Technical Report
NREL/TP-5200-60167
October 2013

Photovoltaic Module Reliability Workshop 2013

February 26–27, 2013

Technical Monitor: Sarah Kurtz

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge
Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

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 2013, the PVMRW was designed to be a regional meeting of the International PV Module Quality Assurance Task Force, first of its kind for the Americas. This regional meeting also had substantial international participation. The workshop agenda mirrored the organization of the Task Force, with a session for each of Task Groups 2 through 5. Each Task Group presented a status report of their discussions and highlighted a small number of technical presentations describing studies related to that Task Group. In addition, the participants presented about 65 posters on topics directly or indirectly related to the work of the four Task Groups. Most of the participants shared their presentations for public posting; this document is a compilation of these. The success of the workshop is a direct result of the participants' willingness to share their results.

We gratefully recognize the excellent contributions that the community has made and thank all of the participants for the time and information they have shared.

In the two days following the PVMRW, a kick-off meeting was held for Task Group 8 of the International PV Module Quality Assurance Task Force. Task Group 8 was organized to address the needs for testing of thin-film modules. The discussions at the kick-off meeting identified reliability issues that thin-film modules experience, prioritized these, assigned some of these to Task Groups 2 through 5, and created subcommittees within Task Group 8 to address the rest. A compilation of the presentations and notes from this kick-off meeting can be found here: www.nrel.gov/ce/ipvmqa_task_force/proceedings.cfm.

The workshop was chaired by John Wohlgemuth. Members of the organizing committee included:

Jasbir Bath
Nick Bosco
Neelkanth Dhere
Chris Flueckiger
Vivek Gade
Charlie Hasselbrink
Mike Kempe
Sarah Kurtz
Jean Posbic
Ralph Romero
Tony Sample
Kurt Scott
Golnas Tassos
Kent Whitfield
Masaaki Yamamichi

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

TABLE OF CONTENTS

POSTER SESSION: FIELD EXPERIENCE OF CRYSTALLINE SI AND THIN-FILM MODULES

POSTER SESSION: THERMAL AND MECHANICAL FATIGUE, OTHER ACCELERATED STRESS TESTS, AND COMBINATIONS OF ACCELERATED STRESS TESTS

2013 PV Module Reliability Workshop
Feb 26- 27, 2013, Golden, CO

SunShot
U.S. Department of Energy

Overview

- The **SunShot** Initiative
- Systems Integration / Technology Validation Activities
- 2013 PV Module Reliability Workshop

SunShot Initiative

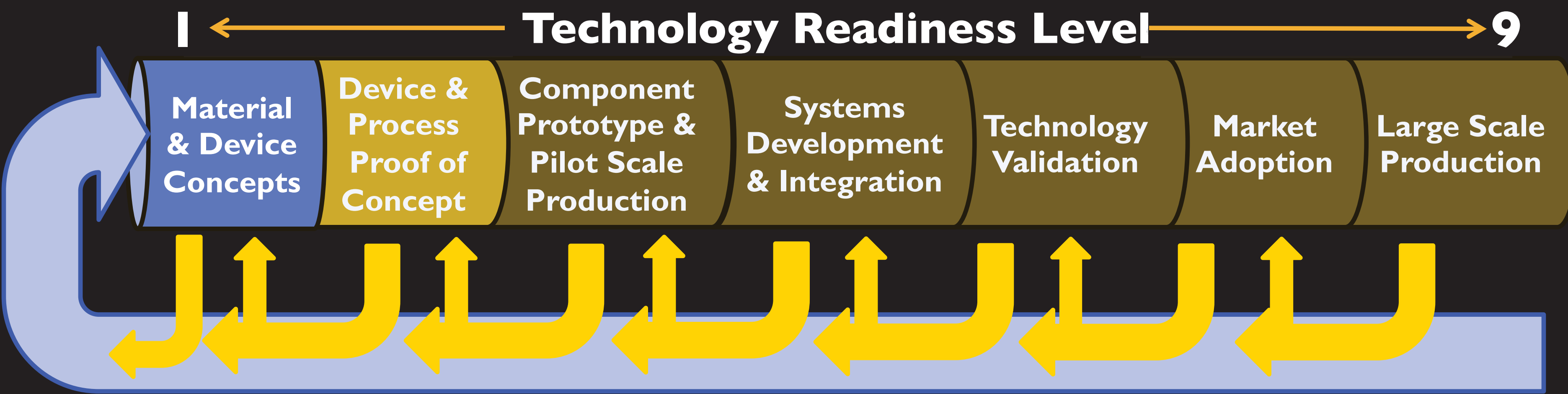
"The SunShot Initiative will spur American innovations to reduce life costs of solar energy and re-establish U.S. global leadership in this growing industry."

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

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

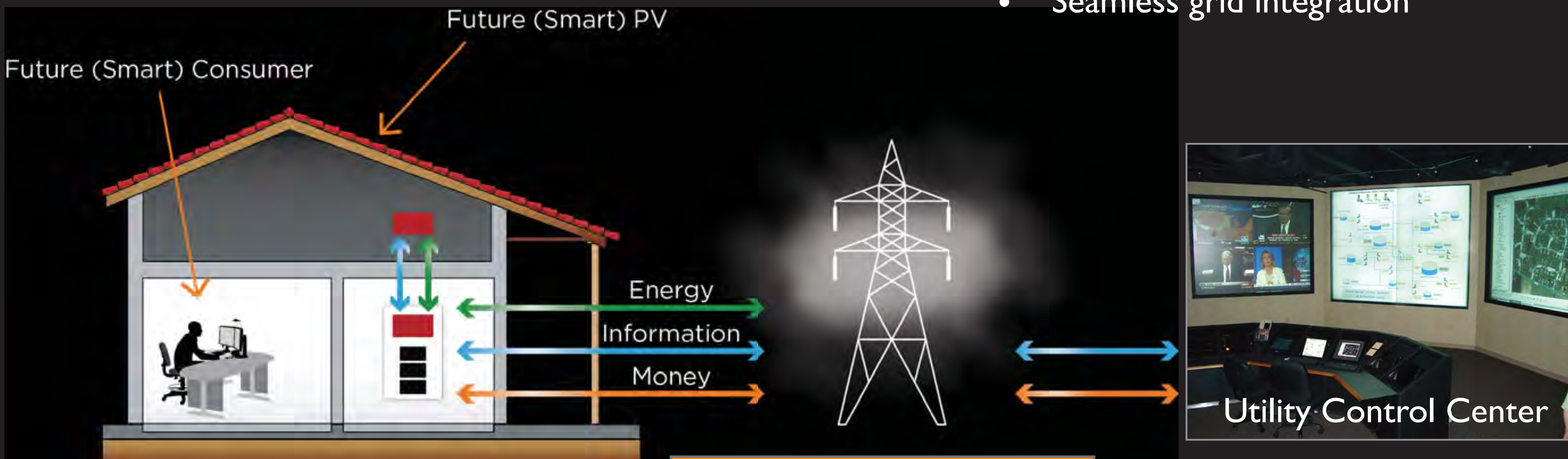
- High Penetration
- Incubator – Soft Costs
- PVMI II: SUNPATH

- Rooftop Solar Challenge
- Non-Hardware BOS

Plug-and-Play Vision

Vision: PV as an Appliance

- No permitting required
- Easy installation
- Seamless grid integration



Future (Smart) Home

- Smart outlet
- Smart circuit
- Smart breaker panel
- Smart appliances
- Home area network (HAN)

Future (Smart) Grid

- Distributed generation
- Two-way power flow
- Communication and control
- Rich energy information and transactions
- Microgrid

Future (Smart) City

- Integrated grid and city planning

Active Funding Solicitations

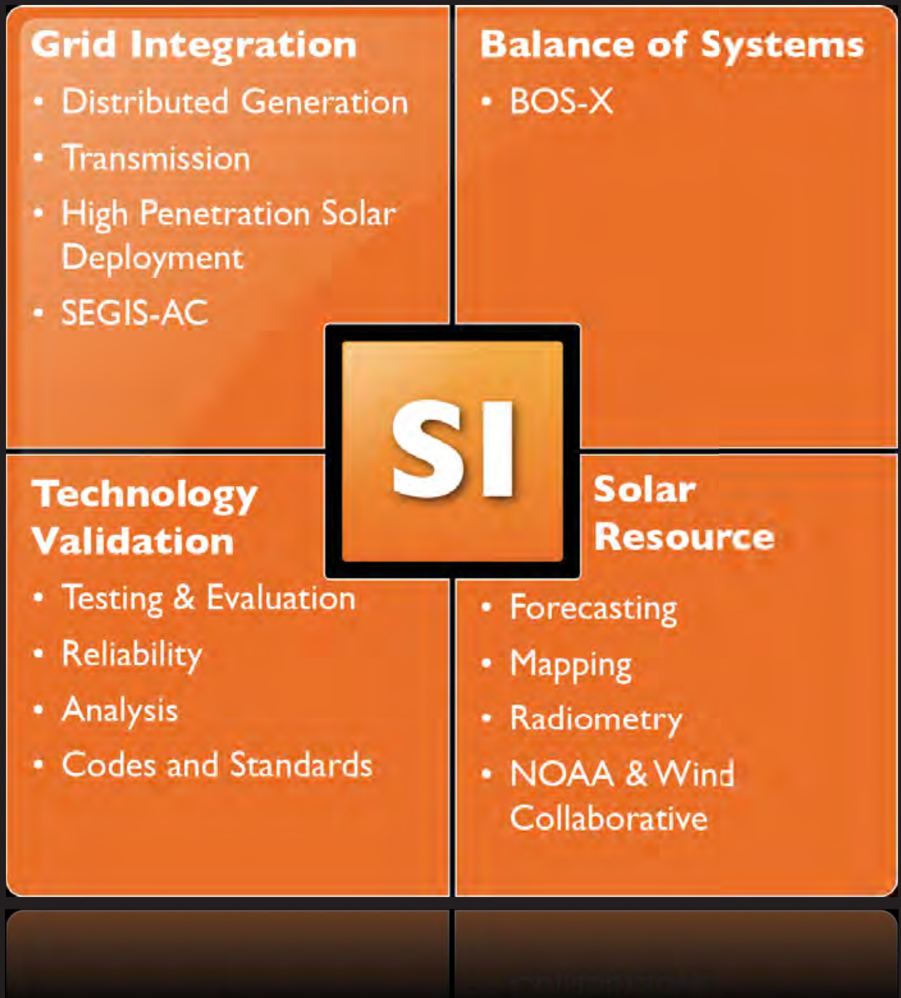
- Solar Manufacturing Technology (SolarMat) - $15M
- Diversity in Science and Technology Advances National Clean Energy in Solar (DISTANCE-Solar) - $3M
- Grid Engineering for Accelerated Renewable Energy Deployment (GEARED) - $12M
- Solar Utility Networks: Replicable Innovations in Solar Energy (SUNRISE) - $10M
- Physics of Reliability: Evaluating Design Insights for Component Technologies in Solar (PREDICTS) - $5M
- Foundational Program to Advance Cell Efficiency II (FPACE II) - $12M
- SunShot Incubator Program (Round 8) - $12M
- Rooftop Solar Challenge II (RSC II) - $12M
- CSP Heat Integration for Baseload Renewable Energy Development - $20M
- Notice of Opportunity for Technical Assistance: Regional Test Centers

- http://www1.eere.energy.gov/solar/sunshot/financial.html

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

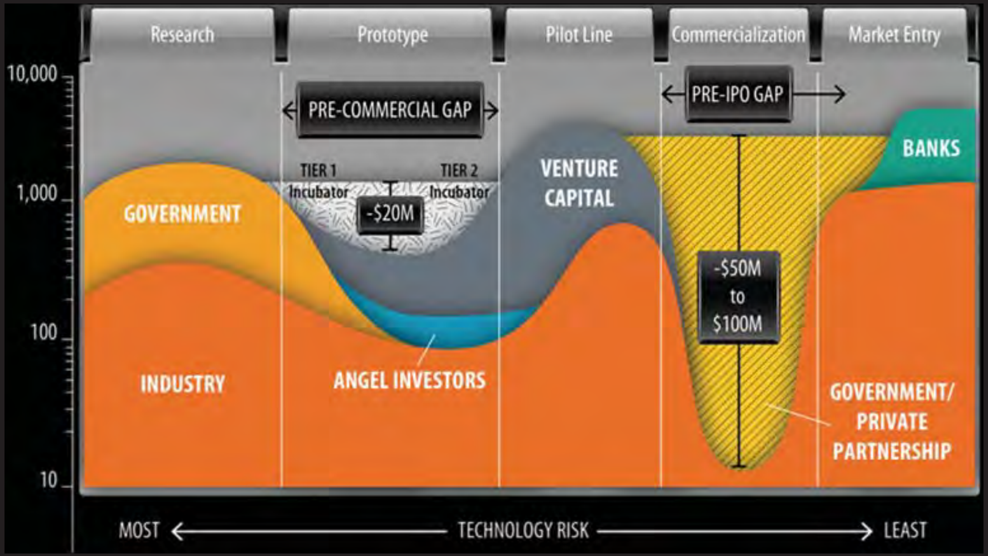
Lifetime Prediction of PV Modules

- 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?

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?

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)

SunShot U.S. Department of Energy

2013 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

<u>Sessions:</u>

- **Monday**
  - **US Technical Advisory Group meeting, IEC TC 82**
- **Tuesday**
  - **Group 2: Thermal and Mechanical Fatigue**
  - **Group 4: Diodes, Shading, and Reverse Bias**
- **Wednesday**
  - **Group 3: Humidity, Temperature, and Voltage**
  - **Group 5: UV, Temperature, and Humidity**
- **Thursday and Friday**
  - International PV Module QA Task Force, Thin Film Task Group, Kick Off Meeting

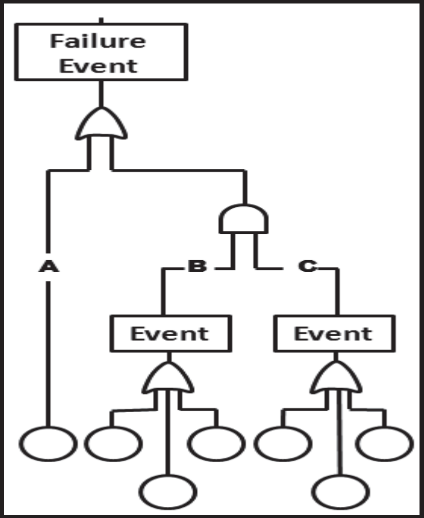
<u>Special Thanks to:</u>

- Sarah Kurtz, *Chair*

SunShot U.S. Department of Energy

PREDICTS

Physics of Reliability: Evaluating Design Insights for Component Technologies in Solar



Topic 1: CSP and PV Components Reliability Models

- Physics-Based Predictive Models for the Degradation and Failure of CSP and PV Components or Sub-systems

Topic 2: Microinverter and Microconverter Reliability Standards

- Creation and Implementation of Industry Standard Tests for Microinverter and Microconverter Reliability

Key Dates	
Webinar	March 6
Concept Papers Due (Mandatory)	March 22
Full Apps Due	April 29
Reply to Reviewer Comments	June 4

Funding Information
Max. Award Duration
3 years
Total DOE Funding Anticipated
$5,000,000 (2-4 awards)
Cost-share Minimum
20%

SunShot U.S. Department of Energy

To View the FOA go to EERE Exchange

SunShot
U.S. Department of Energy

Kevin Lynn

Program Manager, Systems Integration
Kevin.Lynn@ee.doe.gov

February 26, 2013

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Linkage to Previous International PV Module QA Task Force Workshops; Proposal for Rating System

NREL PV Module Reliability Workshop

Feb. 26, 2013

Sarah Kurtz, NREL

John Wohlgemuth, NREL

Tony Sample, EU – JRC

Masaaki Yamamichi, AIST

Michio Kondo, AIST

Outline

- History of International PV Module QA Task Force
- How do we do something useful without doing something harmful?
- Opportunity for Rating System to provide value over current qualification tests
- Technical basis for Rating System
- Next steps for creating Rating System

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 may be worthless if the company is gone)?
- Insurance company: How do I determine rates for insuring PV installations?

A little history

International PV Module Quality Assurance Forum

San Francisco, July, 2011

Goals:

1. Create a QA Rating System to differentiate the relative durability of module designs

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.

Hosted by

NREL

AIST

PVTEC

Supported by

METI

JRC

US DOE

SEMI PV Group

A little history

The PV QA Task Force was formed at the conclusion of the Forum and consisted of five Task Groups:

Task Group 1: PV QA Guideline for Manufacturing Consistency (leaders Ivan Sinicco, Alex Mikonowicz, Yoshihito Eguchi, Wei Zhou, G. Breggemann)

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)

These groups began meeting by teleconference in summer of 2011. Since then, four other task groups have been added.

The PV QA Task Force was formed at the conclusion of the Forum and consisted of five Task Groups:

Task Group 1: PV QA Guideline for Manufacturing Consistency
International meeting in parallel with main sessions during next two days

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)

These groups began meeting by teleconference in summer of 2011. Since then, four other task groups have been added.

A little history

The PV QA Task Force was formed at the conclusion of the Forum and consisted of five Task Groups:

Task Group 1: PV QA Guideline for Manufacturing Consistency (leaders Ivan Sinicco, Alex Mikonowicz, Yoshihito Eguchi, Wei Zhou, G. Breggemann)

Task Group 2:

Task Group 3:

Task Group 4:

Task Group 5:

These four groups are meeting today and tomorrow as a face-to-face regional meeting, with some international participation

Goal: Share technical studies that will guide definition of the most useful tests. Where appropriate: propose useful test structure

These groups began meeting by teleconference in summer of 2011. Since then, four other task groups have been added.

Additional Task Groups:

Task Group 6: Communication of PV QA Ratings to the Community
(leaders David Williams, Sarah Kurtz)

Rest of this talk

Task Group 7: PV QA Testing for Wind and Snow Loads
(leader Joerg Althaus)

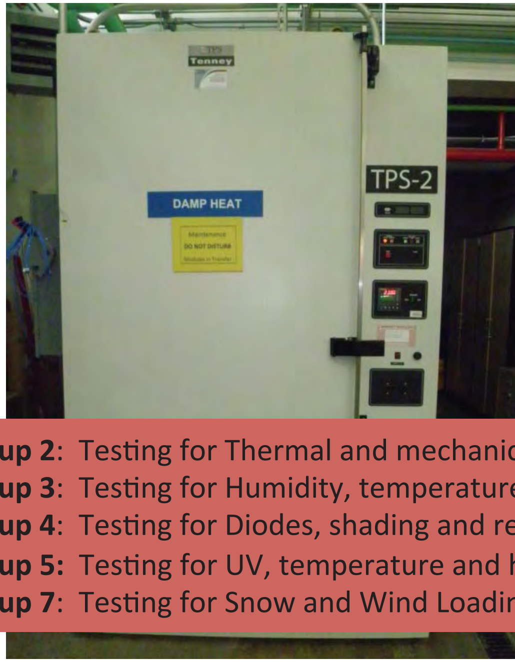
Task Group 8: Thin Film Testing
(leaders: Neelkanth Dhere, Veronica Bermudez, Tobias Roschek, Shuuji Tokuda)

Kick off Feb. 28 – March 1, Golden, CO

Task Group 9: CPV Testing
(leaders: Itai Suez, Nick Bosco)

Need for Rating System

Task Groups develop accelerated tests to predict experience in the field



Task Group 2: Testing for Thermal and mechanical fatigue
Task Group 3: Testing for Humidity, temperature, and voltage
Task Group 4: Testing for Diodes, shading and reverse bias
Task Group 5: Testing for UV, temperature and humidity
Task Group 7: Testing for Snow and Wind Loading

How do we communicate the results?

Rating System

Principles for creating tests/rating system

- Must be predictive & relevant
  - (correlate with decades of field experience, not 1 y or 300 y)
- Must be communicated in useful ways
  - (both simple and detailed for different audiences)
- Must be cost and time effective
  - (manufacturers must bring the product to market)
- Must be beneficial to PV community
  - (use wisdom of community to identify good choices)

To Define the Rating System, First ask: When are failures slipping past Qualification testing?

What are we missing?

Rating System – What are we missing with current qualification tests?

Prioritize two types of wear-out mechanisms that are being reported:

- Broken interconnections, solder bonds, diodes
- Encapsulant discoloration and/or delamination

We choose to focus first on these; later we'll address the longer list of wear-out mechanisms.

Rating System – First address wear out that is slipping past the qualification tests

1. In response to:

- Broken interconnections, solder bonds, diodes

Add:

- Additional thermal cycling or mechanical stress, plus bypass diode/shading testing

2. In response to:

- Encapsulant discoloration and/or delamination

Add:

- Additional UV stress

Need to apply additional stress to detect early wear out

Level	Humidity	High Temperature	Thermal cycling and diode testing	UV
Qualification test	No new	No new	No new	No new
Wear out comparative test	No new	No new	New	New

To gain confidence in long-term performance in almost all climates, we need to add tests related to thermal cycling, diodes, and UV exposure

Need to apply additional stress to detect early wear out

Level	Humidity	High Temperature	Thermal cycling and diode testing	UV
Qualification test	No new	No new	No new	No new
Wear out comparative test	No new	No new	New	New

To gain confidence in long-term performance in almost all climates, we need to add tests related to thermal cycling, diodes, and UV exposure

What about for extreme climates?

Marine ✔(salt spray)

Snow loads ✔ (mechanical loads)

Hail ✔ (hail impact)

Heat

Humidity

✔Note: We already have comparative tests for marine, hail, and snow, so we can include these test results in the rating

Additional stress may be needed for extreme climates.

New Tests Will Require Additional Stress						Targeted Meaning of Rating	
Failure types, loosely grouped	Thermal cycling & diode testing	UV	High Temperature	High humidity	Proposed labels	★ or "C"	★★★★★ or "A"
Infant mortality	-	-	-	-	**Qualification test**	-	-
Interconnects, discoloration, delamination	✔	✔	-	-	Hot-cold	Better than qualification test	30 y in location/appl. w worst thermal cycling
Heat-induced failures	✔	✔	✔	-	Hot-dry	Better than qualification test	30 y in location/appl. w worst heat-induced degradation
Humidity-induced failures	-	✔	✔	✔	Hot-humid	Better than qualification test	30 y for location/appl. w worst humidity-induced degradation

The two primary extremes that have not yet been addressed are:

Heat

Humidity

So add additional stress for these, indicated by ✔

Rating System – *Targets* for defining the min/max meanings for tests

	New Tests Will Require Additional Stress					Targeted Meaning of Rating	
Failure types, loosely grouped	Thermal cycling & diode testing	UV	High Temperature	High humidity	Proposed labels	★ or "C"	★★★★★ or "A"
Infant mortality	-	-	-	-	**Qualification test**	-	-
Interconnects, discoloration, delamination	✔	✔	-	-	Hot-cold	Better than qualification test	30 y in location/appl. w worst thermal cycling
Heat-induced failures	✔	✔	✔	-	Hot-dry	Better than qualification test	30 y in location/appl. w worst heat-induced degradation
Humidity-induced failures	-	✔	✔	✔	Hot-humid	Better than qualification test	30 y for location/appl. w worst humidity-induced degradation

With these ranges, we can address the full range from today's qual test to the harshest environments on earth

A few climate zones may not be well represented; can we postpone addressing these?

Rating System Proposal – Communicate four ways:

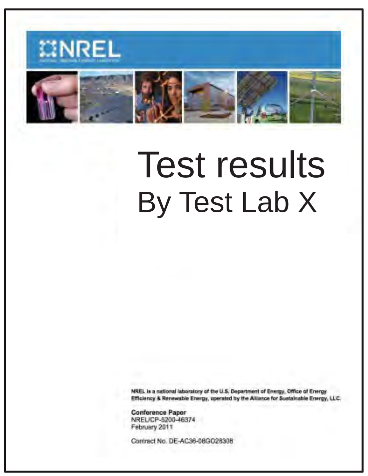
1. Nameplate:

Pmax	205 W
Durability rating:	
Hot-cold	★★★
Hot-dry	★ ★
Hot-humid	not rated
Snow/wind	2400 Pa
Salt spray	
etc.	

A high level summary on the nameplate will allow researchers to correlate tested rating with field experience 20 y from now.

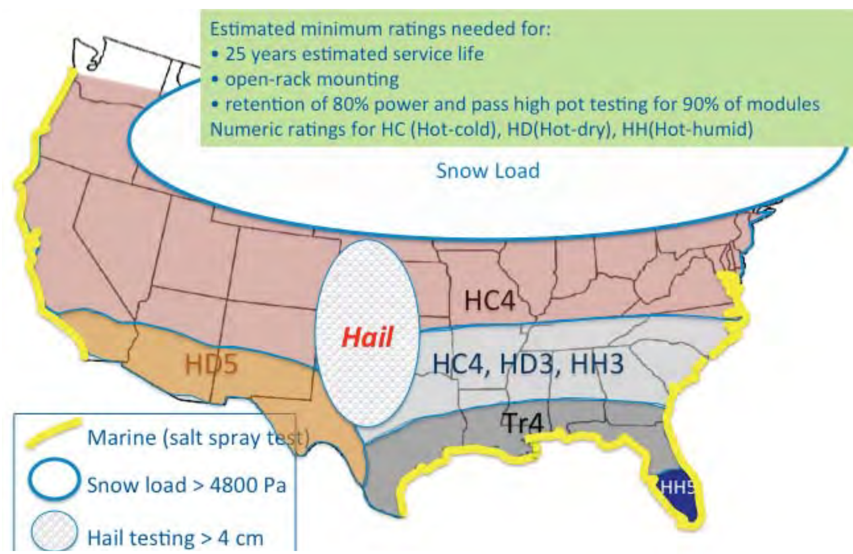
2. Report:

Standards


NREL

Test results
By Test Lab X

A detailed report can be used by engineers to more closely compare specific products



3. Interpretive maps:

Publications/Guides

4. Climate charts that link climates with stresses (not shown):

Next Steps

- A New Work Item Proposal has been submitted to IEC Technical Committee 82, Working Group 2 as a starting point for discussion
- Some countries will identify individuals to participate in rewriting this draft
- Each Task Group will create tests that will be connected by this proposal
- International discussion and voting will determine details.

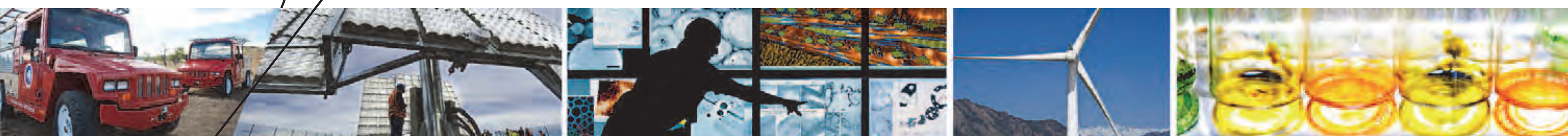
Summary

- The International PV Module QA Task Force is developing comparative accelerated test standards
- A Rating System is necessary for the success of the QA Task Force
- The Rating System must be developed in parallel with the Test Protocols
- The New Work Item Proposal will serve as a starting point for discussion within WG2
- All of you are welcome to join ongoing international discussion (~ once per month)

Sarah.Kurtz@nrel.gov

Thank you for your attention!

Accelerated Stress Testing, Qualification Testing, HAST, Field Experience – what do they all mean?



John Wohlgemuth

February 26, 2013

NREL PVMRW 2013

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.

Introduction

- **The commercial success of PV is based on long term reliability and safety of the deployed PV modules.**
- **Today most PV modules are warranted for 25 years with a maximum allowable degradation rate of 0.8%/year.**
- **These 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.**

Introduction (Continued)

- **What we would really like is to have a set of tests that we could perform on the modules that would predict their long term field performance.**
- **Such a set of tests does not exist today.**
- **That was a major reason for the formation of**

International PV QA Task Force

Goals of Talk

- Try to describe the relationships between
  - Field test results
  - Accelerated stress tests
  - Qualification tests
- Will try to do this in the logical manner that they developed i PV.
- Define HAST Tests and explain why PV seldom uses this approach.
- Summarize the International PV Module QA Task Force

What is our overall goal

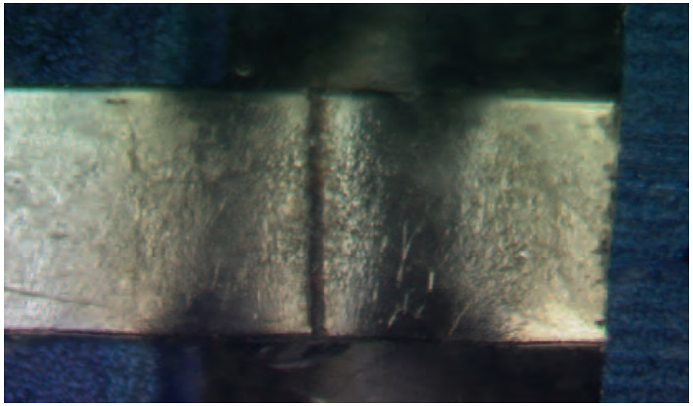
- To evaluate the long term performance of PV modules in a variety of terrestrial climates.
- Really should use outdoor performance data to do this.
- However, none of us wants to wait 25 years to determine if a particular module type is going to have a 25 year lifetime.
- Therefore, we use accelerated stress tests to try to predict what is going to happen outdoors.
- These accelerated stress tests are based on duplicating the failure modes observed in the field.
- 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 of cells, metals and connectors
- Delamination/loss of adhesion between layers
- Loss of elastomeric properties of encapsulant or backsheet
- Encapsulant discoloration
- Solder bond failures
- Broken glass
- Glass corrosion
- Hot Spots
- Ground faults due to breakdown of insulation package
- Junction box and module connection failures
- Structural failures
- Bypass Diode failures
- Open circuiting leading to arcing
- Potential Induced Degradation

Examples of Field Failures

Broken Interconnects



Corrosion
From JPL

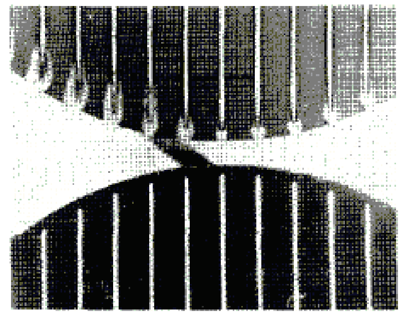
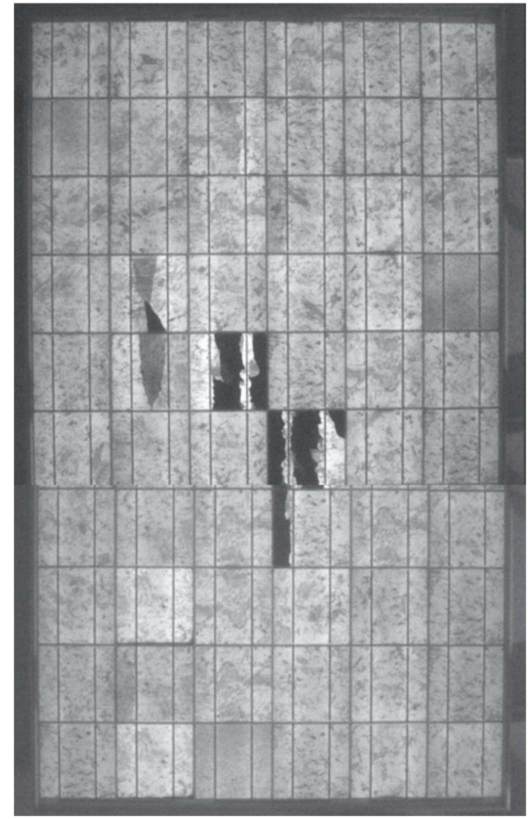


Figure 2. Solar-Cell Electrochemical Corrosion

Broken Cells



From Peter Hacke, NREL

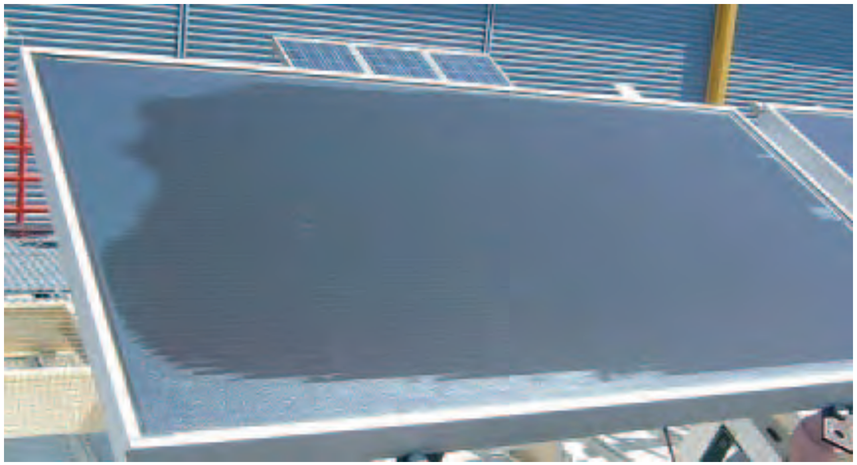
Delamination

Additional Failure Modes for Thin Film Modules

- Electro-chemical corrosion of TCO.
- Light Induced Degradation
- Inadequate Edge Deletion
- Shunts at laser scribes
- Shunts at impurities in films
- Diffusion of metals from contacts through the junction

Additional Field Failures for Thin Films

Electro-Chemical Corrosion of TF Module
From Neelkanth Dhere, FSEC

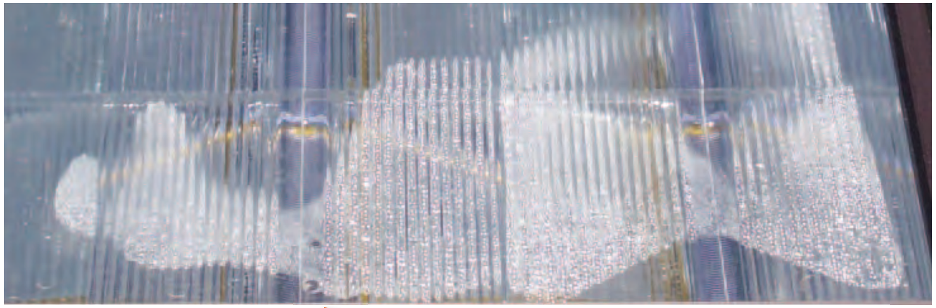


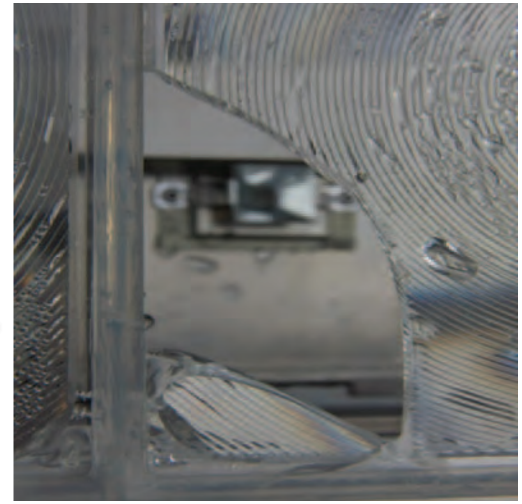
Broken Glass Leading to Corrosion

Additional Failure Modes for CPV Modules

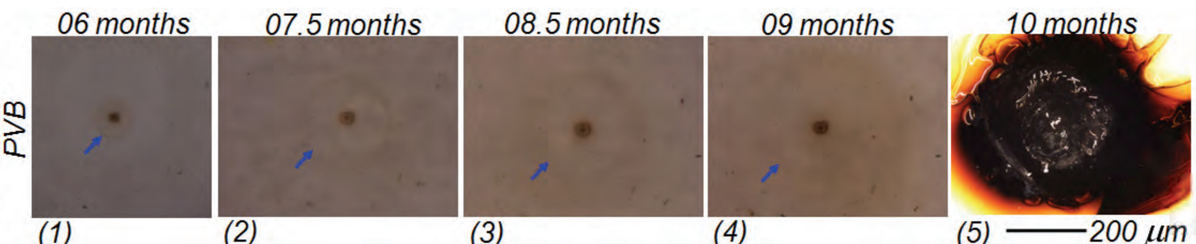
- Tracker misalignment
- Tracker failures
- High current densities leading to overheating
- Rapid and numerous thermal cycles stressing the cell to substrate bond
- UV degradation of optics
- Moisture condensing with optical package
- Overheating of the encapsulant due to UV darkening

Additional Failures for CPV

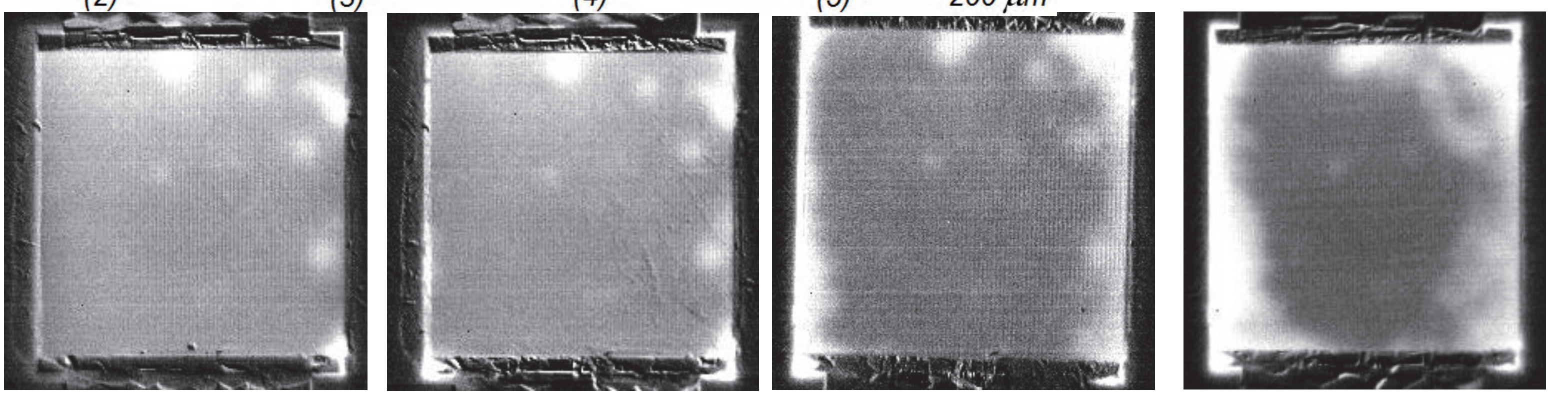




From Matt Muller, NREL



From Dave Miller, NREL



initial | 500 cycles | 1000 cycles | 1500 cycles

Progression of IR images illustrating die-attach cracking through thermal cycling from Nick Bosco, NREL

Developing Accelerated Stress Tests

- Need to look at each of the failure modes and try to determine what stress or stresses in terrestrial environment caused the failure.
- Was it?
  - Operation at high temperature
  - Changes in temperature due to diurnal variations or clouds
  - High humidity
  - Wind or snow loading
  - UV exposure
  - Or maybe a combination of several or all of the above or something else.
- Once the driving force for the failure mode has been identified we can then try to accelerate that stress to cause the failure to occur in a shorter time period.
- Some examples
  - Operate at higher temperature
  - Cycle temperature quickly
  - Use higher humidity and temperature than seen in the field

Some Rules Governing our ASTs

- In developing accelerated stress tests (AST) we must cause degradation.
- The degradation occurring in the AST must be due to the same failure mechanism we saw outdoors.
- Because the AST is causing the same failure there is   chance tha   we can extrapolate the test date to provide   lifetime prediction for this one failure mode.
- The 35 years of PV history with ASTs has given us a good background to build on.

