReCycling headquarted in Tucson Arizona with additional collection points in San Jose CA.

ENERGY and GLASS

Most PV technologies lose 1% per year in performance consistent with typical 20 year, 80% power warranties. A module with an original standard test condition (STC) power output rating of 100 watts will probably be producing 90 watts at STC after ten years, 80 watts after 20 years. Used modules can be tested for their performance using a max power point current / voltage meter, correcting for module temperature and actual solar radiation normalized to the STC conditions of 1,000 watts per square meter and 25 degrees centigrade cell temperature.

It is important to note that the SMUD salvage sales illustrates a-Si on breakable float glass has considerable less salvage value than single or poly silicon technologies using tempered glass. CdTe might have similar issues with removability and transportability of the more fragile glass compared with tempered glass of crystalline PV. Even tempered glass is subject to breakage during decommissioning, removal transportation and storage activities. If flexible PV like United Solar or other newer flexible PV players in the market were designed for removability, it is possible the salvage value would be even higher than glass based PV.

Visual factors including browning of EVA was an important factor for resale, with large amounts of browning, as shown in the 15 year old single crystals cells of Photo 2, reducing the resale value dramatically.

PHOTOS OF SALVAGED PV MODULES

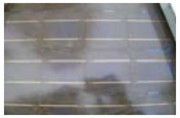


Photo 2 & 3: 1995 Solec SP-102's piled up in 2010, EVA discoloration

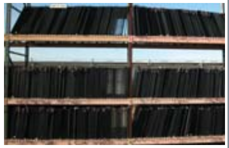


Photo 4 & 5: Well stacked float glass a-Si for bid in 2009.

PHOTOS OF SALVAGED PV MODULES

Photo 6: Well cared for and stacked modules obtain best resale bid price.

Photo 7: Panorama of poorly handled float glass a-Si for bid 2005.

Photo 8 & 9: Selling PV in CA, Broken and good quality modules.

2011 Salvage Operation

In 2011 we examined the 144 Solec SP-102's 24 volt modules shown in photo #2 for the actual resale value. Operating modules produced approximately 85 watts in full sun, consistent with a 1%/year degradation. Performance was measured with a 100 watt variable resistor providing voltage open circuit, short circuit current and an approximation of voltage and current at max power in full sunlight. Good modules with junction boxes sold on a roadside in Grass Valley CA for between $30 and $50 each. Modules without junction boxes sold in bulk for $20 each. Approximately 15% of the modules were discarded because of glass breakage, delamination, serious browning of EVA, obvious burn marks on interconnections or damaged backsheets. Angle aluminum used to panelize the modules was salvaged at a high value. The time needed to transport, warehouse, clean, examine, sort, inventory, and sell the surplus modules considerably reduced the value of the salvage operation. Ideally modules are taken out of service with immediate installation in a new location.

CONCLUSION

There is a healthy resale market for PV modules that should be recognized in project level economic calculations. As systems costs become lower and lower, salvage value have more significant ramifications. Functioning modules will have a revenue value based on life/performance expectations with the additional shipping and handling costs in comparison to other alternative to electric generation costs. The fragility due to glass used in PV modules has important resale value ramifications. There exists a healthy used PV module market. Safety and performance standards for used modules will become more important as salvaged modules show up in greater numbers in future years.

ACKNOWLEDGMENTS / REFERENCES

Thanks and appreciations are extended to Brian Robertson, Jigar Shah, Daniel Shugar, Eric McCabe, Jennifer Woolwich, ASES and SMUD (Jon Bertolino and Lynne Valdez).

Personal Communication, January 26, 2009, Dan Shugar.

Personal Communication, January 25, 2009, Jigar Shah.

Personal Communication, January 26, 2009, Brian Robertson.

Personal Communication, On-going, Jennifer Woolwich.

SMUD Salvage Sales, 2005 – 2010 (http://www.smud.org/).

NREL PVRW 2010 BP Solar presentation pvrw2010_wohlgemuth.pdf

A novel insulated solder tail assembly for use with aluminum core backsheets

M. McNeeley, J. Norman, A. Turner, M. Kerr, M. Stocks, J. White

Transform Solar Pty. Ltd. ,8000 South Federal Way Boise, ID 83716 USA

Introduction

Performance degradation of long term photovoltaic installations has been linked to moisture ingress into the modules through observations of moisture related corrosion and encapsulant adhesion loss. Multiple methods to reduce moisture penetration have been investigated over the years. These studies have primarily focused on the internal (encapsulant) or external (topsheet and backsheet) components of the module. These layers are typically classified by their water vapor transmission rating (WVTR). It has been shown in various studies that backsheets composed of thin continuous aluminum core have a significantly lower WVTR than conventional backsheet materials and are therefore one of the most effective ways to prevent moisture ingress into the module.

The use of aluminum core backsheets can unfortunately lead to other module reliability and performance issues. On conventional modules, the cell to cell bus bar material is typically extended through a narrow slit in the encapsulant and backsheet materials. This slit facilitates the electrical connection to the backside mounted junction box. The conductive nature of the aluminum in the backsheet poses a unique challenge. If the electrical leads are not properly insulated from the conductive layer, electrical shorting of the module leads to each other or to ground through the frame can occur. This shorting can manifest during the manufacturing process, or in the field as module materials age.

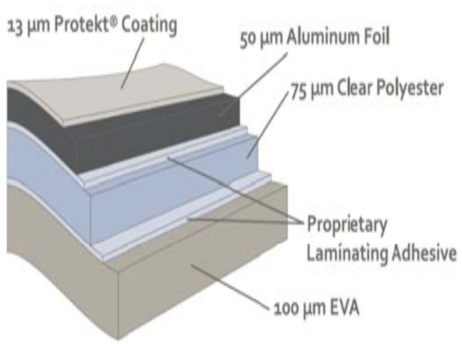


Figure 1. Cross-section of Madico's "Protekt TFB" aluminum core backsheet. Madico is one of multiple manufactures of aluminum core backsheets for use in the PV industry. Image is taken from Madico's product brochure available at: http://www.madico.com/wp-content/uploads/2011/06/Protekt-TFB-Datasheet-2011_web.pdf

This poster contains no confidential or proprietary information

Design Considerations

The backsheet of a PV module is considered an accessible component per the UL and IEC certification definitions. With the addition of the conductive layer an aluminum core backsheet can potentially be considered an accessible metal part. With these considerations in mind, the typical technique of passing bare bus bar material through the backsheet is no longer sufficient to satisfy the minimal acceptance creepage and clearance distances, as published in IEC 61730-1 and UL 1703. The electrical connection to the junction box must be made while the electrical insulation between current carrying components and accessible metal components is maintained per the safety standards of the product classification. The electrical insulation must also remain stable through the effective service life of the module as described in IEC 61215 and UL 1703. In addition to the safety and certification issues, relative ease manufacture and cost considerations must be evaluated for a product to be competitive in the market.

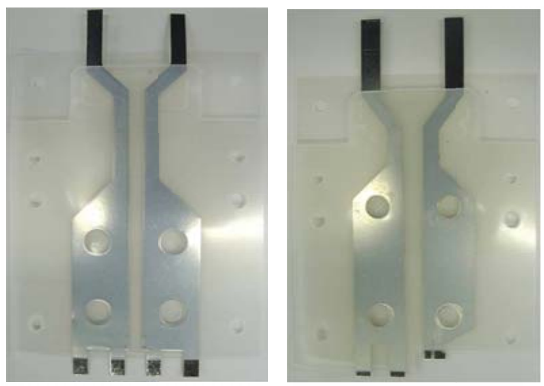


Figure 2. Two versions of Transform Solar's solder tail subassembly. Each of the individual module designs at Transform Solar have a unique tail configuration to accommodate the certification requirements

Tail Design

Transform solar has developed a novel solder tail subassembly which successfully over comes all the safety, certification, and reliability issues associated with aluminum core backsheets. The transform design consists of two legs composed of a standard Ag/Sn plated Cu alloy. The legs are surrounded with three layers of a commonly used insulating polymer that is designed to bond with the encapsulant material. The insulating layers allow the subassembly to be placed directly behind the active cells of the module, which helps decrease module size, weight, and materials costs.

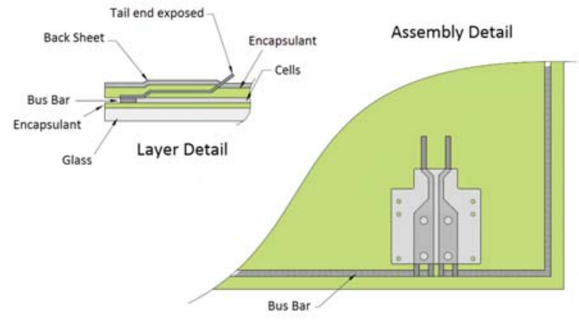


Figure 3. Assembly detail of Transform's solder tail subassembly

During the module assembly process the subassembly is soldered to conventional cell to cell BB material within the module and passed through a slit in the aluminum core backsheet. The module then goes through a typical laminating and final assembly procedure. The tails sub-assembly was first implemented with our series IV SLIVER™ module, which received IEC (TUV) certification in August, 2011.

About Transform Solar and SLIVER™ Technology

Transform Solar is a joint venture between Origin Energy and Micron Technology. Micron and Origin brought together their respective expertise in green energy and semiconductor manufacturing to contribute stability and strength to a visionary company with a leading new technology.

Our innovative SLIVER™ technology uses advanced semiconductor manufacturing techniques to create new opportunities for monocrystalline silicon solar power through a markedly different design. SLIVER™ technology was invented and developed at the Australian National University's Centre for Sustainable Energy Systems with financial support from Origin Energy. It produces ultra-thin, elongated monocrystalline cells that are perfectly bifacial and highly flexible. The SLIVER™ cell process uses an innovative micromachining technique to slice the wafer into thousands of tiny strips. The strips form fully functional solar cells, which are then separated from the wafer. The unique properties of these cells create potential for lighter panels, conformable structures, and a host of other new applications that were previously inaccessible to monocrystalline based technology . For more information visit: www.transformsolar.com

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CanadianSolar & PV EVOLUTION LABS
ADVANCING SOLAR

Characterization of Potential Induced Degradation Sensitivity of Crystalline Silicon Modules

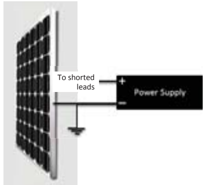
Jenya Meydbray, PV Evolution Labs & Wenda Zheng, Canadian Solar Inc

ABSTRACT

With the cost of PV modules plummeting and production volumes expanding to record levels, module manufacturers are experiencing increasingly aggressive cost pressures. An estimated 26 GW of nameplate PV capacity was installed globally in 2011. A one-percent performance degradation translates to a loss of 260 MW of nameplate power - roughly the total installed PV in 2000. This staggering number underscores the importance of maintaining a focus on PV module quality and durability. PV modules are subjected to a wide range of harsh environmental stress conditions: temperature swings, humidity, hot and freezing temperatures, high voltages, and UV radiation are a few examples. This work focuses on the impact that elevated voltage levels can have on PV module performance. This degradation mechanism is commonly referred to as potential-induced degradation (PID). We present experimental results of over sixteen commercially available modules subjected to positive and negative biases of 1,000 volts in damp-heat conditions (85C / 85% RH). PV module degradations induced by the experimental conditions range from negligible to catastrophic and depend strongly upon bias polarity. Observed degradation in power ranges from less than 1% to almost 50%.

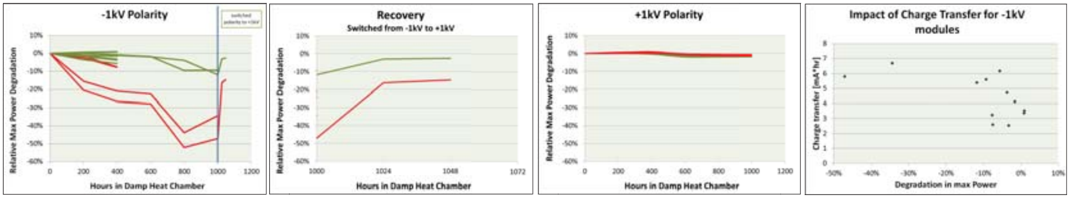
TEST DESCRIPTION

- »Damp heat conditions (85° C / 85% RH)
- »Four module types evaluated
- »Two modules per type at +1kV
- »Two modules per type at -1kV
- »Modules characterized every 200 hours



TEST RESULTS

Canadian Solar Modules; competitor modules



CONCLUSIONS

- »PV modules built with Canadian Solar cells showed greater PID stability
- »70% - 80% of the degradation was recovered by reversing the polarity for 48 hrs
- »Leakage current has no correlation to PID sensitivity
- »All modules exhibited minimal degradation with positive bias
- »Charge transfer had no correlation to degradation magnitude

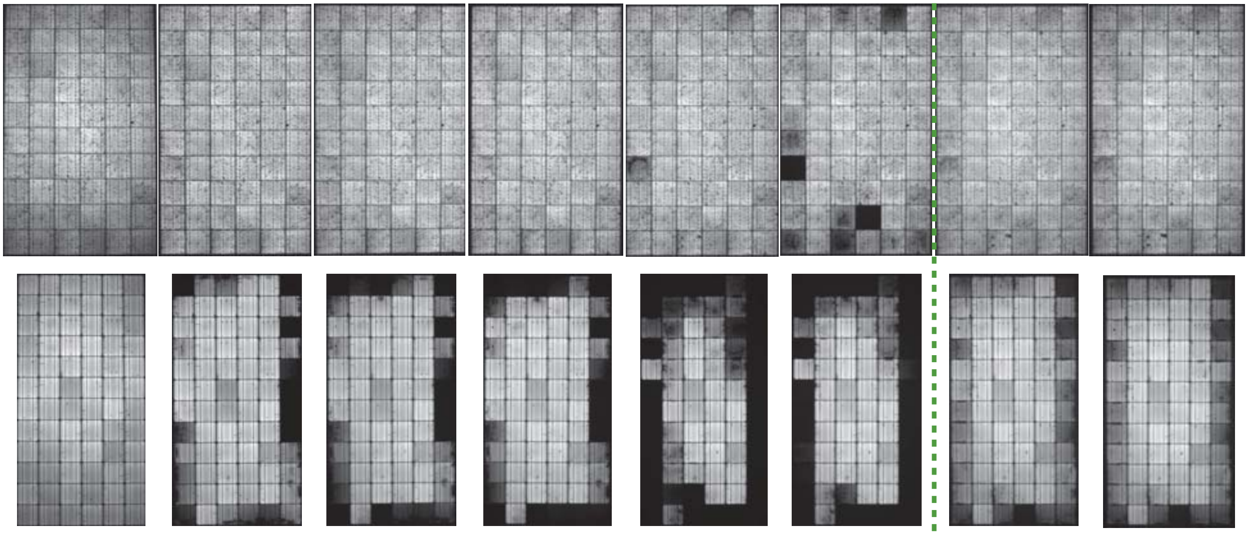
ELECTROLUMINESENCE IMAGES

« -1kV | +1kV »

0 hours | 200 hours | 400 hours | 600 hours | 800 hours | 1000 hours | 1024 hours | 1048 hours

CANADIAN SOLAR MODULES

COMPETITOR MODULES



Quantifying Adhesion and Debonding of Encapsulations for Solar Modules

Fernando Novoa* and Reinhold H. Dauskardt

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Stanford CA 94305-4034, *email: novoa@stanford.edu

David Miller, Michael Kempe, Nick Bosco, Sarah Kurtz

National Renewable Energy Laboratory, Golden, CO

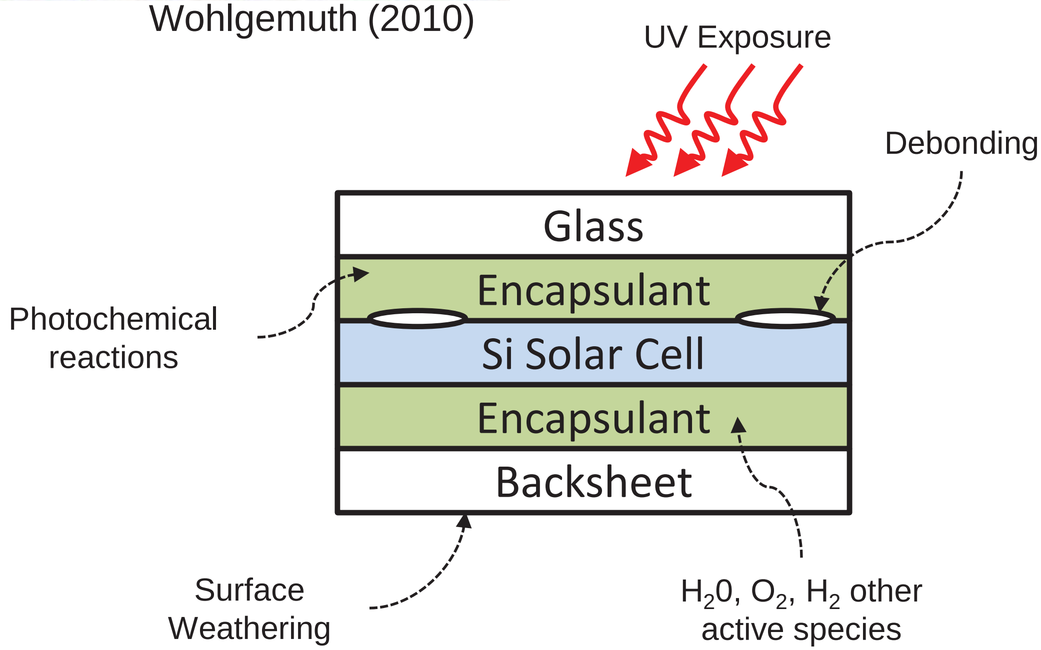
Encapsulant Debonding in Field Modules

Wohlgemuth (2010)

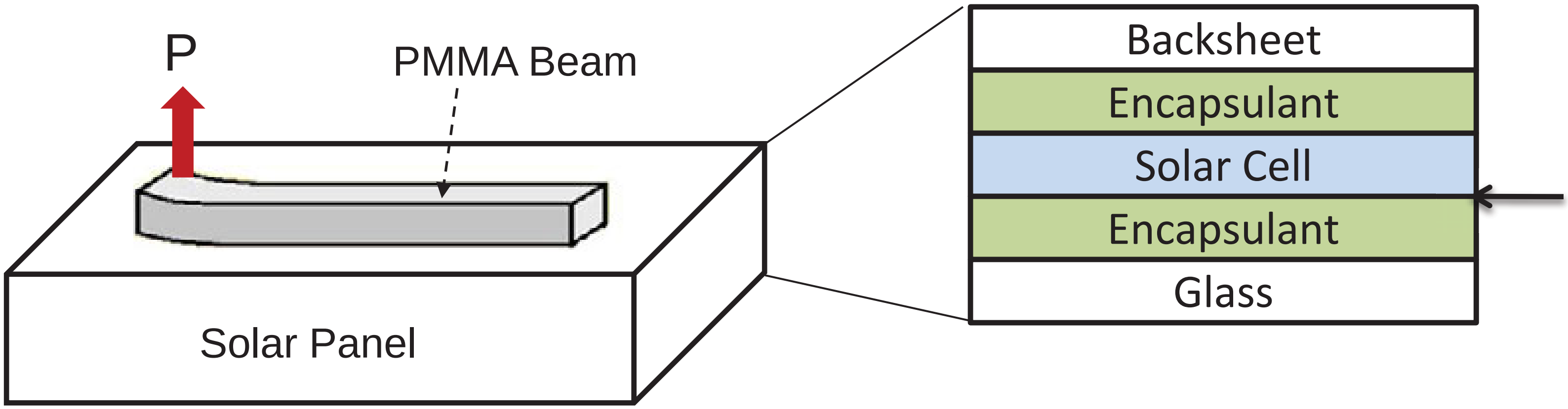
Severe operating environments.

Exposure to thermal cycling, stress, moisture, chemically active environmental species, and UV.

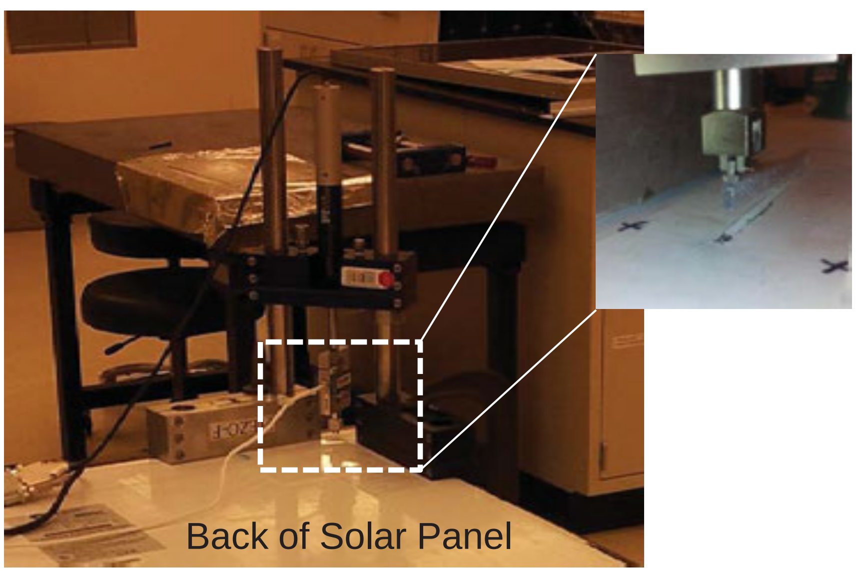
Uncertain degradation kinetics and reliability models.



Quantifying Adhesion in Field-Aged Panels



Delaminator Setup



Adhesive Energy

$$G = \frac{6P^2a^2}{EB^2h^3}$$

P = load
a = crack length
E = Young’s modulus
B = beam thickness
h = beam height

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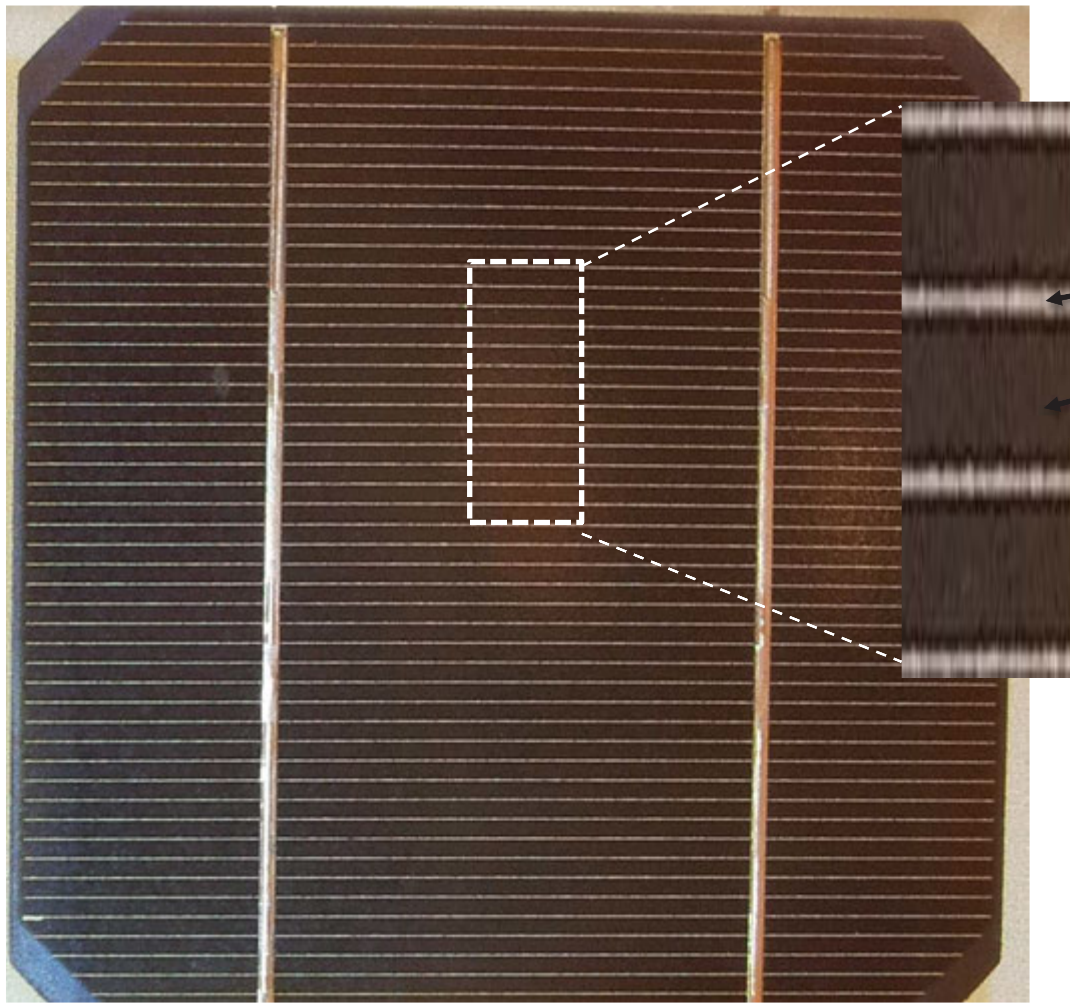
Encapsulant Delaminates from Si and Electrodes

Encapsulated Solar Cell



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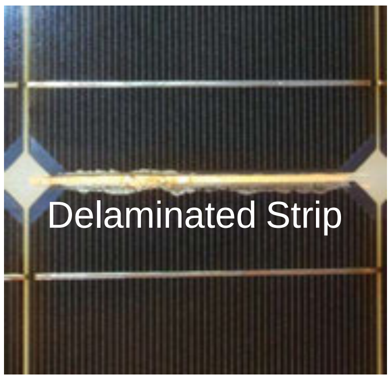
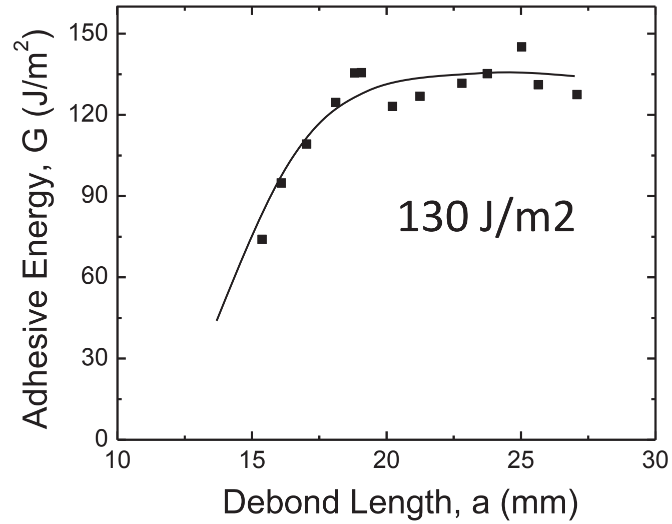
Adhesive Energy is Strongest in the Electrodes

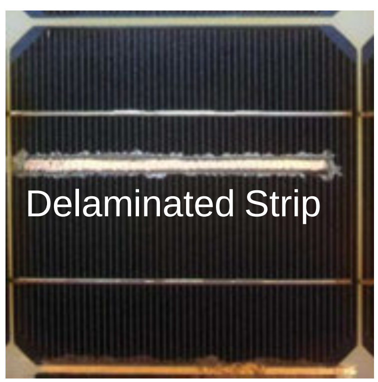
Adhesion Test on
EVA Encapsulant –electrode



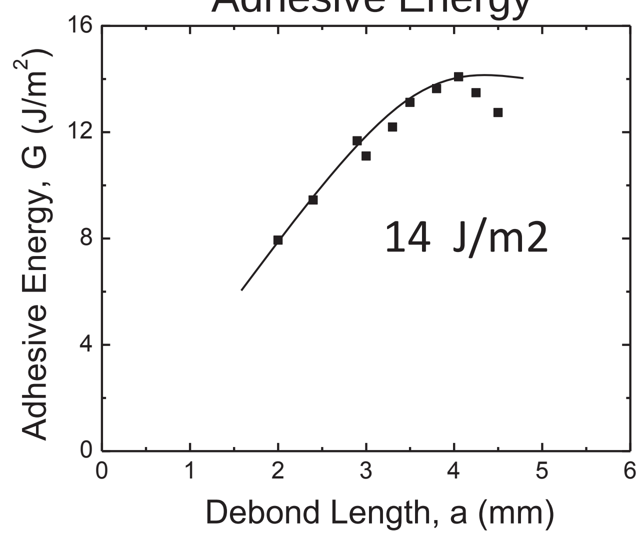
Encapsulant-electrode
Adhesive Energy



Adhesion Test on
EVA Encapsulant – Silicon+electrode



Encapsulant-Si+electrode
Adhesive Energy



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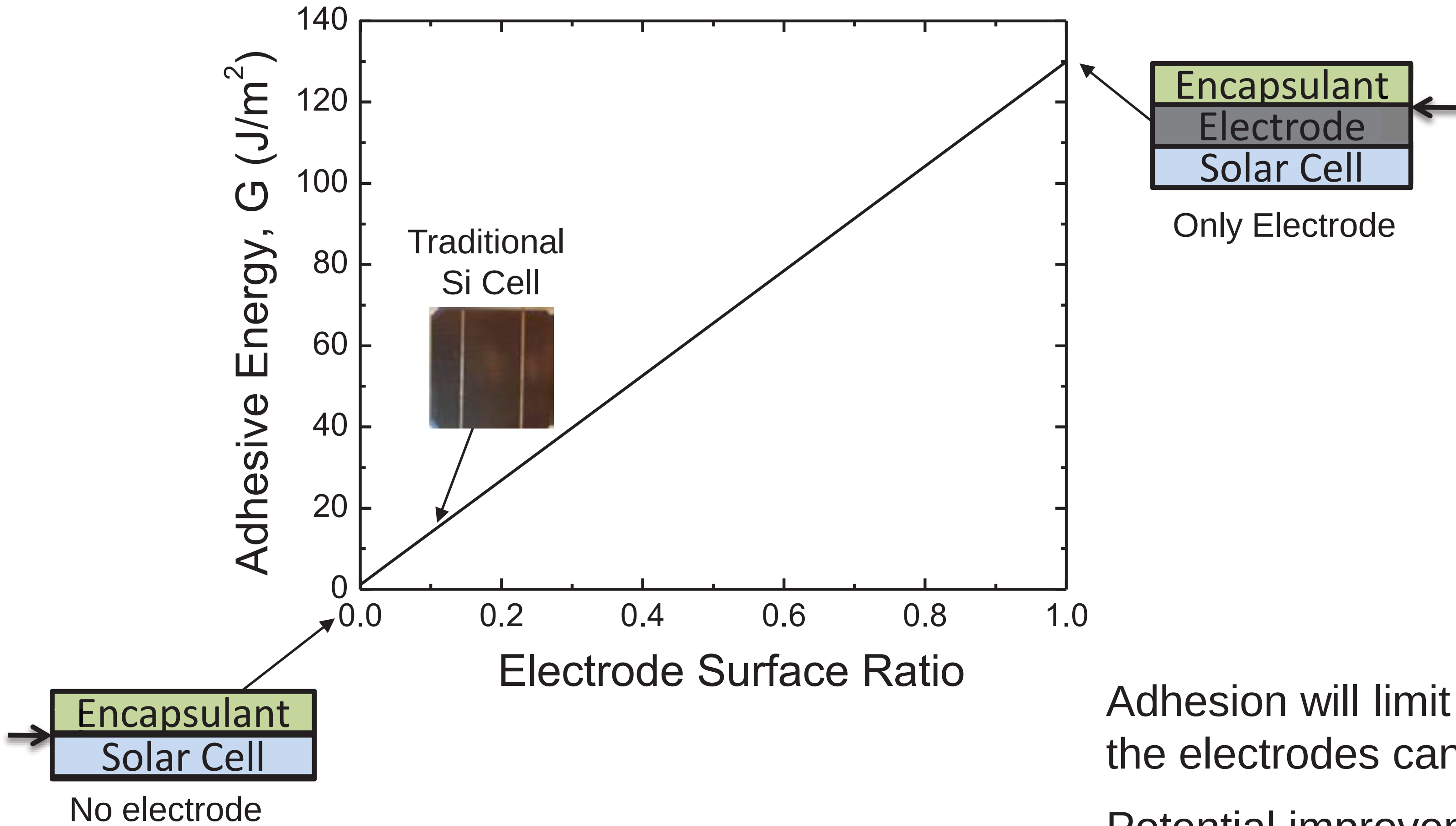
Adhesive Energy Increases with Electrode Surface



Adhesion will limit how thin the electrodes can be.

Potential improvements on EVA-Si adhesion will reduce delamination.

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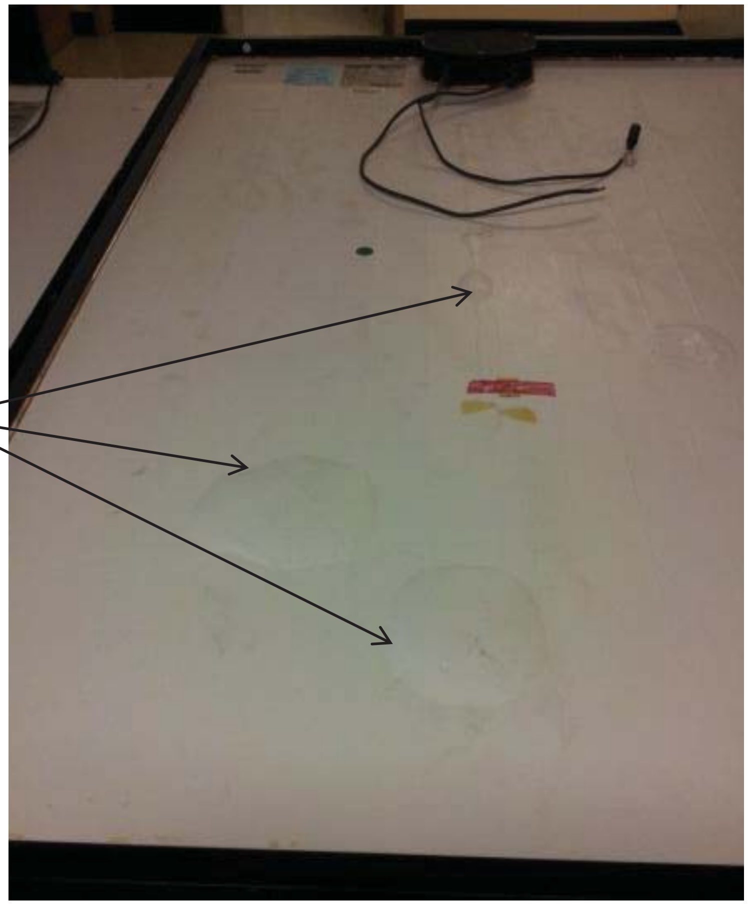
Backsheet Delamination in Field Modules

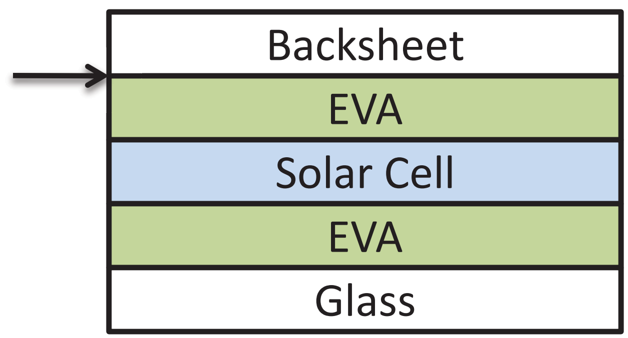
Backsheet Delamination



Severe operating environments.

Exposure to thermal cycling, stress, moisture, chemically active environmental species.

Uncertain degradation kinetics and reliability models.



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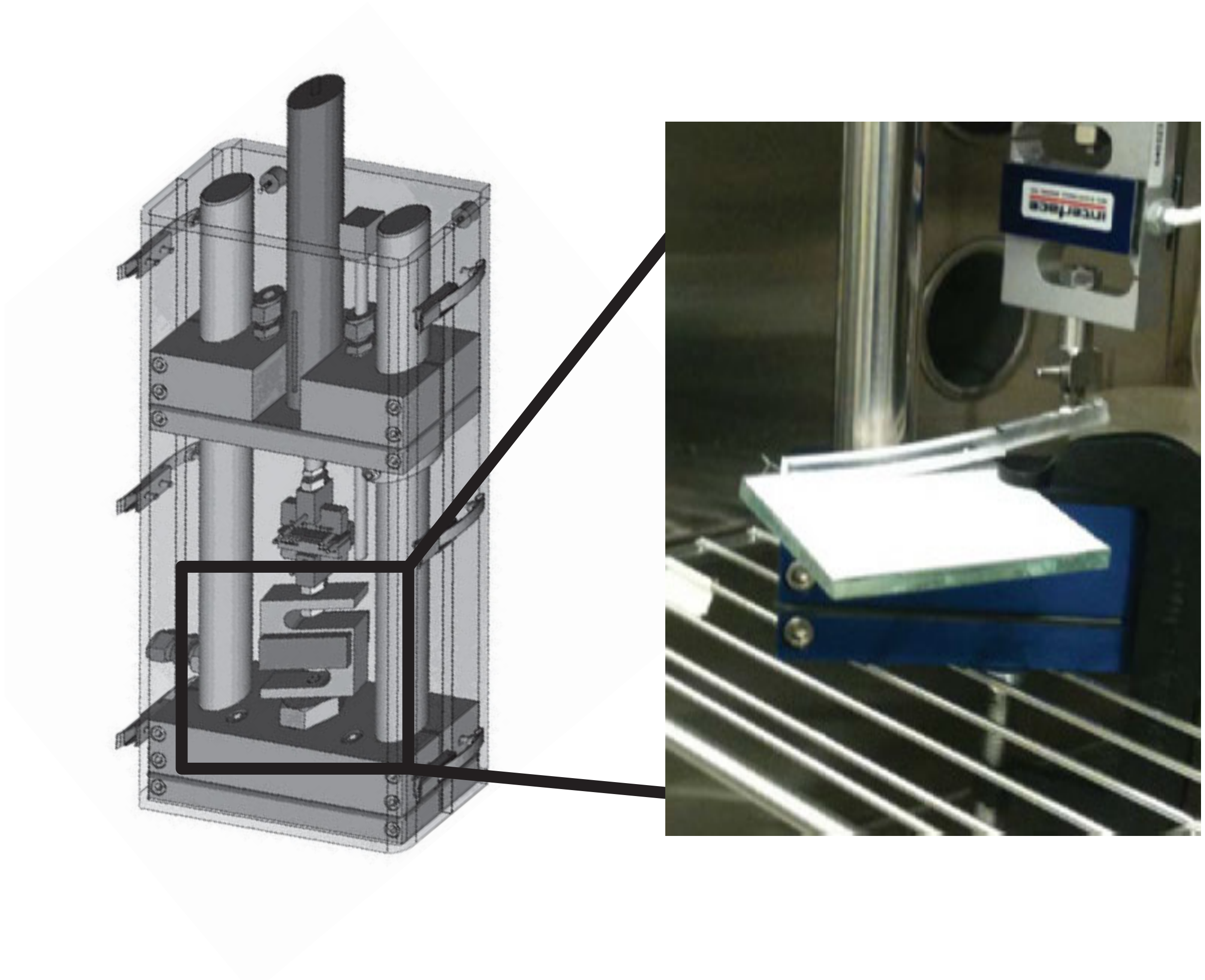
Quantifying Backsheet Delamination



$$G = \frac{6P^2a^2}{EB^2h^3}$$

P = load
a = crack length
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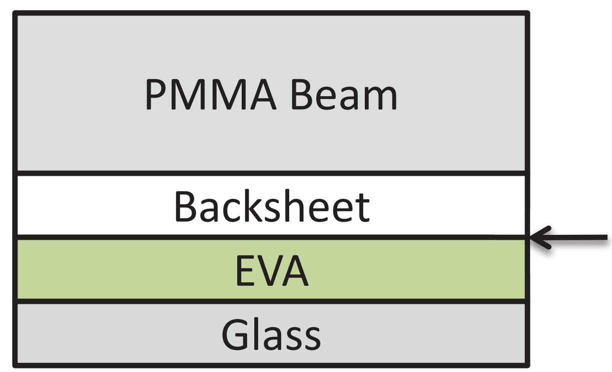
B = beam thickness
h = beam height



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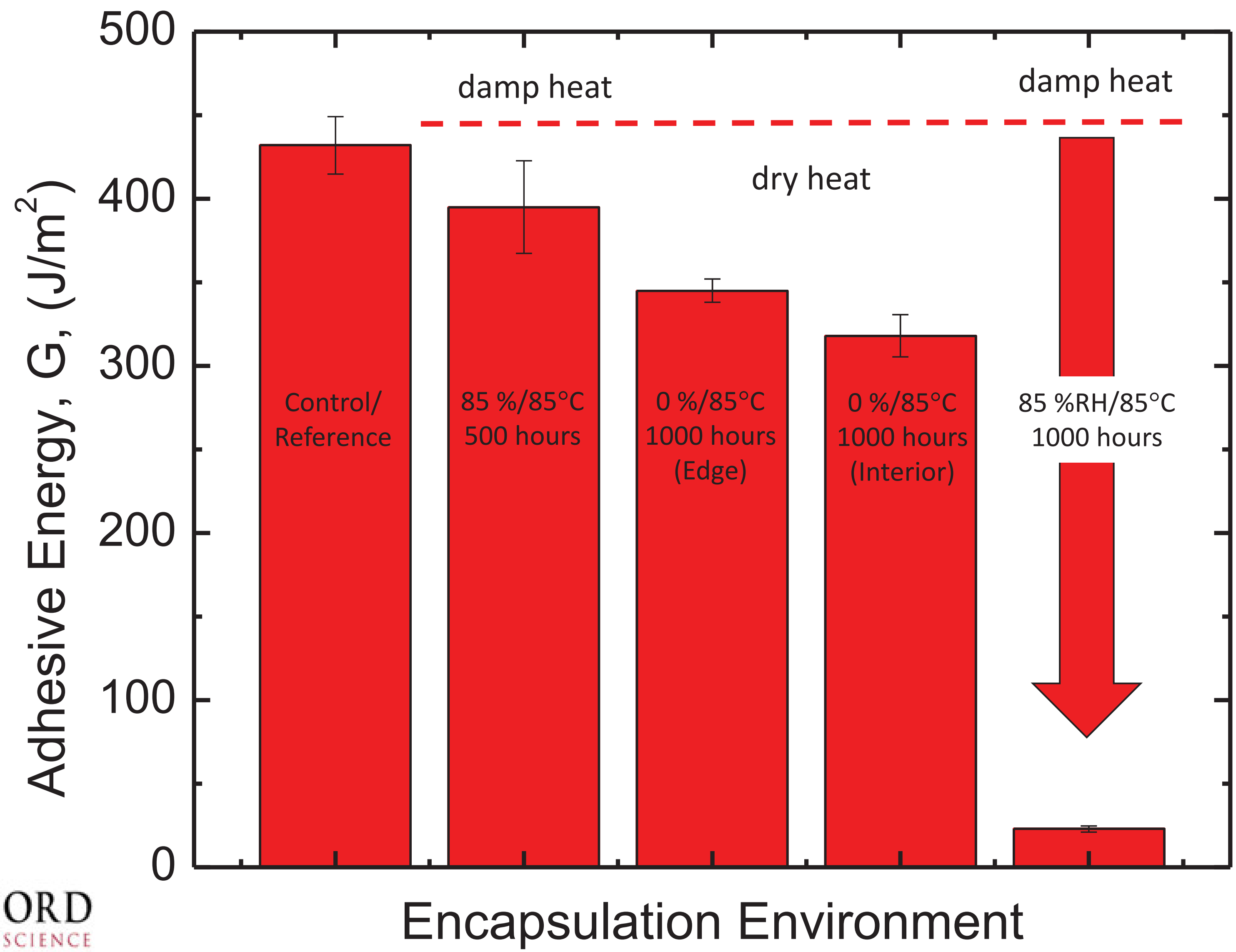
Anneal Treatment Effect on Backsheet Adhesion



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Ranking PV Materials for Weathering Performance

Greg O'Brien, Amy Lefebvre, Steven Hahn, Anthony Bonnet

PV Module Reliability Workshop - Silicon
February 28, 2012

PV Module Reliability

- PV module's return on investment is directly related to the module's lifetime and performance.
- Photovoltaic power can only truly be considered "green" when modules can produce safe and reliable electricity for very long periods of time.
- Module makers should be able to select component materials of construction that have proven long lasting performance.
- Current certification standards (UL and IEC) are focused on safety and short term output performance.
- Long term weathering durability for materials of construction support long PV module lifetimes.

Module Makers Cannot Wait 25 Years for Materials Selection

- Without 25 year weatherability and performance data, the PV industry can utilize accelerated testing to evaluate the effect of UV light with oxygen, temperature cycles, and humidity cycles on materials of construction.

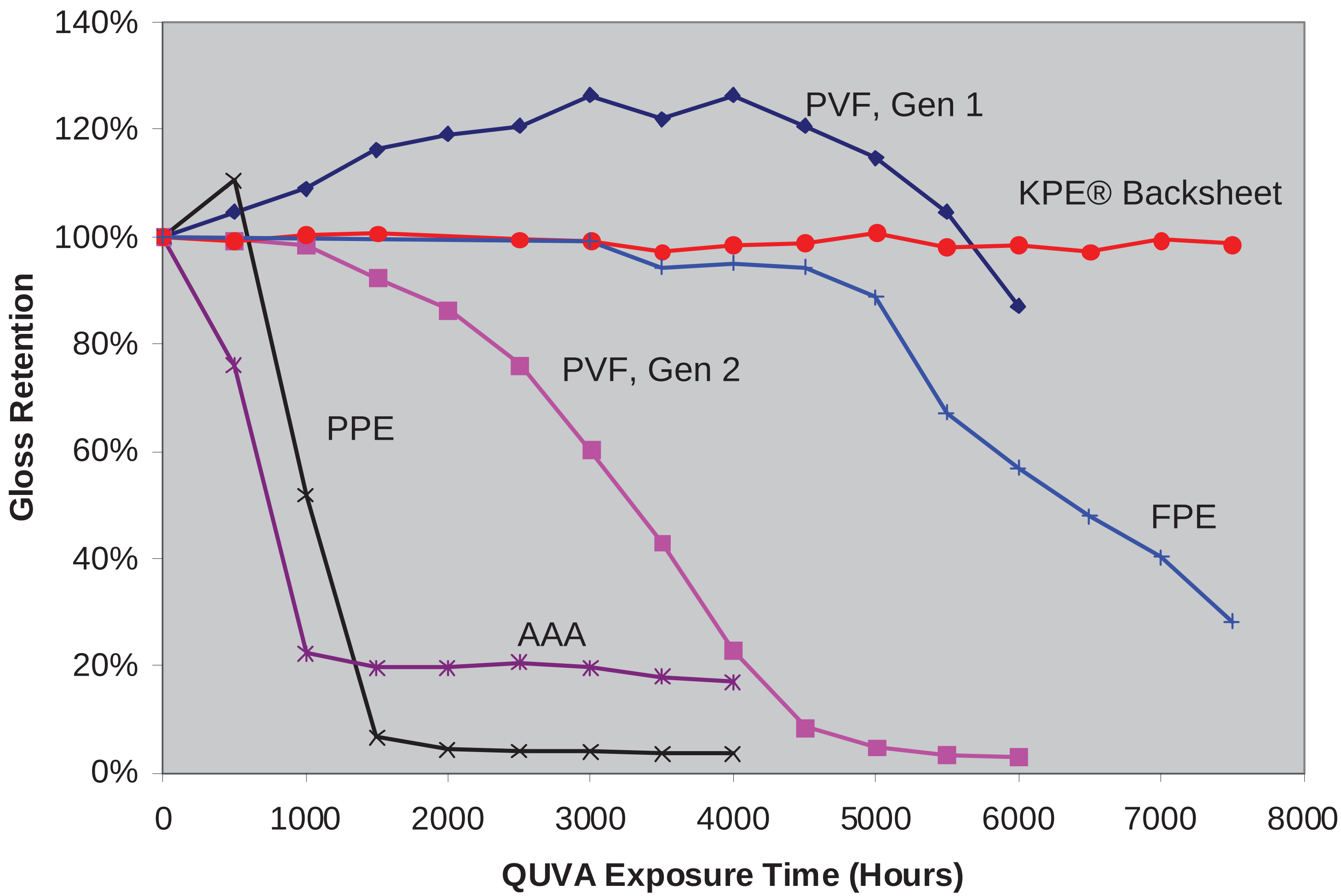
- Long term exposure to these elements stresses the polymer components and can shorten their lifetime.

- Early indicators of photo-degradation of white polymeric materials are
  - Gloss Loss
  - Chalking
  - Oxidation of the polymer chains

Backsheet Weathering Study

- Arkema initiated a weatherability study to establish ranking of backsheets.
  - Based on accelerated weathering QUV A.
  - Photo-degradation monitored by gloss retention, SEM microscopy, chalking evaluation, and FTIR spectroscopy.
  - Compare with outdoor weathering results – Florida Exposure.
- QUV A - Accelerated Testing Conditions:
  - Irradiance of 1.55 at 340 nm, 8 hrs light at 60°C and 4 hrs dark at 50°C with condensation (ASTM G154 Cycle 6).
  - UV irradiance 295 – 385 nm = 85 W/m^2 or 4.91 MJ/m^2 in 24 hrs
  - 6000 hrs exposure has equivalent UV radiation to 48 months in Florida.
  - Backsheet exposure is a percentage of direct exposure.
- Backsheet Materials Tested:
  - KPE® sheet – Kynar® Film / PET / Kynar® Film backsheet
  - PVF, Gen 1 - PVF Generation 1/PET/PVF Generation 1 backsheet
  - PVF, Gen 2 - PVF Generation 2/PET/PVF Generation 2 backsheet
  - FPE - Partially fluorinated coating based backsheet
  - PPE - Weatherable polyester backsheet
  - AAA - Polyamide based backsheet

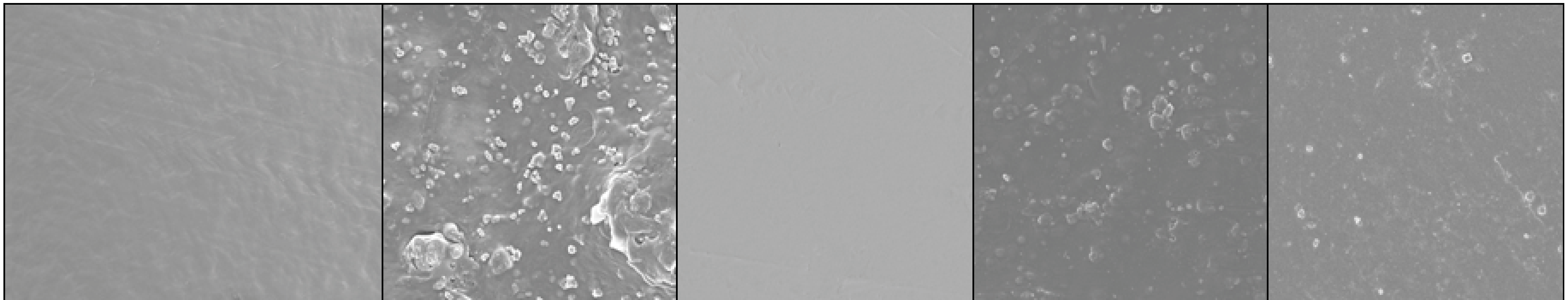
Accelerated UV-A Weathering Study: Degradation of Backsheets: Gloss Retention



QUV Accelerated Weathering Conditions
QUVA: Irradiance = 1.55 at 340 nm

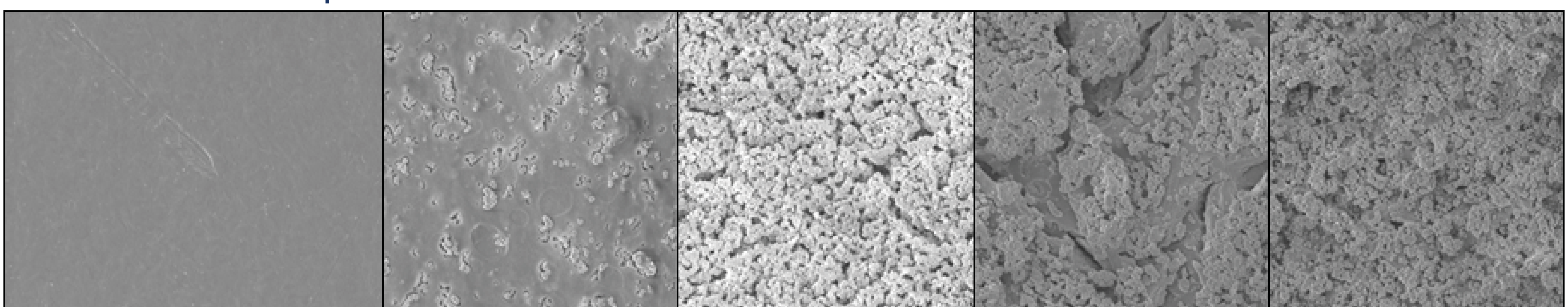
UV Stability of Backsheets: SEM Images

Before Exposure



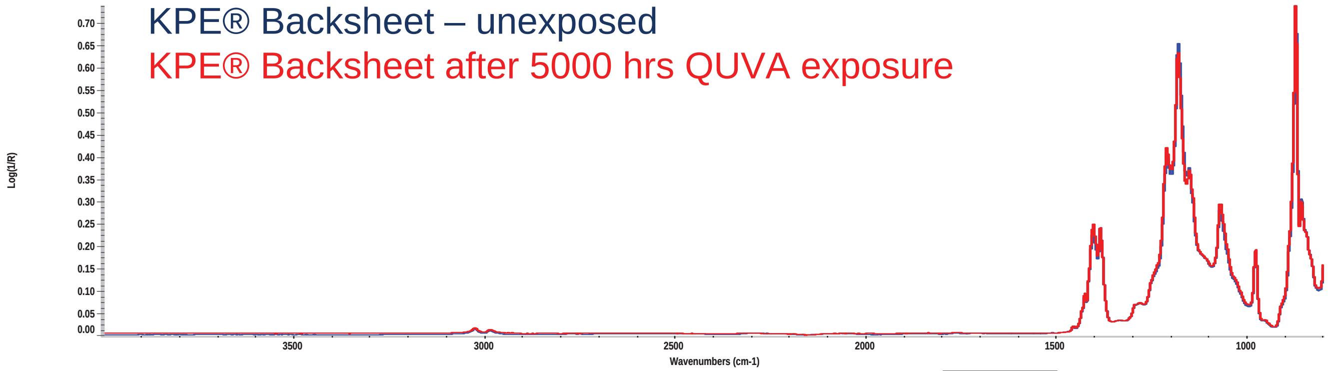
KPE® Backsheet	PVF, Gen 1	FPE	PPE	AAA
Unexposed	Unexposed	Unexposed	Unexposed	Unexposed

After QUVA Exposure

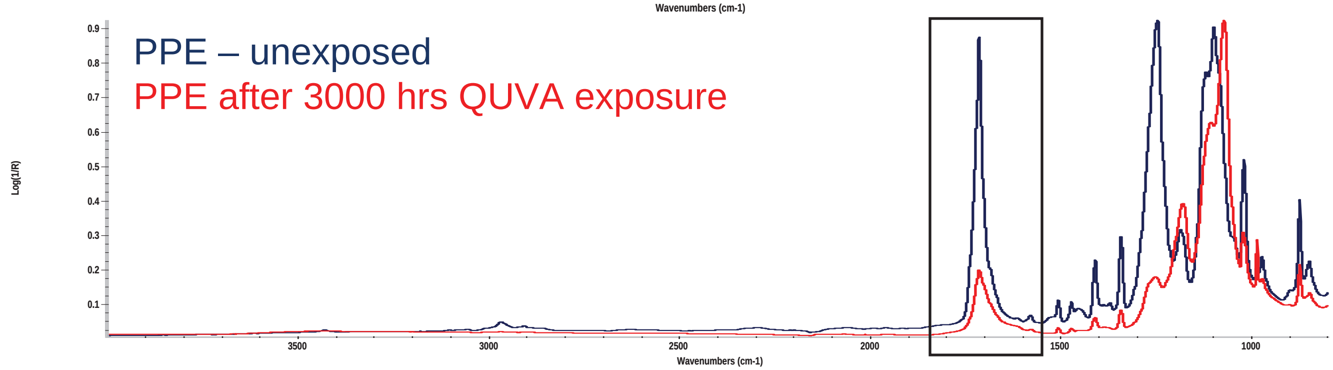


KPE® Backsheet	PVF, Gen 1	FPE	PPE	AAA
After 5000 hours	After 5000 hours	After 5000 hours	After 3000 hours	After 3000 hours

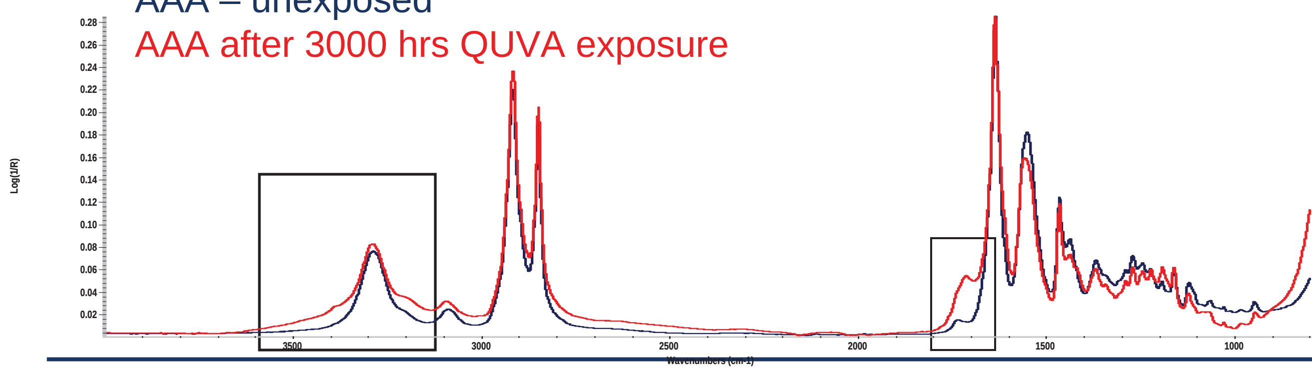
Accelerated UV-A Weathering Study
Degradation of Backsheets: FTIR ATR Analysis of Oxidation



- No spectral changes KPE® Backsheet Surface
- No sign of degradation



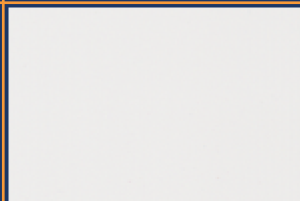
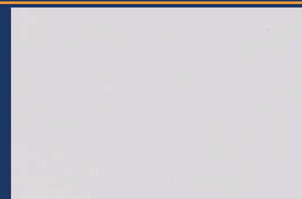
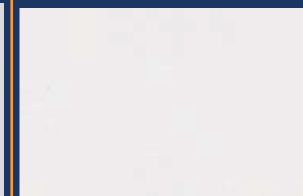
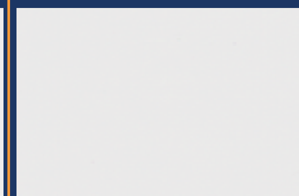
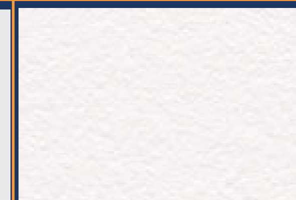
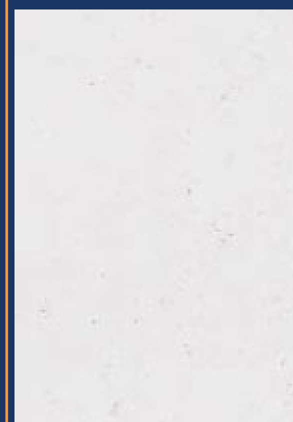
- Spectral changes in PPE indicate degradation
- C=O band has decreased substantially



- Changes in spectrum indicate degradation
- NH/OH spectral region indicates increasing OH

ARKEMA

Real-time Weathering Study
Degradation of Backsheets: 1 Year South FL Exposure Results

	KPE® Sheet	PVF, Gen 1	FPE	PPE	AAA
Before Exposure					
After 1 Year South Florida Exposure, unwashed					
Gloss Retention	101%	105%	97%	42%	25%
Chalking* (ASTM D4214-07 D)	2	2	2	3	6

Gloss retention after outdoor FL exposure is showing the same trend as gloss retention after QUVA exposure

*Chalking rating: 2 is no chalking and 6 is high level (2 – 7)

ARKEMA

Gloss Retention for Weathering Ranking of Materials

Backsheet	Gloss Retention %, 3000 Hr.	Gloss Retention %, 6000 Hr.	**Time to 50% Gloss Retention (Hrs.)**	**Weathering Ranking (Best =1)**	**Weathering Class**
KPE® Backsheet	100	99	**> 7500**	**1**	**A**
PVF, G1	126	87	**> 6500**	**2**	**A**
FPE	99	56	**6400**	**3**	**B**
PVF, G2	60	3	**3300**	**4**	**C**
PPE	4	NA	**1100**	**5**	**D**
AAA	20	NA	**750**	**6**	**D**

QUV Accelerated Weathering Conditions
QUVA: Irradiance = 1.55 at 340 nm

Proposal for Ranking Backsheets Based Upon Accelerated Weathering Testing

- Utilize QUV A Accelerated Test.
  - Includes UV light, oxygen, and humidity to simulate worst conditions
  - Gloss loss easiest indicator to monitor
  - Common and relatively inexpensive weatherometer

- Propose 3 Class Rankings.
  - Based on time to Gloss Retention using ASTM G154 Cycle 6
    - Class A – minimum 80% retention after 6000 hrs of exposure
    - Class B – minimum 80% retention after 4500 hrs of exposure
    - Class C – minimum 50% retention after 3000 hrs of exposure
    - Class D – less than 50% retention after 3000 hrs of exposure

- Same trends observed with Outdoor Weathering.
  - After one year south Florida exposure– gloss loss for Class D is evident
  - Surprising finding: Mold growth on some backsheets.

- Weatherability is one axis of backsheet performance. Other testing is needed for a complete evaluation.

Estimation of Amount of Free Acetic Acid Desorbed in EVA Encapsulant with Infra-Red Spectrum

Kaoru Ohshimizu

Mitsui Chemicals, Inc.

Back Ground

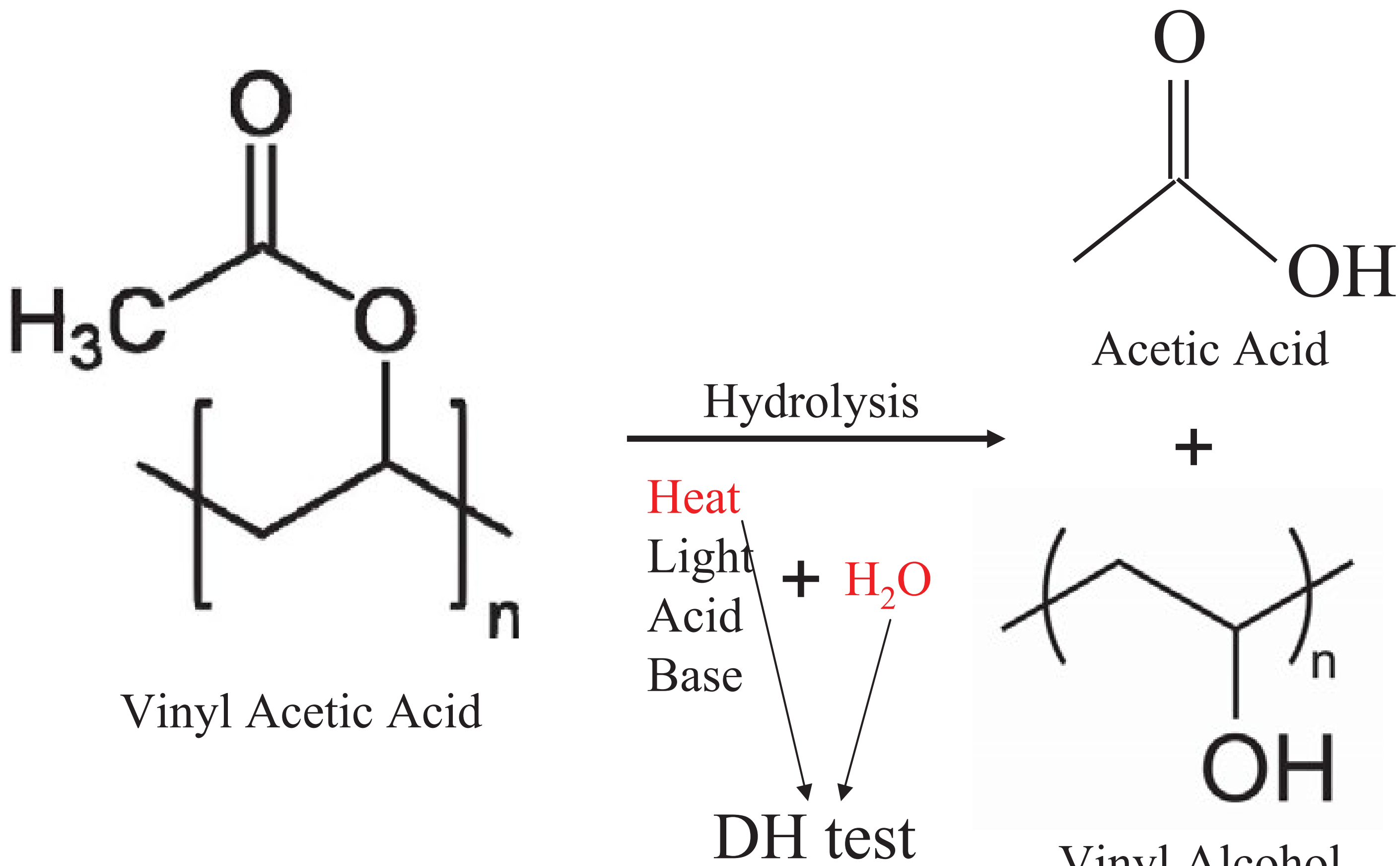
Understanding of PV module degradation mechanisms involved in encapsulant is very important for predicting the lifetime of PV modules for encapsulant manufacturers. In general, Ethylene Vinyl Acetate (EVA) desorbs free acetic acid by high stresses with moisture. The generation of free acetic acid causes degradation of PV module. However as far as we know, there have been no data for the amount of free acetic acid in EVA desorbed during accelerated test.

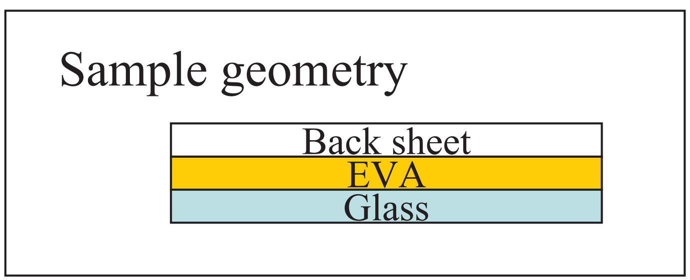
Our goal in our study is to understand the correlation between amount of free acetic acid of encapsulant and module properties. First of all, we have attempted to come up with a method to estimate easily the amount of free acetic acid in EVA.

This work

In this study, we propose a method with infra-red (IR) spectrum to measure the amount of free acetic acid in EVA desorbed during damp heating (DH) test. Generally, free acetic acid is able to be measured by hot water extraction method (HWEM), because the acetic acid can be directly detected with ion chromatograph technique. However in HWEM, large amount (large area) of sample is needed. In addition, when backsheet with low moisture barrier is used, acetic acid penetrates the backsheet. As a result, detected amount of acetic acid is underestimated. To avoid these problems, we have attempted to detect chemical changes in EVA with infra-red spectrum.

Hydrolysis of Vinyl Acetic Acid Groups

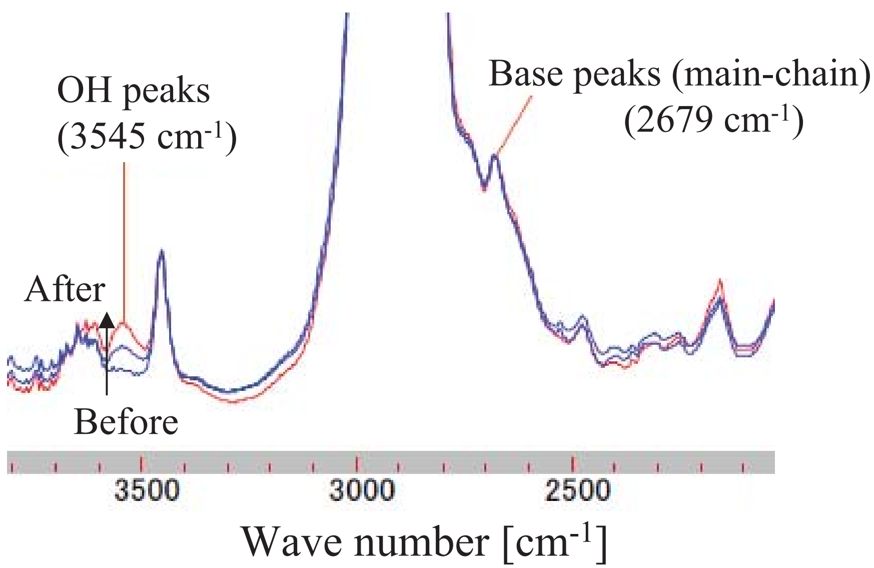




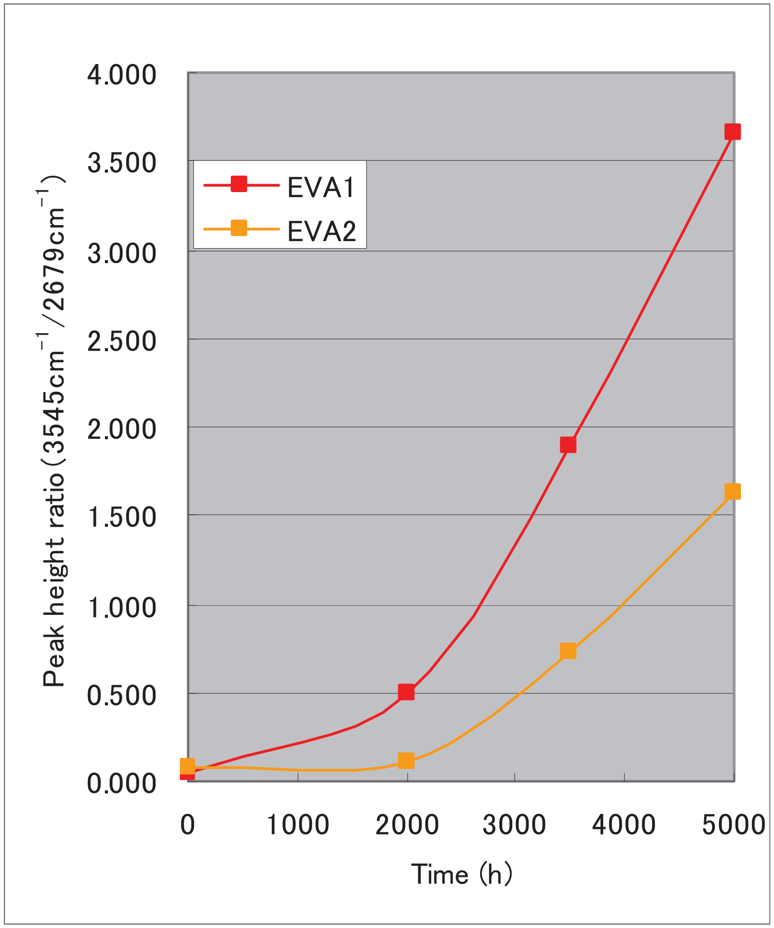
Hydrolysis needs water and high stress.
After hydrolysis, OH groups appear and main-chain does not change.

Infra-red (IR) spectra seem to be useful.

IR Method (IRM)



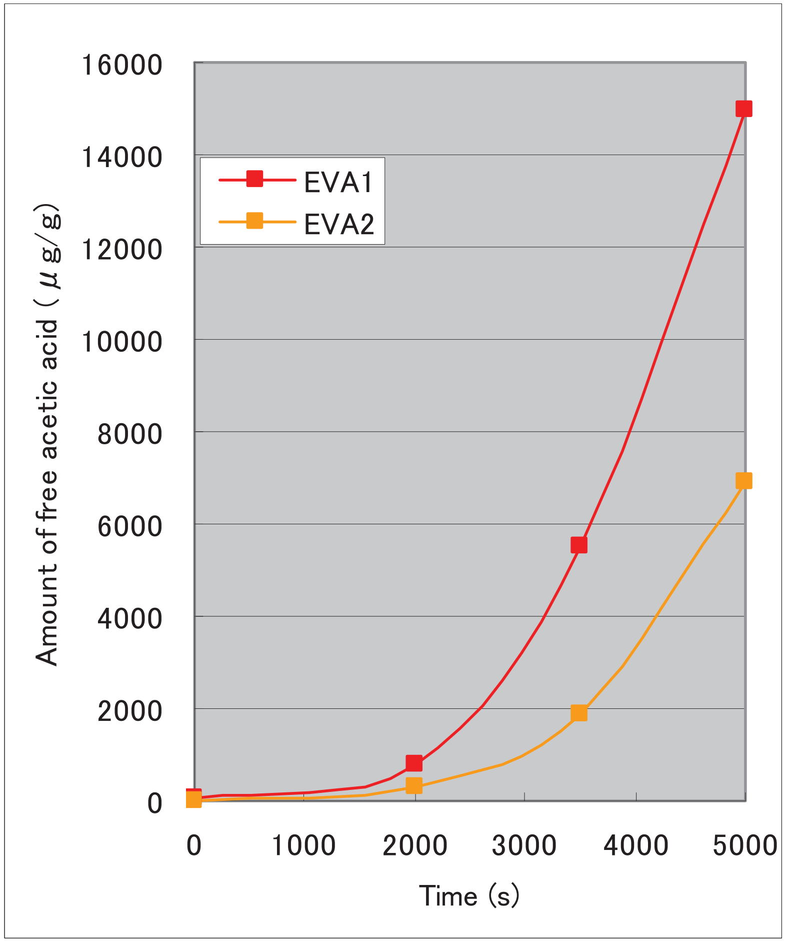
Change in IR spectra during DH test. The peak height at the wave number of 3545 cm^{-1} increases during DH test, because carbonyl groups change hydroxyl groups.



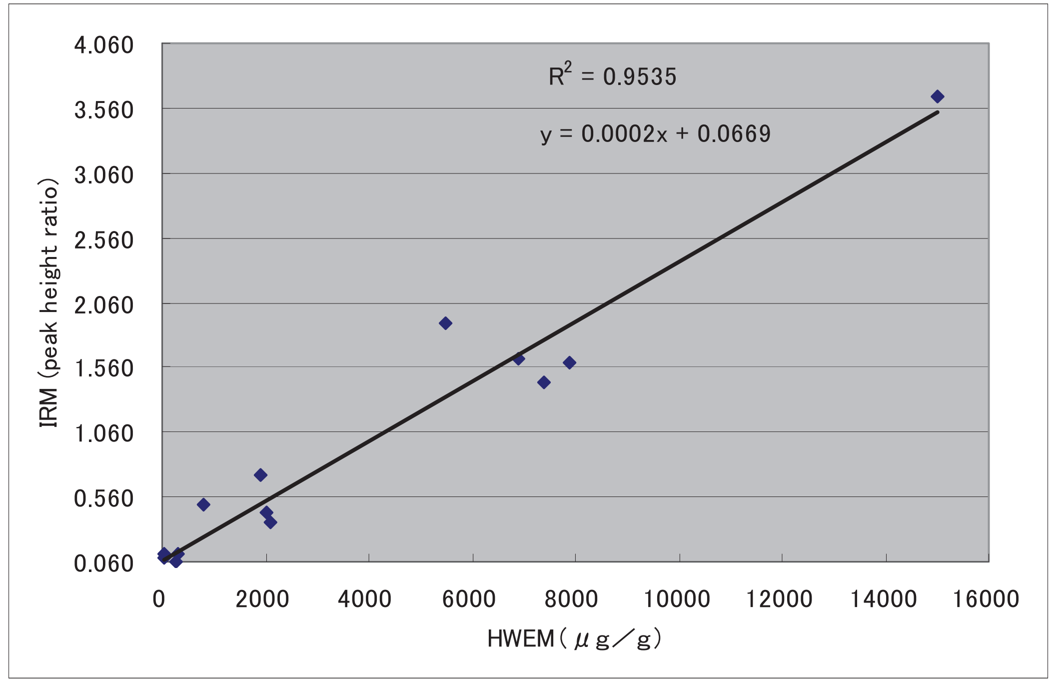
Increasing in peak ratio of (3545cm-1) / (2679cm-1) during DH test by IR method (IRM).

As we expected, the peak height of OH groups increases and the peak height of main-chain does not change during DH test.

Relationship of IRM and HWEM



Increasing in amount of free acetic acid during DH test by hot water extraction method (HWEM).



Correlation between amount of free acetic acid obtained by HWEM and the peak height ratio of (3545 cm-1) / (2679cm-1) by IRM.

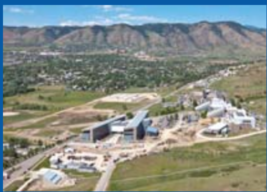
The curves of IRM and HWEM are very similar curves, and moreover the calibration curve is reasonable. These results reveal IRM is simple and easy method to estimate amount of free acetic acid.

Summary

The curves of IRM and HWEM are very similar curves, and moreover the calibration curve is reasonable. These results reveal IRM is simple and easy method to estimate amount of free acetic acid. IRM does not need large amount of samples. In addition, even though acetic acid penetrates the backsheet, we can detect chemical changes due to hydrolysis

The difference of amount change of free acetic acid during DH test in two products of EVA encapsulant. To figure out the difference is under investigation.

Development of a Visual Inspection Checklist for Evaluation of Fielded PV Module Condition



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ABSTRACT

A visual inspection checklist for the evaluation of fielded photovoltaic (PV) modules has been developed to facilitate collection of data describing the field performance of PV modules. The proposed inspection checklist consists of 14 sections, each documenting the appearance or properties of a part of the module. This tool has been evaluated through the inspection of over 60 PV modules produced by more than 20 manufacturers and fielded at two different sites for varying periods of time. Aggregated data from a single data collection tool such as this checklist has the potential to enable longitudinal studies of module condition over time, technology evolution, and field location for the enhancement of module reliability models.

OVERVIEW OF VISUAL INSPECTION CHECKLIST

- Uses IEC/UL standard terminology
- Attempts to balance collection of sufficient detail for failure mode evaluation against minimizing recording time per module
- Consists of 14 sections- based on module component
- Additional detail can be found in the full NREL report

DESCRIPTION OF TEST FACILITIES

Photovoltaic modules from 2 sites served as the principle testbeds for the development of the inspection checklist, supplemented with the experience and knowledge of other professionals (identified in the Acknowledgements). Modules from Site 1 were inspected on location at the APS STAR Center ® (Arizona Public Services Solar Test and Research Center) in Tempe, Arizona USA. Modules from Site 2 were shipped from the field site at the Solar Energy Center (SEC) in New Delhi, India* to NREL for evaluation.

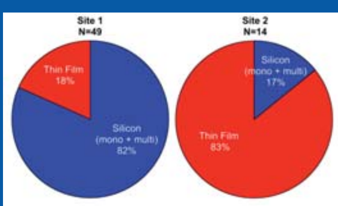


Figure 1. Composition of module sets at Site 1 and Site 2 used for early testing of the inspection checklist.

In all, more than 60 modules were inspected, representing more than 20 manufacturers. In addition to covering a broad range of technologies and manufacturers, these modules experienced different exposure times in the field: modules were fielded between 1-12+ years at Site 1 and 1-10 years at Site 2*.

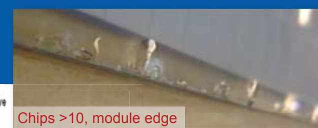
*O. S. Sastry, *et al.*, "Degradation in performance ratio and yields of exposed modules under arid conditions," in *26th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, Germany, 2011.

VISUAL INSPECTION CHECKLIST

- **Composed of 14 sections**
  - Sections 1-2: field site, system configuration, and module identification
  - Sections 3-13: individual module components, starting from the back and ending at the front of the module
  - Section 14: locations of electronic records (I-V curves, infrared images, etc.)
- Detailed instructions are given in the full report for each part of the checklist to reduce ambiguity and variation in survey responses
- **Required and optional tools:**
  - a tape measure with centimeter and millimeter gradations, a pen or other recording implement, and any personal protective equipment required by the facility (required)
  - a digital camera, an I-V curve tracer, and an infrared camera (optional)
- A full visual evaluation can be **completed in approximately 8 minutes** by a pair of experienced inspectors, though this can be reduced significantly for data sets consisting of a large number of similar modules or by the use of the abbreviated inspection list.

EXAMPLES

Section 3: Rear side glass



Damage: ☐ no damage ☑ small, localized ☐ extensive
Damage Type (mark all that apply):
☐ crazing or other non–crack damage
☐ shattered (tempered) ☐ shattered (non-tempered) ☐ Cracked (a.) ☑ Chipped (b.)
(a.) Cracks (#): ☐ 1 ☐ 2 ☐ 3 ☐ 4–10 ☐ >10
Crack(s) start from: ☐ module corner ☐ module edge ☐ cell ☐ junction box
(b.) Chips (#): ☐ 1 ☐ 2 ☐ 3 ☐ 4–10 ☑ >10
Chipping location: ☐ module corner ☑ module edge

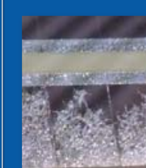
Section 9: Frameless Edge Seal

Appearance: ☐ like new ☐ discoloration (a.) ☑ visibly degraded
(a.) Fraction affected by discoloration:
☐ <5% ☐ 5–25% ☐ 50% ☐ 75% –100% (consistent overall)
Material problems:
☑ squeezed/pinched out ☐ shows signs of moisture penetration
Delamination: ☐ local only ☐ widespread
Fraction Delaminated: ☐ <5% ☐ 5–25% ☐ 50% ☐ 75% –100% (consistent overall)

Section 12: Silicon (mono or multi) module

Discoloration: ☐ none/like new ☐ light discoloration ☑ dark discoloration
Number of cells with any discoloration: 36
of those, average % discolored area:
☐ <5% ☐ 5-25% ☐ 50% ☐ 75% ☑ 100% (consistent overall)
Discoloration location(s) (mark all that apply):
☐ module center ☐ module edges ☑ cell centers ☐ cell edges
☐ over gridlines ☐ over busbars ☐ over tabbing ☐ between cells
☐ individual cell(s)darker than others ☐ partial cell discoloration
Junction box area: ☑ same as elsewhere ☐ more affected ☐ less affected

Section 13: Thin film module



Damage: ☑ no damage ☐ small, localized ☐ extensive
Damage Type (mark all that apply): ☐ burn mark(s) ☐ cracking
☐ possible moisture ☐ foreign particle embedded
Delamination: ☐ no delamination ☐ small, localized ☑ extensive
Location: ☐ from edges ☐ uniform ☐ corner(s) ☐ near junction box ☑ near busbar ☑ along scribe lines
Delamination Type: ☑ absorber delamination ☐ AR coating delamination ☐ other

PRELIMINARY RESULTS

We have not yet developed a large enough database to make conclusive statements about climate-zone dependent degradation but a preliminary analysis illustrates the types of data that become available through visual inspection.

Most frequently observed issues at Sites 1 & 2

Site 1 Observation	% of Modules	Site 2 Observation	% of Modules
Glass (front): Lightly soiled	55%	Glass (front): Small, localized damage	50%
Glass (front): Bird droppings	24%	Wires: Pliable but degraded	43%
Connectors: Pliable but degraded	22%	Glass (front): Lightly soiled	43%
Encapsulant: Major discoloration	20%	Junction box: seal will leak	36%
Backsheet: Small, localized damage	20%	Thin film module: Distance between frame and cells <10mm	36%

If visually observable defects can be correlated or conclusively linked with the measured electrical performance degradation rates, visual inspection may provide a relatively low impact method for assessing which PV installations may be more likely to see accelerated degradation based on the frequency and types of defects that develop.

FUTURE

- Availability of the checklist, a data collection spreadsheet, and NREL report with detailed instructions for using the checklist
- Availability of a database for compiling user-submitted field data

Please contact Corinne Packard if you are interested in participating in data collection

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory. We also acknowledge the contributions of Ulrike Jahn (TÜV Rheinland Immissionsschutz und Energiesysteme GmbH, Germany), Karl Berger (Austrian Institute of Technology), Thomas Friesen (Scuola Universitaria Professionale della Svizzera Italiana), and Marc Koentges (Institut fuer Solarenergieforschung GmbH Hameln/Emmerthal) (Lead of IEA PVPS Task 13 Subtask 3.2) in developing the format and content of the checklist. Special thanks are also due to Cassius McChesney of Arizona Public Service for providing access to modules that were deployed there.

Performance & EL Studies on Single Crystalline Silicon Modules from Three Different Manufacturing Sites Exposed to TC 500 and Damp Heat 2500 Hrs

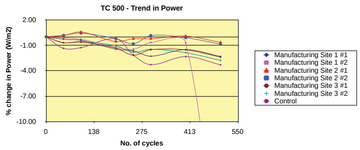
Intertek

Valued Quality. Delivered.

A study was initiated to determine if differences could be detected in modules constructed with the same materials and processes but assembled in different manufacturing locations. To detect changes performance measurements (Isc, Voc, Pmax, Imax, Vmax) were made along with visual and electroluminescent imaging as the modules were subjected to repetitive environmental conditions.

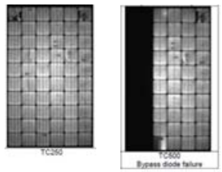
Thermal Cycling

Power Change for Thermal up to 500 Cycles

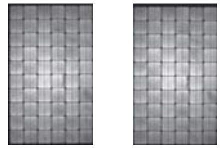


Pmax of Pink Sample decreased by 35% had a diode failure with diode removed the power drop was -2.73%

EL Image of Diode Failure Manufacturing Site 1 #2

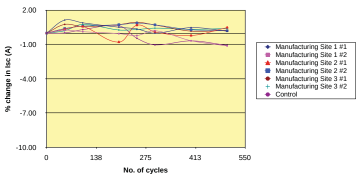


EL Images Manufacturing Site 1 #1

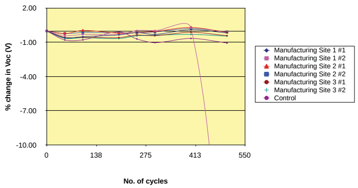


TC250 TC500

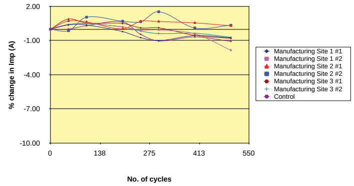
Isc Changes for TC 500



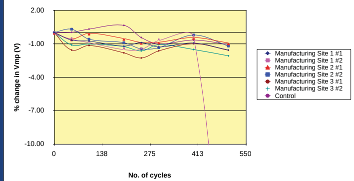
Voc Changes for TC 500 exposure



Imp Changes for TC 500



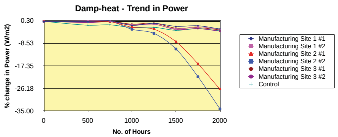
Vmp for TC 500



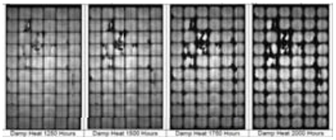
Pink sample dropped by 34%

Damp Heat

Power Change for Damp Heat to 2000 hours

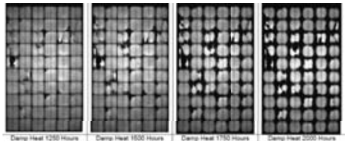


EL Images Damp Heat 2000 hrs Manufacturing Site 2 #1



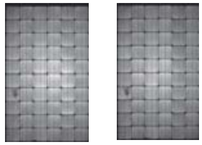
Increased Cell Damage

EL Images Damp Heat 2000 hrs Manufacturing Site 2 #2



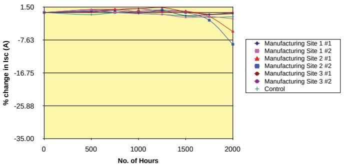
Increased Cell Damage

EL Images Damp Heat 2000 hrs Manufacturing Site 3 #1

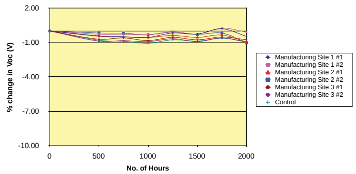


1250 Hours 2000 Hours

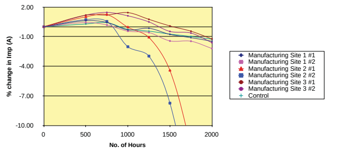
Isc for Damp Heat 2000 hrs



Voc for Damp Heat 2000 hrs

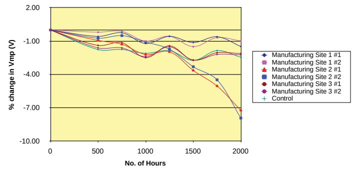


Imp for Damp Heat 2000 hrs



Modules from Manufacturing Site 2 had outdoor exposure for a few months. Visual Inspection showed signs for localized discoloration

Vmp for Damp Heat 2000 hrs



Summary: Three different manufacturing sites have shown different initial failures

- Diode from one site
- Discoloration proved to have shorter life time from a different site
- Implies Process/Materials not the same at each manufacturing site

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Impact of module construction in providing reliability redundancy through accelerated lifetime testing

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Introduction

Crystalline silicon modules manufactured using solder coated copper ribbon and fired glass frit metallization have shown excellent reliability. In this study, we show that the robustness of modules can be attributed to the redundant nature of the module construction whereby even poor mechanical interfaces can be reinforced in the module laminate and maintain high electrical performance.

Module construction and test conditions

Three different test vehicles were fabricated for interval measurements:

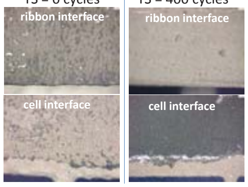
- Bare cells for peel testing
- Unencapsulated strings (2x1 cells)
- Laminated modules (2x1 cells)

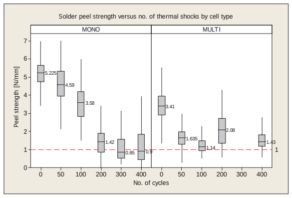
Each of the test vehicles were subjected to two different stress conditions. For accelerated damp heat testing, HAST testing at 120C/100%RH was performed whilst, for accelerated temperature cycling, samples were subjected to thermal shocks from 85C to -40C at a rate of 50 cycles per day. Module construction was made with representative industry standard materials (SnPb ribbon, EVA encapsulant, low iron glass and TPE backsheet) and commercially available multi-crystalline and mono-crystalline cells.

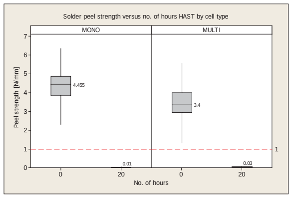
Peel strength measurements

Accelerated life testing is believed to reduce the peel strength of the ribbon/paste soldered interconnect due to a combination of thermo-mechanical stresses in the case of thermal shock and oxidation in the case of HAST. The peel strength drops from a median value of 4.5N/mm to approx. 1.5N/mm after 400 thermal shocks and less than 0.1N/mm after just 20hours of HAST. The optical microscope images below show the peel interface after beginning of life peel testing with cohesive failure in the paste/solder interface and after 400 thermal shocks with failure at the paste/silicon interface.

TS = 0 cycles TS = 400 cycles







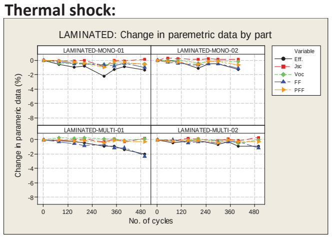
IV performance—bare strings and encapsulated modules

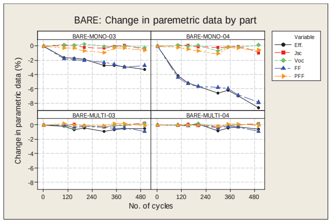
For comparison, both multi- and mono-crystalline cells were fabricated into modules. For the bare strings, the mono- cells show areas of GICS induced micro-cracks (Grid Interruptions Caused by Soldering)[2] in the EL images whereas the multi-crystalline cells do not (see discussion in Analysis section).

Despite the significant decrease in peel strength and increase in GICS, the electrical performance of bare strings shows only a modest change in performance for both 400 cycles of thermal shock and 60hrs of HAST (see plots below). For HAST exposure, the performance change was less than 1% despite a reduction in peel strength of >95%. In the case of HAST testing, although the peel strength is lower than thermal shocked samples, the stress on the interface is also less since the samples are exposed to an isothermal environment closer to the zero stress condition observed at the soldering temperature.

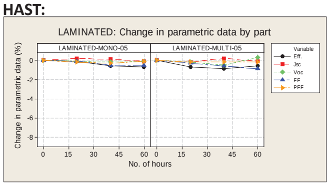
As expected, all laminated samples show good performance during thermal shock and HAST with all modules well within the IEC -61215 specification of 5% degradation both at the test requirement of 200 cycles and beyond.

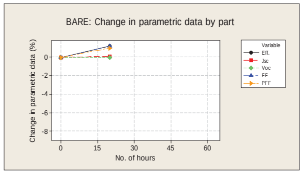
Thermal shock:





HAST:



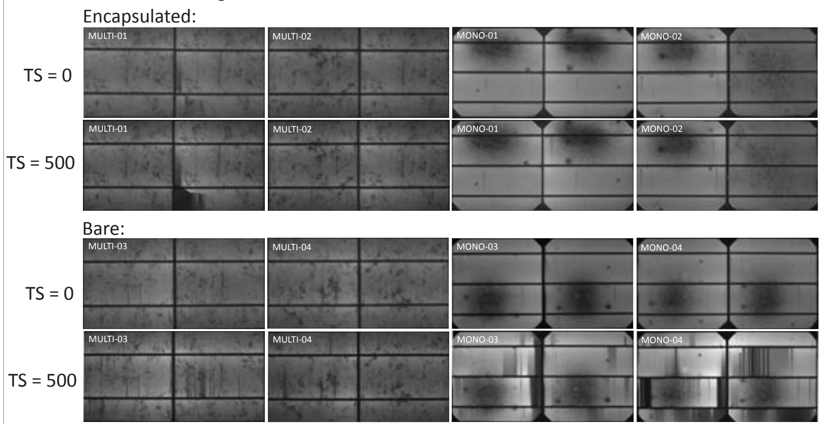


Analysis

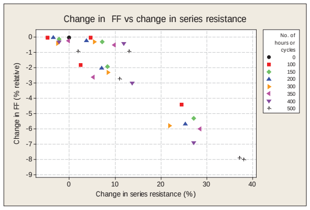
The electroluminescence images below show a clear difference in GICS between bare multi- and mono-crystalline cells. Typically, we have observed that multi-crystalline cells are more susceptible to GICS than mono-crystalline cells. However, as noted by Wiese et al,[1] interconnection stresses are sensitive to the ribbon/busbar width ratio. For this study, the same 1.5mm wide ribbon was used for both the two busbar multicrystalline and 3 busbar mono-crystalline cells but the busbars were 2mm wide for the multicrystalline cells thereby reducing the peak stresses in the joint.

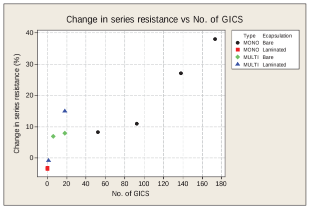
In addition, the electroluminescence images show no GICS for either the laminated mono-crystalline or laminated multicrystalline cells confirming that the laminate provides additional compressive force on the interconnects ensuring good electrical contact during both reliability testing and outdoor exposure.

Electroluminescence images:



It is surprising that the electrical performance of several of the samples studied here is maintained despite a dramatic degradation in peel strength. For the modules that did show degradation, the efficiency drops due a drop in FF (shown in the IV data at left) and this drop in FF correlates with a series resistance increase (plot below, left) and an increase in the number of GICS (plot below, right):





Conclusions

Solar modules have successfully demonstrated many decades of failure free operation in the field. Accelerated testing shows that the industry standard laminate construction and cell interconnection is resistant to both thermo-mechanical and humidity induced failures when combined despite the individual interface connections showing degradation over relatively short test periods.

References

1. Wiese, S.; Kraemer, F.; Betzl, N.; Wald, D.; " Interconnection technologies for photovoltaic modules - analysis of technological and mechanical problems". Thermal, Mechanical and Multi-Physics simulation and Experiments in Microelectronics and Microsystems, 2010. EuroSimE. 11th International Conference on
2. J.Wendt, M. Träger, M. Mette, A. Pfennig, B. Jäckel; "The link between mechanical stress induced by soldering and micro damages in silicon solar cells". Q-Cells SE.

CFV solar test laboratory

Variability in NOCT Standard Test Results as a Function of Day, Time of Day, and TC location

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CFV Solar Test Laboratory (Albuquerque, NM)

Purpose

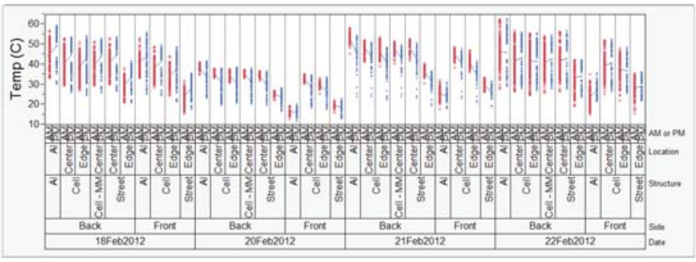
The purpose of this investigation is to quantify the major components of variation in the Determination of NOCT test as performed according to section 10.5 of the IEC 61215 standard.

Test Setup

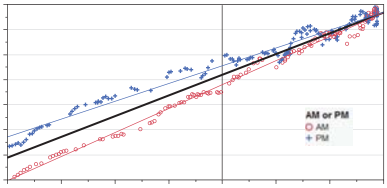
- Tests conducted at CFV Solar Test Laboratory in Albuquerque, NM
- Test stand setup according to IEC 61215 requirements

Config. #	TC IDs
1	Cal 156, 155,152
2	Cal 157, 156, 155
3	Cal 153, 154, 152
4	Cal 157, 156, 153, 154, 155, 149, 152
5	Cal 156, 154, 155, 152, 237, 244, 236

Results



- Module component temperatures are similar for Al plates, center cells, edge cells, and street regions in the center of the module
- Temperatures on the front side of the module are lower than the back side
- Temperature of mis-matched cell under short circuit is approximately the same as other center cell temperatures during NOCT test



Difference in temperature delta from morning and afternoon on a previously tested crystalline module

Conclusion

NOCT TEST DATA- OPEN CIRCUIT, DIFFERENT TC KONFIGURATION FEBRUARY 2012

Date	18-Feb	20-Feb	21-Feb	22-Feb	Average	Range
Time (start/end)	9:15-16:35	11:04-16:37	09:57-15:53	8:31-16:34		
# data points	432	321	340	470		
Ambient Temp C, average	9.7	7.3	11.4	13.7		
Wind Speed m/s, average	1.03	1.6	1.6	1.30		
Irradiance range W/m^2	404.7-1133	400.4-1165	520.5-1142	415.1-1184		
Irradiance W/m^2, average	932.78	942.36	1003.68	851.87		
NOCT correction factor, C	-1	0	0	0		
NOCT reported, TC config 1	44.5	45.8	45.5	43	44.7	1.3
NOCT reported, TC config 2	46.9	42.8	45.6	47	45.6	4.1
NOCT reported, TC config 3	44.2	40.3	43.1	44.4	43.0	3.9
NOCT reported, TC config 4	45.6	41.8	44.5	45.9	44.5	3.8
NOCT reported, TC config 5	42.9	39.1	42.1	43.3	41.9	3.8
NOCT average C, TC config 1-5	44.8	42.0	44.2	44.7		
NOCT range C, TC config 1-5	4.0	6.7	3.5	4.0		

- Accurate estimate of module temperature is critical to NOCT measurements
- Based on these data, the estimate of module temperature using estimates from the back side, center proved most repeatable from day to day
- Estimates of module temperature result in a 4 degree difference depending on TC configuration, even on a clear day with low wind

Literature Review:

- IEC 61215. Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval 2006
- M. Pellegrino, C. Cornaro, S. Bartocci, G D'Angiolini, G.Flaminio, V. Giglio, A. Matano, G. Nardelli, A. Ortense, and A. Spena, Proceedings of the 24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany
- Ruhi Bharti, Joseph Kuitche, Mani G. TamizhMani, ''Nominal Operating Cell Temperature (NOCT): Effects of module size, Loading and solar spectrum" in: Proceedings of the IEEE Photovoltaic Specialist Conference, September, 2009.
- Matthew Muller, "Measuring and Modeling Nominal Operating Cell Temperature (NOCT)" in: PV Performance Modeling Workshop Albuquerque, NM, September 22-23, 2010.

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Systematic Approaches to Determining Degradation Rates from Continuous Meteorological and System Production Data

2012 PV Module Reliability Workshop, NREL, Golden, Colorado, February 28-29, 2012

Kenneth J. Sauer

1.

BACKGROUND

- Project size and financing are governed by the confidence investors have in the projected energy production of a photovoltaic (PV) system over the term of its power purchase agreement or planned asset lifetime.
- Production estimates are largely a function of anticipated annual degradation rates (R_d), which are known to vary within and across PV technologies and systems.
- The ability to more accurately and objectively quantify degradation rates is fundamental toward yielding more favorable energy production exceedance probabilities and improving the overall financial viability of large-scale PV.

APPROACH

- Systematic approaches in qualifying and translating raw, continuous meteorological and system production data into performance time series are developed for the purpose of identifying linear trends in PV system performance as a function of time (R_d).
- The developed approaches are implemented using data from a large-scale, commercial PV array of multicrystalline silicon modules in operation for over 2.5 years.
- Initial steps toward model validation are taken through measurements conducted on a sample of modules after two years of outdoor exposure.

REFERENCES

1. D. L. King, W. E. Boyson, J.A. Kratochvil, "Photovoltaic array performance model", Sandia National Laboratories Publication #SAND2004-3535, August 2004.
2. STC: 1,000W/m² global POA irradiance (G_{STC}), 25°C module temperature (T_{STC}), AM1.5 spectrum according to EN 60904-3.
3. International Standard IEC 61724. Photovoltaic system performance monitoring – Guidelines for measurement, data exchange and analysis, First Ed., International Electrotechnical Commission (IEC), Geneva, April 1998.
4. List of Eligible Inverters per SB1 Guidelines – Go Solar California. (2011). Retrieved, May 23, 2011, from http://www.gosolarcalifornia.org/equipment/inverters.php

2.

Meteorological & Production Data

- For implementing (and reporting on) approaches in R_d analysis, 2.5 years of non-spectrally corrected data with a 1-min sampling interval (τ_s) are used. Data at each τ_s include date, time, system AC energy output (E_{AC}, kWh), instantaneous global plane-of-array irradiance (G_{POA}, W/m²), instantaneous module temperature (T_{MOD}, °C) and instantaneous ambient temperature (T_{AMB}, °C).
- Nominal uncertainties of G_{POA}, T_{MOD} and T_{AMB} measurements are ±5%, ±0.5°C, and ±0.3°C, respectively. A calibrated silicon photodiode pyranometer and temperature sensor fixed to the backsheet behind a cell were used to measure G_{POA} and T_{MOD}, respectively.
- A kWh meter was used to measure E_{AC} at the combined output of (5) inverters.

Cell Temperature Model

- Eq. 1 is used to convert T_{MOD} to cell temperature (T_{CELL}, °C) at each indexed τ_s. The difference between backsheet and cell temperature (ΔT) is 3°C for the modules in the chosen system [1, 2].

$$(1)\quad T_{CELL,i,\tau_s} = T_{MOD,i,\tau_s} + \left(\frac{G_{POA,i,\tau_s}}{G_{STC}}\right)\cdot \Delta T$$

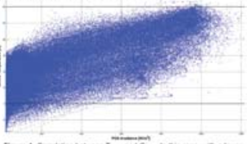


Figure 1. Correlation between T_{CELL} and G_{POA}. In this case, with a lower data acceptance criterion of G_{POA} in place (for example, $G_{POA} \geq 700W/m^2$), T_{CELL} is effectively constrained to 0-60°C.

Energy Models

- G_{POA} and E_{AC} are used to derive insolation (H_{POA}, Wh/m²) and power (P_{AC}, kW), respectively, over each τ_s per IEC 61724-1 Section 8 [3].

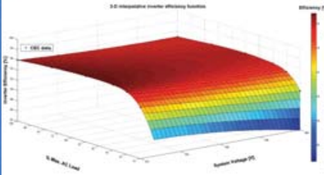
3.

Inverter Efficiency Model

- The nominal module MPP voltage and temperature coefficient of voltage (β_{Vmpp}=-0.46%/°C) are used to derive operating system voltage from T_{CELL} and the series string size, N_s (Eq. 2) [2].

$$V_{mpp,SYST,i,\tau_s} = N_s \times V_{mpp,Nom,MOD} \times \left[1+\beta_{Vmpp}\cdot(T_{CELL,i,\tau_s} - T_{STC})\right] \quad (2)$$

- An empirical, 2-D cubic-spline interpolation-based model (f_i) describing inverter efficiency as a function of power and input voltage is used to translate AC to DC production data (Eq. 3, Fig. 2). Inverter performance data made public by the California Energy Commission and California Public Utilities Commission (CEC & CPUC) provides the basis for the model [4]. DC energy (E_{DC}, kW) is derived from P_{DC} per IEC 61724-1 Section 8 [3].



$$P_{DC,i,\tau_s} = \frac{P_{AC,i,\tau_s}}{f_i\left(V_{mpp,SYST,i,\tau_s}, \frac{P_{AC,i,\tau_s}}{P_{AC,Max,Inv}}\right)} \quad (3)$$

Figure 2. 2-D cubic-spline interpolation fit of inverter efficiency. Normalized data can yield additional insights regarding degradation of the DC or AC side of the inverter, depending on the direction of translation. The small amount of data outside the limits of the CEC & CPUC data (here, 300-480V_{DC} and 10-100% of the max. rated AC load, $P_{AC,Max,Inv}$) is removed to avoid extrapolation errors.

4.

Recording Interval

- A data recording interval (τ_r, where $\tau_r \geq \tau_s$) is user-defined (here, 5-min is used). E and H_{POA} at each τ_s are summed over each indexed τ_r, while P, T_{AMB}, T_{CELL}, and G_{POA} are averaged.

Performance Model

- System efficiency (η_{DC}, Eq. 4) is calculated over each τ_r [2].

$$\eta_{DC,i,\tau_r} = \frac{E_{DC,i,\tau_r}}{H_{POA,i,\tau_r}\cdot A_{SYST}} \quad (4)$$

Power Temperature Coefficient

- The temperature coefficient of MPP power (γ_{Pmpp}) is derived from the slope of η_{DC} vs. T_{CELL} following a robust linear regression fit (Fig. 3). In Fig. 4, γ_{Pmpp} is shown to vary when the lower data acceptance limit of G_{POA} is set at a level <700W/m².

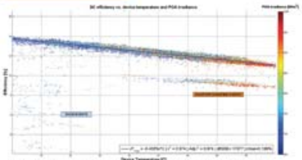
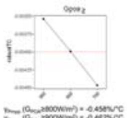


Figure 3. γ_{Pmpp} is extracted from the production data using a robust linear regression fit. The robust fit method is used for its stability in the presence of outliers (in this case, stemming from snow and inverter downtime events).



γ_{Pmpp} ($G_{POA}\geq 800W/m^2$) = -0.458%/°C
γ_{Pmpp} ($G_{POA}\geq 900W/m^2$) = -0.462%/°C

Figure 4. The response of γ_{Pmpp} to the lower G_{POA} filtration cutoff (with the upper limit fixed at 1,000W/m²) is demonstrated with a main effects plot. γ_{Pmpp} remains highly stable for lower data acceptance limits ≥700W/m². In this work, a lower limit of 700W/m² is applied.

5.

STC Rating

$$(5)\quad E_{DC,STC-Adj,i,\tau_r} = \frac{E_{DC,i,\tau_r}}{\left(\frac{H_{POA,i,\tau_r}}{H_{STC}}\right)\cdot\left[1+\gamma_{Pmpp}\cdot(T_{CELL,i,\tau_r} - T_{STC})\right]}$$

$$(6)\quad E_{DC,STC} = f_H(H_{STC})$$

- A robust linear fit of STC-adjusted E_{DC} ($E_{DC,STC-Adj}$, kW, Eq. 5) vs. H_{POA} over the range of device linearity (Fig. 5) is used to approximate performance at STC (Eq. 6) for use in Eq. 7 [2]. H_{STC} is derived from G_{STC} over τ_r following IEC 61724-1 Section 8 [2, 3].

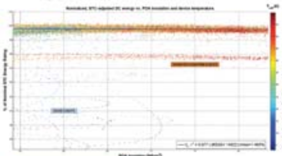


Figure 5. $E_{DC,STC-Adj}$ (normalized to the nominal rating) is plotted vs. H_{POA} (and T_{CELL}). A robust linear regression is used to fit $E_{DC,STC-Adj}$ over the range of device linearity ($700W/m^2 \leq G_{POA} \leq 1{,}000W/m^2$). Substitution of H_{STC} into f_H (Eq. 6) yields an approximation of the system energy rating at STC that can be applied in Eq. 7.

Relative Efficiency Delta from STC

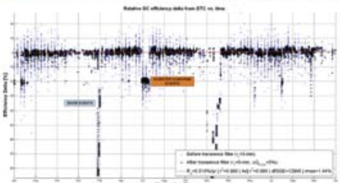
- f_H is used in Eq. 7 to compute the relative efficiency deviation (delta) from STC ($\Delta\eta_{DC,STC}$) over each indexed τ_r [2]. R_d can be extracted from a linear fit of $\Delta\eta_{DC,STC}$ vs. time (Fig. 6, Eq. 10).

$$\Delta\eta_{DC,STC,i,\tau_r} = \left\{\frac{E_{DC,i,\tau_r}}{f_H(H_{STC})\cdot\left(\frac{H_{POA,i,\tau_r}}{H_{STC}}\right)\cdot\left[1+\gamma_{Pmpp}\cdot(T_{CELL,i,\tau_r} - T_{STC})\right]}\right\} - 1 \quad (7)$$

6.

Irradiance Transience Model

- An irradiance transience allowance criterion (ΔG_{POA}) is applied within each τ_r (Eqs. 8-9, Fig. 6) to remove unrepresentative data from imprecise measurements collected during transient (cloudy) ambient conditions. A robust linear regression is used to extract R_d using Eq. 10, where N_t is a time index multiplier.



$$\left[\frac{\max(G_{POA,i,\tau_r} \geq 0)}{\min(G_{POA,i,\tau_r} > 0)}\right] \leq 1 + \Delta G_{POA} \quad (8)$$

$$\left[\frac{\min(G_{POA,i,\tau_r} \geq 0)}{\max(G_{POA,i,\tau_r} > 0)}\right] \geq 1 - \Delta G_{POA} \quad (9)$$

$$R_d\left(\frac{\%}{yr}\right) = \left(\frac{N_t \cdot m}{b}\right)\cdot 100 \quad (10)$$

N_t=1 (yr.), 12 (mo.), 52 (week), 365 (day), depending on the reporting interval (τ).

Figure 6. $\Delta\eta_{DC,STC}$ vs. time, with 1.) no transience filter applied, and 2.) ΔG_{POA}=5%. R_d is reported for case (2).

Noise Events

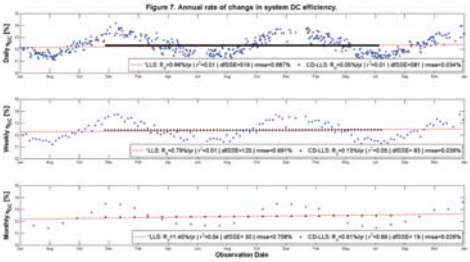
- Noise events (snow, inverter downtime) are removed prior to final analysis of R_d. Filtration criteria based around the median $\Delta\eta_{DC,STC}$ can in some cases be applied as a categorical filter.

Reporting Intervals

- Final system R_d results are derived from η_{DC} time series (Eq. 4), computed over daily, weekly and monthly reporting intervals (τ).

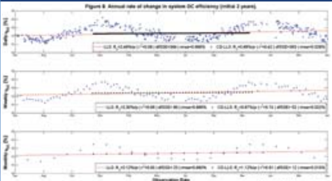
7.

Figure 7. Annual rate of change in system DC efficiency.

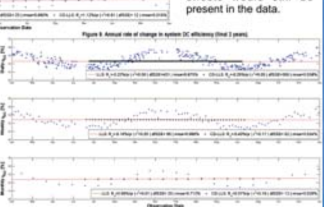


- The time series of η_{DC} at each indexed τ are plotted. Simple linear least squares fit (LLS) is used to derive R_d (Eq. 10). *With LLS, it is best if data begins and ends at the same time of year, to avoid seasonality effects – note that Fig. 7 includes the full data set (2.5 years).
- Classical decomposition (CD) method is applied to deseasonalize the η_{DC} time series, ideally such that all available data can be used. Centered moving averages are computed over periods of N_t. Moving average time series are fit using LLS to derive R_d (CD-LLS).

8.



- In this case, resultant positive R_d values (Figs. 6-7) were thought to relate to a faulty inverter that was repaired on two occasions during the initial "wear-in" period of system operation. Since DC production data was derived (Eq. 3), such effects would still be present in the data.
- The R_d analysis was (thus) run twice more: first, using the initial two full years of data from the system (Fig. 8), and then using the final two years (Fig. 9). As anticipated, R_d results converged toward a more positive rate in the first two years, and a more negative rate in the final two years.



9.

Model Validation

- A first model validation effort was carried out through testing a sample of modules (n=32) from the same system after two years in operation (t), according to the on-site (field) and laboratory protocols outlined in Fig. 10. Module R_d results are computed using Eq. 11 and summarized statistically in Fig. 11.

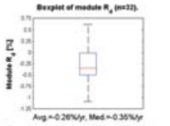
On-site (outdoor)
- Randomly select sample of modules.
- Photograph modules.
- IR image under MPP load.
- Electrically isolate modules.
- Light I-V sweep using portable curve tracer following IEC 61829-1.
- IR image in short-circuit (SC) condition.
- Dismount modules and prepare for shipping.
- Re-install modules.
- IR image (MPP and SC condition).
- Light I-V using portable curve tracer following IEC 61829-1.

Laboratory (indoor)
- Photograph modules and packaging.
- Visual inspection per IEC 61215-10.1.
- Electroluminescence imaging (low and high current).
- Wet leakage current per IEC 61215-10.15.
- Dark I-V sweep (two current levels).
- Temperature coefficients per IEC 61215-10.4.
- Light I-V sweep using flash-based solar simulator per IEC 61215-10.3.
- Package modules and return to site.

Figure 10. Test protocols used for R_d model validation. The testing will be repeated on a recurring basis using the same sample of modules.

$$R_d\left(\frac{\%}{yr}\right) = \left[\frac{\left(\frac{P_t - P_0}{t}\right)\cdot N_t}{P_0}\right]\cdot 100 \quad (11)$$

Boxplot of module R_d (n=32).



Avg.=-0.26%/yr, Med.=-0.35%/yr

Figure 11. Boxplot of module R_d values calculated using Eq. 11, where the initial power, P_0, represents light-stabilized, factory-tested values, and the power after two years of operation, P_t, is based on indoor laboratory measurements. Results align well with R_d derived from the model using the final two years of data from the chosen system.

Yingli Americas

SOLAR WIND

Reproducing the Effects of Wind-Induced Field Vibration on PV Modules in the Laboratory Without the Requirement of a Wind Tunnel

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WESTPAK, INC.
EXCELLENCE IN TESTING

Presented at the 2012 PV Module Reliability Workshop, February 28 – March 1, 2012, Golden, Colorado

INTRODUCTION

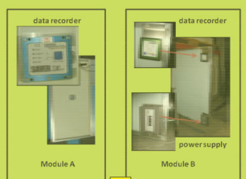
- There is a 100% probability that all PV modules will be exposed to vibration during handling, transportation, installation, and exposure to high winds in the field. What is not well understood are the effects of vibration stimuli on PV modules with respect to the module's ability to produce electrical power throughout its expected lifetime.
- In order to study the effects of vibration stimuli, an efficient and economical method to reproduce the effects of vibration in the laboratory must be established and utilized.

OBJECTIVES

- Determine if we could adequately reproduce wind vibration response in the laboratory without a wind tunnel.
- Determine the effect vibration induced flexing has on module reliability, and to what extent a combination of environmental stresses including vibration, temperature extremes, and humidity had on PV module reliability.

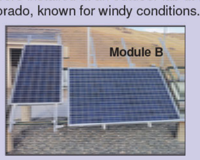
APPROACH

1. Vibration sensors and data recorders were attached to two c-Si PV test modules of significantly different physical dimensions.



	Tech	No. of Cells	Pmax	Dims (L x W)	Weight
Module A	c-Si	72	170 Watts	1.6m x 0.8m	17 kg (37.5 lbs)
Module B	c-Si	216	270 Watts	1.9m x 1.3m	47 kg (104 lbs)

2. Modules were installed at an outdoor lab at NREL in Golden, Colorado, known for windy conditions.



Field installation at NREL

3. Wind speed and response to the wind-induced vibration of each module was monitored and recorded for a six month period.

4. Modules were returned to the test lab where the module's field response using mechanical vibration input was reproduced.

Vibration machines at Westpak

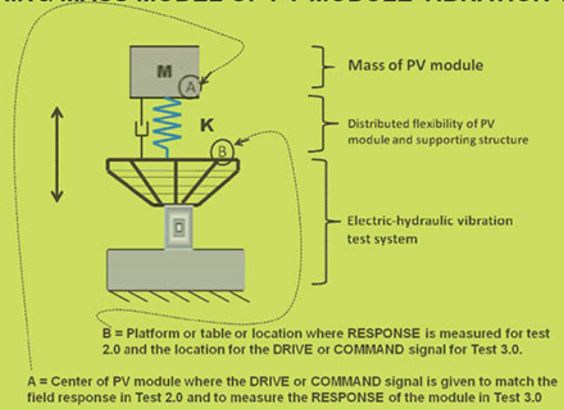
5. After initial vibration input on the machine, modules were characterized (visual, I-V, EL).

6. Modules were subjected to small amount of high intensity wind excitation, which was followed by 36 hrs of Damp Heat (+85°C / 85% RH) and Thermal Cycling TC50 (-40°C to +85°C, no v-bias) exposure.

7. Modules characterized (visual, I-V, EL).

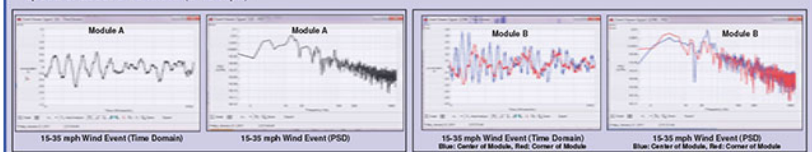
8. Repeat the vibration input with small increases in excitation and/or duration until significant module change is noted .

SPRING MASS MODEL OF PV-MODULE VIBRATION TEST

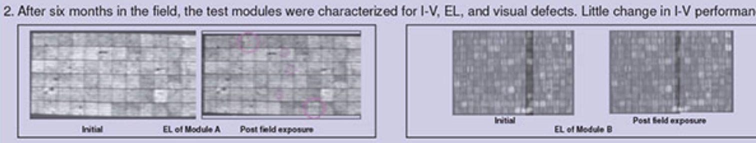


RESULTS

1. Commercially available recording devices can easily record vibration (acceleration) response levels as low as 2 m/s2 (equal to wind speed of about 8-16 km/hr (5-10 mph)



2. After six months in the field, the test modules were characterized for I-V, EL, and visual defects. Little change in I-V performance.



3. (Test 2.0) Using the RESPONSE spectrum from field data as the CONTROL for the vibration input command, the vibration machine reproduced the wind-induced vibration response on each module. The base table spectrum was recorded.

(Test 3.0) The test module was then EXCITED with the table data from the previous test data from the previous test and the RESPONSE on the module was compared to field data (Test 3.0)

Spectra of field response and vibration excitation response for Modules A and B

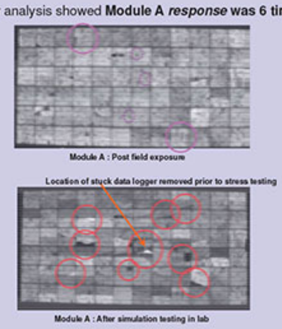
<u>Lab data is a reasonable match for field data for both modules</u>

4. (Test 3.0) Test modules were then subjected to 5 minutes of excitation equivalent to 29 m/s (65 mph) wind speed following 36 hrs DH (+85°C / 85% RH) and TC50 (-40°C to + 85% RH, no v-bias).

<u>SIGNIFICANT</u> degradation in Module A performance as judged from EL and visual inspection. I-V showed ~10% decrease in Pmax.

Module B showed no change in Pmax.

Later analysis showed **Module A *response* was 6 times the input** while Module B *response* was nearly equal to the input.



Module	Pmax (Watts)			Change from initial (%)	
	Initial , (data Sept 2010)	Post NREL Field, (data Nov 2011)	Post simulation testing (Dec 2011)	Post NREL fie d	Post simulation testing
Module A (control)	168.1	164.2		-2.3%	
Module A (test)	170.1	166.7	153.5	-2.0%	-9.8%
Module B (control)	280.8	283.6		1.0%	
Module B (test)	271.9	272.9	277.1	0.4%	1.9%

I-V Performance of Modules A and B

CONCLUSIONS

1. It is feasible and acceptable to reproduce field level wind-induced vibration excitation on mounted PV modules in the laboratory using standard vibration test equipment in order to help evaluate the resistance of modules to the negative effects of wind excitation.

2. When used in combination with Damp Heat and Thermal Cycling, vibration excitation <u>*may be*</u> an important tool in reliability studies for PV modules.

UN-ANSWERED QUESTIONS

1. Is it necessary to get field wind data (spectrum, Test 1.0) for each module or is there a method of determining this in the lab?

2. Can we predict the performance of a module beyond the measured input? (at 80 mph?)

3. What is the vibration excitation level suggested for possible R&D or certification tests?

4. What is a "good" combination of vibration and other tests (i.e. TC, DH, HF) to give better reliability data?

ACKNOWLEDGEMENTS

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Silicon Cracking in Plated c-Si Solar Cells

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TetraSun

Introduction

Several batches of C-Si solar cells were processed through electrolytic plating for deposition of Cu bus bars and finger grids in TetraSun's pilot line.

The solar cells were subsequently tabbed with both manual and automated soldering process for the fabrication of small modules.

EL imaging of the tabbed solar cells shows that some portions of the device are electrically disconnected. This is leading to a severe reduction of the expected module output power (Figure 1).

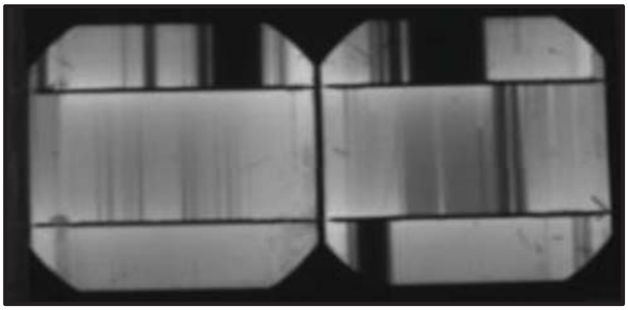


Figure 1: EL image of two tabbed solar cells showing electrically disconnected areas within the device

Pull Test Data

Some solar cells were prepared with PV ribbon soldered to the bus bars. These cells were first inspected with EL imaging and then sorted in defected cells and defect free cells. EL images of defected cells were showing the characteristic signature of the electrically disconnected areas while a typical EL image of defect free cells is shown in Figure 2. A standard pull test was completed on both groups of solar cells. The pull test data of defected solar cells is very different with respect to defect free cells. A comparison of the pull test for defected cells and defect free cells is show in in Graph 1.

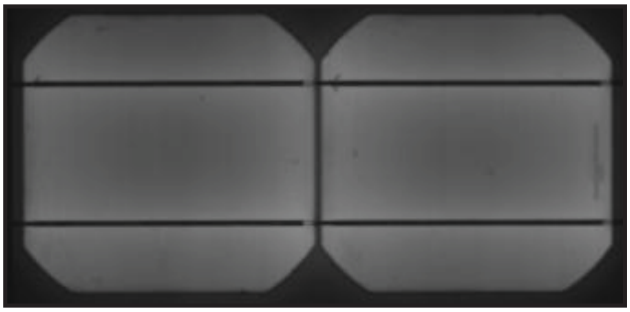
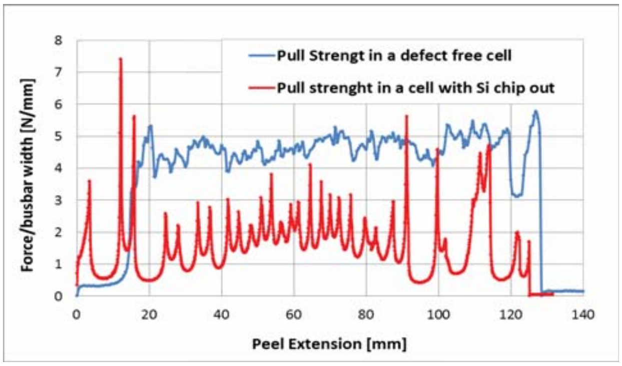


Figure 2: EL images of two tabbed solar cells free form soldering defects



Graph1: Pull test comparison of defected cells and defect free cells

Failure Analysis

SEM inspection in the corresponding dark regions of the EL images does neither show adhesive failure between the silicon and the metal layer nor adhesive failure within the metal stack.

In these areas the silicon is clearly cracking at the edges of the bus bar (Figure 3). The cracking can be so severe to induce dislocation or chip out of the silicon which eventually results in cut metal fingers. (Fig 4). This is the reason for the electrical discontinuity observed in the device with the EL inspection.

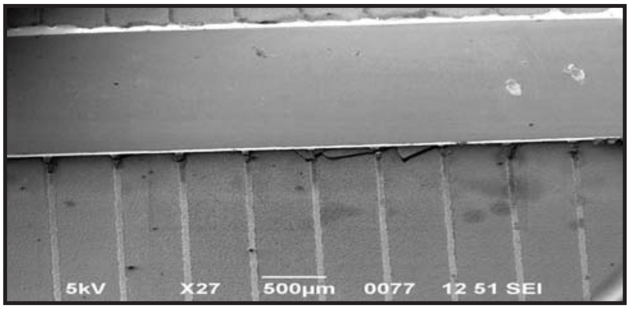


Figure 3: SEM image of cracked silicon along the bus bar

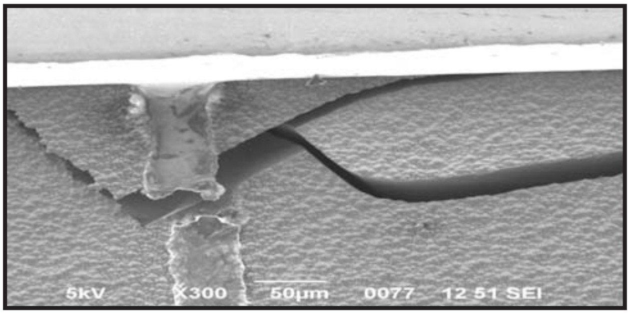


Figure 4: SEM image of cut metal finger due to Silicon chip out

CONCLUSIONS

TetraSun c-Si cells with plated bus bars and finger grids show a very good pull strength around 5 N/mm. A reduced pull force approaching the ≥1 N/mm criteria is directly correlated to defected solar cell that show electrically disconnected areas under EL inspection.

SEM analysis confirms that the periodically reduced pull strength is not a failure related to the metallization but is physically correlated to a cracking of the silicon itself. The cracking can be so severe that occasionally it leads to break the metal fingers detaching them from the bus bar. This results in electrical disconnect of section of the solar cell from the rest of the device.

Though this failure mode can be reduced by adjusted parameters of the soldering process, the physical mechanism that leads to the silicon fracturing is not yet entirely understood [1], [2].

REFERENCES:

[1]: THE LINK BETWEEN MECHANICAL STRESS INDUCED BY SOLDERING AND MICRO DAMAGES IN SILICON SOLAR CELLS
J.Wendt, M. Träger, M. Mette, A. Pfennig, B. Jäckel. Q-Cells SE

[2]: SOLDERING INDUCED DAMAGE TO THIN SI SOLAR CELLS AND DETECTION OF CRACKED CELLS IN MODULES
Andrew M. Gabor, Mike Ralli, Shaun Montminy, Luis Alegria, Chris Bordonaro, Joe Woods, Larry Felton. - Evergreen Solar, Inc.

Acknowledgement
We gratefully acknowledge the support of NREL and DOE under the Incubator Program subcontract No. NAT-0-99013-04.

Influence of elastic modulus of encapsulant on solder bond failure of c-Si PV modules

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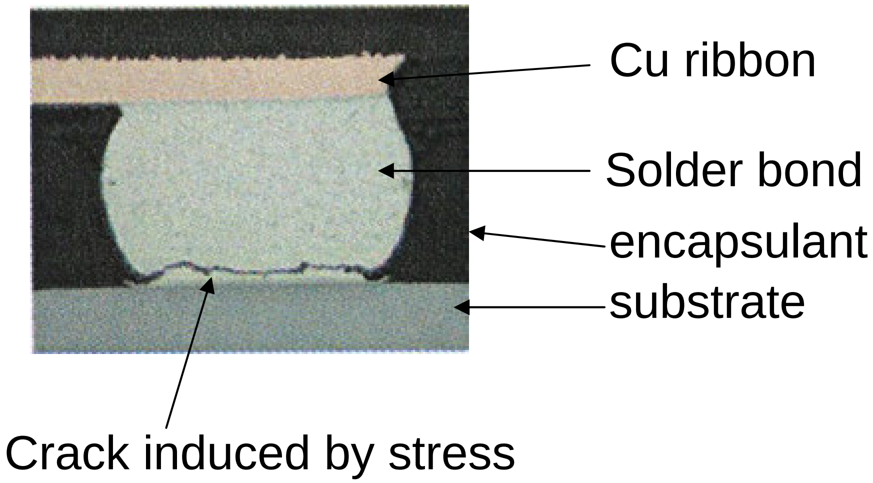
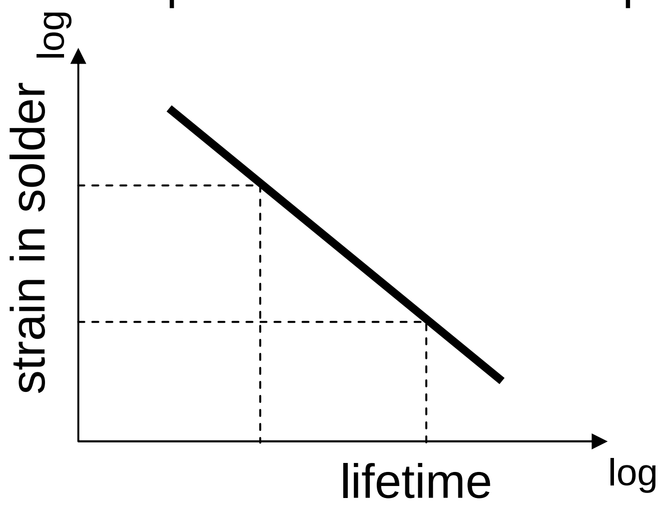
Mitsui Chemicals Tohcello, Inc.
Mitsui Chemicals, Inc.

Solder bond failure

Our approach for lifetime prediction of solder bond failure

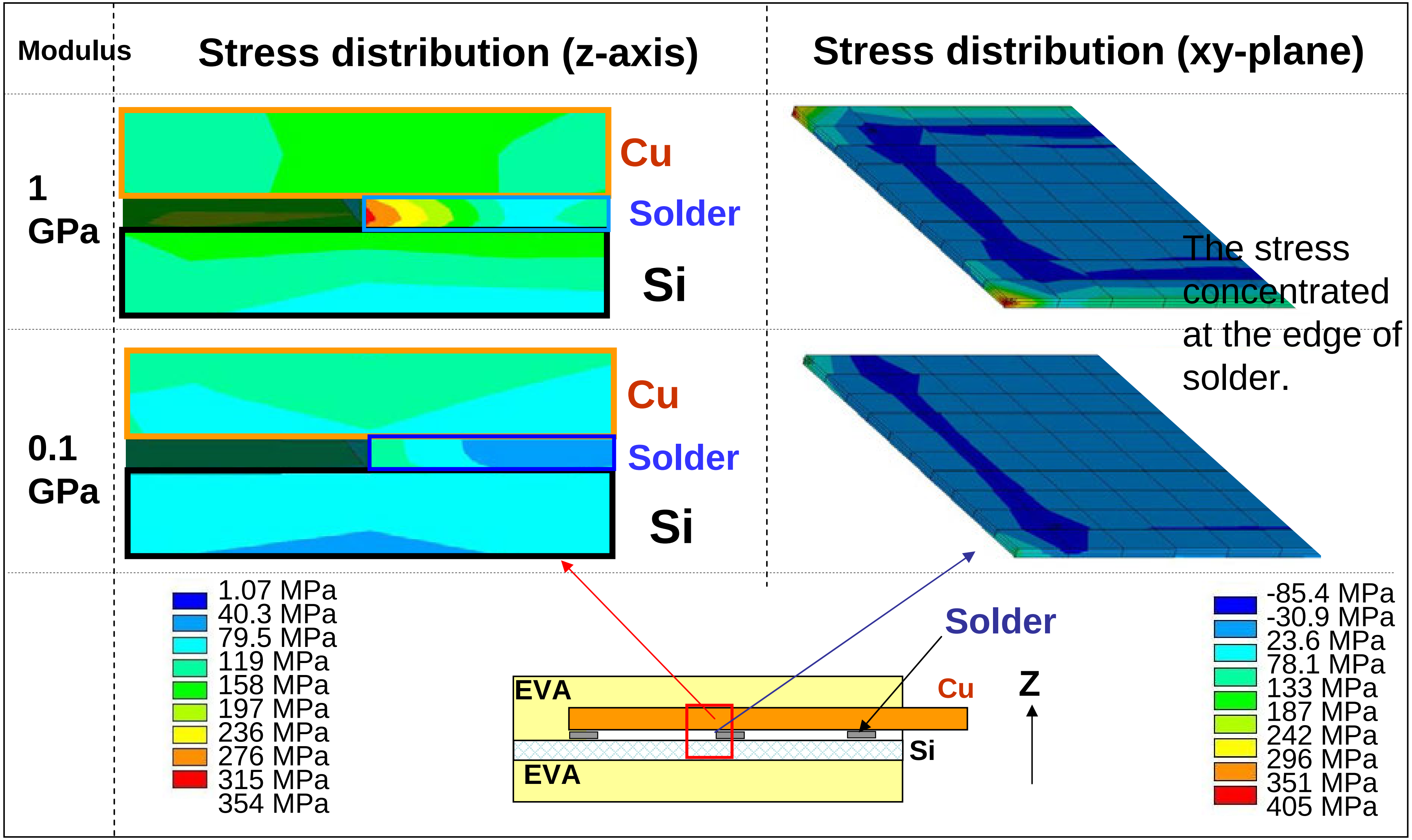




Low strain (stress) leads to long lifetime.

We have calculated stress distribution in solder changing elastic modulus of encapsulant by using finite element method (FEM).

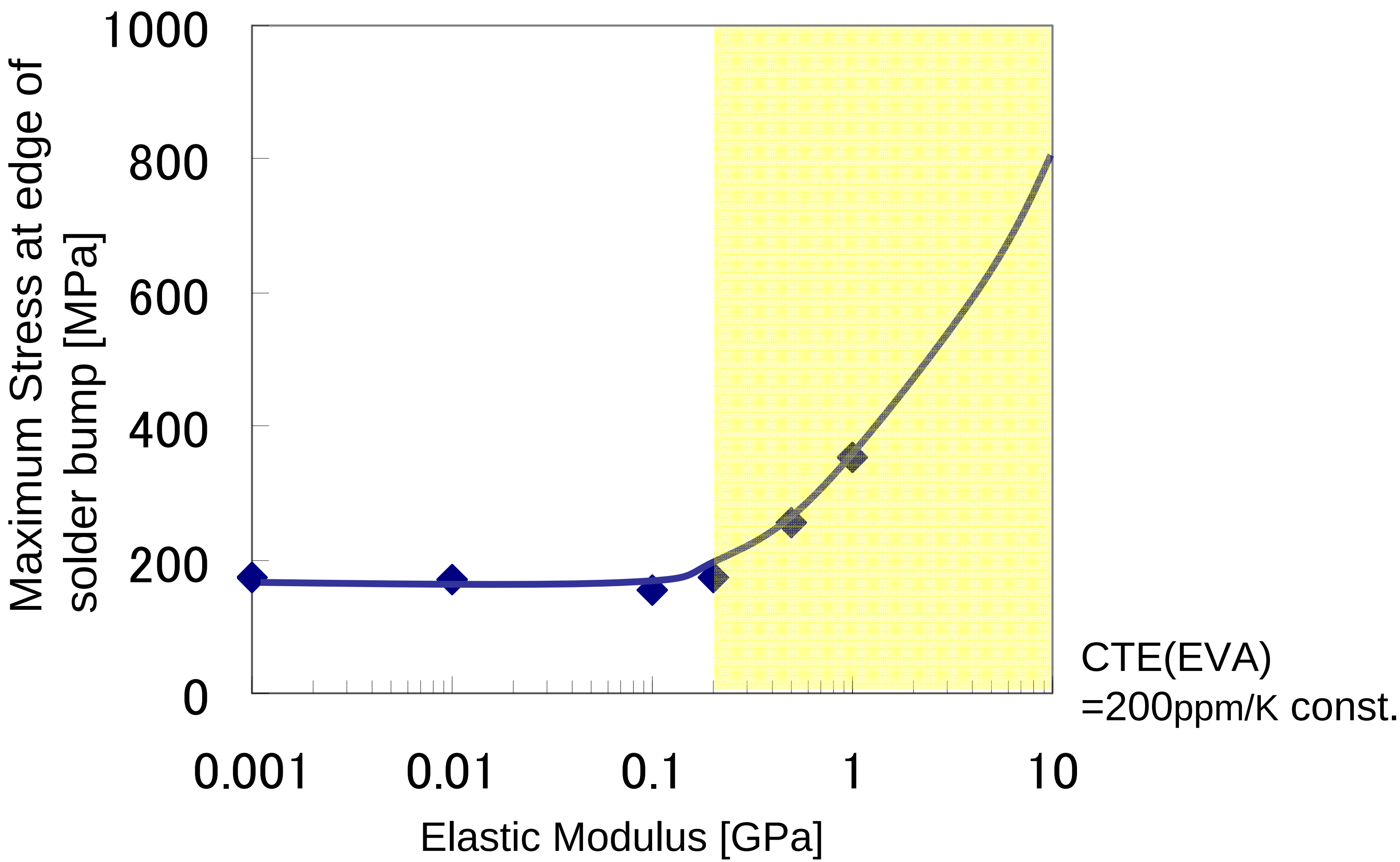
Solder bond failure -simulation-



Stress due to thermal expansion of EVA increases with high modulus of EVA

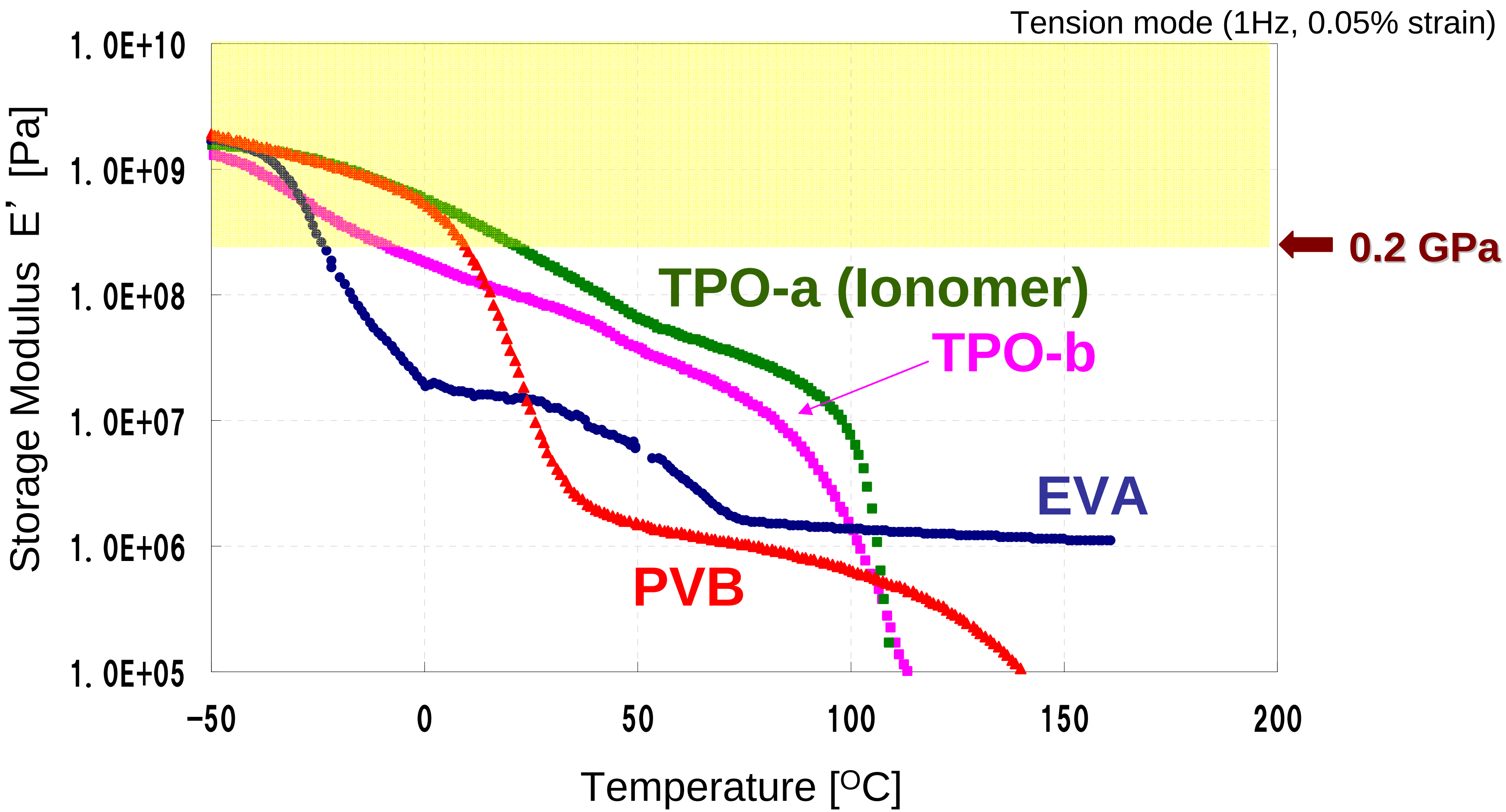
Stress as a function of Elasticity

Mitsui Chemicals Group



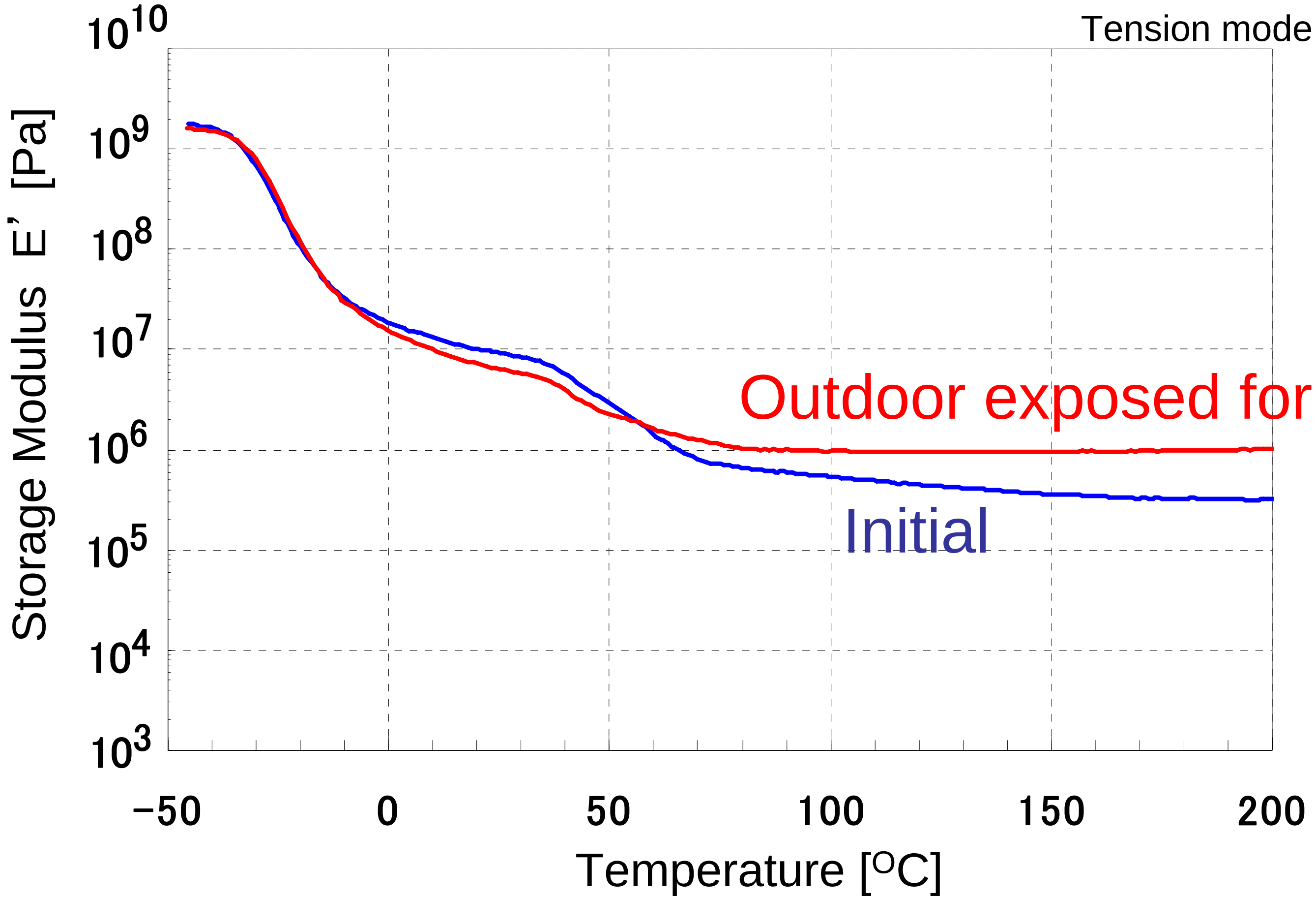
The elastic modulus >0.2 GPa of encapsulant leads to high stress at the solder bump.

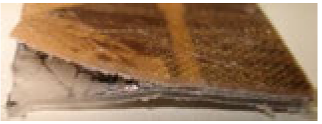
Elastic modulus for several encapsulants



TPO-a has high elasticity >0.2 GPa at room temperature and high risk for solder bond failure, according to our simulation.

Change in elastic modulus of EVA sheet





There are no changes significantly in elastic modulus, caused by decomposition of EVA. This result indicates EVA encapsulant is reliable.

Mitsui Chemicals Tohcello, Inc

Summary

✓We estimated maximum stress at solder bond as a function of elastic modulus of encapsulant using FEM.

✓The elastic modulus >0.2 GPa of encapsulant leads to high stress at the solder bump.

✓TPO-a (Ionomer) has high elasticity >0.2 GPa at room temperature and high risk for solder bond failure, according to our simulation.

✓There are no changes significantly in elastic modulus, caused by decomposition of EVA. This result indicates EVA encapsulant is reliable.

✓We speculate that risk of cell-crack of c-Si cells in a PV module depends on elastic modulus of encapsulant as well as solder bond failure. To find out the trend is ongoing.

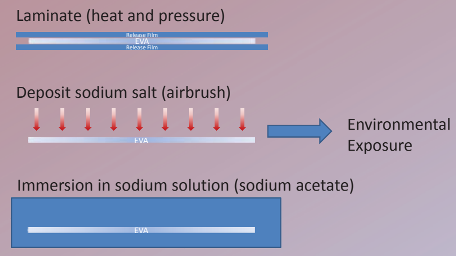
The Effect of Na on the Electrical Breakdown of EVA

Rob Sorensen, Jim McElhanon, Michael Quintana, Roger Rasberry
Sandia National Laboratories

Test Plan

This study will develop an understanding of the changes in dielectric properties that occur in EVA as a function of age and exposure to different environments. The study can take several paths.

- Creating an accelerated test to validate the model(s).
- Validation efforts that test dielectric strength of samples.
- Modules with >5 years service in humid climates could be brought back for validation efforts.
- Ultimately use this information to
  - develop standardized accelerated test protocols
  - study safety/reliability issues

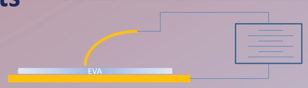


Proof Test
EVA in solution of NaAcetate - 3 days.
Rinse in DI water & dry.
Measure Na on surface.
Measure Na in bulk of EVA

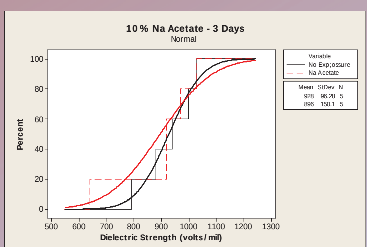
Na (ug/cm2)	1	10	100
	Exposure (%RH) at 70C		
Time	20%	50%	85%
1 week	X	X	X
3 weeks	X	X	X
6 weeks	X	X	X

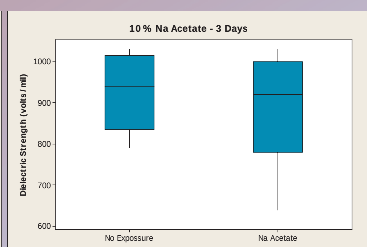
Voltage Breakdown Measurements

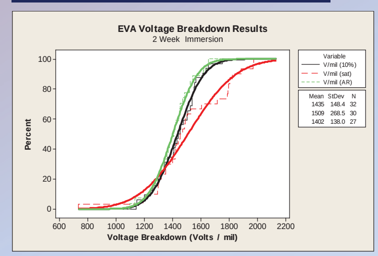
Initial Results (3 day immersion)
- No change in breakdown characteristics
- Measured at external lab

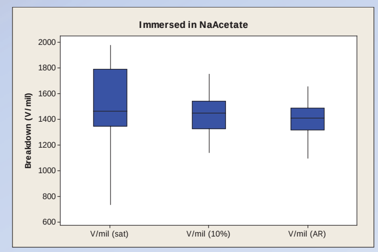


Round 2 (2 week immersion)
- No change in breakdown characteristics
- Measured internally
- No evidence of Na in the EVA

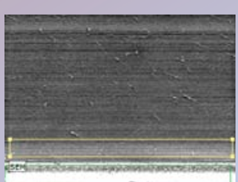


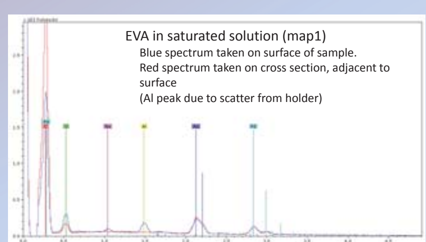


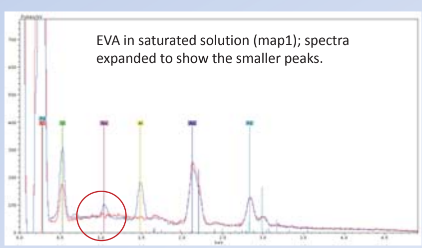




Compositional Analyses (SEM / EDS)





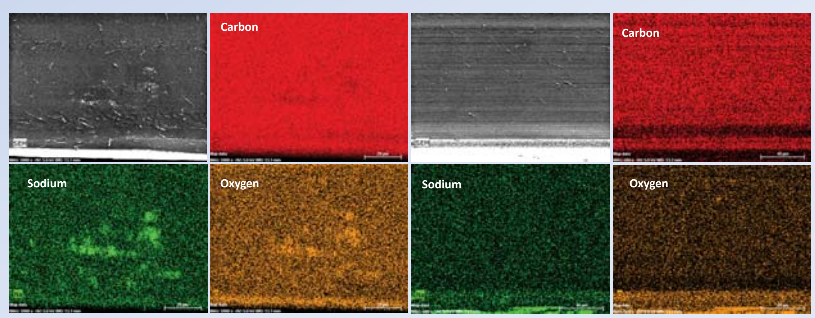


Sample cut to expose cross section. Spectra were taken that compare surface and internal composition (Na). Na was found on the surface, but not on the interior.

No evidence of Na diffusion into the EVA.
- Insufficient time?
- Wrong chemistry?

Elemental Maps:
Na found on surface. It is present as discrete deposits. Simple rinsing did not remove the Na.
Sodium was not seen on the cross section, indicating little or no diffusion had occurred.

EVA Surface **EVA Interior**



Summary

Status
With limited data, no evidence of Na effects
- No difference in breakdown (short exposures)
- No Na in the EVA

Ongoing Work
Continue immersion tests
- Longer time exposure
- Additional solutions

Harvest samples from modules
- New, good in the field, failed in the field.
- Use coring technique to obtain EVA
- Measure Na content
- Measure breakdown voltage

References
Neelkanth G. Dhere, Nachiket R. Raravikar, Effect of Glass Na Content on Adhesion Strength of PV Modules, *Proc. 29th IEEE Photovoltaic Specialists' Conference, New Orleans, LA, May 2002*
Spooner, Edward D., Wilmot, Nigel, Safety Issues, Arcing and Fusing in PV Arrays, *ISES-AP - 3rd International Solar Energy Society Conference – Asia Pacific Region (ISES-AP-08).*
J.A. del Cueto and S.R. Rummel, Degradation of Photovoltaic Modules Under High Voltage Stress in the Field, *SPIE 2010 Optics and Photonics Conference San Diego, California, August 1-5, 2010*

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Sandia National Laboratories

The Influence of Various c-Si Module Encapsulants on WIR Performance

Chris Stapelmann, Johannes Kirchner^Δ, Robert Fritz*, Tarek Chaibederraine**

**SolarWorld Industries America, Hillsboro, OR, ^ΔSolarWorld Innovations, Freiberg, Germany*

Introduction:

Wet Insulation-Resistance testing according to IEC61215[1] is one of the regular manufacturing sampling tests performed at all SolarWorld production sites to ensure the continued high quality of our products. A designed experiment was performed to determine the impact of different module encapsulation materials on the measured Wet Insulation-Resistance (WIR) of crystalline silicon (c-Si) based modules. It was observed that compared to the other encapsulants, ethylene vinyl acetate (EVA) is the greatest contributor of variation in WIR performance. Wet leakage current, if sufficiently large and occurring on multiple modules within an PV array string, can lead to inverter faults and impact overall system reliability.

Figure 1 shows the different leakage paths through a typical c-Si module during WIR testing. The crystalline cells are embedded in an EVA material which itself is sandwiched between a sheet of glass on the front of the module and a back sheet on the rear of the module which is a laminate film consisting of layers of fluoropolymers and polyethylene/polyester based materials. Cross connectors, junction box, silicone sealant, and frame complete the list of materials for a c-Si module.

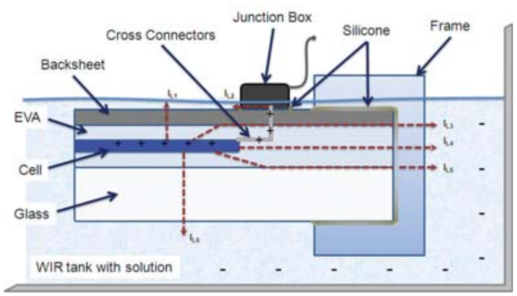


Figure 1 – Schematic of leakage paths of a typical c-Si PV module during WIR testing

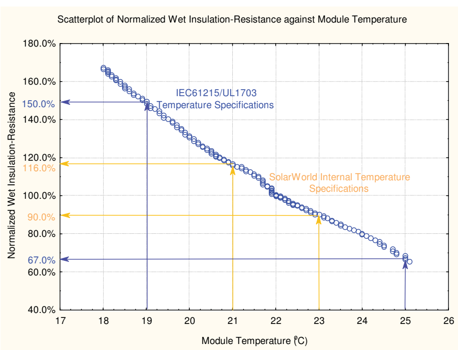


Figure 2 –Influence of the temperature of an exemplary module on measured wet insulation-resistance

Methodology:

A designed experiment was performed to determine the impact of different encapsulation materials on the WIR performance of c-Si modules. Multiple modules with different glasses, EVA, and backsheet materials were produced at three different SolarWorld production sites. The wet insulation-resistance (WIR) of each module was measured at both the respective production site and the IEC17025 certified module test laboratory at SolarWorld Innovations (SWIN).

Test Set-Up:

The IEC61215/UL1703 standards specify the set-up of the WIR test with a temperature control range of 22 ±3°C [1,2]. To assess the influence of temperature changes on the measured WIR values, we varied the temperature of the module and WIR test solution over the entire range of the test specification (19-25°C). The wet insulation-resistance varied by up to 50% even over this small temperature range (figure 2).

Subsequently, a tight temperature control of the device under test of 22±1°C was introduced as part of the standardization of the WIR test across all SolarWorld production and laboratory sites to reduce the measurement variability.

The resulting WIR test set-up adopted by SolarWorld is schematically shown in figure 3. Standardization of the entire WIR test set-up between production sites and the certified module test laboratory at SolarWorld Innovations in Germany allows for a very good reproducibility of WIR test results at various test locations (figure 4). All tests were performed using a 1000V bias corresponding to the maximum system voltage for the modules under test (according to IEC61215).

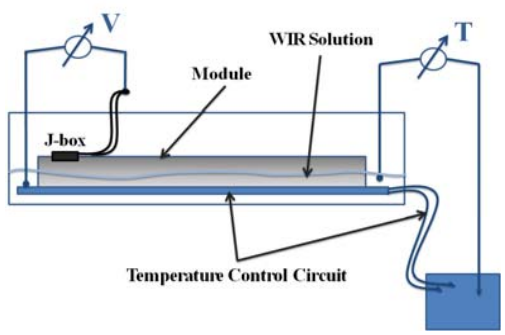


Figure 3 – Schematic of standardized WIR test set-up at SolarWorld

Results:

Although all modules surpassed the specifications of the IEC61215/UL1703 standard of 40MΩ·m², results varied widely among the different material combinations (figure 5). EVA was identified as the main driver for this variability. Figure 6 shows the difference in WIR due to EVA for the same type of glass and backsheet. One EVA material stands out due to exceptional WIR performance. Figure 7 shows the relatively small contribution of glass and backsheet to the WIR variation between the tested modules .

Discussion:

The measured wet insulation resistance and leakage current depend strongly on the temperature of the electrolytic test solution. A tight control of the test solution temperature during WIR sampling of manufacturing products ensures that WIR measurements are consistent over time and across manufacturing sites.

The analysis of our DOE showed that the quality of the EVA tends to have a significantly higher impact on WIR performance than different types of glasses or back sheet materials. It was observed that WIR of EVA varied widely (by orders of magnitude) between different vendors. In the case of one evaluated vendor, EVA supplied from different manufacturing locations (EVA C and EVA D) showed a significant difference in performance due to different additives used at the respective vendor plants. The results reinforce SolarWorld's strategy to closely monitor the incoming quality of encapsulation materials and to audit and qualify each vendor production site separately. SolarWorld has standardized its testing methods globally and has implemented regular and frequent material tests in production.

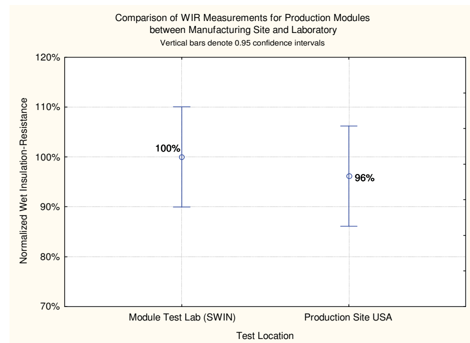


Figure 4 - WIR test reproducibility between test sites for actual production modules

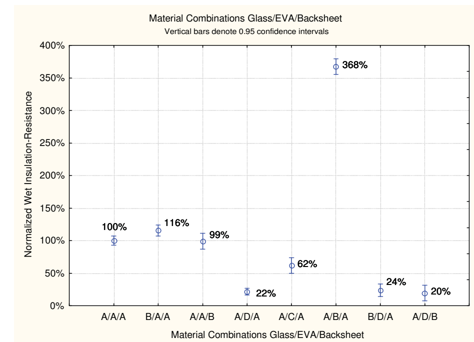


Figure 5 – Comparison of WIR performance of different combinations of encapsulants

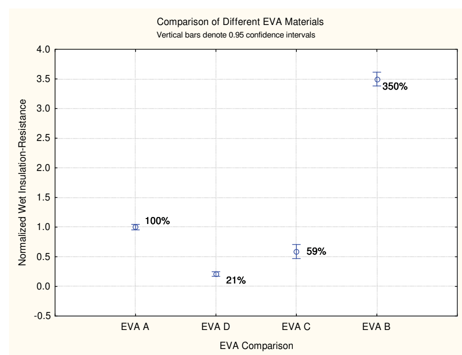


Figure 6 – Differences in WIR performance of different EVAs for same glass and backsheet

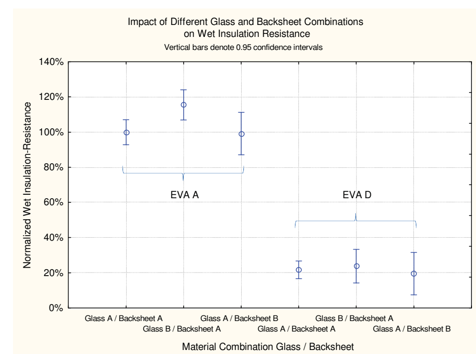


Figure 7 – Contribution of glass and backsheet on WIR for two different EVA materials

References:

[1] IEC61215 Ed.2, 2005

[2] UL1703 Ed.3, 2002

Acknowledgements:

Michael Eberspächer*, Jens Weisse*, Rainer Thiel*, Nestor Rigonan, Max Selahi, Nguyen Dinh, Jason Wiser, Emili Woody^Δ, Ryan Kumler^Δ, Wolfgang Klemm*, Stephen Hunter
SolarWorld Industries America, *SolarWorld Innovations, *SolarFactory, ^ΔOregon State University

We turn sunlight into power.

Photovoltaic Module Reliability Testing: 400°C/hr

Early Failure Detection of Interconnection with Rapid Thermal Cycling in PV Modules

Yuichi Aoki [1], Manabu Okamoto [1], Atsushi Masuda [2], Takuya Doi [2], David Jung [1], and Tadanori Tanahashi[1]

[1] ESPEC, Japan / USA, [2] National Institute of Advanced Industrial Science and Technology (AIST), Japan

Introduction & Procedures

Backgrounds

Ordinary Thermal Cycling [TC] (< 100 ℃ / hr)

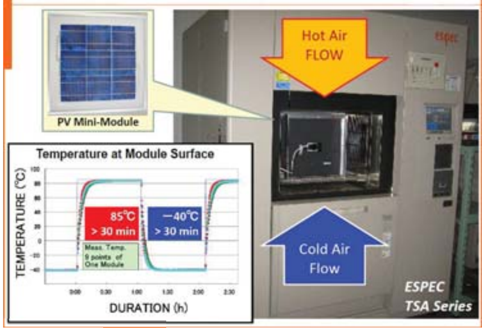
- Qualification / Type Approval (TC 200) : Low Failure Rate
- Power-loss with the increasing of cycling number in TC

Osterwald *et al.*	: TC 400	< Δ 8 %	2000
Wohlgemuth *et al.*	: TC 1,500	< Δ 4 %	2008
Jaeckel *et al.*	: TC 400	< Δ 3 %	2011
	: TC 500	< Δ 5.5 %	2011
Geipel *et al.*	: TC 400	< Δ 0.5 %	2011
Dethlefsen	: TC 400	< Δ 5 %	2011
Funcell	: TC 400	< Δ 0 %	2011
	: TC 600	< Δ 3 %	2011
	: TC 700	< Δ 4 %	2011

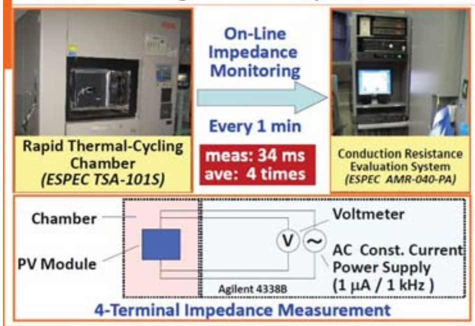
Require More Stress to Detect Thermal Fatigues ???

→ Rapid Thermal Cycling (ca. 400 ℃ / hr)

Rapid Thermal-Cycling Test : Equipment



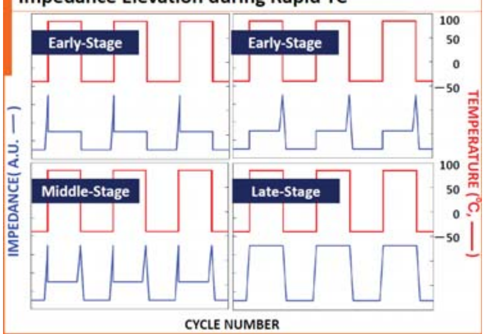
In Situ Monitoring of Module-Impedance



Summary & Schematic Conclusion

- The module impedance was measured with *in-situ* monitoring during rapid thermal-cycling.
- The impedance was stepwise elevated (Early -> Middle -> Late Stage), according to the increasing of cycle number in rapid thermal-cycling.
- All of modules were mostly deteriorated with the interconnection failures.
- The rapid thermal-cycling with *in-situ* monitoring of module-impedance may be a useful procedure for the early detection of interconnection failures.

Impedance Elevation during Rapid TC



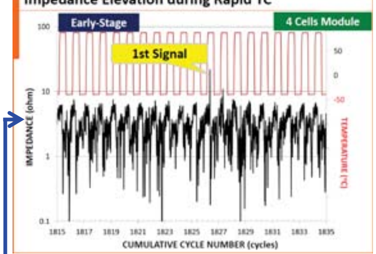
Experimental Results

4 Cells Module

Multi-Crystalline Silicon PV Cells (156 x 156 mm)
- wired with Cu/Solder Tab-Line
- laminated with EVA and T/P/ T Back-Sheet
- held with Aluminum Frame

Module Size = 400 x 400 mm, Cell No. = 2 x 2 cells

Impedance Elevation during Rapid TC

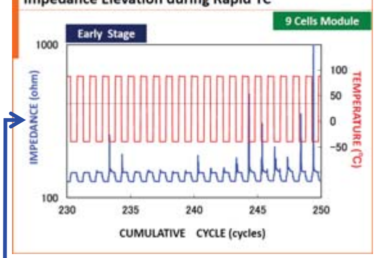


9 Cells Module

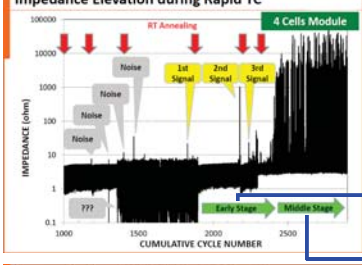
Multi-Crystalline Silicon PV Cells (100 x 100 mm)
- wired with Cu/Solder Tab-Line
- laminated with EVA and T/P/ T Back-Sheet
- held with Aluminum Frame

Module Size = 400 x 400 mm, Cell No. = 3 x 3 cells

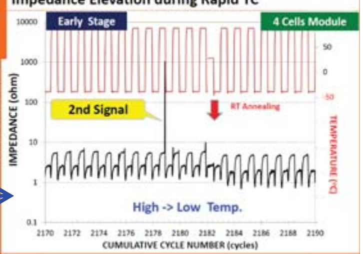
Impedance Elevation during Rapid TC



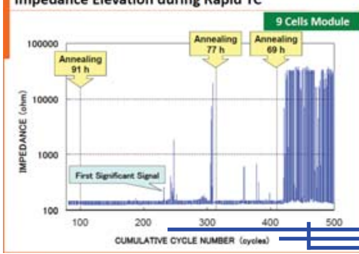
Impedance Elevation during Rapid TC



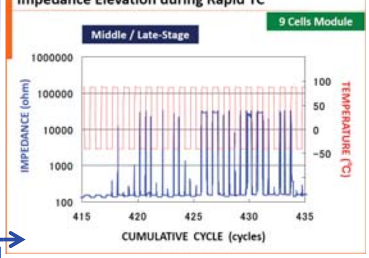
Impedance Elevation during Rapid TC



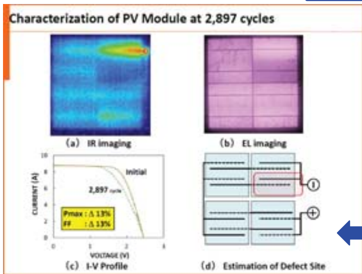
Impedance Elevation during Rapid TC



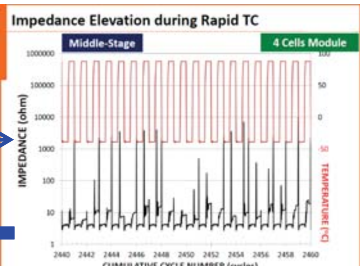
Impedance Elevation during Rapid TC



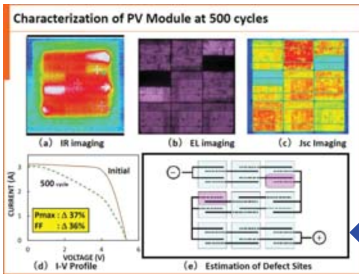
Characterization of PV Module at 2,897 cycles



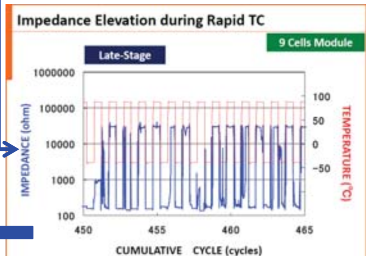
Impedance Elevation during Rapid TC



Characterization of PV Module at 500 cycles



Impedance Elevation during Rapid TC



For the Results in Commercial Mini-Module, Please Contact the Poster-Presenters.

Contact Person: Tadanori Tanahashi (t-tanahashi@espec.co.jp) or David Jung (djung@espec.com)

This work was supported by the Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability (National Institute of Advanced Industrial Science and Technology, Japan).

15-year Review of Field Performance of EVA-based Encapsulants

Joseph T. Woods and Dr. Ryan T. Tucker

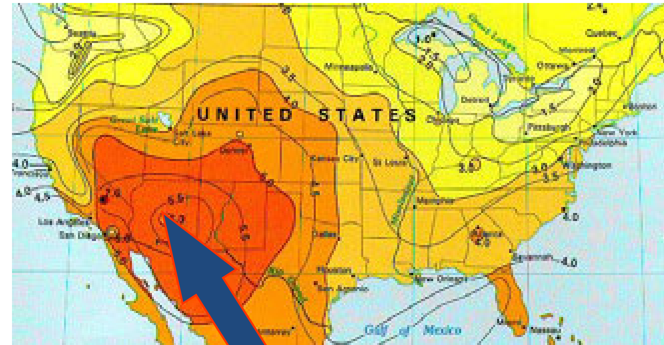
STR Solar

Introduction

- As part of PVMaT subcontract, STR fielded modules with various EVA-based formulations at Tempe, Arizona
- 36 modules with 5 different EVA-based formulations currently on test
- Module fielding initiated on September 6, 1996
- Visual inspection and I-V measurements performed on periodic basis

Introduction

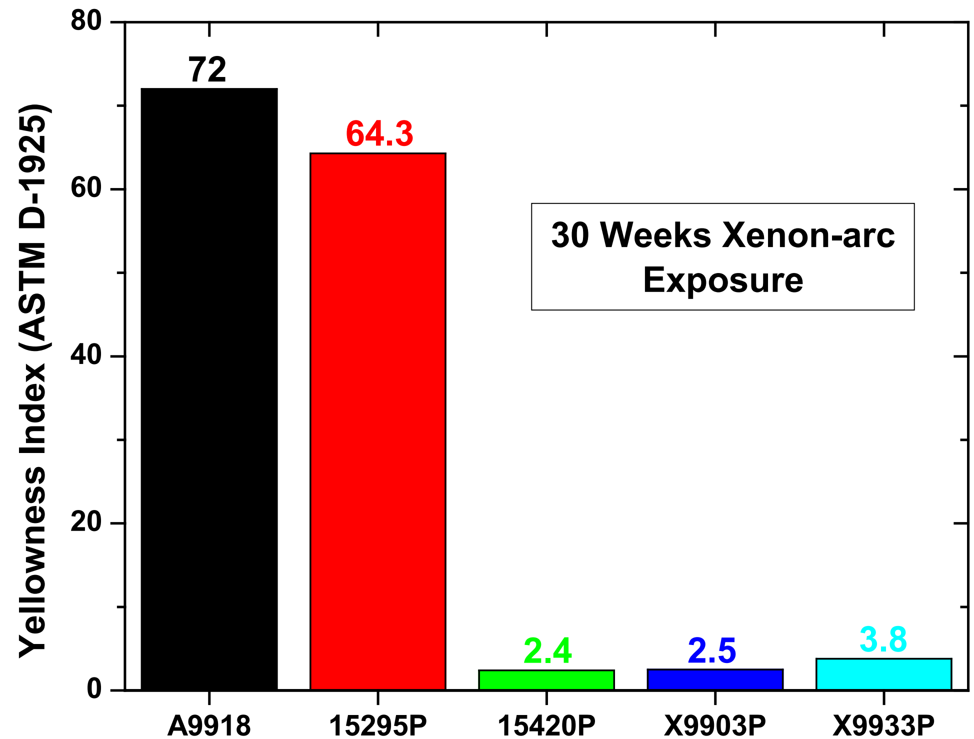
- Modules installed on two-axis tracker
- 4 PV module manufacturers
- 5 encapsulant formulations



Formulation	Curing Schedule
A9918P - control	Standard
15295P	Fast
15420P	Fast
X9903P	Standard
X9933P	Standard

Introduction

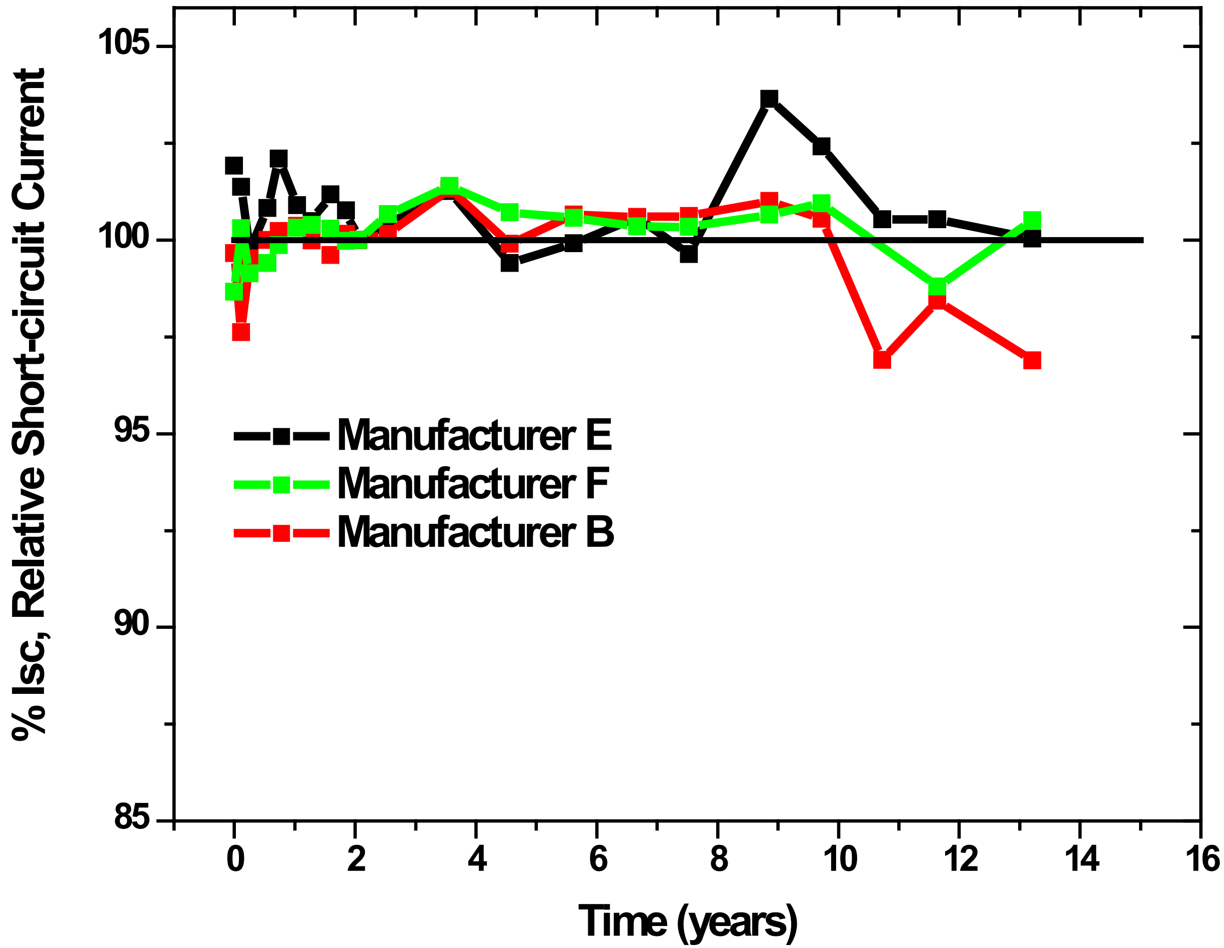
- All fielded formulations evaluated under Xenon-arc accelerated aging
- How does accelerated aging data correspond to data from fielded modules?



Accelerated aging performed in Xenon Arc Weather-o-meter with glass/glass constructions. Irradiance at 340 nm is 0.55 W/m^2; equal to an exposure of ~2 suns. Glass/glass laminates. Non-UV-screening glass utilized.

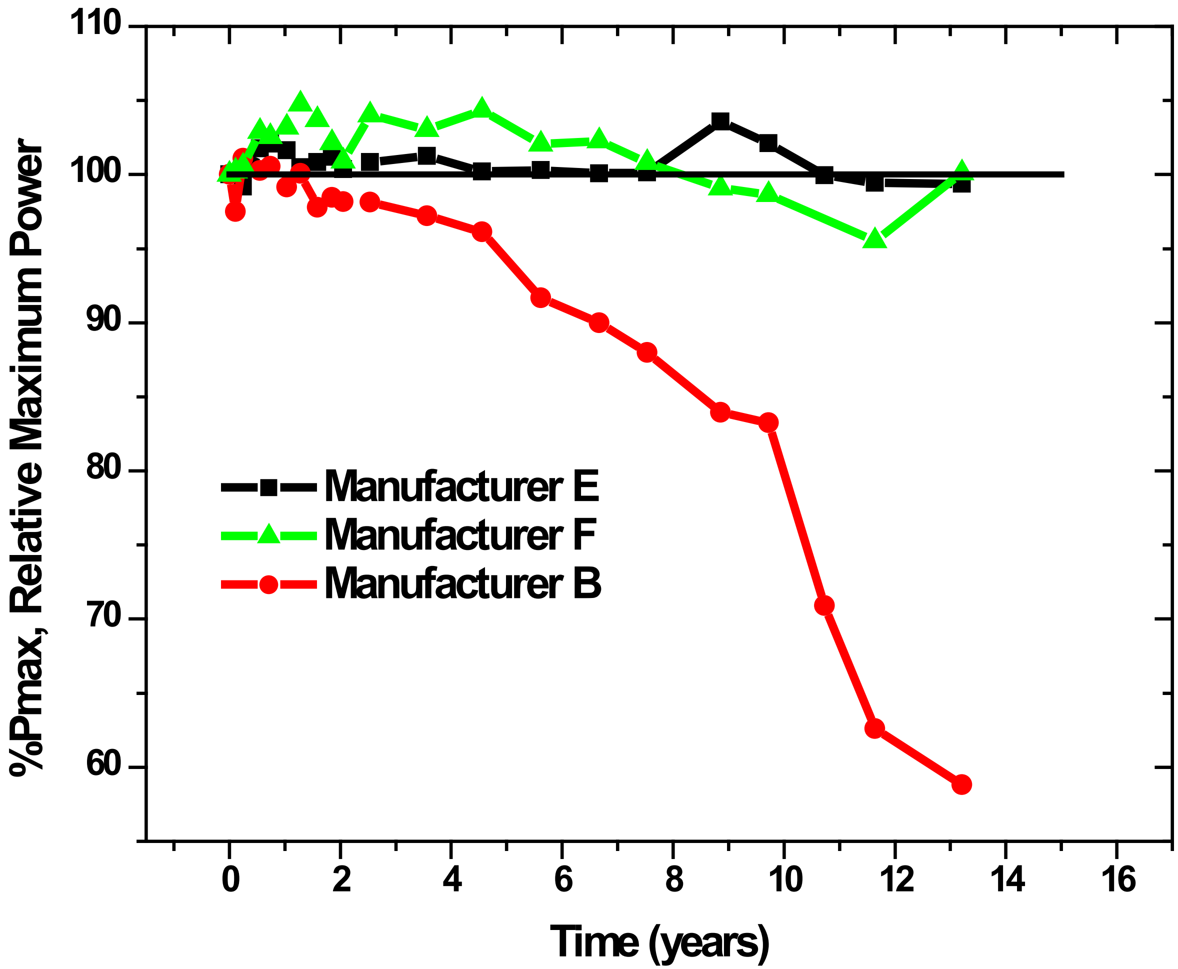
15420P

- 3 module manufacturers
- Relative Isc (short-circuit current) performance:
  - E = 100.04%
  - F = 100.51%
  - B = 96.89%
- Isc related to incident light reaching PV device



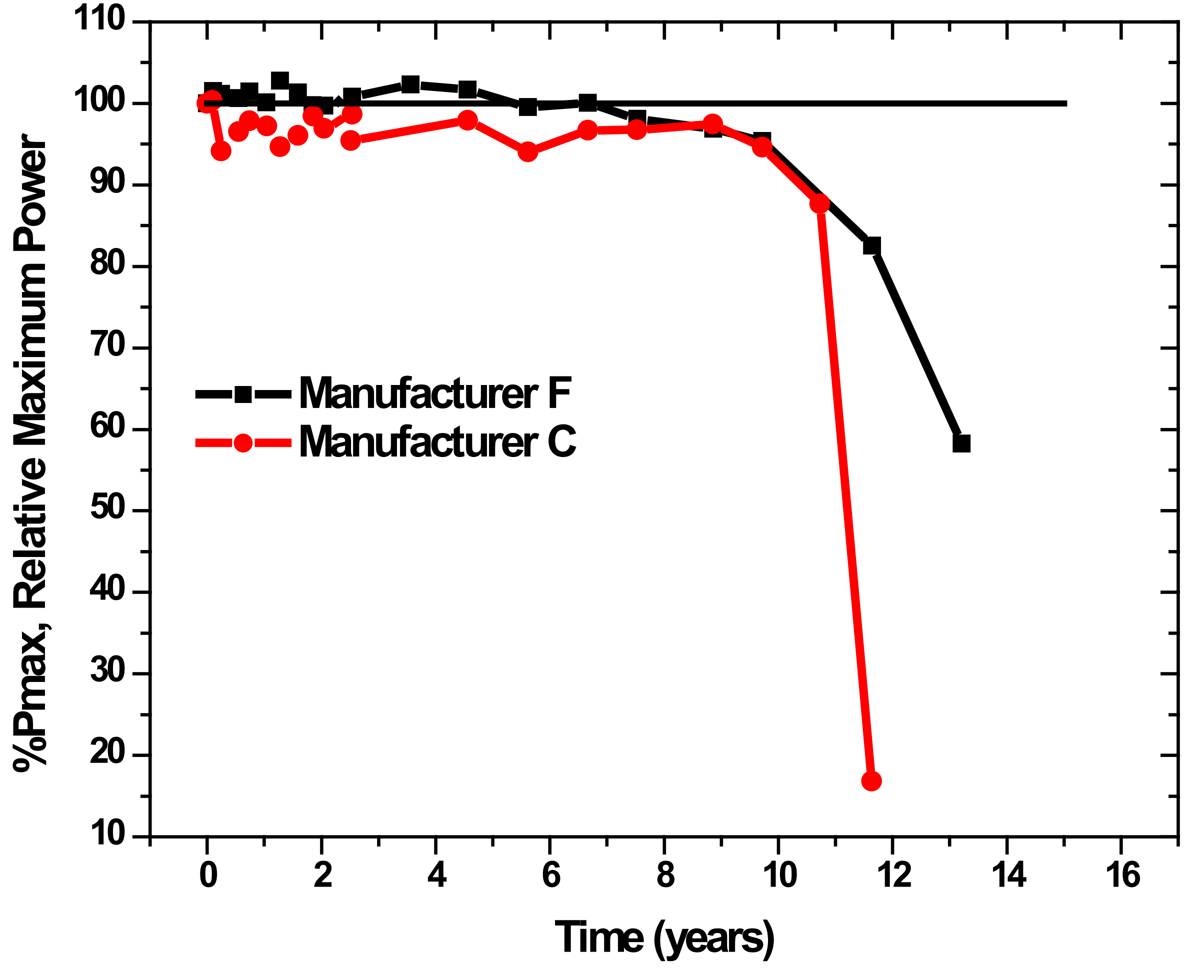
15420P

- Relative Maximum Power (Pmax)
  - **E = 99.39%**
  - **F = 100.12%**
  - **B = 58.81%**
- Cell backside corrosion observed only in modules from Manufacturer B



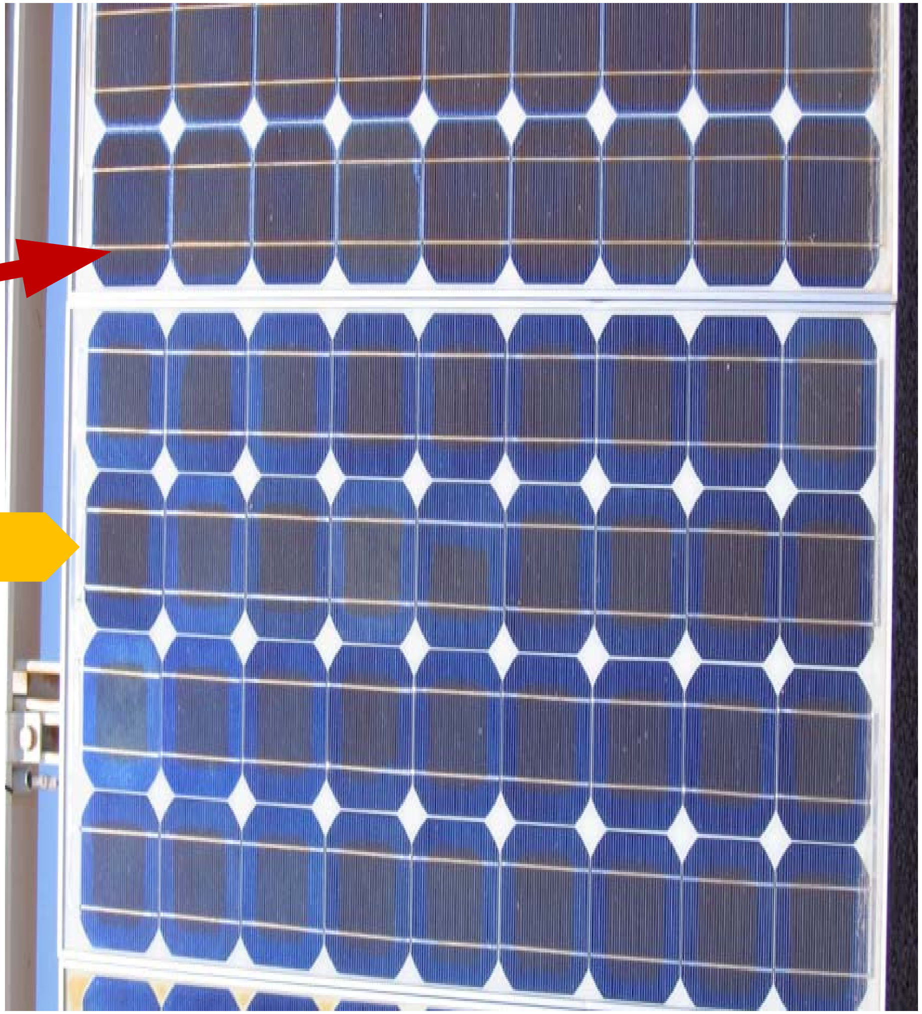
15295P

- Pmax performance corroborates poor accelerated aging data
- Discoloration observed over PV cell
- Manufacturer C modules also had corrosion within junction box



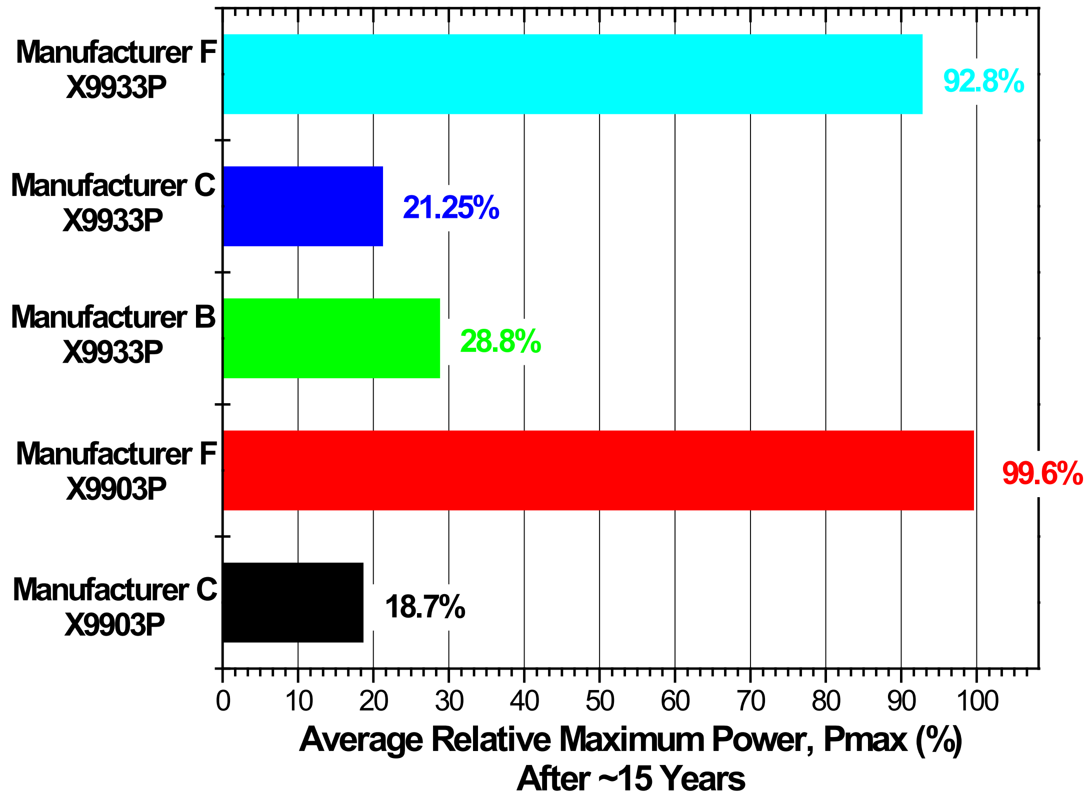
15295P

- Module discoloration of 15295P
- Typical discoloration is over cells
- Discoloration between cell ribbons only in “F” modules
    - Further investigation needed

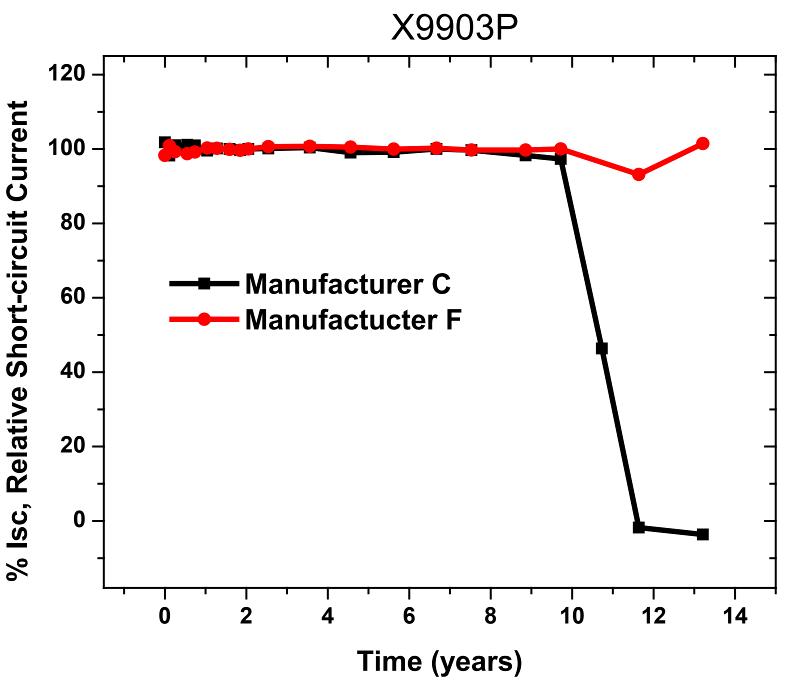


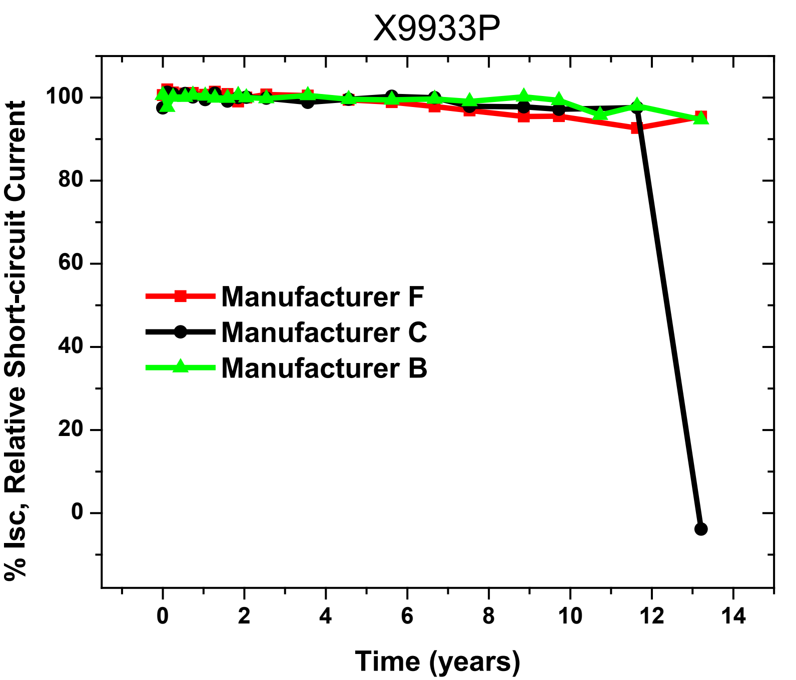
Experimental Standard-cure Formulations

- Experimental standard-cure formulations
  - X9903P, X9933P
  - Typically utilized in 2-step processes
- Manufacturer C = corrosion at junction box
- Manufacturer B = dark areas and delamination behind every other cell string



Experimental Standard-cure Formulations





Relative Isc is consistent with accelerated aging data

- Low YI for X9903P and X9933P after 30 weeks XAW
- J-box corrosion in Manufacturer C Panels

A9918P - Control

- Modules fielded in 1997
- Half of modules utilize UV-screening (i.e., cerium) containing glass
- Isc performance correlates with glass type and XAW accelerated aging data - A9918P high YI after 30 weeks XAW

Glass	Module ID	Relative Isc at ~ 14 years (%)
UV-screening	68	99.94
	64	94.59
	66	98.20
	72A	94.80
	71A	97.48
Non-UV-screening	67	85.97
	70A	87.13
	73	89.03
	70B	86.67

Conclusions

- Stabilization strategies developed demonstrate effectiveness in minimizing encapsulant discoloration
- 15420P (2nd gen. encapsulant) performing well; no statistical loss of Isc
- Discoloration with 15295P observed as predicted by Xenon-arc accelerated aging
- Relative short-circuit current correlates well and is consistent with Xenon-arc accelerated aging data
- Presence of UV-screening glass improves photothermal stability of encapsulant

US TG 4 activities of QA Forum

QA Task Force 4 ; Diode, Shading & Reverse Bias

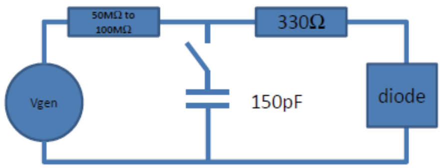
Contains no confidential information.

Feb. 28 – Mar. 1, 2012 ***@NREL PV Reliability work-shop***

**Vivek Gade(Jabil Circuit) and
Paul Robusto(Intertek)**

Overview, Working groups and areas of focus

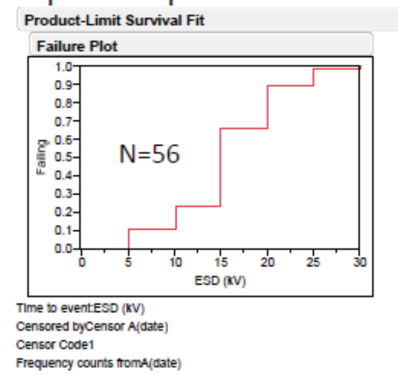
- Working group 1: Lead by Kent Whitfield working on HBM surge testing
  - PV Manufacturing facility static voltage measurement
  - Performed ESD event in combination with reverse bias at high temperature
  - Conduct tests and compare life distributions from the 10-surge and 100-surge program
- Working group 2 and 3: Lead by Vivek Gade and Paul Robusto
  - Reverse bias at high temperature and reverse bias transition survivability
  - Forward bias thermal cycling and fatigue issues.
  - Scope of the testing not limited to diodes but apply to Junction box level testing.
- Working group Task 4 Japan Lead by Yasumori Uchida, JET
  - Human body model ESD
  - Thermal runaway at reverse bias



HMB surge testing

- Handling by personnel on the manufacturing line and in the field results in surge events that damage Schottky diodes.
- Surge events can lead to higher reverse bias leakage current which can exacerbate a thermal runaway failure. Some failure analysis suggesting root cause of diode shorting events indicates surge damage
- Basis of ESD Test – IEC 61000-4-2
- 150pF, 330 ohm impendence circuit. This is interpreted to be a human-body-model impedance circuit.
- This work did NOT confirm a correlation between reverse leakage current and ESD event below the failure threshold.
- A fifth group of 56 diodes (restricted to a suspect date code) was subsequently subjected to an ESD-to-Failure test exhibited 100% mortality.
- This work does suggest that there is significant difference between the failure distribution of diodes subjected to an ESD-to-Failure test program and reports on a significant change in the failure distribution for one diode type when restricted to a particular date of manufacture.

A-Fails
Groups 5 suspected date code

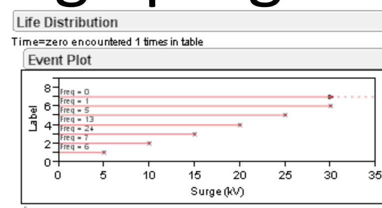


Typical failure: ESD mark observed after die top metal removal.

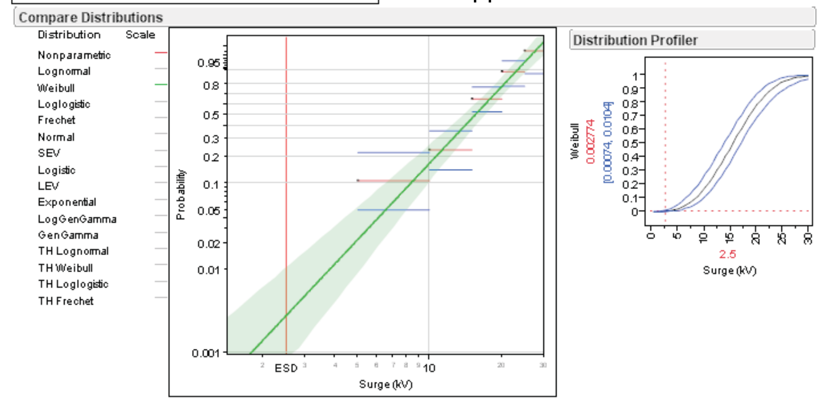
JBOX INSTALLATION STEP (measurement date 10 Oct 2011)	Measured Voltage (V)
Opening shipping container and measuring jbox potential while still in box	+1,260
Preparation table resting voltage	+90
Removal of Jbox from box and placement on table. Resulting jbox voltage.	+470
Placing two strips of double-sided tape on jbox. Max voltage.	+120
Jbox voltage after applying perimeter silicone adhesive.	+130
Jbox voltage after removing double-sided tape release liner. Max voltage.	+2500
Placing Jbox on laminate. Maximum box voltage.	+50
MODULE TESTING CONDITIONS	
Flash simulator curtain voltage. (NOT JBOX)	+200
Flash simulator structure voltage. (NOT JBOX)	+50
LAMINATE CONDITIONS	
Laminator outfeed belt voltage (NOT JBOX).	+250
Laminate on outfeed conveyer belt (NOT JBOX)	+110
Laminate on table post backsheet trimming operation	+110
SEPARATE WORK AREA KNOWN TO HAVE A HIGH STATIC POTENTIAL	
EVA Roll	-3500
Backsheet Roll	-56,000

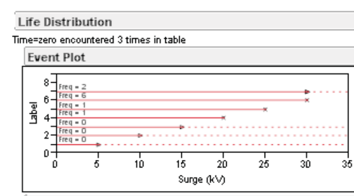
HMB 10 surge and 100 surge program

- 56 parts per group and three groups tested.
  - Surge-to-failure program in 5kV steps using simple DMM check for short-circuit following surge (no elevated temperature reverse current leakage test).
- 5 surges anode + 5 surges cathode with 10 seconds between surges per stress step.
  - A group of ten diodes was tested using 50 surges anode + 50 surges cathode (100 total) with a 10 second rest between surges and the life distribution from this sample is compared to the baseline 10 surge program.
- A Weibull curve used to fit data enabling estimation of number of failures that may occur at a specific level of ESD potential.
  - We have substituted surge voltage for time in this analysis
  - The cumulative distribution function is thus interpreted to mean fraction of all units in the population which will fail by V voltage of ESD.
  - Shaded region indicates a 95% confidence interval around the median line.
- Static voltage measurement used to estimate ESD potential levels in a PV facility
- Significant difference seen in resulting failure distributions.
- Good similarity between the life distributions from the 10-surge and 100-surge program is indicated.

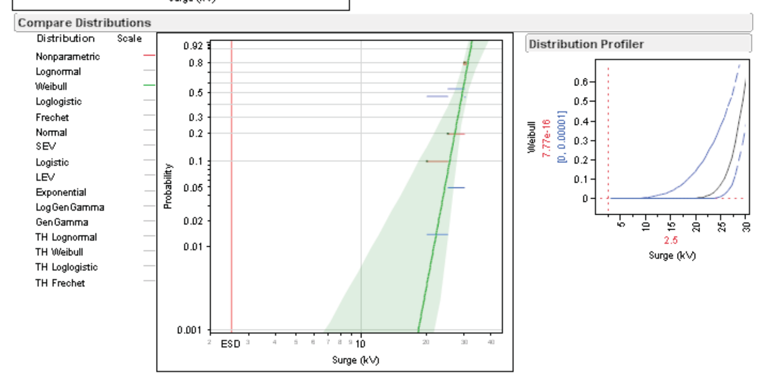


0.28% of population fails
56 samples, 2800ppm, Group A,
Group C 56 samples was 7.2ppb





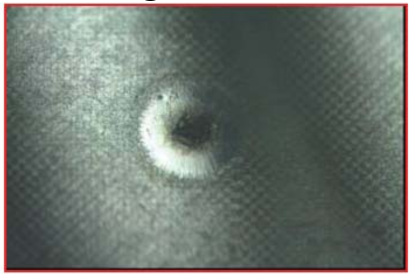
Group C, 10 samples, 0-100ppb



HTRB, Transition and forward bias testing

- The reliability is currently not determined by HTRB by Tj Reverse voltage resistance of diode in J-box similar to "By pass Diode Thermal Test(IEC61215) need to be considered
- The reverse current does experience increase by orders of magnitude with increasing temperature and needs to be considered. Reverse bias thermal runway due to transition and thermal cycling will be studied by working group 2.
- Elevated temperature combined with repeated power cycling could drive fatigue at the die attach.

Forward bias extended testing and issues such as fatigue, cracks in case, solder joints were observed and nee



- Reliability problems are rarely reported and rectifiers are very low on the Pareto analysis for returns
- Schottky diode failure is seldom due to wear out mechanisms.
- Several known quality problems in the manufacturing process exist
  ESD problems of up to 50kV (ESD remains the Nr 1 problem in the industry)
- A bigger source of problems than reliability concerns is latent defects introduced according to diode manufacturers.

Japan Task force #4

- Machine Model (M.M) for ESD
  MM should be applied to avoid ESD failure experienced during PV module manufacturing process and field installation. The diode in J-box should be evaluated by the reverse bias at high temperature in order to avoid the thermal runaway. Arrive at rationale to pursue most relevant tests under specific conditions.
- The diode in J-box should be evaluated by the reverse bias at high temperature in order to avoid the thermal runaway.
- Consideration of reverse bias withstand voltage of diode in J-box as for "Bypass Diode Thermal Test(IEC61215)".
- Report on recommendations and applicability to diodes and J-box testing.
- Arrive at rationale to pursue most relevant tests under specific conditions.

Construction of a Hail Gun for Solar PV Module Testing

R. B. "Dutch" Uselton, PE (TX)
Senior Principal Engineer, Applied Research Group
Lennox Industries Inc.
February 28, 2012

ABSTRACT

Solar modules sold in the United States do not have to be tested for resistance to hail impact. Our customers expressed concern about the possibility of their significant investment in solar modules being lost due to a hail storm. After reviewing the scientific literature, we decided we could evaluate the hail resistance of modules we planned to sell and provide some assurance to our customers.

INTRODUCTION

The Jet Propulsion Laboratory conducted several durability tests of solar panels, including simulated hail impact, in 1978 and issued a report[1]. The National Bureau of Standards (NIST) issued a procedure[2] for hail impact testing of "solar covers" in 1982. The *Standard Test Method for Determining Resistance of Photovoltaic Modules to Hail by Impact with Propelled Ice Balls*, ASTM E1038, was first issued in 1985. Despite this long history of attention to determination of solar module hail resistance, there is still no required test for solar modules sold in the United States. Underwriters Laboratories Standard 1703 includes an impact test but it does not simulate the impact of hail and visible damage does not necessarily mean failure of the test. IEC 61215 contains a hail test that is very similar to the ASTM test and solar modules sold in Europe must pass this hail test.

We wanted to be able to tell our customers that we had investigated the hail resistance of the solar modules and found them suitable for conditions in the United States. (Note: Hail stones are associated with thunderstorms. We can estimate the falling terminal velocity for a certain sized hail stone, but the coincident wind conditions around the thunderstorm can have an unpredictable effect on velocity at impact.)

Rather than having candidate solar modules tested at a third-party laboratory, we designed and built our own hail gun and developed the skills to do this testing at our product development center in Carrollton, Texas.

General Outline of IEC 61215 Hail Impact Test Protocol

Sub clause 10.17 of IEC 61215 describes the Hail Impact Test protocol. The solar module is impacted with ice balls in eleven different locations. There must be no major defect caused by the impacts and the maximum power output of the module is measured before and after this test to check for problems that might not be visually detectable. Likewise, the dielectric strength is checked to look for a change.

The following table shows the range of ice ball sizes that can be used during this test. The manufacturer decides which size ice ball they wish to certify to. The velocity goes up with the size of the ice ball. (This is to match what have been found to be typical terminal velocities for hail stones of a given size.)

Diameter (mm)	Mass (g)	Velocity (m/s)	Kinetic Energy Joules
12.5	0.94	16.0	0.116
15	1.63	17.8	0.24
25	7.53	23.0	1.85
35	20.7	27.2	7.18
45	43.9	30.7	19.5
55	80.2	33.9	43.4
65	132	36.7	84.7
75	203	39.5	150

According to TUV, a leading solar PV testing laboratory, they see very few solar modules fail the Hail Impact test. They also indicate that most modules are only tested with 25mm ice balls… at the request of the PV module manufacturer.

THE NEED TO CONDUCT OUR OWN TESTING

For the WOW-factor, we calculated the ice ball kinetic energy for each ice ball size (and corresponding velocity) and included it in the above table. The energy rises rapidly with ice ball size! Here is why:

Kinetic Energy = ½ * mass * $(\text{velocity})^2$

But: terminal velocity $\propto$ $(\text{diameter})^{1/2}$

(Resulting from balance of gravitational and aerodynamic forces)

And: mass $\propto$ $(\text{diameter})^3$ (for a spherical object)

So: Kinetic Energy $\propto$ $(\text{diameter})^4$

The upshot of this is that the impact energy of a 35 mm (1⅜") hail stone is almost four times as great as one 25 mm (1") in diameter.

This image, from the National Severe Storms Laboratory (NSSL), shows the climatological probability of 2" (or larger) hail occurring within 25 miles of any point for that day. This image is for the first few days of May. For North Central Texas, this probability is 2.5%. The highest frequency zone moves northward during the summer, and then back down. The hail concern we have is well-founded.

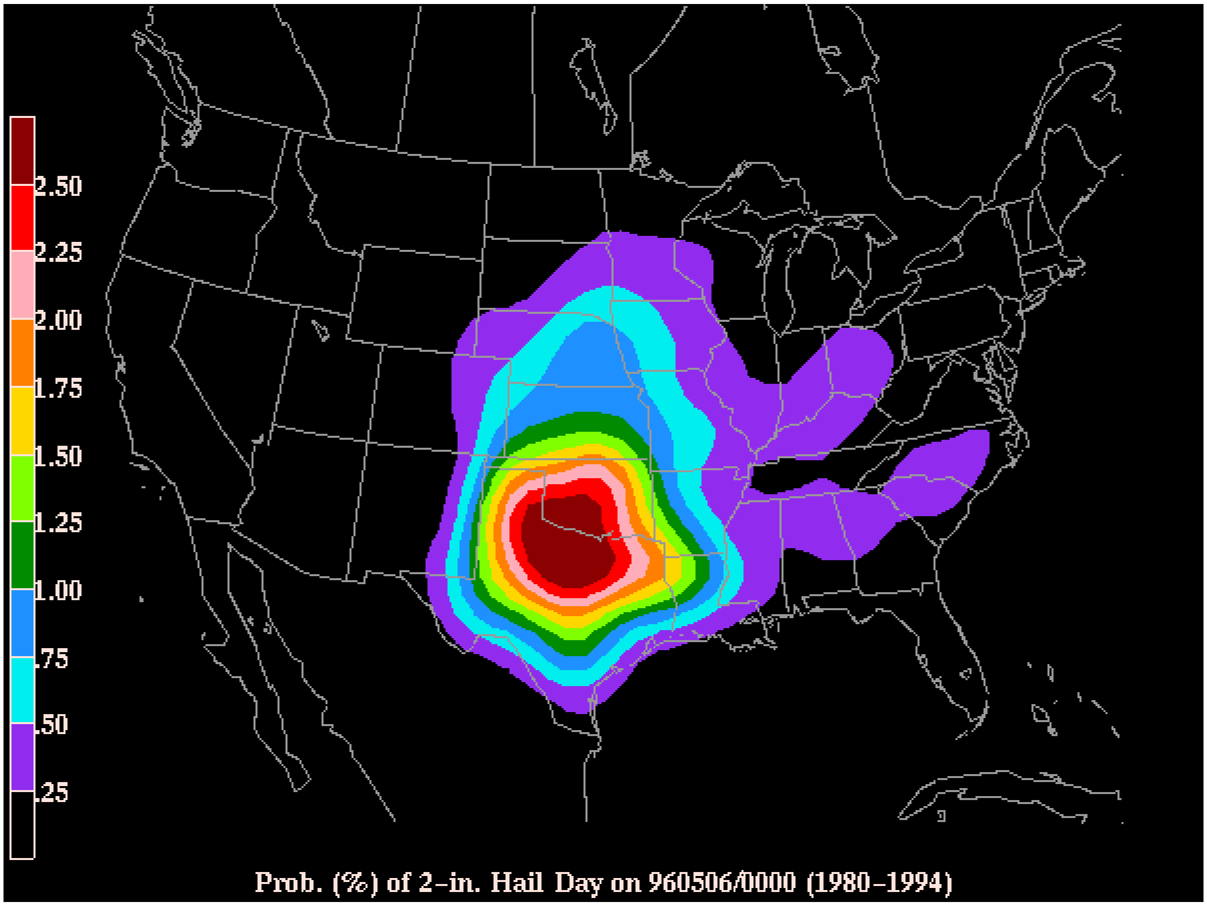


Figure 1. Hail Probability Map

Development of the Hail Gun

We found an old paper that mentioned a pneumatically operated hail gun developed at Sandia Laboratories. We also found several hobbyists "air cannon" descriptions on the internet. One of the better posts described an air cannon that ham radio operators fabricate as part of emergency preparedness. The cannon uses compressed air to launch a tennis ball high in the air. A temporary antenna wire is attached to the tennis ball. This gear is used to reestablish radio communications in a disaster area; the antenna wire is strung up to the highest object still standing in the area. We first built the hail gun along the lines of the ham radio air cannon. We made a video of the first test-firing, using a racquetball. Sure enough, it looked like we were going in a good direction: the hang-time of the racquetball was 5 seconds.

This first design used a very simple “trigger”: a burst disc made of aluminum foil. We found that to be a limitation because we did not have good control of the ball’s velocity. A more repeatable trigger system would be needed.

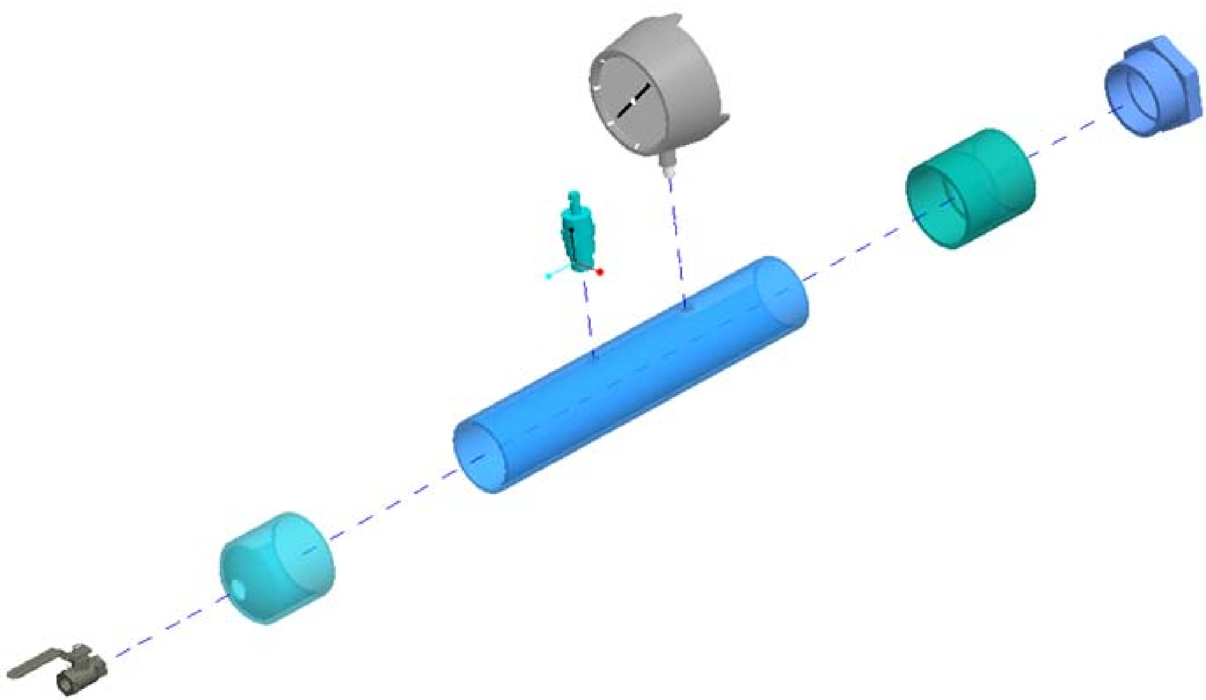


Figure 2. Components for Gun Air Chamber

The same website showed a scheme that used a poppet valve to release the large volume of air rapidly. The poppet is held closed by considerable force when the air tank is pressurized. A “pilot valve” system is used to provide the needed opening force. The pilot valve is a smaller air valve (a quarter-turn ball-type valve) that would connect to the left end of the tank shown in the figure below. A loose-fitting piston toward the left end of the tank is connected to the poppet valve by a rod. The air tank is pressured and the pressure is the same on each side of the piston. When the pilot valve is rapidly opened, the piston moves to the left because the air pressure has been reduced on that side. The poppet valve is rapidly drawn back, releasing the compressed air into the barrel.

Figure 3. Poppet Valve and Piston Assembly

We fabricated the additional parts needed to make the pilot-operated air release system work. We also added a pressure gauge and a pressure relief valve. The device is made primarily of schedule 40 PVC pressure water pipe. The air tank portion is nominal 3" diameter with a 260 psi pressure rating. We have found we don't need to operate the hail gun with pressures higher than 20 psi.

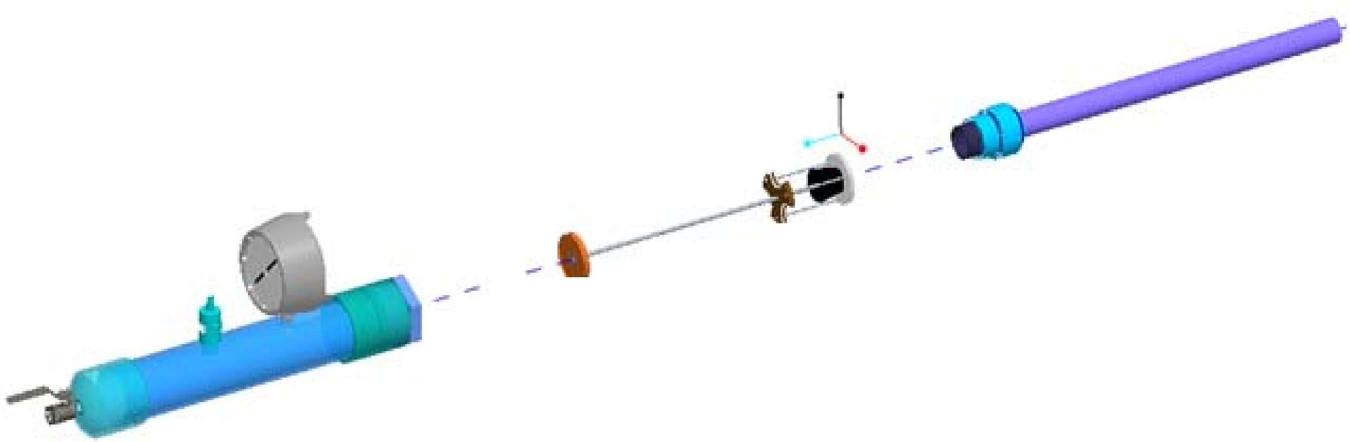


Figure 4. Gun, Valve Assembly and Barrel (Exploded View)

Figure 5. Photo of Assembled Gun with Various Interchangeable Barrels

Figure 6. Hail Gun Ready for Use in Test Chamber (1.375" Barrel Shown)

ICE BALLS

We have tried two different methods for making ice balls. We have had the best success using silicone molds made for casting balls of chocolate. A household refrigerator/freezer is used to freeze the ice balls in the mold. We use butter to help seal the mold parting line and use a graduated syringe to precisely fill the voids with water. There is always either a flat spot or a bump on the ice ball left as an impression from the fill port of the mold. With practice, we have learned to minimize the size of the imperfection. The picture below shows a silicone mold for casting 1” ice balls. Also shown is an individual mold we made out of PVC for casting 1.375” ice balls. The IEC standard calls for checking the weight of the ice ball and for discarding any that have cracks in them. We seem to have more cracks in the ice balls made in the harder mold.

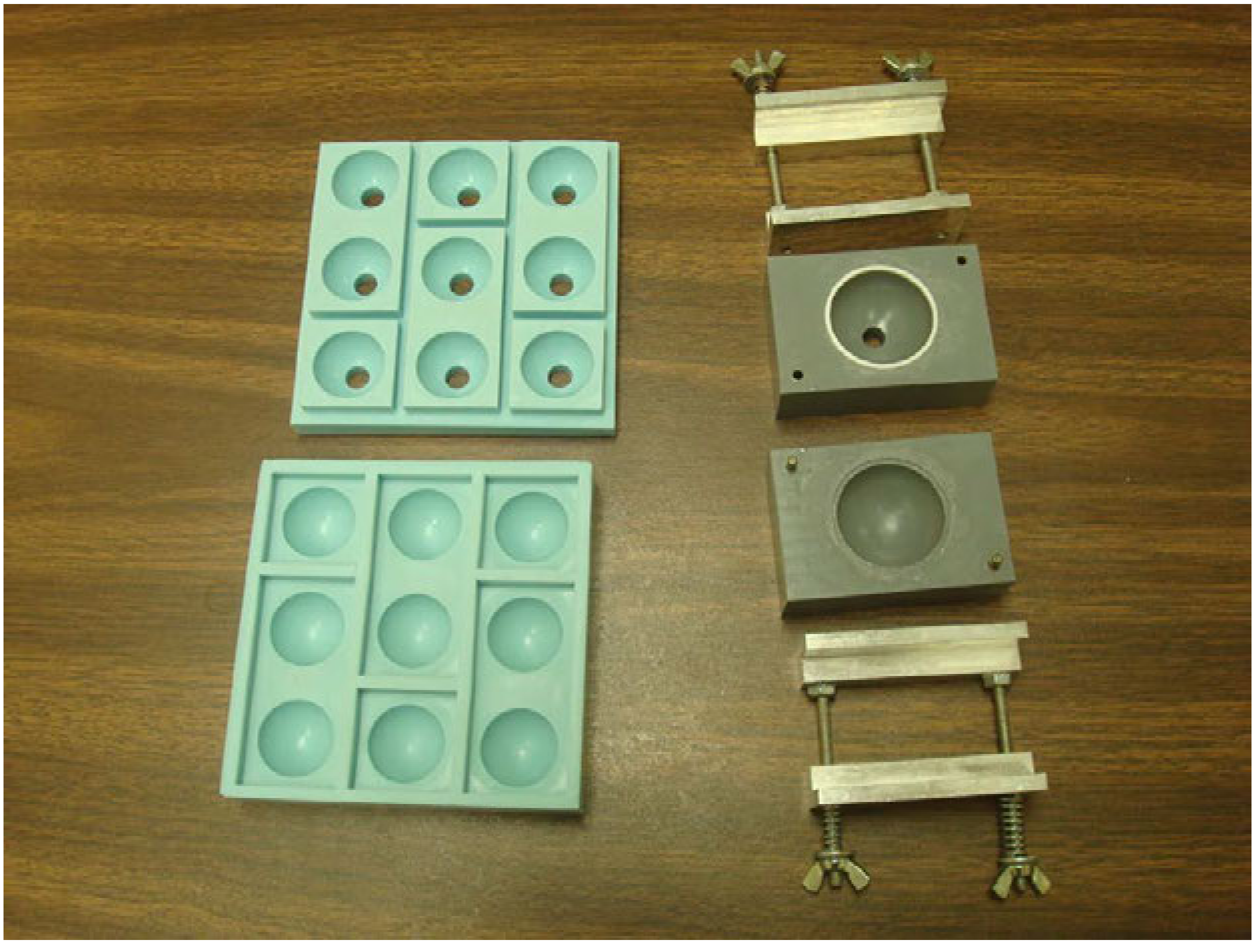


Figure 7. Ice Ball Molds

VELOCITY MEASUREMENT

Again, we tried a couple of different devices before settling on a radar speed gun available at sporting goods stores for about $100. These devices are used by coaches to measure the speed of baseball pitches and the like. The accuracy is advertised as “to +/- 1 mph” but we have not attempted to check calibration. The radar gun has been very reliable, giving us a velocity for each ice ball launched. We have fired ice balls in the range of speeds from 30 mph to 190 mph.

POST-TEST EXAMINATION

The PV module is visually examined after each successive ice ball strike. Mainly we are looking for cracks in the glass. After all eleven ice balls have been shot we use Infra-Red Imaging (using a FLIR camera) to check for possible damage to cells or interconnects. Shown below are IR images of two different PV modules tested.

For IR imaging, the by-pass diodes are removed and a dc power supply is used to drive current through the module. At the start, the solar module has been soaked-out to a controlled ambient temperature of 60°F. The current flow is increased to a value perhaps 25% higher than the module's rated short-circuit current by carefully adjusting the voltage of the dc supply. Within 30 minutes, the module will have heated up enough to be near steady-state temperature (90°F to 95°F). The current flowing through the module shows up as heat on the IR image and cold areas would indicate abnormally low current flow, possibly due to impact related damage.

Figure 8. IR Image of 235 Watt Solar Module

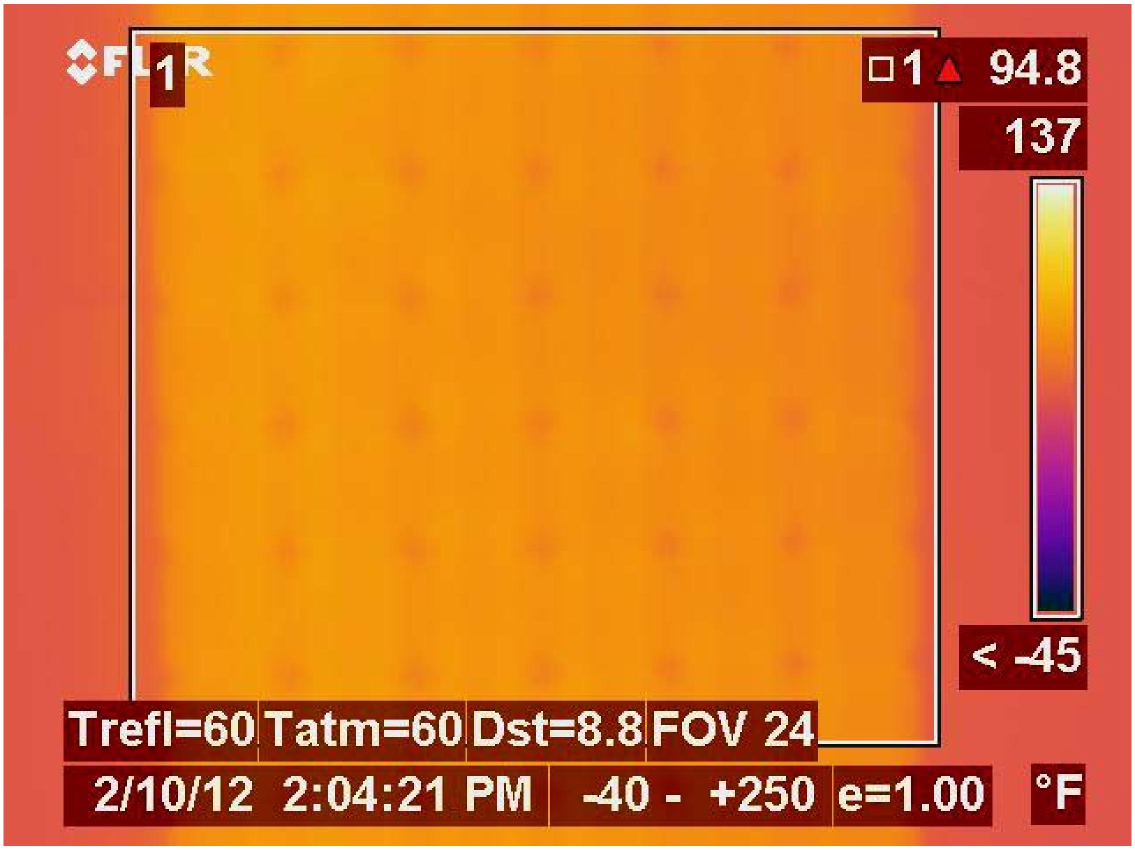


Figure 9. IR Image of 180 Watt Solar Module

We did not find any obvious damage to either of these solar modules. (We should have taken IR images before the test so that we could compare back. We plan to do this next time.)

CONCLUSION

The project to develop in-house hail test capability turned out to be relatively quick and inexpensive. Future work will include more and better module pre and post test evaluation. We also plan to switch to a solenoid operated pilot valve to improve consistency of ice ball velocity and targeting.

The ability to conduct hail tests on solar PV modules helped us address a concern our customers had about the likely longevity of solar modules in hail-prone climates. We have also incorporated video documentation from testing into our product marketing materials.

FOOTNOTES

1. Moore, D., and Wilson, A., “Photovoltaic Solar Panel Resistance to Simulated Hail,” Low-Cost Solar Array Project Report 5101-62, Jet Propulsion Laboratory, Pasadena, CA, 1978. Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161-0001

2. Jenkins, D. R., and Mathey, R. G., “Hail Impact Testing Procedure for Solar Covers,” NBSIR 82-2487, National Bureau of Standards, April 1982. Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161-0001

PARTS LIST

Hail Gun Parts List			23-Feb-12	
Item #	Qty	Description	Source	Mfg's Part Number
1	1	3" Sch. 40 PVC Cap	Spears Manufacturing	447-030
2	1	3" Sch. 40 PVC Coupling, Slip x Slip	Spears Manufacturing	429-030
3	1	3" x 2" Bushing, SPIG x FPT	Spears Manufacturing	438-338
4	1	2" x 2" Sch. 40 Adaptor PVC Slip x MPT	Spears Manufacturing	436-020
5	1	1.25" Sch. 40 PVC Coupling (modified)	Spears Manufacturing	429-012
6	1	2" x 1.5" Sch. 40 PVC Bushing	Spears Manufacturing	437-251
7	1	1.5" x 1.25" Sch. 40 PVC Bushing	Spears Manufacturing	437-211
8	1	Tube, Clear Polycarbonate 1.5" od x 1.375" id x 24"	McMaster Carr	8585K43
9	1	Pipe, 3" Nominal Sch. 40 PVC x 18"	Home Depot	
10	1	Rod, steel 0.250" diameter x 20", threaded nc both ends	Home Depot	
11	1	Disk, PVC 3.000" diameter x 0.375" thick (3.25" turned)	McMaster Carr	87025K74
12	1	Disk, PVC 3.040" diameter x 0.375" thick "scalloped" (3.	McMaster Carr	87025K74
13	1	Rubber Stopper, Tapered, #11.5, (1 and 31/32" diameter	McMaster Carr	9545K61
14	4	nut, 1/4" nc	Home Depot	
15	4	washer, steel for 1/4" diameter rod	Home Depot	
16	1	1/2" nominal 1/4 turn ball valve	RUB	S92D45
17	1	1/2" nominal close pipe nipple	Home Depot	
18	1	Pressure gauge, 0 - 30 PSI	Omega Engineering	PGH-45B-30
19	1	Pressure relief valve	Universal Pneumatic	ST25-30
20	1	Tire valve stem	Patchboy.com	17-500B
21	3	Screw, machine, #8 - 32 x 0.75"	Home Depot	

EVA Adhesion Test Method,180^{o}-peel vs. T-peel, in PV applications

- Investigation on Avery Dennison coated and a commercial TPT* backsheets

Hugh Yang, PhD
Photovoltaics & Clean Energy
Avery Dennison

Abstract

In all technical specifications of PV backsheets from various suppliers, peel strength with EVA is a key criteria to evaluate long term durability and reliability in the field. However, current test methods (such as 180°-peel or 90°-peel) aggressively overexert any potential forces experienced in the field. Moreover, the peel tests themselves ‘contaminate’ results since they introduce possible failure. Specifically, defects such as micro cracks are likely to form due to high force and peel angle applied.

Avery Dennison developed a coated backsheet formulation based on its 30 years of experience formulating and producing highly engineered UV protection coatings for outdoor applications in auto, aerospace, and housing. Avery’s backsheet has been tested for damp heat (2000 hours), thermal cycles (400) and humidity freeze (20 cycles), and the results highlight excellent (100%) interlayer adhesion (coating←→PET) according to cross hatch adhesion testing (ASTM D 3359).

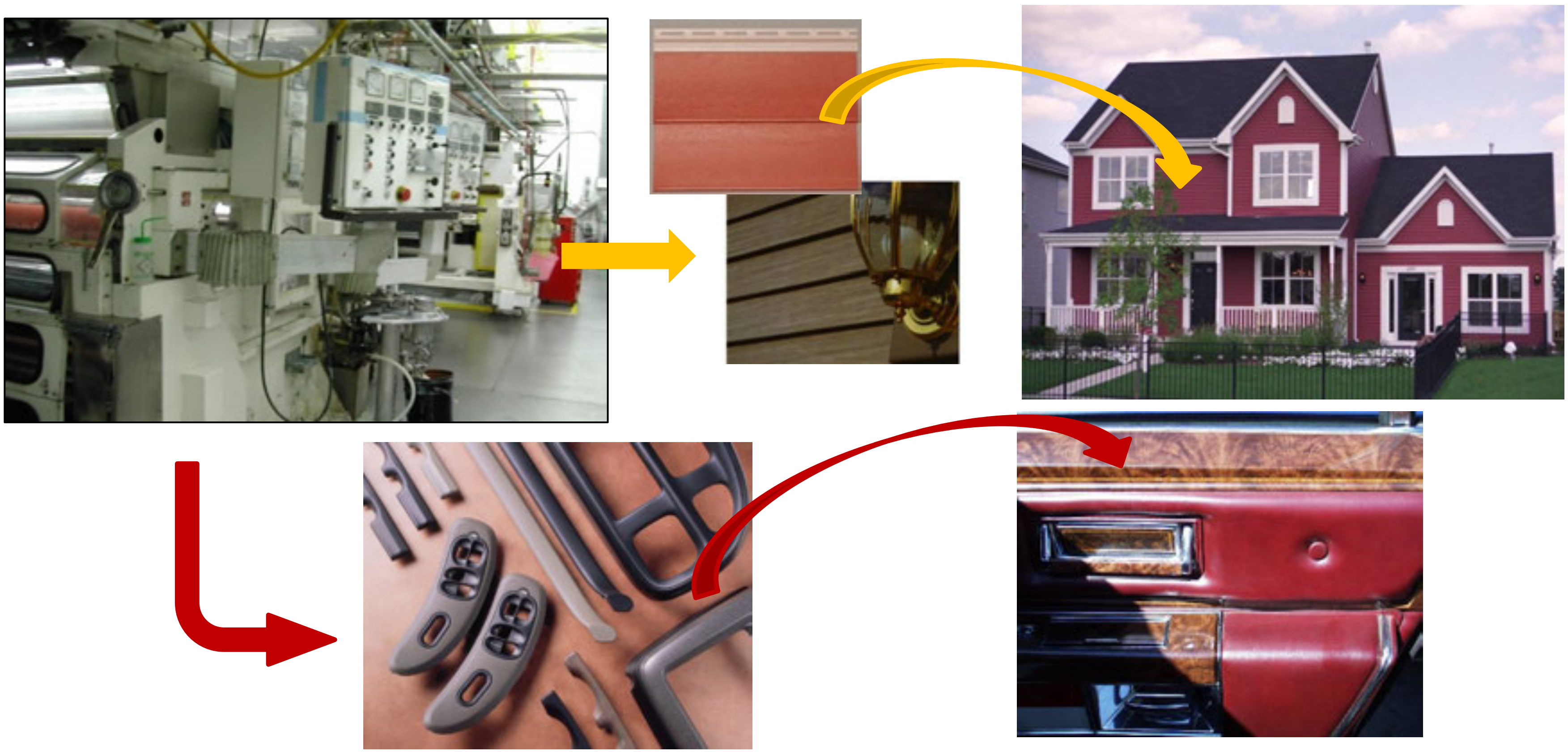
In order to measure bond strength between EVA and the backsheet, Avery Dennison has concluded that T-peel testing (ASTM D 1876) is a appropriately aggressive test of adhesion to proxy for possible module conditions and 25+ year long life *without* introducing failure itself (such as micro cracks when the peel starts), and is both reproducible and consistent unlike 180° peel. Avery Dennison bases its conclusion both on results in its own PV labs and on its extensive experience in the paints and coatings industry where 90° peel testing has been the industry standard for many decades. Using T-peel testing, Avery Dennison’s backsheet delivers high bond strength to EVA (>60 N/cm), with high consistency/reproducibility.

Due to the general nature of laminates versus coatings, a 180-degree peel test could favor one construction (laminates) over others (coated) in an aggressive angled peel test, creating otherwise non-existing failure and therefore misleading conclusions about lifetime, forcing module fabs to purchase unnecessarily higher cost backsheets.

Therefore, Avery Dennison recommends eliminating 180° peel testing with T-peel testing and focusing on test data from damp heat, thermal cycling, humidity freeze, MWTR and cross hatch to demonstrate reliable long term performance in any environmental conditions.

Technology Based on More than 20 Years Out-door Products

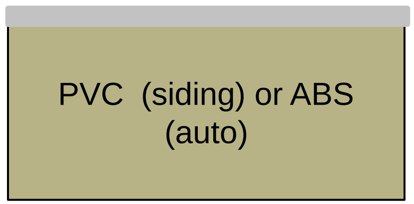
- Avery Dennison has **20+ years expertise** manufacturing high-performance outdoor films for aerospace, automotive, and architectural applications
- PV backsheets employ the **same manufacturing process know-how**



Avery Dennison's Fluoropolymer coated PV Backsheet

20+ years of Avery Dennison fluoropolymer coating technology for vinyl siding

Weather proof fluorocoat

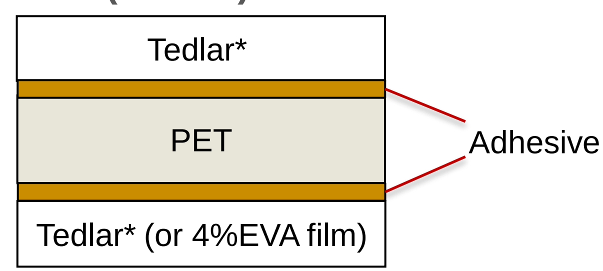


Technology transfer

Avery Dennison
FPF Backsheet

Comparison
To TPT*

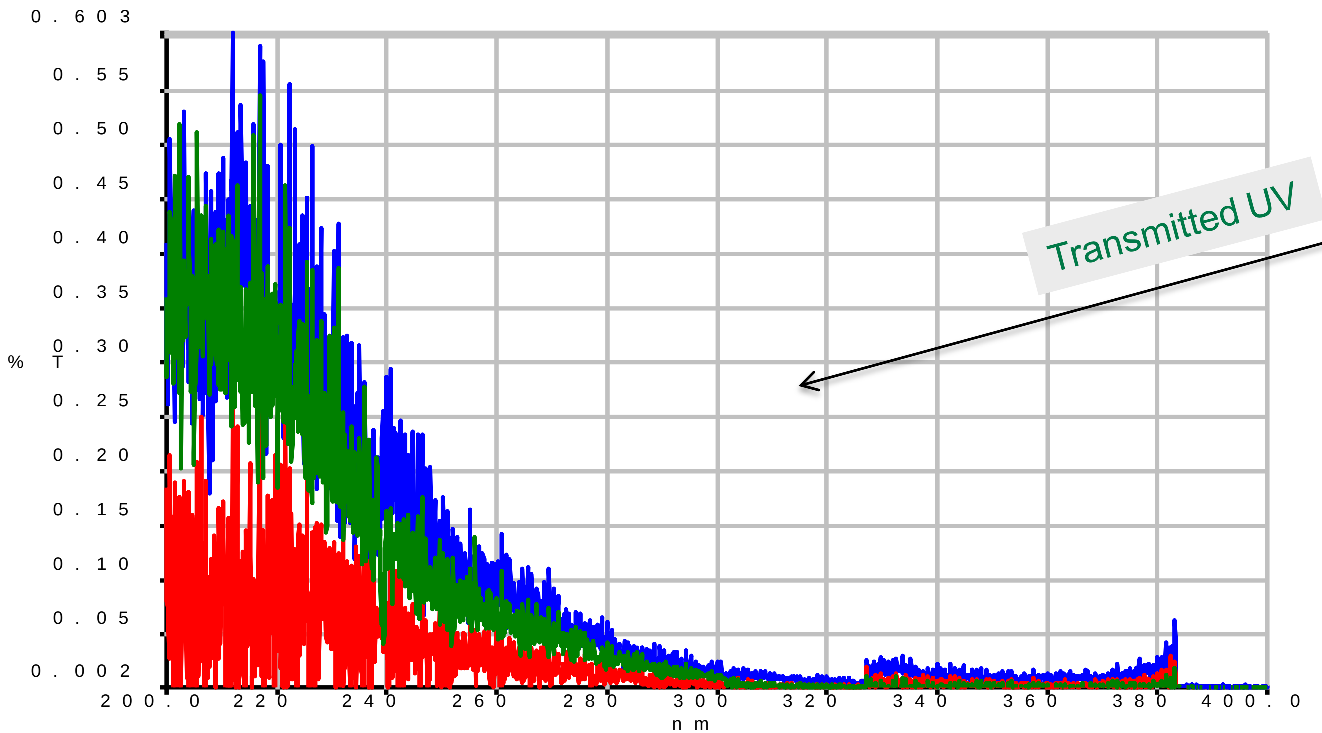
TPT* (or TPE) Backsheet

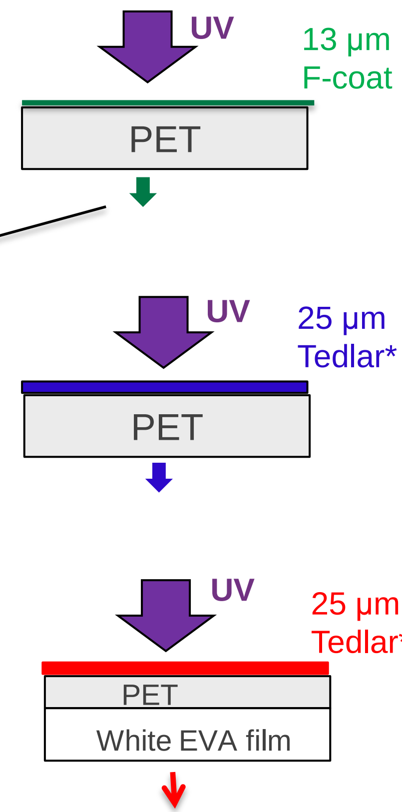


- The fluoropolymer coating is strongly bonded to PET in a high-speed coating process that precisely meters the coating onto the PET web, delivering impressive aesthetic and long-life *exterior* performance
- By coating vs. laminating, half the thickness of fluoropolymer (13um coat vs. 25um laminate) and <u>no</u> adhesives delivers equal or better performance

UV Protection

For protection of UV, a layer of 13 µm fluoropolymer coating (green) equals to 25 µm Tedlar* (blue), which translates into less material, lower cost, and +/- comparable performance required for 25+ year lifetimes





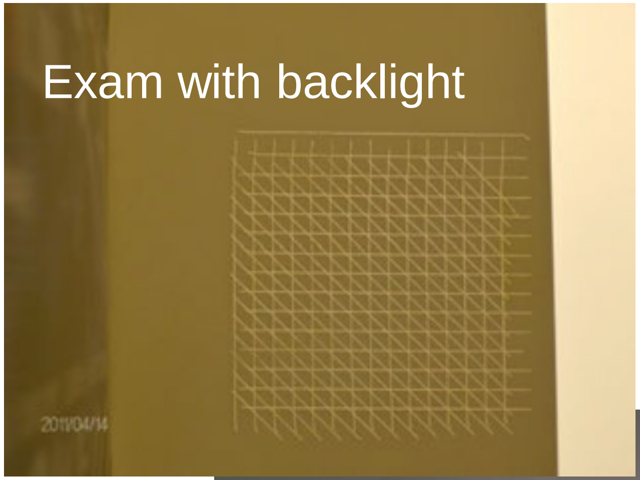
Avery fluoropolymer coating (13 µm)
Tedlar* film (25 µm)
TPE backsheet (25 µm Tedlar*+125 µm PET+50 µm EVA film)

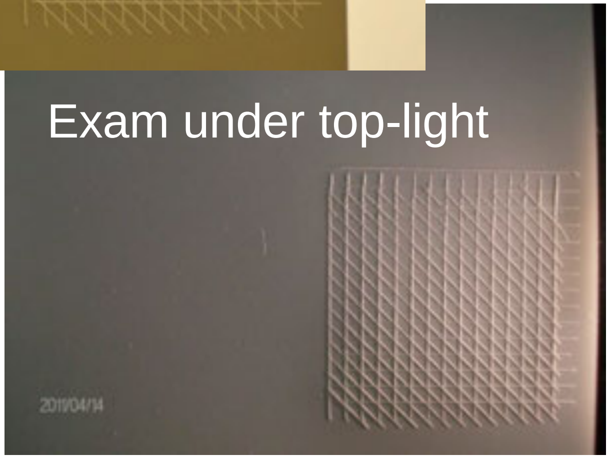
Avery Dennison's FPF Backsheet Delivers ~Double IEC Standards

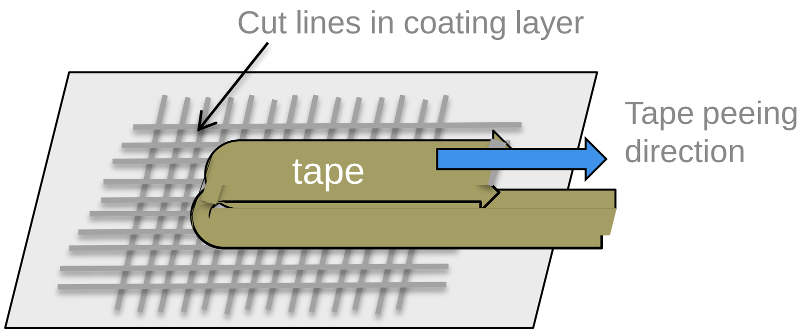
Testing Name	Test Method	Units	value	2X / extra test
EVA peel strength	ASTM D1876 (T-peel)	N/cm	> 60	180^o peel, large data variation
Water vapor transmission rate (WVTR)	ASTM F1249 (ASTM E96)	g/m^2day	< 1.4 (23℃/100%RH) < 2.5 (38℃/100%)	after 1000 hours of DH, no change (free standing backsheet)
Damp heat 85/85	IEC61215.10.13	1000 hr	No visual defects, no delam, slight discoloration (ΔE< 2)	**2000 hr**, no visual defects, slight discoloration (ΔE< 2) and **no delam**
Thermal cycling	IEC61215.10.11	200 cycles	No visual defects, no delam, no discoloration (ΔE< 1) ,	**400 cycles**, no visual defects, **no delam**, (ΔE< 1)
Humidity freeze	IEC61215.10.11	10 cycles	no visual defects, no discoloration, no delam	**20 cycles**, no visual defects, no delam, no discoloration, **no delam** (ΔE< 0.5)
Evaluation coating adhesion to PET (cross hatch)	ASTM D3359	%	100% (or 5B)	100% after QUV 1000hr 100% after DH 2000hr 100% after TC 400 cycle 100% after HF 20 cycles

Highest Rating (ASTM 3359) of Coating-PET Bonding

After crosshatch test (tape lift/adhesion test), 100% coating adhesion (5B rating) achieved.
Note: shown below, diagonal cut lines are more aggressive/hasher than the ASTM 3559 standard

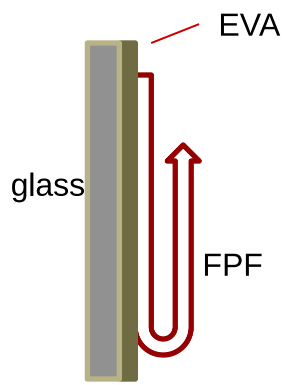




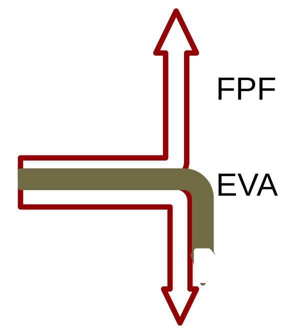


ASTM 3559 Classification	percent area of removed coating
5B	0%
4B	<5%
3B	5-15%
2B	15-35%
1B	35-65%
0B	>65%

Coated Backsheet
- Difference observed between 180º-peel and T-peel



180-peel variation



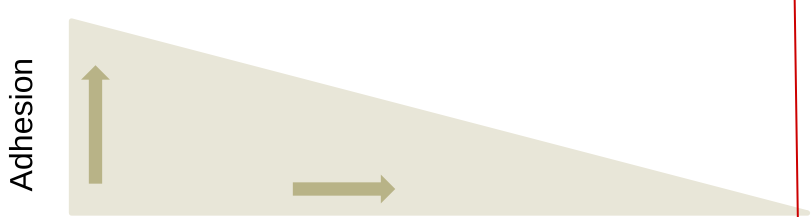
T-peel variation

180-peel variation

adhesion (N/cm)	failure mode
14	PET / coating
104	coating / EVA

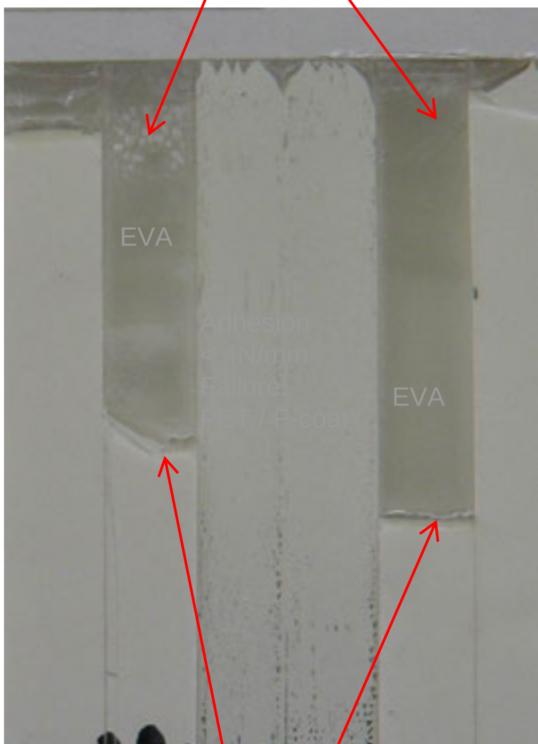
T-peel variation

adhesion (N/cm)	failure mode
68	coating / EVA
81	coating / EVA

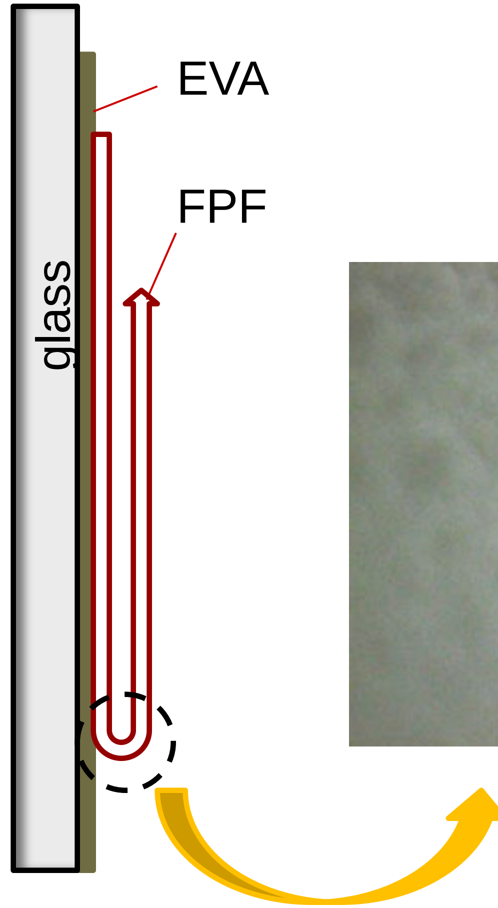


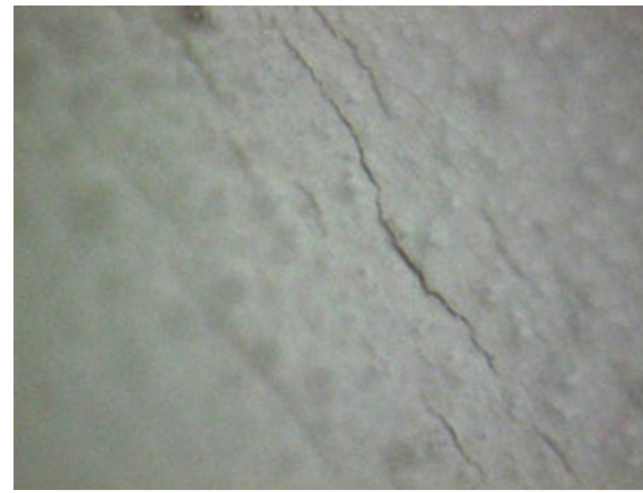
Concerns for 180º Peel of Coated Backsheet

Adhesion >> 40 N/cm
Failure: F-coat / EVA

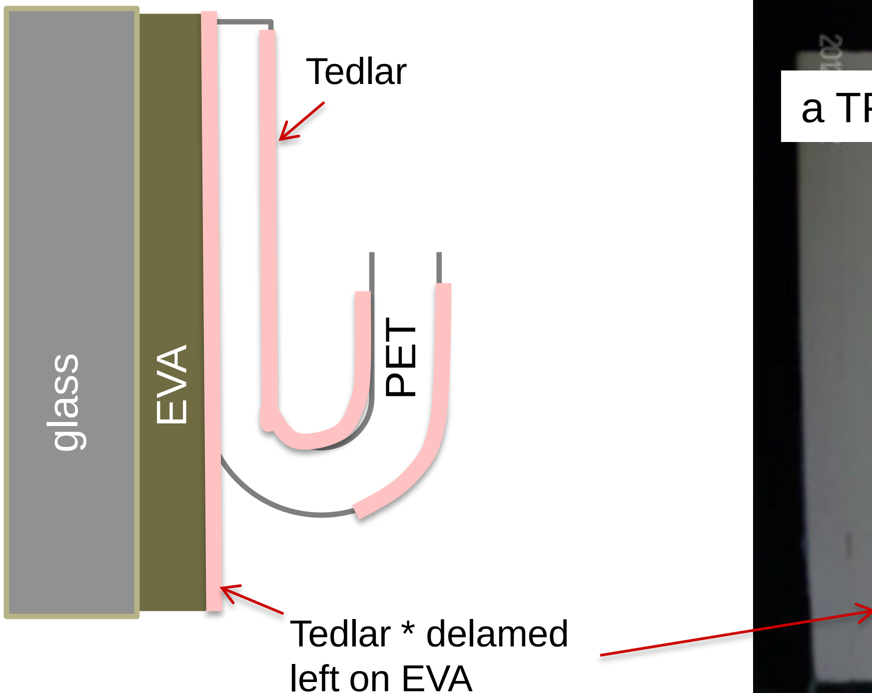


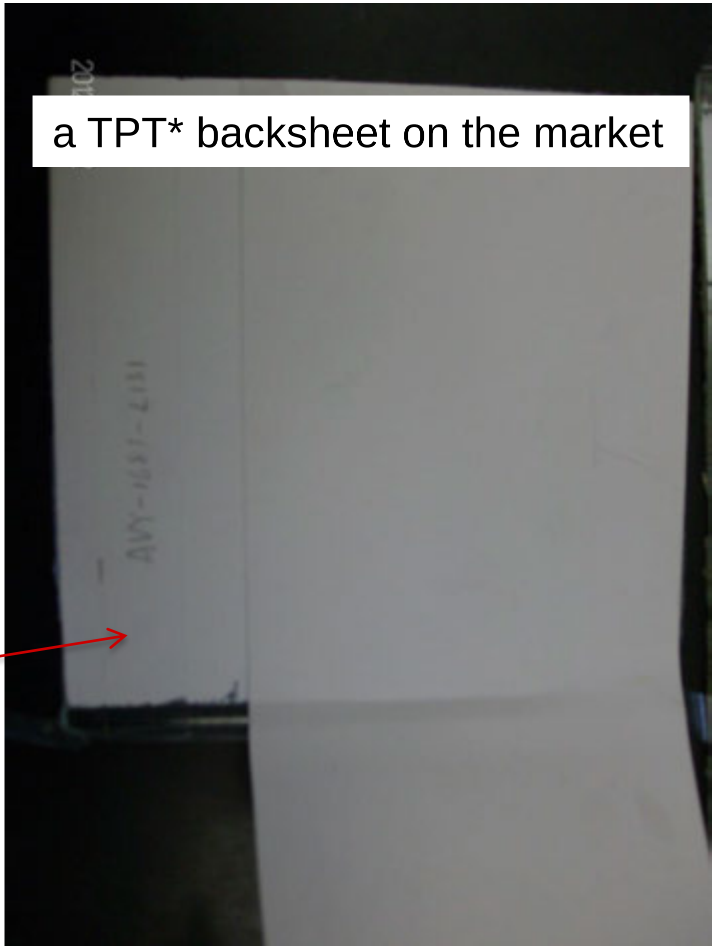
Backsheet
Broken point





Concerns for 180º-peel of Laminated Backsheet (TPT*)





Inter layer failure, T layer 100% delam'ed from PET, adhesion = 6 N/cm

Conclusions

- Historical data indicates that A PV module will not encounter forces like 180º, 90º, or T-peel[1]; therefore, 180º peel does not truly reflect a realistic failure mode in PV modules

- Comparing to 90º, or T-peel, 180º peel is highly likely to *create* defects, such as cracks, when the test starts, especially for a sharper folding at a high bond strength between backsheet and EVA

- Compared to 180º peel, T-peel is sufficiently aggressive and appropriate for all current backsheet constructions and can also be equally aggressively/ accurately applied to measure EVA adhesion and no glass needed (backsheet/EVA/backsheet laminate)

- Adhesion failure in a backsheet laminate sample (backsheet/EVA/glass or backsheet/EVA/backsheet) highlights interface with lowest interfacial adhesion (so measuring the peel strength prior to failure indicates lowest interfacial adhesion strength for layers between two 'clamped' layers)

- 180º peel testing is no longer appropriate (in fact inaccurate as it introduces failure mechanisms) for back sheet constructions on the market today and may lead to backsheet over-engineering and higher cost

[1] **J.Wohlgemuth, NREL,** "Module Component of PV Tutorial", Integration of Renewable & Distributed Energy Resources Conference, 6 Dec 2010; and **David DeGraaf, et al., Sun Power Corp,** "Degradation Mechanisms in Si Module Technologies Observed in the Field; Their Analysis and Statistics", NREL 2011 Photovoltaic Module Reliability Workshop, 16 Feb 2011

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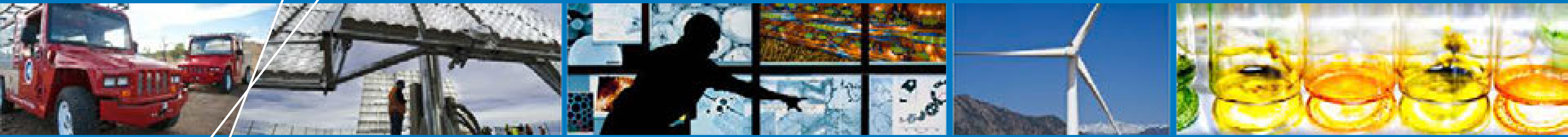
Testing Protocol for Module Encapsulant Creep



National Renewable Energy Laboratory – Photovoltaic Module Reliability Workshop

NREL-PVMRW

Michael D. Kempe, David C. Miller, John H. Wohlgemuth, Sarah R. Kurtz, John M. Moseley, Qurat (Annie) Shah, Govindasamy Tamizhmani, Keiichiro Sakurai, Masanao Inoue, Takuya Doi, and Atsushi Masuda

February 29, 2012

NREL/PR-5200-54583

Background, Concerns and Objectives

- **Background:**
  - Creep is the permanent deformation of a solid material under the influence of mechanical stresses.
  - PV manufacturers are using thermoplastic materials.
  - Qualification tests only test to 85^{o}C whereas modules can reach 105^{o}C outdoors, though only for a short time.
- **Concerns:**
  - Live components may be exposed.
  - Cells, tabbing, busbars, and etc. may be stressed and broken.
  - Internal short circuits may be created.
- **Objectives:**
  - Evaluate the potential for creep in outdoor exposure.
  - Provide guidance for the risks and for the design needs with thermoplastic materials.
  - Provide a basis for modifying standards to account for materials with the potential to creep

Outline

- Experimental Materials Used
- Outdoor Exposure Results
- Indoor Exposure
- Conclusions

Eight Representative Encapsulants Studied

Encapsulant Material Type		DSC Determined Transitions			DMA Determined Transitions at 0.1 rad/s	
		T_g (°C)	T_m (°C)	T_f (°C)	T_g (°C)	T_m (°C)
Commercial PV EVA resin	EVA	-31.4	55.1	45	-30	47
Commercial PV EVA Resin with all components but the peroxide	NC-EVA	-30.6	65.4	45.3	-28	69
Polyvinyl Butyral	PVB	14.8	NA	NA	17	NA
Aliphatic Thermalplastic Polyurethane	TPU	1.8	NA	NA	3	NA
Pt Catalyzed, Addition Cure Polydimethyl Silioxane Gel	PDMS	-158.6	-39.7	-80.3		
Thermoplastic Polyolefin #1	TPO-1	-43.1	92.9	80.6	-35	105
Thermoplastic Polyolefin #3	TPO-3	-44.2	61.0	55.3	-41	79
Thermoplastic Polyolefin #4	TPO-4	-33.5	105.5	99.2	-21	115

Thin Film Mock Modules

(1) 3.18 mm TCO glass with edge delete
(2) Encapsulant
(3) 3.18 mm back glass with through hole for electrical contact to TCO
(4) Black Paint, thermocouples and rails on back
(5) 2.5 cm fiberglass matte insulation, 46.5 m^2K/W^2 (R 6.7)
(6) 2.5 cm polyisocyanurate sheating foam insulation board, 45.1 m^2K/W^2 (R 6.6)
(7) 1.3 cm plywood back

Thin Film Mock Modules

(1) 3.18 mm TCO glass with edge delete
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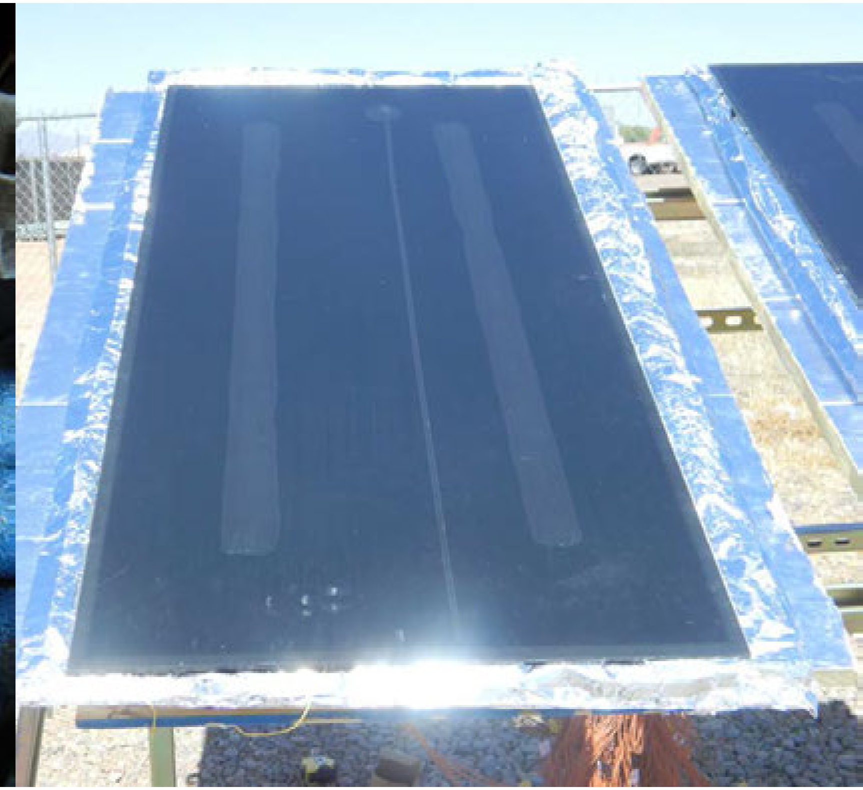
Thin Film Mock Modules



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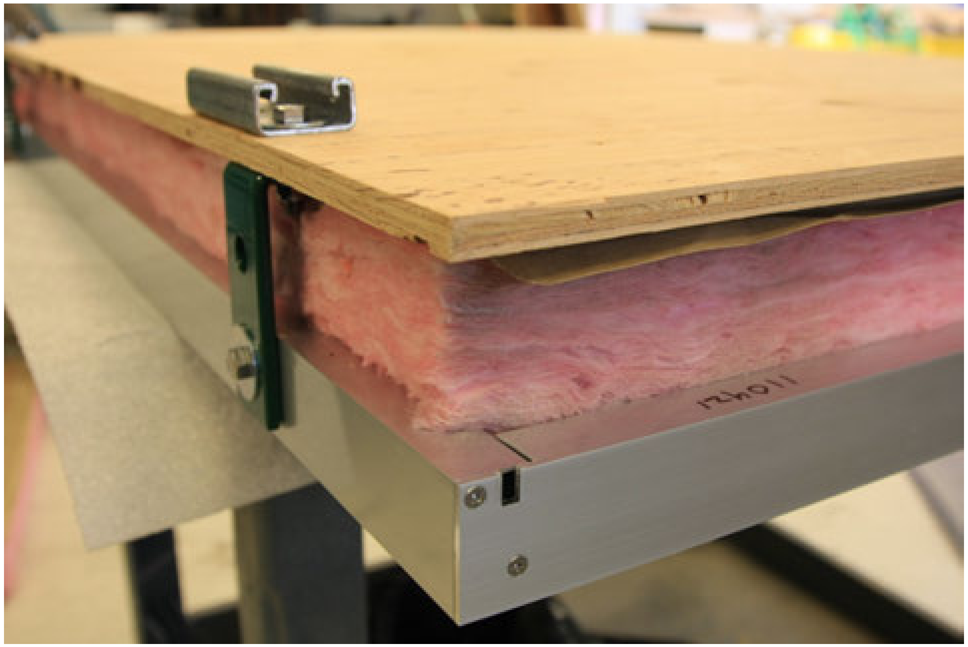
(7) 1.3 cm plywood back

Crystalline Silicon Module Setup

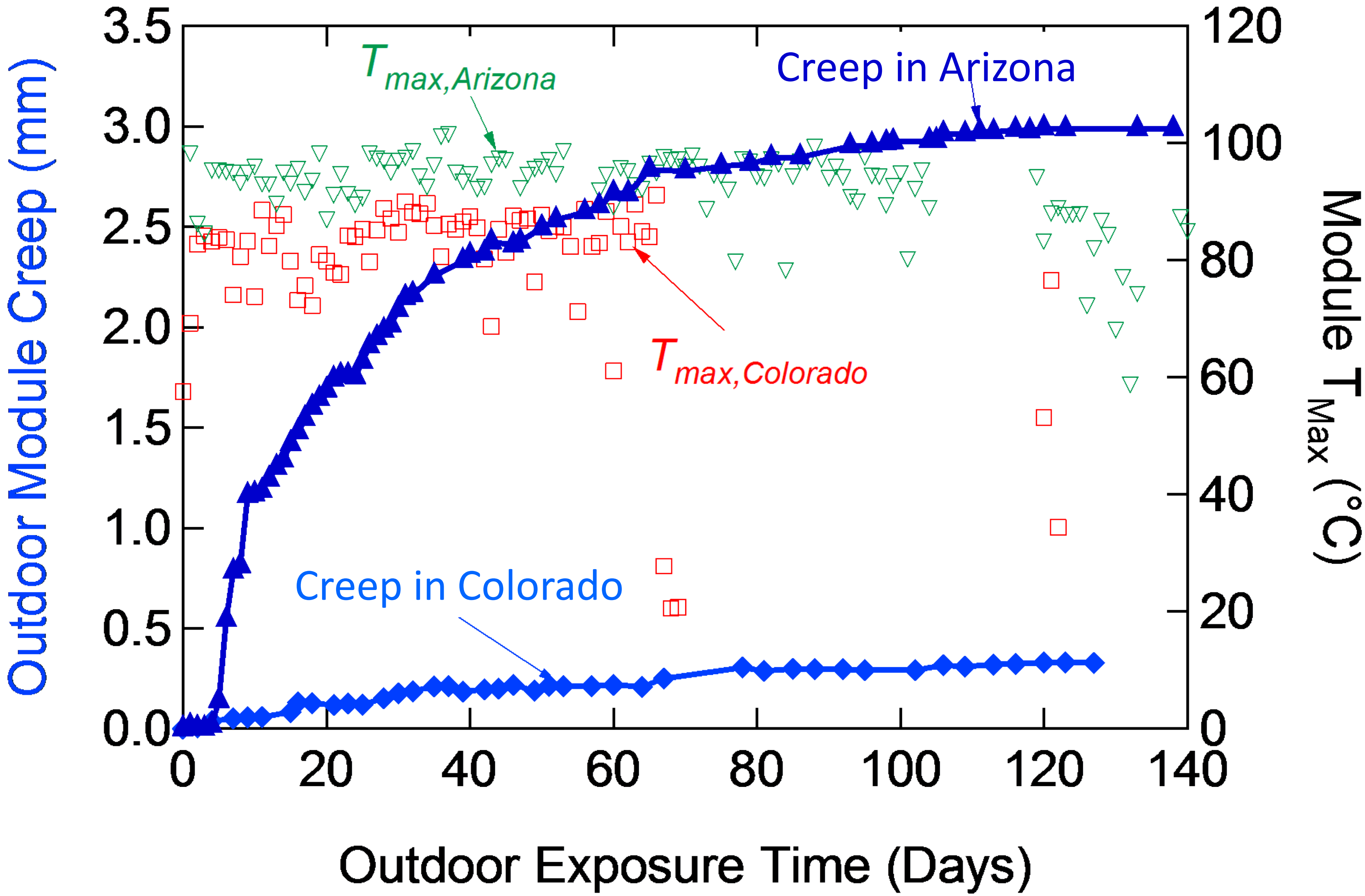


(1) 3.18 mm glass
(2) Encapsulant
(3) UMG polycrystalline Si Solar Cells
(4) Encapsulant
(5) PVF/PET/PVF backsheet
(6) 9 cm Fiberglass matte insulation, 104 m^{2}K/W^2 (R 15)
(7) 1.3 cm plywood

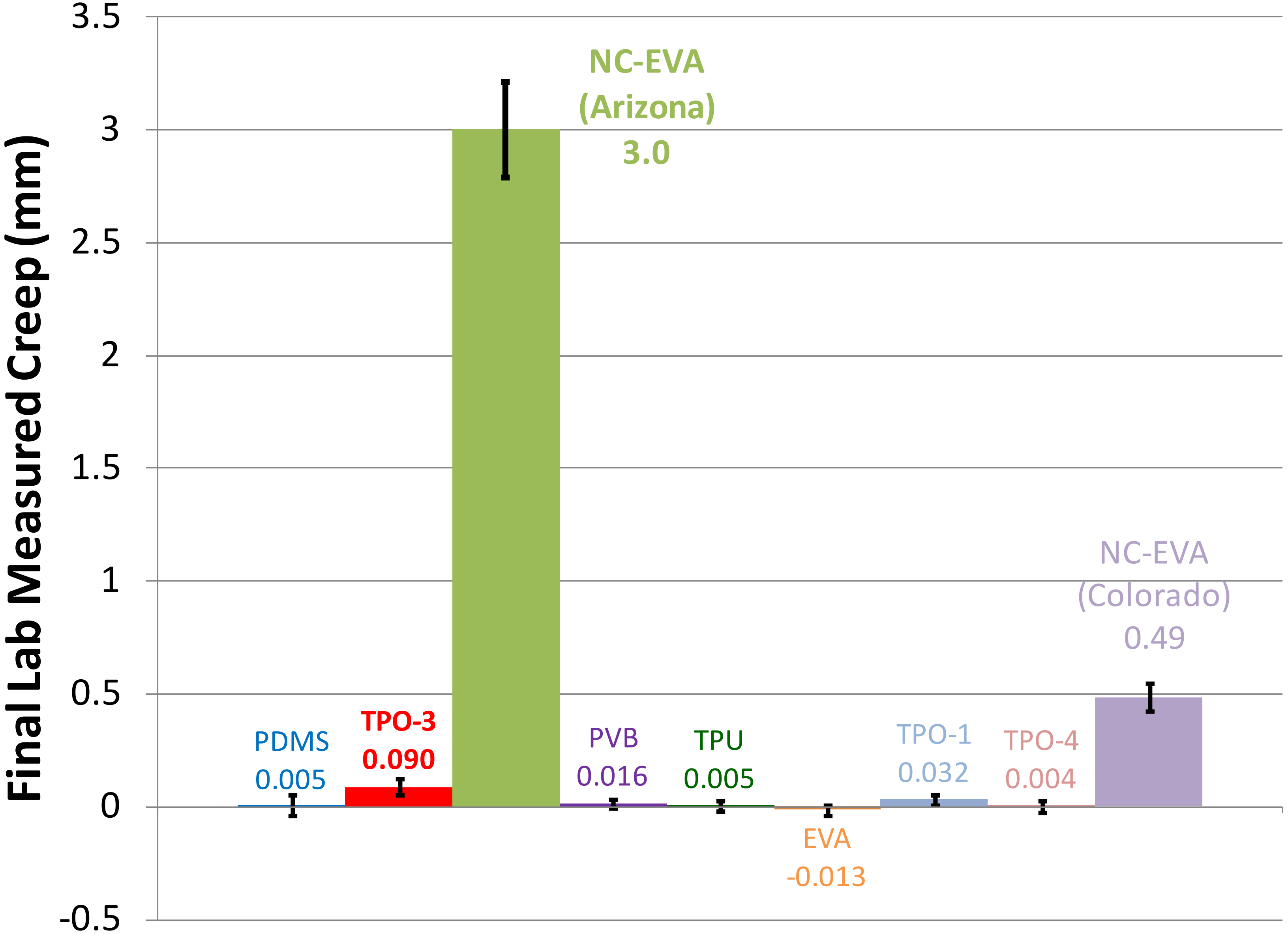
Deployed in Arizona Summer 2011

- Modules mounted in Mesa Arizona from May to September, 2011.
- Array oriented at a 33^{0} tilt and an azimuth of 255^{0} south so that the array more directly faced the sun at the hottest part of the day.
- A single no-cure-EVA mock module was deployed in Golden Colorado.

Only the No-Cure-EVA Module Crept Significantly



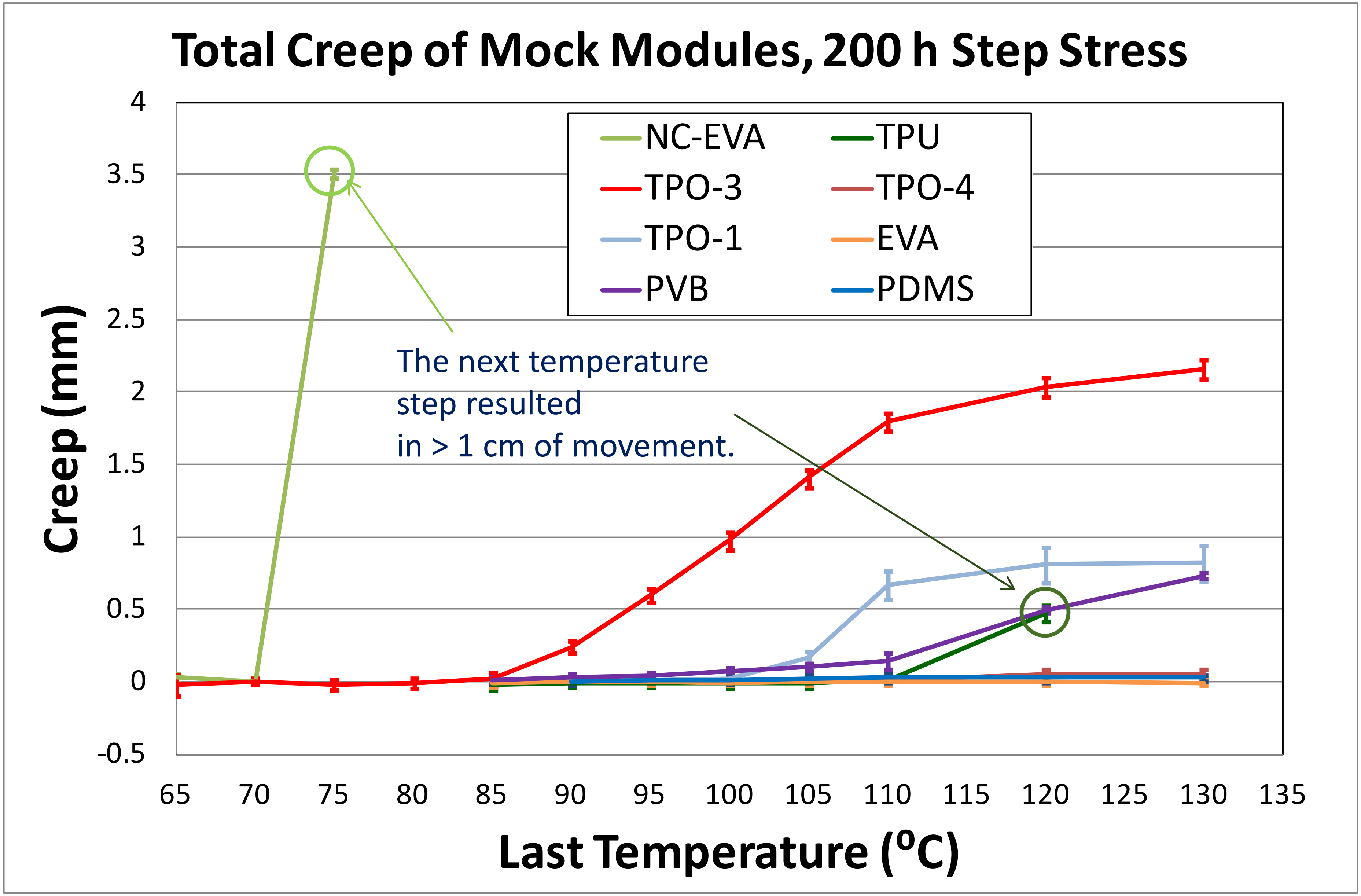
Minor Creep in TPO-3 and TPO-1



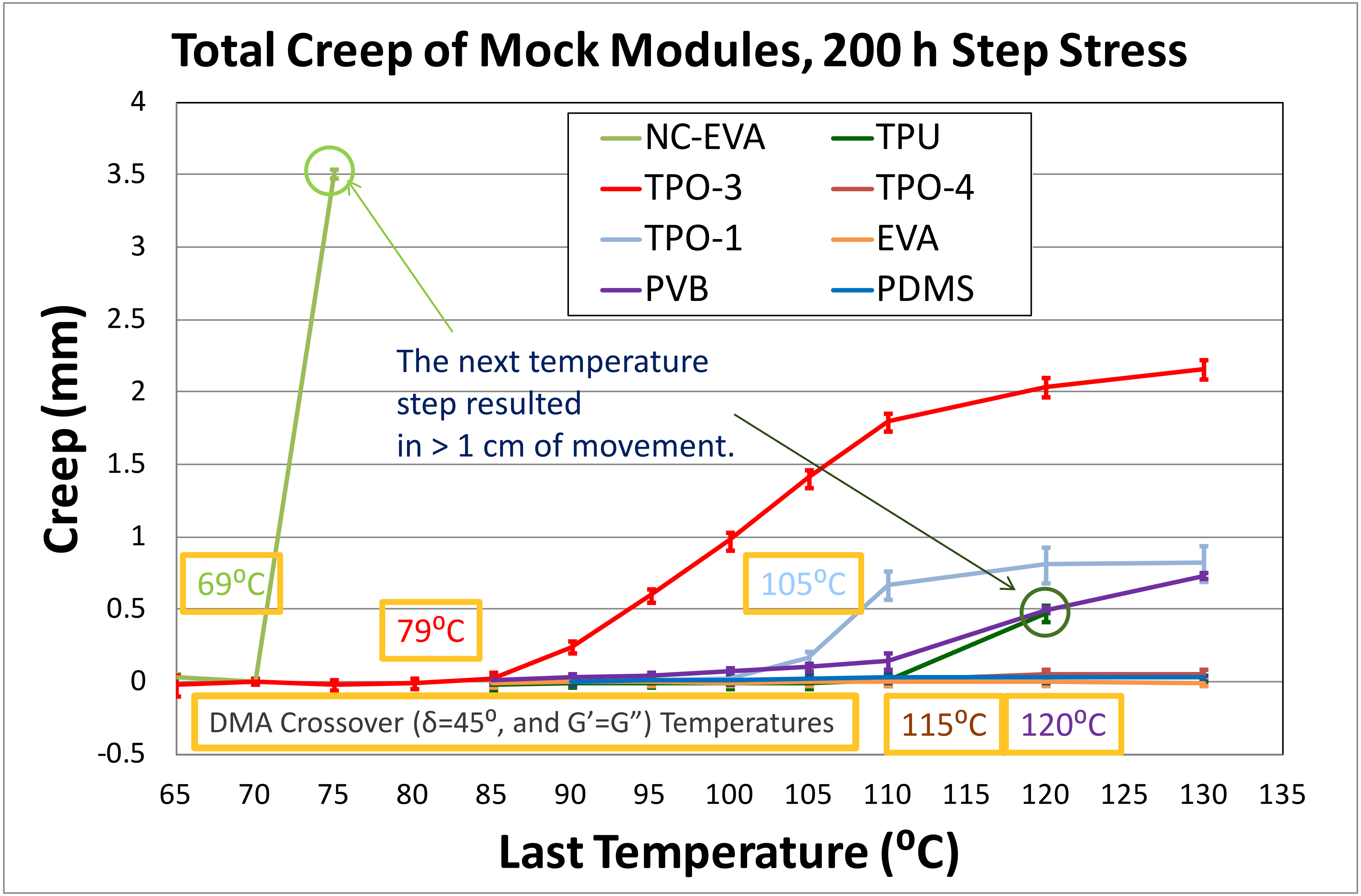
Outdoor Results Summary

- **Crystalline Si Modules**
  - No Signs of Creep
  - All Passed Wet High Pot
  - Only TPO-4 showed performance loss attributable to cell breakage. Probably from the lamination process.
- **Thin Fim Mock Modules**
  - The NC-EVA Module Crept 3 mm.
  - The NC-EVA appears to be crosslinking as it ages.
  - The TPO-1, and TPO-3 crept 32 and 90 microns, respectively.
  - All Passed the Wet High Pot Test.

Step Stress Test Parallels Outdoor Data



Step Stress Test Parallels Outdoor Data



TPU Thin Film Mock Module Formed Bubbles Upon Heating

TPU after 100^{o}C
No Creep
Pass Wet Hi-Pot

TPU Thin Film Mock Module Formed Bubbles Upon Heating

TPU after 100^{o}C
No Creep
Pass Wet Hi-Pot

TPU After 105^{o}C
No Creep
Pass Wet Hi-Pot

TPU Thin Film Mock Module Formed Bubbles Upon Heating

TPU after 100°C
No Creep
Pass Wet Hi-Pot

TPU After 105°C
No Creep
Pass Wet Hi-Pot

TPU after 110°C
0.023 mm Creep
Pass Wet Hi-Pot

TPU Thin Film Mock Module Formed Bubbles Upon Heating

TPU after 100^{o}C
No Creep
Pass Wet Hi-Pot

TPU after 110^{o}C
0.023 mm Creep
Pass Wet Hi-Pot

TPU after 120^{o}C
0.482 mm Creep
Pass Wet Hi-Pot

TPU Thin Film Mock Module Formed Bubbles Upon Heating

TPU after 100^{o}C
No Creep
Pass Wet Hi-Pot

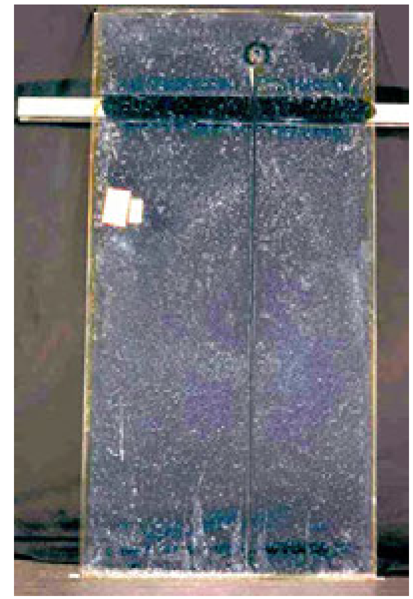
TPU after 110^{o}C
0.023 mm Creep
Pass Wet Hi-Pot

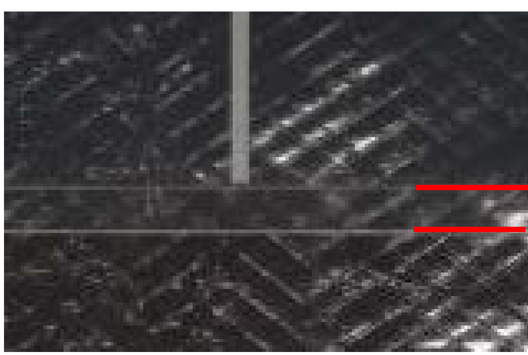
TPU after 130^{o}C
>1 cm Creep
Fail Wet Hi-Pot

NC-EVA Did not Form Bubbles

NC-EVA Mock Module
After 80^{o}C Exposure.

TPU Mock Module
After 130^{o}C exposure.

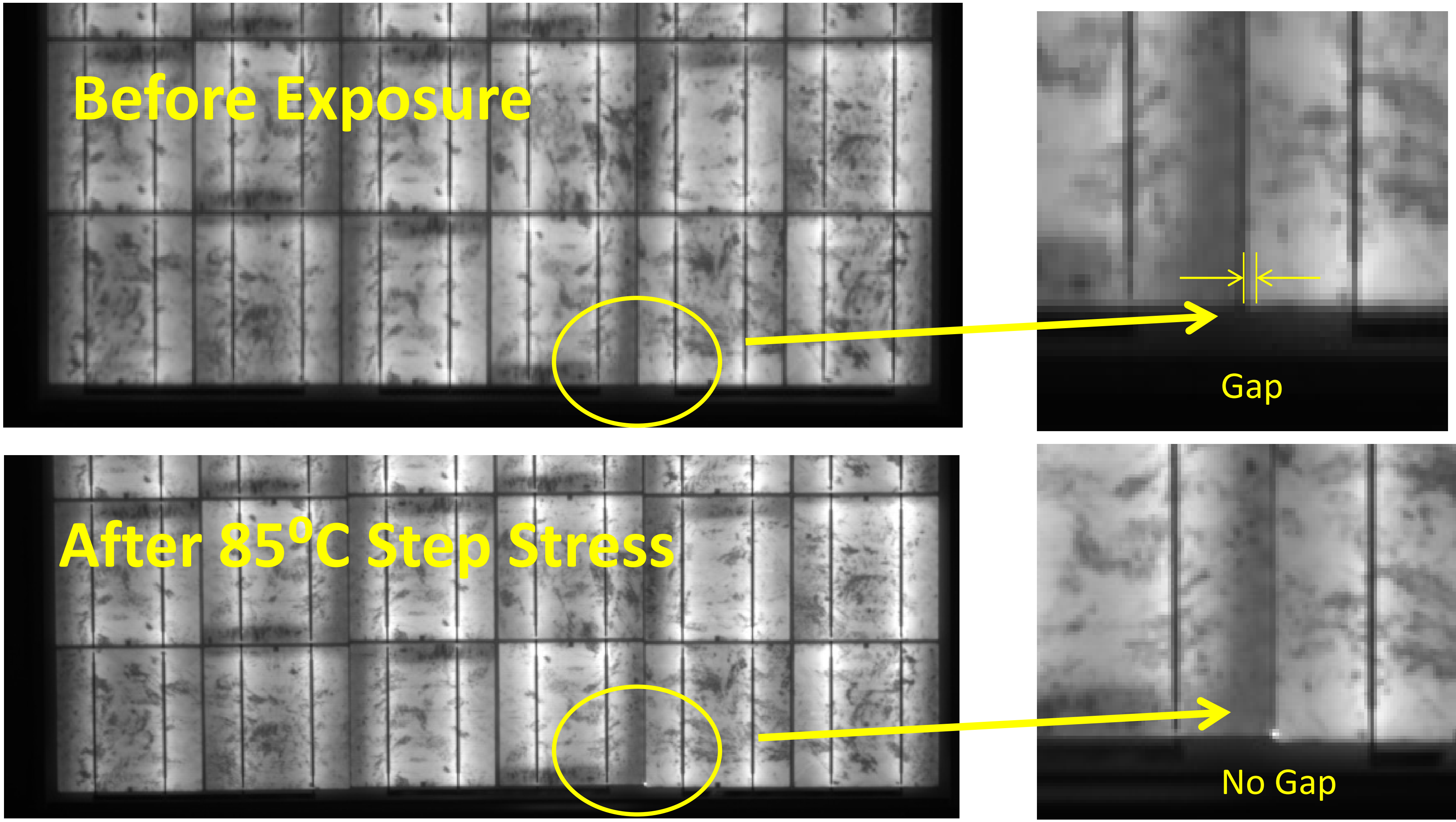




Glass
Displacement

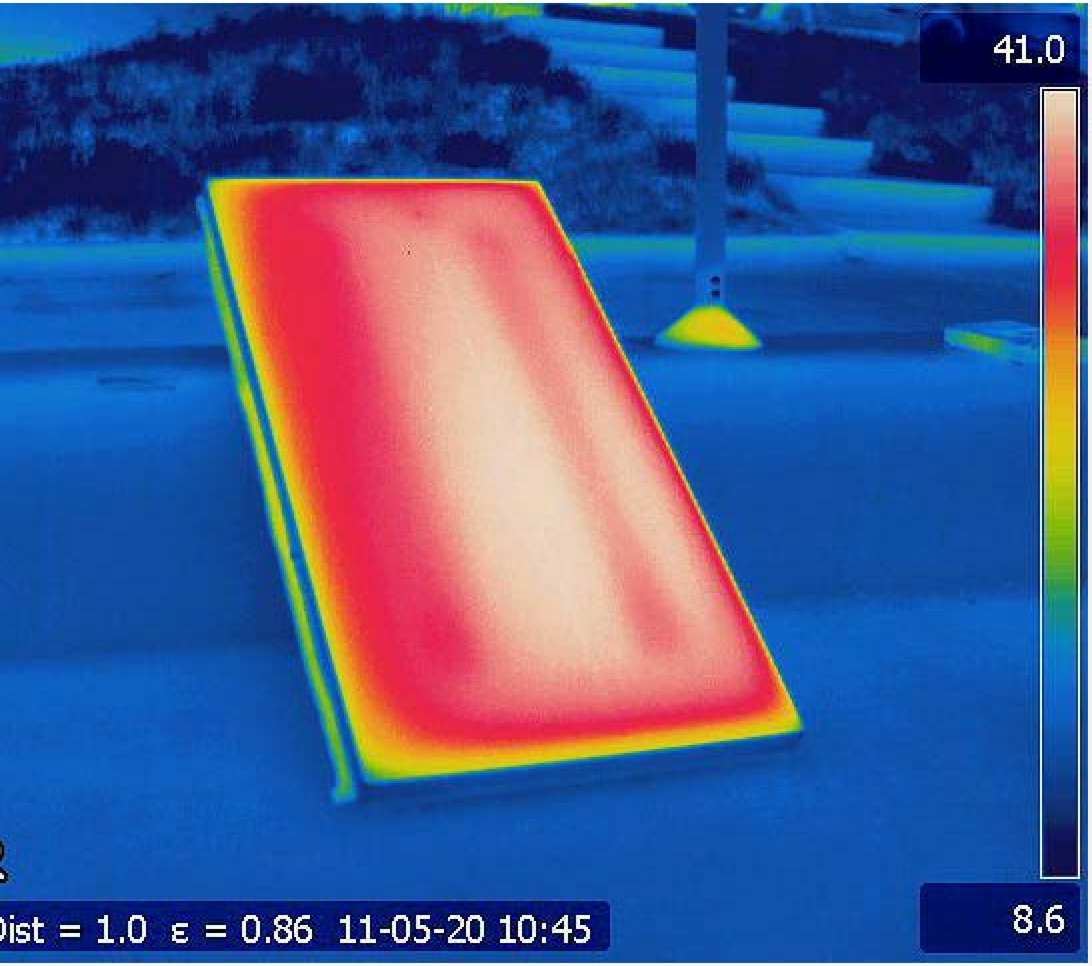
Some Creep in NC-EVA in Chamber at 85^{o}C

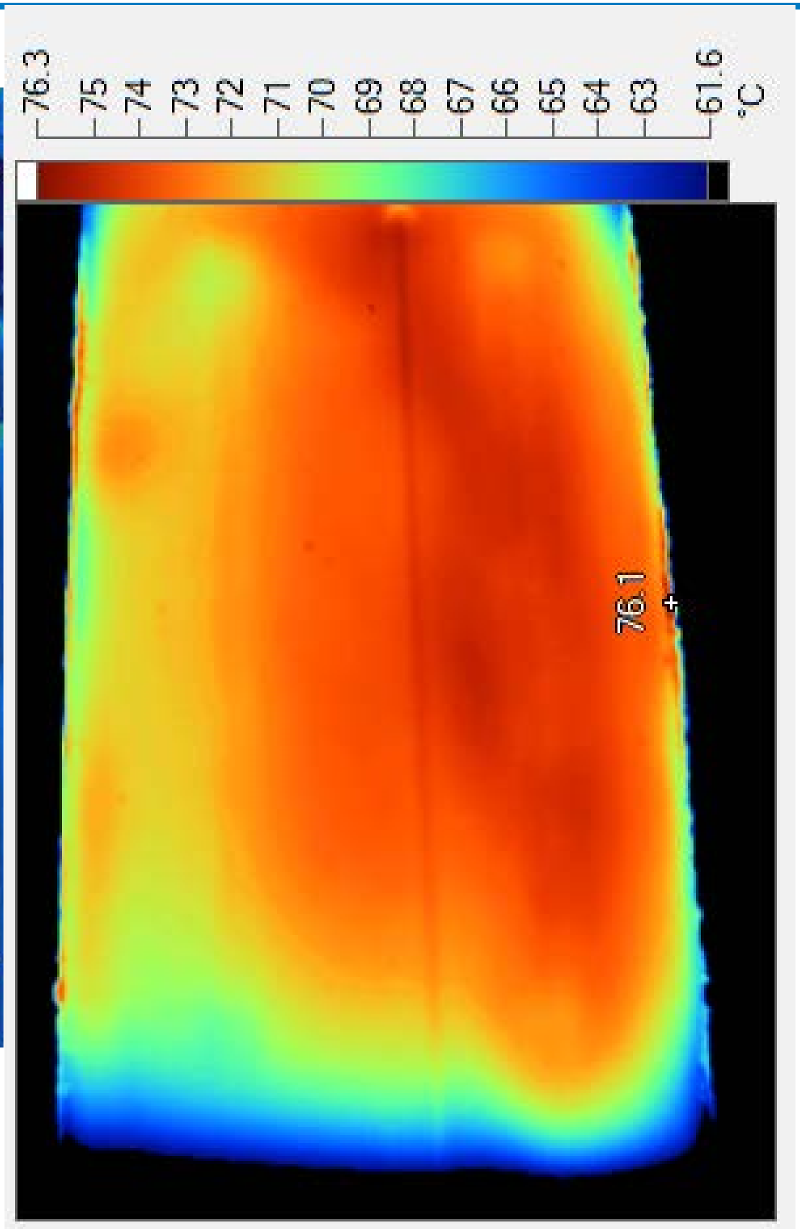
NC-EVA Crystalline Si Module (Electroluminescence)



However, there was no performance loss.

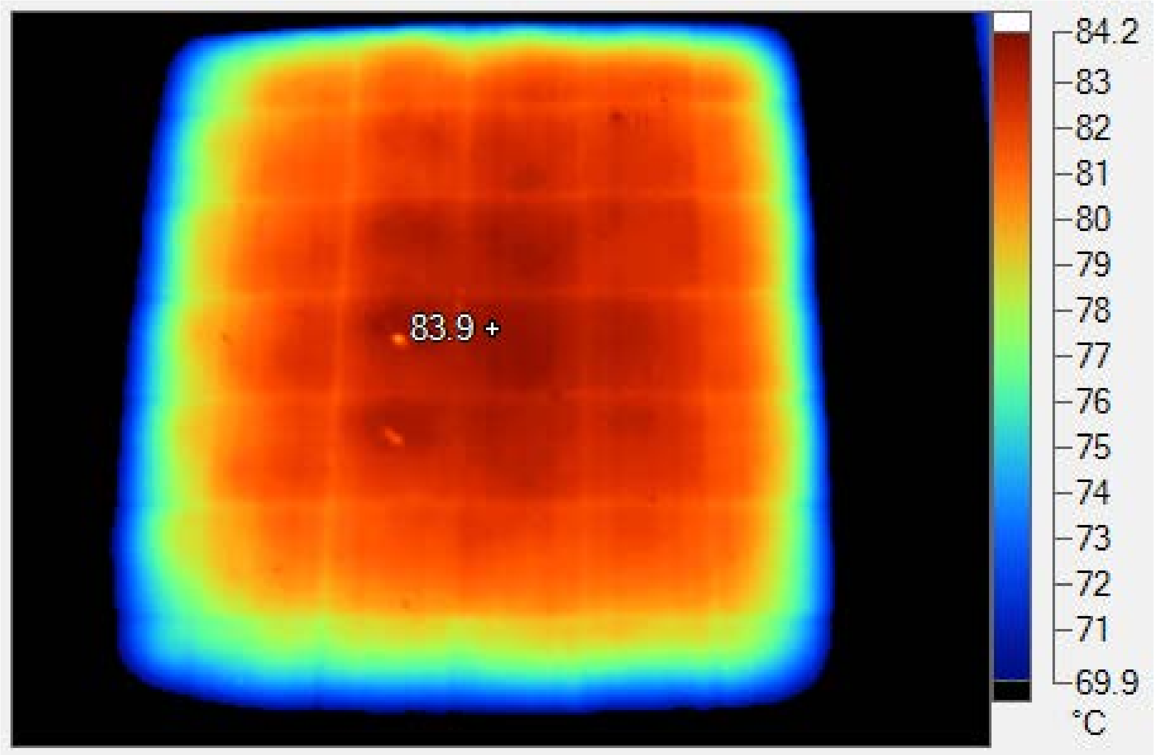
Temperature Non-Uniformity Decreases Creep





Up to a ~15^{o}C temperature variation was seen.

X-Si Modules Show Similar Thermal Gradients



Despite reaching very high temperatures around 102^{o}C, the module tabbing and backsheet were able to prevent large cell movements.

Strings were connected vertically, if it had been mounted with horizontal strings, cells in the center may have been more likely to move.

Conclusions

- Even without any peroxide for curing, NC-EVA, modules are not likely to creep significantly in most environments and mounting configurations.
- A Creep evaluation test should account for the possibility of polymer chain scission or cross-linking.
- Thermal non-uniformities dramatically reduce the propensity for creepage.

- The current proposal for IEC 61730 part 1, is to expose all modules for 200 h to a temperature between 100 and 110 ^{o}C.

Acknowledgements

- Adam Stokes, Alain Blosse, Ann Norris, Bernd Koll, Bret Adams, Casimir Kotarba (Chad), Crystal Vanderpan, David Trudel, Dylan Nobles , Ed Gelek, Greg Perrin, Hirofumi Zenkoh, James Galica, Jayesh Bokria, John Pern, Jose Cano, Kartheek Koka, Keith Emergy, Kent Terwilliger, Kolakonu, Mowafak Aljasim, Nick Powell, Niki Nickel, Pedro Gonzales, Peter Hacke, Ryan Smith, Ryan Tucker, Sam Samuels, Steve Glick, Steve Rummel, Tsuyoshi Shioda, and Yamamichi Masaaki

- This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

NATIONAL RENEWABLE ENERGY LABORATORY

"A Proposed Junction-Box Stress Test (Using an Added Weight) for Use During the Module Qualification"

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*** David.Miller@nrel.gov**

2012 PV Module Reliability Workshop

(Denver West Marriot, Golden, CO)

2012/2/29, 8:20 – 8:40 am (Wednesday)

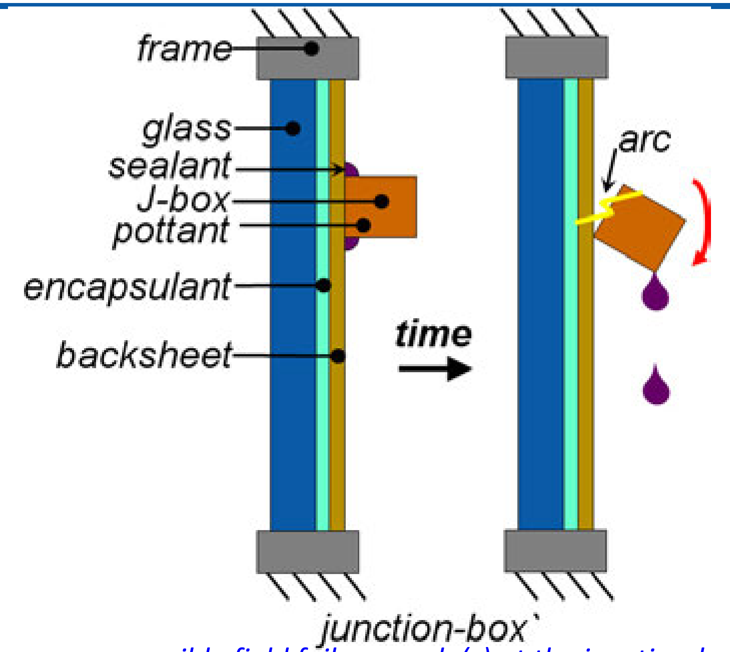
Golden Ballroom

-this presentation contains no proprietary information-

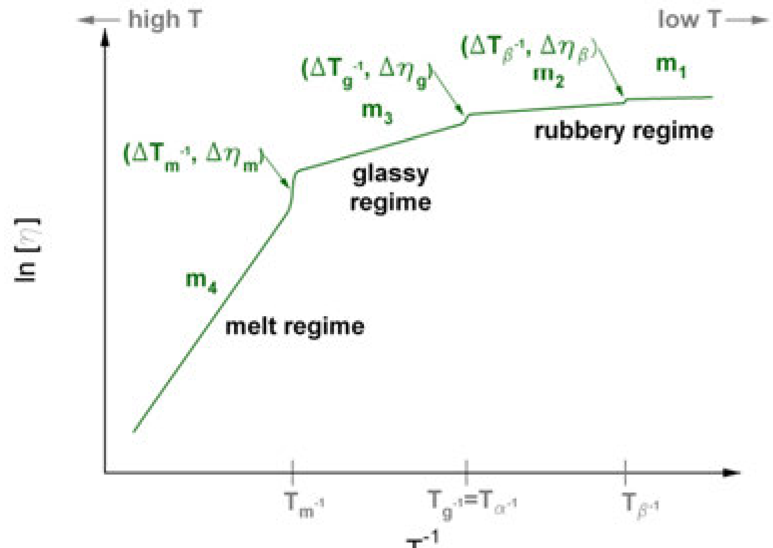
NREL/PR-5200-54525

Motivation for the Project

- J-box attachment often proves a milestone to module manufactures … possible consequences of field failure
- Possible failure mechanisms: phase transformation, creep, *cohesive failure*, **delamination** of the -adhesive system-
- Present qual. test: "robustness of termination" (pull ⊥ against j-box 40 N load) after [UV preconditioning, thermal cycling, humidity-freeze], and at room temperature
- Discovery experiments suggest that problematic systems can be more readily identified with applied weight during damp heat



possible field failure mode(s) at the junction-box
D.C. Miller et. al., Proc. IEEE PVSC, 2010, 262-268.



viscosity (flow rate) vs. 1/T for thermoplastic polymer

(Temperature) Conditions Present in the Field

- The cell (module) temperature can be predicted from popular models (King, Faiman, etc.)

  D.L. King et. al., SAND2004-3535 2004; 1-43.
  D. Faiman D, Prog. Photovolt: Res. Appl. 2008; 16: 307–315.

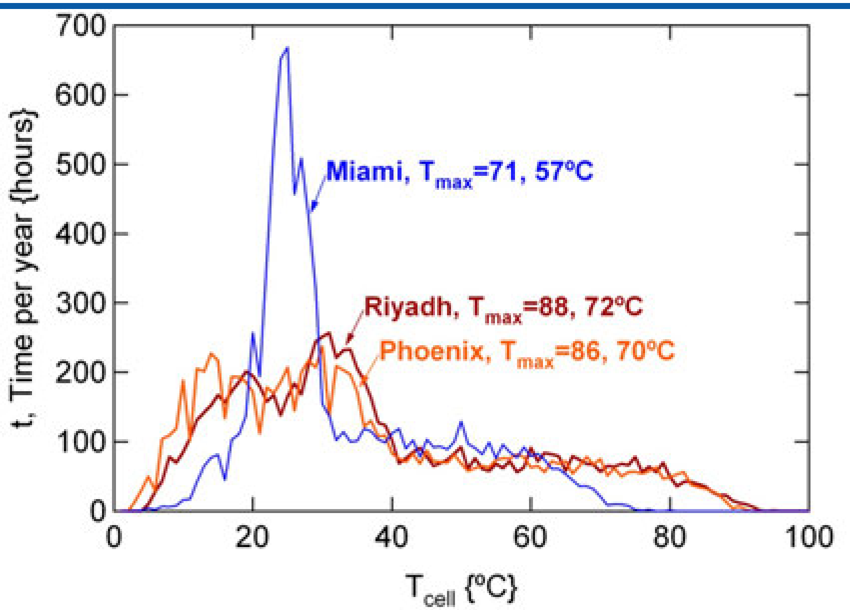
- T_{max} of 105°C achievable for open circuited, roof-mounted modules in desert location

- A greater T_{max} may be realized during the reverse bias condition induced by partial shading, current mismatch, cell or interconnect failure

- Localized $T_{max} \geq 150°C$ achievable during the "hot-spot" condition

  E. Molenbroek et. al., Proc. IEEE PVSC 1991; 547-552.
  Oh and TamizhMani, Proc. IEEE PVSC, 2010; 984 – 988.

- Other factors (*e.g.*, moisture) are also present in the field



Time-temperature histories for the cell in roof-mounted modules for a typical year. T_{max} given for roof and rack-mounted modules.

LOCATION	T_{max}, ROOF {°C}	T_{max}, RACK {°C}	$T_{max, record}$, AMBIENT {°C}
Death Valley, CA	108	90	57
Riyadh	103	84	48
Phoenix, AZ	103	85	50
Yuma, AZ	100	83	51
New Delhi	97	79	45
Seville	97	79	45
Kuwait City	99	83	51
Daytona, FL	90	73	39
Denver, CO	89	72	40
Miami, FL	86	70	37
Bangkok	85	69	38
New York, NY	89	73	41
Munich	79	64	36
Fairbanks, AK	70	59	36

*T_{max} predicted from 30 year **record** temperature data*
D.C. Miller et. al., Proc. IEEE PVSC, 2010, 262-268.

Summary of Experiments

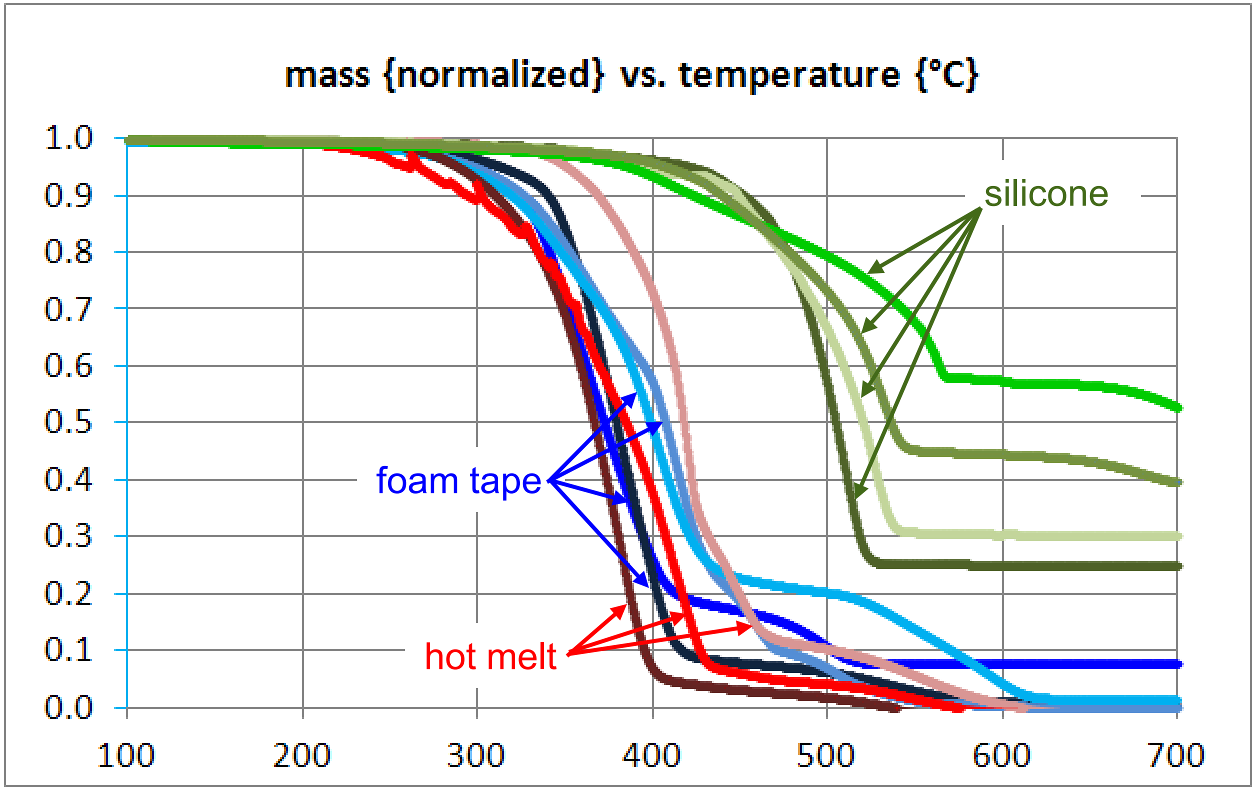
- Specimens:
  - foam tapes (closed cell: acrylic, polyurethane, polyethylene)
  - silicones (condensation cure: acetoxy, oxime, alkoxy cure)
  - hot melt (thermoplastics: EVA, polyolefin, polyamide)

- Material-level tests:
  - thermogravimetric analysis (TGA)
  - differential scanning calorimetry (DSC)
  - dynamic mechanical analysis (DMA)

- Component-level tests:
  - indoor chamber: 1000 hours @ 85°C, 85% RH
  - polyester (PET) “substrate”
  - glass “substrate”

The Decomposition Temperature: Measured vs. Required

- To ensure long term durability in the event of a prolonged hot spot condition:
  - $T_{5\%} > 200°C$ (approximation for test @ $20°C \cdot min^{-1}$)
  - → Examining the event of prolonged hot-spot condition ~ 150°C
  - → $T_{5\%}$ could occur on the order of 50°C lower at slower test rate
- No overt failures relative to this criteria
- Only PU tape, alkoxy silicone, and EVA hot melt approach this criteria: evaluate at slower test rate to verify



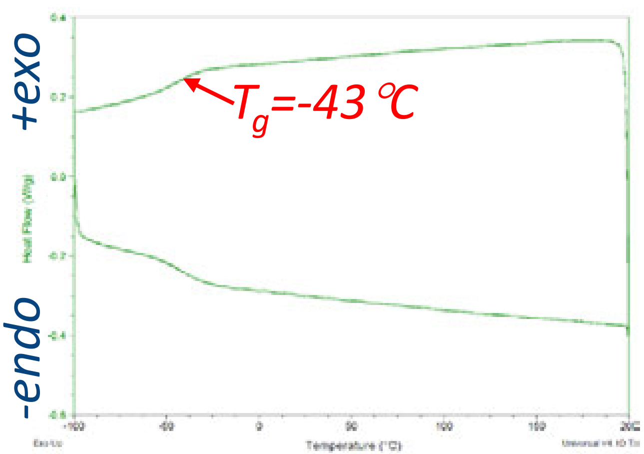
TGA characterization of silicones, foam tapes, and hot melts

DSC Identifies the Likelihood of Creep

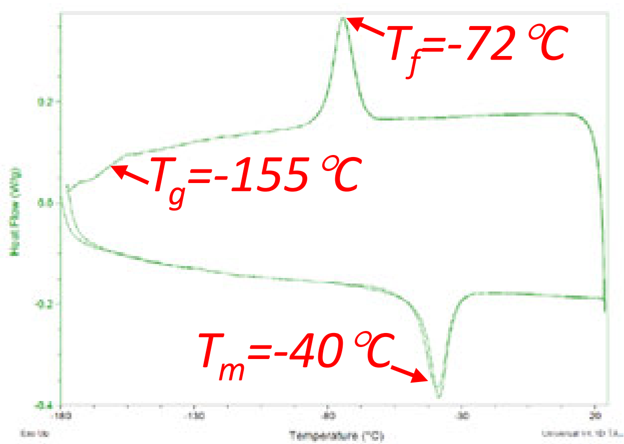
- Glass transitions (T_g aka T_α) may signify likelihood for creep
- The T_g's here are well below the typical operating temperature within fielded modules

- Melt & freeze transitions (T_m & T_f) more commonly correlate to creep in thermoplastics
- The silicones are cross-linked during cure, preventing creep
- T_m hot melts: 75°C (EVA), 81°C (PO), 68°C (PA)

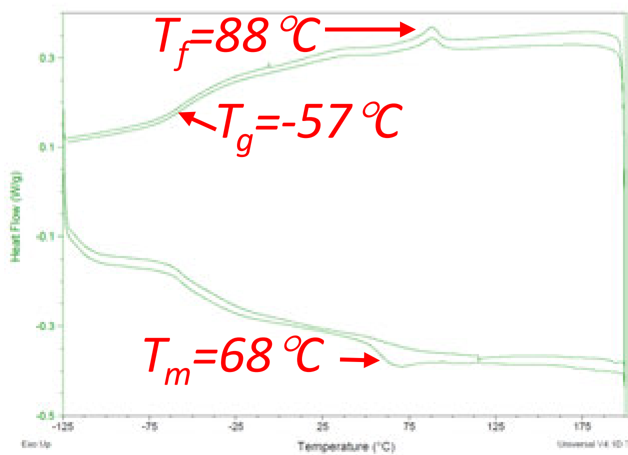
How will the hot melts fare in component tests?



DSC for acrylic foam tape

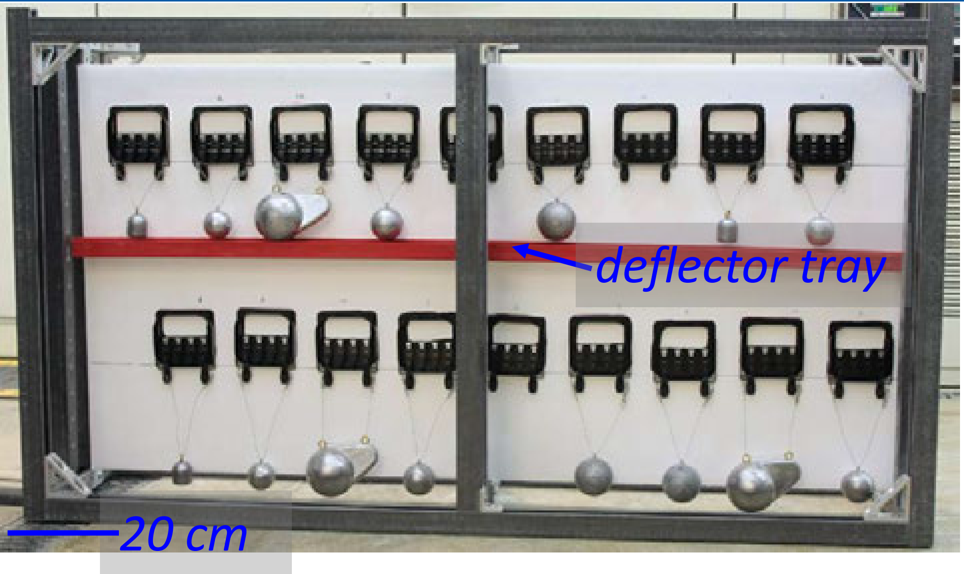


DSC for condensation silicones



DSC for PA hot melt

Two Sets of Discovery Experiments Examine the Adhesives



TF j-box (2 rail) on glass:

- Pb Weights: 0, 0.5, 0.9, 1.4, 2.3, 4.5 kg
- Adhesives:

acrylic tape, PU tape, acetoxy silicone, alkoxy silicone (Ti), oxime silicone, PO melt, PA melt

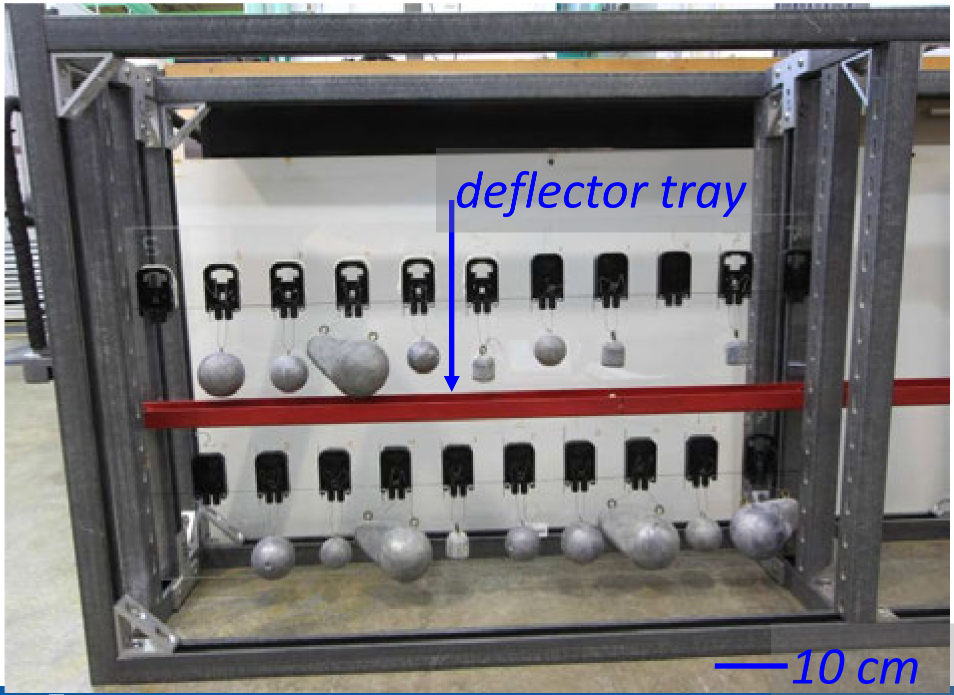
- Attached to Sn side of (cleaned) glass
- Primer applied when recommended

c-Si j-box (4 rail) on PET:

- Pb Weights: 0, 0.5, 0.9, 1.4, 2.3, 4.5 kg
- Adhesives:

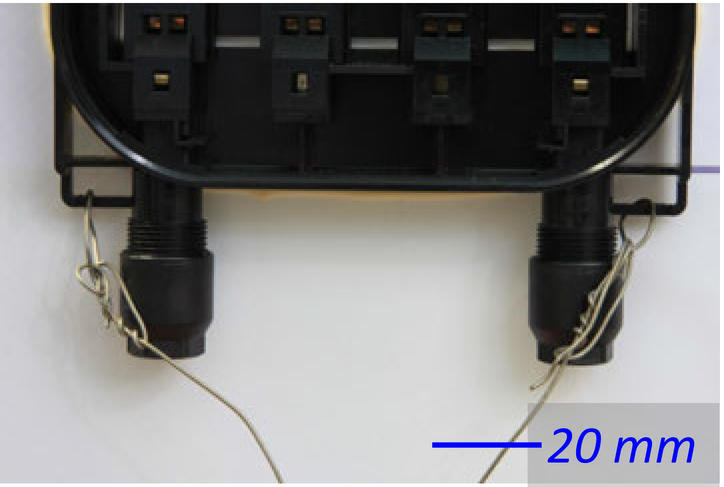
  acrylic tape
  acrylic tape
  PE tape
  acetoxy silicone
  alkoxy silicone (Ti)
  oxime silicone

- Primer applied when recommended



The Details of the Weight Attachment

- All weights were attached using 0.81mm ∅ stainless steel wire
- Wire ends secured with knots



c-Si j-box (4 rail) on PET:

- Wire attached to tab features
- Slight torque possible

TF j-box (2 rail) on glass:

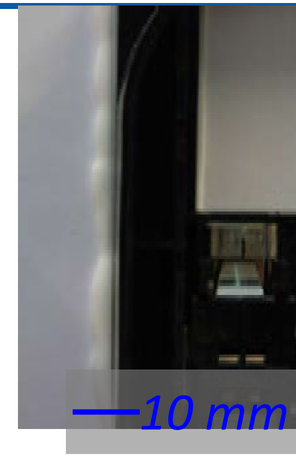
- Wire attached thru vias (cable & glands removed)

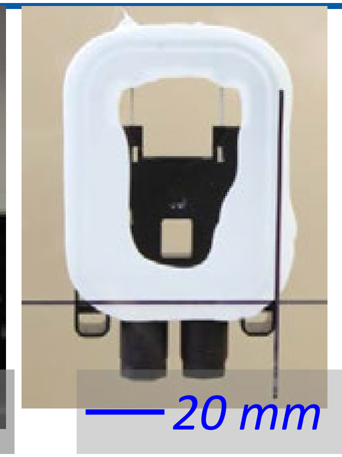
All:

- Predominant shear loading mode
- Boxes left uncovered through the test

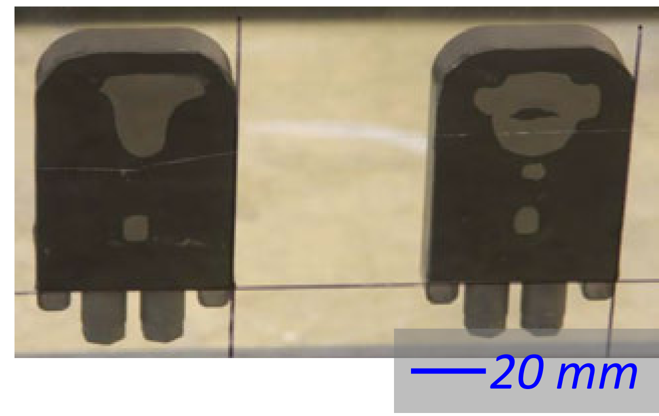
Details of the Specimen Attachment

- Easily visualized through substrate for TF specimens

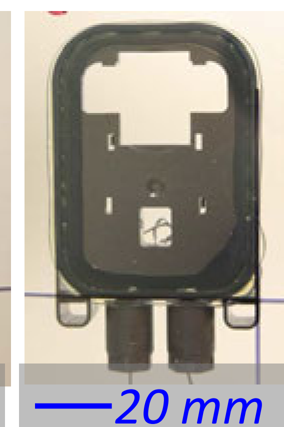




- Silicones adhered by (flatten) bead placed around periphery using “gun”

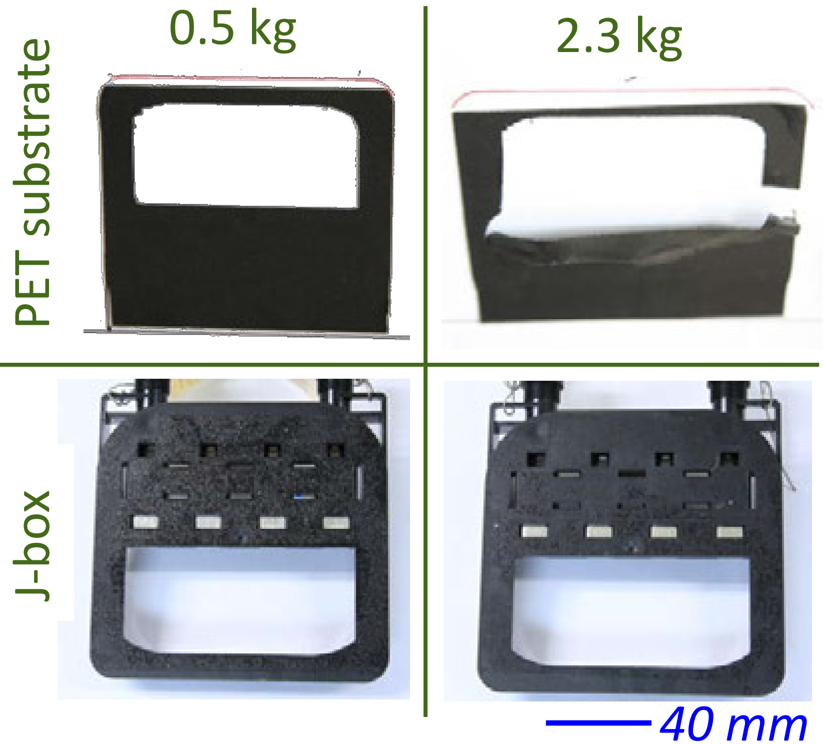


- Tapes: good wet-out, except @cut-out regions (TF)
- No tape used at cut-outs in c-Si specimens



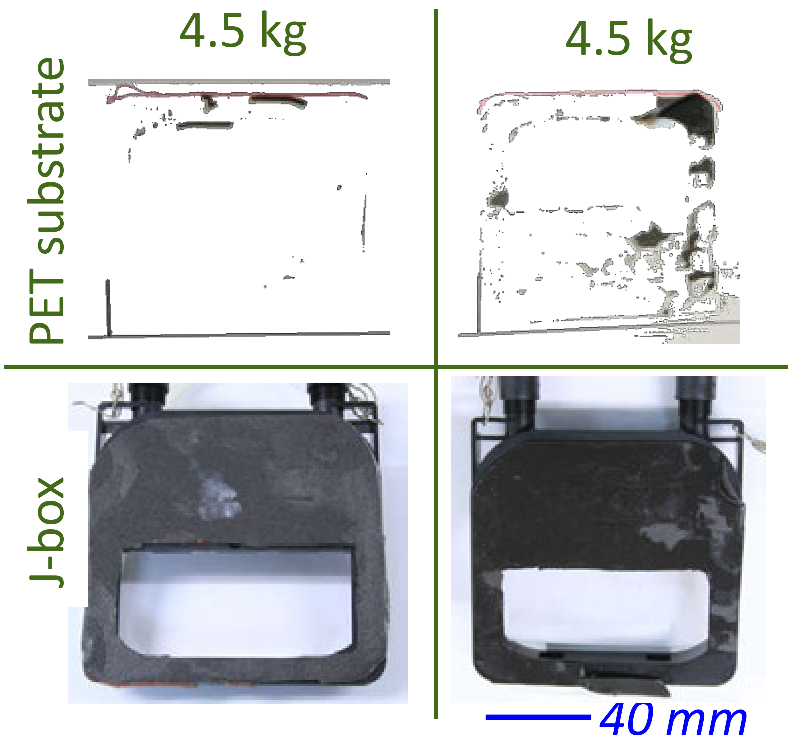
- Melts: adhered by (flatten) bead placed around periphery using heated “gun”
- Original bead for melts smaller than that for silicones

Loss of Adhesion for Tape During the c-Si Test

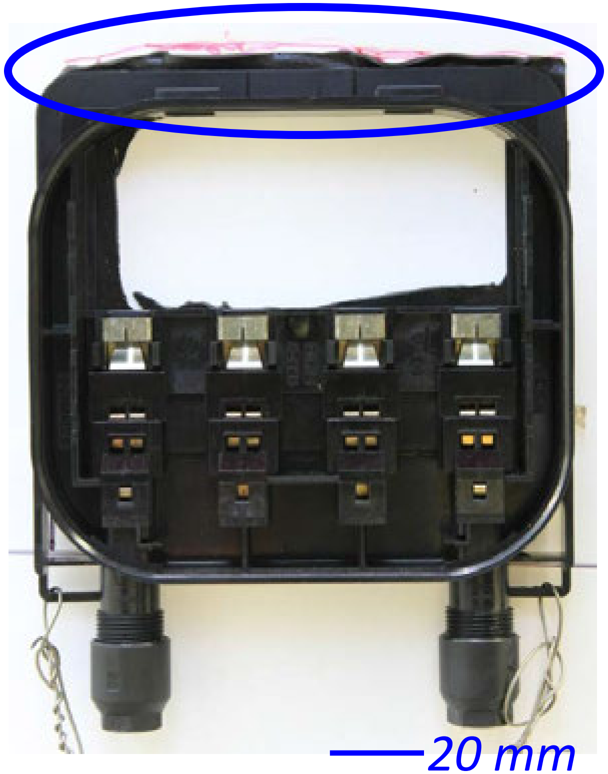


- all PE tape lost adhesion within 24 hrs
- delamination @ tape/j-box interface
- 2.3, 4.5 kg weights: torn tape (mixed mode failure)
- use system of compatible materials (j-box, adhesive, and substrate)

- acrylic tape lost adhesion 6-7, 7-14 days (4.5 kg weights only)
- delamination @ tape/substrate interface
- loaded exceeding the manufacturer's design guideline



Deformation of Tape During the c-Si Test



- Elongation of acrylic tape observed for 1.4, 2.3 kg weights @ 7-14, 14-21 days

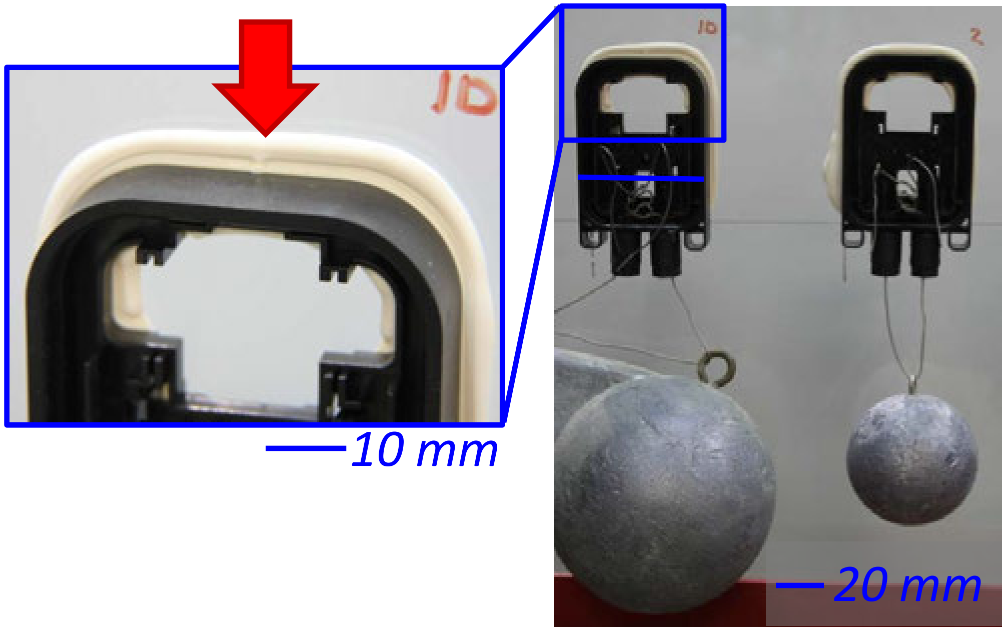
- Remained attached through test (41 days)
- Consistent with intended dissipative behavior: adjustment facilitating mechanical support
- Not observed during TF test for same material (similar load)

- Careful not to stretch tape during application

- Polymeric adhesives: H_2O may plasticize

Perceived Deformation of Silicone During the TF Test

•4.5 kg weighted alkoxy (Ti) silicone appeared displaced @ 5-7 days

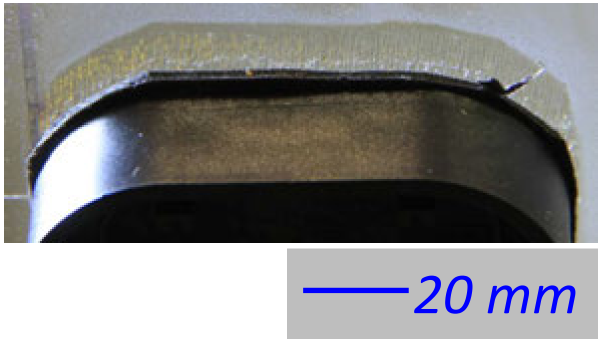


•Actually displaced (bumped) during specimen preparation and unchanged through the test

•Condensation silicones require H_2O to cure (CO is dry)

•21 day cure recommended prior to material tests in dry climates

Loss of Adhesion for Tape During the TF Test



creep of 0.5 kg weighted PU tape at 14 days

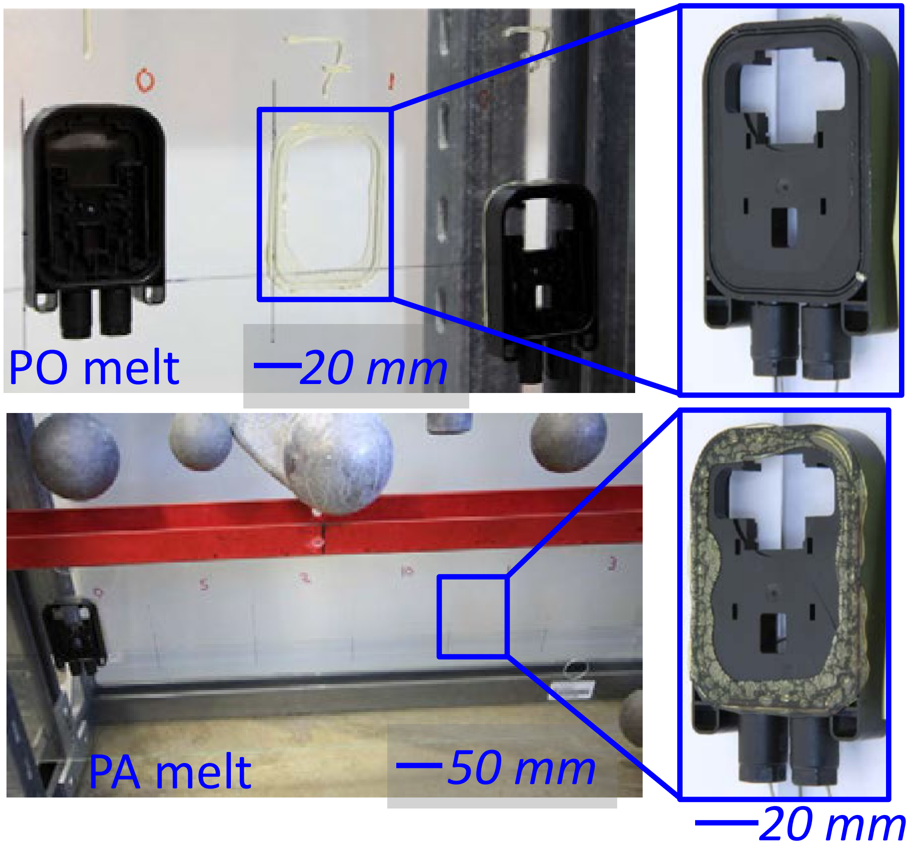
<u>PU tape:</u>

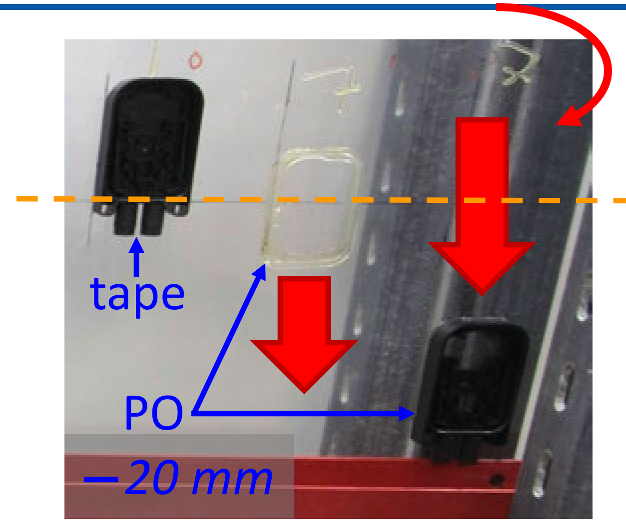
- Weights > 0.5 kg lost adhesion within 24 hours
- Delamination at tape/glass interface (tape remains on j-box)
- 0, 0.5 kg weighted specimen remained attached through test
- *0.5 kg weighted specimen displaced (adhesive/glass) during the test*

<u>acrylic tape:</u>

- Only 2.3, 4.5 kg weighted specimens lost adhesion within 24 hours
- Delamination at tape/j-box interface (tape remains on glass)
- Results as expected from manufacturer’s design guideline

Delamination & Creep in Hot Melts During the TF Test





- Delamination of weighted PO & PA melts within 24 hrs
- PO adhered to glass; PA to j-box

- Unweighted PO & PA melts displaced over days, even without the j-box!
- Melt composed lettering rotated through test

- Result consistent with DSC characterization
- Melts identified by material vendor:
  understanding product (field) requirements can be critical! 85°C<105°C

DMA Confirms the Behaviors Observed in the Component-Level Tests

silicones:

•Stable modulus after melt transition @ low temperature

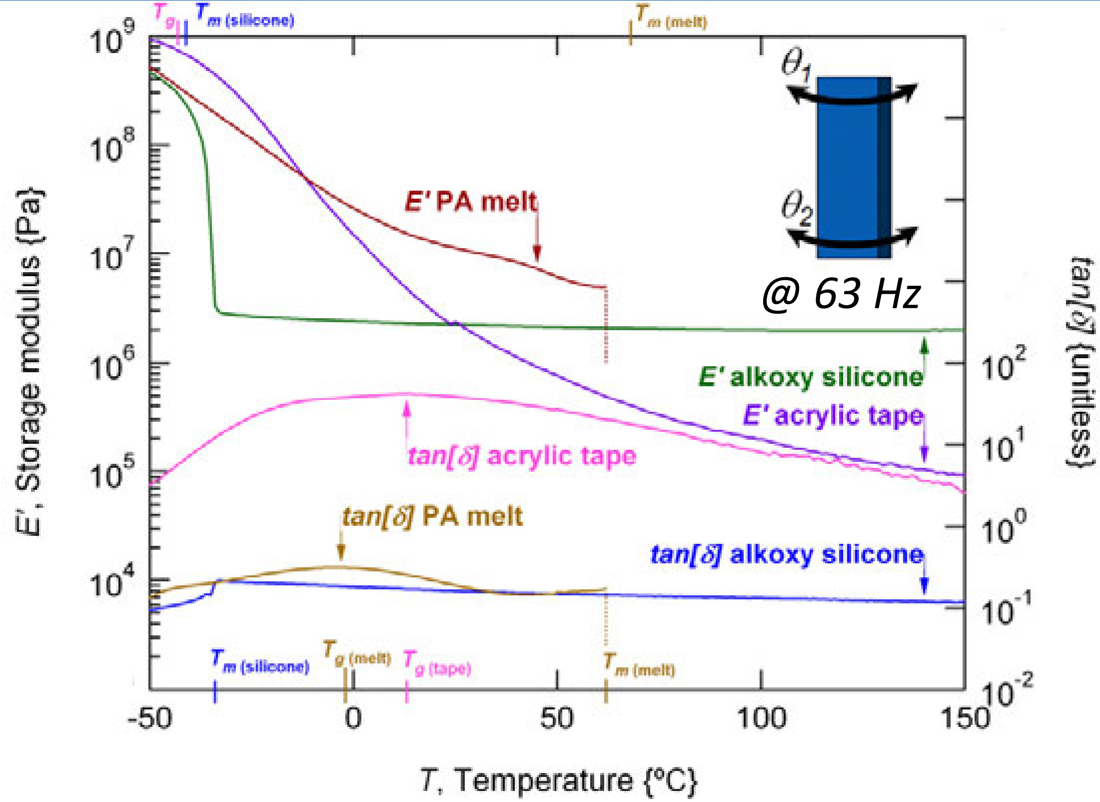
•Would likely creep, if not cross-linked (cured)

tapes:

•Significant (10^4x) softening of modulus with temperature

•Significant mechanical dissipation (tan [δ]) at all *T* (advantagous in vibration or impact-prone environment)

•Some tapes melt @ T>100°C



10's of Hz: order of magnitude for mechanical resonance
K.-A. Weiss et. al., Proc. SPIE, 7412, 2009, 741203.

melts:

•Softening of modulus with glass transition

•More significant softening of modulus (terminates test) with melt transition

•Phase transition confirmed in component-level (TF) test

The Formal Experiment (Future)

Goal: Test the proposed test (indoor vs. field) using a representative set of known good, known incompatible, and intermediate systems

Weights

- 0, 0.5, 1 kg (0, 1, 2 lbs). Consider 4x weight of (2) 1.5m connector cables = 0.7 kg

Adhesives

- 13 examined in the discovery experiments
- Down-selected to 7 (some likely failures, many expected successes)

[acrylic tape, PE tape, PO hot melt, acetoxy cure silicone, oxime cure silicone, alkoxy cure silicone (Ti), alkoxy cure silicone (Ti, high green strength)]

J-boxes

- A c-Si and thin film version have been selected

Substrates

- TPE, PET, THV, glass

Test sites

- Miami (FL), Phoenix (AZ), Golden (CO – outdoors), indoor test chamber

Test orientation

- 45° (shear & tensile) or 0° (vertical: shear only, indoors)

Test duration

- 1 year (outdoors) or 1000 hours (indoors)

Summary

- Proposed modification to qual. test: add weight to j-box during DH
- Discovery experiments to select weights & adhesive systems

- Silicones: allow adequate curing prior to handling
  - cross-linking limits deformation above T_m
- Foam tapes: some incompatible material systems, *e.g.*, PE/j-box
  - adhesion within manufacturer's design guidelines, *e.g.*, acrylic
  - possible feature: significant mechanical dissipation (all)
- Hot melts: delamination & creep observed
  - T_m too low for materials examined (not cross-linked)
  - know the product (field) requirements

- The formal experiment (intended to validate the test) will:
  - distinguish between proposed weights (0.5 or 1 kg)
  - compare indoor and outdoor environments
  - compare adhesive/substrate systems

Acknowledgments

•NREL: Dr. Peter Hacke, Dr. Michael Kempe, Dr. Heidi Pilath, Ed Gelak, Kent Terwilliger, David Trudell

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory.

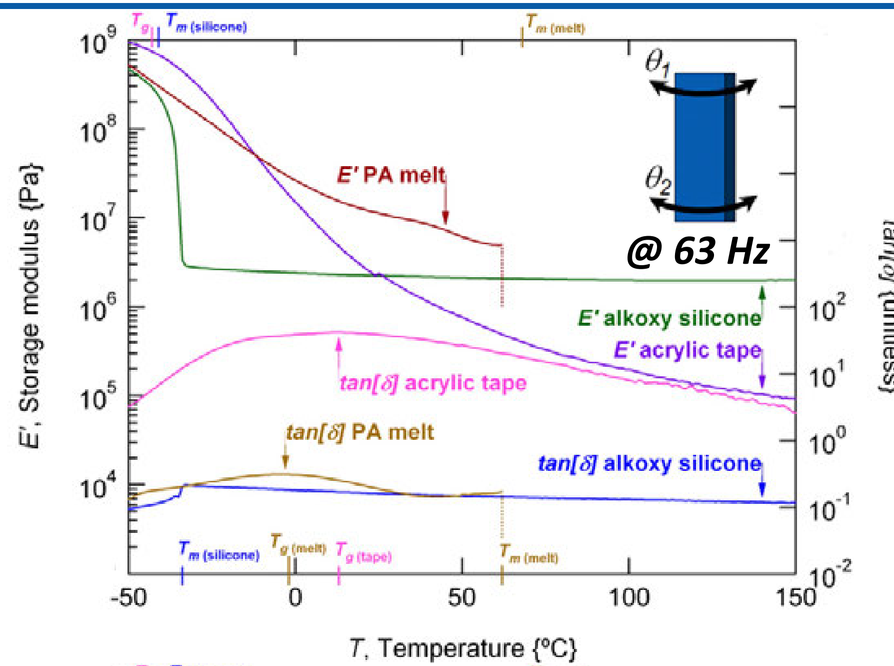
Pending manuscript: “Initial Examination of a Junction-Box Adhesion Test for Use in Module Qualification”, Proc. SPIE 2012.

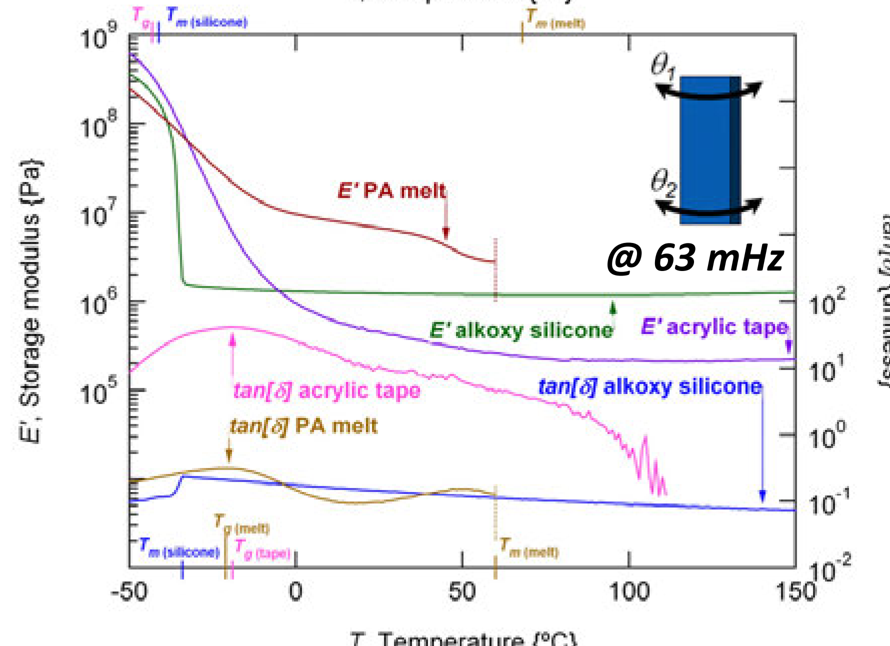
A Comparison of the DMA Results at Different Test Rates

- 10's of Hz: mechanical resonance vs.

  1's of mHz: thermal time constant

  K.-A. Weiss et. al., Proc. SPIE, 7412, 2009, 741203.
  D.C. Miller et. al., Proc. IEEE PVSC, 2010, 262-268.
- T_m for PA is more obvious from the *tan[δ]*
- The melt temperatures are not strongly strain rate dependent
- T_g reduced with strain rate for PA melt, more so for acrylic tape
- The tape is less dissipative at low strain rates (reduced T_g, reduced area of *tan[δ]* envelope)





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NATIONAL RENEWABLE ENERGY LABORATORY

A Giant Leap Forward toward Quality Assurance of PV Modules

2012 PV Module Reliability Workshop

Golden, CO

Sarah Kurtz[1], John Wohlgemuth[1],
Tony Sample[2], Masaaki Yamamichi[3]

[1]NREL

[2]EC-JRC
[3]AIST

Feb. 29, 2012

NREL/PR-5200-54567

Outline

- Motivation – Customers want to know quality of PV modules
- Two parts of quality assurance (QA) (during design and manufacturing phases)
- QA Task Force – formed July, 2011
- Plan for today:
    - Review IEC 61215 as a starting point
    - Review proposed new tests
    - Task Groups 2-5: introduction and updates
    - Discussions: consensus building; identification of issues

Motivation: the question on the street "How do I predict lifetime of PV modules?"

- Reliability engineer: How do I test to determine the number of years for the warranty?
- PV customer: How do I choose the PV module that will last longer?
- PV investor: How do I know that I'm making a safe investment of $1 billion (if the modules fail after 10 yr, the warranty will be worthless because the company will be gone)?
- Insurance company: How do I determine rates for insuring PV installations?
- PV Manufacturer: How do I differentiate my product from other products?

Two parts of Quality Assurance

1. Is the *design* durable for the intended application?
   - Depends on location (hot & humid; hot & dry, temperate, etc.)
   - Depends on mounting (close-roof mount runs hotter; partially shaded modules undergo different types of stress)
   - Depends on application (a customer may plan to resurface the roof 10 years from now and only cares about the modules lasting that long)
2. Are the modules *consistently manufactured*?
   - Could variations in the material composition or manufacturing processes result in premature failure of some fraction of the modules?

International PV Module Quality Assurance Forum was held in July, 2011, San Francisco

General agreement to work together on PV QA

Formed International PV QA Task Force:

Group of volunteers/professionals working toward a common goal

The PV QA Task Force formed at the conclusion of the Forum consists of six Task Groups:

Task Group 1: PV QA Guideline for Manufacturing Consistency (leaders Ivan Sinicco, Alex Mikonowicz, Yoshihito Eguchi, Wei Zhou, G. Breggemann)

140 volunteers; held meeting last night

Task Group 2: PV QA Testing for Thermal and mechanical fatigue including vibration (leader Chris Flueckiger, Tadanori Tanahashi)

Task Group 3: PV QA Testing for Humidity, temperature, and voltage (leaders John Wohlgemuth, Neelkanth Dhere, Takuya Doi)

Task Group 4: PV QA Testing for Diodes, shading and reverse bias (leaders Vivek Gade, Paul Robusto, Yasunori Uchida)

Task Group 5: PV QA Testing for UV, temperature and humidity (leader Michael Köhl, Kusato Hirota, Jasbir Bath)

Task Group 6: Communication of PV QA ratings to the community (leader David Williams)

230 volunteers for Task Groups 2-6

International PV Module Quality Assurance Forum
July, 2011, San Francisco
Formed International PV QA Task Force:

Goals of International PV QA Task Force:

1. ***To develop a QA rating system that provides comparative information about the relative durability of PV modules to a variety of stresses as a useful tool to PV customers and as a starting point for improving the accuracy of quantitative PV lifetime predictions.***
   1) Compare module designs
   2) Provide a basis for manufacturers' warranties
   3) Provide investors with confidence in their investments
   4) Provide data for setting insurance rates

2. **Create a guideline for factory inspections of the QA system used during manufacturing.**

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   2) Provide a basis for manufacturers' warranties
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   4) Provide data for setting insurance rates

2. Create a guideline for factory inspections of the QA system used during manufacturing.

Task Group 1: PV QA Guideline for Manufacturing Consistency met last night (Feb. 28th):

- The regional task groups are each working on a PV-specific version of ISO 9001:2008
- This will define an ISO 9001-like quality management system with technical specifics relevant to PV: e.g., documentation of control of solder-bond quality
- The procedure for turning this ISO-like document into a standard is not yet clear, but is being investigated; may involve ISO and/or IEC
- Chinese regional group is planning to complete their draft by the end of March
- It is currently envisioned that this certification would be a way to differentiate products, not be required for a baseline IEC 61215 certification. For example, an insurance company might reduce the rate based on adding the PV-specific ISO 9001-like certification

Introduction to Today – What can we accomplish today?

Challenge is to accomplish our goals quickly

- Many ideas
- Not enough experience/wisdom for the path to be clear

- We will need to work together effectively and pool the wisdom we do have!

- Move decisively on the information we have
- Plan to modify approach as more information becomes available

Introduction to Today

1. Current status: IEC 61215 – what it does and doesn't do
2. Overview of many test methods that are out there
   - IEC 61215 on steroids; Accelerated simulation of weather; New tests
   - Beware: Many details lead to much confusion
   - Listen: What makes each test method valuable?
3. Overview of status of the QA Task Groups 2-5
   - Listen: What are the questions that need to be resolved?

Lunch

4. Community input/discussion
   1. Discuss the value we found in the proposed tests – see hand out
   2. Consensus building – what can we agree about? – see hand out
   3. Your concerns/questions
   4. Next steps

Requirements for a comparative QA rating system

- Customer's perspective
  - #1 desire: A number that indicates the service life (would this be meaningful?)
  - Relevant to customers' application
  - Easy to understand, but sophisticated customers would like detail
  - Tests that do not add to the cost
- Manufacturer's perspective
  - Single set of tests (applied under ILAC: International Laboratory Accreditation Cooperation)
  - Tests that require minimal time and minimal expense
  - Ability to differentiate products
- Scientific perspective
  - Must be meaningful (based on data, not guesses)
  - Logical approach may be helpful

Today we are limited to a *comparative* test, but we want to lay the groundwork for *quantitative predictions* in the future

My requests to you for today and going forward:

- Keep your eye on the goal – inexpensive, comparative standards that correlate with field performance
- Look amongst us for wisdom of what is most useful to the community, setting aside personal agendas

- Take a giant leap forward toward creating comparative test standards that go “beyond” IEC 61215

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

IEC 61215: What it is and isn't

2012 PV Module Reliability Workshop

John Wohlgemuth

February 29, 2012

NREL/PR-5200-54714

Introduction

• The commercial success of PV is based on long term reliability of the PV modules.

• Today's modules are typically qualified/certified to:

  - IEC 61215 for Crystalline Silicon Modules
  - IEC 61646 for Thin Film Modules
  - IEC 62108 for CPV Modules

•These qualification tests do an excellent job of identifying design, materials and process flaws that could lead to premature field failures.

•This talk will provide a summary of how IEC 61215 was developed, how well it works and what its limitations are.

Evaluating Long Term Performance

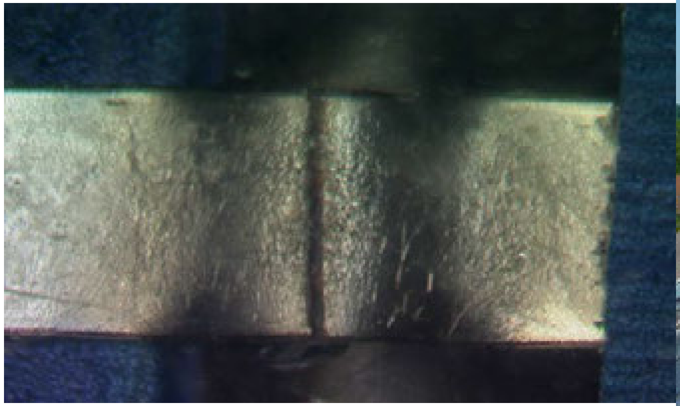
- To evaluate long term performance outdoors we really need outdoor performance data.
- On the other hand we can not wait 25 years to determine if a module is going to have a 25 year lifetime.
- Therefore, we have to utilize outdoor test data to develop accelerated stress tests.
- The first step in this process is to identify the various field failures that have been observed for different types of PV modules.

HISTORY OF FIELD FAILURES for Cry-Si

- Broken interconnects
- Broken cells
- Corrosion
- Delamination and/or loss of elastomeric properties of encapsulant
- Encapsulant discoloration
- Solder bond failures
- Broken glass
- Hot Spots
- Ground faults
- Junction box and module connection failures
- Structural failures
- Bypass Diode failures
- Open circuiting leading to arcing

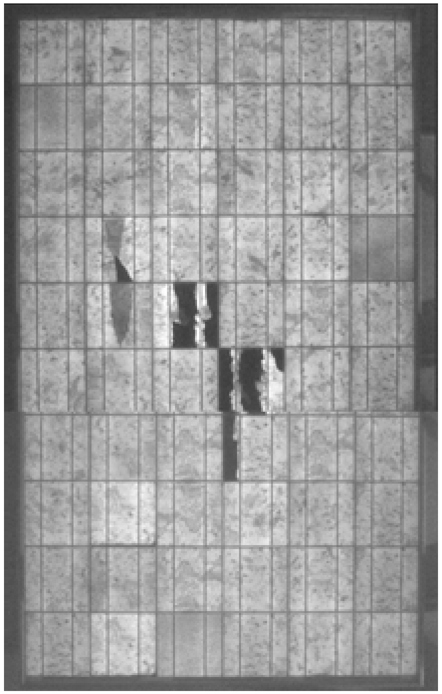
Examples of Field Failures

Broken Interconnects



Ground Fault

Broken Cells



Delamination

Corrosion

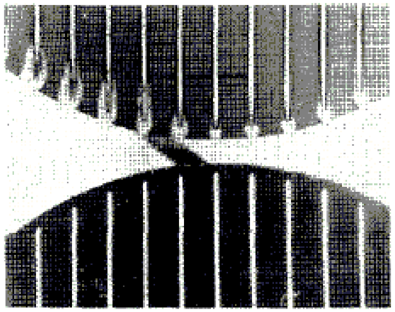


Figure 2. Solar-Cell Electrochemical Corrosion

Accelerated Stress Tests

- Now that we have a list of failures, we can develop tests that duplicate the failures in a fairly short time frame (at least compared to outdoor exposure).
- Our goals should be:
  - To identify accelerated stresses that cause the same types of failures as seen in the field.
  - To determine approximately how long the accelerated stress test must be performed in order to duplicate a reasonable amount of field exposure.
- In developing accelerated stress tests we must cause degradation in order to verify that our accelerated test is duplicating the failure mechanism we saw outdoors.

Accelerated Stress Tests

Accelerated Stress Test	Failure Mode	Technology
Thermal Cycles	Broken interconnect Broken cells Electrical bond failure Junction box adhesion Module open circuit – potential for arcing	Cry-Si & CPV Cry-Si & CPV All All All
Damp Heat	Corrosion Delamination Encapsulant loss of adhesion & elasticity Junction box adhesion Electrochemical corrosion of TCO Inadequate edge deletion	All All All All TF TF
Humidity Freeze	Delamination Junction box adhesion Inadequate edge deletion	All All TF

Accelerated Stress Tests for PV (cont)

Accelerated Stress Test	Failure Mode	Technology
UV Test	Delamination Encapsulant loss of adhesion & elasticity Encapsulant & backsheet discoloration Ground fault due to backsheet degradation Degradation of Optics	All All All All CPV
Static Mechanical Load (Simulation of wind and snow load)	Structural failures Broken glass Broken interconnect ribbons Broken Cells Electrical bond failures	All Cry-Si & TF All Cry-Si & CPV All
Dynamic Mechanical Load	Broken glass Broken interconnect ribbons Broken Cells Electrical bond failures	Cry-Si & TF All Cry-Si & CPV All

Accelerated Stress Tests for PV (cont)

Accelerated Stress Test	Failure Mode	
Hot spot test	Hot spots Shunts in cells or at scribe lines Inadequate by-pass diode protection	All All All
Hail Test	Broken glass Broken cells Broken Optics	Cry-Si & TF Cry-Si CPV
By-pass Diode Thermal Test	By-pass diode failures Overheating of diode causing degradation of encapsulant, backsheet or junction box	All All
Salt Spray	Corrosion due to salt water & salt mist Corrosion due to salt used for snow and ice removal	All All

Qualification tests

- Qualification tests are a set of well defined accelerated stress tests developed out of a reliability program.
- They utilize stress tests to duplicate failure modes observed in the field.
- They incorporate strict pass/fail criteria.
- The stress levels and durations are limited so the tests can be completed within a reasonable amount of time and cost.
- The goal for Qualification testing is that a significant number of commercial modules will pass.

(If not there will be no commercial market.)

- Qualifies the design and helps to eliminate infant mortality

History of JPL Block Buys

JPL Block buys incorporated a set of qualification tests in each procurement document.

Modules had to pass a test sequence before manufacturer could deliver production quantities of modules.

So where did tests come from?

Block I tests were based on NASA tests utilized on space arrays.