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 Potential Induced Degradation	All All All All TF TF Cry-Si & TF
Humidity Freeze	Delamination Junction box adhesion Inadequate edge deletion Insufficiently cured encapsulant	All All TF All

Accelerated Stress Tests for PV (cont)

Accelerated Stress Test	Failure Mode	Technology
UV Test	Delamination	All
	Encapsulant loss of adhesion & elasticity	All
	Encapsulant & backsheet discoloration	Cry-Si, some CPV & TF
	Ground fault due to backsheet degradation	Cry-Si & TF
	Degradation of Optics	CPV
Static Mechanical Load (Simulation of wind and snow load)	Structural failures	All
	Broken glass	Cry-Si & TF
	Broken interconnect ribbons	All
	Broken Cells	Cry-Si & CPV
	Electrical bond failures	All
Dynamic Mechanical Load	Broken glass	Cry-Si & TF
	Broken interconnect ribbons	All
	Broken Cells	Cry-Si & CPV
	Electrical bond failures	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 & TF 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 accelerated 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

Passing IEC 61215, IEC 61646 or IEC 62108

- So what does it mean if a module type is qualified to IEC 61215, IEC 61646 or IEC 62108?
- Passing the qualification test means the product has met a specific set of requirements.
- Those 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 the qualification tests do not provide a means of rankings within the group that has passed the requirements.

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 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
  - ✓ 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**
- **Address failure mechanisms for all climates and system configurations**
- **Differentiate between products that may have long and short lifetimes**
- **Address all failure mechanisms in all module designs**
- **Quantify lifetime for different applications or climates.**

HAST Tests

- **What are HAST Tests?**
  - Highly Accelerated Stress Tests
- **How is HAST used?**
  - To identify design and component weaknesses by exposing the product to increasing stress until failure occurs.
  - To increase margin of strength of design, not to predict qualitative lifetime or reliability of product
- **Examples of HAST.**
  - Temperatures > 100 °C with > 1 atmosphere of pressure at 100% RH
  - Rapid thermal cycling (to > 85 °C) plus high vibration levels

So what tests do we use in PV?

- **Field results are used to guide AST but take too long to be PV's main reliability tool.**
- **Accelerated stress tests are the main research tests used i PV.**
  - **Trying to duplicate field failures**
- **Qualification tests are the main commercial tests used i PV.**
  - **Looking for design/infant mortality issues that have been observed in the field.**
- **For PV modules HAST is seldom used:**
  - **In PV we are trying to reduce the cost not make product robust to failures not observed in the field.**

International PV Module QA Task Force

- **~ 150 of us met in July, 2011 in San Francisco**
- **Prepared Goals on next page**
- **Chartered first 6 Task Groups**
  - o Group 1 – Guideline for PV Module Manufacturing QA so modules are made correctly
  - o Groups 2 to 5 – Selected 4 sets of stresses that were judged to cause the most field failures in Cry-Si modules.
    2. Thermal cycling and mechanical fatigue
    3. Humidity, temperature and voltage
    4. Diodes, shading and reverse bias
    5. UV (light), temperature and humidity
  - o Group 6 – How to organize and communicate the proposed QA rating system

International PV Module 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.

PV QA Task Force

Task Group 1: Guideline for Manufacturing Consistency

Task Group 2: Thermal and mechanical fatigue including vibration

Task Group 3: Humidity, temperature, and voltage

Task Group 4: Diodes, shading and reverse bias

Task Group 5: UV, temperature and humidity

Task Group 6: Communication of PV QA ratings to the community

Task Group 7: Wind and Snow Loading (New group)

Task Group 8: Thin Film PV (New group)

Task Group 9: CPV (New group)

Testing for Wear-out. What groups 2-5 are doing

- Determine which accelerated stress test or combination of accelerated stress tests best duplicates a failure seen in the field.
- Study each failure mode to determine what parameter or parameters in the field exposure are most responsible for the phenomena – Is it temperature, humidity, light exposure, change in temperature, vibration or combinations of the above?
- Perform experiments or use published data to determine the reaction rate of the failure mechanism.
- Model the system to determine the equivalence between the accelerated stress test(s) and field performance.
- Use model to predict results at some different stress level.
- Perform experiments to validate model.
- Propose test for wear-out based on selected climates around the world.

Summary

- Accelerated stress testing beyond the qualification test levels is necessary to predict PV module wear-out.
- Development of such tests requires understanding the science behind the observed failure modes.
- This effort is now underway as part of the PV Module QA Task Force, involving hundreds of people around the world.

ARIZONA STATE UNIVERSITY
PHOTOVOLTAIC RELIABILITY LABORATORY

Failure and Degradation Modes of PV modules in a Hot Dry Climate: Results after 12 to 26 years of field exposure

Mani G. Tamizh-Mani
Joseph Kuitche
&
Research Students of ASU-PRL

Acknowledgement

Arizona Public Service (APS)
Salt River Project (SRP)
Science Foundation Arizona
NREL
Solar One Community
PVRI

OUTLINE

- **Objective of this presentation**

  To identify the key failure and degradation modes in a hot-dry climate

  (Future works will include: hot-humid and hot-cold climatic conditions)

- **Two hot-dry climatic sites**
  - **Site 1**
    - ✓ **Tempe, Arizona: 12-13 years; ~ 1700 modules**
  - **Site 2**
    - ✓ **Phoenix, Arizona: 26 years; ~ 4000 modules**

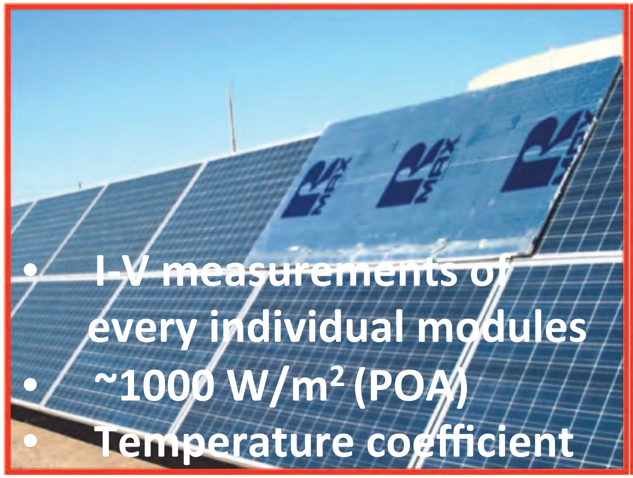
- **Characterizations and Results**
  - **I-V characterization**
  - **Visual inspection**
  - **Infrared imaging**

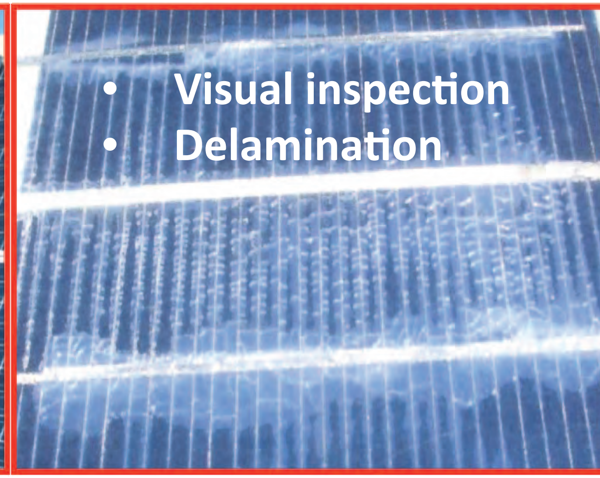
- **Conclusions**

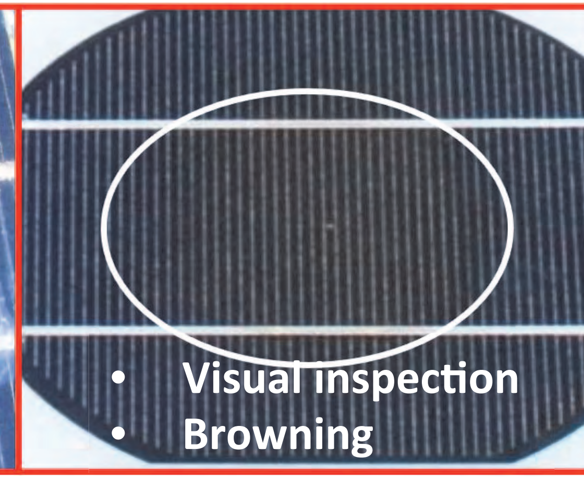
Hot-Dry Climate:
Site 1
(~1700 Modules; 12-13 Years Old)

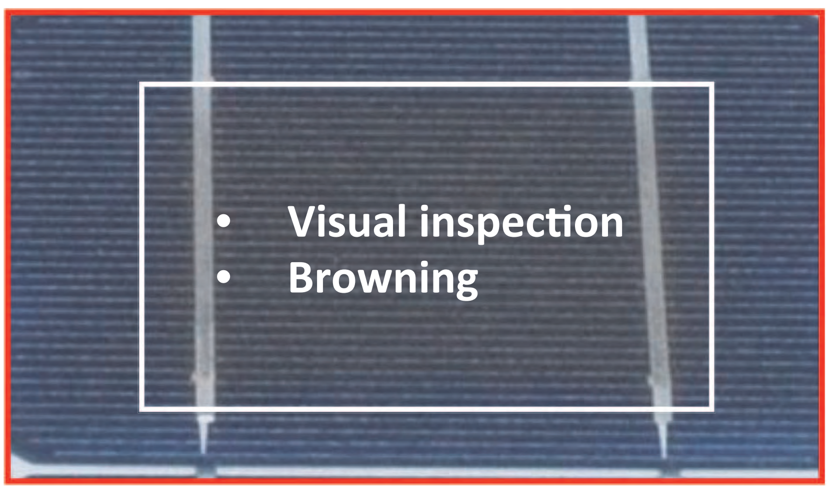
Site 1: Modules Evaluated - Six Manufacturers and 1-Axis Tracking

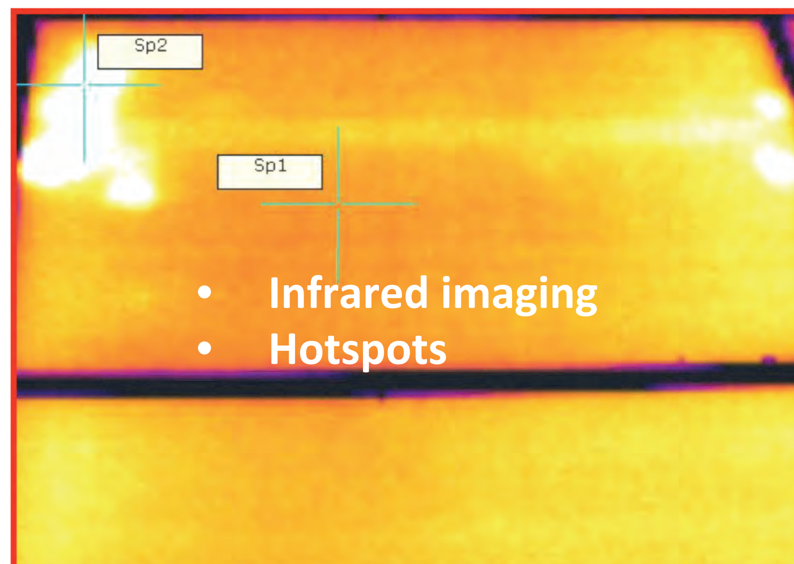
Site 1: Characterizations – Visual Inspection, IR Imaging & I-V Curves











Site 1: Results – Visual Inspection and Hotspots

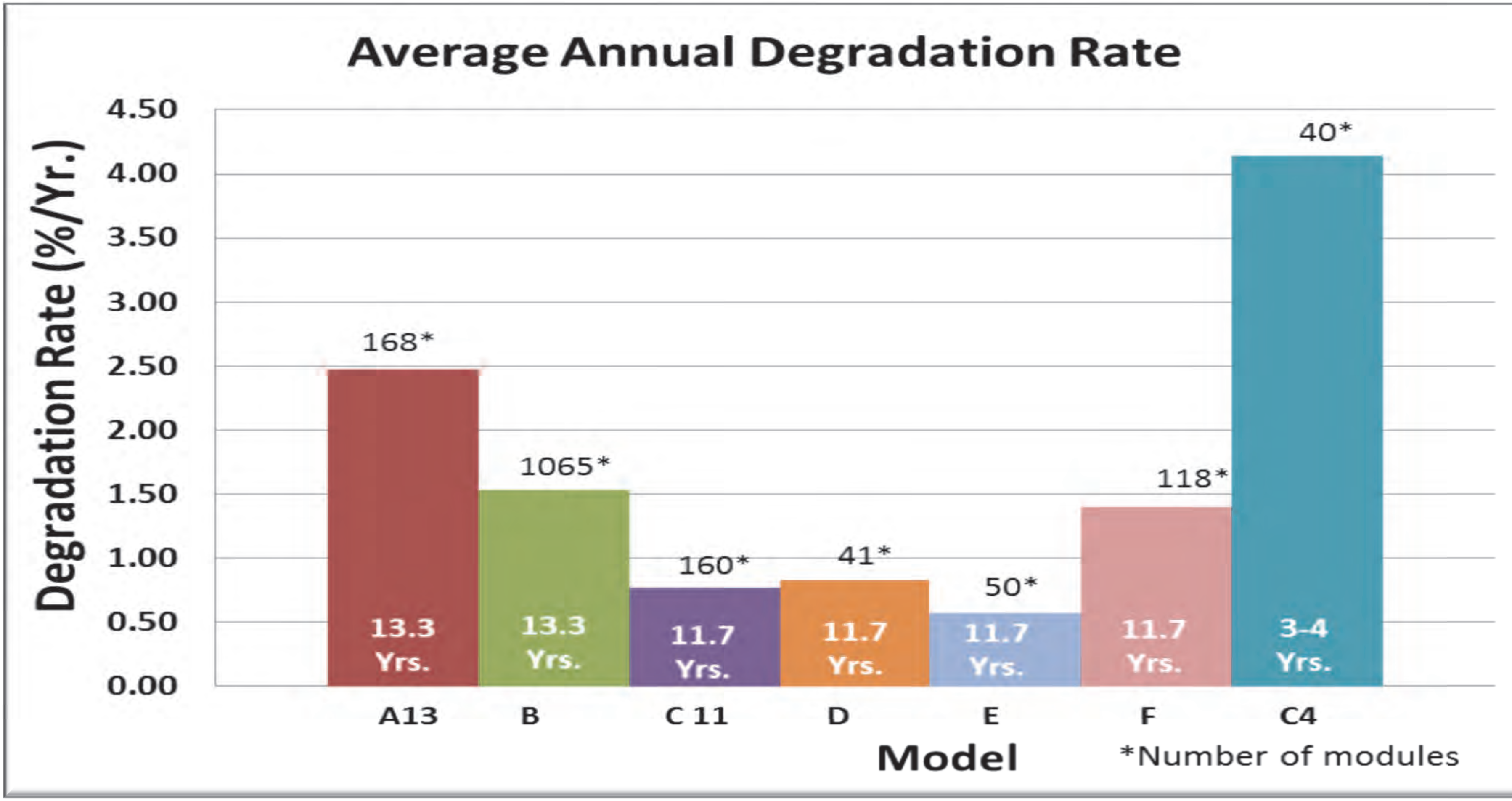
Model ID	No. of samples	Years Fielded	Cracked cells	Delamination	Discoloration (Browning) of Encapsulant	Cell Chipping	Cell Interconnect Failure	Connector Deterioration	Substrate (backsheet) Warping/Detaching	Burn Through Backsheet	Metallization discoloration	Seal Deterioration	Solder Melted	Hotspot with IR Camera
A13	168	13	0	0	168	0	0	0	0	0	0	168	0	4
B	1153	13.3	0	4	1153	0	0	0	630	0	0	0	1	7
C4	39	2.5 - 4	6	0	0	0	0	0	0	0	1	0	1	5
C11	177	11.7	45	74	1	2	0	0	0	0	1	0	0	20
D	48	11.7	0	0	37	0	0	0	0	0	0	0	0	4
E	50	11.7	0	0	0	0	0	0	33	0	0	0	0	0
F	120	11.7	0	0	0	0	0	0	1	2	22	15	0	6

Encapsulant Browning

Replaced modules

Glass/Glass modules

Site 1: Results – Average Annual Degradation Rate



C4 = Replaced modules under warranty

Power degradation appears to be primarily due to current drop (encapsulant browning) and fill factor drop (series resistance increase due to thermo-mechanical fatigue of solder bonds)

Site 1: Results – Hotspot modules degrade at higher rate

Model of Module	All Modules % Degradation/Year	Only Hotspot Modules % Degradation/Year
A 13	-2.47%	N.A
B	-1.53%	-2.95%
C 11	-0.77%	-1.90%
C 4	-4.14%	N.A
D	-0.83%	-1.25%
E	-0.57%	N.A
F	-1.40%	-4.96%

Modules with hotspot issues seem to degrade at higher rate than the non-hotspot modules. Periodical IR scanning may be useful for the early identification and potential removal of the hotspot modules from the power plants to mitigate future module mismatch issues.

Site 1: Conclusions

- **The degradation rate of these 12-13 years old modules ranged between 0.6%/ year and 2.5%/year depending on the manufacturer**

- **Primary degradation modes in this hot-dry climate site appear to be encapsulant browning and (thermo-mechanical) fatigue of solder bonds. Encapsulant browning leads to current drop and solder bonds fatigue leads to fill factor drop**

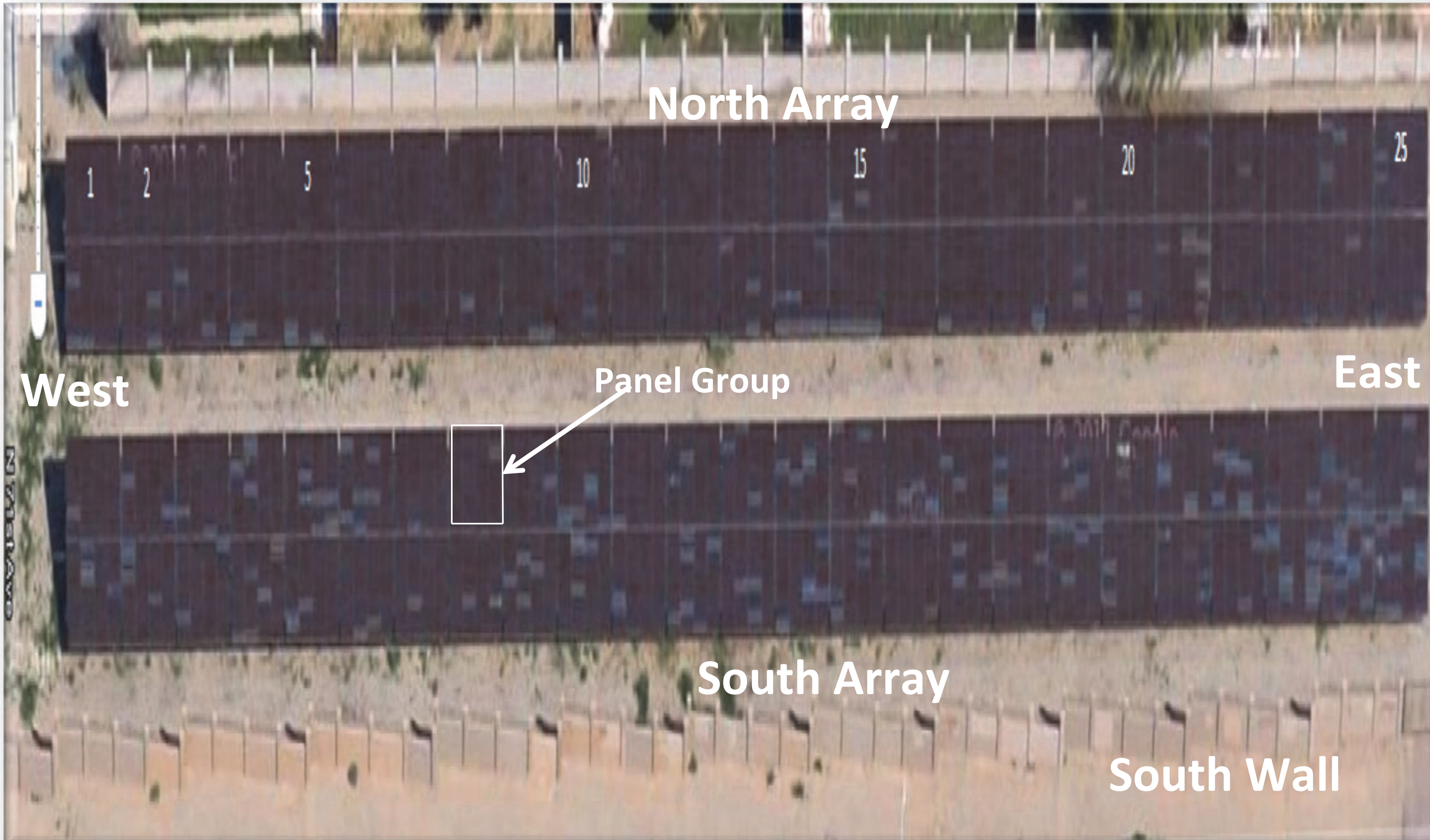
- **Modules with hotspots appear to degrade at higher rate than the non-hotspot modules (which could lead module mismatch issue in a module-string)**

Hot-Dry Climate:

Site 2

(~4000 Modules; 26 Years Old)

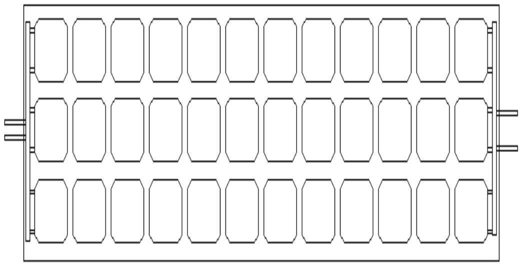
Site 2: Modules Evaluated - One Manufacturer and Fixed Latitude Tilt

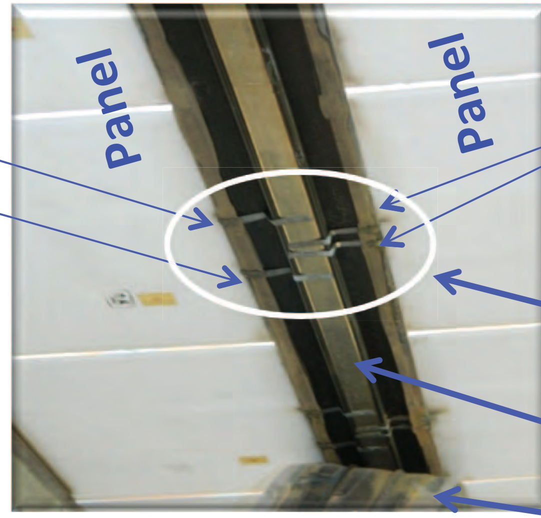


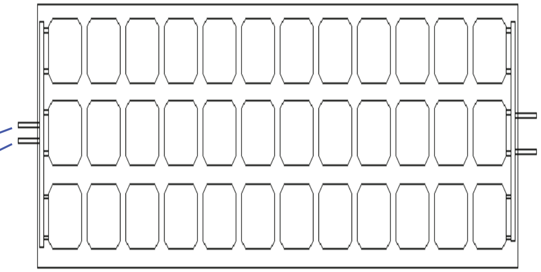
4000 Modules = 100 Panel Groups (4 panels per group with 10 modules in each panel)

Note: White spots on the photo are due to the replaced modules or modules with glass cracks leading to encapsulant bleaching. Modules were often replaced due to vandalism (stone throwing across the south wall)

Site 2: Modules Evaluated – Construction of Module and System







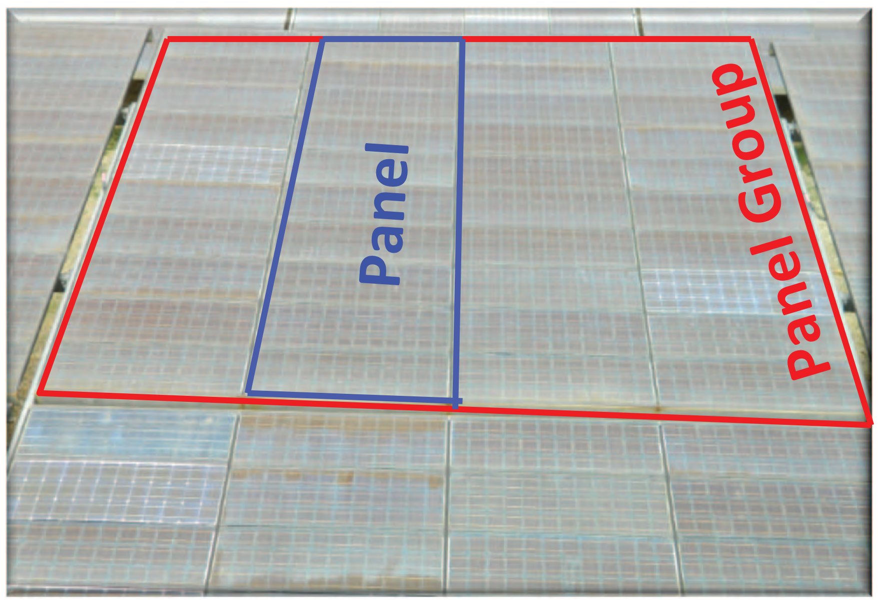
Non-cell interconnect ribbons

Inter-Panel Busbar

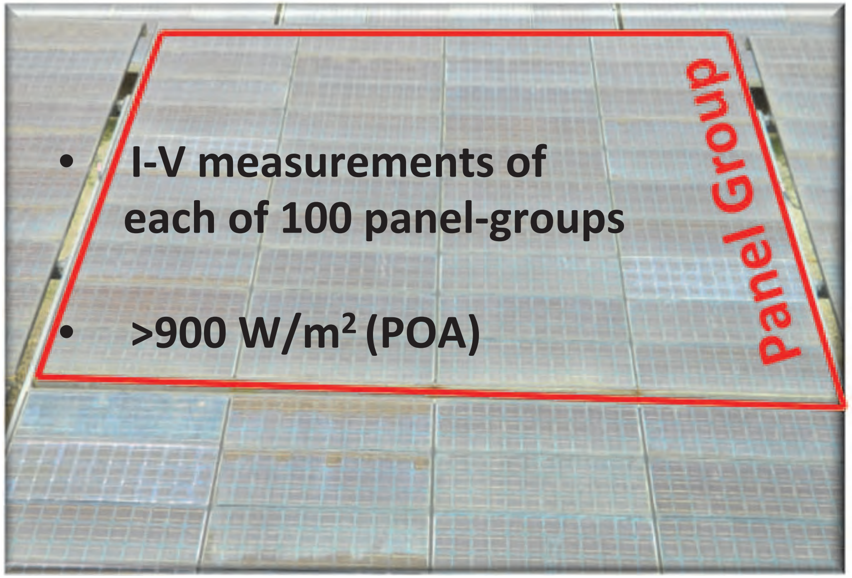
Plastic cover to protect busbar and interconnects (leaky cover; corrosion)

Note: OUTDATED CABLIG METHOD

- No module cable
- No module connector
- Non-cell interconnect ribbons are directly welded on inter-panel busbar

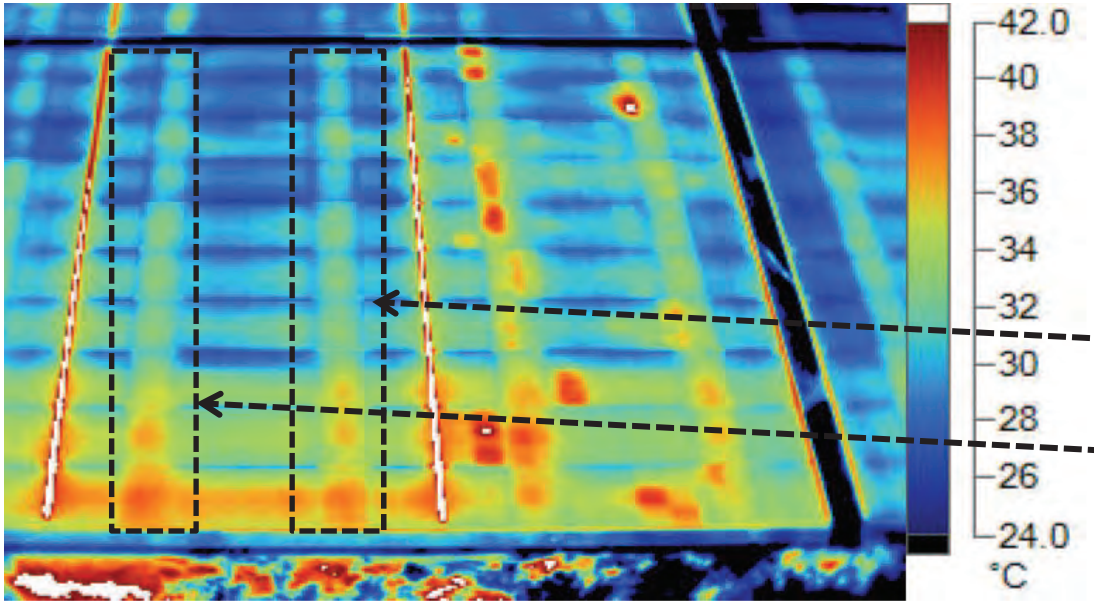


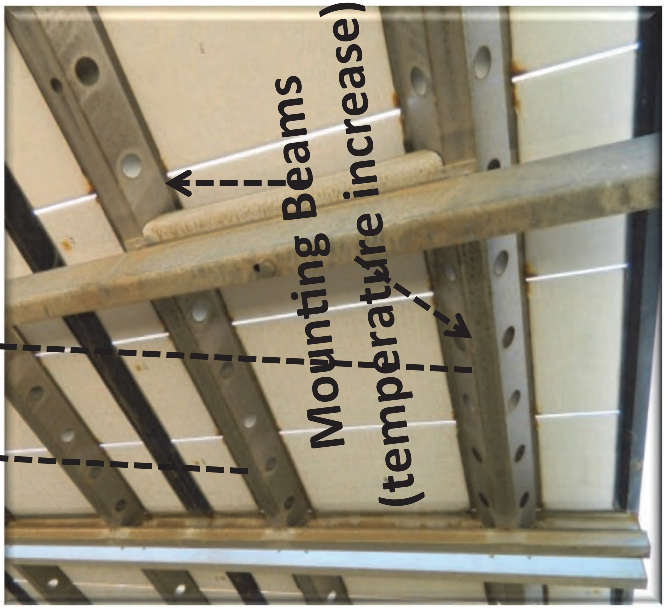
Site 2: Characterizations – Visual Inspection, IR Imaging & I-V Curves



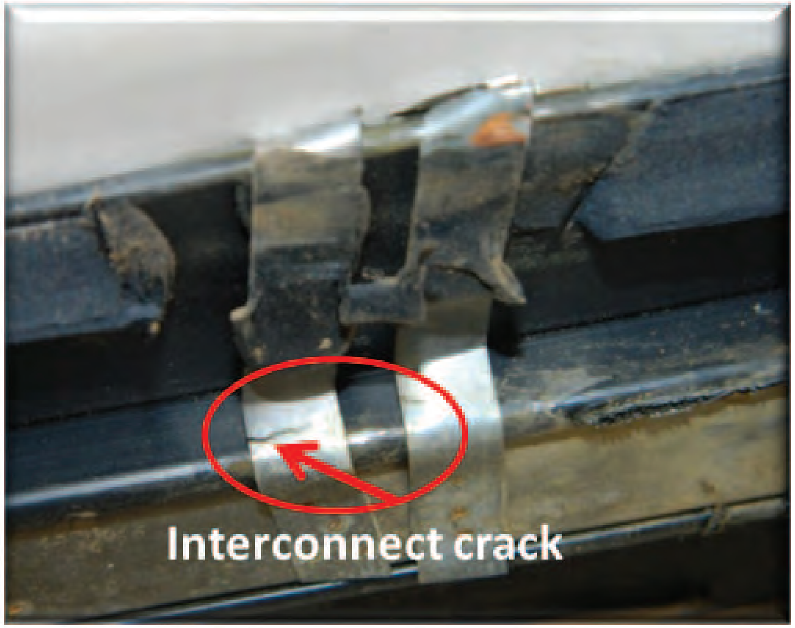
- I-V measurements of each of 100 panel-groups
- >900 W/m² (POA)