- Thermal cycles extremes selected as -40 and +90 °C based on guesses for worst case conditions in terrestrial environment.
- The humidity test was for a short time because for space arrays exposure to humidity was limited to the time they were exposed before launch.
- These were really the only accelerated stress tests in Block I

JPL Block Qualification Tests

Test	I	II	III	IV	V
Thermal Cycles	100 -40 to +90C	50 -40 to +90C	50 -40 to +90C	50 -40 to +90C	200 -40 to + 90C
Humidity	70C,90% 68 hrs	5 cycles 40 to 23C 90%	5 cycles 40 to 23C 90%	5 cycles 54 to 23C 90%	10 cycles 85 to -40C 85%
Hot Spot (intrusive)					3 cells 100 hrs
Mechanical Load		100 cycles ± 2400 Pa	100 cycles ± 2400 Pa	10000 ± 2400 Pa	10000 ± 2400 Pa
Hail				9 impacts ¾" –45 mph	10 impacts 1" – 52 mph
High Pot		<15 μA 1500 V	< 50 μA 1500 V	< 50 μA 1500 V	< 50 μA 2*Vs+1000

Block Field Experience

The earliest Block modules were typically utilized in small remote site systems.

JPL report stated that "the major cause of module failure to date was by gun shot".

- Black or blue CZ cells on white background are good targets
- Squares cells on non-white back sheets reduced problem

Many early failures were due to cracked cells:

- Because of module design one cracked cell resulted in total loss of power.

Non glass superstrate modules suffered from significant soiling and delaminations usually due to UV.

Testing Development

Future procurements utilized modified qualification test specifications based on feedback from field failures.

Block II

- Added 100 mechanical load cycles – once again probably from space experience based on launch damage
- Added a High Pot Test to insure electrical isolation
- Changed the humidity test from a constant to 5 cycles between 23 and 40 C (Still was too mild a humidity test)
- Reduced the number of thermal cycles from 100 to 50

  This was clearly a mistake. I don't know why they reduced the requirement except to guess that Block I modules had a lot of trouble passing the 100 cycle test.

Block III

- Changed the High Pot failure level from > 15 μA to > 50 μA as modules were getting bigger.

Block II and III modules were utilized in some larger systems and started to experience new failure modes.

Lessons from Blocks II and III

Many Block II and III modules were used in desert environments

- Pagago Indian Reservation in AZ
- Tanguze, Upper Volta
- Natural Bridges, Utah

Modules that survived 50 thermal cycles began failing in the desert after 3 to 5 years due to broken interconnects and/or broken cells that resulted in total loss of module power.

- Module manufacturers started building in redundant interconnects and stress relief.
- Most new module types used glass superstrate construction, reducing the thermal expansion and contraction.
- In Block V Thermal Cycles increased to 200 to better evaluate module performance.

Lessons from Blocks II and III (cont)

Hail did significant damage to modules built without tempered glass superstrates:

- Broken cells
- Broken annealed glass

Hail test added in Block IV.

Large (60 kW), high voltage system at Mt. Laguna, CA

- Part of array built with Solar Power modules (40 – 4" diameter CZ in series) with no by-pass diodes.
- Modules began suffering from hot spot failures – that is they burned up.

Hot Spot Test Added in Block V

Block V

Major differences in Block V were

- Thermal cycles increased from 50 to 200
- Humidity freeze implemented (before that it was a much milder humidity cycle)
- Addition of hot spot test

Whipple reported on 10 years of field results in 1993 (using data from Rosenthal, Thomas and Durand) that

- Pre-Block V modules suffered from 45% field failure rate
- Post- Block V modules suffered from < 0.1% field failure rate

Clearly the addition of these 3 tests dramatically reduced the infant mortality rate of PV modules.

One can argue that the Block V test made growth of commercial PV possible.

Block VI

JPL was in the process of finalizing a Block VI Specification when the program fell victim to Reagan budget cuts.

Additions they were planning in 1985:

- **Test for bypass diodes**
- **UV exposure test**
- **Damp heat (85C/85% RH) – To simulate the corrosion failures observed in fielded PVB modules.**

IEC 61215

International Standard incorporating the best ideas from around the world – but also remembering that it was developed by international compromise.

Block VI was the basis for 61215.

EU 502 provided UV Test, Outdoor Exposure Test and lower maximum temperature in thermal cycle.

Several tests from Block VI were not included in IEC 61215 – most notably:

- Dynamic Mechanical Load Test, because the test defined in Block V was unsuitable for large sized modules.
- Bypass Diode Thermal Test, because international community didn't think the test was adequately developed.

IEC 61215 rapidly became the qualification test to pass in order to participate in the PV marketplace, especially in Europe.

IEC 61215 Edition 2

Twist test was eliminated – no product ever failed it

Wet leakage current test was added from IEC 61646

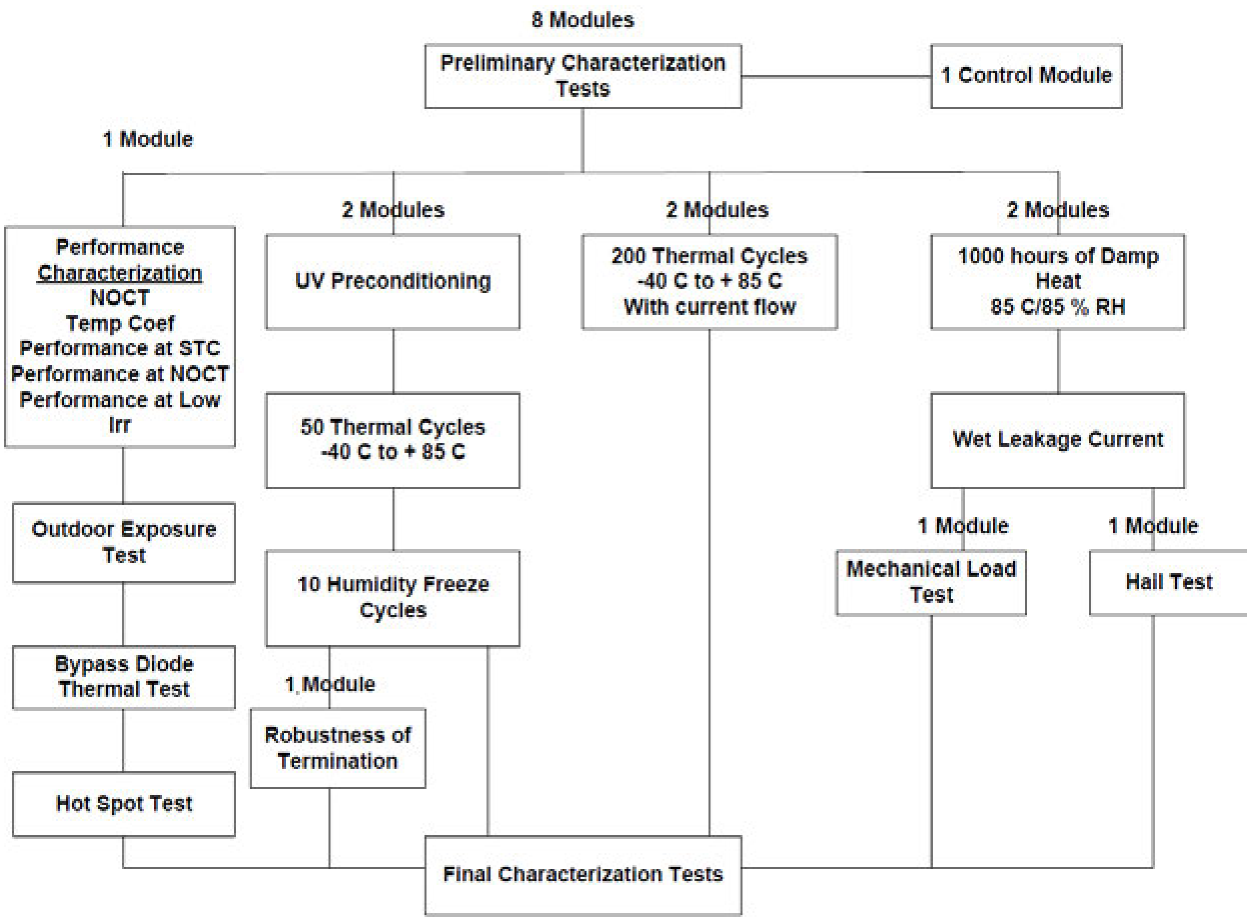
Bypass diode thermal test was added from IEEE 1262

Pass criteria for dielectric withstand and wet leakage current tests were made dependent on the test module area.

UV test was clearly labeled a preconditioning test

Added the requirement to run peak power current through the module during the 200 thermal cycles to evaluate a failure of solder bonds observed in the field.

IEC 61215 Outline



Passing IEC 61215

- So what does it mean if a module type is qualified to IEC 61215?
- Passing the qualification test means the product has met a specific set of requirements.
- Those modules that have passed the qualification test are much more likely to survive in the field and not have design flaws that lead to infant mortality.
- Most of today's commercial modules pass the qualification sequence with minimum change, meaning that they suffer almost no degradation in power output from the test sequence.
- In many markets passing IEC 61215 is a minimum requirement to participate.

How Successful are the Qualification Tests?

- They must be fairly successful because the PV industry has been growing rapidly.
- Reports of Field Failures/ Warranty Returns:
  - ✓ Whipple report of < 0.1% field failures in 10 years
  - ✓ Hibberd from 2011 PVMRW – 125,000 modules from 11 different module manufacturers deployed for up to 5 years with only 6 module failures. (0.005%)
  - ✓ Wohlgemuth et. al. from 20th EU PVSEC – Solarex/BP Solar multi-crystalline Si modules deployed from 1994-2005 with 0.13% warranty return rate (1 failure every 4200 module years of operation)
  - ✓ Wohlgemuth et. al. from 23rd EU PVSEC – Solarex/BP Solar multi-crystalline Si modules from 2005 onward with an annual return rate of 0.01%

Limitations of Qualification Tests

By design the qualification tests have limitations.

They were designed to identify early infant mortality problems, but:

- **Not to identify and quantify wear-out mechanisms**
- **Not to address failure mechanisms for all climates and system configurations**

(PID is an example of something that wasn't addressed because it wasn't important in the JPL deployments and wasn't seen early on in the typical low voltage applications)

- **Not to differentiate between products that may have long and short lifetimes**
- **Not to address all failure mechanisms in all module designs**

(New designs may fail for different reasons - e.g. PCB required different testing than EVA)

- **Not to quantify lifetime for the intended application/climate.**

A New Approach for Holistic PV Module Quality Assurance by Extended Stress Testing and Production Monitoring

[1]D. W. Cunningham (BP)

[2]B. Jaeckel (Q-cells)

[3]A. Roth (VDE)

This presentation is based on a publication by the authors at the 26th EUPVSEC meeting in Hamburg, Germany, September 2011

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Approach

- Validates the design/longevity of crystalline silicon PV products and improves product "bankability"

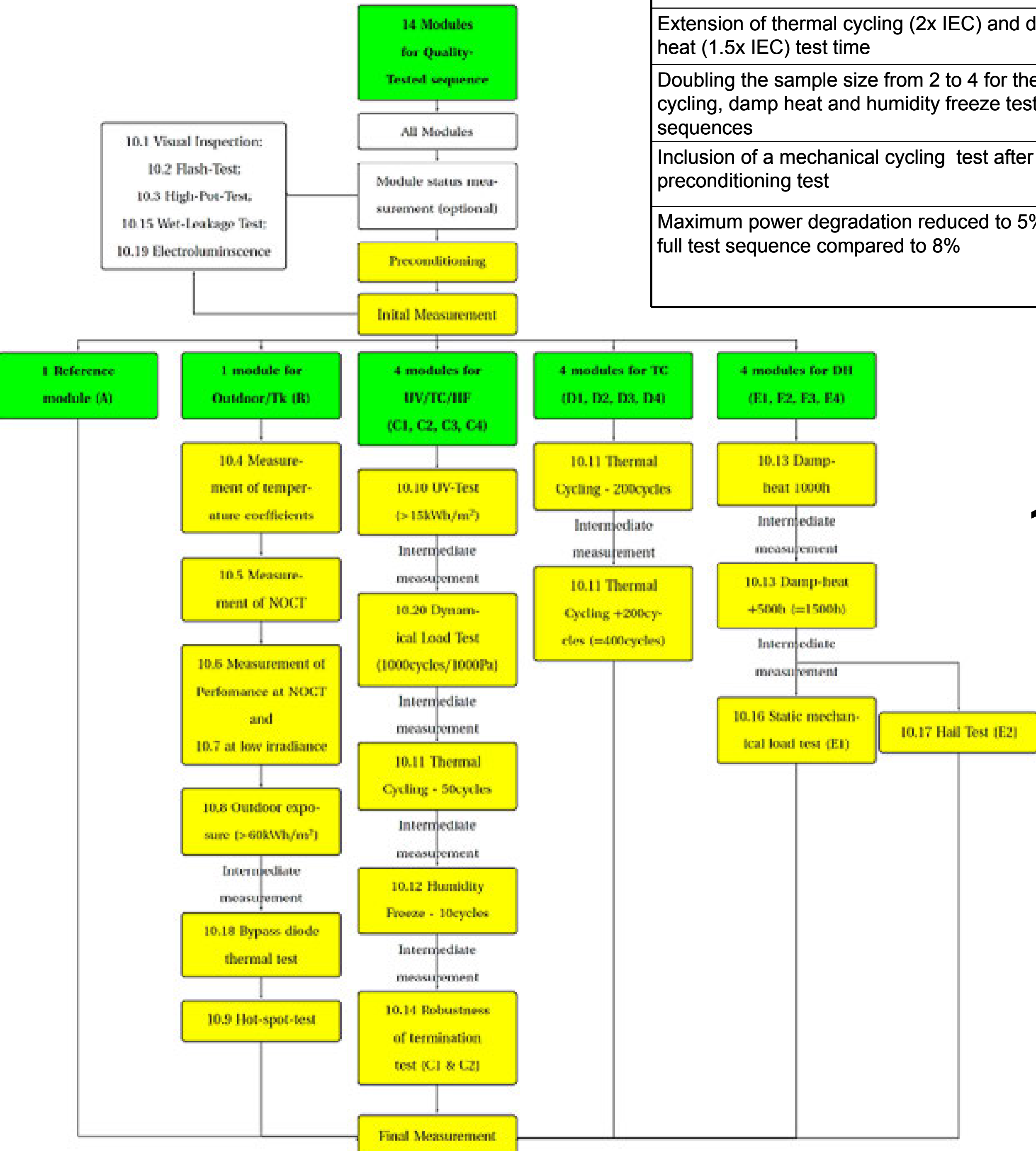
- Three areas of validation
  1. Robustness of design
  2. In line Quality monitoring
  3. Off line product quality assurance
- Available to the industry as a VDE standard

•The requirements for the quality standard are based on IEC61215/61730 and UL1703

•The conditions were extended to better validate the reliability and safety as well as activate potential latent failure mechanisms

•Based on real failure modes/mechanism from field data

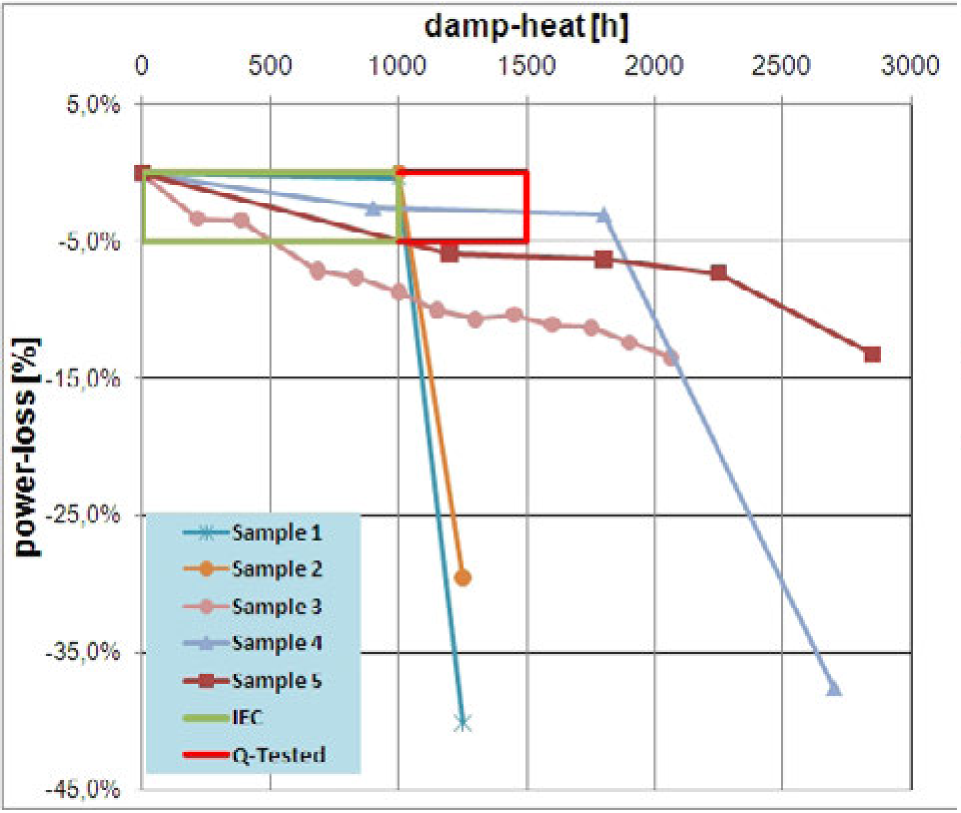
•The following table and flow chart describes the specific changes and provides an explanation for why those changes were included.

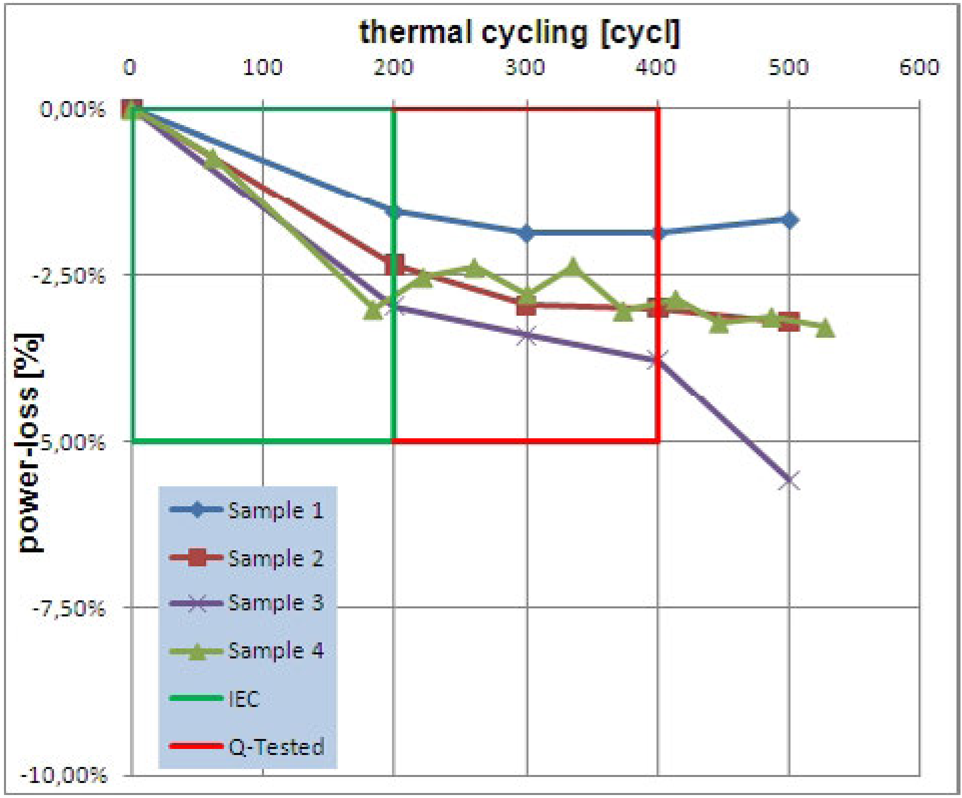


Changes compared to IEC	Reason for change
Extension of thermal cycling (2x IEC) and damp heat (1.5x IEC) test time	Better validate the reliability of products
Doubling the sample size from 2 to 4 for the thermal cycling, damp heat and humidity freeze test sequences	Increase statistical significance of results
Inclusion of a mechanical cycling test after the UV-preconditioning test	Study the impact of wind loading on the modules performance and reliability
Maximum power degradation reduced to 5% after a full test sequence compared to 8%	Increased confidence level for return of investment as well as minimizing the risk for early failures by combining lower allowed power degradation with increased test times.

1. Robustness of Design

Module Performance under extended accelerated testing





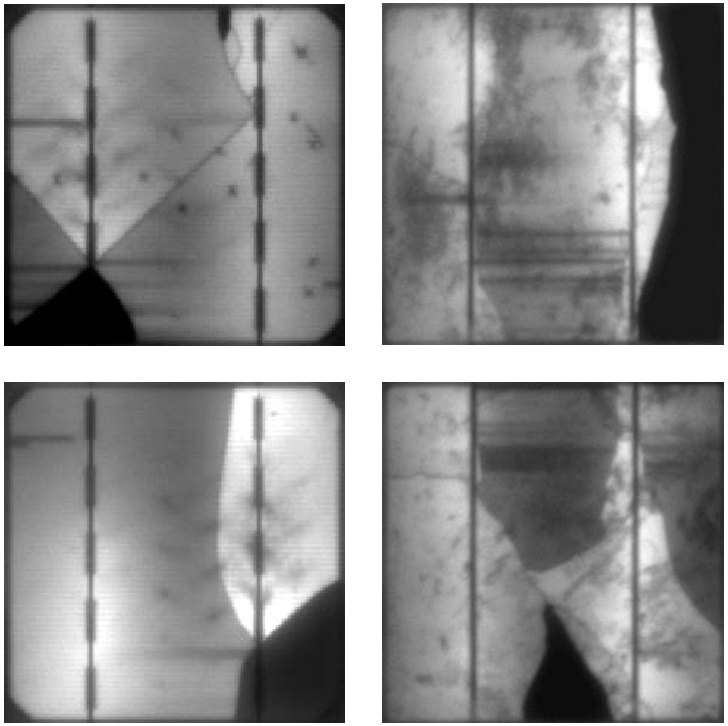
2. In line Quality monitoring

For a module to bare the quality label it must be produced in manufacturing facilities that use specific in-line testing. An example of some of the inline tests include:

Extra inline test	Reason for inclusion
Post lamination electroluminescence Imaging Standard includes a catalogue of EL images with failure modes and criteria for pass/fail	Cell cracking can cause performance, reliability and safety concerns. The EL-test is implemented to reduce the risk of power loss and loss in energy yield due to cracked of defective cells.
Wet-leakage test on 1% of production	A safety test designed to evaluate the insulation of the module.
Ground continuity test on 1 module per site per day	A safety test that ensures that a module can be adequately grounded in a PV system
Reverse current overload test on 1 module per site per day	A safety test that verifies a module’s ability to dissipate heat under reverse current fault conditions

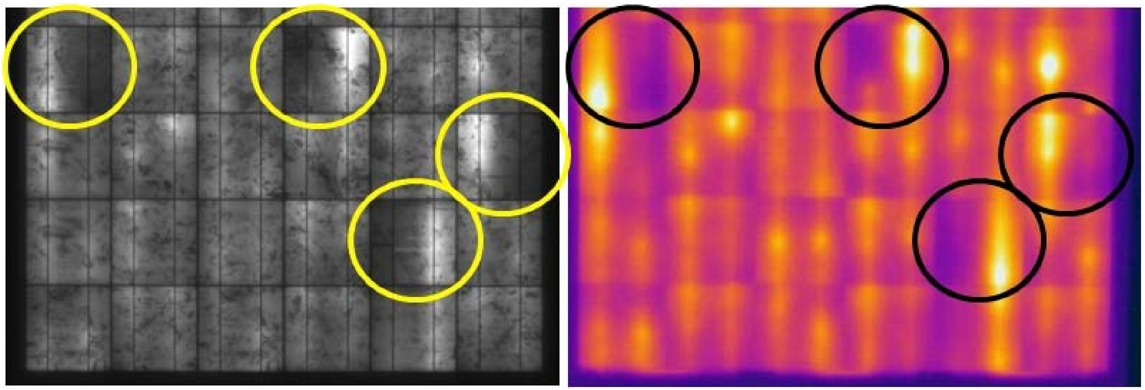
2. In line Quality monitoring

Electroluminescence testing



These images provide examples of cases in which modules would be rejected during electroluminescence testing due to excessive cell cracking

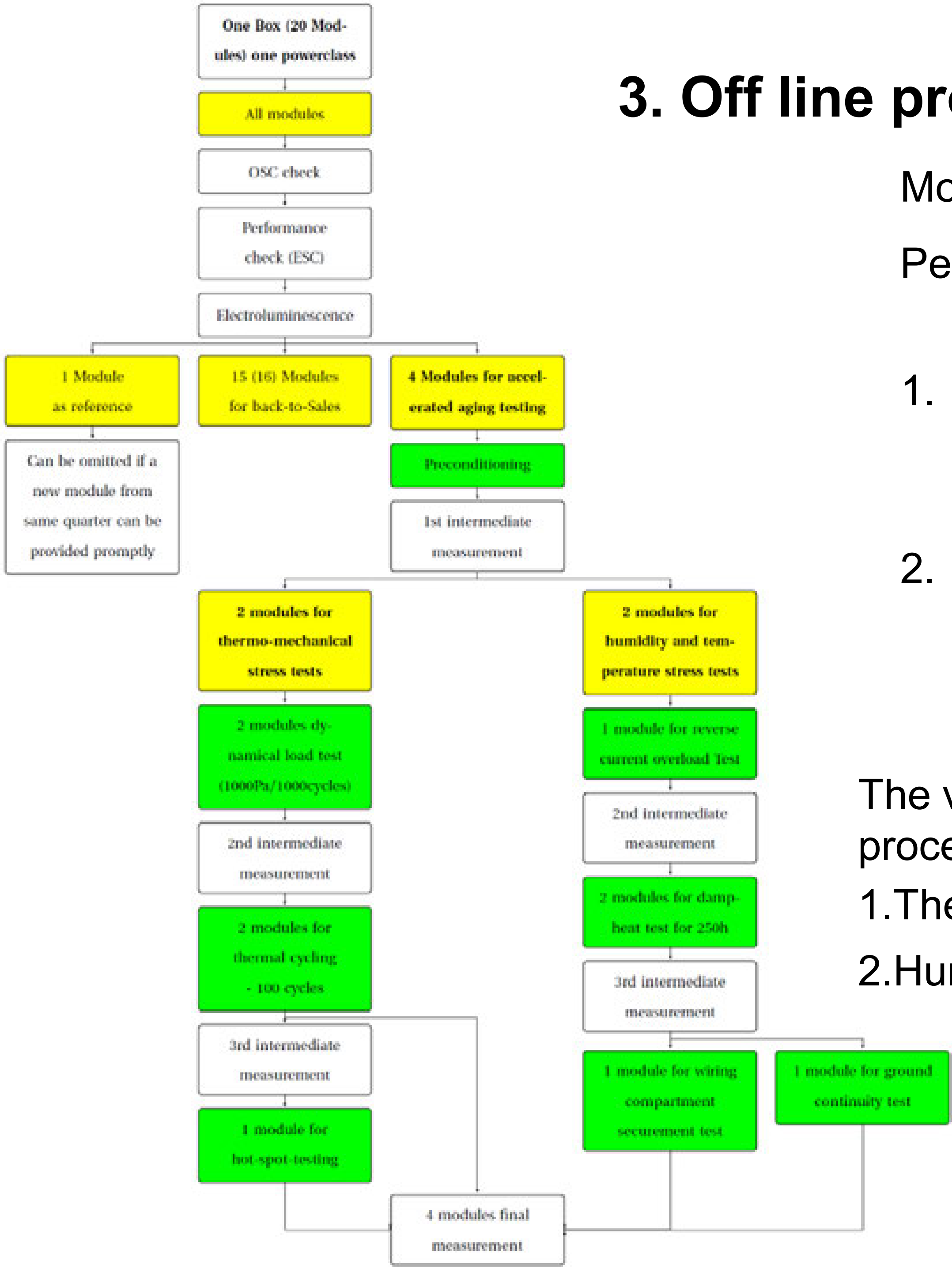
Reverse current overload testing



Example IR and EL images show how soldering problems can be detected using IR imaging. Left: electro-luminescence image; Right: corresponding IR image

Using IR imaging in the Reverse current overload test these soldering problems would be recognized quickly and the problem can be solved promptly.

3. Off line product quality assurance



Monitoring product manufactured.

Performed **quarterly** and serves two main purposes:

1. Confirmation that measurement systems used for inline quality checks are consistent
2. To verify, through a shortened environmental testing sequence that there are no manufacturing defects

The verification is done in a two sequence procedure:

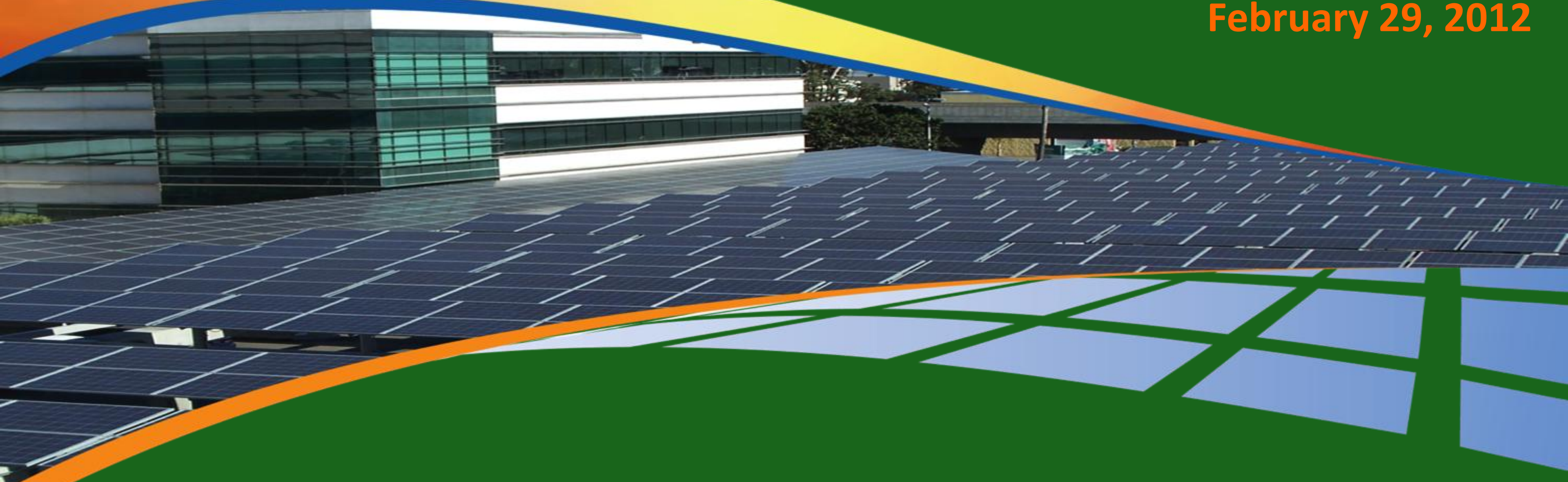
1.Thermal mechanical stress tests

2.Humidity and temperature stress tests

"The Thresher Test"
Crystalline Silicon Terrestrial Photovoltaic (PV) Modules Long Term Reliability and Degradation

NREL PV Module Reliability Workshop

February 29, 2012



Certification Services: IEC61215 – IEC61646 – IEC62108 – IEC60904 – IEC61730 – IEC61853 – IEC62688
UL1703 – UL8703 – UL2703 – UL1741

BOS Component Testing: Junction Boxes, Cables, Connectors, Inverters

Outdoor Performance Validation: Energy Yield Validation, Soiling, Degradation and Site Commissioning

Presented by:
Alelie Funcell
Renewable Energy Test Center

Thresher Test Protocol: Motivations / Objectives

"The Thresher Test Protocol was developed specifically to create a *de facto* accelerated testing protocol which would provide buyers of PV modules with a set of *apples-to-apples long-term reliability data* to use in their PV buying decisions.“

<u>The genesis of the TTP was sparked by:</u>

- the absence of established and accepted accelerated test of a module's long term performance and reliability. Therefore, many manufacturers have proprietary testing regimens, and are using their in-house testing to ensure that their products will hold up well overtime (25+ years), as well as to privately test their competitors' modules for internal benchmarking.
- several module manufacturers are spending a considerable amount of time and money on quality, and are not able to monetize that quality given the perceived "commoditization" of the PV module market.
- the desire of sophisticated Project Developers looking to validate this quality (in terms of long-term performance expectations) with ***one standardized test protocol*** that could be consistently implemented by independent authorities or 3rd Party Labs.
- concerns of Project Developers / Owner-Operators about the dependability of their energy yield models in 10-25 years (the years beyond the IEC61215 testing schema).
- buyers’ wish “that there is a ***standardized accelerated testing*** to much longer cycle times, beyond IEC 61215, *to* ***separate the wheat from the chaff***.”

This was an industry joint effort ……

A critical mass of Manufacturers, 3rd Party Test Labs and NCBs, got together and jointly developed an agreed upon long term reliability and degradation testing protocol that can be implemented by independent testing authorities / laboratories.

Govindasamy Tamizh-Mani, ASU/TUV Rheinland
Daniel Cunningham, BP SOLAR
Matthew Blom, DuPont Photovoltaics Solutions
Sunil Panda, DuPont Photovoltaics Solutions
Keith Shellkopf, KYOCERA
Glenn Tomasyan, MITSUBISHI
Peter Hacke, NREL
Jenya Meydbray, PVEL
Cherif Kedir, RETC
David King, Sandia Labs
Alex Marker, SCHOTT

Paul Wormser, SHARP
Michael Lasky, SHARP
Bill Richardson, SOLON
Neil Shey, SOLON
Jan Carstens, SOLON
Monali Joshi, SUNTECH
Wei-Tai Kwok, SUNTECH
Jon Haeme, TRINA SOLAR
Anthony Chia, TRINA SOLAR
Regan Arndt, TUV SUD
Robert Puto, TUV SUD
Kenneth Sauer, YINGLI SOLAR

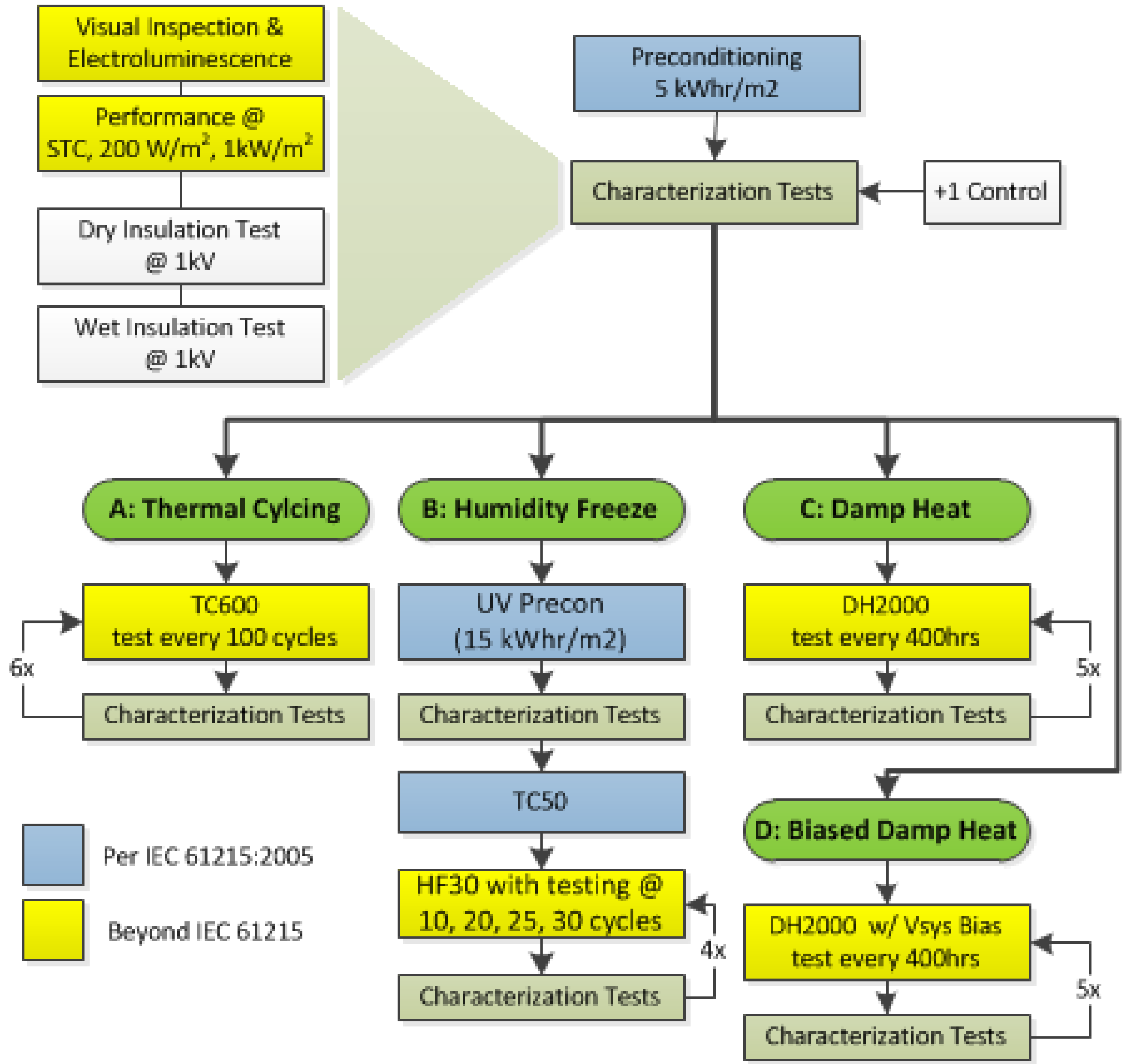
Hugh Kuhn, MAC, - **Program Leader**
Alelie Funcell, RETC - **Program Coordinator**

So what is "The Thresher Test" ?

Thresher Test Protocol was derived based on several c-Si PV manufacturers' in-house long term reliability regimens.

It is meant to describe a new long-term reliability test program that will not only help in *differentiating products* but also in *determining the degradation patterns* of different c-Si solar modules.

"Thresher Test for c-Si PV", intends to *bring long-term performance test data beyond IEC 61215* to the market.



THANK YOU!

“Thresher Test Protocol ..... *separates the wheat from the chaff*.”

- **differentiates c-Si PV modules**
  - **shows products degradation patterns**
    - **brings long term performance reliability *beyond IEC 61215***

“The Thresher Test” Team

For further questions, please contact:

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Reliability Demonstration Test

Mission Statement

- Provide the industry a **robust** and **comprehensive** test protocol to evaluate long-term PV module aging behavior for a reasonable price in a reasonable amount of time.
  - **Robust**: only a fraction of module types tested will perform well
  - **Comprehensive**: stimulates all failure behaviors witnessed in the field while avoiding non-realistic failures

- Designed with the most current knowledge – protocol evolves with experience

Reliability Demonstration Test

Test	Duration	Primary Degradation Behaviors Stimulated
Thermal Cycling	600 cycles	Solder joint degradation, cell cracks, Jbox failure, Polymer embrittlement, solder peaks cutting through backsheet
Damp Heat	2,000 hours	Delamination, Corrosion, polymer embrittlement, discoloration, cell degradation, Jbox failure
Damp Heat w/ +1kV	600 hours	In addition to aging behavior above: Ion migration, electrolytic corrosion, polarization
Damp heat w/ -1kV	600 hours	
Humidify Freeze	30 cycles	Solder joint degradation, cell cracks, Jbox failure, Polymer embrittlement, delamination, cell degradation
1. Mechanical Load 2. Thermal Cycling 3. Humidity Freeze	1. 1,000 cycles 2. 50 cycles 3. 10 cycles	Cell cracks leading to performance loss, solder joint degradation, delamination, frame fatigue
UV Exposure	90 kWh	Discoloration, embrittlement, cell degradation, delamination

- Details and frequency of module characterization is very important
- All modules sun soaked before testing starts

PVEL Services

- Reliability & Performance Testing
- PV Module Latent Defect Screening
- Ongoing Degradation Testing
- Supplier Qualification
- Solar Reference Cells
- Warranty Support
- PAN Files
- PV-EPI[1]

In Partnership with

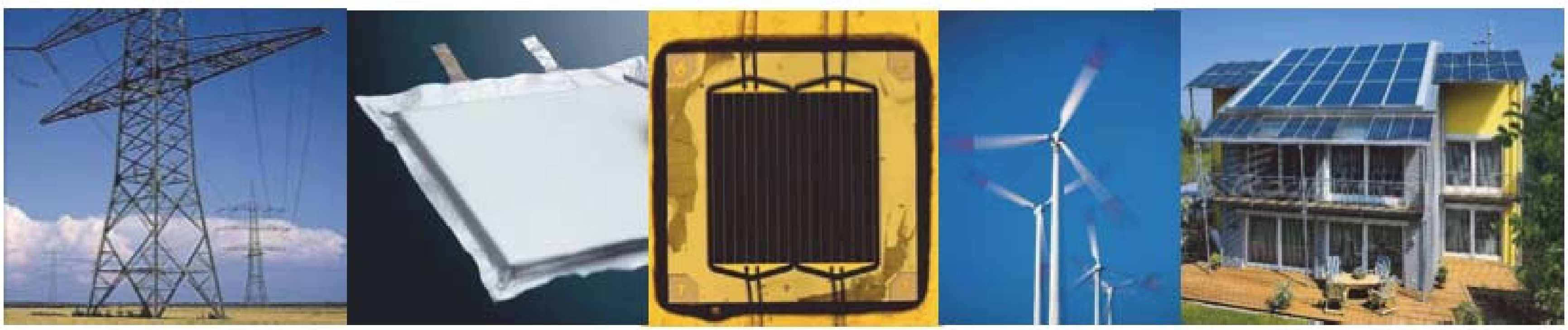
BLACK & VEATCH

1. Energy Performance Index

Photovoltaic Durability Initiative (PVDI)
A Durability Program Providing Bankability and Marketing Leverage

NREL PV Module Reliability Workshop

Golden, CO February 29th, 2011



David H. Meakin
Fraunhofer Center for Sustainable Energy Systems
Advanced PV Modules Group

Fraunhofer USA

Agenda

- Motivation and Goals
- Key Test Protocol Features
- Reporting of Results
- Improvement Strategy

A Fraunhofer ISE and Fraunhofer CSE joint program

Fraunhofer USA

Motivation

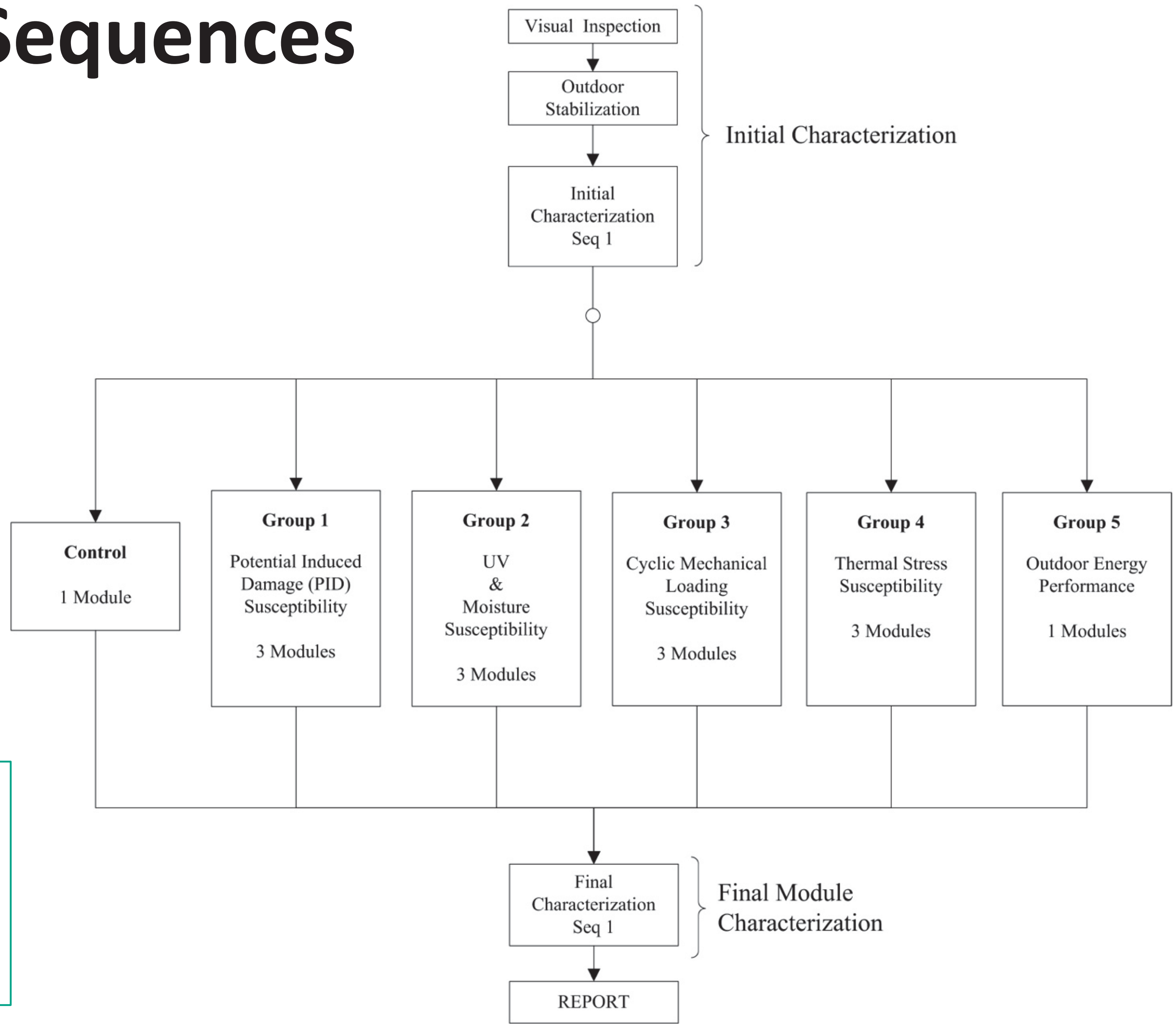
- Demand from financial sector, installers, and module manufacturers for “Module Bankability” testing protocol
- Protocol to provide quantitative comparative data for modules in various operating environments
- Guidance with regards to module service lifetime/durability

Program Goals

- To regularly publish durability reports and rankings
- To enable PV system developers and financiers to make educated deployment decisions
- To reduce cost of PV systems by reducing deployment risks

To provide ranking of PV modules relative to their likelihood to perform reliably over their rated service life

PVDI Test Sequences



Module Component Testing

- Diode
- Junction Box
- Hotspot

Fraunhofer USA

Test Protocol Features

- PID test sequence looking at both positive and negative grounding configuration
- UV combined with damp heat.
  - UV exposure equivalent to at least 1 year with partial saturation
- Cyclic and static loading
  - Cyclic loading at -40 °C
  - Followed by thermal cycling to exacerbate crack separation
- Extended thermal cycling
- Long term outdoor exposure at MPP with intermittent IV measurements
- Use of infrared, EL imaging to better identify failure mechanisms
- In situ dark I-V to track module degradation modes
- Test completed in 6 months with the exception of continuing outdoor testing

Other Key Features

- All module are purchased through distribution channels
- Tests are designed
  - To identify wear-out characteristics and EOL failure modes using moderately censored data
  - To manifest failure modes based on operating environments
  - To be sufficiently long to manifest some degree of degradation
- All results are quantitative, as opposed to Pass/Fail
- Iteration is used to generate multiple intermediate data points and preserve the degradation history.
- Multiple modules in each sequence aid in identifying anomalistic behavior (outliers)

Reporting

- Three levels of test report, participant, all participants, and public
- Information is considered confidential with the exception of the public report
- Public report will be provided to technical journals and trade publications

Reporting by Operational Environments

Test sequences are designed to provide durability assessments of 4 operational environments

- High Voltage Stress
- Radiation Stress (High UV Radiation Environments)
- Thermal Mechanical Stress (High Wind, High Snow Environments)
- Thermal Stress (Environments with High Temperature Variance)

Continuous Improvement through R&D

- Improve the test protocol through continuous R&D.
- Generate data necessary to predict probabilistic module lifetimes
- Continuous outdoor testing for a minimum of 3 years to facilitate correlation to actual lifetime estimation
- Provide data for international standards development efforts

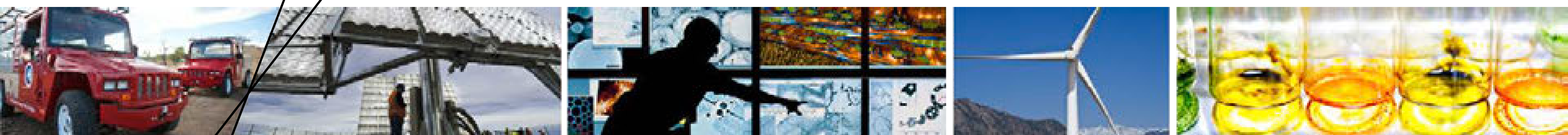
Fraunhofer USA

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Peter Hacke

2012 PVMRW

NREL Test-to-Failure Protocol



Based on:

Terrestrial Photovoltaic Module Accelerated Test-to-Failure Protocol

Technical Report
NREL/TP-520-42893
March 2008

C.R. Osterwald

With Tom McMahon, John Wohlgemuth, Kent Whitfield, and Liang Ji

References:
http://www.nrel.gov/docs/fy08osti/42893.pdf
http://www.nrel.gov/docs/fy11osti/47755.pdf

NREL/PR-5200-54713

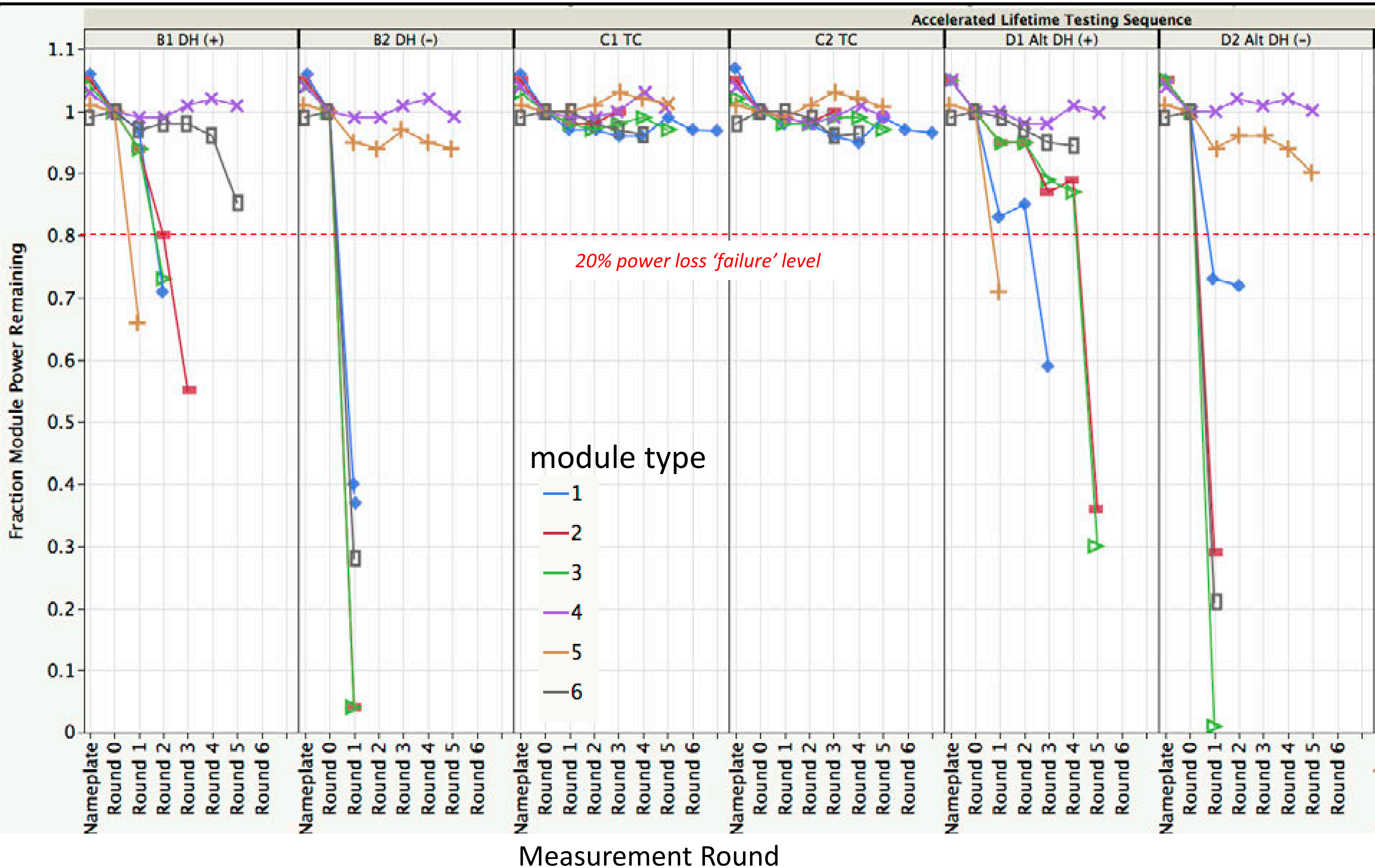
Motivation

Field Reliability Experience

Qualification Test | Test-to-Failure | Lifetime Prediction

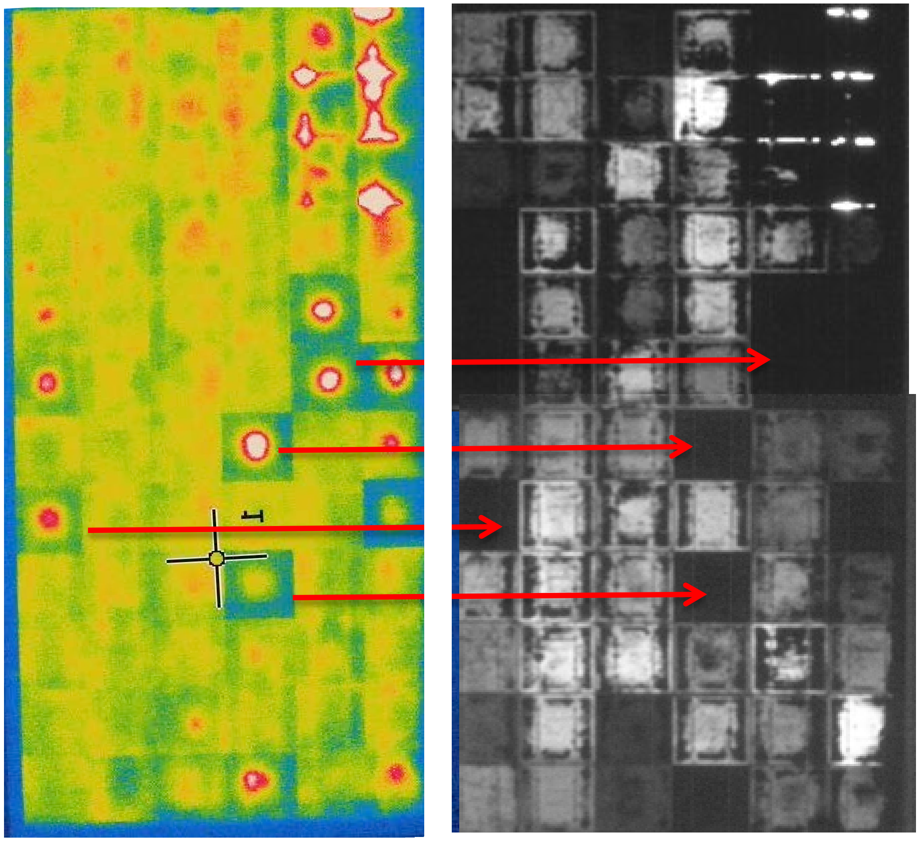
- **Test module technologies on a comparative basis in a highly accelerated manner**
- **Perform due diligence between various module technologies before large capital outlays for PV power plants are committed**
- **Characterize potential performance and reliability problems for increasingly higher voltage systems**
  - 600 V systems in USA (NEC)
  - 1500 V 'Low DC Voltage' systems in EU (IEC)
- **Accelerate the onset of failure so that failure mechanisms can be analyzed, validated against field failures, and then addressed**

85°C 85%RH Damp Heat with + & – 600 V bias 1000 h, Thermal Cycling 200 cl., Alternating DH with bias & TC
6 modules for test (+ 2 controls)



Two examples of discovered failure modes

- **Shunting in cells "PID"**



Thermal image

Electroluminescence

After 1 round of DH 1000 w/ -600 V bias

- **Embrittlement of junction box**

After 3 round of DH 1000 w/±bias

Long-Term Sequential Testing (LST) of PV Modules

Mani G. Tamizh-Mani

TUV Rheinland PTL
gtamizhmani@tuvptl.com

TÜVRheinland®
Precisely Right.

Quality Assurance Testing @ TUV Rheinland

One-Stop Solution: From Components to Power Plants

Global PV Component and PV Module Certification

Junction Boxes, Cables, Connectors, PV & CPV Modules, Rack and Mounting

Consultation → Testing → Certification

Junction Box

DIN V VDE 0126-5; 2008

Cable

TÜV 2Pfg1169; 2007

Connector
EN 50521; 2008

www.tuv.com
TÜV
TÜV Rheinland
ID:0000000001

- **Periodic inspection**
- **Qualified, IEC 61215**
- **Safety tested, IEC 61730**
- **Long-term sequential testing**

PV/CPV Module
IEC 61215
IEC 61646
IEC 61730
IEC 62108
ANSI/UL 1703 (NRTL)

Seal with Plant-ID

Installer Training

Global PV Power Plant Certification

Planning → Installation → Operation

TÜVRheinland®

Comparative Testing: Types

Long-Term Sequential Testing

DH2000

↓

TC400

↓

HF40

↓

Bypass Diode

vs.

Conventional Extended Testing

↓ TC400

↓ DH2000

↓ HF40

Sequential	Extended
Multi-variable & variable preconditioning	Single-variable & No variable preconditioning

TÜVRheinland®

LST: Test Samples (3) and Stress Test Blocks (13)

Blocks	Sample 1 1	
	Receiving	
	PreCon-Setup	
	PreCon-Test	
	PreCon-Teardown	
	Visual Insp	
	MaxPower	
	DielWithstd	
	WetLeak	
	DampHeat-Setup	
1	DampHeat-Test 1000h (accumulated)	
	DampHeat-Teardown	
	DielWithstd	
	WetLeak	
	Visual Insp	
	MaxPower	
	DampHeat-Setup	
2	DampHeat-Test 1250h (+250 h)	
	DampHeat-Teardown	
	DielWithstd	
	WetLeak	
	Visual Insp	
	MaxPower	
3	DampHeat-Test 1500h (+250 h)	
	DampHeat-Teardown	
	DielWithstd	
	WetLeak	
	Visual Insp	
	MaxPower	
4	DampHeat-Test 1750h (+250 h)	
	DampHeat-Teardown	
	DielWithstd	
	WetLeak	
	Visual Insp	
	MaxPower	
5	DampHeat-Test 2000h (+250 h)	
	DampHeat-Teardown	
	DielWithstd	
	WetLeak	
	Visual Insp	
	MaxPower	
	TC200-Setup	

Blocks	Sample 2 1	
	Receiving	
	PreCon-Setup	
	PreCon-Test	
	PreCon-Teardown	
	Visual Insp	
	MaxPower	
	DielWithstd	
	WetLeak	
	DampHeat-Setup	
1	DampHeat-Test 1000h (accumulated)	
	DampHeat-Teardown	
	DielWithstd	
	WetLeak	
	Visual Insp	
	MaxPower	
	DampHeat-Setup	
2	DampHeat-Test 1250h (+250 h)	
	DampHeat-Teardown	
	DielWithstd	
	WetLeak	
	Visual Insp	
	MaxPower	
3	DampHeat-Test 1500h (+250 h)	
	DampHeat-Teardown	
	DielWithstd	
	WetLeak	
	Visual Insp	
	MaxPower	
4	DampHeat-Test 1750h (+250 h)	
	DampHeat-Teardown	
	DielWithstd	
	WetLeak	
	Visual Insp	
	MaxPower	
5	DampHeat-Test 2000h (+250 h)	
	DampHeat-Teardown	
	DielWithstd	
	WetLeak	
	Visual Insp	
	MaxPower	
	TC200-Setup	

6	TC200-Test (accumulated)	
	TC200-Teardown	
	Visual Insp	
	MaxPower	
	DielWithstd	
	WetLeak	
	TC300-Setup	
7	TC300-Test (+100 cycles)	
	TC300-Teardown	
	Visual Insp	
	MaxPower	
	DielWithstd	
	WetLeak	
	TC400-Setup	
8	TC400-Test (+100 cycles)	
	TC400-Teardown	
	Visual Insp	
	MaxPower	
	DielWithstd	
	WetLeak	
	HumFreez-Setup	
9	HumFreez-Test 10 (accumulated)	
	HumFreez-Teardown	
	DielWithstd	
	Visual Insp	
	MaxPower	
	WetLeak	
	HumFreez-Setup	
10	HumFreez-Test 20 (+10 cycles)	
	HumFreez-Teardown	
	DielWithstd	
	Visual Insp	
	MaxPower	
	WetLeak	
11	HumFreez-Test 30 (+10 cycles)	
	HumFreez-Teardown	
	DielWithstd	
	Visual Insp	
	MaxPower	
	WetLeak	
12	HumFreez-Test 40	
	HumFreez-Teardown	
	DielWithstd	
	Visual Insp	
	MaxPower	
	WetLeak	
	BypassD-Setup	
13	BypassD-Test	
	BypassD-Teardown	
	Visual Insp	
	MaxPower	
	DielWithstd	
	WetLeak	

6	TC200-Test (accumulated)	
	TC200-Teardown	
	Visual Insp	
	MaxPower	
	DielWithstd	
	WetLeak	
	TC300-Setup	
7	TC300-Test (+100 cycles)	
	TC300-Teardown	
	Visual Insp	
	MaxPower	
	DielWithstd	
	WetLeak	
	TC400-Setup	
8	TC400-Test (+100 cycles)	
	TC400-Teardown	
	Visual Insp	
	MaxPower	
	DielWithstd	
	WetLeak	
	HumFreez-Setup	
9	HumFreez-Test 10 (accumulated)	
	HumFreez-Teardown	
	DielWithstd	
	Visual Insp	
	MaxPower	
	WetLeak	
	HumFreez-Setup	
10	HumFreez-Test 20 (+10 cycles)	
	HumFreez-Teardown	
	DielWithstd	
	Visual Insp	
	MaxPower	
	WetLeak	
11	HumFreez-Test 30 (+10 cycles)	
	HumFreez-Teardown	
	DielWithstd	
	Visual Insp	
	MaxPower	
	WetLeak	
12	HumFreez-Test 40	
	HumFreez-Teardown	
	DielWithstd	
	Visual Insp	
	MaxPower	
	WetLeak	
	BypassD-Setup	
13	BypassD-Test	
	BypassD-Teardown	
	Visual Insp	
	MaxPower	
	DielWithstd	
	WetLeak	

1 YEAR SEQUENCE

Eventual Goal: Acceleration Factor

Accelerated Testing
(LST)

+

Field Testing
(LST PLUS)

Acceleration Factor

Field Test Locations

Test Locations

LST Locations:

TÜV Japan (Competence)
TÜV PTL (USA)
TÜV Germany
TÜV Shanghai
TÜV Taiwan
TÜV India

Outdoor Locations:

Hot-Dry
Cold-Dry
Hot-Humid

Atlas 25 + - Long Term Durability Test for PV Modules

NREL PV Durability Workshop, February, 2012

Kurt P. Scott, Director of Renewable Energy Business Development

Allen Zielnik, Senior Consultant, Solar Energy Competence Center

Atlas 25⁺ Unique features

- **Atlas 25⁺ "First principles" of weathering**
- **Heat, Solar Radiation and Moisture act in synergy producing effects they don't alone.**
- Heat, Solar Radiation and Moisture are delivered in both short term (daily) and longer term (seasonal) cycles, not in steady-state conditions
- Nature doesn't alter weather and climate delivery based on your product. Neither should weathering tests
- The empirical view is not entirely from the perspective of the module, but rather from the way that nature delivers the stresses. The product is treated somewhat as a "black box"

- **Atlas' "semi- empirical approach" . .**
- Fundamental weathering testing
- Experience of other industries – **critical to have laboratory & outdoor testing**
- Does incorporate "realistic" elements known to be important to PV degradation – MPP load , tracking, thermal & freeze\thaw cycling, analysis,
- Takes advantage of technology from weathering and reliability testing
- Acknowledges basic limitations & constraints
- Complements IEC-type qual testing
- An accelerated weather aging protocol, not a service life predictor

Weathering cycle

ATLAS
MATERIAL TESTING SOLUTIONS
An AMETEK Company

Modules electrically operated under resistive load at MPP whenever exposed to Solar – natural or simulated

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

1 module

- UVA / UVB exposure
- Salt spray corrosion
- Condensing humidity
- Solar – Thermal – Humidity Cycle
- Solar – Thermal – Humidity/Freeze Cycle
- Arizona solar tracking including peak summer

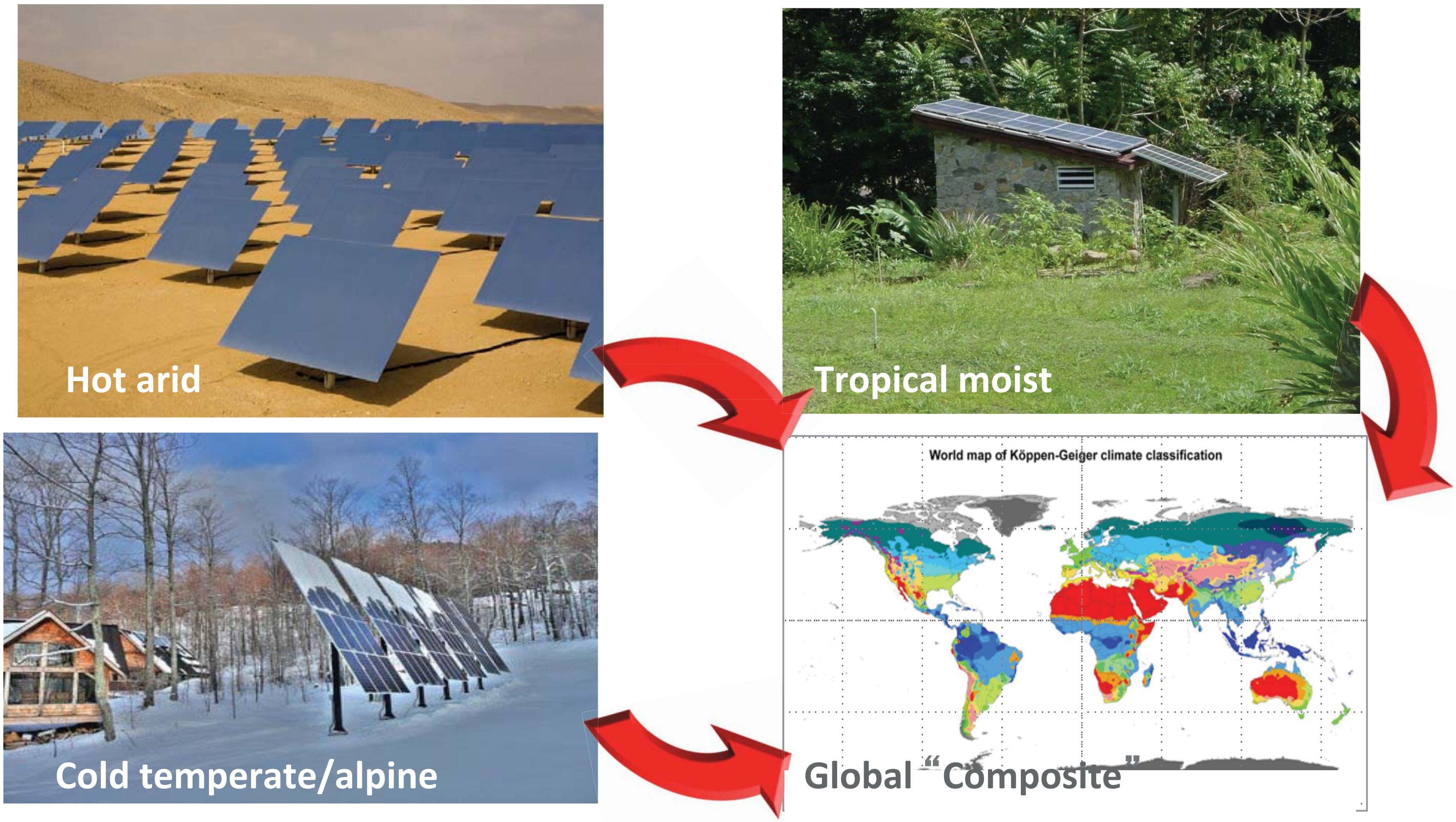
1 module FL | 1 module AZ

1-year solar tracking South Florida & Arizona

Total test program duration: 12 months

Four different test tracks

Identify & incorporate PV service conditions for each…



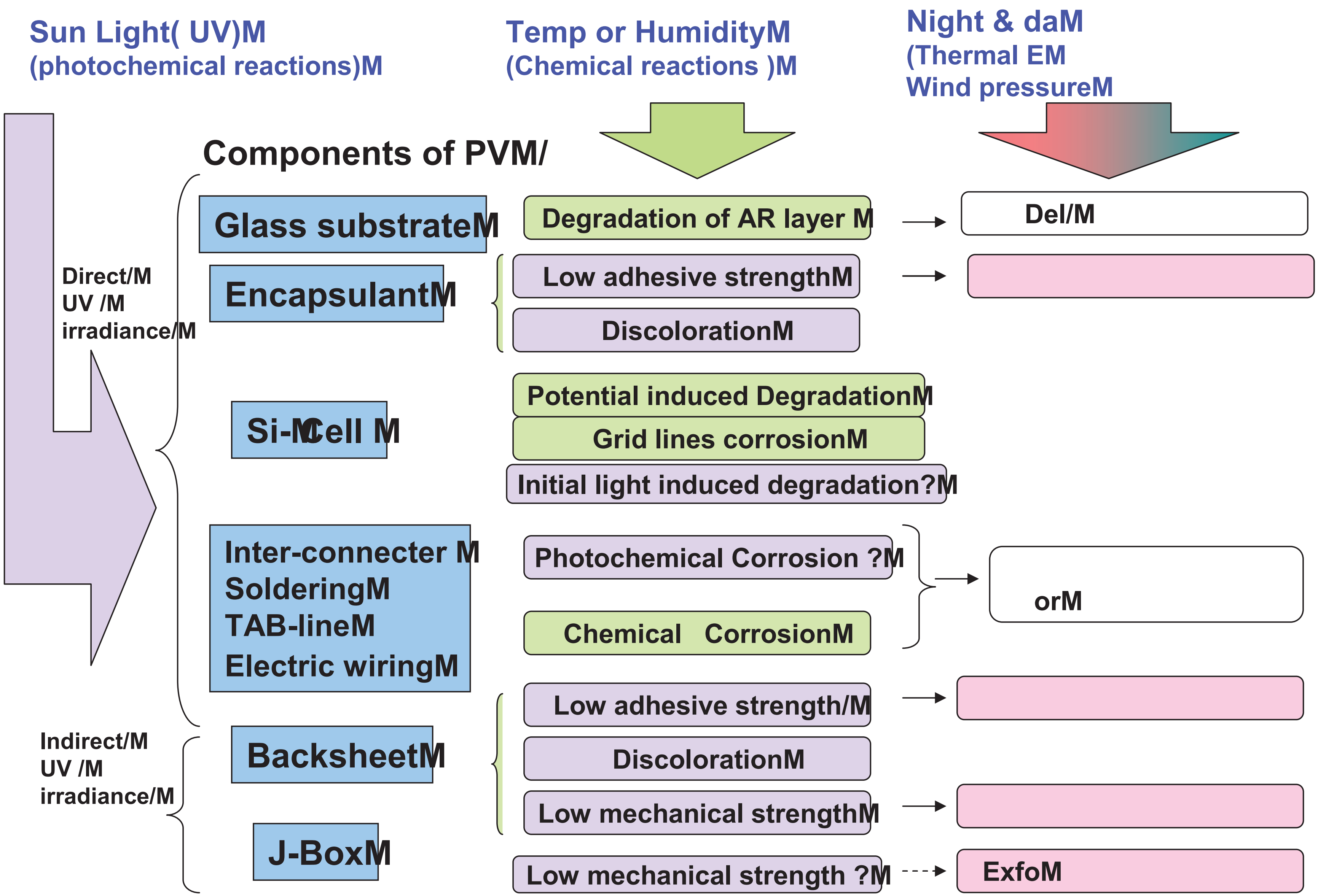
PV Module Reliability Workshop 2012M
Denver West Marriott, Golden, ColoradoM

UV-Thermal Combined Stress Acceleration Test/M

Kusato Hirota

Environment & Energy Development Center
Technology Planning Sect.
Toray Industries Inc./M

Degradation and Defect by Stress Factor/M



Key point which should be taken into considerationM on UV acceleration test of PV moduleM

1. Photochemical reactions of polymer materialM

Amount of decomposition product & reaction products which deC

Temperature , C

Water (Humidity) , C

Acid , Metal ions as Catalyst (created by Hydrolysis or Corr

UV light spectrum

At least 2 levels test condition (temperature and humidM

2. Invisible or undetectable degradation of Materials in UV tesM of PV modules M

e.g.)

- Weak Adhesive-strength of EVA Encapsulant or Backsheet
- Weak Mechanical-strength of Backsheet

In actual installation environment, defects, such as delamination of EVA and a crack of Backsheet, occur by exposing a module to the **mechanical stressM** by day-temperature cycle or wind pressure.

HF (TC) or the dynamic mechanical test followingM sequentiallyM

UV-Thermal, Humidity Combined Test/M

1stM stepM
(materials degradation) M

2ndM stepM
(OccurrenM

Test 1: UV with High Temp. M
For High temperature, an arid regionM

e.g. (to be discussed in TG5)M
3or 5 SUN at 70 to 85deg C (DRY?)M
2000 hours or moreM
Light source: Xenon Lamp or other ?M

Test 2: UV with High Temp & Humidity M
High humidity and/Mr tropical regionM

e.g. (to be discussed in TG5)M
3or 5 SUN at 85deg C , 85%RH M
2000 hours or moreM

orM
3or 5 SUN at 70 or 85degMCM
2000 hours or moreM
\+ Sequential DHTM(85degM 85%RH)M
2000 hours ? or more M

HF 10cyclesM
(or TC 100 cycles)M

orM

Dynamic MecM
Load testM

Note :For Backside of module, 15%Mof front-side irradiance UV test will be/M

PV Module Reliability Workshop – Standards
Proposed Test Protocols – New Tests:

Accelerated TC Test

Tadanori Tanahashi (ESPEC CORP.)
2012/02/29

Task Statements 1/3

2nd International PV Module Quality Assurance Forum
Dec. 8, 2011, Tokyo

< Thermal-Cycling Test >

No significant power loss is revealed in the increasing of cycle number up to 1,500. Therefore, we do not require the increasing of cycle number in TC test.

- Options:
Instead of the increasing of cycle number, we would like to propose to raise the upper level of the temperature to accelerate the degradation.

We think that the damp heat (DH) or humidity freeze (HF) test prior to the TC test is significant. For this sequential testing, we will have joint meetings with domestic Task Group-3 and Task Group-5.

Targets

- Time Saving : TC200 + alpha

- Effective stress(es) to induce the degradation of PV modules, which closely-associated with the thermal fatigue

- For the deteriorations by thermal fatigue, the highly accelerated test-procedure should be proposed for the rating of PV modules.

Accelerated TC Test [INITIAL PROPOSAL]

ESPEC

A1*: Damp Heat
(500 or 1,000 h)

(*A1 and B1 are options)

B1*: Humidity Freeze
(10 cycles)

Thermal Cycle (A2 / B2)

1. Cycling Profile (A2/B2 : not determined so far)

A2) Thermal Cycling with High Temp.:
- -40 / 95 °C or -40 / 100 °C
- 100 °C/h
- 200 cycles
- max. 6 h/cycle (dwell : > 10 min)

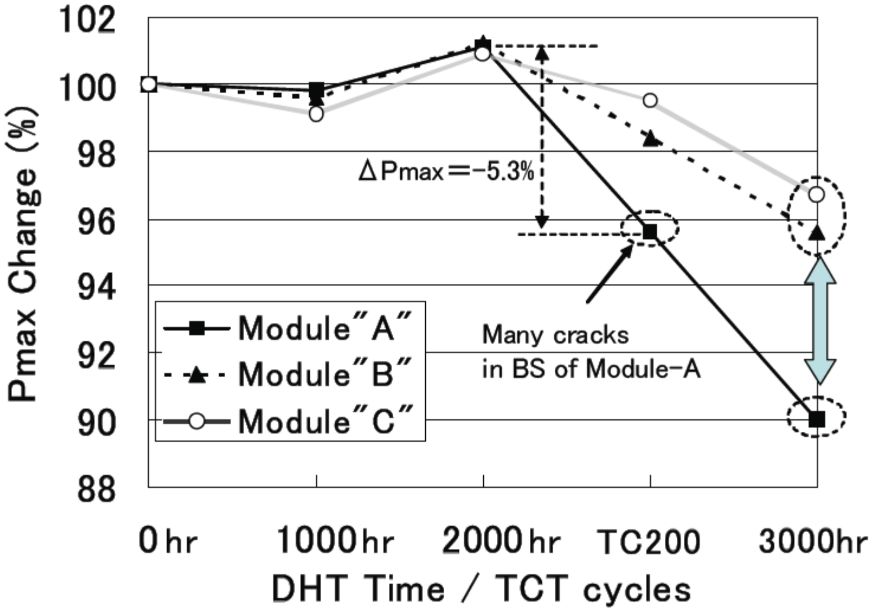
B2) Rapid Thermal Cycling:
- -40/85 °C
- ca. 400 °C/h
- max. 600 cycles
- 2 h/cycle (dwell: >ca. 15 min)

2. Measurements
- Visual Inspection (IEC 61215 -10. 1)
- Power Loss (IEC 61215 -10. 2)
- Insulation (IEC 61215 -10. 3)
- WLCT (IEC 61215 -10.15)
- EL Imaging to quantify the cell-crack
- IR imaging to detect the compensating heat interconnectors with the interconnector-failures
- *In situ* Impedance Monitoring

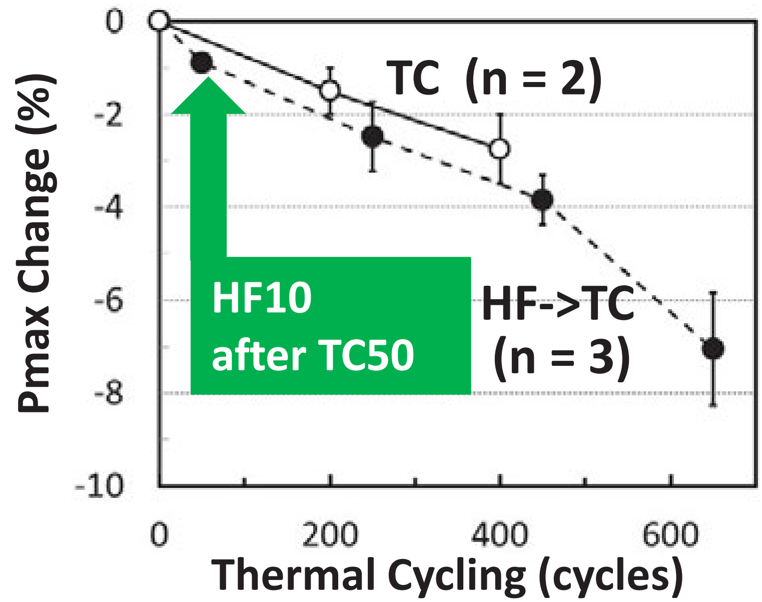
APPENDIX

Effect of Humidity-Stress prior to Thermal-Cycling

DH -> TC*



HF -> TC**



DH -> TC: **Pretreatment with DH induced the variance of power-loss with TC.**

HF -> TC: **It seems that the pretreatment with HF (Humidity Freeze) likely to change the degradation rate during TC.**

These effects should be faithfully confirmed in the various types of PV modules.

*Arai, T. et al., "Observing Mini PV Module Deterioration Through Successive Damp Heat Testing and Thermal Cycle Testing Procedure", 21st PVSEC, 2011, Fukuoka, Japan.

** "Research Report of the Consortium Study on Fabrication and Characterization of Solar Modules with Long life and High Reliability (AIST, Japan)", 2011.

Elevation of Upper-level Temp. in Thermal Cycling

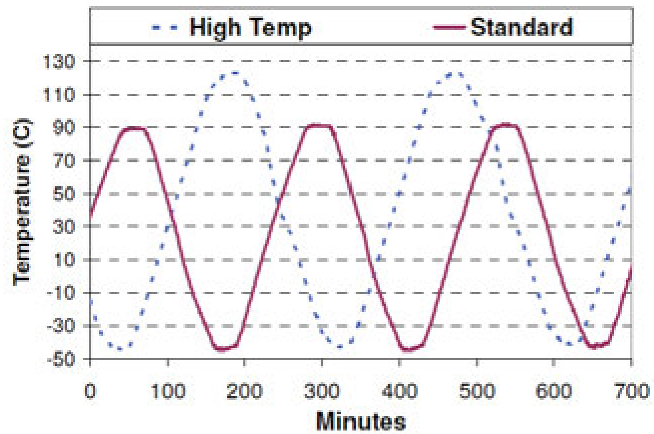


Figure 5: Thermal cycling profiles
High Temp Profile: -40 to 125°C
Standard Profile: -40 to 90°C (UL Thermal Cycling test)

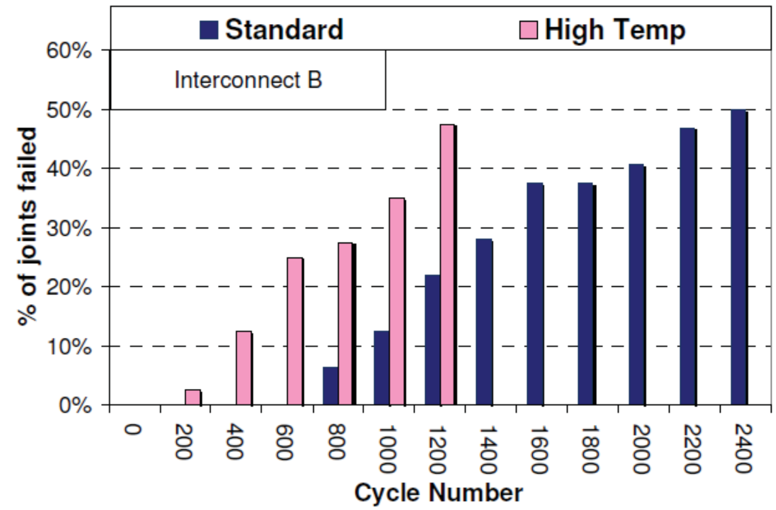


Figure 7: Joints failed with interconnect B

By the raising of upper level of temperature in TC (125°C), the acceleration of degradation concerned with thermal fatigue was observed in the test vehicle (Back contact type).

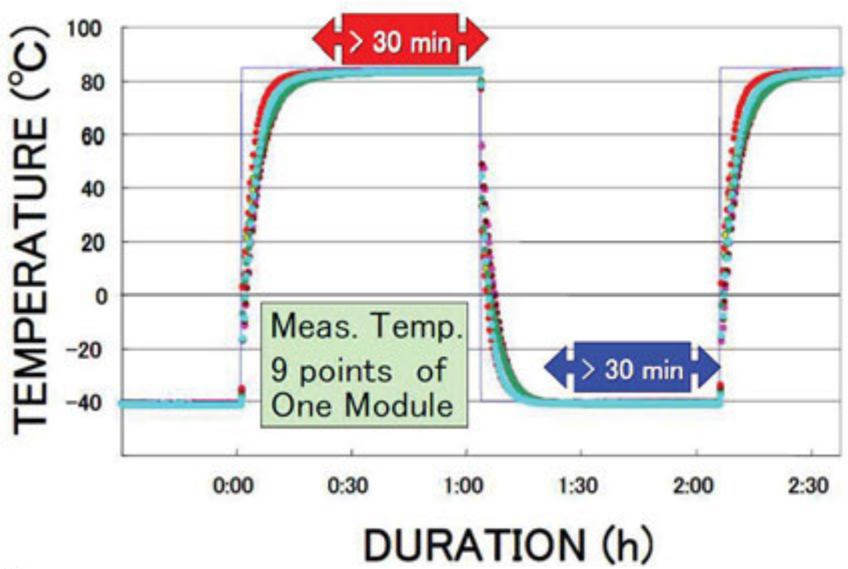
It would be crucial to higher the temperature to save the testing-period, but it is difficult because the components of PV modules (including Junction Box and Cable) have a limit at ca. 100°C.

Then, we are planning the thermal cycling test with 95-100°C as upper temp.

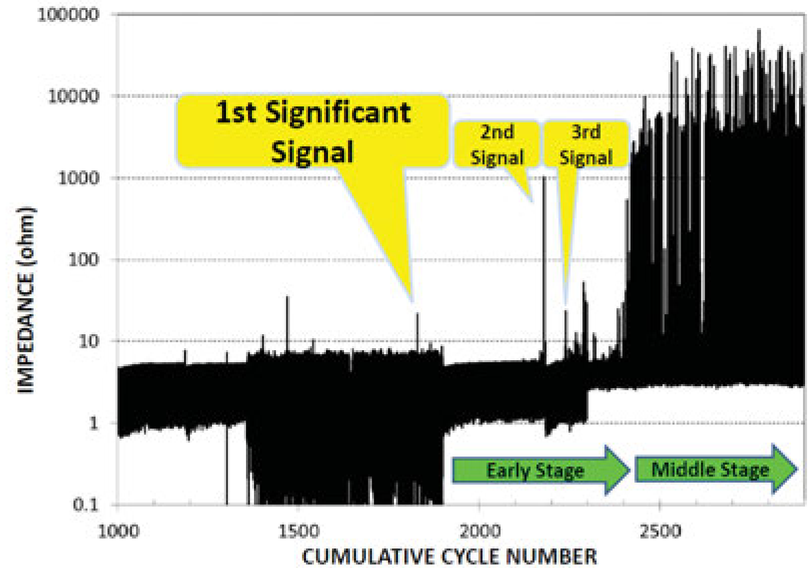
Meydbray, Y. et al., "Solder Joint degradation in High Efficiency All Back Contact Solar Cells", 22nd European PVSEC, 2007, Milano, Italy.

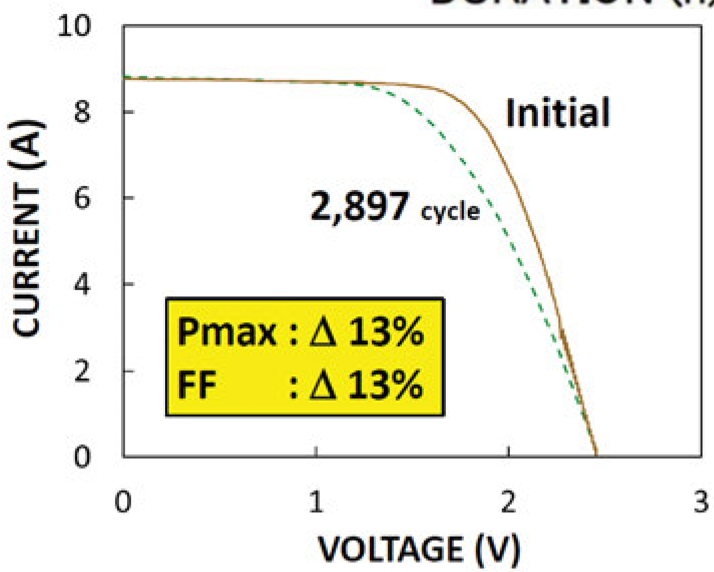
Rapid Thermal-Cycling with *in situ* Impedance Meas.

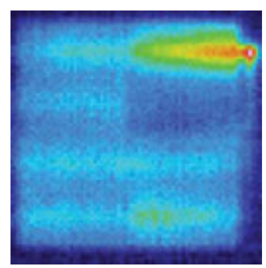
Temperature on Module Surface during Rapid TC



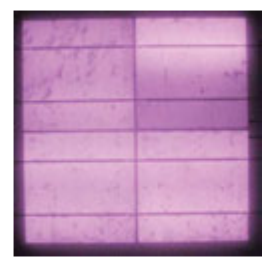
Impedance Elevation during Rapid TC







IR Imaging



EL Imaging

The rapid thermal-cycling with *in-situ* monitoring of module-impedance may be a useful procedure for the early detection of inter-connection failures.

Tanahashi, T. "Photovoltaic Module Reliability Testing: 400°C/hr", 2012 PV Module Reliability Workshop

SOLAR WIND

Premise (summary)

- The same module response (to wind excitation) can be reproduced in a laboratory using vibration test systems (that is, modules can be modeled as spring/mass systems) (Source: Shock & Vibration Handbook)
- High level wind induced vibration response combined with lower levels (or durations) of TC and / or DH can reproduce module field failures in the laboratory easily and efficiently (Source: Westpak, Inc.)

Test Methodology Overview

- **Install test modules in field at a "known" windy spot with meteorological data availability (NREL at Golden, CO)**
- **Return test modules to lab and attempt to reproduce measured module field response in the lab using mechanical vibration input**
- **Repeat the process with small increases in excitation and/or duration until significant module change is noted**

SOLAR WIND

WESTPAK, INC.
EXCELLENCE IN TESTING

Data Recorders, Shipping Crates, Field Installation

Module A

data recorder

power supply

Module B

Test modules with vibration data recorders attached

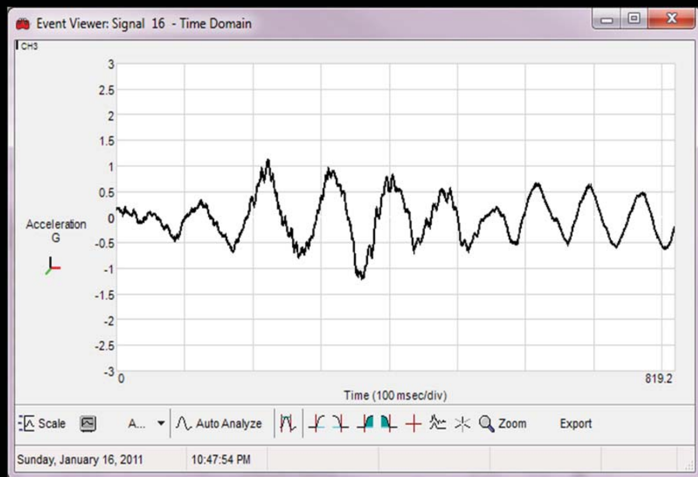
Custom shipping crates

Module A Module B

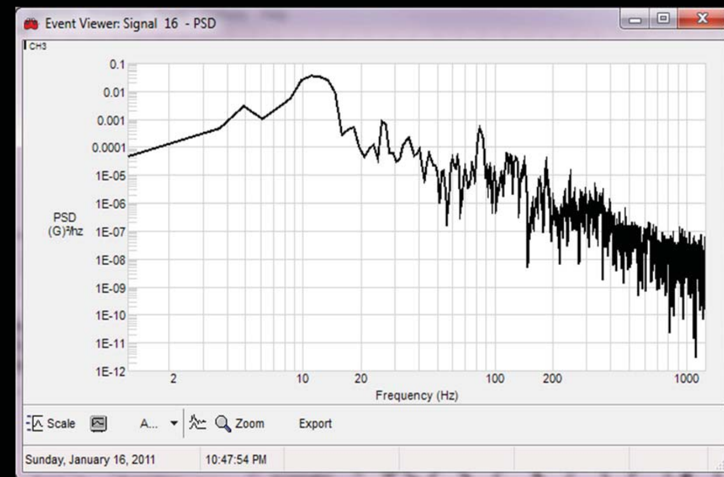
Field installation at NREL

Spectra & time domain for Modules A and B at field (NREL): 50 - 60 MPH wind (Test 1.0)

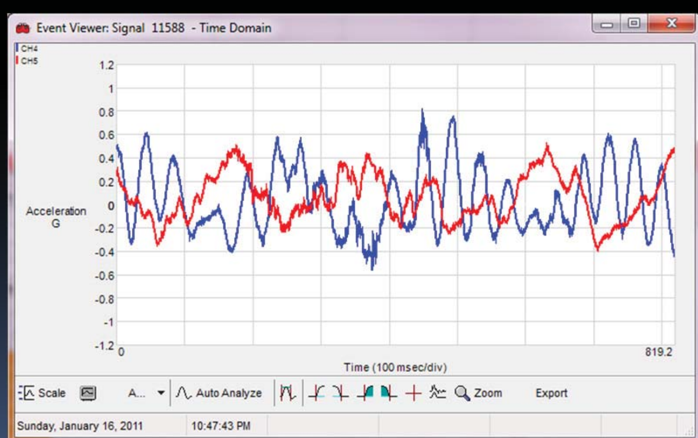
WESTPAK, INC.
EXCELLENCE IN TESTING



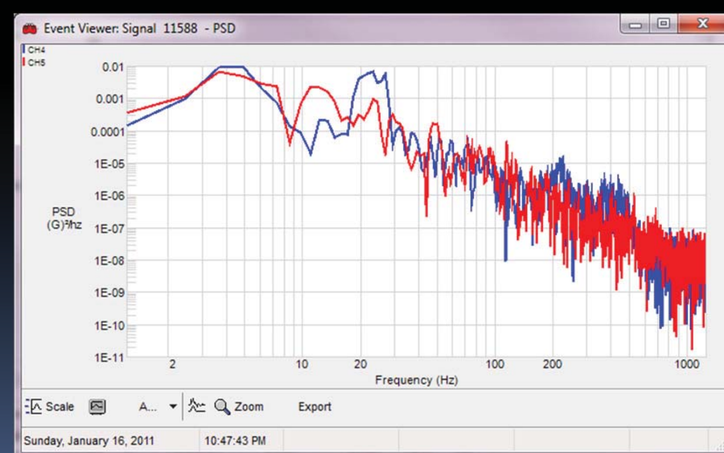
50-60 mph Wind Event (Time Domain) – 3X90 Module A



50-60 mph Wind Event (PSD) – 3X90 Module A

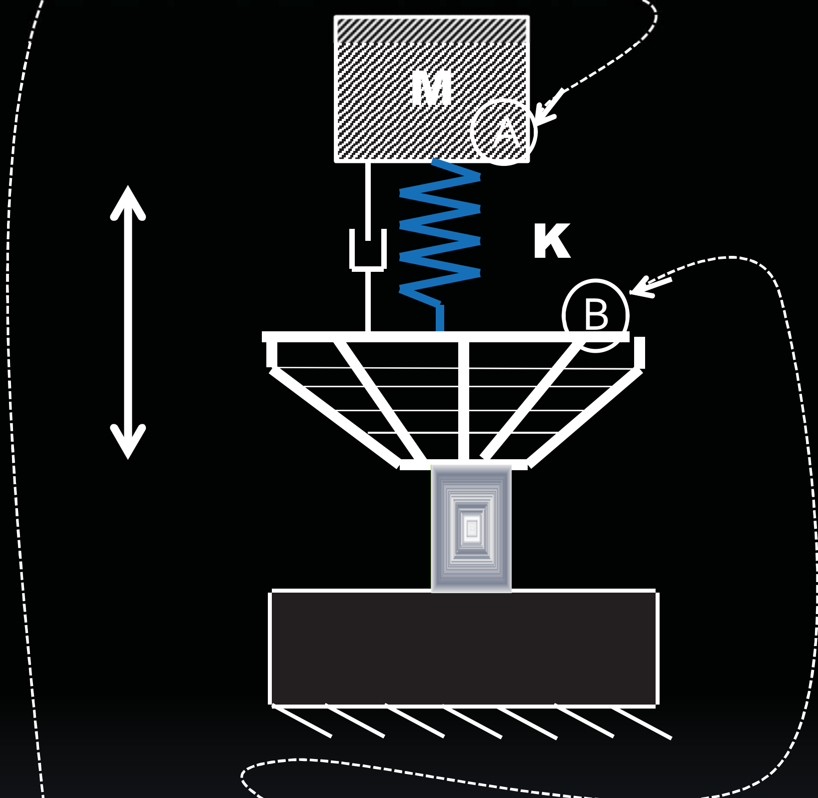


50-60 mph Wind Event (Time Domain) – 9X30 - Module B
Blue: Center of Module Red: Corner of Module



50-60 mph Wind Event (PSD) – 9X30 - Module
Blue: Center of Module Red: Corner of Module

SOLAR WIND



Mass of PV module

Distributed flexibility of PV module and supporting structure

Electric-hydraulic vibration test system

B = Platform or table or location where RESPONSE is measured for test 2.0 and the location for the DRIVE or COMMAND signal for test 3.0.

A = Center of PV module where the DRIVE or COMMAND signal is given to match the field response in test 2.0 and to measure the RESPONSE of the module in test 3.0

<u>Lab data is a reasonable match for field data for both modules.</u>

Scuola universitaria professionale della Svizzera italiana
Dipartimento ambiente costruzioni e design
Istituto sostenibilità applicata all'ambiente costruitc

SUPSI

EXTENDED MECHANICAL TEST

1. STATIC LOAD TEST on PV MODULES
2. STATIC LOAD TEST on PV MODULES and STRUCTURES
3. EXTENTED HAIL TESTS on PV MODULES

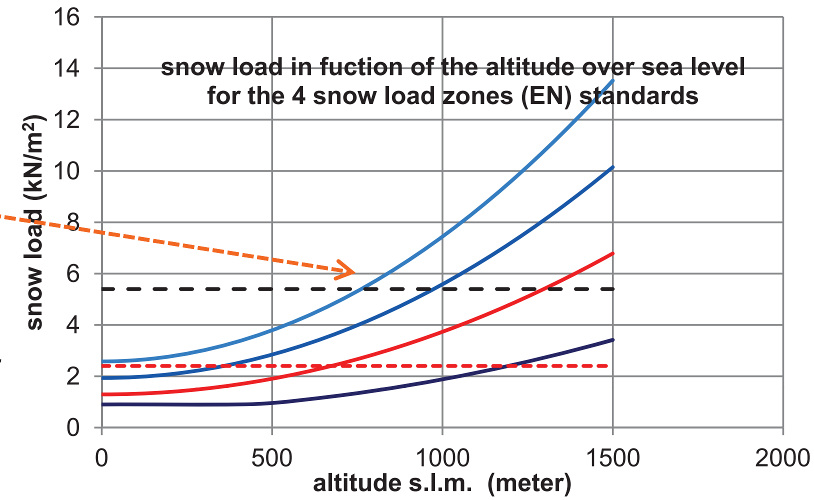
Thomas Friesen
Head SWISS PV Module Test Centre

SUPSI
Swiss PV Module Test Centre
Accreditated ISO 17025
by SAS under n.531

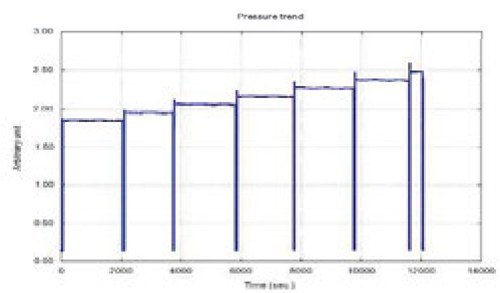
23 febbraio 2012

Extended mechanical load test

Why: IEC snow load test is not enough for all regions



Solution: Static testing on the front of the module for heavy snow load in dependence of the local requirements and PV system configuration!



$$s = \mu * C_e * C_t * s_k$$

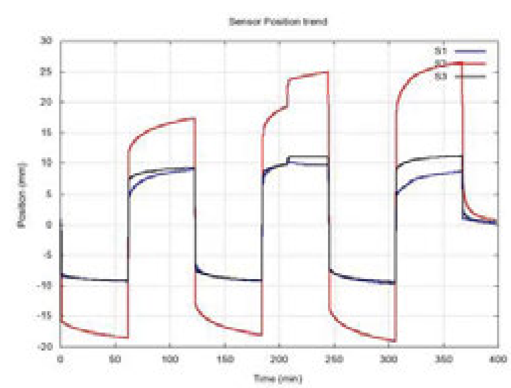
s_k horizontal snow load on ground
C_e exposure coefficient (0.8 – 1.2)
C_t thermal coefficient (0.8 – 1.2)
μ inclination of modules (°)

Test procedure:

Incremental load on the front for max. load determination

End of test: broken or max. permitted deflection ?

Conditioning (TC – DAH ??)



Control measurements:

EL – power at STC – WL – INS - deflection

STATIC MECHANICAL LOAD TESTING WITH STRUCTURE

Special requirements – related problems:

PV mounting structures under high loads → regulated by building codes

<u>But:</u>

PV modules with clamping (glass) and high snow load → no tests

Frame / laminate resistance under cold conditions and ice – snow loads

Structures with snow retaining systems (or similar safety installation)

Clamping (type – clamping force – geometry – positions) is important in traction and in pressure

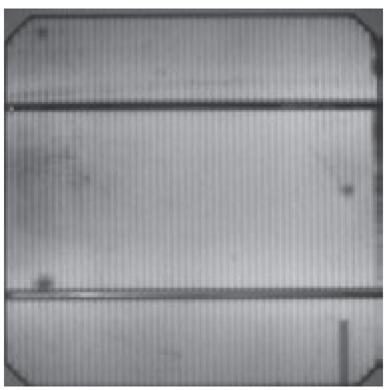
HAIL TESTING

Switzerland		IEC Standard	
DIAMETER (mm)	Kinetic Energy (J)	DIAMETER (mm)	Kinetic energy(J)
10	0.04	15	0.25
20	0.7	**25**	**1.9**
30	3.5	35	7.65
40	11.1	45	20.7
50	26.9		

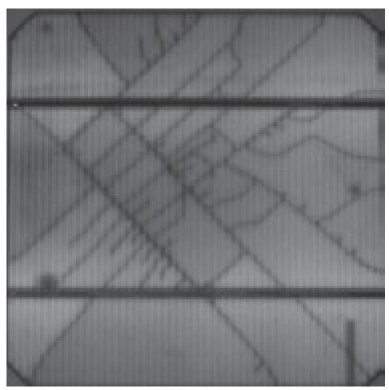
Testing with extend conditions in accordance to the local requirements – hail classes

Test parameters:

- Ice temperature
- Hail diameter
- Speed
- Impact angle
- Number of impacts



before



after impact

35 mm – 50 m/sec – 45° - Ice temp -1° – 5 impact on cell
Backsheet - 4 mm tempered glass – mc-Si cells

Possible reference values:

Kinetic energy to simplify the comparison
Correction for different ice temperature

Control measurements:

EL – power at STC - VI

FLORIDA SOLAR ENERGY CENTER

Creating Energy Independence Since 1975

Inclusion of Outdoor High-Voltage Bias Testing in the Quality Assurance Methodology

Neelkanth G. Dhere

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A Research Institute of the University of Central Florida

Damp Heat Testing Inadequacy

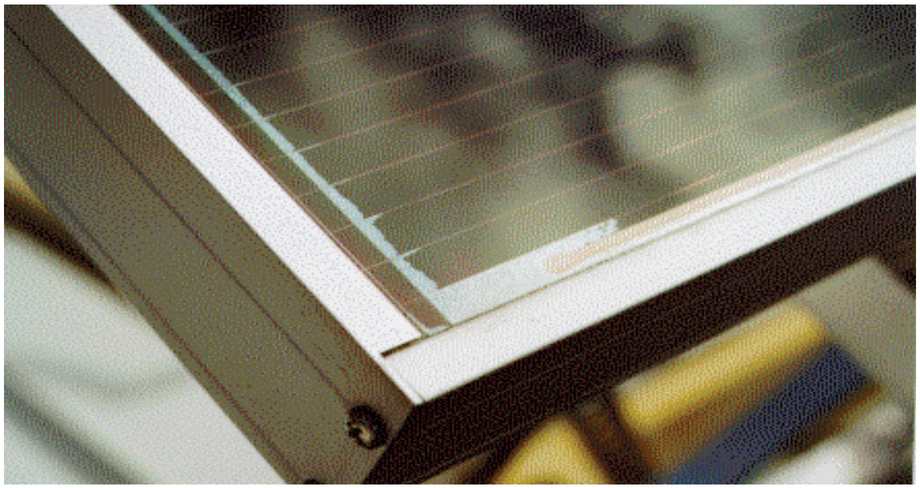
- As shown by Mike Kempe, the outdoor condition at various locations: Riyadh, Bangkok, Miami etc are all significantly different from the damp heat test conditions of 85 ^{0}C at 85% relative humidity (RH).
- Results at different temperatures can be correlated.
- Results under different RH are very difficult to correlate because the activation energies of different modes of degradation vary significantly with RH.
- In this respect outdoor high-voltage bias testing under hot and humid conditions is superior to high-voltage bias testing in the damp heat chamber.

High voltage Bias Testing

- The relatively slow degradation may be accelerated by two means:
  - higher bias voltage compared to the system voltages of 600 V in the USA and 1000 V in Europe and elsewhere and
  - continuous application of voltage bias even at night.
- It would be possible to determine the Acceleration factors for both by having other modules biased at lower voltages as well as only during the day.
- Looking for PV module manufacturers interested in participating in these tests.

Acceleration Factors

- We should compare the modules taken from arrays reaching high positive and negative voltages with individual modules biased to high voltages in hot and humid conditions.
- We should stress the importance of latitude tilt, periodic cleaning, visual inspection and I-V measurements.
- This comparison would result in direct correlation and acceleration factors with good statistics.



-600 volts
after 8 months

Quality Assurance Methodology

- **Instead of relying exclusively on PV measurements, we should monitor physical changes at various interfaces for gauging the changes that are taking place using both non-destructive and destructive techniques.**
- **We can then apply the principles of Physics of Failure to elucidate failure modes and mechanisms.**

Task Group 2: Thermal and Mechanical Fatigue Including Vibration

Christopher Flueckiger

Task Group 2 Thermal and Mechanical Fatigue Including Vibration

Scope:

Failures of cell interconnects and solder bonds have been identified as a key cause of long-term failure of PV modules. The primary stresses affecting the failure rates have been shown to be thermal and mechanical. There is evidence that vibration during transportation and/or caused by wind can contribute. This task group will study how to best induce stress and quantify quality.

Task Group 2: Proposed Sequential Test Plan

Visual Inspection and Electrical Characterization

↓

Dynamic Mechanical Load

↓

Visual Inspection and Electrical Characterization

↓

Temperature Cycling

↓

Visual Inspection and Electrical Characterization

↓

Humidity / Freeze Cycling

↓

Visual Inspection and Electrical Characterization

Task Group 2: Proposed Test Parameters

Visual Inspection and Electrical Characterization: Power-Loss, Wet Leakage Current, Electroluminescence, Insulation Resistance

Dynamic Mechanical Load: max: 1,000 Pa, 1,000 cycles, 2 – 3 cycles/min

Temperature Cycling: 50 cycles with no current flow, increased temperature range and rate of change being considered.

Humidity / Freeze Cycling: Same as IEC / UL

Electroluminescence

1. Task Group 2 collaborates with SEMI PV Committee to create EL/IR measurement standards.
2. Task Group 2 creates the rating system for modules using these standards.

PV QA Task Group #2: Current Status

Interim Goals by Apr-12	Thermal Cycling / Dynamic Mechanical Load: 1st Draft (Proposal) Creation for the Rating Standard ->Agreement in Int'l WG2
Interim Action Plan by Apr-12	Thermal Cycling: Discussion for the Upper Level of Temperature / Sequential Testing (e.g.: DH/HF -> TC) Dynamic Mechanical Load / Vibration: Request to SEMI PV Committee for the Establishment of EL/IR Measurement Standards
Mid-term Goals	Thermal Cycling / Dynamic Mechanical Load: Improvement of Rating Standard (Autumn 2012) Vibration: 1st Draft (Proposal) Creation for the Rating Standard ->Agreement in Int'l TG2 (Autumn 2012)
Mid-term Action Plan	Thermal Cycling: Analysis of Accumulated Experimental-Data Dynamic Mechanical Load / Vibration: 1st Draft (Proposal) Completion in SEMI PV Committee (EL/IR Measurement Standards)
Remarks	Last meeting was February 21, 2012. Ongoing monthly teleconferences globally and (hopefully) regionally

THANK YOU.

Christopher Flueckiger
Underwriters Laboratories
Email: christopher.flueckiger@ul.com

Humidity, Temperature and Voltage

2012 PV Module Reliability Workshop

Golden, CO

John Wohlgemuth

NREL

March 1, 2012

NREL/PR-5200-54836

Humidity, Temperature and Voltage

Scope:

The ingress of moisture with or without electrical bias has been shown to cause corrosion and charge movement in PV modules. Temperature and humidity have been used as accelerated stress tests for PV modules for many years. However, the use of constant exposure tests, such as the existing Damp Heat Test of 85 C and 85% RH for 1000 hours, appears to result in relative humidity levels far above that which will ever be seen outdoors for breathable package designs and may overstress the module. On the other hand, for semi-hermetic designs, 1000 hours may not be long enough to simulate 20 years of moisture ingress through the moisture barriers. There are multiple humidity and humidity/electrical bias degradation modes with widely varying acceleration factors. The group's development of true accelerated lifetime tests must take variation of environmental conditions into account.

Created 2 groups – Japan and Rest of World

Methodology

How we should develop lifetime tests for humidity

- **Determine outdoor failure modes**
- **Try to duplicate failures using accelerated tests**
- **Model water ingress in field versus test chamber and then how moisture leads to observed degradation in order to determine acceleration factors**

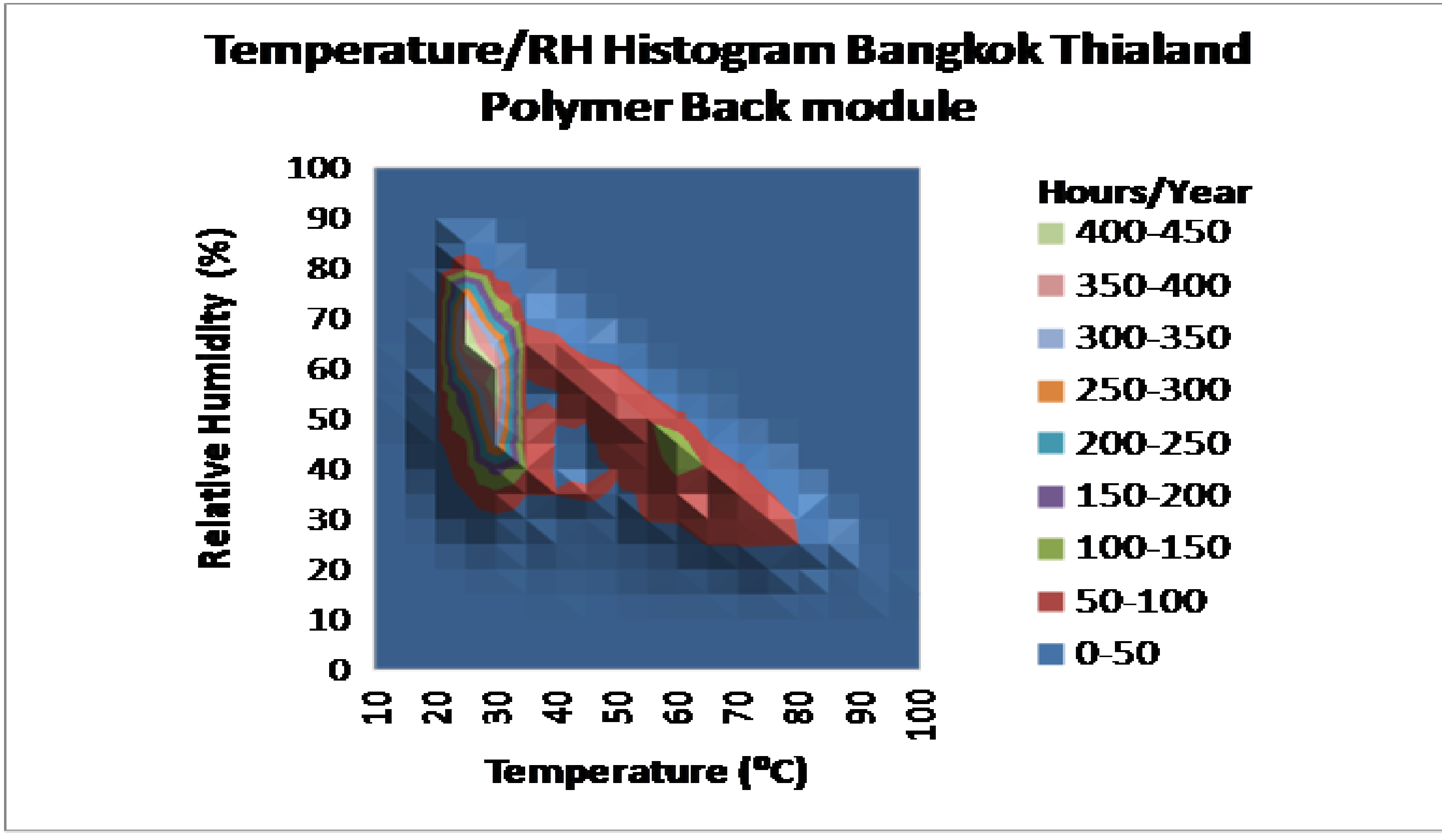
Most proposals for lifetime tests for humidity

- **Extend the 85/85 damp heat test**
- **Determine which modules perform better**
- **Assume this relationship will hold in field**

Problems with this approach

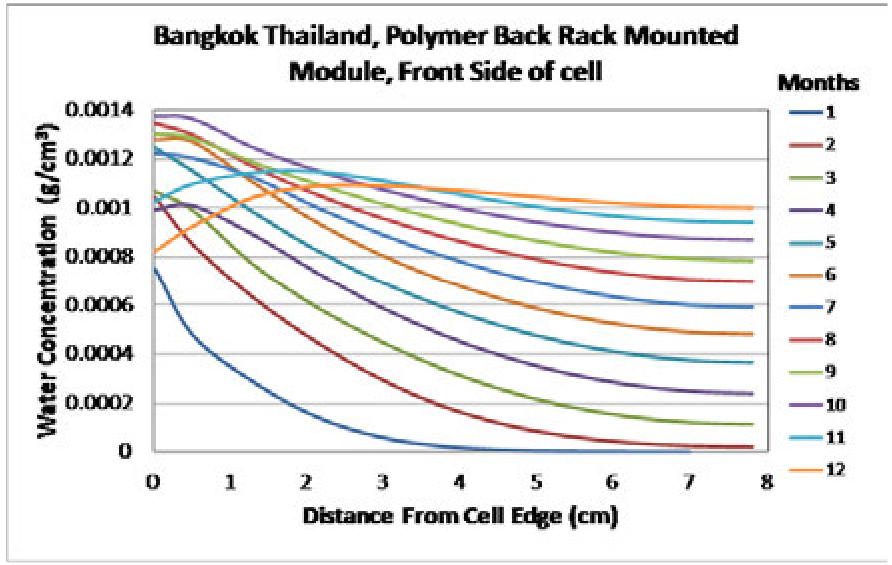
- **85/85 never occurs in real world**
- **Failure mode occurring after long term 85/85 testing is not observed in field**

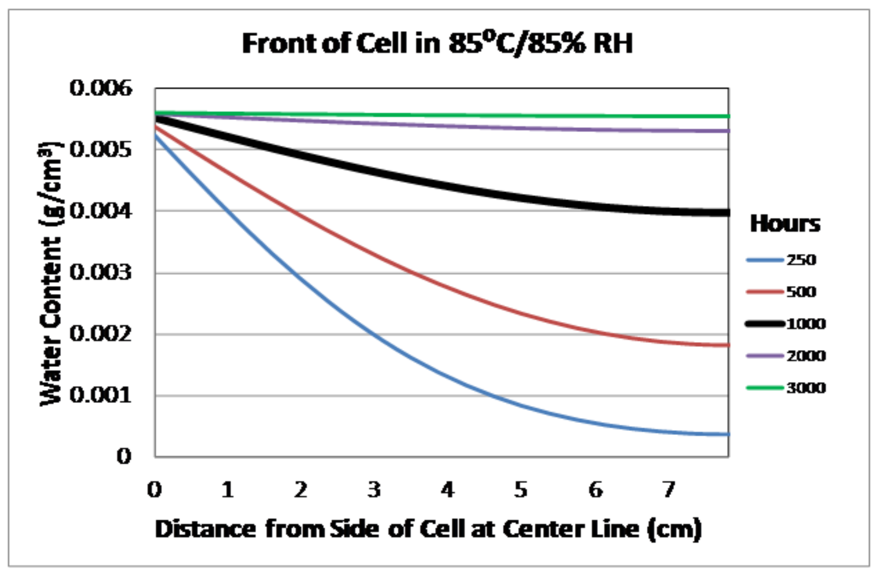
Modeling of Humidity Ingress into backside of Modules



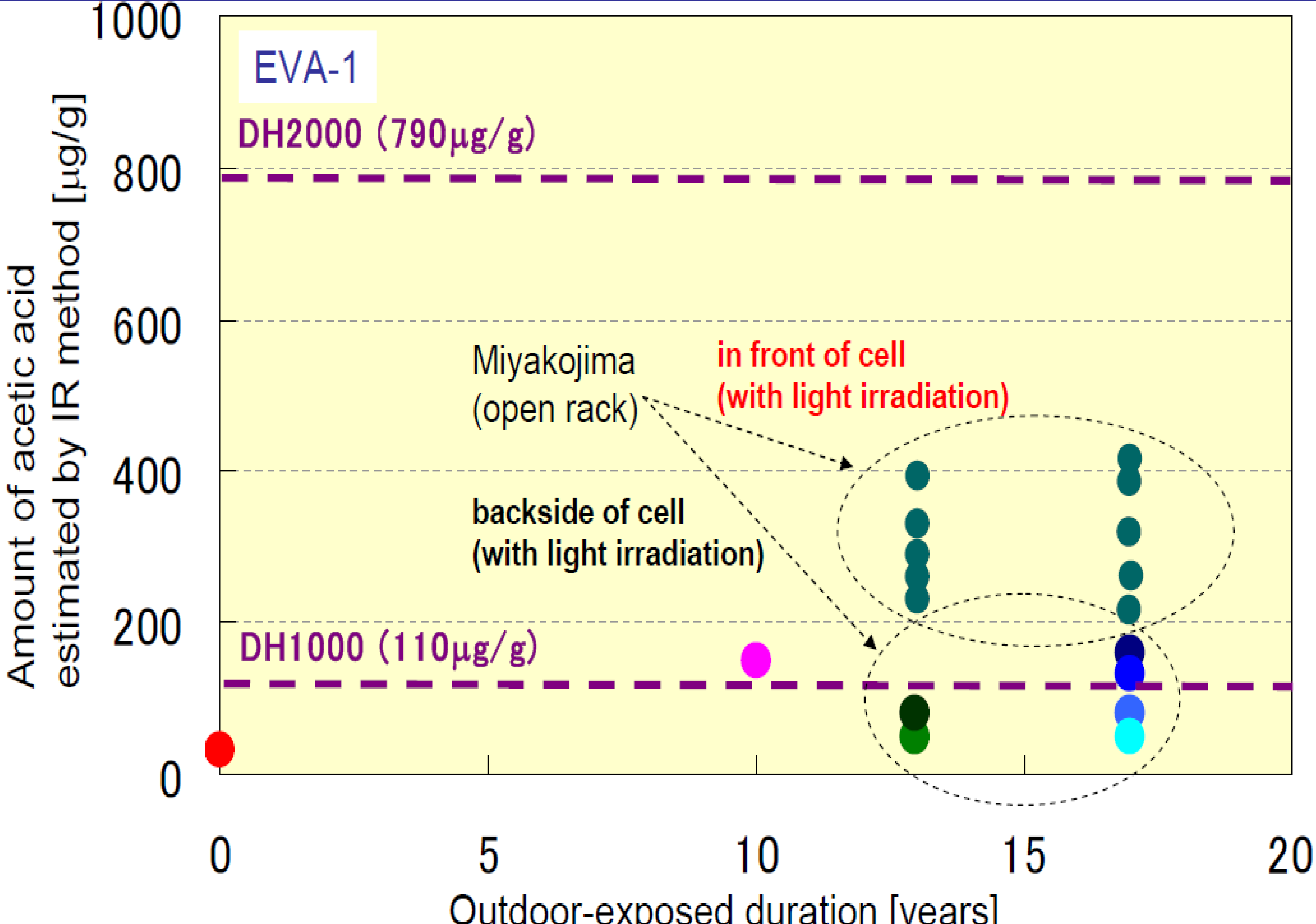
- **Modeling of humidity levels in back of PV module with polymeric backsheet in Bangkok, Thailand.**
- **Damp heat test conditions (85/85) never occurs within module.**
- **When module has high humidity it cool.**
- **When module is hot it has low humidity.**

Modeling of Humidity Ingress into front side of Modules





Comparison of amount of acetic acid in EVA between long-term outdoor exposure and DH accelerated aging (tentative)



Conclusions/Recommendations

- Bake-offs (long times at 85/85) do not duplicate field failures.
- Need field data, samples & analysis methods

  (probably for all 4 groups)

  - Lets discuss how we can set up a system to collect this data without identifying specific manufacturers or giving away proprietary information.
- Need to determine exactly what mechanism(s) are leading to module degradation in field.
- Will have to perform modeling to understand those degradation mechanisms and how they can be accelerated.
- Then will have to design new accelerated stress tests that can duplicate the field failures.

US TG 4 activities of QA Forum

QA Task Force 4 ; Diode, Shading & Reverse Bias

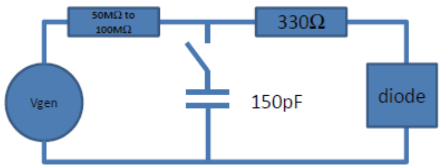
Contains no confidential information.

Feb. 28 – Mar. 1, 2012 ***@NREL PV Reliability work-shop***

Vivek Gade(Jabil Circuit) and
Paul Robusto(Intertek)

Overview, Working groups and areas of focus

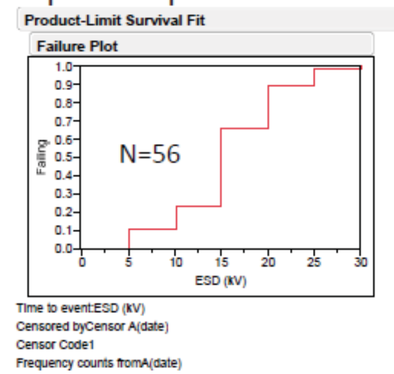
- Working group 1: Lead by Kent Whitfield working on HBM surge testing
  - PV Manufacturing facility static voltage measurement
  - Performed ESD event in combination with reverse bias at high temperature
  - Conduct tests and compare life distributions from the 10-surge and 100-surge program
- Working group 2 and 3: Lead by Vivek Gade and Paul Robusto
  - Reverse bias at high temperature and reverse bias transition survivability
  - Forward bias thermal cycling and fatigue issues.
  - Scope of the testing not limited to diodes but apply to Junction box level testing.
- Working group Task 4 Japan Lead by Yasumori Uchida, JET
  - Human body model ESD
  - Thermal runaway at reverse bias



HMB surge testing

- Handling by personnel on the manufacturing line and in the field results in surge events that damage Schottky diodes.
- Surge events can lead to higher reverse bias leakage current which can exacerbate a thermal runaway failure. Some failure analysis suggesting root cause of diode shorting events indicates surge damage
- Basis of ESD Test – IEC 61000-4-2
- 150pF, 330 ohm impendence circuit. This is interpreted to be a human-body-model impedance circuit.
- This work did NOT confirm a correlation between reverse leakage current and ESD event below the failure threshold.
- A fifth group of 56 diodes (restricted to a suspect date code) was subsequently subjected to an ESD-to-Failure test exhibited 100% mortality.
- This work does suggest that there is significant difference between the failure distribution of diodes subjected to an ESD-to-Failure test program and reports on a significant change in the failure distribution for one diode type when restricted to a particular date of manufacture.

A-Fails
Groups 5 suspected date code

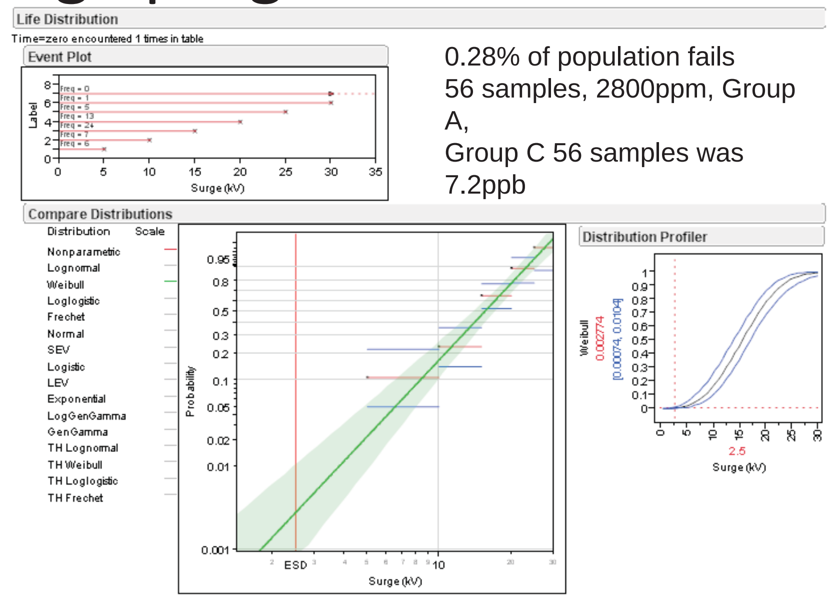


Typical failure: ESD mark observed after die top metal removal.

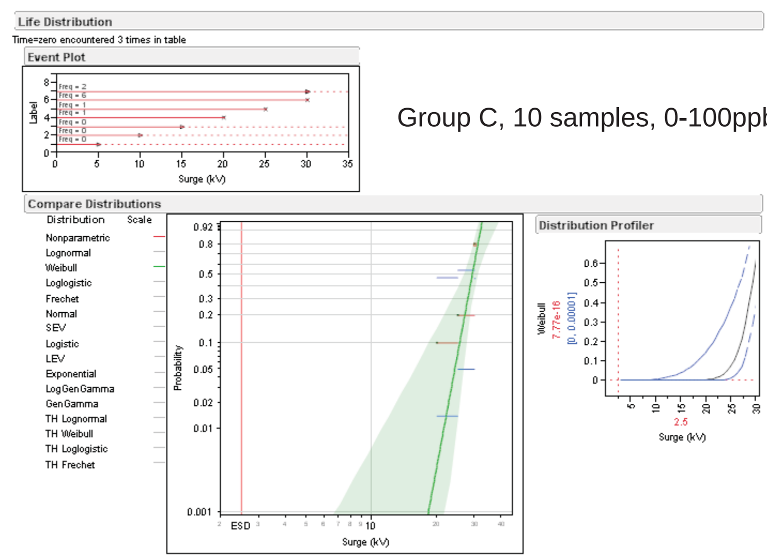
JBOX INSTALLATION STEP (measurement date 10 Oct 2011)	Measured Voltage (V)
Opening shipping container and measuring jbox potential while still in box	+1,260
Preparation table resting voltage	+90
Removal of Jbox from box and placement on table. Resulting jbox voltage.	+470
Placing two strips of double-sided tape on jbox. Max voltage.	+120
Jbox voltage after applying perimeter silicone adhesive.	+130
Jbox voltage after removing double-sided tape release liner. Max voltage.	+2500
Placing Jbox on laminate. Maximum box voltage.	+50
MODULE TESTING CONDITIONS	
Flash simulator curtain voltage. (NOT JBOX)	+200
Flash simulator structure voltage. (NOT JBOX)	+50
LAMINATE CONDITIONS	
Laminator outfeed belt voltage (NOT JBOX).	+250
Laminate on outfeed conveyer belt (NOT JBOX)	+110
Laminate on table post backsheet trimming operation	+110
SEPARATE WORK AREA KNOWN TO HAVE A HIGH STATIC POTENTIAL	
EVA Roll	-3500
Backsheet Roll	-56,000

HMB 10 surge and 100 surge program

- 56 parts per group and three groups tested.
  - ➢ Surge-to-failure program in 5kV steps using simple DMM check for short-circuit following surge (no elevated temperature reverse current leakage test).
- 5 surges anode + 5 surges cathode with 10 seconds between surges per stress step.
  - ➢ A group of ten diodes was tested using 50 surges anode + 50 surges cathode (100 total) with a 10 second rest between surges and the life distribution from this sample is compared to the baseline 10 surge program.
- A Weibull curve used to fit data enabling estimation of number of failures that may occur at a specific level of ESD potential.
  - ➢ We have substituted surge voltage for time in this analysis
  - ➢ The cumulative distribution function is thus interpreted to mean fraction of all units in the population which will fail by V voltage of ESD.
  - ➢ Shaded region indicates a 95% confidence interval around the median line.
- Static voltage measurement used to estimate ESD potential levels in a PV facility
- Significant difference seen in resulting failure distributions.
- Good similarity between the life distributions from the 10-surge and 100-surge program is indicated.



0.28% of population fails
56 samples, 2800ppm, Group A,
Group C 56 samples was 7.2ppb

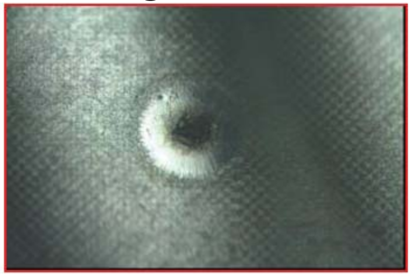


Group C, 10 samples, 0-100ppb

HTRB, Transition and forward bias testing

- The reliability is currently not determined by HTRB by Tj Reverse voltage resistance of diode in J-box similar to "By pass Diode Thermal Test(IEC61215) need to be considered
- The reverse current does experience increase by orders of magnitude with increasing temperature and needs to be considered. Reverse bias thermal runway due to transition and thermal cycling will be studied by working group 2.
- Elevated temperature combined with repeated power cycling could drive fatigue at the die attach.

Forward bias extended testing and issues such as fatigue, cracks in case, solder joints were observed and nee



- Reliability problems are rarely reported and rectifiers are very low on the Pareto analysis for returns
- Schottky diode failure is seldom due to wear out mechanisms.
- Several known quality problems in the manufacturing process exist
  ESD problems of up to 50kV (ESD remains the Nr 1 problem in the industry)
- A bigger source of problems than reliability concerns is latent defects introduced according to diode manufacturers.

Japan Task force #4

- Machine Model (M.M) for ESD
  MM should be applied to avoid ESD failure experienced during PV module manufacturing process and field installation. The diode in J-box should be evaluated by the reverse bias at high temperature in order to avoid the thermal runaway. Arrive at rationale to pursue most relevant tests under specific conditions.
- The diode in J-box should be evaluated by the reverse bias at high temperature in order to avoid the thermal runaway.
- Consideration of reverse bias withstand voltage of diode in J-box as for "Bypass Diode Thermal Test(IEC61215)".
- Report on recommendations and applicability to diodes and J-box testing.
- Arrive at rationale to pursue most relevant tests under specific conditions.

International PV Module Quality Assurance Forum

UV, temperature and humidity

Task-Force coordinated by

Michael Koehl, Fraunhofer ISE, Germany

Kusato Hirota, Vice-coordinator for Japan

Jasbir Bath, Vice-coordinator for USA

Golden, March 2012

Fraunhofer ISE

Needs and Approaches

- ☐ How much UV-stress should be expected under operation ?

⇒Different typical climatic locations

⇒Different typical installations (free, roof-top, BIPV)

⇒Different components (back-sheets, encapsulants, glazing)

- ☐ Are there degradation processes caused by combined UV and humidity?

⇒Collect info about observed failure mechanisms

⇒Find appropriate models for Accelerated Life Testing (ALT) procedures

Needs and Approaches

- What suitable artificial UV radiation sources are available for ALT?

⇒ Collect info about available equipment

⇒ Set-up procedure for the evaluation of spectral irradiation

⇒ Establish a procedure for qualification of the equipment

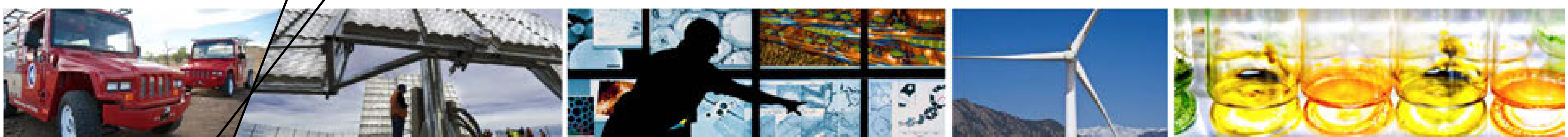
- Proposal for Accelerated Life Testing procedure

⇒ For testing components, model modules (when proven to be appropriate), complete modules

⇒ Combination humidity/UV or sequential testing ?

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

CIGS Material and Device Stability: A Processing Perspective



Kannan Ramanathan, NCPV

PV Module Reliability Workshop, March 1, 2012
Golden, Colorado

NREL/PR-5200-54569

CIGS landscape

- Multiple companies trying to get to high volume, low-cost manufacturing. Challenged to increase efficiency, control variability and ensure reliability. Efficiency bar is rising.
- Diverse approaches, cell designs. Different stages of maturity. Process details largely proprietary.
- Process control and understanding of ‘cause and effect’ still needed, desired.
- Precursor selenization/sulfurization and co-evaporation based processes have an edge.

Connecting the pieces

- Solar cell fabrication method, tool, process details
- Process to property correlation
- Cause and effect analysis of variability
- Performance improvement
- Device level changes and mitigation
- Packaging/ Protection of circuits
- Above pieces are connected, must work together to address stability issues.

Stability Topics

- Light soaking
- Post lamination loss
- Changes due to moisture ingress
- Reverse bias leakage
- Shunts
- Hot spots
- Weak diodes

Outline

- CIGS Material Properties: Basics
- CIGS Devices: Basic features
- Cell level changes
- Examples of previous work
- What do we need to measure? Interpret? Improve?

CIGS(S) Absorber

- Quaternary and pentenary alloys derived from base compound $CuInSe_2$. Band gap is increased by alloying with Ga and/or S.
- Band gap may not be uniform across the depth of the film, often graded.
- Phase purity and stoichiometry are important to control.
- Single crystal/ epi knowledge base is weak.
- Adequate working knowledge of physical and electronic properties, bear great resemblance to II-VI 'parents'.

Absorber: desired properties, process

- **Durable metal contact to the p-side (Mo)**
  - Minimally reactive, ohmic contact stabilized by $MoSe_2$.
  - Needs proper process conditions to be the best
- **P-type absorber**
  - Doping by native defects (close compensation)
  - Some elements enhance p-type doping (Na, Sb)
  - Higher temperature growth preferred
  - Chalcogen rich growth preferred
  - Crystal quality = efficiency (stability?)

Absorber: Electrical

- $CuInSe_2$ can be n- or p-type
- Thin films are p-type when grown Cu-poor in Se-rich conditions.
- With Ga and Na included, p-type is likely stabilized.
- If grown in Se-poor conditions, material can be high resistivity p-type or even n-type (more compensation, low lifetime).
- Electrical properties are a sensitive function of the growth method, tool, recipe.
- No direct measure of absorber's electrical properties!

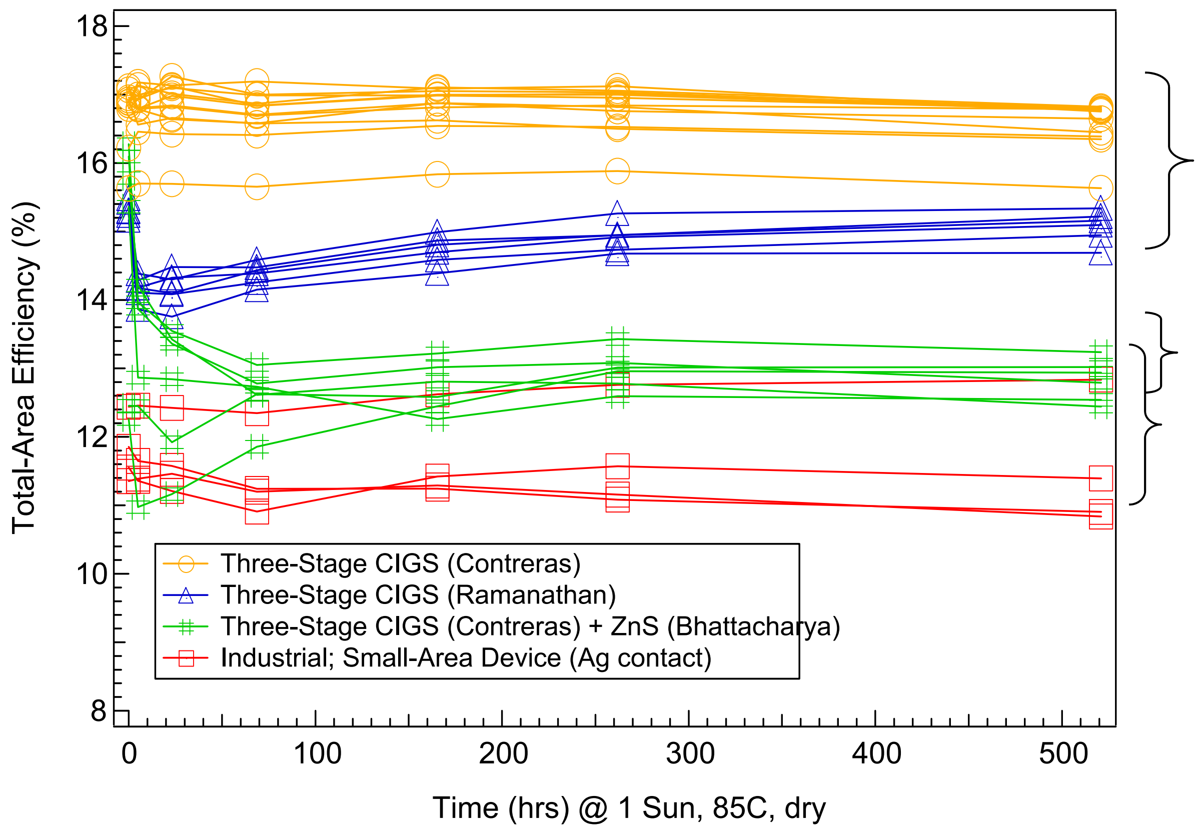
Junction

- Chemically grown CdS layers form the n-type emitter. Preferred junction partner.
- CBD bath induces change in electronic properties in addition to the growth of a compatible “buffer layer”
- Alternative emitter layers (ZnOS, In_2S_3) promising, come with unique characteristics.
- ZnO conductivity can degrade upon carrier compensation.

Device stability/ Metastability

- **1992: Siemens Solar asked for help in understanding "transient effects"**
  - Device properties changed dramatically when exposed to light, voltage bias etc.
- **2012: Similar products in vogue, exhibit similar characteristics.**
- **Device characteristics are a function of how they are made. NREL ≠ Miasole ≠ Stion. Specifics of each device to be taken into account when solving cell/ module optimization.**

Prior NREL work: D. Albin



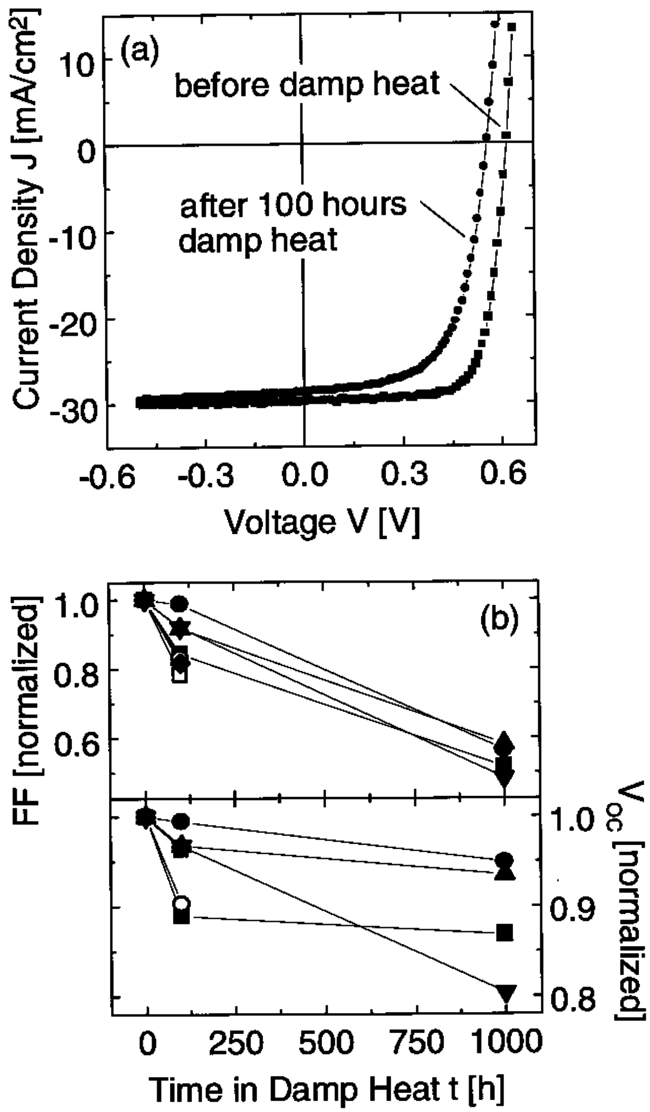
identical 3-stage process; yet very different transient recovery behavior; distinguishing difference = Mo

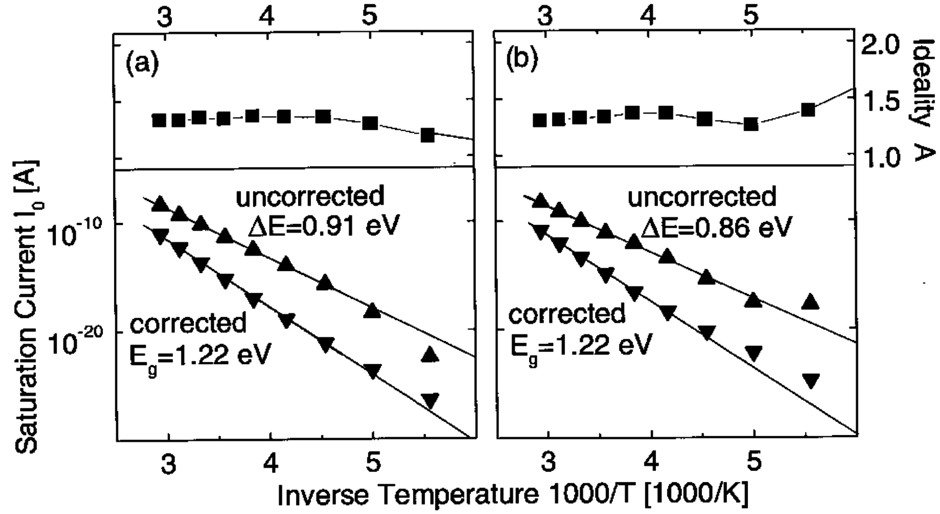
Modified "ZnS" junction; different characteristics on the same substrate

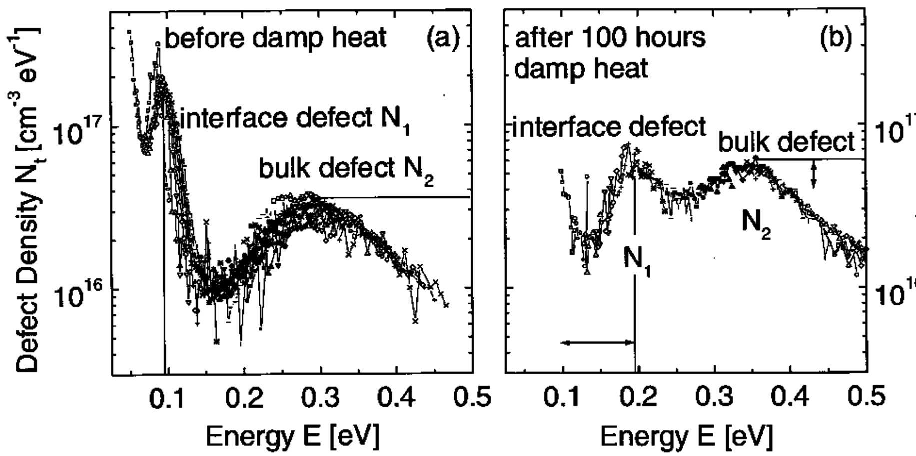
"industrial" samples showed biggest spread in light-soak behavior

All devices show attainment of a "stabilized" level

Cell in DH; no encapsulation







M. Schmidt et al. / Thin Solid Films 361±362 (2000) 283±287

PL of cells after damp heat exposure

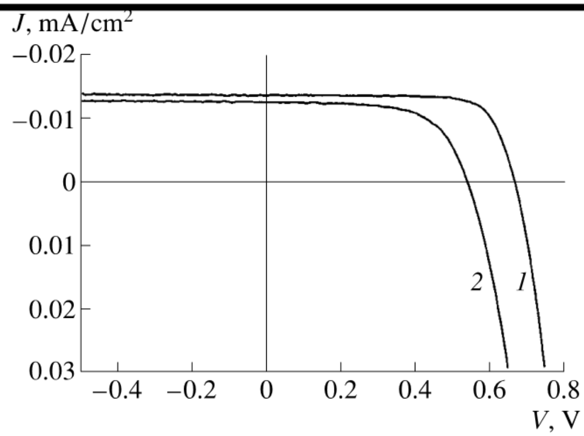


Fig. 1. Load characteristic of solar cells (*1*) prior to and (*2*) after treatment in a humid atmosphere at an elevated temperature. The measurement temperature $T = 25°C$.

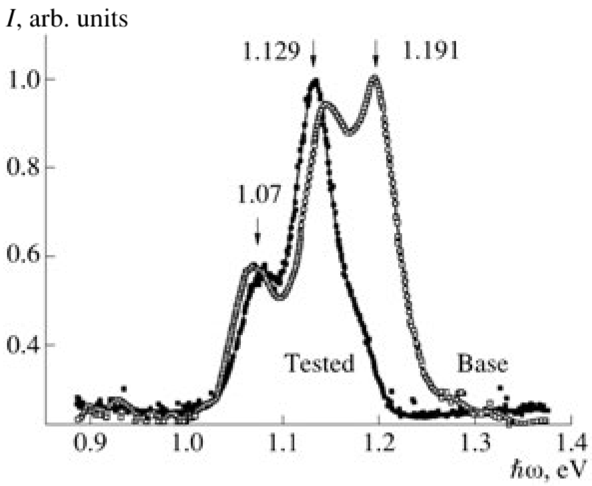


Fig. 2. PL spectra of CIGS solar cells prior to and after heating in humid atmosphere. The measurement temperature $T = 20$ K, the excitation wavelength $\lambda = 532$ nm, and the excitation power is 50 mW. Characteristic energies are given in eV.

DH effects:

- Decrease in absorber doping

(increase in defect level density)

- Increase in junction recombination

Light soaking: early Siemens cells

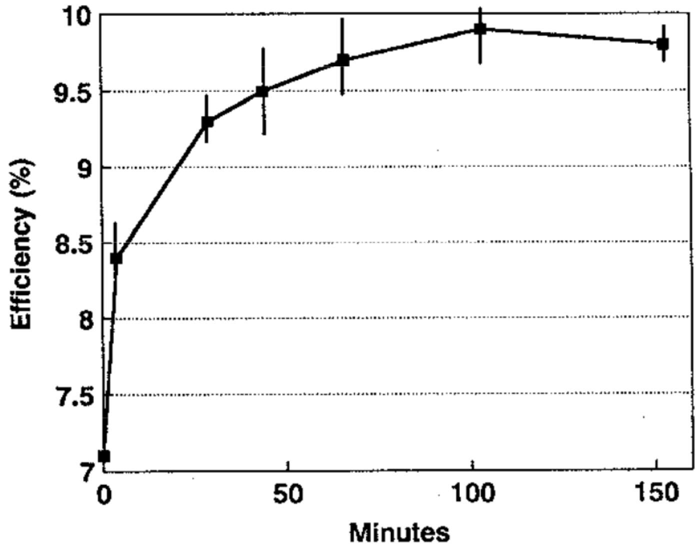


Fig. 6. Efficiency gains during light soaking by eight relatively poor CIS cells.

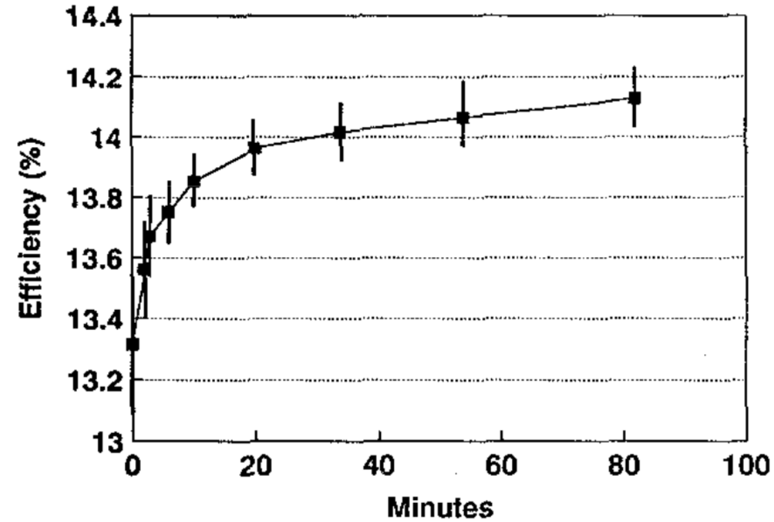
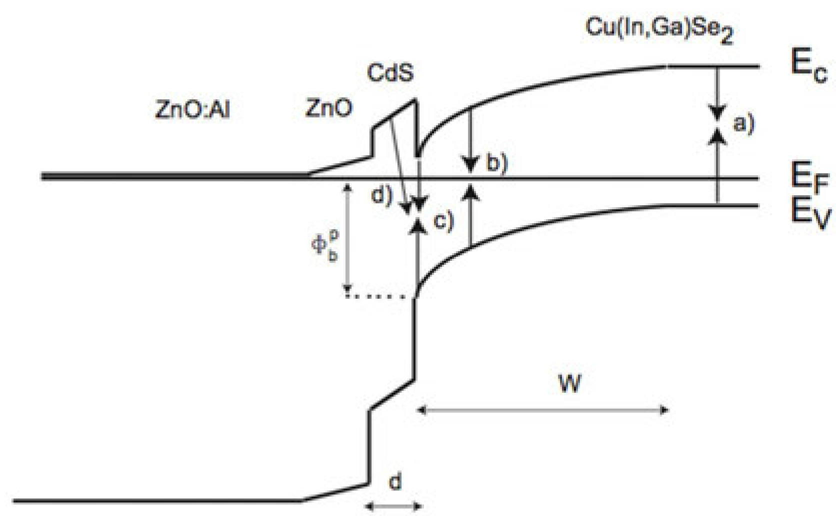
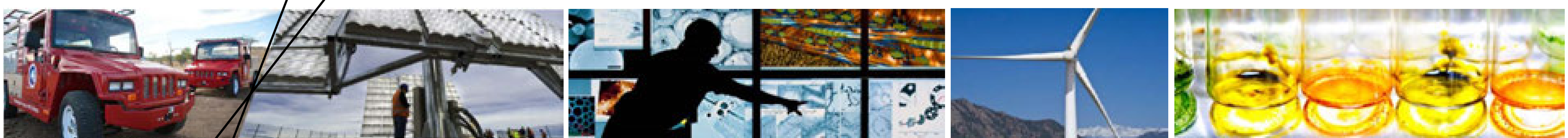


Fig. 7. Efficiency as a function of light soaking of 16 cells of high efficiency $CuInSe_2$ based materials.

D. Willett, IEEE PVSC, 1993

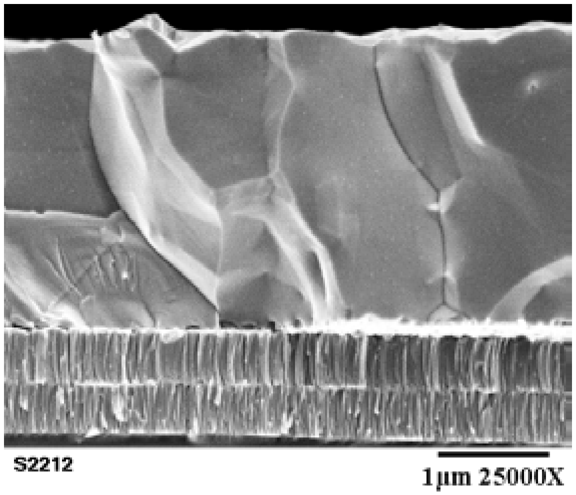


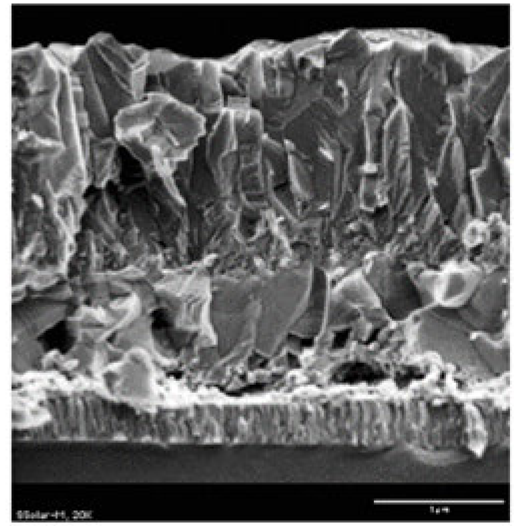


Process understanding/ quality improvement:

Case studies from past NREL work

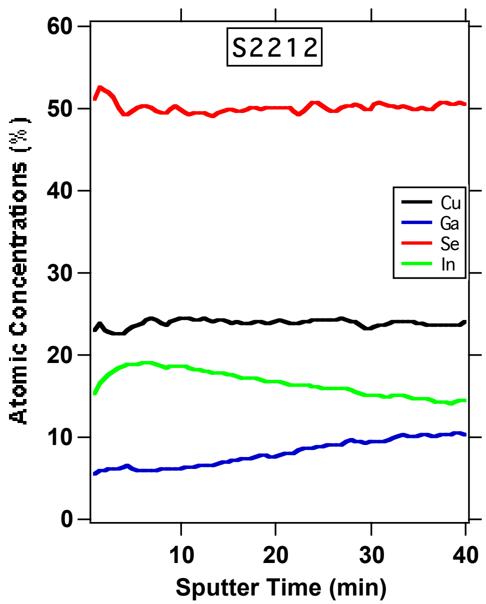
Comparison of NREL and SSI absorbers

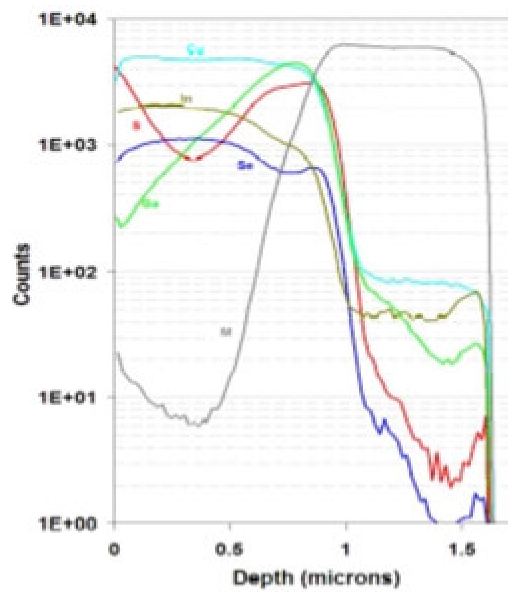




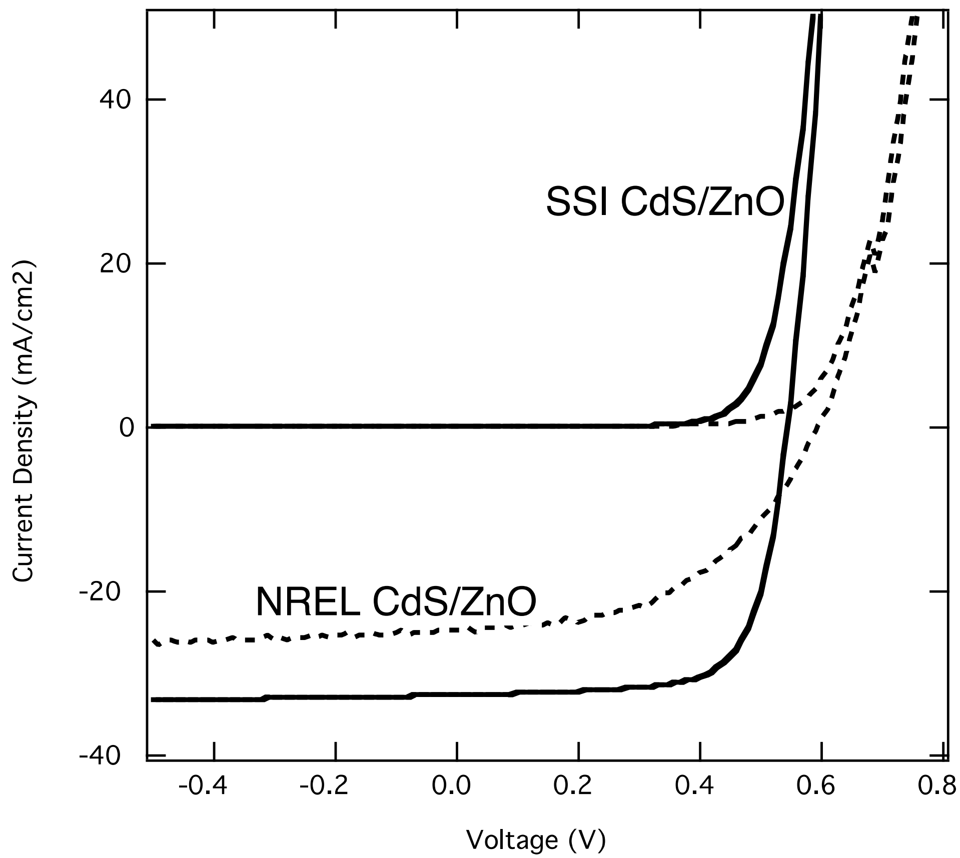
ZnO

CIGSS



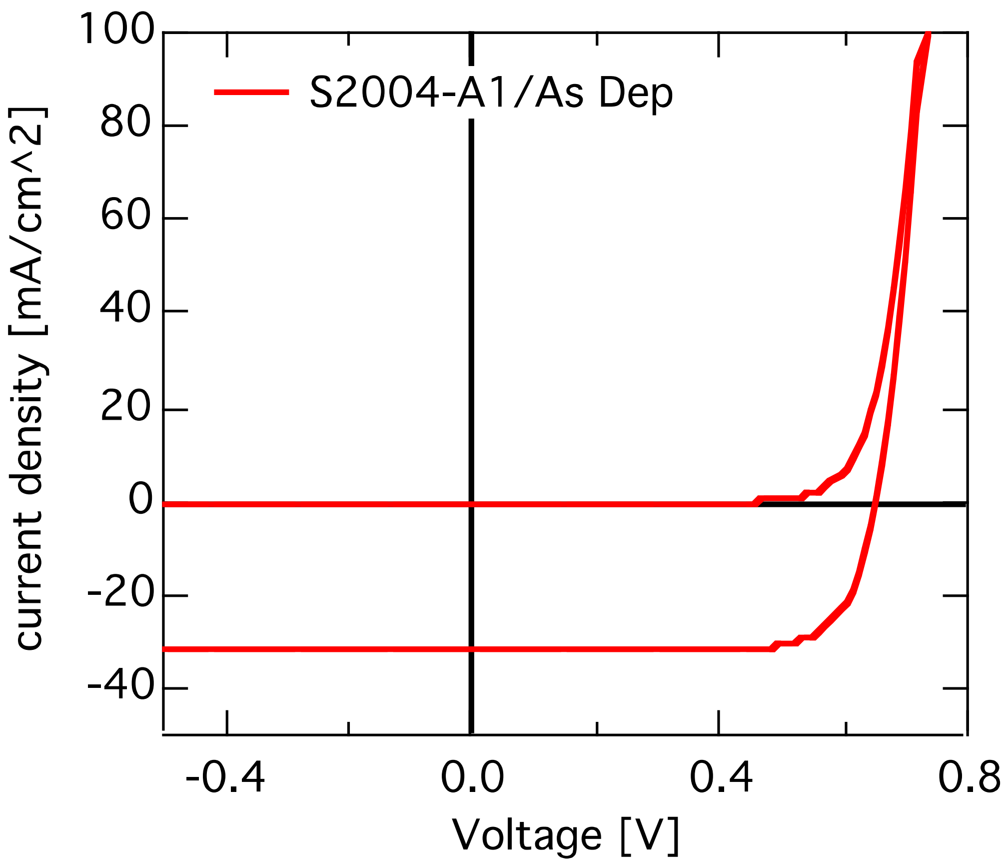


Example 1: SSI Absorber deviation



Common absorber
Lower performance with NREL CdS/ZnO
(not typical)

K. Ramanathan, CIS National Team, 2002

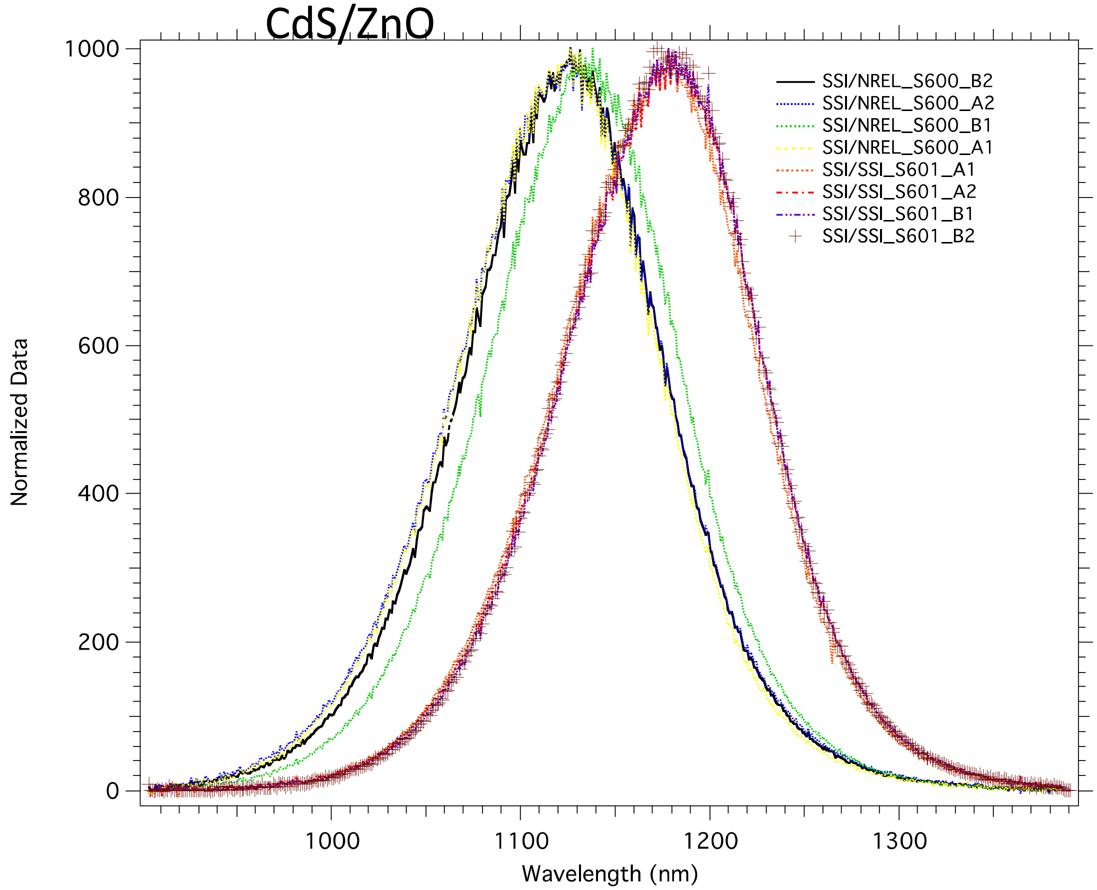


NREL absorber/ windows OK!

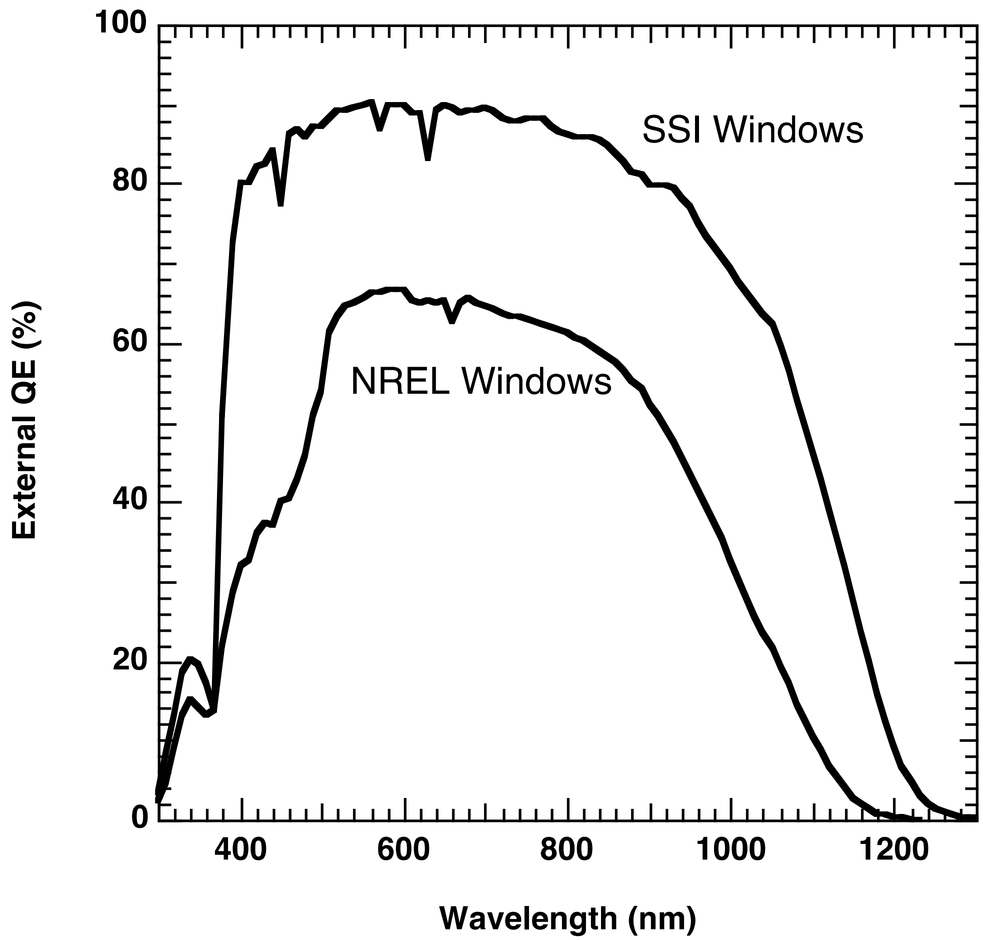
PL Spectra

NREL CdS/ZnO

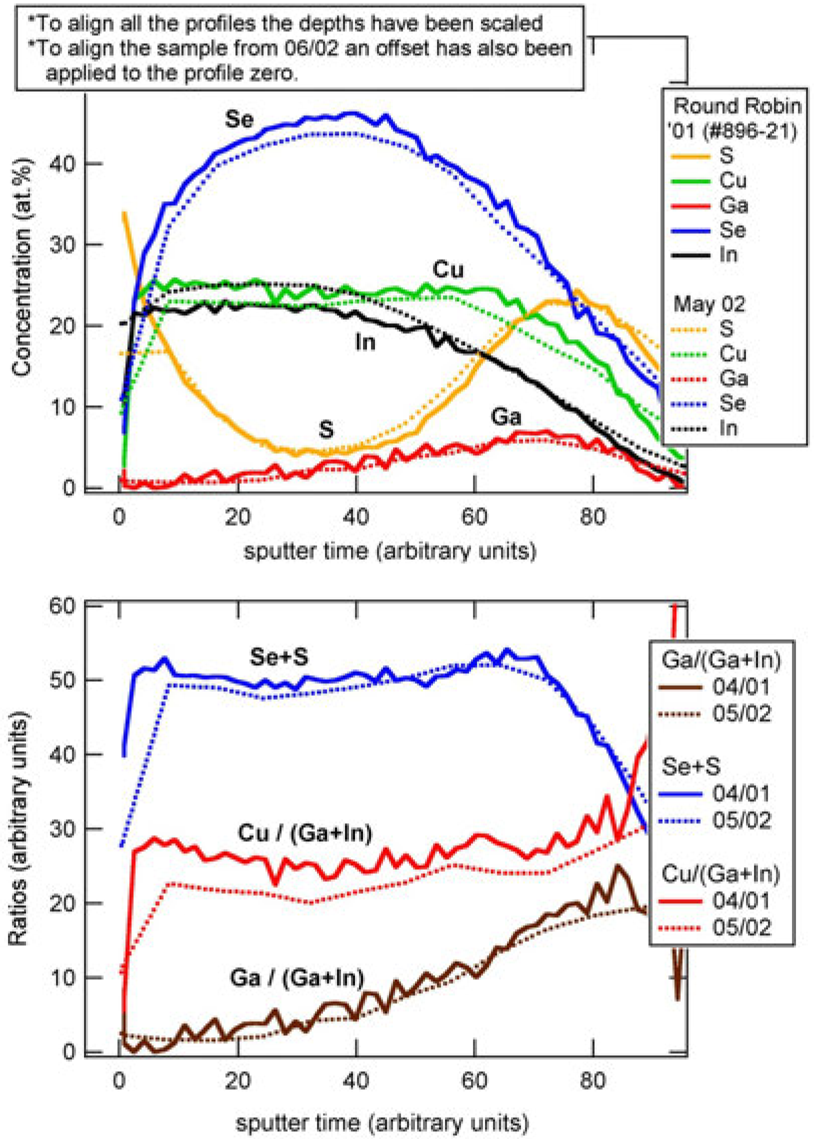
SSI CdS/ZnO



Quantum efficiency

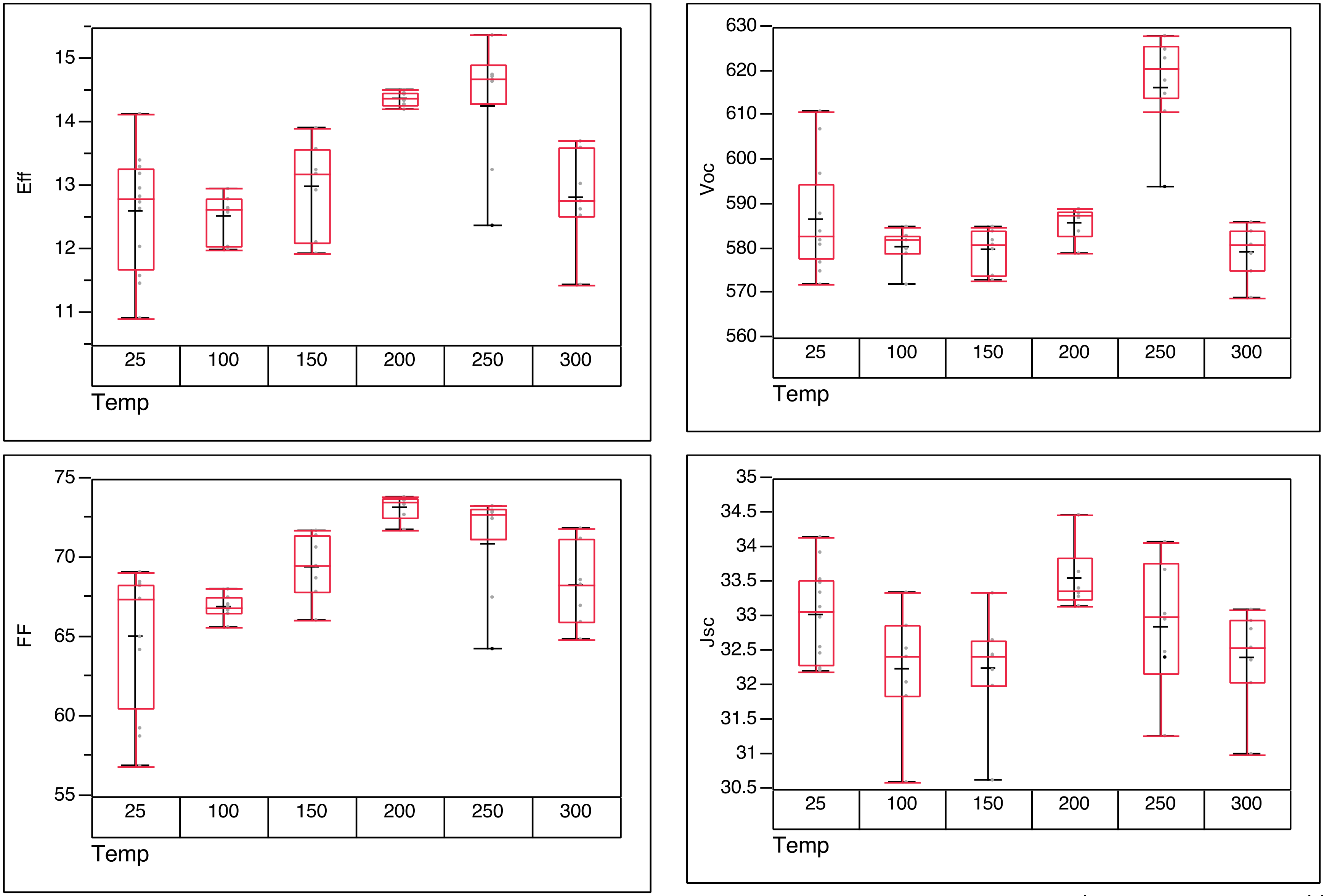


Compositional analysis



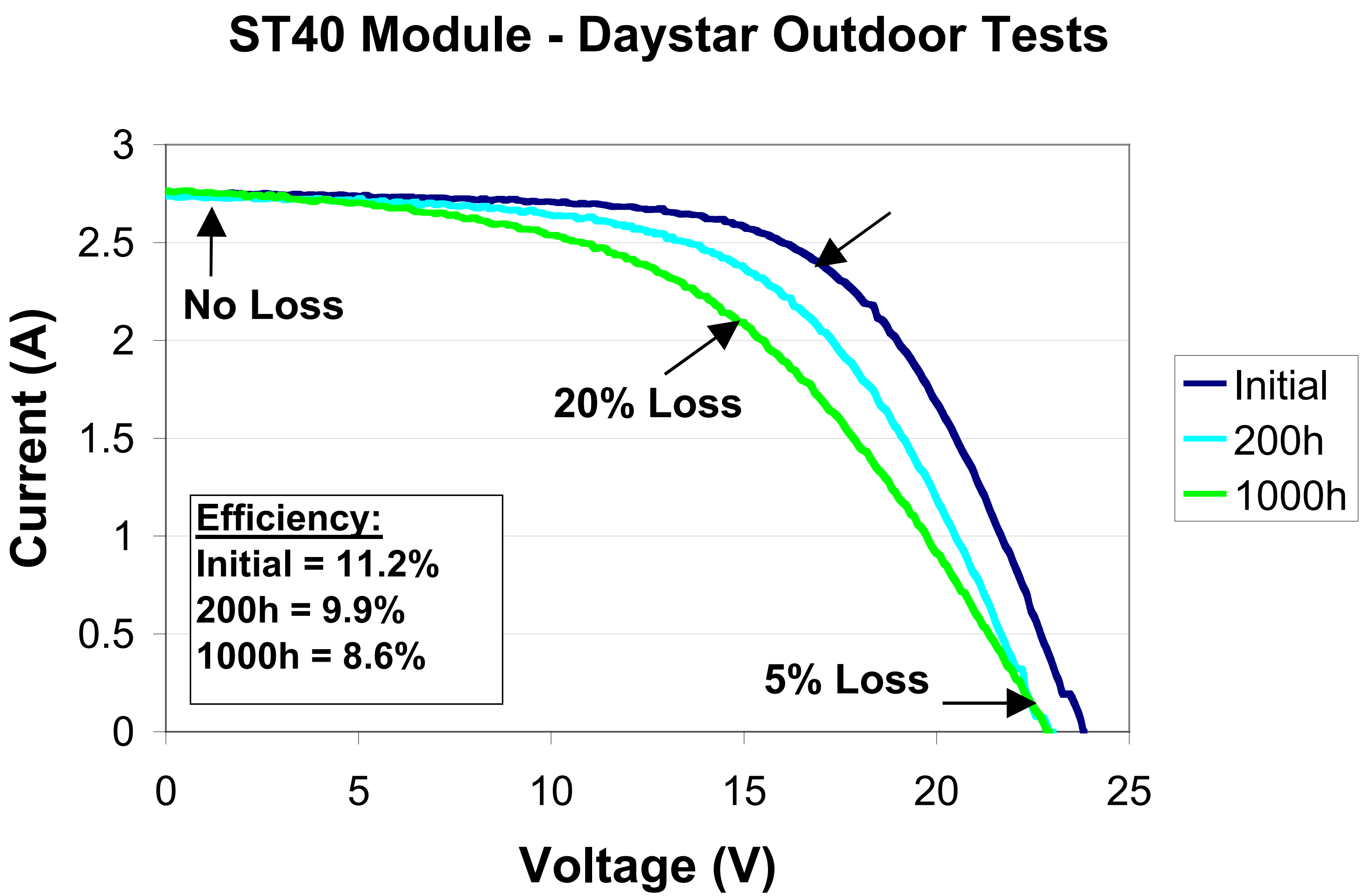
Revealed a large drop in the Cu ratio for the batch of absorbers.

Example 2: Junction anneal to improve performance



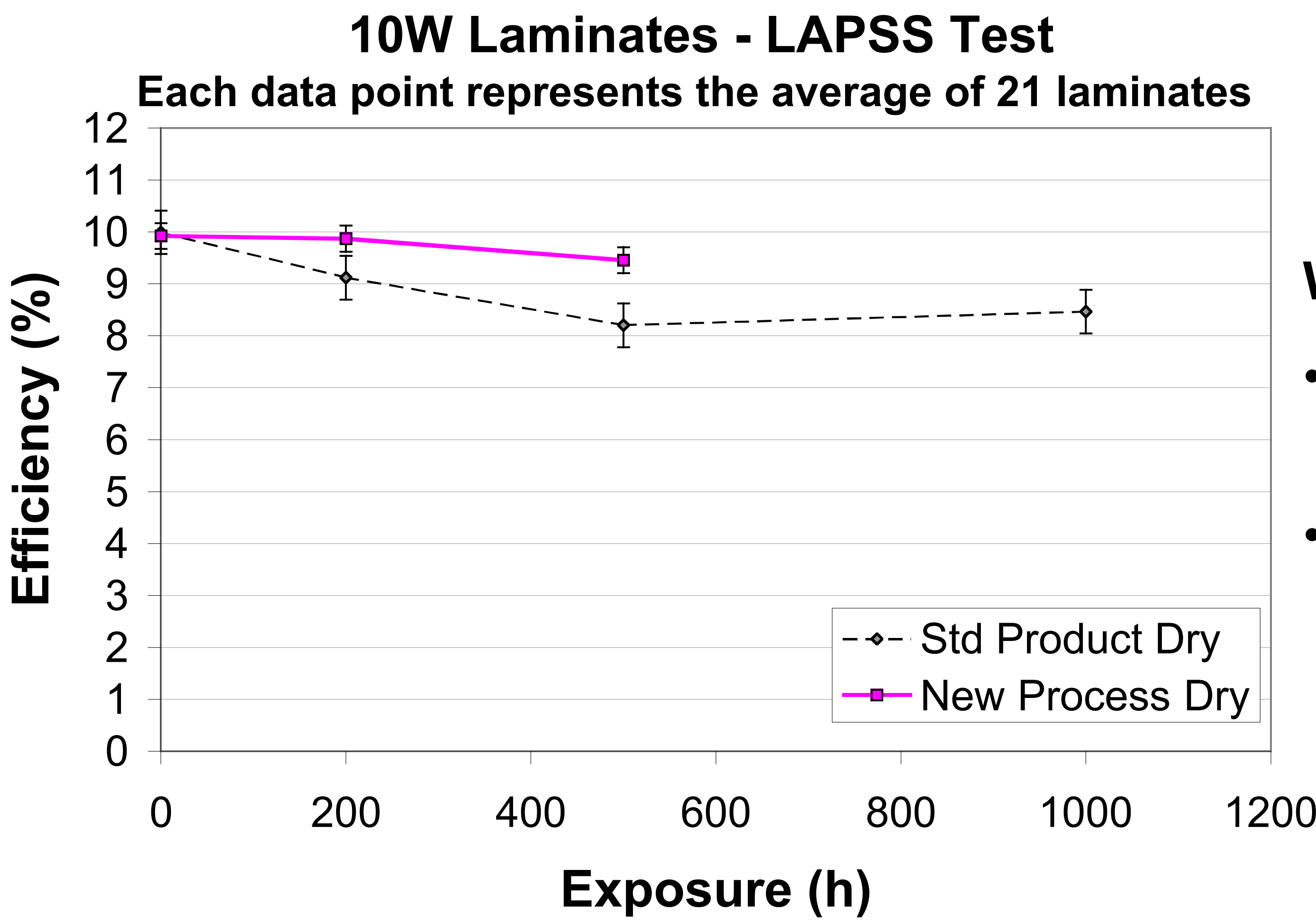
K. Ramanathan, NREL, 2002, unpublished

Thermal Degradation Characteristics



Modified Processing for Thermal Stability

Dry Heat Test Only



What was changed?

- **Increased CdS thickness**
- **Low CIG ratio**

Summary

- Proper encapsulation of CIGS devices can alleviate much of the moisture driven performance degradation.
- It is possible the high efficiency devices exhibit fewer metastable effects. Efficiency improvement efforts may pay off in stability.
- A case by case approach is needed to optimize devices for performance and long term stability.

Note added March 5, 2012

- Important questions were raised in the afternoon discussion session that call for clarifications and further work on how CIGS devices are affected by moisture.
- Siemens/ Shell Gen II arrays have demonstrated stable operation at the OTF.
- A recent NREL study of Shell's Eclipse 80 modules showed excellent stability and negligible effect of moisture because of improved packaging and edge seals. A paper that just appeared [Solar Energy Materials & Solar Cells 98 (2012) 398–403] showed that a new edge seal design enabled stable performance for 3000 h in damp heat.
- It is not possible to draw definitive conclusions about the moisture sensitivity of CIGS based on the available reports on unencapsulated cells.

Light Soaking Effects in Commercially Available CIS/CIGS Modules

Lawrence Dunn[1] and Michael Gostein

NREL PV Module Reliability Workshop, March 1, 2012

Non-Confidential Information

[1]lawrence.dunn@atonometrics.com

www.atonometrics.com

Background

- CIGS devices exhibit performance changes with continuous light exposure (a.k.a "light soaking")
  - For literature summary, see Ref. [1]
- Therefore, preconditioning protocols needed for performance rating in the lab / factory
- Understanding of metastabilities needed for analysis of field performance data

Ref. [1]: "Light Soaking Effects On Photovoltaic Modules: Overview and Literature Review", by M. Gostein and L. Dunn, presented at the 37th IEEE PVSC, Seattle WA, 2011.

Project Overview

- Objectives
  - Investigate CIGS performance changes with light soaking and dark relaxation
  - Demonstrate useful preconditioning protocols
  - Simulate effects of day/night cycles
- Experiment
  - Tests conducted on three commercially available CIGS modules from different manufacturers
  - Used Atonometrics Continuous Solar Simulator with integrated I-V system

Questions We Want To Answer

- What level of performance change can be seen upon light exposure for commercially available CIGS modules?
- How long must modules be exposed to light to stabilize?
- What effects may be seen outdoors with diurnal light/dark exposure?
- How quickly do modules relax in the dark?
- What are the implications for module performance rating protocols? In the lab? Outdoors?

Experimental Apparatus

Module Loading

Integrated I-V System

Atonometrics Continuous Solar Simulator & Light Soaking Chamber

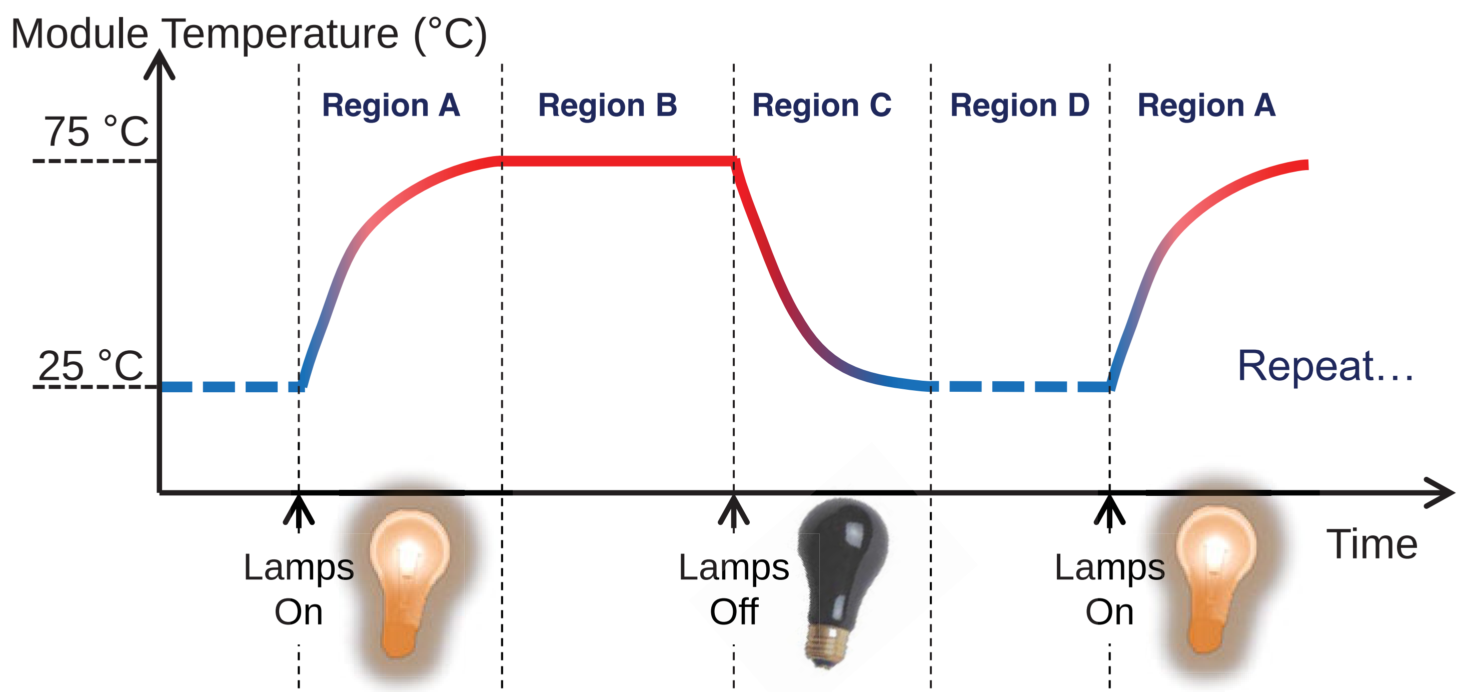
ATONOMETRICS

Experiment Details

- Tests performed using 3 different CIGS modules
  - Commercially available products
- All data corrected for light intensity and temperature to STC.
- Tests carried out at 1000 W/m^2
- Modules kept at MPP with periodic I-V curves taken.

- Future plans: explore module behavior with Voc and Isc tracking.

Test Recipe Diagram



Light Intensity	**1 sun**		**Dark**		**Repeat…**
I-V	**MPP with periodic I-V**		**None**		
Time	**<30 min**	**2-8 hrs**	**<30 min**	**1-16 hrs**	

Dunn and Gostein, NREL 2012 PVMRW

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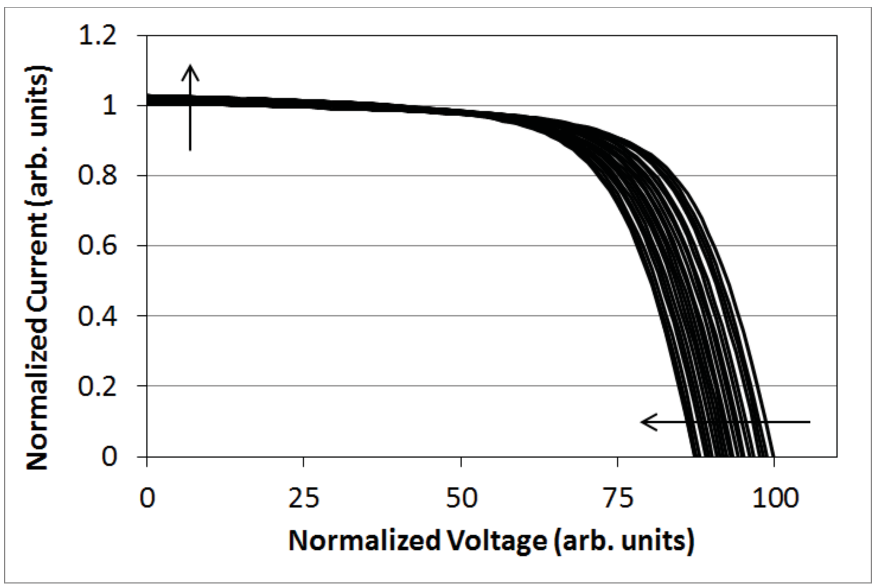
Test 1 Details

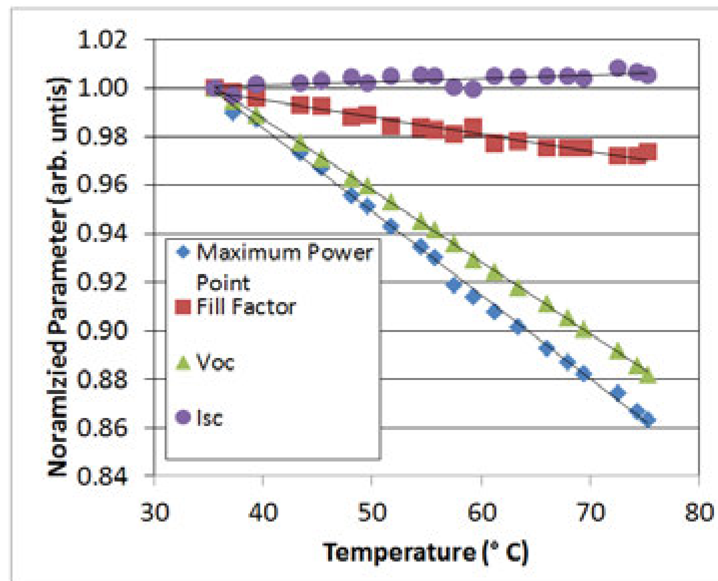
- Modules stabilized ~30 days in the dark prior to test
- Test Details:
  - Each cycle = 8 hours of light + 16 hours dark.
  - 16 day test (*i.e.*, 16 light/dark cycles)
  - Intensity: 1000 W/m^2
    - Measured using NREL-calibrated c-Si reference device
  - Module Temperature held at 75 °C after warmup
- Temperature coeffs. measured during module warmup.
- All I-V curves corrected to 25 °C and 1000 W/m^2.

Temperature Coefficient Extraction

- Temp. coeffs. extracted during module warmup
- Used temp. coeffs. to correct subsequent data to STC

Representative Temperature Coefficient Extraction Data for Module #3





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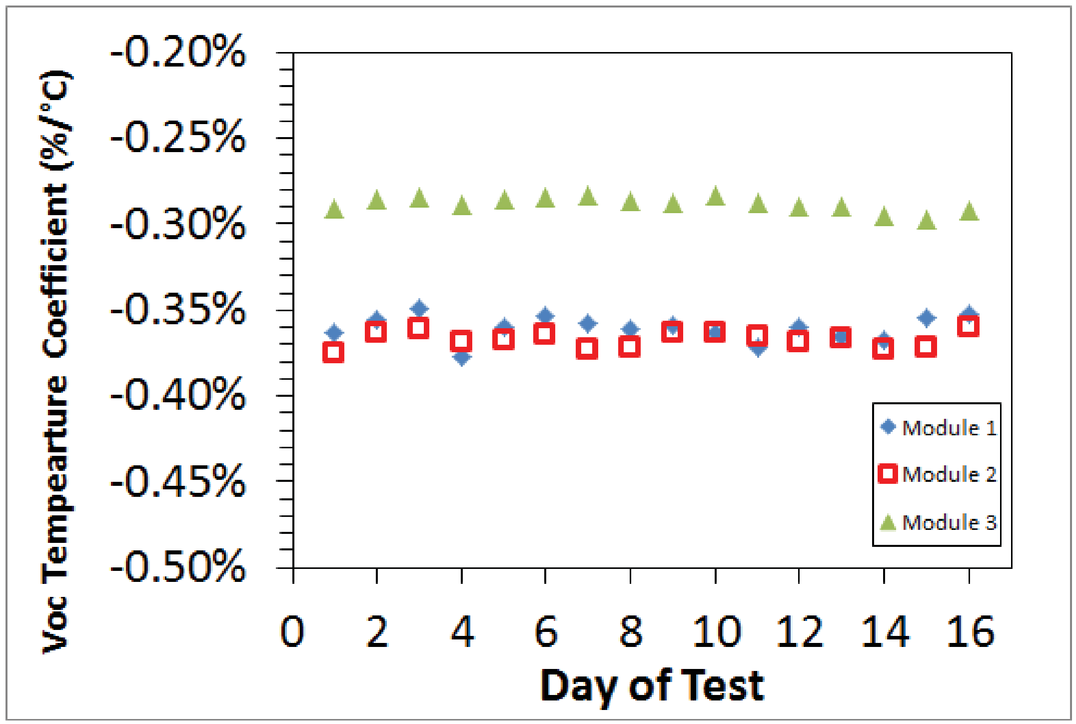
Dunn and Gostein, NREL 2012 PVMRW

Compiled Voc Temperature Coefficients

- Extracted temperature coefficients were repeatable for multiple test cycles
- Temperature coefficients appeared stable for duration of test



ATONOMETRICS

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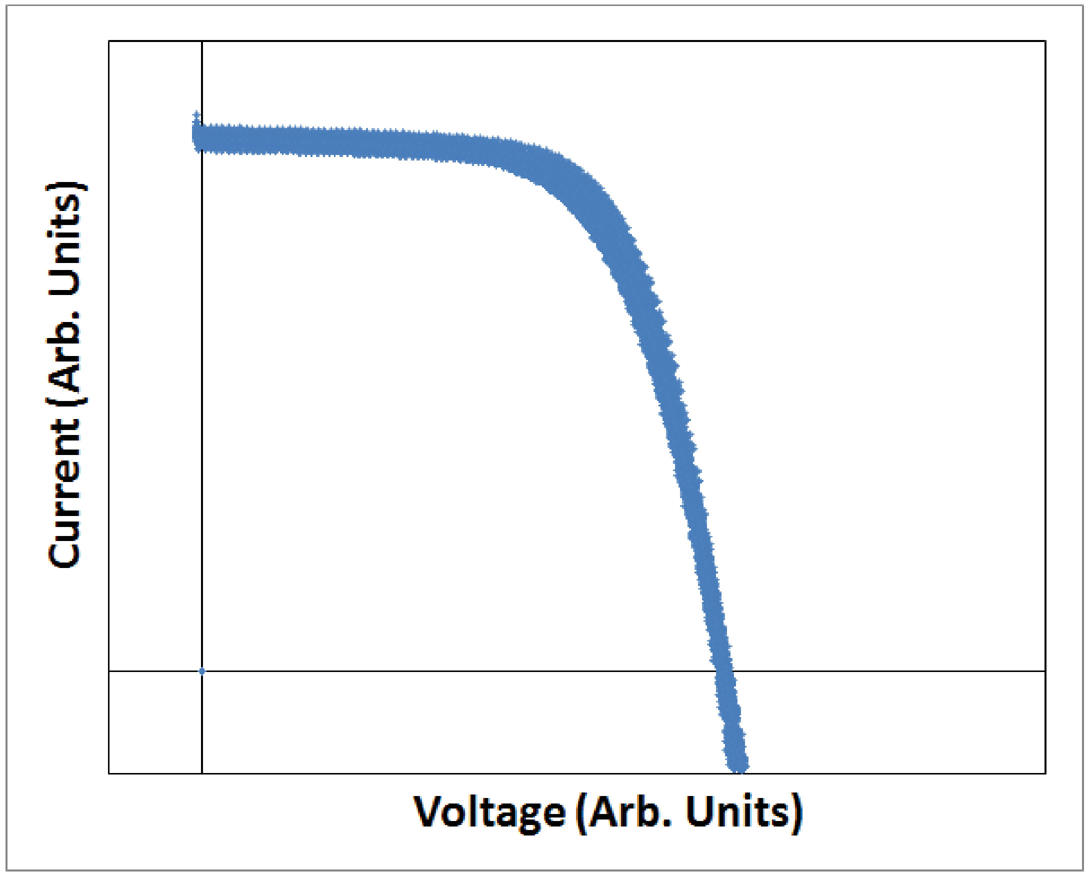
I-V Curve Correction to STC

- All I-V curves corrected for temperature and irradiance to 25 °C and 1000 W/m^2.

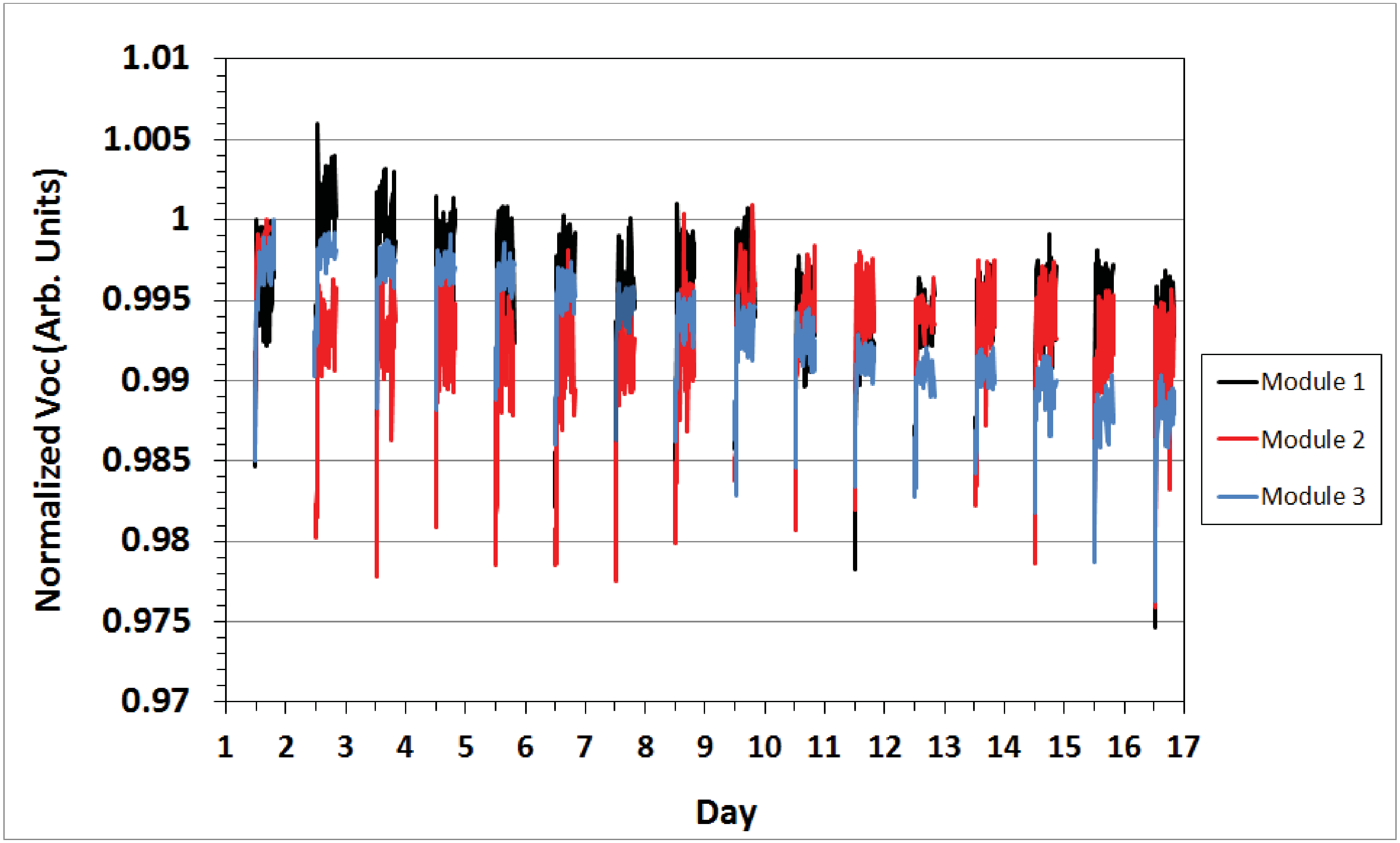
~1000 Representative I-V Curves for Module #1



Dunn and Gostein, NREL 2012 PVMRW

ATONOMETRICS

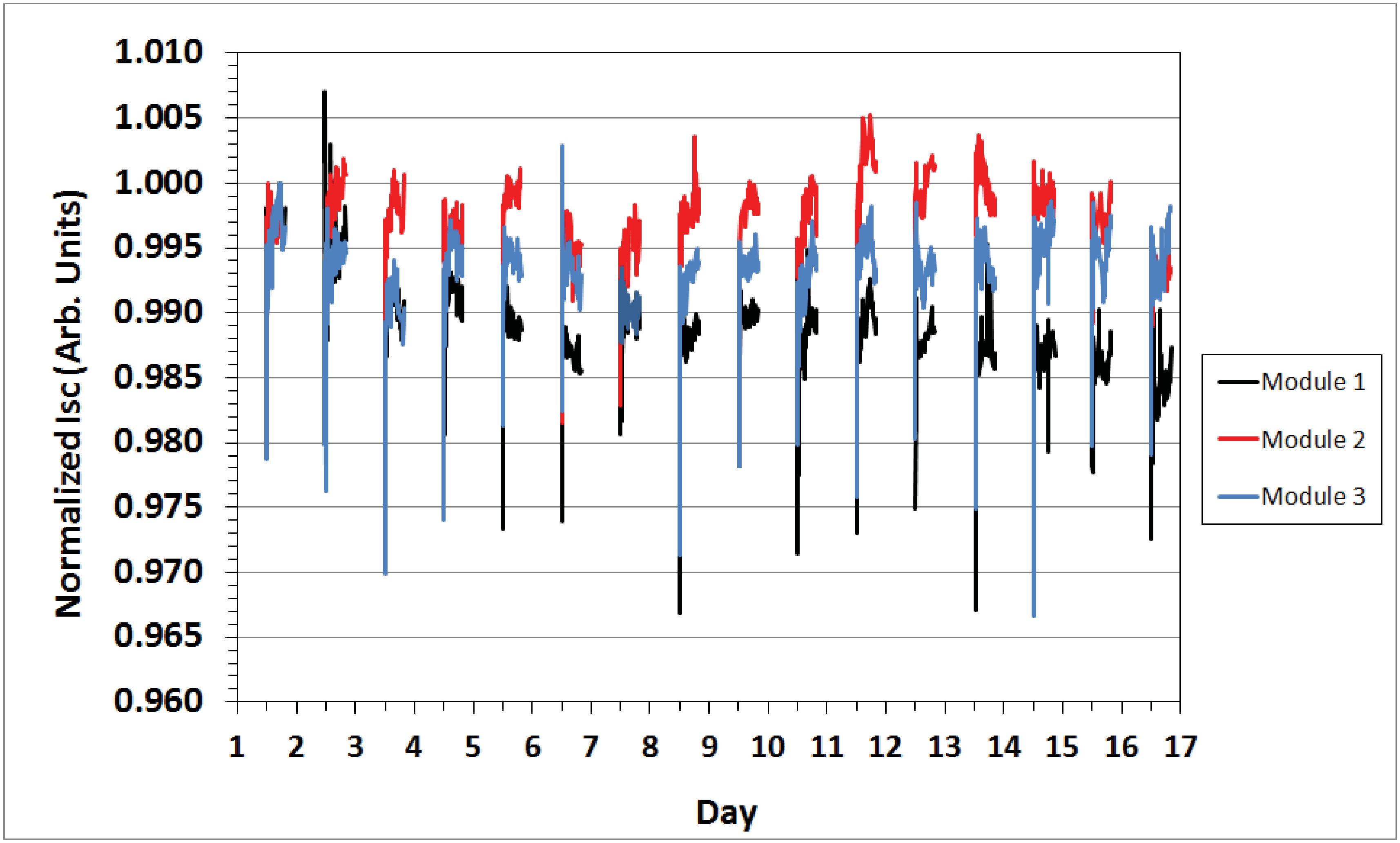
Test 1 Results: Normalized Voc



ATONOMETRICS

Dunn and Gostein, NREL 2012 PVMRW

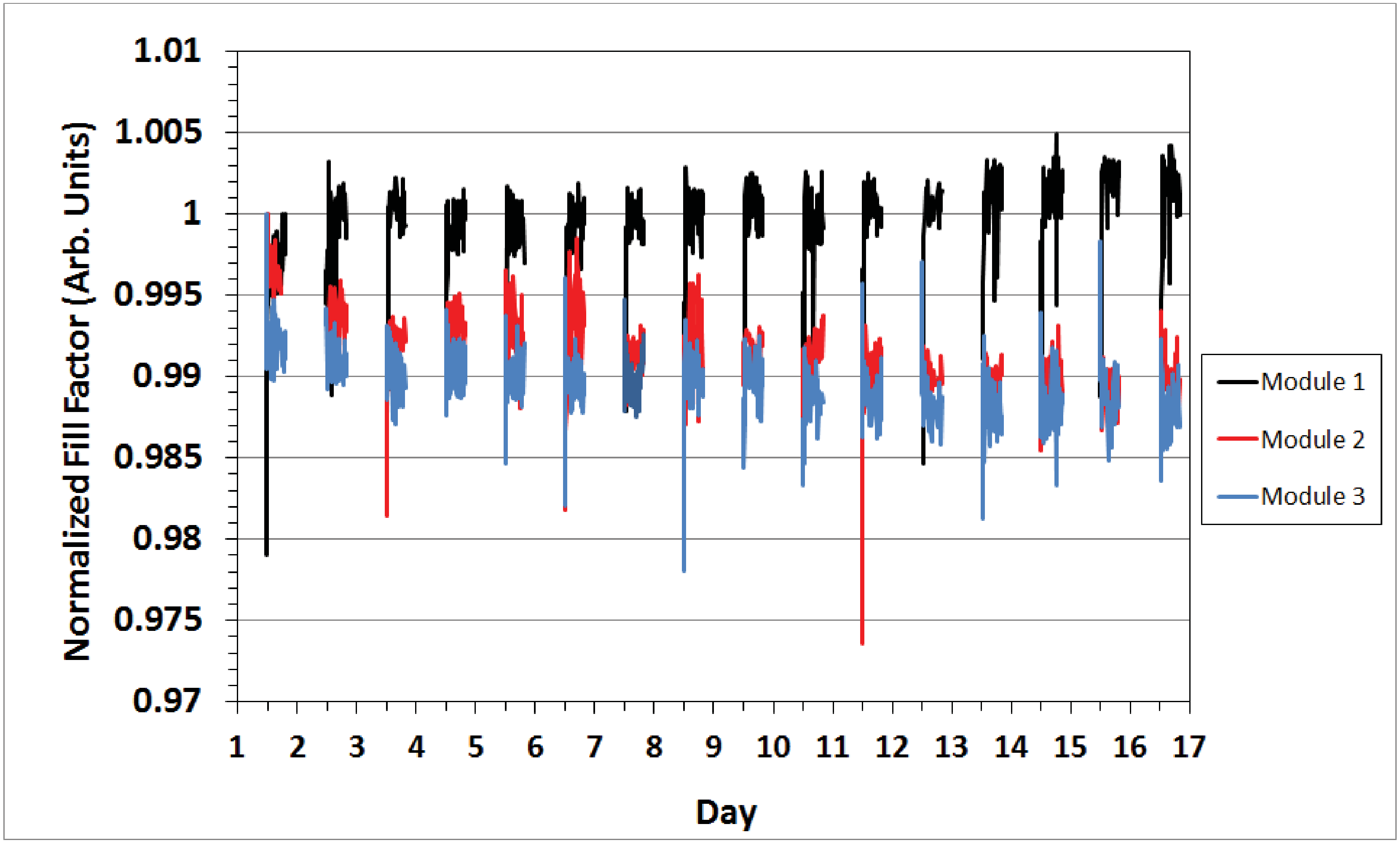
Test 1 Results: Normalized Isc



ATONOMETRICS

Dunn and Gostein, NREL 2012 PVMRW

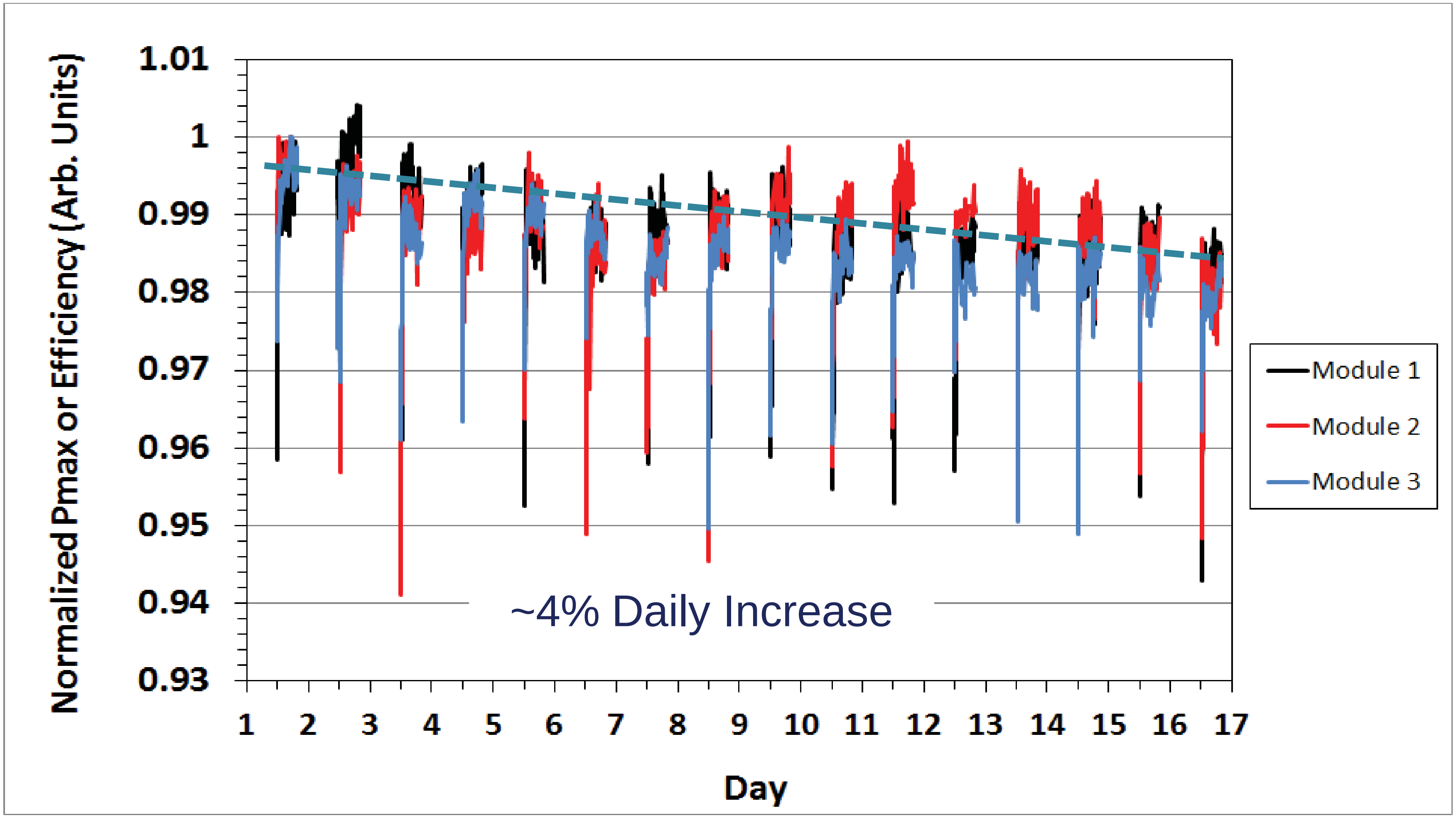
Test 1 Results: Normalized FF



ATONOMETRICS

Dunn and Gostein, NREL 2012 PVMRW

Test 1 Results: Normalized Efficiency



ATONOMETRICS

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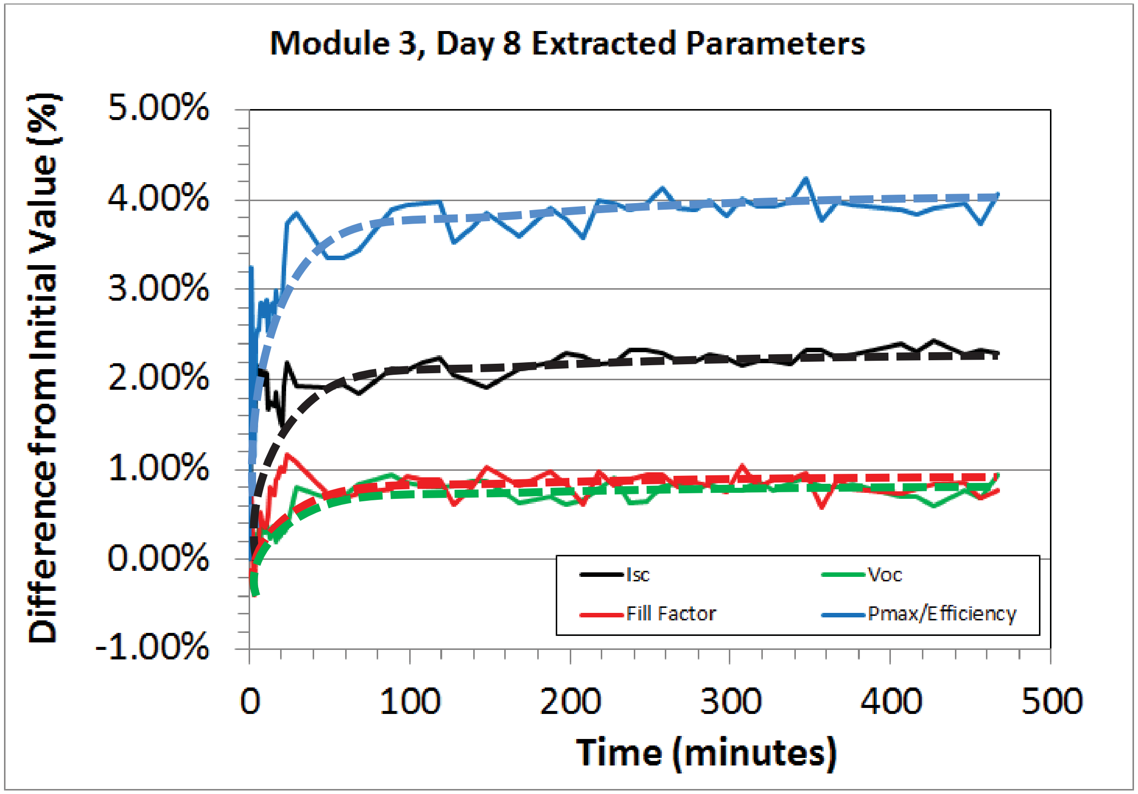
What is happening on a shorter time scale?



- Trends
  - FF -> FF * 1.01
  - Isc -> Isc * 1.02
  - Voc -> Voc * 1.01
  - Pmax -> Pmax * 1.04

ATONOMETRICS

Test 1 Conclusions

- All 3 module types seemed to undergo an approximately 3%-5% relative increase in efficiency within one hour of light exposure.
- Modules seemed to fully relax during 16 hours in the dark.
- After 16 days the modules had experienced an approximately 1%-2% loss in stabilized efficiency from their initial value.

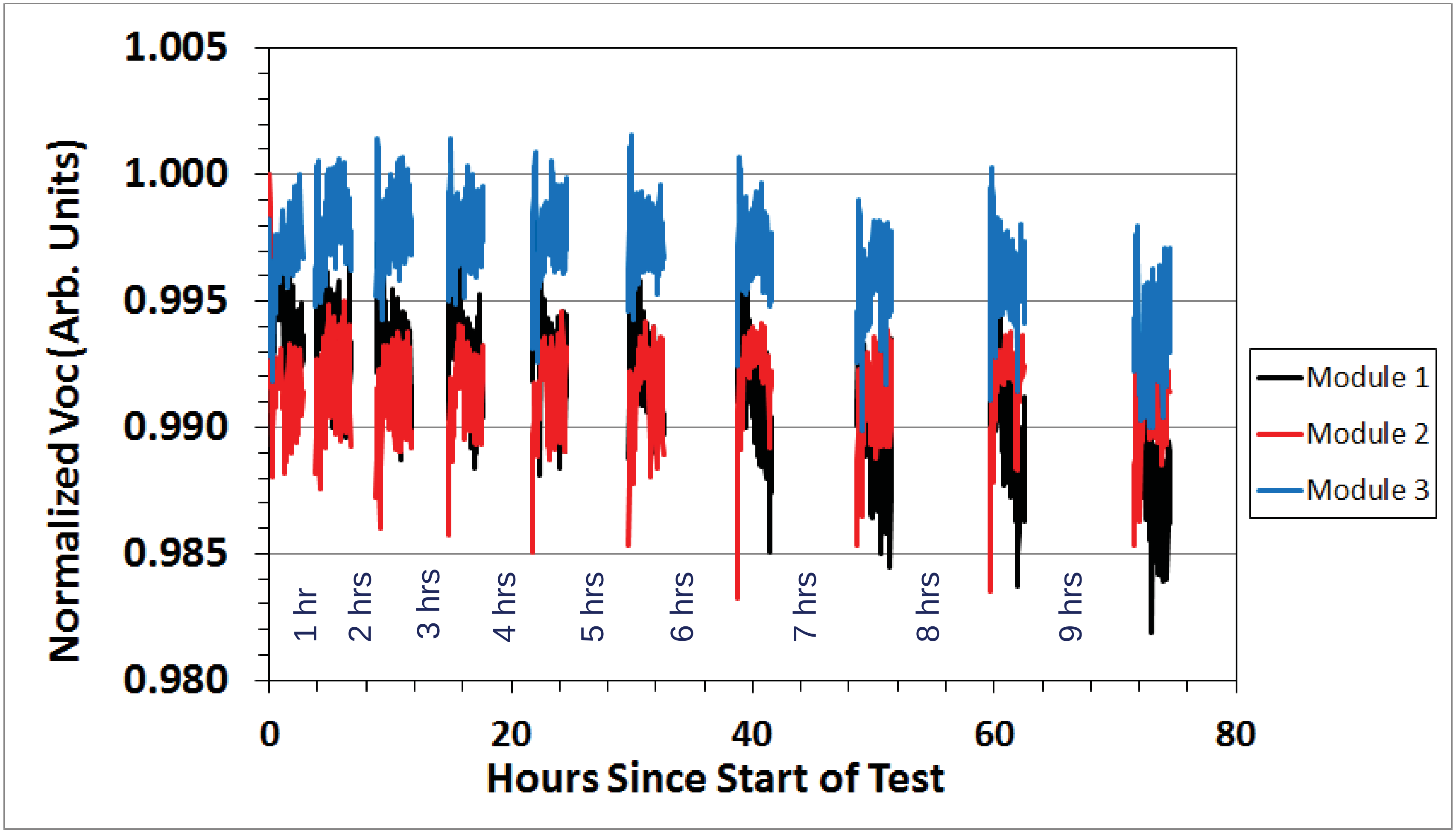
Test 1 Questions Raised

- After preconditioning, how long can modules remain in the dark before needing to be preconditioned again?
- How many cycles needed for long-term stabilization?
- How would this phonemenon change with module temperature? Irradiance Intensity? Electrical bias condition? Etc.?
- Are we correctly quantifying the effect? Could we be missing something in our test methodology?

Test 2 Details

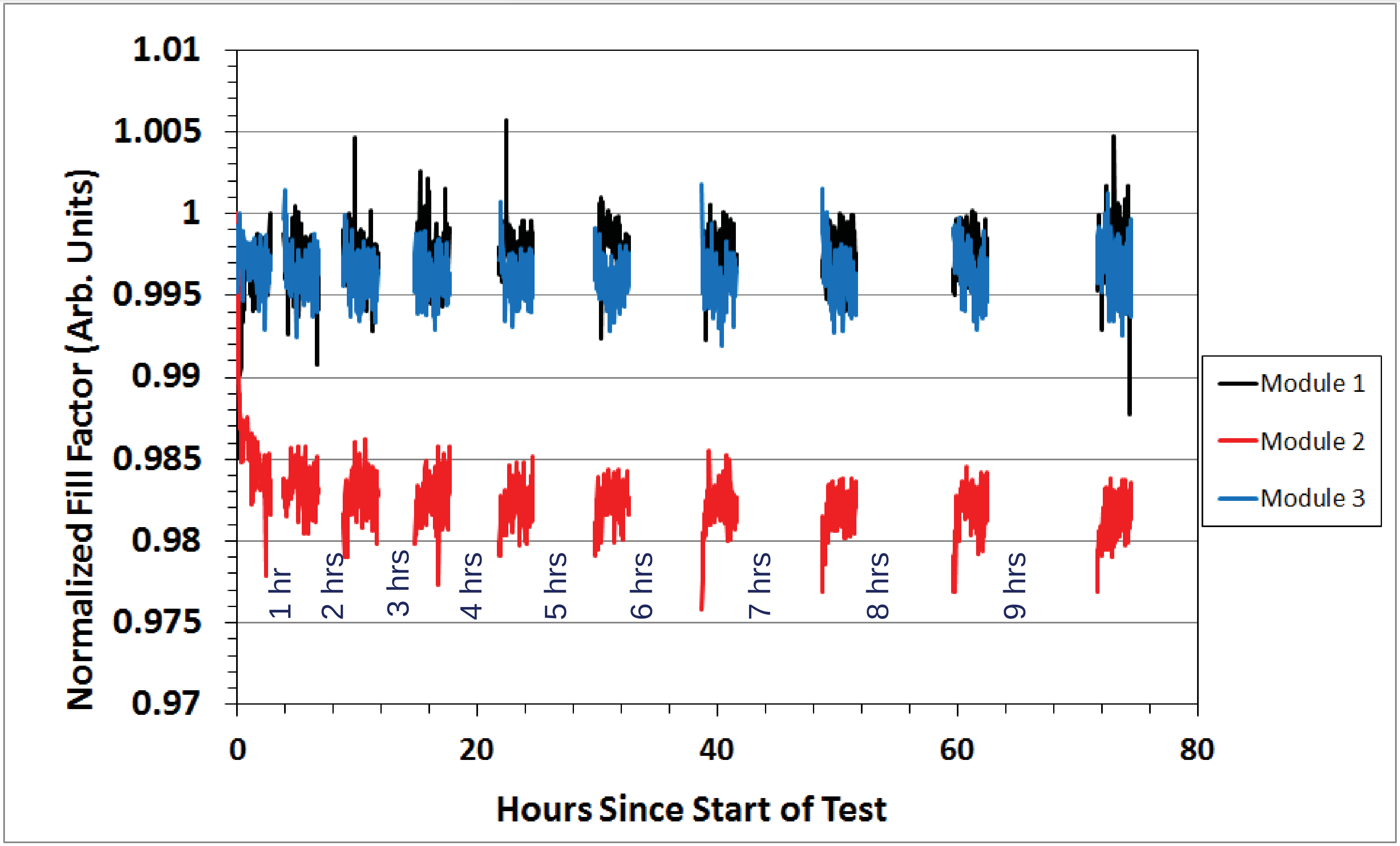
- Goal: Determine dark relaxation time
- Test Details:
  - Modules held in the dark 7 days prior to start
  - Each cycle: 2.5 hrs light exposure + variable time in the dark
    - 1 hour dark time, then 2 hours, etc., up to 9 hours
- All other details as in Test 1

Test 2: Normalized Voc



ATONOMETRICS

Test 2: Normalized FF



ATONOMETRICS

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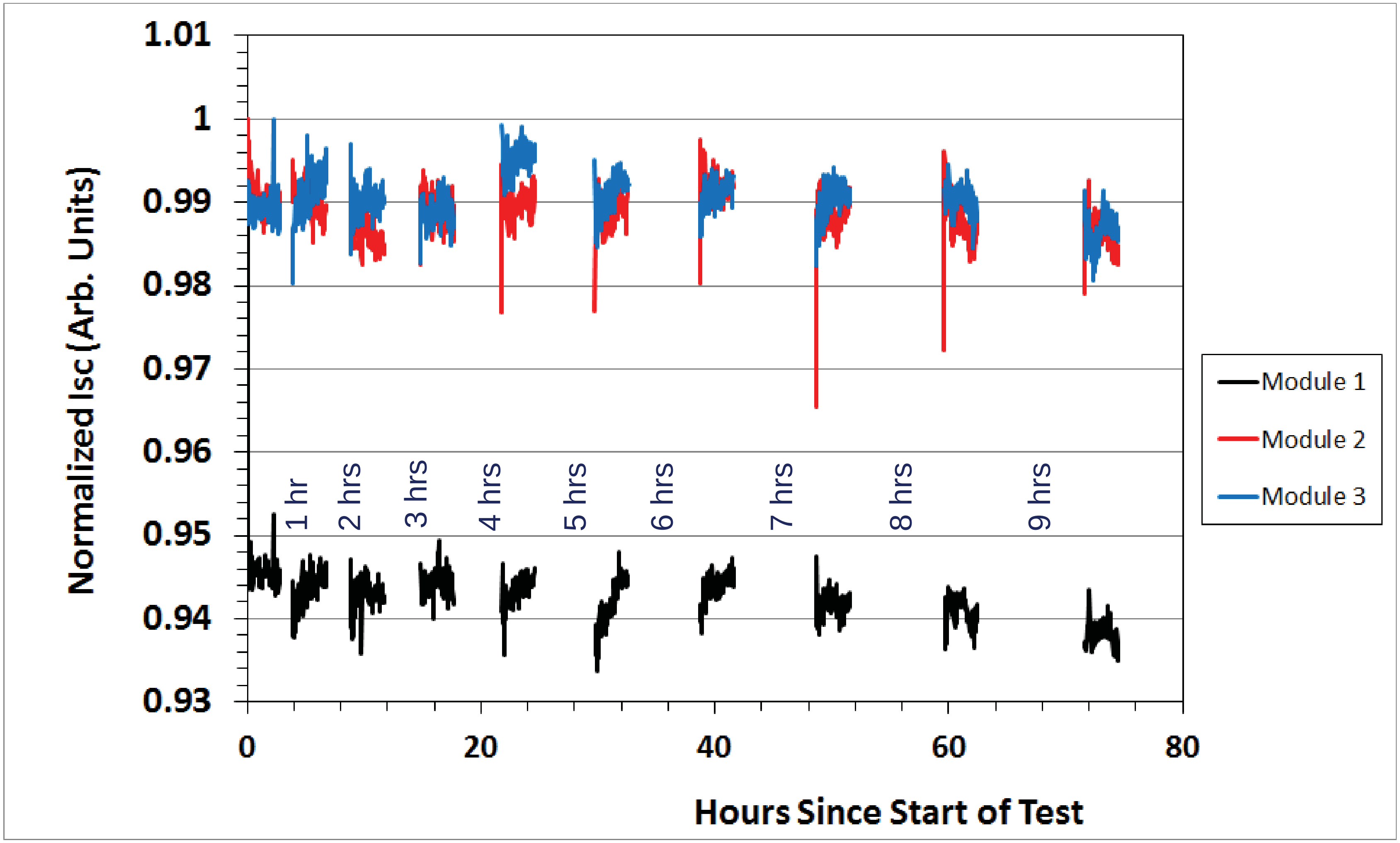
Test 2: Normalized Isc



ATONOMETRICS

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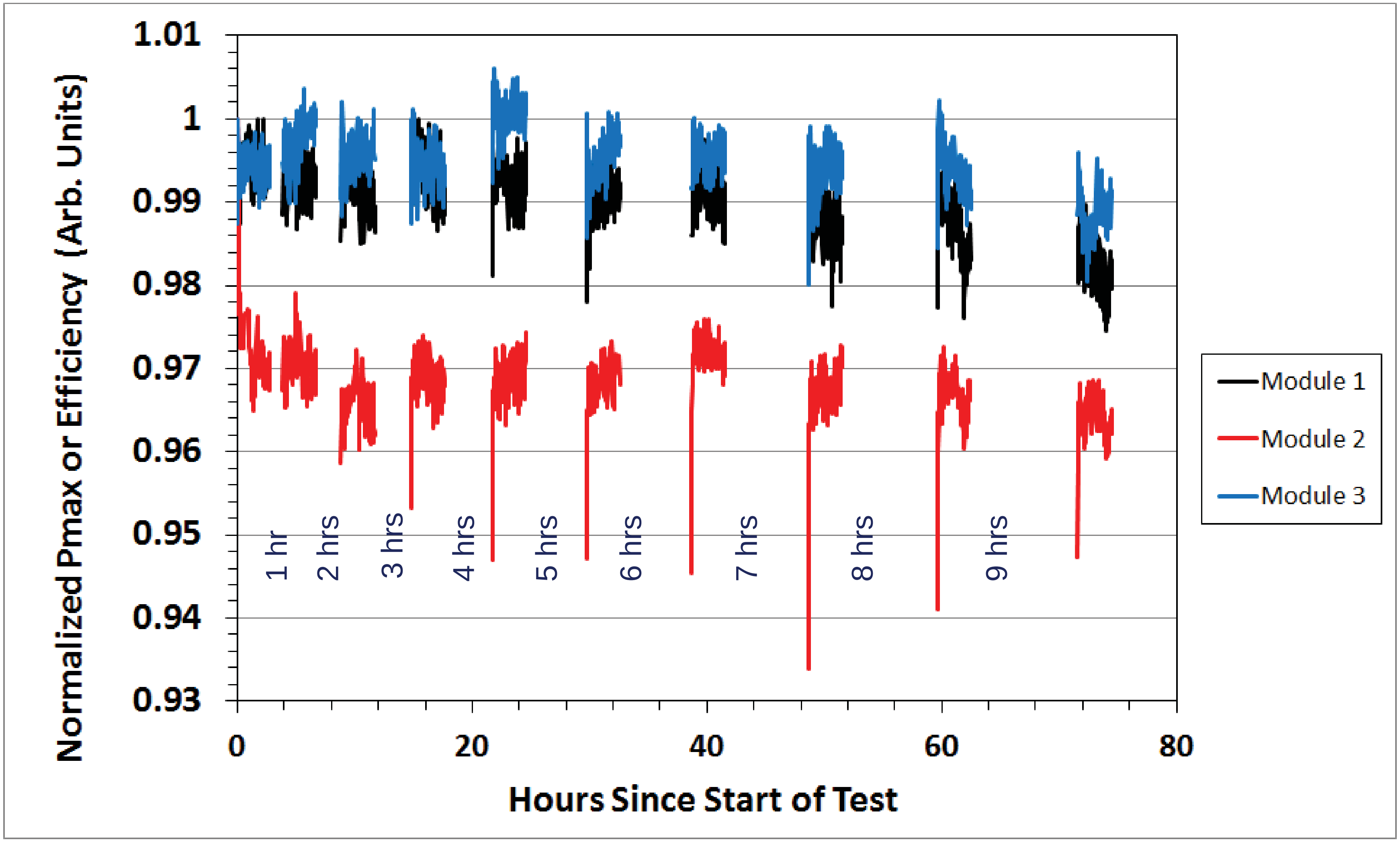
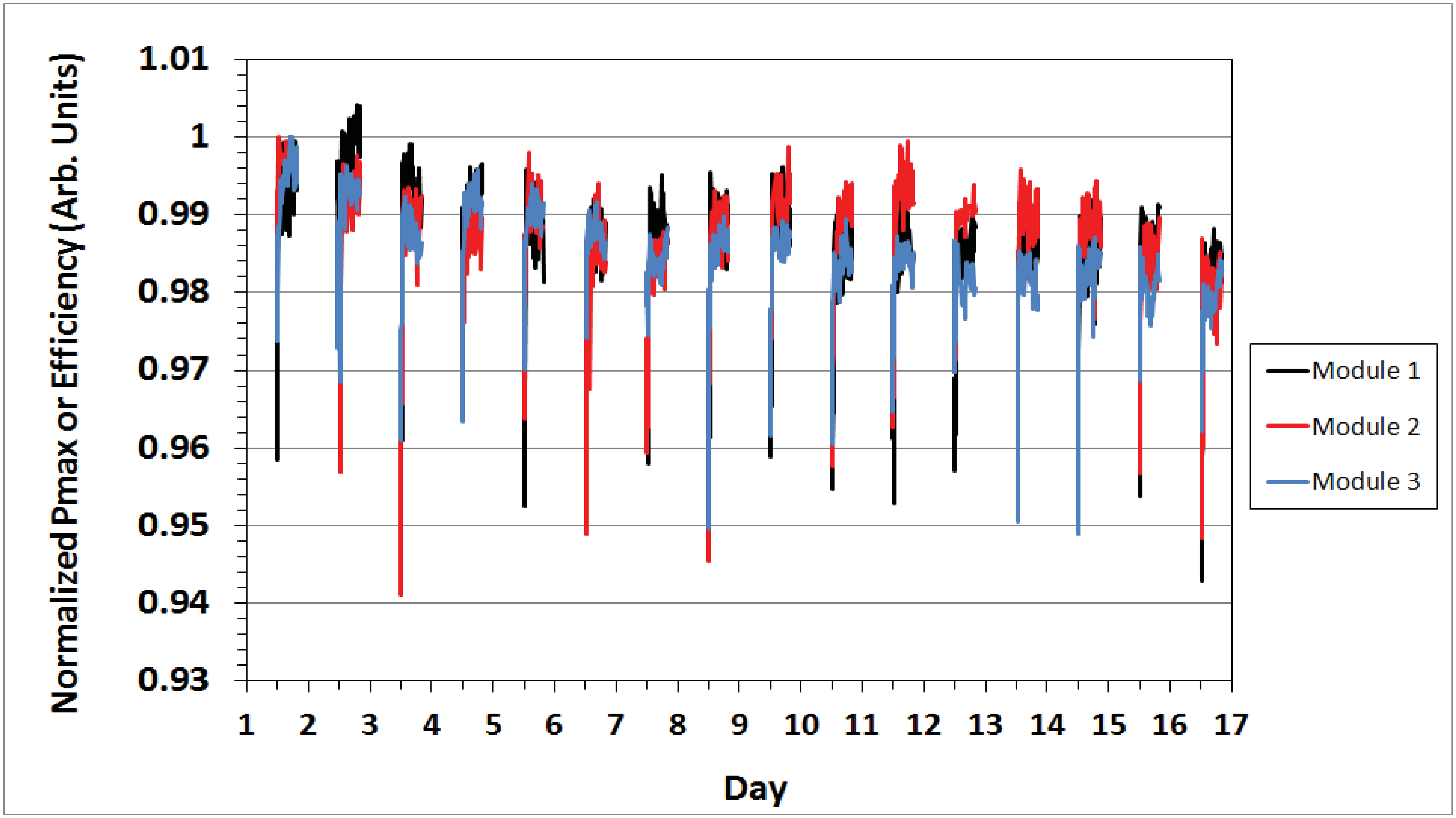
Test 2: Normalized Pmax/Efficiency



Dunn and Gostein, NREL 2012 PVMRW

Compare to Test 1 Results



ATONOMETRICS

Dunn and Gostein, NREL 2012 PVMRW

Test 2 Conclusions

- Module 2 appeared to fully relax after >3 hrs in the dark
- Modules 1 and 3 fully relaxed after 16 hours in the dark (from Test 1) but shorter time scale not definitively determined

Future Work

- Quantify preconditioning extent and time scale for different temperatures
- Investigate effect of different electrical bias conditions on preconditioning (and dark relaxation) behavior
- Repeat study with additional module types

ATONOMETRICS

We welcome questions, comments, and suggestions.

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Preconditioning of Thin-Film PV Modules Through Controlled Light-Soaking

Tony Sample
DG-JRC Ispra, Italy

Based in Ispra, northern Italy

Overview

General introduction to meta-stabilities in Thin-Film devices

- *Some examples of what has been observed in the literature*

Methods used to stabilize Thin-Film devices

- *Light-soaking according to IEC 61646 ed 2 (2008)*

Outline of light-soaking experiments with various Thin-Film modules

- *Modules used in the experiments*
- *Results*
- *Conclusions from the experiments*

Overall Conclusions

Amorphous Silicon, including Tandem, micromorph and triple junction

Exhibit a long-term meta-stable behaviour in which their maximum power decreases with light exposure but improves through thermal annealing, the Staebler-Wronski effect [1]

Micromorph silicon (a-Si/µ-Si) materials are also affected because they contain an amorphous layer, but it is more stable than single junction amorphous silicon [2,3]

All exhibit a slow decrease in power due to cold soaking and a much faster recovery through thermal annealing [2,3]

The impact of the different time constants is reflected in the observed seasonal variations [2-4]

[1] D. L. Staebler, C. R. Wronski, 1997
[2] J. A. del Cueto, and B. von Roedern 1999.
[3] M. Nikolaeva-Dimitrova et al 2010
[4] D.L. King et al 2000

Copper Indium Gallium (di)Selenide (CIGS)

CIGS modules are also subject to light-induced change of the module efficiency [5].

Not as clear behaviour pattern for CIGS

- *Some authors have shown that they may degrade [6, 7] with light exposure*
- *but in some cases it has been shown that they remain stable [7] or improve [8].*

The behaviour is very dependent on the deposition and exact material composition.

In general these modules exhibit a short-term meta-stable behaviour modulated by light and for this reason they have to be measured quickly following light exposure [8]

[5] A. G. Aberle, 2009
[6]. E. L. Meyer and E. E. van Dyk, 2003
[7] C. Radue et al 2009
[8] R. P. Kenny et al 2006

Cadmium Telluride (CdTe)

Early generation CdTe modules exhibited a long-term meta-stable behaviour but modules could either degrade or improve with light exposure [9]

However, recent modules have been shown a more uniform behaviour in that they tend to increase their maximum power with light exposure, especially following storage in the dark [9-11]

[9] J. A. del Cueto and B. von Roedern 2006
[10] First Solar, Inc. 2009.
[11] Z. Jingquan et al 2009

Methods used to stabilize Thin-Film devices

Some groups have experimented with the use of current injection to stabilize CIGS devices, in particular to overcome the very fast degradation on dark storage. However, this approach will not be detailed here.

Light-soaking according to IEC 61646 ed 2 (2008) [12]

Stabilization occurs when measurements from two consecutive periods of at least $43kWh/m^2$ each integrated over periods when the temperature is between 40°C and 60°C, meet the following criteria:

$$(P_{max} - P_{min}) / P_{average} < 2\%$$

[12] IEC 61646 2008

Light-soaking apparatus

Large climatically controlled chamber containing a class BBB solar simulator (on the limit for spectral match CBB)

Irradiance: 850-870 W/m²

Duration per period ~48 Hours

Module temperature 45-55°C

- Stability better than ±2°C

Operation under resistive load

Module P_{max} determined on class AAA simulator at 25°C

Power measurements

The IV characteristics are measured by sweeping the device from I_{sc} to V_{oc} using a SpectroLab X25 LAPSS has a light pulse of 2 ms duration with a flat irradiance of 1000 W/m^2.

- Measured IV characteristics according to IEC 60904-1. It is noted that this standard may be applicable to multi-junction test specimens, if each sub-junction generates the same amount of current as it would under the reference AM1,5 spectrum in IEC 60904-3.
- It is assumed that the spectral mismatch between the various modules and the reference cell remains constant throughout the repeated light exposures.
- It is also assumed that the limiting junction of the multi-junction devices does not switch due to light-soaking when measured using the solar simulator

Relative uncertainties of

I_{sc} ±1.3%, V_{oc} ±0.3%, FF ±0.72%, P_{max} ±1.5% [13]

[13] H. Muellejans et al 2009

Modules used in the study

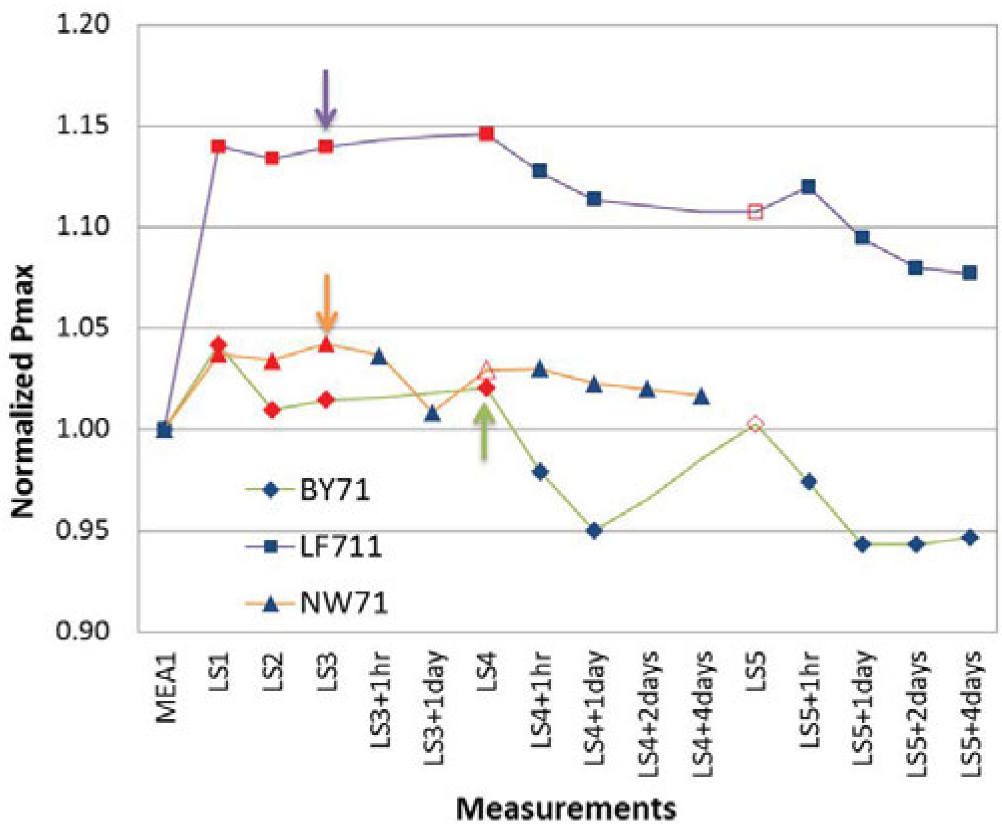
ESTI CODE	*TECHNOLOGY*
BY71	CIGS *(Copper-Indium-Gallium-diselenide)*
LF711	CIGS *(Copper-Indium-Gallium-diselenide)*
NW71	CIGS *(Copper-Indium-Gallium-diselenide)*
KX711	CdTe
NW73	CdTe
LK711	Triple junction a-Si
LK712	Triple junction a-Si
KW711	a-Si/ μ -Si
KW712	a-Si/ μ -Si
HJ410	a-Si/ μ -Si
NW74	Crystalline Silicon on Glass *(CSG)*

Note:

Modules with the same two letter code are from the same manufacturer and batch.

The modules had taken part in different projects in the past and have therefore had varying histories of light and temperature exposure. After the end of these previous projects they were stored in the dark, near to 25°C. The length of storage is different for each one of them and varies from several weeks to several months.

Results for CIGS modules



Modules measured within 30 minutes of leaving the light-soaking chamber

All modules exhibit an increase of P_{max} with light-soaking

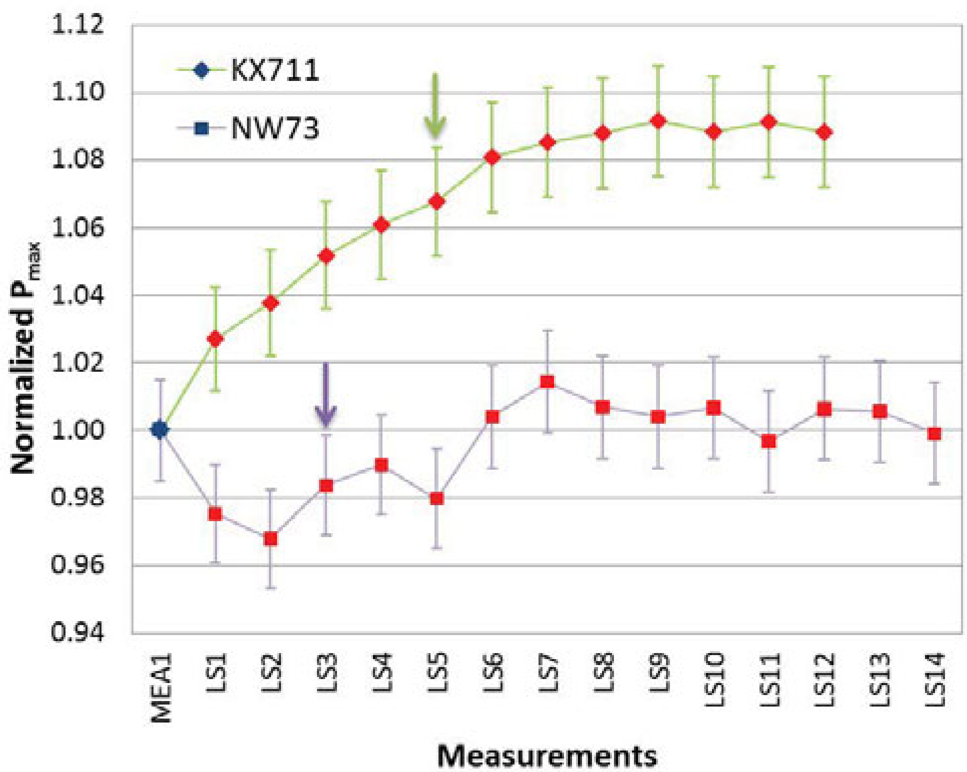
Stabilised after 3-4 exposure cycles

Dark storage leads to a decrease in P_{max}

Note:

Open symbols indicate a faulty connection leading to a lower than expected power

Results for CdTe modules

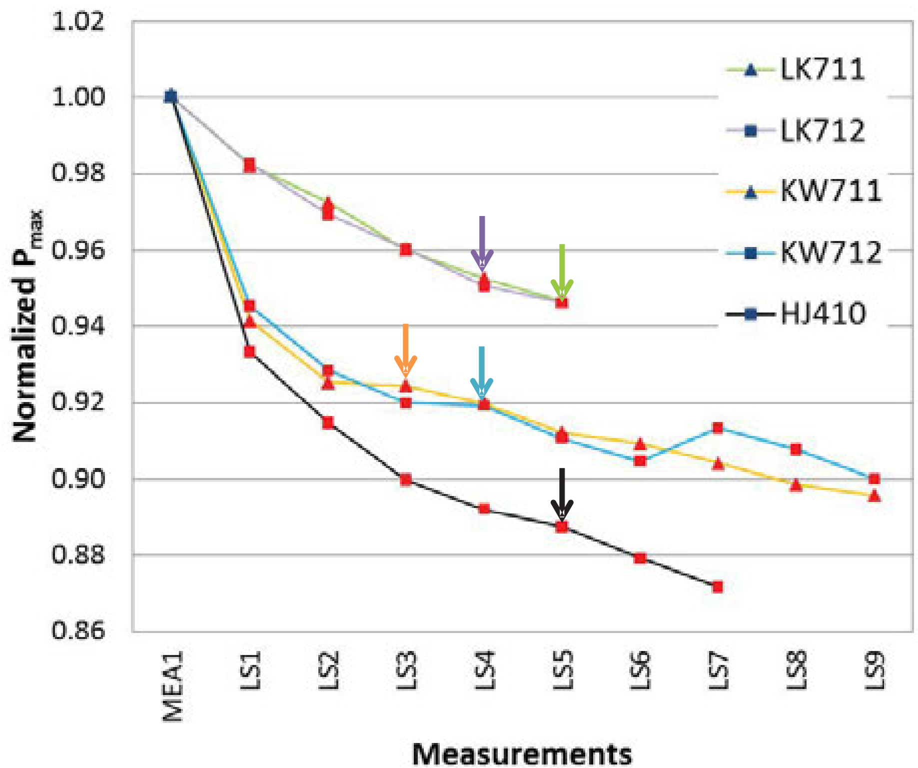


Light-soaking has improved the maximum power

Difference between the two modules due to their prior history

Continued to improve following point of stabilisation

Results for a-Si/µ-Si and Triple junction

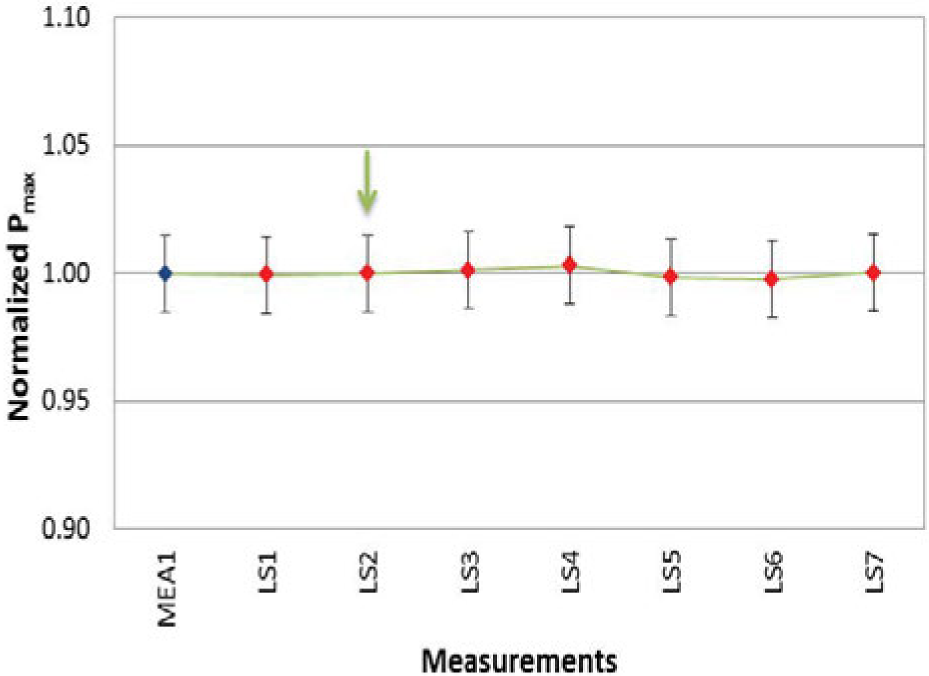


Light-soaking has improved the maximum power

The two triple junction modules exhibited a smaller decrease in power than the a-Si/µ-Si modules

Continued to decrease following point of stabilisation

Results for CSG



CSG material clearly not meta-stabile

No need to be subjected to light-soaking

Conclusions

For the purposes of module qualification, the stability procedure of IEC 61646 ed 2 is probably satisfactory, given the need to stay "within reasonable constraints of cost and time".

- For a-Si containing modules this will tend to lead to an over estimation of the power output
- For CdTe modules this would tend to lead to an underestimation
- Valid for CIGS
- not required for CSG

For thin-film module calibration, in general applying the stability procedure of IEC 61646 is not sufficient, therefore:

- More stringent stability criteria are suggested, such as more periods of light soaking and/or tighter stability limits.
- The a-Si community has tended to use 1000 hours @ 1 Sun

European Commission

Conclusions

One aspect of the stabilization process not explicitly studied here, but worthy of further examination is the choice of irradiance level and temperature. The standard calls for;

- A class CCC solar simulator, in accordance with the IEC 60904-9, or natural sunlight
- ..consecutive periods of at least 43 kWh·m^{-2} each integrated over periods when the temperature is between 40°C and 60°C, meet the following criteria: $(P_{max} - P_{min})/P_{average} < 2$ %.

If using controlled indoor light-soaking you could choose a target temperature from 40 to 60ºC

- Amorphous silicon devices will have the greatest maximum output at the highest temperature

For outdoor light-soaking under natural sunlight

- No control of temperature
- The integrated exposure can be calculated, but what happens if the module exceeds 60ºC ?

References

[1] D. L. Staebler, C. R. Wronski, "Reversible conductivity changes in discharge-produced amorphous Si", Appl. Phys. Lett. 31, pp 292-294

[2] J. A. del Cueto, and B. von Roedern "Temperature-induced Changes in the Performance of Amorphous Silicon Multi-junction Modules in Controlled Light- soaking" Prog. Photovolt: Res. Appl. **7**, 101-112 (1999)

[3] M. Nikolaeva-Dimitrova, R. P. Kenny, E. D. Dunlop, "Controlled Conditioning of a-Si:H Thin Film Modules for efficiency prediction", Thin Solid Films, Vol. 516/20, 2008, pp. 6902-6906.

[4] D.L. King, J. A. Kratochvil, and W. E. Boyson "Stabilization and Performance Characteristics of Commercial Amorphous-Silicon PV Modules" Proceeding of the 28th IEEE PVSC Anchorage USA, September 2000, pp. 1446-1449

[5] A. G. Aberle, "Thin-film solar cells", Thin Solid Films, Vol. 517, No. 17, July 2009, pp. 4706-4710.

[6] E. L. Meyer and E. E. van Dyk, "Characterization of degradation in thin-film photovoltaic module performance parameters", Renewable Energy, Vol. 28, No. 9, July 2003, pp. 1455-1469.

[7] C. Radue, E. E. van Dyk, E. Q. Macabebe, "Analysis of performance and device parameters of CIGS PV modules deployed outside", Thin Solid Films, Vol. 517, No. 7, February 2009, pp. 2383-2385.

[8] R. P. Kenny, M. Nikolaeva-Dimitrova, E. D. Dunlop, "Performance Measurements of CIS Modules: Outdoor and pulsed simulator Comparison for Power and Energy Rating", Proceedings of the 4th WCPEC, Hawaii, May 2006. pp. 2058-2061.

[9] J. A. del Cueto and B. von Roedern "Long-term Transient and Metastable Effects in Cadmium Telluride Photovoltaic Modules" Prog. Photovolt: Res. Appl. 2006; 14:615–628

[10] First Solar, Inc., "Application Note: Best Practise for Power Characterization", PD-5-434, Rev 1.0, downloaded from www.firstsolar.com, 2009.

[11] Z. Jingquan F. Lianghuan, L. Zhi, C. Yaping, L. Wei, W. Lili, L. Bing, C. Wei, Z. Jiagui, "Preparation and performance of thin film CdTe mini-module", Solar Energy Materials and Solar Cells, Vol. 93, No. 6-7, June 2009, pp. 966-969.

[12] IEC 61646. Thin-film terrestrial photovoltaic (PV) modules - Design, qualification and type approval (2nd ed.). IEC Central Office: 2008.

[13] H. Muellejans, W. Zaaiman, R. Galleano, "Analysis and mitigation of measurement uncertainties in the traceability chain for the calibration of photovoltaic devices", Meas. Sci. Technol., 20, (2009): 075101 (12pp).

Acknowledgments

Anatoli Chatzipanagi, Robert Kenny, Mike Field and Ewan Dunlop

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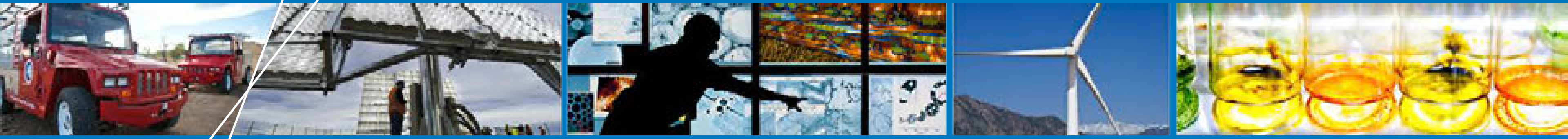
Predicting the Performance of Edge Seal Materials for PV



National Renewable Energy Laboratory – Photovoltaic Module Reliability Workshop

NREL-PVMRW

Michael Kempe
Dhananjay Panchagade
Arrelaine Dameron
Matthew Reese

March 1, 2012

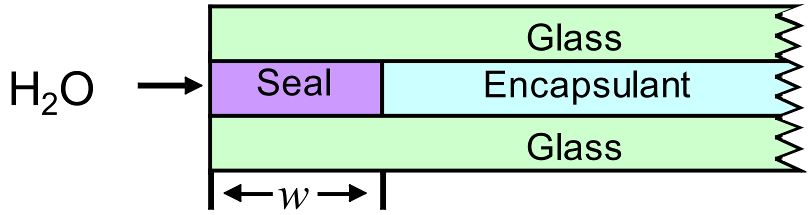
NREL/PR-5200-54582

Edge Seals - Introduction

•Many PV technologies are sensitive to moisture. Even with impermeable front- and back-sheets, moisture can penetrate from the sides. Edge seals are incorporated around the perimeter to prevent this ingress.

•Here we use a Ca-based method to evaluate the moisture ingress time for edge seal materials.

•Then we use this data to model the performance when deployed outdoors.

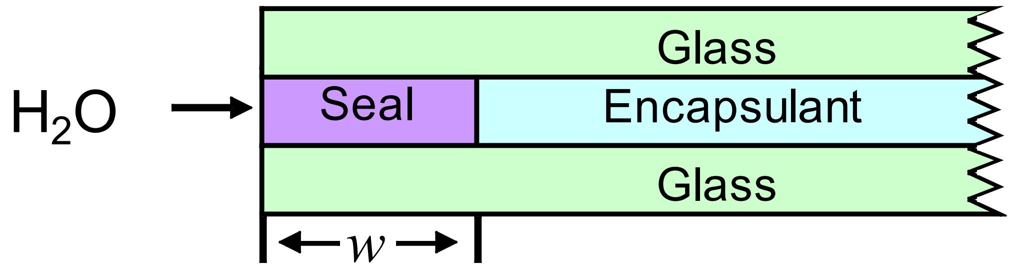


Outline

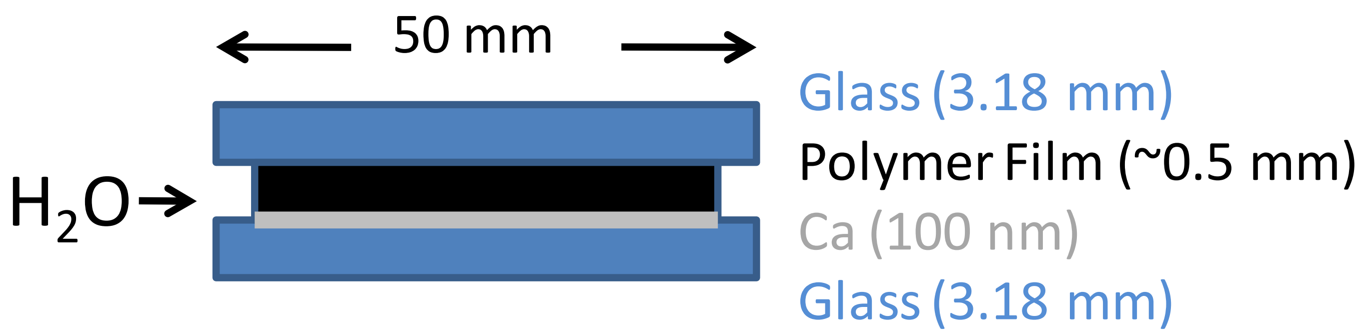
- **Ca film method for moisture ingress determination.**
- **Finite element modeling of moisture ingress.**
- **Investigation of failure modes.**
  - Edge Pinch
  - UV Light
  - Heat and Humidity

Test Sample Designed to Mimic Module Edge

Module Edge



Test Sample

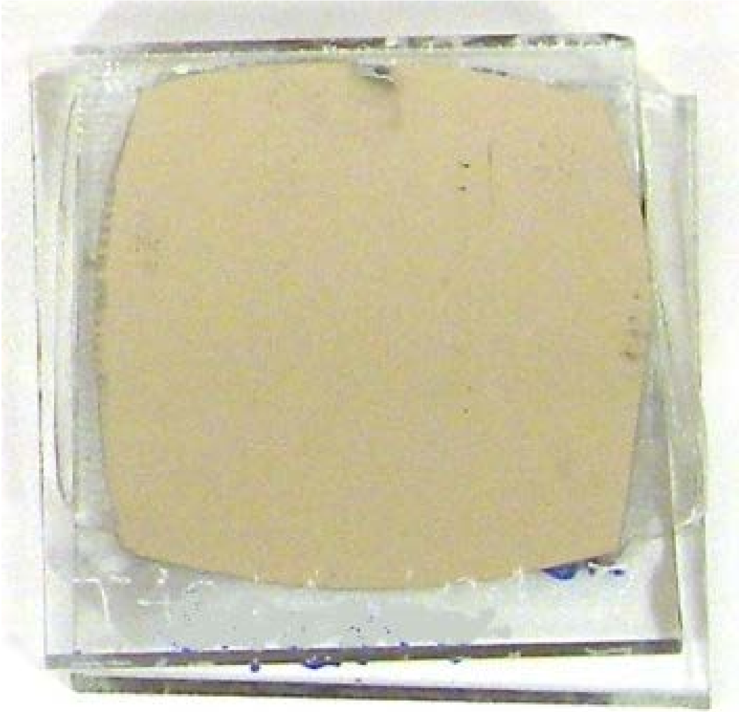


$$Ca + 2\ H_20 \rightarrow Ca(OH)_2 + H_2$$

Oxidation of Ca Indicates Moisture Ingress

$$Ca + 2\ H_2O \rightarrow Ca(OH)_2 + H_2$$

Mirror-Like → Transparent



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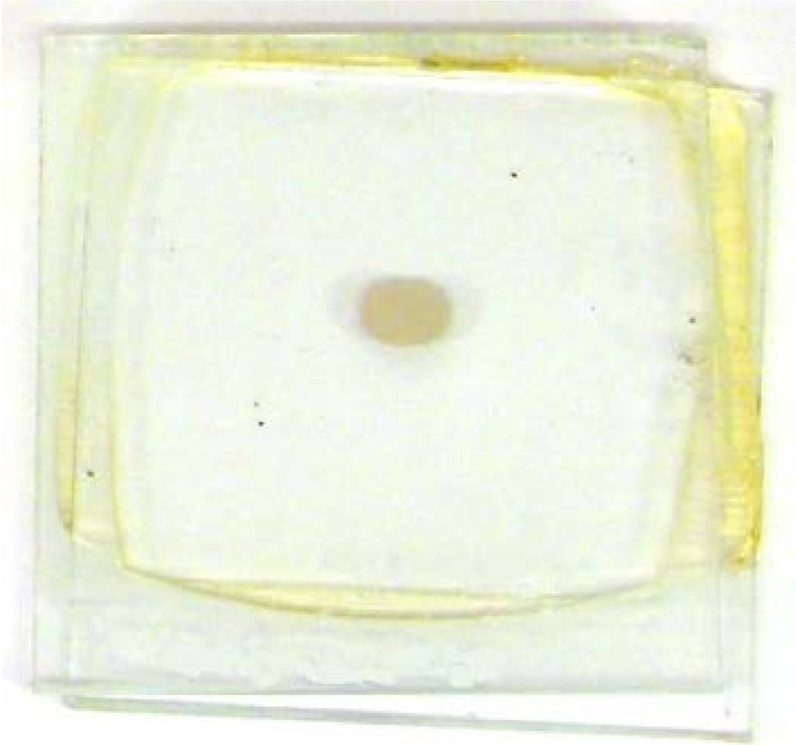
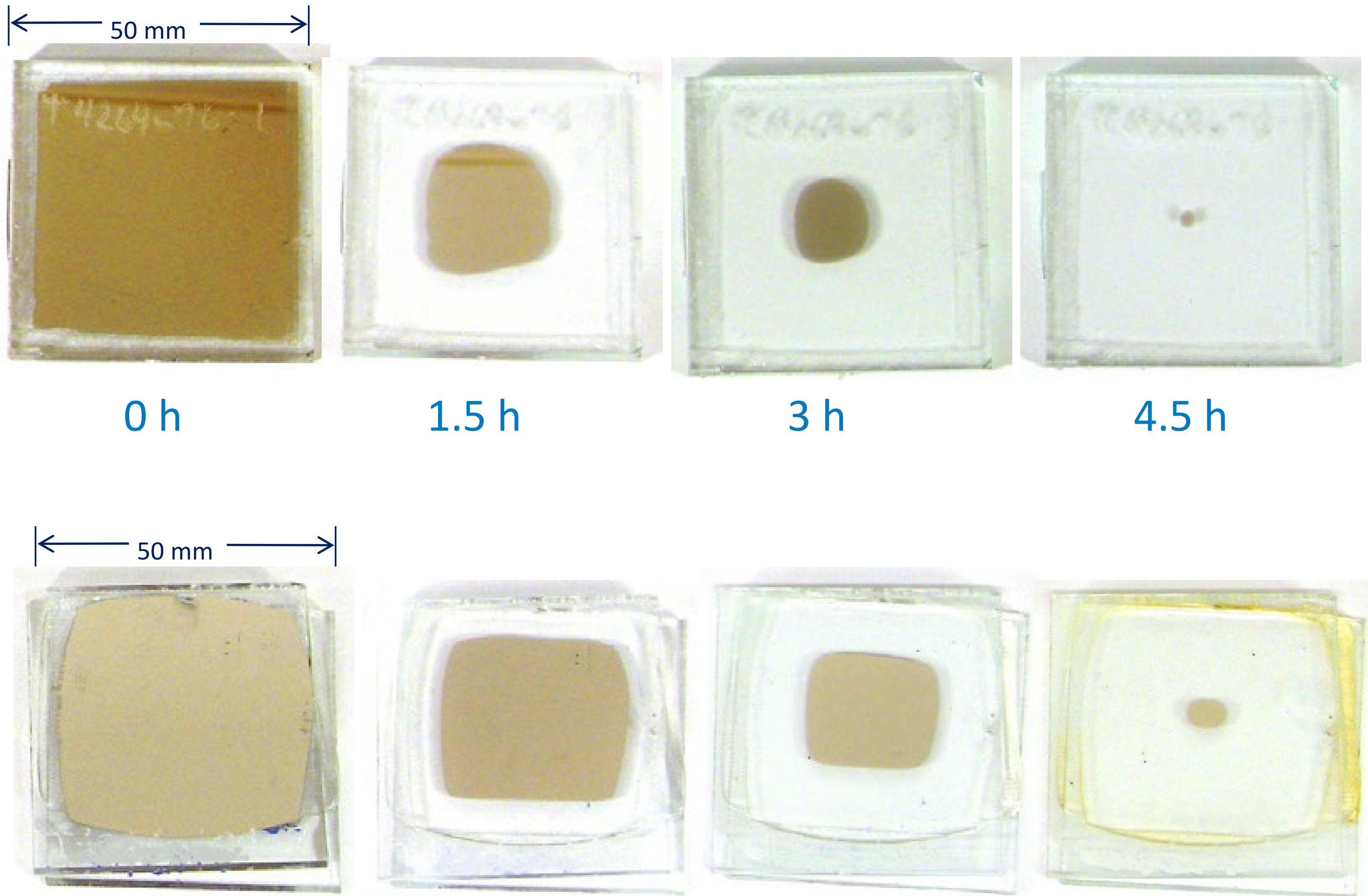


Moisture Ingress Varies Greatly in Encapsulants

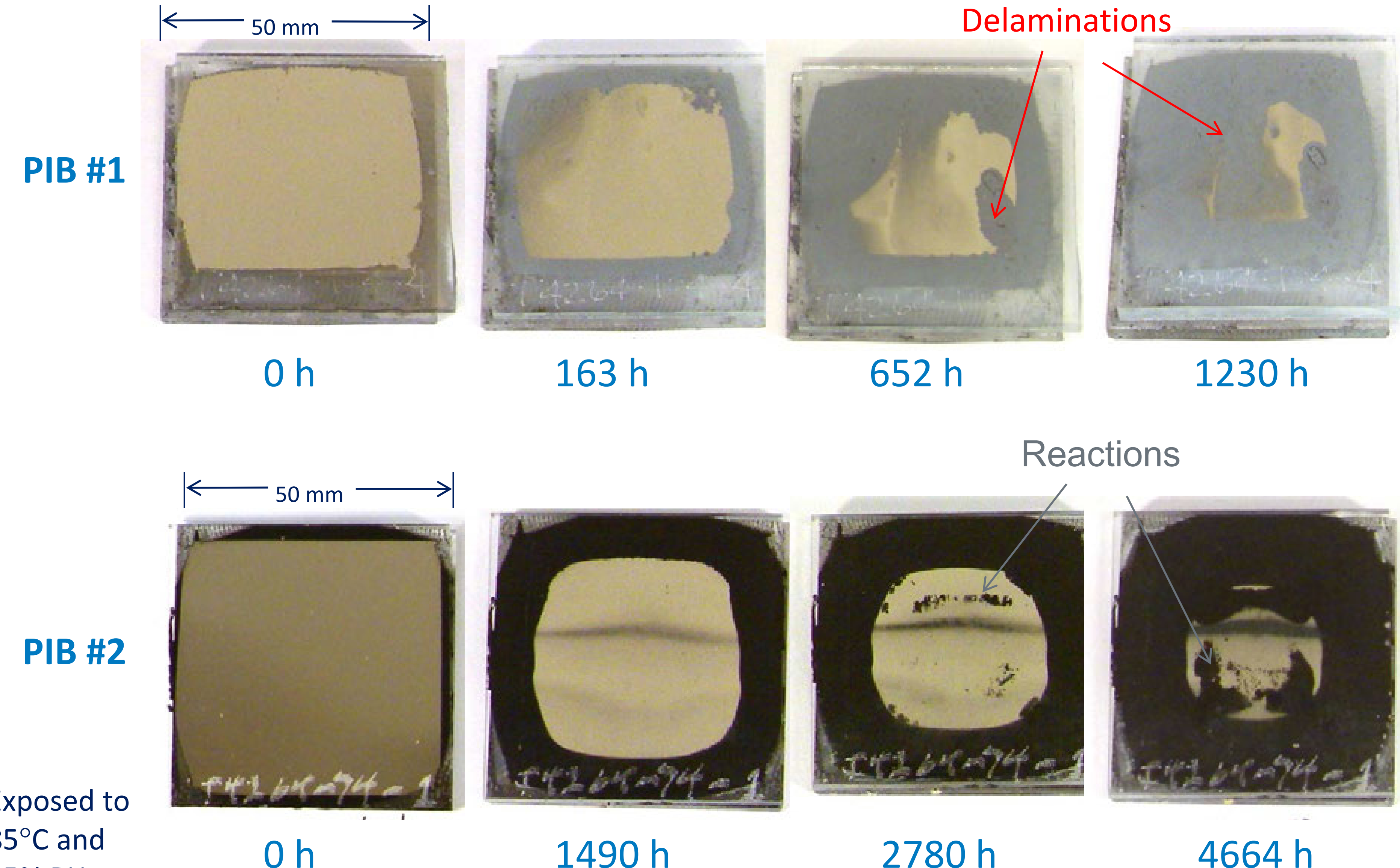


PDMS: 0 h, 1.5 h, 3 h, 4.5 h

Ionomer #1: 0 h, 67 h, 240 h, 652 h

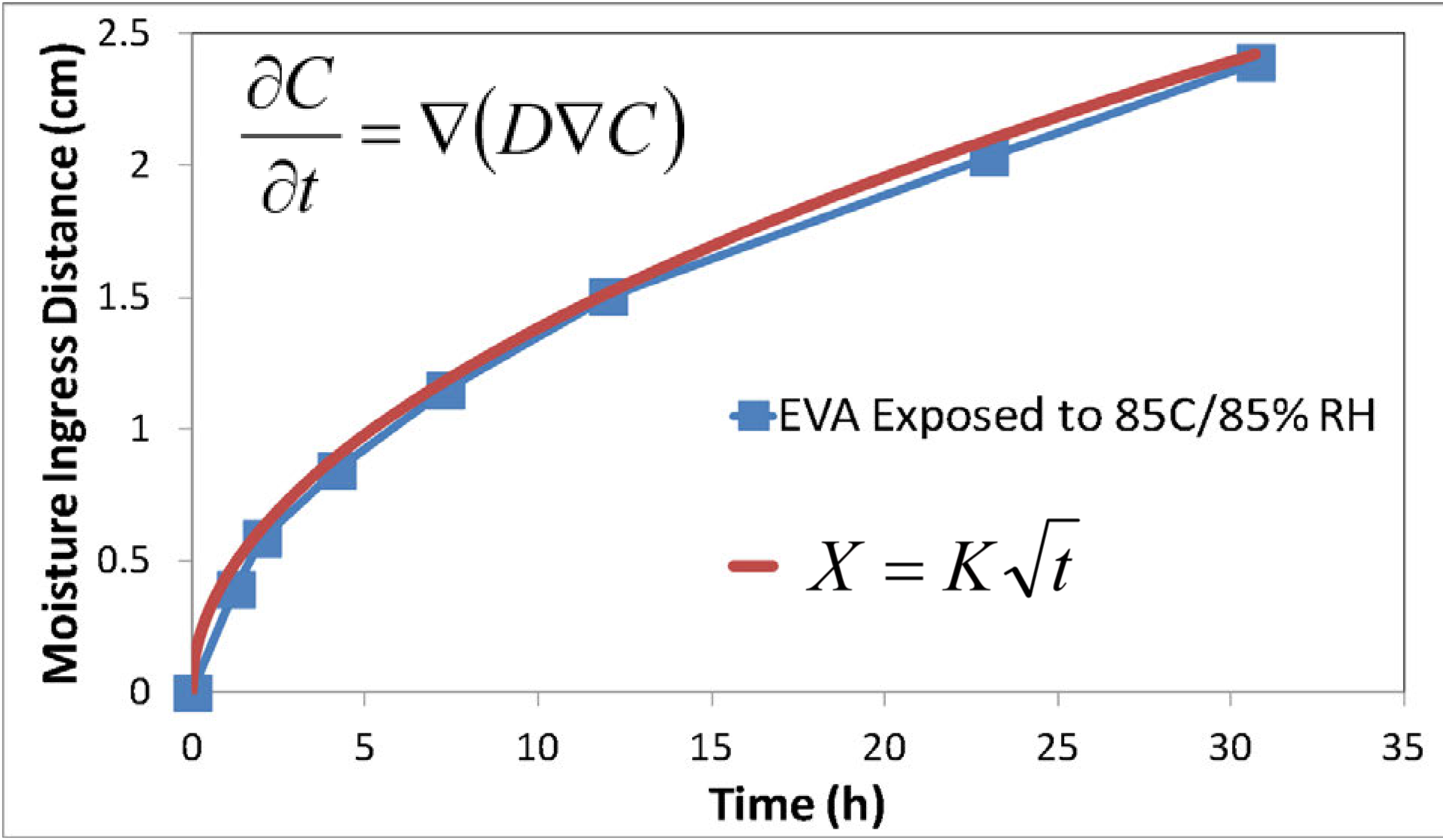
Exposed to 85°C and 85% RH

Polyisobutylene Edge Seals Slow Ingress



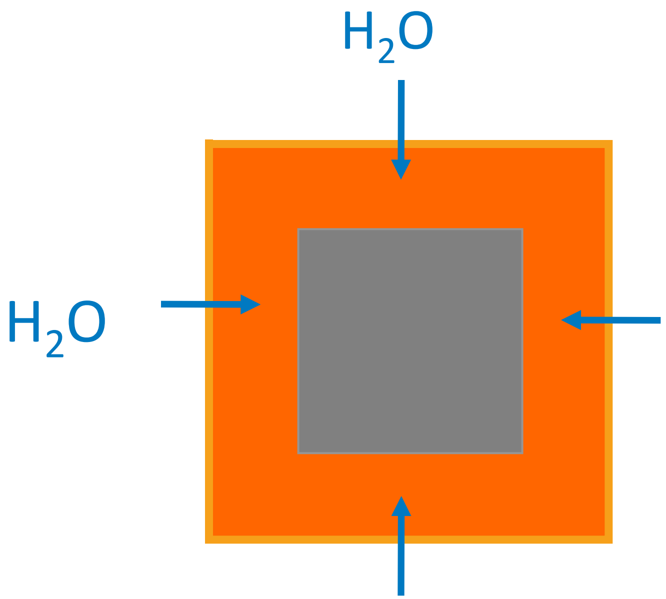
Exposed to 85°C and 85% RH

Moisture Ingress Rate Governed by Diffusion



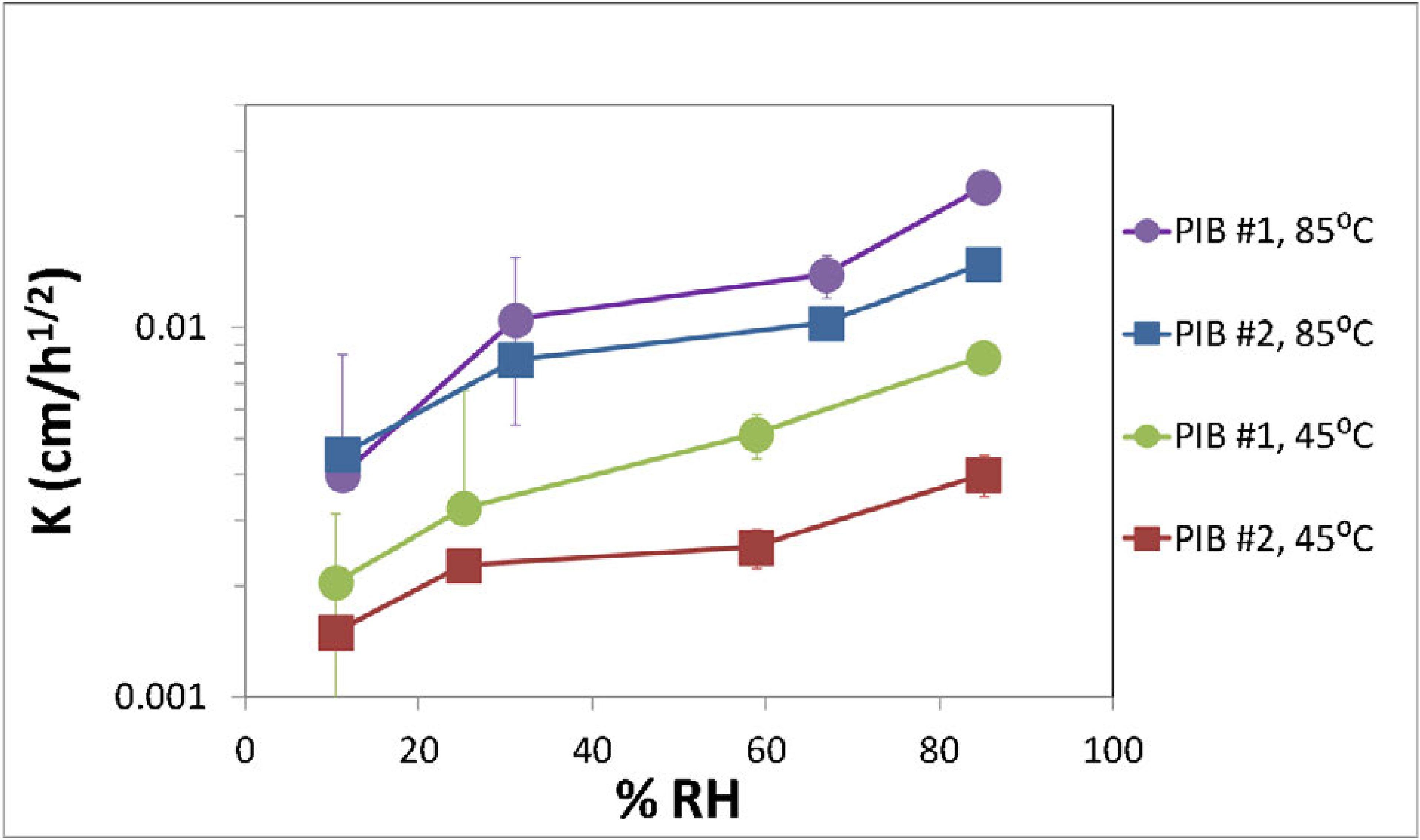
Moisture Ingress Rate Governed by Diffusion

$$\frac{\partial C}{\partial t} = \nabla(D \nabla C)$$

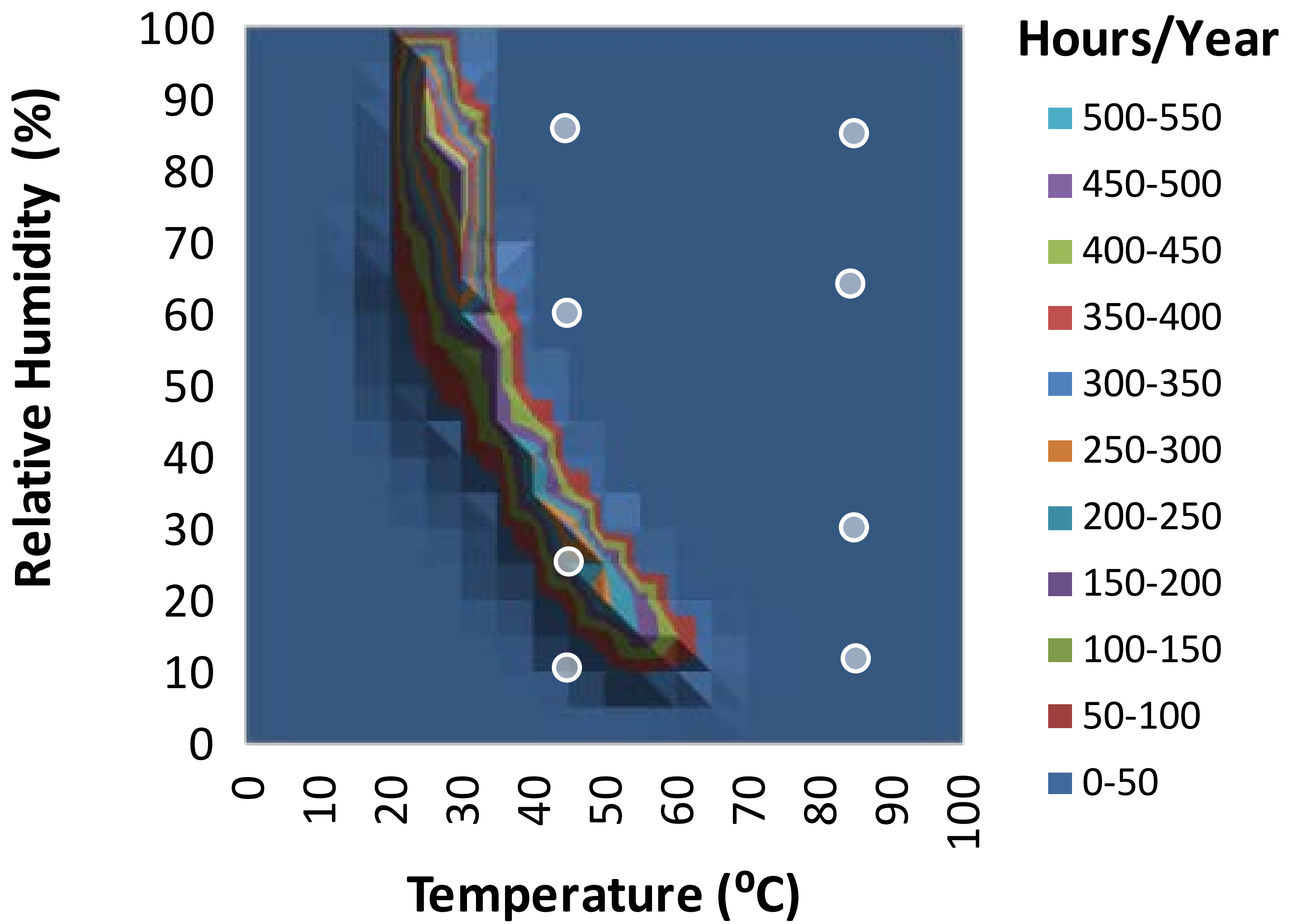


$$C_{m,n}^{P+1} = \frac{D\Delta t}{(\Delta X)^2}\left(C_{m+1,n}^{P} + C_{m-1,n}^{P} + C_{m,n+1}^{P} + C_{m,n-1}^{P}\right) + \left[1 - 4\frac{D\Delta t}{(\Delta X)^2}\right] C_{m,n}^{P} - (Calcium)$$

Permeation Measured at Low RH



Low RH Measurements Reduce Extrapolation Errors



Bangkok Thailand RH and Temperature for outside of a Glass/Glass Rack Mounted Module

Edge Seal Modeling

- **The use of fillers, pigments, and desiccants makes the determination of modeling parameters much more difficult.**

$$S_m = S_o e^{\left(-\frac{Ea_s}{kT}\right)} \frac{RH\%}{100\%}$$

Mobile phase water absorption is split between the polymer matrix and the mineral components. Assume linearity with relative humidity.

$$D_{eff} = D_o e^{\left(-\frac{Ea_D}{kT}\right)}$$

Mobile phase water diffusivity is an effective diffusivity. This accounts for a rapid equilibration between adsorbed and dissolved water.

$$R_{H_2O}$$

A non-reversible reaction with water that immobilizes the water.

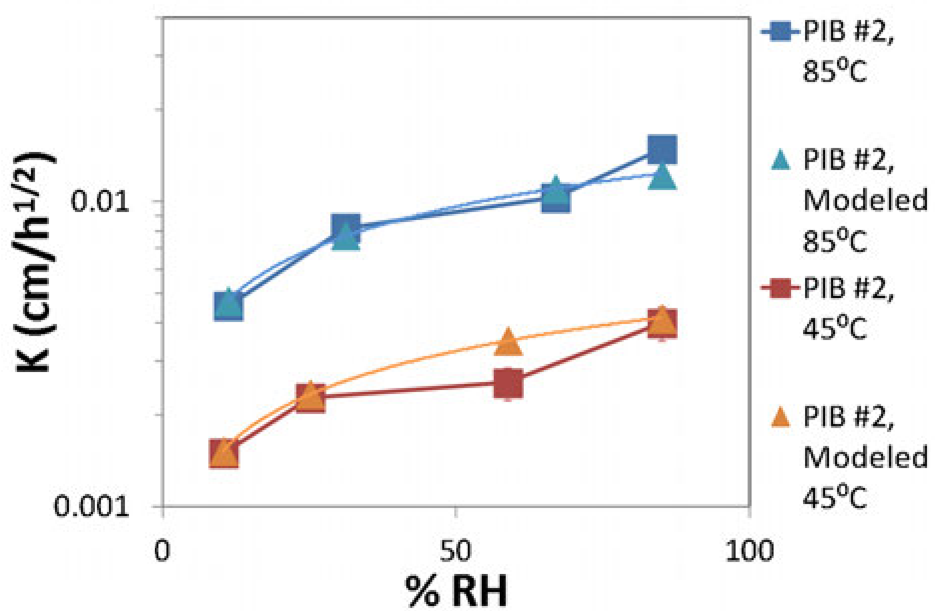
Getting the Modeling Parameters

R_{H_2O} Measured by weighing samples before humidity exposure, after humidity exposure, and after drying.

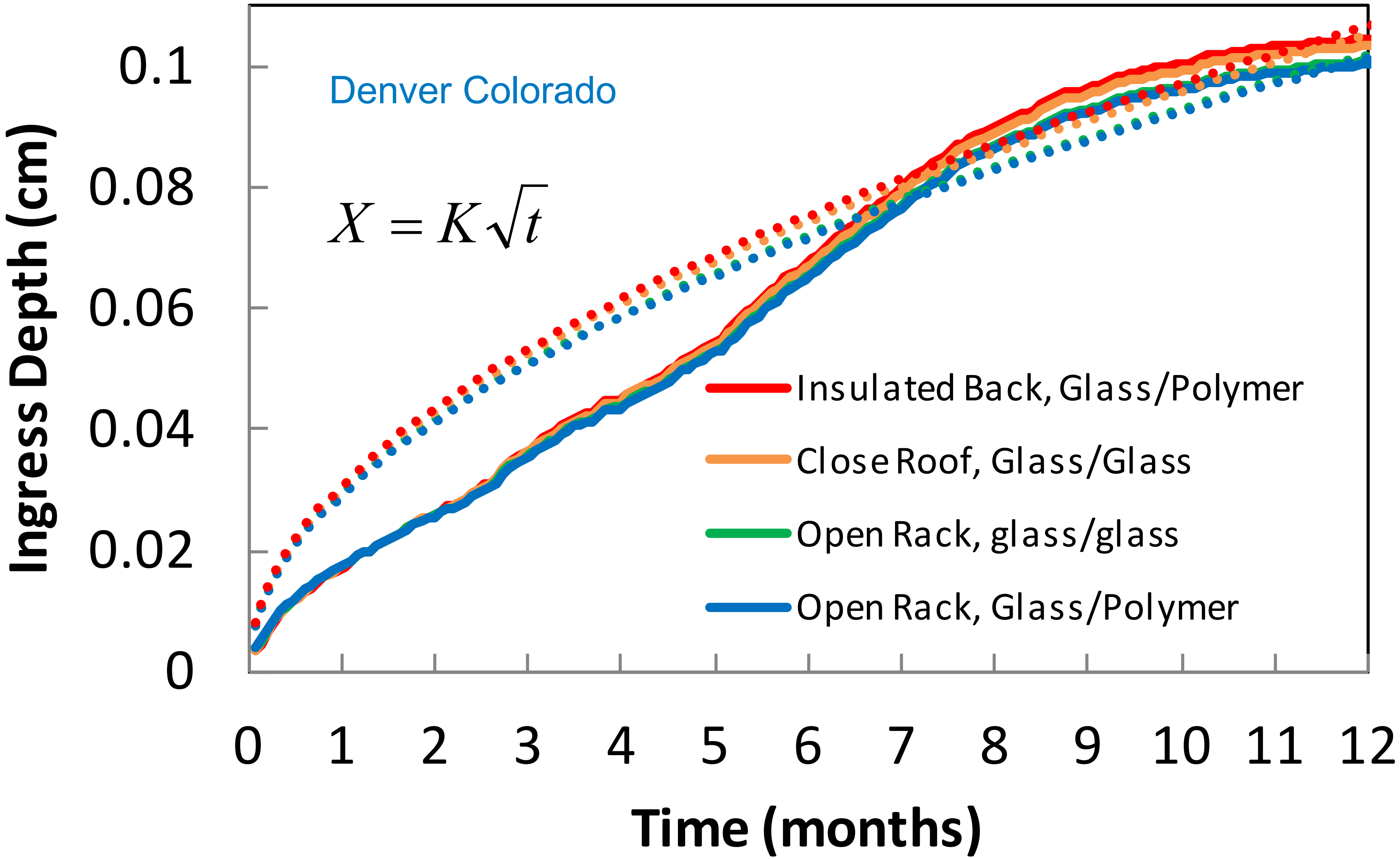
$S_o\ ,\ Ea_S$ Measured by exposing to controlled humidity then drying in a TGA to determine moisture loss.

Curvature of K vs %RH is determined by the ratio of S to R_{H2O}

$D_o\ ,\ Ea_D$ Estimate from other parameters and fit to Ca data. Specifically the difference between 45 and 85°C curves.

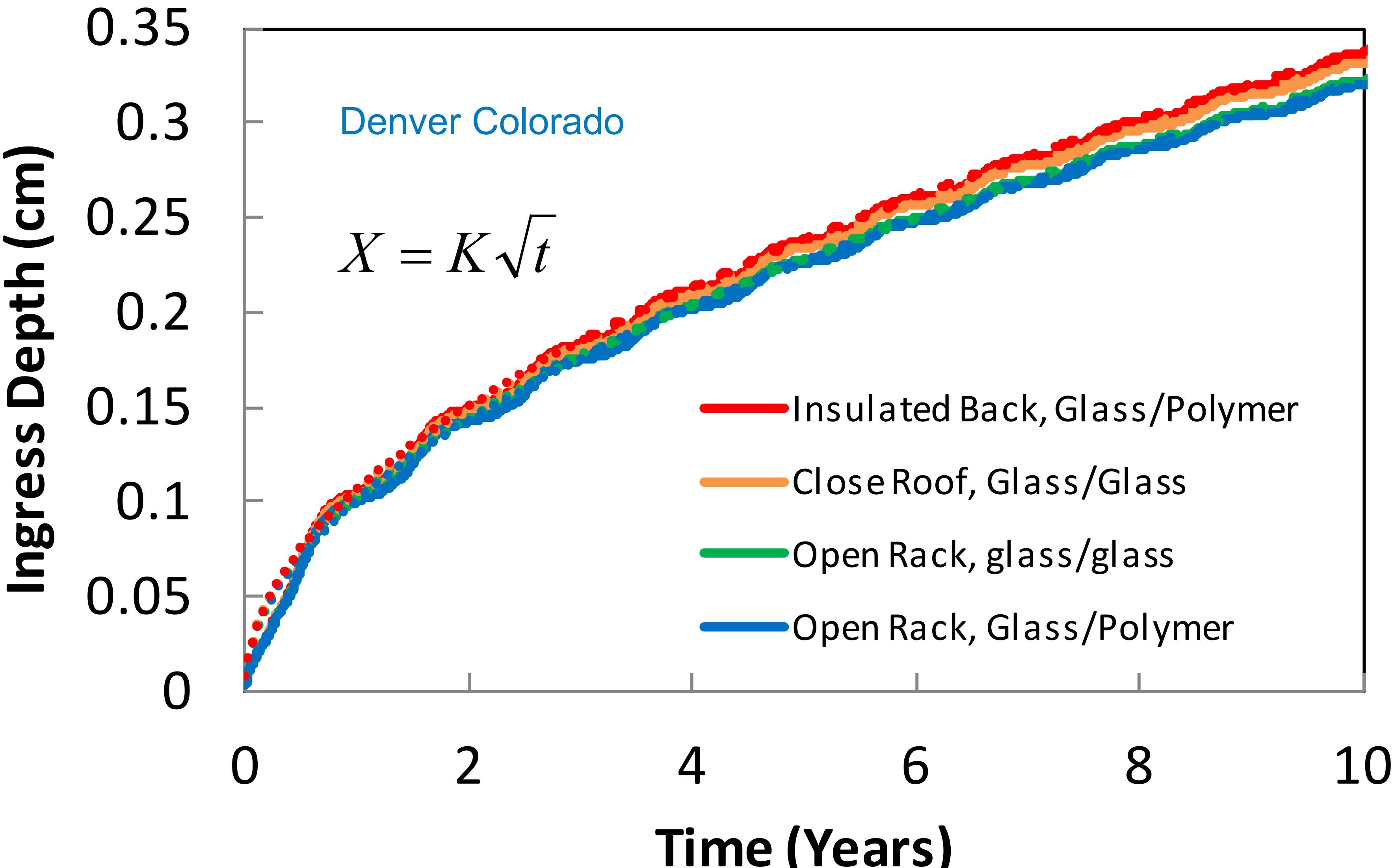


Ingress Estimated Using Finite Element Analysis



Used TMY3 Data and Temperature estimates similar to King et al, and Kurtz et al.

Square Root Relation Works to Longer Times



Used TMY3 Data and Temperature estimates similar to King et al, and Kurtz et al.

Preliminary Results for Different Climates

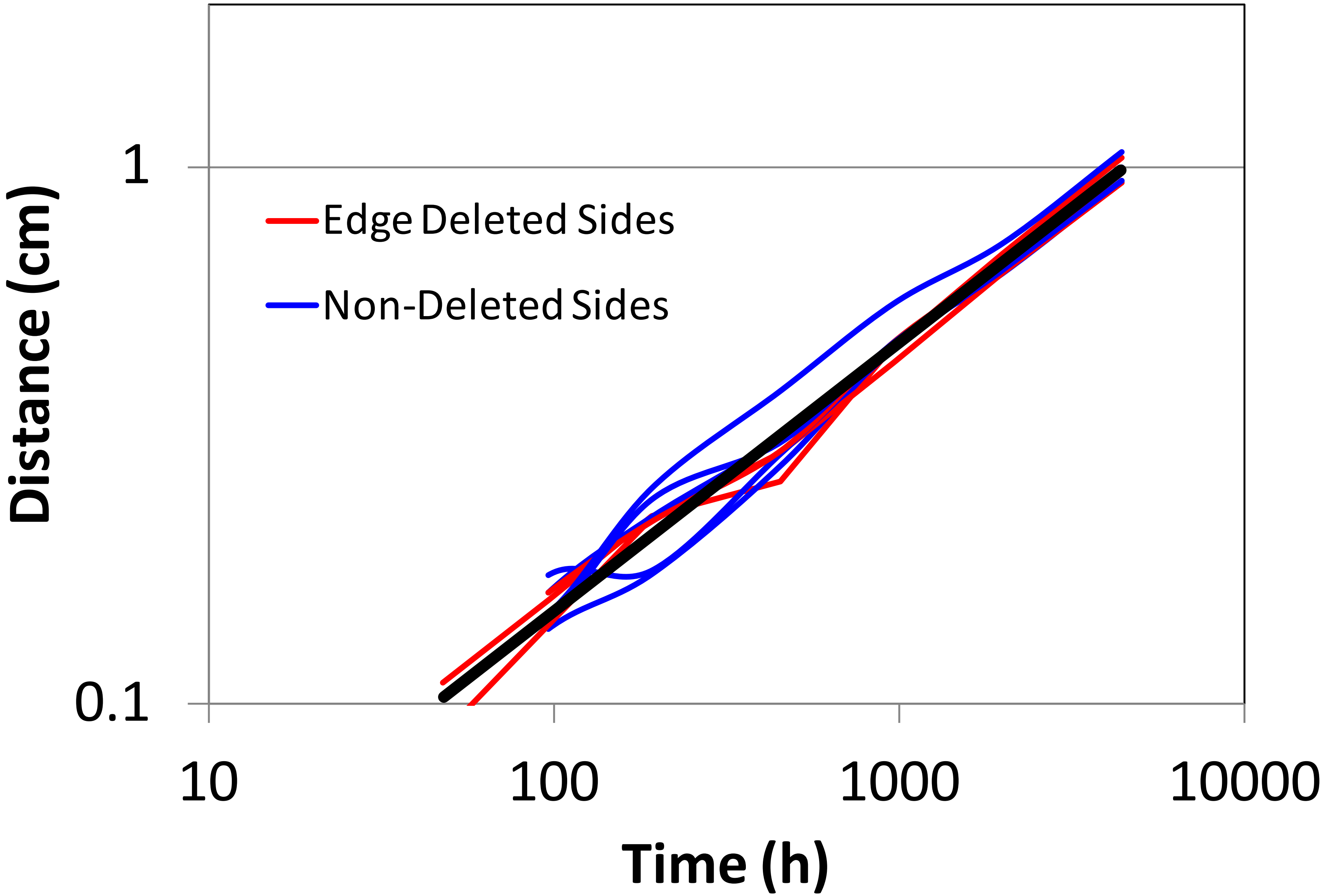
			K	20 y required width	20 yr equivalent at 85°C/85% RH	20 yr equivalent at 45°C/85% RH
D_o (cm^2/s)=		0.33				
Ea_D (kJ/mol)=		47				
S_o (g/cm^3)=		0.16				
Ea_S (kJ/mol)=		5				
Reactive Ca absorption (g/cm^3)=		0.047	($cm/h^{1/2}$)	(cm)	(h)	(years)
DENVER/CENTENNIAL [GOLDEN - NREL]	Open Rack, Glass/Polymer		0.00087	0.45	623	1.4
	Open Rack, glass/glass		0.00089	0.45	630	1.5
	Close Roof, Glass/Glass		0.00098	0.46	661	1.5
	Insulated Back, Glass/Polymer		0.00103	0.47	676	1.6
RIYADH	Open Rack, Glass/Polymer		0.00102	0.48	712	1.6
	Open Rack, glass/glass		0.00104	0.48	721	1.7
	Close Roof, Glass/Glass		0.00117	0.50	765	1.8
	Insulated Back, Glass/Polymer		0.00124	0.50	787	1.8
MUNICH	Open Rack, Glass/Polymer		0.00096	0.50	761	1.8
	Open Rack, glass/glass		0.00097	0.50	767	1.8
	Close Roof, Glass/Glass		0.00103	0.51	795	1.8
	Insulated Back, Glass/Polymer		0.00107	0.51	808	1.9
PHOENIX SKY HARBOR INTL AP	Open Rack, Glass/Polymer		0.00128	0.58	1035	2.4
	Open Rack, glass/glass		0.00131	0.58	1048	2.4
	Close Roof, Glass/Glass		0.00145	0.60	1113	2.6
	Insulated Back, Glass/Polymer		0.00153	0.61	1145	2.6
MIAMI INTL AP	Open Rack, Glass/Polymer		0.00199	0.87	2332	5.4
	Open Rack, glass/glass		0.00202	0.87	2361	5.5
	Close Roof, Glass/Glass		0.00218	0.90	2490	5.8
	Insulated Back, Glass/Polymer		0.00225	0.91	2555	5.9
BANGKOK	Open Rack, Glass/Polymer		0.00228	0.98	2980	6.9
	Open Rack, glass/glass		0.00232	0.99	3015	7.0
	Close Roof, Glass/Glass		0.00249	1.02	3182	7.4
	Insulated Back, Glass/Polymer		0.00258	1.03	3261	7.5

A sensitivity analysis gave about ±15% on K and Width, and ±30% on 20 yr equivalent time.

Edge Seal Failure Modes and Stresses

- Heat.
- Humidity (85C/85% RH).
- Adhesion to edge delete region.
- UV Light.
- Edge Pinch

Laser Edge Delete Did Not Increase Ingress



Edge-Seals May Have Edge Pinch

Schematic side views of module edge

Idea Edge Profile

(no bend in glass at the module perimeter)

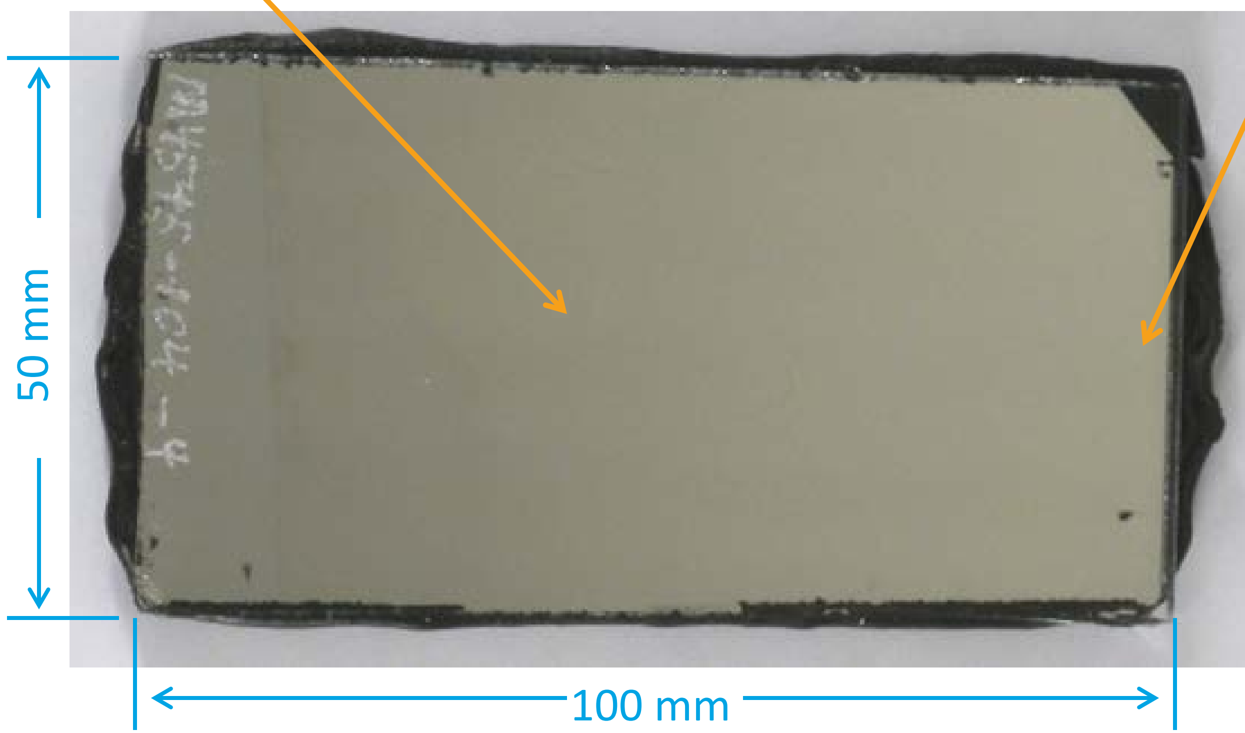
Edge Pinch

(lamination pressure cause the glass to bend around the perimeter)

Edge Seal Test Specimen

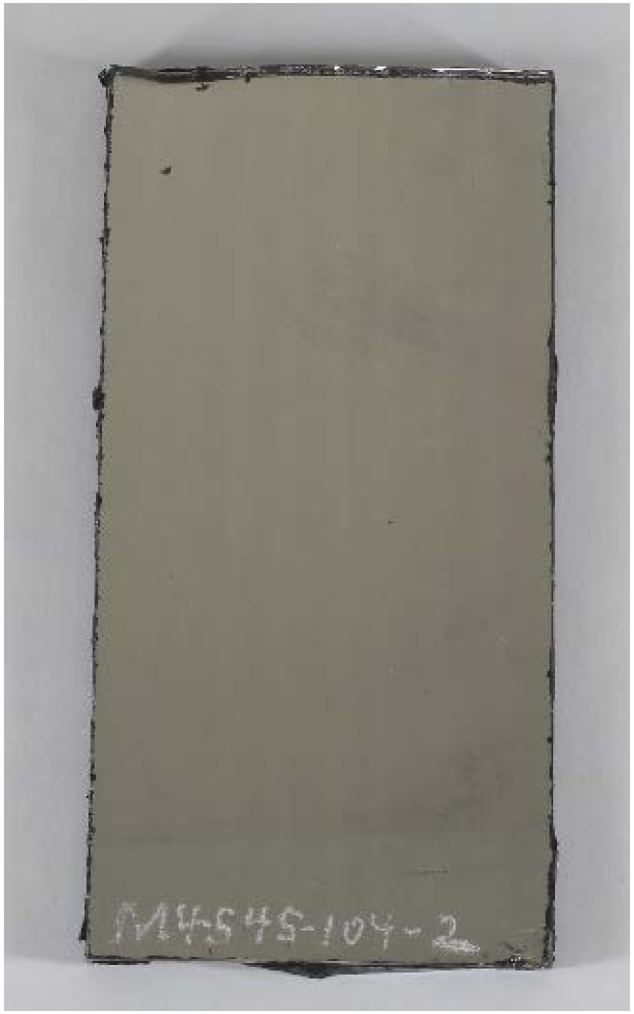
Schematic side view of test sample

Photographic top view



0.30 mm of edge pinch

Edge Seals With Pinch Resist 85°C and 85% RH



No Exposure

170 h 85°C/85% RH

674 h 85°C/85% RH

Only small signs of minor delamination on ends exposed to tensile stress.

Edge pinch is 0.31±0.01 mm for all exposures.

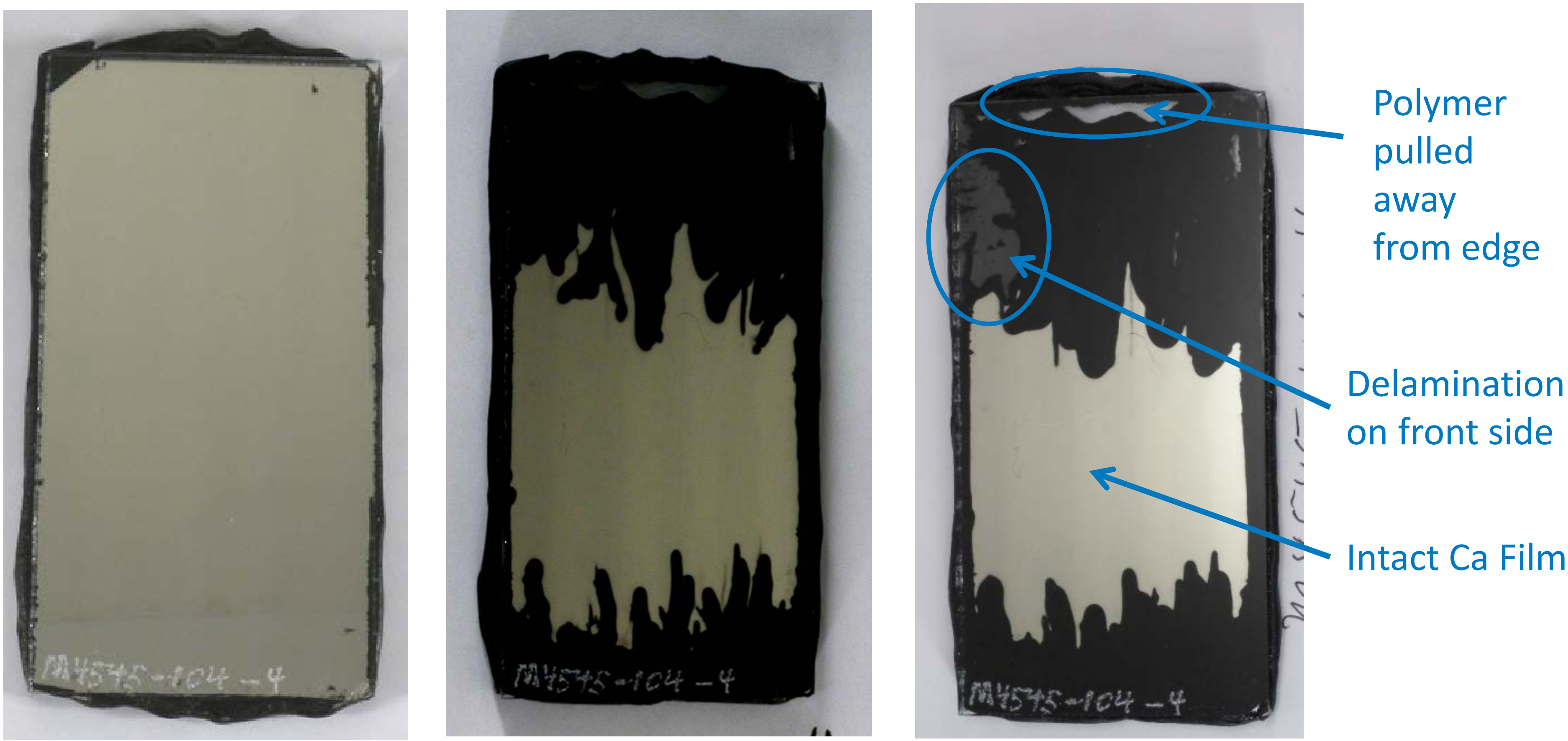
UV Light Can Delaminate Edge Seals With Pinch

No Exposure
0.32±0.01 mm pinch

165 h
60°C/60% RH/ 2.5 UV Suns
0.02±0.01 mm pinch

621 h
60°C/60% RH/2.5 UV Suns
0.02±0.01 mm pinch

UV Light Can Delaminate Edge Seals With Pinch



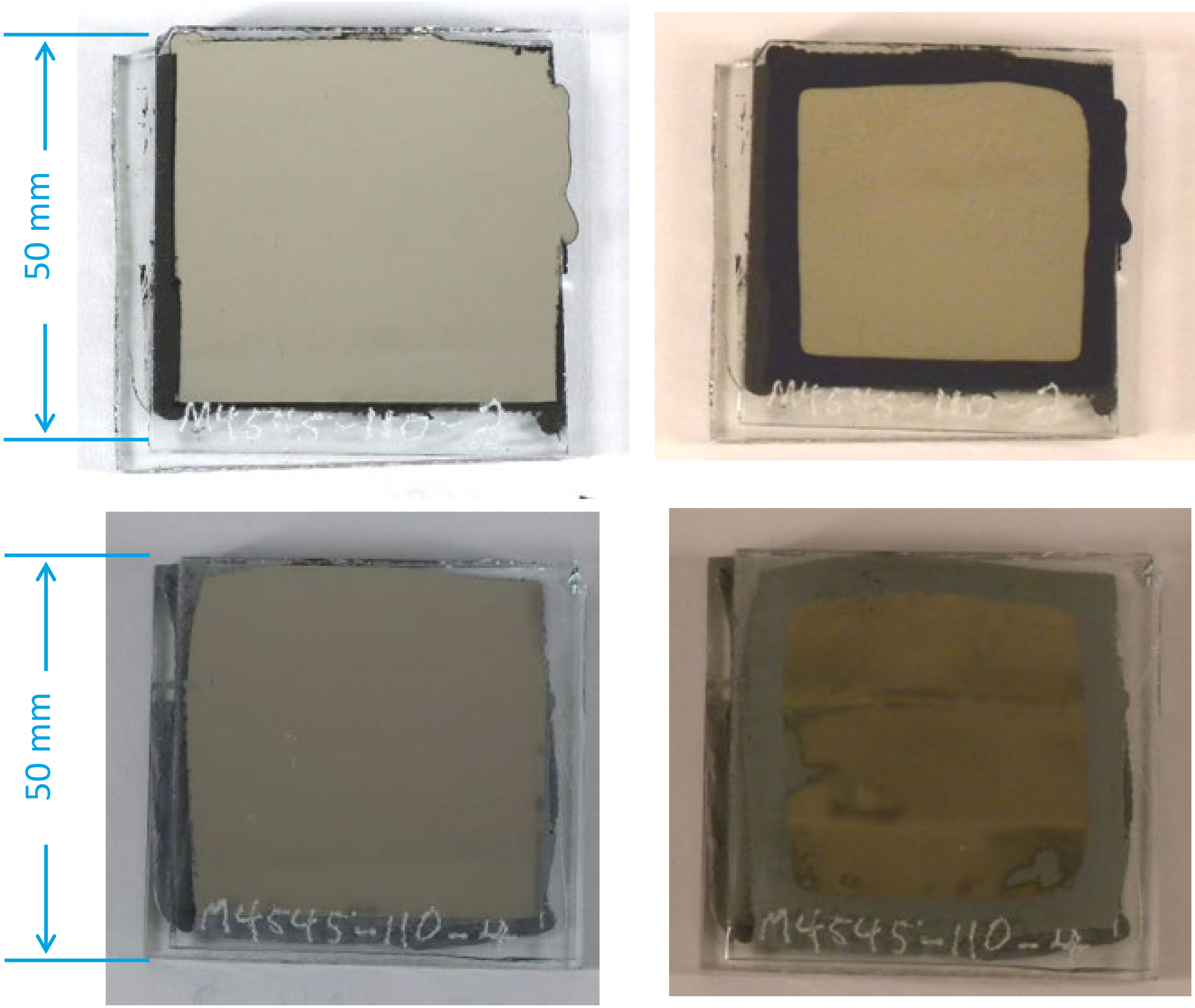
No Exposure
0.32±0.01 mm pinch

165 h
60°C/60% RH/ 2.5 UV Suns
0.02±0.01 mm pinch

621 h
60°C/60% RH/2.5 UV Suns
0.02±0.01 mm pinch

Light exposure on non-Ca film backside.
Very significant delamination on ends exposed to tensile stress.

UV Light Alone is Much Less Damaging



PIB #2

PIB #1

Unexposed

1962 h 60°C/60%RH/2.5 UV suns

IEC TC82 WG2 Edge Seal Standards Development

- **Under IEC TC82 WG2 a group has formed to work on developing standard test methods for testing PV packaging materials.**
  - Encapsulants
  - Back Sheets and Front Sheets
  - Adhesives
  - Edge Seals/Pottants

- **If you would like to help with the edge seal standards development, please contact me.**

What edge seal parameters are important?

1. **Adhesion is the most important parameter.**
   a) **Must be maintained after environmental exposure.**
   b) **Residual stress in glass will affect adhesion.**
   c) **Material may expand as it absorbs water.**
   d) **Good surface preparation is necessary.**
2. **Breakthrough time is the next most important.**
   a) The 12 mm edge delete perimeter should be wide enough to keep moisture out.
3. **Module mounting configuration is not important.**
   a) Hotter installations tend to dry out the module partially countering the effects of increased diffusivity.
4. **The steady state transmission is less important.**
   a) The amount of permeate is very low.
   b) Ideally one will not reach steady state.

Conclusions

- An edge seal width of 1 cm can be capable of keeping moisture out for 20 years in almost any climate.
- Delamination is the main concern for edge seal performance.
- Edge Seals should be assembled without edge pinch to ensure good adhesion.

Acknowledgements

Sarah Kurtz

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David Miller

Joshua Martin

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Demonstrating Reliability of Ultra Barrier Solar Films for Flexible PV Applications

Tracie Berniard
Mark Roehrig
Bill Murray
Alan Nachtigal
Joe Spagnola
Joe Pieper

2012 NREL PV Module Reliability Workshop
Golden, Colorado

February 28 – March 1, 2012

3M

Outline

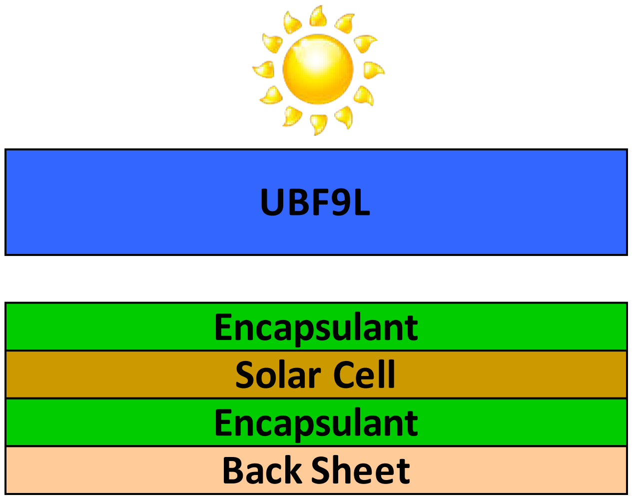
1. 3M Ultra Barrier Solar Film Product Overview
2. Challenges Measuring WVTR at Ultra Barrier Levels
3. Demonstrating Reliability
4. Summary

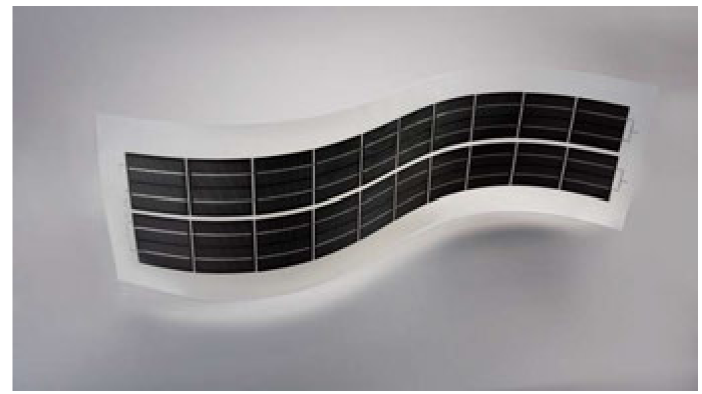
3M Ultra Barrier Solar Film Overview

March 1, 2012

Advantages of Flexible PV Modules

- Durable film with outstanding moisture barrier properties and high light transmission
- Enables high efficiency flexible PV modules to significantly reduce installation costs





Light weight →1/8th compared with glass-on-glass

Lower Balance of System costs → less labor and no mechanical racking

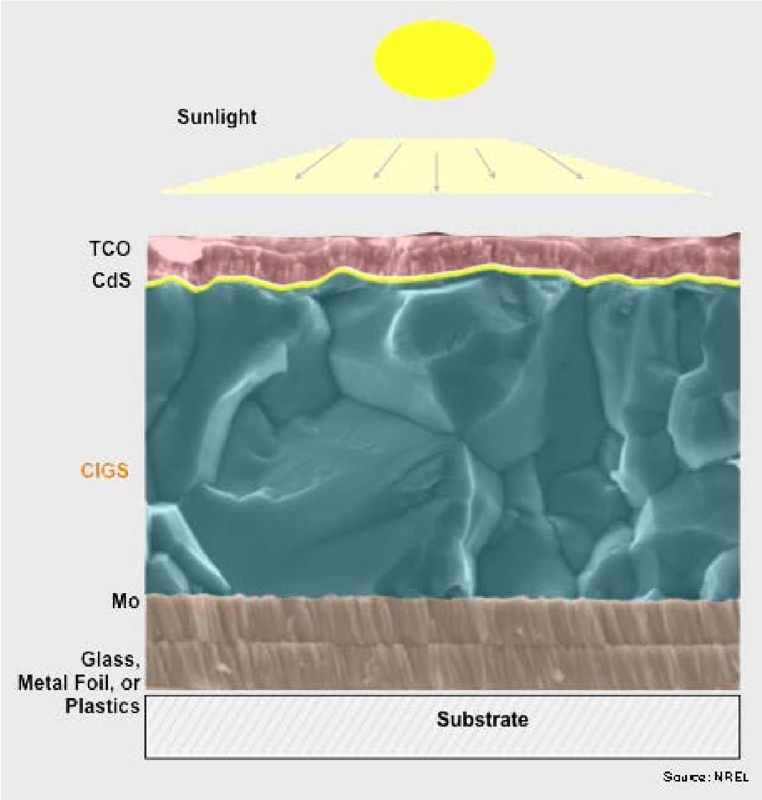
Higher packing density → Significantly more kW per shipping container

Higher energy output → Better transmission and off-angle performance

Large area modules → Lower relative "fixed" module costs

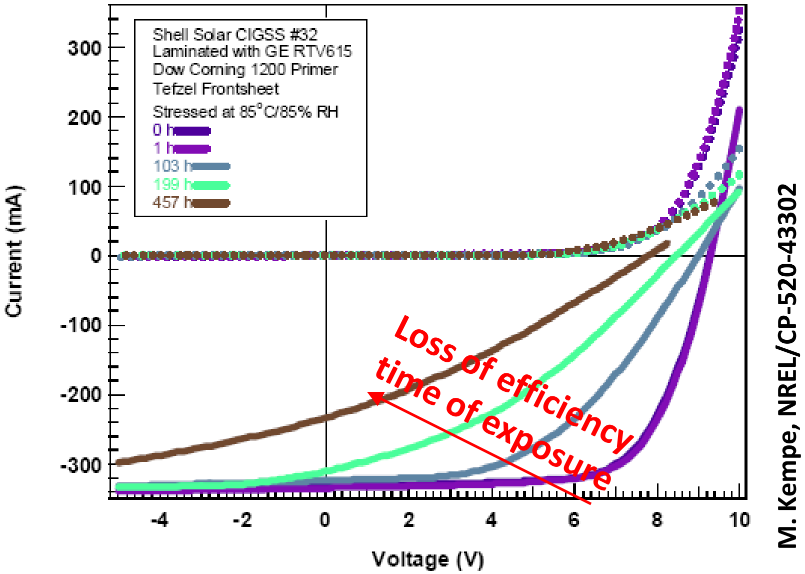
Lower manufacturing cost → Fully automated roll to roll processing

Ultra-Barrier Requirements: 10^{-6} to 10^{-4} g/m^{2}day for 25 year



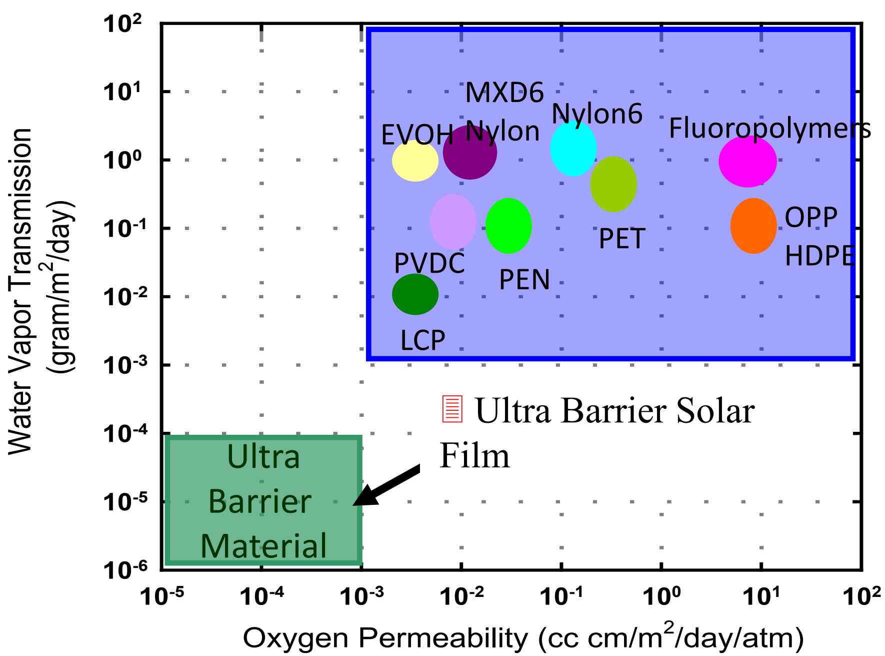
Water vapor migrates to electrode and degrades electrical contacts

Degradation in Efficiency in CIGS Exposure to Water (85%RH & 85°C)



•D.J. Coyle, etal , 2009 34th IEEE, pg. 001943 (2009)

- 3M has been developing ultra barrier technology for over a decade
- Over 50 applications and 20 granted patents
- Currently validating 1.2m wide film from manufacturing line



Description

Designed to address the needs of the flexible thin film solar manufacturers, 3M™ Ultra Barrier Solar Film acts as a replacement for glass with its high light transmission, superb moisture barrier performance and excellent weatherability. 3M combined its knowledge of polymer films, adhesives and advanced materials to deliver a high performing, multi-layered front sheet barrier film to the solar industry.

Features

- Good optical transmission from 400-1400 nm
- Very low moisture vapor transmission rate
- Excellent UV stability
- Flexible

Key Highlights

- UL Certified Component (E316895)
- WVTR = 5×10^{-4} g/m²/day @ 23°C 85% RH
- Transmission >89% (Avg 400 nm-1400 nm)
- Low Shrinkage
- Partial Discharge 1,000V
- Low CTE

Typical Properties (Data not for specification purposes)

Property	Test Method	Value*	Comment
Mechanical			
Thickness	ASTM D 6988	.229 mm (.009")	
Width		1.2 meters (47.24")	
Tensile Strength	ASTM D 882	106 MPa	
Elongation	ASTM D 5026	157%	
Optical			
Optical Transmission	3M	>89%	Average (400 – 1400 nm)
Thermal			
Processing Temperature		150°C for <15 min	
Operating Temperature		-40 to 100°C	
Storage Temperature		0 to 40°C	
Electrical			
Dielectric	ASTM D 149	>10KV	
Partial Discharge	IEC 61730-2 MST 15	>1000V	
Other			
Moisture Vapor Transmission Rate	See Application Guide	$<5 \times 10^{-4}$ g/m²/day	@ 23°C 85% RH
Outdoor Exposure	UL746C	f2	Water immersion and UV exposure
Certifications	UL Recognized Component		E316895
	TUV		

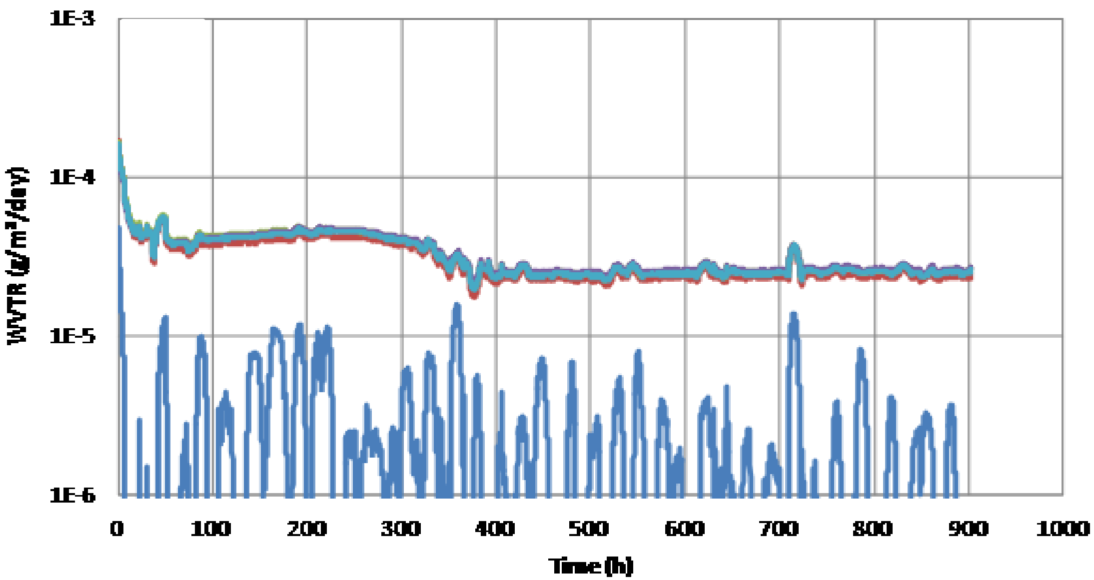
* Values listed are preliminary and for reference only.

3M

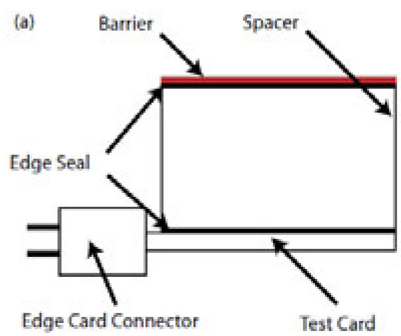
Enabling Lightweight, Flexible, Roof Top Solar Modules

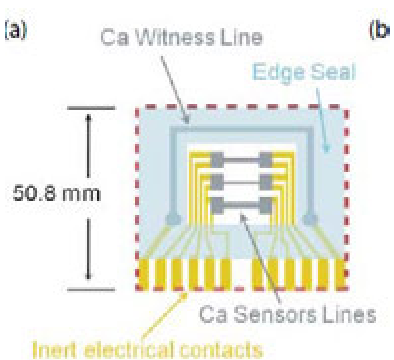
Property	Status	Goal	Current	Comment
WVTR (g/m²day)		As low as 10^{-6}	5.0×10^{-5}	NREL independently verified w/eCa >6000hrs 45C/85RH
Transmission		Entitlement of 94%	90%	2% gain through processing changes
Production Scale		Up to 2m	1.2m	1.2m wide films being made for qualification and certification
Product Certification		Certified Component and Module	UL, IEC certified from pilot line	Certifications with 1.2m film in progress
Product Lifetime (yr)		>25	Validation in progress	Service Life Prediction work and outdoor correlations in testing

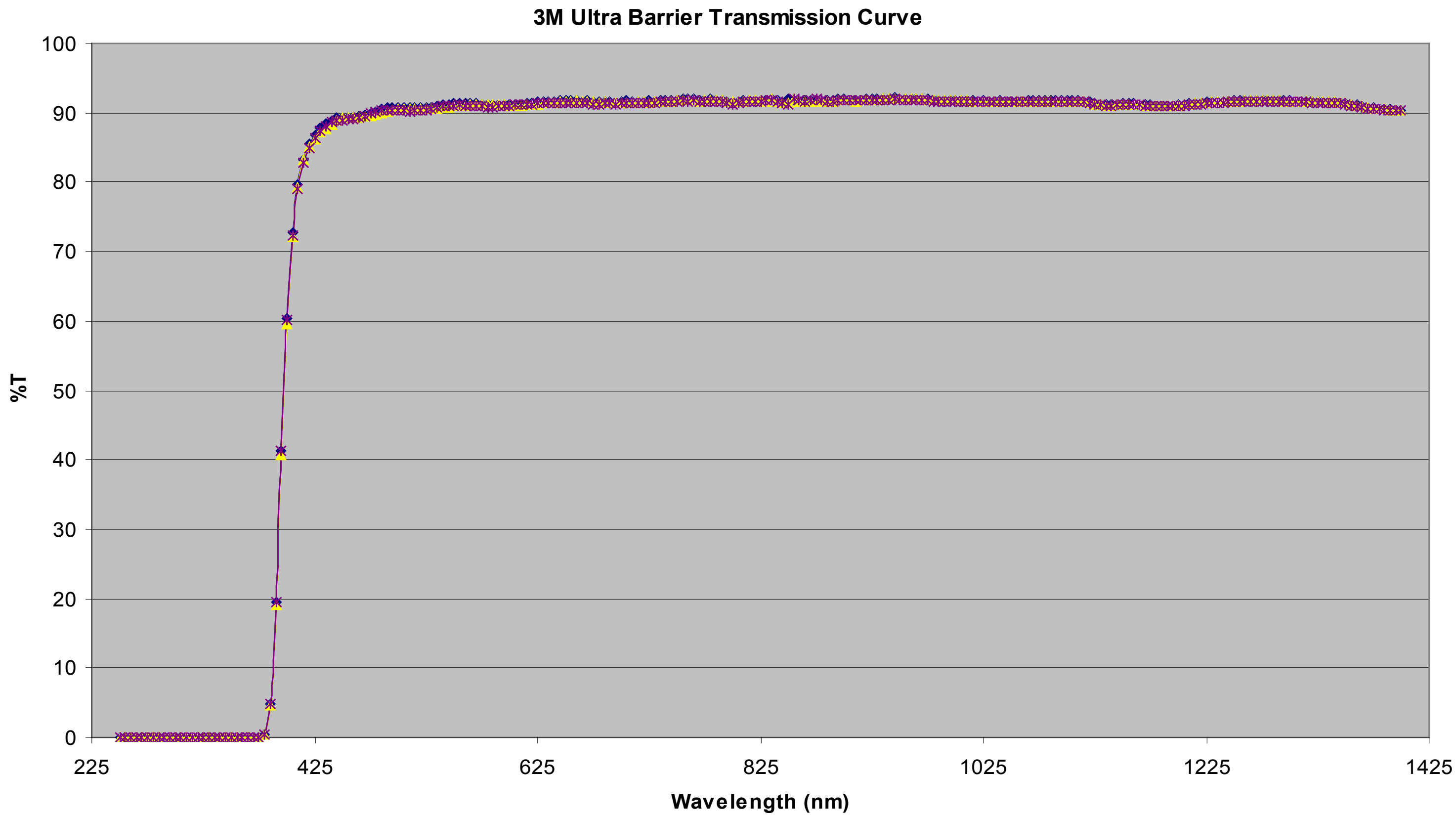
NREL e-Ca Test 45C, 85%RH



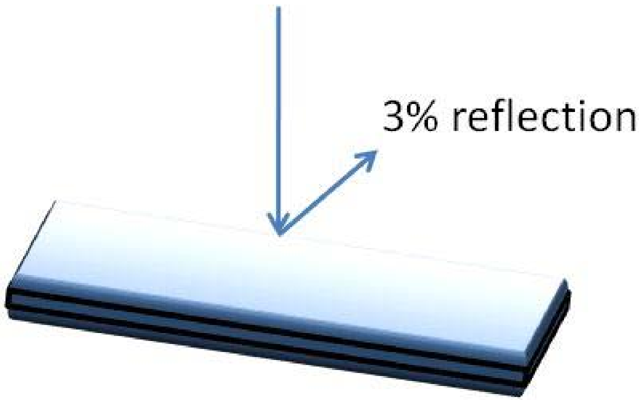
For information on e-Ca test method: Quantitative calcium resistivity based method for accurate and scalable water vapor transmission rate measurement, *Reese, M.O. , Dameron, A.A., Kempe, M.D. ,National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401, United States*
Review of Scientific Instruments, Volume 82, Issue 8, August 2011, Article number 085101



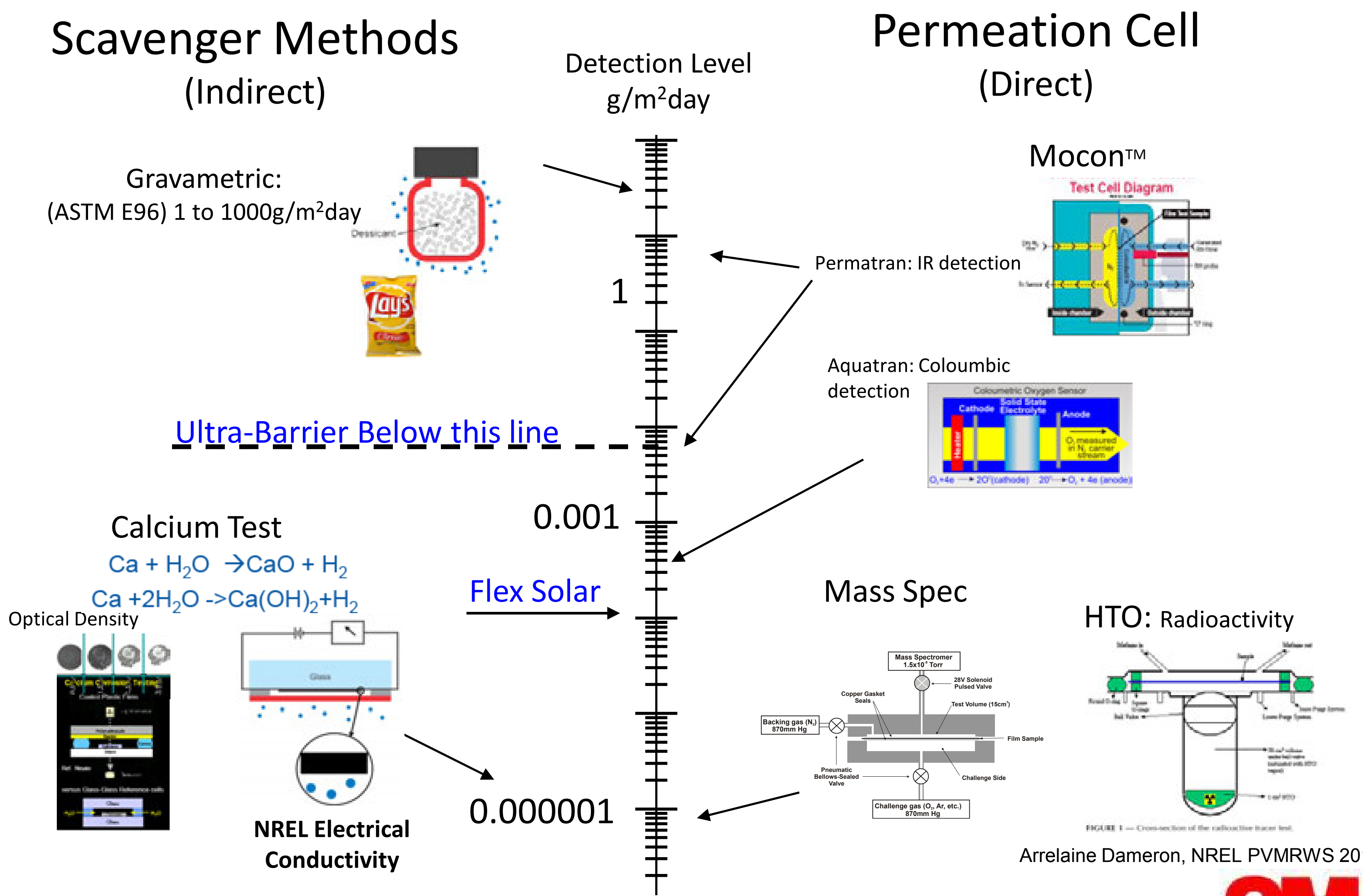




Average = 89-91% (400nm to 1400nm)



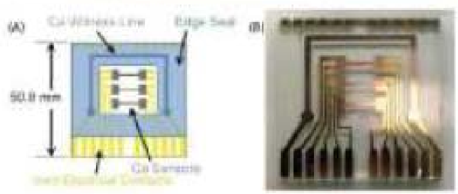
Challenges in Measuring WVTR



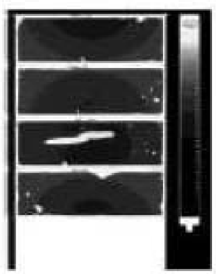
Arrelaine Dameron, NREL PVMRWS 2010

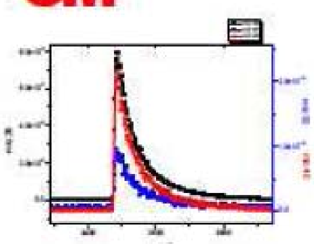
3M

Comparative Measurement Capability



3M





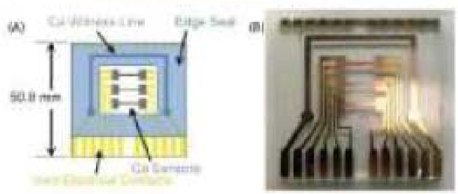
GENERAL ATOMICS

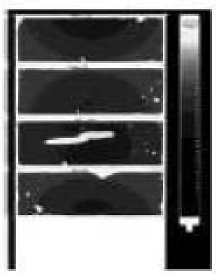
Measurement Methods

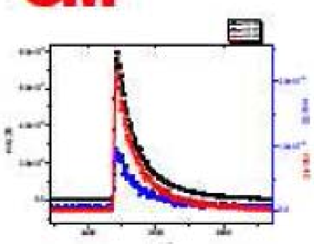
Measurement	Source	Lower Detection Limit ($g/m^2/day$)	Minimum Test Time Required (hours)
Infrared Sensor	Mocon™	$5x10^{-3}$	50 hours
Coulometric Sensor	Mocon™	$5x10^{-4}$	200 hours
Calcium (Resistance)	NREL	$1x10^{-6}$	200-1000
Calcium (Optical)	3M	$1x10^{-6}$	200-1000
Pulsed Valve Mass Spectrometry	3M	$1x10^{-5}$ demonstrated; Lower correlation possible	8
Tritiated Water	General Atomics	$1x10^{-8}$	100

3M

Comparative Measurement Capability







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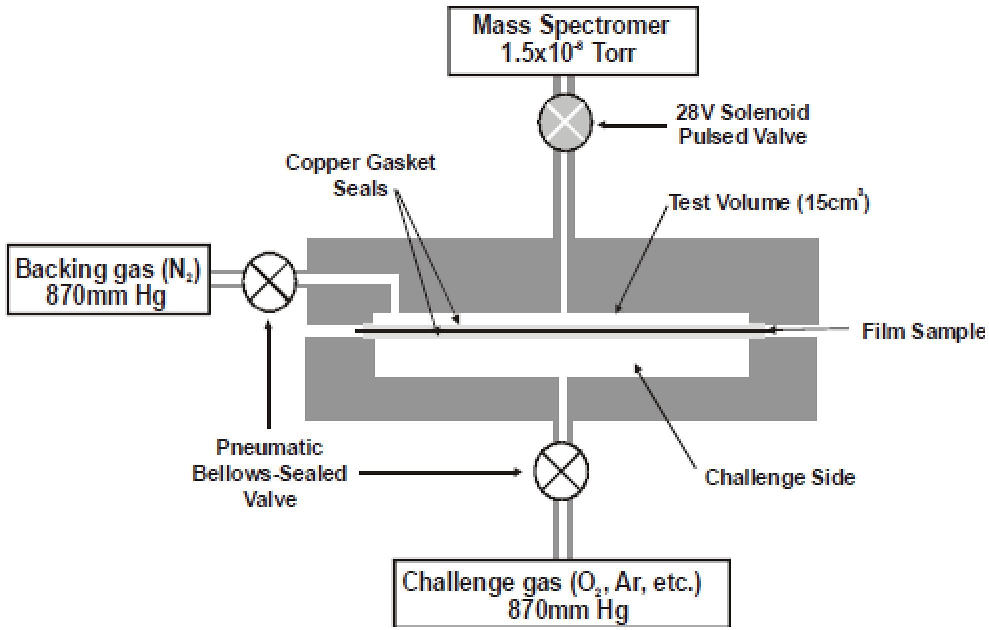
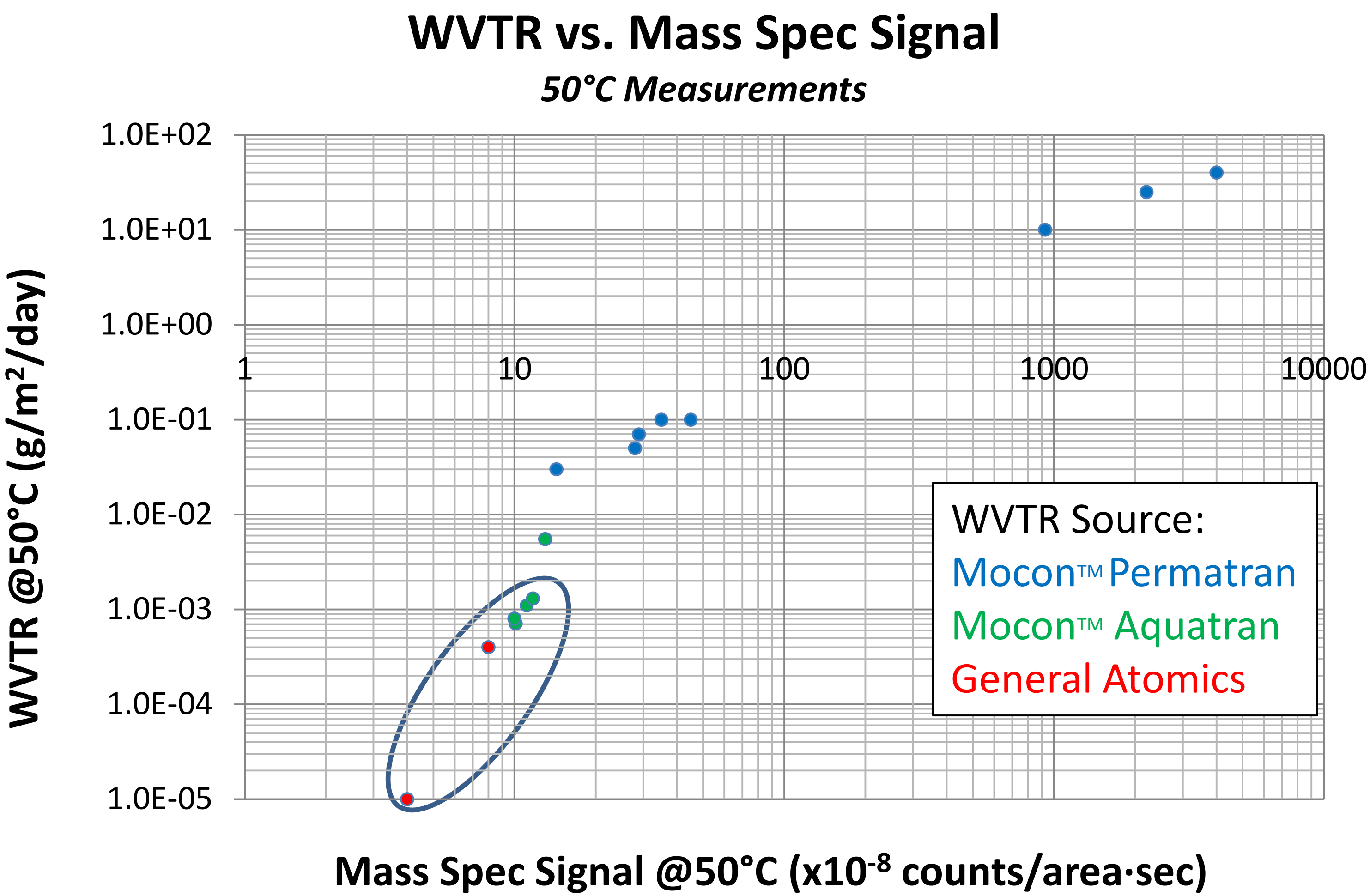
3M Developed Mass Spec Tool

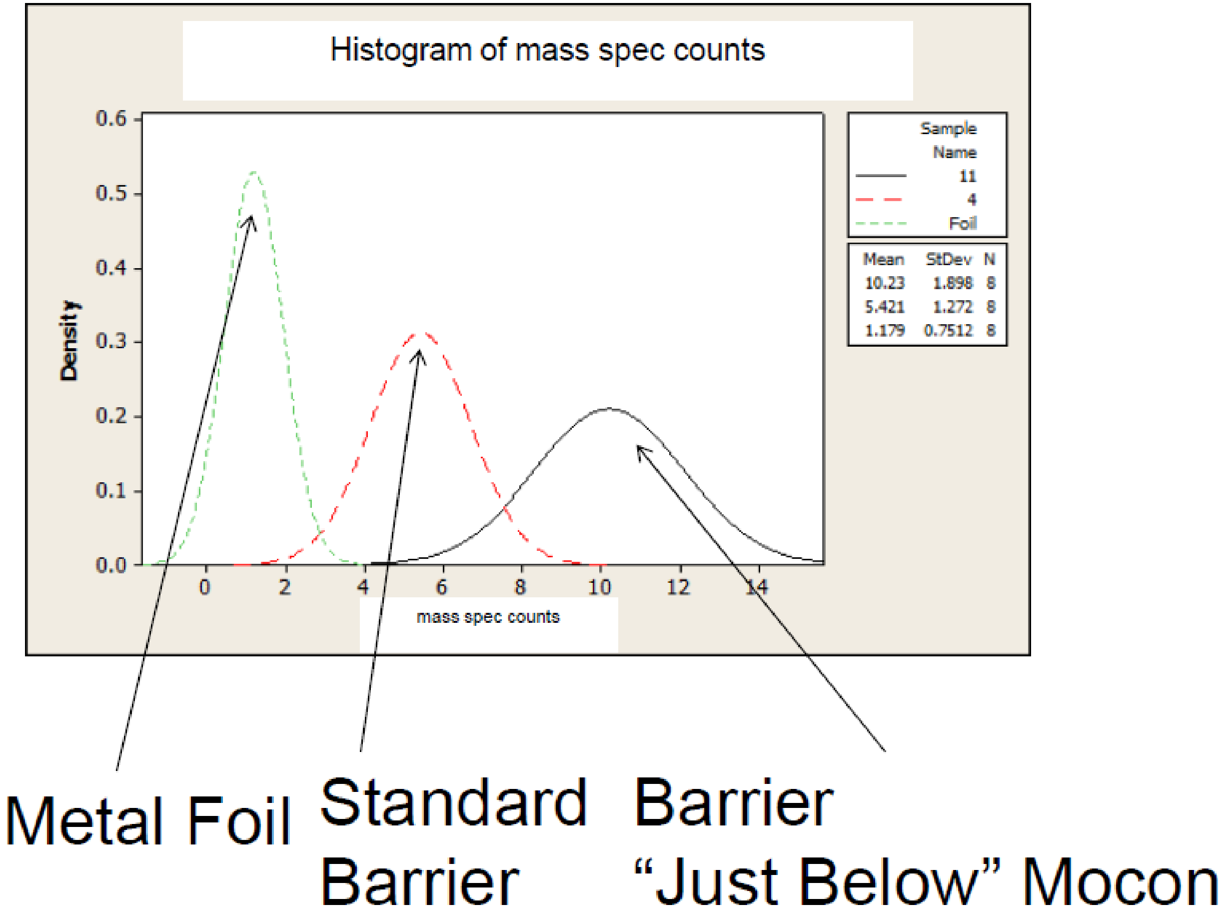


5x higher throughput than Mocon™ Permatran
100x improved barrier quality detection

Mass Spectrometry Measurements Correlate to WVTR



Recent MSA


Histogram of mass spec counts
Density
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
10
12
14
mass spec counts
Sample Name
11
4
Foil
Mean StDev N
10.23 1.898 8
5.421 1.272 8
1.179 0.7512 8
Metal Foil
Standard Barrier
Barrier "Just Below" Mocon

Demonstrating Reliability

Demonstrating Reliability

Flex modules and "mock" modules

Outdoor Field Test Data

Indoor Testing

Qualification

Test to Failure

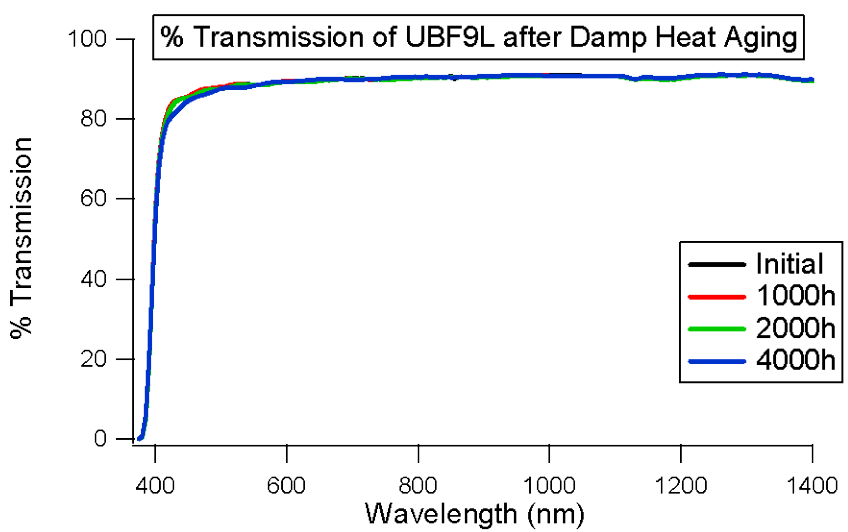
Service Life Prediction

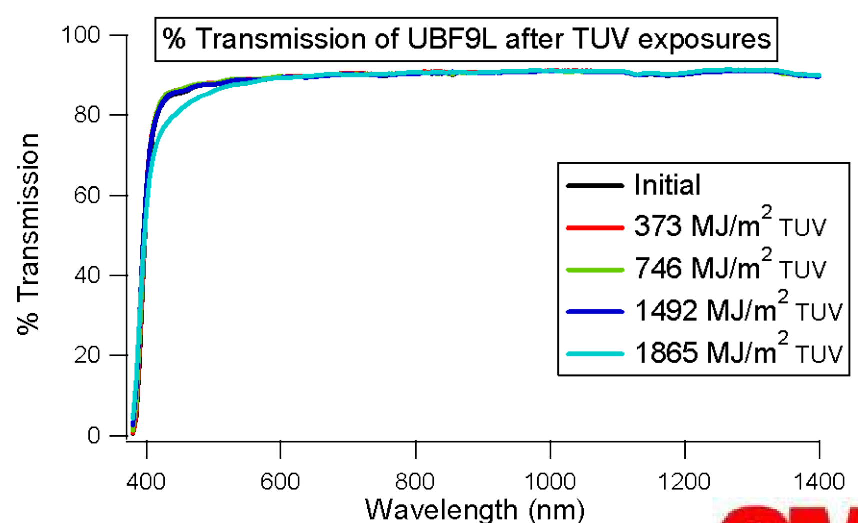
Product Lifetime

Cycle	Equivalent TUV (MJ/m2)*	WVTR (gm/m2-day)
ASTM G155 (modified)	373	<.005
	746	<.005
	932	<.005
	1865	<.005
Cycle	**Time (hours)**	**WVTR (gm/m2-day)**
85C/85RH DH	1000	<.005
	2000	<.005
	4000	<.005

*Total UV Dose (TUV) is the time integrated energy over the range 295-385 nm

Note that 1,000MJ/m^2 is roughly equivalent to 9,300 hours in ASTM G155 Cycle 1





Natural Outdoor Exposure

Multiple Locations and Environments

Static Racks (5^{o} or latitude w/ backing)

Accelerated Outdoor Exposure

2x to 5x UV range acceleration

Mirrored Enclosure

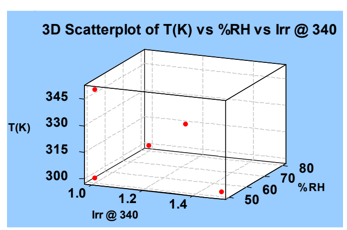
G90-type

Large area G90-type

Accelerated Indoor Exposure & Lifetime Modeling

Controlled

- Irradiance
- %RH
- Temperature



SWAT Exposure

Sequential **W**eathering **A**ccelerated **T**est

Accelerated Outdoor

+ Damp Heat
+ Humidity Freeze
+ repeat

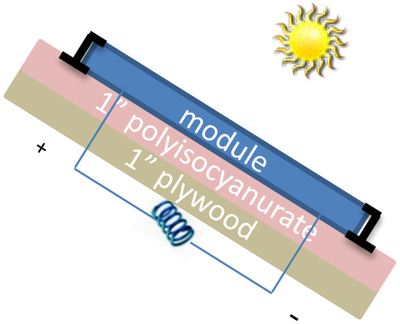
3M

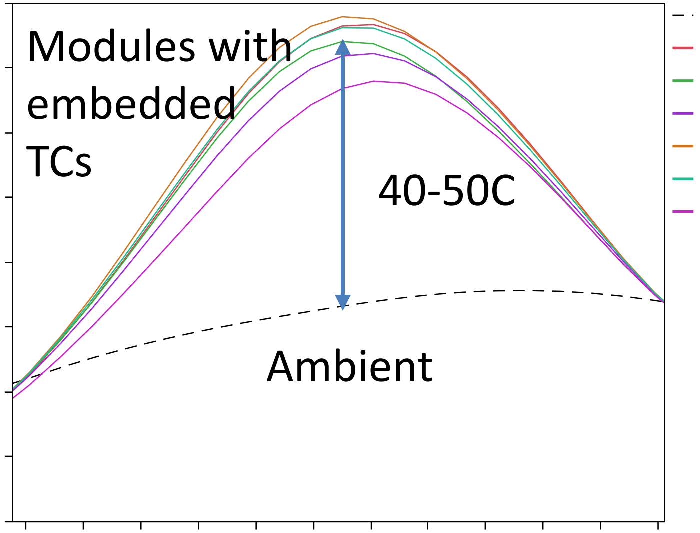
		2011												2012											
Location	**Exposure Type**	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Arizona	Natural Outdoor Static Rack																								
	Accelerated Outdoor 2.1x																								
	Accelerated Outdoor 5x																								
	SWAT																								
	Outdoor Tracking Bed																								
Florida	Natural Outdoor Static Rack																								
Colorado	Natural Outdoor Static Rack																								
Minnesota	Natural Outdoor Static Rack																								
	SWAT																								
	Indoor																								

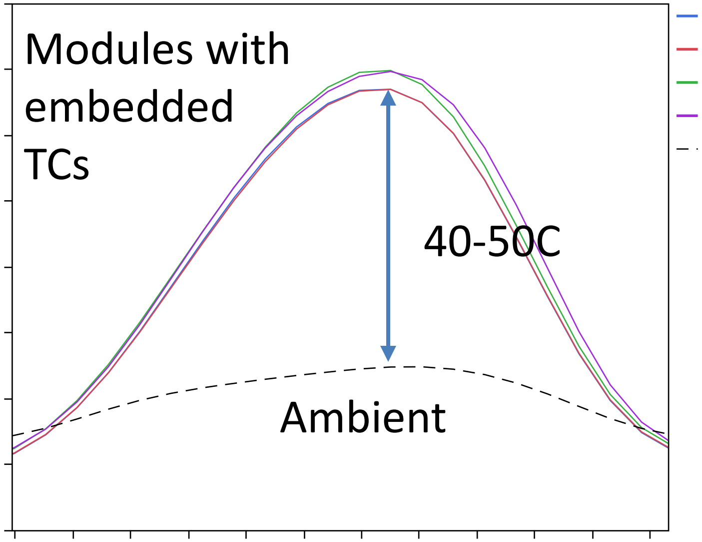
- outdoor with no acceleration
- accelerated w/ night spray
- indoor humidity-freeze
- indoor damp-heat
- indoor controlled T, RH & irrad.