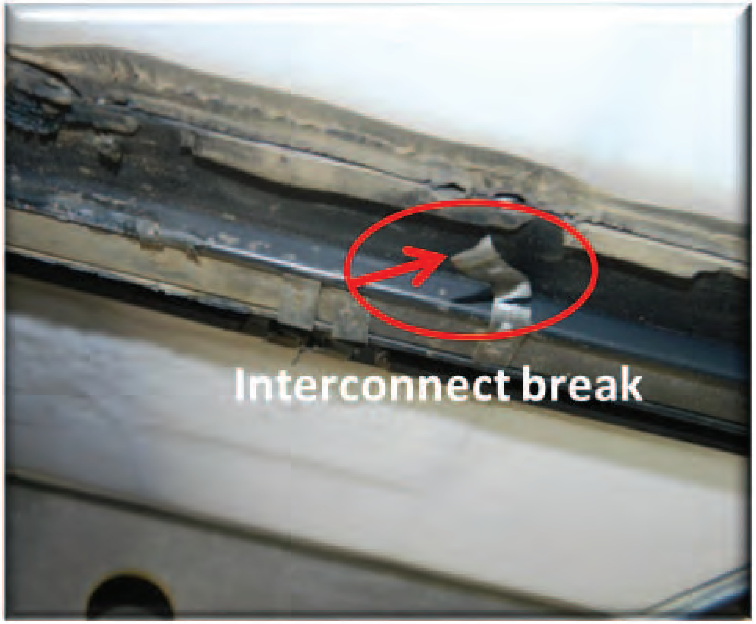
- Infrared imaging
- Hotspots

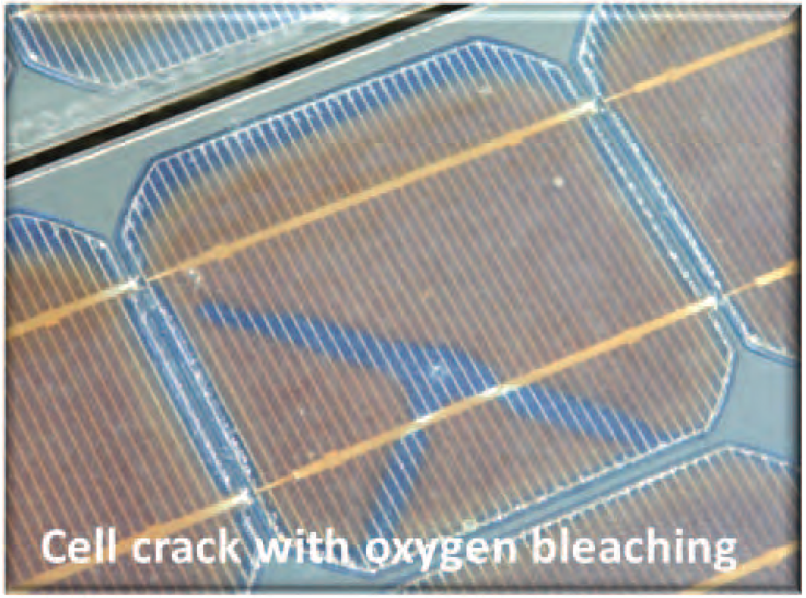


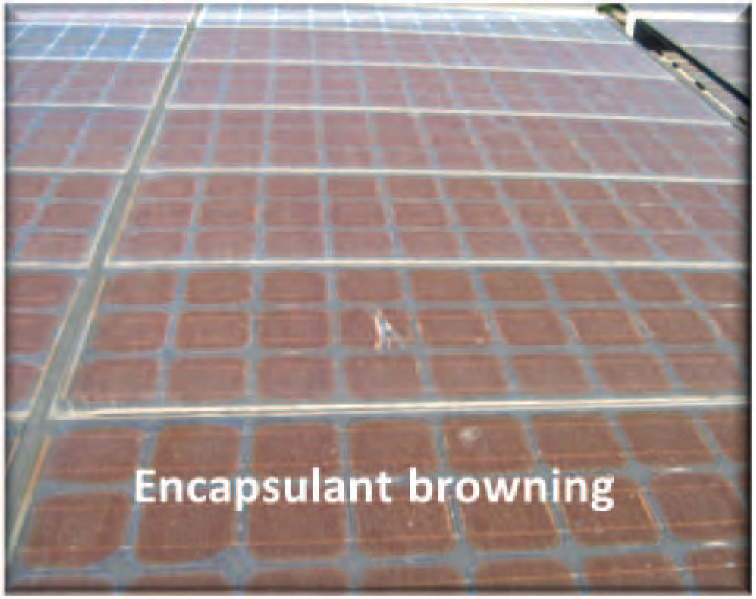


Site 2: Characterizations – Visual Inspection, IR Imaging & I-V Curves



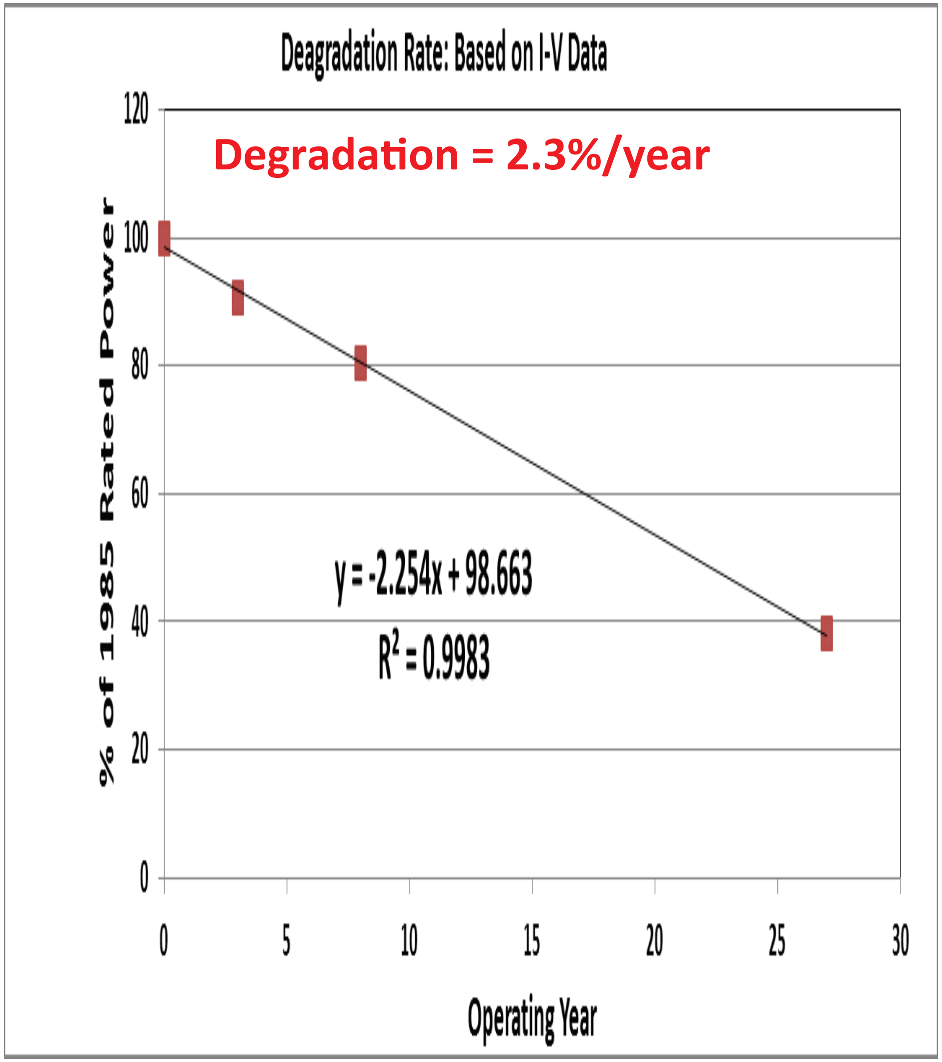




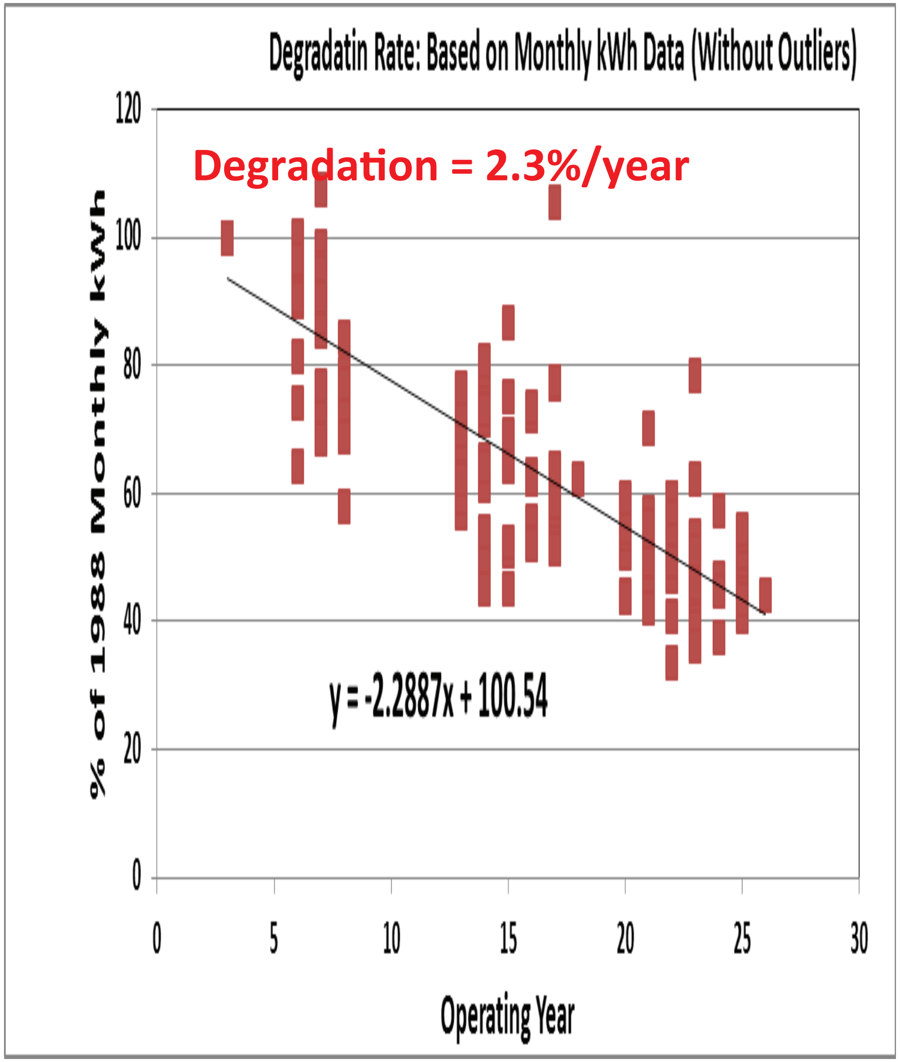


Site 2: Results – Average Annual Degradation Rate

Measured DC Power Data

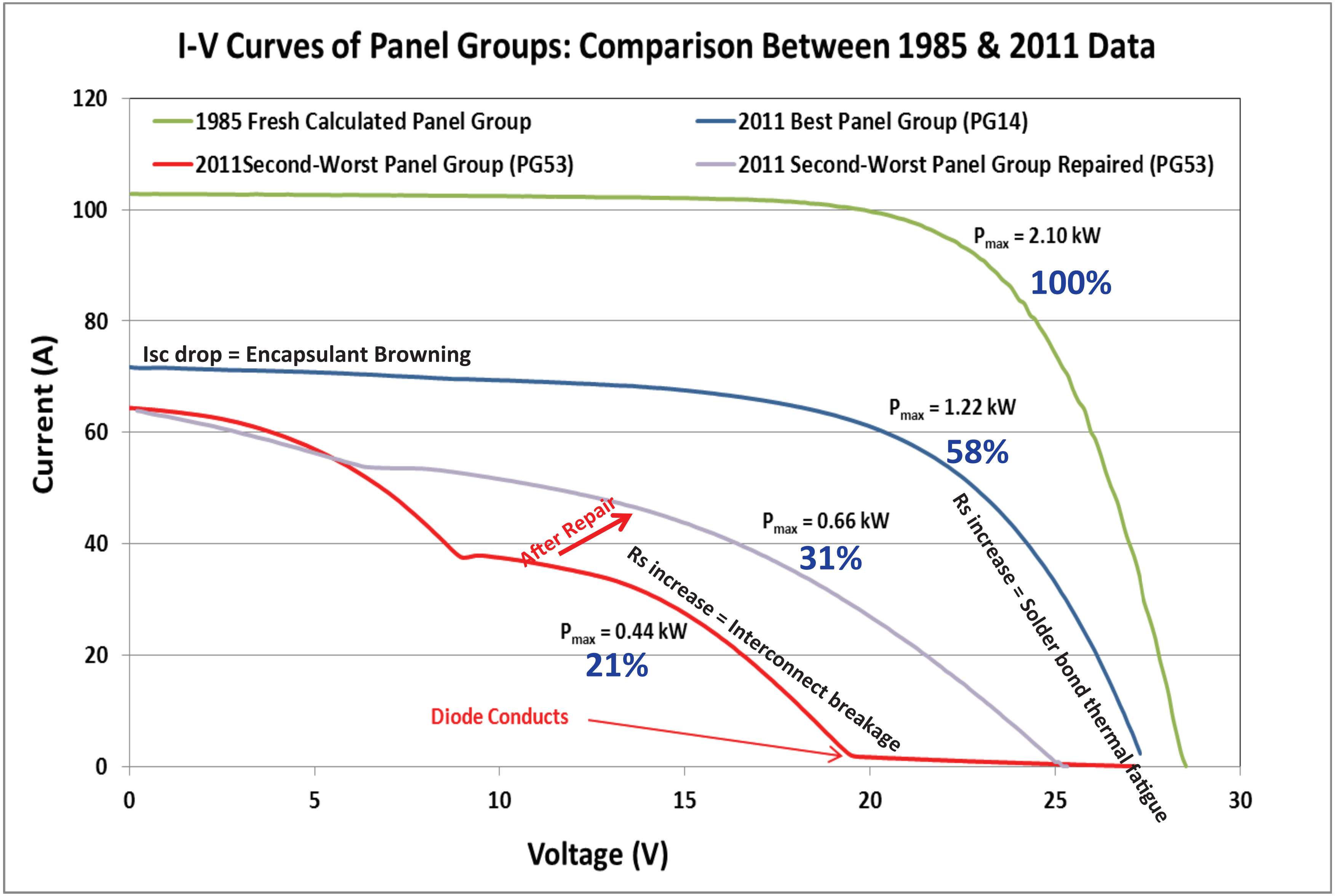


kWh_{ac} Metered Data

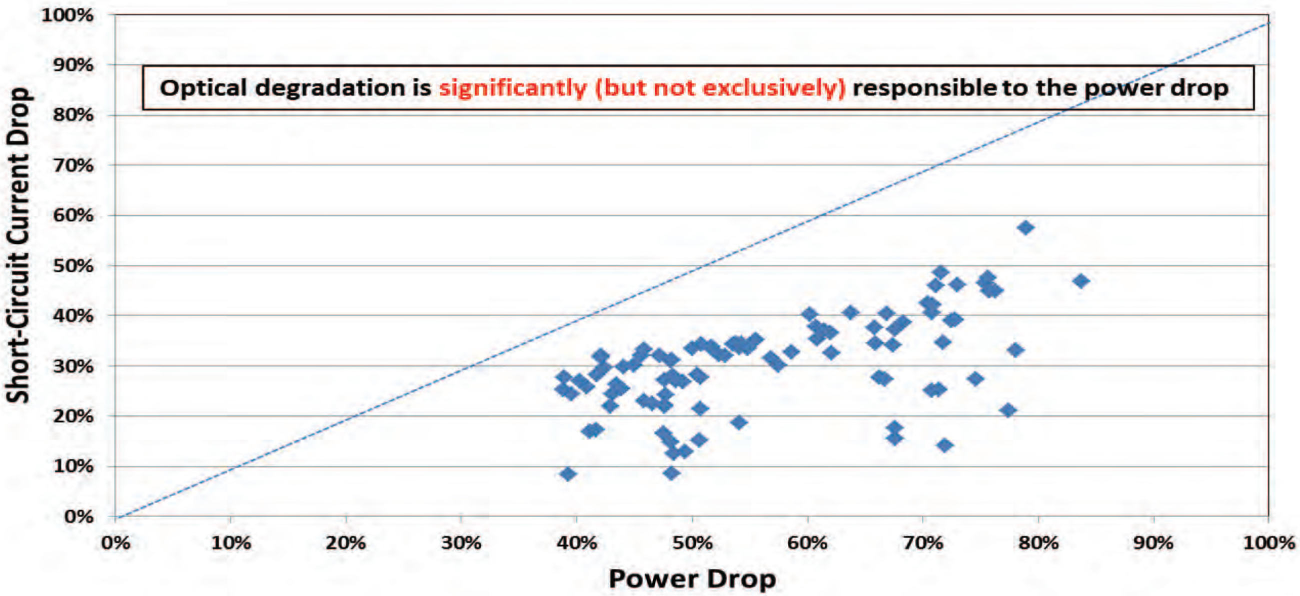


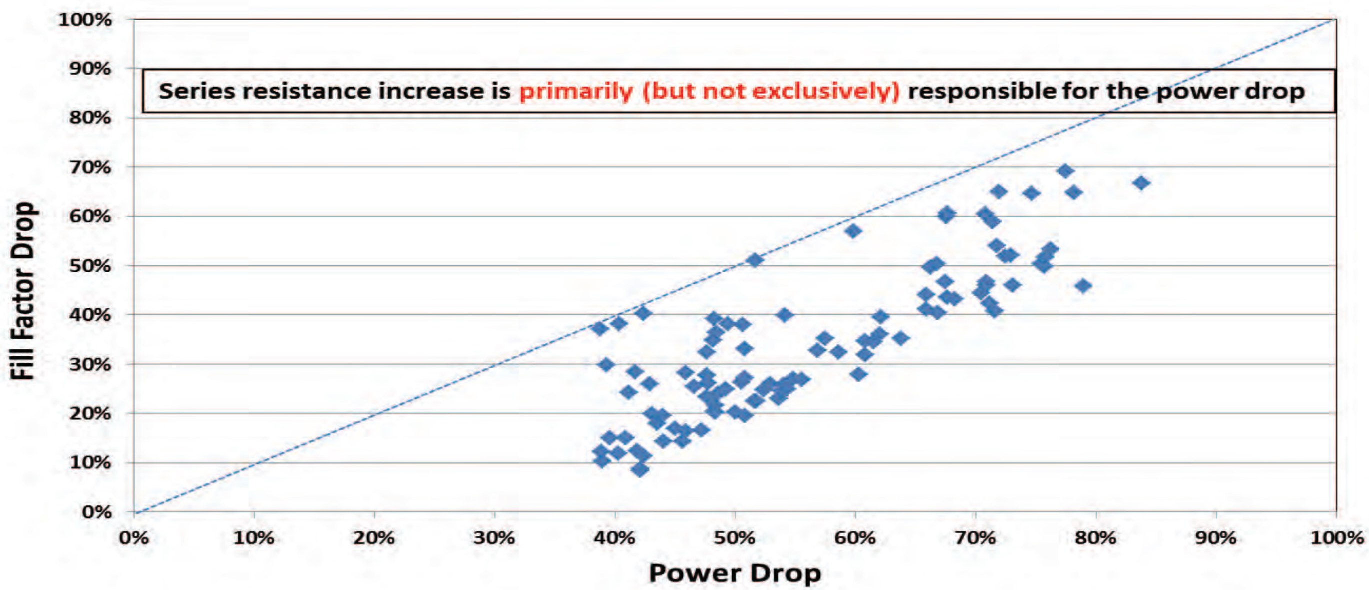
Currently, the plant is operating at about 40% of its rated capacity!

Site 2: Results – Degradation due to encapsulant browning and Rs increase

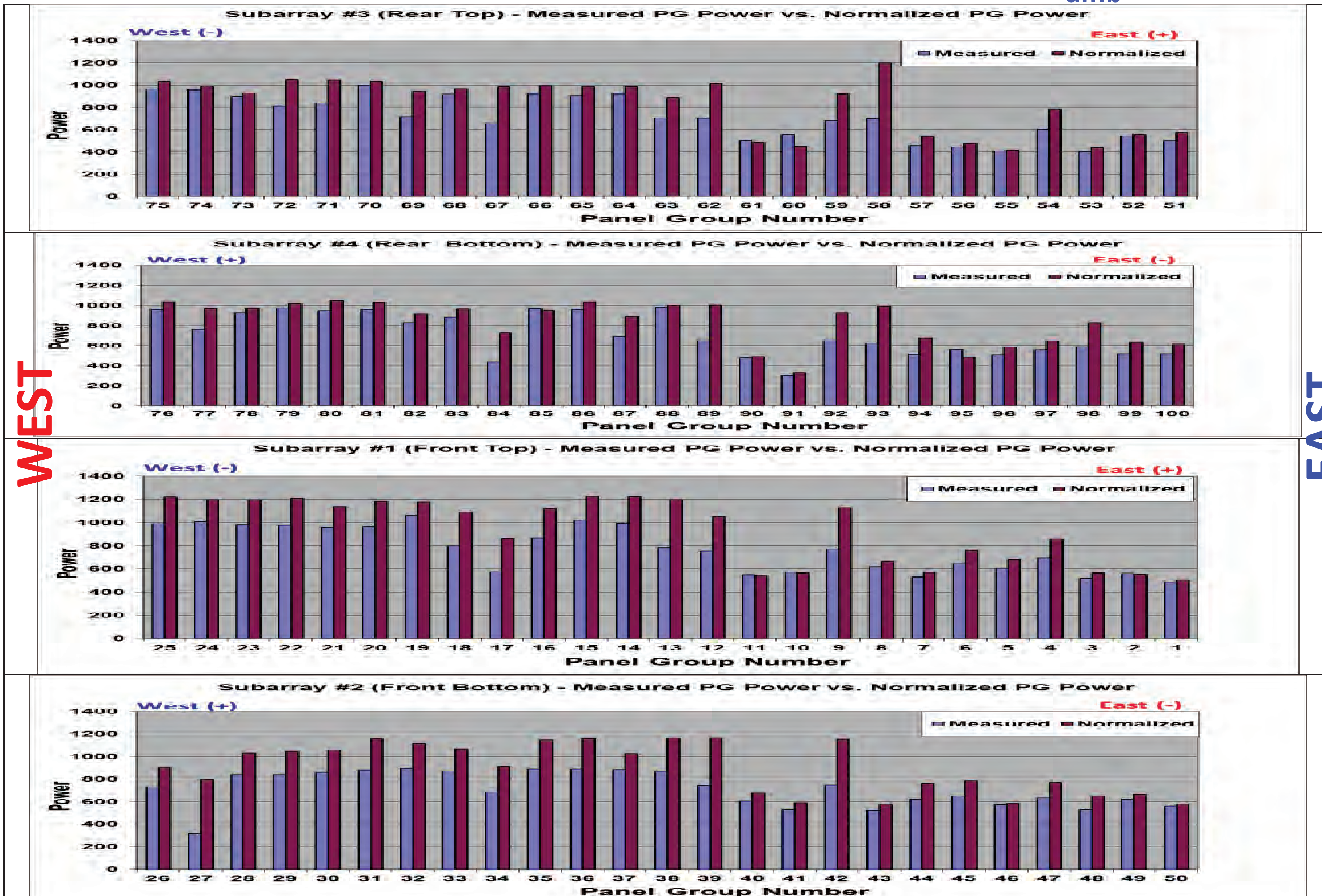


Site 2: Results – Power loss is significantly due to current loss (encapsulant browning) and primarily due to FF loss (solder bond fatigue)





Site 2: Results – East array degrades at much higher rate than west array!! Wind direction effect?? (S-W wind direction when T_{amb} > 40°C)



Site 2: Conclusions

- The degradation rate of these 26 years old modules is determined to be 2.3%/ year

- Primary degradation modes in this hot-dry climate site also appear to be encapsulant browning and (thermo-mechanical) fatigue of solder bonds. Encapsulant browning leads to current drop and solder bonds fatigue leads to fill factor drop

- Currently, the plan operates at about 40% of its rated capacity

- East side modules have degraded at higher rate than the west side modules. The reasons are unknown (wind direction effect?)

Overall Conclusions

Primary degradation modes in hot-dry climatic sites appear to be encapsulant browning and solder bond fatigue. These degradation modes turn to become failure modes when the performance degradation exceeds the warranty limit, e.g., > 20%.

Contact

Mani G. TamizhMani
manit@asu.edu

ASU PRL

ARIZONA STATE UNIVERSITY
PHOTOVOLTAIC RELIABILITY LABORATORY

2013 NREL PV Module Reliability Workshop
@ Marriott Denver West

2013.02.26

Delamination failures in long-term field-aged PV modules from point of view of encapsulant

Tsuyoshi Shioda

Mitsui Chemicals, Inc.

Mitsui Chemicals

Outline

1. Background
2. Mitsui's approach
3. Analyses results -delamination failure-
   3.1 Appearance
   3.2 Electrical performance
   3.3 Destructive analyses
      3.3.1 Interface for delamination
      3.3.2 Encapsulant
   3.4 Other failures
4. Summary

1. Background

✓There have been some failure modes of PV modules concerning encapsulant. ex) discoloration, delamination, corrosion, etc…

✓We have not known clearly correlation between these failure modes and encapsulant yet. But many people hears a "rumor " that degradation of EVA encapsulant is the root of all evil, especially, for over-stressed accelerated tests. We believe that most of rumors have not been based on scientific evidence.

✓To understand properly and quantitatively these failures is necessary for prediction of lifetime of a PV module or a PV component and improvements of their performances.

2. Mitsui's approach

Mitsui Chemicals

✓We have attempted to figure out correlation between power reduction of a PV module and degradation of an EVA encapsulant using long-term field aged PV modules and then disclose these information as much as possible.

✓We, Mitsui Chemicals groups, have 30-year-old history for commercialization of EVA encapsulant sheet. Furthermore, we have been manufacturing old grade EVA sheets since 1992, thus we can compare performances of field aged EVA with initial one.

✓First of all, we have focused on understanding properly and quantitatively what happened in a long term field aged PV modules for each failure mode from point of view of encapsulant.

2. Mitsui's approach

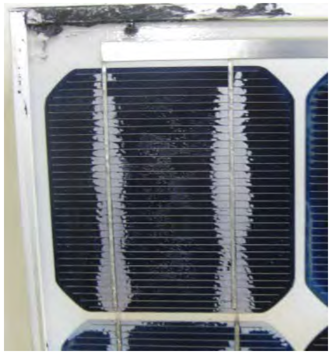
Failure modes related to encapsulant

- Discoloration
- Corrosion
- Delamination

Photos of typical examples for each failure mode

We have already proposed degradation prediction by appropriate UV irradiation.

Ongoing.
We already reported very low amount of free acetic acid in 17y field aged modules, as compared to over-stressed DH test results.



Report today.

3. Analyses results –delamination failure–

2013.02.26

Mitsui Chemicals

Our analyses flow

Aged PV module

Module level

- Appearance (eye, EL, thermo-view)
- Performance check (IV curve, insulation)

Destructive analyses

- Appearance
- Adhesion strength (under development)
- Analysis for encapsulant
  - Mechanical (DMA)
  - Electrical (resistivity)
  - Optical (transmission)
  - Chemical (acetic acid, etc)
- Analysis for cell / interconnectors
- Analysis for back-sheet

3.1 Appearance

We have 17y field aged PV modules with “typical” delamination failure.

(photo)

(EL image)

Manufacturer A
Module “A”

(photo)

(EL image)

Manufacturer B
Module “B”

3.1 Appearance

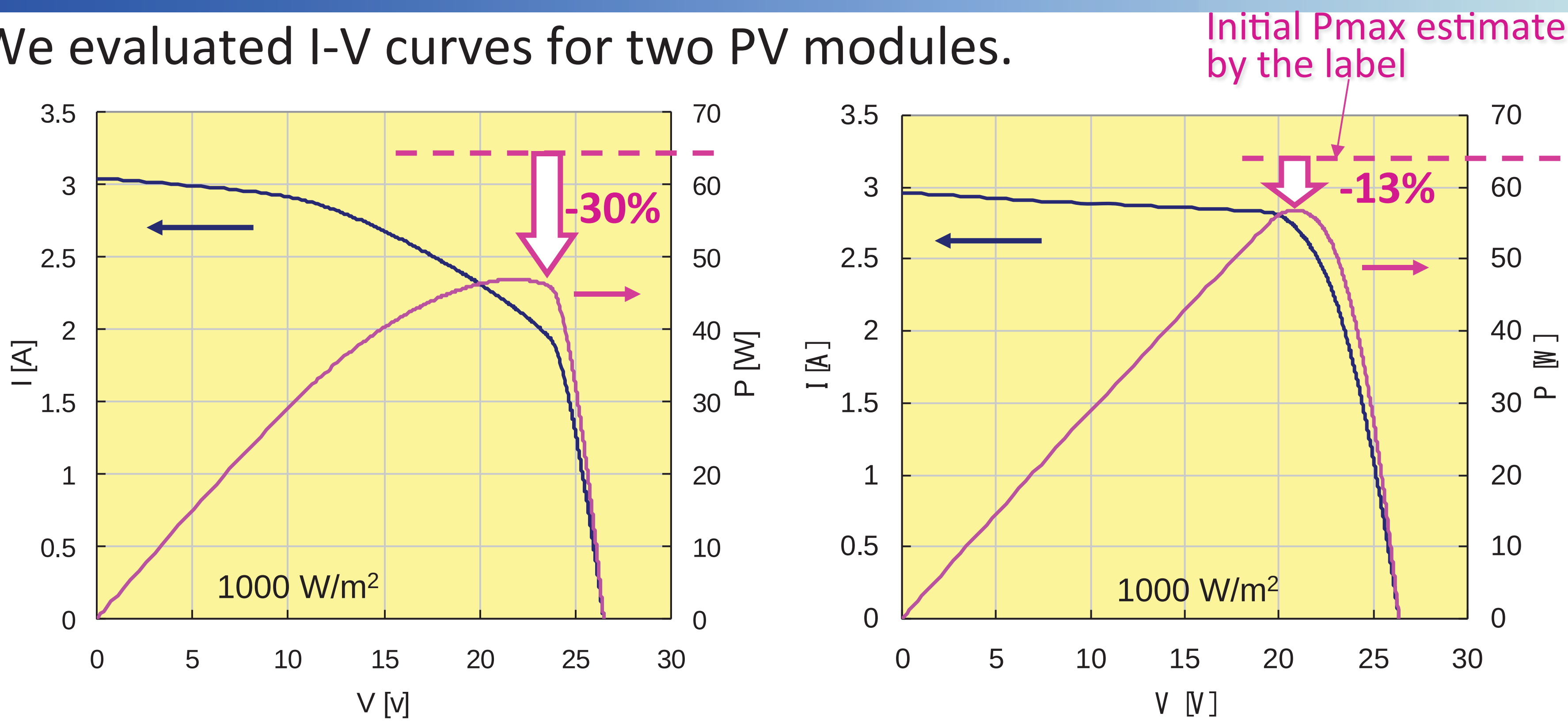
Features of these PV modules :

1. Delamination is mainly observed in the vicinity of interconnectors on cells.
2. Delamination is observed at the outer portions in a plane of the PV module.
3. We can not see a clear correlation between delamination failure and dark portions in EL images.

3.2 Electrical performance

2013.02.26

We evaluated I-V curves for two PV modules.



Module "A"

Decreases in Isc by 13% and FF by 17%

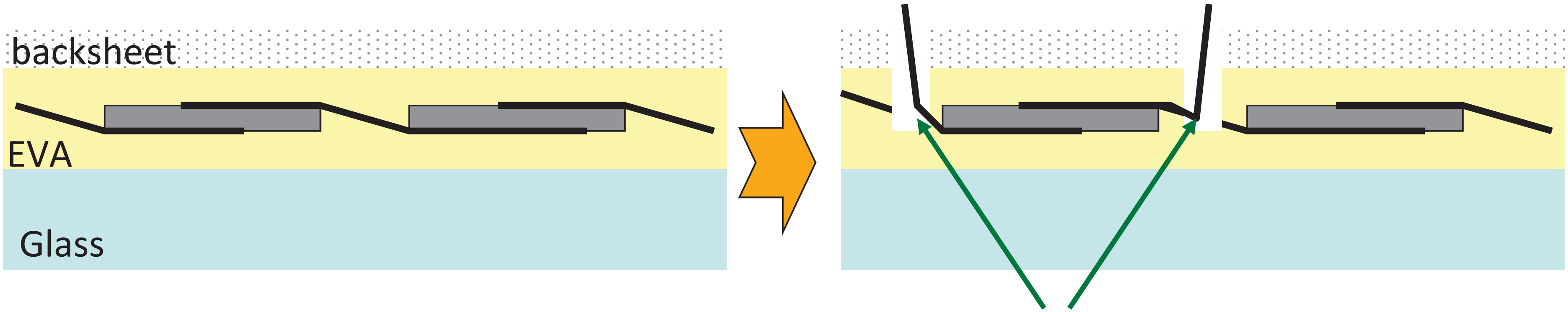
Module "B"

Decrease in Isc by 14%

✓Decrease in Isc mainly depends on discoloration of EVA and delamination.

3.2 Electrical performance –cell level–

We attempted to evaluate an I-V curve for each cell in Module “A” in order to find out a correlation between delamination and power reduction.

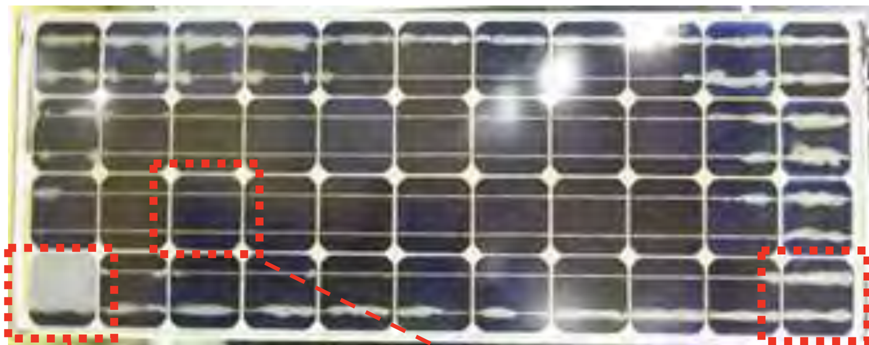


1. Cut these ribbons (isolation)
2. Connect probes to cut ribbons
3. Put a whole module on a solar simulator in order to obtain I-V curve for each cell.

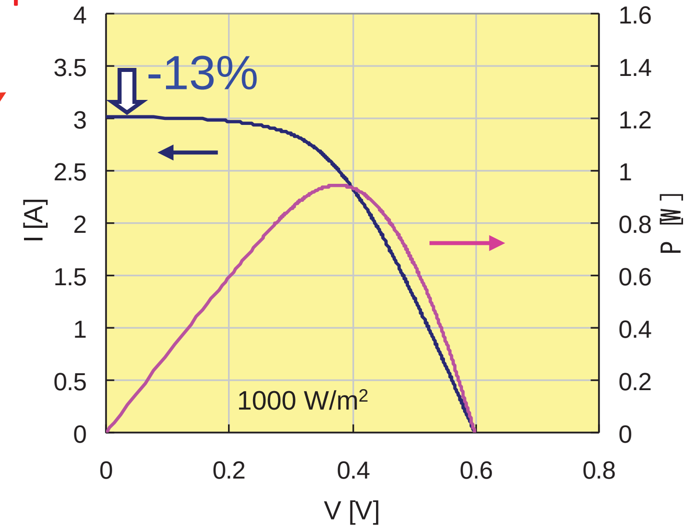
3.2 Electrical performance –cell level–

2013.02.26

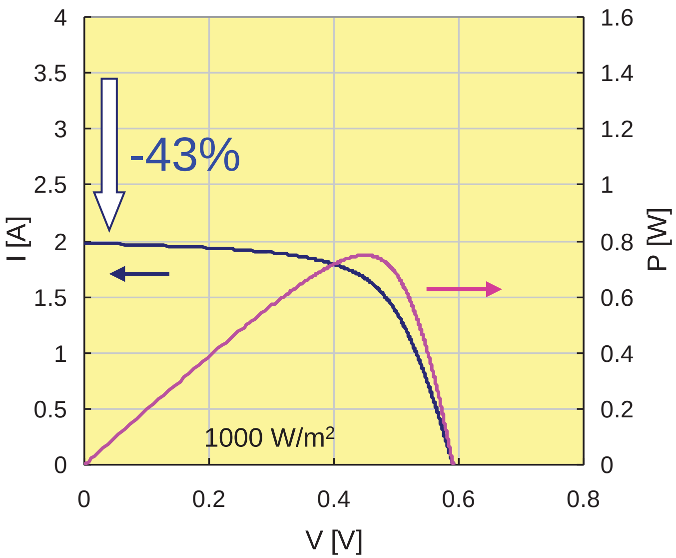
Mitsui Chemicals



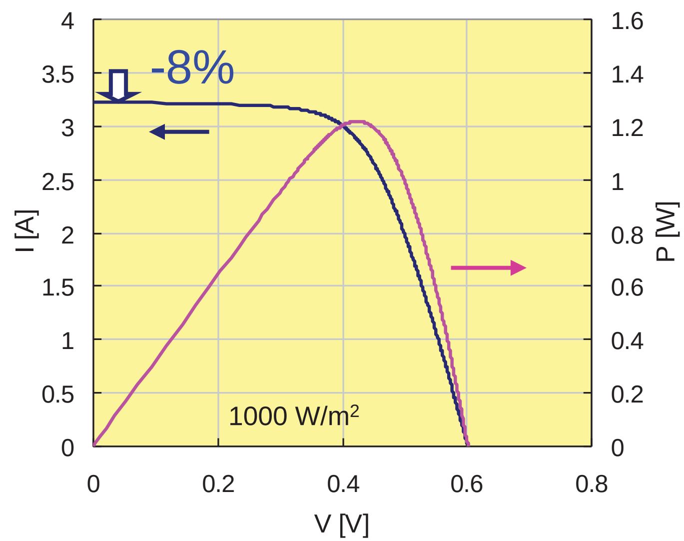
partial delamination



Large delamination

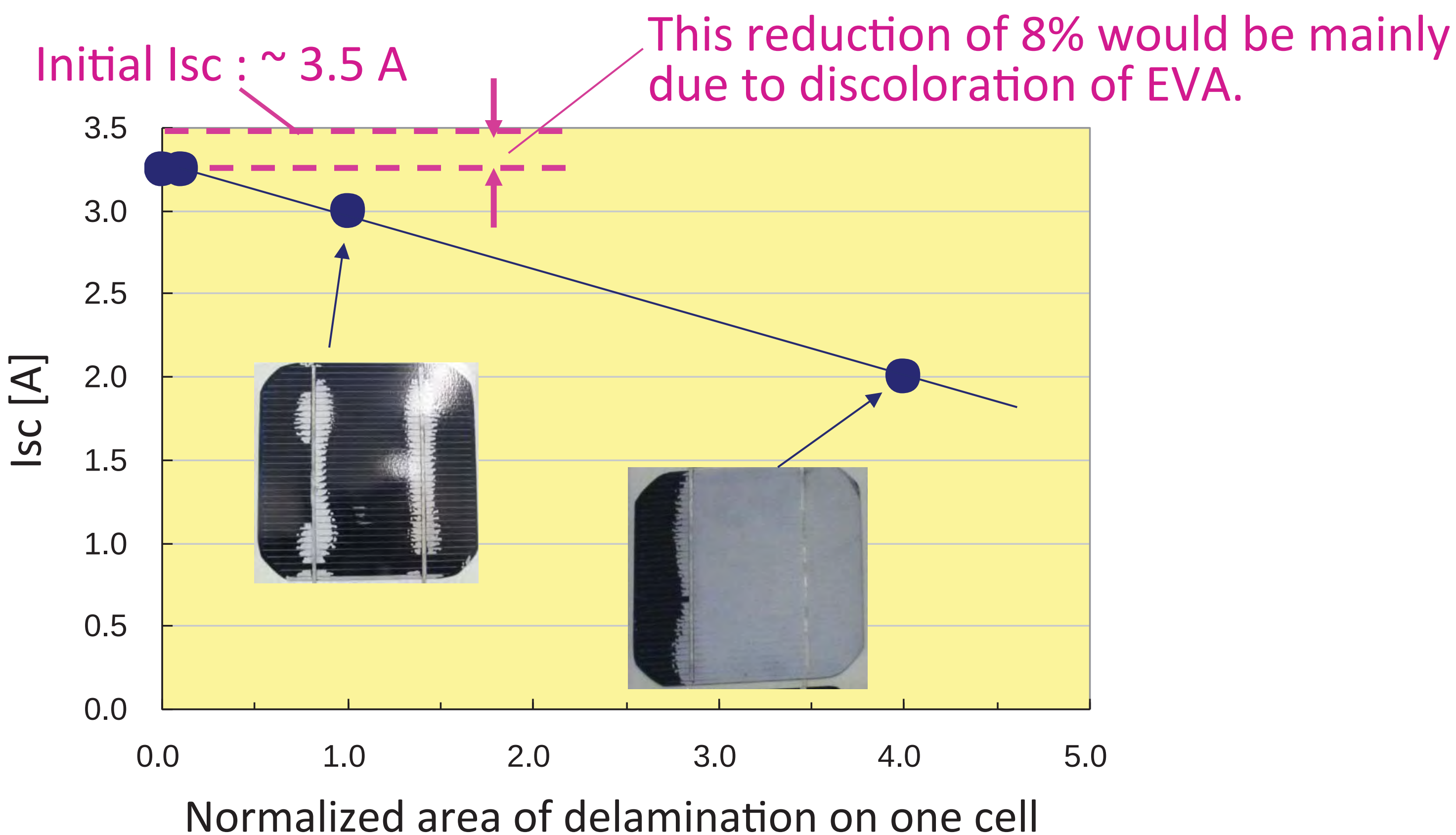


No delamination



3.2 Electrical performance

✓Delamination area was estimated roughly by image processing for each cell. We estimated Isc change as a function of delamination area.