3M

Data for Simulated Rooftop Mounted Flex Modules Outside





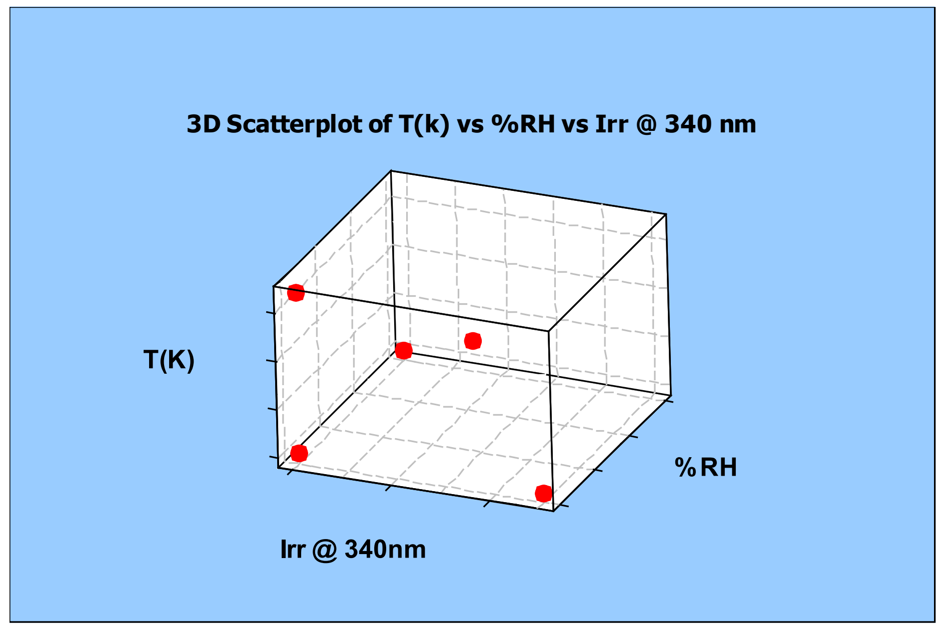


Accelerated Indoor Exposure & Lifetime Modeling

Controlled
- Irradiance
- %RH
- Temperature

Temperature	Relative Humidity	Irradiance at 340nm
BPT1	RH1	Irr1
BPT2	RH1	Irr1
BPT1	RH3	Irr1
BPT1	RH1	Irr3
BPT2	RH2	Irr2

- **Five unique accelerated stress conditions**
- **Multiple specimens per condition**
- **Performance parameters measured monthly**
- **Time to failure (80% initial Pmax) estimated by regression, per specimen**



Summary

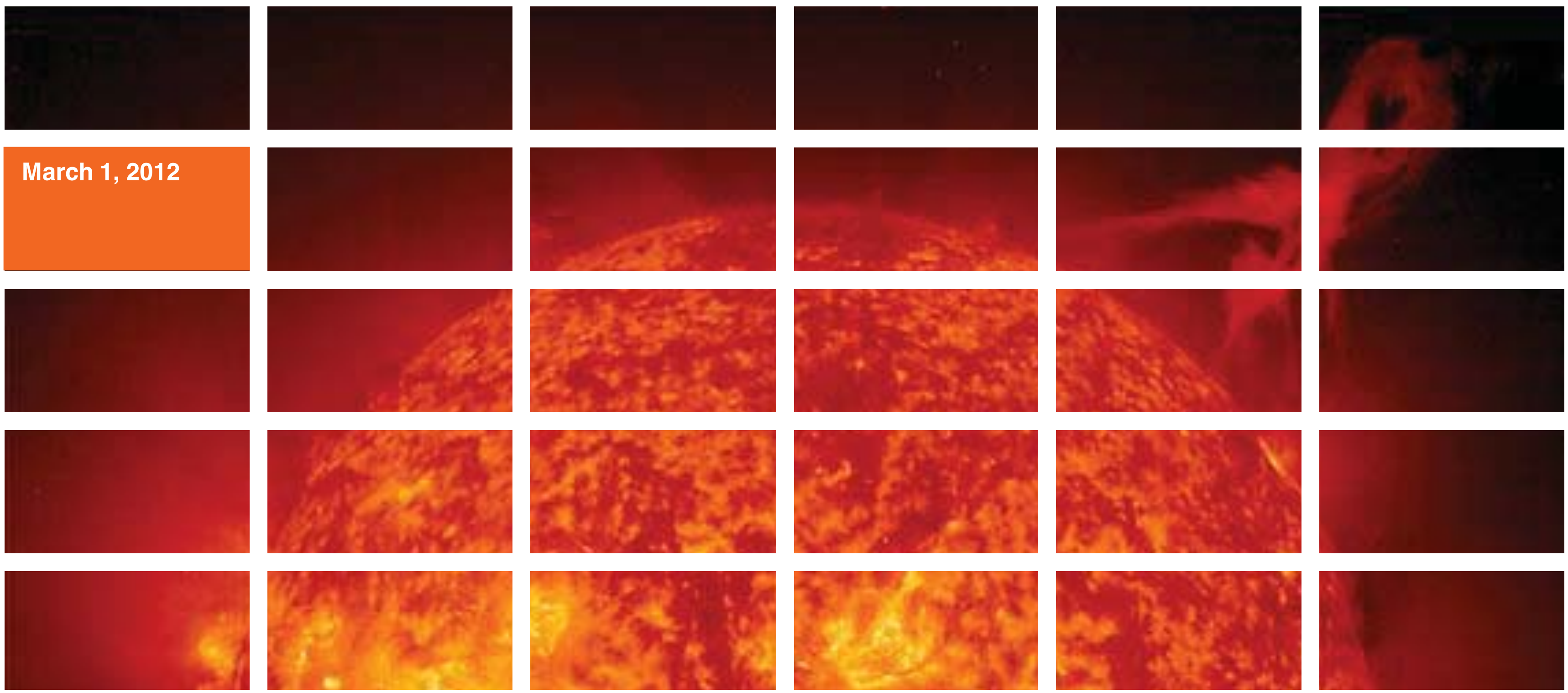
- WVTR as low as 10^{-5} g/m^2 day
- Developing fast, sensitive test for WVTR based on mass spec
- Reliability Test Plan Initiated and Collecting Data on Flex Modules, Glass Module controls and Film-Only Performance (%T, color, T&E, WVTR)
- Scale-up: Manufacturing Line in Columbia, Missouri
- 1.2m wide film with capability to go to 2m
- Launch of product expected Q2 2012

Acknowledgment: "This material is based upon work supported by the Department of Energy under Award DE-EE0004739."

abound solar

Metal Buss Tape Reliability

Jason Hevelone, Nikesh Dhar, & Chris Richardson



March 1, 2012

Why am I here?

Wisdom

Experience

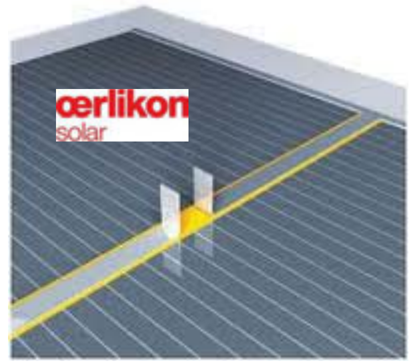
Failures

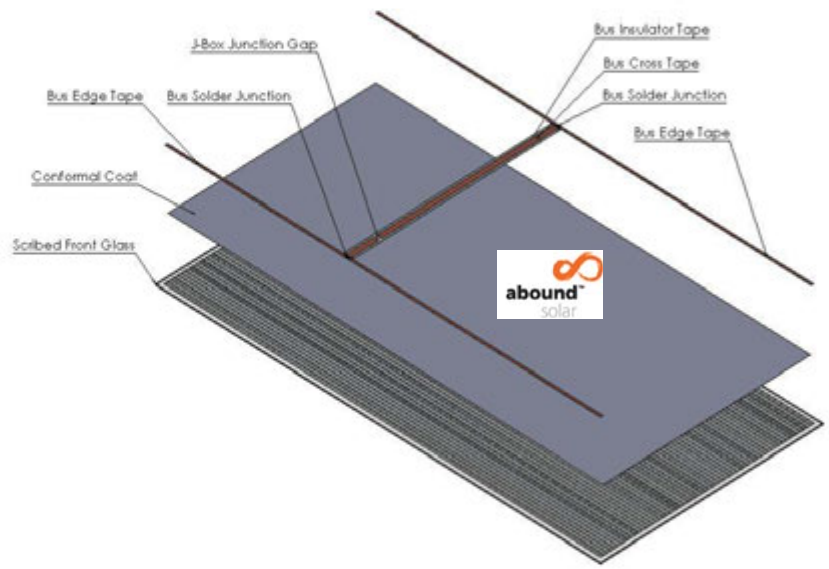
"There are no failures – just experiences and your reactions to them"

-Tom Krause

What exactly are metal buss tapes?

- Typically used for interconnect within a thin-film module to route generated power to the junction box.
- Most were derived from EMI shielding tape products and have evolved over time to meet the durability needs of PV modules





Buss Tape Technologies

Possibilities

- Metal foil with pressure-sensitive adhesive (PSA)
- Metal foil with epoxy adhesive
- Metal foil with ultrasonic soldering / resistive welding
- Metal foil with no adhesive (contract force alone)
- Others…

Embossed

Smooth

Variations

- Embossed vs. smooth
- Conductive vs. non-conductive adhesive
  - Make up and size distribution of conductive filler particles
  - Inclusion of carbon
  - Balance between adhesive and filler – conduction vs. adhesion
- Foil metallurgy
- Width and thickness
- Adhesive properties over temperature

Possible Reliability / Quality Concerns

Contact resistance shift (Rs)…worst case 'dead open'

- Joint failure
- Loss of adequate tape adhesion
- Arcing / fusing of conduction points

Current carrying capacity (ampacity)

- Tape itself
- Tape-to-back metal
- Tape-to-tape joint

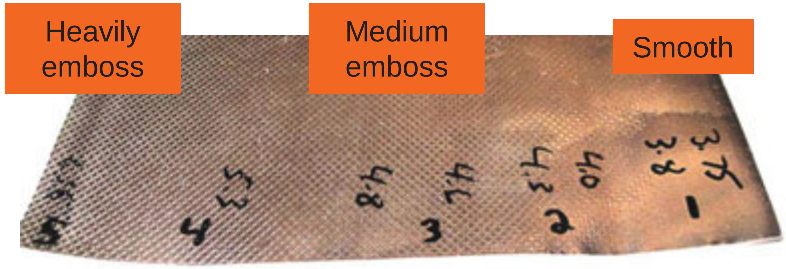
Arcing between tapes at junction box (spacings)

Shorting out adjacent cells (loss of power)

Metallurgical compatibility (galvanic corrosion)

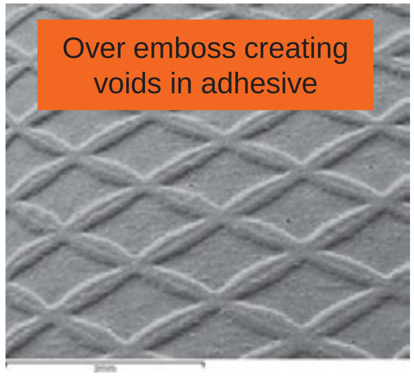
Material CTE mismatches (Coefficient of Thermal Expansion)

Process Variability



- Roller pressure
- Roller durometer
- Roller wear out
- Speed of tape application
- Adhesive wetting
- Embossing depth control
- Conductive filler particle size & distribution
- Uniformity of conductive filler particles in adhesive
- Ability of tape vendors to monitor quality factors important for PV durability
- Slitting quality (coining, slitting tool wear, adhesive contamination, liners, etc)
- Tape batch variations and ability to detect good vs. bad (i.e. quality controls)
- Adhesive voids (i.e. trapped air pockets)
- Cleanliness of surface in contact with tape
- Topology of surface in contact with tape

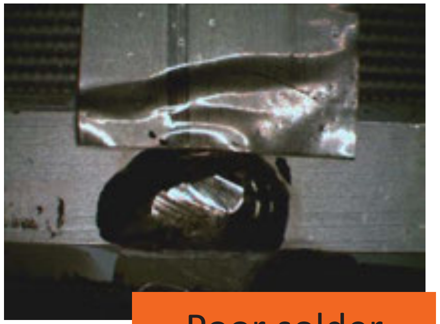
And the worst…variability you don't know that you don't know about (ignorance is not bliss!)



Catastrophic ~~failures~~ experiences and your reactions to them

Buss damage along length of collector buss

Buss damage as seen from the backside of the module



Poor solder joint wetting

T-Joint failures

Film damage at burned conduction points

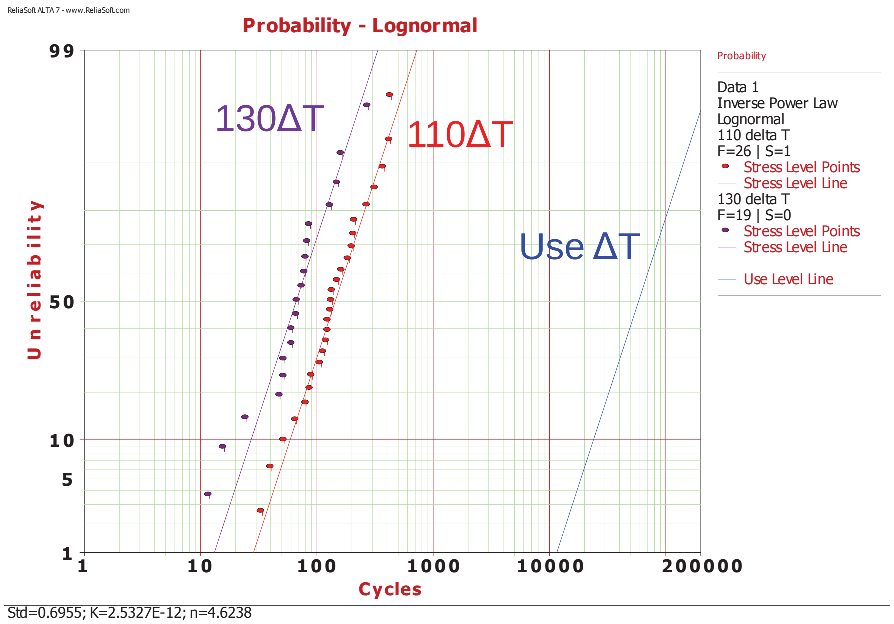
How best to accelerate buss tape failure mechanisms?

Stress Test	Catch Buss Failure Mechanism?	Reason
Temperature Cycling Test: UL1703, 35 (-40C to +90C, 200 cycles, small fwd bias current to assure continuity during cycle)	Occasionally	Failure mechanism requires both thermal fatigue and ***high current flow*** during cycles
High Temperature Bake (90C, 1000 hours, with and without high fwd bias current)	No	Failure mechanism requires both ***thermal fatigue*** and high current flow
Reverse Current Overload: UL1703, 28 (Fwd bias at 130% of fuse rating, 1 hour)	Occasionally	Failure mechanism requires ***thermal fatigue***. Much higher current flow (>200-500% of Isc) and longer stress duration increase chances of detecting failure mechanism. Hard to correlate to product lifetimes.
Damp Heat: IEC61646, 10.13 (85C, 85% R.H., 1000 hours, unbiased)	No	Failure mechanism requires both ***thermal fatigue*** and ***high current flow***
Humidity Freeze: UL1703, 36 (-40C to +85C/85%R.H., 10 cycles, small fwd bias current to assure continuity during cycle)	No	Failure mechanism requires both thermal fatigue and ***high current flow*** during cycles. Ten cycles is insufficient to provide enough thermal fatigue.
High Current Stress Temperature Cycling (-40C to +90C, test to failure, high fwd bias current, >2x-4x Isc)	Yes	Failure mechanism requires both **thermal fatigue** and ***high current flow*** during cycles. Must test to failure in order to get to tape wear-out.

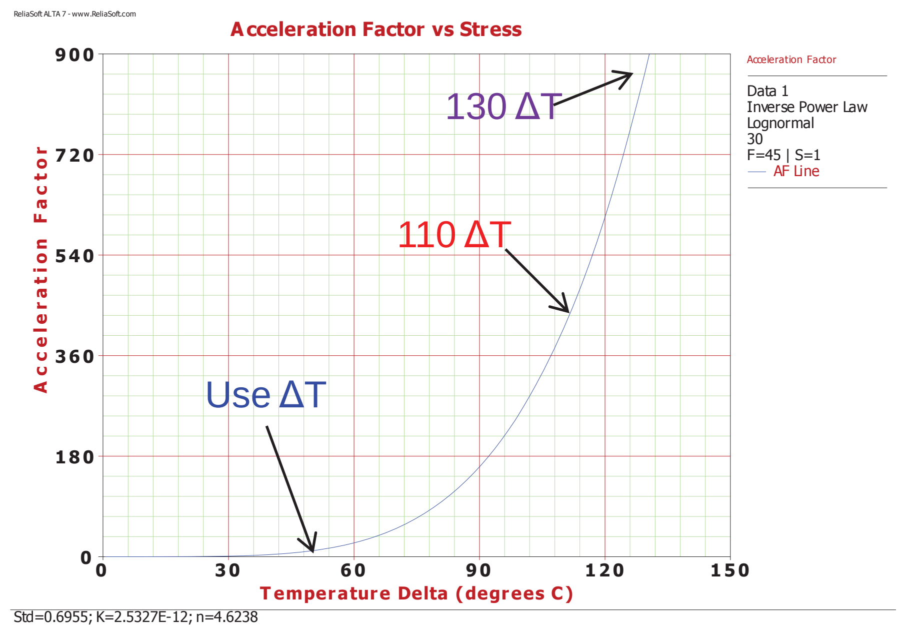
Existing UL/IEC test methods are often insufficient to catch buss tape durability failure mechanisms

Temperature Cycle with varied ΔT, constant DC current

Looking at effects of two different ΔT stress levels



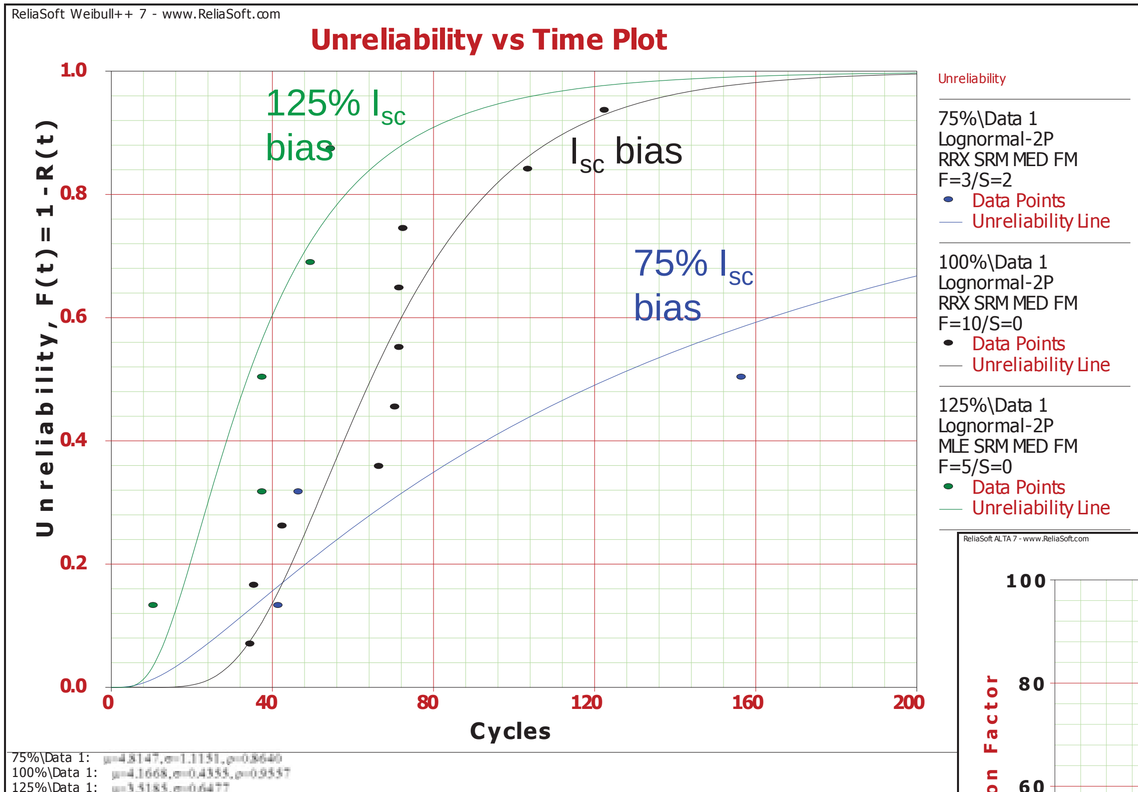
Buss Tape Details:
- Conductive adhesive
- High temperature rated adhesive
- UL Listing for PV



Observations:
- Thermal fatigue (Δ T) is a significant accelerant for buss tape failure
- The use of two or more stress conditions allow for extrapolation to use conditions and hence projections on ability to meet warranty for different climatic geographies
- A third Δ T condition will improve use condition prediction accuracy and narrow confidence bounds

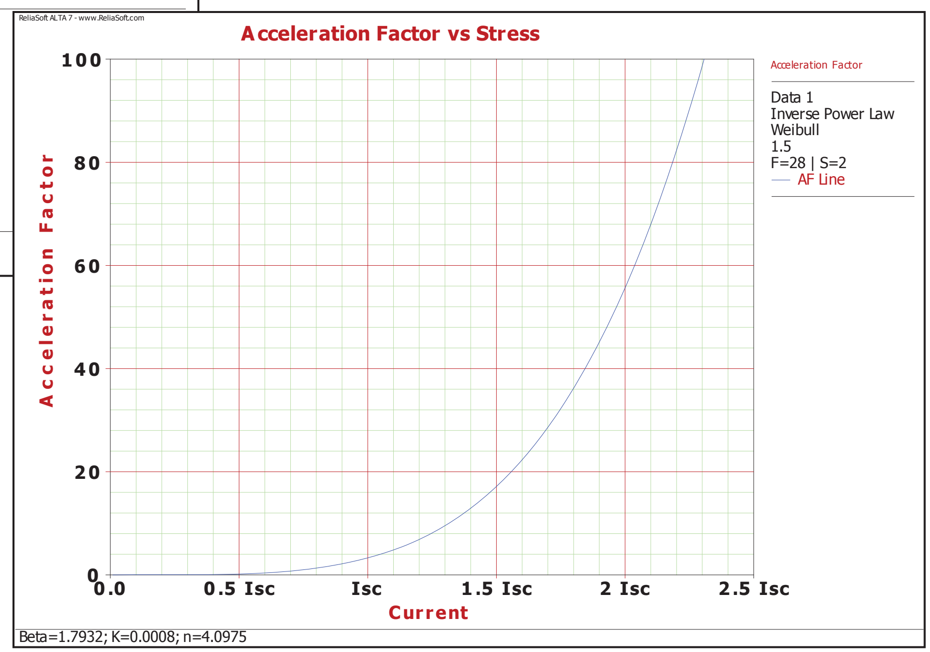
Temperature Cycle with constant ΔT, varied DC current

Looking at effects of three different current (irradiance) stress levels



Buss Tape Details:

- Non-conductive adhesive
- “General purpose” temperature rating (i.e. not high temp rated)
- Former EMI tape with UL Listing for PV

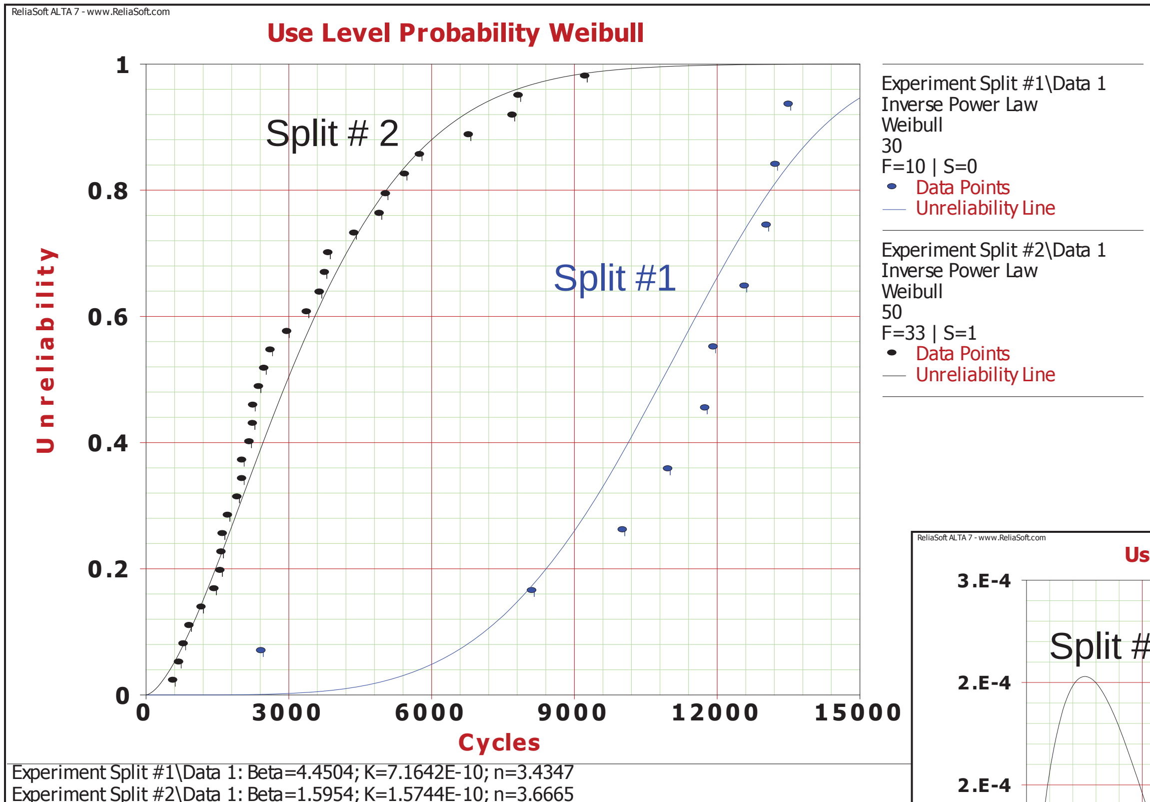


Observations:

- Current (irradiance) is a significant accelerant for buss tape failure (ampacity)
- Tape UL Listing does not guarantee adequate PV reliability

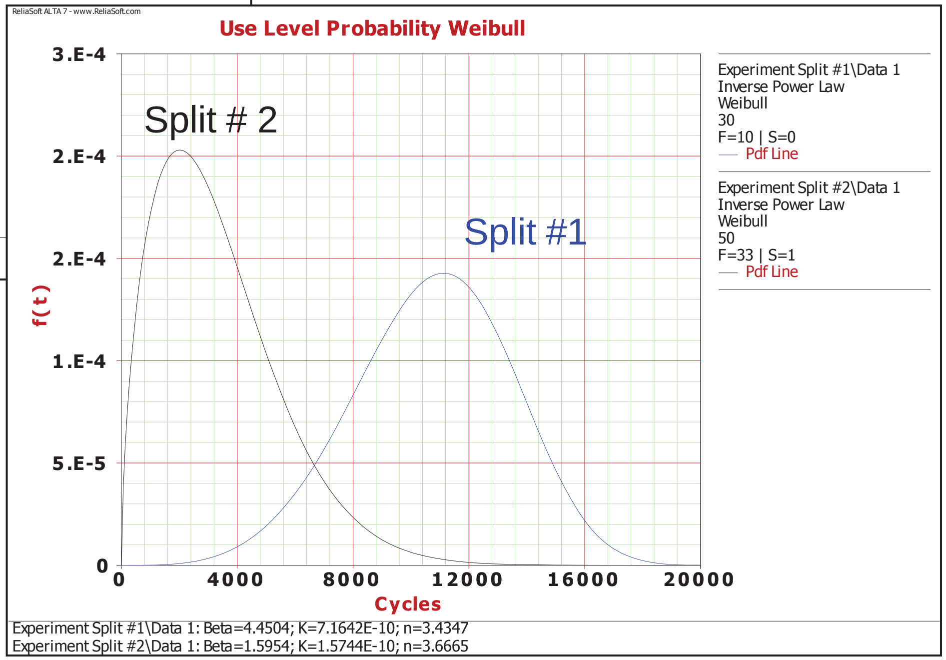
Temperature Cycle with varied ΔT, constant DC current

Looking at effects of two different manufacturing process parameters



Buss Tape Details:

- Conductive adhesive
- High temperature rated adhesive
- UL Listing for PV



Observations:

- Tape reliability can be significantly modulated with processing parameters / variability

Control your variability & optimize your process

Quantifying ΔT Cycle Counts from Weather Data

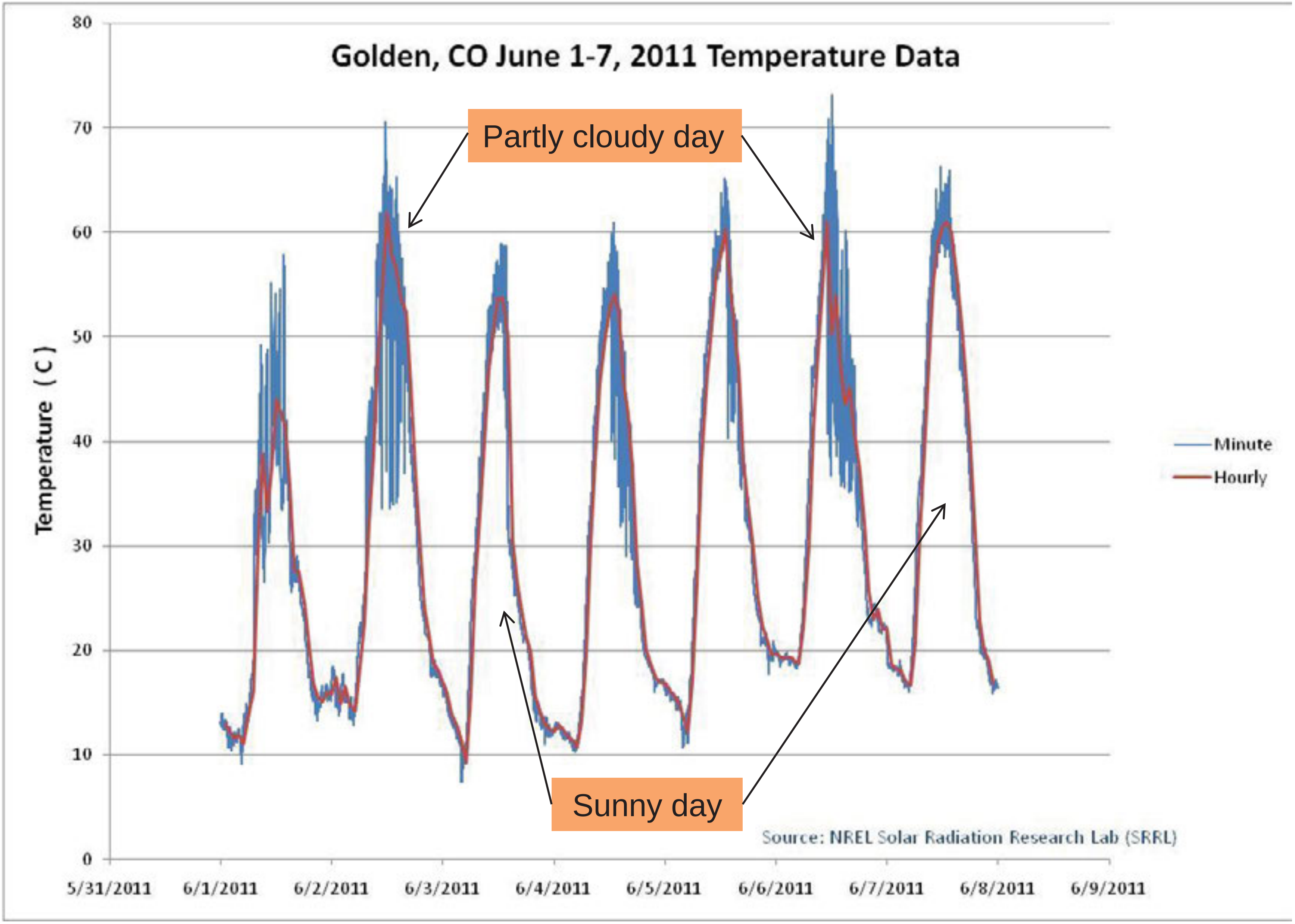
- Need to characterize and establish a Cell Temperature Model for your product based on readily available weather measurements such as ambient temperature, wind speed and irradiance [1, 2]

- Sampling rates of weather data can have a big influence on cycle counts, particularly on partly cloudy days. [3] *This is often an issue with publically available weather data, which tends to average raw data or record measurements too infrequently (ex. hourly)*

- Need to select a cycle counting algorithm[3,4] (ex. Rainflow or Peak & Valley) and means to process weather data into temp cycle counts such as StoFlo™[5]

- Seasonality and geography are huge factors in the accumulation and magnitude of ΔT cycles[3]

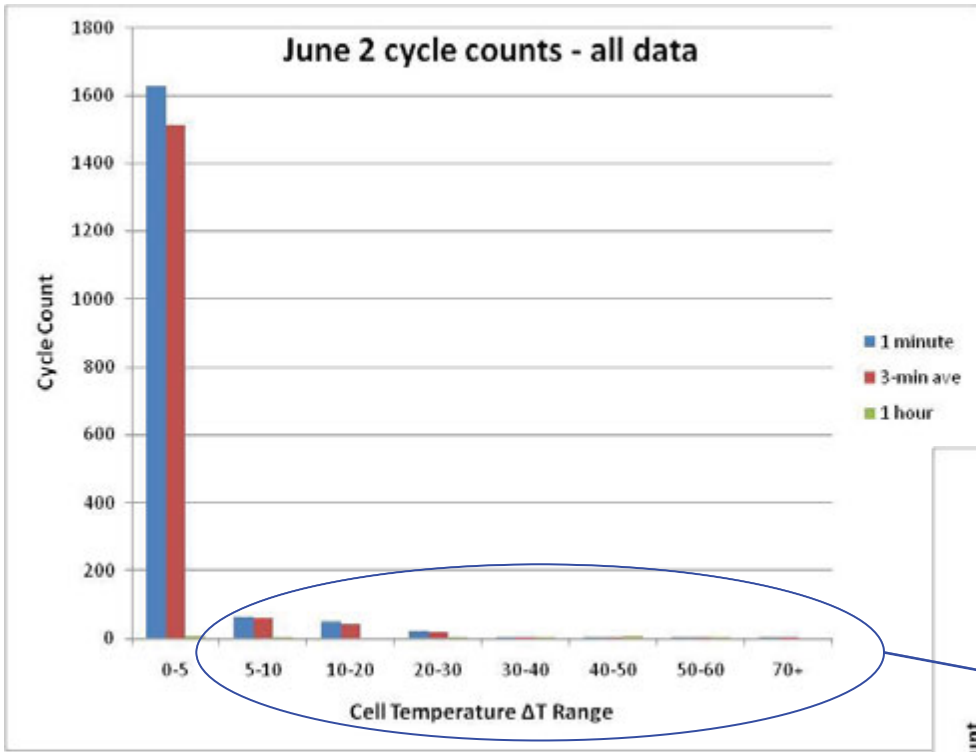
Quantifying ΔT Cycle Counts from Weather Data

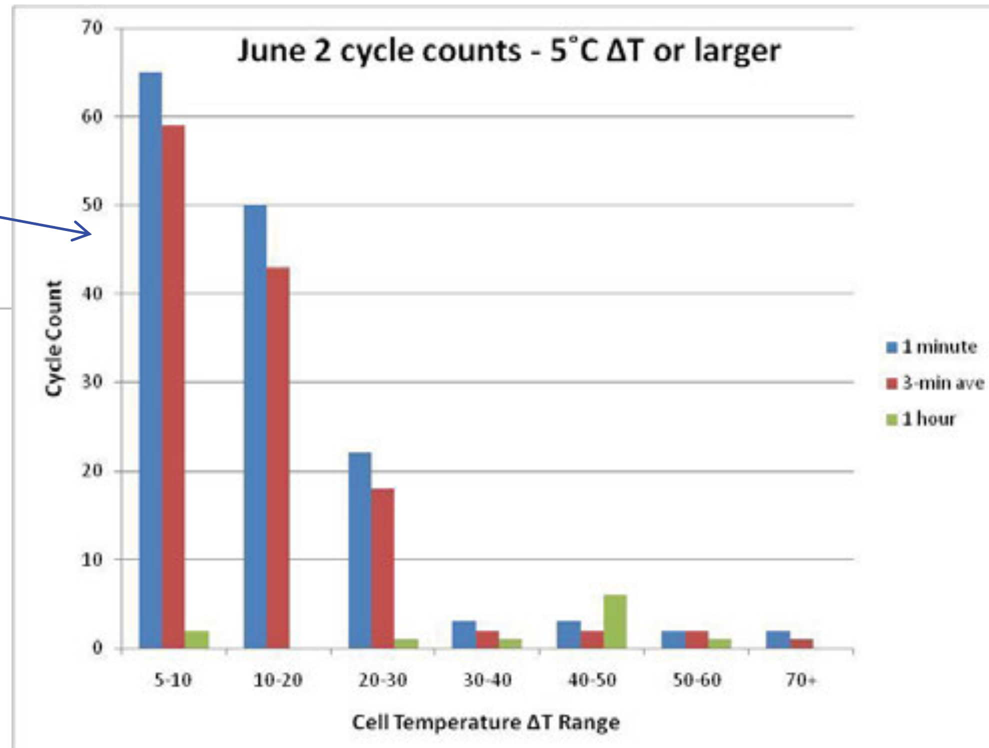


Histograms of Cycle Count data

1 minute data		
Bin	*Frequency*	*Cum %*
5	1627	91.71%
10	65	95.38%
20	50	98.20%
30	22	99.44%
40	3	99.61%
50	3	99.77%
60	2	99.89%
70	2	100.00%

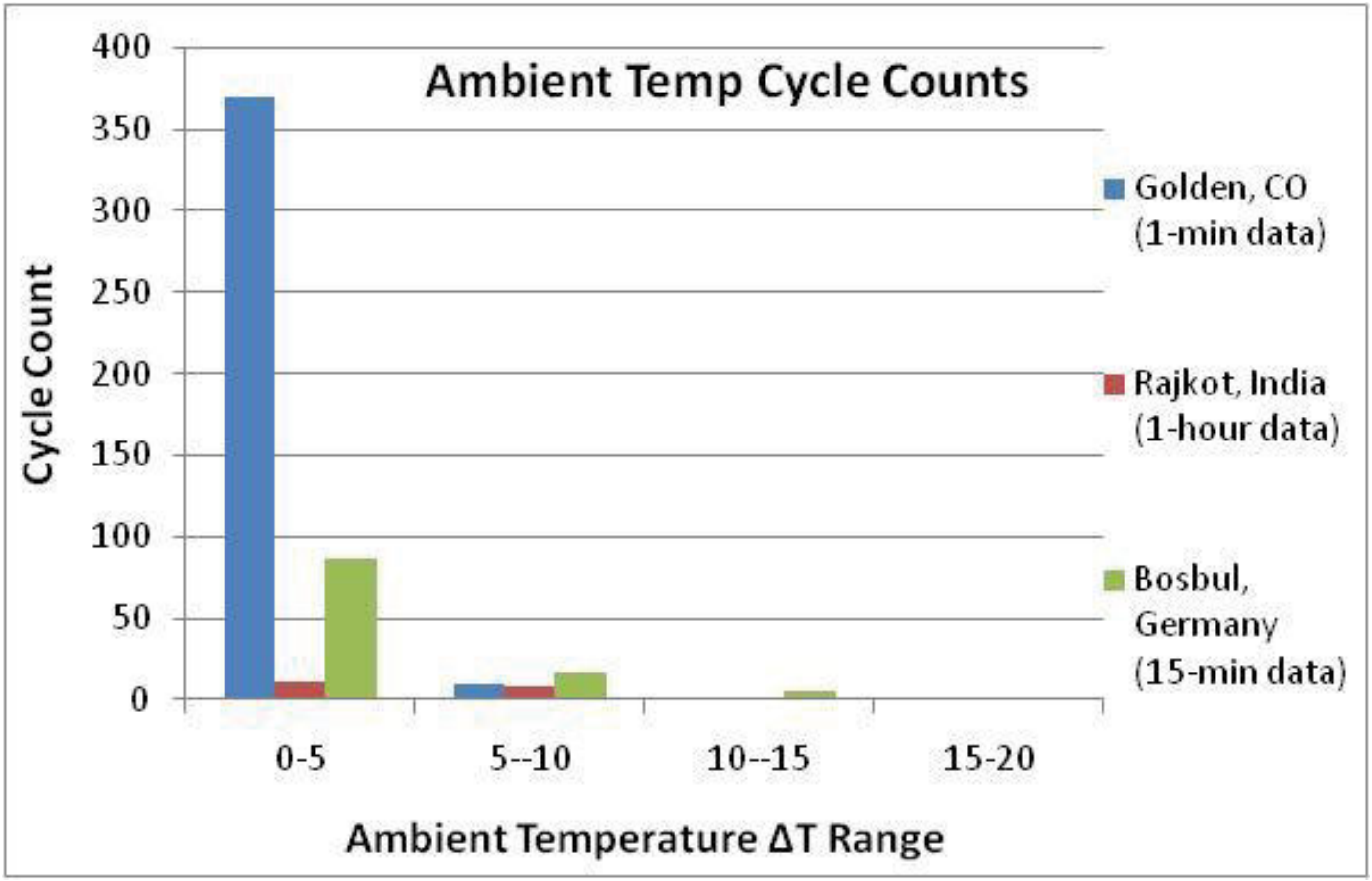
1 hour data		
Bin	*Frequency*	*Cum %*
5	9	45.00%
10	2	55.00%
20	0	55.00%
30	1	60.00%
40	1	65.00%
50	6	95.00%
60	1	100.00%
70	0	100.00%





Hourly data grossly underestimates the amount of thermal fatigue during partly cloudy day

Geography and measurement interval differences



- Cycle count depends largely on location[3]
- Readily available weather measurement data varies considerably
  - 1-hour interval weather data is very gross and inadequate to model predictions
  - 15-minute interval weather data is better, but not ideal
  - 1-minute interval weather data is best and recommended

Tying lab data to weather for field projections

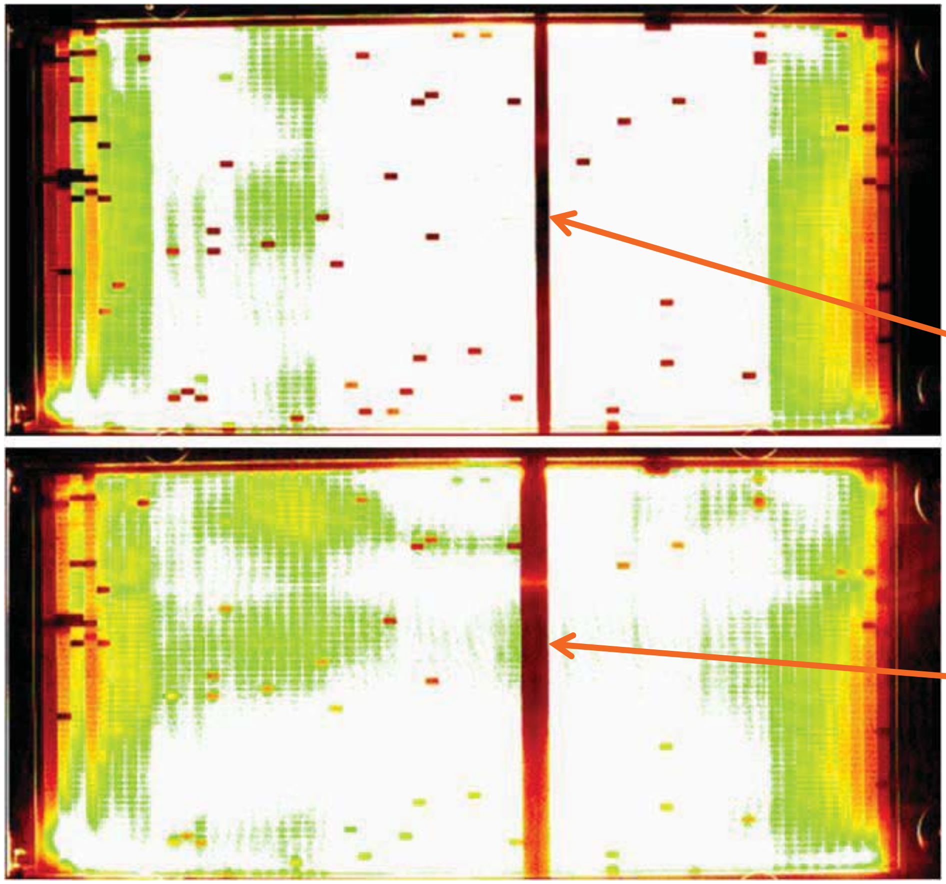
- Multiple condition stress test data and actual field failure data can be entered into an accelerated life test analysis tool such as ReliaSoft's ALTA®

- Data is used to find a best fit failure distribution curve
  - Data can include suspensions (i.e. modules that have survived some amount of time/stress – majority of field samples)
  - Temperature profiles can be fed into software as an input to account for different geographies, times of year, etc.
  - Monte Carlo analysis can be used to tighten confidence bounds when analysis sample sizes are limited
  - Time-to-failure, confidence intervals, failure mechanism activation energies, acceleration factors, and warranty information can be calculated at different geographies

Predictability

FA techniques – LBIC (Light Beam Induced Current)

LBIC used in conjunction with 2 cm lengths of perpendicular laser isolation



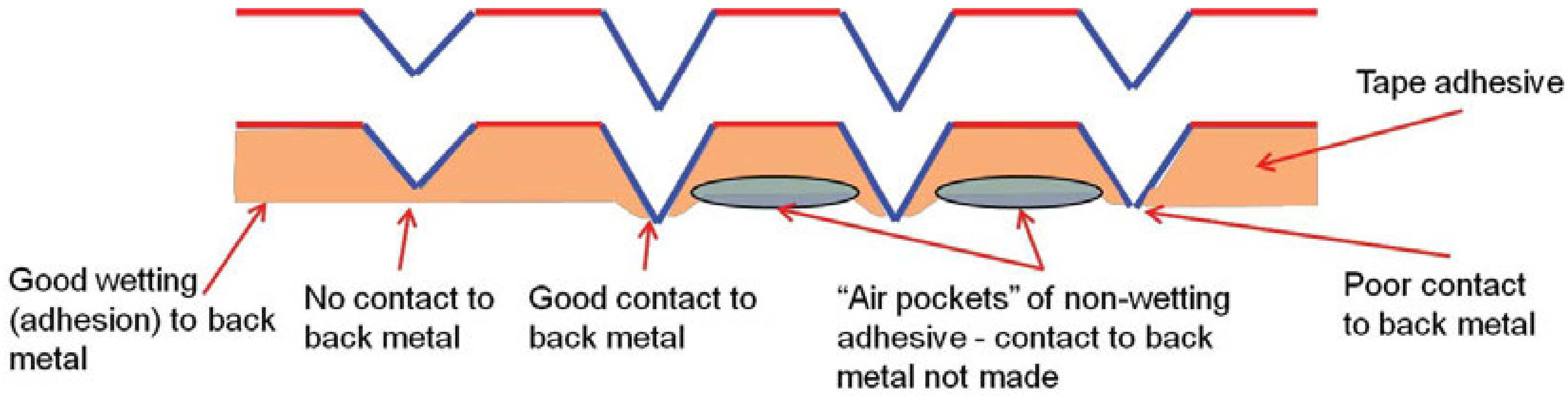
LBIC Description

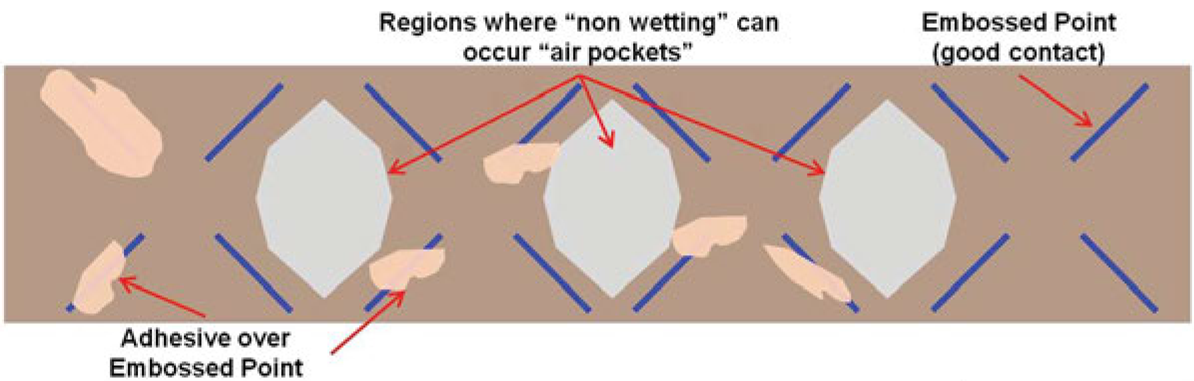
- Scanning of a light beam over a cell while measuring the resulting short-circuit current for each position.
- The collected current variations are correlated to laser locations resulting in a current map.

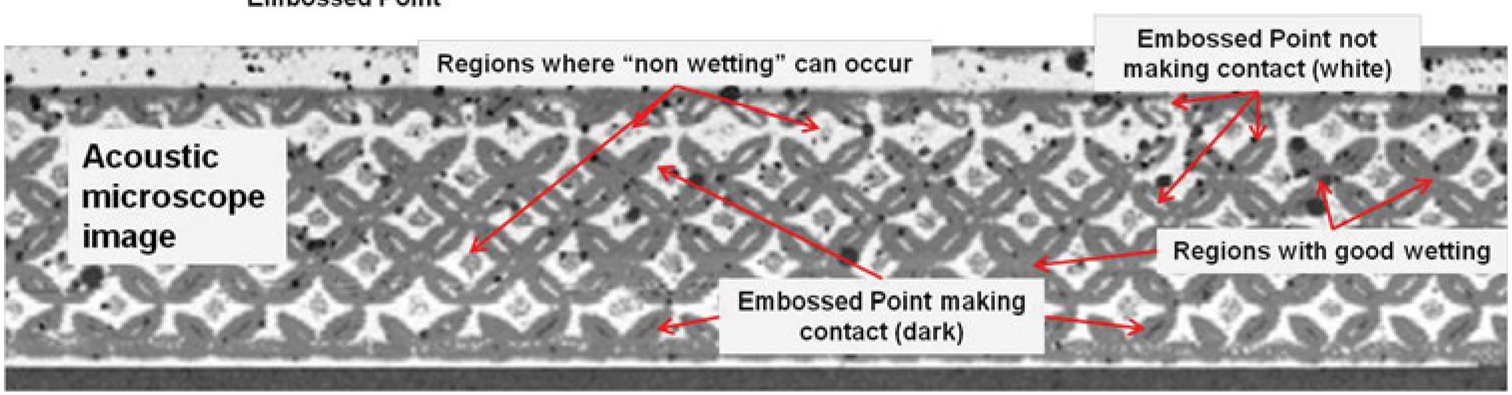
Dark vertical line shows location where a 2 cm length of the metal buss tape is not making contact with the back metal

After additional stress testing, another 2 cm length of metal buss tape has failed

FA Technique – Acoustic Analysis

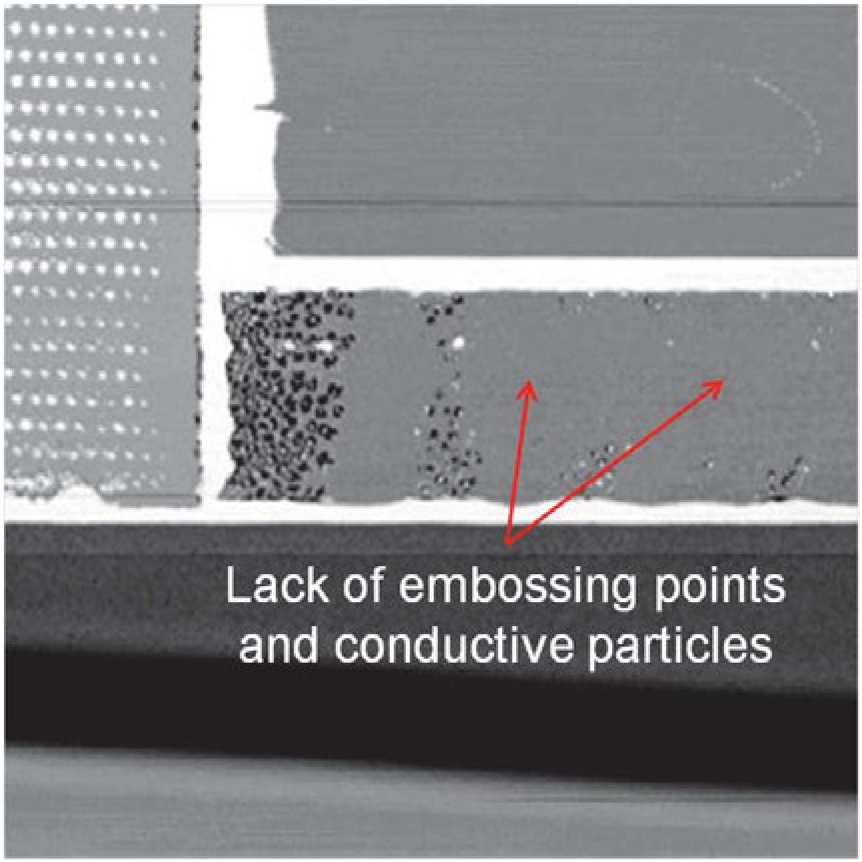




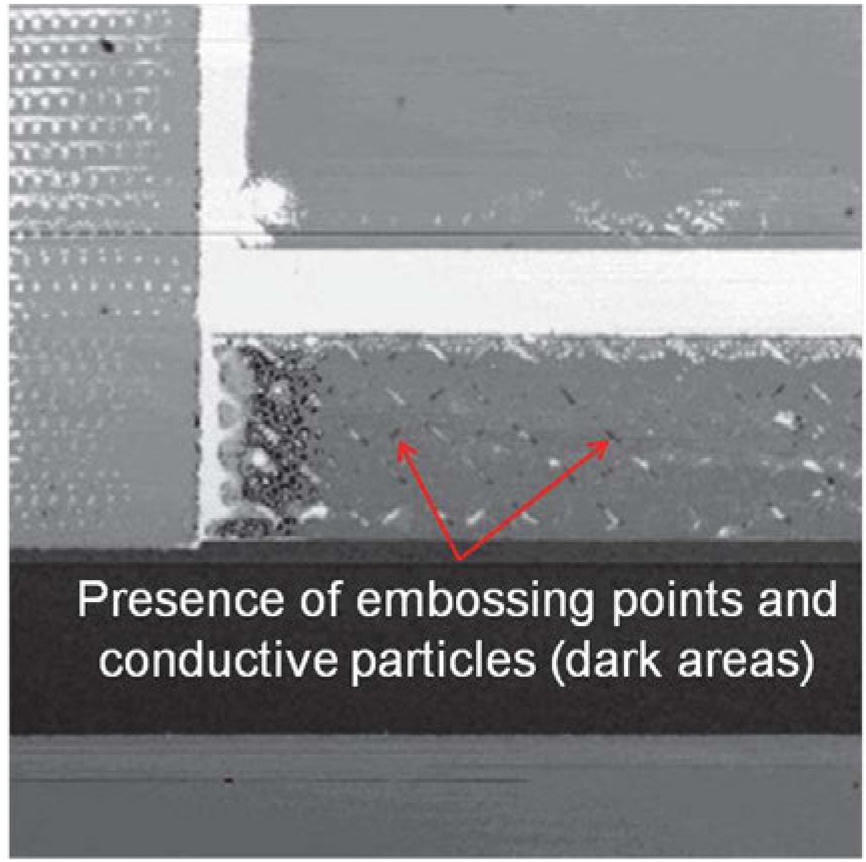


FA Technique – Acoustic Analysis (2)

Acoustic image of poor tape application that results in buss tape failure



Acoustic image of good tape application that results in reliable buss tape

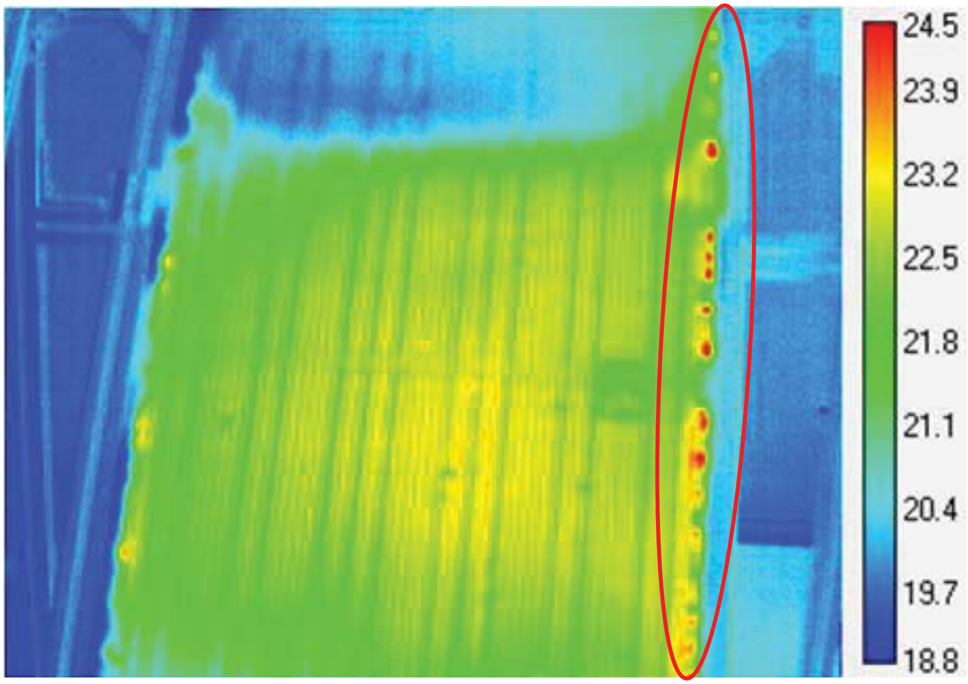


FA Technique - Thermography

- **Infrared (IR)** imaging is a technique that has been in existence for a long time.
    - Great at finding shunt related defects that have a high thermal emission
    - Cannot easily detect series related resistances due to uniform thermal heating
    - Technique is limited by spatial resolution and thermal diffusion due to integrating under full power over time

- **Lock-in Thermography (LIT)** synchronizes the excitation source (light, voltage, etc.) to the IR camera's data acquisition
    - Allows detection of subtle thermal responses beyond the noise floor limitations of the IR camera.
    - Mapping of the weaker shunting/series resistance defects are enabled because of the better detection limits.
    - A much lower excitation is needed to acquire the thermal response on a module, this prevents over current/voltage stressing of the module which will result in damage.

FA Technique - Infrared (IR) camera



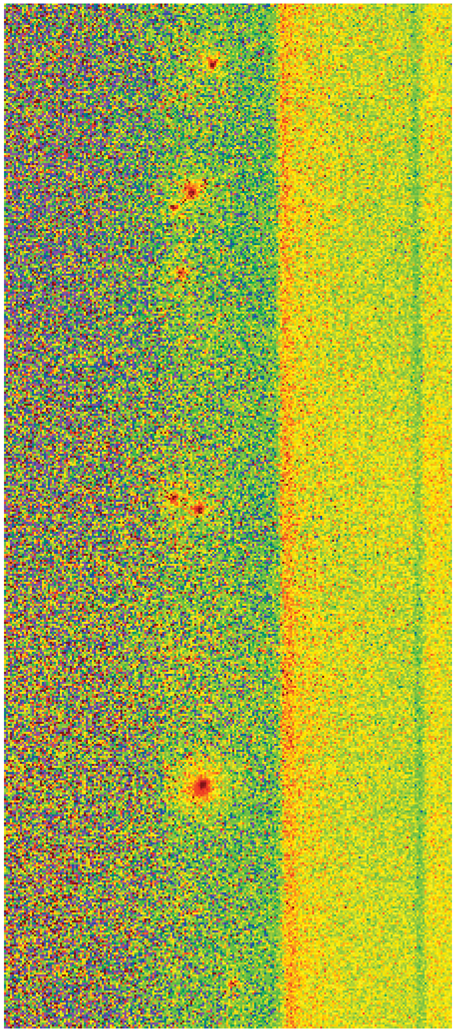
IR image showing poor ohmic contact areas along metal buss tape prior to failure

IR spatial resolution and thermal diffusion usually limit its usefulness for buss tape analysis

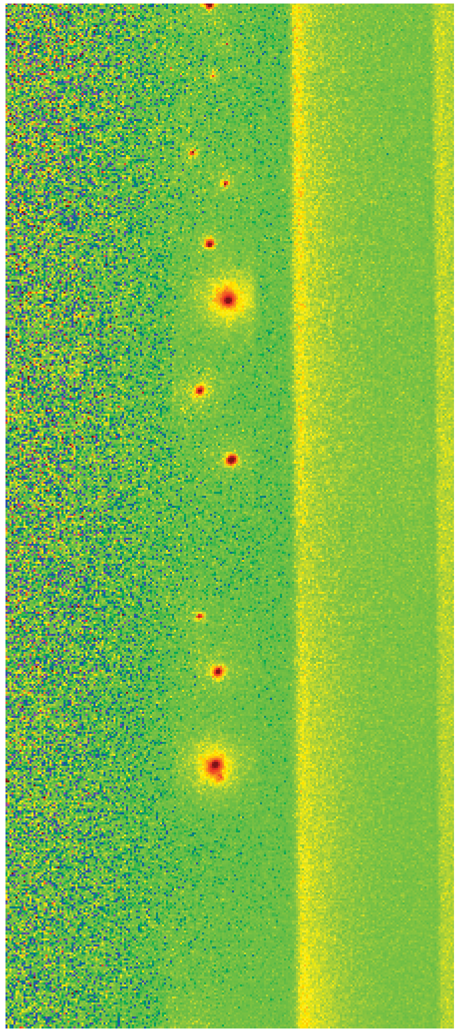
FA Technique – Lock-in Thermography

Inadequate buss tape

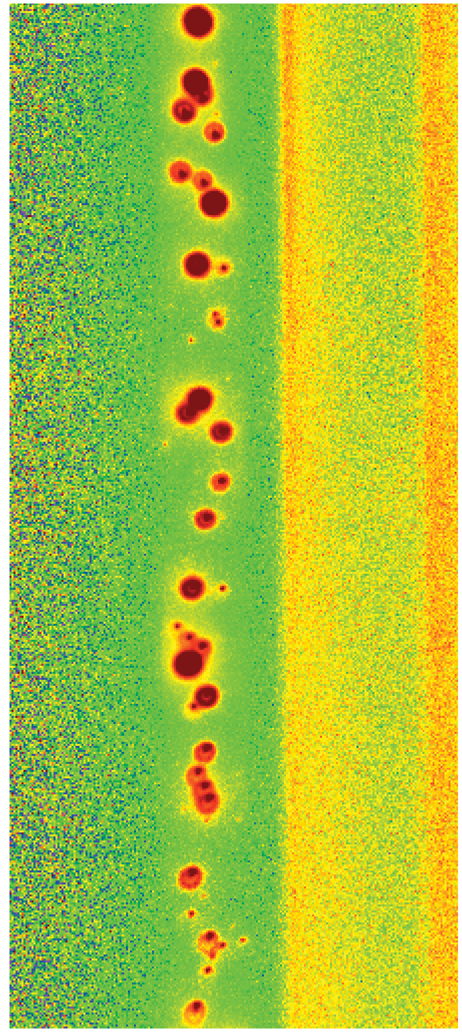
Time Zero



Post 24 Cycles



Post 74 Cycles

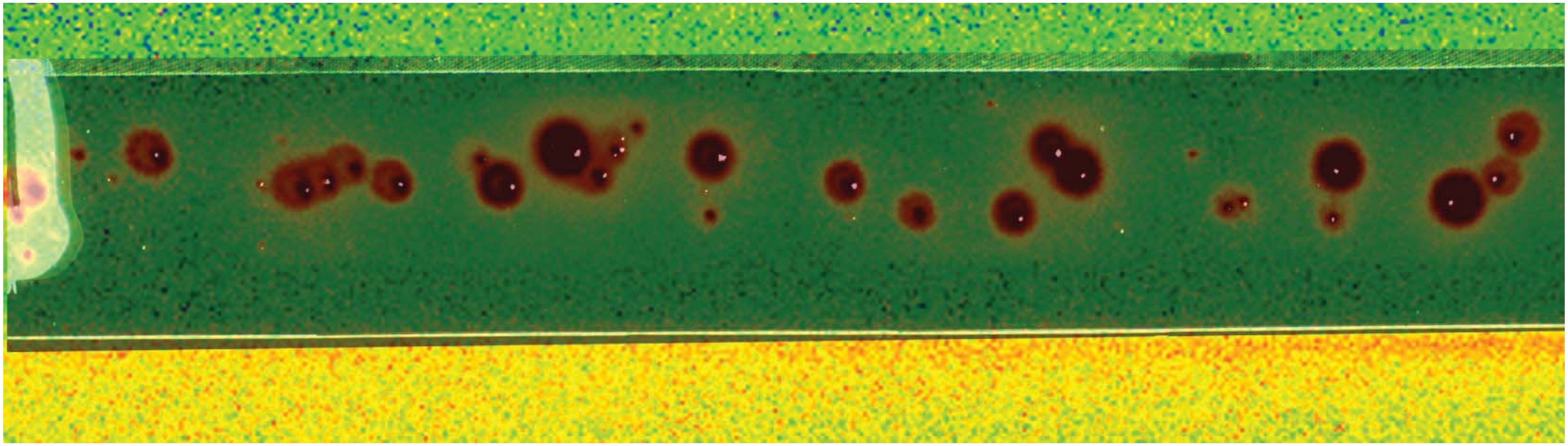


Optical photo of film surface

FA Technique – Lock-in Thermography (2)
Inadequate buss tape

Optical image was overlaid onto the LIT image

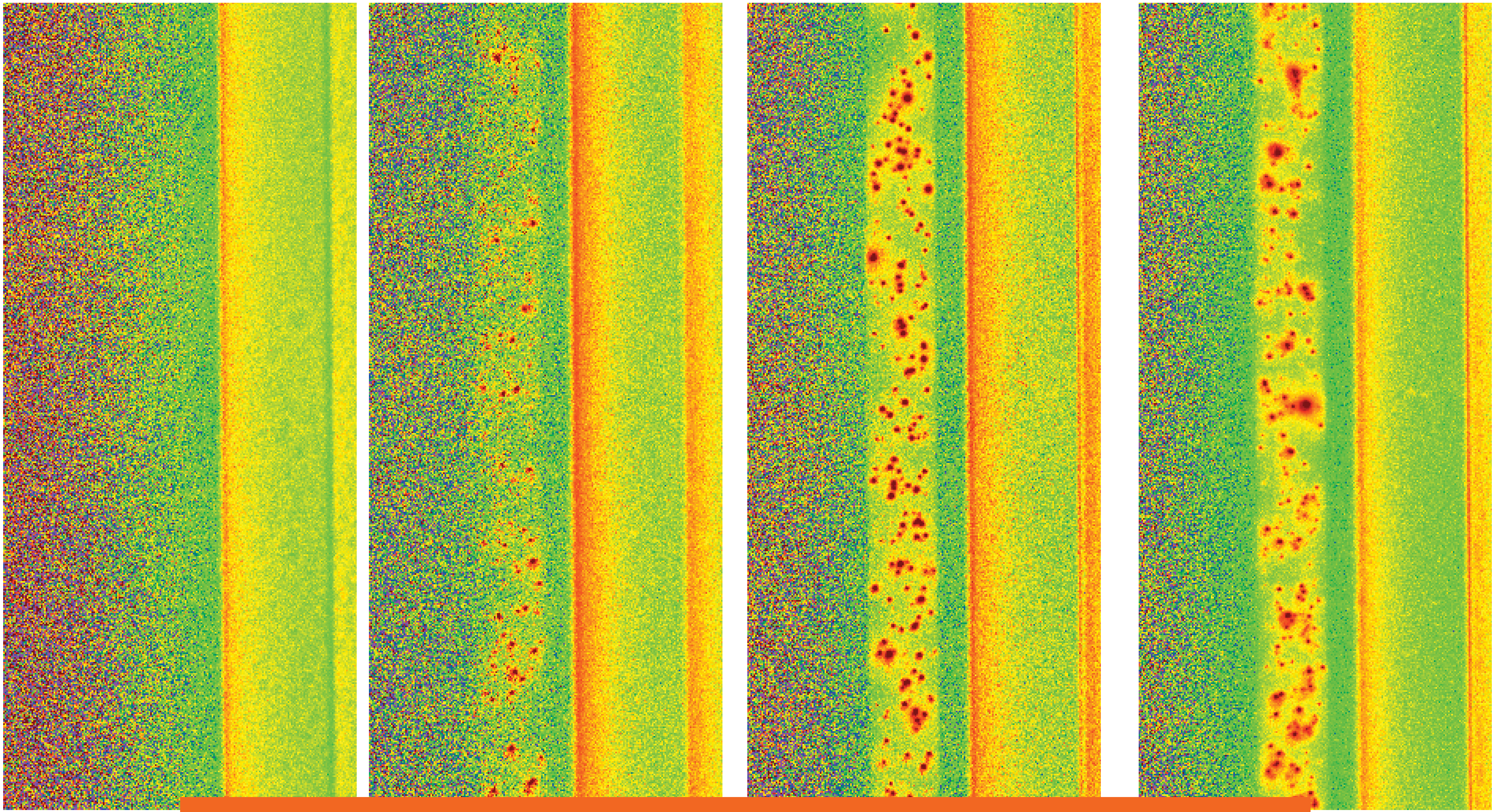
High correlation of visible burned film and the lock-in thermal response.



FA Technique – Lock-in Thermography (3)

Robust buss tape

Time zero | Post 104 Cycles | Post 275 Cycles | Post 507 Cycles



Module shows no signs of film damage or degraded performance

I hope my "wisdom" has convinced you that failures are not only good, but absolutely necessary for understanding your product

"Success is never final; failure is never fatal"

"I didn't fail the test, I just found 100 ways to do it wrong" – Benjamin Franklin

"Try and fail, but don't fail to try" – Dave Checkett

"The greatest barrier to success is the fear of failure" -Sven Goran Eriksson

"Failure is the tuition you pay for success" -Walter Brunell

"There are no secrets to success. It is the result of preparation, hard work, and learning from failure" -Colin Powell

References

1. D.L. King, W.E. Boyson, and J.A. Krotochvil, “Photovoltaic array performance model,” Sandia National Laboratories SAND2004-3535, 2004.
2. A.D. Jones and C.P. Underwood, “A thermal model for photovoltaic systems,” Solar Energy, vol.70, pp. 349-359, 2001
3. N. Bosco, S. Kurtz, “Quantifying the Weather: an analysis for thermal fatigue,” NREL PV Reliability Workshop, 2011
4. “Standard practices for cycle counting in fatigue analysis,” ASTM International Standard E 1049-85, West Conshohacken, PA 2005.
5. D. Storera, StoFlo™ Rainflow Cycle Counting Excel Template with Macros, http://stotera.com/stoflo/

Reliability at PVMC

Jim Lloyd
with
Ross Goodman and Pradeep Haldar
SUNY Albany CNSE
Albany NY
1 March, 2012

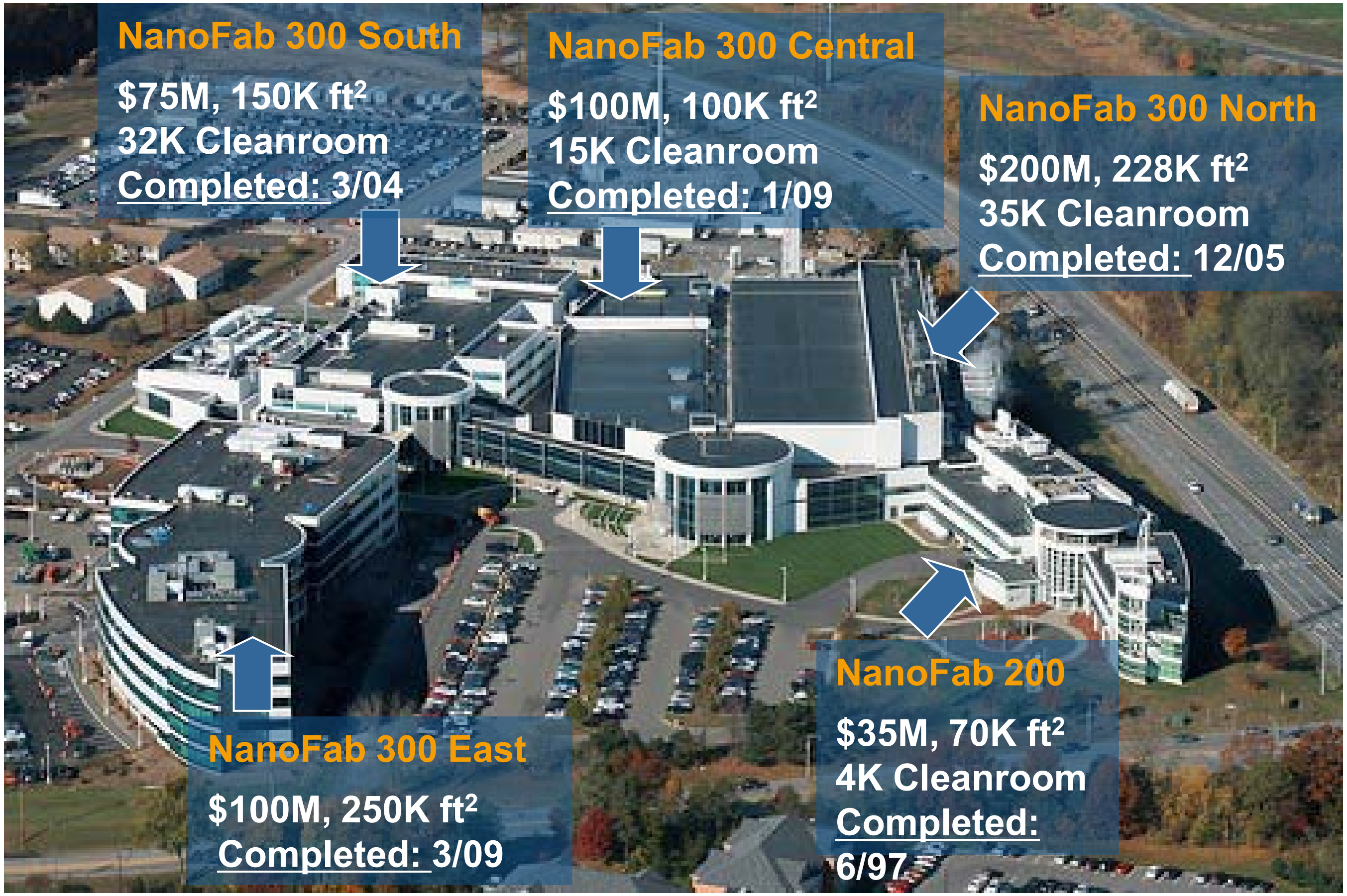
US PVMC program overview

- Hybrid of industry-led consortium and manufacturing development facility (MDF) models with capabilities for collaborative and proprietary activities
- Overall investment of $300M over 5 years from DOE, Industry, New York State.
- Focus on solar PV technology – CuInGaSe (CIGS) thin films – and manufacturing methods
- Expertise of primary partners – SEMATECH, CNSE – in consortium management, technology development, manufacturing productivity, and workforce development
- Breadth of support – partnership with ~60 companies and organizations throughout CIGS industry supply chain

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM PVMC

PVMC: Photovoltaics Manufacturing Consortium

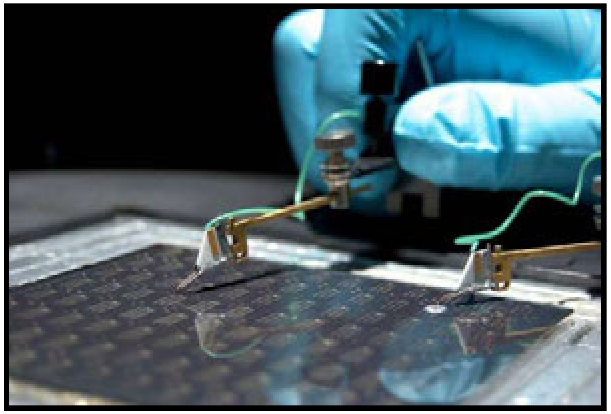
Current CNSE Facilities



- 800,000 sq.ft. of cutting-edge facilities, with 85,000 sq. ft. of 300mm clean rooms with a planned expansion to 1,250,000 sq. ft. and 105,000 sq. ft. of 300mm and 450mm cleanrooms
- More than 250 industry partners including electronics, energy, defense & biohealth
- Over $8B investments and over 2,600 R&D jobs currently on site (projected increase to 3500 R&D jobs by 2013)

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM PVMC

CNSE- Solar Energy Development Center
Pilot Facility for PVMC use (100kW) – Halfmoon, NY



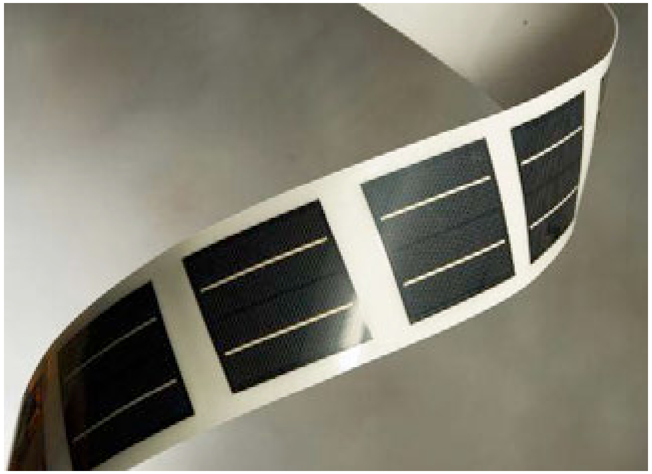



CIGS Cell Test Equipment; Humidity Chamber; Thermal Evaporator for CIGS; Test Chambers; FastLine for Glass; Laminator; Sputtering, Co-Evaporation, Selenization

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM
PVMC

CNSE Process Capabilities - Halfmoon, NY *(Pilot Manufacturing, 100 kW/Year)*

- Pilot Line Scale Solar Cell Fabrication
  - 10cm x 10cm substrates
    - Monolithic Interconnect (Laser & Mechanical Scribes)
    - Top Grid (screen printed grids)
    - $1cm^2$ (Evaporated Ni/Al grids)
  - CIGS by thermal evaporation
  - Chemical Bath Deposition: CdS, ZnOS
  - Bottom and Top Contacts by Sputtering
    - Cr/Mo and iZnO/TCO (ITO – AZO)



- Pilot 1.2m X 0.6m CIGS Deposition on Glass

- Metrology
  - UV-VIS
  - XRF
  - ICP
  - SEM w/ EDX
  - SIMS
  - (4) Pt. Probe
  - Adhesion/Pull-Test
  - J-V measurement, AM 1.5

- Module & Environmental Testing
  - Lamination
  - Humidity/Thermal Cycling
  - Mechanical Loading
  - Hail/Impact

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM PVMC

Strategic Objectives of US PVMC

Establish Roadmaps and Standards

Establish CIGS Manufacturing Development Facility

- Access to 100 kW line
- Front End and Back End of 10 MW (Flexible and Rigid Line)

CIGS Manufacturing Scale-up

- Best Practices and Cost Modeling
- Productivity, Effectiveness and Manufacturing Quality

CIGS Commercialization Support

- Licensing, Attraction, Incubation

Develop Highly Trained Workforce

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM PVMC

Membership Categories

Collaborative Programs

- **Full Members :** PV manufacturing and supply chain companies
  - May **participate in the full program set** and have **access to all pre-competitive, non-proprietary results and related IP**
  - Have more participation in program and operational direction setting through more broad participation in the various governance, advisory, and management roles

- **Program Members:** PV manufacturing and supply chain companies
  - May **participate in select cell and module development**, materials, metrology, reliability, tool infrastructure, benchmarking, manufacturing productivity, or other consortium programs
  - They have **shared access to IP generated from the programs in which they participate**

Proprietary Programs

- **Proprietary Participants and Users:** PVMC members, industry partners, start-up companies, national labs, and universities (collectively "users")
  - May **access the PVMC facilities** as part of a proprietary program or on an individual, fee-for-service basis
  - IP generated by or on behalf of any company in a proprietary program will be owned by the company and not shared with other participants

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM PVMC

Reliability Focus

- The focus is to aid in manufacturing development
  - Stumbling block is reliability testing
- Everything has to be reliable
  - And therefore pass reliability testing
- To help manufacturing we need fast turn around for valid, believable reliability tests
  - Reduce turn around time for process/material changes

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM PVMC

The reliability testing has to be valid

-----------No overstressing-------------

Tests must exercise realistic failure mechanisms
and reproduce observed failure modes

Reliability Goal

- To develop reliability tests that can effectively predict 25 years of life in any chosen environment with a test lasting no more than 1,000 hours (6 weeks)
  - To do this we need to know precisely what the physics of failure is.
  - In some cases (for some modes/mechanisms) we already have this in place.
  - For others that we have little confidence in, there needs to be fundamental research
    - Damp Heat

Reliability Effort

- Substantial funding is available to support the needed research
  - Deemed to be one of the most important tasks for the PVMC
  - We do not intend to recreate already available capability
  - Depending on what resources are available across the U.S. the work could be performed in multiple locations
- Precise direction will be determined by members of the consortium
  - TWGs and roadmap effort
- Results will be available to consortium members
  - Proprietary issues will be protected
  - We know how to do this!
    - Both CNSE and Sematech have extensive experience in this area

To Date

- Four broad tasks were identified at the E-Tab meeting
  - Stickies
- Reliability TWG formed and problems identified
  - Over the past few months have met several times
  - Input limited and nothing definitively decided upon
  - Tentative projects follow

Topic 1 Physical modeling of degradation and failure of layers at device and module level (Doug Jungwirth, Boeing)

Objective: Collect failure mechanisms, lifetimes and related parameters that affect the performance of final modules and develop basic models to predict the future performance of the modules in real world situations.

Challenges	Goals	Resources
Inadequate knowledge of failure and degradation mechanisms for CIGS and other thin film cells	Develop list of degradation and failure mechanisms along with parameters that effect these mechanisms	Previous studies of reliability and failure rates for previous CIGS technologies
Inadequate multi-parameter models which describe the working mechanisms of degradation and failure	Develop several multi-parameters models to quantitatively describe the failure and degradation mechanisms	Previous studies of single and multi-parameter degradation sources
Insufficient field data that can be used to validate these models	Generate or collect field or laboratory data to validate proposed models	Previous and recent field test data
Lack of confidence with the existing models for predictive long term (>25 years) reliability estimates	Use collected or test data to predict reliability. Perform ongoing surveying process to verify these models	Monitoring of present and new solar cell fields

Topic 2: Identify basic module failure modes and mechanisms with the goal of producing acceleration models for testing (Mike Mills, Dow Chemicals)

Objective: Reliability of CIGS based photovoltaic (PV) system for bankability, product and system level warranty

Challenges	Goals	Resources
Variety of module and system failure modes for CIGS based products	identify model systems to mimic individual material, component, module and system failure modes	Testing facilities, post mortem analytical capability
Low confidence in CIGS based PV systems (limited field data) and slow new product development cycles	Validate highly accelerated (>50x) testing for single mechanism testing with correlation to field data	Develop new testing procedures and validate correlation with field experience
Lack of unified reliability modeling and understanding specific to CIGS products	Incorporate US National Labs into development and validation of common reliability approach philosophy	Testing facilities, stable source of CIGS in standard packaging, commercial reliability modeling software

Topic 3 Study of performance degradation based on leakage current rates, high voltage stress and electro-chemical corrosion of contacts (David Gower, Intertek)

Objective: Examine data and create protocols to simulate degradation in a lab environment due to failures other than natural degradation of the CIGS material as a result of exposure to leakage current, high voltage stress and corrosion of contacts.

Challenges	Goals	Resources
Deciding variations of testing protocols that should be used for CIGS as opposed to other PV	Examine existing testing methodology and develop adjustments based on knowledge of CIGS material properties	Access and review of existing approaches, material knowledge of CIGS properties, knowledge of testing procedure development
Correlation of real world and lab results	Simultaneous lab and real world data collection with periodic evaluation of in field samples	Indoor and outdoor testing environments. Lab will need environmental chamber, accelerated UV, and wet lab. Collaboration for outdoor results
Using data to create models for accelerated testing in various environmental conditions	Coordinate outdoor data and run parallel testing in lab to simulate environmental conditions	Researchers, technicians, lab equipment, methods for storing, sharing and interpreting data

Topic 4 Quantify requirements for sealing against moisture (Jim Lloyd, CNSE)

Objective: Conduct experiments and provide theoretical guidance towards formulating a viable physical model for moisture ingress to determine the required performance when subjected to accelerated testing.

Challenges	Goals	Resources
Identify relevant failure modes	Study literature and long term test results	Student and staff Test data from members
Develop Accelerated tests	Identify physical failure mechanism and develop theoretical model	Students and staff
Develop test methods and protocols for identified failure modes	Design test structures, test methods sensors for moisture detection	Students and staff Fab to produce test structures and coupons
Test models	Perform tests for 1000 hr equivalence to 25 year EOL	Testing facilities (T&H chambers, outdoor testing facility)

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM PVMC

Contact us

- For anybody interested in participating in these efforts
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Sunset Technology, Inc.

PV Standards.
What new things does the IEC have for you?

By Howard O. Barikmo, Sunset Technology, Inc.
hbarikmo@aol.com
February 28, 2012

Technical Committee 82 and its Working Groups

• **WG1: Glossary**	Task: To prepare a glossary.
• **WG2: Modules, non-concentrating**	Task: To develop international standards for non-concentrating, terrestrial photovoltaic modules--crystalline & thin-film
• **WG3: Systems**	Task: To give general instructions for the photovoltaic system design, and maintenance.
• **WG6: Balance-of-system components**	Task: To develop international standards for balance-of-system components for PV systems.
• **WG 7: Concentrator modules**	Task: To develop international standards for photovoltaic concentrators and receivers.
• **JWG 21/TC 82 Batteries**	Task: To draw up standard require-ments for battery storage systems intended for use in photovoltaic systems.
• **JWG 1--TC 82/TC 88/TC21/SC21A** (DRE) being	Task: To prepare guidelines for Decentralized Rural Electrification projects which are now implemented in developing countries.

TC 82 WG2

- Standards published by TC 82 can be found on the internet at:

http://www.iec.ch/dyn/www/f?p=103:23:0::::FSP_ORG_ID,FSP_LANG_ID:1276,25

Or simply go to www.iec.ch and search for TC 82 dashboard finder. Select IEC - **TC 82 Dashboard** > Scope and click on Projects/Publications. The TC 82 Work Programmed will be listed. Click on Publications to view all standards that have been published to date.

This report will focus on and list New Work Item Proposals and maintenance work that is underway.

Figures in red indicate expected completion dates, or other status on project. Standards listed in blue—specifically for thin-films.

TC 82
WG1 and WG2

- **Working Group 1**
- **IEC/TS 61836 Ed. 3.0** Solar photovoltaic energy systems - Terms, definitions and symbols 2012

- **Working Group 2**
- **IEC 61215 Ed. 3.0** Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval 2013
- **EC 61646** Edition 2.0 Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval Published
- **EC 61730-1 am2 Ed. 1.0** Amendment 2 to IEC 61730-1 Ed.1: Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction 2013
- **IEC 61730-2 Ed. 2.0** Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing 2014
- **IEC 61853-2 Ed. 1.0** Photovoltaic (PV) module performance testing and energy rating - Part 2: Spectral response, incidence angle and module operating temperature measurements 2012
- **IEC 62716 Ed. 1.0** Ammonia corrosion testing of photovoltaic (PV) modules 2012
- **IEC 62759-1 Ed. 1.0** Transportation testing of photovoltaic (PV) modules - Part 1: Transportation and shipping of PV module stacks 2013
- **IEC 62775 Ed. 1.0** Cross-linking degree test method for Ethylene-Vinyl Acetate applied in photovoltaic modules - Differential Scanning Calorimetry (DSC) 2014

TC 82
WG2

- IEC 62782 Ed. 1.0 Dynamic mechanical load testing for photovoltaic (PV) modules
- IEC 62788-1-2 Ed.1 Measurement procedures for materials used in photovoltaic modules - Part 1-2: Encapsulants - Measurement of resistivity of photovoltaic encapsulation and backsheet materials 2015
- IEC 62788-1-4 Ed.1 Measurement procedures for materials used in Photovoltaic Modules - Part 1-4: Encapsulants - Measurement of optical transmittance and calculation of the solar-weighted photon transmittance, yellowness index, and UV cut-off frequency 2015
- PNW 82-654 Ed. 1.0 Photovoltaic devices - Part11: Measurement of initial light-induced degradation of crystalline silicon solar cells and photovoltaic modules 2014
- PNW 82-668 Ed. 1.0 Future IEC 6XXXX-1-3 Ed.1: Measurement procedures for materials used in photovoltaic modules - Part 1-3: Encapsulants - Measurement of dielectric strength 2015
- PNW 82-669 Ed. 1.0 Future IEC 6XXXX-1-5 Ed.1: Measurement procedures for materials used in photovoltaic modules - Part 1-5: Encapsulants - Measurement of change in linear dimensions of sheet encapsulation material under thermal conditions On hold
- PNW 82-674 Ed. 1.0 Junction boxes for photovoltaic modules - Safety requirements and tests 2015
- PNW 82-675 Ed. 1.0 Connectors for DC-application in photovoltaic systems - Safety requirements and tests On hold

TC 82
WG2 and WG3

- **PNW 82-685 Ed. 1.0** System voltage durability test for crystalline silicon modules - Qualification and type approval Closes Apr 14 2012
- **PNW 82-689 Ed. 1.0** Test method for total haze and spectral distribution of haze of transparent conductive coated glass for solar cells Closes Apr 27 2012
- **PNW 82-690 Ed. 1.0** Edge protecting materials for laminated solar glass modules
- Closes April 27 2012
- **PNW 82-691 Ed. 1.0** Test method for transmittance and reflectance of transparent conductive coated glass for solar cells Closes April 27 2012
- **Working Group 3**
- **EC 61829 Ed. 2.0** Crystalline silicon photovoltaic (PV) array - On-site measurement of I-V characteristics 2013
- **IEC 62548 Ed. 1.0** Design requirements for photovoltaic (PV) arrays 2013
- **IEC/TS 62738 Ed. 1.0** Design guidelines and recommendations for photovoltaic power plants 2012
- **IEC/TS 62748 Ed. 1.0** PV systems on buildings 2012

TC 82
WG6 and WG7

- **Working Group 6**
- **IEC 62109-4 Ed. 1.0** Safety of power converters for use in photovoltaic power systems - Part 4: Particular requirements for combiner box On hold
- **PNW 82-696 Ed. 1.0** Safety of power converters for use in photovoltaic power systems - Part 3: Particular requirements for PV modules with integrated electronics Closes May 18, 2012

- **Working Group 7**
- **IEC 62670-1 Ed. 1.0** Concentrator photovoltaic (CPV) module and assembly performance testing and energy rating - Part 1: Performance measurements and power rating - Irradiance and temperature 2013
- **IEC 62688 Ed. 1.0** Concentrator photovoltaic (CPV) module and assembly safety qualification 2013
- **IEC 62787 Ed. 1.0** Concentrator photovoltaic (CPV) solar cells and cell-on-carrier (COC) assemblies - Reliability qualification 2014
- **IEC/TS 62727 Ed. 1.0** Specification for solar trackers used for photovoltaic systems 2012
- **PNW/TS 82-652 Ed. 1.0** Specification for concentrator cell description On hold

TC 82
JWG 21/TC 82 and JWG 1

- **JWG 21/TC 82 Batteries**
- IEC 61427-2 Secondary cells and batteries for renewable energy storage Part 2: On-grid applications 2014

- **JWG 1--TC 82/TC 88/TC21/SC21A**
- IEC/TS 62257-9-6 Ed. 2 Recommendations for small renewable energy and hybrid systems for rural electrification – Part 9-6 : Selection of Photovoltaic Individual Electrification Systems (PV-IES) [to include selection of PV powered LED lanterns] 2012

The Effect of Copper on Accelerated Life Test Performance of CdTe Solar Cells

Dennis J. Coyle

GE Global Research

1 Research Circle

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1 Abstract

It is well known (McCandless & Sites [1]) that a back contact to CdTe cells can be achieved by first creating a Te-rich layer via selective etching, followed by application of copper which reacts with Te to form the p+ layer that can be contacted with metal or graphite. But copper has high diffusivity, multiple valence states, and a weak bond with Te, all of which contribute to stability issues. Hegedus [2] and others [3-6] have shown that there are multiple modes of degradation induced by long-term light-soaking at forward bias at elevated temperatures, namely formation of a blocking contact, increased junction recombination, and increased dark resistivity. Asher [7] showed accumulation of copper in the CdS layer.

This paper describes how varying the dose of copper used to form the back contact changes both initial efficiency and performance in accelerated stress testing. All test cells were 1 cm^2, and 12 cells were tested per condition. Figure 1 shows the performance of test cells in the standard "ALT" accelerated life test, which is continuous 0.7-sun illumination at open circuit and 65^{o}C. As shown by Hegedus [2], the higher copper dose leads to increased rate of degradation, driven by both voltage and fill-factor loss. This is shown most clearly in Figure 2. The loss of fill factor is driven by increases in both resistance (Roc) and light-shunt conductance (Gsc), shown in Figure 3.

The use of too little copper results in low-performance but relatively stable devices, most of which exhibit a back-contact barrier. Figure 4 illustrates this by plotting Rmax – the resistance at 0.9 volt forward bias (dV/dJ at 0.9V bias). There is extreme noise in the data for low copper dose, since noise in process conditions results in either a good contact or a very poor one. Higher copper dose is required to reliably form a good contact. Figure 5 shows an example of a good cell and one that is degraded exhibiting lower voltage and rollover. Using more copper eliminates the barrier and increases the initial efficiency. Thus a compromise must be made balancing reproducibility, initial efficiency, and long-term stability.

Figure 1. Degradation vs. ALT time for three copper doses.

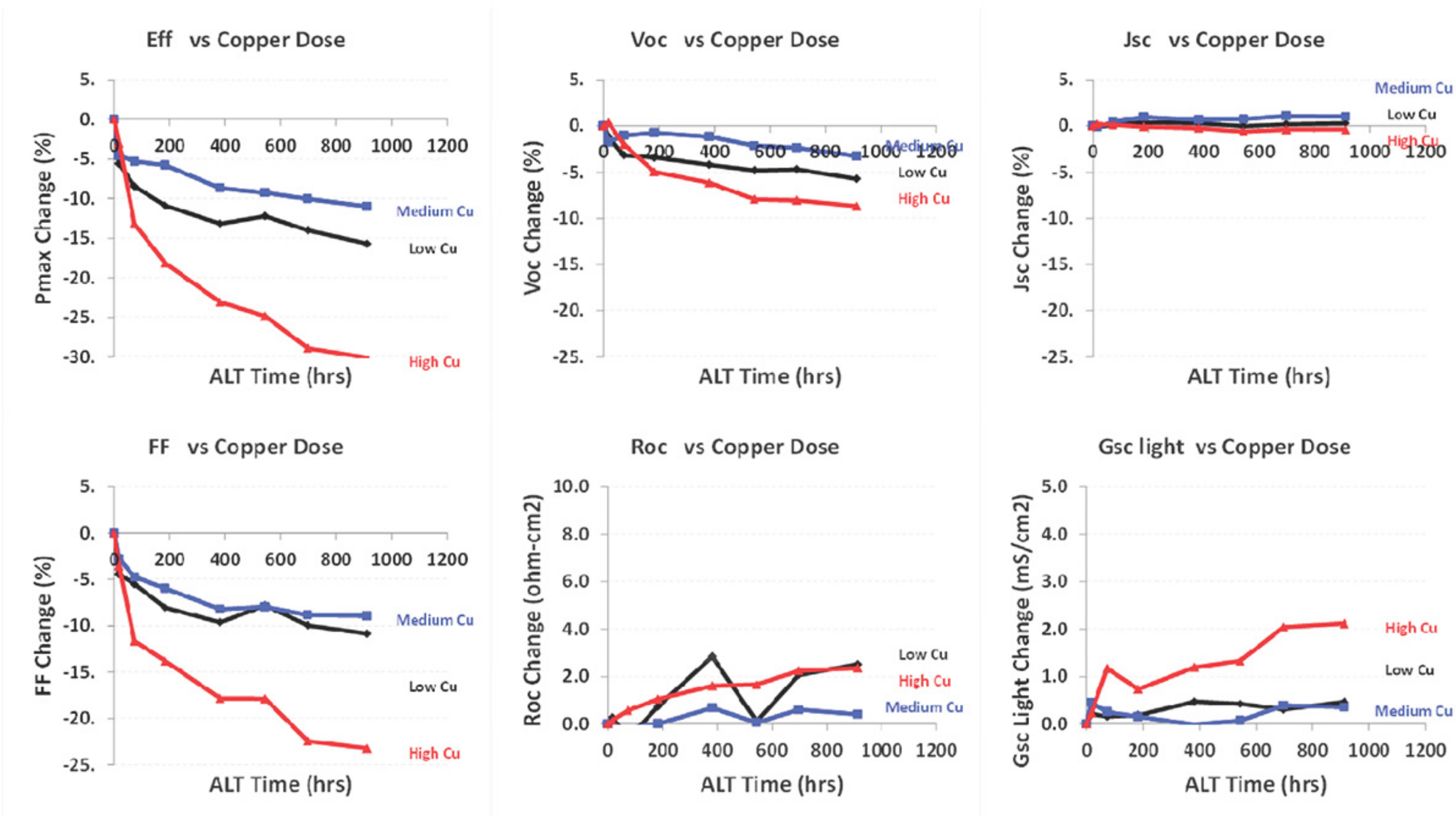


Figure 2. Secondary metrics correlated to efficiency degradation.

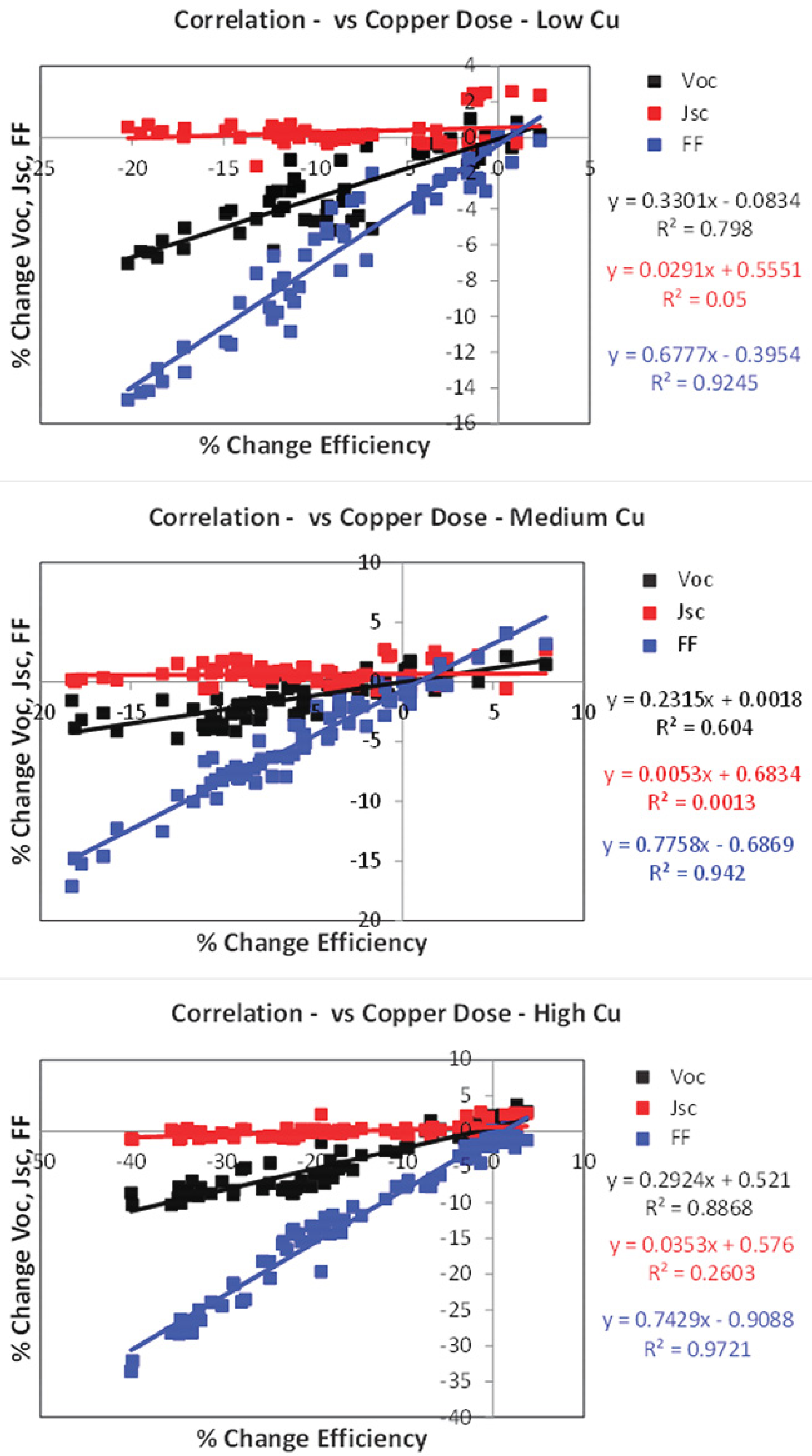


Figure 3. Tertiary metrics correlated to efficiency degradation.

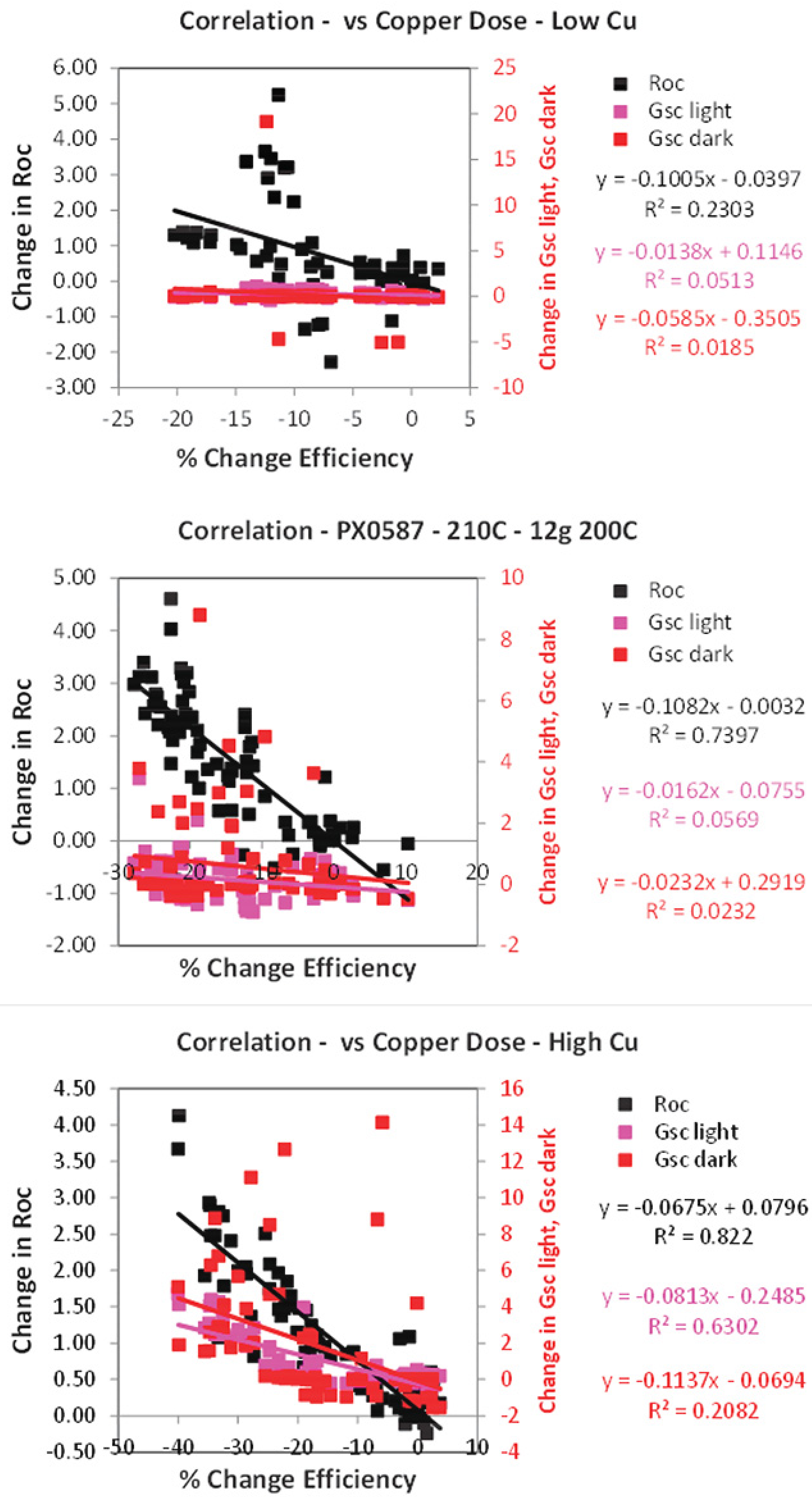


Figure 4. Effect of copper dose on JV rollover, (a) definition, (b) data.

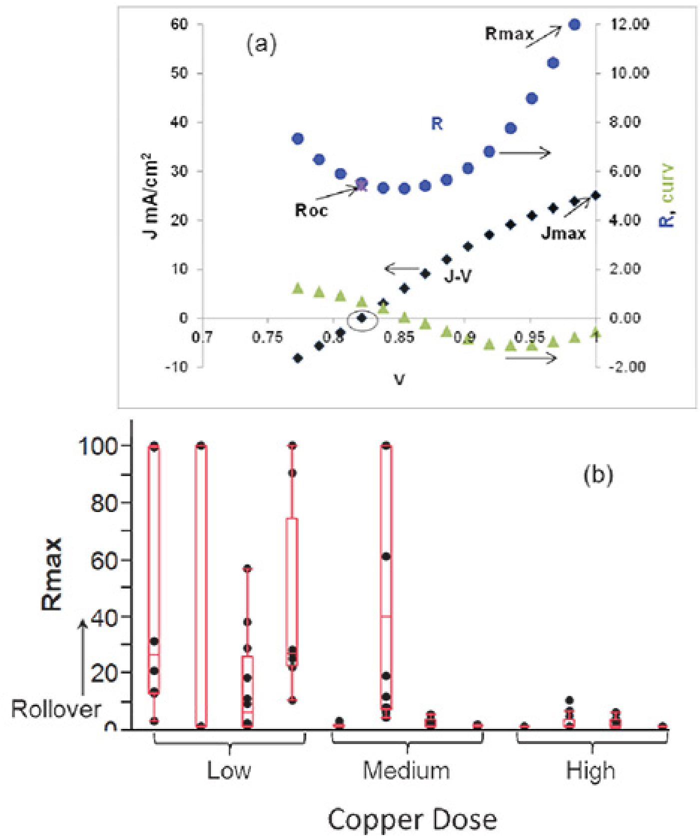
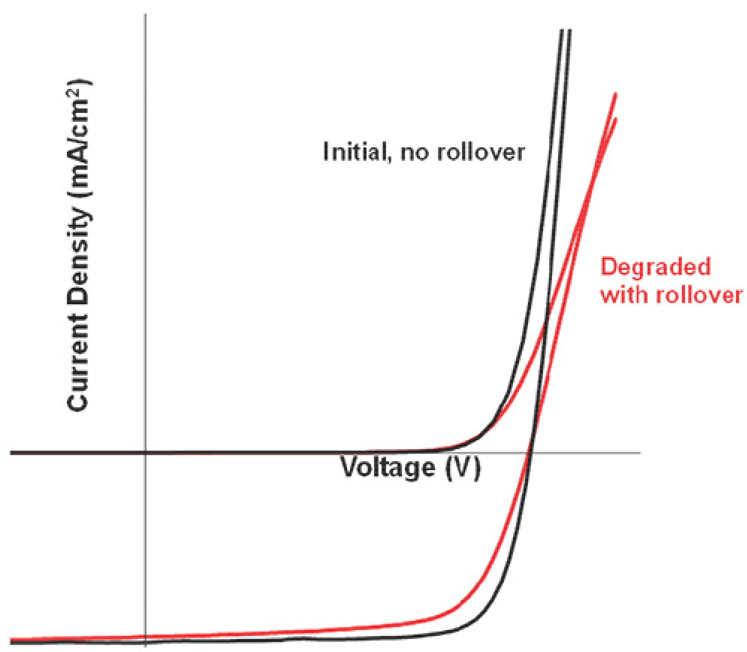


Figure 5. Typical JV curves showing good initial performance and degraded performance with rollover.



2 Literature Cited

[1] B.E. McCandless and J.R. Sites, *Cadmium Telluride Solar Cells*, In: Handbook of Photovoltaic Science and Engineering. Edited by A. Luque and S. Hegedus, Wiley (2003).

[2] S.S. Hegedus, B.E. McCandless, R.W. Birkmire, Analysis of stress-induced degradation in CdS/CdTe solar cells, 28th IEEE Photovoltaic Specialist Conf., 535–538 (2000).

[3] J.F. Hiltner, J.R. Sites, *Stability of CdTe solar cells at elevated temperatures: bias, temperature, and Cu dependence*, AIP Conf. Proc. 462, 170–175 (1998).

[4] Gupta A, Townsend S, Kaydanov V, Ohno T, Conf. Rec. NCPV Rev. Mtg, 271–272 (2000).

[5] D.K.D. Dobson, I. Visoly-Fisher, G. Hodes, D. Cahen, *Stability of CdTe/CdS thin-film solar cells*, Solar Energy Mater. Solar Cells 62, 295–325 (2000).

[6] I. Visoly-Fisher, K.D. Dobson, J. Nair, E. Bezalel, G. Hodes, D. Cahen, *Factors Affecting the Stability of CdTe/CdS Solar Cells, Deduced from Stress Tests at Elevated Temperature*, http://www.nrel.gov/pv/thin_film/docs/cahen_factors_afm.pdf (2002)

[7] S.E. Asher, F.S. Hasoon, T.A. Gessert, M.R. Young, P. Sheldon, J. Hiltner, J. Sites, *Determination of Cu in CdTe/CdS devices before and after accelerated stress testing*, 28th IEEE Photovoltaic Specialist Conf., 479–482, DOI 10.1109/PVSC.2000.915876 (2000).

Test-to-Failure Program for Photovoltaic Modules

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Introduction

In order for a solar panel manufacturer to most efficiently manage risk within a product's lifecycle, a system is required to a) provide reasonable assurance of the reliability of said design, and b) to maximize the likelihood of failure mode detection early in the overall life cycle; i.e. during the design /qualification phases. This presentation outlines one such strategy, whereby a suite of evaluations are conducted on an ongoing basis to provide assurance of product reliability. Performance of the systematically-selected samples during these ongoing checks is compared to internal and/or industry criteria and metrics, primarily to ascertain changes that constitute classification as a failure mode, and secondarily to benchmark performance. In the event that a failure is detected, an escalation is initiated to understand the impact of the failure mode on a module in the field, via the Failure Mode Specific procedural flow that is also defined herein. By sharing an overview of MiaSolé's Test-to-Failure (TTF) Program, it is our intent to highlight the need for more consistency across the industry with respect to ongoing test program protocols, the need for custom programs and specialized analysis dependent upon product design, and the value of this type of program in reducing the risk of failure during a product's lifecycle, thereby enhancing the reputation of both the manufacturer and the photovoltaic industry.

TTF Program Sequence

- Program Sequence is assumed to be of the most value when conducted on an ongoing basis, to capture manufacturing process/vendor/other changes or variations that may not have been captured through a specific qualification activity.

1.0 Select stressor of interest
- Starting point: qualification sequences cast a broad net, and will catch presence of many failure modes.
  - UV, particularly for polymeric components
  - TC, fatigue due to thermal expansion / contraction
  - DH, time-at-temperature, particularly for Arrhenius-type relationships and polymers
  - HF, expansion / contraction of frozen water in spaces
- Tailor additional stressors based on the results of an FMEA for the specific module design
  - Corrosive Atmosphere, SO_2, or NH_3
  - Concentrated sunlight or UV
  - Dynamic loading

2.0 Determine Sampling
- Define both sample size and Frequency
- Sample selection considerations:
  - Difficult to get sufficient quantities for statistical confidence due to Size, Cost, and Test equipment limitations
  - Random selection vs. process window – the TTF Program may define sampling granularity down to lot level or a time interval, presuming that the process window's have been defined separately during individual tool and/or component level qualifications. In other words, TTF Specific area of concern / failure mode to investigate
  - R&D versus production; with respect to effect on the mechanism and failure, signal should be considered. MiaSole's TTF program relies on bi-monthly production sampling to increase likelihood of detecting modes related to production processes and material.

3.0 Test limits
- Confirm that Qualification sequence limits are of relevance for anticipated failure modes or revise limits to account for specific component responses, such as non-linear mechanical or threshold type limits
- Acceleration factors

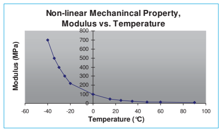

Figure 1. Non-linear responses need to be considered when translating performance data derived from certification or accelerated testing to field predictions. An encapsulant modulus is shown.

4.0 Define evaluation methods and criteria
- Standard characterization methods include:
  - Electrical Performance (I-V)
  - Insulation integrity (dry & wet hypot)
  - Visual Inspection for cosmetic effects
  - Bonding / Grounding Path Integrity
  - Accessibility
- Literature review to capture industry learning on technology specific failure modes
  - Electroluminescence imaging

Figure 2. Example of EL signatures after thermal cycle stress from a monolithically integrated sample exhibiting localized shunting effects (left) and c-Si showing a more traditional failure mode; cell-cracking (right).

- Criteria
  - Standard based (IEC, UL) criteria limits
  - Design based criteria limits such as relative degradation from initial value or standard limit:

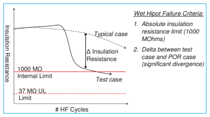

Figure 3. Illustration of wet insulation resistance criteria for evaluation of a junction box design modification. Both absolute and relative change limits are defined.

- Evaluation Intervals
  - Multipliers of standard intervals, or
  - Subsets of standard intervals

5.0 Conduct testing once program scoped

6.0 Detect new failures by comparing monitoring data relative to pre-defined criteria and/or observation of atypical findings.

7.0 Determine if immediate response is needed to contain issue. For example: catastrophic failures, such as complete loss in power production, or severe hazard such as shock or fire

8.0 Initiate failure mode specific investigation -> requires failure mode specific scoping and project activity

Failure Mode Specific Investigation

- Though an offshoot of the ongoing TTF activity, the failure-mode specific investigation provides the requisite feedback for implementing specific mitigation once a product has moved into the manufacturing phase. As such, additional schedule constraints may apply, requiring that these sub-activities, outlined serially herein, be executed in parallel.

8.1 Scope the failure
- Root cause investigation
  - Fish-bone diagram

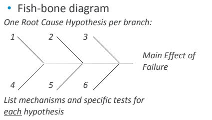

Figure 4. Example of a Fishbone diagram.

- Define the condition that resulted in failure
  - Capture the stressor, test parameters, sample size, and time of failure
  - Construction details; differences between good and failed components
- Define the characteristics of failure versus baseline
  - Non-destructive evaluation
    - Performance readings
    - Visual inspections
    - EL and IR imaging
    - Ultrasonic imaging
    - XRay
  - Destructive evaluations
    - Peel-apart, excavation, or cross-section followed by:
      - optical evaluation,
      - FTIR
      - EDXRF

8.2 Isolate the cause(s)
- Design limits exceeded
  - Manufacturing and supplier process variation
- Single stressor
  - Time at temperature
  - Low temperature excursions
  - Water freezing and expanding at J-box seal
  - Thermal expansion / contraction of interconnects
- multiple stressor / combined effect
  - UV plus heat
  - Temperature plus humidity affecting leakage current
  - Temperature and operating voltage
  - Deflection during snow loading at low temperature

8.3 Attempt to replicate
- Confirm mechanism / root-cause; partition causes where multiple leading causes remain
- Generate statistical data
  - Larger sample size
  - Continue additional samples to failure
  - Fit appropriate distribution
    - Exponential
    - Log-normal
    - Weibull
  - Determine if it is an early, normal use, or end-of-life failure; systematic or random failure
- Revisit the Fish-bone diagram and identify the likely root cause based on learning

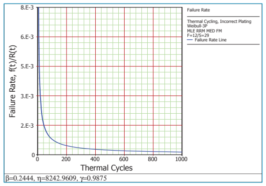

Figure 5. Thermal cycle data gathered from replicate samples with the incorrect plating, showing early failure mode (β<1), using a Weibull 3-parameter distribution.

8.4 Model the failure
- Computer modeling, for example Finite Element Analysis (FEA) Modeling. Input geometries and material properties:
  - Coefficient of thermal expansion (CTE)
  - Elemental composition (from specifications, manufacturer data, EDXRF, FTIR, Auger, etc.)
  - Tensile strength
  - Modulus of elasticity
  - Durometer
  - Melt-point
  - Glass-Transition Temperatures
  - Adhesion

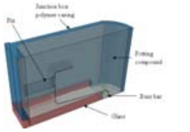

Figure 6. Illustration of MiaSolé's J-box system, as defined in the FEM model.

8.5 Compare test stresses with end-use environment
- Define end-use environment(s) in terms of stressor causing failure
- Consider importance of various factors:
  - Temperature extremes
  - Ambient humidity
  - Sunlight or UV hours

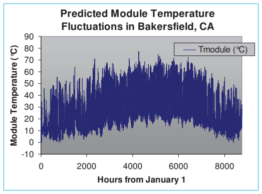

Figure 7. Typical Meteorological Year (TMY) data, converted to module operating temperature, to define dynamic range of temperature excursions at a select location.

8.6 Establish correlation between TTF test levels and field conditions
- Non-trivial
  - Various end-use locations
  - Variable conditions at each location
- Determine lifetime in end-use environment, by assessing failure rate, while varying stress amplitude and duration

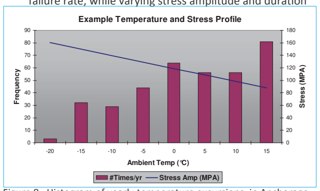

Figure 8. Histogram of yearly temperature excursions, in Anchorage AK, and resultant stress of an interconnect sub-component generated for a fatigue based failure mode – subsequent calculation based on available stress model allowed order-of-magnitude service life prediction.

8.7 Evaluate whether failure mode is likely to manifest itself in the field
- Examine existing field samples for onset of the failure mode

8.8 Develop accelerated test for specific failure mode, which allows:
- Larger sample size
- Component-specific / failure-mode specific test
- Faster turn-around time / larger acceleration factor
- Multiple test stress levels
- Flexibility in acceleration factor(s)
- Confirm correlation with original TTF testing
  - Repeat testing as needed to obtain confidence in results
- Scale to field conditions to replicate field stress
- Evaluate potential solutions and future changes using new test method

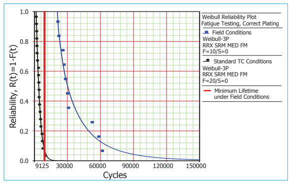

Figure 9. Results of mechanical fatigue testing at MiaSolé, showing that a solution to the incorrect plating meets a 25-year life-time under simulated field conditions (blue line).

8.9 Identify solutions to failure modes
- Design change
- Process Mitigation: Manufacturer changes and/or customer/installation changes and/or supplier/specification changes
- Repeat the TTF Program, mode-specific accelerated testing, and computer modeling to ensure failure mode is addressed, with no unanticipated new failure modes

8.10 Implement mitigation strategy for failure modes
- Modify components and/or manufacturing process

8.11 Identify new pass/fail criteria based on test results
- Modify specifications
- Update Quality procedures and specifications
- Update qualification methods
- Update FMEA with new failure mode

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DERIVATION OF QUALITY SPECIFICATIONS OF GLASS BY PROBABILISTIC EVALUATION OF MECHANICAL MODULE RELIABILITY

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Motivation

Requirements	Reliability	Quality
Product	*Product*	*Product*
■ long life time ■ resistant to high mechanical loads	■ fulfilling function over life time	■ fulfilling requirements over life time

Experiments

- Ring on ring strength test according to DIN 1288-5
  → test of surface (edges excluded)
  - size of specimens 100 x 100 mm²
  - Result: fracture strength
- Weibull statistics for strength evaluation
- Several batches of float glass were tested
- Significant differences of char. strength and scatter
  - Strength values can differ from batch to batch not only from manufacturer to manufacturer

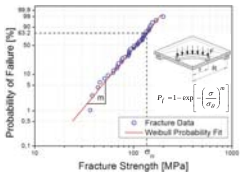


Fig. 1: Weibull probability plot + ring on ring test setup

- Questions:
  - Influence on module reliability?
  - How to design "on the brink" with lowest material consumption?
  - What quality of glass is required?
  - Safety factor?

Fig. 2: Strength values and confidence rings for several glass batches (both sides tested)

Numerical Simulations

- Numerical simulation of 2400 Pa static pressure load → principle stress field
- 4 common types of mounting
- size of module: 1200 x 600 mm²
- double glass setup

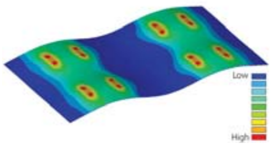


Fig. 3: 1st principle stress for mounting V4 – top view (2400 Pa pressure)

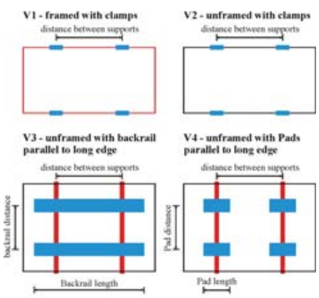


Fig. 4: Mounting concepts for PV modules

Reliability Evaluation

statistical strength parameters derived from experiments + FEA simulation → princ. stress field of complex structures → size effect → probability of failure P_f

Studies in Module Design

- Evaluation of probability of failure shows magnitude of differences of mounting types
- Large influence of material quality on probability of failure

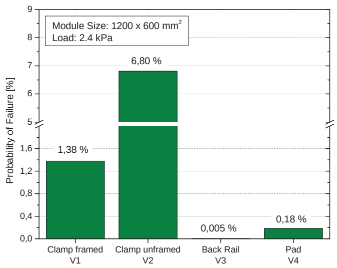


Fig. 5: Probability of Failure for several types of mounting (Batch 5)

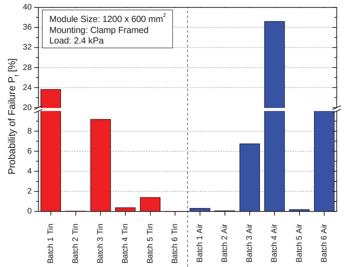
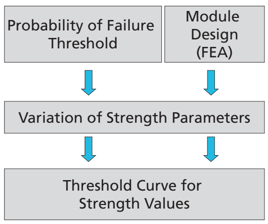


Fig. 6: Probability of Failure of different material strength qualities (mounting V1)

Reliable Design and Quality of Glass Strength

- Large differences between batches of glass lead to uncertain reliability of module designs.
- Module design, mounting and scattering of glass quality should be incorporated in a proper design concept.



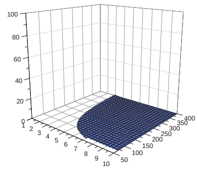


Fig. 7: Surface for probability of failure (P_f) for a variation of strength parameters + setting a threshold value for P_f = 1% (left); projected curve at Pf =1 % (right)

- Combination of module design + Finite Element Analysis + variation of strength parameters leads to threshold curve, which can be used as a definition for **glass quality**.
- Different mounting designs lead to different positions of this curve.

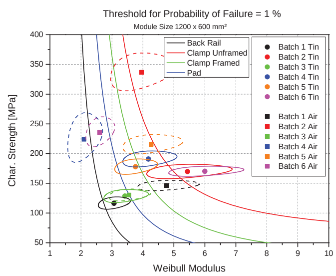


Fig. 8: Threshold curves for glass strength at P_f = 1% for several mounting setups left of curve unsafe, right of curve safe

Conclusion

- Evaluating the mechanical design of PV modules and mounting concepts by a probabilistic approach can give new and exclusive answers on reliability
- Material strength for different batches of glass can differ widely, which leads to shifting reliability of module and mounting designs
- Strength evaluation of glass should be introduced in a QA-system

Acknowledgement

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Edge Sealing Tape with Getter for PV Modules: Very Long Breakthrough Time and Mechanical Properties at High Temperature

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[2]SAES Getters USA Inc., Colorado Springs, Colorado (USA)

Background

Moisture induces different degradation mechanisms in PV modules; especially Thin Film ones are susceptible to the impact of moisture. Utilization of an edge sealant is a widely adopted solution to guarantee long operational lifetime, improving reliability and enhancing the stability of device performances.
An ideal edge sealant should be a very good barrier to moisture, excellent electrical insulator and resistant to prolonged UV exposure. Mechanical stability is also of paramount importance in the range of temperature characteristics seen by PV modules in real field operation.

B-Dry Edge Sealant Tape

Thickness: 0.5 - 1.3 mm
Width: 7, 10, 12 mm.

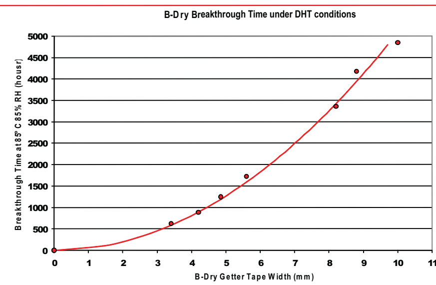
B-Dry is compatible with most common PV module encapsulation processes and materials (EVA, PVB, TPO)
Process temperature range: 140°C to 170°C.

Proposed Edge Sealant Solution

B-Dry® Tape is a new concept of edge sealant combining a low permeability thermoplastic polymer and efficient moisture sorbing materials based on SAES Getters proprietary technology. B-Dry works as an **active barrier** against moisture ingress.
Value of WVTR is null until the saturation of the moisture sorbing species, which happens after thousands of hours of Damp Heat Test at 85°C and 85% RH (breakthrough time is dependent on tape width).

Features and Results

Moisture Breakthrough time @ 85°C & 85% RH



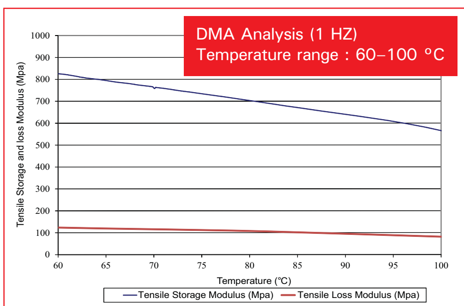
It takes more than 4,500 h for moisture to pass through a 10 mm wide barrier in DH test conditions

Adhesion Characteristics after Aging

Adhesion Strength to Glass (Mpa)			REFERENCE NORM
Lap Shear Test	As received	0.44 ± 0.10	
	After DH test 1000 hours @85°C 85% RH	0.41 ± 0.06	IEC 61646
	After DH test 2000 hours @85°C 85% RH	0.54 ± 0.09	IEC 61646
	After 200 cycles @ -40°C to + 85°C	0.29 ± 0.03	IEC 61646
	After UV aging	0.40 ± 0.03	Xenotest Miami (30 days)

Mechanical Properties

Tensile storage and Loss modules for B-Dry



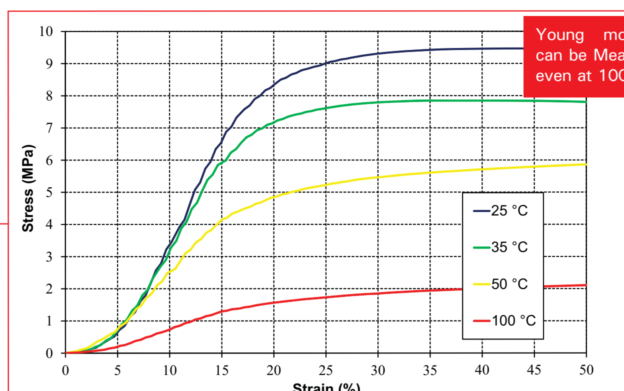
Electrical Isolation Characteristics

UL listing tests
* Dielectric Strength: 35 kV/mm
* Volume Resistivity: 10^{18} Ohm*cm

Before DHT 1000 hours	After DHT 1000 hours
B-Dry: 0.20 µA	B-Dry: 0.25 µA
No B-Dry: 0.20 µA	No B-Dry: 0.99 µA

Wet leakage current of 30 cm x 30 cm CIGS modules encapsulated with PVB before and after 1000 h of damp heat. Measured at ZSW (Stuttgart. D)

Stress-Strain Curves for B-Dry at different Temperatures



Young modulus can be Measured even at 100°C

Predicted peak operating cell Temperature for PV modules (Roof Mounting):
- over 100°C in Death Valley (CA), Riyadh, Phoenix (AZ)
- between 79°C and 89°C in Munich (D) and New York (NY)[1]

(1) D.C. Miller at als., Creep in photovoltaic modules: examining the stability of polymeric materials components, NREL/CP-5200-47718, February 2011

Conclusions

B-Dry ensures:
- Very high moisture barrier property
- Very good damp heat stability
- High electrical isolation
- UV stability
- Good mechanical stability at temperatures between 60°C and 100°C

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Adhesion of Encapsulating Films Used in PV Module Manufacturing

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Fluoropolymer-based films are preferred as frontsheets for thin film flexible PV modules as they provide:

- Excellent resistance to UV, temperature and chemicals for long term weather protection.
- Light weight for flexibility.
- High light transmission for optimal efficiency.
- Low surface energy to reduce soiling.

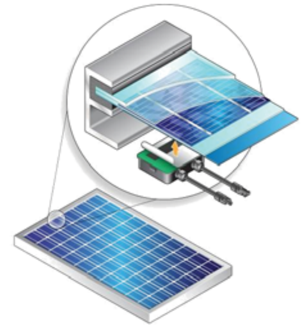
The most common fluoropolymer used today as frontsheets in PV modules is ETFE. The ETFE film is typically bonded to the solar cell with an EVA encapsulant to form a front surface protective laminate.

Strong ETFE-EVA adhesion is a critical requirement to ensure long-term durability of PV modules. However, ETFE's low surface energy and inertness is a challenge to achieve sufficient EVA adhesion.

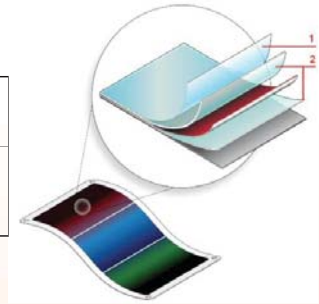
In this study, several surface treatment methods (Corona, Plasma and Saint-Gobain's C-treatment) were explored for their effectiveness in modifying the ETFE surface to achieve adequate adhesion to EVA.

ETFE treated with Corona and Plasma treatments were found to give significantly lower adhesion strength to EVA and are therefore unacceptable for PV applications . Saint Gobain proprietary treatment yielded higher adhesion strength.

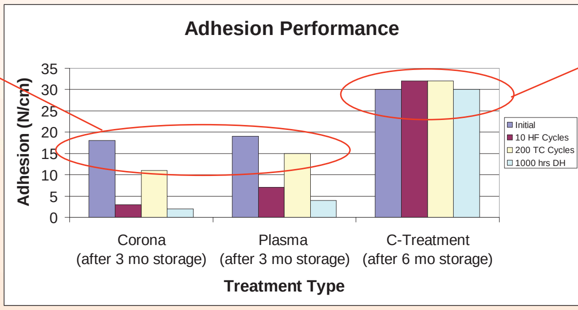
Surface Treatment Technologies



Corona	Plasma	C-Treatment Saint Gobain Proprietary
High Energy Filamentary Discharge	High Energy Glow Discharge	High Energy Treatment



Failure Mode: Peel (Adhesive Failure)

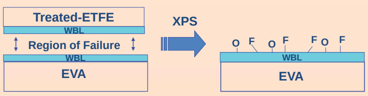


Failure Mode: Film Break (Cohesive Failure)

Lamination Condition: 145°C, 1300 mbar, total lamination time: 12.5 min Test Method: "T"-peel

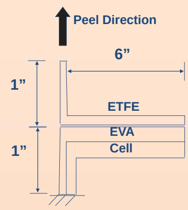
Comparison of Treatment Technologies

Postulated Failure: Weak Boundary Layer (WBL)



Samples	F (%)
EVA surface before lamination	0
EVA surface after peel	27

	Corona	Plasma	C-Treatment
Level of Polar Groups by X-Ray Photoelectron Spectroscopy (XPS)	7.6 %	4.6 %	9 %
Evidence of Weak Boundary Layer	Yes	Yes	No
Adhesion to EVA (After Aging)	X	X	√
Stability of Treatment (> 6 months)	X	X	√



Lightswitch Complete

Advantages

- Production Efficiencies
  - Reduced Lay-up
  - Reduced Defects
- Lower cost
  - Less packaging
  - Less shipping

Pre-laminate of ETFE with EVA

Now available at widths up to 2 m

- Saint Gobain's C-treatment is more stable and long lasting compared to Corona and Plasma treatments.
- Adhesion performance of Lightswitch® ETFE to Lightswitch® EVA remains strong even after undergoing the accelerated aging tests required for PV applications.
- ETFE/EVA pre-lamination (Lightswitch Complete) simplifies processing, reduces defects as well as costs.

SAINT-GOBAIN SOLAR

NREL National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC.

Data Filtering Impact on PV Degradation Rates and Uncertainty

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1 Introduction

Important to know Power decline over time accurately

Degradation rates (Rd)

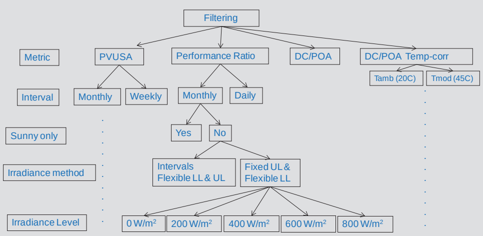
1. Financially:
Cash flow
Uncertainty directly related to risk

2. Technically:
Lifetime prediction
Product improvement

Comprehensive list of uncertainties on known systems including

1. Instrumentation specifications
2. Instrumentation calibrations
3. Data filtering

2 Data Filtering Criteria



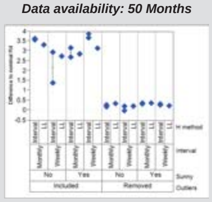
DC/POA Temp-corr = DC Power/ Plane-of-array Irradiance, temperature-corrected

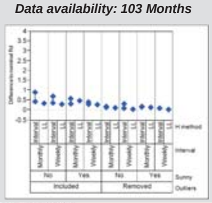
Automation

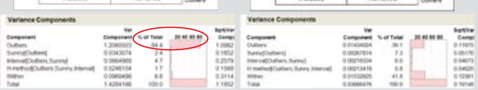
Generates 300 – 500 Degradation rates per System

3 PVUSA Sensitivity to Outliers

Data availability: 50 Months / *Data availability: 103 Months*







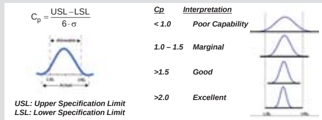
Most of variation for PVUSA comes from outliers
Less critical with more data

4 Evaluation of Rd

Goal: 1. Determine "correct" Rd=nominal Rd accurately
2. Determine it with precision, i.e. small uncertainty

Accuracy vs. Precision

Capability metric: Cp



$$C_p = \frac{USL - LSL}{6 \cdot \sigma}$$

Disadvantage of Cp: No information where in interval distribution falls

Capability Index - Cpk

$$C_{pk} = \min\left[\frac{USL - mean}{3 \cdot Std\,Dev}, \frac{mean - LSL}{3 \cdot Std\,Dev}\right]$$

The more positive the better!

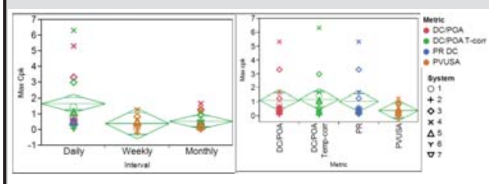
How do you know what the correct/"nominal" Rd interval should be?
↓
Determine Rd in 9 different ways → most likely Rd is included in the interval

Example Table:

Use Cpk to judge accuracy and precision

5 Cpk for 7 systems

Symbols refer to different systems at NREL
Colors refer to different metric



95% confidence interval with mean crossbars shown

Daily interval show significantly higher cpk →i.e. more accurate & precise than monthly

(PVUSA was not done daily but weekly)

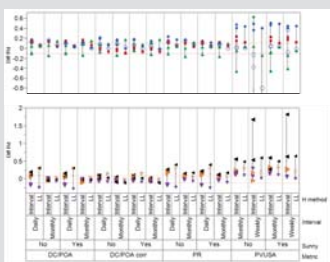
DC/POA, DC/POA Temp-corr and PR significantly higher than PVUSA

Not much difference when all rates are compared for DC/POA, DC/POA Temp-corr and PR but DC/POA Temp-corr has the highest values

Daily metrics preferred over monthly

6 Data Filtering Impact on Rd

Interval: 200 W/m2 Irradiance interval around 800W/m2
LL: Upper Irradiance interval fixed at 1200 W/m2, lower limit at 800 W/m2



DC/POA Temp-corr most consistently w/in 0.1%/year

7 Total Uncertainty Calculation

List of uncertainties:
1. Data logger calibration for DC voltage & current (based on data from historical calibrations)
2. Data logger tolerances (manufacturers' specifications)
3. Pyranometer calibrations (NREL's BORCAL[1])
4. STC rating uncertainty
5. Data filtering sensitivity as determined from previous slide

Use Excel® Monte Carlo Add-in Modelrisk®

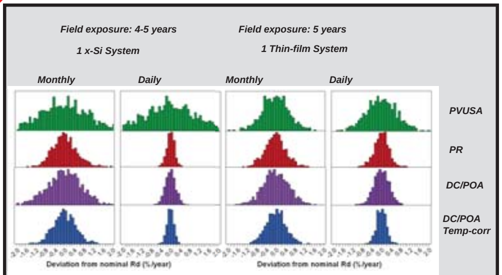
Procedure:
Assign distributions to list of uncertainties (Gaussian, Uniform, Triangle..)
Take random number from each distribution and add to each monthly/weekly/daily value
Repeat 1000 times
Complete entire procedure for each metric/interval/system

Green cells: Input distribution; Blue cell: Output

Spreadsheet Modeling

[1] Myers DR et al., 2004, NREL Conference Paper NREL/CP-560-36320.
[2] http://www.vosesoftware.com/

8 Monte Carlo Results



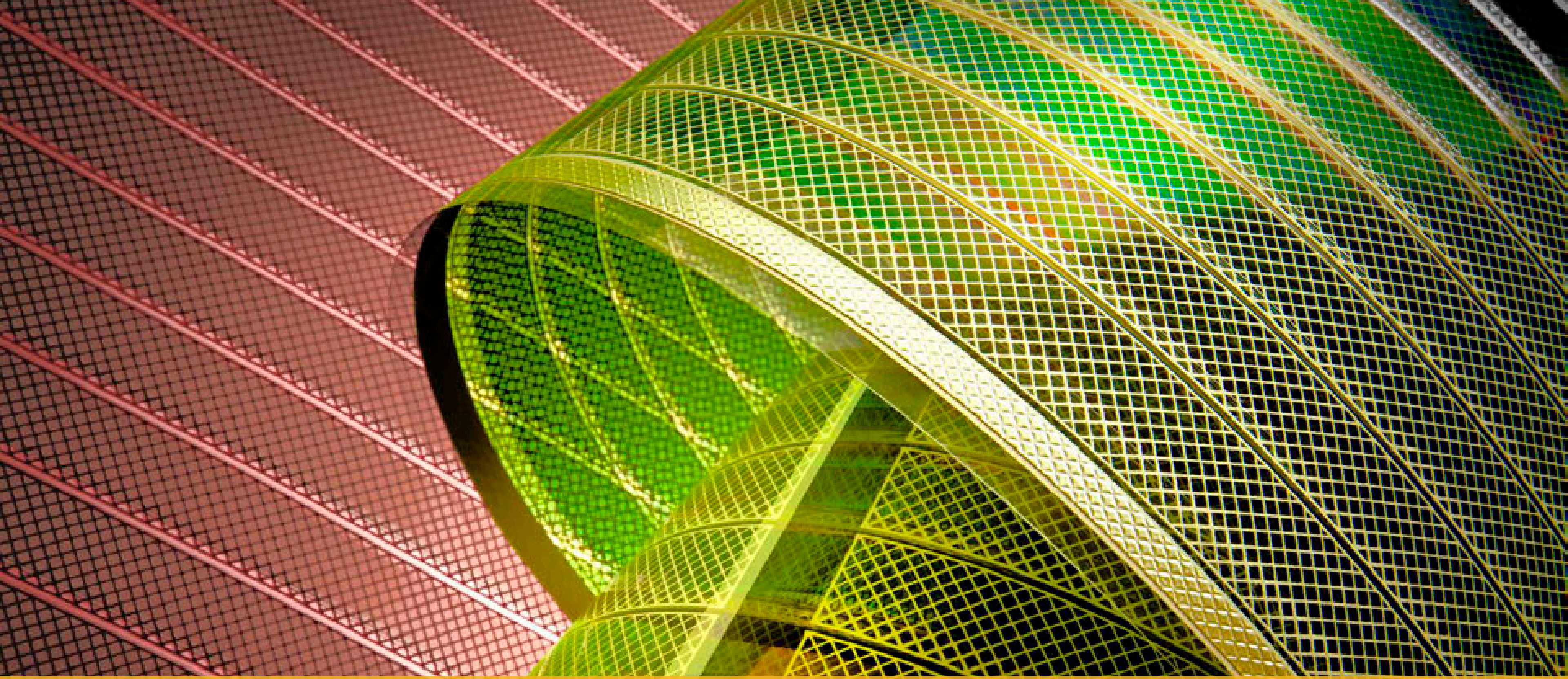
PVUSA least precise
DC/POA Temp-corr most precise

9 Conclusion

- *Data filtering has a big impact on assessing long-term degradation*
- *PVUSA is most sensitive to outliers, particularly for shorter field exposure*
- *Daily metrics are preferred over monthly metrics*
- *DC/POA Temp-corr is most consistent in determining Rd w/in 0.1%/year*
- *Total uncertainty fluctuates somewhat from dataset to dataset – DC/POA Temp-corr best performing*

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory

NREL PV Module Reliability Workshop, Golden CO, Feb.28-Mar.1, 2012



Meeting IEC 61646 Climatic Chamber Test Requirements w/OPV

NREL Photovoltaic Modules Reliability Workshop (PVMRW, February 2012)

Yan, Fadong; Peltola, Jorma; Wicks, Stephen; Balasubramanian, Srini; Kam-Lum, Elsa

KONARKA®

Summary

- A historical milestone for OPV technology worldwide has been achieved.
- A press announcement on 2/15/2012 by Konarka stated that OPV modules laminated in glass passed the IEC 61646 climatic chamber tests.
- This facilitates Konarka's Power Plastic integration into BIPV glass applications.
- The key 61646 test results are presented:
  - for laminated glass products – results by TUV Rheinland
  - for flexible products – Internal results by Konarka. TUV testing is in progress
- Lessons learned are discussed

International Standard IEC 61646

Thin-film terrestrial photovoltaic (PV) modules
Design qualification and type approval

TUV Declaration

Product: PV Modules
Type: Konarka PP120- G/G

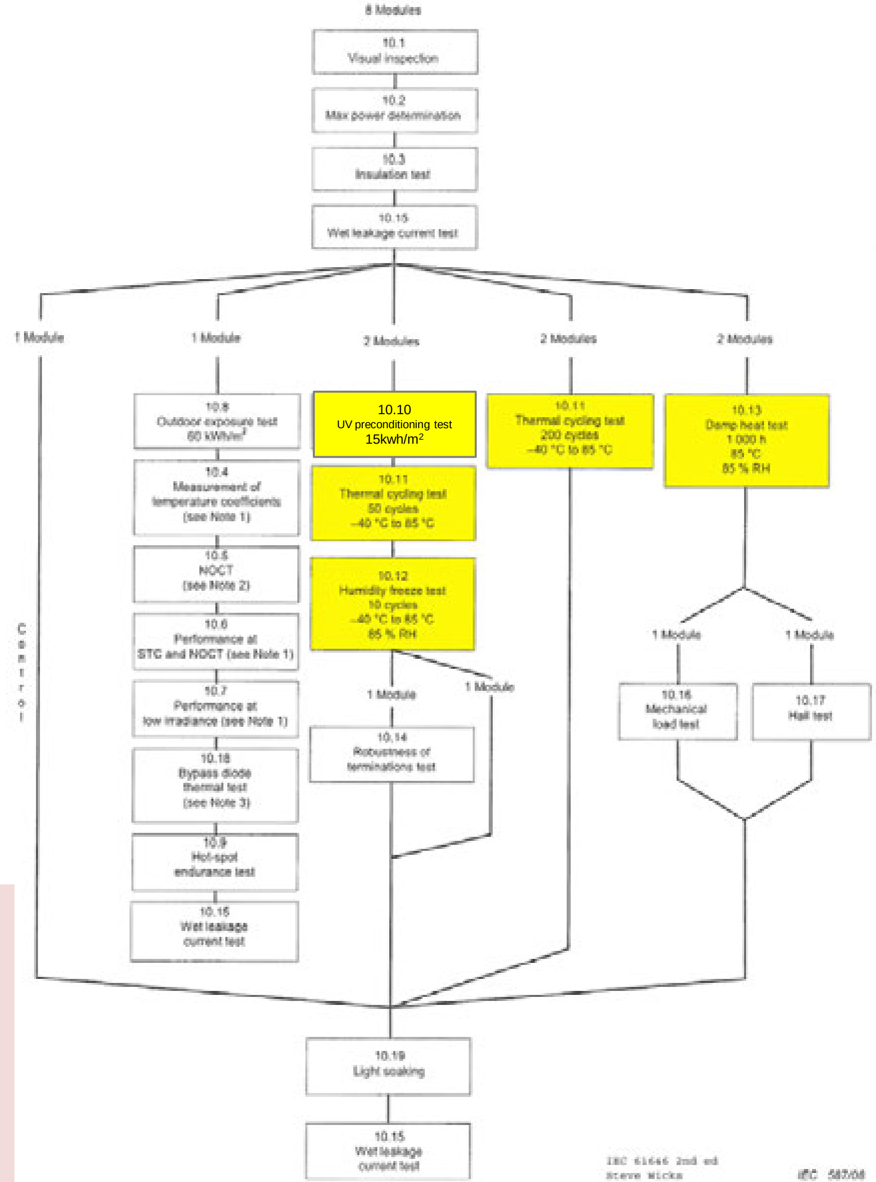
Carbon Neutral Company

Herewith we declare that for the above listed module type
- the UV test sequence (including UV preconditioning, Thermal Cycling Test (50 cycles) and Humidity Freeze Test),
- a Thermal Cycling Test (200 cycles) and
- a Damp Heat Test

acc. to EN IEC 61646:2008 were performed (three modules per test) and that after these tests
- a visual inspection and
- a relative output power measurement

were successfully performed. The determined maximum power degradation caused by the above listed environmental stress tests is 4 %.

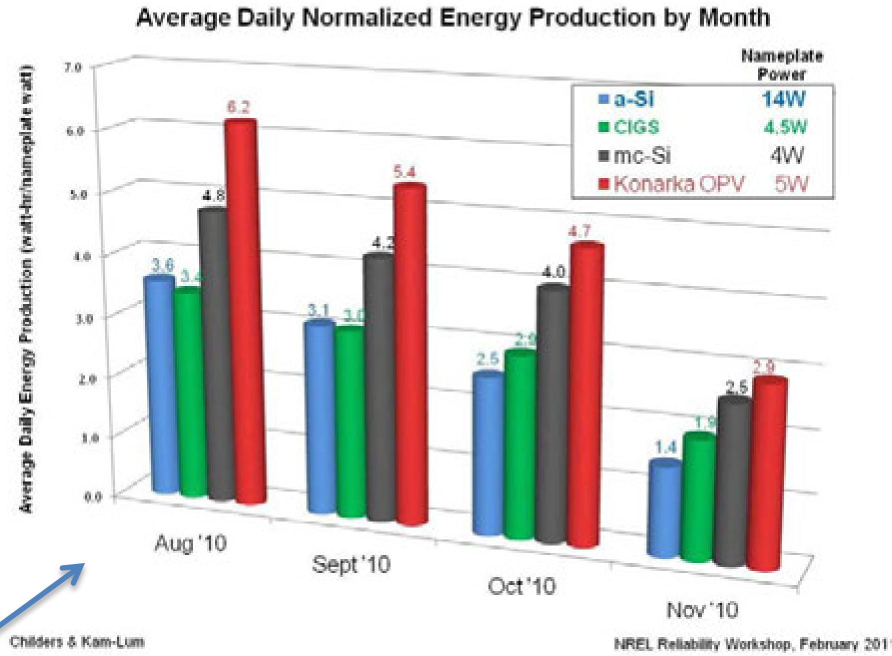
Business Field Solar Energy



Reported Data Include:

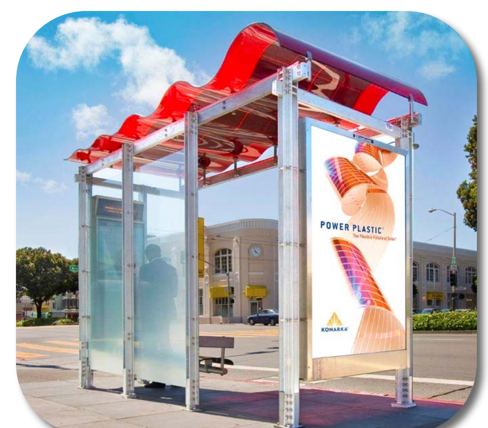
- Rigid Glass/Power Plastic Laminates TUV Rheinland, Cologne, Germany
- Flexible Power Plastic Laminates, Preliminary Internal test results by Konarka Technologies, Lowell, MA

Power Plastic™ Enables Glass, Polymer and Flexible Component Constructions



Advantages:

- •Flexible, thin, lightweight- portable
- •Low light sensitivity, indoor and outdoor
- •Off angle performance
- •Collects energy up to 70 off axis
- •Sunrise to sunset power generation
- •Can be used on vertical surfaces
- •Transparent version in multiple colors
- •Low cost manufacturing/printable
- •Customizable by voltage requirements
- •Tunable cell chemistry can absorb specific wavelengths of light
- •Positive thermal coefficient



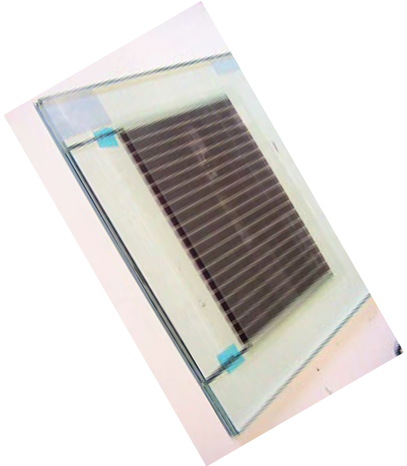
Rigid Laminations Feasible by Industry Standard Process Methods

KONARKA®

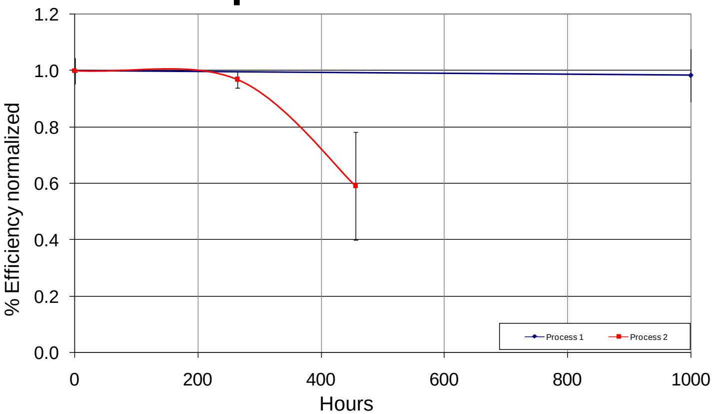
Vacuum Laminator

Vacuum Oven

Autoclave



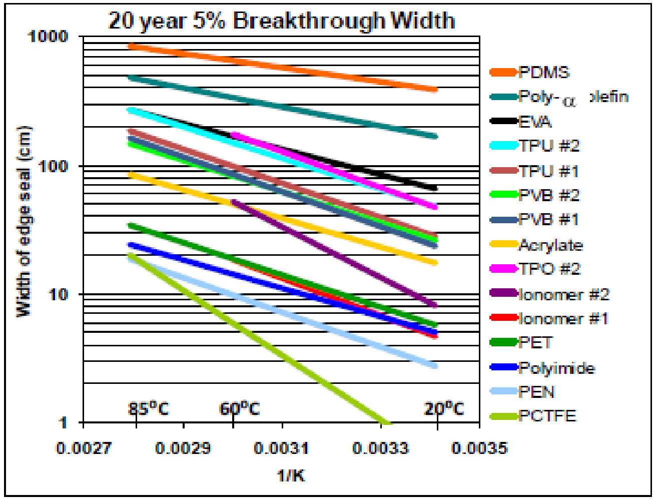
Comparison of Process 1 & 2
Damp Heat 85C/85%RH



Process technology & development optimization required.

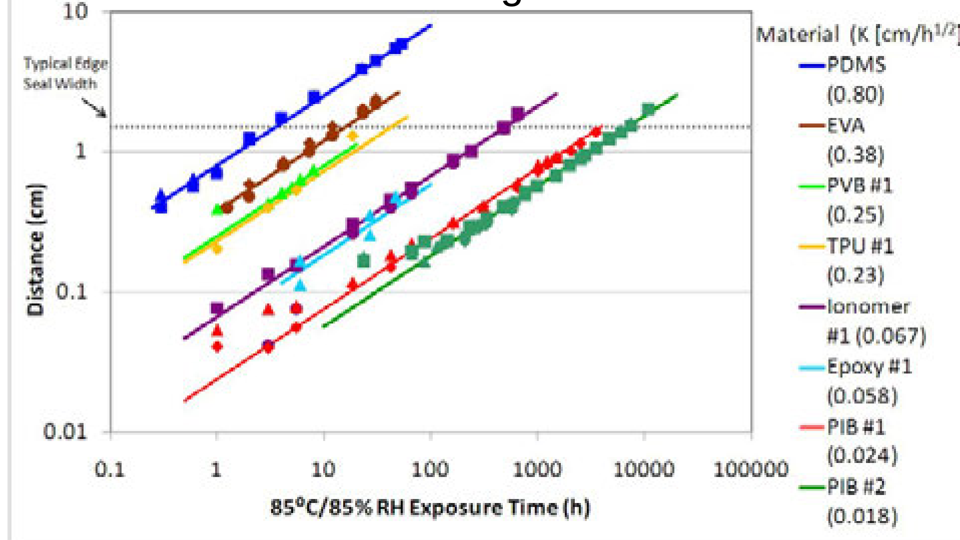
Manufacturing versatility for the fabrication of flat and non-flat rigid glass, polycarbonate and acrylic laminates

Effect of Interlayer in Glass Laminates DH Performance



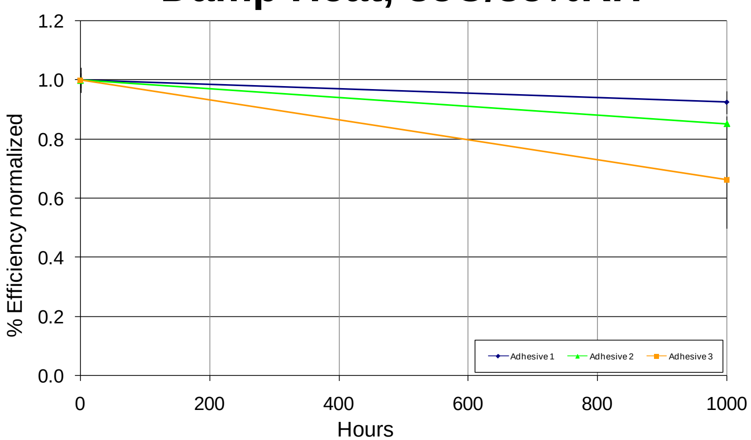
Width of edge seal made from different materials that would be necessary to keep moisture below 5% of equilibrium values at a given temperature*

Moisture Ingress Rate *



Penetration depth of moisture between glass plates laminated with different materials as measured by oxidation of a 100nm film of Ca *

Comparison of Adhesives 1, 2, 3 in Damp Heat, 85C/85%RH

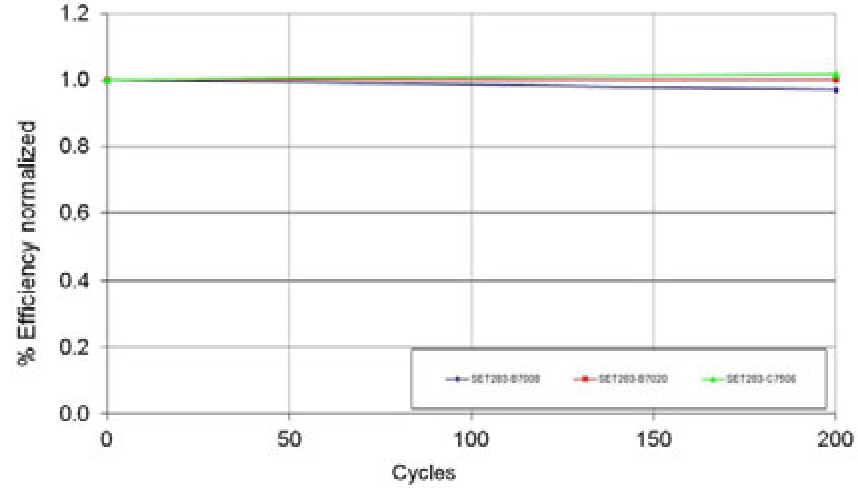


Interlayer Type	Supplier WVTR, g/day/m2 (ASTM F1249)	Average % weight loss @100 oC/30 min by TGA
Type 1	20	2.7
Type 2	40	1.7
Type 3	20	0.6
Type 4	<1.0	<0.01
Type 5	<1.0	0.3

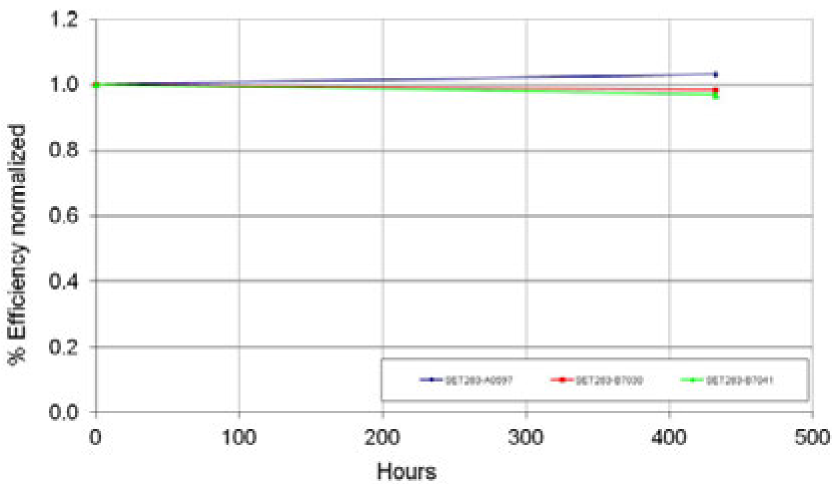
*Kempe, M., "Overview of Scientific Issues Involved in Selection of Polymers for PV Applications", 37th IEEE Photovoltaic Specialists Conference, Seattle, WA June 19-24, 2011

Flexible OPV Modules Laminated in Glass. IEC 61646 – results by TUV Rheinland

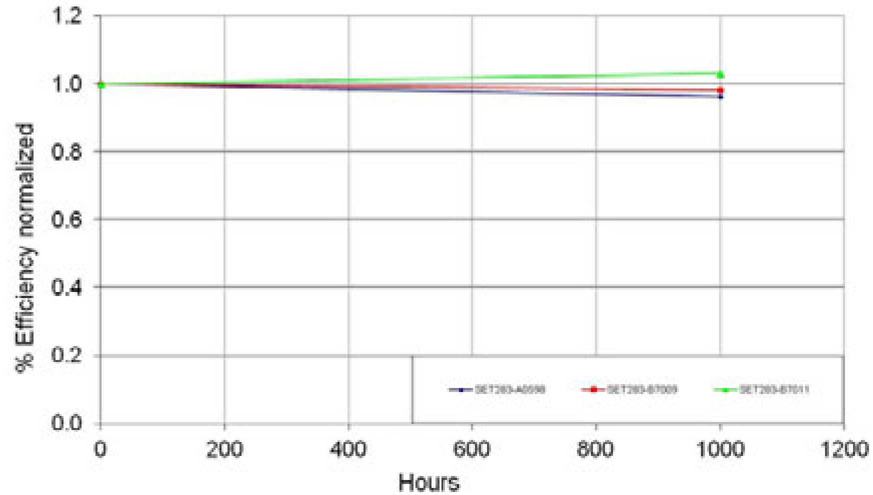
IEC 61646 10.11 TC 200 cycles



IEC 61646, 10.10 UV + 10.11 TC50 + 10.12 HF10



IEC 61646 10.13 DH 1000 hrs 85C/85%RH



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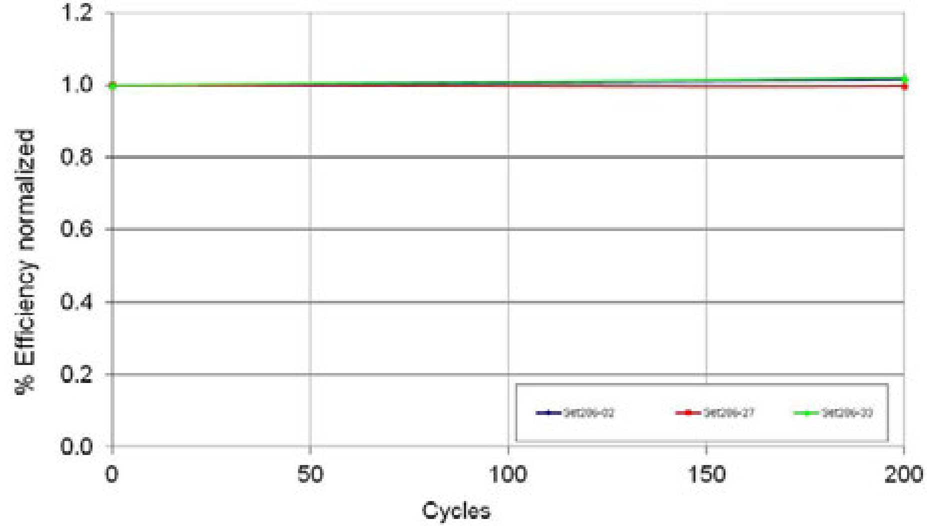
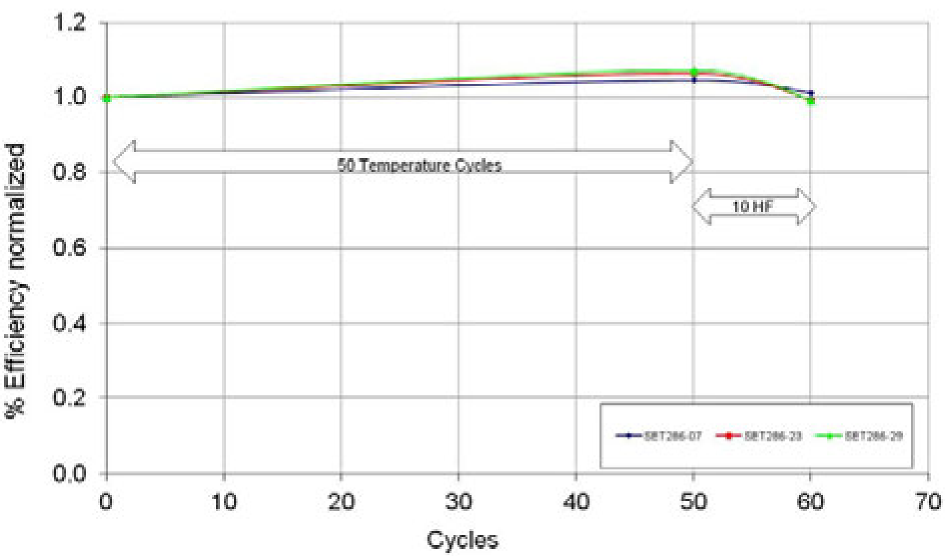
Flexible OPV Modules. IEC 61646 - Konarka Internal Results

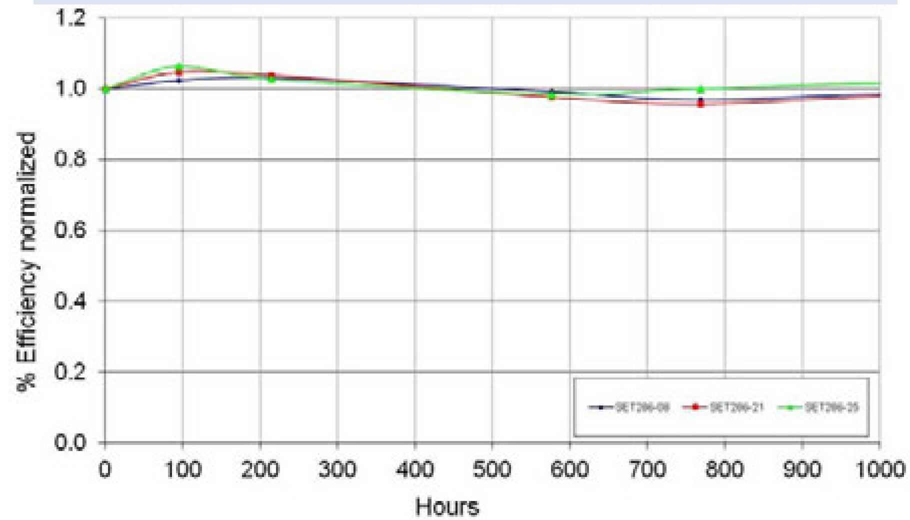
IEC 61646 10.11
TC 200 cycles, -40 C to 85 C



IEC 61646 10.11 TC50 + 10.12 HF10

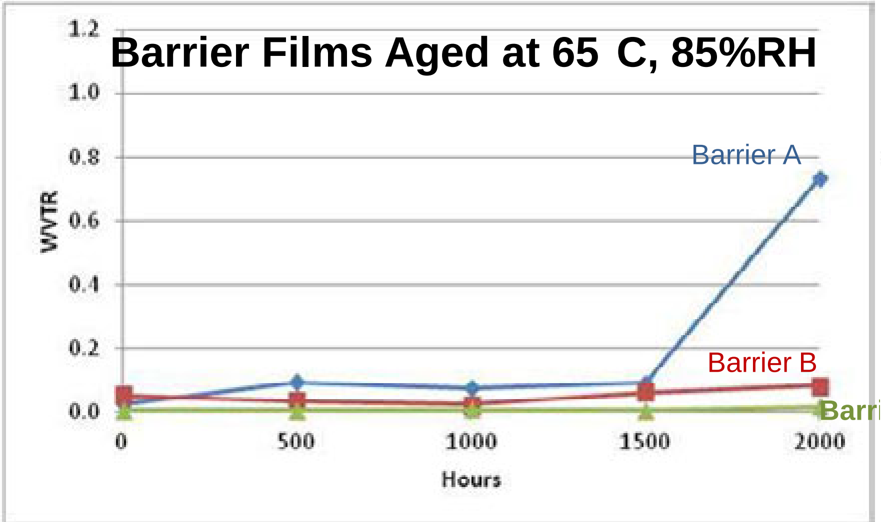


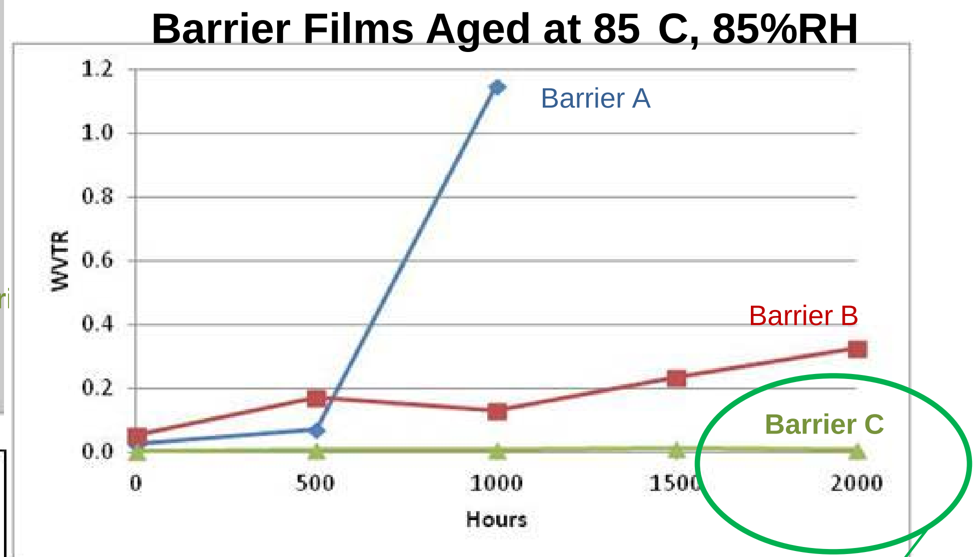
IEC 61646 10.13 DH 1000 hrs 85C/85%RH



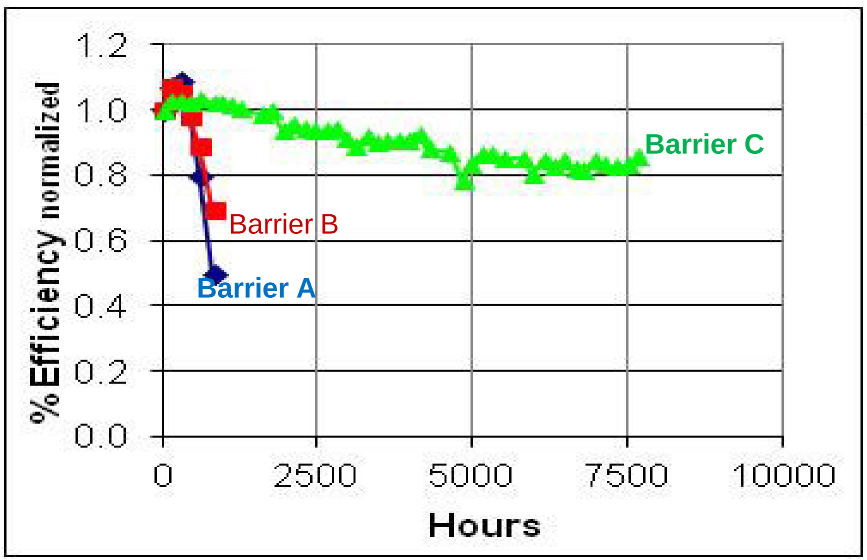
To Pass IEC 61646, Flexible OPV Modules

Require Excellent WVTR Barriers that are Stable Over Long Exposure Time





Barrier C necessary to pass IEC 61646, 10. 13: 1000 hours @85C/85% RH



Modules Performance @65 C/85% RH

Barriers Initial WVTR*

Barrier A: 4 x 10^{-2} $g/m^2/day$

Barrier B: 5 x 10^{-2} $g/m^2/day$

Barrier C: 5 x 10^{-3} $g/m^2/day$

** WVTR derived from internal calcium test conducted at 65 C, 85%RH. Not MOCON WVTR test at 38 C/ 100%RH*

Conclusions

- OPV modules can pass IEC 61646 climatic chamber test requirements with the appropriate outside barrier. For glass laminated modules one combination of optimized layers tested by TUV Rheinland passed. Optimization of the layers and lamination process are necessary.
- OPV modules encased in glass can be manufactured by industry standard process methods
- For flexible OPV modules, internal tests indicate good probability of passing with a stable barrier with WVTR* of $\leq$ 5x 10^{-3} $g/m^2/day$. Tests are in progress at TUV.

** WVTR derived from internal calcium test conducted at 65 C, 85%RH. Not MOCON WVTR test at 38 C/ 100%RH*

Flexible CIGS Modules – Selected Aspects for Achieving long-term stable Products

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Germany

NREL PV Module Reliability Workshop 28.02.-01.03.2012, Golden, CO, USA

This work was supported with financial resources of the European Fund for Regional Development of the European Union and the German State of Saxony.

Europa fördert Sachsen.
EFRE
Europäischer Fonds für regionale Entwicklung

Introduction

Technology

Solarion develops and produces solar modules, based on **CIGS thin-film solar cells on ultra thin polymer substrate** employing a proprietary **ion beam-assisted manufacturing process** that deposits a thin layer of copper indium gallium selenide (CIGS) on the lightest substrate available at **reduced deposition temperatures**. The cell materials are deposited in a continuous roll-to roll-process on the 25 micron PI-substrate. A thin layer of Ag-based contact grid is printed on top of the cell. These will be converted to single cells and sorted to several power classes.

Applications

Due to the **light weight**, the **flexibility** and the possibility of the assembly of **cell matrix in many variations** there is a **wide range of possible module designs, e.g. for BIPV, automotive etc.**

Module R&D Activities

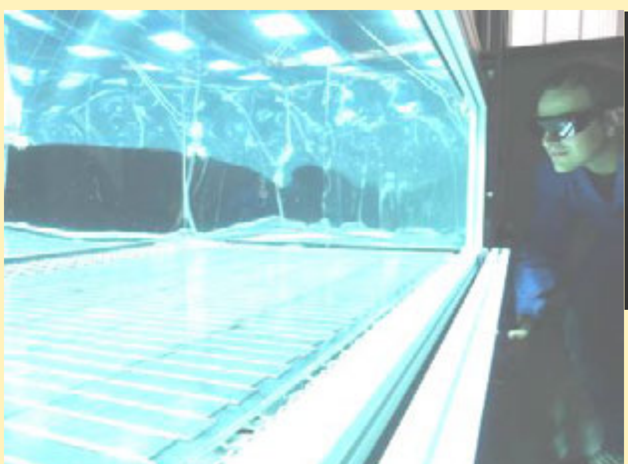
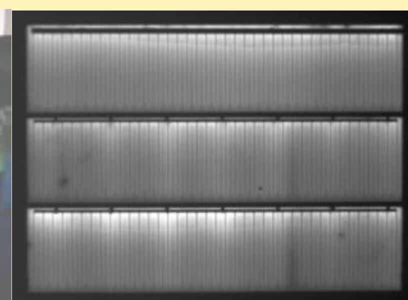
Besides its solar cell R&D, Solarion performs an **intensive solar module research** with focus on **product and technology development, reliability and safety testing**. The majority of the common standard tests are executed **in-house** and advanced reliability tests were conducted by partners.

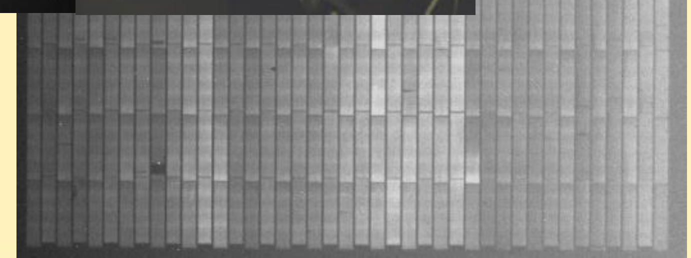
A flexible encapsulation technology was developed for Solarion's cell technology using several polymeric materials. The optimal materials and their system compatibility, also to the solar cell, were identified by intensive research and **testing of 25 conductive adhesives, about 20 barrier films, 20 encapsulants, six edge sealings and several back sheets** over the last years.

Methodes of Material Testing

The following methods were applied to materials, material combinations and module test samples:

- Climate testing according to IEC61646 (TC, DHT, HF, UV), also with extended testing times
- Sequential moisture-UV testing according IEC61646: one week DH – one week UV (alternating)
- Dynamic-Mechanical Analysis (DMA) for investigating thermo-mechanical behavior of polymers (encapsulants, edge sealings, interconnection materials)
- Adhesion testing (peel tests)
- Electrical characterization using steady state and pulsed solar simulators
- Damage analysis using EL, IR thermography, LBIC, LIT and microscopy

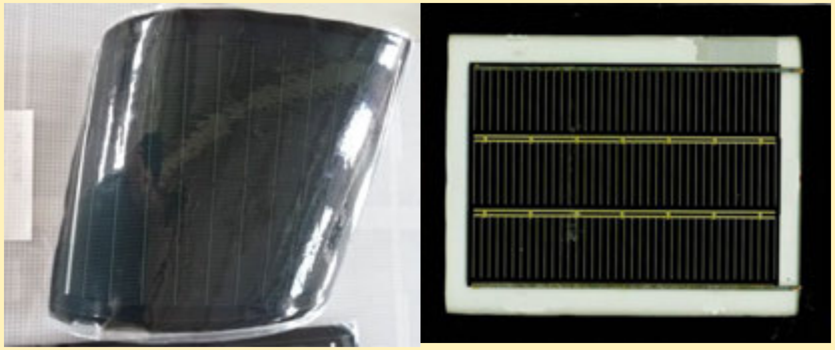





Key Factors for reliable flexible CIGS Module Encapsulation

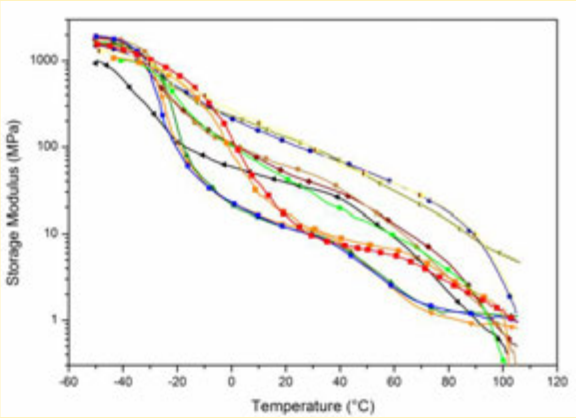
The following key factors, esp. regarding polymeric materials, were identified by experimental work:

- Adhesion and chemical compatibility to neighboring materials
- Thermomechanical behavior (viscoelasticity, creep behavior, CTE, fracture strength)
- Shrinkage
- Phase changes
- Water vapor transmission, moisture resistivity under tensile strain
- Reactive residues
- Conductivity and contact resistance of interconnection materials



Deformation after TCT80 due to unmatched materials (left) and interactions between conductive adhesive / silver paste and encapsulant after UV exposure (right)

Key Results: Encapsulants

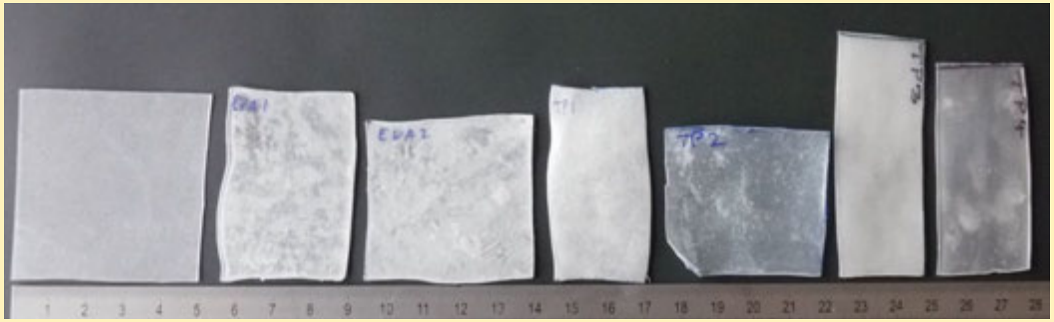


Wide range of Storage Modulus, partly phase changes and glass transitions in relevant temperature range, see also [1]

→ mechanical stress at interfaces

Creep behavior at higer operation temperatures

→ Critical for product stability, delamination



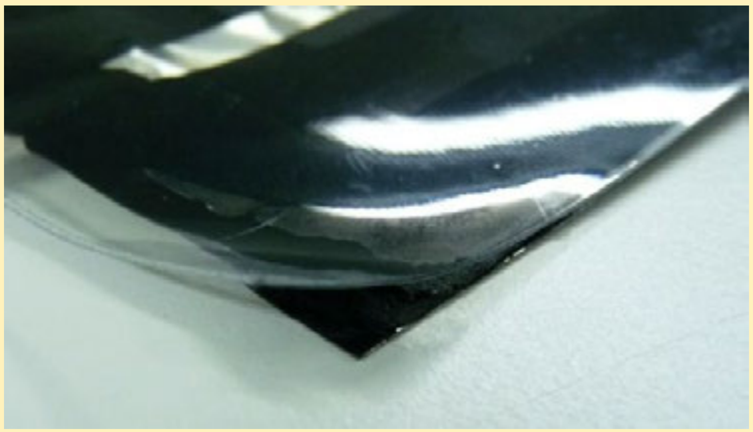
Shrinkage during processing

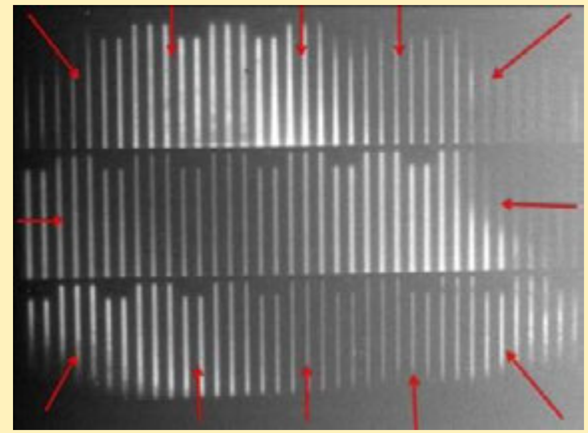
→ internal stress at interfaces, destruction of cell and/or interconnection structures

[1] Michael D. Kempe: Rheological and Mechanical Considerations for Photovoltaic Encapsulants; 2005 DOE Solar Energy Technologies Program Review Meeting November 7–10, 2005 Denver, Colorado

Key Results: Edge Sealings

- **General function and stability shown** in [2] and confirmed by own work





- Adhesion issues possible → Degradation
- Partly, interface degradation under UV-moisture influence observed

[2] Michael D. Kempe, Arrelaine Dameron, Matthew Reese: Calcium Based Test Method for Evaluation of Photovoltaic Edge-Seal Materials; 2011 NREL PV Module Reliability Workshop

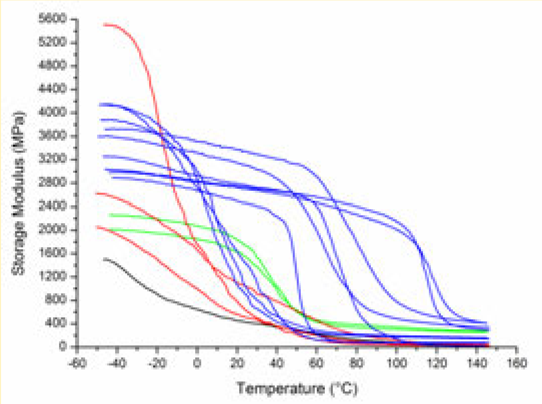
Key Results: Polymer-based Interconnection Material

- **Adhesion** to different materials on cell surface has to be qualified
  → Mechanical Stability of interconnection

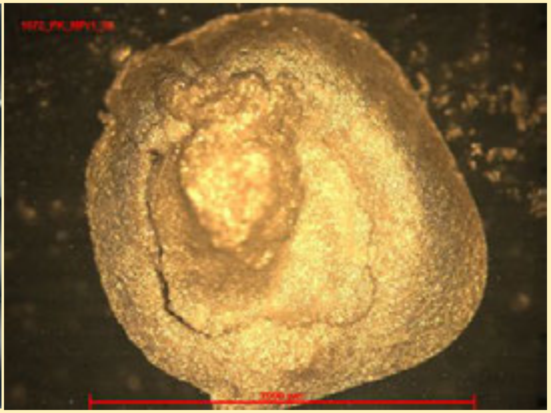
- **Stability of contact resistance** to different materials on cell surface during temperature cycling has to be approved
  → Risk of electrical serial resistance changes

- **Bulk conductivity** has to be increased → Serial resistance reduction

- **Wide range of Young's modulus**, glass transitions at operation temperature range for different interconnection materials
  → materials with high Young's modulus fail / break due to mechanical stress

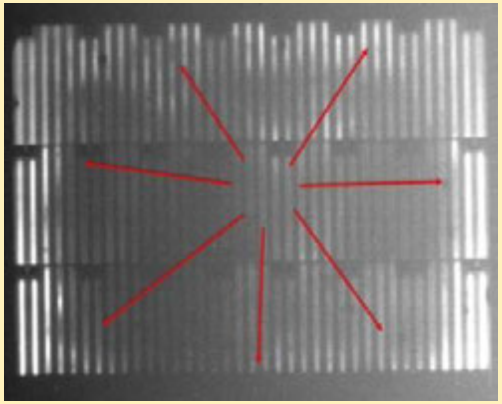


0 Zyklen



Key Results: Front- and Back Sheet Materials

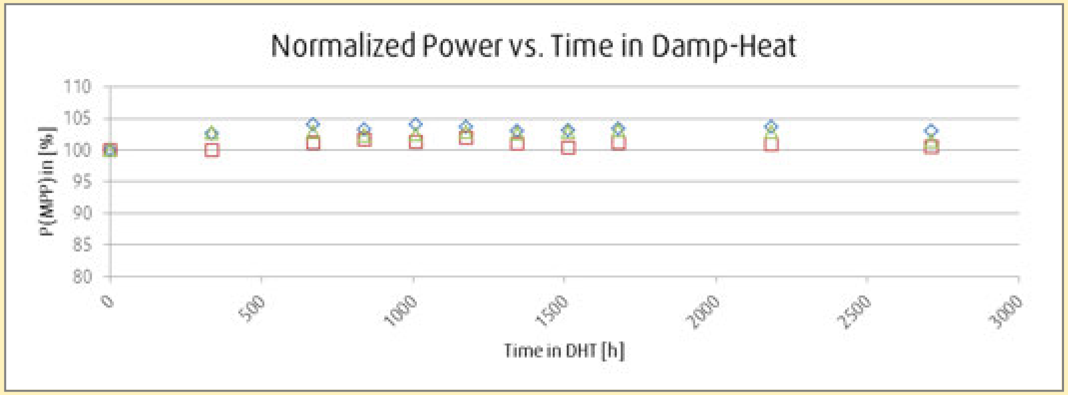
- Stability in climate testing shown with different front and back sheet materials
- Stable adhesion to encapsulants and especially to edge sealings is mandatory
- "functional adhesion" of about 2..3 N/cm apparently enough for a working encapsulation system but too low for mechanical resistivity in the field
- WVTR close to zero necessary

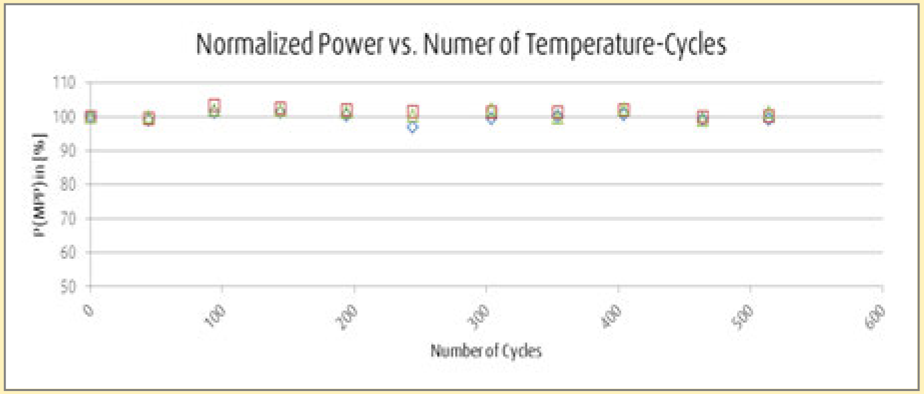


Cell degradation due to moisture ingress via front barrier film

Results on Module Level

A **high long term stability** of flexible modules as shown in following figures can only be achieved by **developing a general understanding regarding the single materials** used in the module sandwich and testing their interactions. This background allows pre-qualifying and selecting suitable materials and material combinations under different ambient or testing conditions.





Normalized power of flexible Solarion modules in DHT (85 °C / 85 % r.h.) and TCT (-40 to +85 °C)

Performance of CIGS flexible module arrays on different field mountings

S. Jayanarayanan, L. Cao, A. Kamer, N. Staud, D. Nayak, B. Metin, E. Lee, M. Pinarbasi

Solopower, 5981 Optical Ct., San Jose, CA 95138

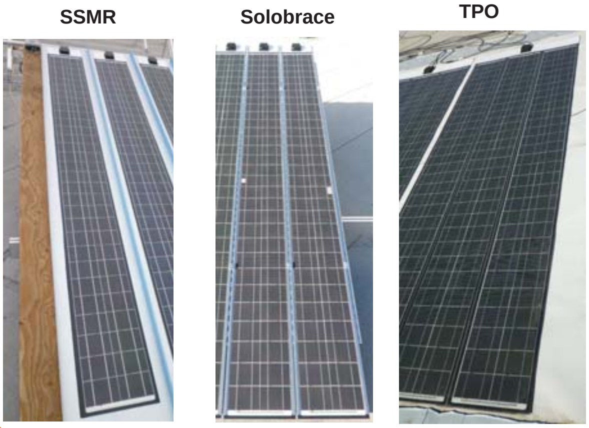
Introduction

- Three Flexible Arrays have been studied with different mountings:
  - Standing Seam Metal Roof (SSMR)
  - Metal brace with open rack ("Solobrace")
  - TPO membrane stuck to Asphalt roof

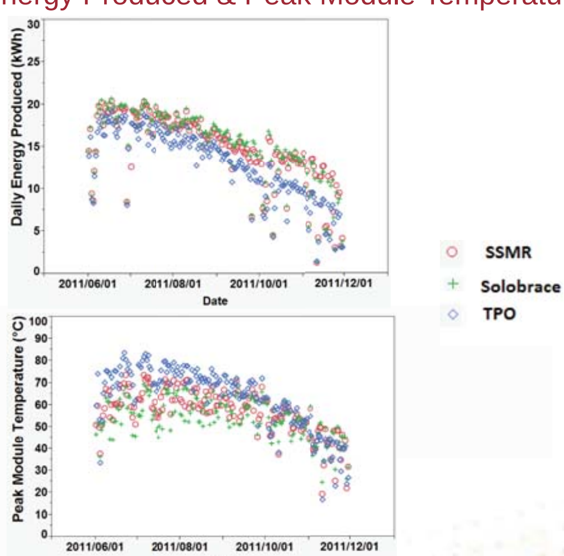
- System Advisor Model (SAM) and PVSyst software programs have been used for simulations.

Photos

SSMR **Solobrace** **TPO**

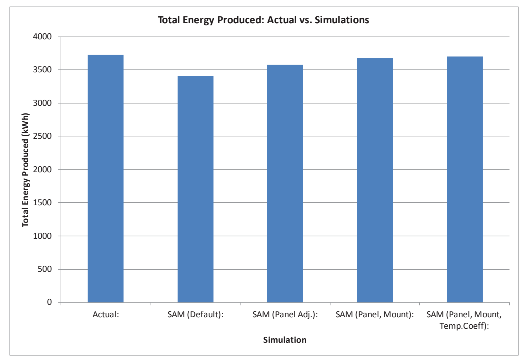


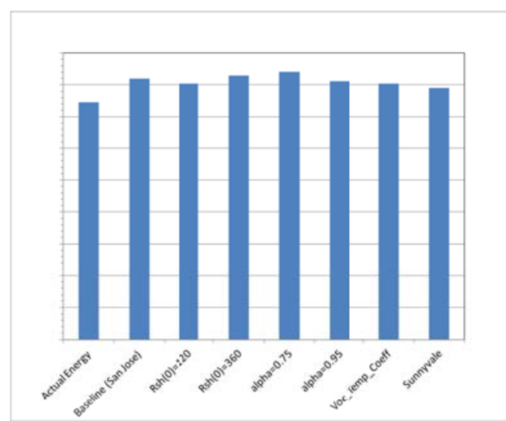
Energy Produced & Peak Module Temperature



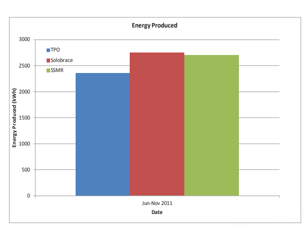
SAM and PVSyst Simulations

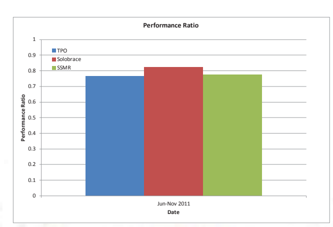
- Simulations were performed with different methodologies and successive simulations closely matched the actual energy produced.
  - Graphs shown for Solobrace Mounting





Conclusion





- TPO (0º tilt) the hottest in summer, Solobrace (Rack-mount, 17º tilt) is the coolest.
- Performance Ratio of TPO is 93% of that of Solobrace (rack-mount) over Jun-Nov 2011.

This poster does not contain any proprietary or confidential information

Which Polymer for Reliable Silicon Thin-Film PV Module?

Laure-Emmanuelle Perret-Aebi*, Valentin Chapuis, Christian Schlumpf, Ségolène Pélisset, Marylène Barnéoud-Raeis, Heng-Yu Li, Christophe Ballif

Ecole Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), Photovoltaics and thin film electronics laboratory, Breguet 2, CH-2000 Neuchâtel, Switzerland.
**laure-emmanuelle.perret@epfl.ch*

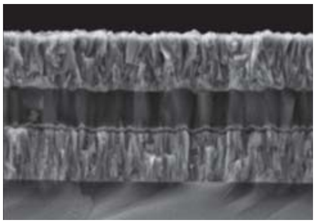
Requirements for Silicon Thin-Film PV Module

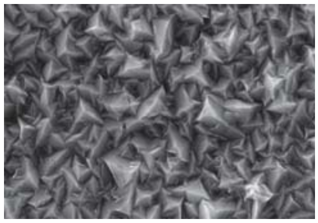
Stable
- UV
- temperatures
- chemical degradation

Compatible
- corrosion, chemical reactions
- diffusion, dissolution
- adhesion

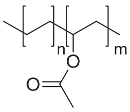
Barrier
- water vapor
- O_2 and other pollutants

Transparent Conductive Oxides (TCO)

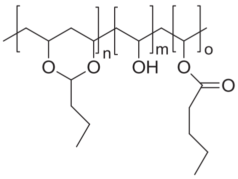




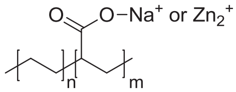
Polymers tested



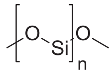
Ethylene Vinyl Acetate (EVA)



Polyvinyl Butyral (PVB)



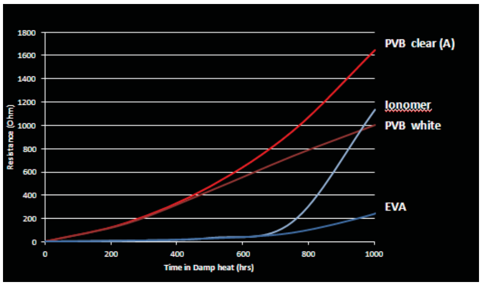
Ionomer



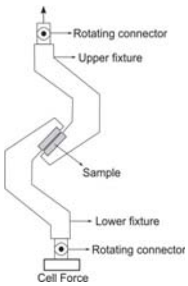
Silicone liquid and foil

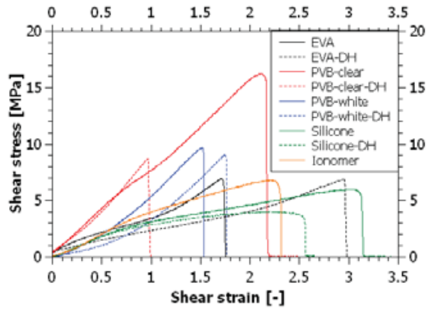
Results

TCO degradation in damp heat conditions



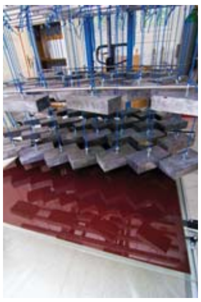
Compressive Shear Test (CST)

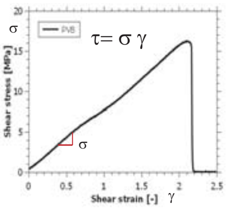


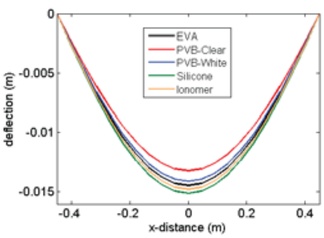


CST results, showing she shear stress as a function of the shear strain for each polymer samples (Valentin Chapuis et al. submitted to PIP)

Mechanical load test







Simulation of the deflection based on the CST measurements

- •EVA shows a positive evolution of adhesion after degradation,
- •PVB has the highest initial adhesion,
- •Silicone module shows a poor adhesion, unsuitable for passing mechanical tests but a considerable energy absorption leading to the highest deflection,
- •Ionomer shows a good compatibility with TCO layers.

Conclusion

Photovoltaic modules are:

- installed in very different environments ,
- used for various applications.

This should influence the choice of the encapsulation materials

This work is supported by the Swiss Federal Office for Energy (SFOE)

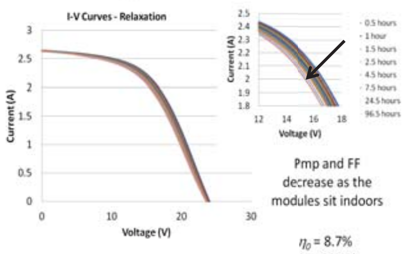
Light soaking behavior and an alternate stabilization method for CIGS modules

Adam Stokes, Chris Deline, John Wohlgemuth, Sarah Kurtz, Steve Rummel, Allan Anderberg, and Matt Weber

Motivation

- **Stabilize CIGS modules for accurate electrical measurements**
- **Gain insight on variability of metastabilities associated with light soaking and forward bias of different CIGS products**
- **Determine whether forward bias is a useful substitute to light soaking**

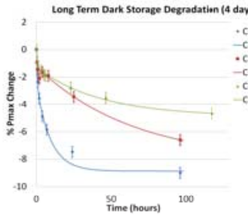
I-V curves, dark storage progression (Typical CIGS Module)

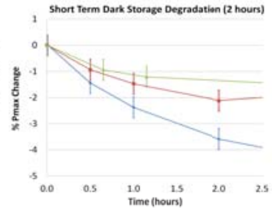


Pmp and FF decrease as the modules sit indoors

η_0 = 8.7%
$\Delta\eta$ = 0.69%

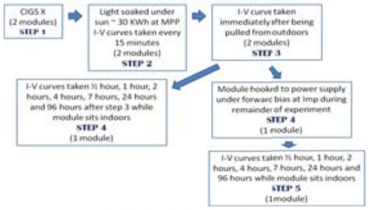
Dark Storage Degradation



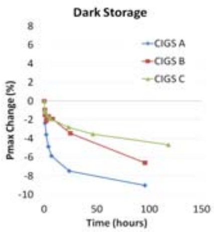


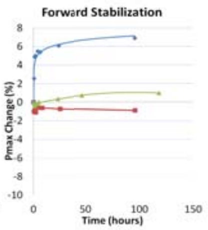
CIGS A: η_0 = 8.7%, CIGS B: η_0 = 11.0%, CIGS C: η_0 = 11.9%

Dark Storage VS Forward Bias 3 CIGS Products Test 1 Flow Chart

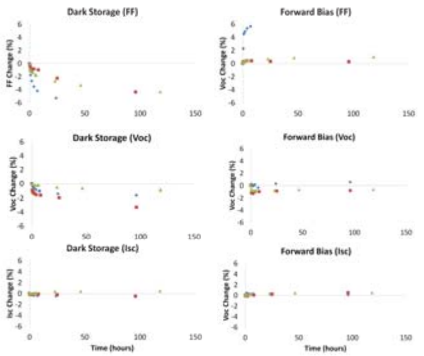


Forward Bias Stabilization VS Dark Storage Relative To First Indoor Point

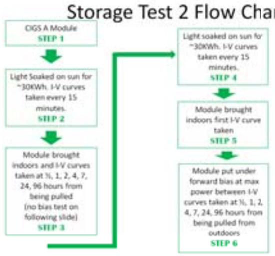




CIGS A: η_0 = 8.7%, CIGS B: η_0 = 11.0%, CIGS C: η_0 = 11.9%



CIGS A Module Forward Bias vs Dark Storage Test 2 Flow Chart

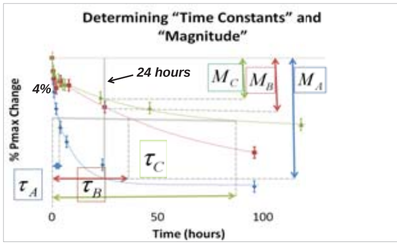


CIGS A module, Forward Bias vs dark storage

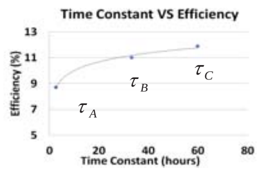
Conclusions

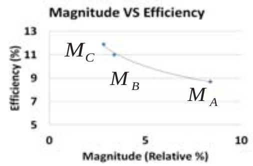
- Dark storage after light soak changes the simulator measured efficiency
- Times range from 3-60 hours for a decrease in Pmax by 4% depending on CIGS product
- Forward bias could be useful for stabilizing the simulator measured efficiency close to an outdoor measured value
- Metastability drivers
  - Isc doesn't vary
  - Change in FF dominates
  - Change in Voc varies with sample
  - Pmax changes in all modules
- Metastability magnitude tends to decrease as STC efficiency increases

Efficiency and Metastability Correlation

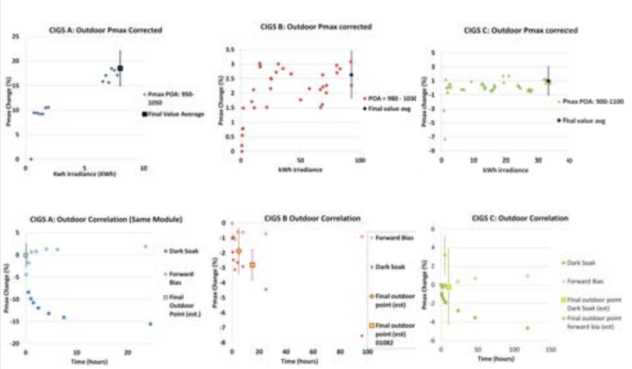


- ***Time constants (τ_A,τ_B,τ_C) are configured as the time it takes to degrade by 4% relative to the first data point taken indoors***
- ***Magnitudes (M_A, M_B, M_C) are configured as the relative percent degradation at 24 hours in dark soak***





Outdoor Correlation

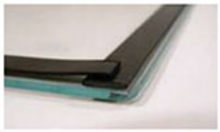


Conference Title
Conference Location - city, state
Conference Dates
NREL/PO-___-_____

SOLAR EDGE SEALANT WITH OPTIMIZED SEALING AND APPLICATION PROPERTIES

Samar Teli and Tim O'Neil
ADCO PRODUCTS INC

RELIABILITY BY CONSISTENT APPLICATION

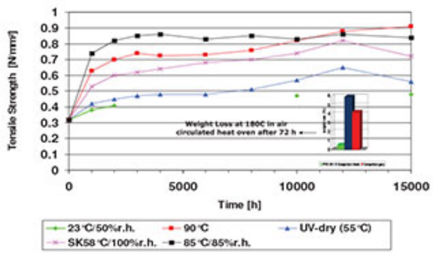

TAPE APPLIED


BULK APPLIED

Availability of a unique pumpable solution improves the consistency of application and reduces the effects of workmanship and process variations. Following are the key benefits of using a pumpable bulk solution for PV modules:

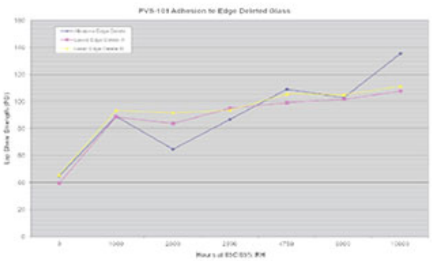
- *Reduced number of seams/knit lines*
- *No need for overlaps at the corners*
- *Flexibility to adjust dimensions based on internal architecture*
- *Reduced process changeovers (versus using tape rolls) reduces process variability*
- *Dimensional controls by end user*
- *Waste reduction*
- *Reduction in process steps*
- *No concern with atmospheric/moisture exposure of tapes for desiccant and reactivity*

THERMAL STABILITY



Thru 15000hr (~625 days) PVS-101 cohesive strength has not decreased under the above environmental conditions and exhibits better thermal stability than the competitive material.

ADHESION : LONG TERM PERFORMANCE



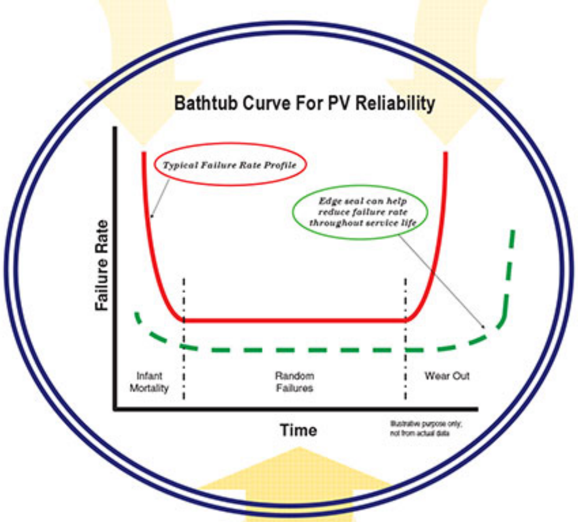
Significant increase in PVS-101 cohesive strength with prolonged exposure and equivalent performance on abrasive or laser edge delete glass

ABSTRACT

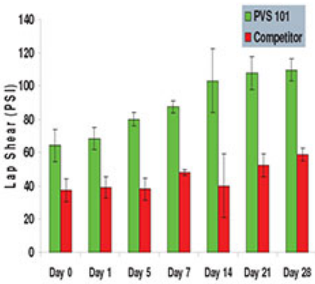
Photovoltaic (PV) modules are sensitive to moisture as it negatively impacts both their safety and long term performance. Edge sealants play a pivotal role in preventing such moisture ingress. PV modules demand edge sealants that have optimized sealing properties in order to maximize these performance considerations. Studies were conducted to develop a solar edge sealant with better moisture vapor transmission rates (MVTR), thermal stability, mechanical properties; and that reacts chemically with glass to form a permanent seal. Apart from surface and bulk properties, highly consistent application is also critical. The delivered form of the edge sealant is key to developing manufacturing procedures that reduce process variability and lower the probability of invoking warranty claims. The results of the various studies to characterize edge seal performance are presented in this poster.

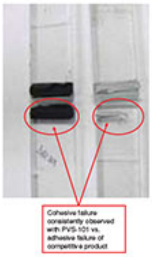
This poster does not contain any proprietary or confidential information

Acknowledgements:
The Authors would like to thank Dennis Booth, Justin Bates, Dr. Harald Becker and Paul Snowwhite for their assistance.



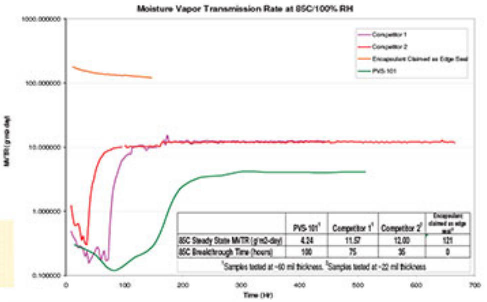
ADHESION : SHEAR STRENGTH TO GLASS





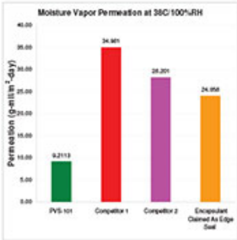
1.7mm thick samples conditioned at 240 ºF for 30 min and compressed to 1.22 mm. Lap shear tests performed at a speed of 4 inch/min

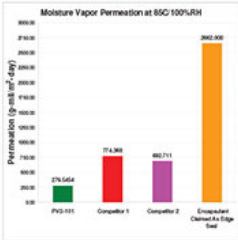
MOISTURE INGRESS



	PVS-101[1]	Competitor 1[1]	Competitor 2[2]	Encapsulant claimed as edge seal[2]
85C Steady State MVTR (g/m2-day)	4.24	11.57	12.00	121
85C Breakthrough Time (hours)	100	75	35	0

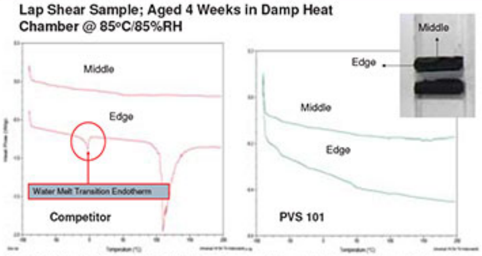
[1]Samples tested at ~60 mil thickness. [2]Samples tested at ~22 mil thickness





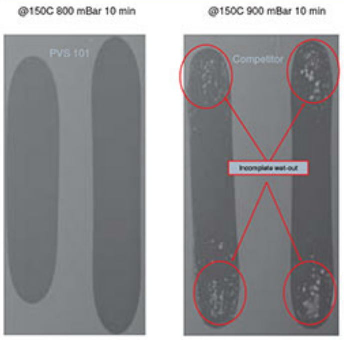
MOISTURE VAPOR PERMEABILITY

Lap Shear Sample; Aged 4 Weeks in Damp Heat Chamber @ 85ºC/85%RH



The Endothermic Transition highlighted in the competitor material above is consistent with the melt transition of water and is present after damp heat exposure toward the outside edge of the competitive lap shear sample. This is not found at the edge of PVS-101 nor at the center of either sample.

ADHESION : WETOUT TO GLASS



- **Acoustic Microscopy technique used to determine wet-out characteristics to glass.**
- **PVS-101 has complete wet-out to the glass vs. the competitive product where discrete/circular voids are observed.**

Contains no confidential information

The effects of device geometry and TCO/Buffer layers on damp heat accelerated lifetime testing of Cu(In,Ga)Se2 solar cells

Christopher P. Thompson†, Steven Hegedus†, Peter F. Carcia*, and R. Scott McLean*

†Institute of Energy Conversion, University of Delaware, Newark, DE, 19716 *DuPont Central R&D, Experimental Station, Wilmington, DE 19880

Introduction and Motivation

•CIGS cells are moisture sensitive. Modeling studies [1,2] suggest that module encapsulation with water vapor transmission rate (WVTR) of 10^{-4} to 10^{-6} g-H_2O/m^2-day is needed for lifetime > 20 yrs

•Damp Heat (D-H) accelerated lifetime testing (ALT) at 85%RH/85°C performed at IEC on CIGS cells encapsulated with a glass or PET top sheet.

•WVTR of PET ~10g/m^2-day >>> greater than WVTR of glass (<< 10^{-6} g/m^2-day)

•Glass and PET sample degraded at the same rate. Why? Was it related to device structure?

Approach

- Devices (SL/Mo/CIGS/CdS/i-ZnO/ITO/Ni-Al grids) on glass with different encapsulation schemes:
  - ❑ 6 pieces with PET, unscribed
  - ❑ 6 pieces with glass, unscribed
  - ❑ PET and glass top sheet bonded to cell with commercial thermoplastic encapsulant
  - ❑ 3 Control pieces, un-encapsulated, 6 cells each, scribed
- Use IEC's CIGS baseline process with variation in cell patterning and i-ZnO integrity (i.e. scribing)
- Subject to D-H ALT for 2000 hrs under ~ 1 sun illumination, Voc.

•I-V characterization at regular intervals

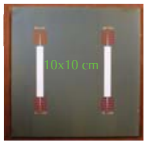
Device Layout

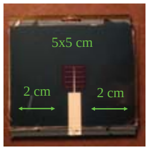
Layout # 1:

1 cm² devices, defined by ITO masking, no scribing, i-ZnO blanket deposition to the edge of substrate

•4 devices (1 cm^2) fabricated on a 10x10 cm substrate, no scribing

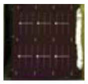
•Cut into four coupons, 1 cell each





Layout # 2: 0.47 cm² scribed devices

•1"x1" substrates comprised of 6 unencapsulated devices ('bare')



Experimental Setup

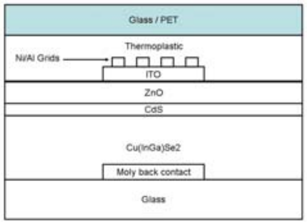
Unique Environmental Chamber

•Metal halide lamp ~1sun illumination intensity

•Electrical contacts allow illumination monitoring and in-situ device testing

Device Structure: Layout #1

- Molybdenum back contact patterned to extend from device to edge of glass (reduces shunting)
- CIGS deposited on glass/Mo using multisource evaporation: EG ~ 1.2 eV, thickness ~ 2 um
- CdS from CBD thickness: ~50 nm
- Intrinsic ZnO: ~50 nm, sputtered on entire area
- ITO: 150 nm, sputtered through mask, defines cell
- Ni/Al grids e-beamed through mask



•ITO: R□ = 27Ω/□ ; i-ZnO: R□ -insulating

•Molybdenum back contact and Ni/Al front contacts run to edge of 5x5 cm substrate

•Encapsulation: 5 mil sheet of PET or glass lid

•Bonding: industrial grade thermoplastic applied at 150°C under pressure

Device Structure: Layout #2

•Same as above except i-ZnO/ITO sputtered over entire 1x1 inch substrate, cell area defined by scribing

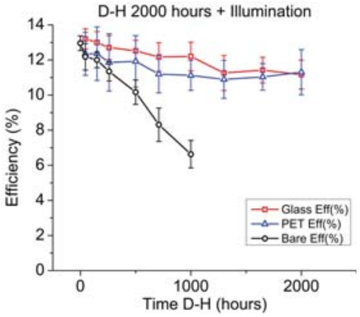
•No encapsulation

Test Results from D-H ALT

Efficiency for 2000 hours of illuminated D-H

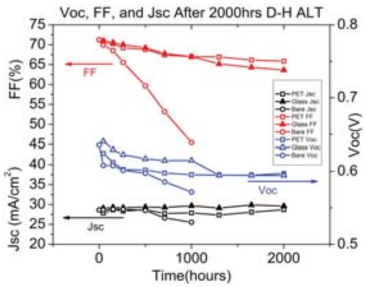
•Layout #1: Average of 6 devices each glass or PET

Layout #2: average of 18 devices, bare, scribed

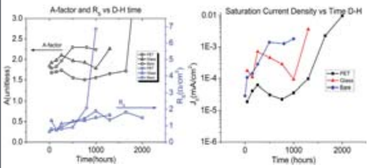


•Glass and PET devices retain 92% initial efficiency after 2000 hours D-H despite very different WVTR

•Bare samples degrade to 52% original eff at 1000 hours, similar to PET samples in previous study [3]



•Degradation: FF most, V_{OC} some, J_{SC} negligible



•All show increase of A and J_o but 'bare' has largest

•All show small but steady increase in R_S

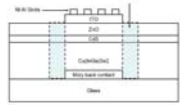
•At 500 hrs, large increase in R_S for 'bare' scribed

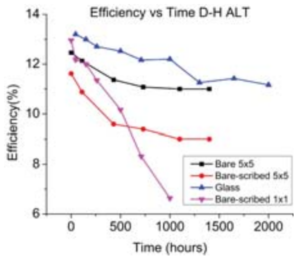
Effects of scribes on D-H degradation

- In [3] i-ZnO deposited through a 1x1cm mask
- Now over entire 5x5cm area (improved thermoplastic bonding adhesion)
- Two experiments to evaluate effect of i-ZnO
  - ❑ Measure WVTR of i-ZnO, ITO and i-ZnO/ITO stack
  - ❑ Two 5x5 cm samples for D-H ALT, no encapsulation or capping layer.

  Layout #3: same as #1, except area defined by scribe, no capping layer 'bare 5x5'

  Layout #4: same as #1, no capping layer, unscribed
- 1400 hrs D-H ALT in the **dark**





•'Bare 5x5' as stable as PET or glass encapsulated

•'Bare scribed 5x5' degraded like 'bare' until ~600 hours, and leveled out

- ❑ Possibly due to ratio of scribe length to device area
- ❑ Possible illuminated vs dark D-H effect

Conclusions and References

•TCO and buffer layers can harden CIGS cells to D-H conditions, up to 2000 hrs

•Scribe lines that provide water vapor a direct path to CIGS/CdS junction shorten device D-H lifetime

•With a WVTR of 2E-3 g/m^2-day, a i-ZnO/ITO stack is an effective water vapor barrier

References

[1] M. D. Kempe, Modeling of rates of moisture ingress into photovoltaic modules, Solar Energy Mater. & Solar Cell 90 (2006) 2720-2738.

[2] D. J. Coyle, H.A. Blaydes, J. E. Pickett, R. S. Northey, and J. O. Gardner, Degradation kinetics of CIGS solar cells, in Proceedings of the 35th IEEE Photovoltaics Specialists Conference (2009).

[3] P.F. Carcia, R.S. McLean, Steven Hegedus, Encapsulation of Cu(InGa)Se2 solar cell with Al2O3 thin-film moisture barrier grown by atomic layer deposition, Solar Energy Materials & Solar Cells **94** (2010) pp. 2375-2378

Contains no confidential information

FLEXOSKIN® - Front Barrier Film for Flexible Solar Modules

BL – High Performance Polymers

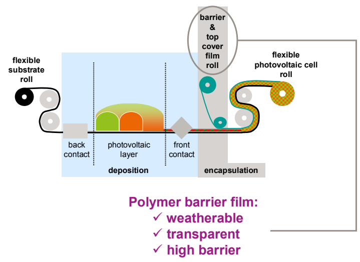
Introduction

- Transparency
- Barrier
- Weatherability

These are the most important properties a front sheet should provide for flexible thin-film photovoltaics.

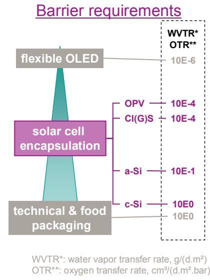
With FLEXOSKIN®, Evonik presents a new barrier film for flexible solar modules.

Future developments will have to provide a cost efficient roll-to-roll process.

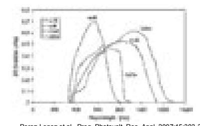


The polymer film has to fulfill special requirements

Barrier requirements



Transparency requirements



Perez-Lopez et al., Prog. Photovolt. Res. Appl. 2007;15:303-315

Barrier properties of polymers

FLEXOSKIN® provides properties by material combination

weatherable layer (PMMA based*)
pre barrier layer
main barrier layer

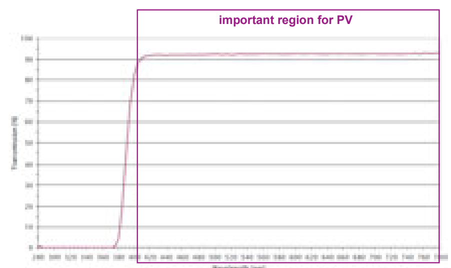
special adhesive

PV module

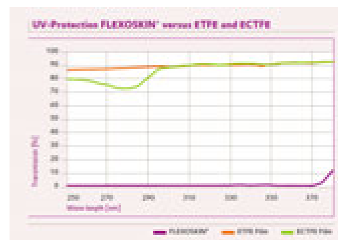
*) **Advantages of PMMA:**

- outstanding weatherability
- very high transparency
- no haze
- high surface hardness
- good heat resistance
- good chemical resistance
- chemically recyclable

Perfect Transparency of PMMA for Solar Cells



Perfect UV protection for the encapsulating material and other polymers in the module.



Barrier Properties of FLEXOSKIN®

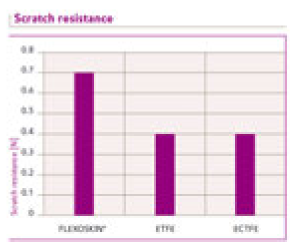
Target: 0,0001 g/(m² d))

weatherable layer
pre barrier layer
main barrier layer

20	1	< 0,001	WVTR g/(m² d) @ 38°C, 85 % r.h.

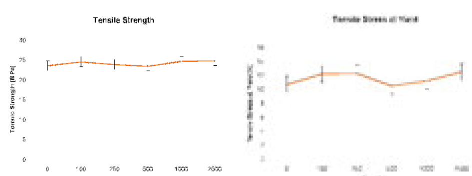
stable for 1000 hrs, test continued up to + 3000 hrs

FLEXOSKIN® provides excellent Scratch Resistance



Erichsen test

Mechanical Properties remain after Aging



Xenotest, 65 °C, partly sprinkling, 60 W/m² > 300 nm
Damp heat test 85 °C / 85 % r.h. ongoing

Further Properties of FLEXOSKIN®

material properties		specification value
Adhesion to EVA-fc	[N/cm]	20
Partial discharge voltage	[V]	> 1000
Film thickness [µm]		300 – 350
Film width [mm]		300 – 1200

Solar module testing according to IEC 61646 - in progress

preconditioning 5kWh*m2;	temp. Coefficient; NOCT; performance @ STC, NOCT; performance @ low irradiance, outdoor exposure test 60 kWh/m2; bypass diode thermal test; hot-spot endurance test
↓ visual inspection;	UV preconditioning test 15kWh/m2; thermal cycling test, 50 cycles -40°C → 85°C; humidity freeze test 10 cycles -40°C → 85°C, 85% RH; robustness of terminations test
↓ max. power determination ↓ insulation test	thermal cycling test 200 cycles 40°C → 85°C
↓ wet leakage current test	damp heat test 1000 h, 85°C, 85% RH; wet leakage current test, mechanical load test; hail test;

Summary & Future Work

- FLEXOSKIN® provides properties necessary for flexible PV
- FLEXOSKIN® combines weatherability, transparency and barrier
- Long term durability tests are ongoing
- Module Testing ist running with FLEXOSKIN®

This poster contains no confidential information

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Experience with CPV Module Failures at NREL

2012 Reliability Workshop, Golden CO

Matthew Muller

3/1/2012

NREL/PR-5200-54838

Outline

- NREL CPV testbed and its purpose
- Definitions for failure and performance related issues
- Hail storm failures
- Cell failures
- Seal and Adhesion failures
- Condensation and dirt performance issues
- Lens temperature performance issues

NREL CPV Testbed & Its Purpose

- Modules are monitored on a 2-axis tracker for various reasons
  - Modeling/Performance analysis
  - Aid in design improvement
  - Standards work
  - Reliability
- Modules from at least 15 manufacturers have been tested
- Wide range of module types
  - Concentration LowX to 1000X
  - Silicon and III-V cells
  - Silicone-on-glass, Fresnel, wave guide, and reflective optics
- Modules on-sun from a few weeks up to three years
- While this presentation shows failures that have occurred over 3 years, NOTE:
  - Modules often prototypes
  - Sometime pre qualification testing
  - Sometimes handmade/not production modules

Definition of “Failure” and “Performance Issue”

As represented hereafter:

“Failure” ----- *the termination of the ability of any component of the CPV module to perform its original designed function*.

For example if one cell has degraded to the point that its bypass diode has been activated this would be considered a failure.

“Performance Issue”-----*defined by a 5% or more decrease in module power that can’t be explained by irradiance variation, spectral variation, cell temperature variation, tracker alignment, module alignment, or external soiling.*

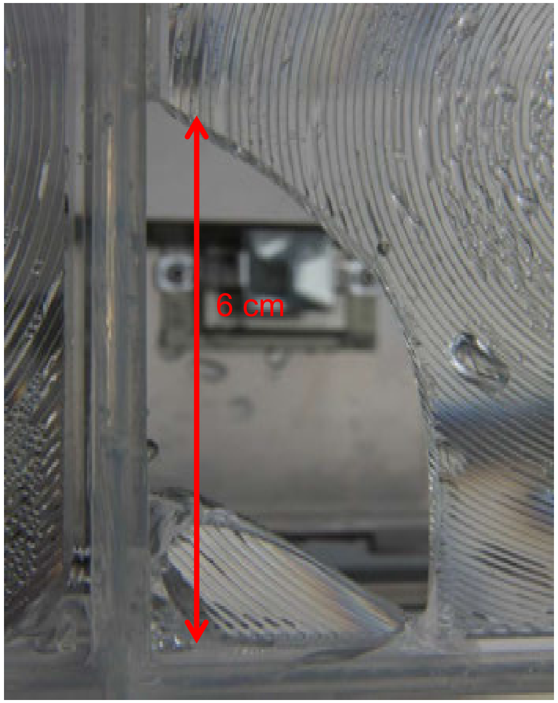
For example condensation inside the module.
Module power often drops more than 5% but after it evaporates performance returns to baseline conditions.

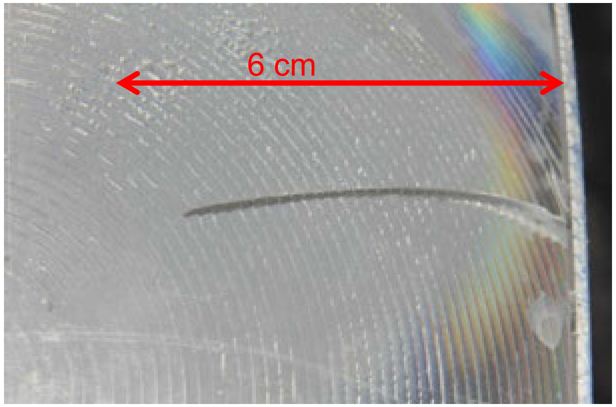
Hail Storm, NREL June 11, 2010 ~14:00MST

- Short hail storm hit lasting 5-15 minutes
  - Most hail stones < 2.5 cm
  - Small quantities of hail stones > 2.5 cm found on NREL's site
  - No statistical analysis in regards to hail stone size
  - Winds from the W to NW, peaked at 10 m/s
  - No damage to hundreds of flat plate modules (S facing/latitude tilt)
  - Silicone-on-glass and polymer CPV lenses failed.
  - Cracked shields on Kipp and Zonen CM11's
  - NOTE: CPV tracker facing oncoming hail due to the time of day. Hail stones likely to have 90 degree angle of incidence with CPV lenses.

Irregular Shape

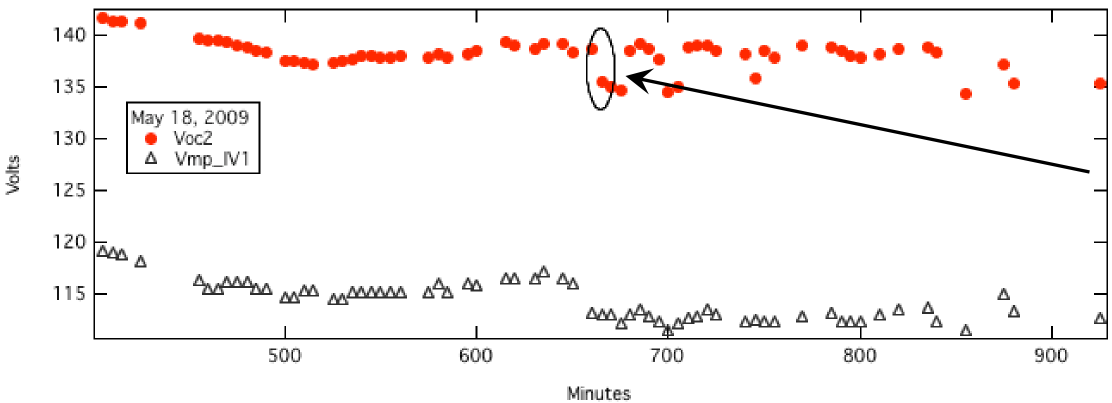
Hail Damage



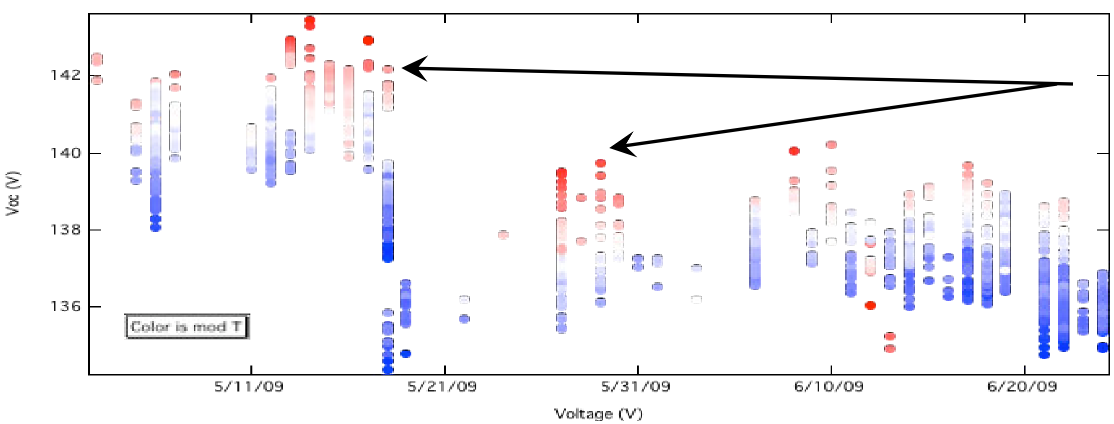


Cell Failures

- Five modules have had failures of the cell/cell package
  - In most cases, thermal runaway is the likely root cause
  - In one case the cell has appeared to tear (silicon not III-V)
  - In another case a ground fault was found associated with a solder connection



Pinpointing time of failure which appears intermittent on the first day



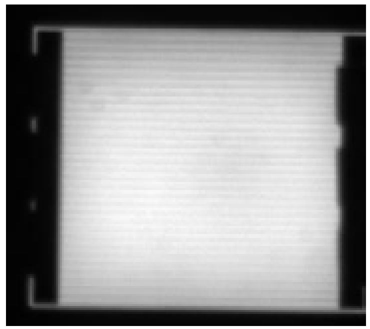
System stabilizes after May 18th

Cell Failures, Diagnostic images

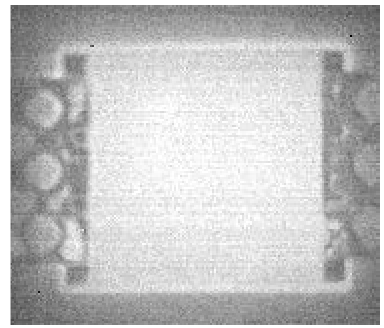
Healthy Cell

Visible

EL

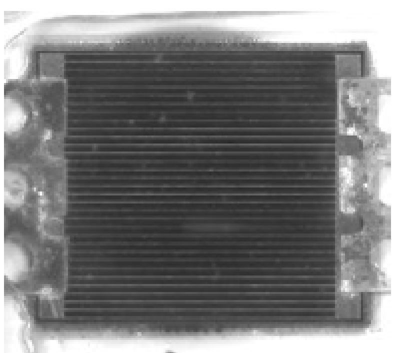


IR

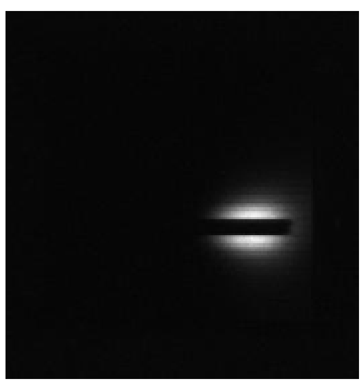


Damaged Cell, Shunted, possible grid finger failure (3 months on-sun)

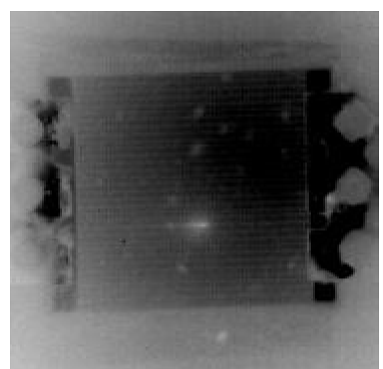
Visible



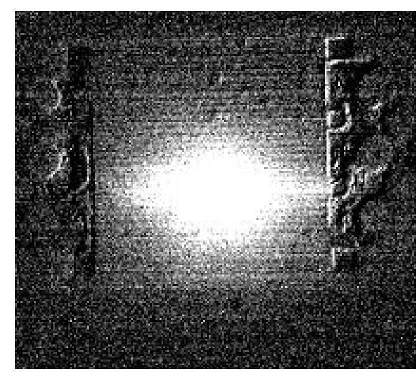
EL



IR

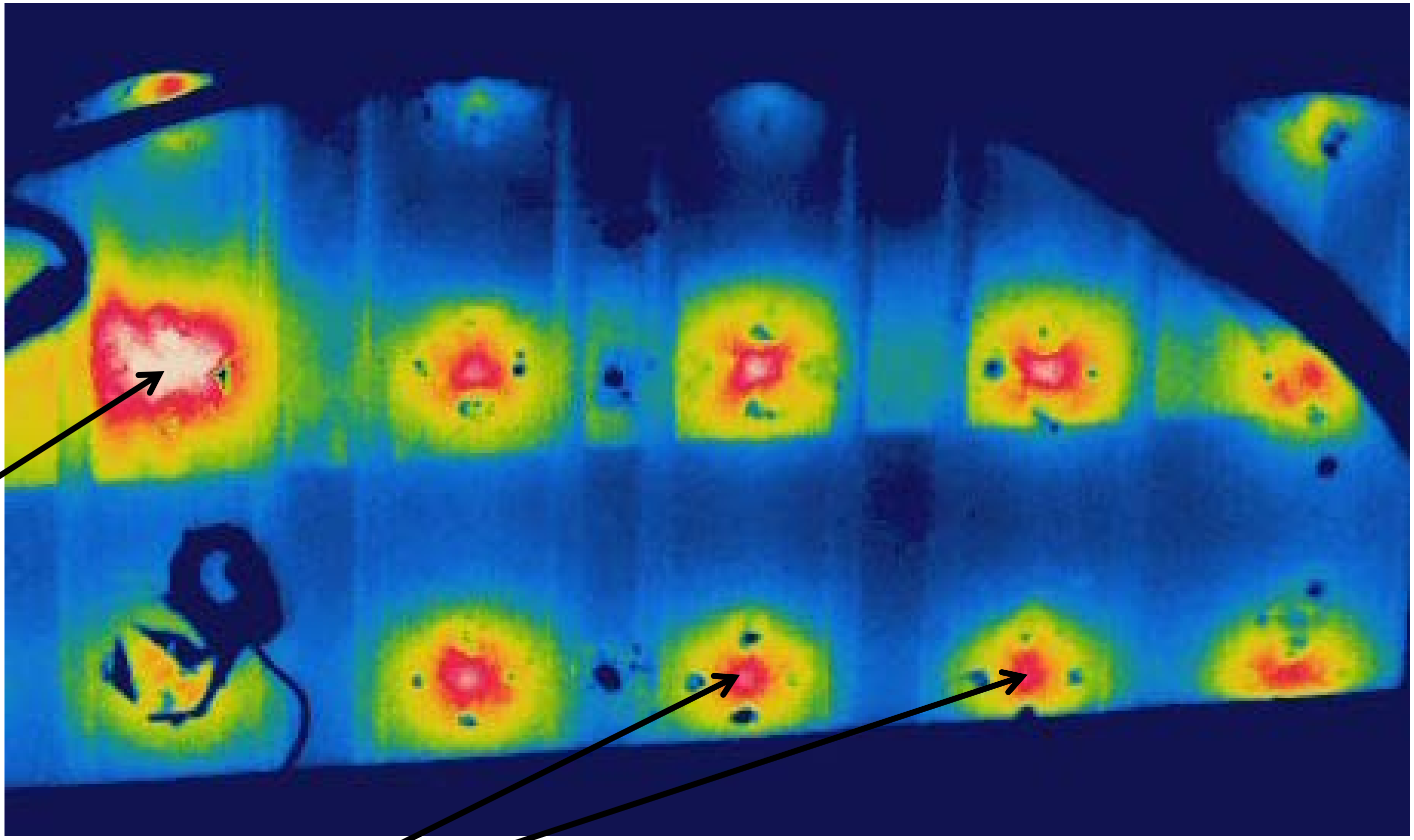


IR contrast (hot–cold)



Images by Nick Bosco

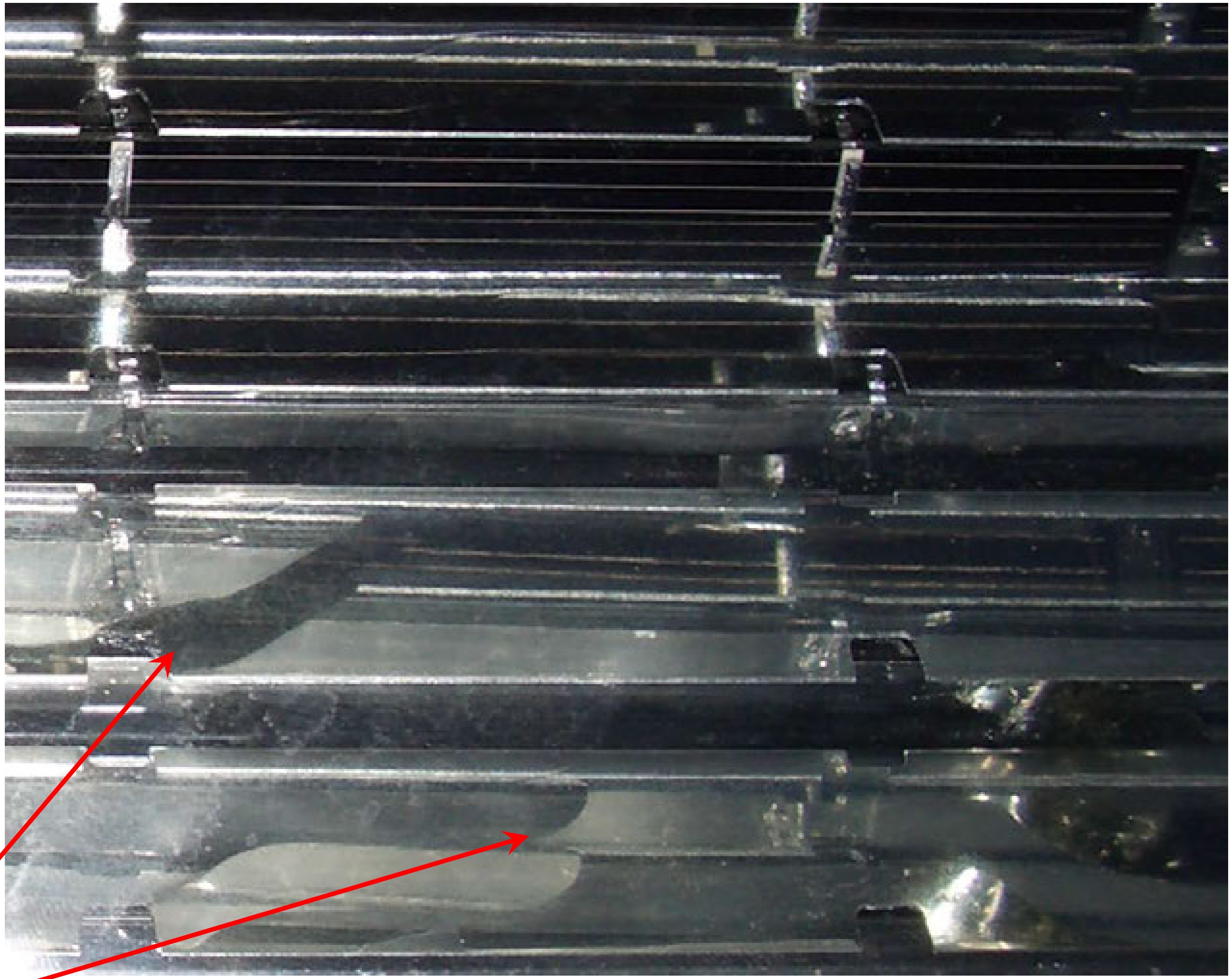
Thermal Image of Cell Failure, Active Module



Failed cell

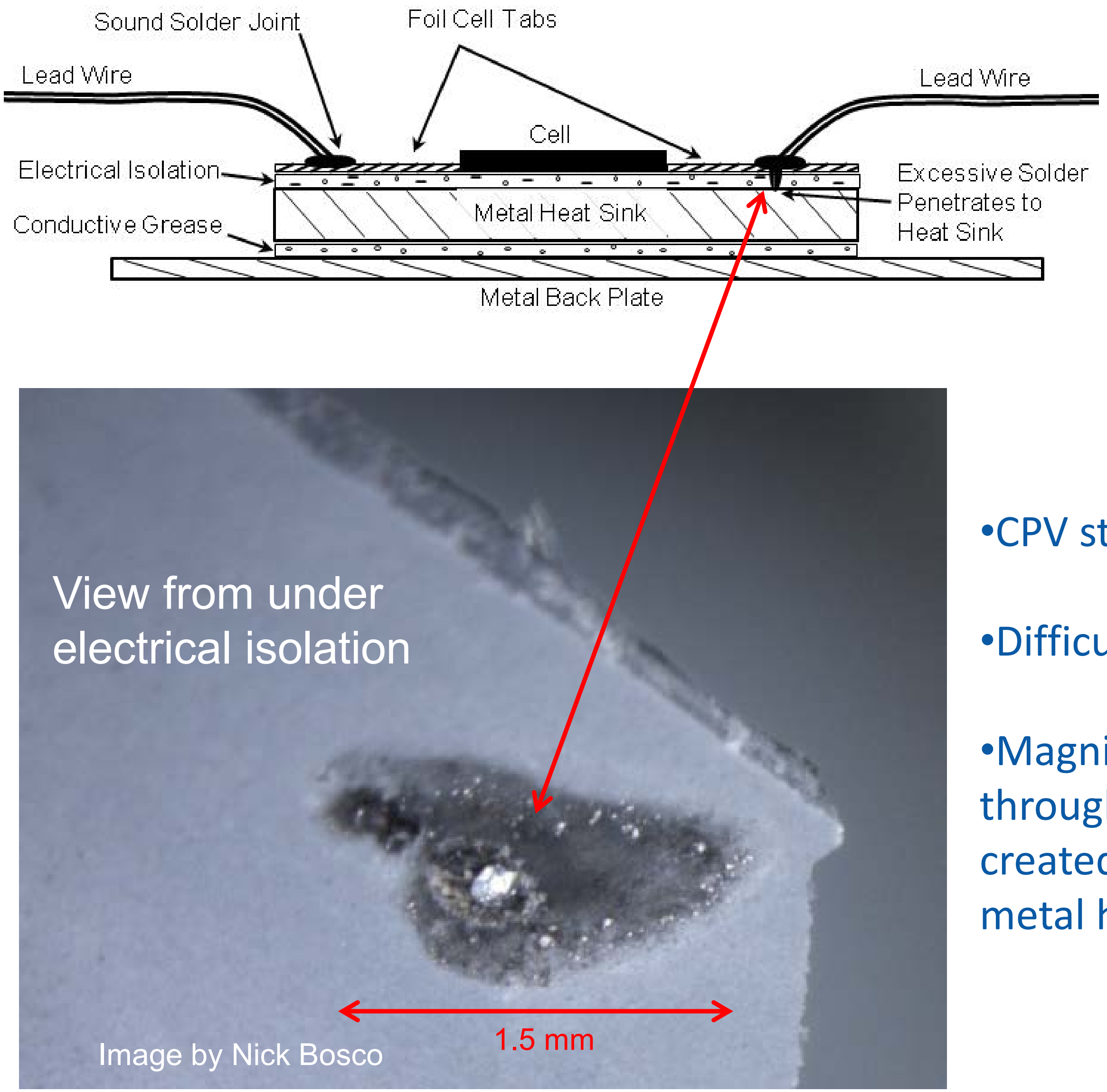
Healthy Cells

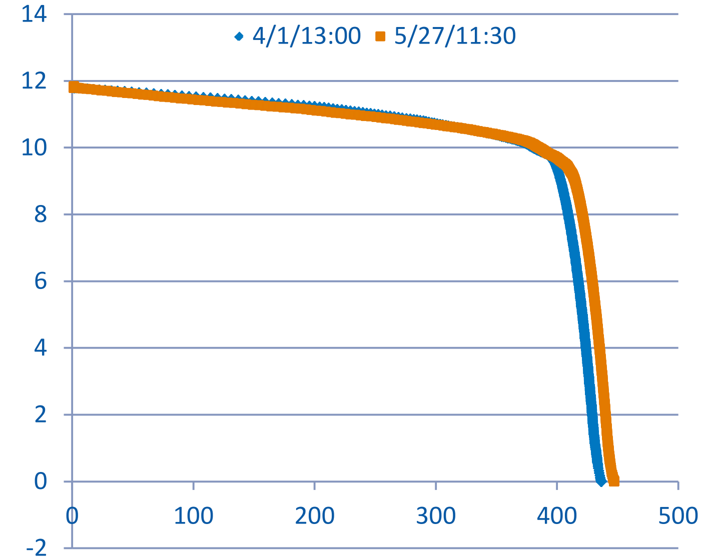
LowX Silicon Cell/Package Failure



Reflector has lost adhesion to substrate, difficult to confirm but reflector and cell appear to have torn, (possibly a thermal mismatch issue)

Cell Interconnection Ground Fault



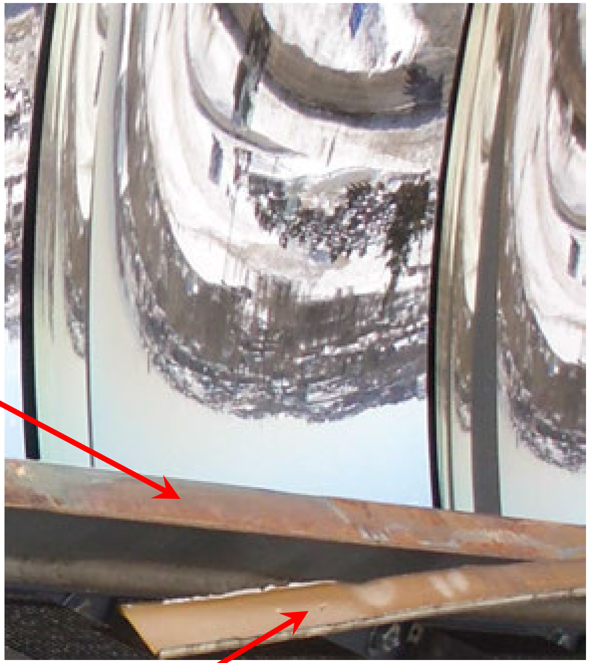


- •CPV string trips inverter ground fault fuse.
- •Difficult to see problem on IV curves
- •Magnification shows solder has protruded through electrically insulating layers and created a grounding contact with the back metal heat sink plate.

Seal/Module Package Failures

- On a cold December day the glass cover fell off this module

Frame corrosion

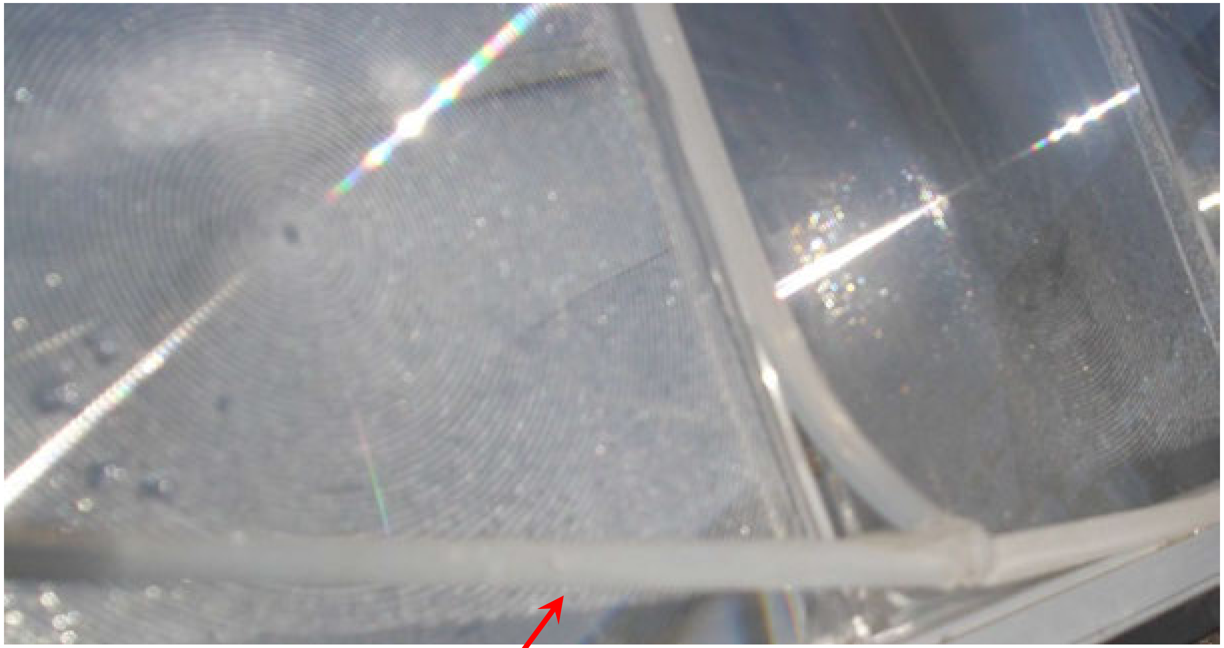


Seal shows UV degradation

Glass on ground

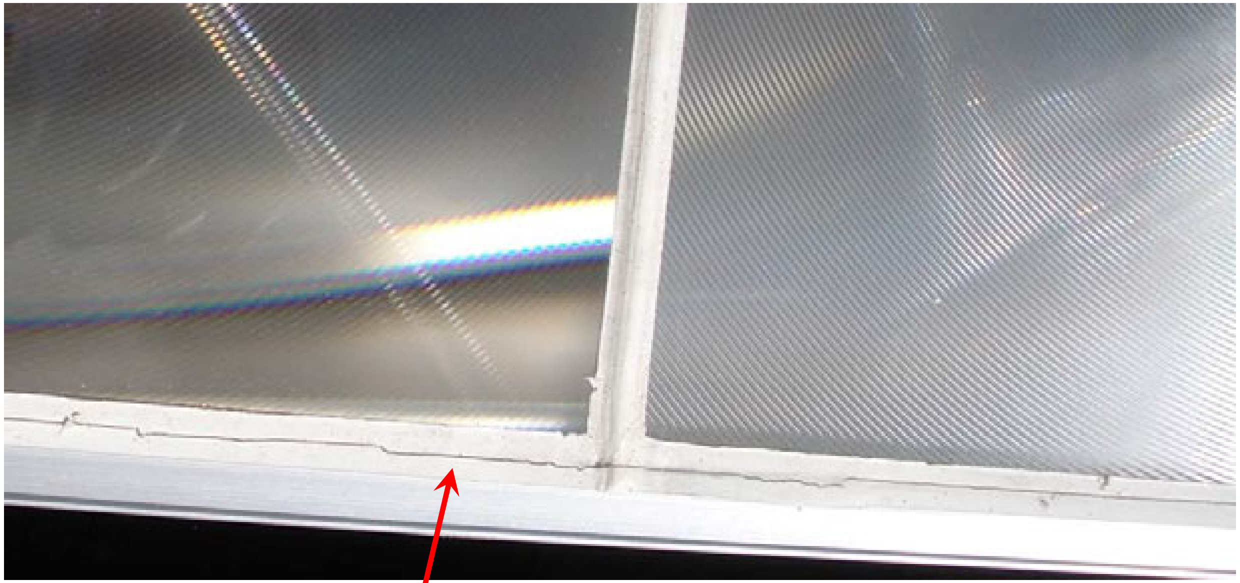
Piece of seal

Seal/Module Package Failures



Over multiple months on-sun this silicone seal lost adhesion between each lens parquet
(in the photo the silicone is being held up for clarity)

Seal/Module Package Failures



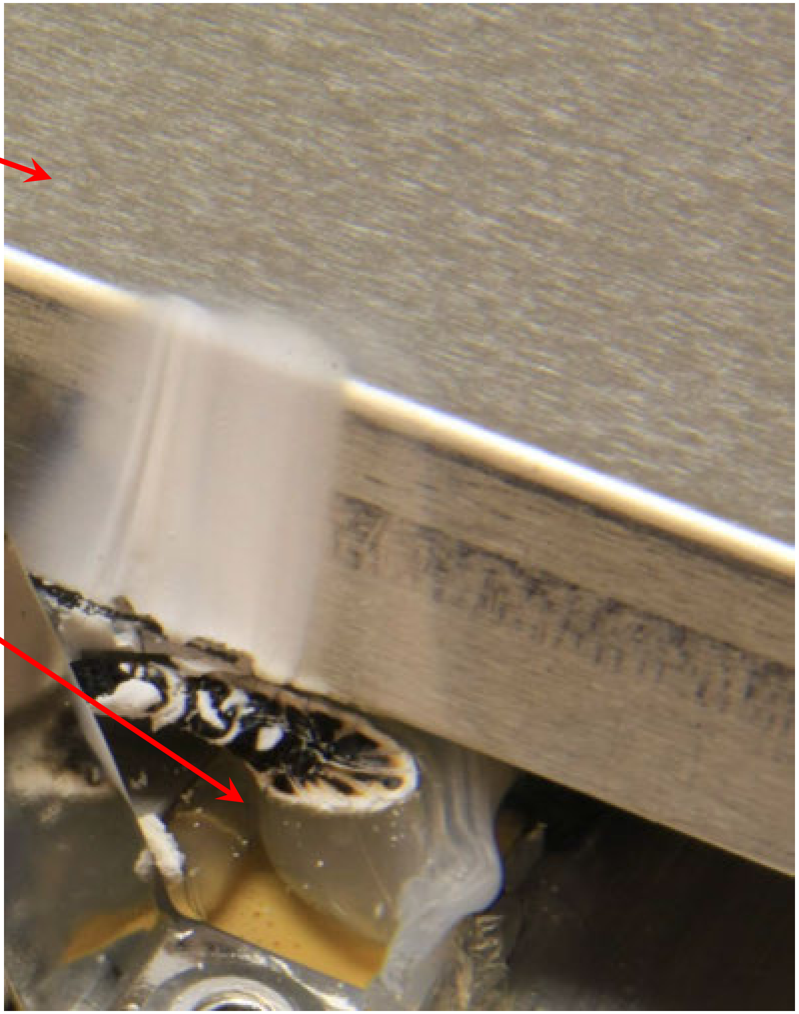
Seal has cracked between lenses and frame as a result of a mechanical impact (NREL was at fault in this case but event was similar to what might happen in transport)

Packaging Issues

Shield to protect wiring and area around cell assembly from concentrated light

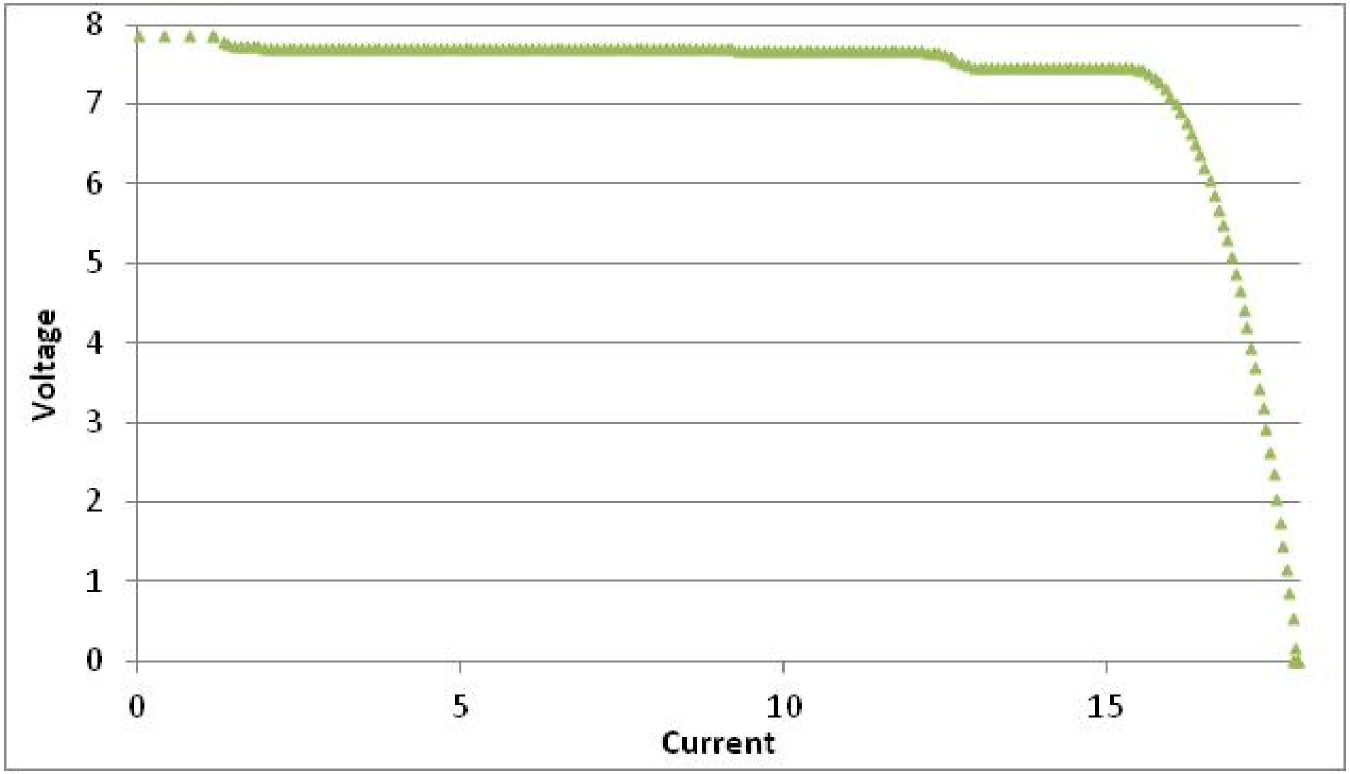
Shield not close enough to secondary optics as silicone was burned

Burn marks suggest ~ 500 °C

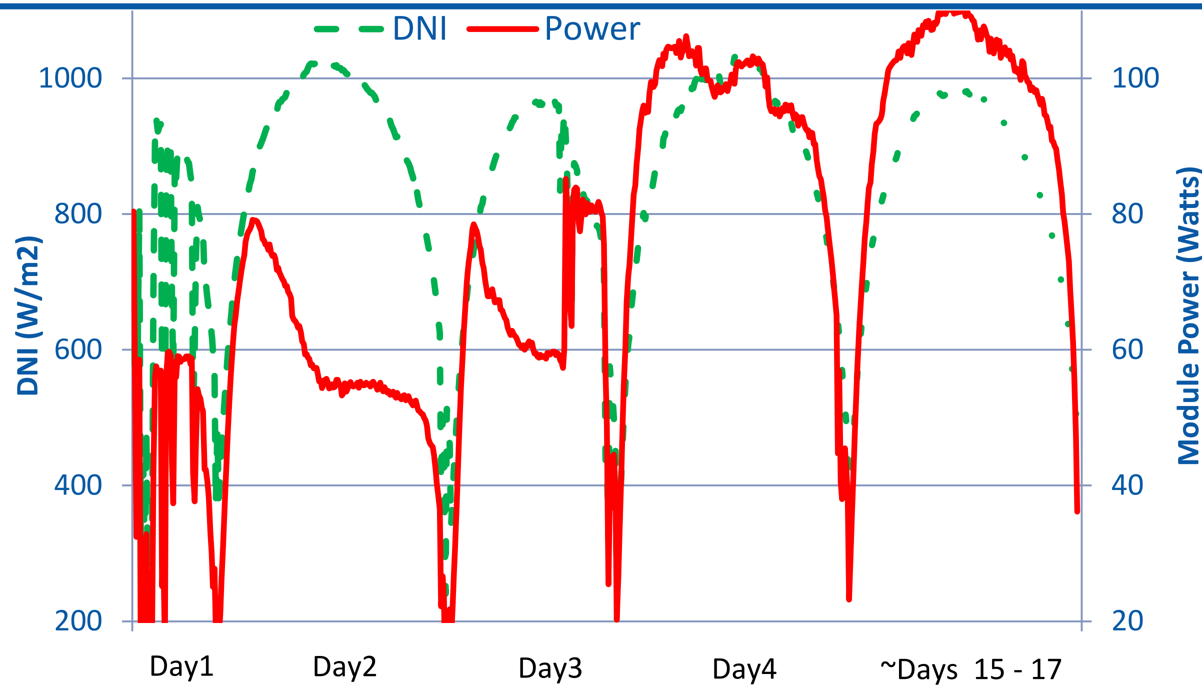


Manufacturing Issue

The steps in this IV curve are assumed to be the result of misaligned optics as the individual cells were closely matched for this module



Condensation Performance Issues



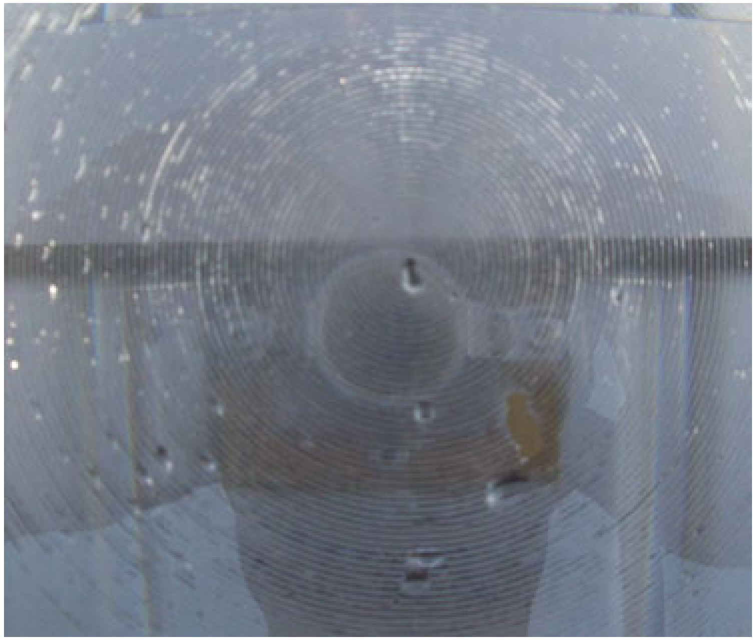
- For the 3 days before Day1 it was rainy

- Day1 the sun was out off and on with no rain
- Day2 it was clear skies, module power does not follow DNI
- Day3, mostly clear skies, module power does not follow DNI
- Day4, clear skies, module power mostly follows DNI
- Days 15-17 represent normal relationship between power and DNI

Condensation Performance Issues

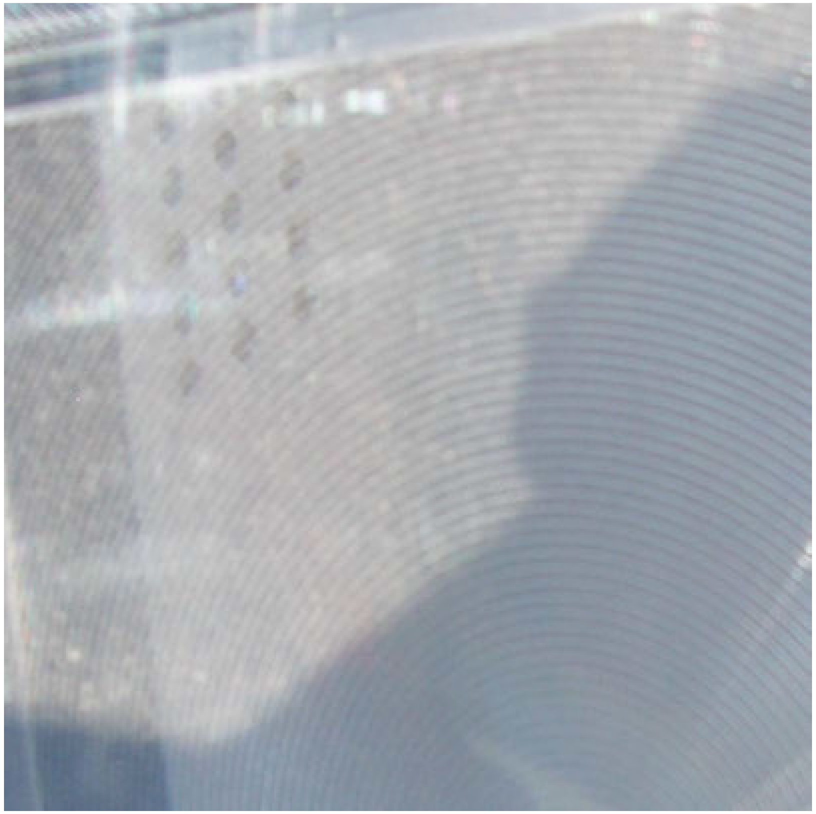
- Many of the modules at NREL allow condensation to enter
- This is intentional in some cases and due to seal failures in other cases
- Some modules use moisture management systems
  - Dry is air is pumped through module
  - If the management system is not smart it can make the situation worse

- Modules with failed seals have allowed moisture in but then trap it inside
- Time for moisture to escape depends on system design an weather
- If a module is going to allow moisture in, difficult to model reduced performance

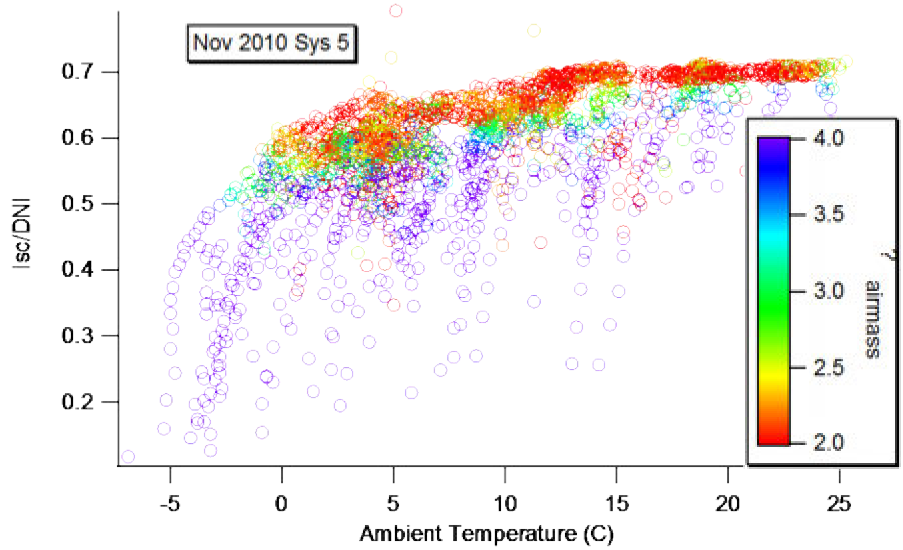


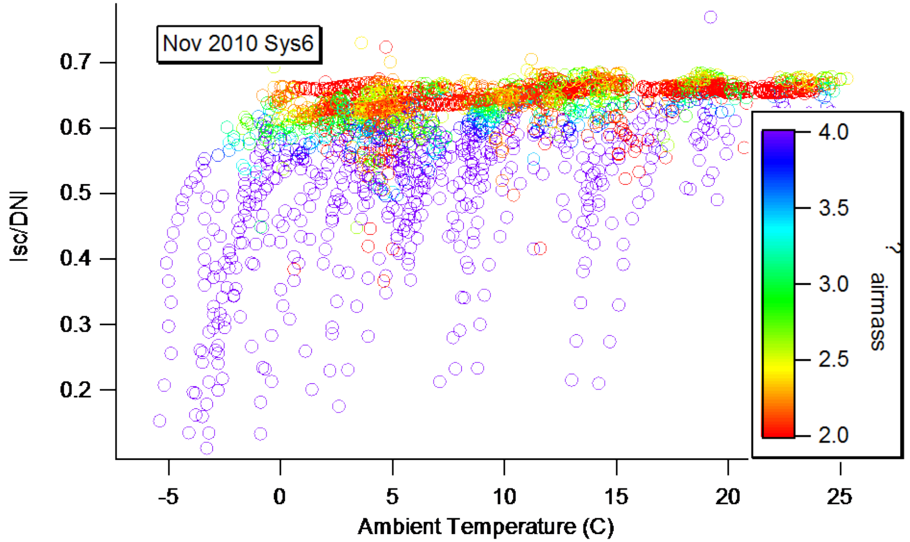
Condensation Soiling

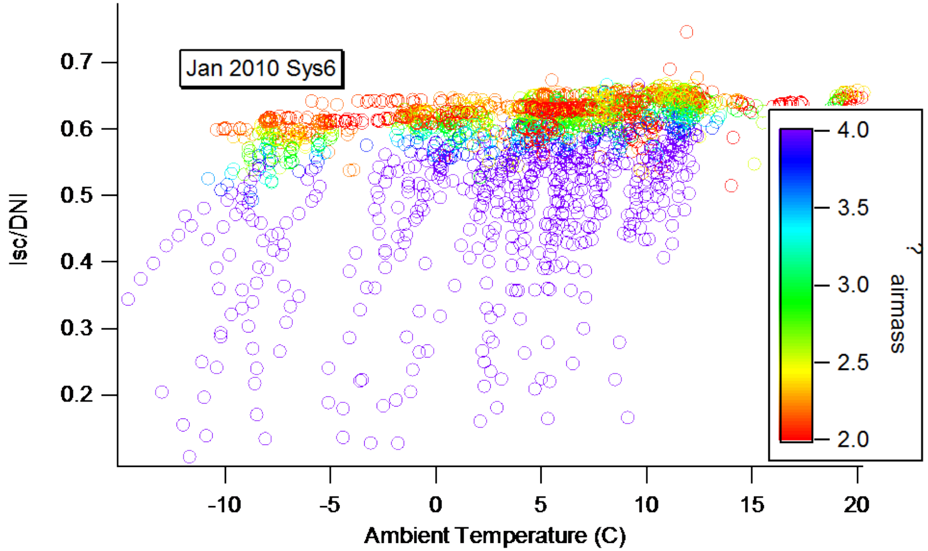
- Internal condensation has resulted in dirt build up on the back side of the lenses.
- This could be considered a failure or a degradation.
- Qualification test won't catch this problem
- CPV qualification test built from flat plate testing/no issues like this



Lens Temperature Performance Issues







Summary

- A wide array of CPV module failures and performance issues have been experienced at NREL
- Many of the modules are prototypes and have not been through qualification testing
- It is assumed that the qualification test would have captured many of the problems
- Internal lens soiling due to condensation is not currently captured by the qualification test
- Lens temperature dependence can be built into modeling if CPV is to operate in cold locations

Thanks!

Questions???

"The Durability of Polymeric Encapsulation Materials for Concentrating Photovoltaic Systems"

David C. Miller[1], Matt Muller[1], Michael D. Kempe[1], Kenji Araki[2], Cheryl E. Kennedy[1], and Sarah R. Kurtz[1]*

1. National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, CO, USA 80401
2. Daido Steel Co., Ltd. 2-30 Daido-cho, Minami, Nagoya 457-8545, Japan
* David.Miller@nrel.gov

2012 PV Module Reliability Workshop

(Denver West Marriot, Golden, CO)

8:30-8:50 am, 2012/3/01 (Thursday)

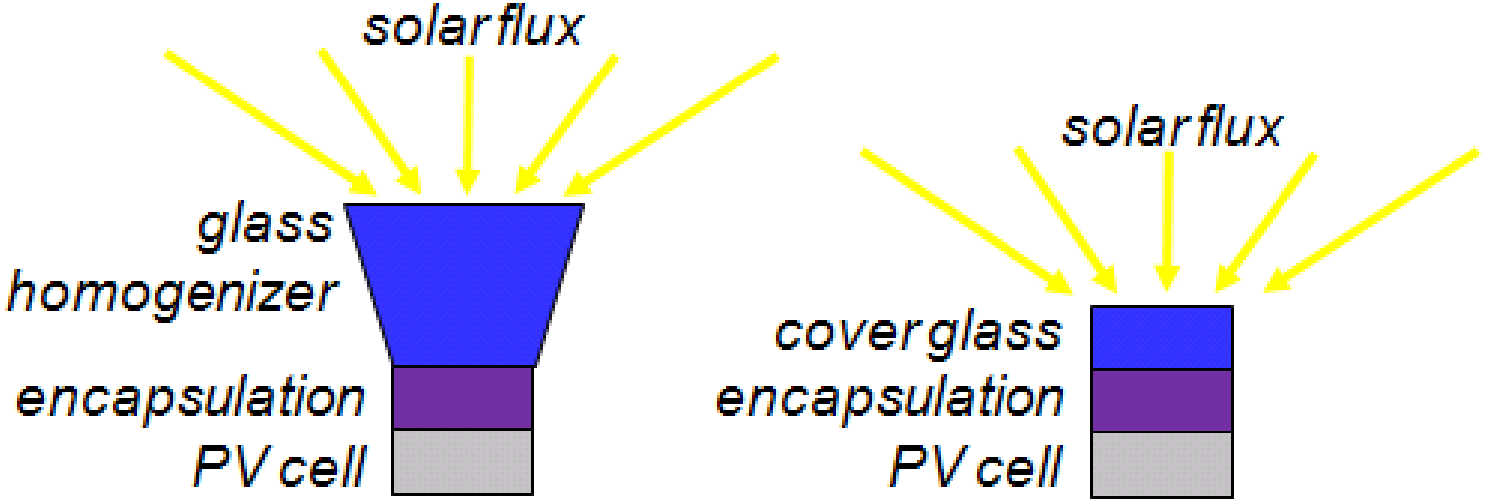
Golden Ballroom

-this presentation contains no proprietary information-

NREL/PR 5200 54524

Motivation for the NREL Field Study

- Concentrating Photovoltaic (CPV) modules use cost effective optics ($) to focus light onto high efficiency (η=44%) multijunction cells ($$$$$)



cross-sectional schematic of the components near the cell in CPV systems (not to scale)

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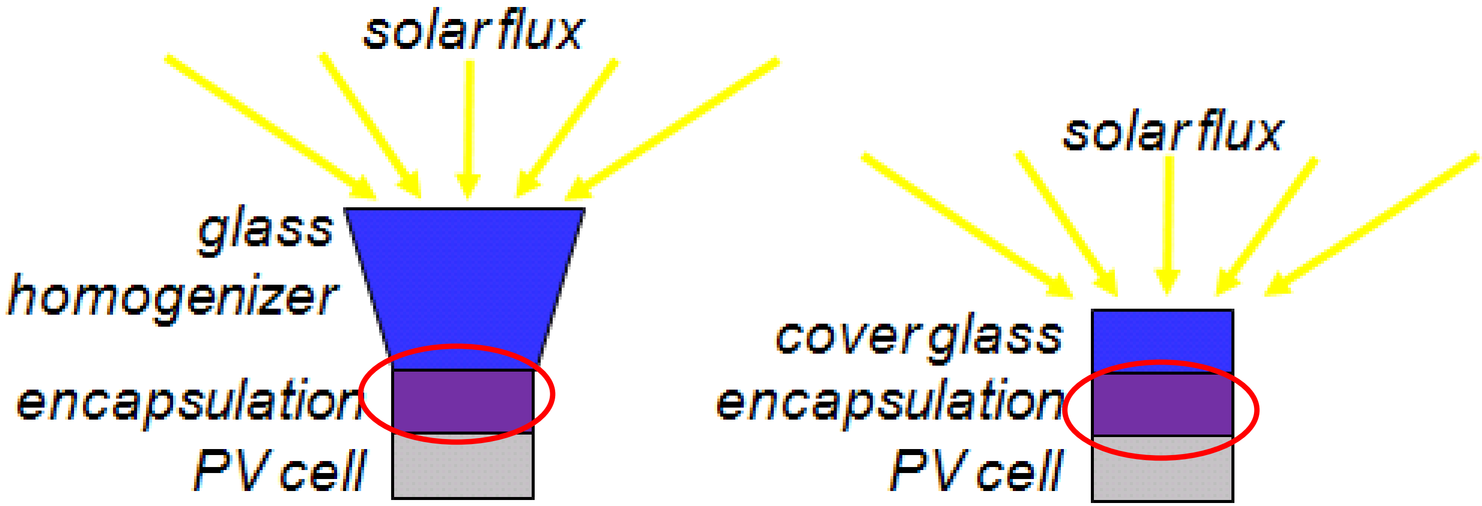

cross-sectional schematic of the components near the cell in CPV systems (not to scale)

corrosion prevention, optical coupling : CPV systems typically use encapsulation to adhere optical component(s) or cover glass to the cell

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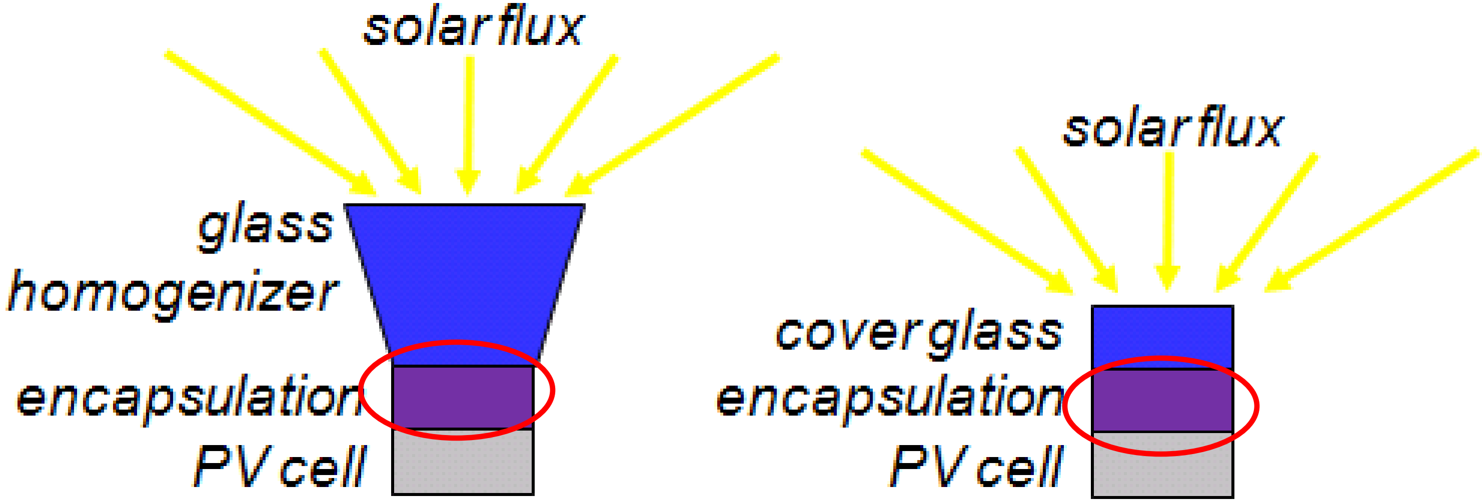


cross-sectional schematic of the components near the cell in CPV systems (not to scale)

corrosion prevention, optical coupling : CPV systems typically use encapsulation to adhere optical component(s) or cover glass to the cell

encapsulation durability (30 year field deployment) is unknown:

- identify field failure modes
- gain insight related to failure mechanisms
- distinguish between material types
- identify materials for future study (HALT & qualification tests)

Details of the Experiment (Specimens & Apparatus)

Miller et. al., PIP, DOI: 10.1002/pip.1241.

MATERIAL	ON-TEST	IN QUEUE
EVA	6	2
ionomer	2	0
polyolefin	1	1
PVB	2	0
TPU	1	2
PDMS	11	5
PPMS	2	1
TOTAL	25	11

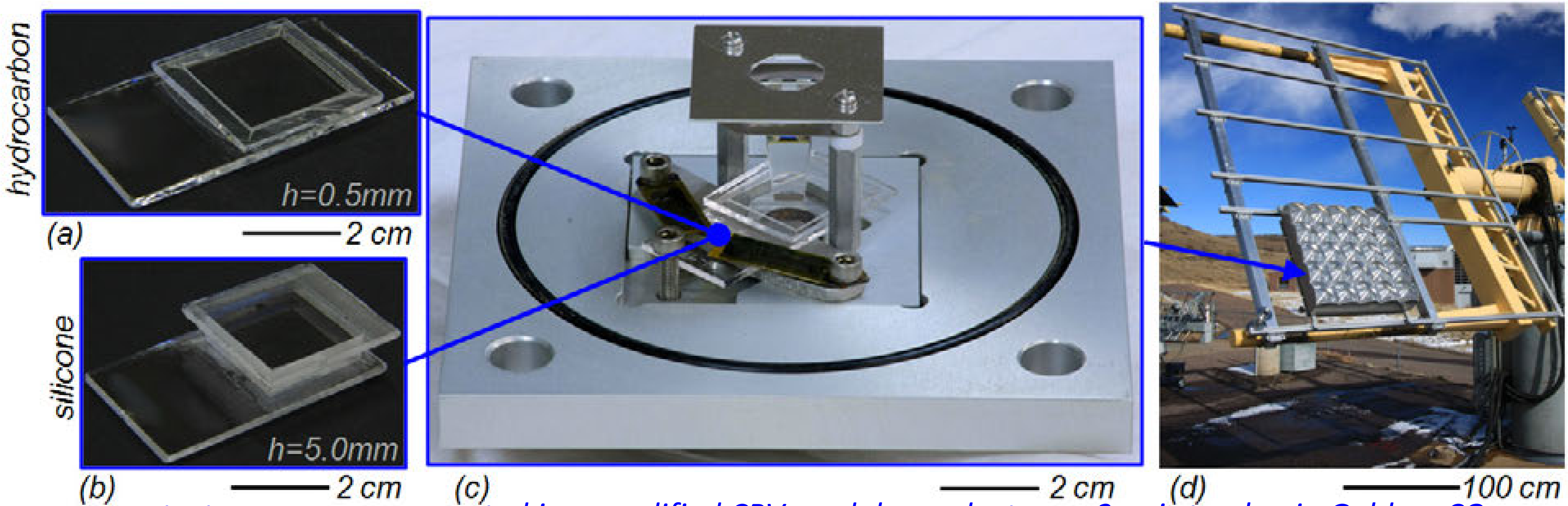
hydrocarbons (representative types): EVA, ionomer, polyolefin, PVB, TPU

silicones (representative grades): PDMS, PPMS

test coupons are mounted in a modified CPV module product on a 2-axis tracker in Golden, CO

Details of the Experiment (Specimens & Apparatus)

Miller et. al., PIP, DOI: 10.1002/pip.1241.



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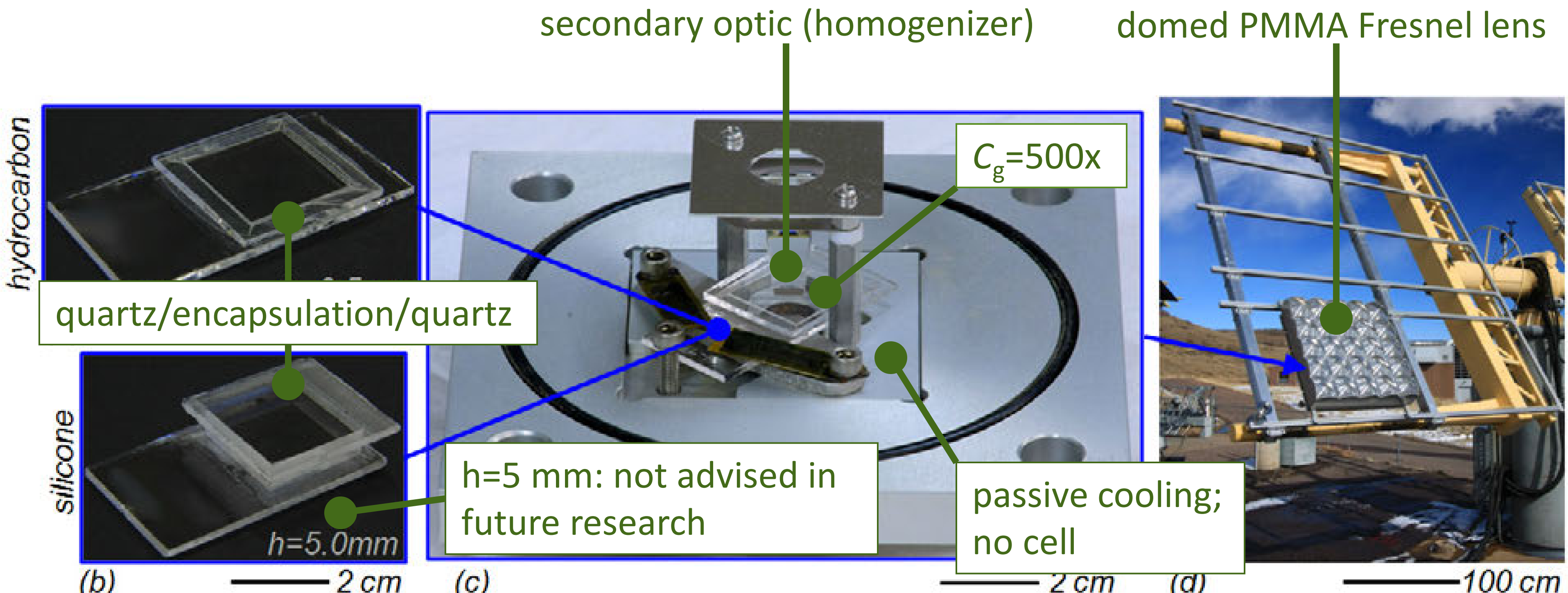

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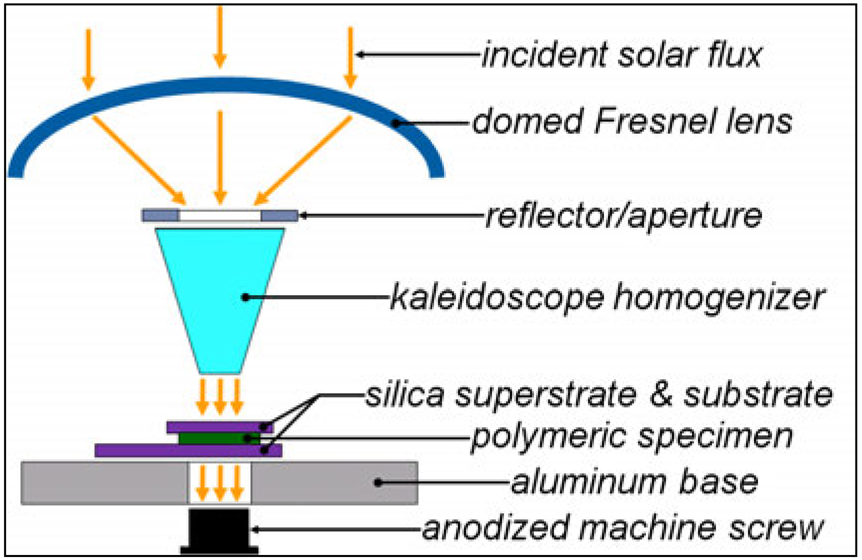
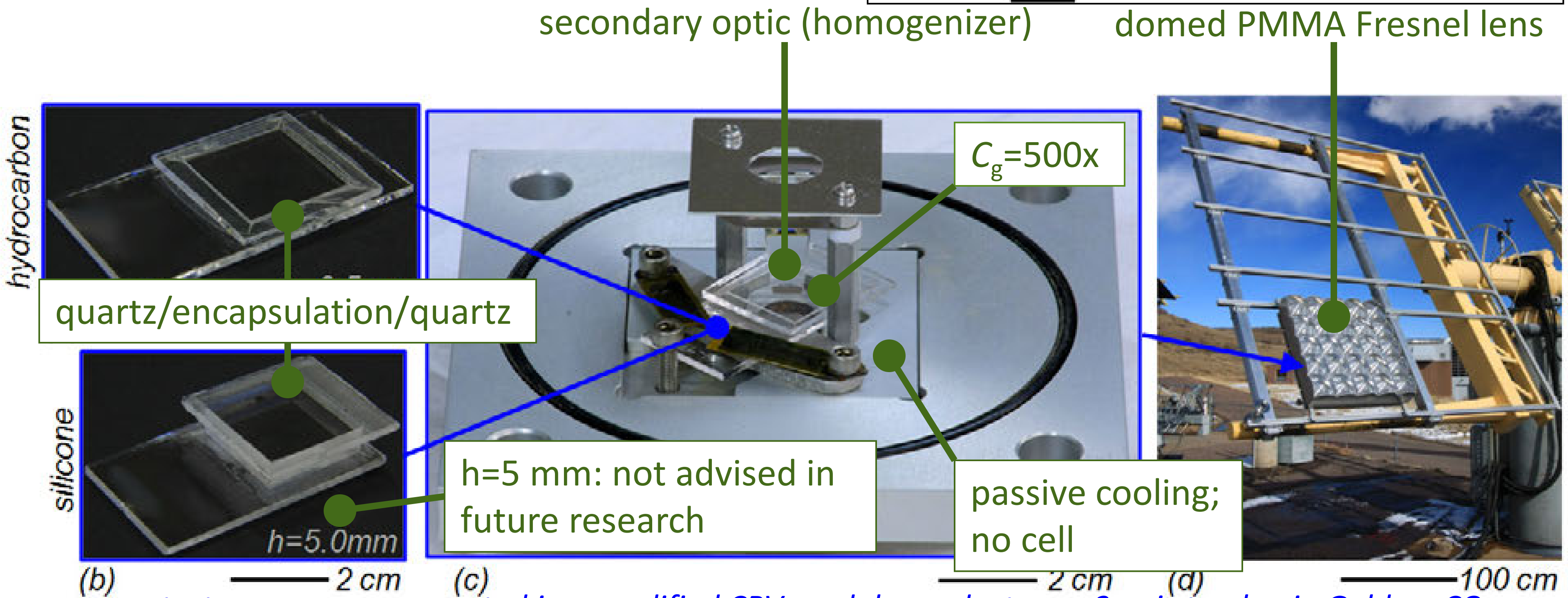




test coupons are mounted in a modified CPV module product on a 2-axis tracker in Golden, CO

Details of the Experiment (Measurands & Schedule)

"Continuous" measurements:

ambient conditions (irradiance, temperature, wind…)
fixture temperature (via thermocouple)

Periodic measurements:

→ transmittance ($T[\lambda]$, hemispherical & direct)
mass
appearance (photograph)

⇒ from $T[\lambda]$, calculate: yellowness index (D65 source,1964 10° observer), haze, $\lambda_{cut\text{-}on}$ …

→ fluorescence spectroscopy

Final measurements:

FTIR, RAMAN, NMR
TGA, DSC (polymer physics)

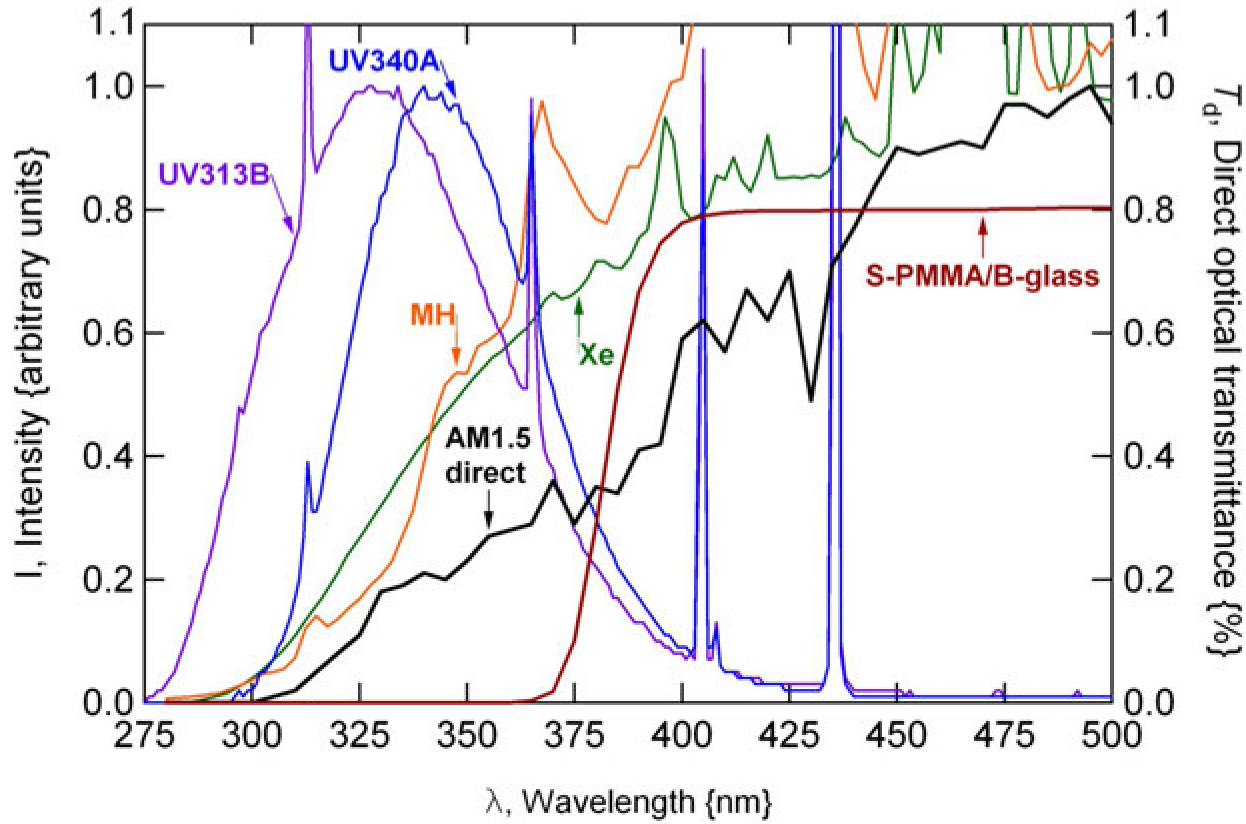
Test schedule:

0, 1, 2, 4, 6, 12, 18, 24, 30, 36 … months

Optical Irradiance May Vary from CPV Transmittance

- PMMA transmits little (T=1%) UV flux, λ>390 nm

- Thermal content therefore has increased significance (coupled UV & thermal degradation)



- Some popular indoor sources (UV 313V, UV340A) are completely inappropriate for a PMMA-enabled CPV system

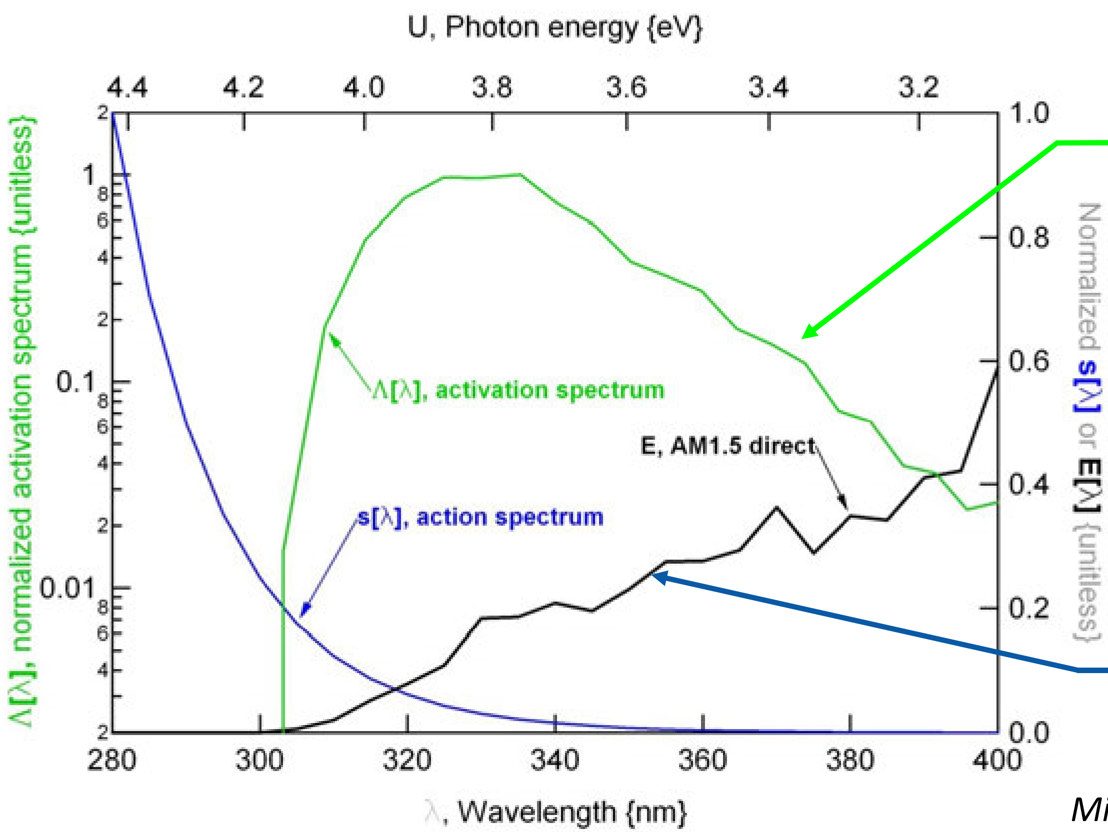
- SoG Fresnel lens is substantially more transmitting (T=89%) of UV

Miller et. al., PIP, DOI: 10.1002/pip.1241

Irradiance for popular optical sources (including the sun) relative to the CPV optical system

UV Radiation: Damaging Dose

- Early weathering studies $\Rightarrow$ total UV dose (damage vs. Joules or hours)
- Activation spectrum instead considers:
    1. characteristics of source & optical system
    2. effectiveness of damage at each λ ("action spectrum")
    3. may be unique to each characteristic (+ and -)



$$\Lambda[\lambda] = E[\lambda]s[\lambda] = E[\lambda]c_1 e^{-c_2\lambda}$$

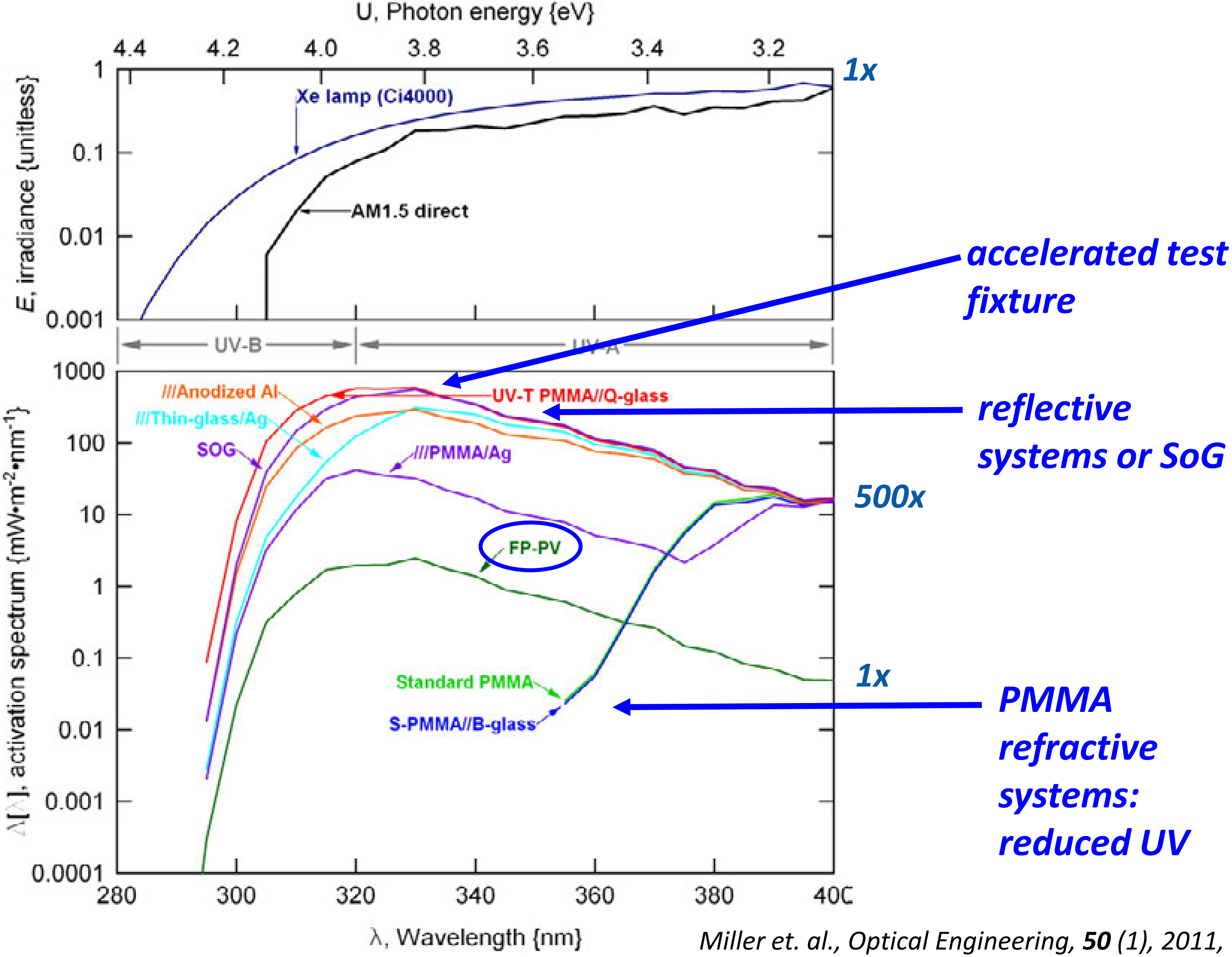
sun

optical system

$$E[\lambda] = E_I[\lambda]C_g \prod_{i=1}^{i=j} \eta_i T_i[\lambda] \prod_{k=1}^{k=l} \eta_k R_k[\lambda]$$

*Miller et. al., Optical Engineering, **50** (1), 2011, 013003*

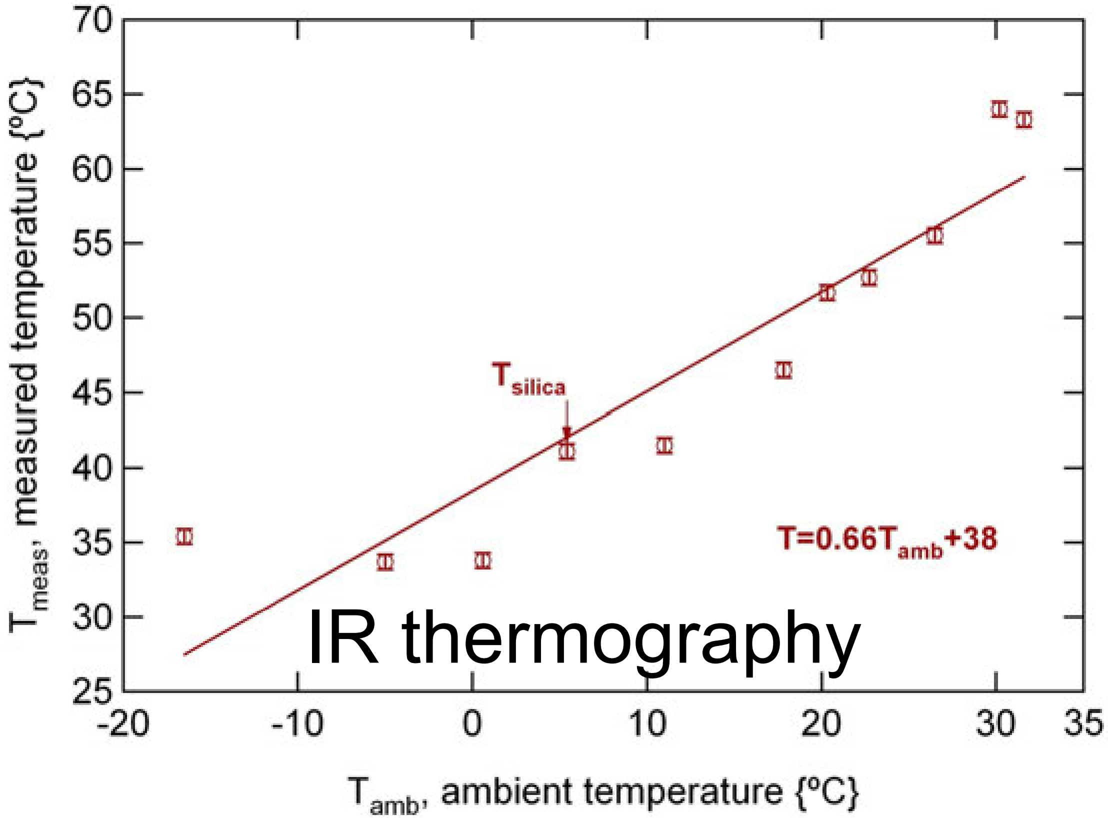
The Optical System Readily Affects UV & IR Dose



Miller et. al., Optical Engineering, ***50*** *(1), 2011, 013003.*

The Field Conditions (Specimen Temperature)

- Specimen temperature proportional to optical (IR) absorptance
  (thermal management "system": conduction to the frame.)
- Measured at solar noon. Factors: T_{amb}, irradiance, wind speed
- ~40°C temperature rise observed. T_{max} 70-80°C in summer.



PDMS specimen temperature, determined using optical thermography

Miller et. al., PIP, DOI: 10.1002/pip.1241.

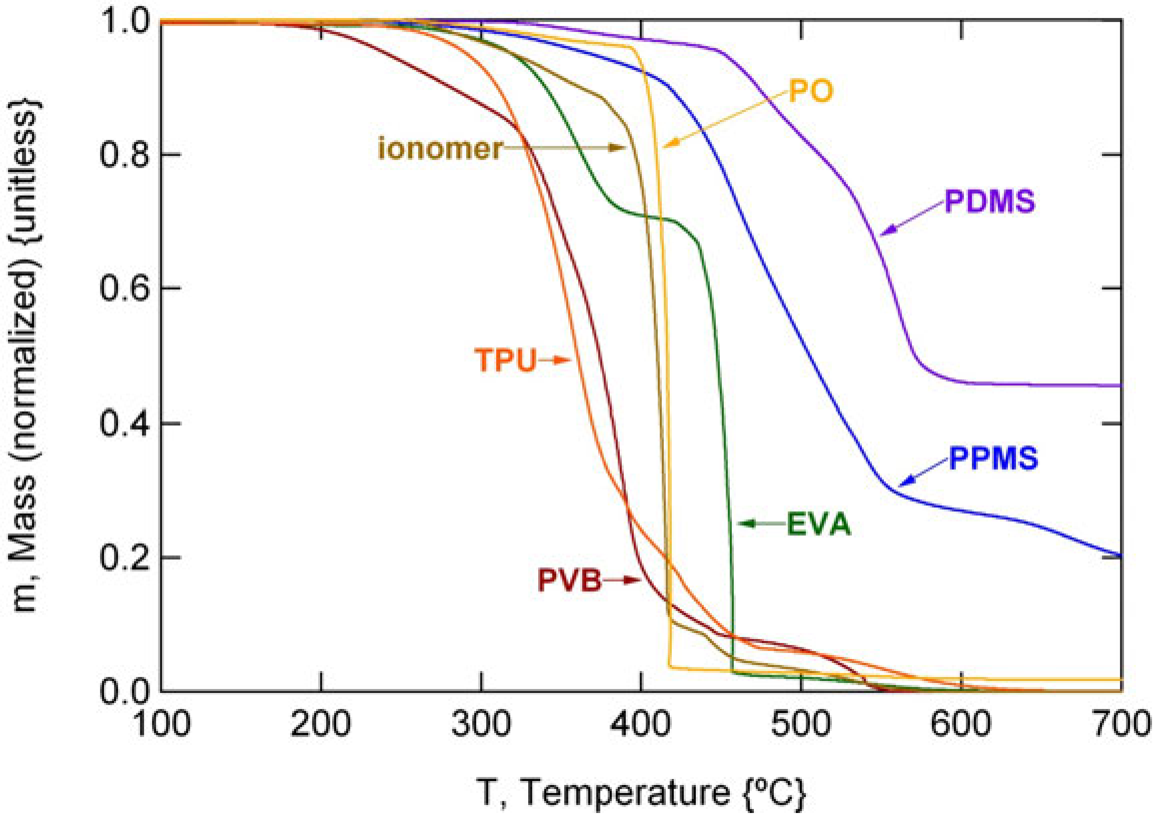
Thermal Decomposition of the Encapsulation May Occur at High Temperature

- Thermal stability compared using thermogravimetric analysis (TGA) @20°C·min^{-1}

- Onset of decomposition for hydrocarbons: 200-300°C

- Silicones more thermally stable: T_{onset} 300-400°C

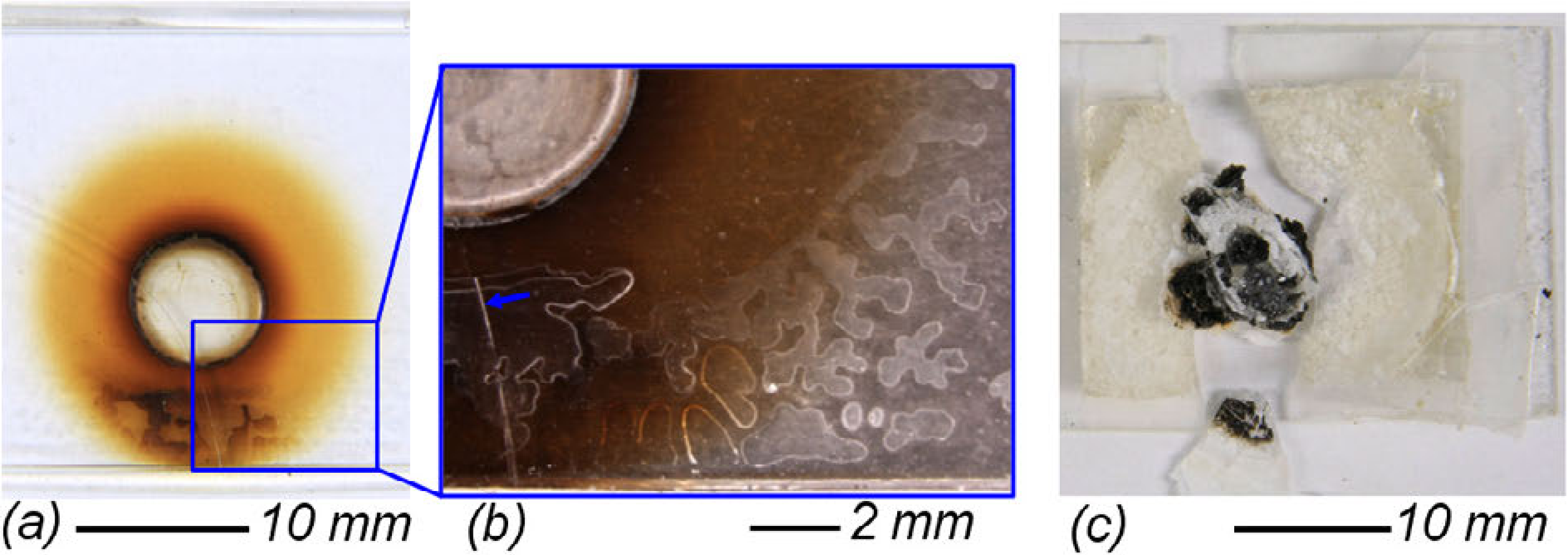
*Remember *T*'s for later!



Thermography data for representative materials from the study
Miller et. al., PIP, DOI: 10.1002/pip.1241

Results of Discovery Experiments
(The Homogenizer)

EVA: without homogenizer, rapid discoloration ⇒ combustion



optical images of EVA in (a) & (b), and PDMS in (c).
inset shows: voided center, char, cracked cover-glass, discoloration, delamination

silicone: without homogenizer ⇒ combustion

- Likely motivated by local hot spots (10^1 to $10^3 \cdot C_g$)

D.C. Miller, S.R. Kurtz, Solar Energy Materials and Solar Cells, 2011.

Results of Discovery Experiments

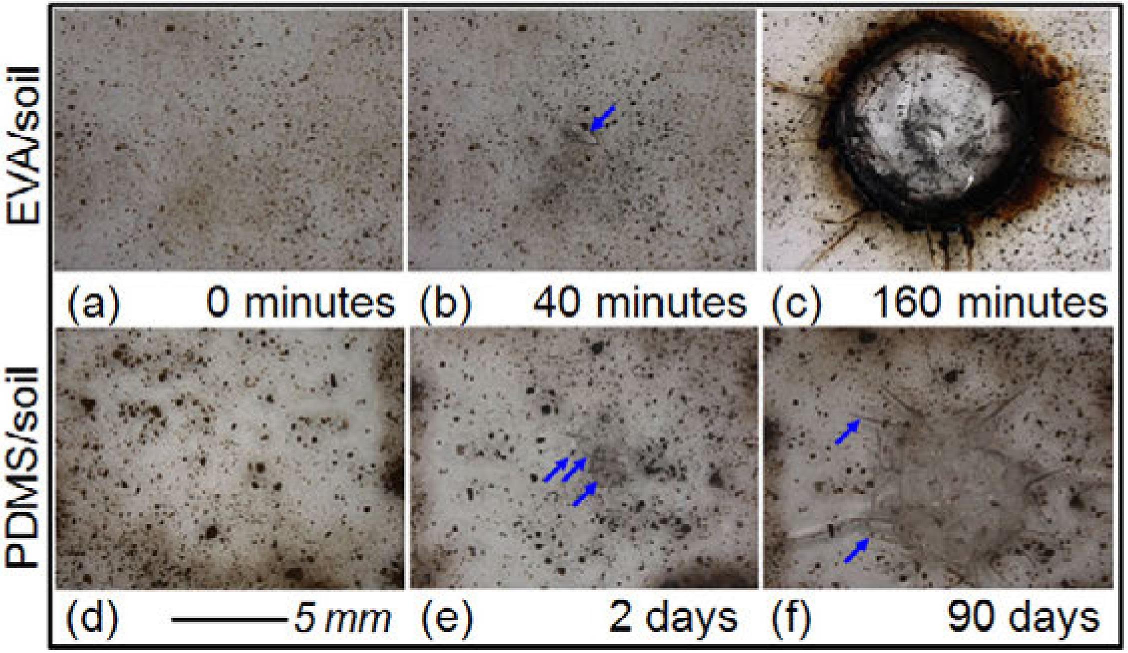
The Effect of Contamination)

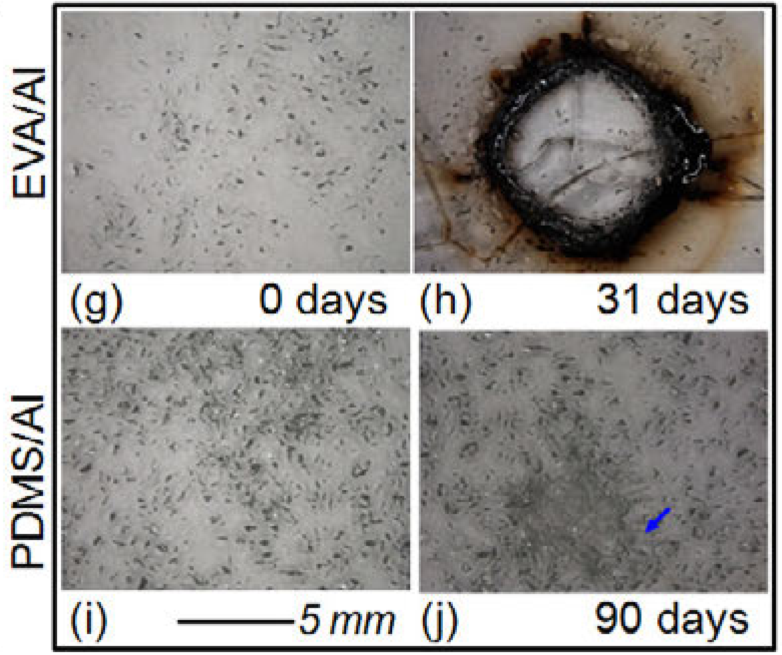
- Intentionally introduce soil, Al, PE, or bubbles into EVA or silicone

EVA: soil, Al, PE motivated localized discoloration ⇒ combustion

silicone: soil, Al ⇒ localized cracking. (no primer present)

- elapsed time: minutes – days/weeks
- bubbles: no failure @C_g=500, despite 4% measured $T[\lambda]$ reduction





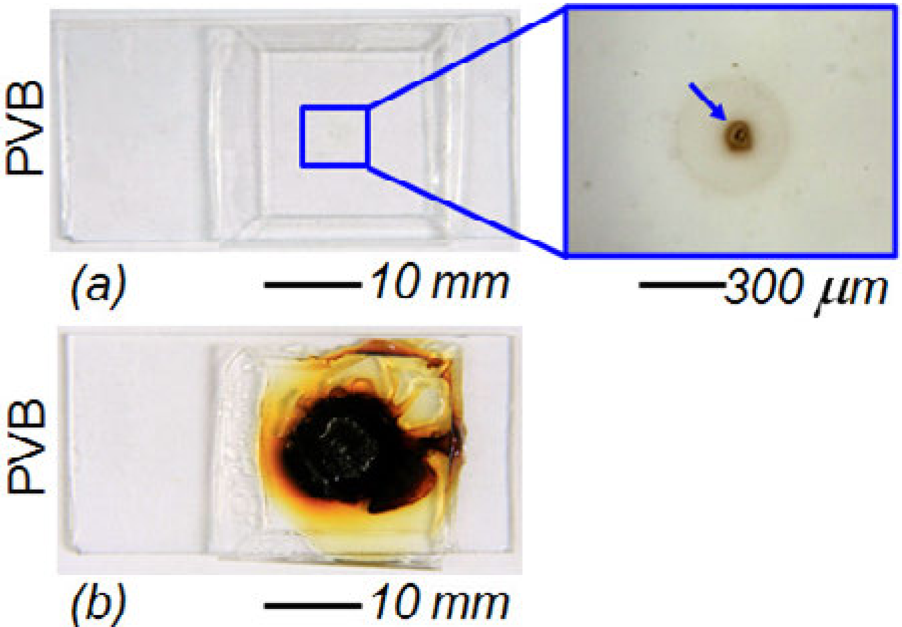
time sequence: optical images of test specimens

Miller et. al., PIP, DOI: 10.1002/pip.1241

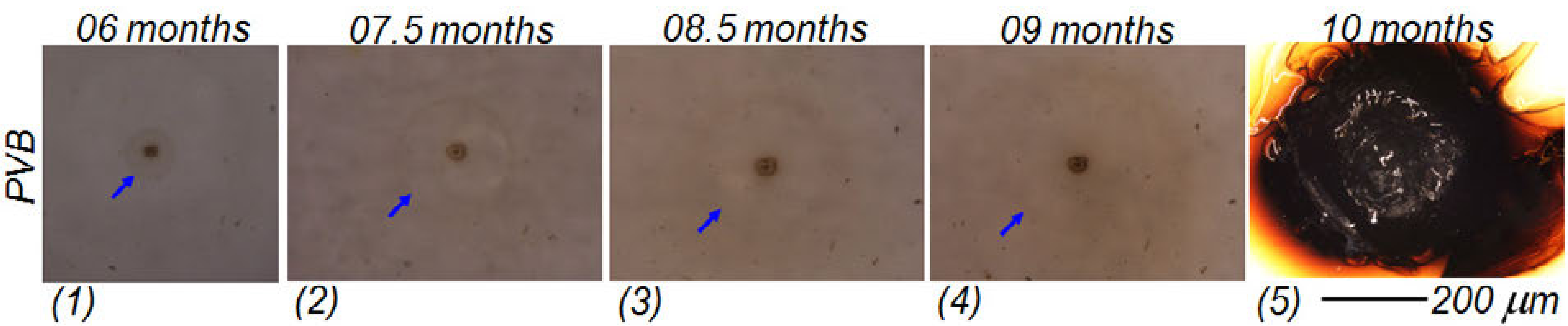
Results of the Formal Experiment
(Hydrocarbon Specimens)

- PVB was the first material to demonstrate thermal runaway mediated failure

- The radius of the affected region was seen to slowly grow during the cold winter months



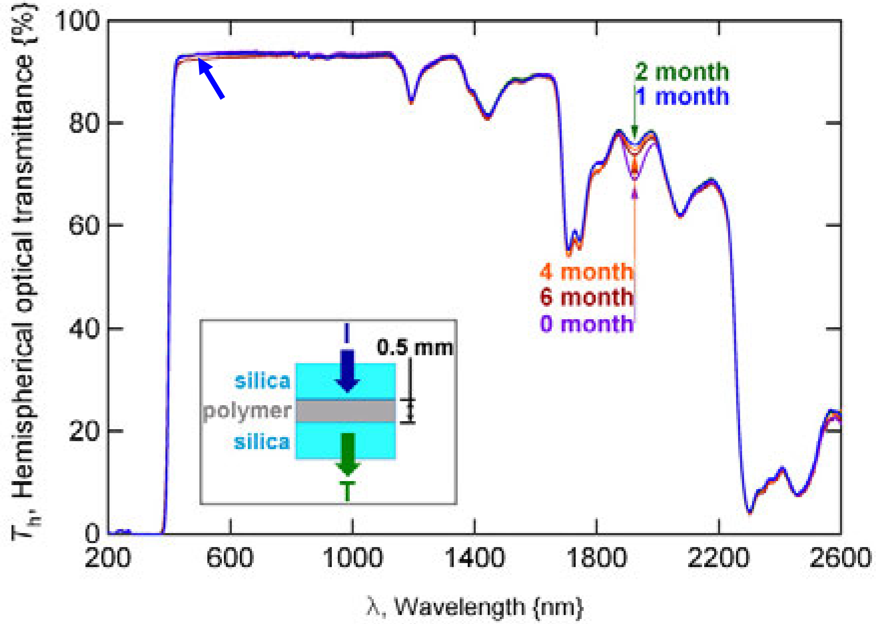
optical images of test specimen at:
(a) 6 months and (b) 10 months



time sequence: optical images of test specimen

Miller et. al., PIP, DOI: 10.1002/pip.1241

Results of the Formal Experiment
(Hydrocarbon Specimens)

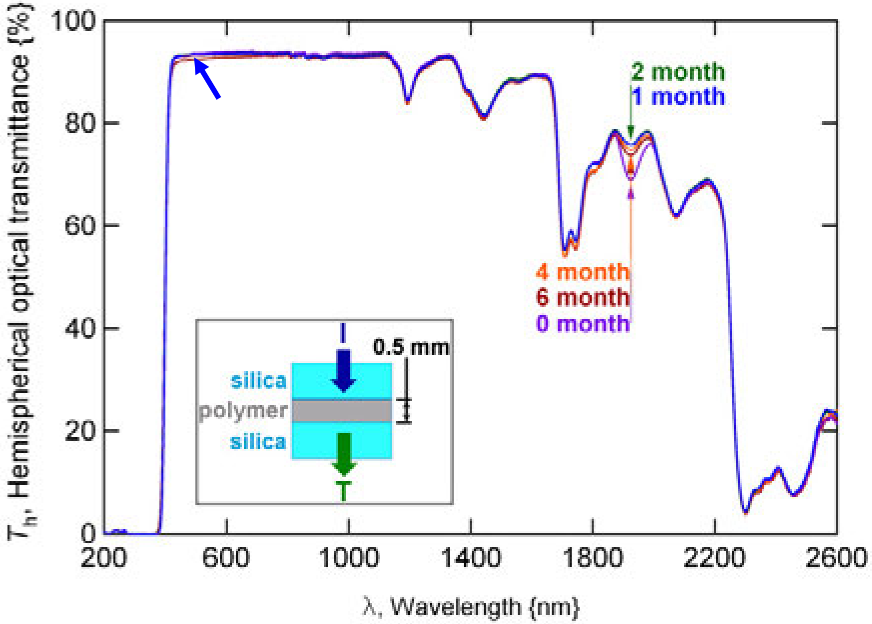


time sequence: transmittance of the PVB specimen

- Transmittance & YI not significantly affected, despite impending failure
- A diagnostic characteristic with predictive capability is preferred!!!

optical fluorescence spectrum of PVB, for λ_I= 280 nm

Results of the Formal Experiment
(Hydrocarbon Specimens)



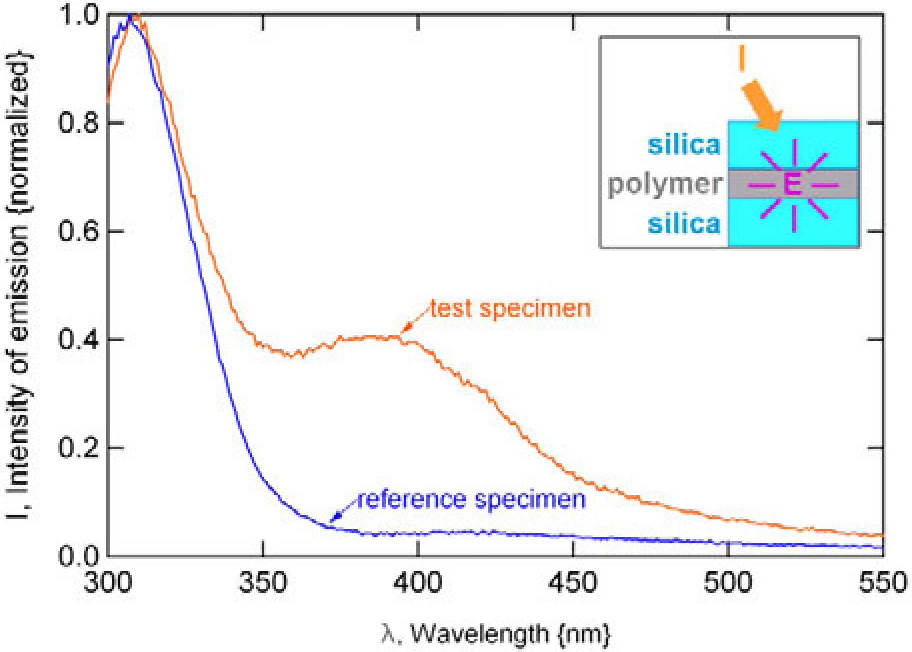
time sequence: transmittance of the PVB specimen

•Transmittance & YI not significantly affected, despite impending failure

•A diagnostic characteristic with predictive capability is preferred!!!

•Optical & Raman spectroscopy clearly indicate fluorescence

•These techniques may help understand the degradation mechanism (*e.g.*, chromophores)



optical fluorescence spectrum of PVB, for λ_I= 280 nm

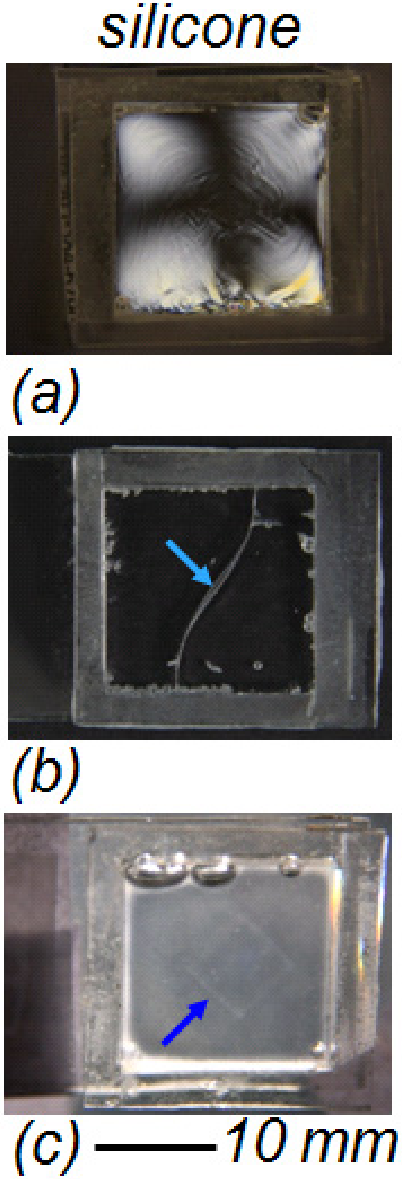
Results of the Formal Experiment
(Silicone Specimens)

•Observations of silicone specimens include: (a) densification, (b) cracking, and (c) haze formation

No mass change with time for the (5) **densified** specimens ⇒ likely occurred during molding

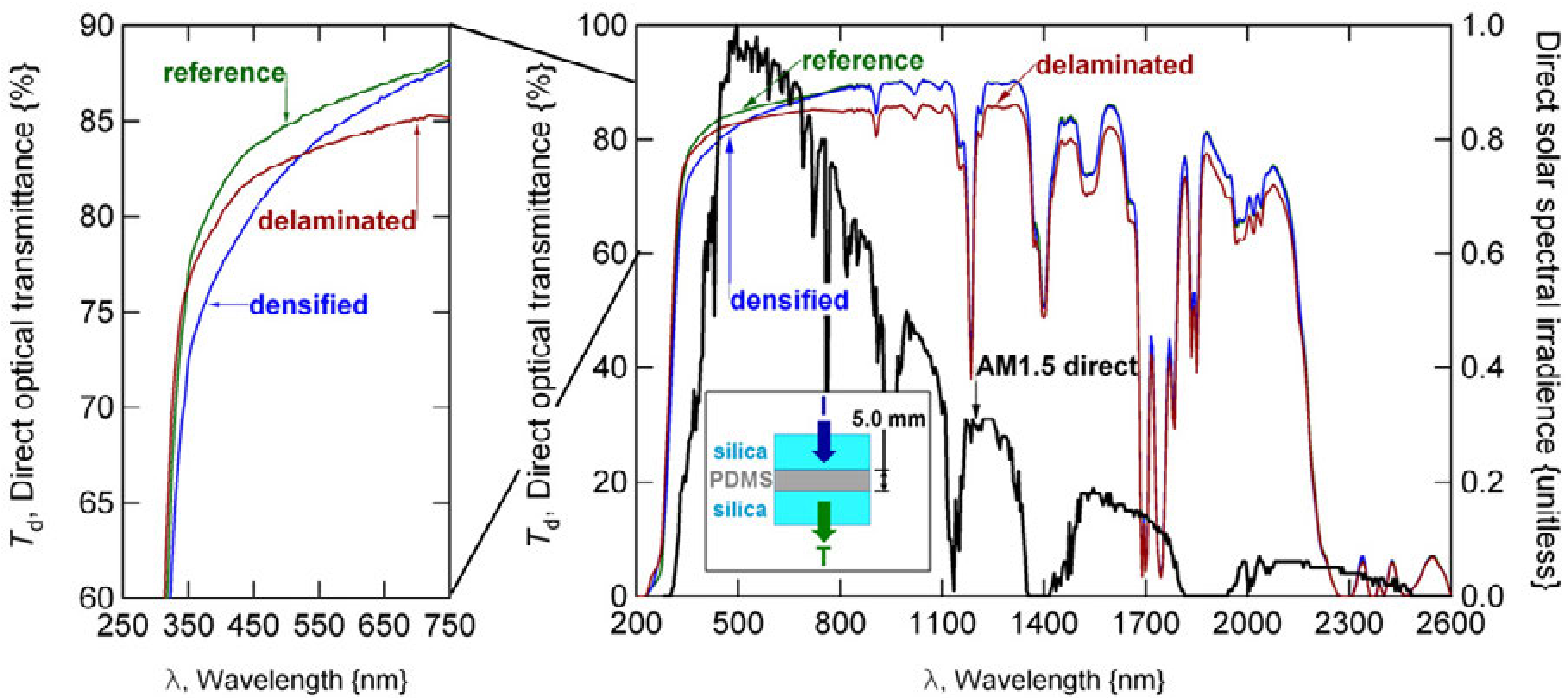
•**Crack** advancement occurred during cold weather periods only ⇒ likely motivated by CTE misfit
•Additional fractured specimens may be emerging

Haze formation is attributed to one material's unique formulation



optical images of silicone specimens, including those obtained using (a) cross-polarization or (c) back-lighting

Results of the Formal Experiment
(Densified Silicone Specimens)



- Densification is not delamination
- Densification does scatter direct light

Problematic for CPV?

- Current limited condition (blue light) • Optical attenuation (less power)

⇒May not be significant in thin bond layers

Miller et. al., PIP, DOI: 10.1002/pip.1241

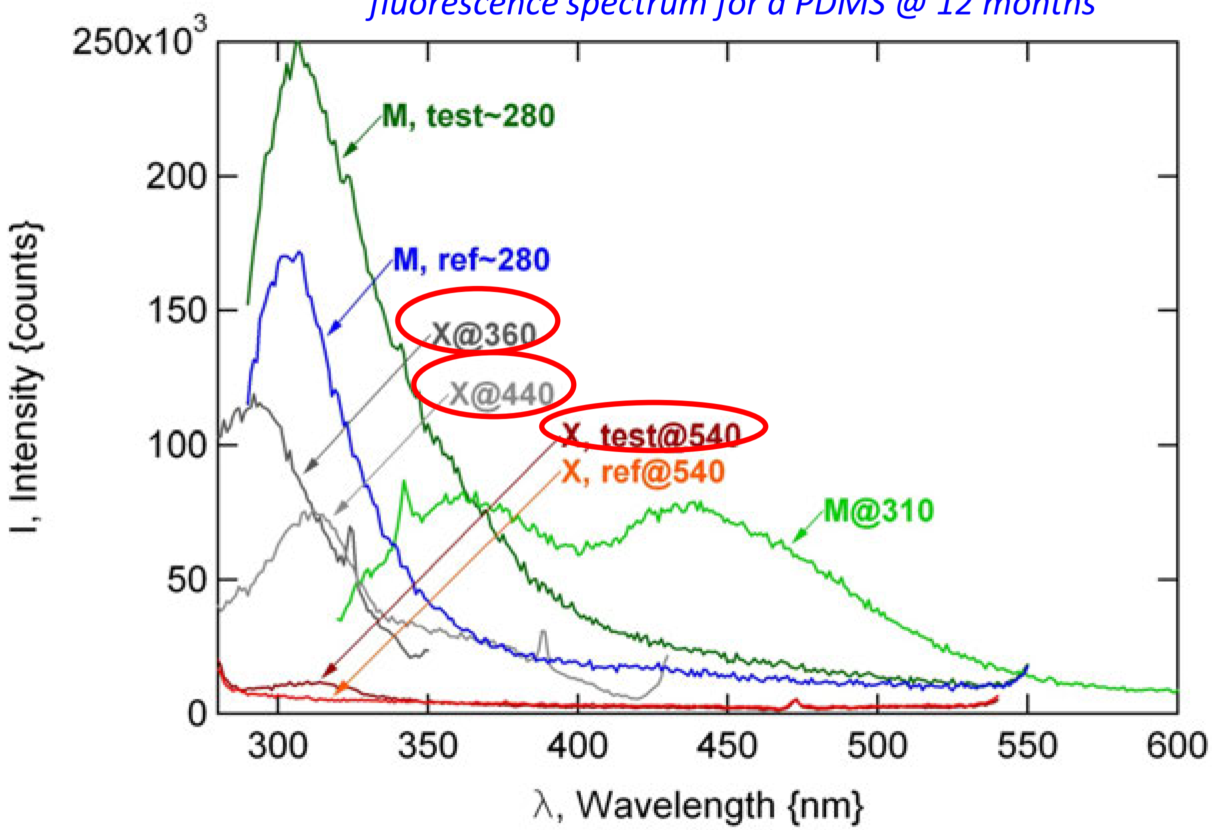
Fluorescence Identifies the Silicones Are Affected!

- Unexpected new peaks identified for all silicone specimens!

- The particular details location and relative intensity of the new M_t peaks varied with formulation

- Attributed to Pt catalyst (working to verify)

fluorescence spectrum for a PDMS @ 12 months



- The implications are unclear. PDMS is historically robust in extreme environments. λ_X… <390 nm for PMMA, ~320 nm for SoG

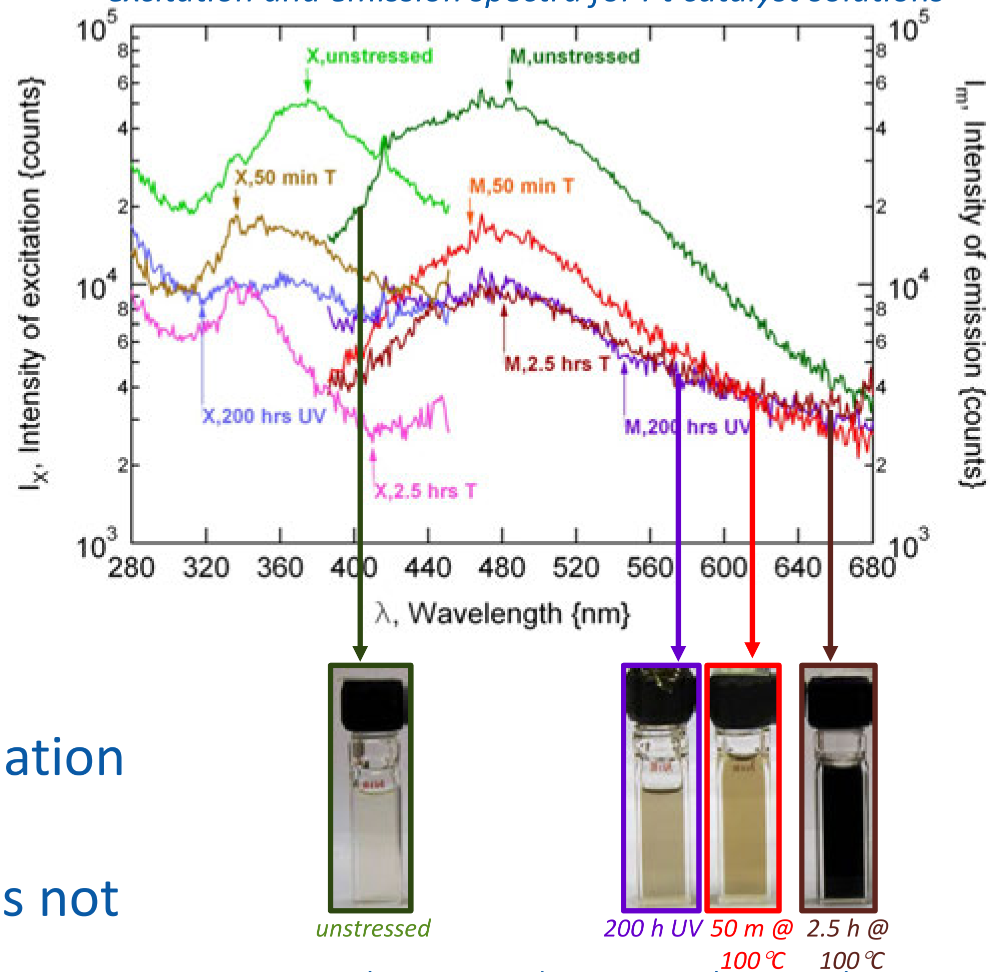
UV and/or Temperature Can Degrade Pt Catalyst

- Karstedt's catalyst, Pt(0), examined in tetramethyldivinyldisiloxane
- Catalyst loses fluorescence with UV or T
- Organometallic literature: mononuclear Pt with ligands → colloidal Pt, 3-5 nm ∅

- Discoloration (optical absorptance) could motivate thermal runaway

- No evidence to date of optical degradation in NREL specimens
- Fluorescence of catalyst solution does not correspond to that in x-linked PDMS

excitation and emission spectra for Pt catalyst solutions



color-corrected specimen photographs

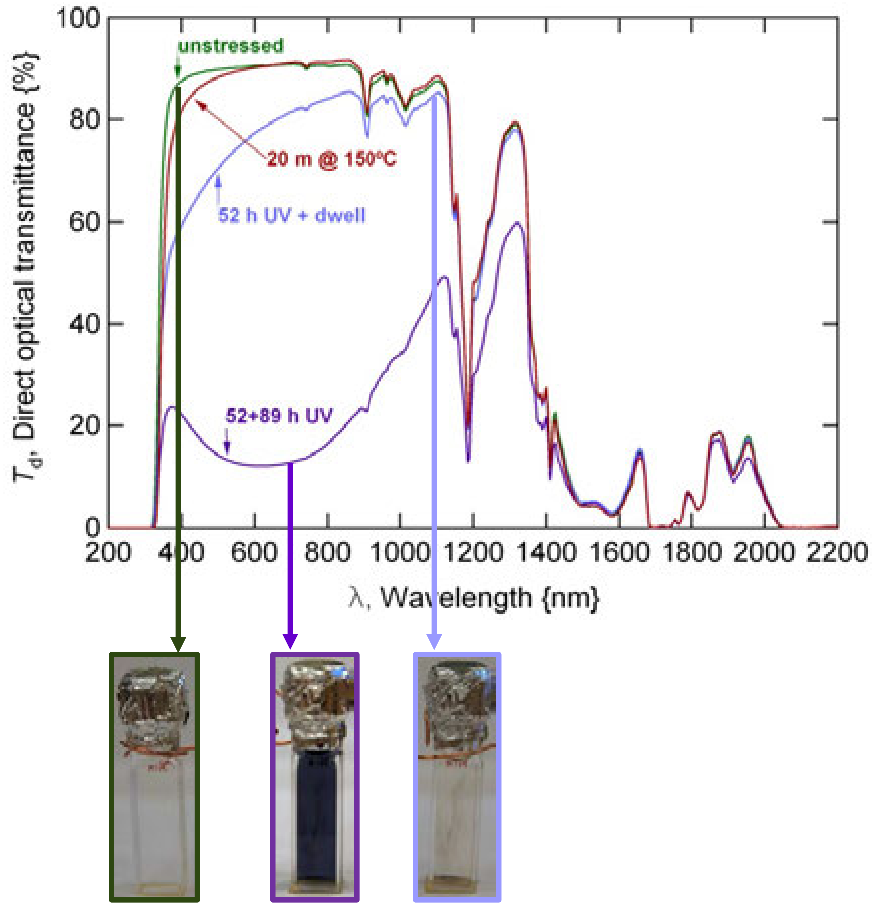
- Alternate pathways: different catalyst type (ligands), peroxide cured silicone, PMMA on glass (PoG) lenses, AR coatings

UV Can Degrade Silicone Primers

- Dow-Corning 92-023 used in all NREL PDMS specimens
- The Ti based primer (on glass) reduces UV transmittance for λ< 300 nm (n TiO_2 = 2.5)

- Experiments identify primer is quite photoactive:
  discoloration with minor fluorescence
- Transparency recovered with time (O_2 facilitated?)

transmittance for primer solutions (in IPA)



unstressed *52+89h UV* *52 h UV + dwell*

- TiO_2 used in self cleaning coatings.
(UV driven consumption of organic contamination). Affect on PDMS is unclear.
- Alternate pathway: Sn catalyzed primers (n SnO=2.1)

Summary & Conclusions

Field study of the durability of polymeric encapsulation materials for CPV

Discovery experiments:

- Quickly confirmed the importance of an optical homogenizer
- Al, soil, polymeric contamination ⇒ *T* runaway & combustion of EVA
- Al, soil contamination ⇒ cracking of silicone

Formal experiment:

- 17 of 25 specimens not discussed today!
- 3 of 25 specimens "failed".

PVB: localized discoloration ⇒ thermal runaway ⇒ combustion

Fluorescence & Raman spectroscopy may diagnose & provide prediction

Silicone: densification, cracking, haze-formation

Densification affects the direct transmittance

PDMS Fluorescence:

- Working to understand observed peaks; alternative "solutions" identified

*Transmittance of optical system and corresponding activation spectrum of the encapsulation are critical to encapsulation durability

Acknowledgements

- NREL: Dr. Keith Emery, Dr. Daryl Myers, Dr. John Pern, Matt Beach, Christa Loux, Tom Moricone, Marc Oddo, Bryan Price, Kent Terwilliger, Robert Tirawat

NATIONAL RENEWABLE ENERGY LABORATORY

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory.

Paper: "The Durability of Polymeric Encapsulation Materials for Concentrating Photovoltaic Systems", Prog. Photovoltaics, *DOI: 10.1002/pip.1241*.

Performance and Reliability of Silicone Polymers in 1000X Concentration CPV Applications

Michael Winter
Ian Aeby
James Foresi

Silicone serves multiple functions in the Emcore CPV module

adhesive

moisture barrier

optical coupling adhesive

Fresnel lens

electrical encapsulant

Emcore CPV system analysis targets specific materials/interfaces for further interrogation

Analysis of the potential weak links in the CPV product have identified silicone needing further reliability testing

As a III-V cell manufacturer, Emcore has a deep knowledge base to draw from during reliability assessments

Due to the nature of CPV, traditional stress acceleration to failure isn't always an option – health monitoring is needed

Targeted testing of other potential concerns is underway using appropriate stress tests

Silicone is a robust material, but is highly stressed in the 1000X light path

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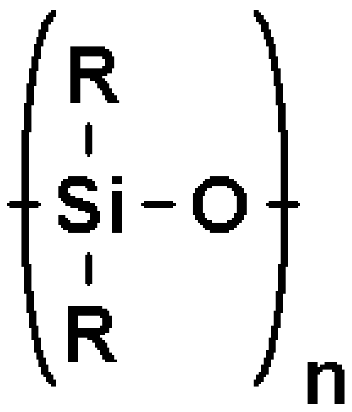


Properties:

- use temperature < 200ºC
- thermal conductivity = 0.16 W/m·K

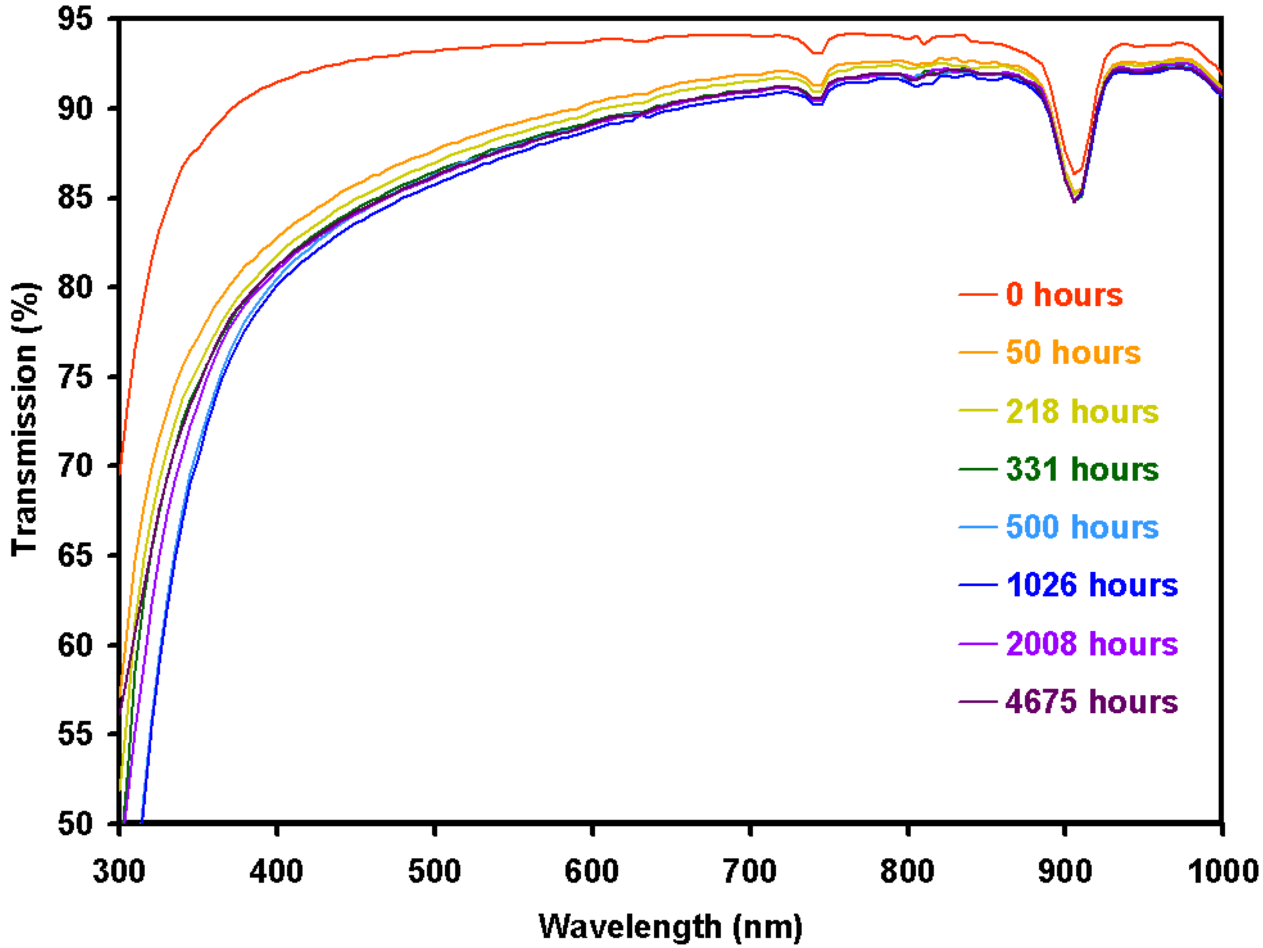
Operating Conditions:

- 1000X concentration
- occasional high temperature
- contact with other materials

Do these properties apply at 1000 suns at 80+ºC for 25 years with thermal cycling and humidity?