Delamination leads to decrease in Isc.

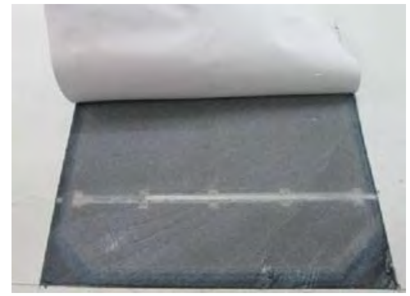
Outline

3.3 Destructive analyses

Sampling procedures

1. Separate backsheet from a module

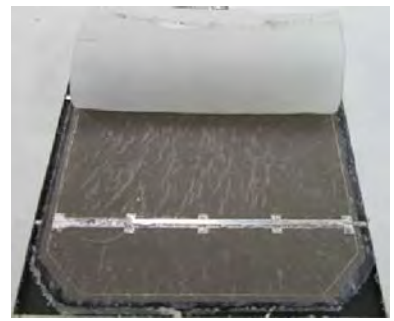
Sampling EVA, backsheet

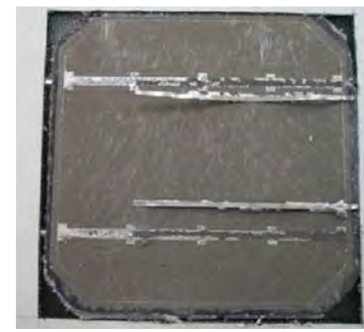


Large delamination portion

2. Separate an EVA sheet backside of a cell
   Detach ribbons from a cell
   (if necessary)

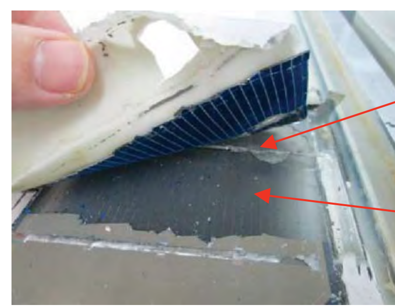
Sampling an electrode, a ribbon





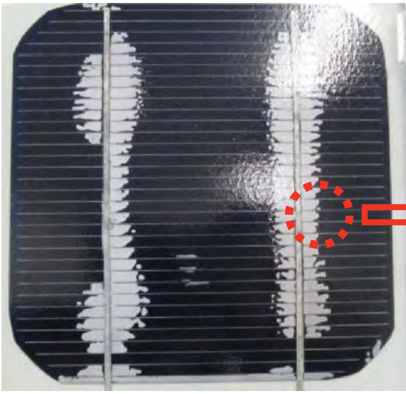
3. Separate a cell from EVA/Glass

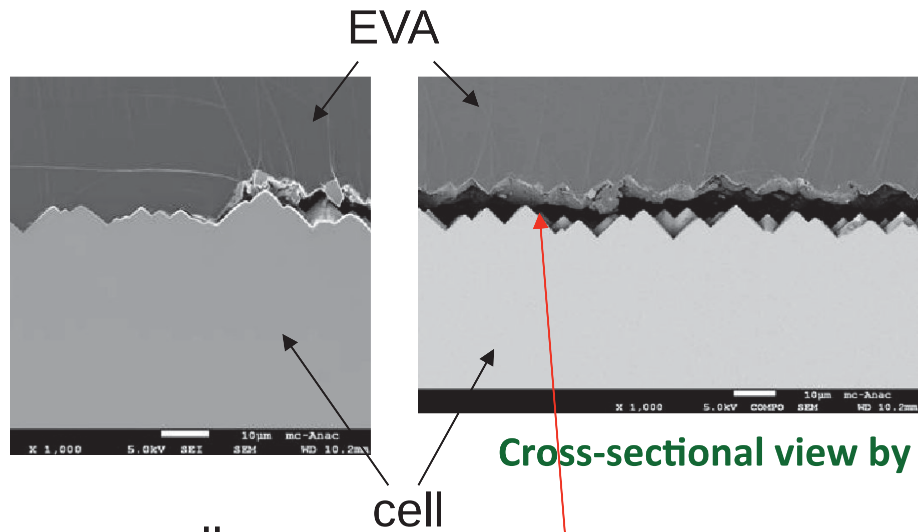
Sampling EVA,
electrodes / solder / AR coat of a cell



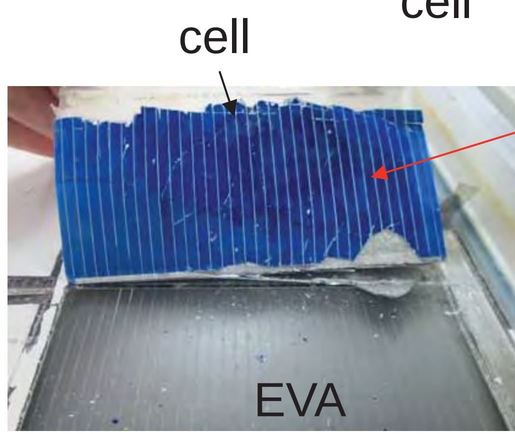
4. Separate an EVA sheet from a Glass

3.3.1 Interface for delamination





Cross-sectional view by SEM

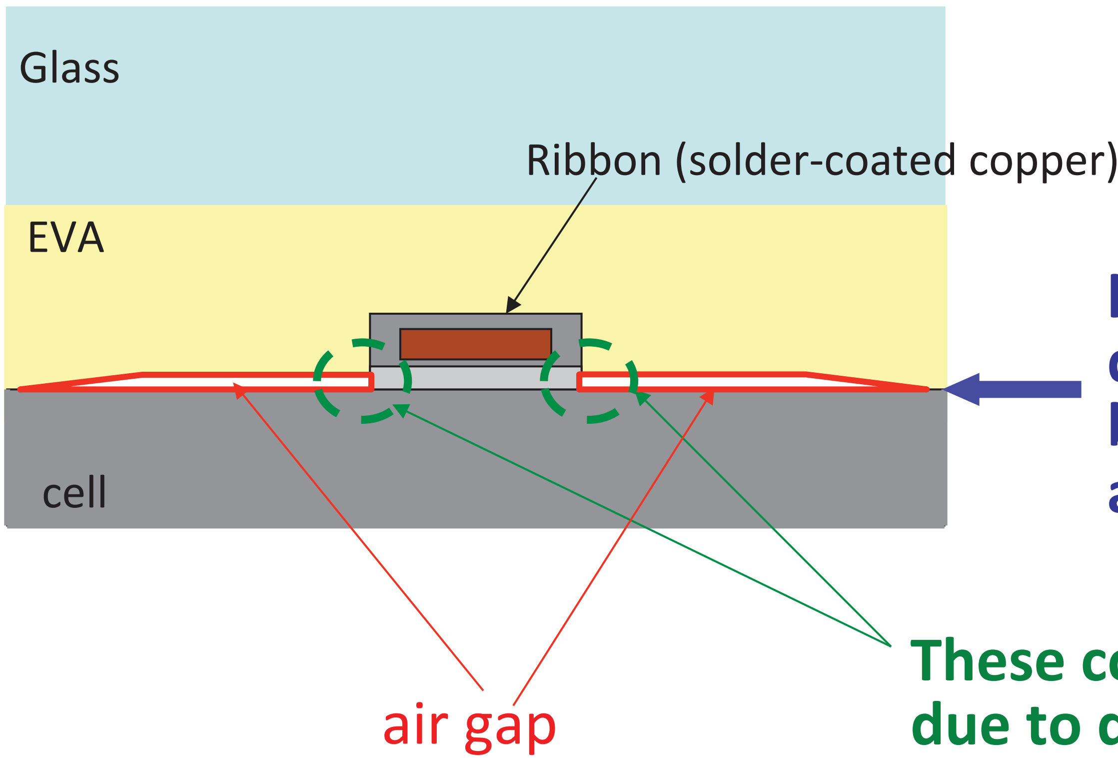


We confirmed that the surface layer of the cell was **TiOx** deposited as an AR-coating of the cell using XPS measurement.

Delamination was observed at the interface between EVA and TiOx.

3.3.1 Interface for delamination

Schematic of cross-section view : upper side of a module



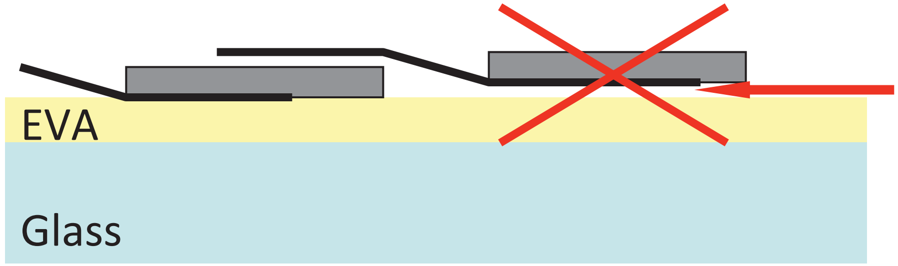
lower chemical bonding during field ageing, because of use of TiOx as an AR coating

These corners have high strain due to difference in CTE among ribbon, cell (Si) and EVA.

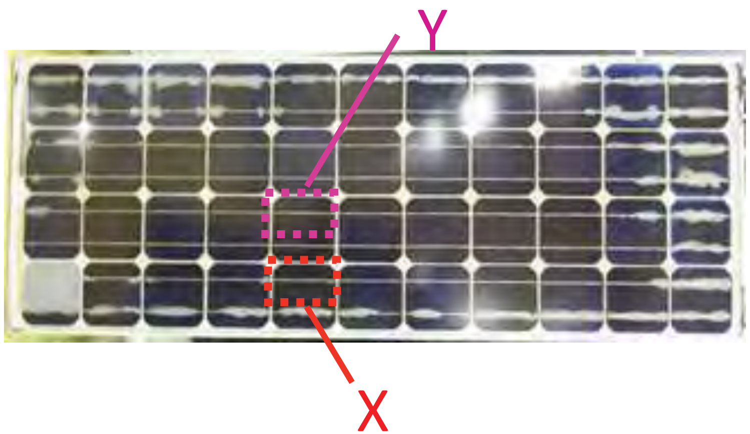
3.3.1 Interface for delamination

2013.02.26

Mitsui Chemicals



When we attempted to separate a cell from EVA/Glass, a cell broke into bits due to brittleness of a cell.



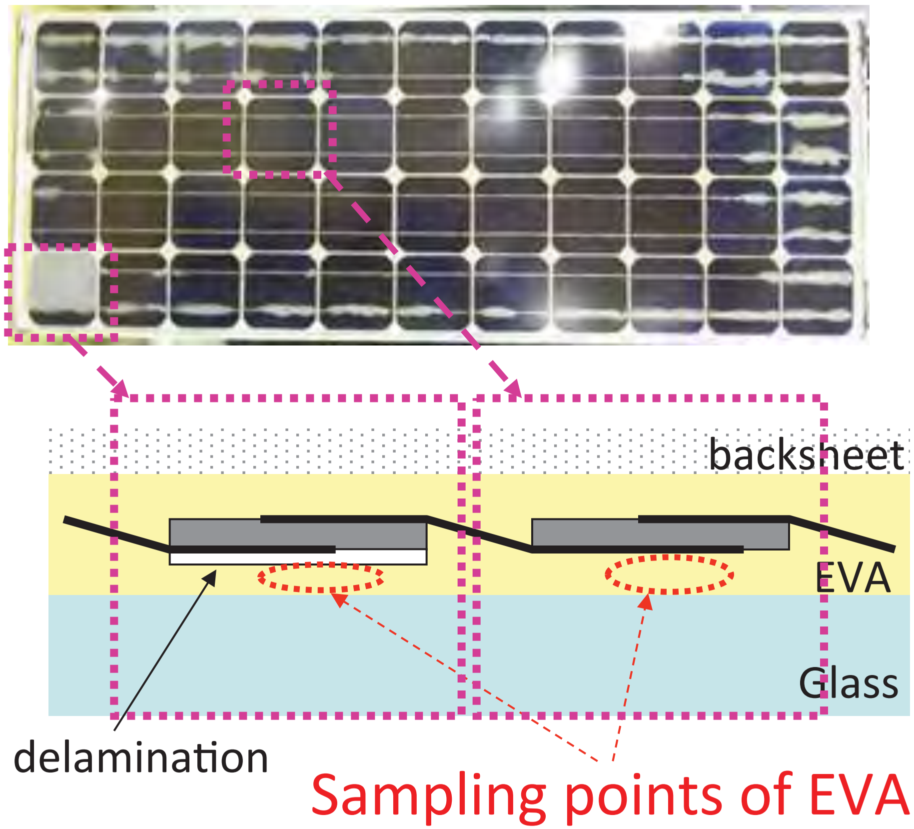
✓To separate a cell from glass side EVA at the **X** is **easier** than that at the **Y**.

✓The stress at the **X** is **higher** than that at the **Y**, because the **X** is **outer** position as compared to the **Y** in a plane of the PV module.

✓We speculate that delamination is induced by weakening chemical adhesion (led by use of TiOx) and high strain at the interface.

✓We should confirm change of performances of EVA encapsulant.

3.3.2 Encapsulant -EVA-

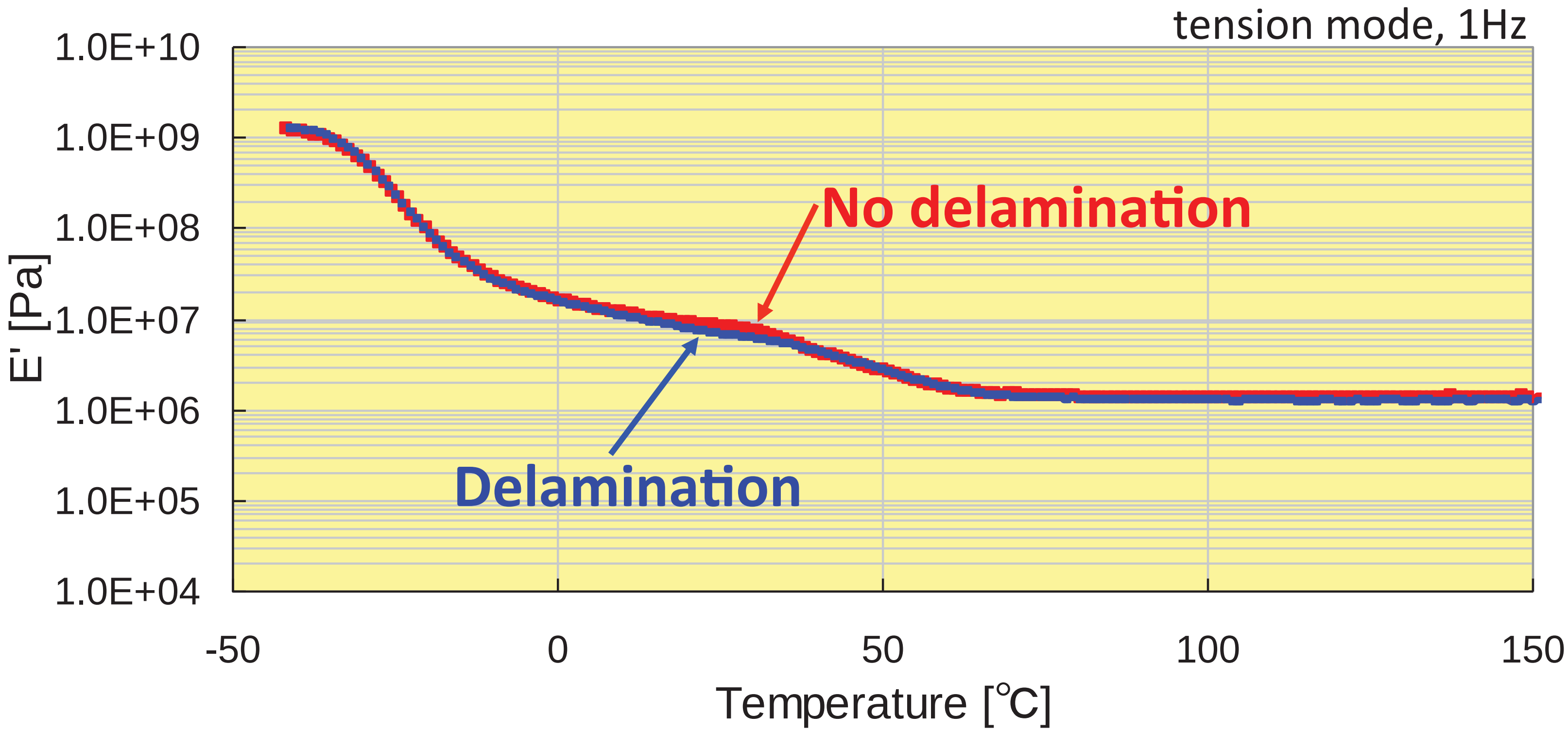


Analysis items

Performance	Delamination Portion (Glass side)	No delamination portion (Glass side)
Mechanical DMA (Dynamic Mechanical Analysis)		
Electrical Volume resistivity		
Optical Transmission		
Chemical Amount of free acetic acid		

Mechanical : DMA

We have obtained viscoelastic curves with a rheometer.



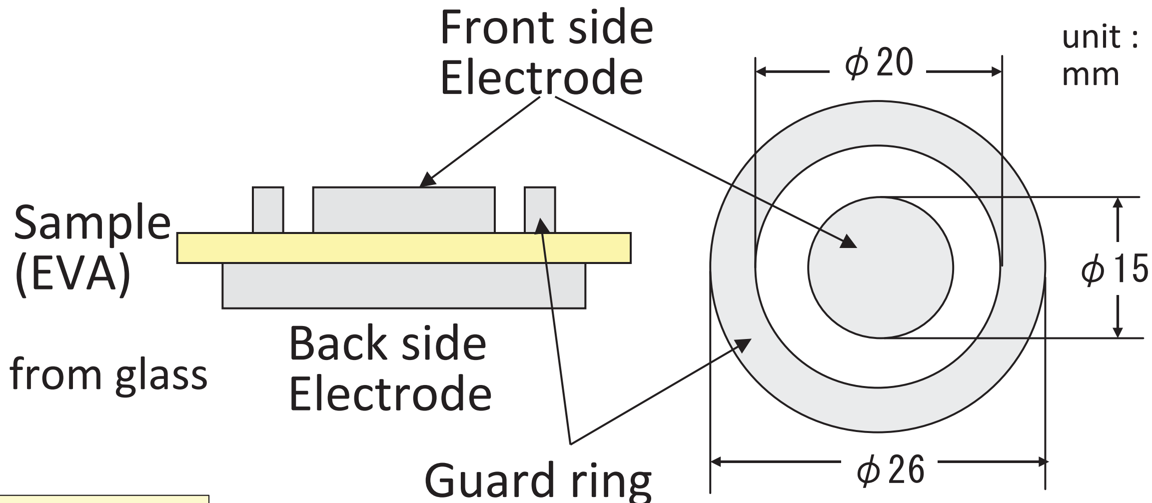
✓There was no difference between E' for delamination and non delamination.

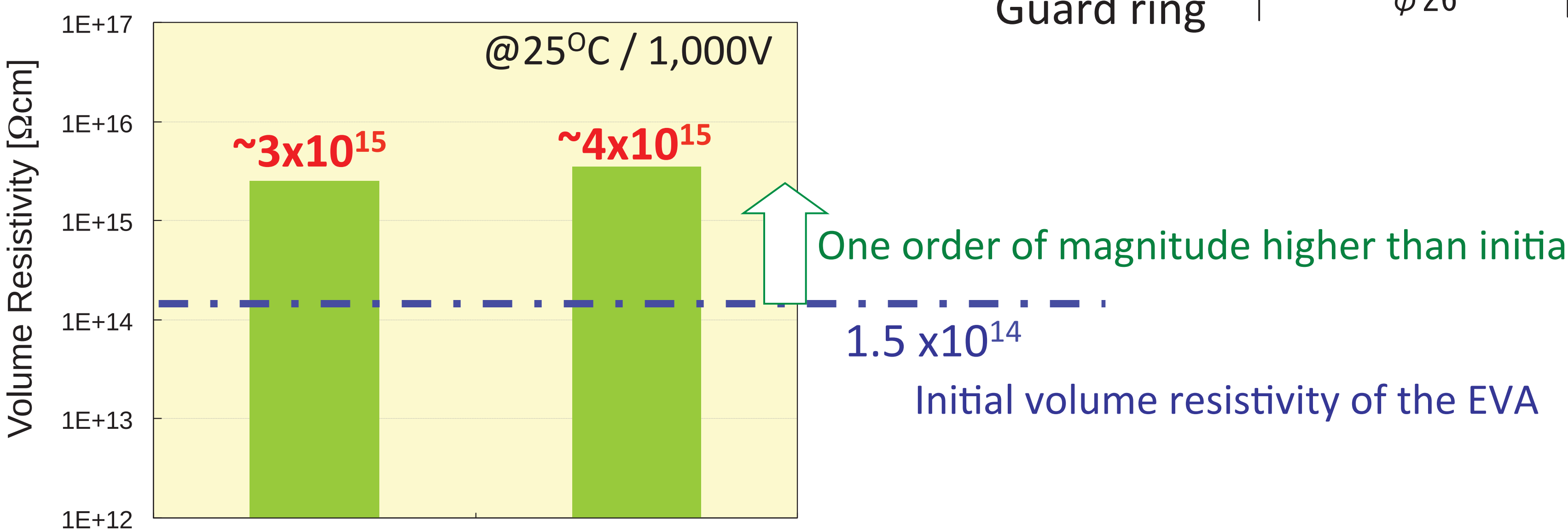
✓We can not see mechanical degradation of both these EVA samples.

2013.02.26

Electrical : Volume resistivity

Photo of EVA sample separated from glass for no delamination portion.

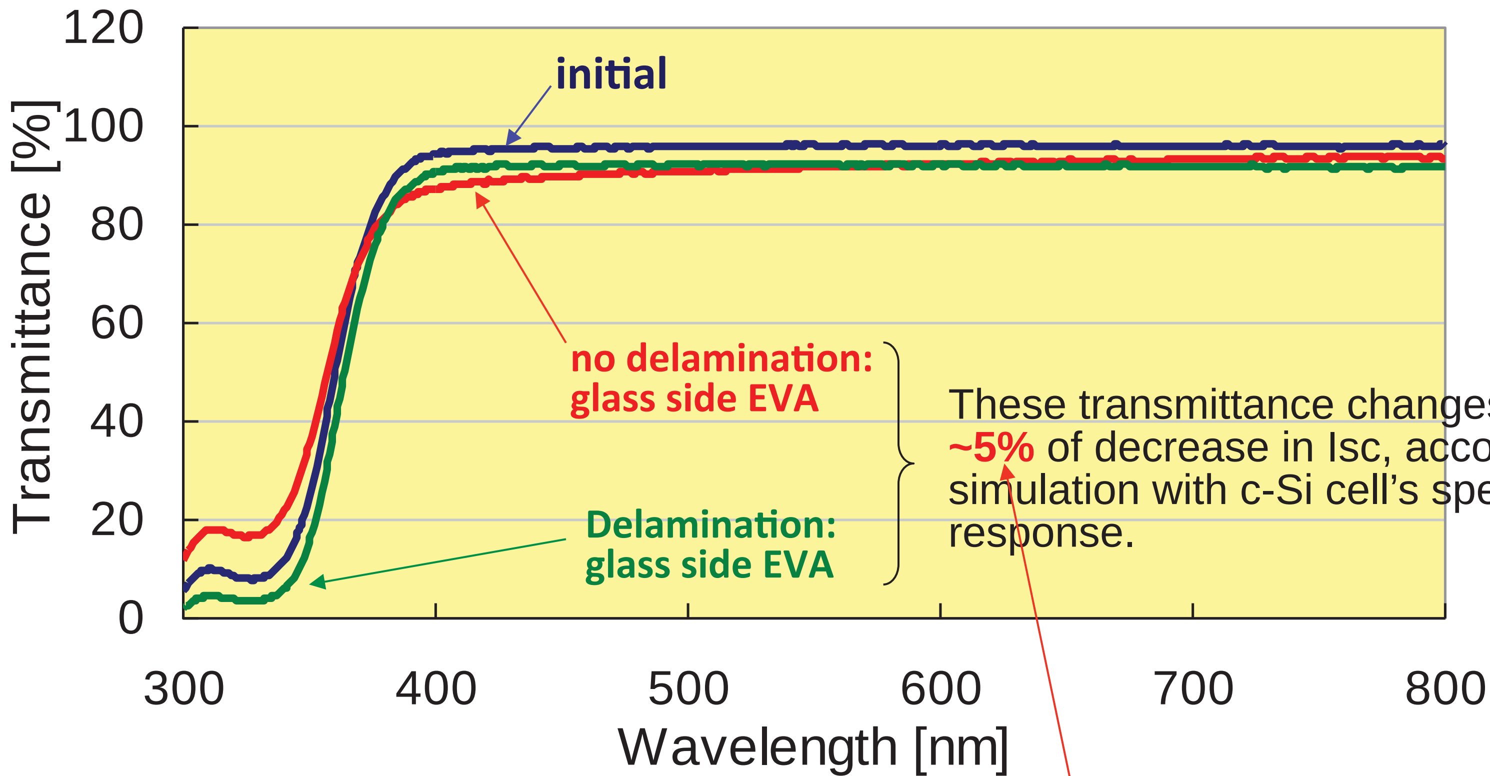




✓There was no difference between volume resistivities of EVA for delamination and non delamination portions.

Optical : Transmittance spectrum

We have observed transmittance spectra of glass side EVA for delamination and no delamination portions and confirmed high transmission over 90%.

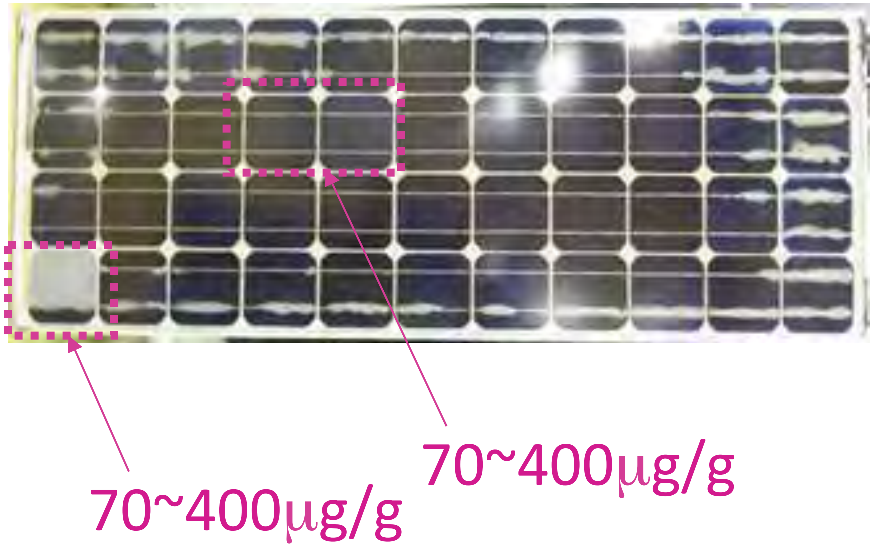


These transmittance changes lead to **~5%** of decrease in Isc, according to our simulation with c-Si cell's spectrum response.

Sample thickness was **~100μm** and we smoothed surfaces preventing from light scattering.

~5% would be underestimated value because of thinner sample than actual encapsulant layer.
More evaluation is necessary.

Chemical : free acetic acid



We have estimated amount of free acetic acid in glass side EVA at delamination and no delamination portions.

✓We observed similar amount of free acetic acid to that for other aged PV modules we already reported.
✓There was no difference between the amounts for delamination and no delamination portions

3.3.2 Encapsulant -Summary-

Mitsui Chemicals

Performance	Delamination Portion (Glass side)	No delamination portion (Glass side)
Mechanical DMA (Dynamic Mechanical Analysis) E'	3×10^6 Pa @25°C 1×10^6 Pa @100°C	3×10^6 Pa @25°C 1×10^6 Pa @100°C
Electrical Volume resistivity	3×10^{15} Ωcm	4×10^{15} Ωcm
Optical Total light transmittance	>90 %	>90 %
Chemical Amount of free acetic acid	70~400 μg/g	70~400 μg/g

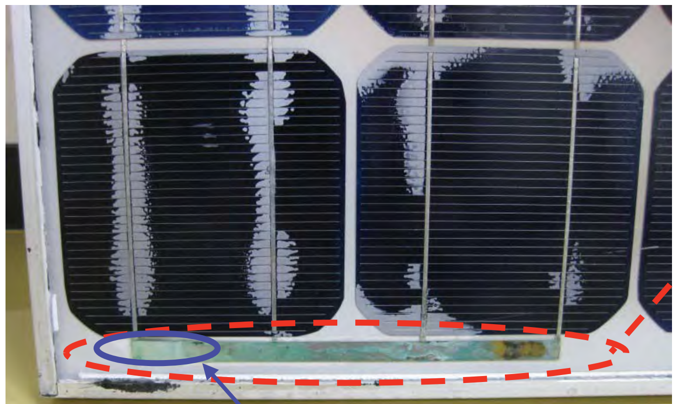
There were no differences between any data for glass side EVA for delamination and no delamination portions

Outline

3.4 Other failures -Corrosion-

2013.02.26

closeup picture



Patina

Severe degradation of copper

A solder layer disappeared.

A part of Copper ribbon disappeared.
= No electrical conduction

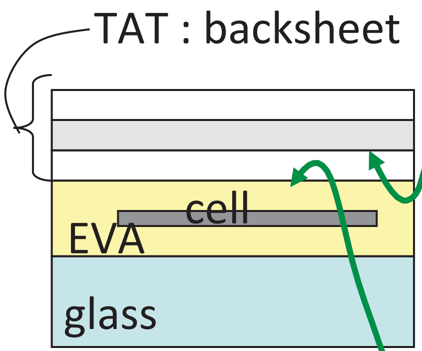
EL image

Backsheet/EVA were cut at the bus-bar portion.
We observed the corroded bus-bar.

✓Adhesion strength among inner layers of the backsheet "TAT" was extremely low.

Mitsui Chemicals

3.4 Other failures -Corrosion-



Inner Al layer of backsheet
(EVA side)

Backside of the module at corrosion portion

water stain
like an arc

$Al(OH)x$, $AlxOy$

evidence of water "liquid" ingress

Corner of Al frame side

Backside of the cell

Severe corrosion of Al layer

We can see clearly "copper".
(= coated solder disappeared.)

We think that this corrosion corresponds to to dark portion of the EL image

Corner of Al frame side

4. Summary

- ✓We analyzed long term field aged PV modules with typical delamination failures.
- ✓Delamination on cells led to decrease in Isc.
- ✓There were no differences between performances of EVA encapsulant of delamination and no delamination portions.
- ✓We consider that delamination is induced due to weakening chemical adhesion (led by use of TiOx) and high strain at the interface.

Future works

✓We also found corrosion failure in the PV module "A".

✓Appearance indicated that "water" ingress into an inner layer of backsheet from a corner of Al frame would lead to severe corrosion of copper ribbon.

✓Detail analyses are ongoing.

Acknowledgment

✓These analyses were carried out collaborating with Mitsui Chemicals Analysis & Consulting Services, Inc (mcAnac).

✓We thank Mr. Yamada and Mr. Kuwahara of mcAnac, for their continuous efforts.

✓If you are interested in detail analyses for aged PV modules, please let me know.

Tsuyoshi.Shioda@mitsui-chem.co.jp

PV QA Task Group #2: Thermal and Mechanical Fatigue including vibration

Christopher Flueckiger

NREL PVMRW

February, 2013

Task Group #2: Scope of Work

Task Group 2: Thermal and Mechanical Fatigue including Vibration
(leaders: Chris Flueckiger and Tadanori Tanahashi)

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 PV module quality.

PV QA TG #2: Accelerated Stress Tests for PV

Accelerated Stress Test	Failure Mode	Characterizing Tests
Thermal Cycles Agreed to be a wear out mechanism	Broken interconnect Broken cell Solder bond failure Junction box adhesion Module open circuit – potential for arcing Delamination (cell to encapsulant, encapsulant to super/substrate) Outgassing Stress Cracking of jbox/cable glands	Wet leakage current, IV (electrical performance) Strain relief test Ground path continuity Visual Electroluminescence (full current and 10% Isc for shunted cells) Thermal imaging Dark IV Diode functionality Combine with dynamic load and humidity freeze specifically to identify cell cracking propensity. In-situ monitoring of continuity frame and circuit, dark IV Wiring compartment securement (final)

PV QA TG #2: Accelerated Stress Tests for PV

Accelerated Stress Test	Failure Mode	Characterizing Tests
Humidity Freeze Group discussion – Could be wear out.	Delamination Junction box adhesion Inadequate edge deletion Adhesion loss of frame to laminate	Static Load Wet leakage current, IV (electrical performance) Strain relief test Ground path continuity Visual Electroluminescence (full current and 10% Isc for shunted cells) Thermal imaging Dark IV Diode functionality In-situ monitoring of continuity frame and circuit, dark IV Wiring compartment securement (final)

PV QA TG #2: Accelerated Stress Tests for PV

Accelerated Stress Test	Failure Mode	Characterizing Tests
Static Mechanical Load (Simulation of wind and snow load) However - ice damming leading to movement of inclined module could lead to wear-out like failure)	Structural failures Broken glass Broken interconnect ribbons Broken Cells Solder bond failures	
Dynamic Mechanical Load **(Simulation of wind load and transportation stress)**	Broken glass Broken interconnect ribbons Broken Cells Solder bond failures Ground path continuity failure Cracking of frame or loss of mounting system	Visual inspection Ground path continuity EL (low and high current) IV Wet leakage current Junction box securement test

PV QA TG #2: New Work Item Proposal (NWIP)

[Document reference]

NEW WORK ITEM PROPOSAL

	Proposer Christopher Flueckiger	Date of proposal 4-23-2012
	TC/SC 82	Secretariat Howard Barikmo
	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 on the introduction of it into the work programme, 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 COMPARATIVE TESTING OF SILICON PV MODULES TO DIFFERENTIATE PERFORMANCE IN MULTIPLE CLIMATES AND APPLICATIONS Part 2: Mechanical and Thermal Cycling Stress Testing	
☐ Standard	☒ Technical Specification

PV QA TG #2: New Work Item Proposal (NWIP)

1 Scope and object

The purpose of this International Standard is to define a test or test sequence that will quickly uncover failures that have been associated with exposure to thermal cycling after many years. IEC 61215 already includes 200 thermal cycles in one leg of the testing and 50 thermal cycles combined in sequence with other stresses. However, field data imply that solder-bond and/or metal-interconnect failures can dominate the failures that are seen in the field, implying that the IEC 61215 test procedure is not adequate to gain confidence in the design in all cases. This test procedure (IEC 62XXX – 2) applies more stress, and, as a part of the rating system described in IEC 62XXX – 1, provides comparative testing to differentiate modules with improved durability to thermal cycling and the associated mechanical stresses.