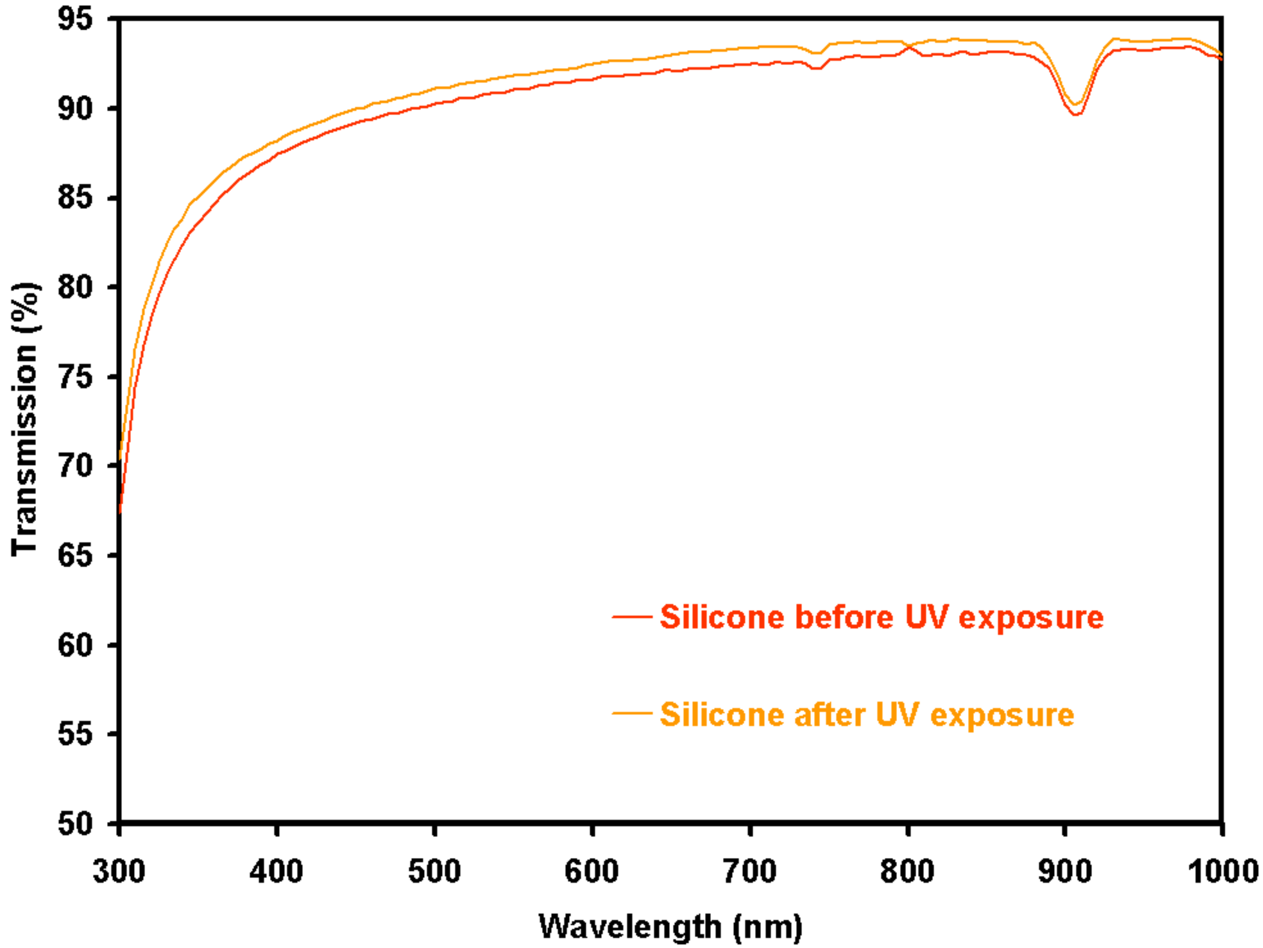
The transmission of silicone decreases shortly after exposure to high temperature

silicone aged at 175ºC in air – 10mm thick



Exposure to UV at ambient temperature has not caused silicone transmission to degrade

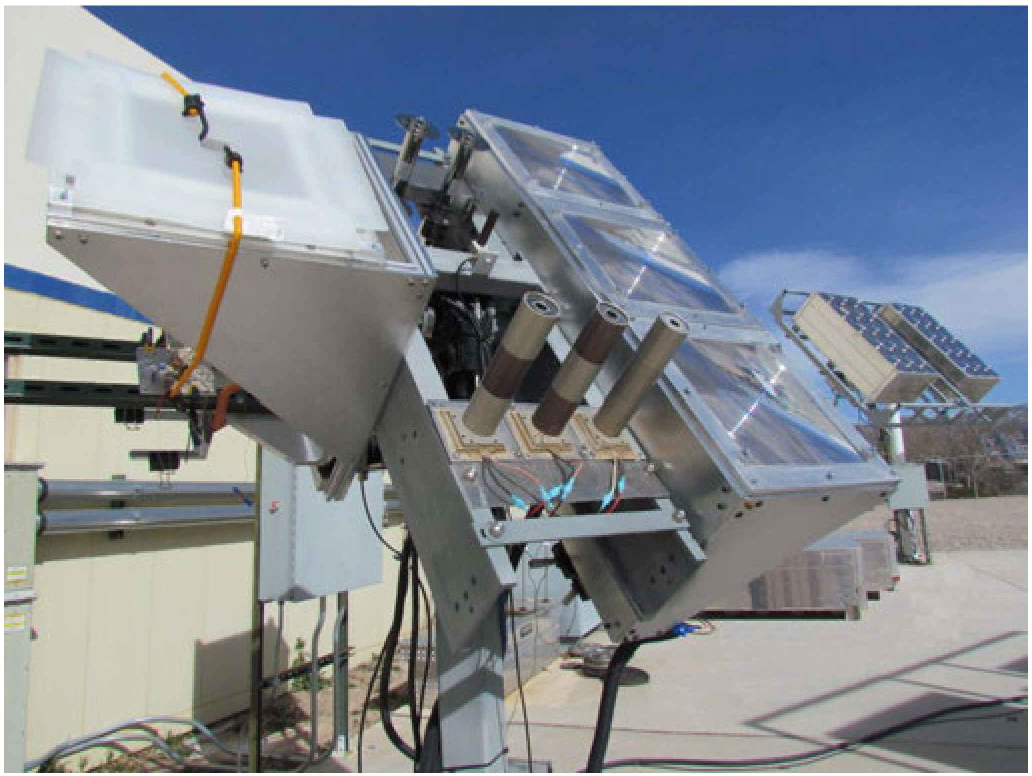
sample aged at 175ºC prior to UV exposure at 25ºC, 5 mm thick



Combined effects testing is a more realistic technique to establishing silicone reliability

emcore empower with light™

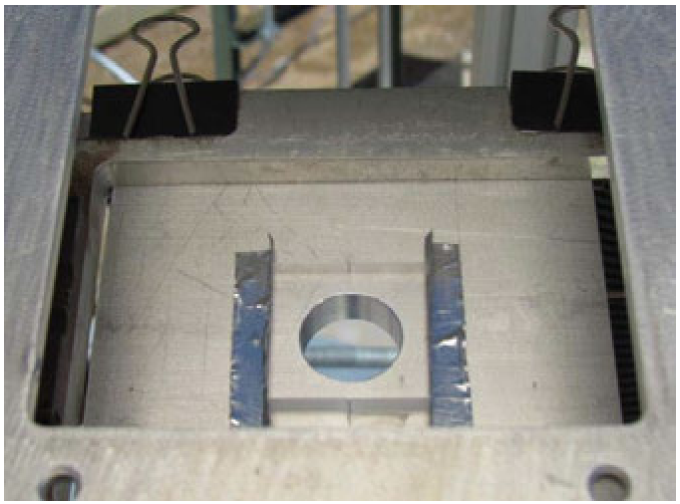
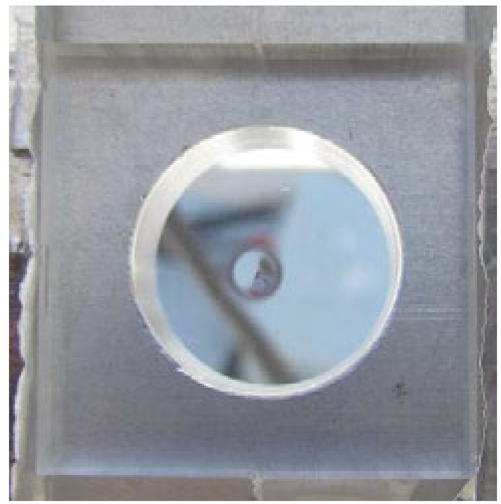
on sun comparison to narrow the field of viable solutions

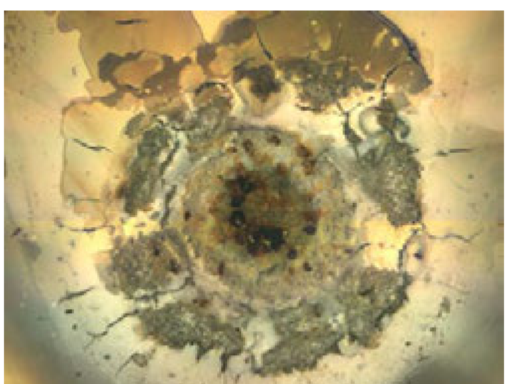


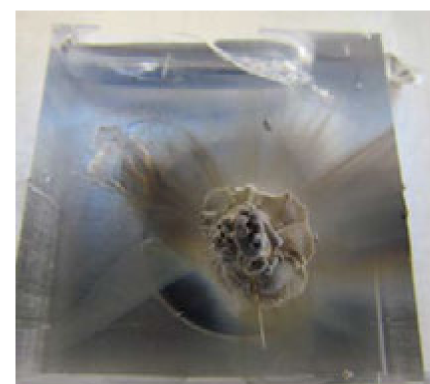
indoor testing for acceleration factors

Bulk silicone testing on-sun yields useful information about silicone degradation

5 mm thick samples tested on-sun in a variety of UV and ambient temperature conditions

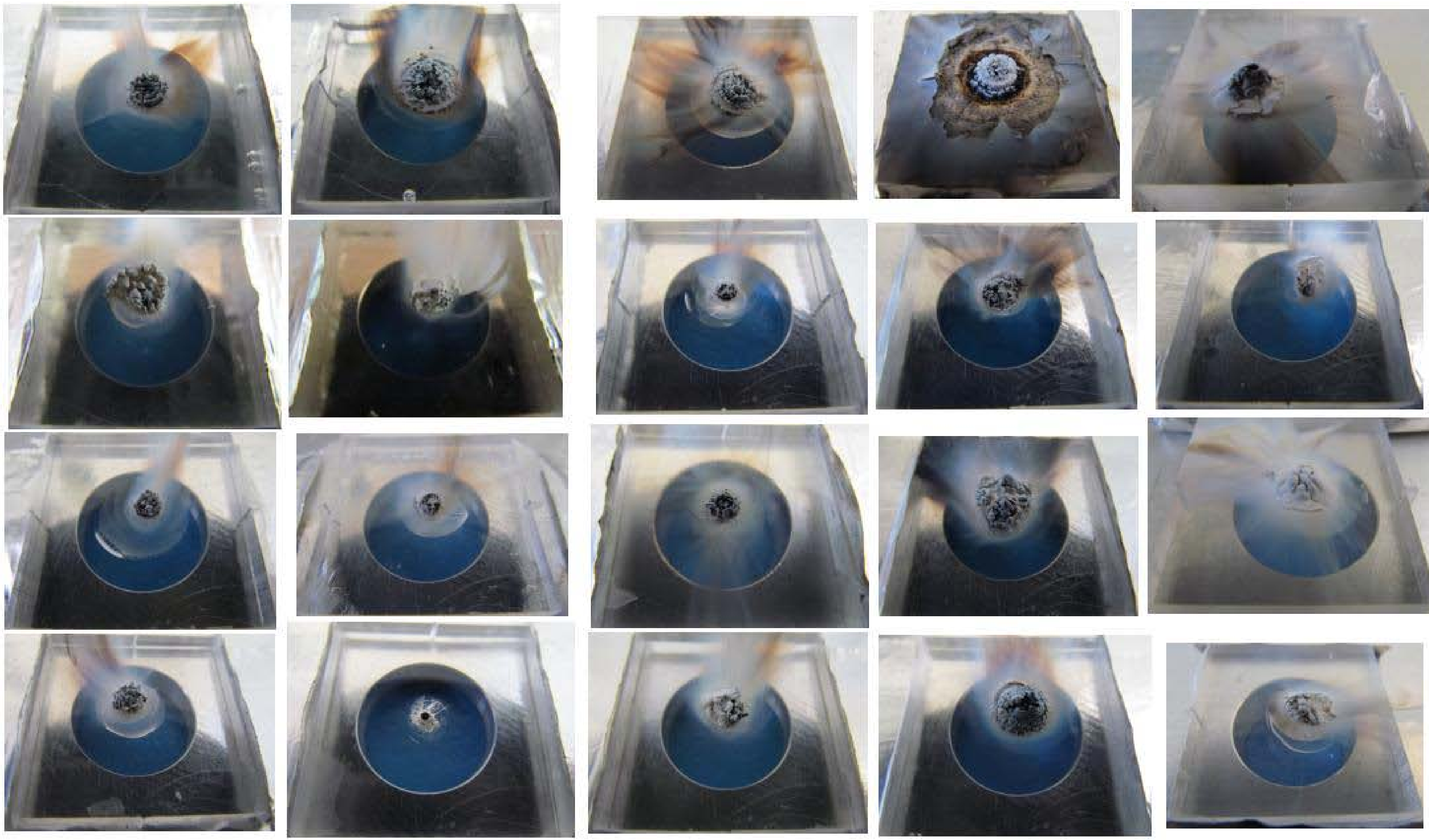







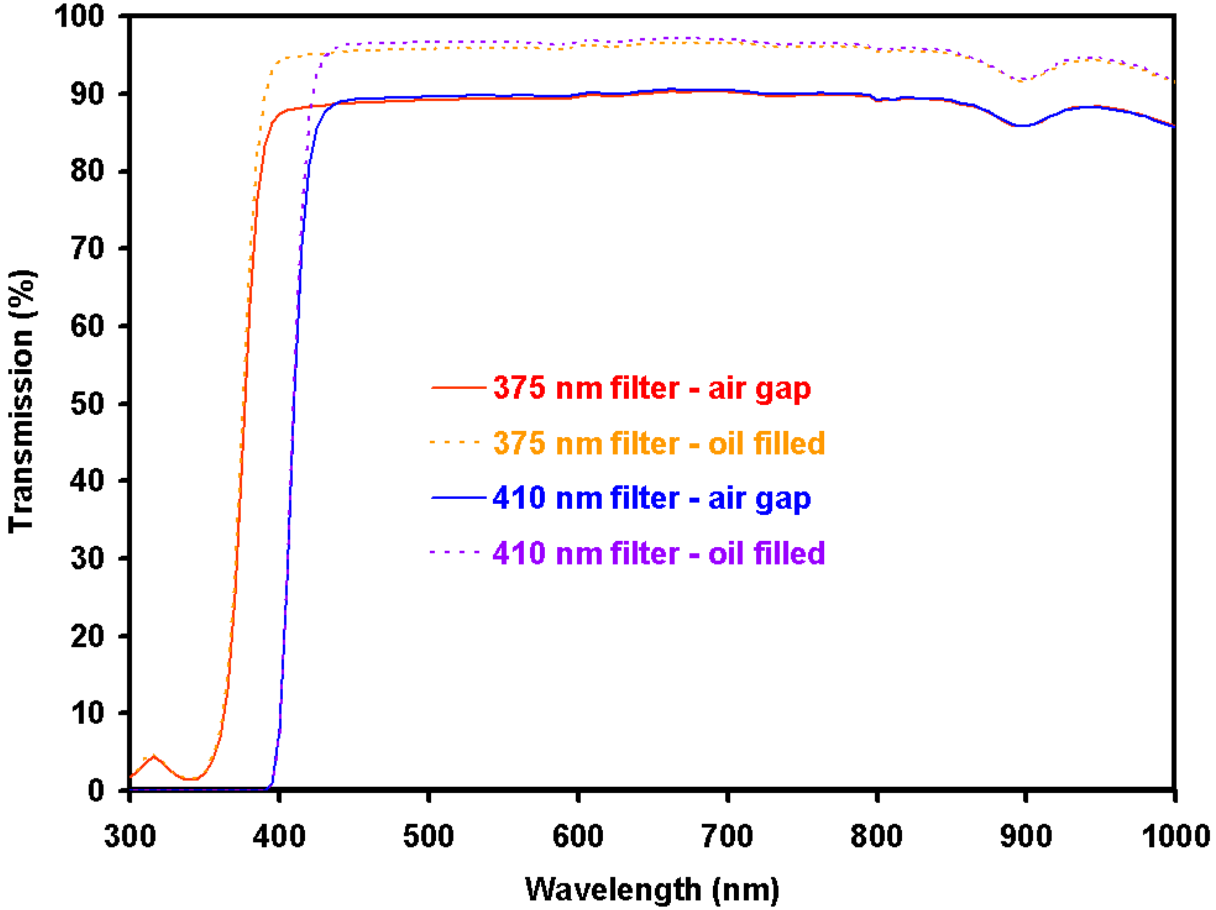
Silicone temperature is not an easy variable to control during on-sun testing

time to decompose depends on manufacturer and thermal history



UV exposure is controlled through the use of filters during on-sun testing

two filters: 50% transmission at 375nm and 410 nm
(30 nm bandwidth between 10% and 90% transmission)



Infrared imaging shows the effect of the UV filter during on-sun testing

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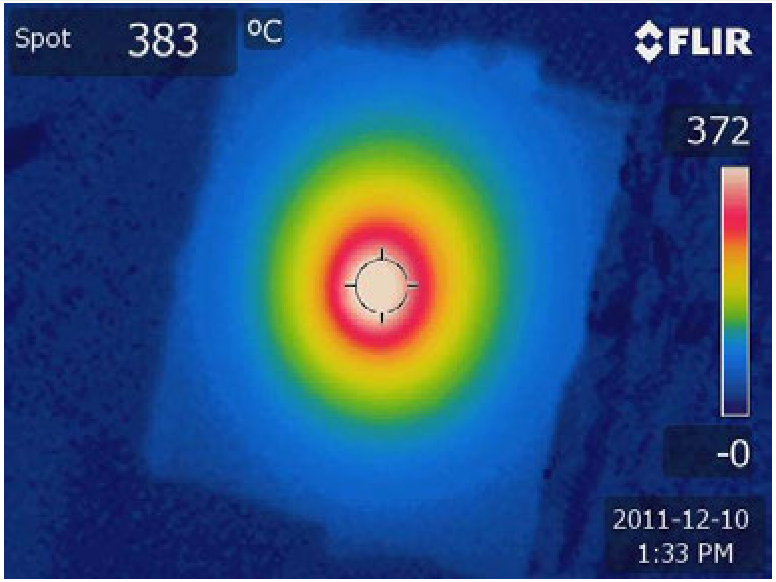
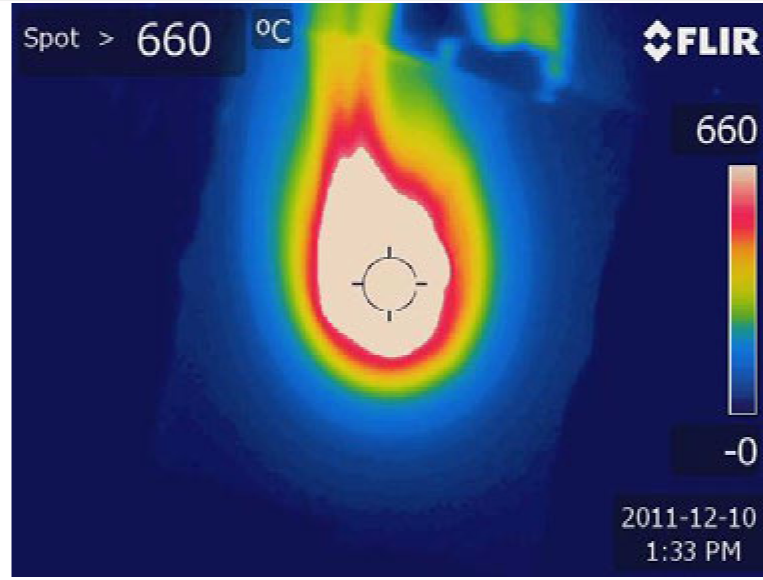
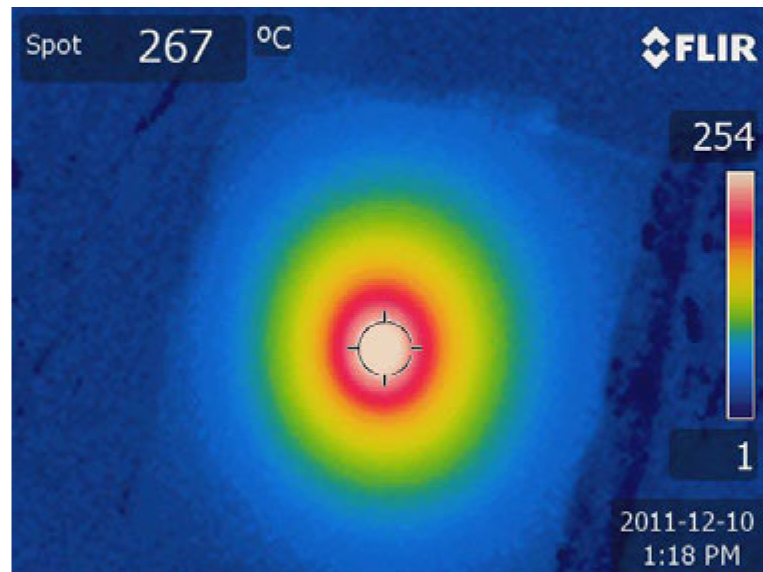
unfiltered
10m on-sun



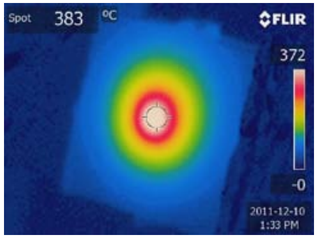


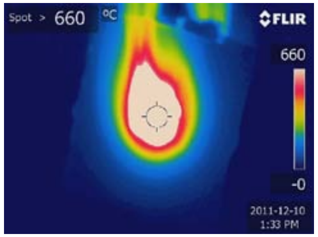
IR imaging of bulk silicone samples shows that inserting a 410 nm cut-off filter significantly reduces the sample temperature and delays decomposition



410 nm filter, 10m on-sun

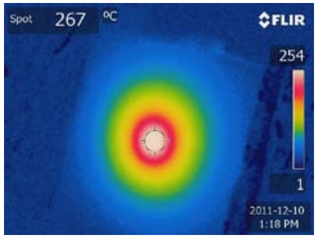
Reducing the UV flux greatly reduces the silicone temperature during on-sun testing

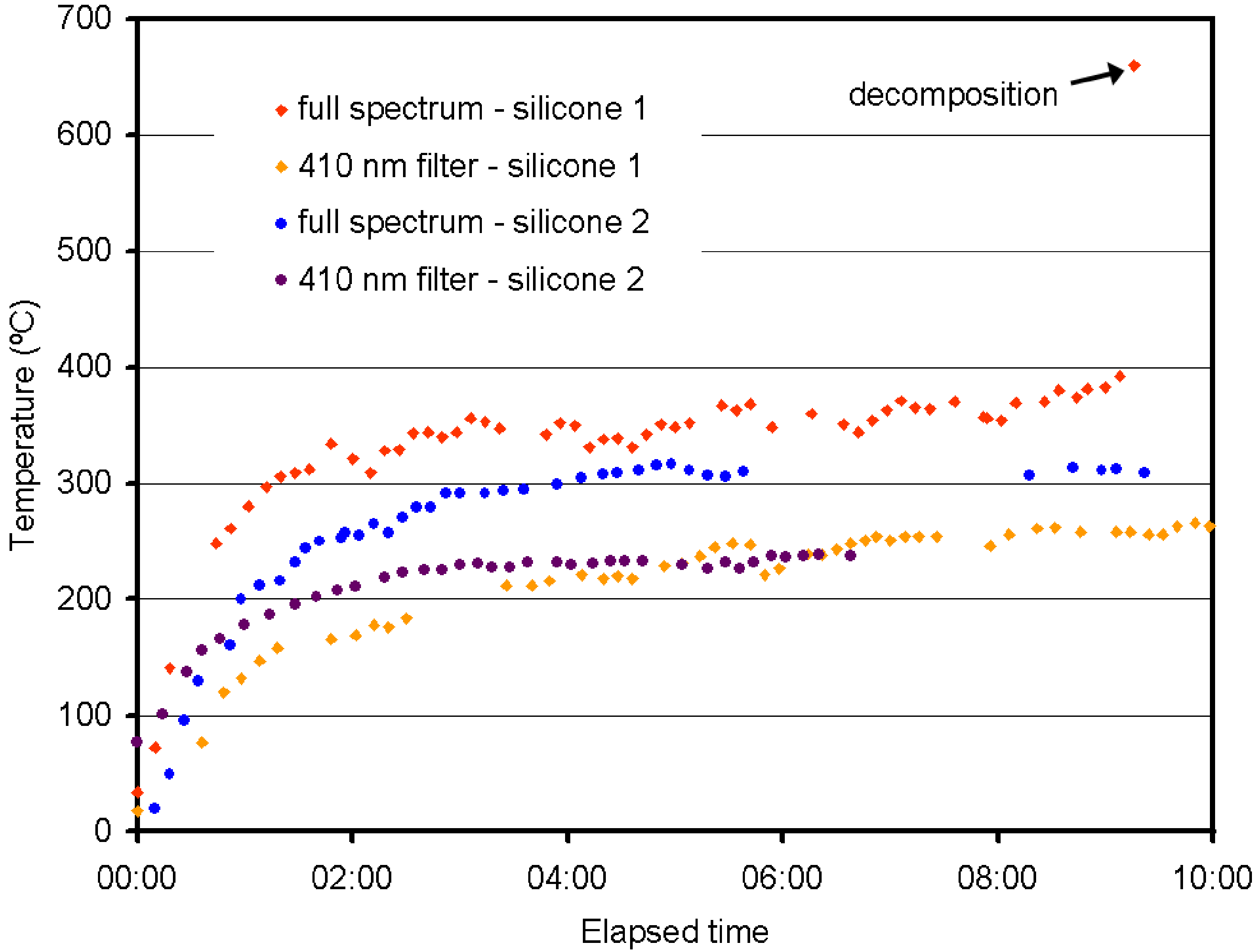




unfiltered

410 nm filtered



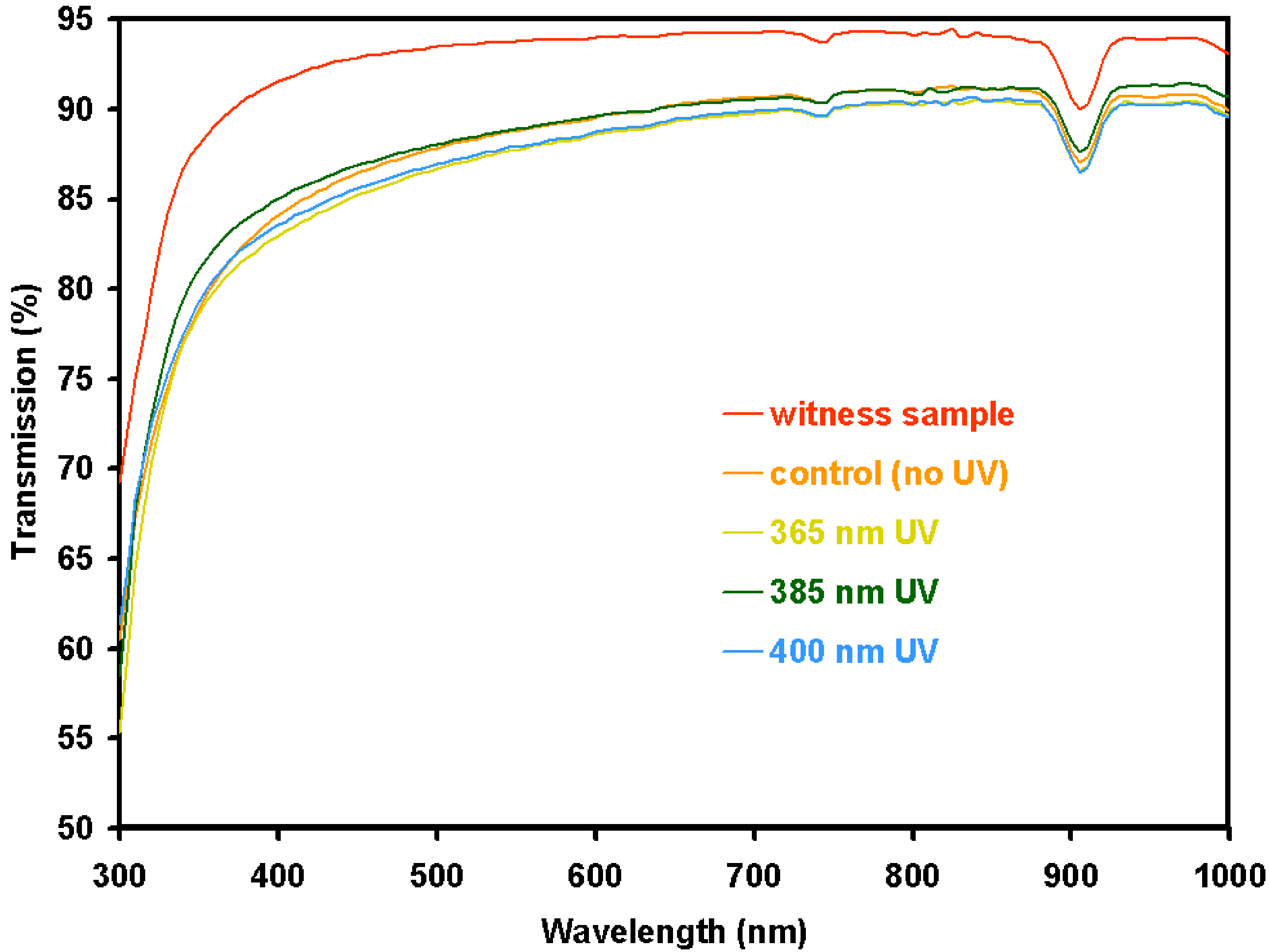


Removing UV wavelengths drastically increases time to decomposition

410 nm filter on the Fresnel with oil between

Time to decomposition		
Full spectrum (m)	410 nm filter (m)	Life Increase (%)
15-32	330	1500
4	30	750
47-52	390	780
4-22	120	850

Combined effects in the lab to determine acceleration factors



Establishing the reliability of polymers in a 1000X CPV system is a tricky business

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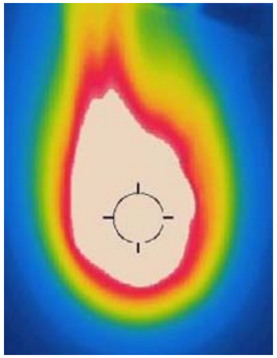
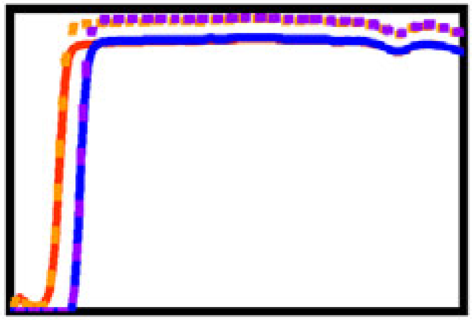


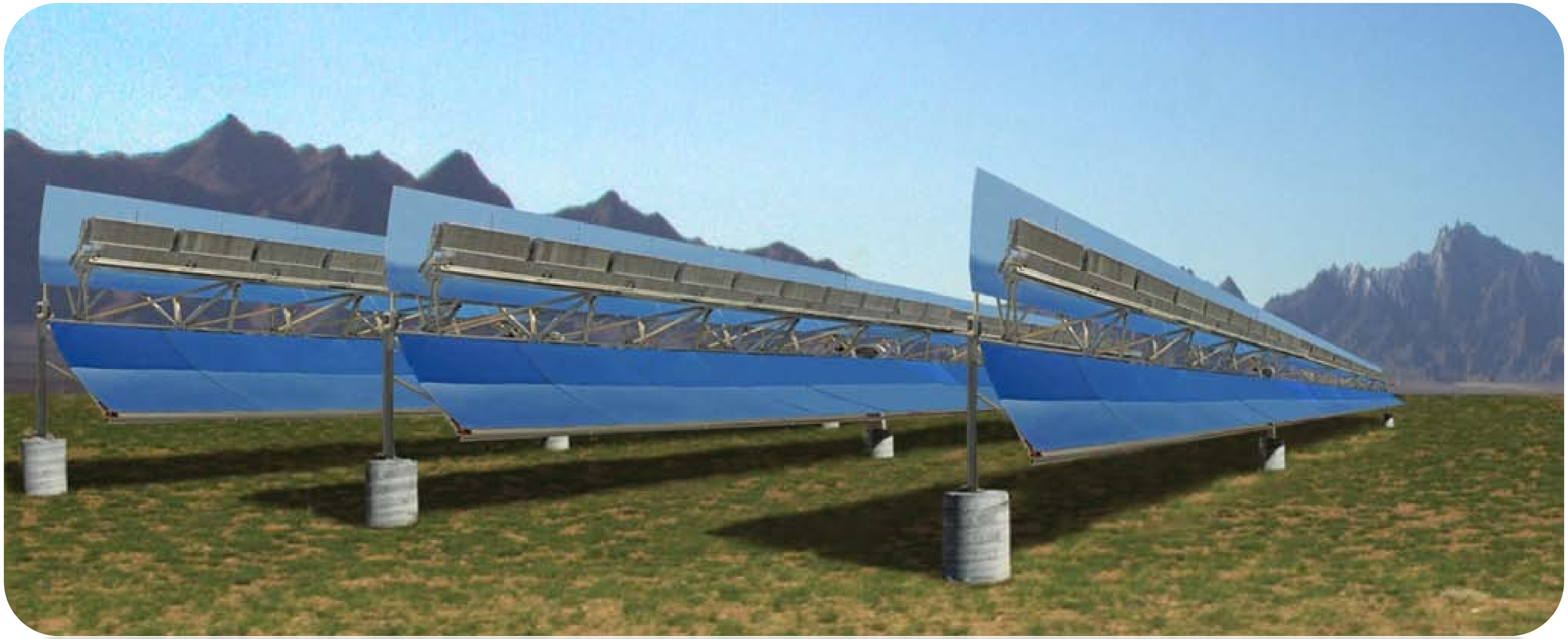
accelerating a 1000X CPV system is not easy

a more sophisticated approach is needed to determine the lifetime of materials and interfaces of concern

elimination of UV appears to greatly enhance silicone longevity



knowledge of materials, interactions and kinetics of failure are essential to ensuring long term reliability



Lessons Learned from Development of Silicon CPV Modules

Robert MacDonald and Mehrdad Roosta

PV Module Reliability Workshop, March 2012

RELIABILITY MATTERS

CREDIT SUISSE

29 February 2012

The warranty issues are a BIG DEAL (to us at least). We are very disappointed that FSLR has now taken a cumulative $253mm of warranty and related charges as its panels are underperforming in the field – these issues we think are VERY concerning. Field reliability of thin film panels are less proven as is – and high temperature degradation of CdTe panels is a known issue (ask us for an NREL study on this topic). We have confirmed FSLR is building the Topaz project to 586MW AC, above the 550MW specified in the contract – we think there is some risk that this "over spec" is to provide protection given the minimum energy performance specs that FSLR has committed to in the project given the lower confidence on field performance.

First Solar, Inc. (Public, NASDAQ:FSLR) Watch this stock

31.92 -0.38 (-1.18%)

Real-time: 9:43AM EST
NASDAQ real-time data - Disclaimer
Currency in USD

Range	31.71 - 32.55
52 week	29.87 - 163.00
Open	32.55
Vol / Avg.	134,800.00/5.35M
Mkt cap	2.77B
P/E	5.27

Div/yield	-
EPS	6.08
Shares	86.42M
Beta	1.37
Inst. own	89%

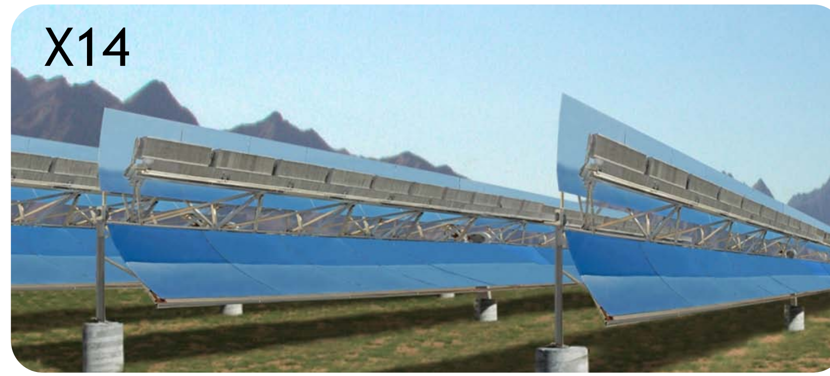
Compare: Enter ticker here Add Dow Jones Nasdaq SPWR ASTI DSTI ESI

Zoom: 1d 5d 1m 3m 6m YTD 1y 5y 10y All

Feb 28, 2012 - Mar 01, 2012 -4.1 (-11.33%)

Introduction

- Skyline Solar has commercialized CPV products using silicon PV cells in a linear concentrator

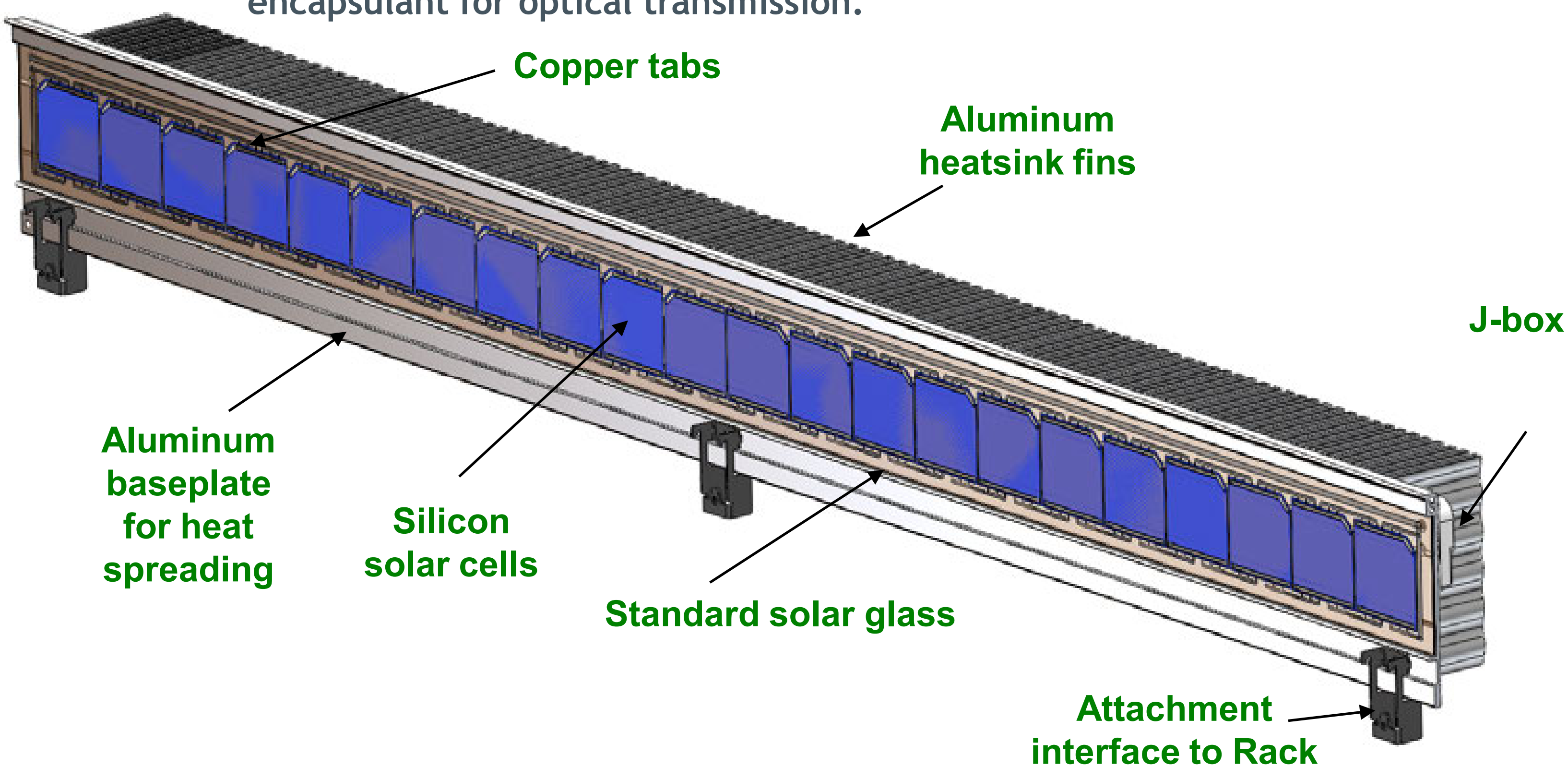


- Key design challenge for Skyline and predecessors (e.g. Euclides): receiver package

- Multiple, conflicting design drivers
  - High durability vs Low materials cost
  - Low thermal resistance vs High electrical resistance

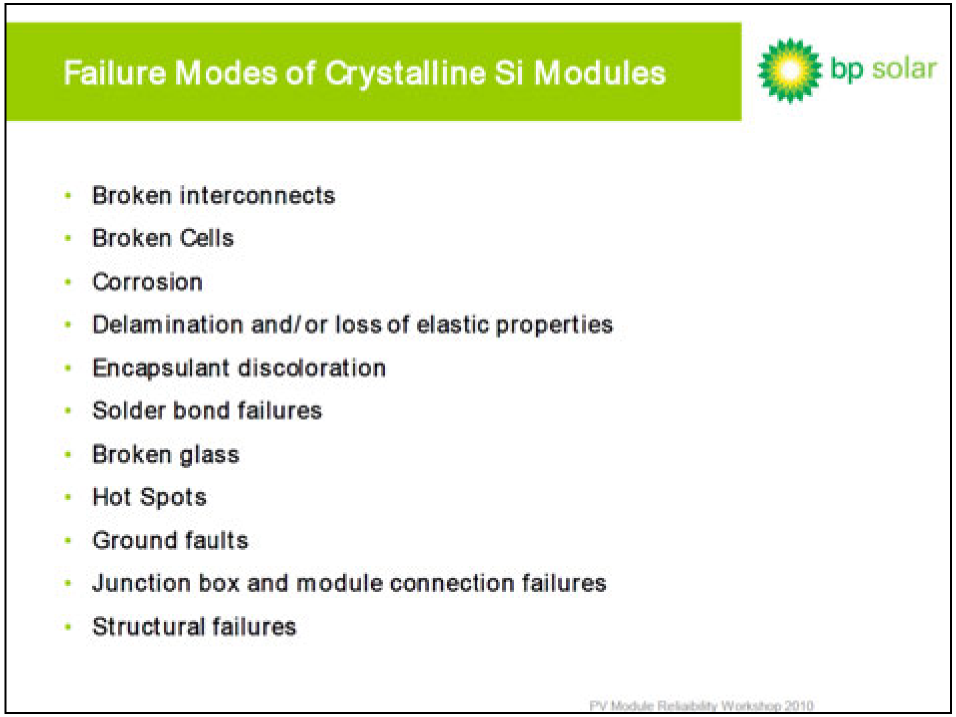
Gen1 Receiver Design

- Design goals:
  - Leverage standard solar panel packaging, processes, and manufacturing partners
    - Common components to standard panels - Examples: Cell processing, stringing/tabbing, encapsulents, glass, Jbox, cables
  - Adapt where required for our application - thermal optimization and optical flux.
    - Aluminum baseplate and heatsink fins in place of Tedlar backsheet
    - Adaptation of backsheet encapsulant for thermal dissipation and frontsheet encapsulant for optical transmission.



KEY COMMERCIAL CONSTRAINTS: RELIABILITY & COST

- Reliability considerations: akin to flat-plate c-Si modules* + high UV



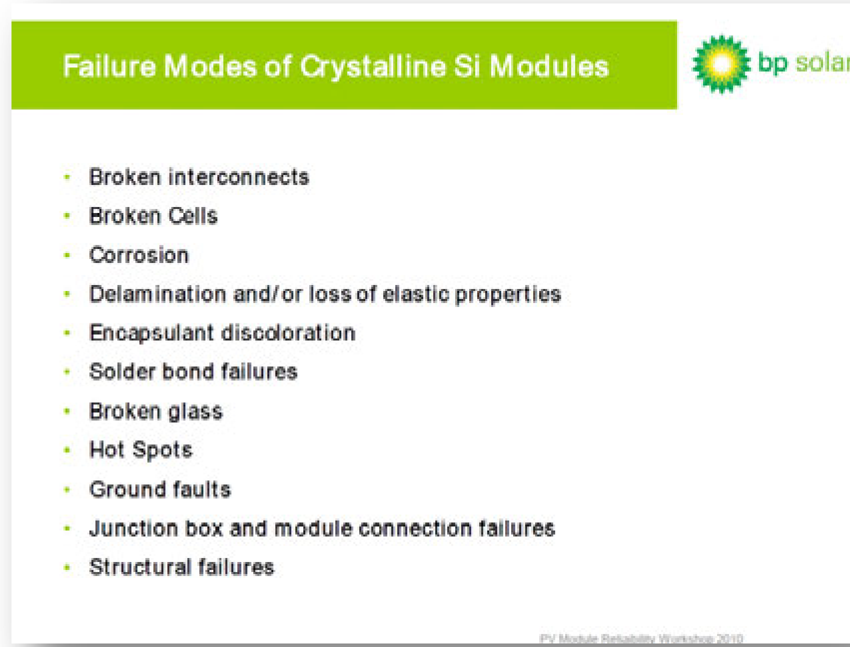
- Cost
  - Limits material choices: e.g. no sapphire substrates
  - Limits manufacturing processes: high throughput, wide tolerances

*Wohlgemuth Cunningham, Nguyen, Kelly and Amin, PV Module Reliability Workshop 2010, Golden, CO

SKYLINE'S EXPERIENCE

Encapsulent Options

- EVA — Discoloration, broken cells
- PVB
- Silicones



Thermal Expansion Effects

- Metal + glass
- Long panels
- Cu + Si joints
- Lamination

Junction Box Considerations

- Small footprint
- Case material composition
- Potting and sealing
- Supplier quality

ENCAPSULATION: GLASS TO ALUMINUM LAMINATION

Robust design

- Low laminate stress during life cycle
- Geometry chosen to manage CTE mismatch
- Minimize material usage

Well matched materials

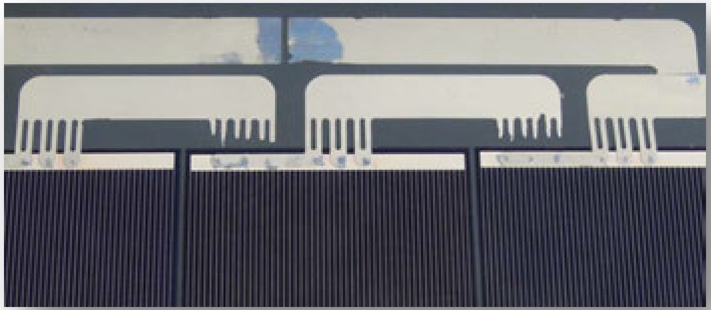
- Chosen for high adhesion between layers
- Low modulus change across temperature range
- Suitable for high UV and thermal management

Robust process

- Stable and safe chemistry
- Process speed + high yield
- Low risk of string damage

Encapsulation: What Can Go Wrong

Delamination or Voiding



Interconnect Failure

Cell String Solder Joints

Wide Process window

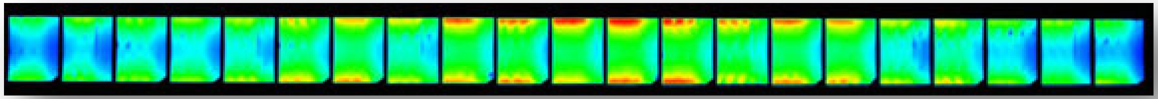
- Proper choices of solder material and thickness
- Proper choices of manufacturing equipment
- Extensive testing and characterization

Tolerant of temperature extremes

- From solder reflow temperature down to -40 ° C
- Daily temperature cycles
- Optimized tab geometry

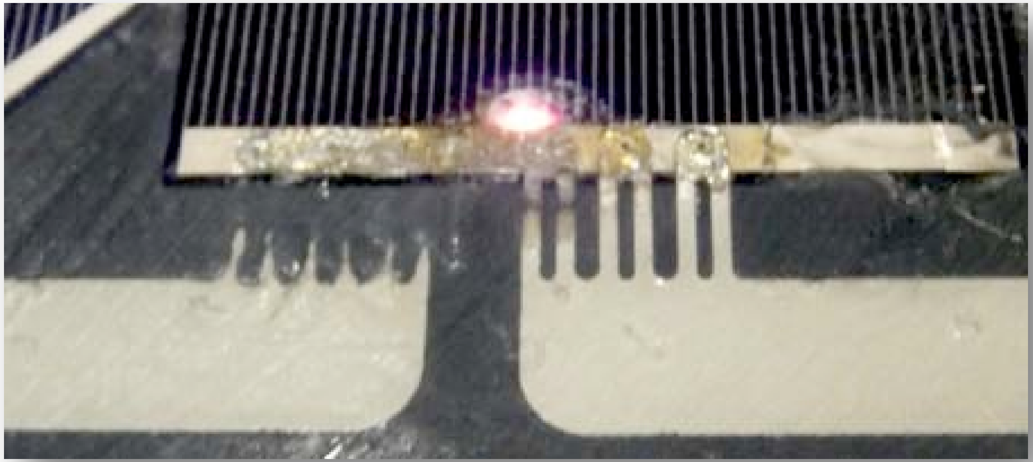
Direct reliability and performance impact

- Poor solder joints can cause high local heating
- Good solder joints will reduce string resistance
- Proper solder joints will not degrade with T/C.

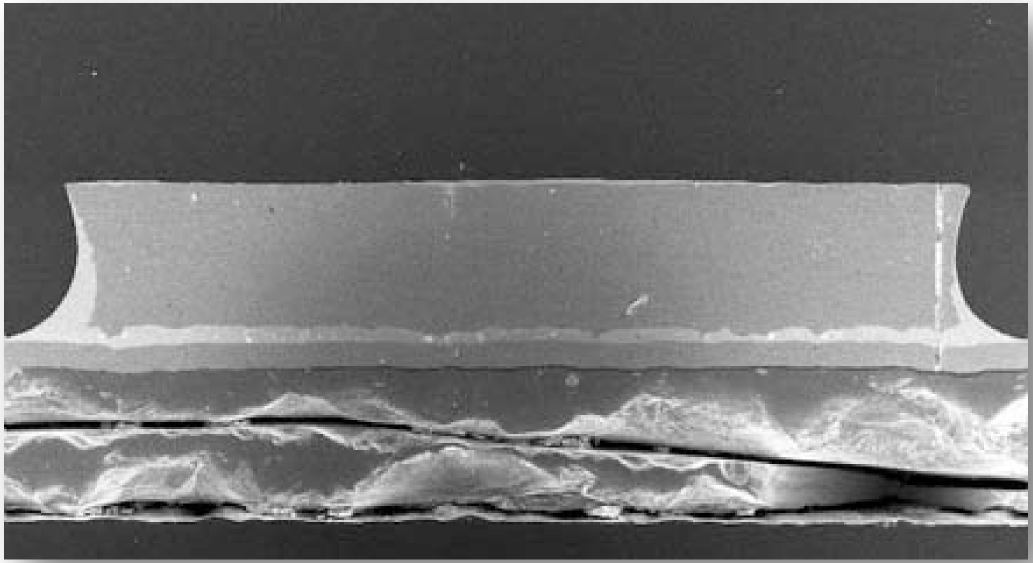


CELL STRING: WHAT CAN GO WRONG

Localized Heating



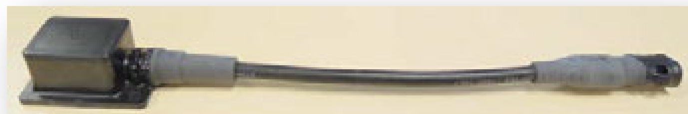
Cell Cracking



JUNCTION BOX

Early in-house testing

- Screened several suppliers
- Uncovered fundamental design and materials issues
- Developed simplified J-Box design



Reliability impact

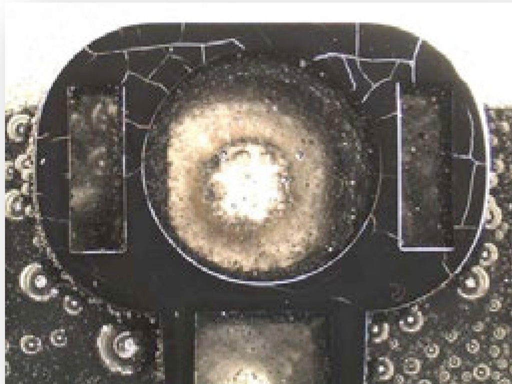
- Many material systems interact in J-Boxes
- J-Box failures caused the largest panel headaches
- J-boxes can be single point of failures

Cost impact

- Too high $$ for a plastic & copper component
- J-Box manufacturing yield issues are expensive
- Poor electrical joints cost in performance and system reliability

J-Box: What Can Go Wrong

Bulk Material



Adhesion

NATIONAL RENEWABLE ENERGY LABORATORY

Overview of Progress on the IEC Tracker Design Qualification Standard

2012 Reliability Workshop, Golden CO

Matthew Muller

3/1/2012

NREL/PR-5200-54837

Outline

- Brief history of work towards a tracker standard
- Tracker technical specification
- Scope of the tracker design qualification standard
- Key testing in the current draft
- Debates/Challenges
- Current status and plans for the next 12 months

Brief History

- Shortly after IEC TC82 WG7 (working group 7 --- Concentrator Photovoltaics) formed, decision to also commence work on a standard for trackers
  - March of 2007, Tracker subgroup formed
    First develop a technical specification , follow with full tracker design qualification standard.
  - March 2008, Working draft in place for the technical specification (TS)
  - September 2010, the TS was approved by WG7 for submittal to IEC
  - September 2010, vote to begin drafting a Tracker Design Qualification Standard (TDQS)
  - April 2011, decision to include the TS text in the new TDQS, when TS expires information will be held in one document
  - Sept 2011, WG7 agrees on TDQS scope/purpose and to submit a new work item proposal (NWIP)
  - The tracker subgroup has prepared a TDQS working draft to submit with NWIP
  - Tracker technical specification assigned TS 62727, IEC is in publication process

Tracker Technical Spec (TS 62727)

- The TS provides:
  - A consistent set of definitions and terminology for discussing and comparing trackers
  - A suggested specification sheet for manufacturers of trackers
  - A procedure to follow for measuring tracking accuracy
  - A statistical means of reporting tracking accuracy

Tracker Technical Spec (TS 62727)

Characteristic	Example	Notes/Clause/Subclause
Manufacturer	The XYZ Company	
Model number	XX1090	
Type of tracker	CPV Tracker, Dual Axis	4.2,4.3
Payload characteristics		
Minimum/maximum mass Supported	100/1 025 kg	4.8.3
Payload center of mass Restrictions	0-30 cm distance perpendicular to mounting surface	4.8.3
Maximum dynamic torques allowed while moving	Azimuth (Θ_z):10 kN-m Θ_x, Θ_y: 5 kN-m [should provide a set of diagrams to clarify torques and which axes they are relative to]	4.13.2,7.3
Maximum static torques allowed while in stow position	[should provide a set of diagrams]	4.13.1,7.3
Installation characteristics		
Allowable foundation	Reinforced concrete	4.6.2
Foundation tolerance in primary axis	± 0,5 degrees	4.9
Foundation tolerance in secondary axis	± 0,5 degrees	4.9
Electrical characteristics		
Includes backup power?	No	N/A
Daily energy consumption	1 kWh typical 5 kWh maximum	4.7.1
Stow energy consumption	kWh typical 1 kWh maximum	4.7.2
Input power requirements	100-240 VAC, 50-60 Hz, 5A	No specifics defined
Tracking accuracy		
Accuracy, typical (low wind, min deflect point)	0,1 degrees	5.4.6
Accuracy, typical (low wind, max deflect point)	0,3 degrees	5.4.6

Tracker Design Qualification Standard

Scope

This design qualification standard is applicable to ***solar trackers for photovoltaic systems*** but may be used for other solar applications. The standard defines ***test*** procedures for both ***key components*** and for the ***complete tracker system***. In some cases, test procedures describe methods to measure and/or calculate parameters to be reported in the defined tracker specification sheet. In other cases the test procedure results in a pass fail criteria.

Purpose and justification

This document ensures to the user of the said tracker that ***parameters reported*** in the specification sheet were ***measured by consistent and accepted industry procedures***. This provides the customer with a sound basis for comparing and selecting a tracker appropriate to their specific needs.

Pass/fail testing criteria have the purpose:

- ***Separating*** tracker designs that are likely to have ***early failures***
- Mechanical and environmental testing gauges the tracker's ability to ***perform under varying operating conditions as well as to survive extreme conditions.***
- Mechanical testing is **NOT** intended to certify structural and foundational designs as this type of certification is specific to local jurisdictions, soil types, and other local requirements.

Overview of TDQS testing

- Tracking accuracy
- Functional validation tests (verify basic functions, stow, tracking limits, etc)
- Basic performance metrics such as energy usage, time to stow, etc
- Mechanical testing
  - drive train pointing repeatability
  - deflection under static load
  - torsional stiffness, drive torque, backlash
  - moment testing under extreme wind loads
- Accelerated environmental testing
  - 250 temperature cycles from -30 °C to 45 °C
  - 10 humidity freeze cycles
  - Freeze/Spray
- Accelerated mechanical testing
  - 3650 cycles (~10 years following sun)
- Salt spray test
- Qualification testing for specific to tracker electronic equipment
  - very similar to IEC 62093 (PV balance of system components)

Debates/Challenges

- The draft of the TDQS is primarily finished but there are still key debates to settle
  - Temperature extremes for environmental testing?
  - To load or not to load during mechanical cycling?
- Should vibration and dust test be included, (Large size could be too costly)
- Do all the tests have a high benefit/cost ratio?
  - There is a lack test data on trackers
  - In lieu of data, industry experts have been involved in the draft writing

Status and plans for the next 12 months

- The NWIP and current draft are being submitted to IEC
- Spring/Fall WG7 meetings, find consensus on key tests
- Respond to comments that come forth from IEC voting members
- If all goes well the document can move to publication stage in 2013

Summary

- Tracker technical spec 62727 is being published.
  - Start using it, if there are problems provide feedback so these issues can be corrected in the TDQS

- An overview has been provided of the TDQS.
  - If you or someone in your company has experience with this type of testing and would like to review the document please contact matthew.muller@nrel.gov . Its not too late to make positive improvements.
  - Requirements: YOUR TIME

THANKS!

CPV Solar Cell and Receiver Package Qualification Standard

Initial Proposal – CPV-5, Palm Desert, Fall 2008

CPV Solar Cell and Receiver Package Qualification Standard

First Draft – PVSC, Philadelphia, Spring 2009

CPV Solar Cell *and Receiver Package?* Reliability Qualification ~~Standard~~ Technical Specification

Draft –PVSEC 24, Aix les Bains, Fall 2009

CPV Solar Cell *and Receiver Package?* ~~**Reliability Qualification Standard**~~ **Performance Technical Specification**

Draft – CPV-6, Freiburg, Spring, 2010

CPV Solar Cell and Receiver Package Combined Reliability Qualification ~~Standard~~ and Performance Technical Specification

Test Tables Only – PVSEC 25, Puertollano, Fall, 2010

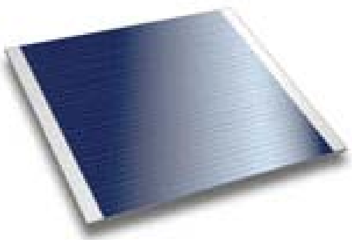
CPV Solar Cell and Receiver Package ~~Combined~~ Reliability Qualification Standard ~~and Performance Technical Specification~~

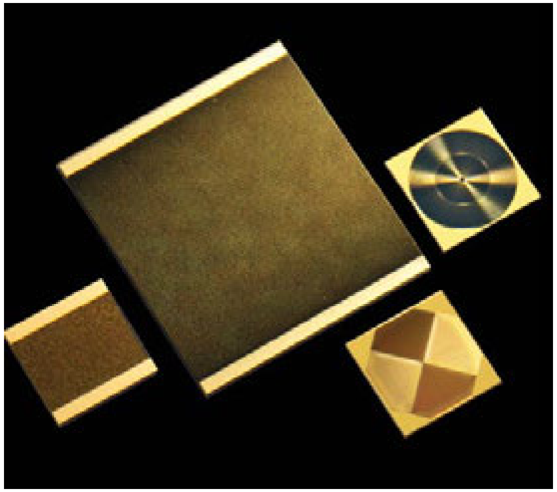
Survey Results – CPV-7, Las Vegas, Spring, 2011

Concentrator Photovoltaic (CPV) Solar Cells and Cell-on-carrier (COC) Assemblies - Reliability Qualification (Standard)

NWIP Approved – PVSEC 26, Köln, Fall, 2011

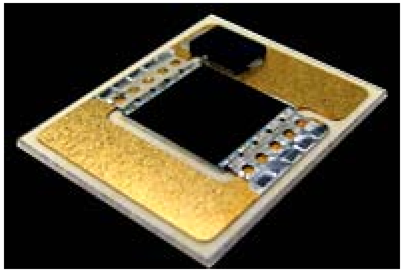
Definitions





Bare Cell

Interconnected Cell



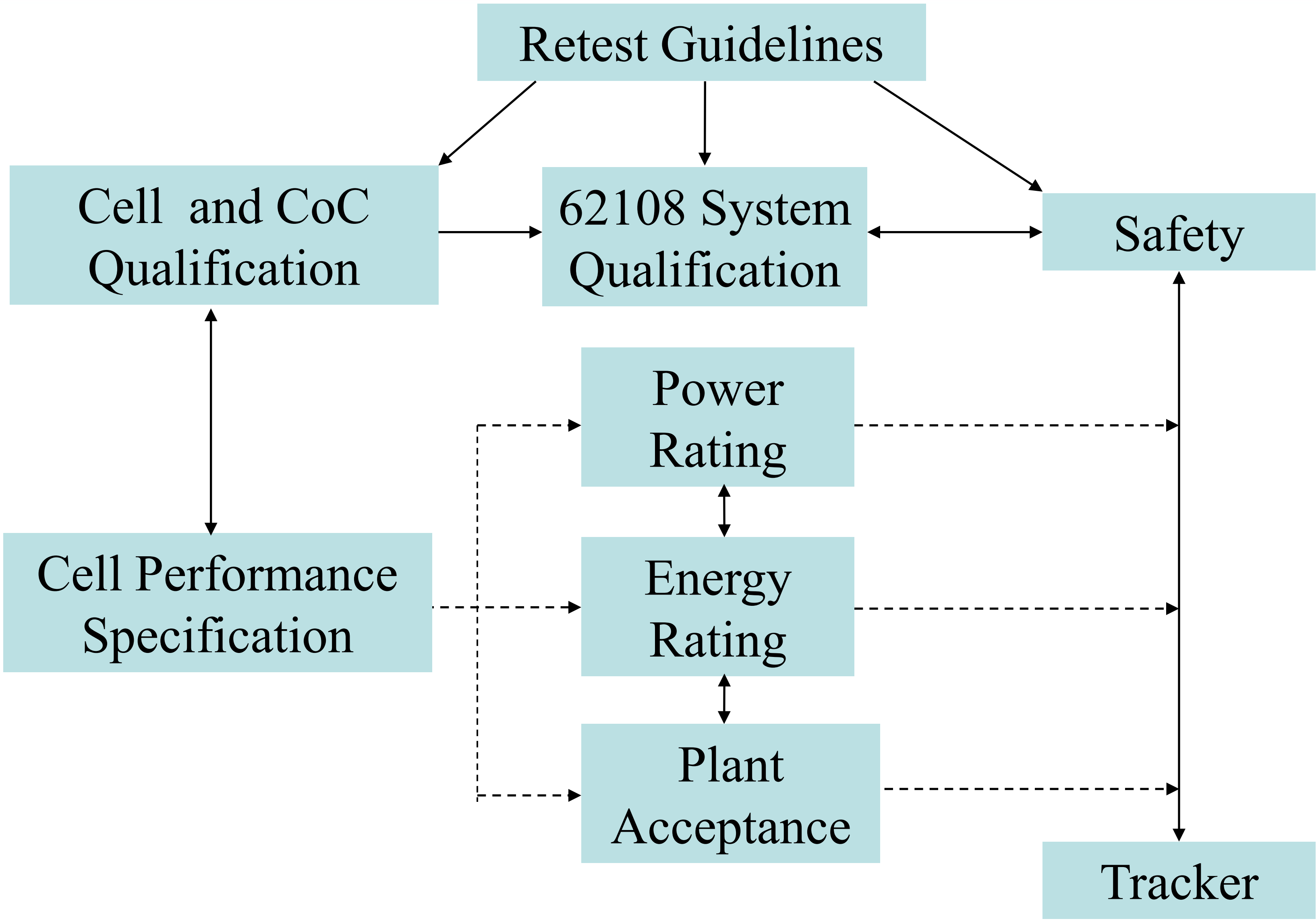
Cell on Carrier

Standards that Informed the Draft

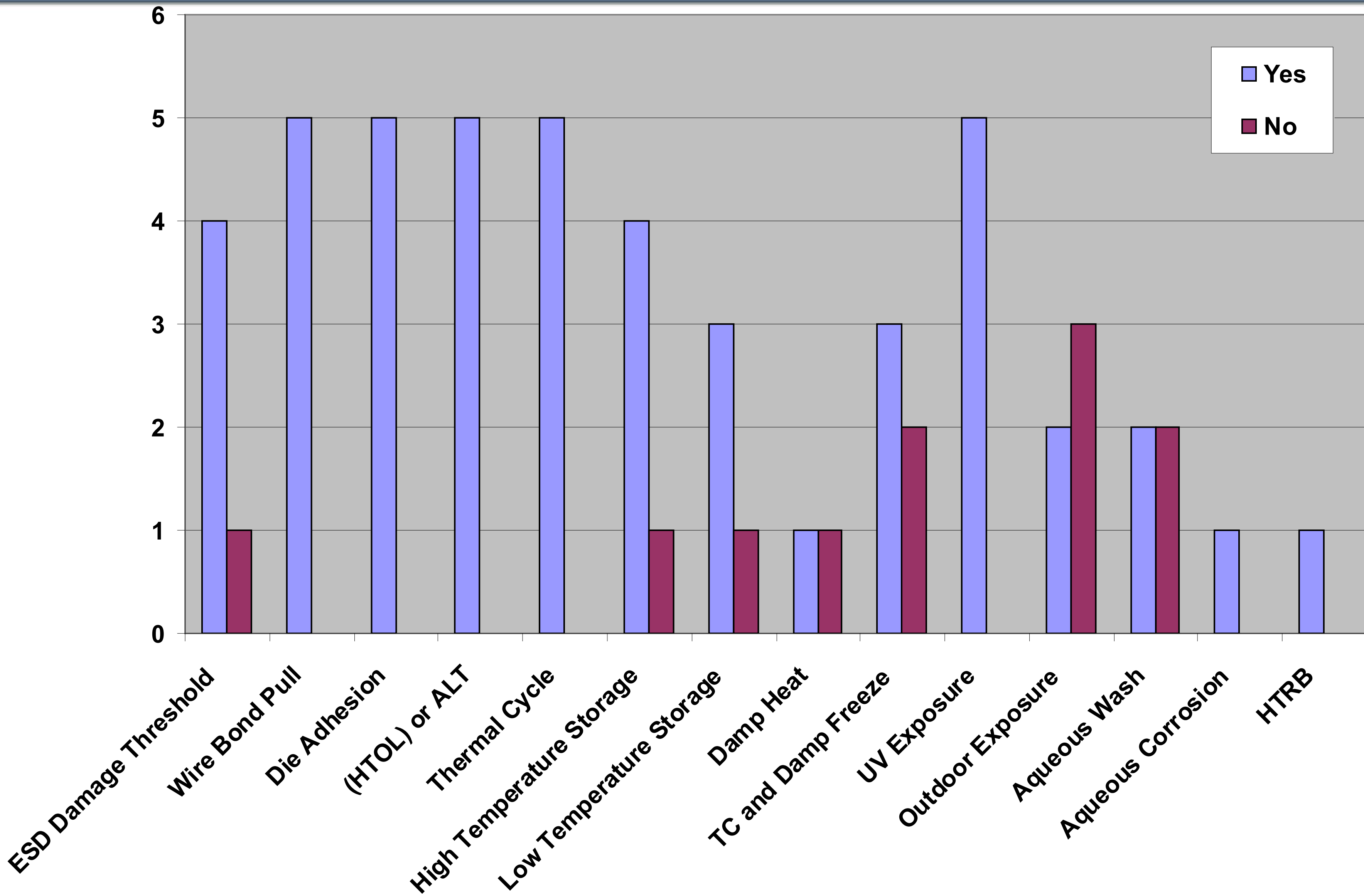
- Electronic and Optoelectronics Component Qualification Standards
  - Telcordia e.g. GR-468-CORE Issue 2, September 2004,
    - Reliability Assurance Requirements for Optoelectronic Devices Used in Telecommunications
  - IEC e.g. 61751 ed1.0,
    - Laser modules used for telecommunication - Reliability assessment.
- PV for Space Power Applications
  - AIAA S-111-2005
    - Qualification and Quality Requirements for Space Solar Cells
  - ECSS-E-ST-20-08C
    - Photovoltaic assemblies and components
- PV Cells
  - Solar America Initiative (SAI) Procurement Specification Proposal
- PV and CPV Modules and System Level
  - IEC 61215 and IEC 62108
    - PV and CPV modules and assemblies – Design qualification and type approval.

Relationship of Standards/Specifications

IEC TAG 82
WG7

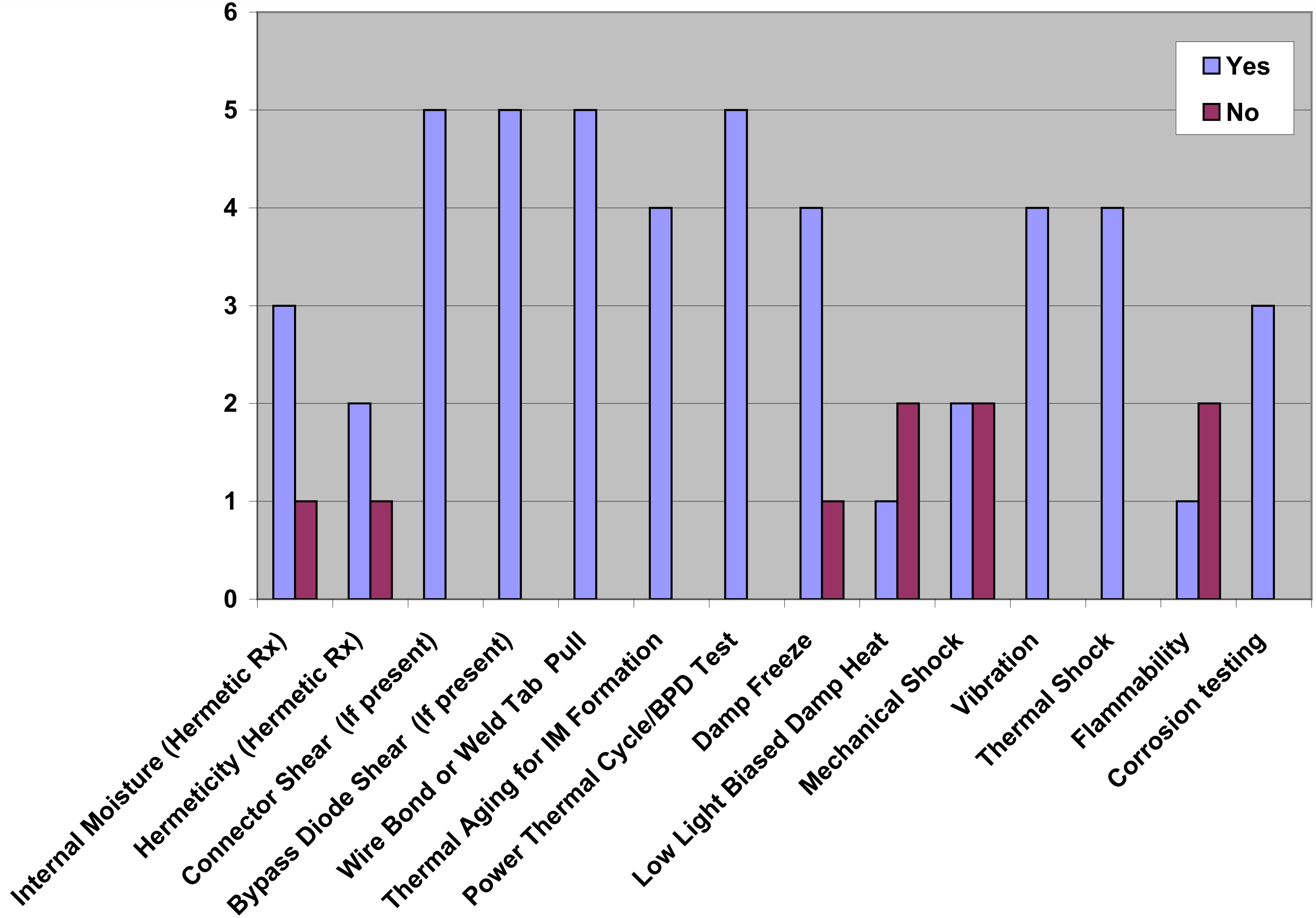


Cell Qualification Poll Results

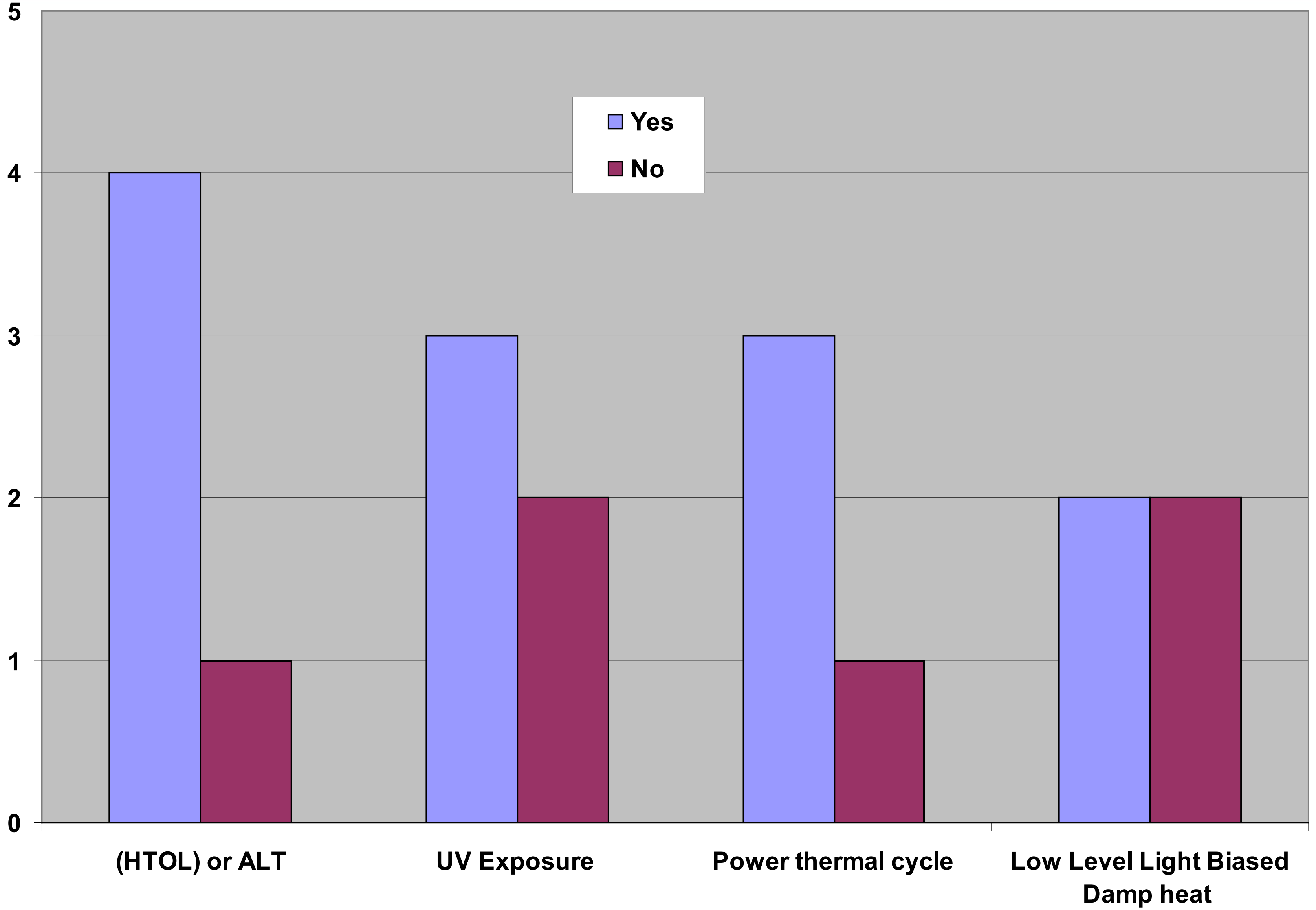


Receiver Package Qualification Poll Results

IEC TAG 82 WG7



Rx Package Qualification ALT Poll Results



Proposed Cell Qualification Plan

IEC TAG 82 WG7

Stress Test Name	Reference Standard	Cell Test Conditions	Sample Size/ Failures	P/F Criteria
ESD Damage Threshold	HBM	Incremental Voltage tests for HBM and CDM to establish damage threshold. Dark IV.	6	Pass all operational parameters per product datasheet
Front Metal Adhesion	Wire bond pull	Wire or ribbon bond, pull until failure, record mode and yield force.	11/0	Per STD
Back Metal Adhesion	Die Adhesion	Solder or adhesive die attach, pull to failure, record mode and yield force.	11/0	Per STD
(HTOL) or ALT		T = T_{OP} (max), I = max tolerable, X hours. DIV (info only) and Flash test pre stress and at periodic pull points.	25	No MVD, < 5% reduction in power output.
Thermal Cycle	IEC 62108 Annex A. Seq. # 10.6	T = -40 C to Tmax. 1k cycles for T max = 85 C, 500 cycles for T max = 110 C, 2k cycles for Tmax = 65 C, periodic light bias or no bias, dwell >10 min within ±3°C of extremes. 10 to 18 cycles per day. DIV (info only) and Flash test pre stress and at end.	11/0	No MVD, <5% power degradation.
High Temperature Storage	EIA/TIA-455-4A<= 40% RH	Ts (max) or 85C for 2000 hours.	11/0	No MVD, <5% power degradation.
Low Temperature Storage	EIA/TIA-455-4A	Ts (min) or -40C 72 hours.	11/0	No MVD, <5% power degradation.
Damp Heat	IEC 62108 Annex A. Seq. # 10.7	1k hours at 85 C, 85% RH or 2k hours 65 C, 85% RH, DIV (info only) and Flash test pre stress and at periodic pull points.	11/0	No MVD, <5% power degradation.
TC and Damp Freeze	IEC 62108 Annex A. Seq. # 10.8	Precondition for 200 cycles, Tmax = 85 C, 100 Cycles Tmax = 110 C, 400 cycles Tmax = 65 C, Tmax and 85% RH for 20 hours, ramp down to -40 C for 4 hours, 20 cycles for Tmax = 85 C, 40 cycles for Tmax = 65 C. DIV(info only) and Flash test pre stress, after precondition, and at end.	11/0	No MVD, <5% power degradation.
UV exposure	IEC 62108 Annex A. Seq. # 10.15	Expose to a total dose of 2.5 kWhrs/cm^2, Lambda < 400 nm. DIV (info only) and Flash test pre stress and at periodic pull points. (Concurrent with HTOL.)	25	No MVD, <5% power degradation.
Optical Exposure	IEC 62108 Annex A. Seq. # 10.16	Expose to a total dose of 5 kWhrs/cm^2, DNI > 30 W/cm^2. DIV (info only) and Flash test pre stress and at periodic pull points. (Concurrent with HTOL.)	25	No MVD, <5% power degradation.

Proposed CoC Qualification Plan

IEC TAG 82 WG7

Parameter	Standard	Conditions	Sample Size/ Failures	Pass/Fail Criteria
Internal Moisture (Hermetic Rx only)		Bake at 100°C for 16 to 24 hours, RGA	11/0 for Qual, AQL if in-line	< 5k ppm H_2O
Hermeticity (Hermetic Rx only)		He bomb, leak detector	11/0 for Qual, AQL if in-line	Per calculation
Connector shear (If present)		Shear tool	11/0 for Qual, AQL if in-line	Per calculation
Bypass Diode shear strength (If present)		Shear tool	11/0 for Qual, AQL if in-line	Per calculation
Wire bond or weld tab pull strength		Pull tool	11/0 for Qual, AQL if in-line	Per calculation
Thermal aging for intermetallic formation		300C for 1 hour aging	11/0	Per calculation
		300C for 1 hour aging	11/0	Per calculation
PTC	IEC 62108, Section 10.6, Option 2 for thermal cycling parameters	-40C to 110C for 500 cycles, IR or joule heating subcycles	11/0	No MVD, 3kV Hipot, on-sun (<13%) or flash(<8%)
Damp Freeze	IEC 62108, Section 10.8	Same sample as power temp cycle (for required TC preconditioning), 85C/85% RH for 20 hours, ramp down to -40 C for 4 hours, 20 cycles.	11/0	No MVD, 3kV Hipot, on-sun (<13%) or flash(<8%)
Low Level Light Biased Damp heat	Similar to IEC 62108, Section 10.7 but with light bias	Light Biased to ≥ 0.9 Voc, 85C/85% RH for 1000 hours	11/0	No MVD, 3kV Hipot, on-sun (<13%) or flash(<8%)
Mechanical Shock		Terminal peak sawtooth of amplitude 30gs and duration of 15 mSec (See figure 516.5-10 and Tables 516.5-III and IV.)	11/0	No MVD, Pass 3kV HiPot, < 10% relative change in DIV parameters
Vibration		Random vibration simulating U.S. Highway truck vibration exposure.	11/0	No MVD, Pass 3kV HiPot, < 10% relative change in DIV parameters
Thermal Shock		Storage temperature extremes, > 60°C/min rate, 1 min dwells	11/0	No MVD, Pass 3kV HiPot, < 10% relative change in DIV parameters
Flammability		For receivers with flammable components only.	3/0	Per flammability rating.

Other Considerations

- **Reliability Tests**
  - Accelerated Life Tests (ALTs)
- **Sample Sizes/distributions**
  - Samples from across distributions
- **Pass/Fail Criteria**
- **On-going sampling or periodic retest**
- **Report format**

IEC	[Document reference] NEW WORK ITEM PROPOSAL	
	Proposer TC 82 Secretariat	Date of proposal
	TC/SC TC 82	Secretariat USA
Classification according to IEC Directives Supplement, Table 1	Date of circulation	Closing date for voting

A proposal for a new work item within the scope of an existing technical committee or subcommittee shall be submitted to the Central Office. The proposal will be distributed to the P-members of the technical committee or subcommittee for voting, and to the O-members for information. The proposer may be a National Committee of the IEC, the secretariat itself, another technical committee or subcommittee, an organization in liaison, the Standardization Management Board or one of the advisory committees, or the General Secretary. Guidelines for proposing and justifying a new work item are given in ISO/IEC Directives, Part 1, Annex C (see extract overleaf). **This form is not to be used for amendments or revisions to existing publications.**

The proposal (to be completed by the proposer)

Title of proposal		
CONCENTRATOR PHOTOVOLTAIC (CPV) SOLAR CELLS AND CELL-ON-CARRIER (COC) ASSEMBLIES - RELIABILITY QUALIFICATION.		
☒ Standard	☐ Technical Specification	☐ Publicly Available Specification
Scope (as defined in ISO/IEC Directives, Part 2, 6.2.1)		
This International Standard specifies the methodology for reliability qualification of photovoltaic cells and Cell-on-Carrier (or other interconnected cell) assemblies used in Concentrator Photovoltaic (CPV) power generation systems.		

We Now Have a Number!

- **Earlier this year TAG-82 voted to approve the New Work Proposal and 5 member countries assigned experts to work on the draft. This resulted in the IEC issuing a number for the standard:**

62787

- **So the clock is ticking and thee real work begins.**
- **And if we are successful, sometime in 2014, this standard number will be rolling off our tongues as easily as 62108!**

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Cell Data Sheet Specification

2012 PV Module Reliability Workshop

Golden, CO

Sarah Kurtz

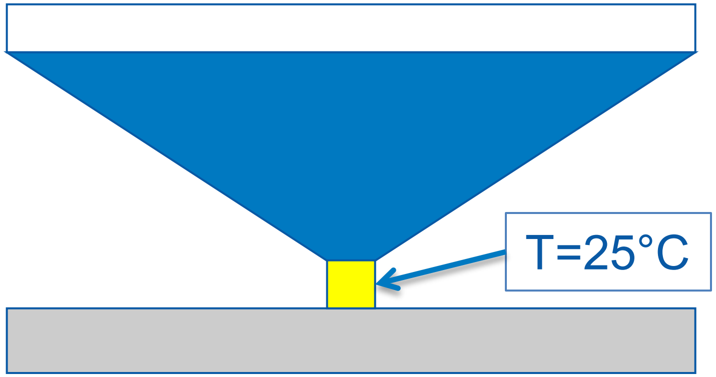
NREL

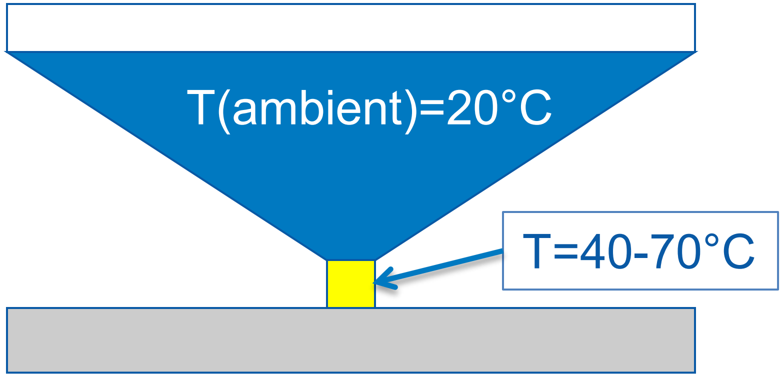
March 1, 2012

NREL/PR-5200-54566

Motivation for Creating Specification of Concentrator Cell Data Sheet

- Provide more consistency and complete info for customers wishing to compare cells
- Provide basis for defining temperature coefficients to be used for relating power rating under test conditions and operating conditions (cell T = 25° C vs ambient T = 20° C)





Status of Specification

- Is approved as new work item
- Draft will be discussed in April at WG7 meeting
- As technical specification, if approved by WG7 in April, it will be submitted and could be approved (go to print) as early as next fall.

Next slides show proposed specification

Product Identification

Manufacturer	The XYZ Company
Model Number	XX1090
Type of Cell	Three junction: GaInP(1.89 eV) /GaInAs (1.39 eV)/Ge (0.67 eV) on germanium substrate

Product Description

Cell Area	1.1 cm X 1.0 cm
Active area Simulator active area	1 cm X 1 cm (see sketch) 1.01 cm^2
Nominal efficiency	39%±2%
Nominal current ratios	Ratio for 1.39 eV/1.89 eV = 1.0 ± 0.03 Ratio for 0.67 eV/1.89 eV = 1.7 ± 0.03
Temperature coefficients (measured at the irradiance for which the product was designed)	α = dIsc/dT = + 0.11%±0.03%/° C when top-cell limited; +0.07%±0.03%/° C when bottom-cell limited β = dVoc/dT = -0.15%±0.02%/° C dPmax/dT = -0.24%±0.06%° C Measured at 100 W/cm^2; AM1.5 Direct; temperature range of 25° C to 70° C. Other conditions may also be documented.
Front metallization	Silver
Front metallization thickness	1 µm
Back metallization	Gold
Maximum current	1 A/cm^2
Anti-reflection coating design	Matched to index of 1.4

Cell processing and use conditions

Recommended operating temperature	-20 °C < T < 150 °C
Recommended processing temperature	< 350 °C for 10 min
Chemical compatibilities/ incompatibilities	?

Graphs/Tables

Typical I-V curve	Measured at 50 W/cm^2; AM1.5 Direct spectrum; 25° C. Isc, Imp, Vmp, Voc, FF, Efficiency specified
Efficiency as function of irradiance	Plotted/tabulated as function of irradiance for 25° C, 40° C, 60° C, and 80° C; AM1.5 Direct spectrum
Voltage at maximum power point	Plotted/tabulated as function of irradiance for 25° C; AM1.5 Direct spectrum
Efficiency distribution for full-wafer production	Fraction of population in 0.25% efficiency bins using manufacturers choice of conditions; indicate number of cells measured
Quantum efficiency (preferably presented as both a graph and a table)	One curve for each junction, measured at 25° C
Angular responsivity	Isc as a function of incidence angle compared with cosine function

Cell testing and screening conditions

LIV test	Example conditions: 50 W/cm2; AM1.5D; 25° C; 100% of samples
Thermal cycling – IEEE 1513	< 10% loss in efficiency after 500 cycles from -40° C to +110° C

Cell Datasheet description will provide for more consistent and complete characterization of concentrator cells

Please send your questions, comments and suggestions by April 10, 2012 to:

Sarah.Kurtz@nrel.gov

surya design

IEC 62670 Update

Sandheep Surendran

NREL PV Module Reliability Workshop

March 1, 2012

History and Background

- Began as CPV version of IEC 61853-1
  - PV module performance testing and energy rating - Irradiance and temperature performance measurements and power rating
- Lacked the necessary foundation of CPV standards
- Now an umbrella/placeholder for CPV module performance assessment methods

Basic Needs in CPV Standards:
Standard Conditions

- PV: IEC 61215 (PV Module Qualification)
- CPV: IEC 62670-1
- Project Leader: Sandheep Surendran
- Status: Targeted for voting by national committees in Spring 2012

Basic Needs in CPV Standards:
Reference Spectrum for DNI

- PV: IEC 60904-3 - Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data
- CPV: IEC 60904-3 Ed 3.
- Project Leader: Keith Emery
- Status:
  – Draft being circulated presently
  – Targeting voting by national committees in Spring 2012

Basic Needs in CPV Standards:

Power Measurement Methods

- PV: IEC 60904-1 - Measurement of photovoltaic current-voltage characteristics
- CPV: IEC 62670-3 (expected)
- Project Leader: Sandheep Surendran / TBC
- Status:
  - Methods have been under development
  - Targeting publication in 2014

Basic Needs in CPV Standards:

Solar Simulator Requirements

- PV: IEC 60904-9 - Solar simulator performance requirements
- CPV: IEC 60904-11 (?)
- Project leaders: Liang Ji and Steve Askins
- Status:
  - Requirements are currently under development

IEC 62670-1
Standard Conditions

- Concentrator Standard Test Conditions
  - – Analogous to PV STC (IEC 61215)
- Concentrator Standard Operating Conditions
  - – Analogous to PV standard reference environment for NOCT measurement (IEC 61215)

IEC 62670-1

Standard Conditions

Parameter	CSTC	CSOC
DNI	1000 $W \cdot m^{-2}$	900 $W \cdot m^{-2}$
Temperature	25 °C (cell)	20 °C (ambient)
Wind Speed	n/s	2 $m \cdot s^{-1}$
Spectrum	Direct normal AM1.5 spectral irradiance distribution consistent with conditions described in IEC 60904-3.	

IEC 62670-1 Standard Conditions

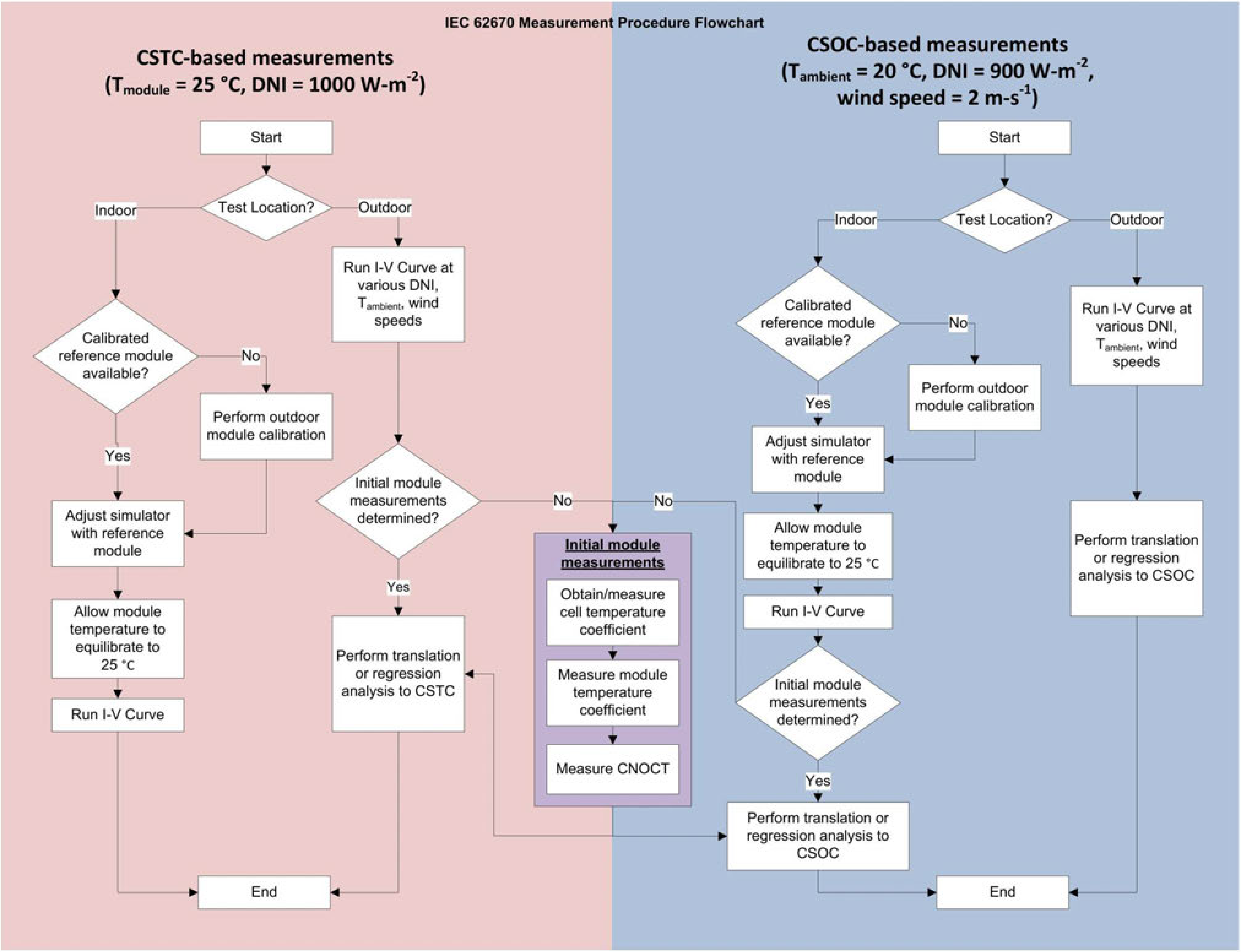
Parameter	CSTC	CSOC
DNI	1000 $W \cdot m^{-2}$ vs. 1000 $W \cdot m^{-2}$ GNI	900 $W \cdot m^{-2}$ vs. 800 $W \cdot m^{-2}$ GNI
Temperature	25 °C (cell)	20 °C (ambient)
Wind Speed	n/s	2 $m \cdot s^{-1}$ vs. 1 $m \cdot s^{-1}$
Spectrum	Direct normal AM1.5 spectral irradiance distribution consistent with conditions described in IEC 60904-3.	

IEC 62670-2
Energy Rating

- Empirical method for predicting system performance based on extended duration monitoring and analysis
- Project Leader: Pierre Verlinden
- Targeting publication December 2012

IEC 62670-3
Power Rating Methods

- Indoor and outdoor methods for assessing module power at CSTC and CSOC
- Method for assessing angular misalignment sensitivity

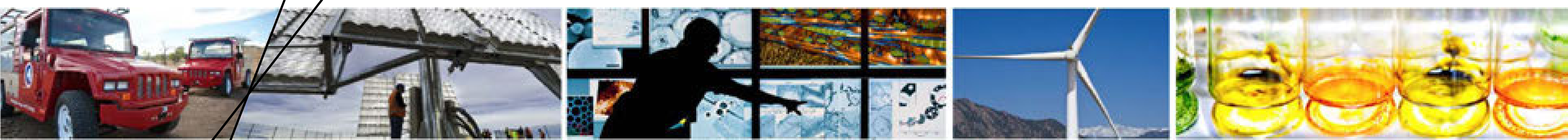


IEC 62670 Measurement Procedure Flowchart
CSTC-based measurements
(T module = 25 °C, DNI = 1000 W-m-2)
Start
Test Location?
Indoor
Outdoor
Calibrated reference module available?
No
Yes
Perform outdoor module calibration
Adjust simulator with reference module
Allow module temperature to equilibrate to 25 °C
Run I-V Curve
Run I-V Curve at various DNI, T ambient, wind speeds
Initial module measurements determined?
No
Yes
Perform translation or regression analysis to CSTC
End
Initial module measurements
Obtain/measure cell temperature coefficient
Measure module temperature coefficient
Measure CNOCT
CSOC-based measurements
(T ambient = 20 °C, DNI = 900 W-m-2, wind speed = 2 m-s-1)
Start
Test Location?
Indoor
Outdoor
Calibrated reference module available?
No
Yes
Perform outdoor module calibration
Adjust simulator with reference module
Allow module temperature to equilibrate to 25 °C
Run I-V Curve
Initial module measurements determined?
No
Yes
Perform translation or regression analysis to CSOC
Run I-V Curve at various DNI, T ambient, wind speeds
Perform translation or regression analysis to CSOC
End

IEC 62670-X Spectral and Cell Temp Effects

- Project Leader: Kenji Araki
- Currently under development/discussion

Comparison of accelerated testing with modeling to predict lifetime of CPV solder layers



2012 PV Module Reliability Workshop

***Timothy J Silverman*, Nick Bosco, Sarah Kurtz**

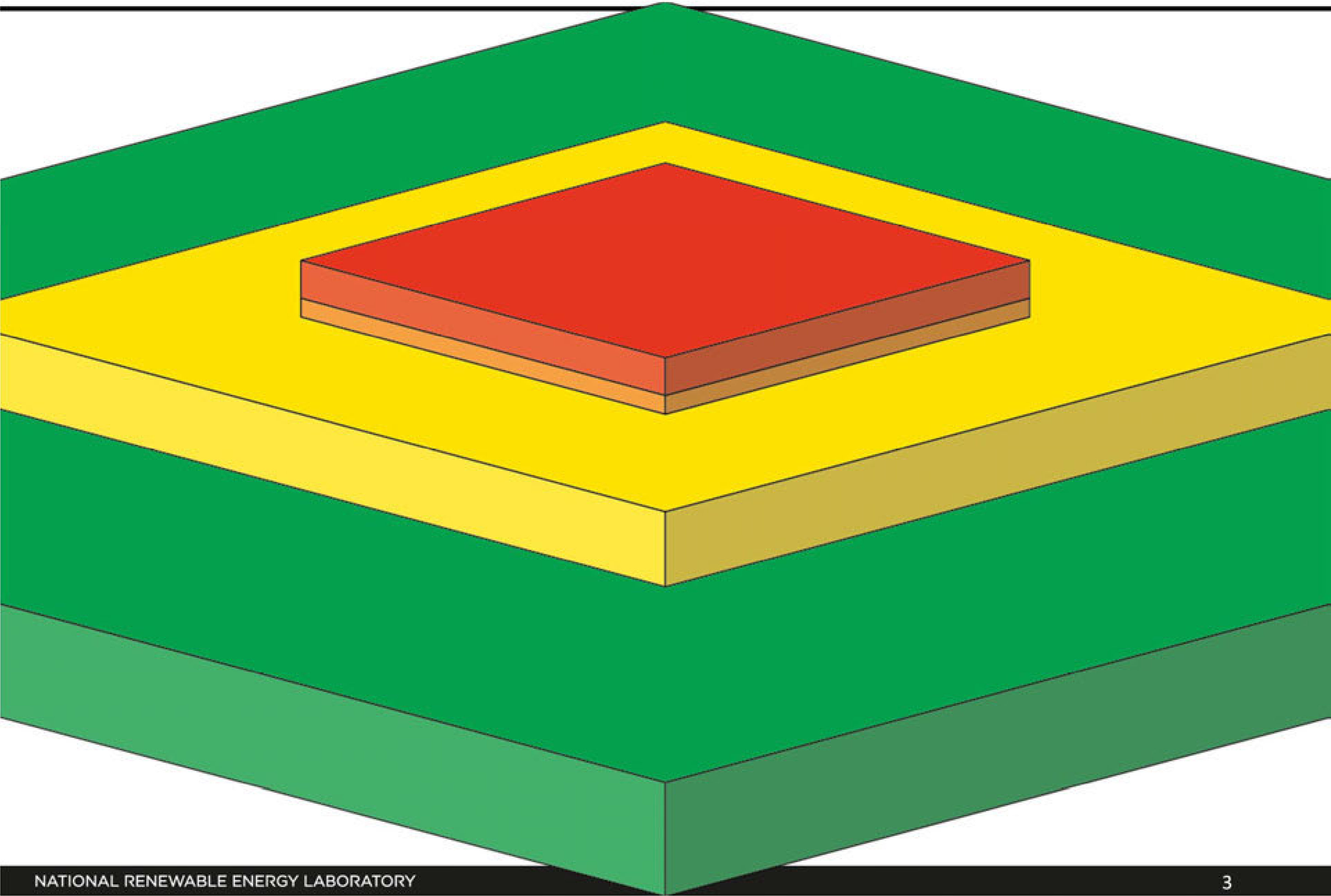
March 1, 2012

NREL/PR-5200-54677

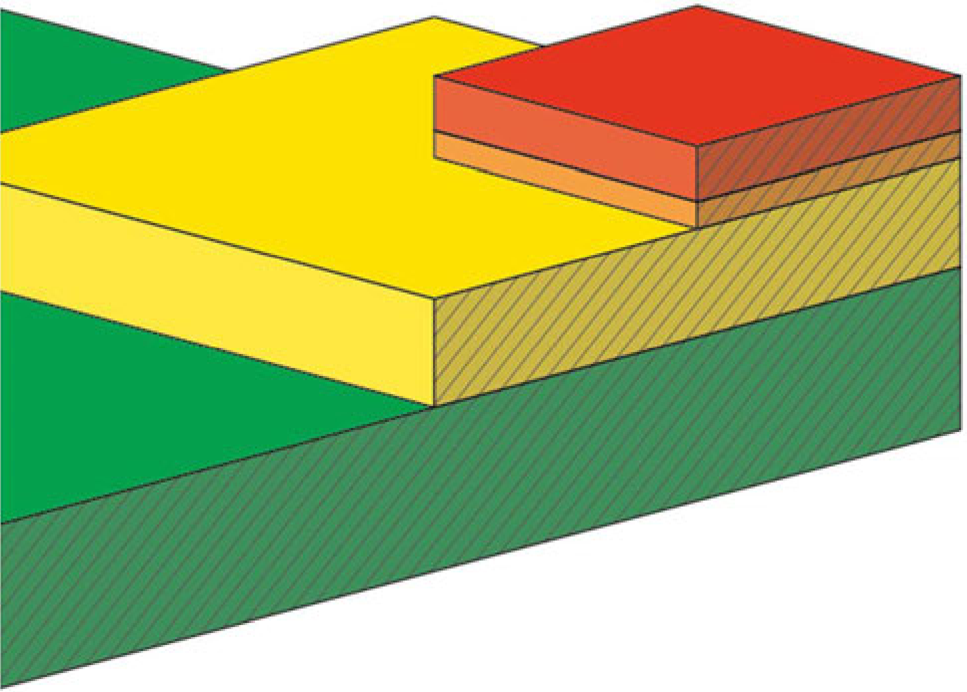
Agenda

- Motivation for studying CPV die-attach reliability
- Experiments with accelerated testing
- Computer simulation of thermal cycling
- Computer simulation of weather

The CPV solder layer

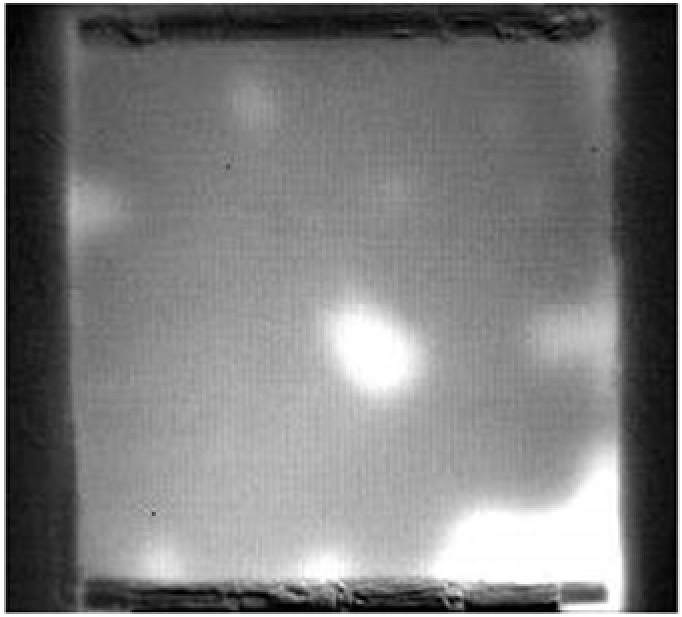


The CPV solder layer



The mechanical integrity of the die-attach layer is critical for the removal of heat

Cracks kill



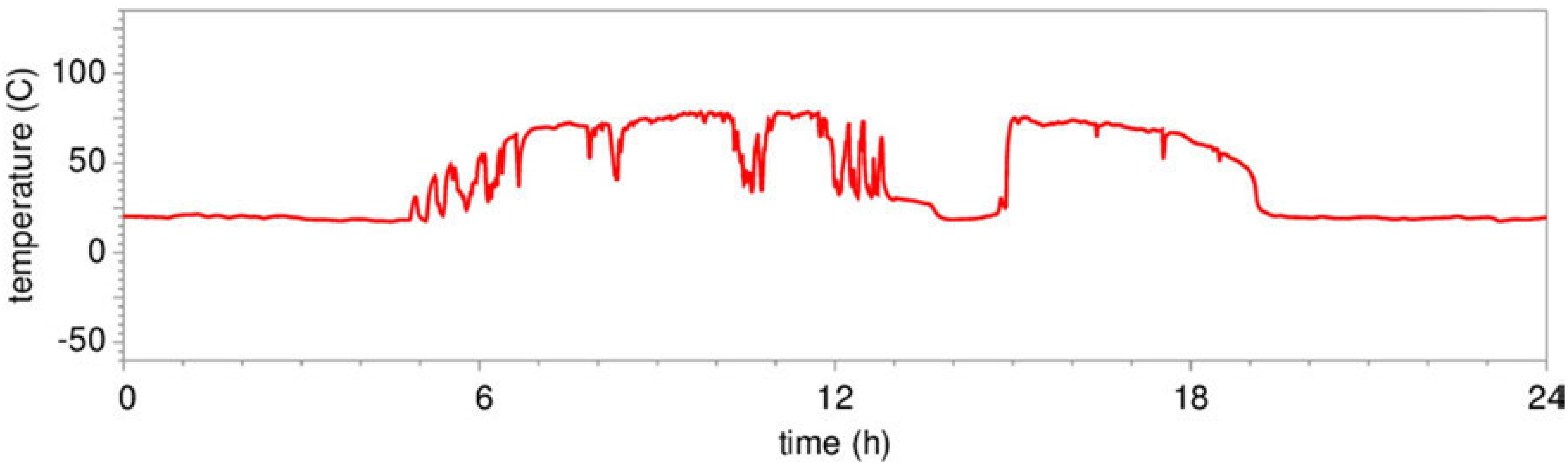
Transient IR image showing cracks from thermal cycling

Steady-state IR image showing shunt caused by sun exposure

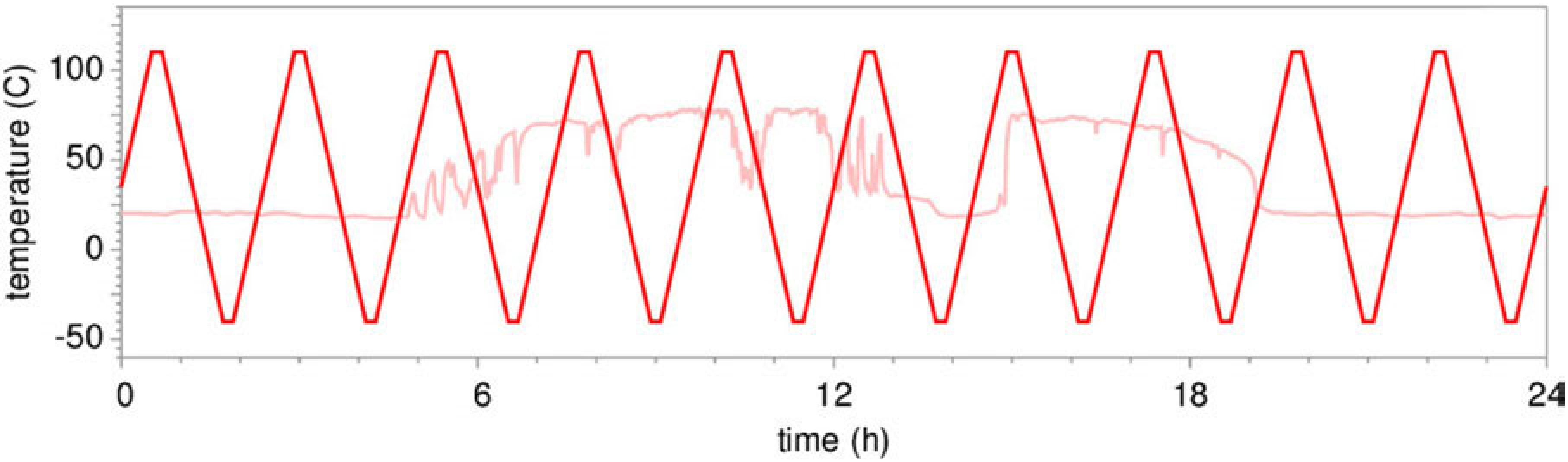
The mechanical integrity of the die-attach layer is critical for the removal of heat

Bosco, N. et al., NREL Report No. PR-5200-49243

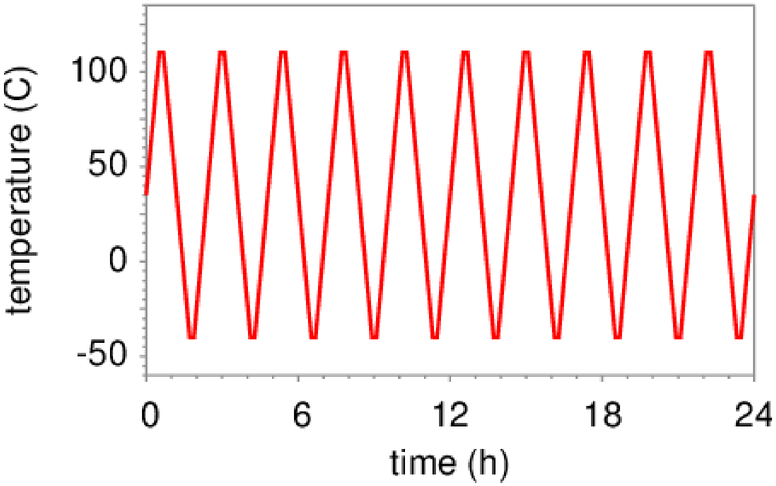
Weather is thermal cycling



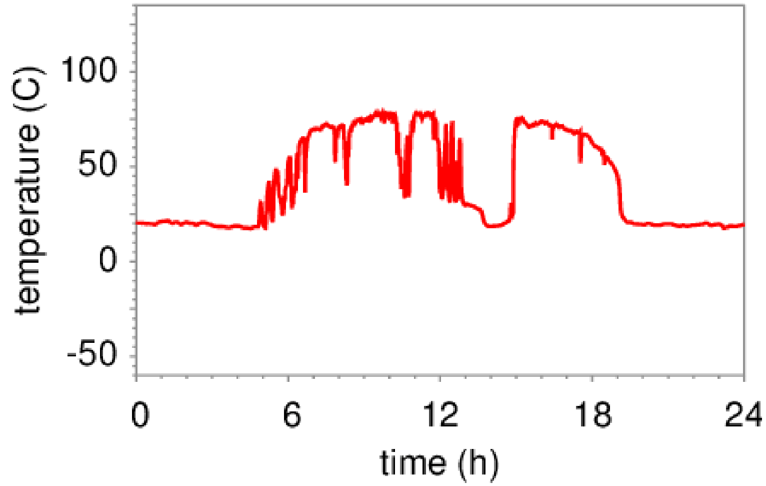
Accelerated testing is a shortcut



How much damage does a day do?

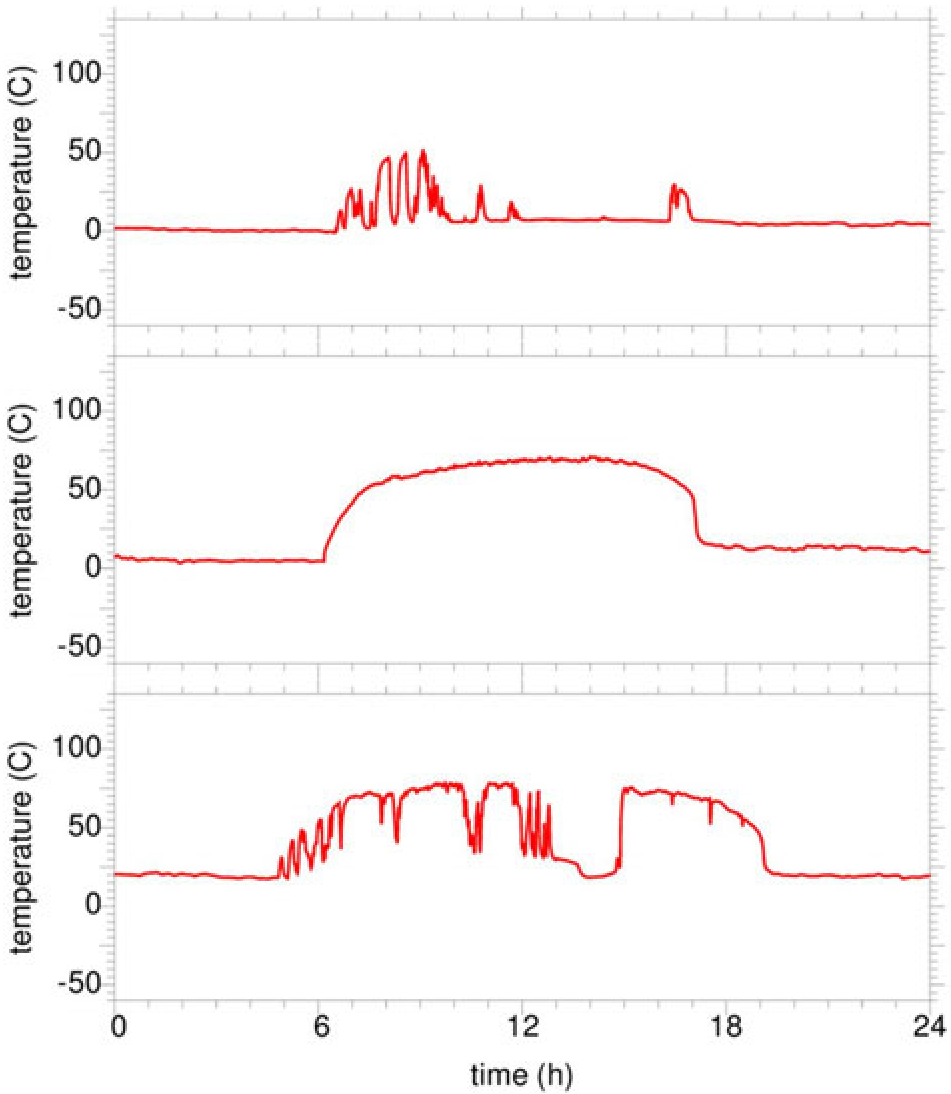


= n ×

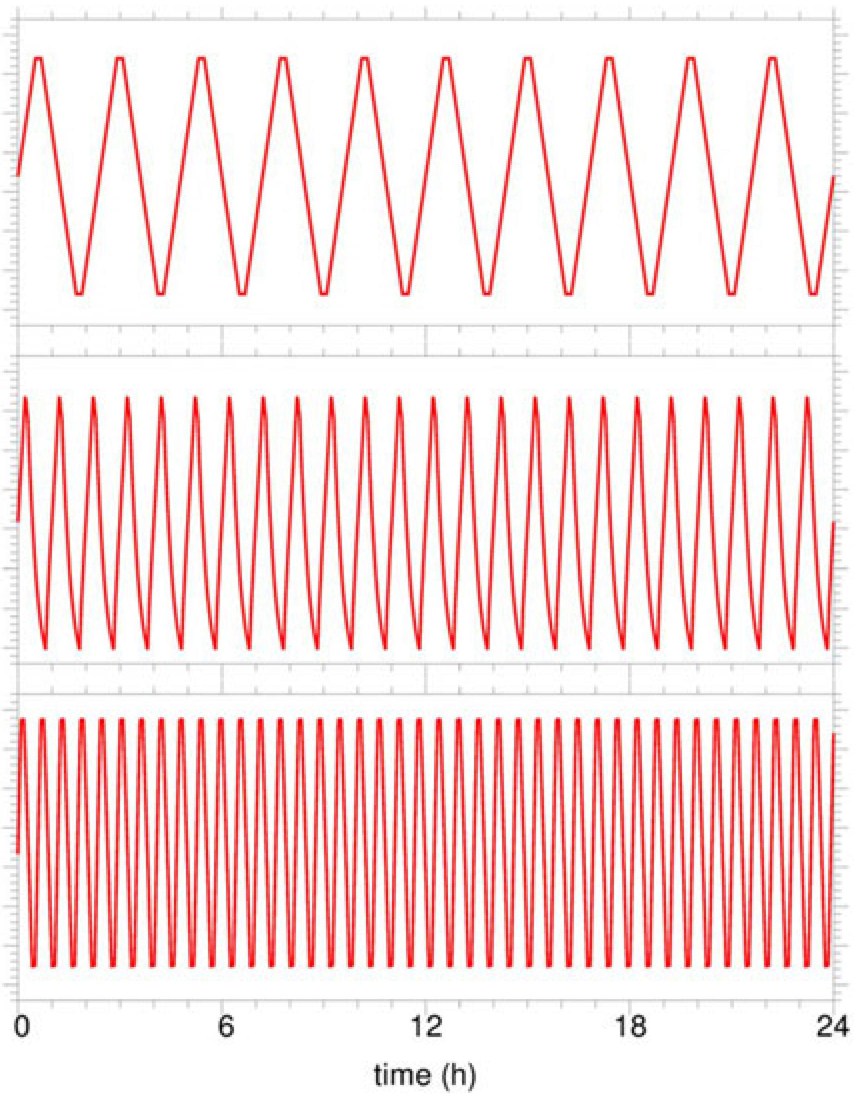


The answer: It depends

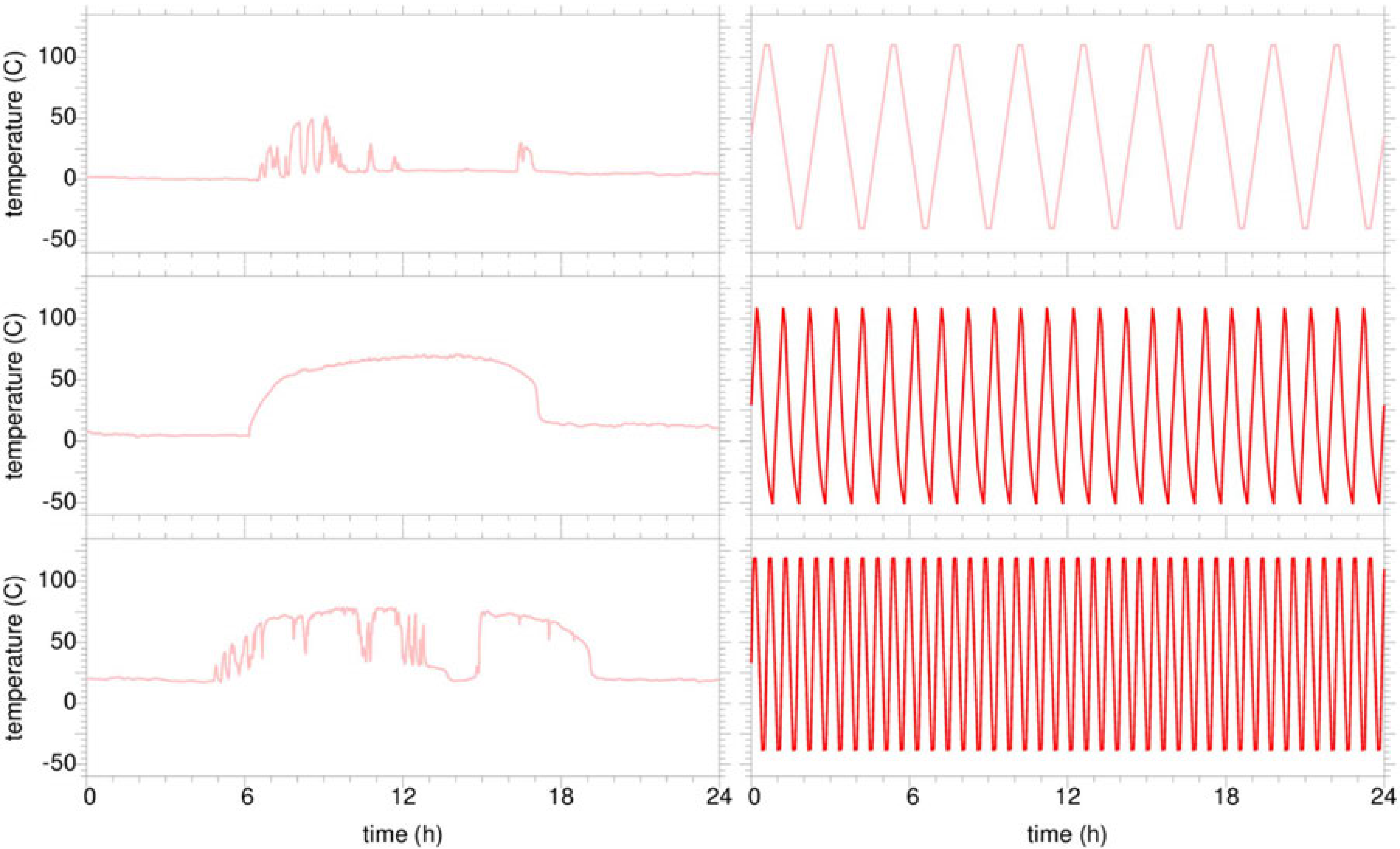
Which day?



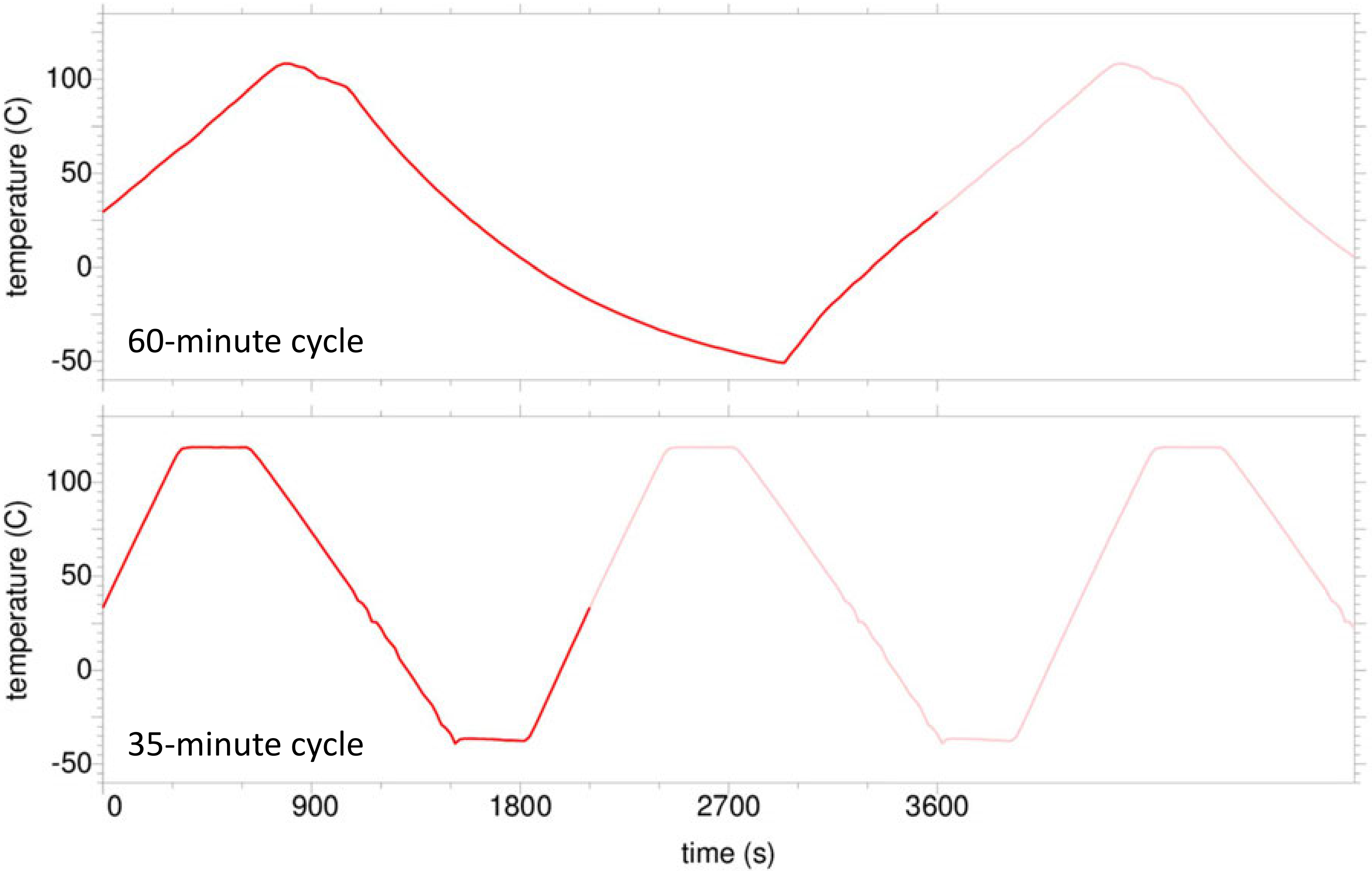
Which cycle?



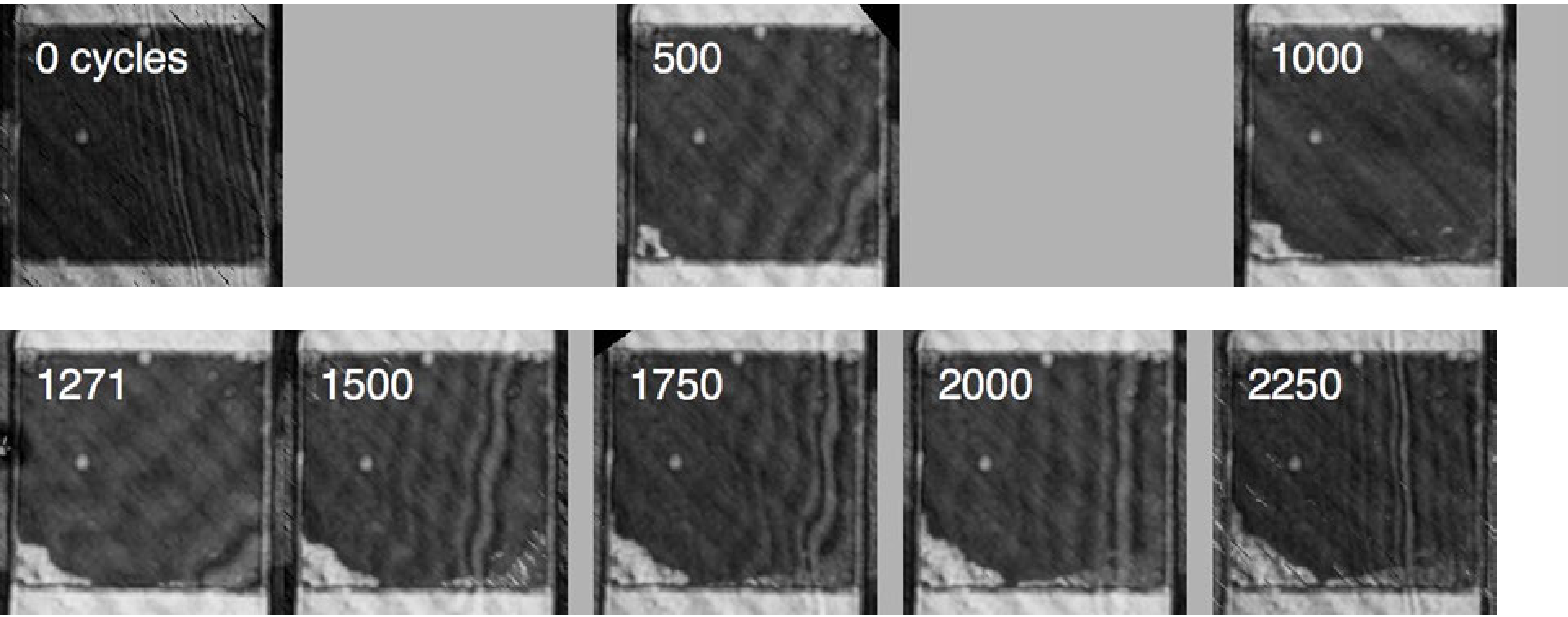
Crack growth experiments with two cycle types



How damaging are these two cycles?

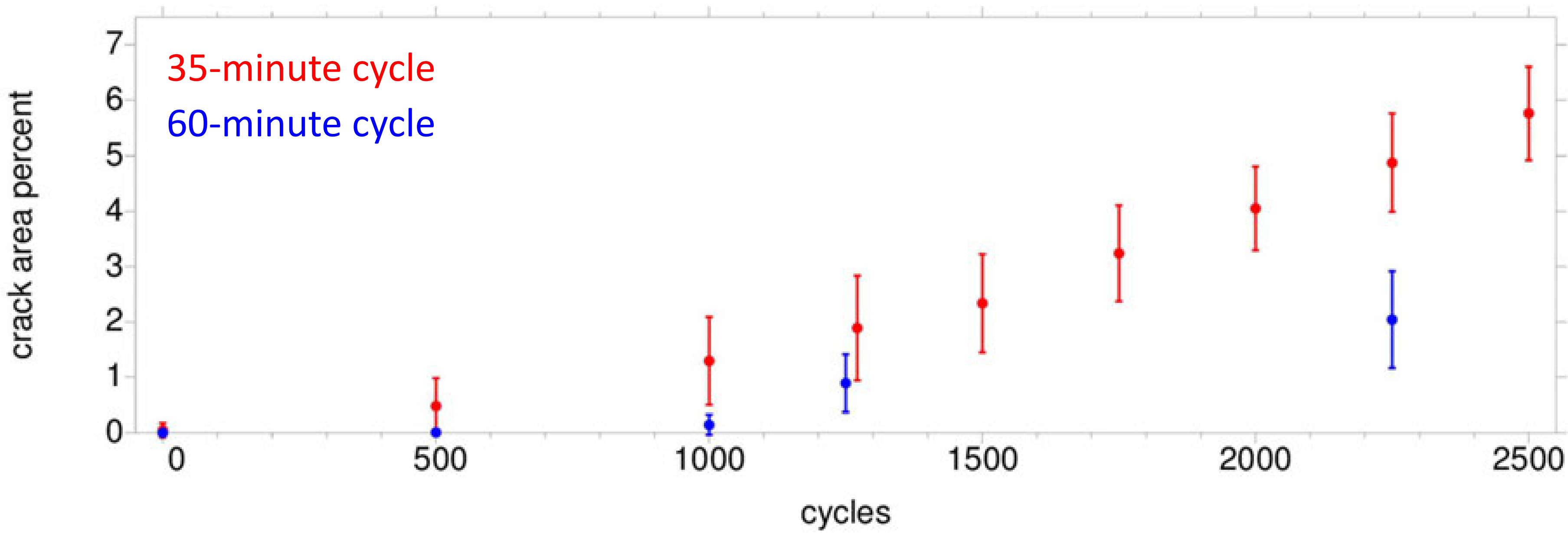


Measuring crack area acoustically

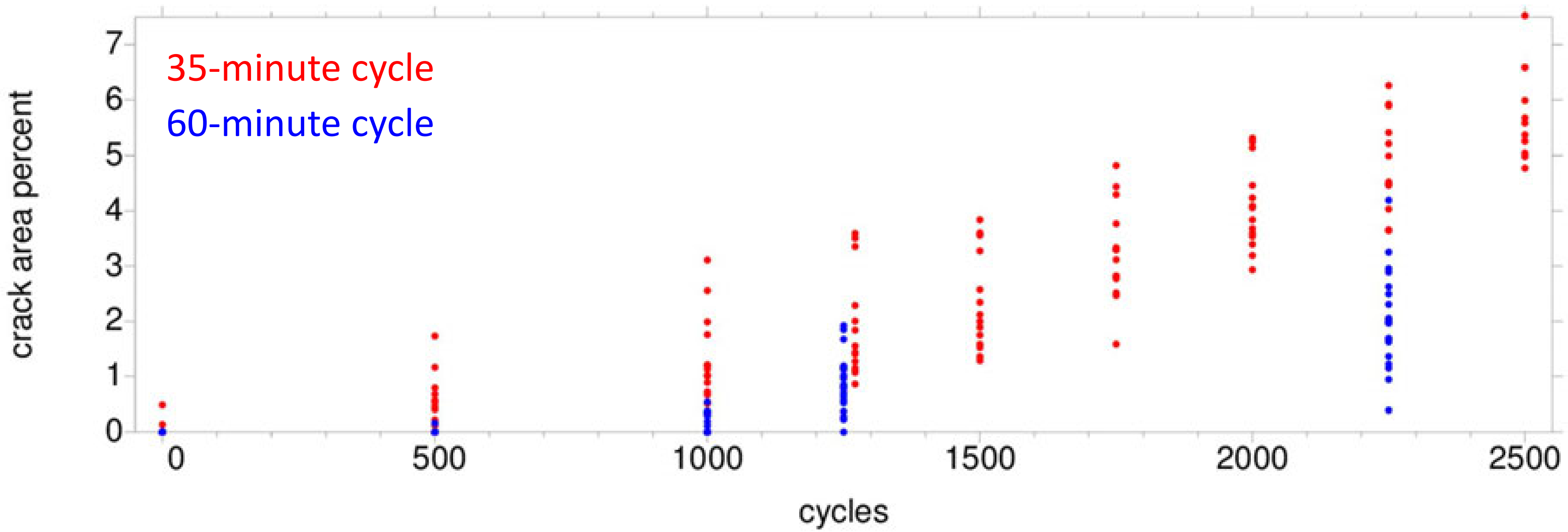


This is a test article intended to accumulate damage quickly
Crack measurement algorithm is still under development

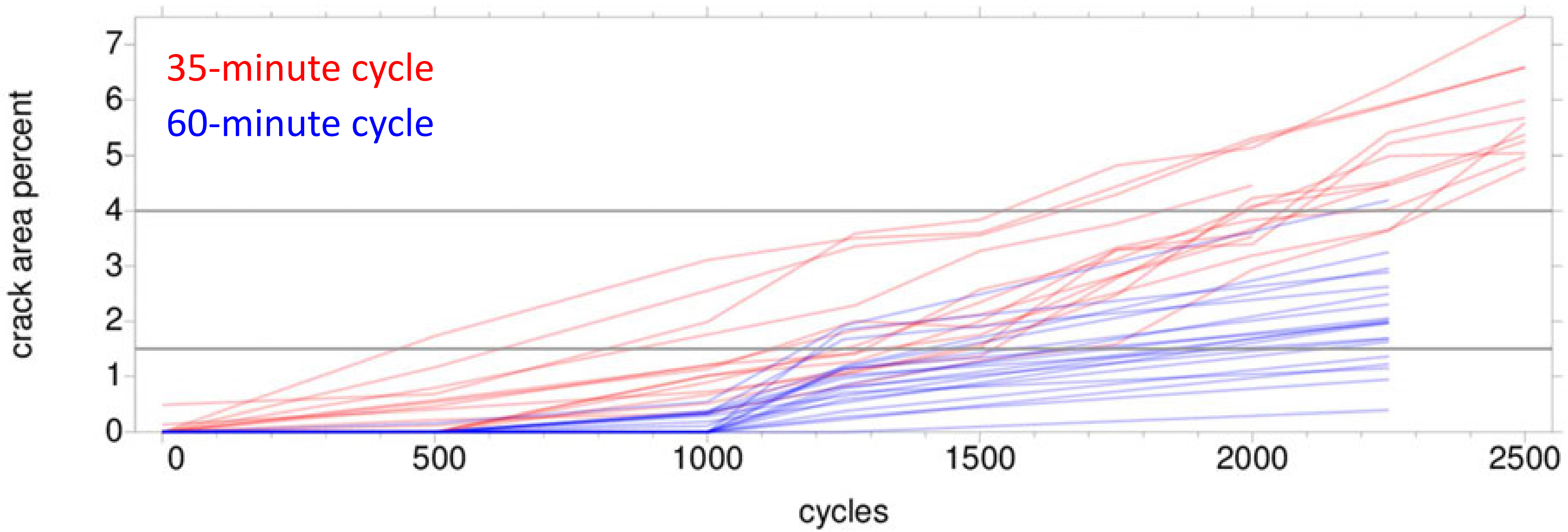
Crack growth due to thermal cycling



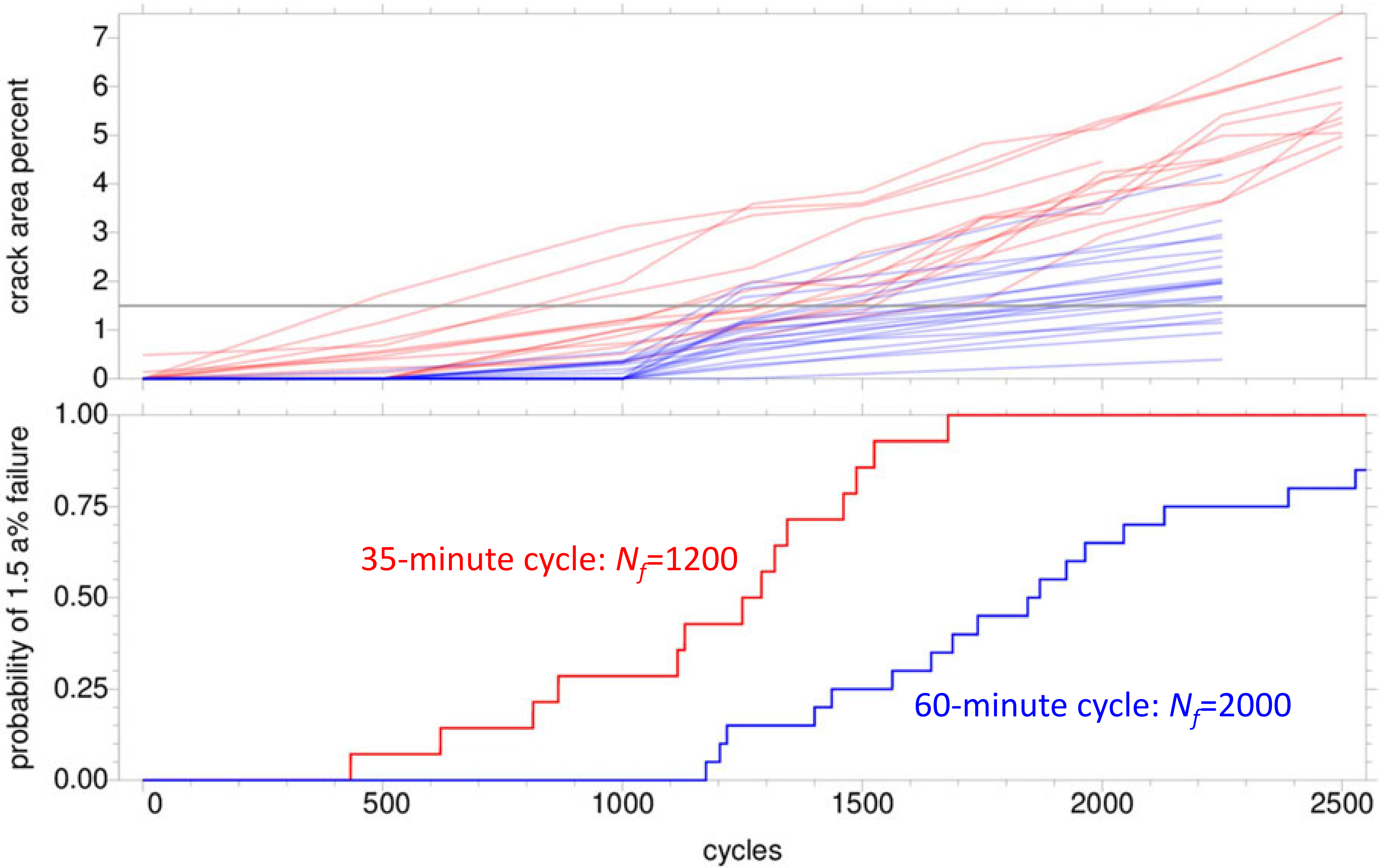
Crack growth due to thermal cycling



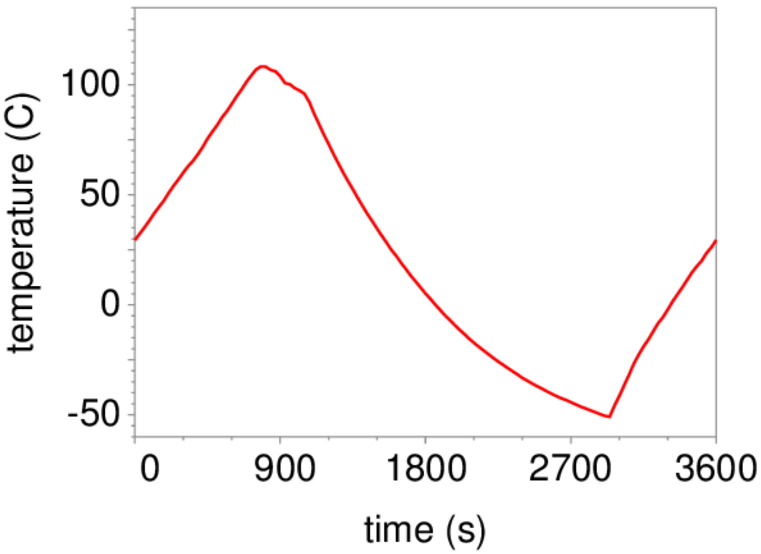
Crack growth due to thermal cycling



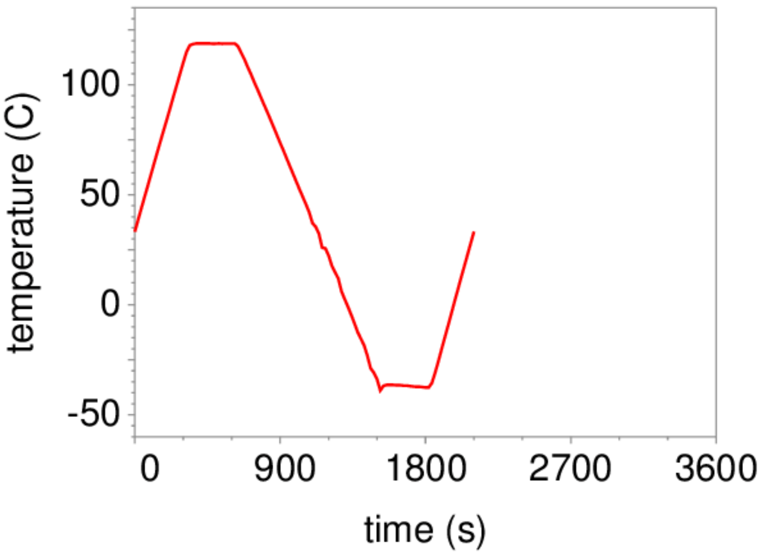
Crack growth due to thermal cycling



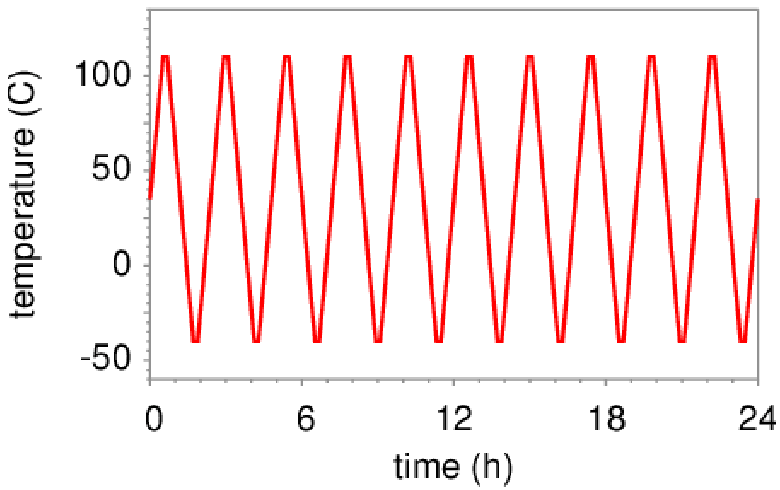
Connecting the two cycle types



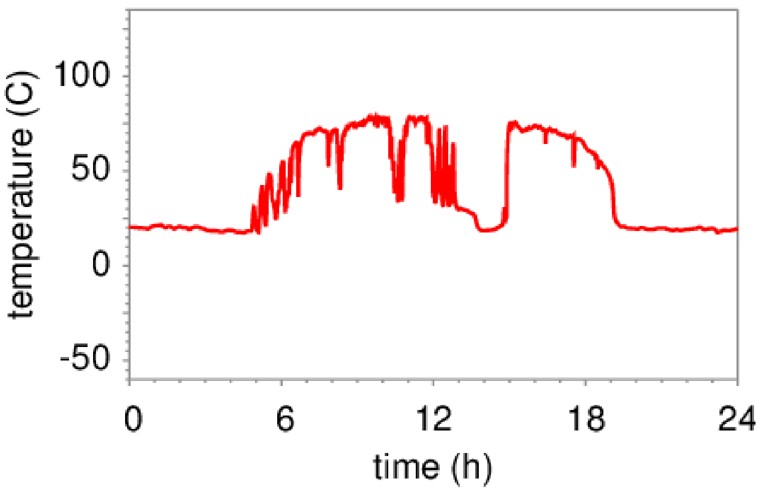
$= 0.6 \times$



How much damage does a day do?

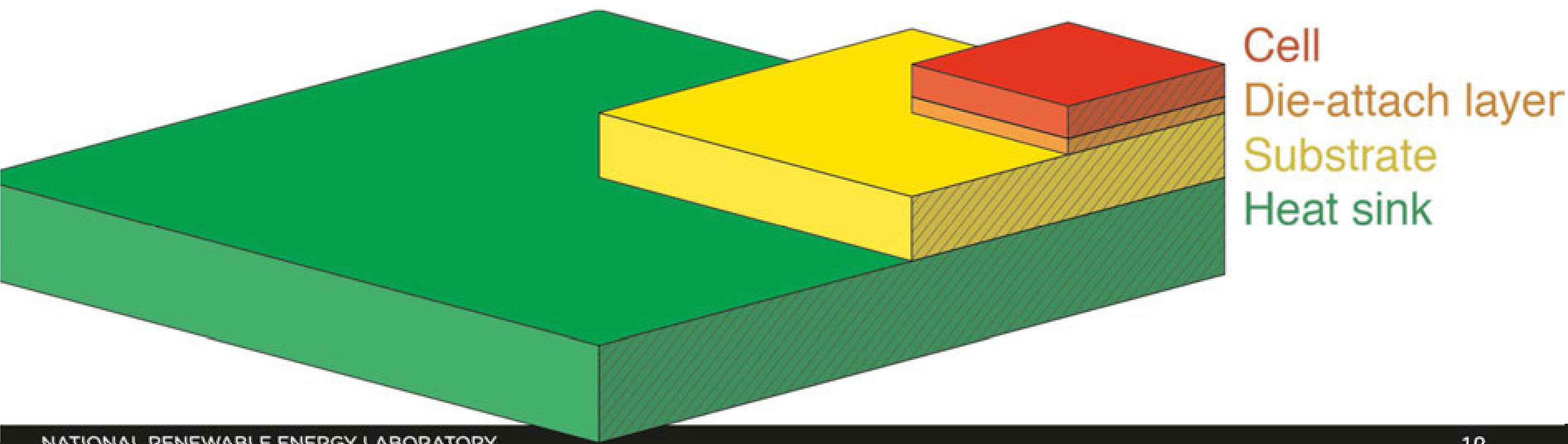


= n ×



Numerical model

- Finite-element method
- Driven by arbitrary temperature history
- Viscoplastic constitutive behavior (Anand model)
- Inelastic deformations and isotropic resistance to hardening
- Geometrically flawless solder layer
- Damage metric: Average inelastic strain energy density



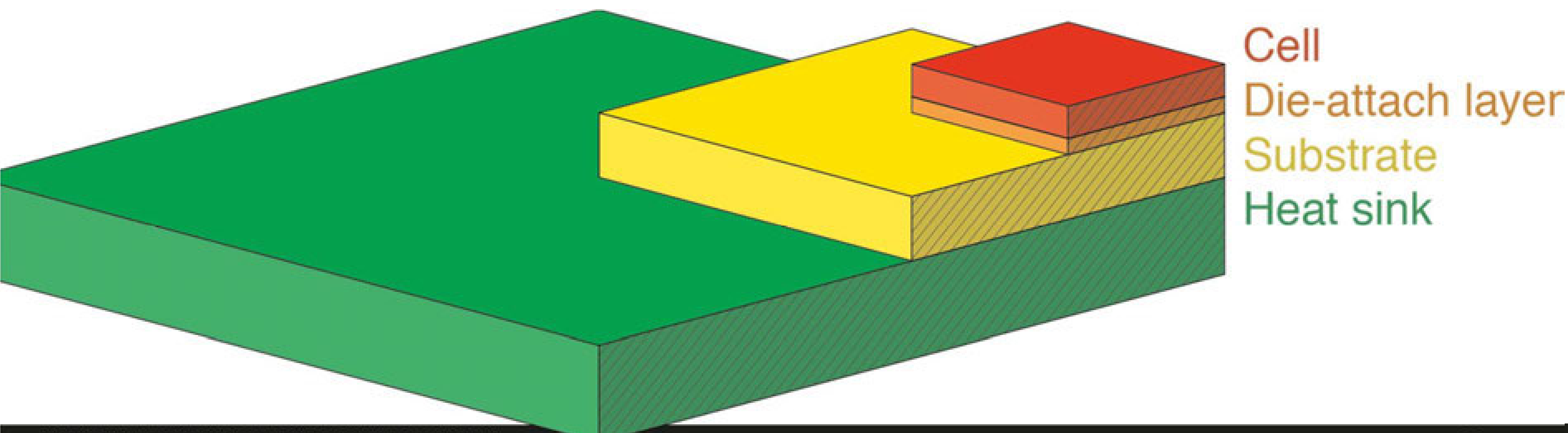
Numerical model

$$\dot{\varepsilon}_{\mathrm{pl,eq}} = A \exp\left(\frac{-Q}{RT}\right) \left[\sinh\left(\xi \frac{\sigma_{\mathrm{eq}}}{s}\right)\right]^{\frac{1}{m}}$$

$$\dot{s} = \dot{\varepsilon}_{\mathrm{pl,eq}} \; h_0 \left|1 - \frac{s}{s^*}\right|^a \; \mathrm{signum}\left(1 - \frac{s}{s^*}\right)$$

$$s^* = \hat{s} \left[\frac{\dot{\varepsilon}_{\mathrm{pl,eq}}}{A} \exp\left(\frac{Q}{RT}\right)\right]^n$$

$$W_{\mathrm{pl}} = \int |\sigma| \, d\varepsilon_{\mathrm{pl}}$$



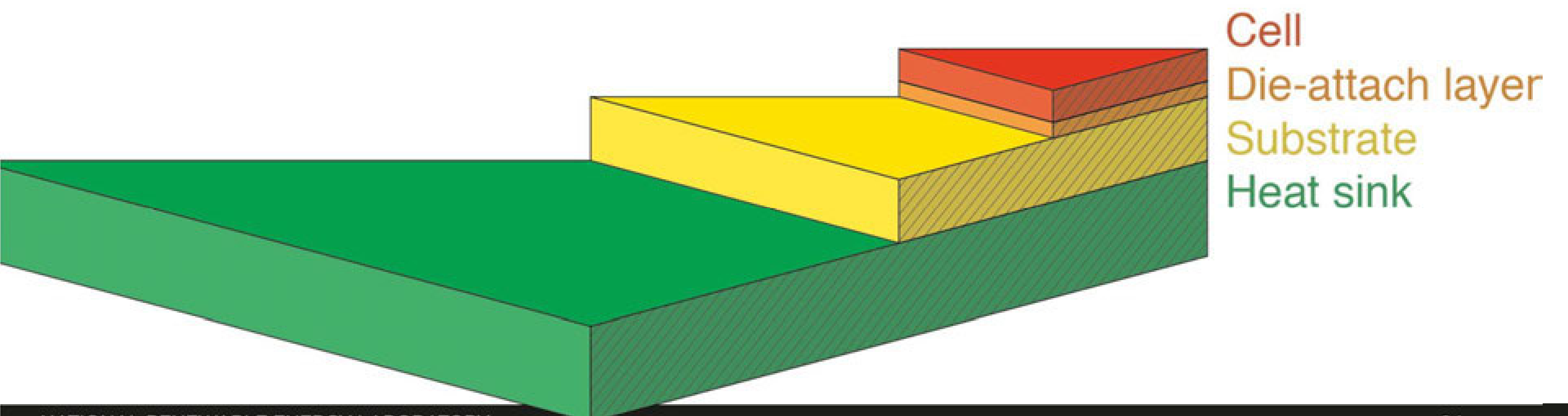
Numerical model

$$\dot{\varepsilon}_{\mathrm{pl,eq}} = A \exp\left(\frac{-Q}{RT}\right) \left[\sinh\left(\xi \frac{\sigma_{\mathrm{eq}}}{s}\right)\right]^{\frac{1}{m}}$$

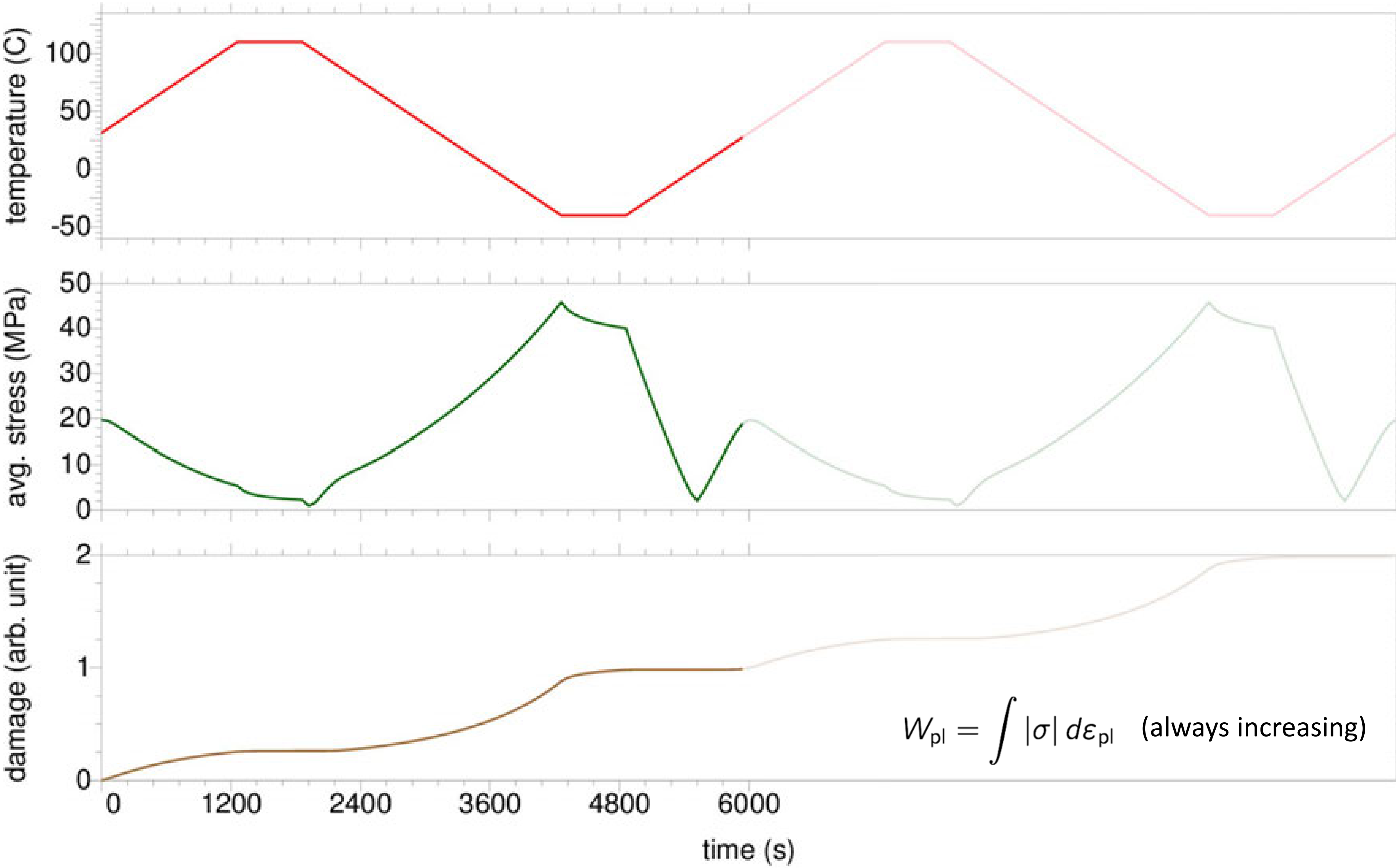
$$\dot{s} = \dot{\varepsilon}_{\mathrm{pl,eq}} \; h_0 \left|1 - \frac{s}{s^*}\right|^a \mathrm{signum}\left(1 - \frac{s}{s^*}\right)$$

$$s^* = \hat{s} \left[\frac{\dot{\varepsilon}_{\mathrm{pl,eq}}}{A} \exp\left(\frac{Q}{RT}\right)\right]^n$$

$$W_{\mathrm{pl}} = \int |\sigma| \, d\varepsilon_{\mathrm{pl}}$$

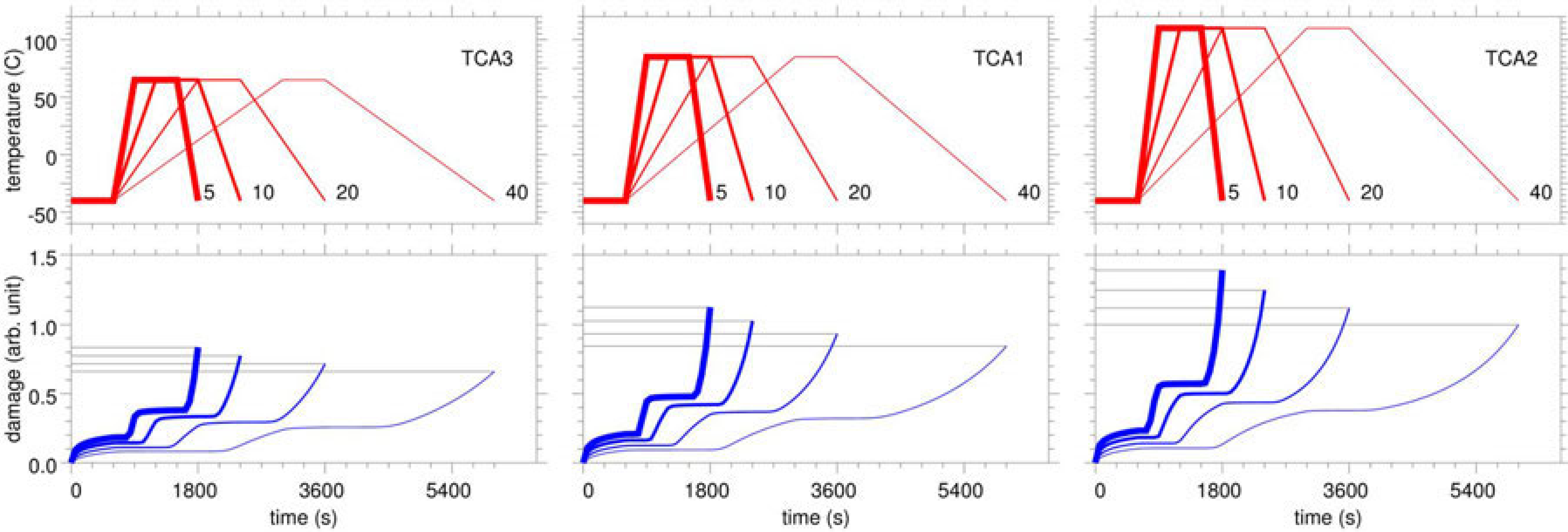


Damage: Progress toward failure



$$W_{\mathrm{pl}} = \int |\sigma| \, d\varepsilon_{\mathrm{pl}}$$ (always increasing)

Comparing various thermal cycles

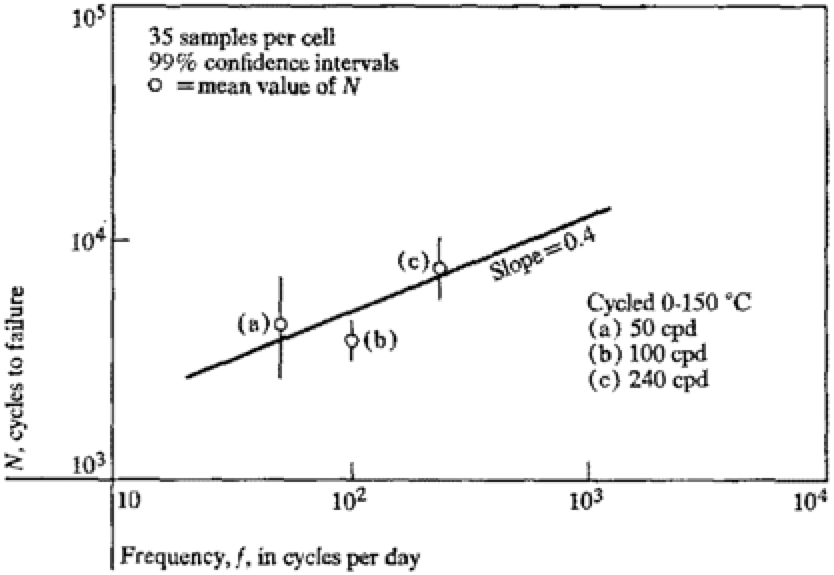


5, 10, 20, 40-minute ramps
Faster cycles cause more damage per cycle
Larger-amplitude cycles cause more damage per cycle

Lifetime dependence on cycle frequency

$$N \propto f^k$$

$$0 \leq k \leq 1$$



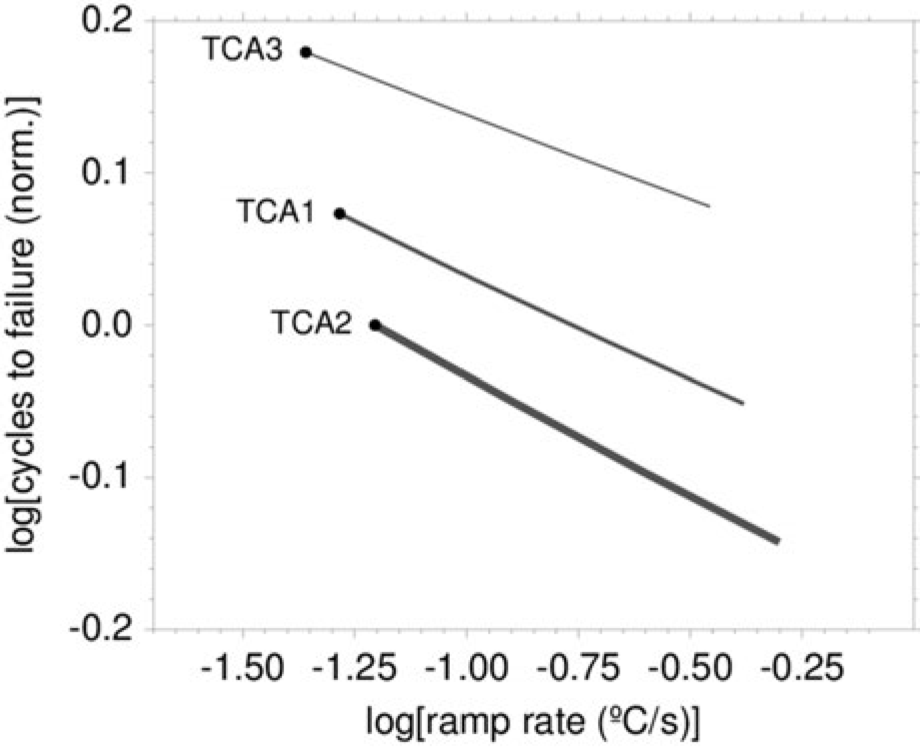
Norris, KC et al., IBM J Res Dev 13:3, 1969

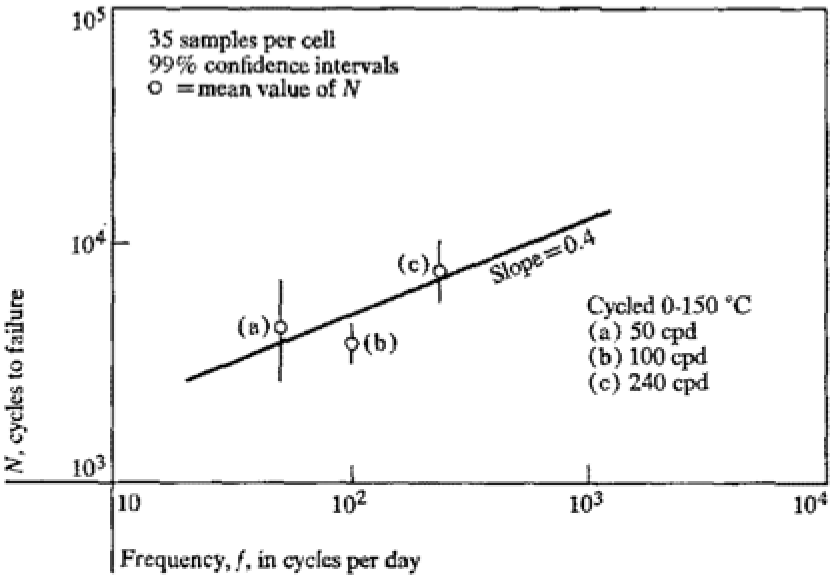
Empirical fatigue models say that faster cycles do less damage

Lifetime dependence on cycle frequency

$$N \propto f^k$$

$$0 \leq k \leq 1$$

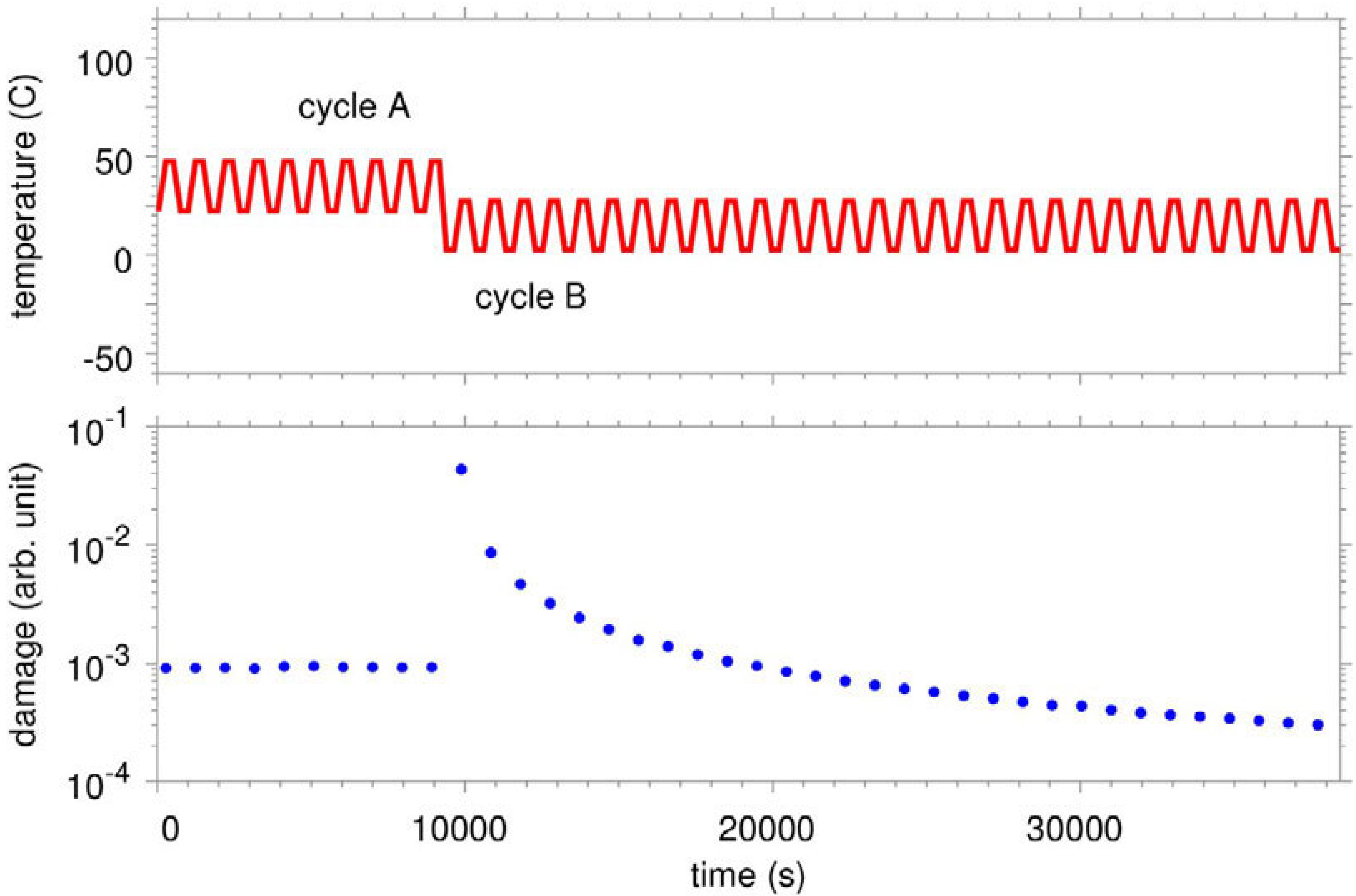




Norris, KC et al., IBM J Res Dev 13:3, 1969

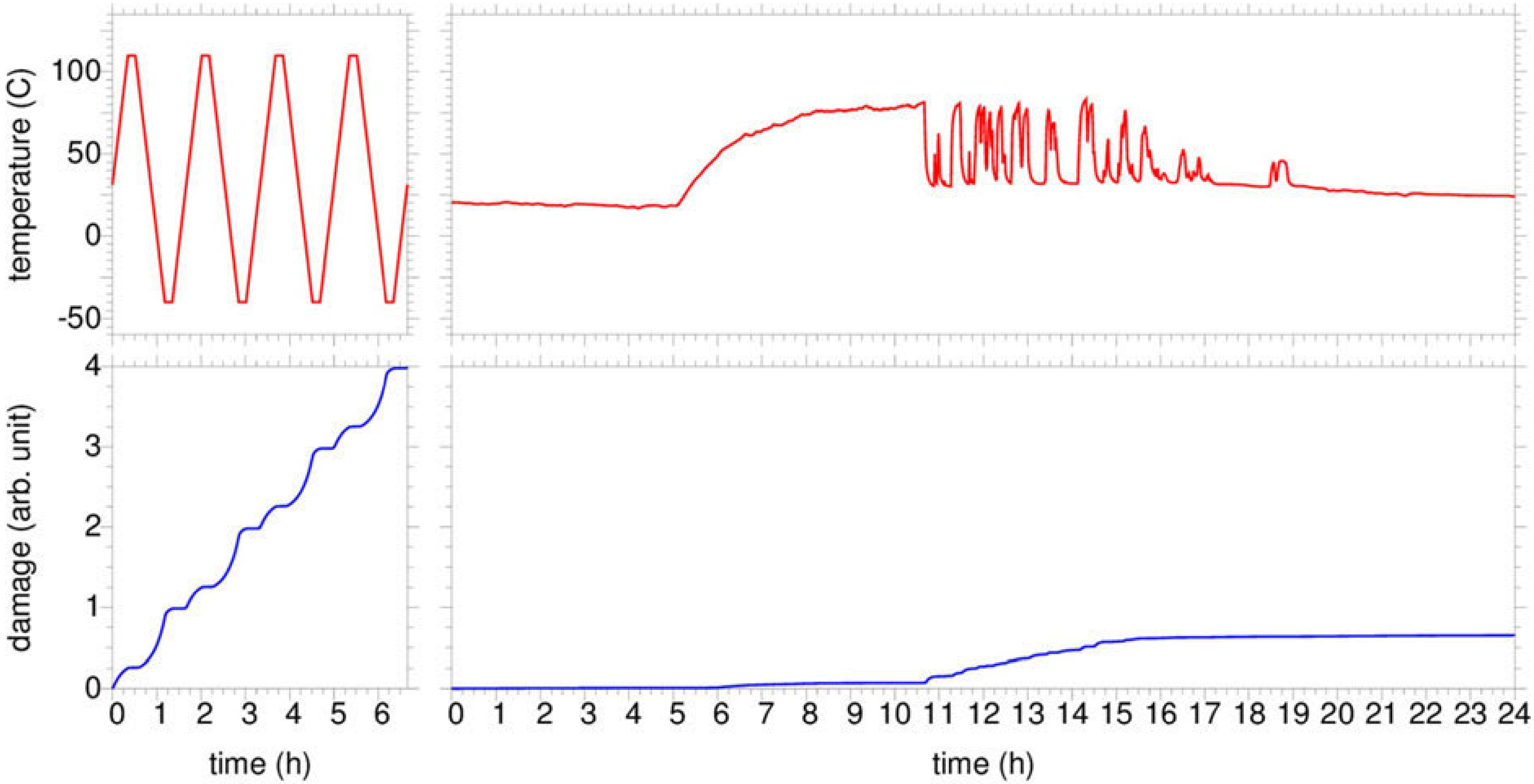
For every cycle we tested, faster cycles caused more damage per cycle

Weather is irregular



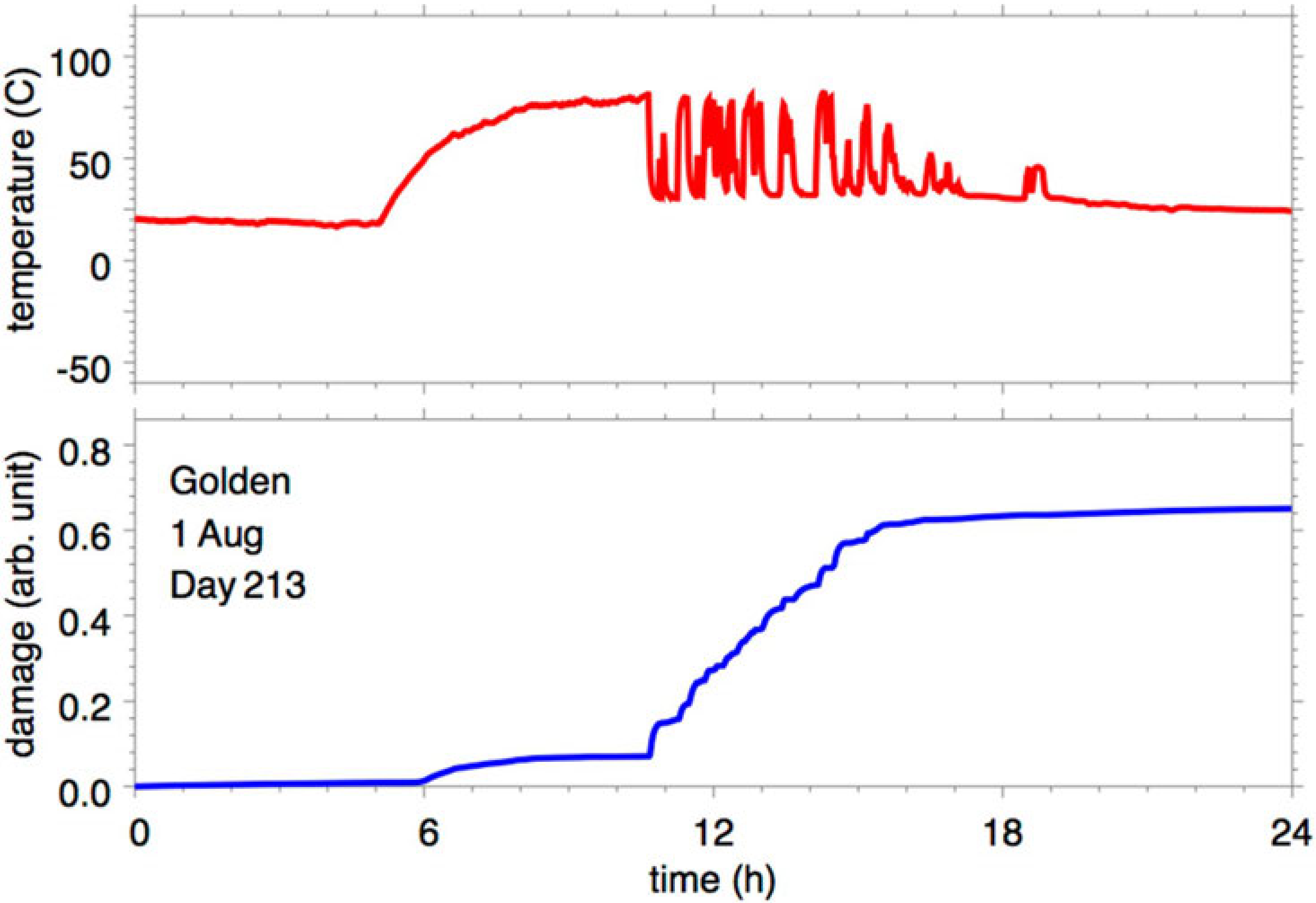
Repeating cycles each do the same damage only after a long sequence

Long-time simulations



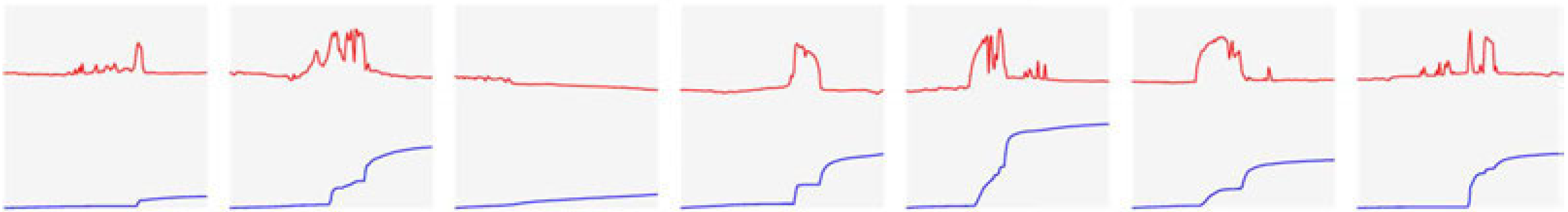
Typical fatigue models simulate only a few hours
Characterizing the weather requires a much longer simulation
Cell temperature history can have more fast variation during outdoor exposure

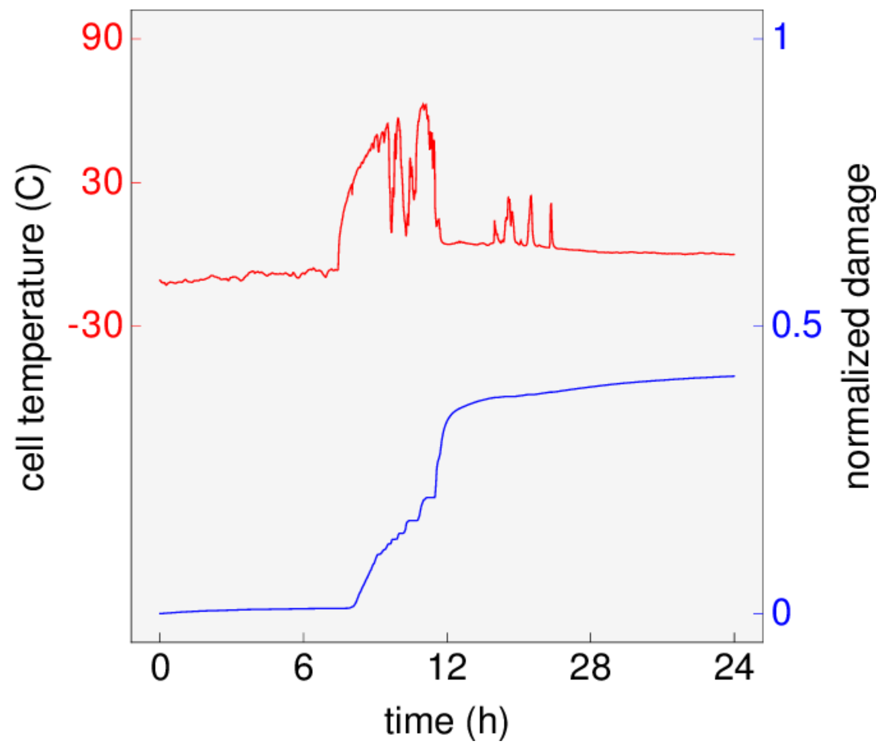
Simulating a day of outdoor exposure



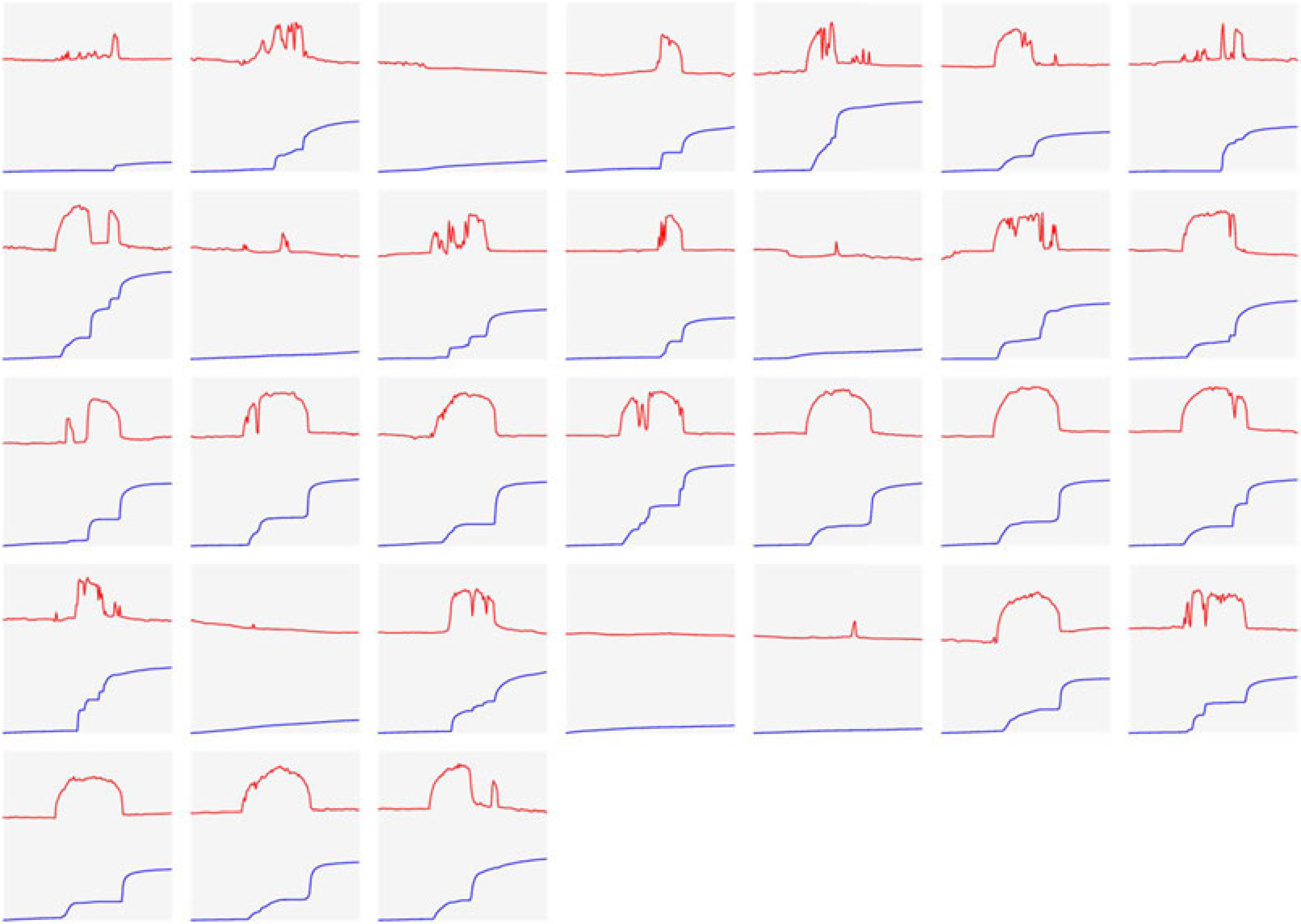
Cell temperature is derived from one-minute samples of meteorological data

Simulating several days

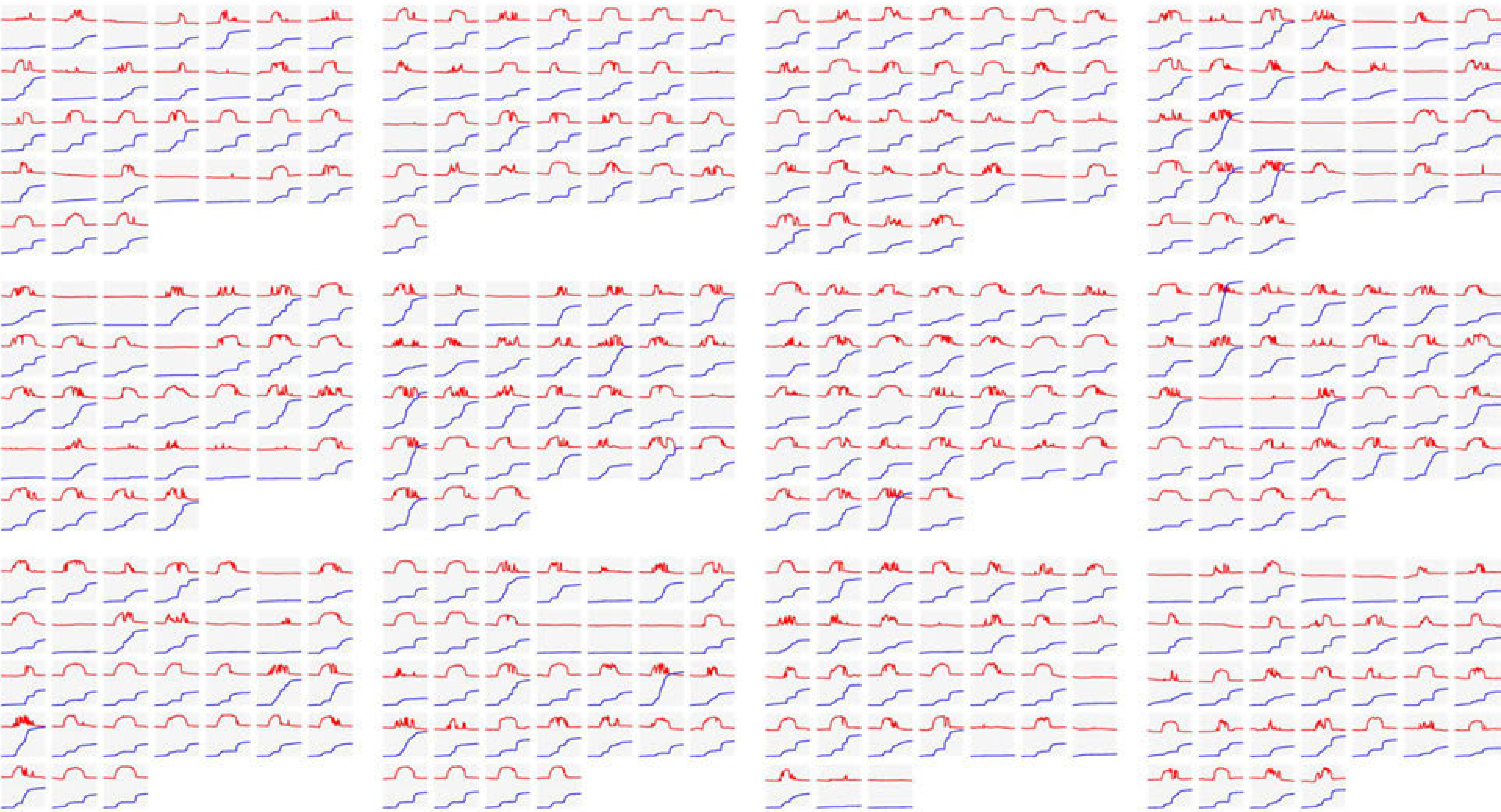




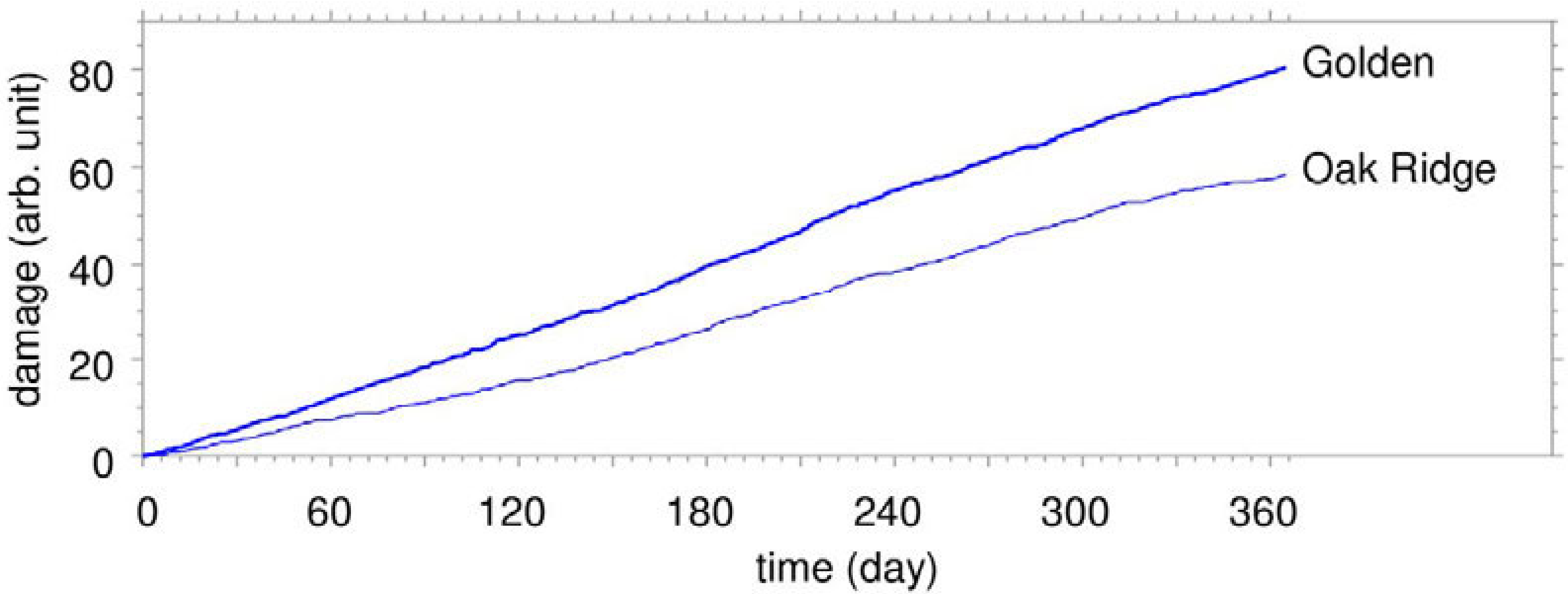
Simulating several days



Simulating an entire year



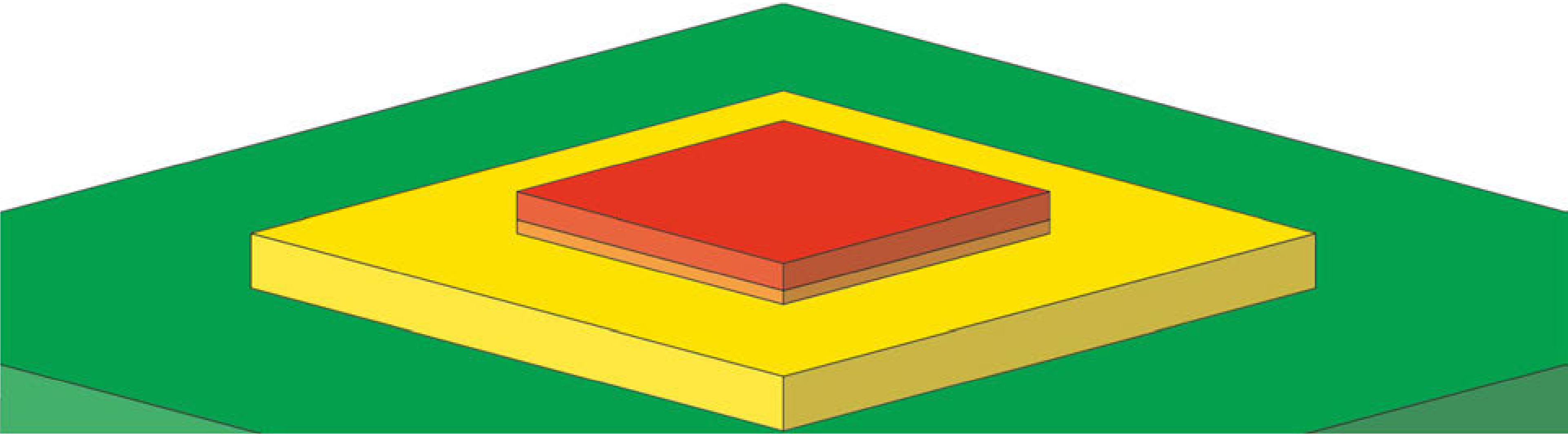
Simulating an entire year



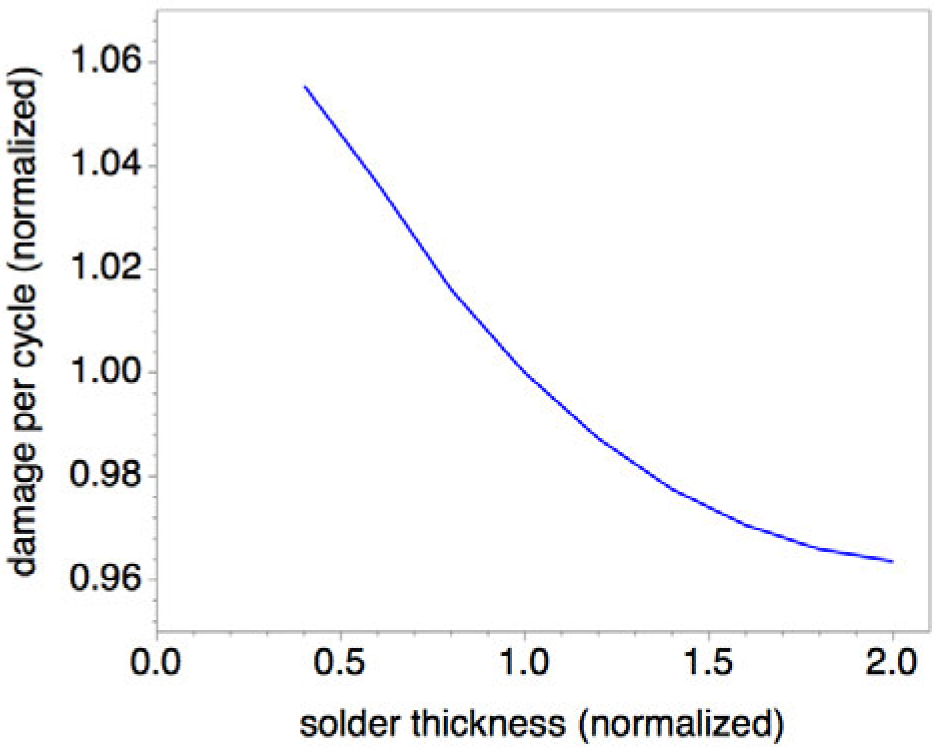
A year in Oak Ridge, Tenn. does 70% as much damage as a year in Golden, Colo.