PV QA TG #2: New Work Item Proposal (NWIP)

1 Scope and object (continued)

Solder-bond and metal-interconnect failures can arise for a number of reasons. Interconnect design that reduces the mechanical stress experienced during thermal cycling can greatly reduce the rate of damage associated with thermal fatigue. Failures have also been associated with cracked silicon cells that then cause increased stress on the metal interconnects that span the cracks. This test method applies thermal-cycling and mechanical stress in a way that will quickly uncover thermal-cycling induced failure after even 10 or 25 years in the field.

PV QA TG #2: Proposed Test Sequence

1. Visual Inspection
2. EL image
3. Power Measurements
4. IR image
5. Insulation Resistance Testing
6. Wet Leakage Current Testing
7. Dynamic Mechanical Load (based on NP 62782 Ed 1.0)
8. Temperature Cycling TC/Humidity Freeze Cycling
   Consideration shall be given to the number of cycles, temperature ranges, rates of temperature change, and dwell times, etc.
9. Visual Inspection
10. EL image
11. Power Measurements
12. IR image
13. Insulation Resistance Testing
14. Wet Leakage Current Testing

PV QA Task Group #2: Current Activities

Dynamic Mechanical Load / Temperature Cycling Sequential Testing

Comparison with long-term Temperature Cycling Tests (TC 600)

.

Nov. – Dec. 2012	DML Testing IEC 62782 Ed. 1.0 +/- 1,000 Pa, 2-3 cycle/ min, 1,000 cycles
Jan. – Feb. 2013	TC Testing IEC 61215 -40~+85oC, 200 cycles, + Imp
Feb. 2013	Interim Report at NREL PVMRW
Feb. – April 2013	Further development of draft proposal in preparation for WG2 meeting in May

International PV Module Quality Assurance Task Group #2

Want to Volunteer!

To volunteer for **Task Group 2**, individuals may contact the Chris Flueckiger directly or request access to the website at

http://pvqataskforceqarating.pbworks.com/

THANK YOU.

Christopher Flueckiger
Underwriters Laboratories
Email: christopher.flueckiger@ul.com

Thermal Cycling Combined with Dynamic Mechanical Load: Preliminary Report

Tadanori Tanahashi
ESPEC CORP.

Feb. 26, 2013
2013 PV Module Reliability Workshop

ESPEC: Products for Testing of Solar Modules

Solar Panel
Large Walk-in Chambers

PID Evaluation System
(Chamber with Insulation Rack & Leakage Current Meas. System)

DML -> TC Sequential Test

1. Recognition of Current Situation
   - TC 200 is not enough (NREL PV Module Reliability Workshop, 2012).
   - Extended TC (ex. TC 600) may effective, but the long-term period is required.
   - In our experience, the interconnectors- / solder bonds- failures have been observed even in the moderate climate (ex. Japan).

2. Basic Concept
   More Intense Stresses in Qualification Testing -> Depression of Infant Mortality -> Long-term Survive (Probably) = Elongation of Service Lifetime

3. Requirements
   - Time Saving
   - Similar Failure Mode with Thermal Cycling?

4. Dynamic Mechanical Load (DML)
   - DML induce the intense strain amplitude in ribbon (interconnector).
   - DML is so fast.

5. Proposal: DML -> TC Sequential Test
   - Consideration shall be given to the test condition (DML / TC)
   - 1st trial is carrying out in TG-2 (JP).

PV QA Task Group #2: Current Status (Discussion in IEC TC82/WG2 Meeting, Stresa & Oslo)

Proposed Test Sequence

1. Visual Inspection
2. EL image
3. Power Measurements
4. IR image
5. Insulation Resistance Testing
6. Wet Leakage Current Testing
7. Dynamic Mechanical Load (based on NP 62782 Ed 1.0)
8. Temperature Cycling, TC/Humidity Freeze Cycling

   Consideration shall be given to the number of cycles, temperature ranges, rates of temperature change, and dwell times, etc.
9. Visual Inspection
10. EL image
11. Power Measurements
12. IR image
13. Insulation Resistance Testing
14. Wet Leakage Current Testing

DML / TC Test --- Notes for Discussion

What are the issues which need to be addressed before we can submit the NWIP?

1. Availability of **Extended TC**

- **Problems**: Become effective testing on the Today's PV modules?
  (in the most recent technologies, components, and manufacturing techniques)
  Become the rejection test for immature manufacturing?
- Massive survey for commercial modules is needed to recognize the current status.
- **To solve this issue**, **METI Project is ongoing.**

2. Availability of **DML**

- **Problem**: Differences / Similarities with the thermal fatigue.
  Does the intense strain by DML induce a large number of cell crack?
- The experimental evidences are needed.
- **To solve this issue**, **NREL-AIST collaboration is carrying out.**

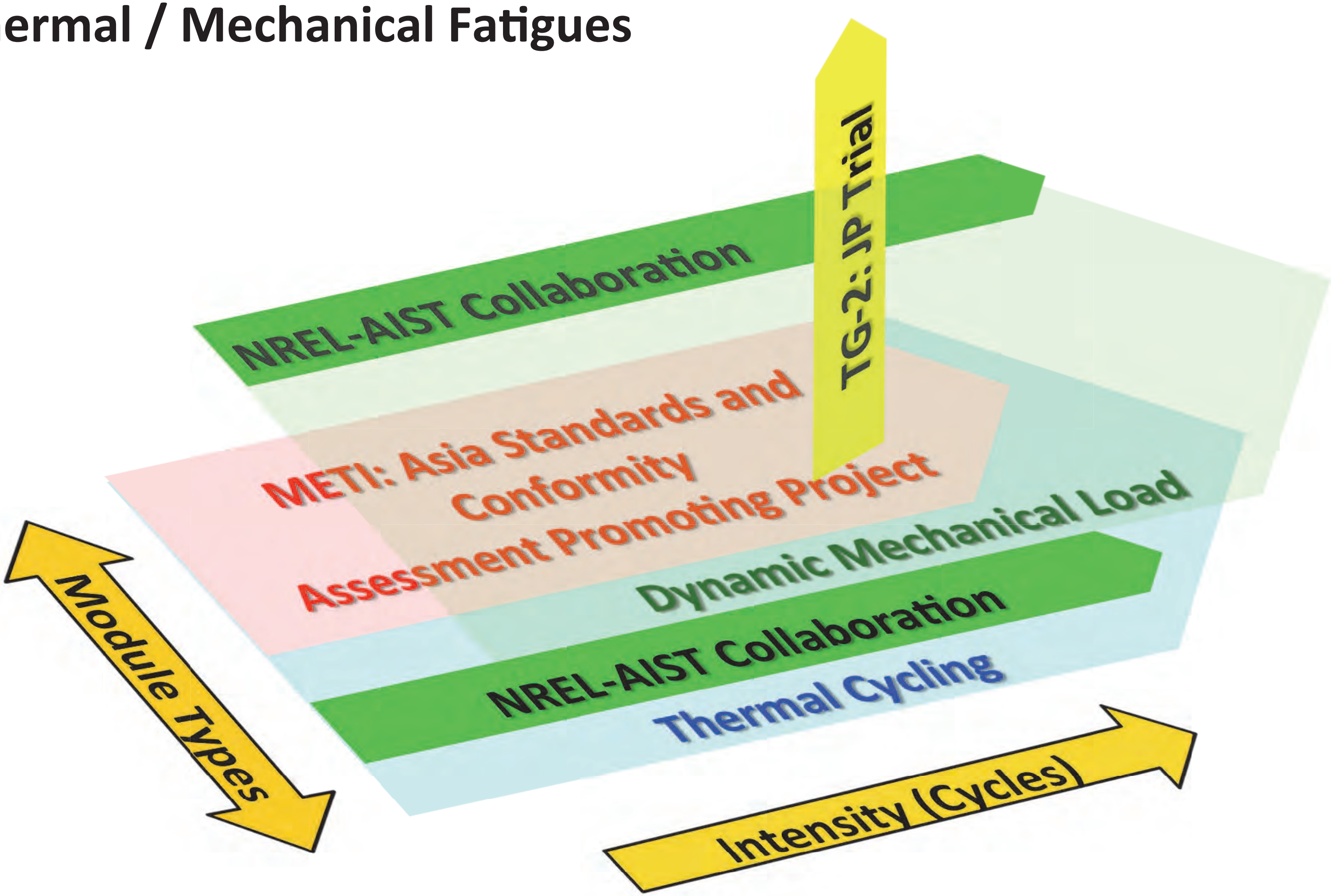
3. Availability of **Sequential Testing**

- **Problem**: To establish the effective test, can the deficit of TC be complemented by DML?
  ribbon crack: induced by DML?
  solder crack/delamination: induced by TC?
- The experimental evidences are needed.
- **To solve this issue**, **PV-QA TG-2 [JP] Trial is ongoing**.

4. Is there any other issues?

DML / TC Test

Ongoing Experiments
for the Establishment of Novel Test Procedure regarding with Thermal / Mechanical Fatigues



METI (JP) Project

Asia Standards and Conformity Assessment Promoting Project
(Supported by Ministry of Economy, Trade, and Industry)

Aim:

Massive Survey for the Degradation Profiles of Commercial PV Modules

<Thermal Cycling Test>

c-Si PV modules:

- 13 Types of c-Si PV Modules (Mono- / Multi- c-Si)
- Sample Size: 10 or 5 Modules/Module Type
- Purchased from Market (JP and Other Manufactures)
- Most Recent Designed PV Modules (> 2011)

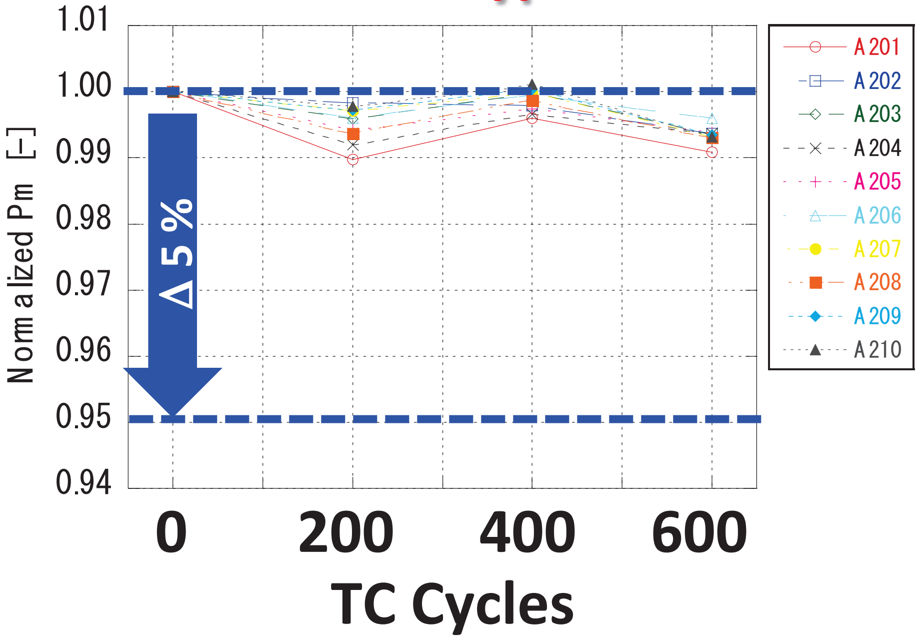
Test Procedure:

- According to IEC 61215
  10.11 Thermal Cycling Test
- Thermal Cycling: 200, 400, and 600 Cycles
  (Extended TC Testing)

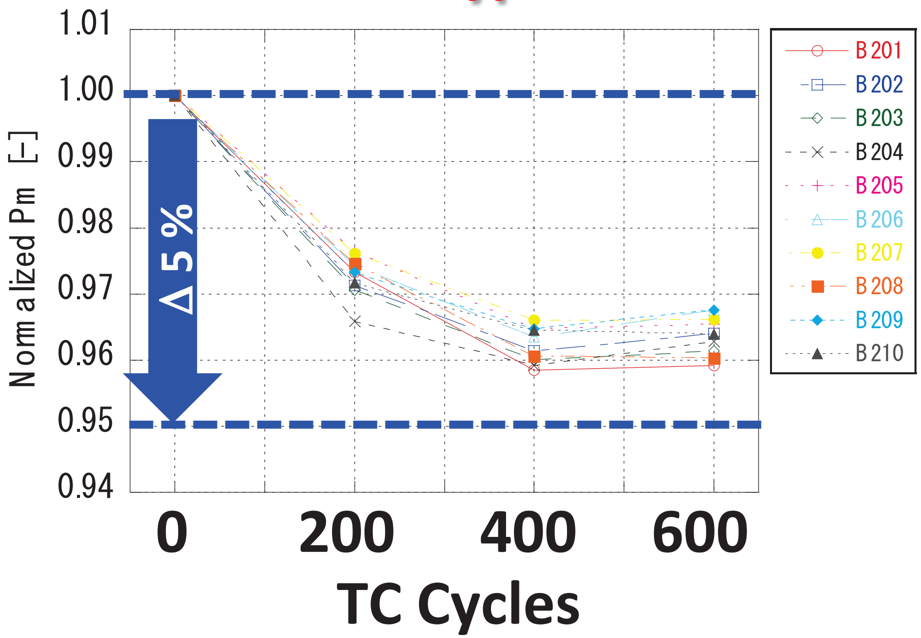
Extended TC Testing (200, 400, and 600 cycles)

Sample: Commercial Available PV Modules (Multi c-Si)
2 Module Types, 10 Modules / Type

Module: Type A



Module: Type B



- **Increase in Rs was observed in both modules (A: 2% , B: 6% in average).**
- **The changes of other I-V Parameters were little (almost stable).**
- **The asymmetrical dark area along bus-bar did not appeared in EL images.**

Ref: T. Doi *et al.*, (2012) Statistical Evaluation of PV Modules with Extended Damp Heat Test and Extended Thermal Cycling Test, 2012 Annual Conference of RCPVT (AIST).

DML-TC Sequential Test

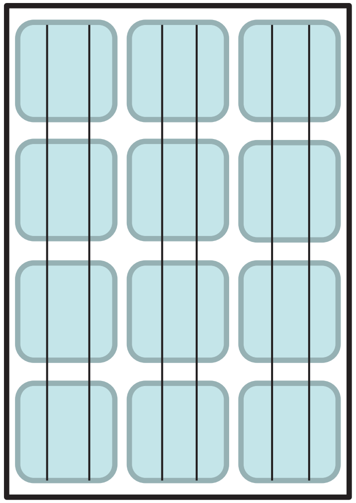
Contributors: AIST: Coordination
JET: Dynamic Mechanical Loading, Inspections
NPC: Laser Jsc Scanning (Inspection of Cell Crack)
ESPEC: Thermal Cycling Test

Objective: Compare with extended TC testing (TC: 600 cycles) ***without Cell Cracks***
- Power Loss
- EL Imaging
  (Multiplication of Asymmetric Dark Area along Bus-Bar)
- Laser Jsc Imaging (Multiplication of Cell Crack)

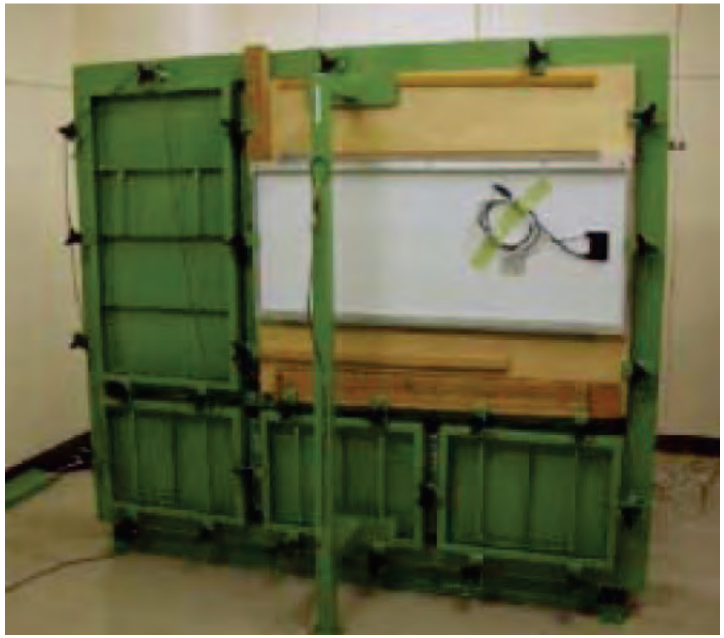
Modules: Type A / B (Multi-c-Si)
(Module types are same with those in TC600 Testing)

DML-TC: Each 2 Modules of 2 Types
Reference: Each 1 Module of 2 Types

DML-TC Sequential Test



DML



Thermal Cycling

Multi-c-Si Modules

Type: A
192.5 W

Type: B
185.0 W

IEC 62782

+ / - 1,000 Pa
1,000 Cycles
3 cycle/min
at RT

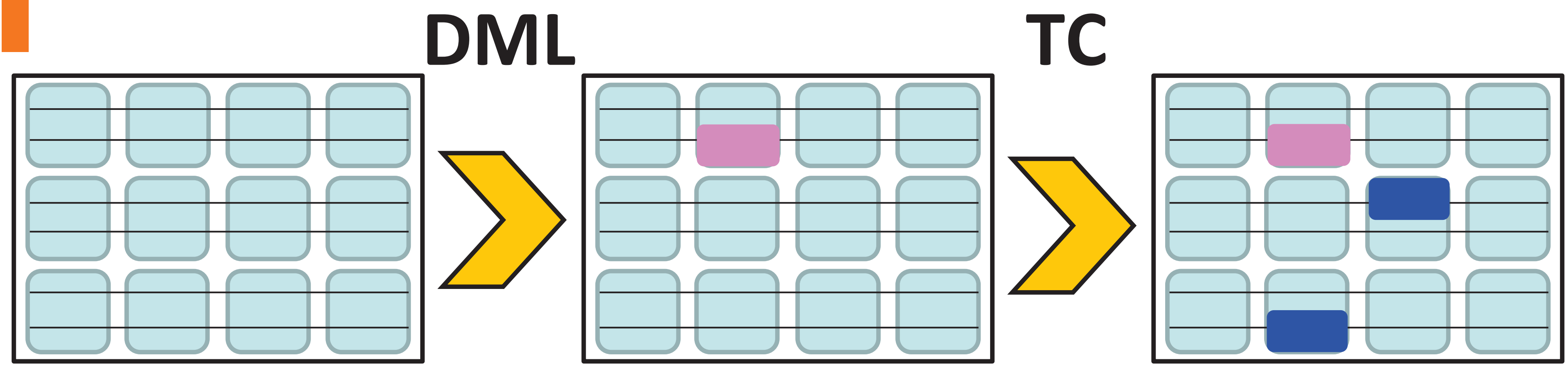
IEC 61215:2008
10.11 Thermal Cycling Test

-40 / 85 °C
200 Cycles
w/ Current (Ipm, at > 25 °C)

DML-TC Sequential Test

Putative Results (Ideal)

Focus:
Ribbon / Solder Crack, but not Cell Crack



Cell	No Crack ?	No Crack ?
Ribbon	Crack ?	Crack ?
Solder Bond	Crack / Delami.?	Crack / Delami. ?
Rs	Increase ?	More Increase?

Asymmetric Dark Area along bus-bar in EL Image

"No Cell Crack" was inspected by Laser Imaging

DML-TC Sequential Test

ESPEC

Laser Scanning Crack Detection

NPC Incorporated : "Module Laser Inspection Machine (NLS-M)"

- Laser scanning (narrow spot) with optimized bias current
  -> Reconstitution of Jsc Image
- SEMI PV Group (JP): Proposed a Standard as "Cell Crack Inspection Method"

Laser Jsc Scanning Image

NPC npcgroup.net

http://www.npcgroup.net/eng/

DML-TC Sequential Test

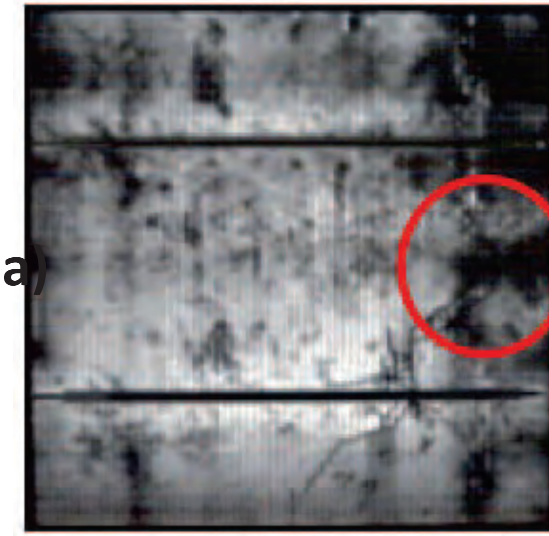
Laser Scanning Crack Detection

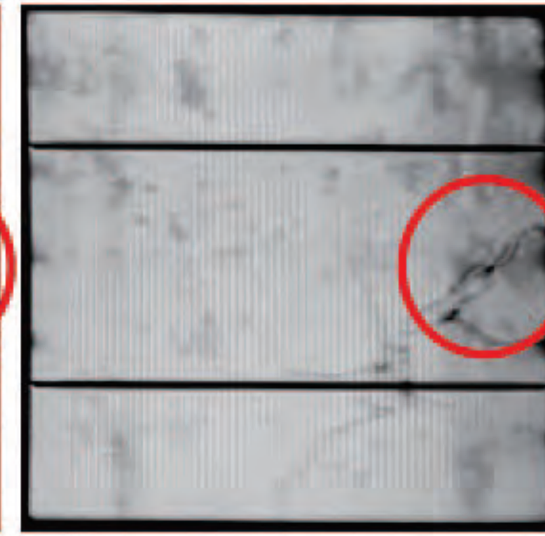
EL Image | Laser Scanning

Cell Crack

EL: Pseudo-Negative
(Not Clear in Dark Area)

LS: Positive
(Clear)

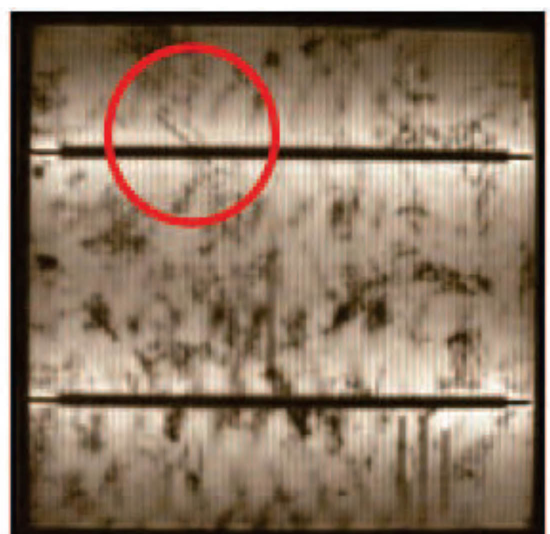




Cell Crack

EL: Pseudo-Positive

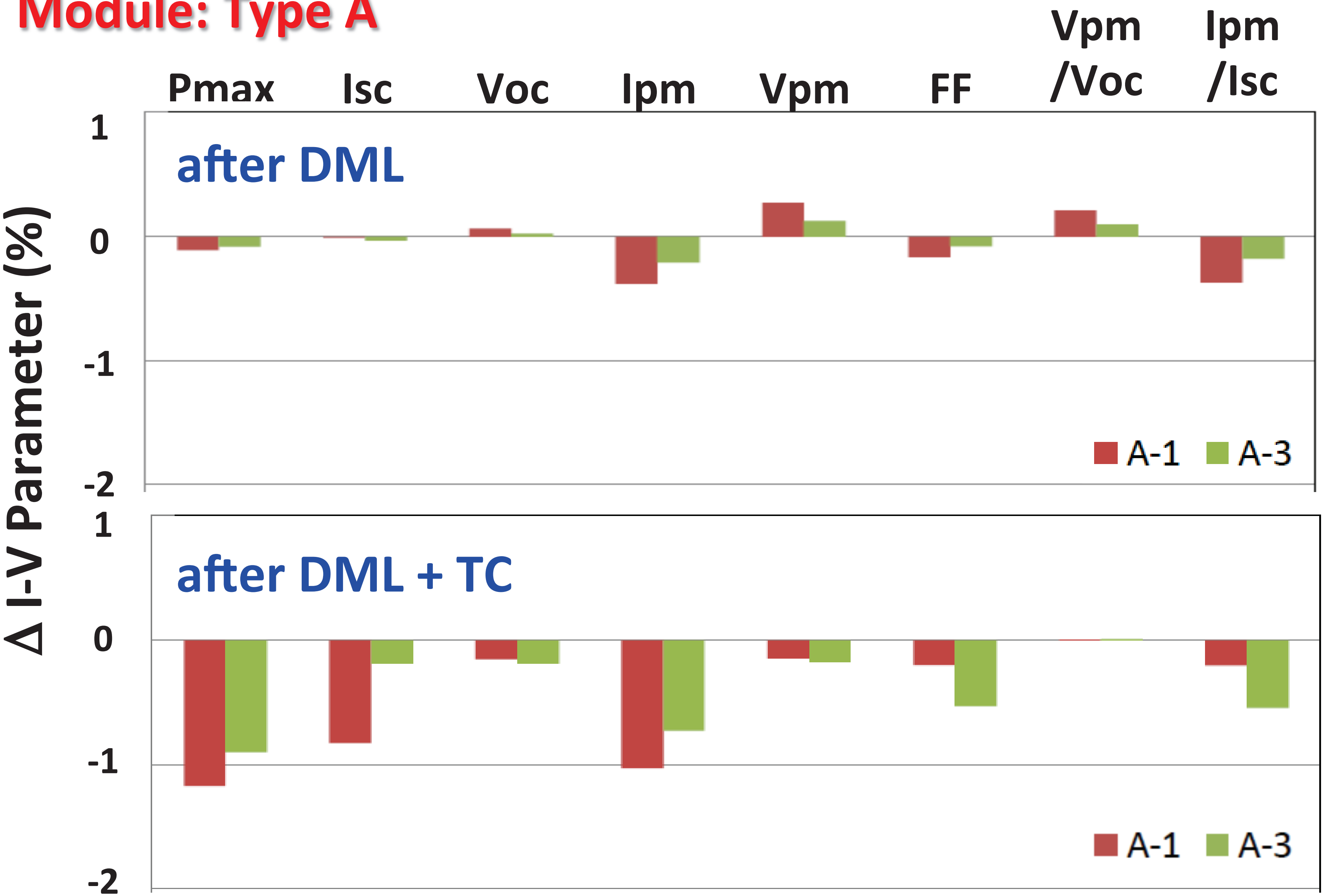
LS: Negative



Changes of I-V Parameters after DML/TC Testing

ESPEC

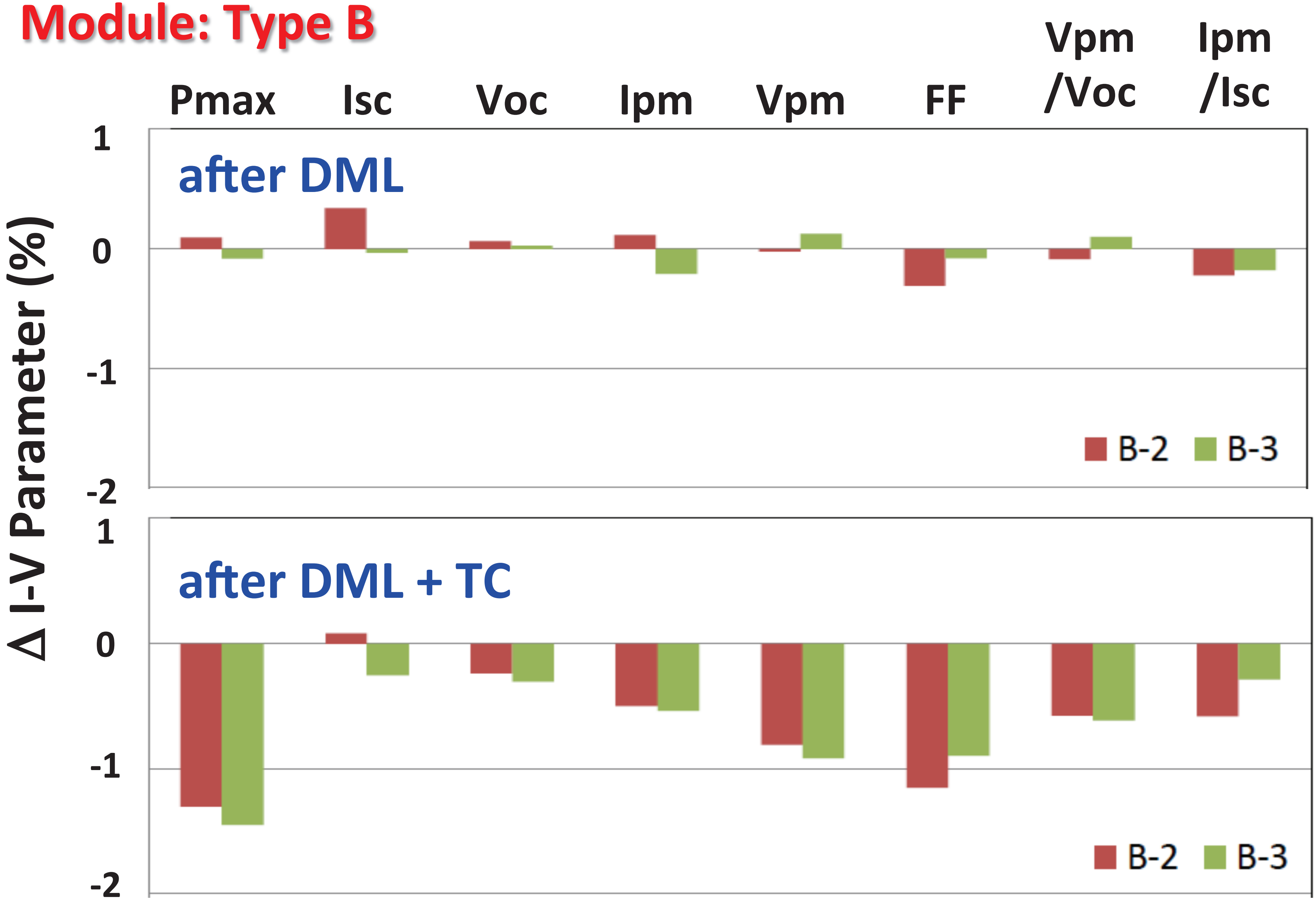
Module: Type A



Changes of I-V Parameters after DML/TC Testing

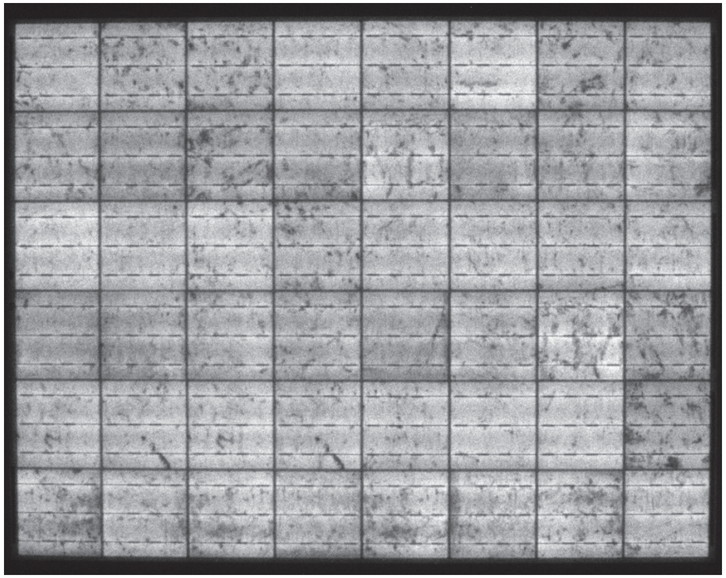
ESPEC

Module: Type B

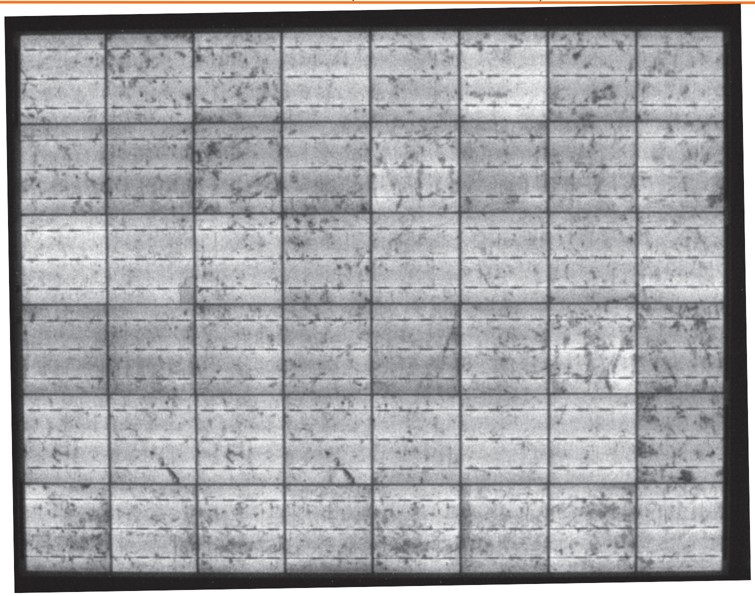


DML-TC Sequential Test (EL Images) : Module A

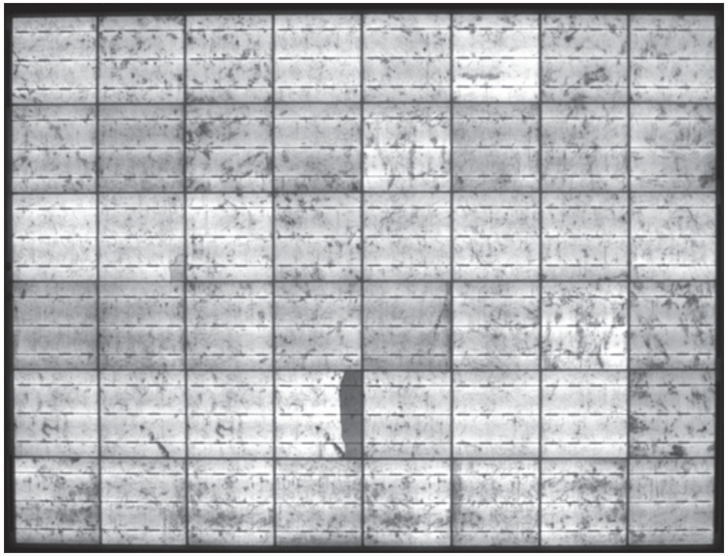
(A-1 Module)



Initial



after DML



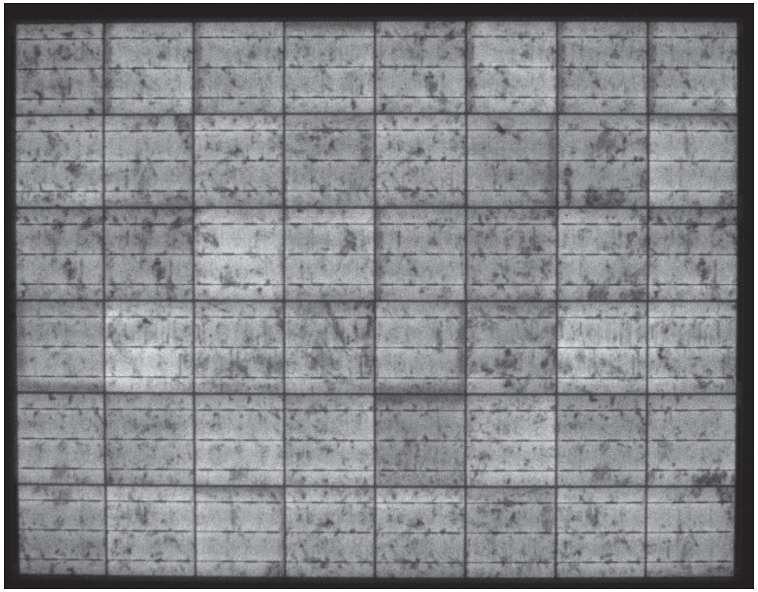
after DML + TC

The multiplication of asymmetrical dark area along bus-bar was not observed in the modules after DML & TC.

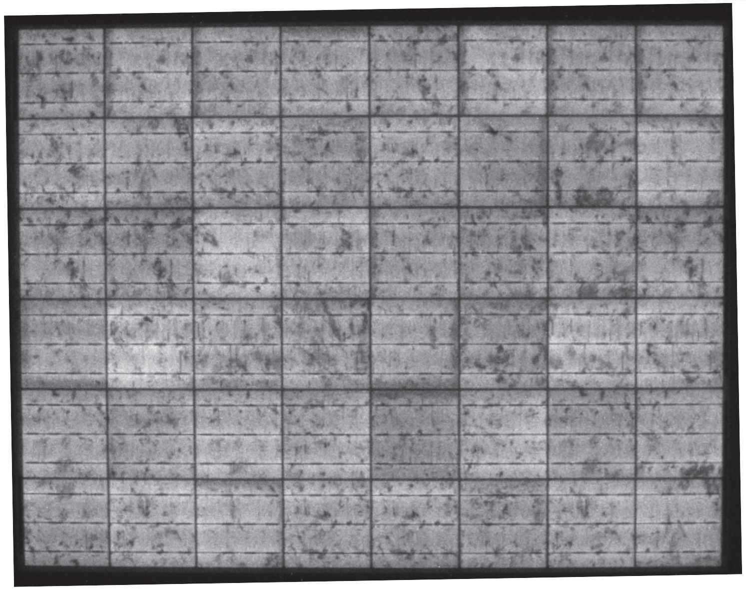
After DML & TC, the cell crack was observed in EL image.

DML-TC Sequential Test (EL Images) : Module A

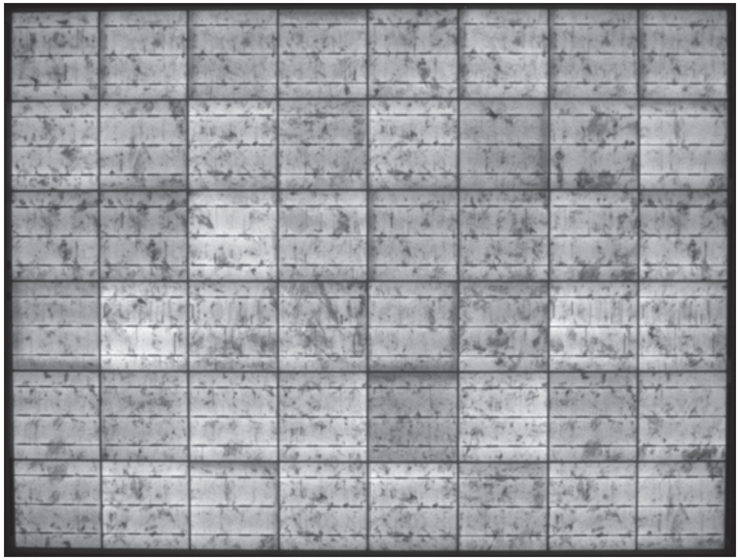
(A-3 Module)



Initial



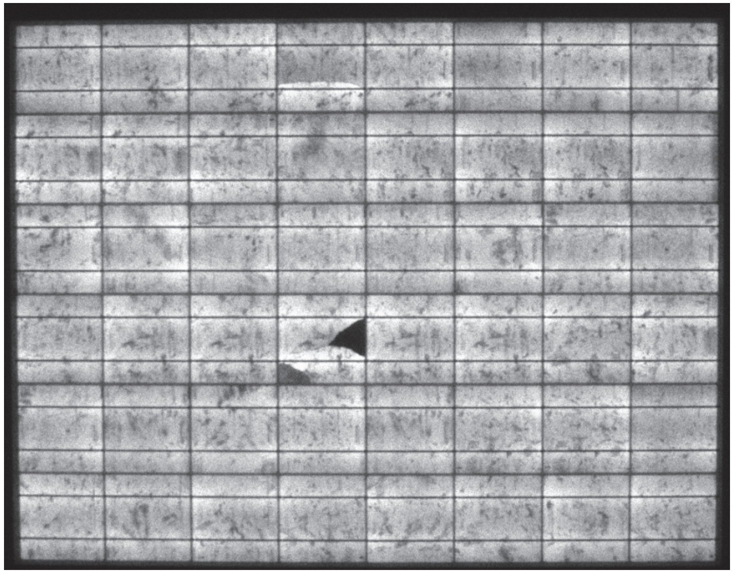
after DML



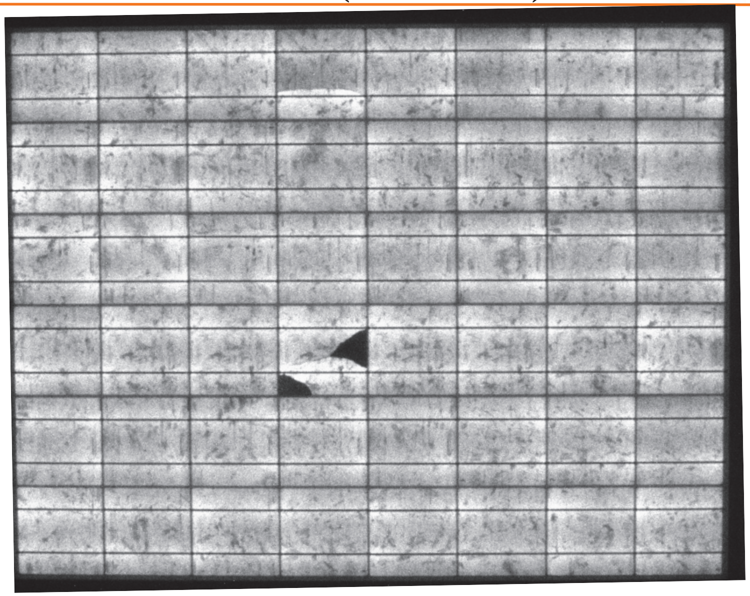
after DML + TC

The multiplication of asymmetrical dark area along bus-bar was not observed in the modules after DML & TC.

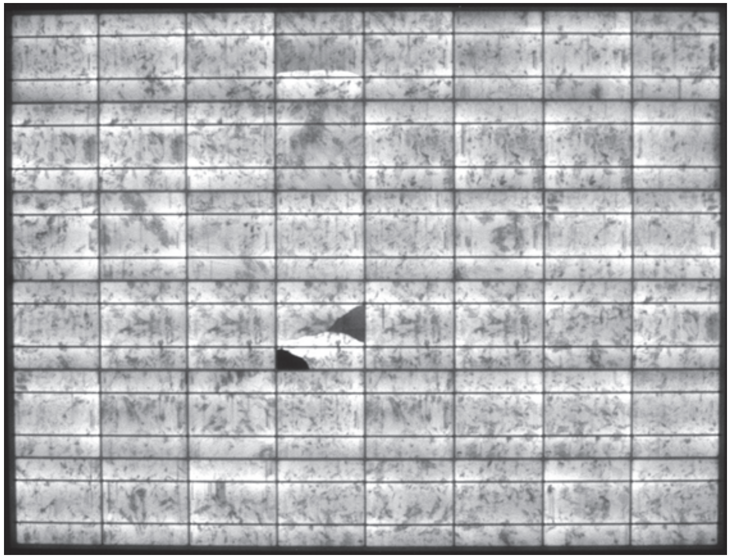
DML-TC Sequential Test (EL Images) : Module B
(B-2 Module)



Initial



after DML

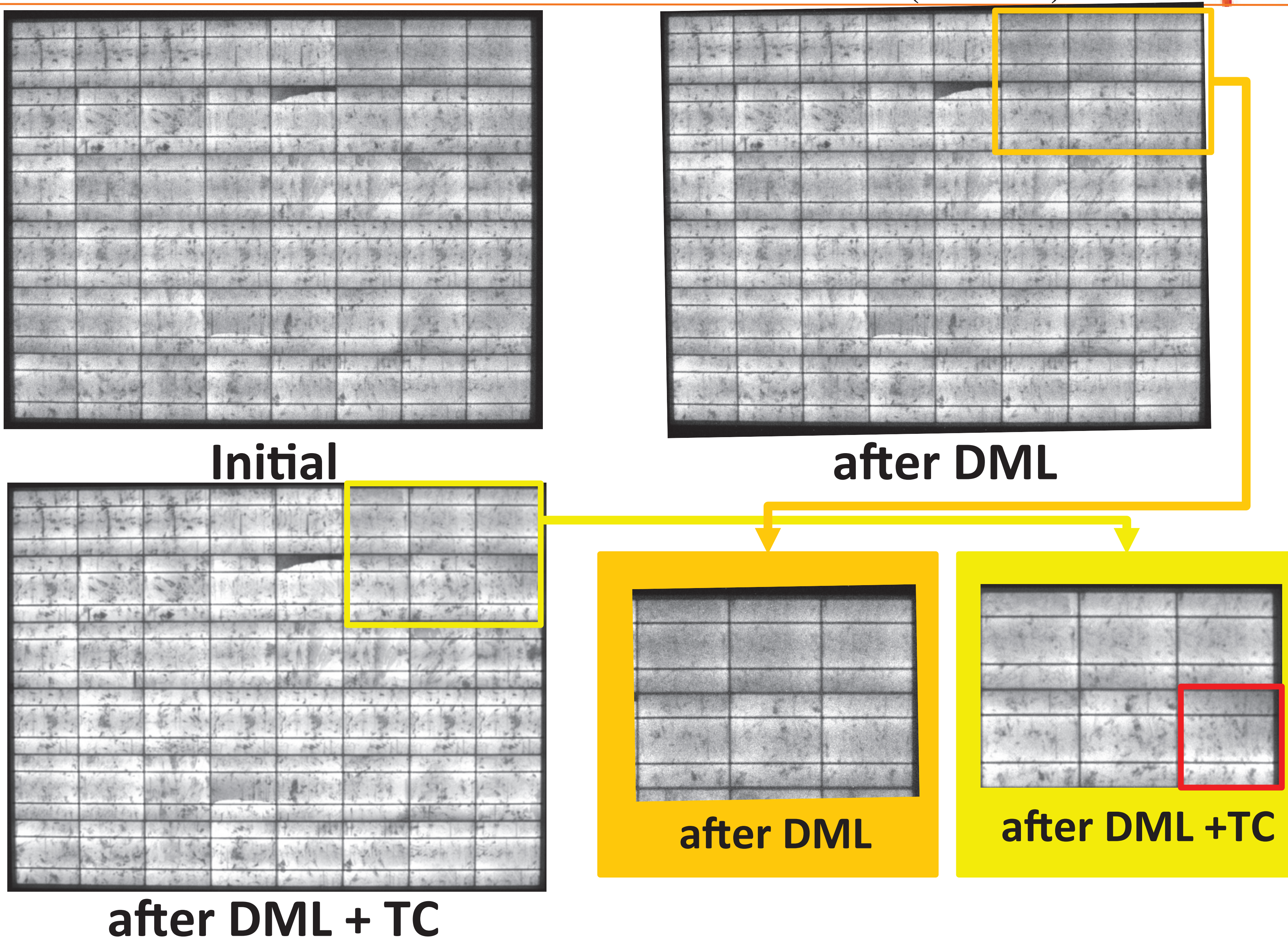


after DML + TC

The multiplication of asymmetrical dark area along bus-bar was not observed in the modules after DML & TC.

DML-TC Sequential Test (EL Images) : Module B

(B-3 Module)



DML-TC Sequential Test

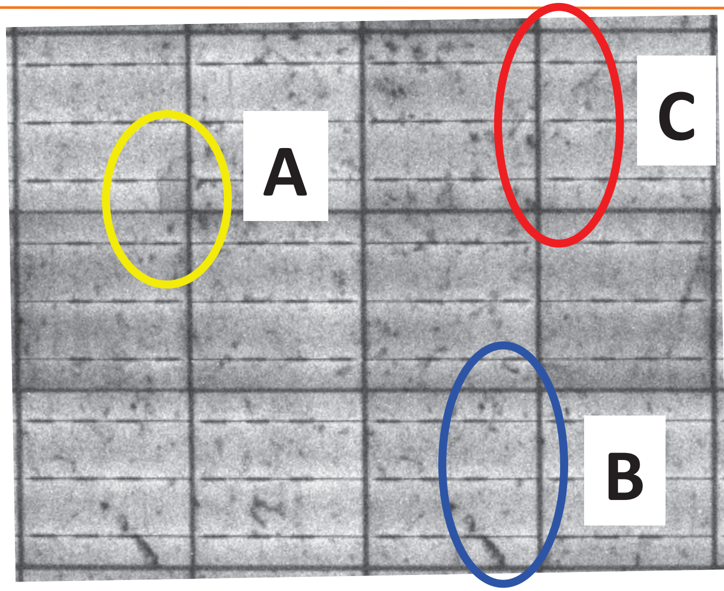
Cracked Cell Number

Module		Initial	after DML	*after TC
Type A	Reference	0	1	
	A-1	0	3	
	A-3	1	3	
Type B	Reference	1	8	
	B-2	4	4	
	B-3	4	5	

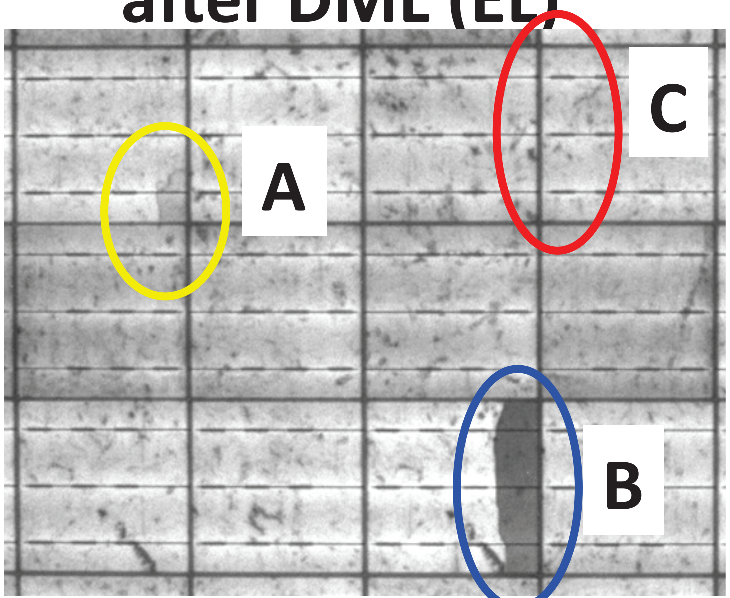
＊ Under the inspection, now

DML-TC Sequential Test (LS Images) : Module A

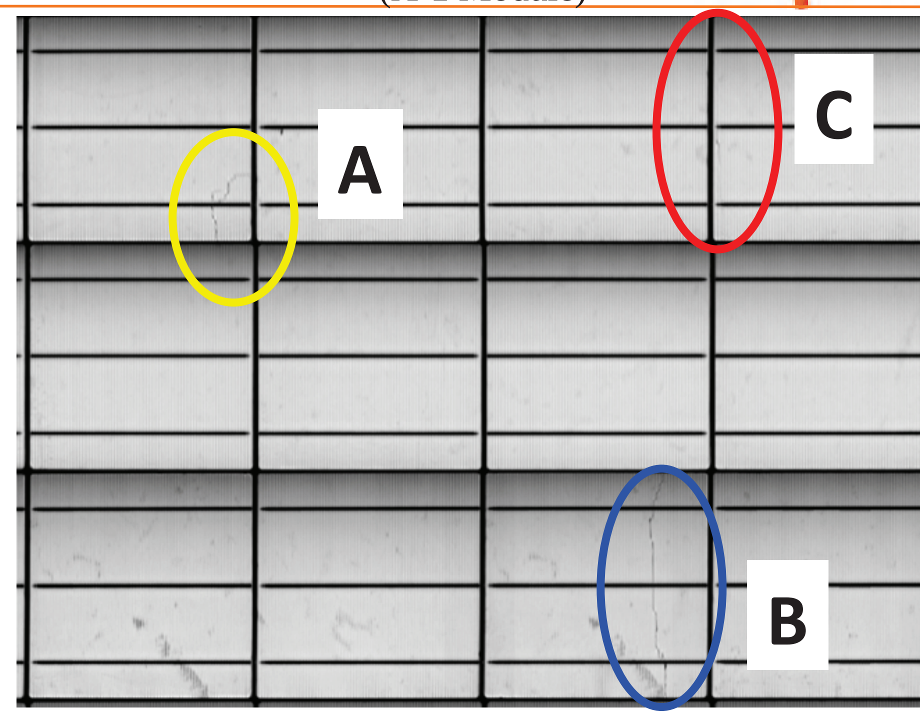
(A-1 Module)



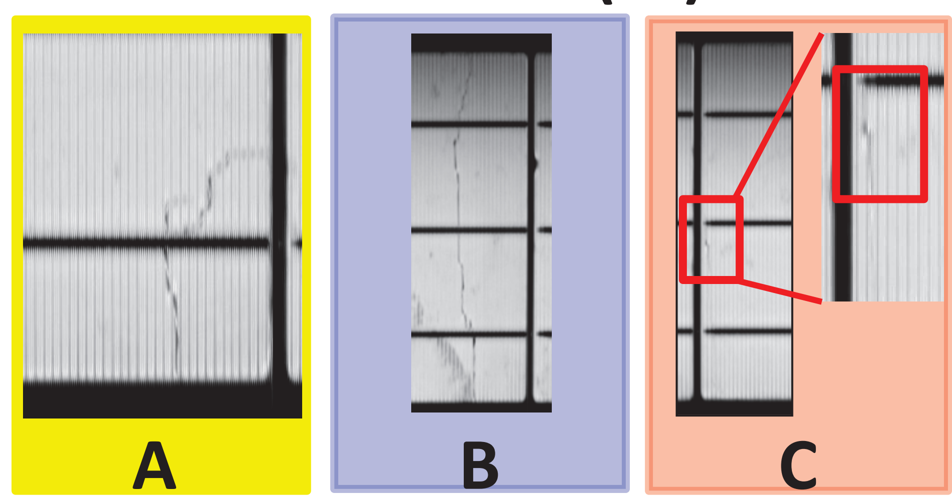
after DML (EL)



after DML + TC (EL)

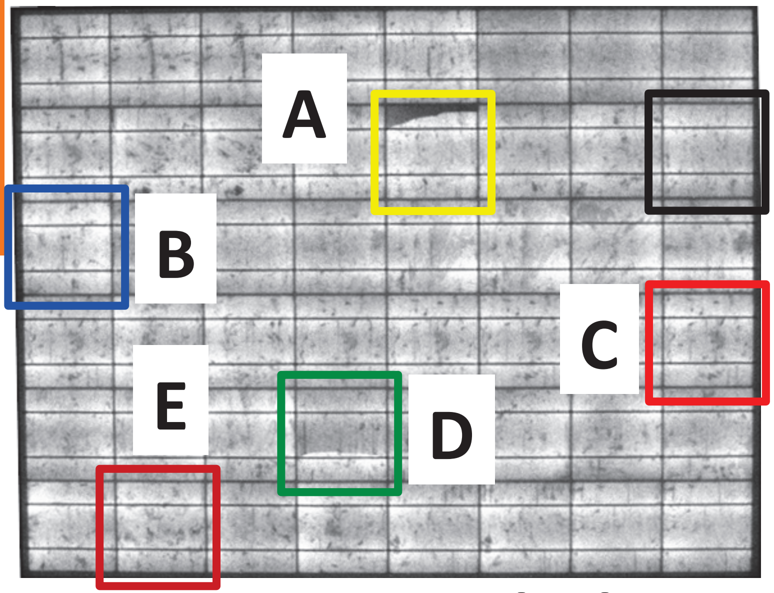


after DML (LS)

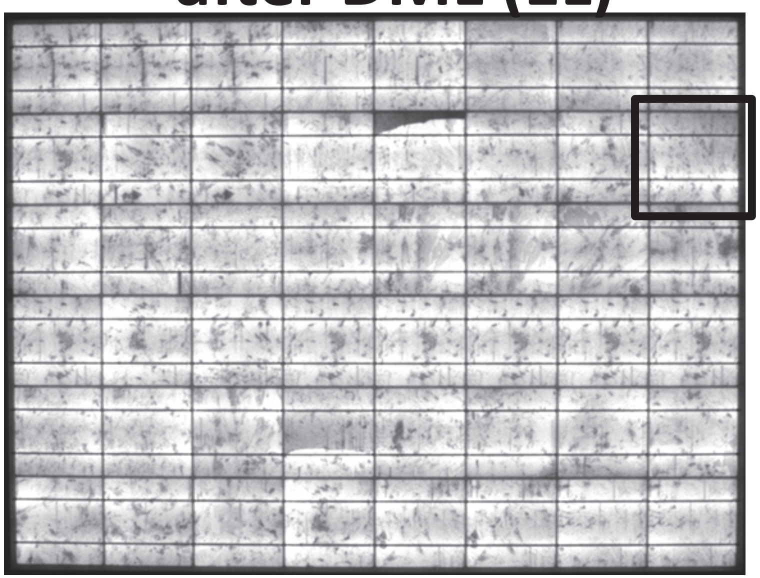


DML-TC Sequential Test (LS Images) : Module B

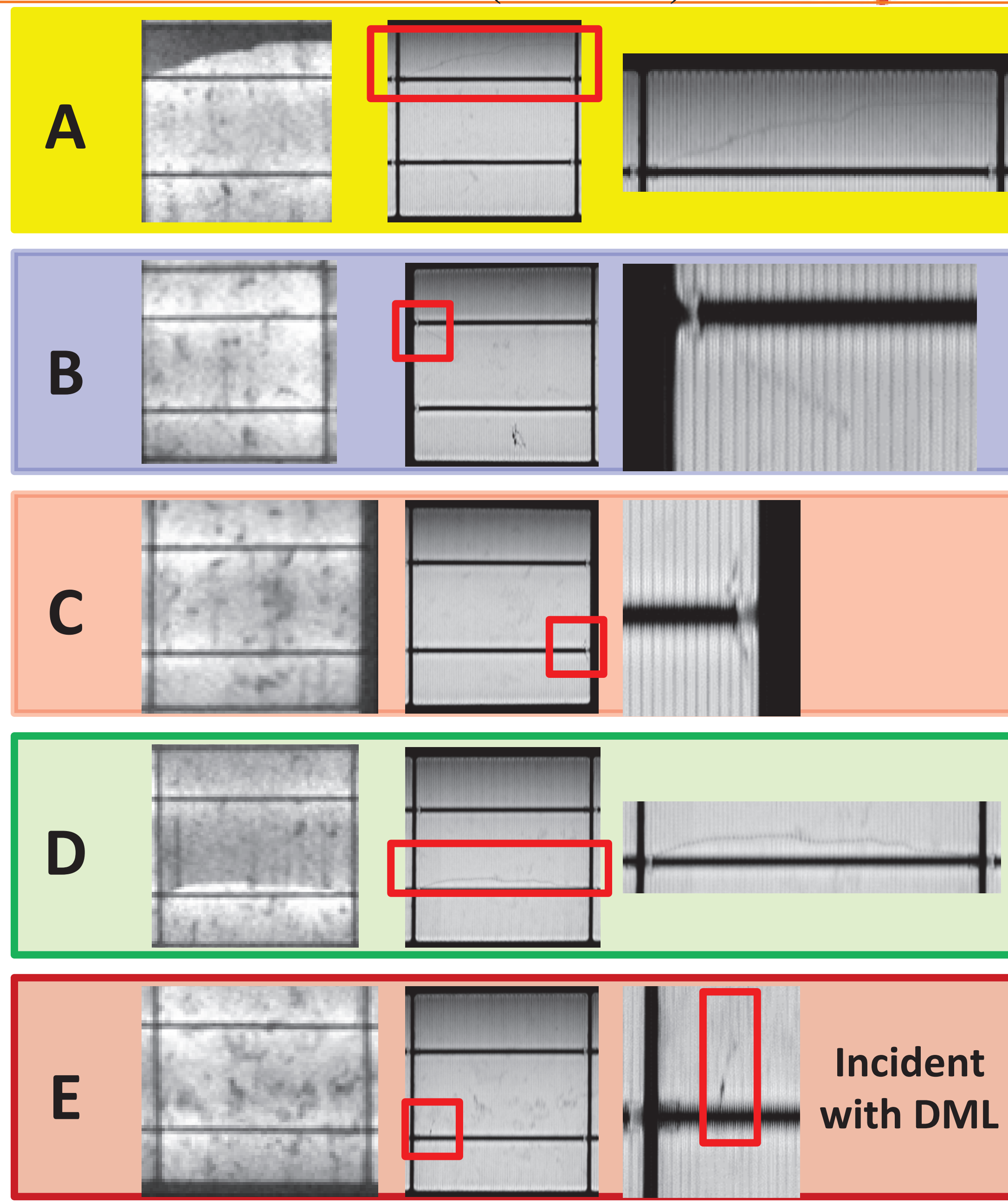
(B-3 Module)



after DML (EL)



after DML + TC (EL)



Summary

1. **Extended TC**
   - Massive survey of commercial PV modules is carrying out.
   - As of now, the drastic failures (> 5% power-loss) have not been observed in almost PV modules at TC 600 cycles.
   - Even in TC 600, the asymmetrical dark area along bus-bar is not detected in EL images.

2. **DML-TC Sequential Test**

   Step 1: DML
   - The changes of I-V parameters is relatively-little.
   - The asymmetrical dark area along bus-bar did not appeared in EL.
   - A little cells are cracked by DML defined in IEC 62782.

   Step 2: DML + TC
   - Power-loss (ca. 1%) was observed in each type of module with the reduction of FF.
   - The asymmetrical dark area along bus-bar appeared in EL images (1 module / 4 modules).
   - For the cell cracks, the inspection is carrying out now.

Conclusion

DML-TC Sequential Test

- For the availability of DML-TC sequential test, it has not been determined by our experiments.
- The optimization of DML condition may be needed to establish the effective DML-TC sequential test.
- However, we found that the asymmetrical dark area along bus-bar appeared in EL image, by the combination of DML with TC, under the condition that the cell cracks were not practically induced.

  This phenomenon may related to the ribbon / solder-bond failures in c-Si PV modules.

- To establish the new test procedures for the comparative rating standard (Part 2), we would like to optimize the DML conditions, in collaboration with global Task Force 2

Contributors to DML-TC Sequential Test

National Institute of Advanced Industrial Science and Technology

Tetsuo Fukuda and Masaaki Yamamichi

Japan Electrical Safety & Environment Technology Laboratories

Hiroshi Kato, Yoshikuni Asano, Kohji Masuda, Yasunori Uchida, and Katsuaki Shibata

NPC Incorporated

Shin Watanabe, Shinji Miyoshi, Seiji Yoshino, Teiji Morita, and Masayuki Oouchi

ESPEC CORP.

Manabu Okamoto and Tadanori Tanahashi

Thank you for your attention.

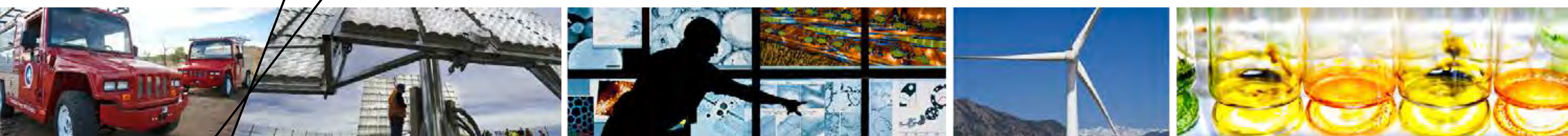
If you have any question, please contact us.

mailto : t-tanahashi@espec.co.jp

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

2013 Photovoltaic Module Reliability Workshop
February 26-27, 2013
NREL/PR-5200-58369

Accelerating Fatigue Testing for Cu Ribbon Interconnects



Nick Bosco, Tim Silverman, John Wohlgemuth and Sarah Kurtz

National Renewable Energy Laboratory

Masanao Inoue and Keiichiro Sakurai

National Institute of Advanced Industrial Science and Technology

Tsuyoshi Shioda and Hirofumi Zenkoh

Mitsui Chemical

Masanori Miyashita

Toray

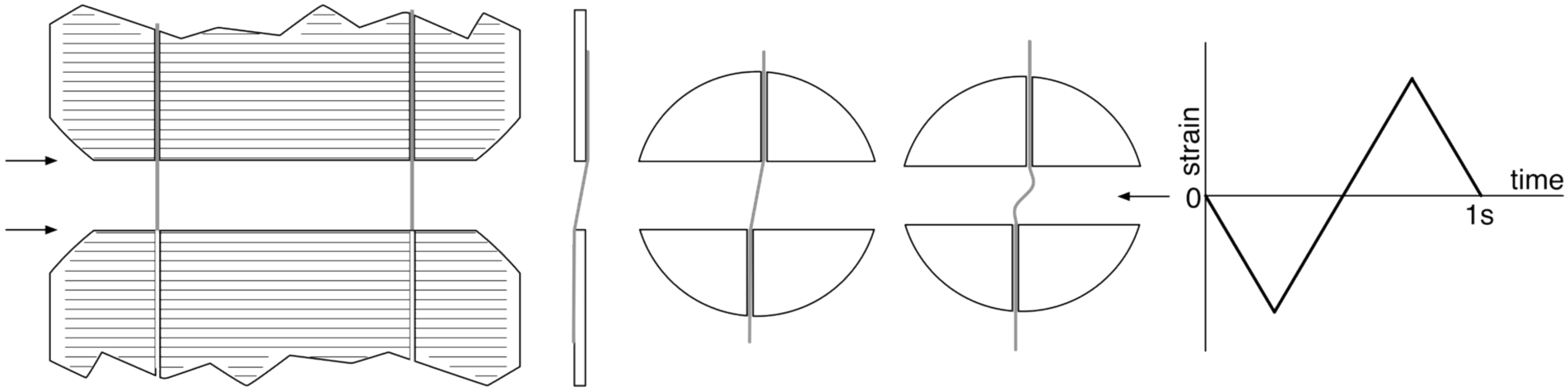
Tanahashi Tadanori and Satoshi Suzuki

Espec

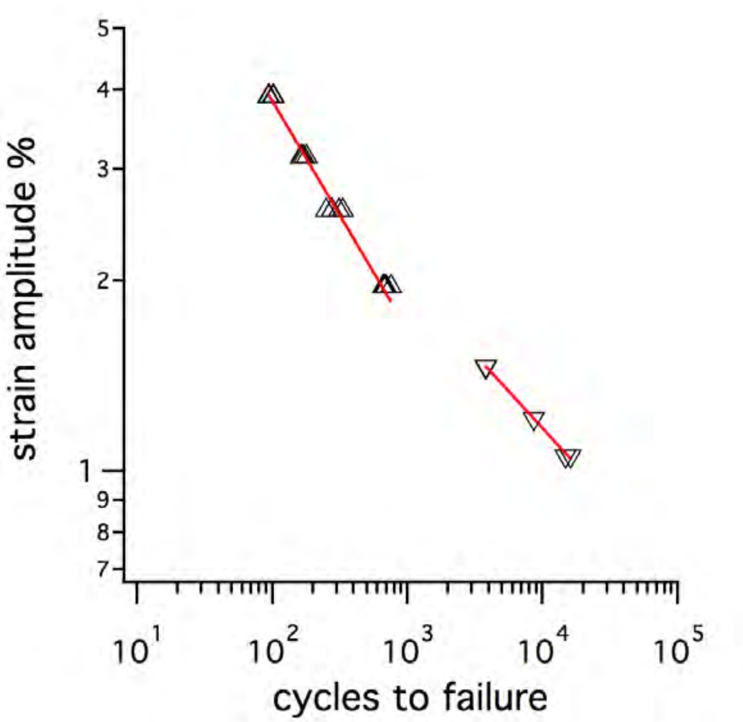
Motivation

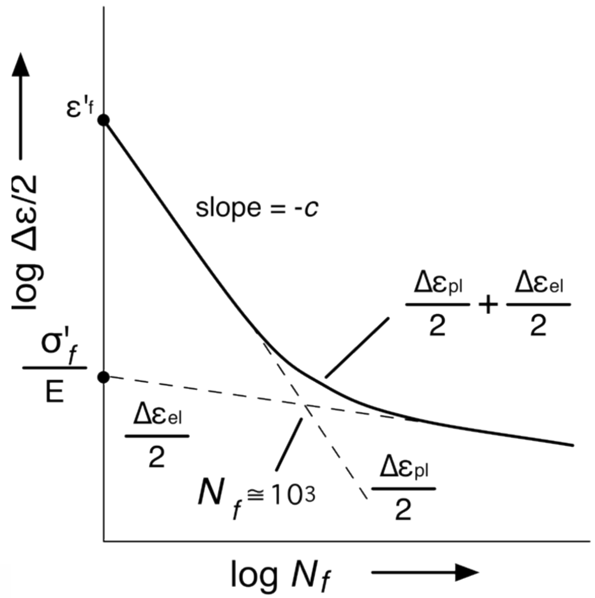
Thermal cycling a module take a long time

2012 NREL PVMRWS: fatigue experiments



2012 NREL PVMRWS: fatigue experiments

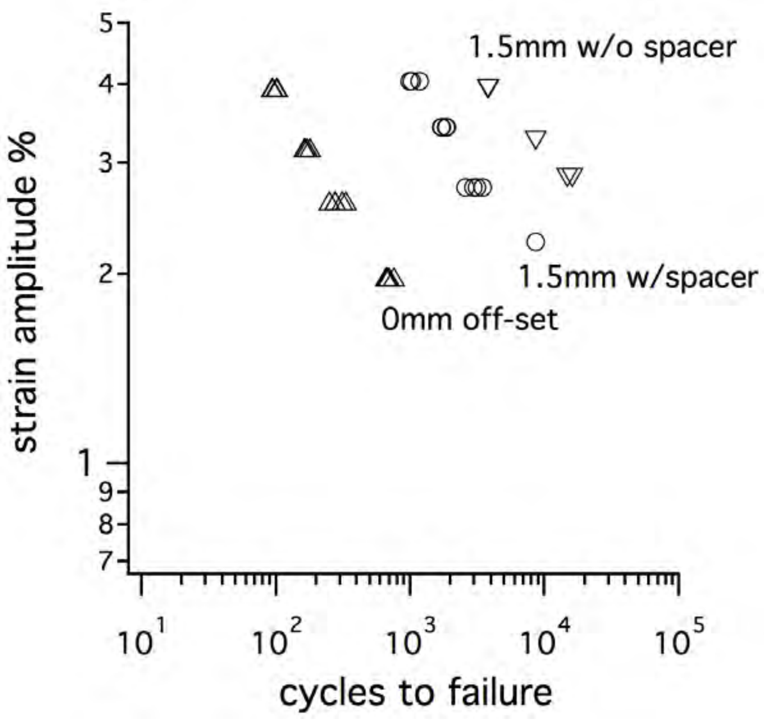


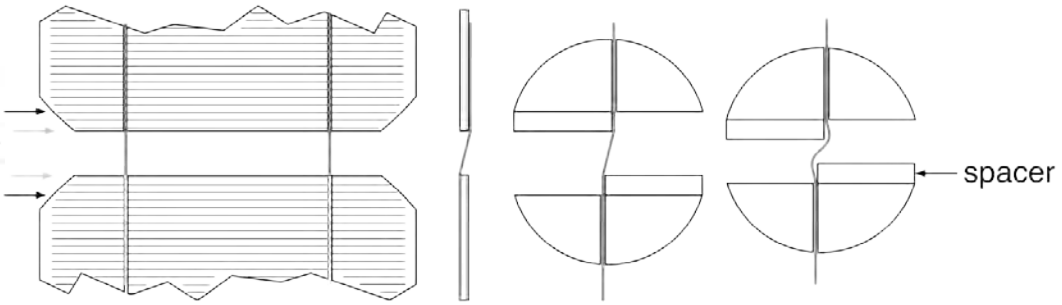


$$\frac{\Delta\varepsilon_{pl}}{2} = \varepsilon'_f \left(2N_f\right)^{-c}$$

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

2012 NREL PVMRWS: fatigue experiments

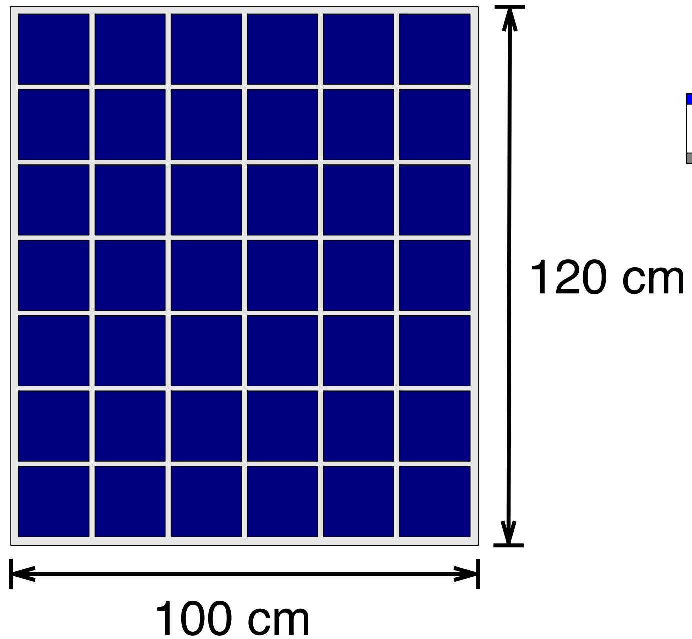




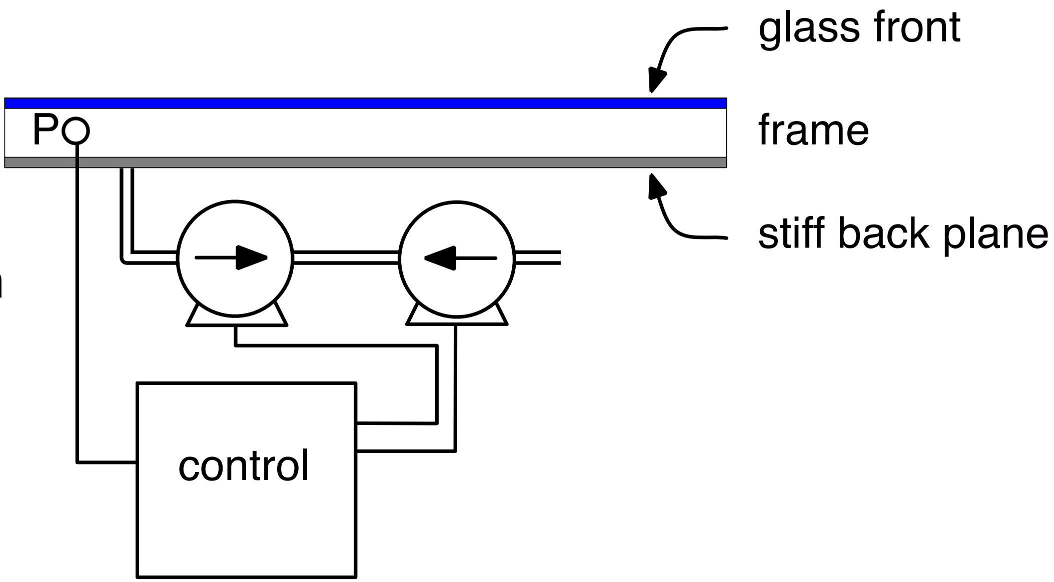
Dynamic Mechanical Loading

- Can we mechanically load a module to induce ribbon strain?
- If so, how is the ribbon strain distributed across the module?
- Can DML cause ribbon failure similar to thermal cycling?
- If so, what is the acceleration factor between DML and thermal cycling?