Improving the model

- More accurate temperature input data
- Understanding of sensitivity to geometry and materials selection: Do these results apply to your cell assembly?
- Improved measurements of material properties

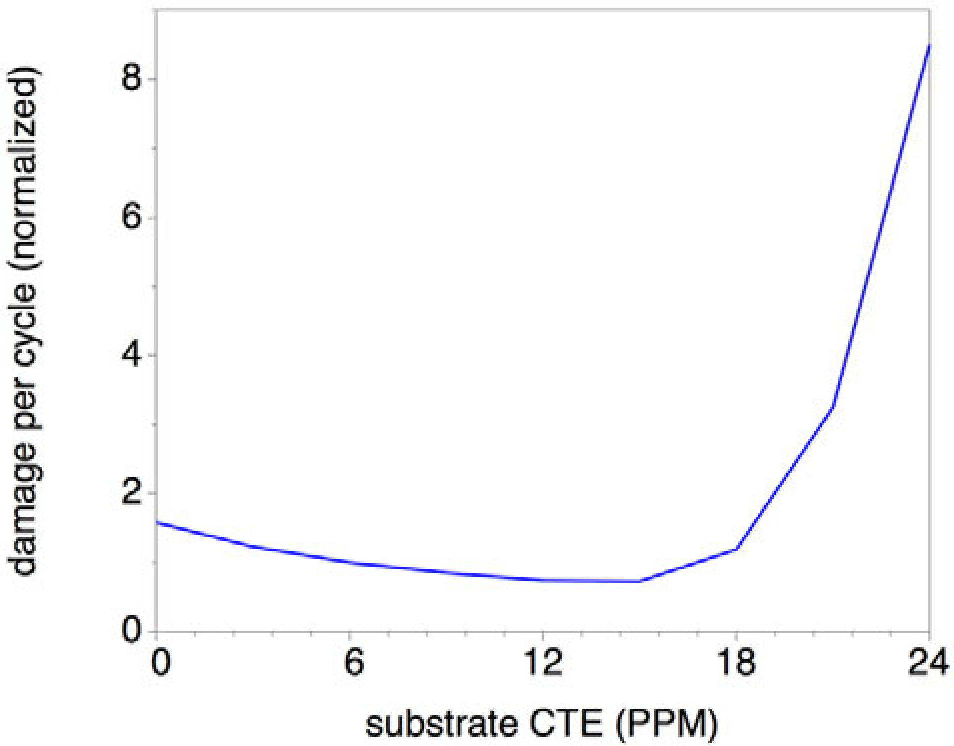


Improving the model: Geometric effects



Solder thickness has a modest effect on the rate of damage accumulation

Improving the model: Material effects



Fixed substrate thickness and stiffness; variable CTE

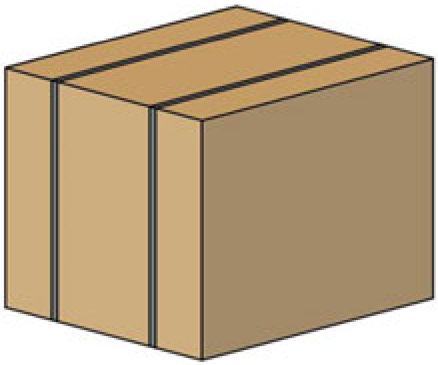
Substrate thermal expansion has a strong effect on the rate of damage accumulation

Improving the model: Material properties

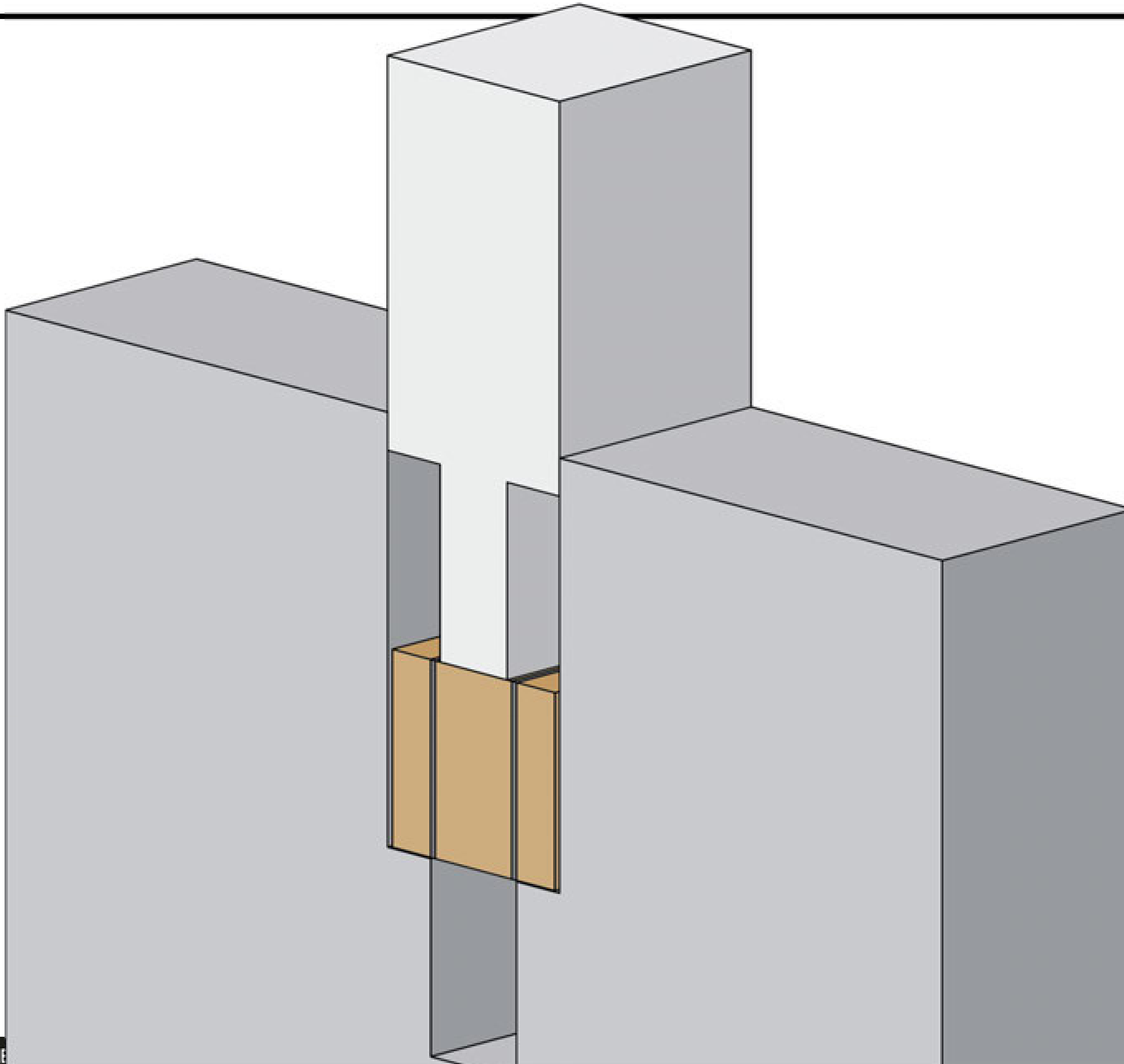
$$\dot{\varepsilon}_{\mathrm{pl,eq}} = A \exp\left(\frac{-Q}{RT}\right) \left[\sinh\left(\xi \frac{\sigma_{\mathrm{eq}}}{s}\right)\right]^{\frac{1}{m}}$$

$$\dot{s} = \dot{\varepsilon}_{\mathrm{pl,eq}} \; h_0 \left|1 - \frac{s}{s^*}\right|^a \; \mathrm{signum}\left(1 - \frac{s}{s^*}\right)$$

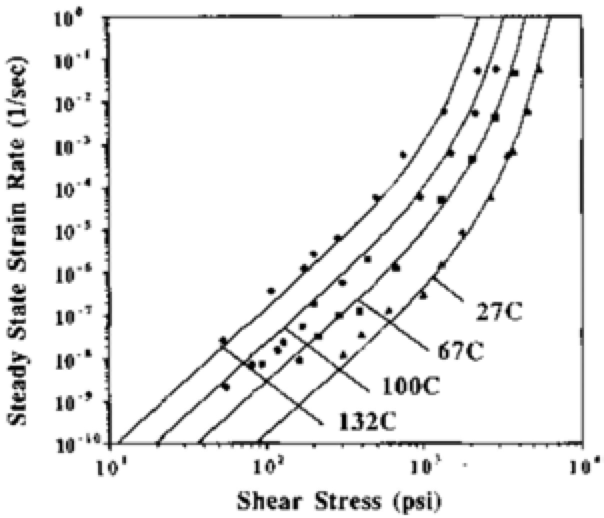
$$s^* = \hat{s} \left[\frac{\dot{\varepsilon}_{\mathrm{pl,eq}}}{A} \exp\left(\frac{Q}{RT}\right)\right]^n$$



Improving the model: Material properties



Improving the model: Material properties



Darveaux, R. et al, IEEE J Compon. Hybr. 15:6, 1992.

$$\dot{\varepsilon}_{pl} = \dot{\varepsilon} = A \exp\left(\frac{-Q}{RT}\right)\left[\sinh\left(\xi \frac{\sigma^*}{s^*}\right)\right]^{\frac{1}{m}}$$

$$s^* = \hat{s}\left[\frac{\dot{\varepsilon}_{pl,eq}}{A} \exp\left(\frac{Q}{RT}\right)\right]^{n}$$

Material properties are fitted to a set of constant-strain-rate or constant-load tests

Summary and conclusion

- By experiment and simulation, fast thermal cycles cause more damage per cycle
- Our model is efficient enough to simulate thousands of cycles or entire years of exposure
- A year in Golden causes more damage than a year in Oak Ridge
- Simulations have come a long way, but need additional refinement before they can be used for absolute lifetime prediction
- Further experiments and model improvements could enable estimation of lifetime from simulation and limited experiments

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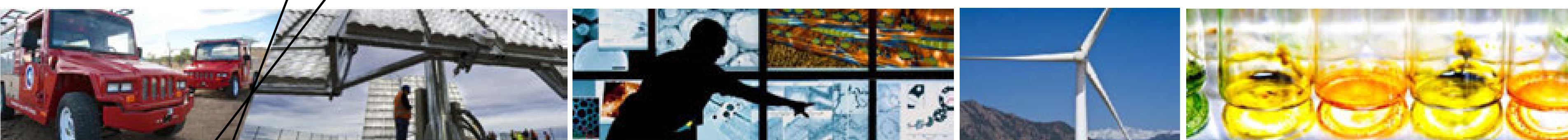

Thermal Effects and Other Interesting Issues with CPV Lenses

Instituto de Energia Solar-UPM
Madrid

R. Herrero, S. Askins, M. Victoria, C. Domínguez, I. Antón, and G. Sala

PV Module Reliability Workshop-CPV, March 1st

Outline

- Temperature dependence of lenses

  - PMMA Vs. SoG

- Lens characterization with temperature

  - Method

  - Measurements

- Recommendations for designing optical systems for SoG concentrators

- Conclusions

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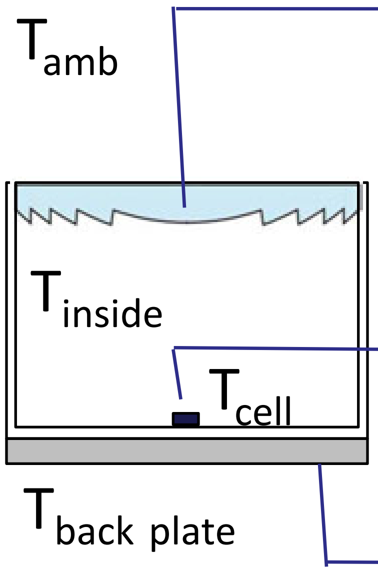
Temperature dependence of CPV modules ([1])



Lens Thermal Dependence

$\approx T_{amb} + 20K$

Cell Temperature Coefficients

- β and α temperature coefficients

$\approx T_{back\ plate} + 20K$

Module Thermal Expansion

-Solar cell shifts from original position

$\approx T_{amb} + 20K$

Which are the effects of temperature on lens performance?

How do we measure these effects?

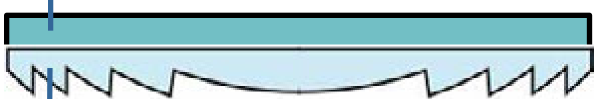
How can we avoid these effects while designing a CPV module?

(1) G. Peharz, J.P. Ferrer, G. Siefer and A. W. Bett , Prog. Photovolt: Res Appl. 2011; 19:54-60

Silicone On Glass (SOG [2]) Vs PMMA Fresnel lenses

Glass

- Flat
- Rigid
- Tough (doesn´t scratch)
- Long-term reliability

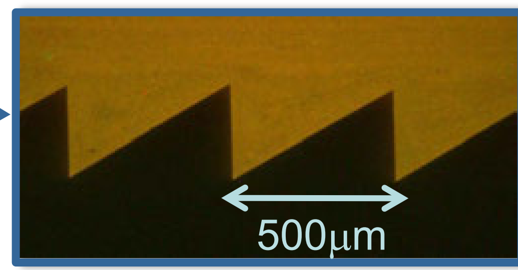


Silicone

- Precise (draft angle)
- Refractive indexes match

PMMA

- Cost ?
- Lower weight



* Image courtesy of Reflexite

How do the lenses perform with temperature?

(2) G. Sala and E. Lorenzo, Hybrid silicone-glass Fresnel lens as concentrator for photovoltaic applications, 2nd EUPVSEC, Berlin, 1979

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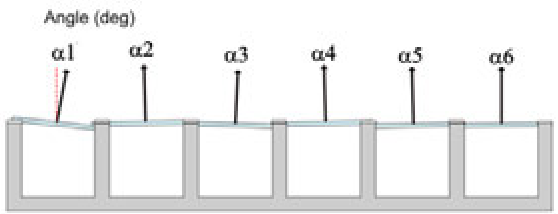
Which are the effects of temperature on lens performance?

Temperature dependence of lenses

Geometry

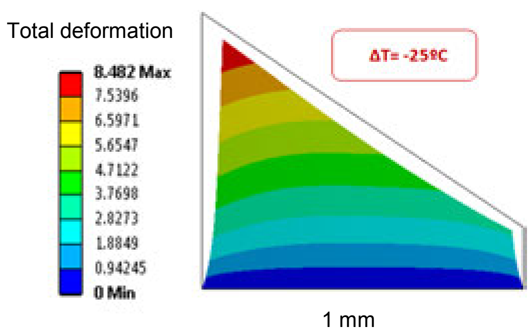
PMMA: Isotropic thermal expansion??

– Lower effect than lens parquet deformation

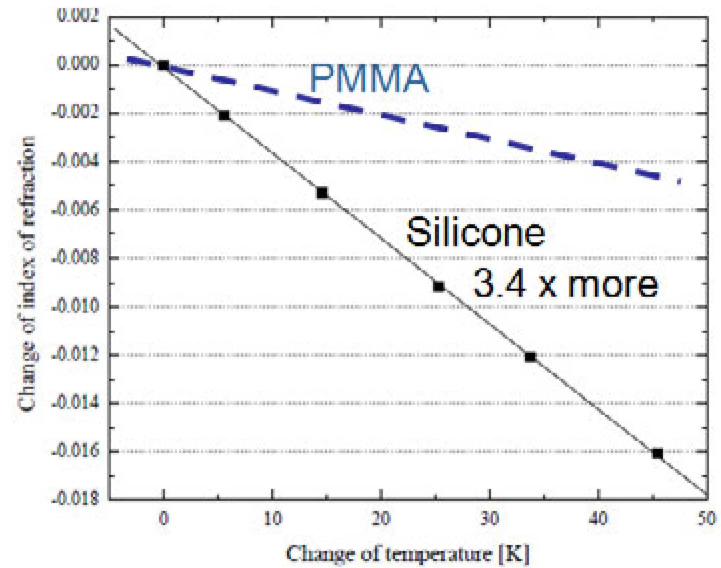


SoG: CTE Mismatch

– Change in facet slope



Refractive Index changes



(3) T. Schult, M. Neubauer, Y.Bessler, P. Nitz, A. Gombert, Proc. of *2nd International Workshop on Concentrating Photovoltaic Optics and Power*, Darmstadt, 2009

Higher change of geometry and refractive index for SoG

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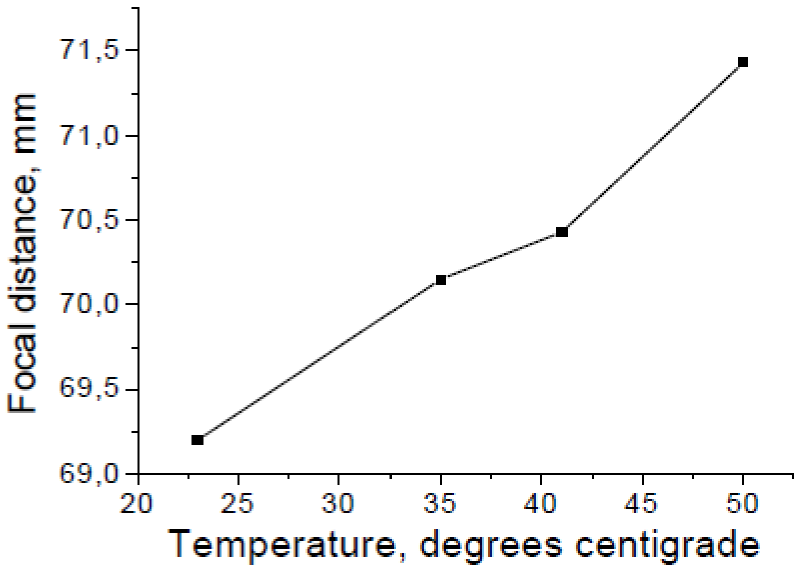
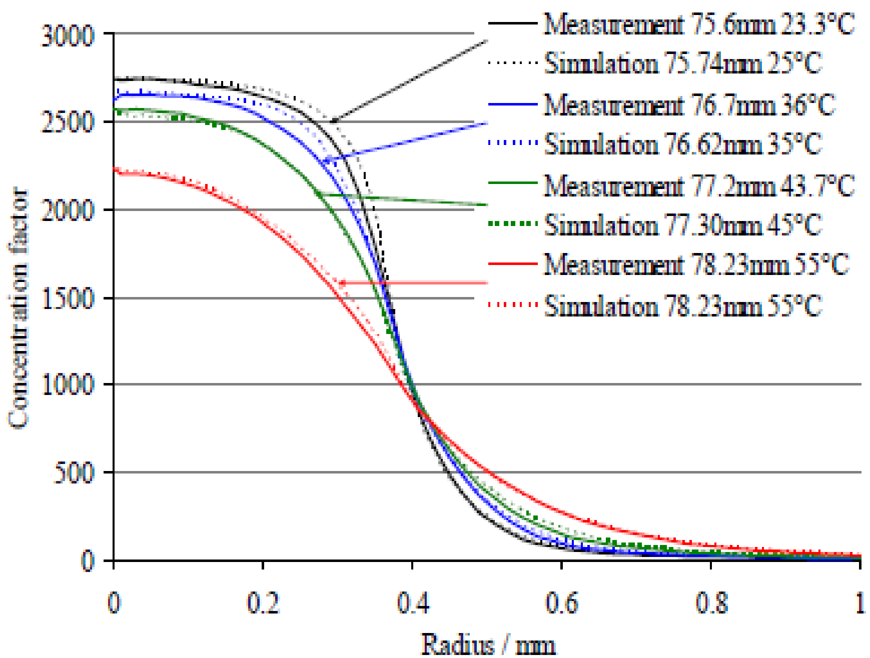
Previous Work I

- Measurements of optimum focus vs. T (SoG)
  - Electrical measurements



(4) Rumyantsev et al., Thermal Regimes of Fresnel Lenses and Cells in "All-Glass" HCPV Modules, CPV-6, Freiburg 2010

- Measurements and simulations of light profile (SoG)
  - Monochromatic light
  - Single focal distance

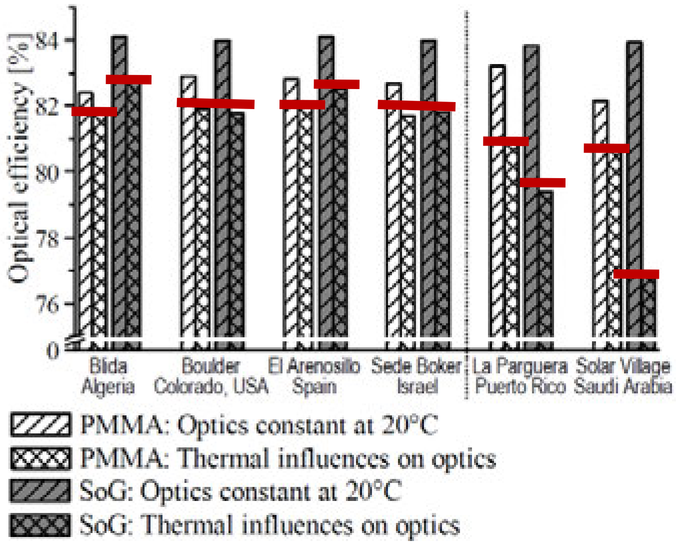


(5) Hornung et al., Temperature Dependent Measurement And Simulation of Fresnel lenses for concentrating Photovoltaics, CPV-6, Freiburg 2010

Focal length increases with temperature causing defocus for fixed lens-to-cell distance

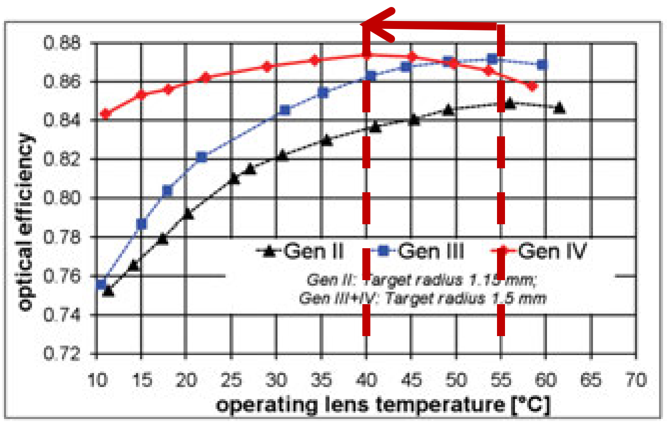
Previous Work II

- Estimation of energy generation:
  - Computer simulations
  - Six different locations
  - PMMA Vs. SoG



(6) Hornung et al.,Estimation of the influence of Lens Temperature on Energy Generation of a Concentrator Photovoltaic System, CPV-7, Las Vegas 2011

- New Fresnel lens design for reducing temperature depence of the optical efficiency



(7) Van Riesen et al.,Concentrix Solar's progress in developing highly efficient modules, CPV-7, Las Vegas 2011

Optimizing lens performance for a lower temperature improves average performance

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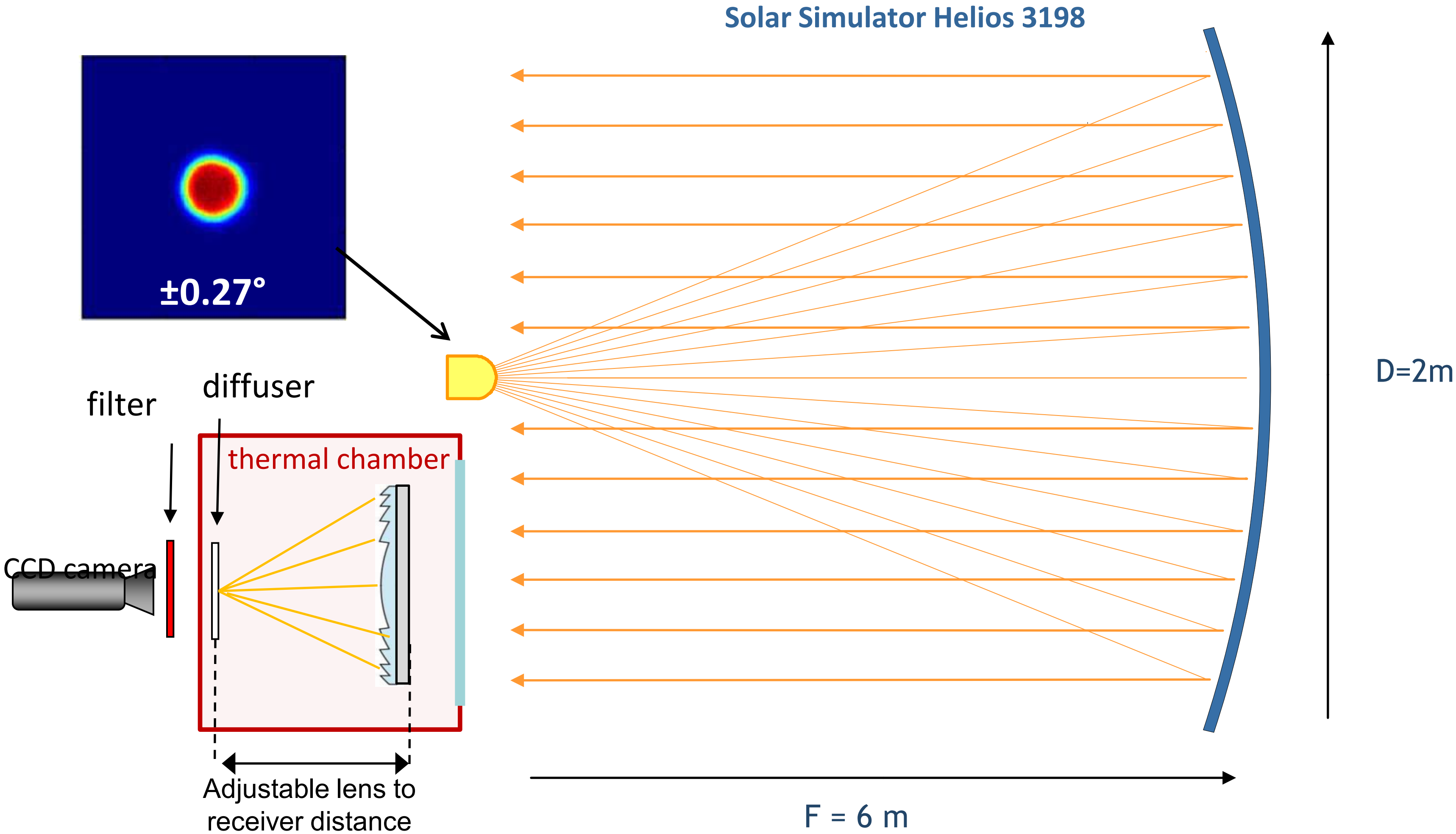
How do we measure these effects?

How do we measure these effects?



CPV solar simulator at IES provides "real" illumination:

White (AM1.5D) light and 0.27°

(8) Askins et al.,Effects of Temperature on Hybrid Lens Performance, CPV-7, Las Vegas 2011

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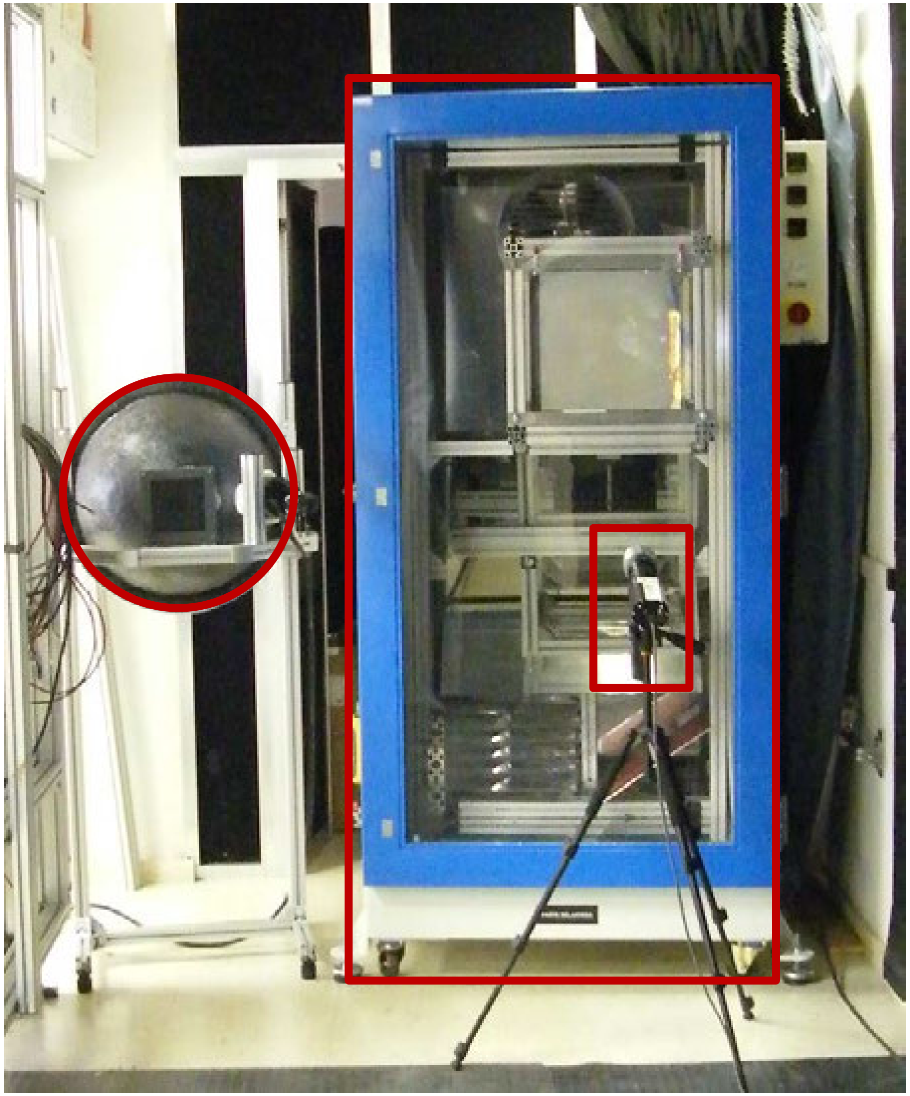
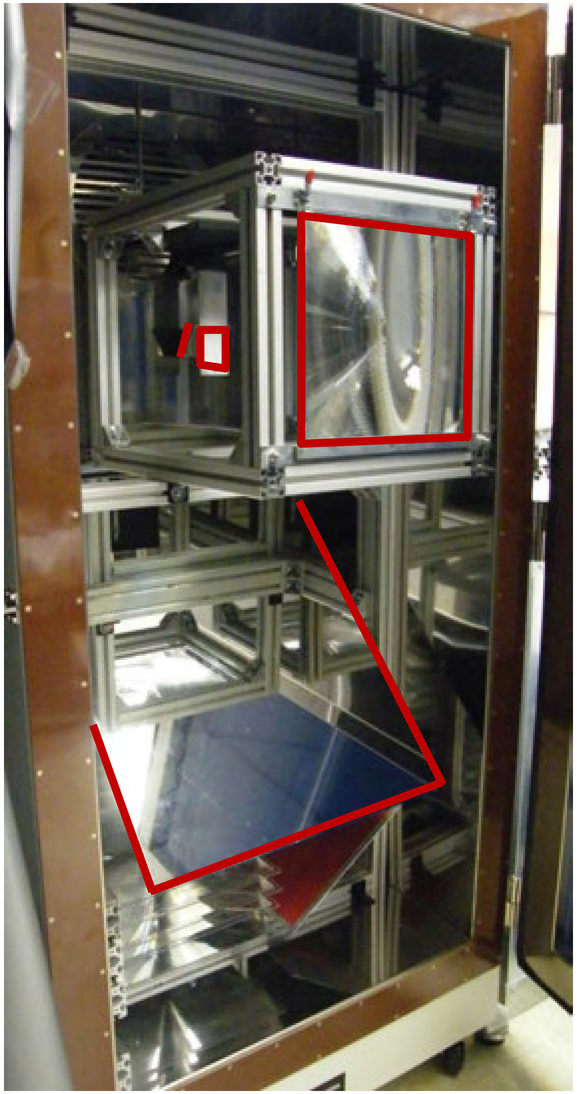
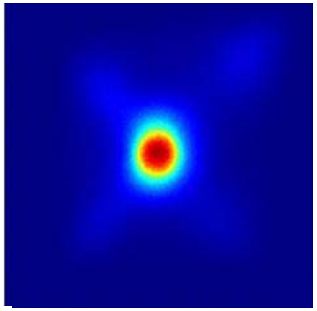
Experimental set up





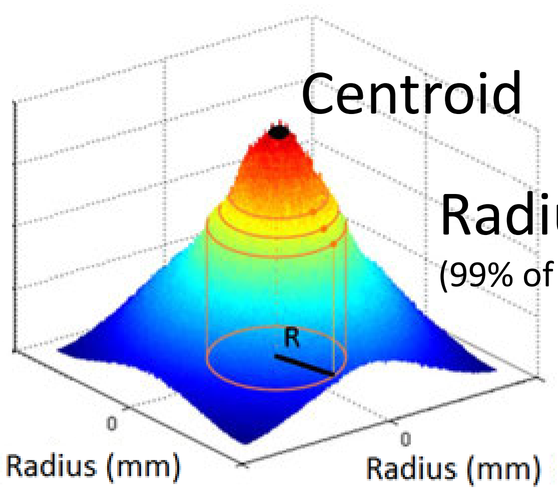
Imaging the Focal Plane



Light spot CCD image

- Lens
- Temperature (25 C - 65 C)
- Focal distance → F number

$$\text{F-number} = \frac{\text{focal distance}}{\text{Lateral lens size}}$$



$$C_{Geom} = \frac{A_{lens}}{\pi \cdot Radius(99\%)^2}$$

Imaging is evaluated using the geometric concentration,

varying focal length and temperature

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Lens characterization

Empirical study SOG lenses performances at different temperatures and lens-to-receiver distances

"Real" illumination: White (AM1.5D) light and 0.27

What is the effect of silicone cure temperature ?

- Can we confirm that lenses behave best at $T_{operation} = T_{cure}$?

Can facets deformation be decreased by increasing the silicone layer?

- Easiest geometrical parameter to change

6 different SOG samples all with the same profile provided by Reflexite ENERGY SOLUTIONS

Reference sample (x2) → Tcure , base thickness (0.9mm)

+ 2 different cure temperatures→ 25º , 35º

+ 2 different silicone base thicknesses→ 1.8mm , 1.1mm

Same Mold

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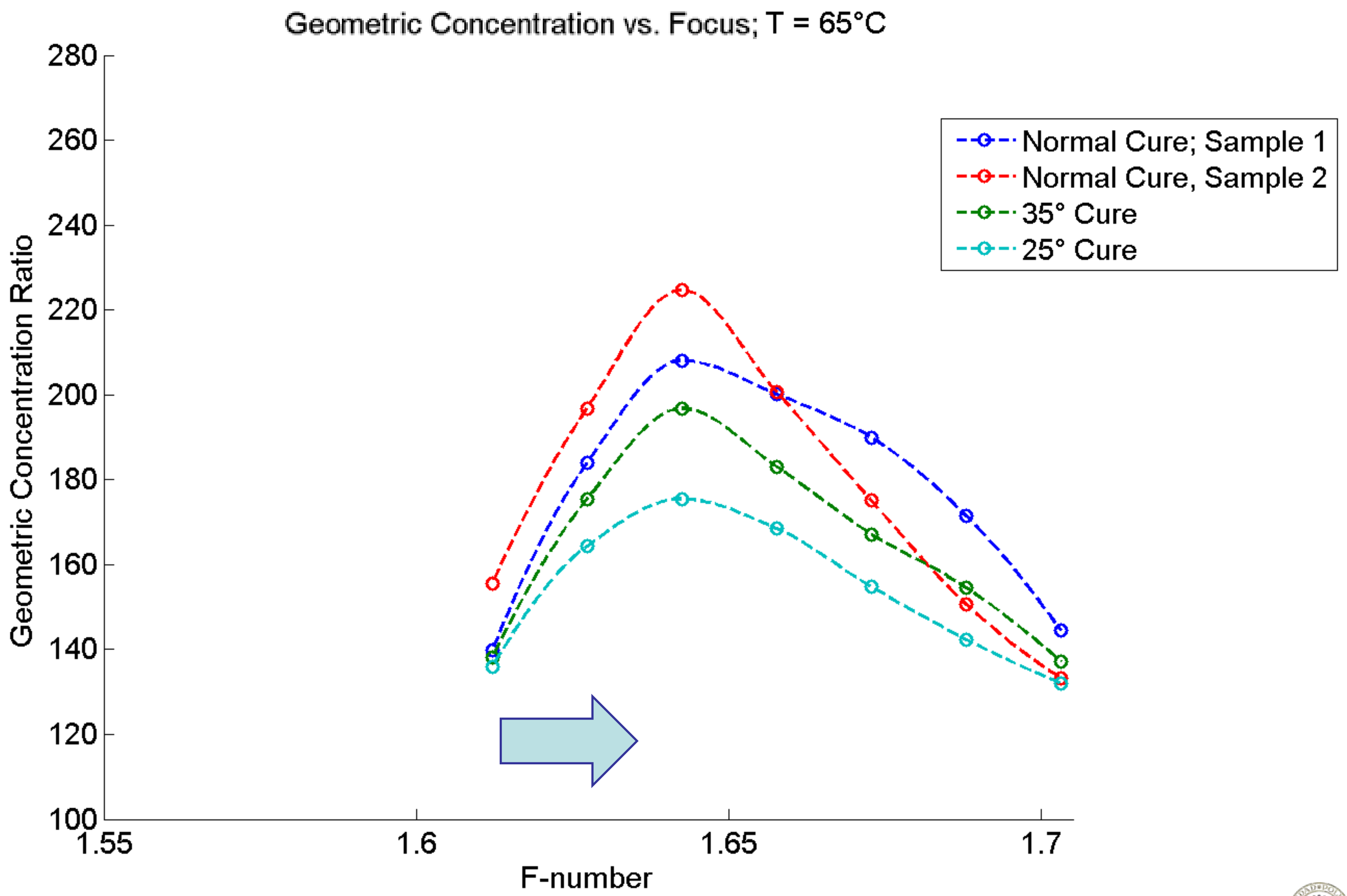
Measurements



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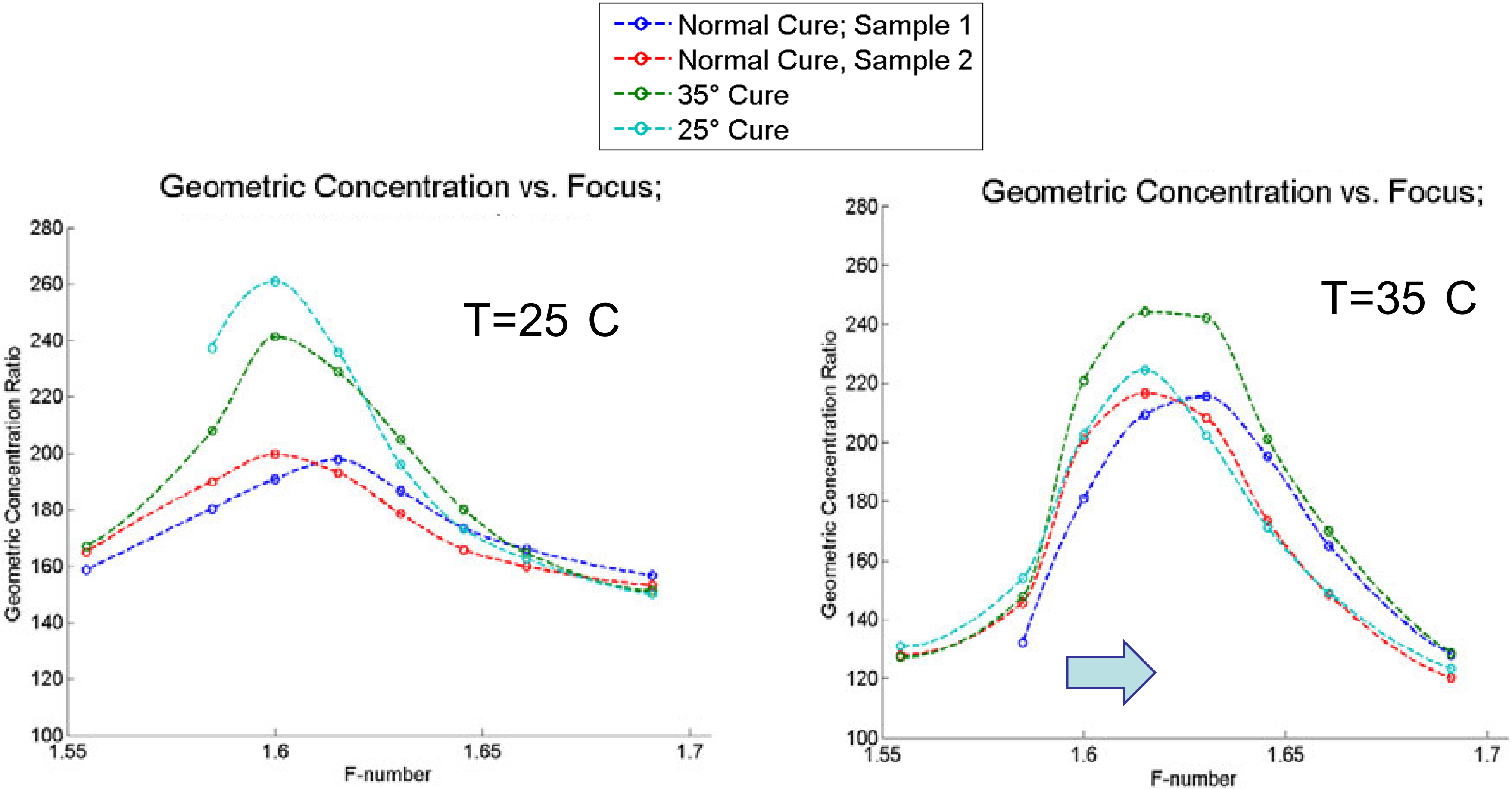
Measurements



Focal length increases with temperature causing defocus for fixed alignment

Highest concentration at cure temperature

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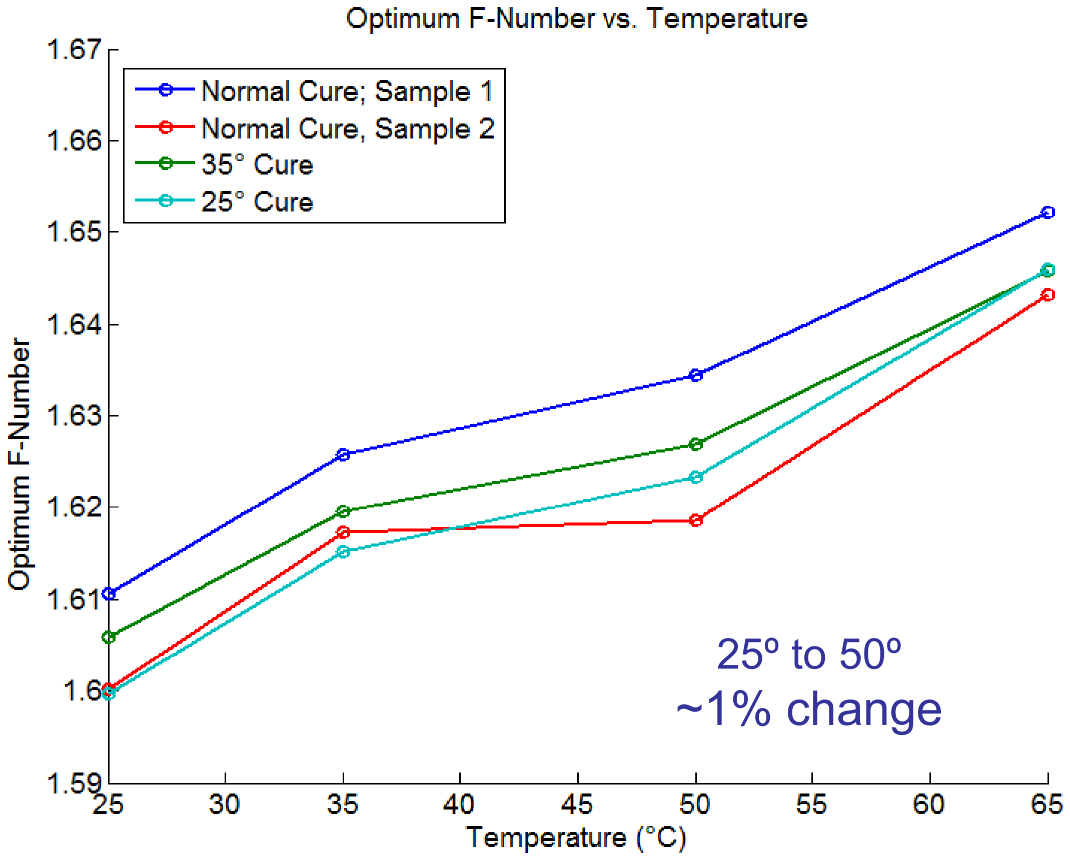
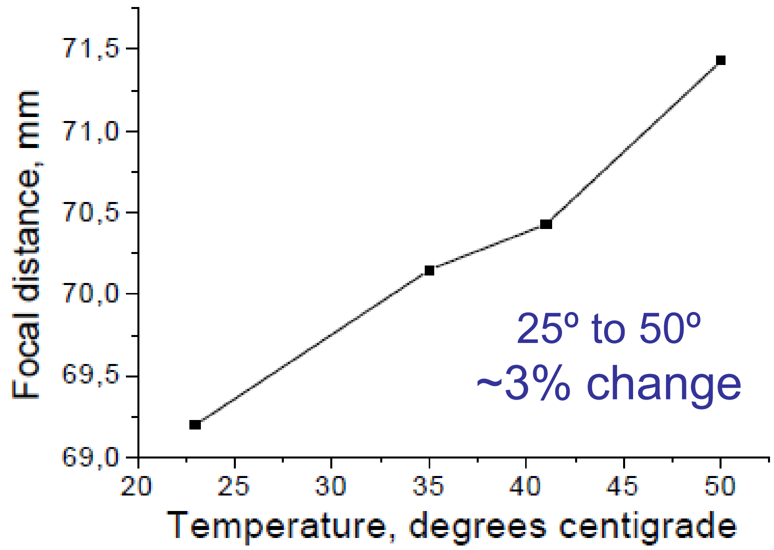
Focal Distance Change





*Rumyantsev et al., Thermal Regimes of Fresnel Lenses and Cells in ”All-Glass” HCPV Modules, CPV-6, Freiburg 2010

Focal distance changes depend only on silicone index change

Un-avoidable for this material

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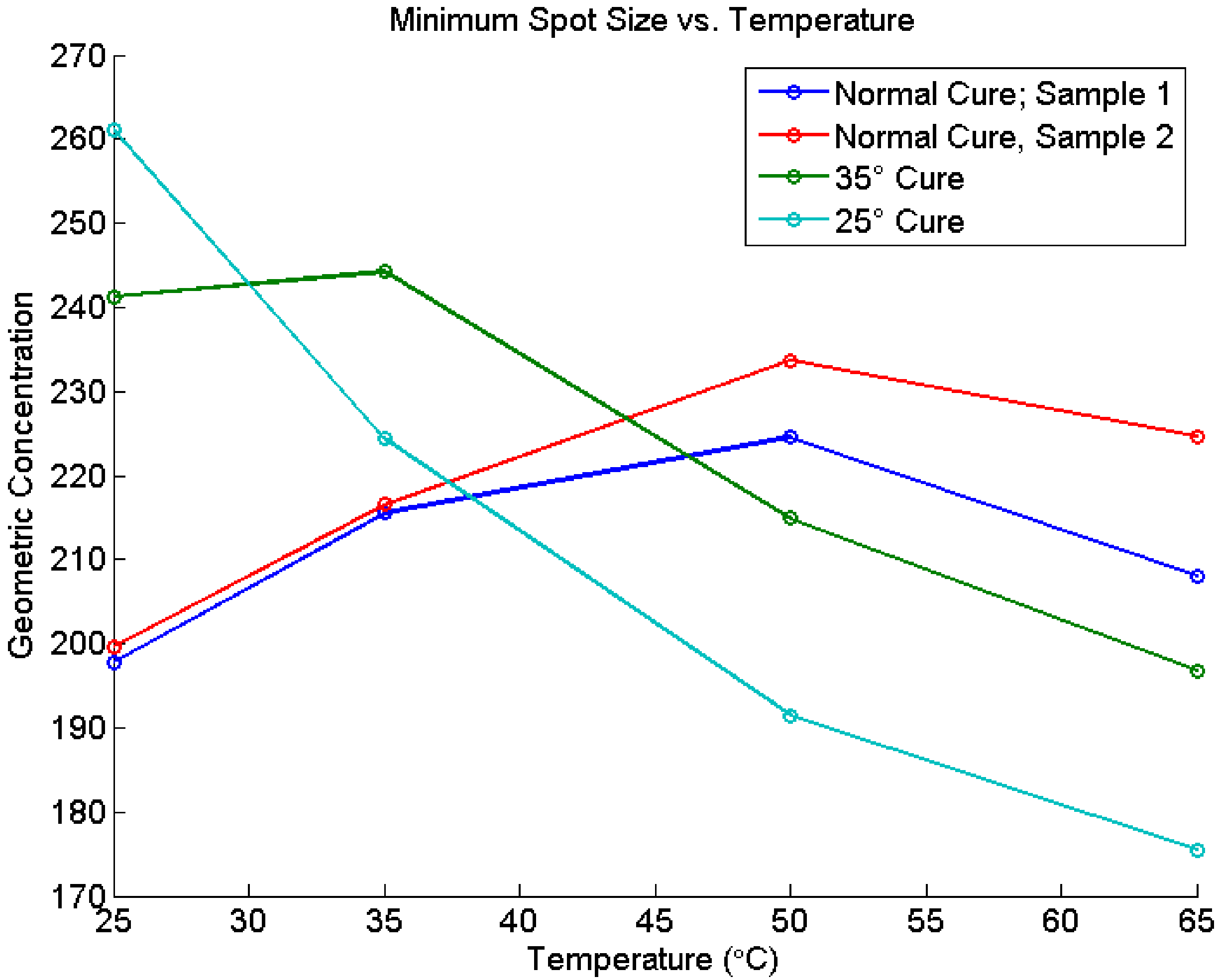
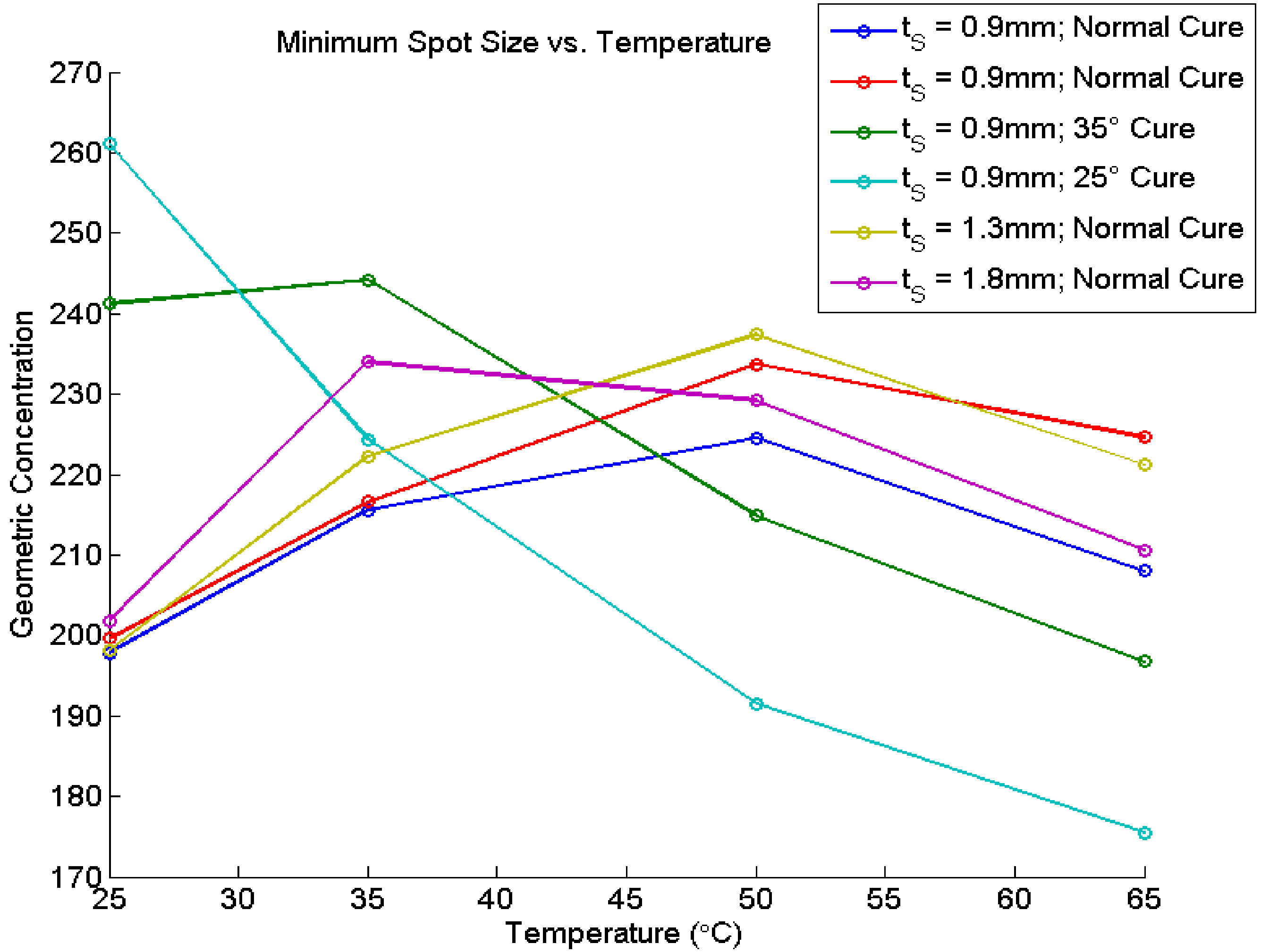
Maximum Concentration vs. Temp



(Optimum focal distance at each temperature)

Lens best performance at cure temperature

Effect of Additional silicone



No measureable effect seen with additional silicone

No stress relief on facets

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How can we avoid temperature effects while designing a CPV module?

Optimization of tolerant optical systems for SoG concentrators [9] I

- Optimum lens focal distance depends on temperature

  (index of refraction change)

  – n(Tdesign)

    -Cure temperature

  – Focal distance optimization at several temperatures

    - Operation temperature

- Lens best performance at cure temperature

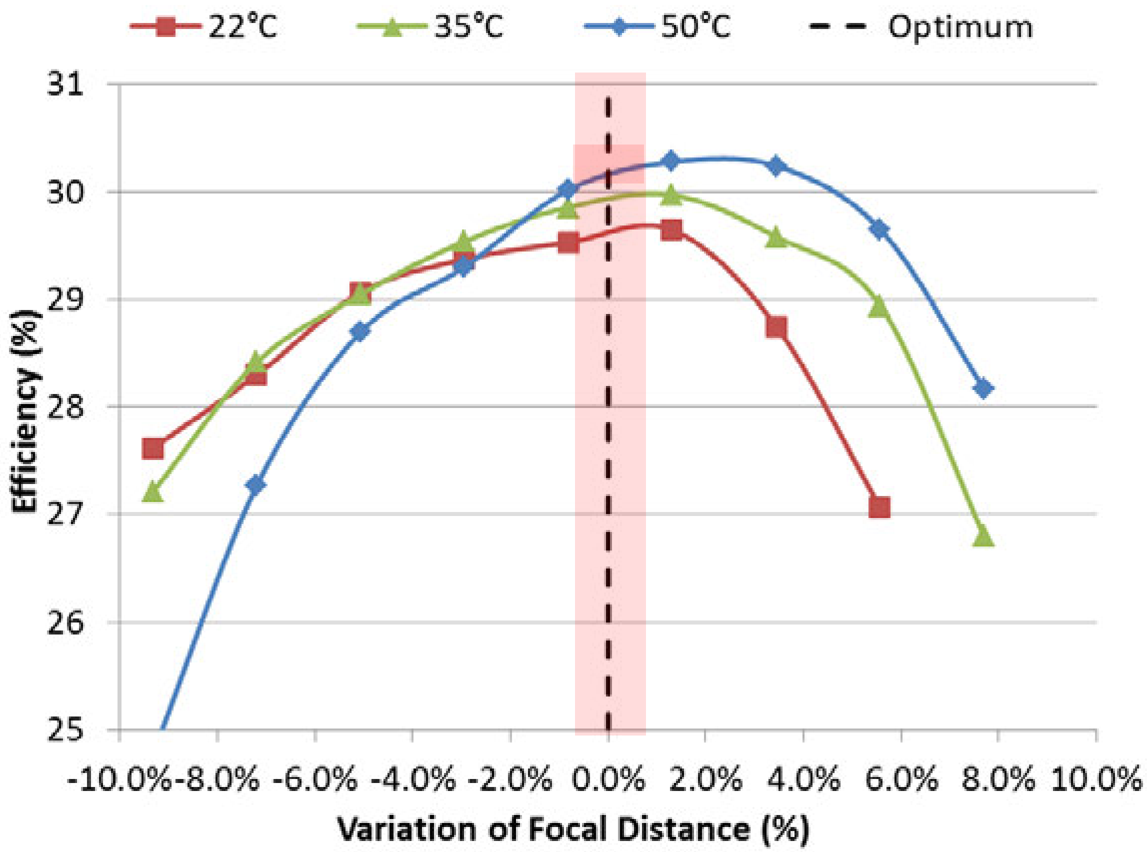
  (geometrical deformation)

  - Operation temperature

(9) Askins et al., Optimization of tolerant optical systems for silicone on glass concentrators , CPV-8, Toledo,2011

Optimization of tolerant optical systems for SoG concentrators (9) II

- Good optical system performance at different temperatures



Electrical measurements for primary Fresnel lens and refractive secondary optical system

Optimum focal distance at several temperatures

Best performance at operation temperature

Secondary Optical Element (SOE) must be tolerant to changes in spot size

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Conclusions

- Focal length increases with temperature causing defocus for fixed lens-to-receiver distance
- Lens geometry changes with temperature when silicon is not in a stress-free state
- Understanding temperature behavior of SOG lenses will allow a good optical system performance at different temperatures
  - SOE tolerant to changes in light spot size

Open questions …

- Is it worth it to design lens facets taking into account the deformation produced by working at different temperature from cure temperature?
  - Several working temperatures

- Is the CPV module performance dependence with temperature well reproduced by this method?
  - Module thermal expansion
  - Multi-Junction solar cell performance

Thank you for your attention…

HIGH INTENSITY LIGHT-CYCLING OF HCPV CELL ASSEMBLIES USING THE XT-30 SOLAR SIMULATOR

R.M. Beal[1], S. Chow [1], F. Asselin Guay[1], E. Graf[1], A. Muron[1], M. Yandt[1], J.F. Wheeldon[1], S. Myrskog[2], J.E. Haysom[1], T.J. Hall[1], K. Hinzer[1]

[1] Centre for Research in Photonics, University of Ottawa SUNLAB, Ottawa, ON, Canada

[2] Morgan Solar, Toronto, ON Canada

1. Introduction

The thermal and electrical loads generated within highly-concentrating photovoltaic systems (HCPV) are significantly greater than those produced in flat plate photovoltaics. In addition, cyclical loading is also more severe, due to the limited acceptance angles of HCPV systems. Subsequently, the long-term reliability of solar cells, and cell-on-carrier (CoC) assemblies, under such operating conditions is of significant interest to the CPV community.

The Spectrolab XT-30 is a high intensity, continuous wave solar simulator capable of emitting 10 - 100 W/cm^2 (100 -1000 suns) onto a 5.5mm x 5.5mm solar cell. As such, it has significant potential as a lab-based tool for investigating the reliability of HCPV cell-on-carrier assemblies. This poster details the use of the XT-30's as a tool for exploring the degradation effects of accelerated, high-intensity light-cycling.

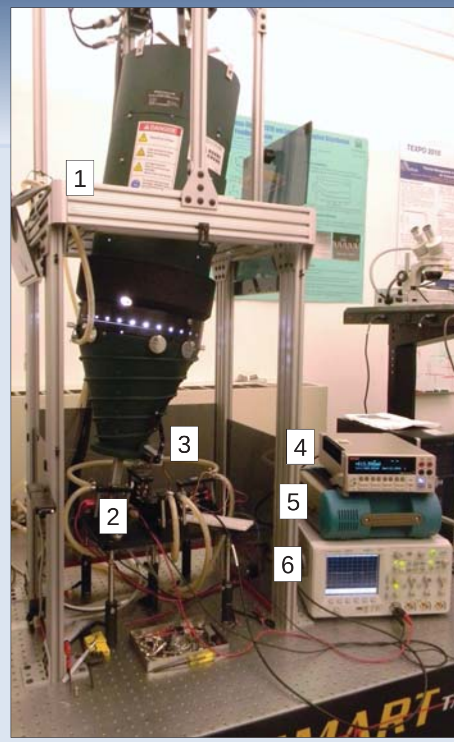

Figure 1. The light-cycle experimental setup showing the XT-30 solar simulator (1), water-cooled sample stage (2), automated shutter (3), SMU (4), spectroradiometer (5) and oscilloscope (6)

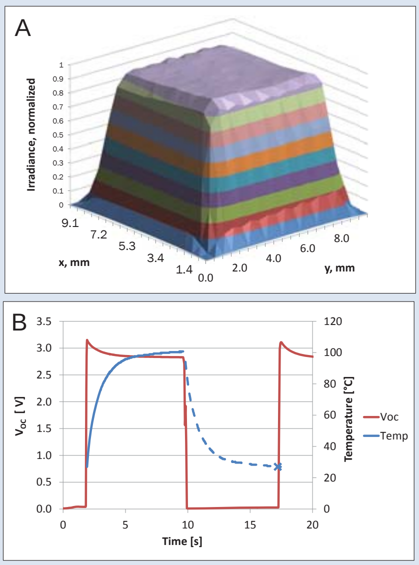

Figure 2. A) Spatial irradiance map of the XT-30 solar simulator beam. B) Transient V_{OC} and estimated temperature of the solar cell under test.

2. Measurement Set-up

- The experimental set-up is shown in Figure 1. The XT-30 was equipped with an automated shutter and CoCs were subjected to approximately 640-suns, at a frequency of 67 mHz (15 seconds per cycle, see Figure 2B), for 9 hours. A water-cooled sample stage was employed to moderate the cell temperature.
- The design of the XT-30 leads to a trade-off between spatial uniformity and total irradiance. Figure 2A shows a spatial uniformity map of the XT-30 beam. Uniformity of 9%. With optimal alignment, the XT-30 has achieved uniformity of 2.9%.
- The test cell's (Spectrolab C3MJ-CCA-030) I-V behavior was measured each hour using a Keithley 2420 SMU and lab-built data acquisition software.
- An ASDi Field Spec 3 spectroradiometer was used to measure the solar simulator spectra at the start and end of the measurement run to check the lamp stability.

3. Temperature Range

- The temperature limits experienced by the CoC during the light cycling tests were estimated using transient V_{OC} measurements (Agilent DSO6014A oscilloscope) and the V_{OC} shift method.
- Figure 2B presents a typical transient voltage trace overlaid with the estimated cell temperature
- Tell experiences a maximum cell temperature of approximately 100 °C, significantly higher than standard HCPV operating temperatures.
- Although the sample stage is water cooled to 15.6°C. The minimum cell temperature is only approximately 27°C, due to the heating effect of the XT-30's fans.

4. Results

- Dark and light I-V curves were measured each hour during the 9 hour experiment. The I-V curve parameters are presented in Figure 3.
- Negligible change is seen in the CoC's I-V characteristics over the course of the experiment.
- Possible that I_{SC} and P_{MAX} exhibit slight signs of degradation but further work is required to ensure this isn't an artifact of the measurement regime.
- The XT-30 data acquisition system has a repeatability error of ± 1.5 % making it impossible to distinguish changes in device performance below this threshold.

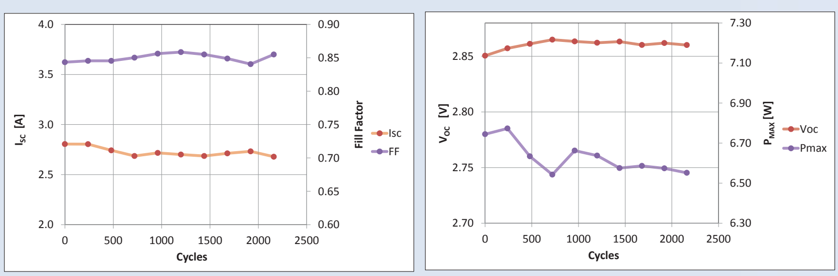

Figure 3. I-V characteristics of the device under test, as a function of the number of light-cycles

5. Conclusions

- The uOttawa SUNLAB has designed and installed equipment to facilitate light-cycling measurements on the XT-30 solar simulator.
- For an irradiance range of 660 suns, the maximum and minimum cell temperatures are estimated as 90°C and 27°C respectively.
- Spectrolab C3MJ CCA-030 cells on commercial carriers exhibited negligible degradation in I-V performance after 2,000, 65 Hz cycles at open circuit conditions.

6. Next Steps

- Optimize cycle time vs. temperature range.
- Light cycling at maximum power point.
- Increase irradiance to 1000 suns.

uOttawa CRPuO

Solar Cell Grid Finger Failure due to Micro-cracking

Ling Cheng, Steven Seel, Mark Ray, Salvatore Bonafede, Etienne Menard, Christopher Bower and Matt Meitl

Semprius Inc. 4915 Prospectus Dr. Suite C

Durham NC 27713

2/24/2012

Contents

Abstract

The Semprius high concentration photovoltaic module (CPV) achieved the world record efficiency by utilizing a micro-transfer printing technique, small high efficiency cells, low loss optics and mature surface mount technology. The III-V triple junction cells are printed on an alumina interposer (Cell on interposer, COI) and a thin film metallization process is used to form the cathode and anode interconnection. Arrays of surface-mountable COI with thru-wafer vias are assembled onto printed-circuit boards using industry standard solder reflow. The combination of these technologies offers additional benefits of high reliability, low cost and scalability to high volume production for Semprius' modules.

Each COI undergoes stringent pass/fail criteria during the wafer probing test, including inspection of the cell electroluminescence (EL) image during forward bias. We have occasionally observed non-uniform EL images after several hundred temperature cycles (-40˚C to 85˚C) in an on-going internal reliability program. The dark-IV and light-IV performance of these defective cells was found to be nearly identical to "good" cells that are within specification.

The root cause of the non-uniform EL images was found to be related to micro-cracking of the metallization near the junction of interconnect metal and the cell grid finger, thereby resulting in an electrical open, along that grid finger.

We reduced the incidence of micro-cracking of metallization significantly by optimizing the plated metal thickness in the thin film metallization process. Modeling of the strain energy near the grid finger junction indicated that reducing the plated metal thickness would mitigate the incidence of micro-cracking.

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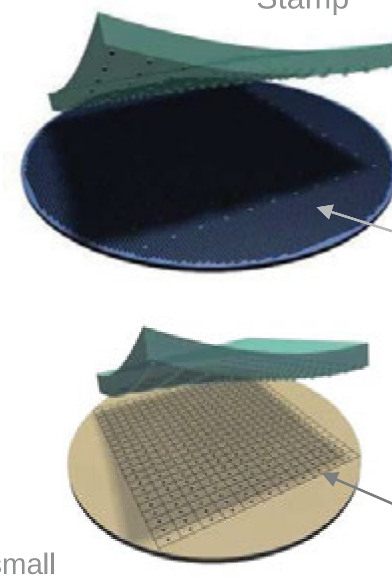
Key Semprius CPV technologies

- Micro-transfer printing
  - Release and transfer large arrays of cells from EPI source wafer onto interposer substrate
  - Reduce wafer level processing and re-use source substrates
  - Is compatible with SMT technology
- Small and thin high efficiency cells on interposer
  - III-V triple junction cells printed on an alumina interposer (COI)
  - Forming the cathode and anode interconnect by a thin film metallization process
  - No need for active thermal management
- Low loss optics
  - Plano-convex primary and glass lens secondary
- Mature surface mount technology
  - Assembling arrays of surface-mountable COI with thru-wafer vias onto backplane using industry standard solder reflow
  - High reliability, low cost and scalability to high volume production

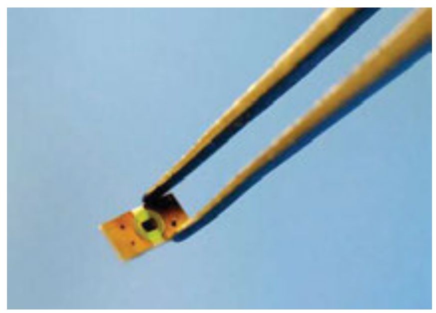
Stamp

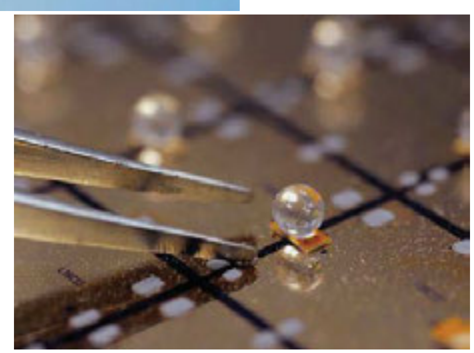


CPV cells on GaAs wafer

CPV cells on alumina substrate

COI-High efficiency small receiver (>40%)





COI mounted on backplane using standard surface mount technology

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Selection of COI for backplane assembly

- Each COI undergoes stringent pass/fail criteria, ensuring reliable operation of the module with a large number of cells.
- The COI substrate level testing before dicing includes:
  - Dark IV (DIV)
  - Light IV (LIV)
    - Determine I_{sc} (short circuit current), V_{oc} (open circuit voltage) and other parameters using a spot focused Xenon light source
  - Cell temperature rises
    - Derived from the band gap shift of the InGaP sub-cell at a fixed power load
  - Quality of EL image

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On-going reliability testing

- COI bonded on the test boards (using with the same material and re-flow process as the backplane used for the module) for on-going reliability testing:
  - Temperature cycle (TC from -40˚C to 85˚C)
  - Damp heat (DH) exposure (85˚C/85%RH)
  - High temperature and current aging

Onset of dark grid fingers after temperature cycles

- Observed dark grid fingers in some EL images after several hundred temperature cycles
- Cells with or without dark grid finger, showed no significant difference in DIV/LIV characteristics
- Dark grid fingers or other EL defects were identified by a comparison of EL images with a reference cell EL image

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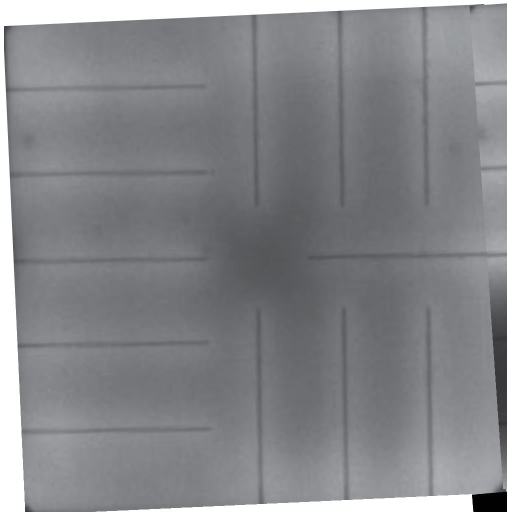
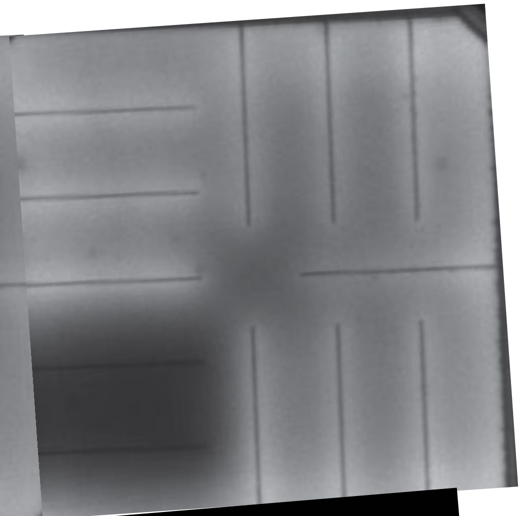
EL images at t=0 and after 427 TC for a cell (L2C2) with dark grid fingers

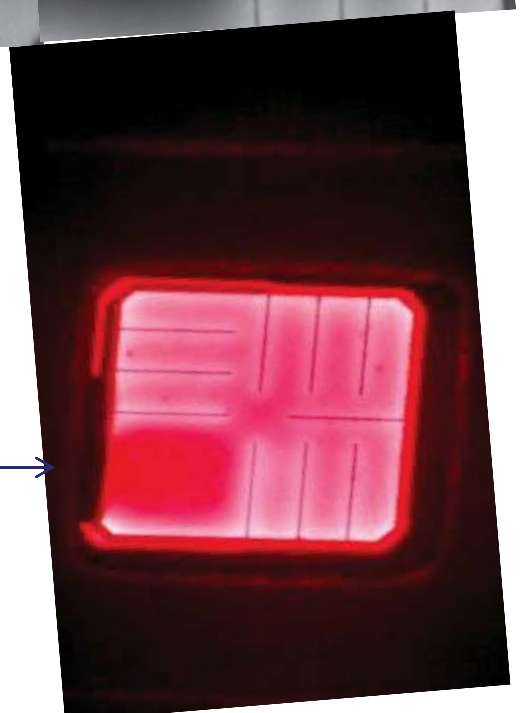
L2C2

EL image at t=0



EL image after 427 TC





Interconnect metal

- Two dark grid fingers were observed after 427 TC.
- The entire cell EL image indicates the dark region started from the interconnect metal edge.

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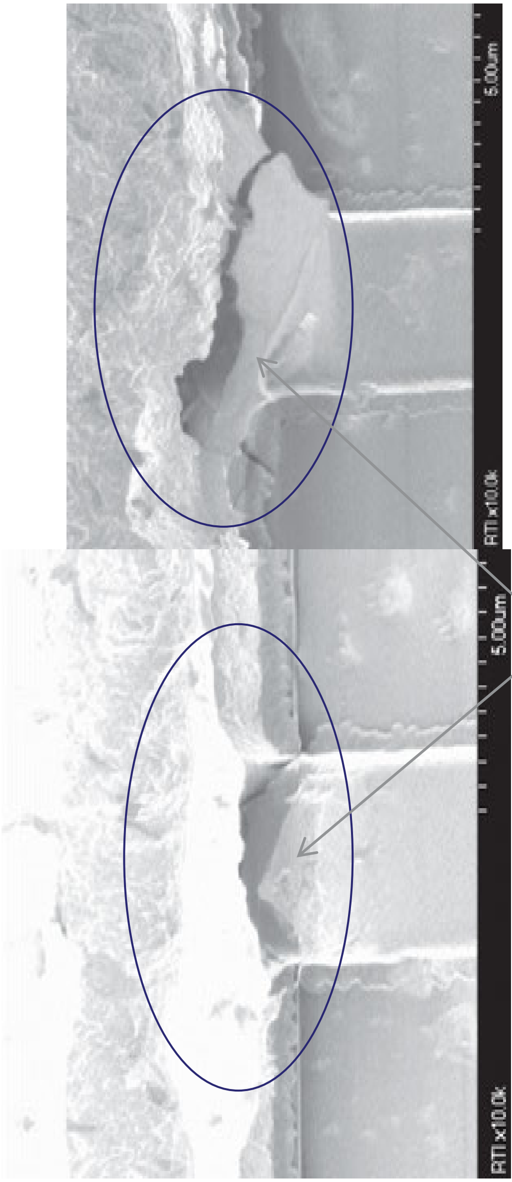
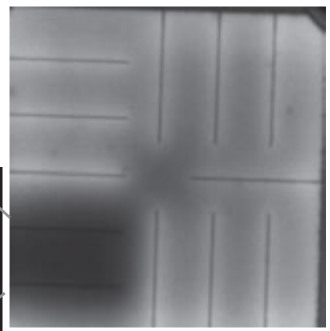
SEM images near the junctions of interconnect and grid finger (L2C2)

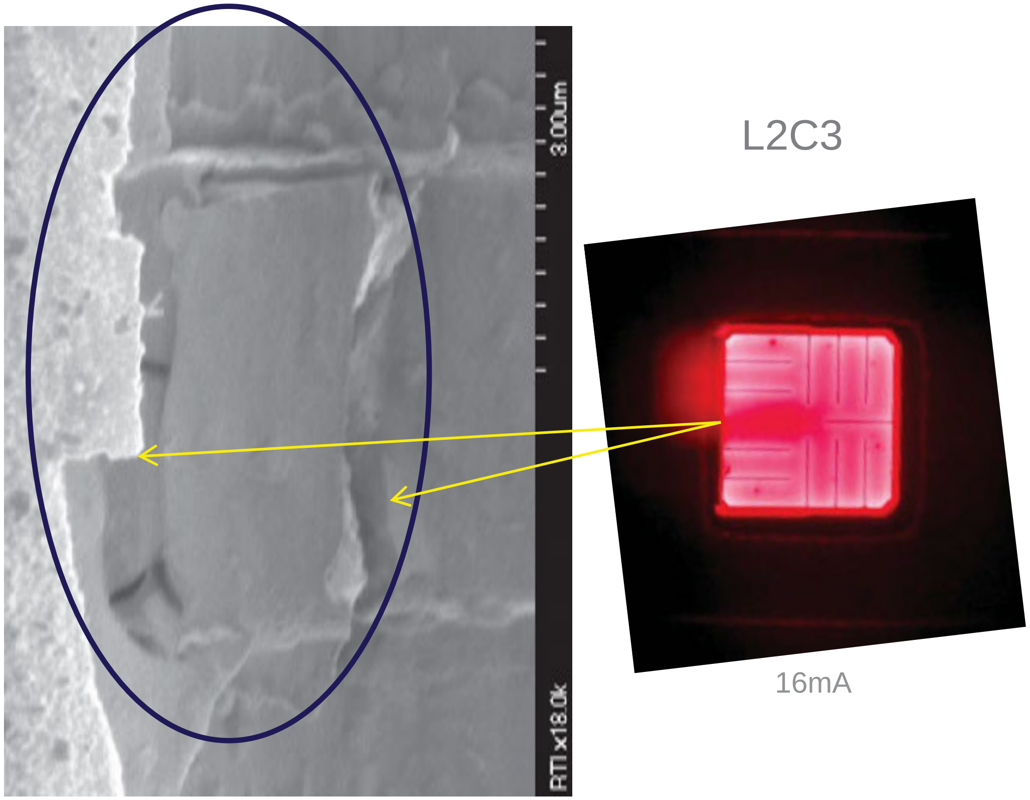


SEM and EL images after 427 TC



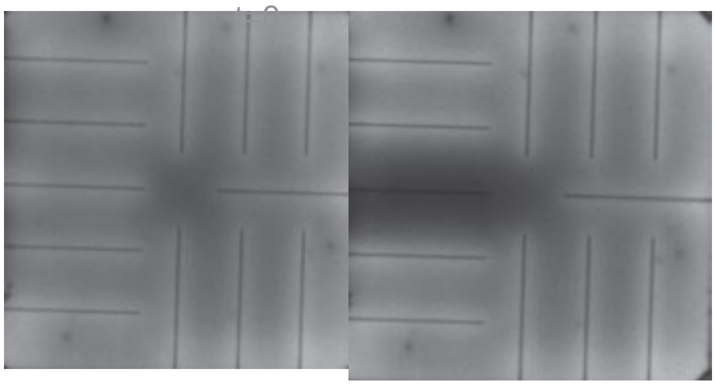
- Two micro-cracking occurred near the junctions of interconnect and two dark grid fingers
- This cell with thick plated interconnect metal

The 2nd example showing a dark finger after 427 TC



EL image at t=0

EL image at t=427



- A micro-cracking occurred near the junction of interconnect and the dark grid finger.
- This cell with thick plated interconnect metal.

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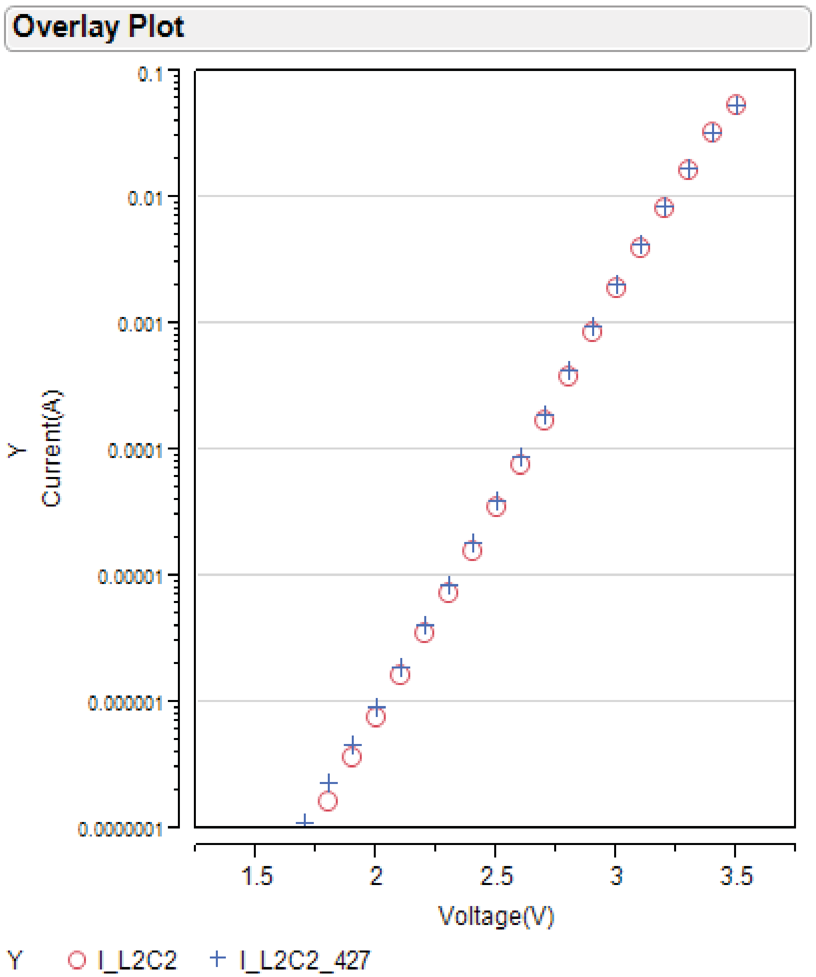
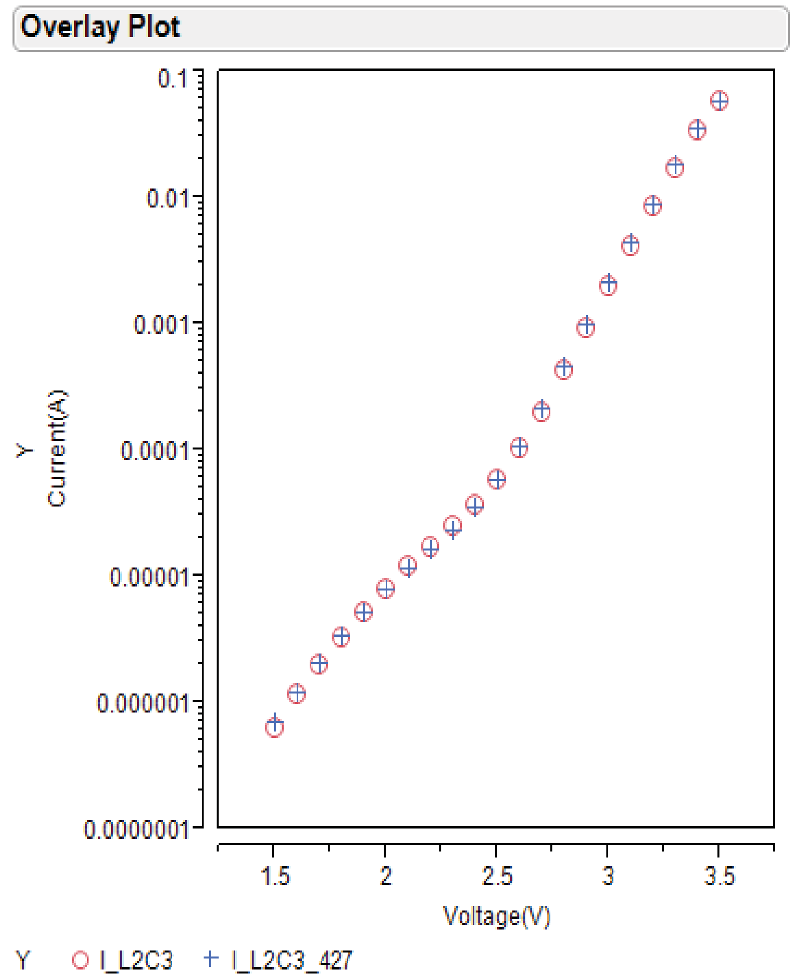
Comparison in DIV characteristics before and after 427 TC for cells with micro-cracking

- Nearly identical DIV characteristics (Current measured at t=0 and after 427 TC were plotted as a function of voltage), as shown below, for these cells (L2C2 and L2C3) with micro-cracking





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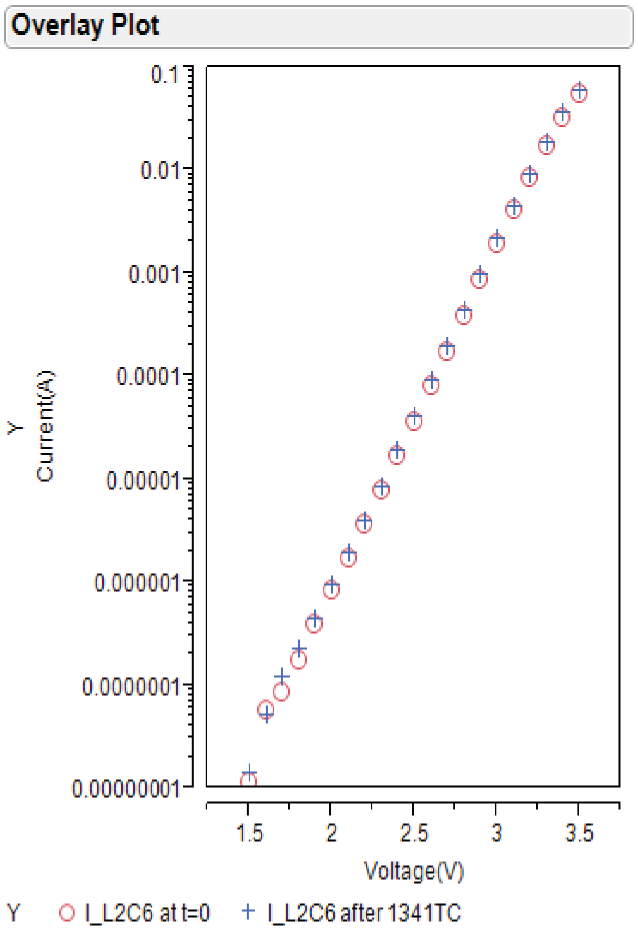
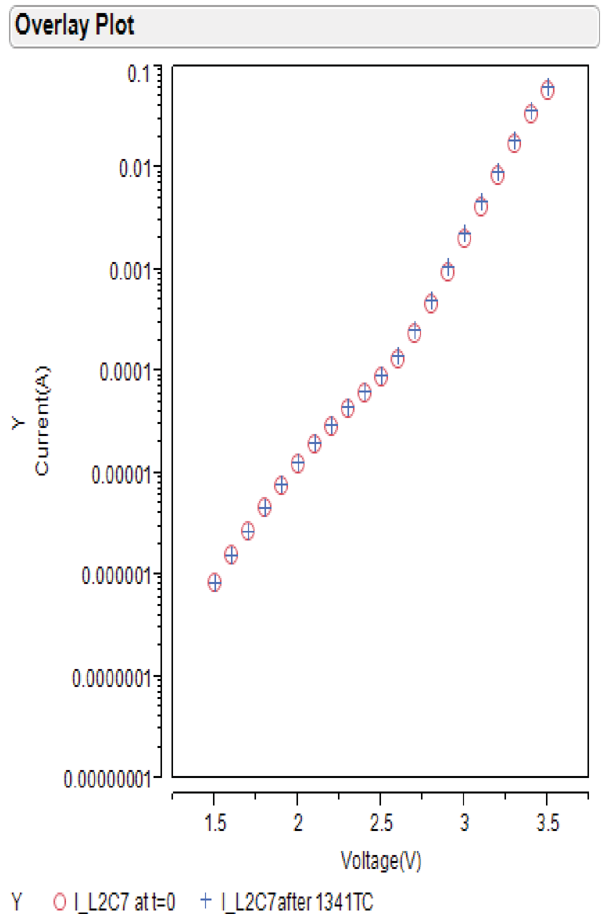
Comparison in DIV characteristics before and after 1341 TC

- No significant change in DIV characteristics (Current measured at t=0 and after 1341 TC were plotted as a function of voltage) for cells with or without dark grid finger
- These cells with thick plated metal

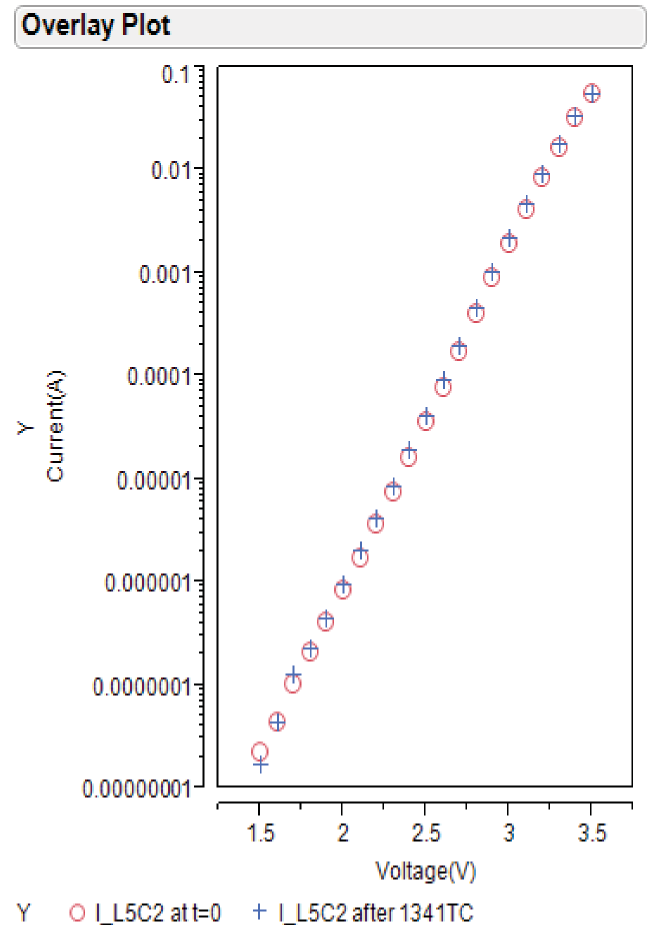
Cell without dark finger



Cell without dark finger



Cell with one bad grid finger



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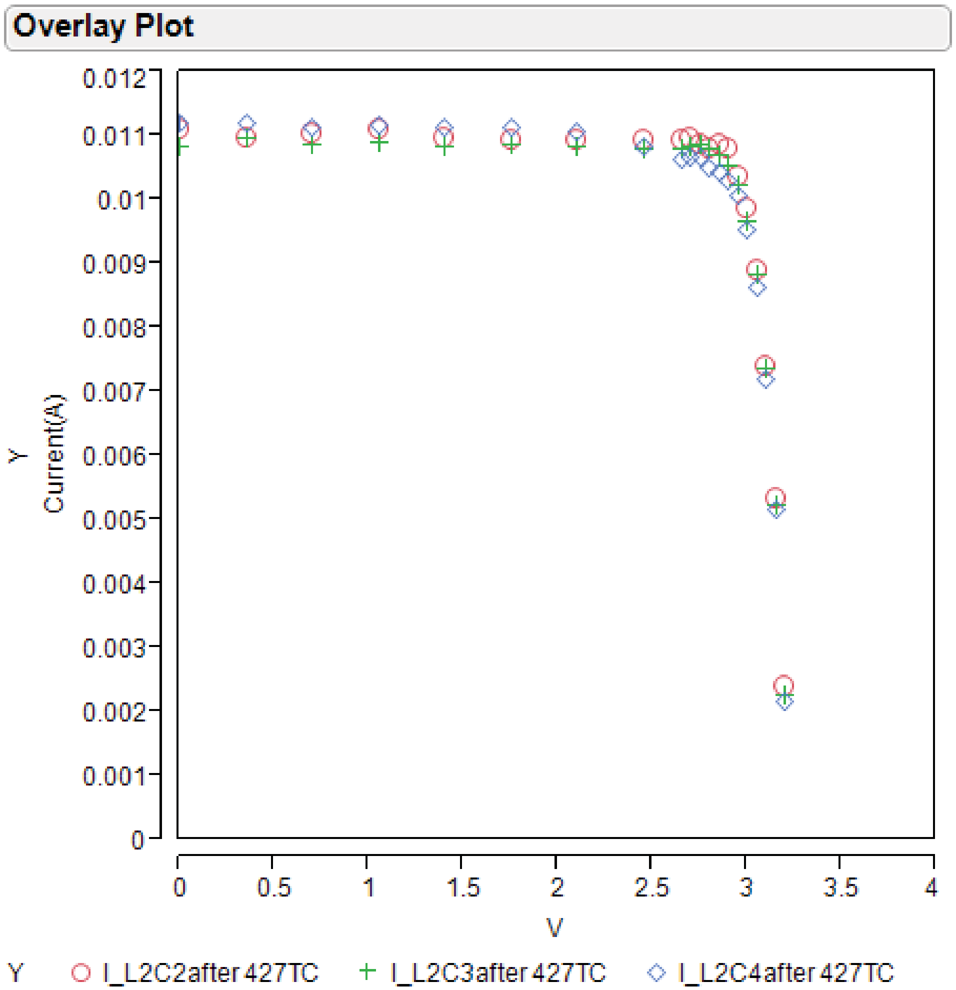
Comparisons in Light IV (LIV) characteristics for cells with or without dark grid finger after 427 TC



- L2C4-no dark grid finger
- L2C3 with one (1) and L2C2 with two(2) dark grid fingers, respectively.
- Nearly identical LIV traces for cells with/without dark grid finger
- These cells with thick plated metal

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Comparison in LIV characteristics for cells with different numbers of dark grid fingers from the same COI substrate after 1341 TC

- Below showed the mean and standard deviation of I_{sc} ,V_{oc} and field factor(FF) with different numbers of dark grid fingers.
- Due to a rather large standard deviation, the differences listed below are not statistically different.
- Due to small changes in LIV characteristics and instability of the Xenon light source, it is not feasible for monitoring LIV changes as a function of TC.

	I_{sc}			V_{OC}			FF		
Number of dark grid fingers after 1341 TC	Mean (mA)	Mean (ratio)	Std. Dev. (mA)	Mean (V)	Mean (ratio)	Std. Dev. (V)	Mean (%)	Mean (ratio)	Std. Dev. (%)
0	11.54	1.000	0.459	3.246	1.000	0.0076	88.95 (Note1)	1.000	0.69
1	11.39	0.987	0.486	3.240	0.998	0.0059	88.44	0.994	0.78
2	11.27	0.977	0.259	3.237	0.997	0.0049	88.04	0.990	0.87

Note1: Due to cell current matching, higher operating temperature and current in the module, the module level has a lower FF, compared to the individual COI.

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Strain energy simulation

- Dark grid fingers were observed mainly on the left side of cell (cathode side)
- We suspected that the high strain, resulting from the high step coverage and large mismatch in CTE of various layers, was the root cause of the micro-cracking after temperature cycles.
- Strain simulation by the finite element analysis with:
  - A fixed dielectrics thickness
  - Different plated metal thickness

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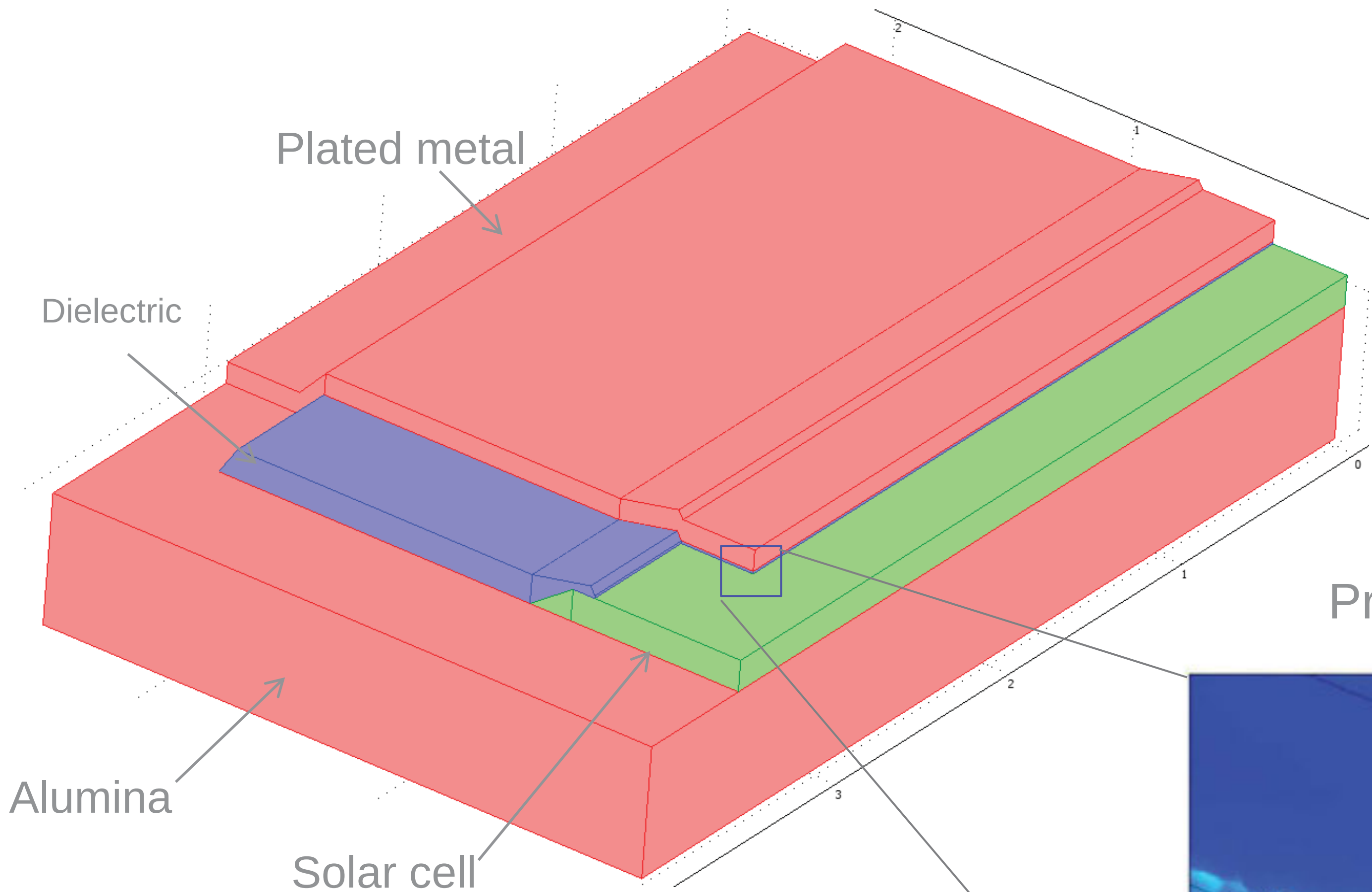
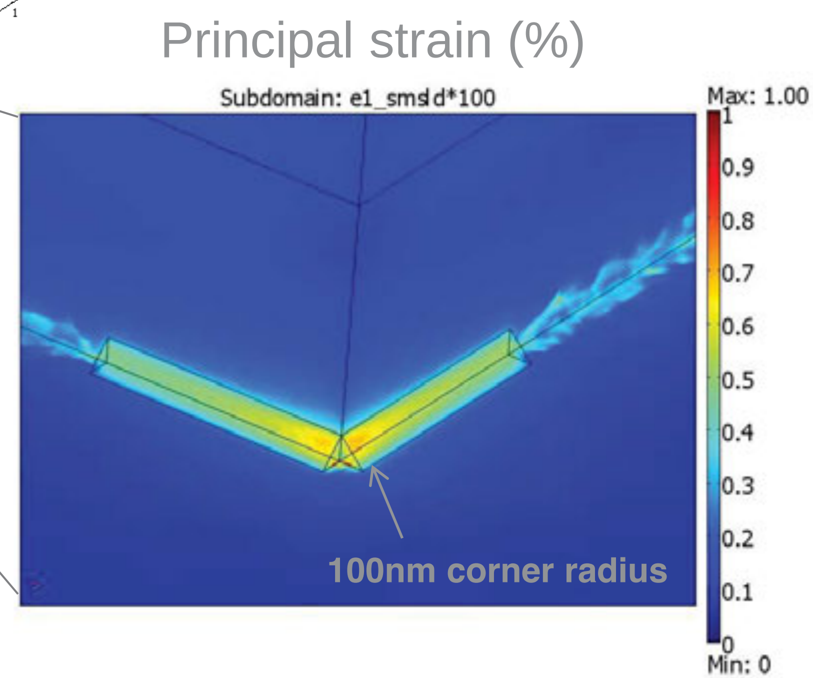
Finite Element Analysis for strain energy





Structure is fully relaxed at 20C
Temperature raised to 85C (65C delta)

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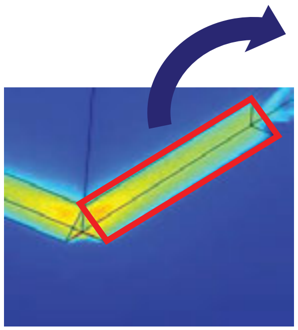
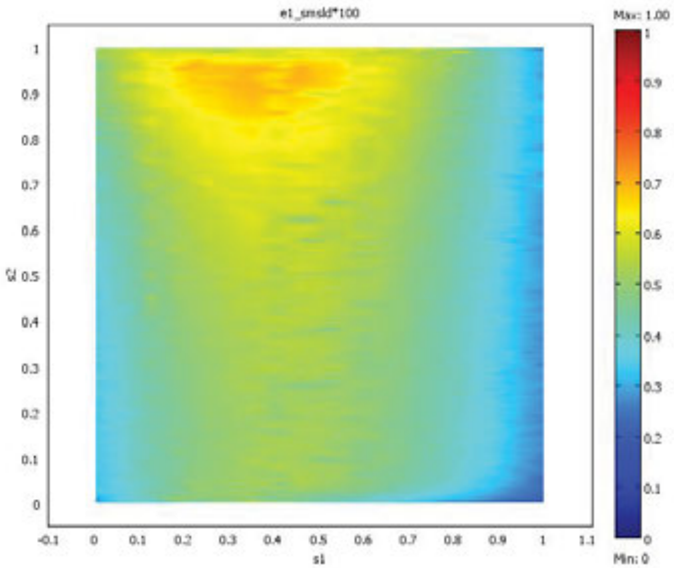
Strain with different plated metal thickness

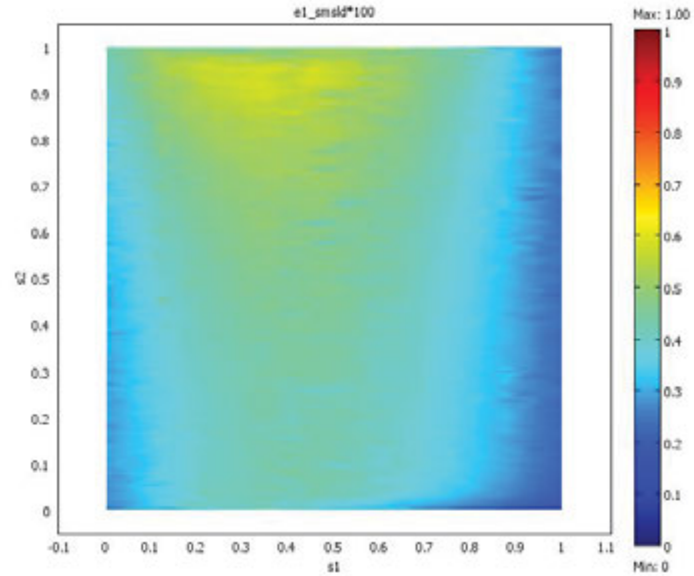


Principal strain (%)

Plated metal thickness : 4 AU (arbitrary unit)

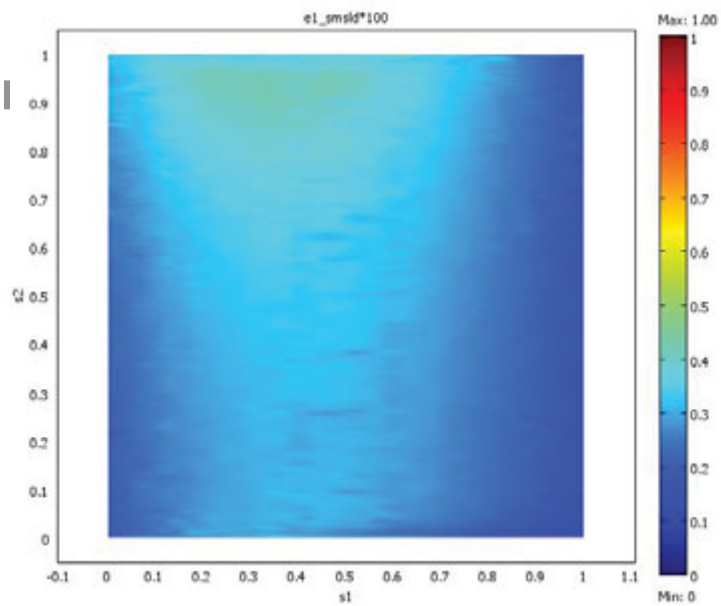


Plated metal thickness : 3 AU

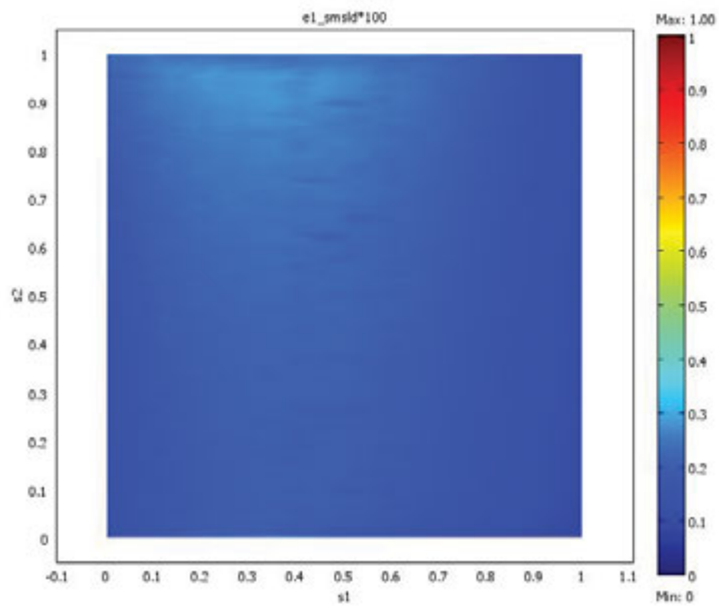


~2x reduction in strain by using thin plated metal

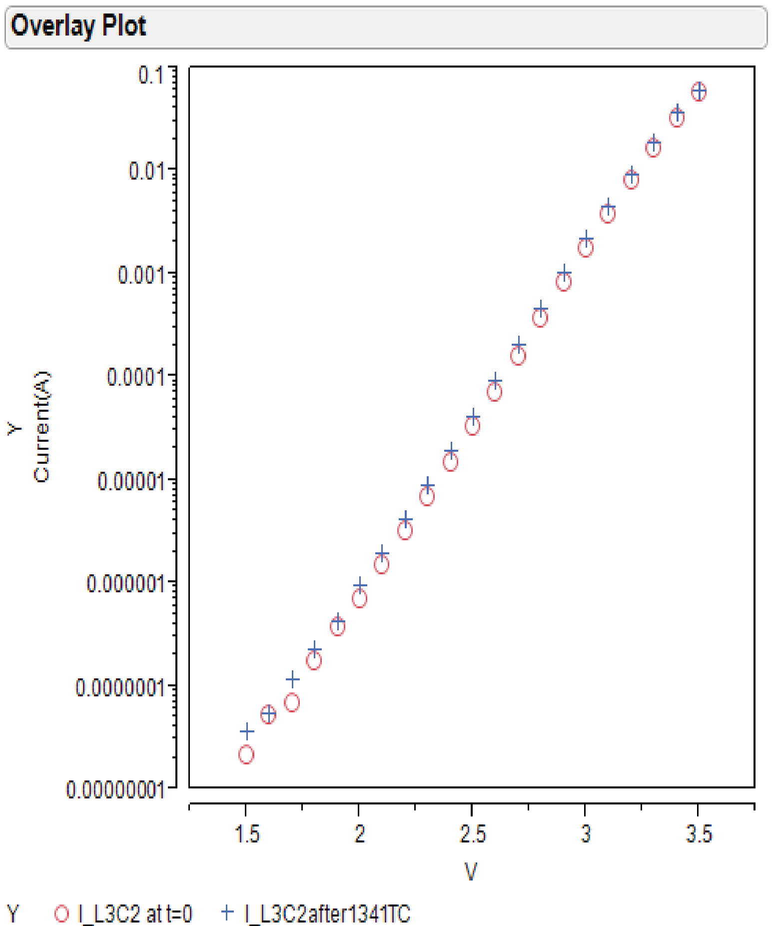
Plated metal thickness : 2 AU

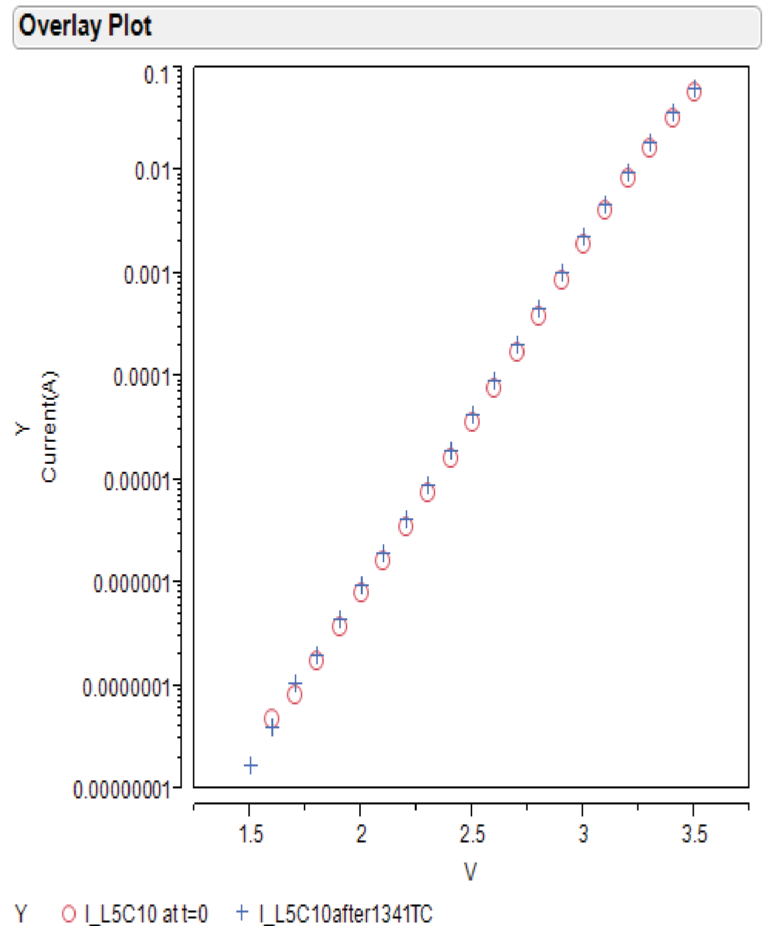


Plated metal thickness : 1AU



Examples of DIV characteristics before and after 1341 TC for cells with thin plated metal





Comparison in LIV characteristics for COI with two different plated metal thickness

- Comparison in LIV characteristics after 1341 TC, between two COI substrates with different plated metal thickness (cells printed from the same source wafer)
- Two COI substrate tested at about the same time frame
- Observed a significant number of cells with dark grid fingers from the COI substrate with thick plated metal after TC
- No dark grid finger from the COI substrate with thin plated metal
- Slightly higher mean and lower standard deviation for COI with thin plated metal

	I_{sc}		V_{OC}		FF	
After 1341TC	Mean (mA)	Std. Dev. (mA)	Mean (V)	Std. Dev. (V)	Mean (%)	Std. Dev. (%)
COI without dark grid finger (with thick plated metal)	11.54	0.459	3.246	0.0076	88.95	0.69
COI without dark finger (with thin plated metal)	12.00	0.224	3.247	0.0043	89.02	0.38

SEMPRIUS

Summary

- SEM images indicated that the dark grid fingers were related to micro-cracking of the metallization
- No significant degradation in DIV and LIV with the onset of the dark grid finger, resulting from the temperature cycling
- COI with thin plated interconnect metal showed a significant reduction in micro-cracking, which is consistent with the strain simulation results
- The elimination of dark grid fingers could be responsible for the slight improvements in LIV characteristics

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Reliability Characterization of an Exposed Spherical Ball Lens in a Dish-Based CPV System

Blake Coughenour[a], Brian Wheelwright[a], David Lesser[b], Roger Angel[a, b]
The University of Arizona [a]College of Optical Sciences and [b]Steward Observatory

Abstract

Our CPV solution uses a 3.1x3.1 m square paraboloidal reflector to bring sunlight initially to a high power point focus [1]. A spherical lens at this focus reformats the concentrated sunlight onto secondary optical concentrators so as to uniformly illuminate 36 triple-junction cells at 1200x geometric concentration [2]. This 120 mm diameter ball lens (Figure 1) made of fused-silica acts as the entrance aperture into our self-contained Power Conversion Unit (PCU) where the triple-junction cells are integrated with a closed-circuit active cooling system. As originally envisaged, the ball lens would be preceded by a protective window, transmitting at a lower flux level comparable to that of the glass vacuum tubes of trough reflectors. However, based on current experience, such a window may not be necessary. The lens in operation without a window is seen in Figure 2, at the entrance to the PCU. In over 200 hours of on-sun reliability testing, our prototype system has consistently generated 2 kW of power, with no measureable deterioration of the ball lens surface. Efforts are being undertaken to develop field-relevant accelerated lifetime testing to understand optical durability, surface scatter, and corrosion of anti-reflective coatings on the glass substrate. Soiling is of particular concern, chiefly due to high flux levels incident on particulates present at the ball lens surface (Figure 3). We present some initial analysis of our field-tested ball lens and soiled fused-silica slides under high concentration. Our goal is to understand the long-term effects of particle accumulation and surface reflectivity loss, with the intent of mitigation.

Optical System

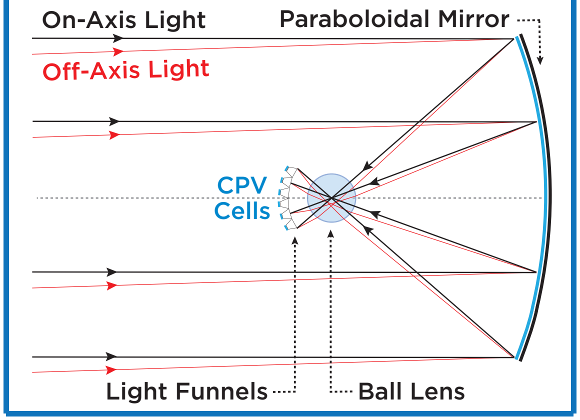


Figure 1: Ball Lens

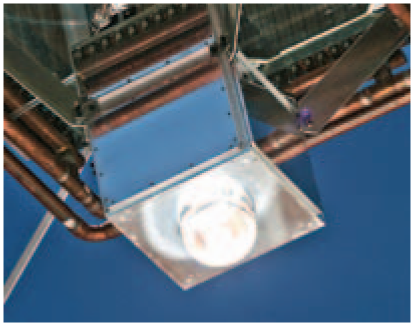


Figure 2: Ball Lens in Operation

Figure 3: Dust Accumulation on Ball Lens

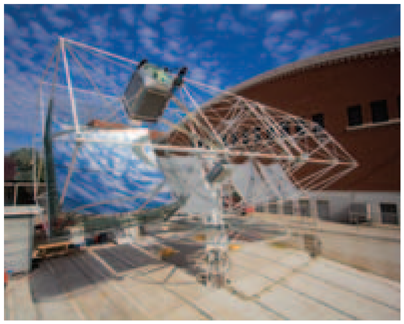
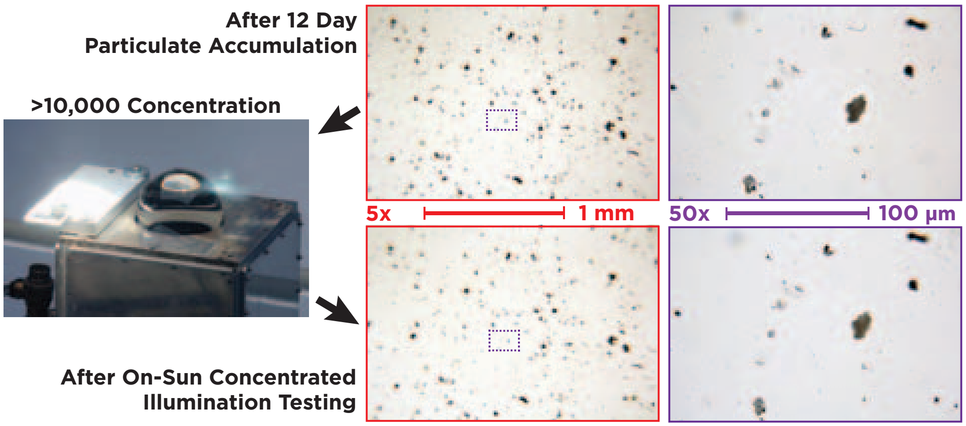


Figure 4: 20kW Solar Tracker Unit

Soiled Fused Silica under High Concentration

In this test, we sought to simulate and image the effects of concentrated sunlight passed through a Fused-Silica ball lens after it had been soiled with several days of particulate accumulation. To do this, we took Fused-Silica slides and subjected them to 12 days of horizontal dust accumulation at our solar tracker installation. After taking pictures of the particulates, we mounted the slides near the focus of our tracker and illuminated the slides with nearly the same concentration factor as the ball lens experiences for a few minutes. Re-examining the slides, we noticed very little change in the concentration of surface particulates, which are easily removed with water. This suggests that the solar flux the ball lens experiences is insufficient to damage the un-coated surface. We will soon revisit this test to simulate a soiled AR coating on a ball lens.



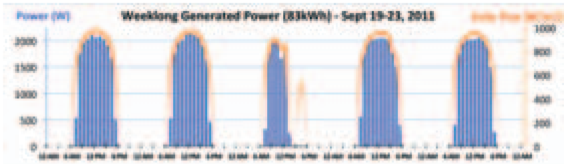
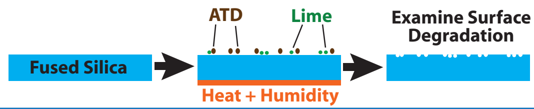


Figure 5: Example of Consistent Power Generation

Accelerated Testing

We recognize the importance of validating our concentrator's optical system lifetime under environmental conditions and understanding the consequent operation and maintenance implications and expect to work closely with NREL to develop appropriate testing procedures. One facet of our current test plan will involve exposing optical elements to Arizona Test Dust (ATD) powder at high humidity and temperature to see etching of the fused silica and it's AR coating by hydrated lime scabs. Over time, we will measure transmission degradation and use scanning electron microscopy to characterize etch pits in the glass substrate and coating. By using concentrated doses of ATD and lime, we hope to gauge the long-term effects on optical transmission.



References

[1] J. Roger P. Angel, Tom Connors, Warren Davidson, Matt Rademacher, Blake Coughenour, Guillaume Butel, and David Lesser "Development and On-Sun Performance of Dish-Based HCPV" in 7th International Conference on Concentrating Photovoltaic Systems: (CPV-7), 4-6th April, 2011, Las Vegas, Nevada, (USA), AIP Conf. Proc. 1407, pp. 34-37
[2] G. Butel, T. Connors, B. Coughenour, and R. Angel, "Design, Optimization and Characterization of Secondary Optics for a Dish- Based 1000x HCPV System," in Renewable Energy and the Environment, OSA Technical Digest (CD) (Optical Society of America, 2011), paper SRWC3.

Solar Durability and Lifetime Extension Center at Case Western Reserve University: Degradation of Acrylic Polymer and Acrylic Mirrors

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Solar Durability and Lifetime Extension (SDLE) Center

Determining Lifetime and Degradation Science for Photovoltaics

Motivation: Lifetime & Degradation Science for Photovoltaics

2010 Science For Energy Technology Workshop
- Convened by U. S. DOE, Basic Energy Sciences

Science challenges across 9 areas of energy

PV prioritized research directions
- Photovoltaic module lifetime and degradation science
- Fundamental properties of photovoltaic interfaces
- Advanced photovoltaic analysis & computational modeling for scale-up

Qualification testing of systems
- Is not sufficient for reliability & lifetime
- To avoid excessively high degradation rates
- Dramatically reduced service lifetimes

Determine degradation mechanisms and rates
- Scientific underpinning of reliability and qualification standards

Quantitative degradation rate modeling
- Connects materials, components, system
- To overall degradation rate, linearity, reciprocity
- And system lifetime performance

Overview of the SDLE Methodology

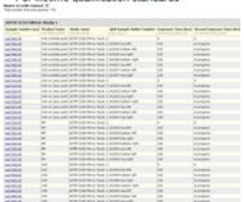
Does Current Qualification Testing Advance PV Reliability & Lifetime?
- Provides no lifetime validation
  - Only pass/fail results
- Testing doesn't produce scientific insights
  - Into degradation mechanisms and rates
- Reliability testing not founded
  - In the physics of failure
- Qual. testing doesn't advance PV research

Lifetime and degradation science
- A scientific foundation for advancing PV lifetime
- Quantitative degradation mechanisms & rates
- Real time and accelerated testing
- Single and multi-factor studies

Material, component & system approach
- Causation of failure arises in
  - complete systems and their interactions
- Must study component and material degradation
  - To identify degradation mechanisms

Structured approach: study protocols
- For exposures and evaluations

Development of new study protocols
- For lifetime qualification standards



Engineering epidemiology
- For lifetime prediction
  - e.g. PV Power degradation rates

SDLE Exposure Capabilities

Outdoor Testing
- SDLE SunFarm
  - Irradiance
  - Temperature and Humidity
  - Yang Hu et. al. in Silicon Poster Session

Indoor Testing
- Irradiance
  - Newport Solar Simulator 1-50x Suns
  - SpectroLab XT 30 CW 100-1200x Suns

Irradiance, Temperature, & Humidity
- Q-Labs QUV/Spray Weathering Chamber
- Q-Labs Q-Sun Weathering
- CSZ ETC 100 cu. ft. with 1 Sun Light Rack

Temperature & Humidity
- CSZ ETC 8 cu. ft.

SDLE Evaluation Capabilities

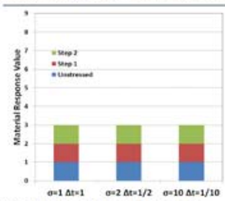
Optical Properties
- Cary 6000i with DRA-1800
- Filmetrics PARTS-UV
- HunterLabs UltraScan Pro
- Woollam VUV-Vase
  - Spectroscopic Ellipsometer

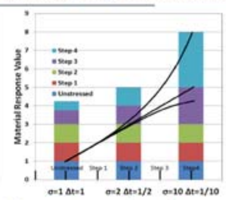
Light Scattering Properties
- ScatterMaster 3D
- Wyatt Dawn Helios II

Surface and Bulk Properties
- Kruss DSA Surface Chemistry
- Olympus Confocal Microscope
- PHI VersaProbe XPS Microprobe

Mechanical Properties
- Nanoindentation
- Peel Strength

Stress Response Framework for Lifetime & Degradation Science





System response to applied stress

Study response of system
- At many stress levels
- With many applied stresses (multi-factor)

If system is only linear response
- Then increased stress rate
- Reduces time required for given net stress

If systems response is non-linear
- Then sub-, supra-linear response observed

Cross-correlation of stress/response
- Defines the system's response function
- Captures linear and non-linear phenomena
  - As a matrix transform of stress to response

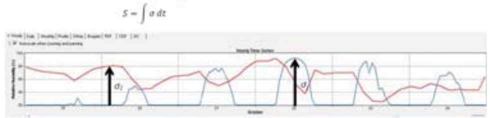
Stressors: How to Quantify Damaging Conditions

Stress Intensity (σ)
- Graph of daily irradiance TMY3

Net Stress is a Stress Intensity over time

$$S = \int \sigma \, dt$$

Perform stress tests with
- Higher Net Stress
- AND Higher Stress intensity



Real world exposures have more than one stressor

$$\sum S = \int (\sigma_i \otimes \sigma_j \ldots \otimes \sigma_n) dt$$

Graph is of daily Irradiance and Relative Humidity TMY3

10.2 Times Higher AM1.5 Irradiance

$$A_\sigma = \frac{\text{AM1.5}}{UVA340} = \frac{618.3\ MJ/m^2}{60.65MJ/m^2}$$

9.0 Times Higher AM1.5 Dose

$$A_\sigma = \frac{\textbf{AM1.5}}{\textbf{UVA340}} = \frac{977.6MJ/m^2}{108.7MJ/m^2}$$

Responses: Materials change as a function of stressors

Various levels of stress
- Stress intensity σ and integrated stress **S**
  - Such as solar irradiance and solar dose

Measure responses
- Optical responses: abs/cm, index of refraction, YI, haze …
- Mechanical: embrittlement, crazing, haze …

Cross-correlation defines transferability
- Reciprocity between irradiance and time
- Linearity over dose or time
- Additivity over wavelength

Determine range of applicability of materials, components, systems
- Not just applicability to one set of stresses

Response a function of
- Stress level σ
- Net stress S

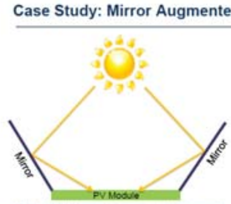
$$R = f({}^{\sigma}S) = \int f(\sigma)\sigma dt$$

Materials show many responses
1) Fundamental Absorption Edge
2) Light Stabilizer Package
3) Visible Yellowing

Expansion to multiple stresses gives:

$$R(S_i, S_j, \ldots S_n)$$
$$= f(\sigma_i, \sigma_j, \ldots \sigma_n) \int (\sigma_i \otimes \sigma_j \ldots \otimes \sigma_n) dt$$

Case Study: Mirror Augmented PV (MAPV) with Acrylic Mirrors



MAPV Value Proposition
- Increased irradiance on PV module
- Decreases LCOE
- Mirrors cost less than modules

Components in Acrylic:
- 1) Base resin
  - Residual monomer
- 2) Light stabilizer package
  - UV absorbers, radical scavenger

Acrylic Back Surface mirrors
- Use acrylic transmission
- To reduce UV and IR load on module

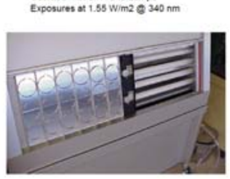
Durability Questions
- Are acrylic mirrors durable for 25 years?
- Do increased module stressors decrease service life

REPLEX PLASTICS

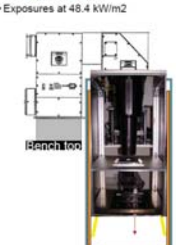
Stressors: Inducing Responses in Materials

Compare 2 irradiance tools
- Full spectrum Xe AM1.5D
- Fluorescent UVA 340

QUV at 1.55W/m² at 340 nm
- Fluorescent weathering chamber
- Outfitted with UVA 340 Lamps
- Exposures at 1.55 W/m2 @ 340 nm



48.4 kW/m² Newport Solar Simulator
- Diverging Xenon Arc AM1.5
  - With 13X Concentrator
- Exposures at 48.4 kW/m2



Compare MP Responses: For 3 Degradation Mechanisms

Incremental absorbance to dose

$$Incremental\ \frac{Abs}{cm}\ per\ \frac{GJ}{m^2}\ Dose$$

$$= \frac{Abs_{i+1}(\lambda)/_{cm} - Abs_i(\lambda)/_{cm}}{Dose_{i+1} - Dose_i}$$

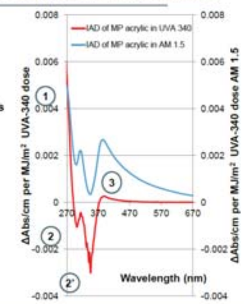
For AM1.5 and UVA-340 Experiments

1) Base resin photodegradation
- Agreement in IAD rate
  - For Mechanism 1

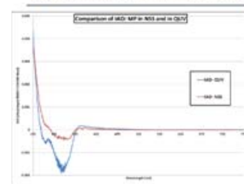
2) Stabilizer package bleaching
- Photobleaching Rates Comparable
- Rates Determine Package Lifetime

3) Visible region yellowing
- AM1.5 Yields Greater YI Yellowing
- Spectral Differences AM1.5 vs UVA340
  - Produce different amounts of yellowing

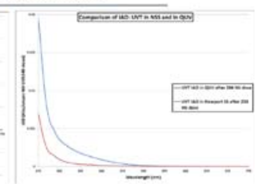
Degradation Mechanisms & Rates
- To Estimate Lifetime Performance



Comparison of 2 Different Types of Acrylic



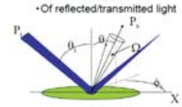
IAD Results for Multipurpose Acrylic
- Two different stress conditions
  - Newport Solar Simulator
  - QUV Weathering Chamber
- QUV 206 MJ dose
- NSS 253 MJ dose



IAD Results for Ultra-violet Transmitting Acrylic
- Two different stress conditions
  - Newport Solar Simulator
  - QUV Weathering Chamber
- QUV 206 MJ dose
- NSS 253 MJ dose

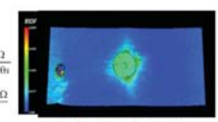
Acrylic Mirrors after Exposure to Corrosive Environment

Bidirectional Scatter Distribution Function (BSDF)
- Of reflected/transmitted light

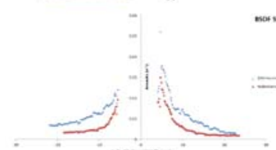


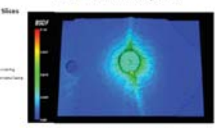
$$BRDF = \frac{Ps/\Omega}{Pi\cos\theta_s}$$

$$CCBRDF = \frac{Ps/\Omega}{Pi}$$



Baseline Mirror Response





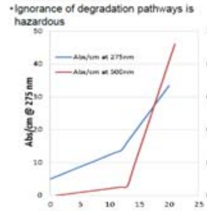
Mirror Response after 1000 hours of salt fog corrosion in a Q-Fog

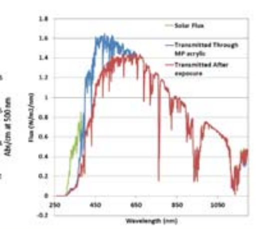
Examples of Lifetime Prediction Metrics for MAPV

Lifetime Prediction: After 12 years
- Optical absorbance will increase like UVT
- Due to consumption of stabilizers

PV technologies rely on 25 year warranted lifetimes
- Ignorance of degradation pathways is hazardous

Leading to 7% loss in transmitted flux
- after 76 MJ/m² flux
- 8 years 1 sun exposure





Conclusions

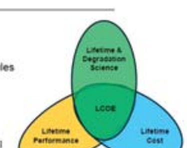
Lifetime and Degradation Science
- Furthers the understanding of PV reliability
- Determine degradation mechanisms and rates
- Beneficial for achieving 25 year lifetimes in PV modules

Current qualification testing
- Doesn't advance PV research

SDLE Center
- Significant Outdoor and Indoor Testing Capabilities
- Optical, Light Scattering, Surface & Bulk, Mechanical Evaluation Capabilities

Stress/Response Framework
- Cross-correlation of stress/response defines the system's response function

Acrylic Case Study
- Compare 2 different types of acrylic in 2 different types of stresses



Acknowledgements
- Funding support from Ohio Third Frontier under Tech 11-060 & Tech 12-004
- Replex Plastics

This poster does not contain proprietary or confidential information.

Concentrix. Focus on Power.

Reliability of Concentrix^{TM} CPV Modules

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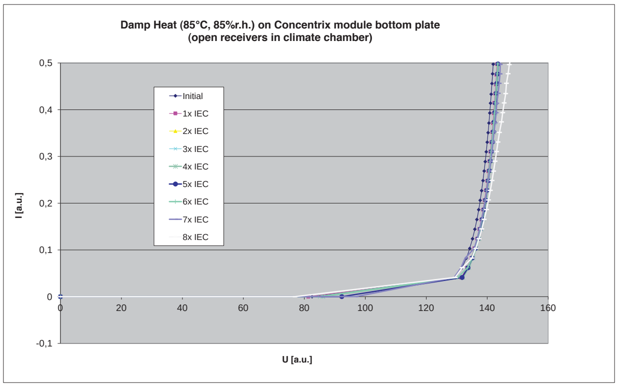
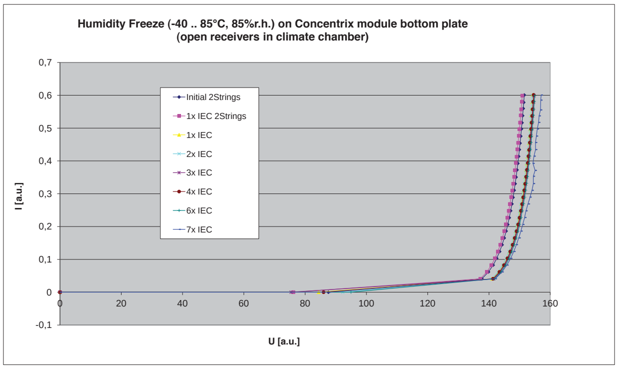
INTRODUCTION

- Reliability and durability of all (C)PV power plant components is very much impacting the overall life cycle costs of a (C)PV power plant.
- Due to it’s intended permanent exposure to intense sun radiation the CPV module is stressed more than other components.
- This is reflected in a significantly more demanding IEC design qualification test program for CPV modules compared to PV modules.
- Soitec’s Concentrix^{TM} CPV modules are designed to exhibit an outstanding robustness and reliability even under hash environmental conditions.
- The last three Concentrix CPV module generations have all been certified according to IEC 62108:2007.
- Based on Soitec’s field experience of more than 550,000 months of Concentrix CPV module operation there are no indications as how to improve module reliability have been found. Therefore, we focus on indoor tests here.
- Additionally, field test results available so far provide no indication for any performance degradation (ISFOC and Soitec data analyses).
- To prove and further improve the CPV module robustness, extensive internal and external accelerated ageing tests are executed at Soitec.

CLIMATE CHAMBER TESTS ON OPEN RECEIVERS

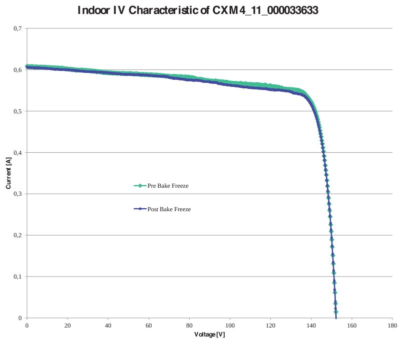
- To increase the hydro-thermal stress applied, electrically connected receivers were stressed without any protective module shell in Damp Heat and Humidity Freeze for a duration exceeding the IEC requirements by far.
- Dark IV and EL measurements were executed after each 1000 hour or 20/40 cycles interval of accelerated ageing.





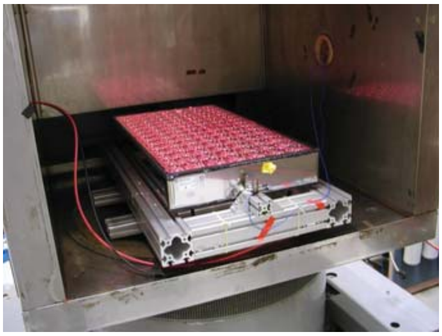
BAKE FREEZE TEST

- To verify the temperature stress resistance of the Concentrix CPV module design, an extreme temperature test was conducted in which a CPV module was baked 160°C for one hour and then frozen at -70°C for an additional hour.
- Indoor flasher IV curve measurement results taken before and after this severe stress test show no significant differences in the IV curve.



VIBRATION TESTING

- In normal operation, a CPV module in not expected to be exposed to vibration load. But during transportation to the site it might be exposed to significant vibration stresses. Considering the Concentrix CPV module design specifics, the bond wires and the 6 module shell surfaces are potentially sensitive to resonances.
- The bond wires showed resonances at around 1 kHz. The CPV module shell (glass plates) resonances were determined to be at around 60 Hz.
- While in EL operation mode the CPV module was subjected and passed a random vibration test with an acceleration up to 31 g (10 PSD).



CONCLUSION

- Besides the test results shown, Concentrix CPV modules and/or components have also been subjected to other tests as well such as salt spray test (IEC 61701 Ed.2), IPX6 tests, sand storm test, and temperature and UV tests.
- After greatly prolonged accelerated hydro-thermal ageing, the wired receivers show some significant resistance increase which will need to be further investigated.

ABENGOA

Innovative technology solutions for sustainability

ABENGOA SOLAR

Abengoa Solar develops and applies technologies to generate electricity from the sun, working to limit climate change and to develop local communities using mostly concentrating solar thermal, but also photovoltaic technologies.

Abengoa Solar CPV field testing capabilities

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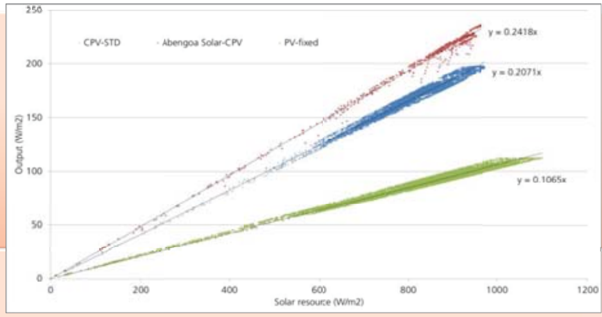
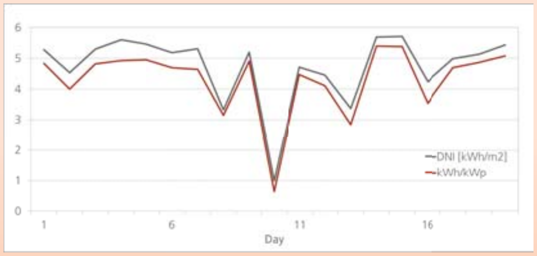
Abengoa Solar PV Inc., Lakewood, CO 80215

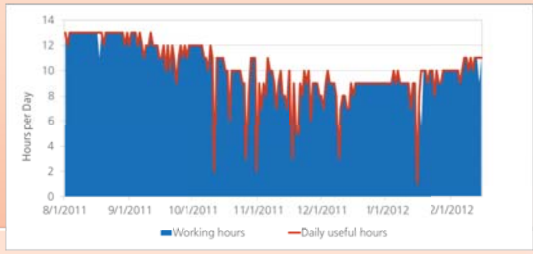
Abengoa Solar operates a field testing Photovoltaic Laboratory in the south of Spain, located in the Solúcar Platform, a 300 MW solar generation facility. This laboratory provides the capabilities to evaluate new PV technologies, such as CPV, comparing them with other commercial and under development technologies. The systems in the laboratory are monitored exhaustively, analyzing the performance under different operating conditions and the evolution over time. Monitoring these systems is important to understand the technology and identify reliability issues. The information generated is critical to introduce new technologies in the market, providing backtrack data and increasing the confidence in the technology.

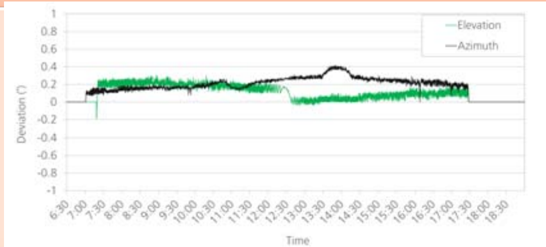


Comparison of various technologies under test and at different sizes in our PV Lab. Output versus input in terms of power per active area of the system is a key performance parameter that allow the direct comparison and variability evaluation for technologies deployed in different ways and sizes. Slope of the graphs are a direct measure of the efficiency of the technology. The graph above includes only quartiles 2 and 3 of the data distribution. Each data point has been collected at different intervals that may range from 5 minutes to 15 minutes. Si PV mounted on a fixed structure, first generation CPV and Abengoa Solar commercial CPV new generation are compared.



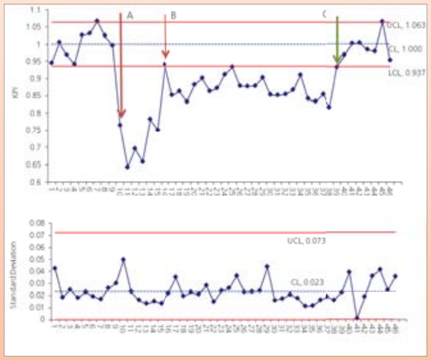
Stringed and single modules are monitored, operating at the maximum power point, analyzing the evolution over time. The availability of the installation is monitored continuously, allowing the opportunity to identify the origin of any problem in the data. The production of the CPV system is compared with the performance models for the specific meteorological conditions, identifying any variation in the performance of the system over the time. The graph above shows the energy yield of a system compared with the available solar resource.





A reliable tracking system is mandatory for a commercial CPV technology. CPV trackers are monitored in the laboratory to validate the tracking accuracy, considering daily and seasonal evolution and to evaluate the availability of the system. The graph above shows the availability of a tracker over a period of six months, while the graph on the left shows the tracking accuracy measured over one day. Demonstrating the reliability and correct performance of the tracking system is critical for the commercialization of a new technology such as CPV. Other important issues related to the operation and maintenance of the trackers are also evaluated, such as the correct movement over the whole range and the energy consumption or the behavior in emergency conditions.

As an example of test follow up, the graph on the right shows an Statistical Process Control approach which allows for identification of deviation and variability on the performance of the systems under tests. The sample graph shows how an material assembly tests failed after heavy rain (A) period which led to >10% performance degradation after returning to dry weather condition (B) and back to standard performance after manual intervention and drying out of the assembly (C).



Abengoa Solar - CPV testing capabilities

- Monitoring of CPV individual and stringed modules operating on the maximum power point
- IV measurement of modules, strings and trackers
- Meteorological station and measurement of DNI and GNI on the trackers
- Measurement of spectral distribution
- Measurement of tracking accuracy

Solar Junction

Reliability Testing of Triple Junction Solar Cells with GaInNAs Bottom Layer Using Dilute Nitride

	Initial Flash Data					Final Flash Data				
Wafer name and piece	Voc (V)	Isc (A)	Fill Facto	Irradiance (W/cm^2)	Effic.	Voc (V)	Isc (A)	Fill Facto	Irradiance (W/cm^2)	Effic
C485-4 P1	3.431	2.273	87.0%	53.4	40.7%	3.421	2.213	86.8%	52.2	40.3%
C485-4 P7	3.439	2.271	86.8%	53.3	40.7%	3.419	2.220	86.5%	52.3	40.2%
C486-4 P2	3.434	2.289	86.3%	53.4	40.7%	3.419	2.236	86.2%	52.2	40.4%
C486-4 P6	3.431	2.271	86.5%	52.9	40.8%	3.429	2.239	85.7%	52.3	40.3%
C493-4 P3	3.431	2.292	85.8%	53.3	40.6%	3.436	2.256	85.6%	52.3	40.7%
C493-4 P5	3.429	2.294	86.0%	53.3	40.7%	3.419	2.258	85.5%	52.5	40.3%
	Reference Cells									
C485-4 P4	3.43	2.297	85.6%	53.768768	0.402	3.432	2.240	85.4%	52.7	39.9%
C486-4 P4	3.425	2.284	86.1%	53.67863	0.402	3.419	2.243	86.7%	52.8	40.3%
C493-4 P4	3.427	2.304	85.8%	53.511983	0.405	3.420	2.267	85.9%	52.7	40.5%

- Under Sun Tests
- Six Piece Sample Stressed
- Three Piece Sample Unstressed

HALT

Matrix of Sun-Years of Cell Life for Different Activation Energies and Operating Temperatures based on No Failures of 22 cells after 166 hours at

Operating Temp (°C)	Activation Energy (eV) 0.7	0.8	0.9	1.0
80	179	369	763	1576
90	95	179	338	637
100	52	90	156	271
110	30	47	75	120

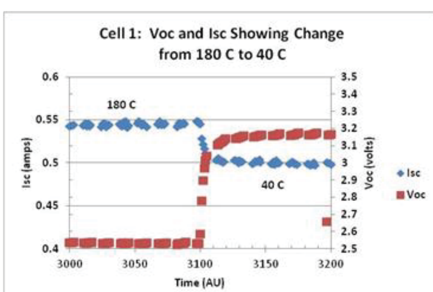
1 sun-year = 9 sun-hrs/day*365 days/yr = 3285 hrs

- Probability of Failure After 30 Years ≤ 1%

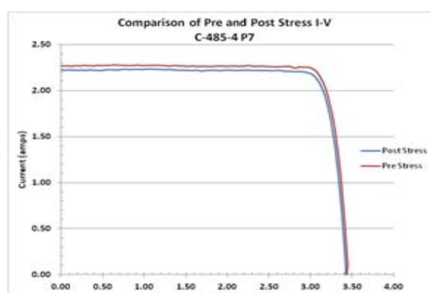
Under Sun Chamber
100 – 1000 Suns

Cell ID	Delta after 6931 total cycles. ΔVoc	ΔIsc	ΔFF	ΔEff
C-485-4 P1	-0.29%	-2.68%	-0.21%	-0.96%
C-485-4 P7	-0.58%	-2.24%	-0.40%	-1.18%
C-486-4 P2	-0.43%	-2.34%	-0.05%	-0.56%
C-486-4 P6	-0.06%	-1.39%	-0.94%	-1.18%
C-493-4 P3	0.12%	-1.57%	-0.19%	0.25%
C-493-4 P5	-0.29%	-1.55%	-0.61%	-0.95%
Ave.	-0.26%	-1.96%	-0.40%	-0.77%
References				
C-485-4 P4	0.04%	-2.48%	-0.15%	-2.03%
C-486-4 P4	-0.18%	-1.78%	0.67%	-1.63%
C-493-4 P4	-0.18%	-1.57%	0.15%	-1.43%
Ave.	-0.11%	-1.94%	0.22%	-1.70%

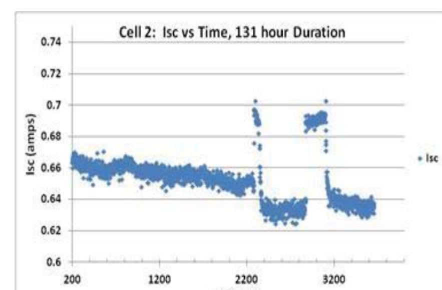
- Under Sun Testing 30 Sec on 30 Sec off
- Six Piece Sample Stressed
- Three Piece Sample Unstressed



- High Temp Storage
- 22 Piece Sample



- High Temp Storage
- 22 Piece Sample



- High Temp Storage
- 22 Piece Sample

Data Supplied by Dr. John Herb

*** This Poster Contains No Confidential Information**

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morgansolar™
sunsimba™

NREL NATIONAL RENEWABLE ENERGY LABORATORY
2012 PV Module Reliability Workshop
February 28–March 1, 2012 - Golden, Colorado; CPV March 1, 2012
Workshop sponsored by the DOE Solar Energy Technologies Program.
U.S. DEPARTMENT OF ENERGY

RELIABILITY OF PMMA UNDER CONCENTRATION

The Sun Simba™ Light-guide Solar Optic

Morgan Solar's CPV system operates using TIR within a PMMA waveguide. Studies of PMMA reliability in regards to solar application have been performed and show that certain grades show excellent durability[1]. However PMMA has not been extensively studied when it is operating at concentration.

Here we examine the optical transmission of PMMA as used in the Morgan Solar CPV system. The material stack is replicated for both outdoor and indoor experiments, showing different degradation rates depending on the incident spectral shape.

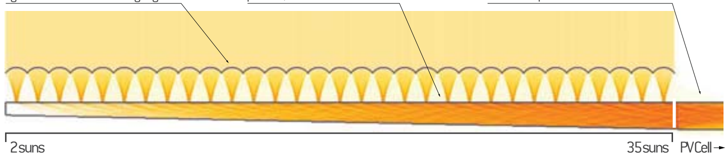
[1] D. Miller et. al. Durability of poly(methyl methacrylate) lenses used in concentrating photovoltaic modules, Proc. SPIE ,7773, 777303 (2010)

System Description

Deflector: Outward facing component. Accepts incoming light and directs it into the Light-guide.

Light-guide Layer: Receives light from deflector along multiple locations. Light intensity varies as a function of position, from 2 suns to 35 suns.

Secondary Optical Component: Couples light from LGL to cell. Final concentration to 900 suns occurs in this component.

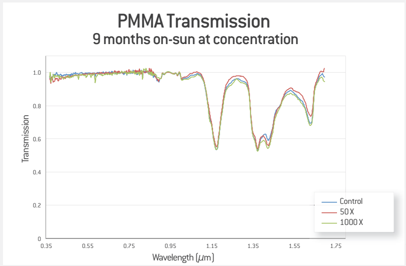


Materials

The deflector (DEF) and Light-guide Layer (LGL) are composed of PMMA., with an absorber additive package to protect against UV damage. The secondary optical component is composed of B270 glass to handle high concentration, and bonded to the high-efficiency cell.

Outdoor Testing

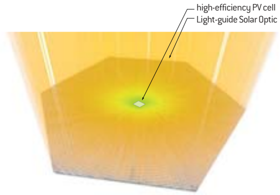
Outdoor testing on a dual-axis tracker.
Outdoor testing on a dual-axis tracker. A simple optical system focuses sunlight 1000X onto the sample. The lens is composed of B270 glass for UV transmission. A sheet of PMMA with UV absorbers is placed in front of the lens to mimic the spectral transmission of the deflector.



The testing setup was placed on the sun tracker system with routine alignment verification. After 9 months continuous tracking at 1000X concentration, equivalent to 17 years of normal operation, we observe a decrease of 8% in transmission at 400nm.

Inherent outdoor testing uncertainties and potential sources of error include tracking accuracy (broaden exposed area, effectively reducing total irradiance) and local weather (Toronto has lower DNI than SW California, and is at a higher latitude, therefore receiving less UV). Additionally, unknown heritage and composition of PMMA UV filter layer.

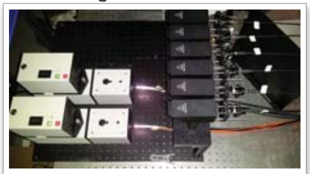
To corroborate the findings, experiments under more controlled conditions were conducted indoors.

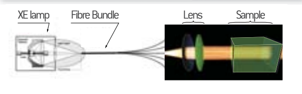


Raytrace

This 3D raytrace image, generated using optimization software, illustrates incident light being captured, concentrated and directed to a high-efficiency PV cell at the Light-guide's center.

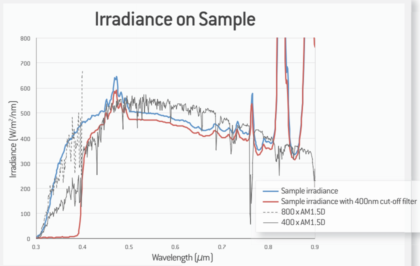
Indoor Testing



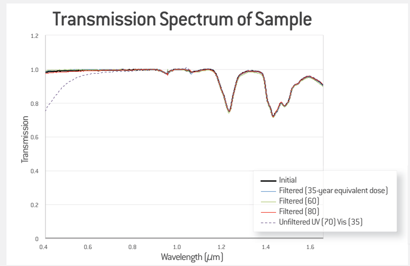


Instrument Setup: Broad-band Xe lamp was used to closely match solar spectrum. Output from the lamp was coupled to a fiber-bundle, up to 500mW per fiber. Light focused onto sample at concentration up to 400X (visible). UV filter with cut-off wavelength of 400nm was placed before some samples to emulate spectral transmission of primary optical component of Sun Simba.

Measurement: Sample transmission spectrum were measured bi-weekly for two months. Incident spectrum was measured at the same time to account for lamp, fiber and lens degradation. Transmission measurement system uses a smaller spot size to measure only the central portion of the illuminated area.



Spectrum incident on samples
Shape of the spectrum incident on samples is a good match to the AM1.5D in the visible. Concentration factor begins at 400X at start of experiment. The Xe lamps contain a larger fraction of UV than the AM1.5D spectrum. Ultraviolet portion of the incident spectrum is 800X AM1.5D UV.



Transmission spectrum of light-guide material with filtered and unfiltered light
Material under a filtered spectrum shows almost no degradation even after the equivalent of 80 years of 1 sun illumination (solid lines).
Material under unfiltered light (dashed line) is shown with the equivalent of 35 years of 1-sun illumination and almost 70 years of UV exposure. The transmission at 400nm drops by 15%. This amount of yellowing results in a 4.5% decrease in top-cell current production with an AM1.5D spectrum.

Conclusion

The results presented here are at extreme concentration level for PMMA, and well beyond standard levels of acceleration. Due to the intense concentration, a thermally induced degradation of the PMMA top layer which may not be present during normal operation may occur. The relationship between concentration and degradation rate (ie. linear, super-linear etc.) will be established to corroborate extent of acceleration and estimation of damage.

Spectral filtering to eliminate the UV portion of the spectrum can greatly reduce yellowing of PMMA, even under concentration. To better understand the rate and extent of damage a greater resolution at early aging need to be established. Therefore, more measurements will be taken early during testing.

Actual service conditions will contain variations in temperature as well as in spectrum; making accelerated testing that completely mimics natural conditions difficult. Due to this natural variability in temperature and spectrum, outdoor experiments will be repeated with UV-filtering PMMA of known composition and a more rigorous tracking and focusing system.

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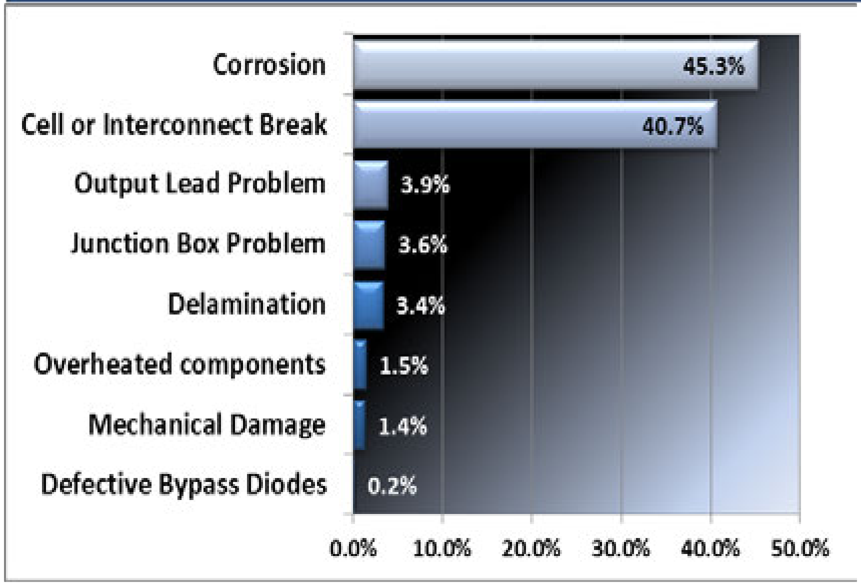
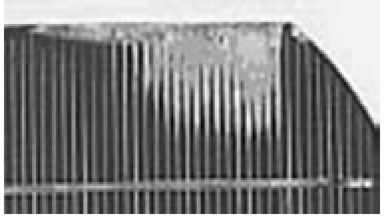
Lessons Learned From Flat Panel that can be applied to CPV

Lessons Learned – Flat Panel PV

Flat Panel Field Returns



Source: "Long Term Reliability of PV Modules", J.H. Wohlgemuth, D.W. Cunningham, A.M. Nguyen & J. Miller, BP Solar International



Source: "Commonly Observed Degradation in Field-Aged Photovoltaic Modules", M.A. Quintana[A], D.L. King[a], T.J. McMahon[b] and C.R. Osterwald; [a]Sandia National Laboratories, [b]National Renewable Energy Laboratories

Source: "Lifetime Performance of Crystalline Silicon PV Modules", Ewan D. Dunlap, European Commission, Joint Research Centre, Institute for Environment and Sustainability, Renewable Energies Unit

<u>Reliability Issues to Consider for most PV Modules</u>

- Loss of electrical connections (to cells, in junction box, or leads coming out of module)
- Delamination with subsequent moisture ingress
- Improper installation
- Glass Fracture
- Hot spots that are not adequately controlled by bypass diodes (hot spots can also be caused by loss of electrical connection, see above) or bypass diode failure
- Junction box failure

Source: "Photovoltaic-Reliability R&D toward a Solar-Powered World", Sarah Kurtz[a], Jennifer Granata[b], and Michael Quintana[b], [a]National Renewable Energy Laboratory, [b]Sandia National Laboratories

Lessons Learned – Flat Panel PV

Carrisa Plains – Brown EVA or Something Else?

Source: "Improved boost mirror for Low-Concentration Photovoltaic Power Systems, David Nelson Wells, Consultant

Statement of Problem: A field installation of 5.2MW rapidly degraded to 3.0MW

1988 ca Root Cause: Using Low-Concentration mirrored light created higher concentration of UV and temperature which then caused the EVA to degrade and turn yellow or brown.

1988 ca Solution: Add UV blockers to glass and EVA to absorb UV and avoid the EVA degradation. Cerium was added to glass to block the UV. Unknown at the time Cerium also causes solarization of glass (reduction in the transmission of the glass) which in of itself was a degradation mechanism.

2002 ca Root Cause: Initial degradation caused by light induced degradation (LID) from boron-oxygen couplets (specific to solar cell manufacturer). Further degradation caused by Isc degradation above 700 nm not in the UV region.

2002 ca Solution: Solar cell manufacturers have learned about how to reduce LID but reducing the oxygen content of the silicon and other techniques. Several other solutions have been implemented to reduce other degradation mechanisms in Crystalline Silicon Solar Cells.

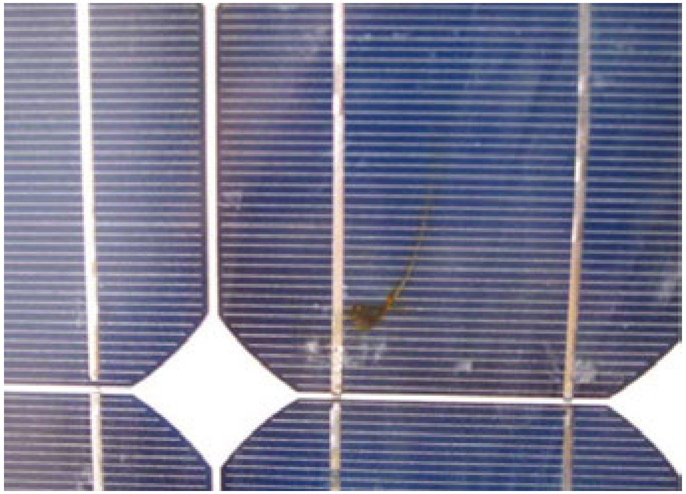
Lesson Learned: Know *RIGHT* root cause to avoid solving the *WRONG* problem

Lesson Learned: Know RIGHT root cause to avoid solving the WRONG problem

Lessons Learned – Flat Panel PV

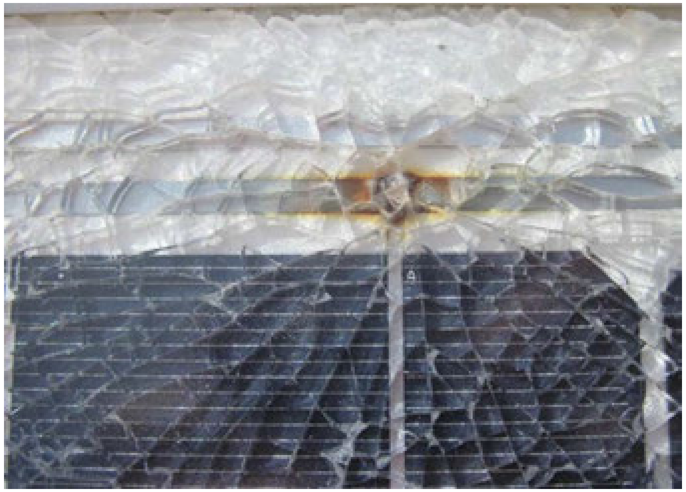
More Power = More Heat – 2 types of Hot Spots

Hot Spot caused by crack in the cell



Source: "Hot Spot Evaluation of Photovoltaic Modules", Govindasamy (Mani) Tamizhmani and Samir Sharma, Photovoltaic Testing Laboratory (ASU-PTL)

Hot Spot caused by poor solder joint



Source: "PV Module Arc Fault Modeling and Analysis", Jason Strauch, Sandia National Laboratories

Process Control – Electroluminescence (EL) scan on each module before releasing the product.

Process Control – Certified Soldering Operator – recertified annually and inline test developed to test solder joint integrity.

Lesson Learned: Control the critical processes or pay for it in the field.

Lesson Learned: Control the critical processes or pay for it in the field.

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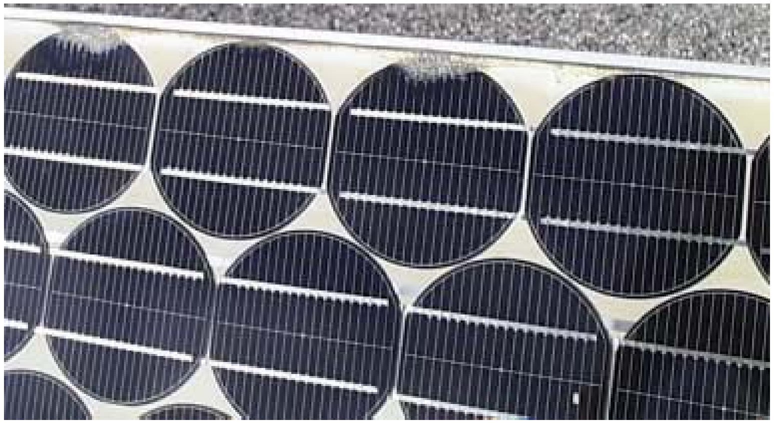
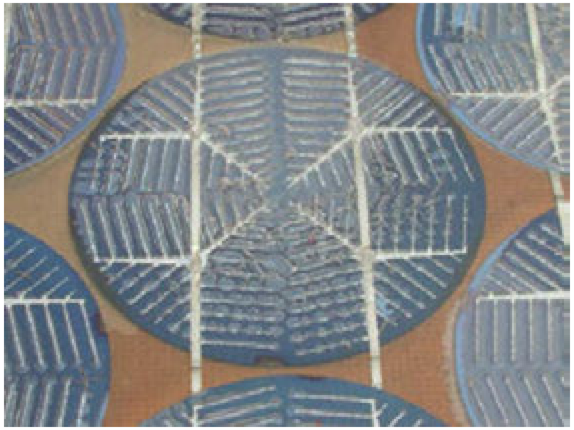
Lessons Learned – Flat Panel PV

Moisture is your enemy



Source: "TISO 10 kW Array – Born on May 13, 1982", G. Travaglini[a], J. Bishop[b], Et al., [a]LEEE-TISO, Univeristy of Applied Sciences of Southern Switzerland, [b]ESTI, JRC, Ispra



Source: "Lifetime Performance of Crystalline Silicon PV Modules", Ewan D. Dunlap, European Commission, Joint Research Centre, Institute for Environment and Sustainability, Renewable Energies Unit

A change in Anti-reflective coating (ARC) caused an interaction between the encapsulant and the ARC which caused delamination in the field.

Lesson Learned: Understand paths of moisture ingress and interactions

Lesson Learned: Understand paths of moisture ingress and interactions

Lessons Learned – Flat Panel PV

Design and Validate

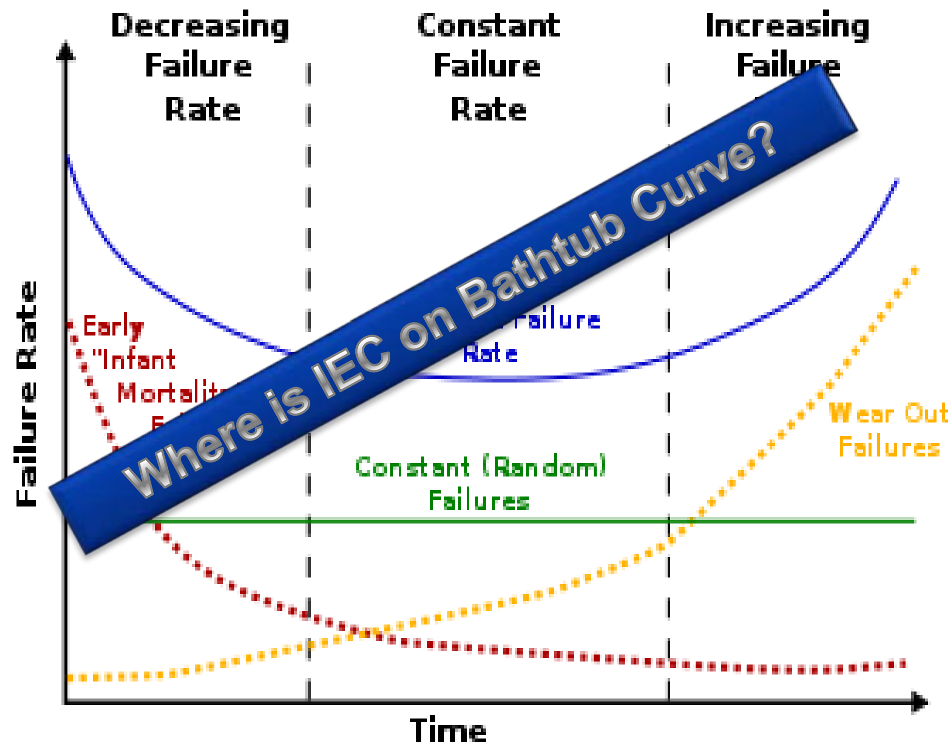
During standard product improvement cycle, a new design for a Junction Box was created. Initial verification showed great performance. Samples were summited to stress tests and were found to develop a wet insulation resistance failure. Failure analysis was conducted and root cause was determined. J-Box design was changed and passed wet insulation resistance test after the environmental stresses had been applied. No field problems were seen.

Source: Kostal Junction box – ***NOT ACTUAL J-Box used. Only for example***

Lesson Learned: Design and Validate – field returns are too late.

Lessons Learned – Flat Panel PV

Go Beyond IEC



$$k = A\,e^{-E_a/RT} = A\exp(-E_a/RT) \qquad (1)$$

$$\ln k = \ln A - \frac{E_a}{R}\left(\frac{1}{T}\right) \qquad (2)$$

$$\ln\left(\frac{k}{A}\right) = -\frac{E_a}{RT} \quad \text{or} \quad \ln\left(\frac{A}{k}\right) = \frac{E_a}{RT} \qquad (3)$$

$$\ln\frac{k_2}{k_1} = -\frac{E_a}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \qquad (4)$$

Failure mechanisms may not be exactly know but we do know several of the types of stress – humidity, temperature cycling and freezing. Testing to failure in these stresses help compare relative performance between design choices.

Lesson Learned: Stress until failing creates more information than stress alone

Lesson Learned: Stress until failing creates more information than stress alone

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Lessons Learned – Flat Panel PV

Know *RIGHT* root cause to avoid solving the *WRONG* problem

Control the critical processes or pay for it in the field.

Understand paths of moisture ingress and interactions

Design and Validate – field returns are too late.

Stress until failing creates more information than stress alone

CPV Standard Conditions

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Introduction

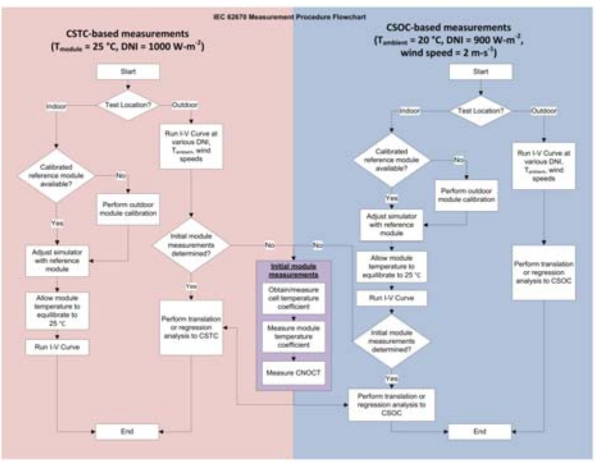
As the CPV industry matures, there is greater need for standard methods to assess module power. These methods must be flexible enough to accommodate both the wide variety of CPV architectures and the challenges of indoor testing. At the foundation of these methods are standard conditions under which the modules are to be assessed. This poster presents the standard conditions for CPV as proposed in IEC 62670-1 and the rationales behind them.

Approach

To maintain consistency with the precedent set by PV standards , IEC 62670-1 provides two standard conditions:

- Concentrator Standard Test Conditions (CSTC) - similar to PV standard test conditions
- Concentrator Standard Operating Conditions (CSOC) - similar to PV standard reference environment for determining nominal operating cell temperature (NOCT)

Though CSTC and CSOC facilitate indoor and outdoor testing respectively, performance at either condition can be assessed in both locations.



Conditions and Rationale

CSTC – Concentrator Standard Test Conditions		
Irradiance	1000 $W \cdot m^{-2}$ direct normal irradiance	• Numerically consistent with PV STC (IEC 61215) • Often defined as "one sun" • Precedent from Progress in Photovoltaics
Temperature	25 °C	• Consistent with PV STC (IEC 61215)
Temperature Location	Cell	• Easily measured in indoor testing
Spectrum	Direct normal AM1.5 spectral irradiance distribution consistent with conditions described in IEC 60904-3	• Consistent with PV STC (IEC 61215)

CSOC – Concentrator Standard Operating Conditions		
Irradiance	900 $W \cdot m^{-2}$ direct normal irradiance	• Accounts for reduced irradiance in the direct beam in CPV -appropriate locations • IEC 62108 references 900 W/m2 DNI • This irradiance is readily available in the field for outdoor testing
Temperature	20 °C	• Consistent with PV standard reference environment for determining NOCT (IEC 61215)
Temperature Location	Ambient	• Easily measured in outdoor testing
Wind Speed	2 $m \cdot s^{-1}$	• This is a compromise between average wind speeds in CPV-appropriate locations and the measurement consistency achieved on calm wind days.
Spectrum	Direct normal AM1.5 spectral irradiance distribution consistent with conditions described in IEC 60904-3	• Consistent with PV STC (IEC 61215)

Next Steps

These standard conditions will be up for vote as IEC 62670-1 by the IEC national committees later this year. There is an effort underway to amend IEC 60904-3 to include the direct spectrum.

Progress continues on the CPV module performance assessment methods which are targeted to be published at IEC 62670-3 in 2014.

References and Acknowledgements

[1] S. Kurtz et al., "Considerations for How to Rate CPV," in 7th International Conference on Concentrating Photovoltaic Systems, 2011 © American Institute of Physics.

[2] *Concentrator Photovoltaic (CPV) Module and Assembly Performance Testing—Standard Conditions*, IEC Standard 62670-1, 2012 (expected).

Special thanks to all members of IEC Technical Committee 82, Working Group 7 for their contributions toward this standard.

Overview of CPV Tracker Safety

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Introduction

Until recently in the United States, the safety evaluation of CPV Trackers was relatively directionless in that safety certification agencies were left to put together a "best fit" evaluation approach because of a lack of an available standard for trackers in general. With the publication of the Outline of Investigation for Solar Trackers, UL 3703, in May 2011, a clear evaluation approach was established for CPV Trackers. This UL 3703 overview offers a glimpse of the key safety construction and testing considerations and how the evolution of this outline will affect evaluation of future CPV Trackers.

Key Tests in UL 3703

The following are key UL 3703 safety tests for a CPV Tracker system:

1. Maximum-Voltage Measurements Test – This test is used as a basis for the Dielectric Voltage Withstand Test and determination of minimum electrical spacings
2. Temperature Test – Determines if maximum rated temperatures are exceeded for the tracker system and its components during normal operation
3. Dielectric Voltage Withstand Test – Evaluates the electrical insulation of the tracker
4. Overload Test – Evaluates the tracker in an abnormal electrical overload condition
5. Grounding Impedance Test – Evaluates the grounding continuity between the equipment bonding conductor and any other metal part that is required to be grounded
6. Strain Relief Test – Determines if mechanical strain is transmitted to field-wiring leads or an input/output cord
7. Bonding Conductor Test – Evaluates the bonding circuit's ability to hold an overload current and limited short-circuit current
8. Static Load Test – Evaluates the tracker's structural ability during a weight overload condition
9. Rain and Sprinkler Tests – Evaluates the tracker's ability to keep water away from live parts during rain/sprinkler conditions
10. Flexing Test – Evaluates wiring which is subject to flexing or movement during normal use
11. Power Restoration Test – Evaluates the tracker's ability to prevent risk of injury to persons during a loss of power condition
12. Locked Platform Test – Evaluates the tracker's ability to operate safely during a locked rotor condition
13. Emergency Stop Test – Evaluates the tracker's ability to stop in a timely manner during an emergency stop condition

Key Construction Considerations of UL 3703

The key UL 3703 safety construction considerations are mainly mechanical in nature and place an emphasis on the following key topics for a CPV Tracker system:

1. Tracker Enclosure – All live and moving parts must be enclosed and protected from mechanical damage to reduce risk of fire, shock, etc.
2. Grounding System – An NEC compliant grounding system is required for all dead metal parts, giving consideration to the grounding connection means, location, intended application, etc.
3. Tracker Controller - The burden of proof is on the manufacturer to establish how the control circuit works and how it controls the CPV Tracker. It is essential to establish if a given control circuit is being relied upon for safety.
4. Protection of Users and Service Personnel – Covers requirements for accessibility of live parts in order to protect users and service personnel from electric shock or injury.
5. UL 2703 – The platform, which supports PV modules, is to be evaluated per the Outline for Rack Mounting Systems and Clamping Devices for Flat Plate PV Modules, UL 2703. Such an evaluation is not insignificant in cost.
6. Installation Manual - An Installation Manual shall be provided for the tracker, which describes assembly, grounding means, required cautionary statements/markings, operation of the tracker, etc. This is one of the first things that is looked at during an evaluation.
7. Electrical Spacings - Minimum spacings must be maintained between uninsulated live parts and dead metal or uninsulated live parts of opposite polarity, based on the voltage potential involved.

Outstanding Questions

- As CPV Trackers evolve, how will these designs fit into a one size fits all approach anticipated within the construct of UL 3703?
- How will a hazard based engineering approach evolve for CPV Trackers?
- How will UL 3703 find a way to harmonize to its IEC counterpart?

Conclusion

With a clearer safety evaluation direction provided by UL 3703, this outline has paved a uniform approach when evaluating CPV Trackers in the United States. Understanding the key construction considerations and tests in UL 3703 will enable a CPV Tracker manufacturer to proactively design a tracker system which complies with the safety certification requirements of UL 3703.