Dynamic Mechanical Loading



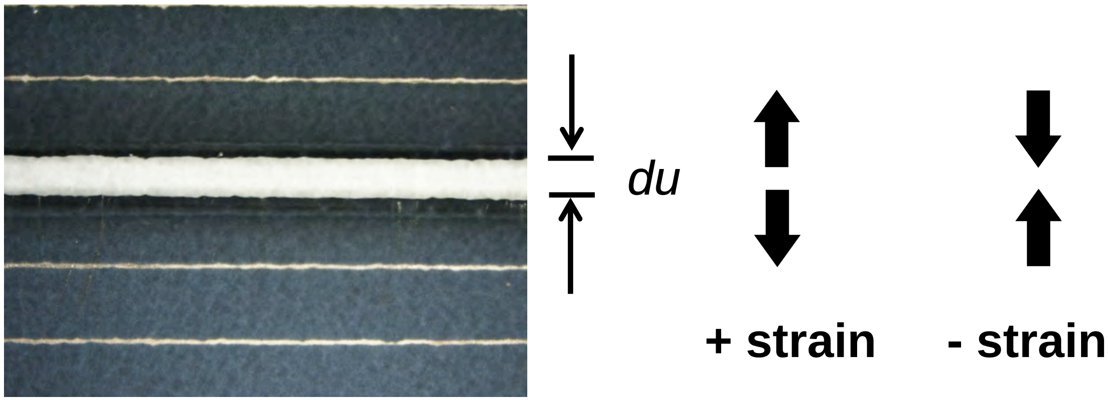
Modules fabricated by AIST and collaborators



DML set up fabricated and employed by NREL

strain measurements

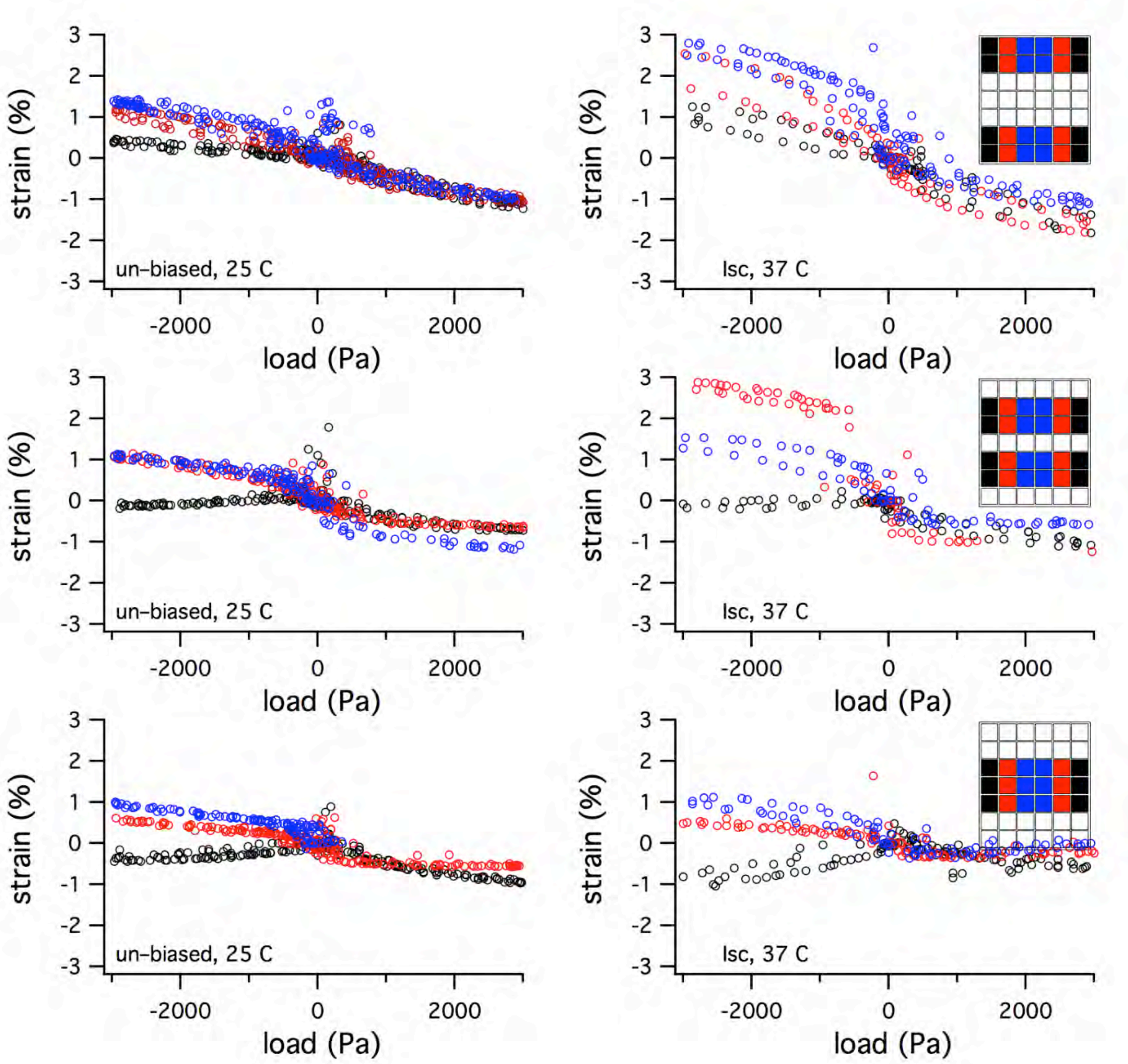
- **Measuring cell-to-cell spacing**



- **Calculating ribbon strain**

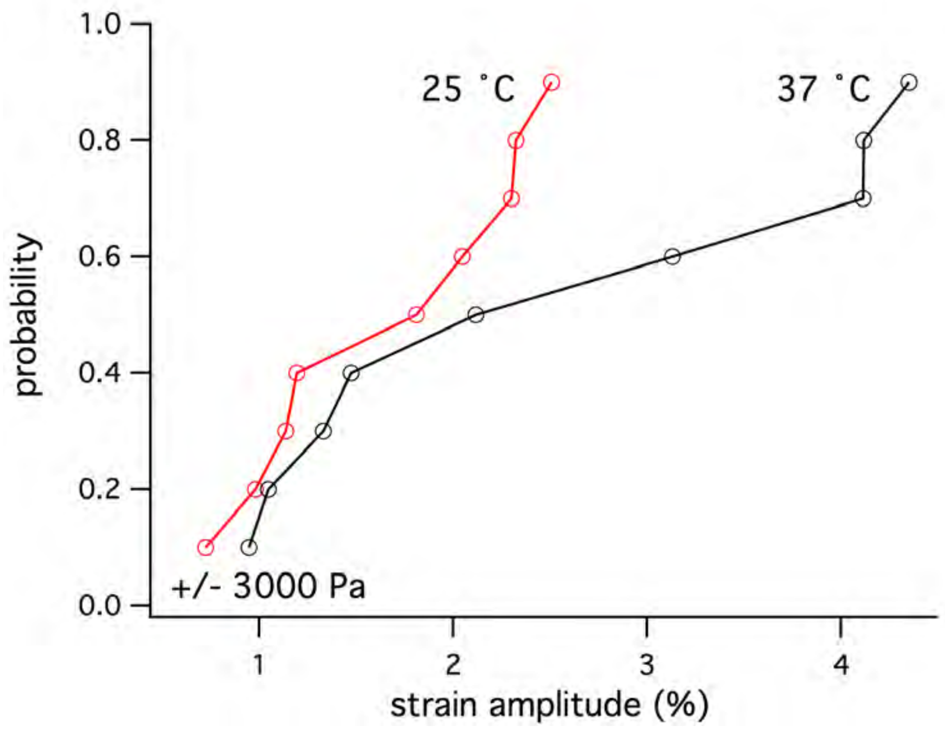
$$\varepsilon = \frac{\left(du_L - du_i\right)}{du_i}$$

strain measurements

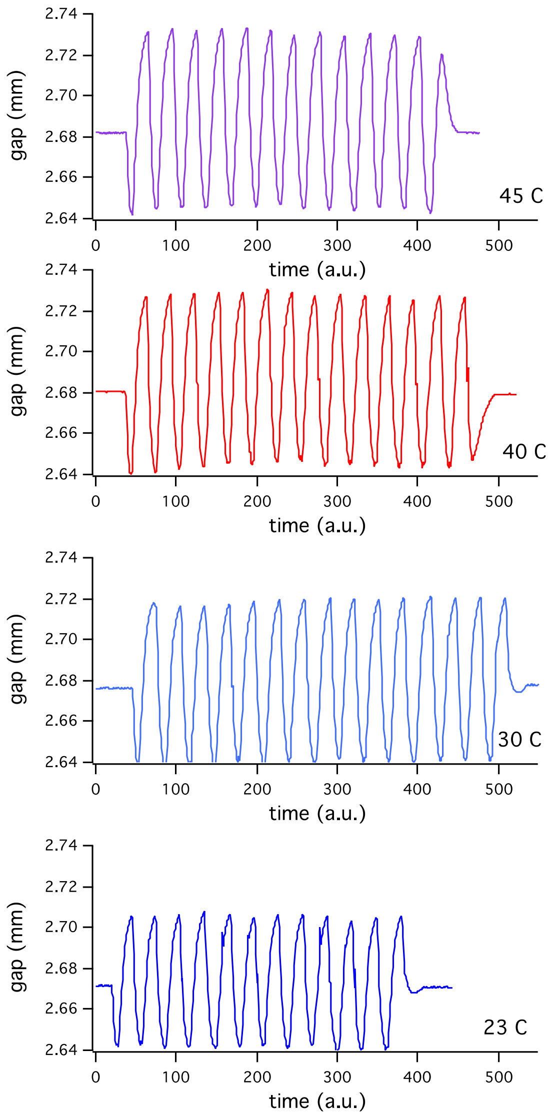


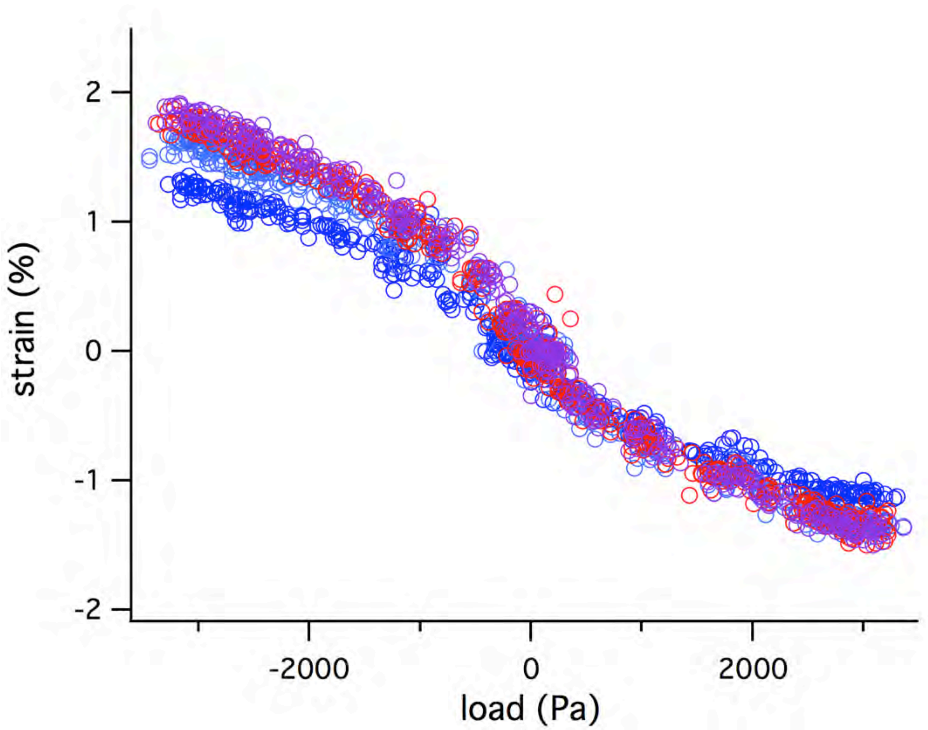
Increasing module temperature allows more strain for similar loads

strain measurements



strain with cycling

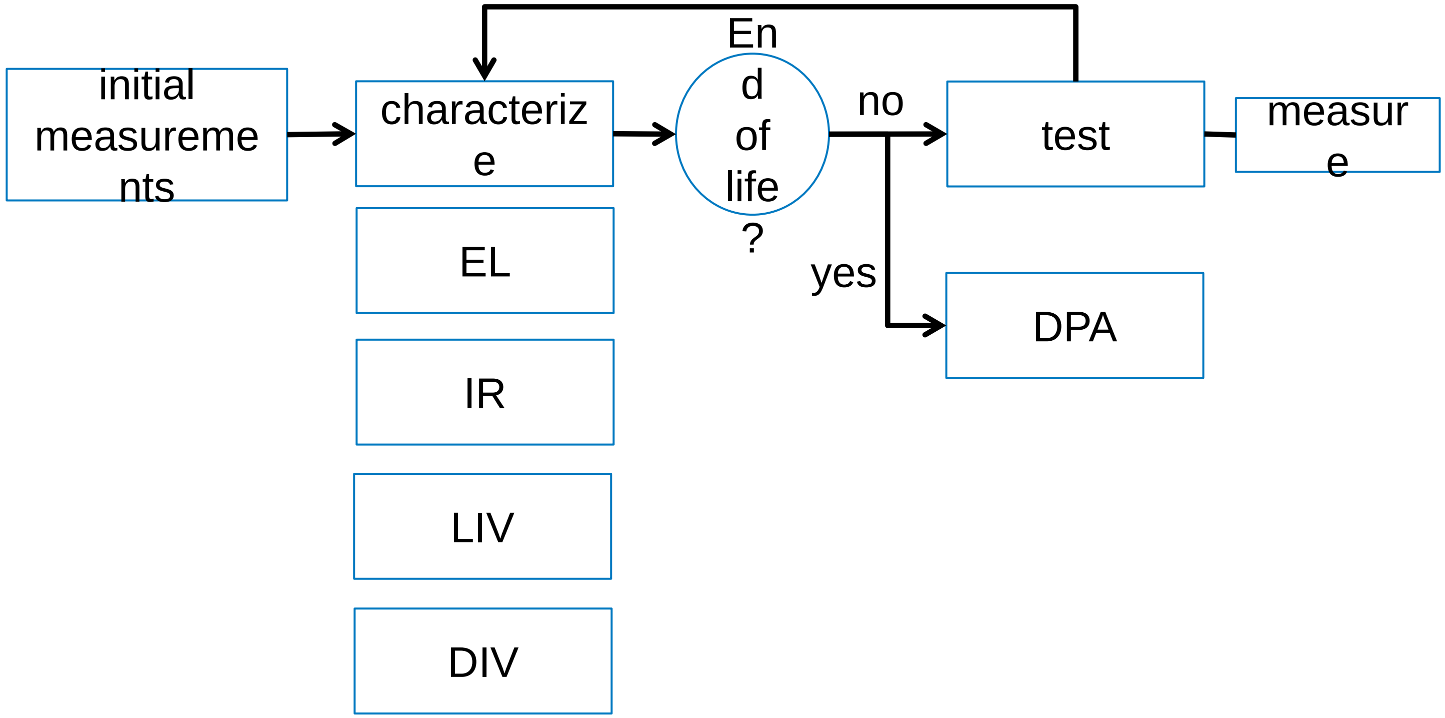




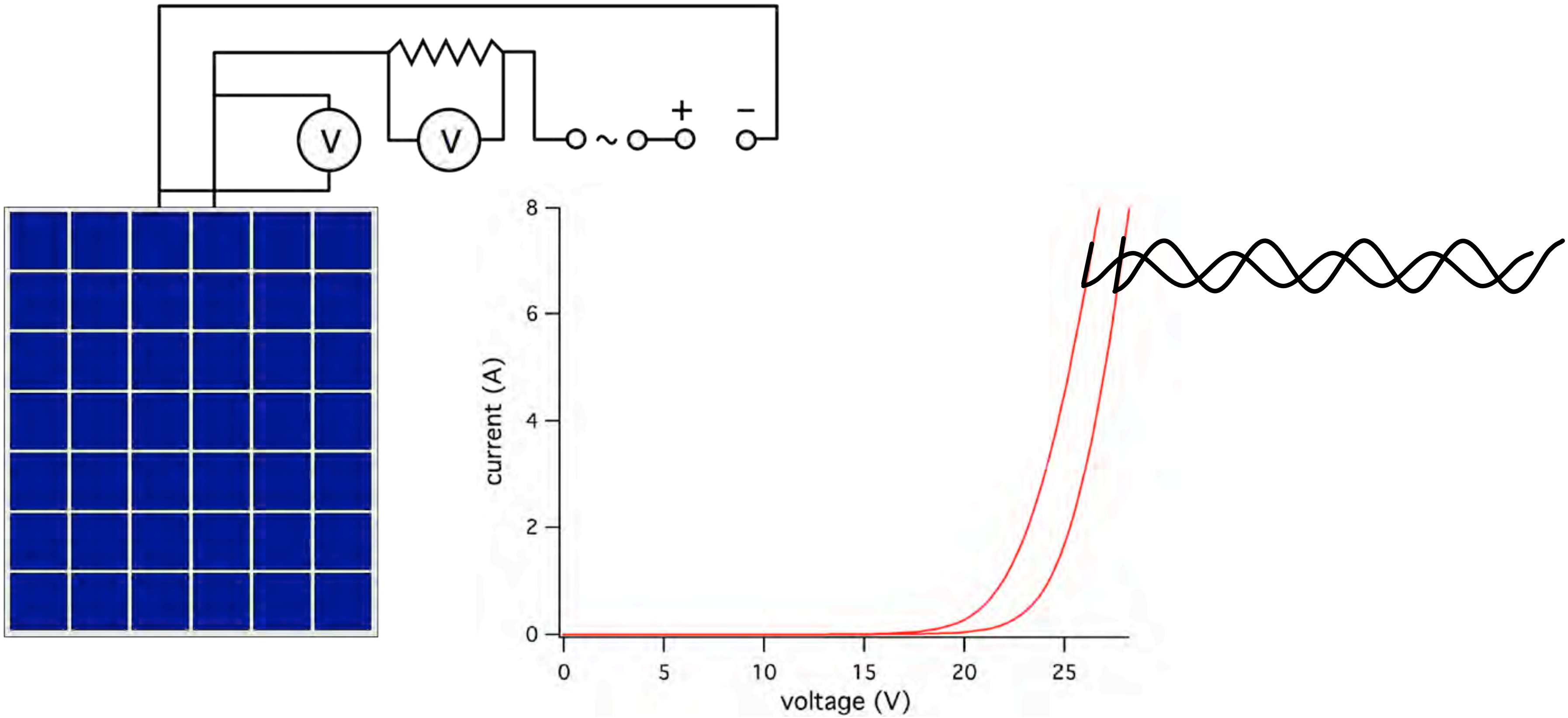
Effects of the encapsulant's viscoelasticity are not observed

test plan

	dynamic mechanical loading			thermal cycling
	high w/bias	low w/bias	high	
2mm offset	2	2	2	2
10mm offset	2	2	2	2

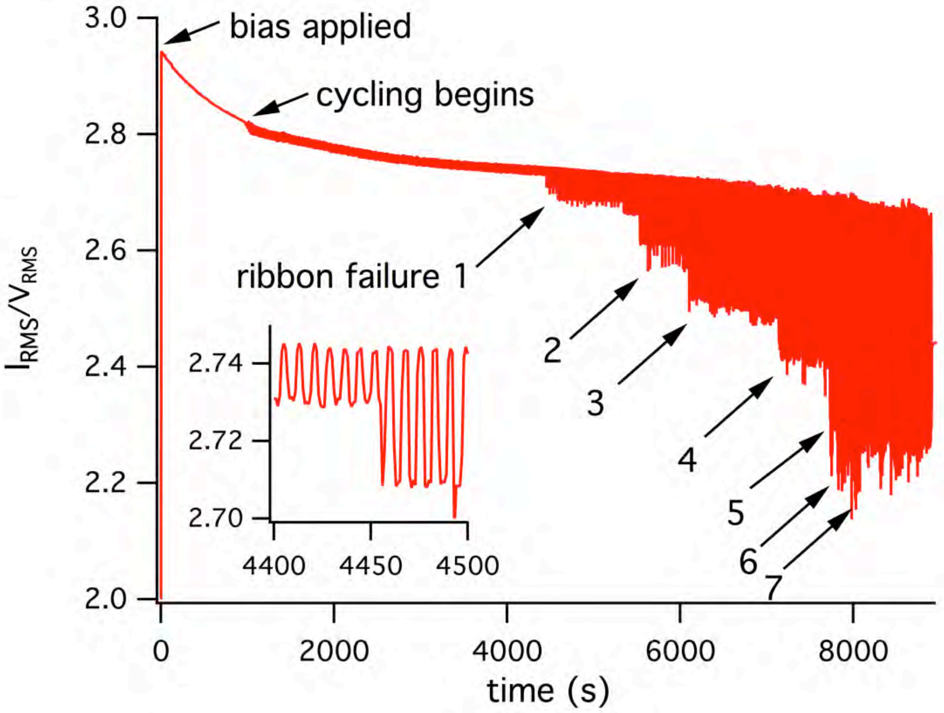


differential conductance (*dG*)



- Forward bias with short circuit current
- Apply a small sinusoidal voltage superimposed on the DC bias
- Monitor the AC voltage across and AC current through the module

DML +/-3000 Pa Isc



dG declines with increasing module temperature as it heats under fwd bias.

dG becomes periodic with cycling (mechanical connections).

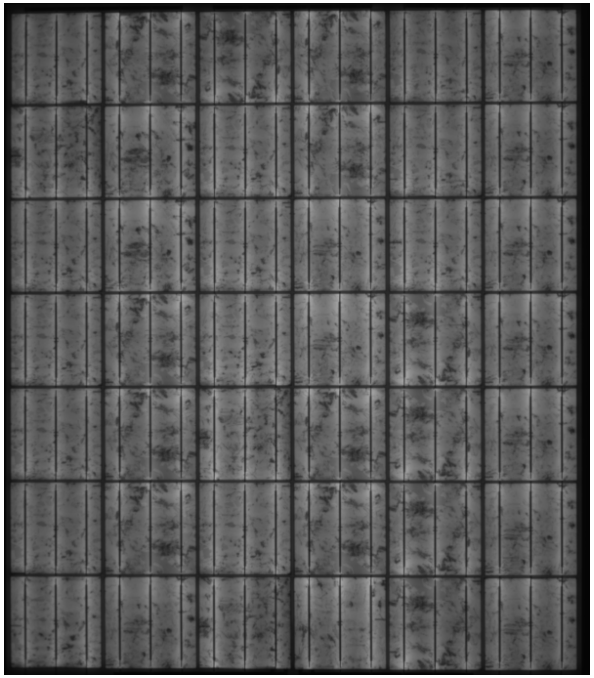
dG's low side drops with ribbon failure as negative pressure causes positive strain pulling the ribbons open.

Steps are seen with every subsequent failure.

Following cycling, *dG* becomes some intermediate value.

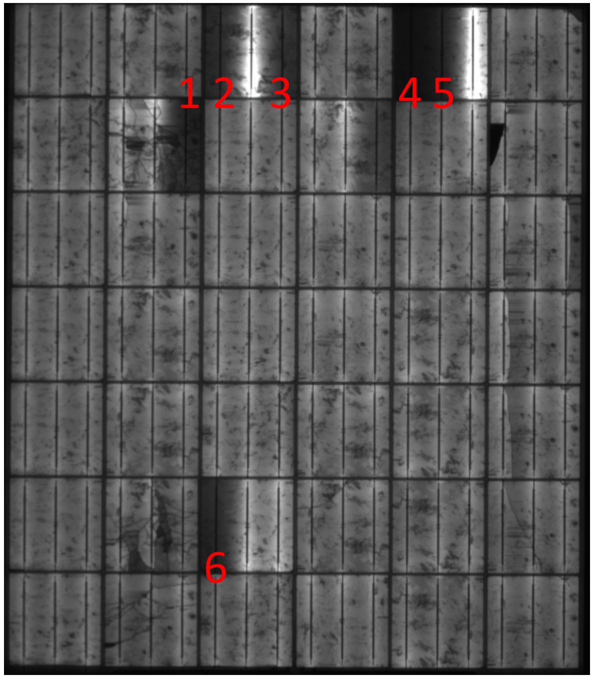
M1212_0003

DML +/-3000 Pa Isc



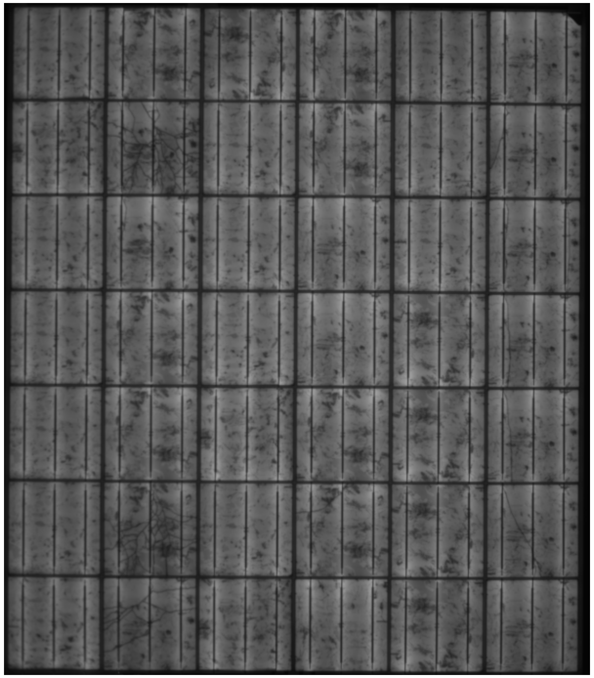
Initial as-received EL image

0 Pa



EL image following 1000 DML cycles. Roughly 7 ribbon failures obvious

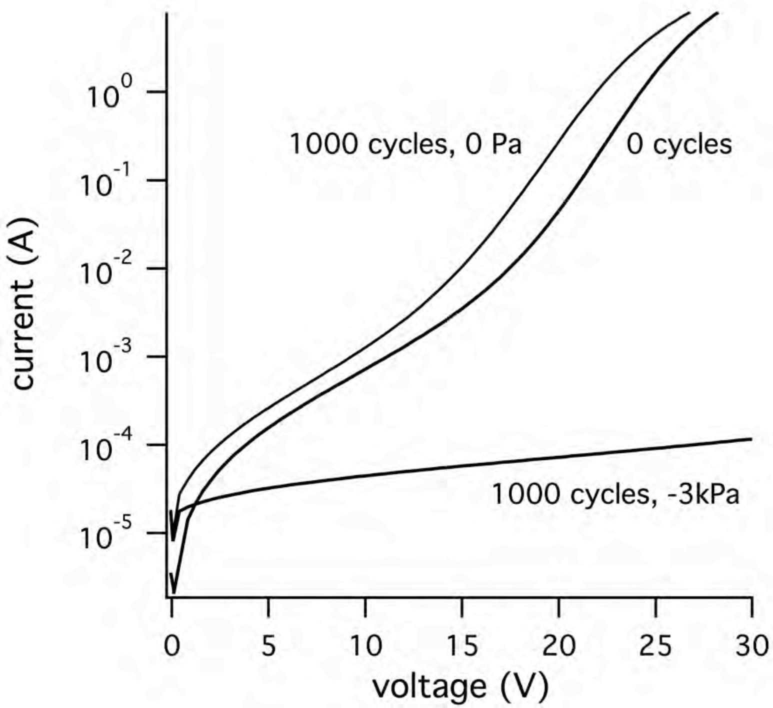
+ Pa



Under positive pressure, failed ribbons close. Under negative pressure, the module becomes open suggesting at least one more failure.

M1212_0003

DML +/-3000 Pa Isc

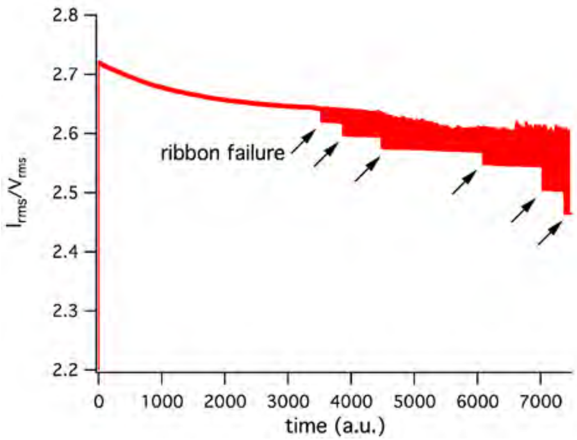


Module shows higher series resistance under zero pressure, and is open under negative pressure.

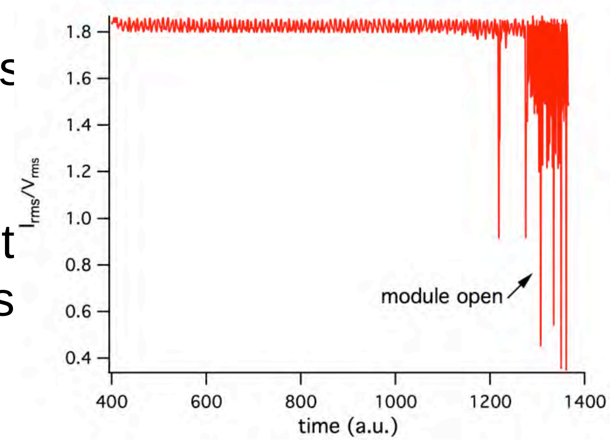
Consistent with monitoring and EL images.

M1212_0003

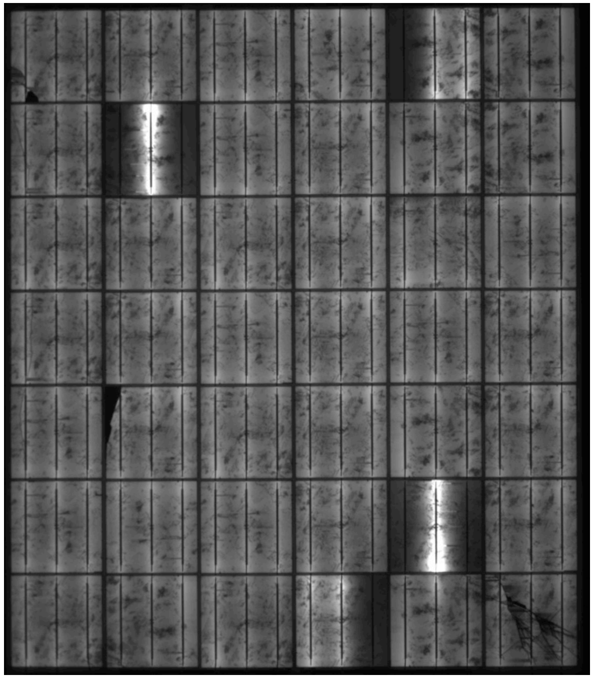
DML +/-3000 Pa Isc

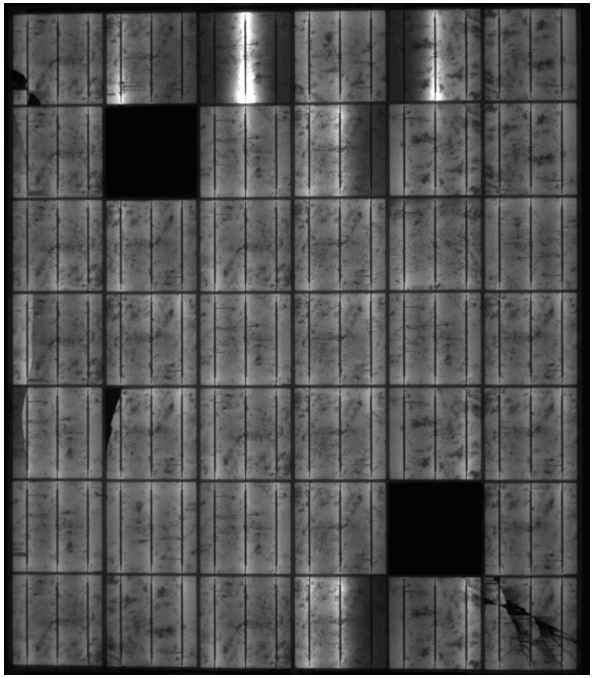


dG captures ribbon failures through first 1000 cycles



Shortly after 1000 cycles, module becomes open. Those cells are bypassed to continue experiment

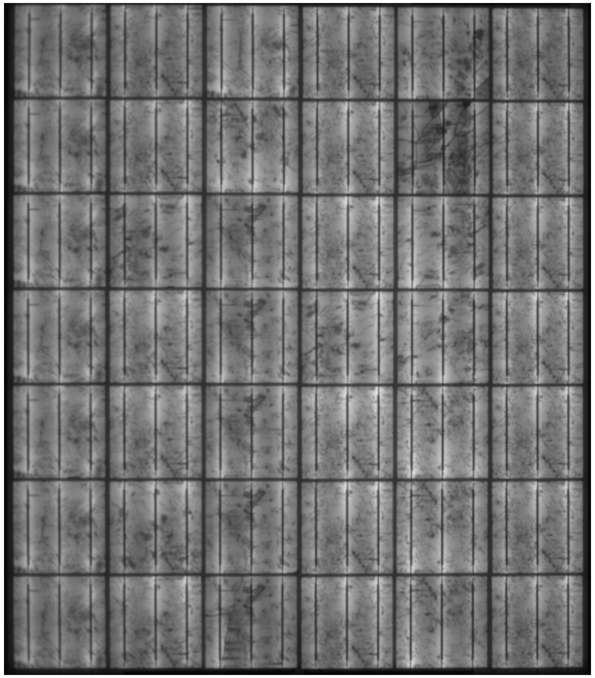




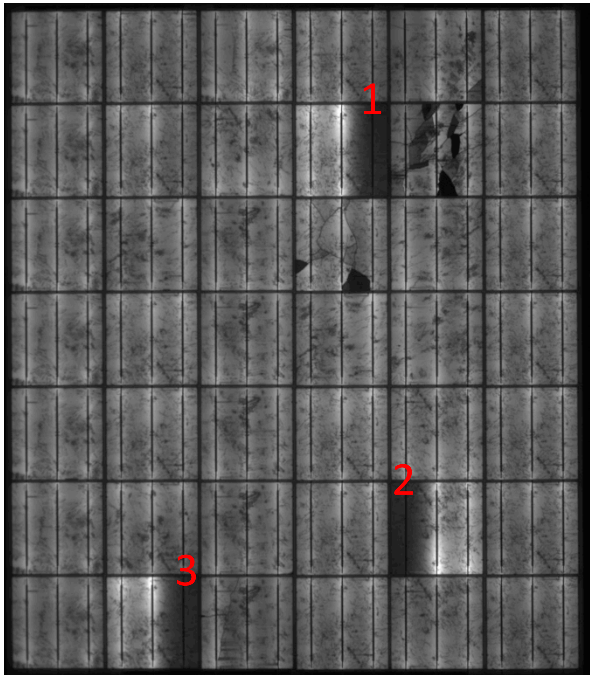
M1212_0003

DML +/-3000 Pa no bias

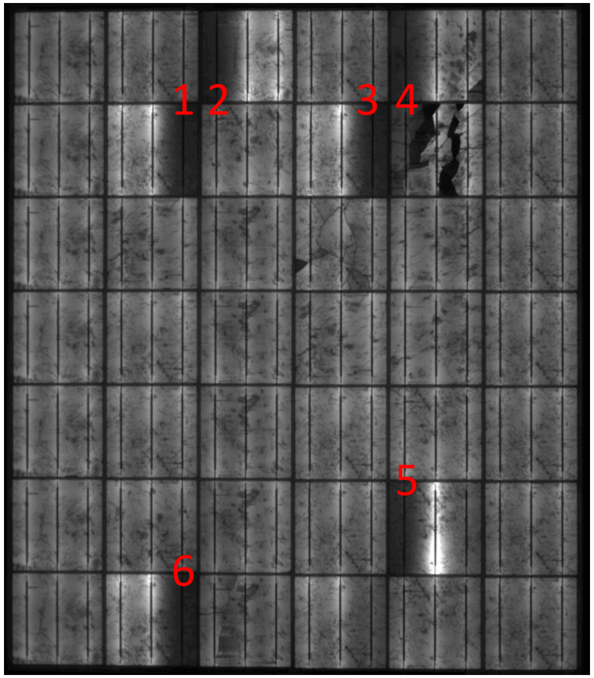
10 mm offset



1000 cycles



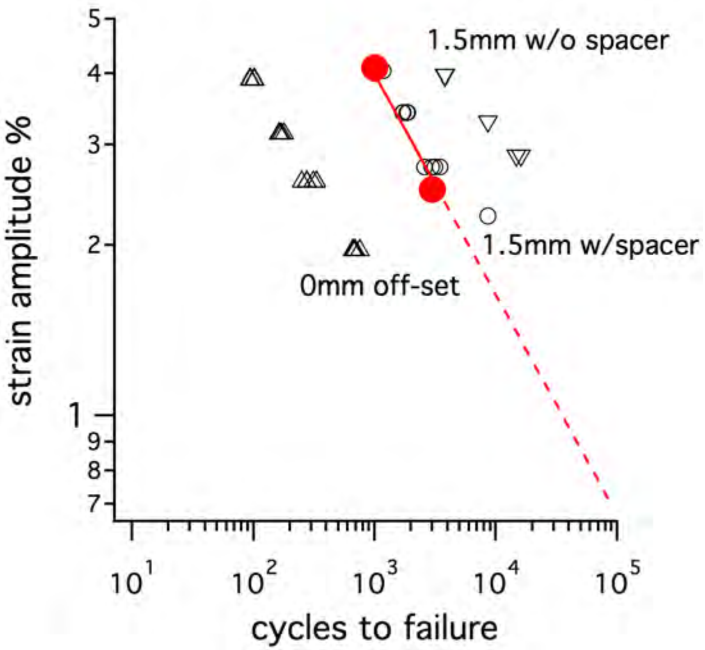
2000 DML cycles
3 ribbon failures obvious

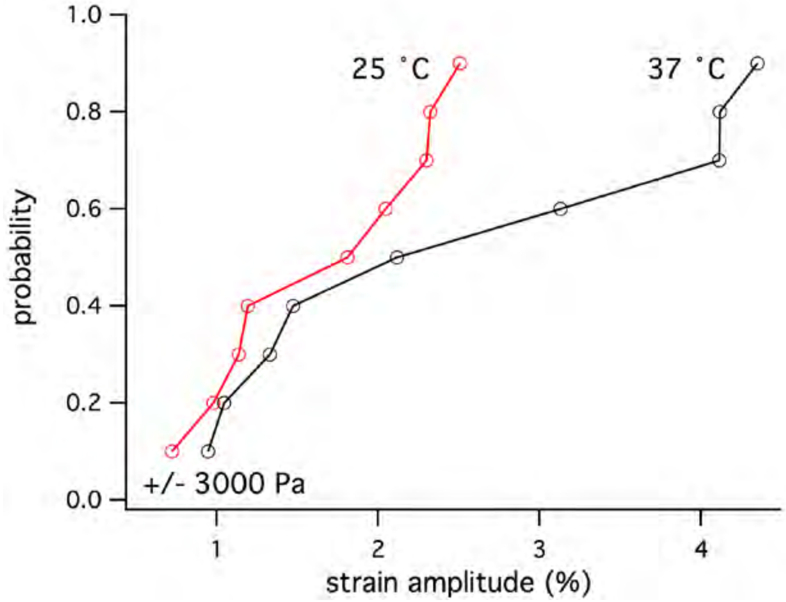


3000 DML cycles
6 ribbon failures obvious

M1212_0012

DML and fatigue measurements





Half of the module's ribbons should fail within 6000 cycles

Dynamic Mechanical Loading

- Module ribbon strain with DML has been characterized
- Fatigue failures are realized first for those with the highest strain amplitude
- *dG* monitoring captures failures
- Stay tuned for:
  - Acceleration factor with TC
  - FEM for strain amplitudes with module size

US & Japan TG 4 activities of QA Forum

QA Task Force 4 : Diode, Hot Spot, Shading & Reverse Bias

- Paul Robusto (Intertek)/Vivek Gade (Jabil) Co-Leaders US Team

February 26, 2013

Overview

- Introduction
- Summary of Testing (Jabil, NREL, Japan, Solaria)
- Presentation - Testing at Solaria and Summary of Testing (ESD)
  - Kent Whitfield
- Presentation - Testing by the Japan Team (ESD, Diode, J-box & Module-Thermal Runaway)
  - Y. Uchida (JET) & Y. Konishi (Onamba)
- Poster - Testing at NREL (Diode, Hot Spot, J-box)
  -Zeng Zhang (Chandler), John Wohlgemuth, and Sarah Kurtz
- Poster - Testing at MEMC/SunEdison (High Temp Rev. Bypass Diodes bias & Failures
  - Jean Posbic, Eugene Rhee and Dinesh Amin

Introduction

- Several failures have been known to exist primary are: sustained over heating over a long period of time, Reverse bias thermal run away, Shading and un-shading resulting in thermal runaway and electrostatic discharge related events.
- Team of module manufacturers, diode manufacturers and researchers in Task group 4 investigated several scenarios and how failures modes can be recreated through reliability testing.
- Few working groups were formed. Work performed by those working groups is introduced in this presentation. Few of the specific presentations detailing results will follow this introduction.
- Correlation is hampered due to limited Field failure data.

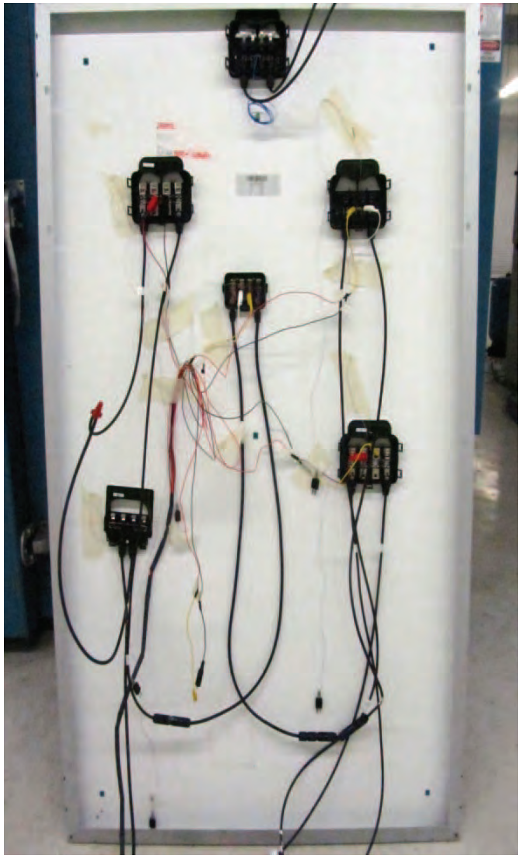
History

- **2011: Task Group 4 reviewed testing standards and identified potential gaps:**
  - **Accuracy of diode technical data sheet.**
  - **Qualification tests that ensure reliability.**
  - **Electrostatic Discharge (ESD) susceptibility.**

- **2012: Task Group performed series of experiments**
  - **ESD testing HBM, MM, IEC Model**
  - **Statistical and Weibull analysis**
  - **HTFB/RB and thermal cycling testing**
  - **Thermal Runaway Tests of J-boxes**

Jabil Tests Status/Plans

- **Extended test time for standard bypass diode test with 1.25 Isc at 80˚C (720 hours)**
  - **1) No issues of fatigue or drop in voltage seen.**
  - **2) Sample size 6**
  - **3) 12A rated diodes with different junction box designs**



Ongoing tests and future Tests Plans

- Reverse bias testing of cells at High Temperature (on going on random samples)

  1) No issues of early breakdown at 50C observed so far at 12V for one hour testing. (Monitoring with an IR camera for local hot spots and temperature rise)

  2) Four different cell manufacturers

- Diode testing with Reverse bias at high temperature and reverse bias transition survivability (Not initiated yet, tentative start date April 2013)

  1) Reverse bias voltage levels: 80% of the rated reverses voltage.

  2) Temperature levels: Maximum rated Junction temperature.

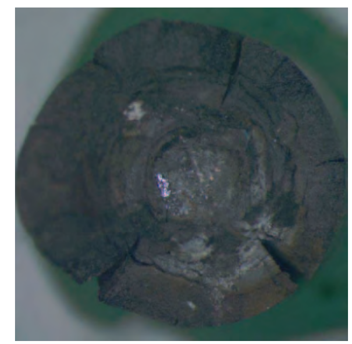
  3) Sample size 10

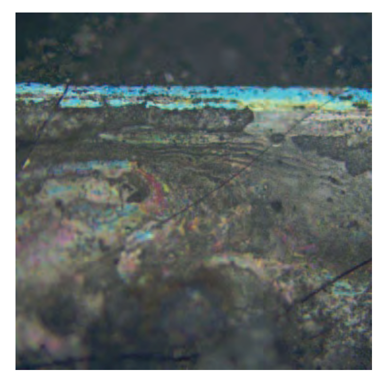
- Validation of test results obtained at NREL (April 2013)

Field failed diode analysis

Failure analysis of field failed diode provided by NREL was facilitated. This was the only failed sample that the group had received from the field. Unfortunately little could be learned from the failure analysis due to the extent of the damage to the diodes; resulting in the die fracturing in several places and the epoxy mold compound carbonizing on the front face of the die, preventing it from being removed by standard chemical methods. It was clear from the damage to the die, packages and the surrounding

plastic unit that the over-stress event was very severe, generating significant temperatures.





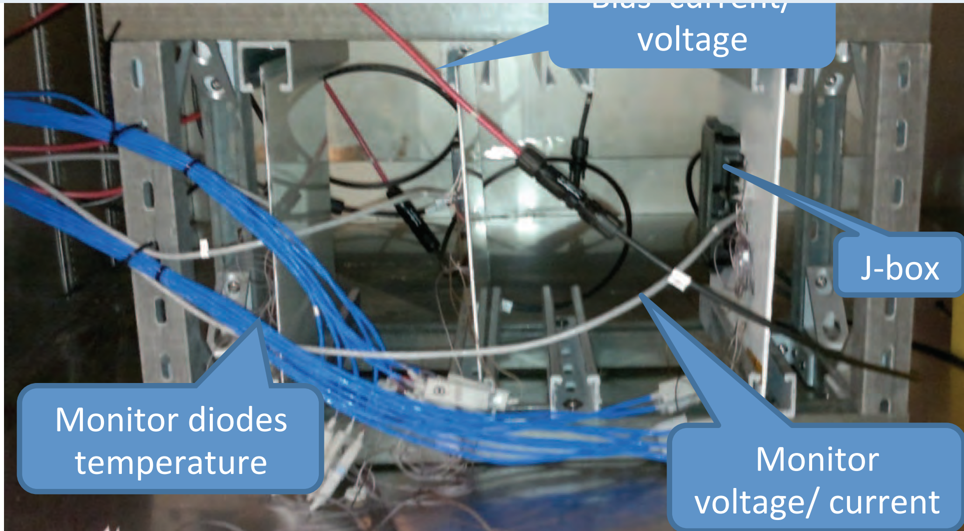
NREL Thermal reliability testing for PV diodes

Three types of J-boxes were used for the thermal reliability testing:

- **Test 1--- High temperature endurance testing with forward biased current.**
  - Objective: To assess diodes operating performance under long-term hot spot condition (50C/60C/70C),10A, 1000 hrs
  - Result: No diode failed. The diode temperature rises and forward voltages of J-box 1 and 3 increased after testing. Diodes in J-box 2 were very stable
- **Test 2 ---Thermal cycle plus forward bias/reverse bias.**
  - Objective: To assess diodes reliability under thermal cycling (-40 to 85C) caused by ambient temperature change combined with hot spot current flow (10 A above 25C) for first 100 cycles, -12V for above 25C for second 100 cycles.
  - Result: After the testing, diodes of Box-1 totally failed (middle diode); diodes forward bias voltage of Box-3 increased by 0.5V; diodes forward bias voltage of Box-2 were stable.
- **Test3 --- Thermal cycle plus reverse bias.**
  - Objective: To assess diodes reliability under thermal cycling caused by ambient temperature change without hot spot.
  - Result: There is no abnormal appearance of diode were found and no appreciable changes in terms of reverse diode characteristics were detected.

- **Next step:**

Design experiment to simulate the field condition of momentary shading on the PV modules caused by cloud or bird, etc.



Reporting contents from J-TG4

1. Thermal runaway test results of J-boxes

Reverse bias test at high temperature (Thermal runaway test)

① for J-box-A / with potting

② for J-box-B-1 / without potting

③ for J-box-C / without potting

2. Tj (junction temperature) measurement method for Bypass diode

Comparison with Vf-Tj method and Tlead method

Recommendation: we should use the Vf-Tj method in accordance with "paragraph 10.18 Bypass diode thermal test / procedure 2 specified in IEC61646".

ESD Testing Program – Status

- Diode ESD Susceptibility identified as a gap in current qualification testing programs in the Task Group 4 white paper issued September 2011 (pbworks QA Rating Wiki).
- Extensive research and testing program started in October 2011 and has, thus far:
  - Identified ESD as a failure mode of concern for Schottky diodes
  - Corroborated that some manufacturing line and 3rd party failures of diodes can be traced to ESD events. Field data remain elusive.
  - Found that a step-stress ESD testing method using a standard IEC impedance model appears effective at uncovering differences in susceptibility between similarly rated Schottky diodes and:
    - Only positive surges against the cathode side produce failures
    - A minimum of ten surges on each of ten samples is required to produce a Weibull cumulative distribution function that matches well with a higher number of surge events on a larger sample size.
    - Been able to correlate test method results to one manufacturer's experience with in-house failure rates.
- Present effort is to obtain other manufacturer's input on method.
  - Likely to use IEC Test Method as a vehicle to allow inter-manufacturer comparison with method and results.

Technical Presentations

- ESD Surge Characterization of Schottky Diodes

  by Kent Whitfield (Solaria)

- On the occurrence of thermal runaway in Diode in the J-box

  by Y. Uchida (JET)

Poster Session

1. The Thermal Reliability Study of Bypass Diodes in Photovoltaic Modules

by Zhang, Zhen., Wohlgemuth J. 1, Kurtz,
National Renewable Energy Laboratory, Golden, Colorado, USA
State Key Lab of Photovoltaic Science and Technology, Trinasolar Co. Ltd., Changzhou, China

. If the heat dissipation is not good enough, there is still some possibility of diodes degradation or failure in PV modules under hot spot condition. Thermal cycle condition with forward biased current to diode, are representative of hot spot conditions, can impose a strong thermal fatigue stress to diode, and may cause failure for bypass diodes of some PV module that may be able to pass present criteria of IEC 61215

2. High Temperature Reverse By-Pass Diodes Bias and Failures

by Jean Posbic, Eugene Rhee and Dinesh Amin (MEMC/SunEdison)

They developed a very simple method to test diodes in a j-box or individually in the lab without the need for a sophisticated thermal chamber.

US TG 4 activities of QA Forum

QA Task Force 4 ; Diode, Shading & Reverse Bias
Diode ESD Characterization

Contains no confidential information.

Kent Whitfield

with thanks to Solaria for their support of this work

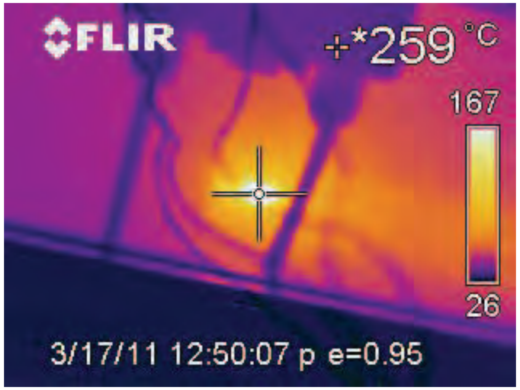
Overview of Presentation

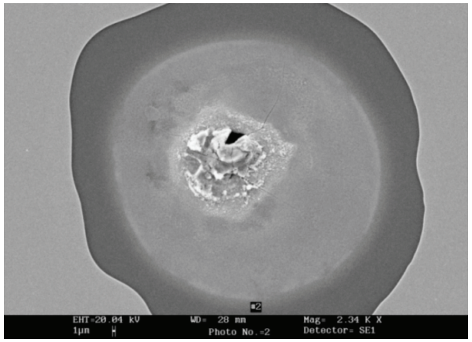
- ESD Surge Characterization of Schottky Diodes
  - Motivation – Why ESD characterization of diodes might be important
    - History
    - Case study
    - Observations from failed diodes
  - Methods to characterize a diode's ESD tolerance
    - Environment
    - Testing methods
    - Proposed procedure
    - Data analysis
    - Correlation to failures encountered
  - Next steps

A Completely Selective History

- 1985: General diode reliability guidelines based primarily on operational temperature.
- 1993: 20k modules had a 50% failure rate over ten years.
  - 90% of the failures were from common causes that included lack of adequate bypass diode protection (hot spot failures).
- 2011: Task Group 4 reviewed testing standards and identified potential gaps:
  - Accuracy of diode technical data sheet.
  - Qualification tests that ensure reliability.
  - *Electrostatic Discharge (ESD) susceptibility.*

Diode Type	Maximum Allowable Junction Temperature	Derated Temperature for Long-Term Reliability
p-n	175°C	125°C
Schottky	125°C	75°C



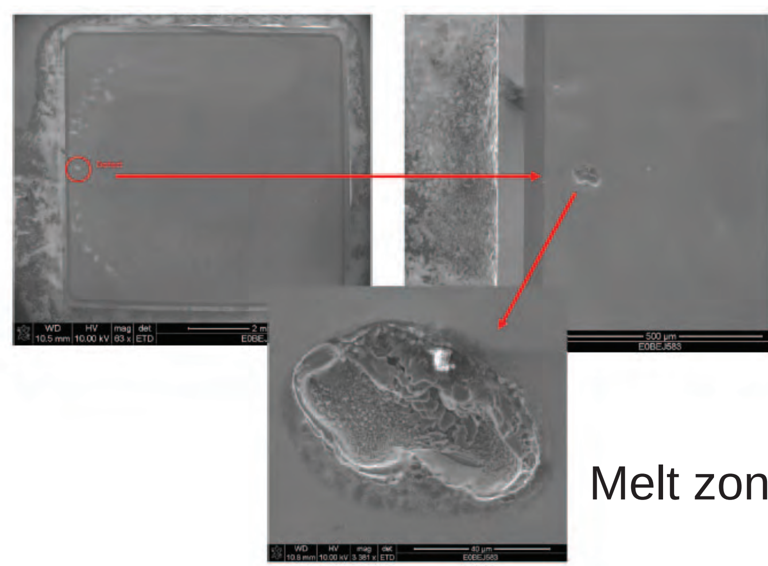


Case Study

- Field Failure Data: Anecdotal, mostly onesy-twosey, occasional large scale at _A_ site. Suggests some batch/site-specific behavior.
- Undisputed: Schottky diodes are found to fail at a measurable rates in production – Final IV curve/EL.
  - 2011: Sudden onset of certification samples and production modules being found with shorted diodes.
  - No process or design change and some certification tests NOT related to diodes:
    - TC50, TC200, DH1000, Preconditioning???
  - Failure rate goes from 0.0% to 0.4% in one facility, but in another with ESDS 20.20 compliance, rates stays at 0.0%.

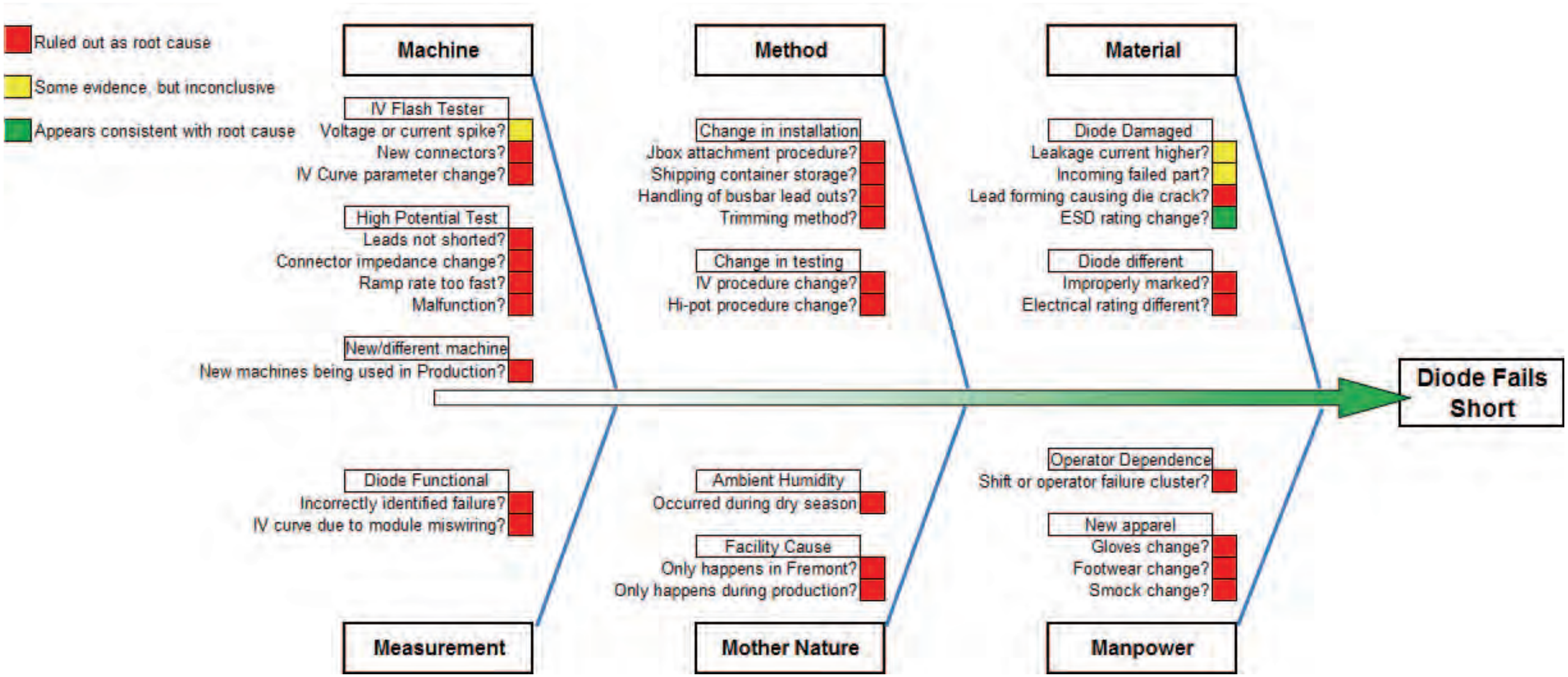
More Observations

- Decap and FA indicates all diodes of suffering from electrical overstress – but inconsistent from ESD alone due to presence of melted regions.
- Failed diodes happen to conform to a specific date code range.



Melt zone

Ye' Ol' Fishbone



- Evidence seems to point to ESD susceptibility change *in this case study only*.
- Bigger question is what is the susceptibility?

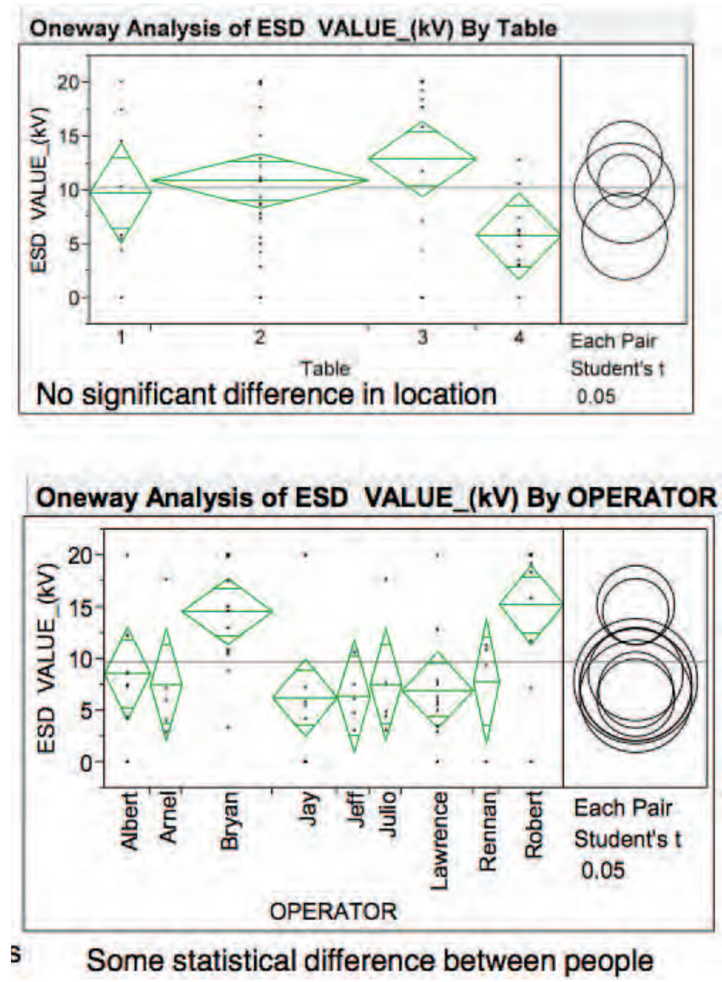
Characterization of Environment

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

- Electrostatic voltage in the facility.
  - Simple, low-cost test equipment and fast to characterize.
  - Cannot gauge charge transfer which is critical to the ESD failure mode.
- ESD event meter.
  - Simple, but higher-costing test equipment.
  - Can gauge peak voltage stress associated with standard charge transfer models.

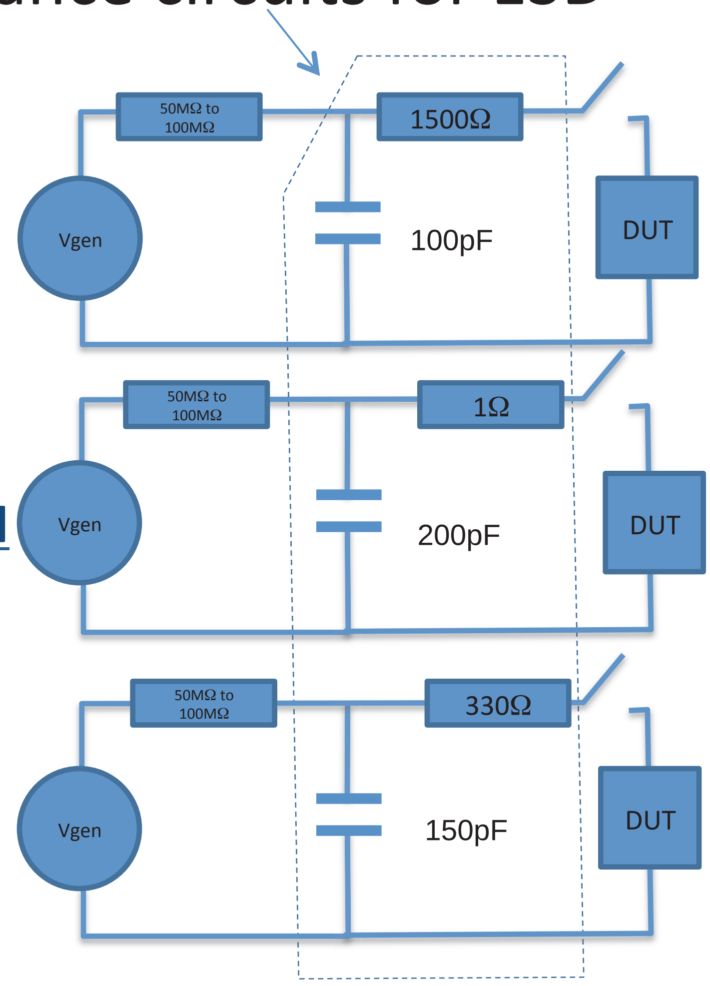
Knowns

- Schottky diodes more susceptible to ESD damage.
- ESD events may occur from
  - human contact only, or
  - In-house charged-device/ operator interaction such as jbox installation, connecting to test equipment (hi-pot, IV, EL), or
  - 3rd party charged device interaction, or
  - In field installation.

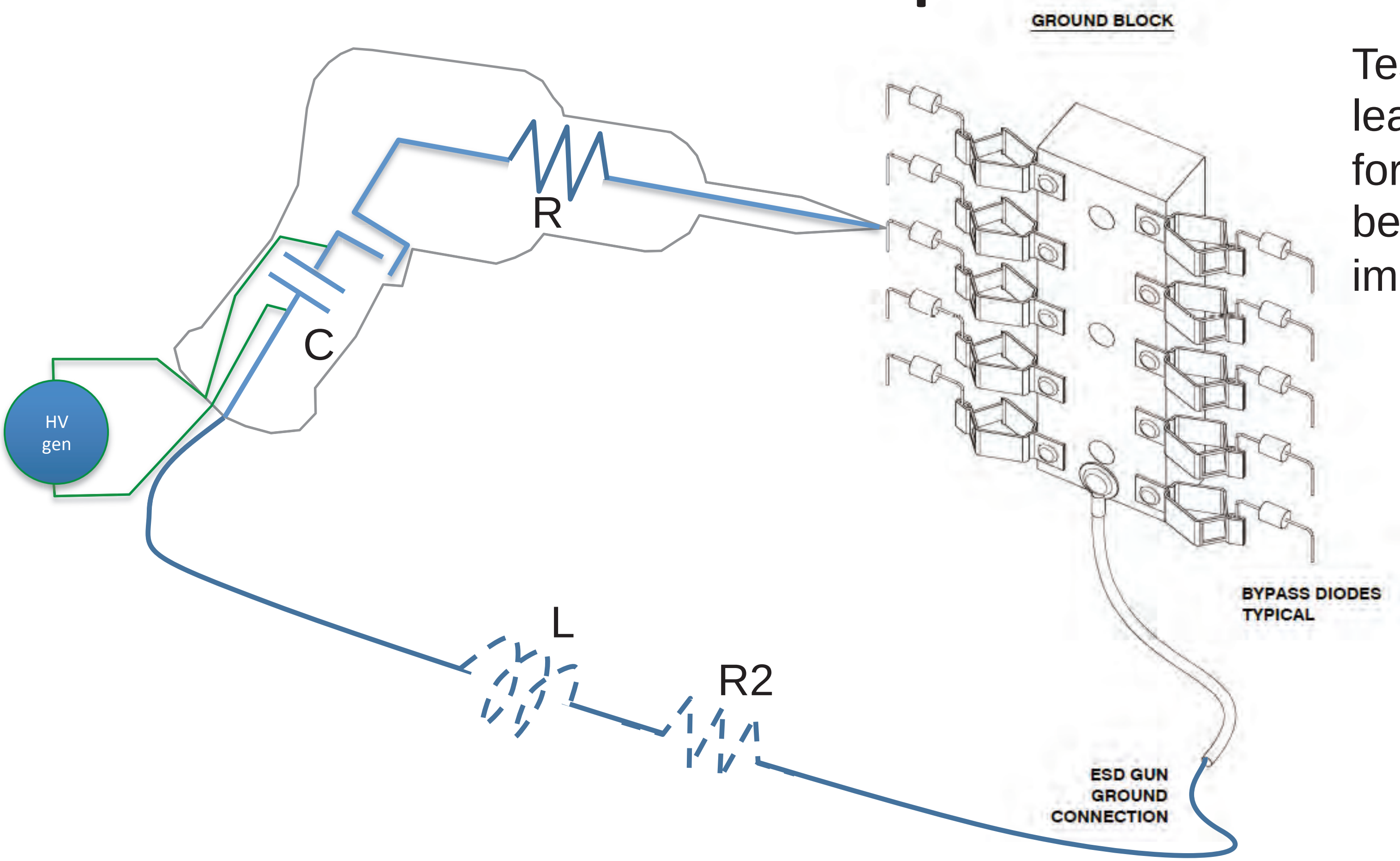


How to Characterize Susceptibility

- Most commonly used impedance circuits for ESD testing are:
  - Impedance Circuits:
    - ANSI/ESDA/JEDEC JS-001 – Human Body Model
      - Bare finger
    - JEDEC JESD22-A115C – Machine Model
      - Charged machine
    - IEC 61000-4-2 – ESD Immunity
      - Discharges from operators



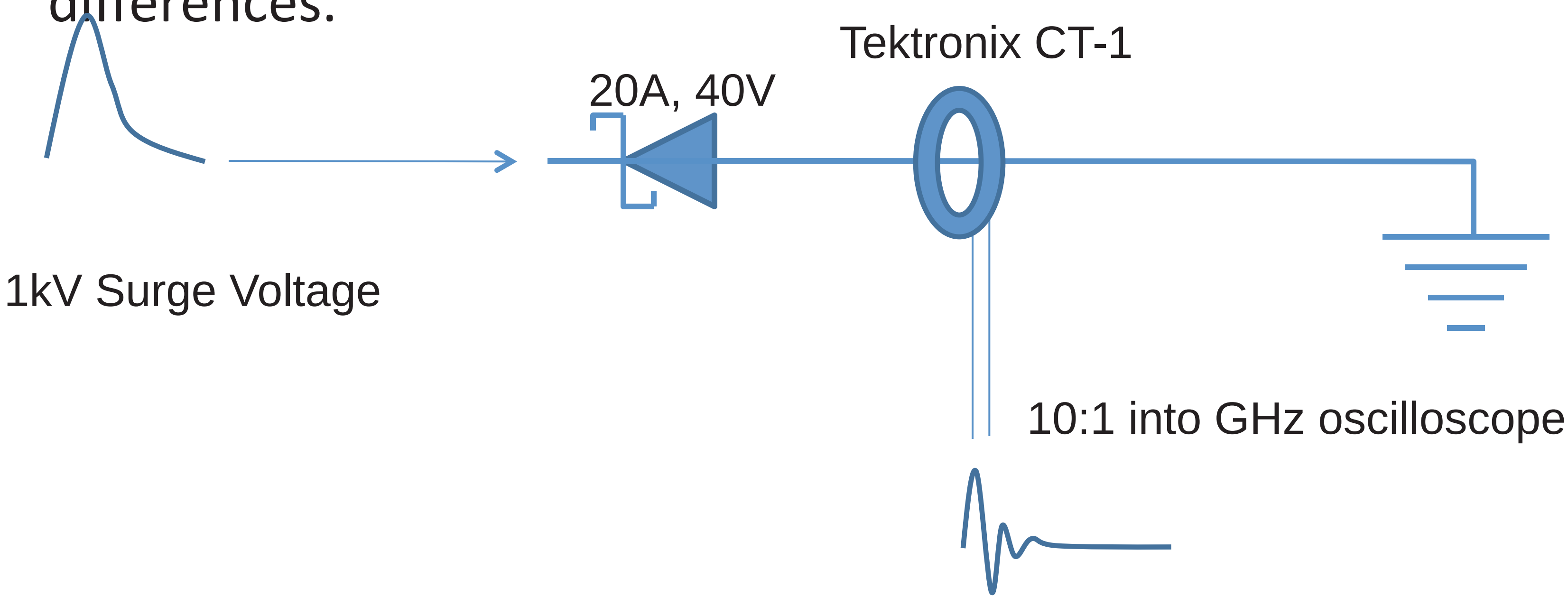
Set Up



Testing with leads already formed for jbox believed to be important.

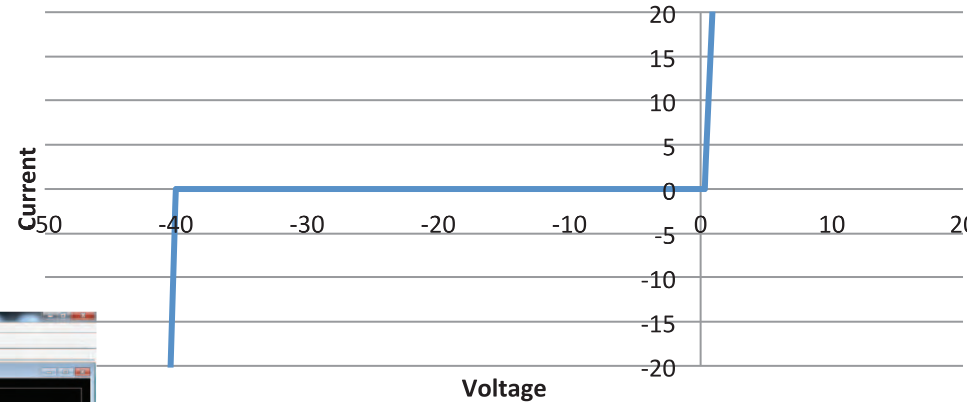
Differences in the Impedance Circuits

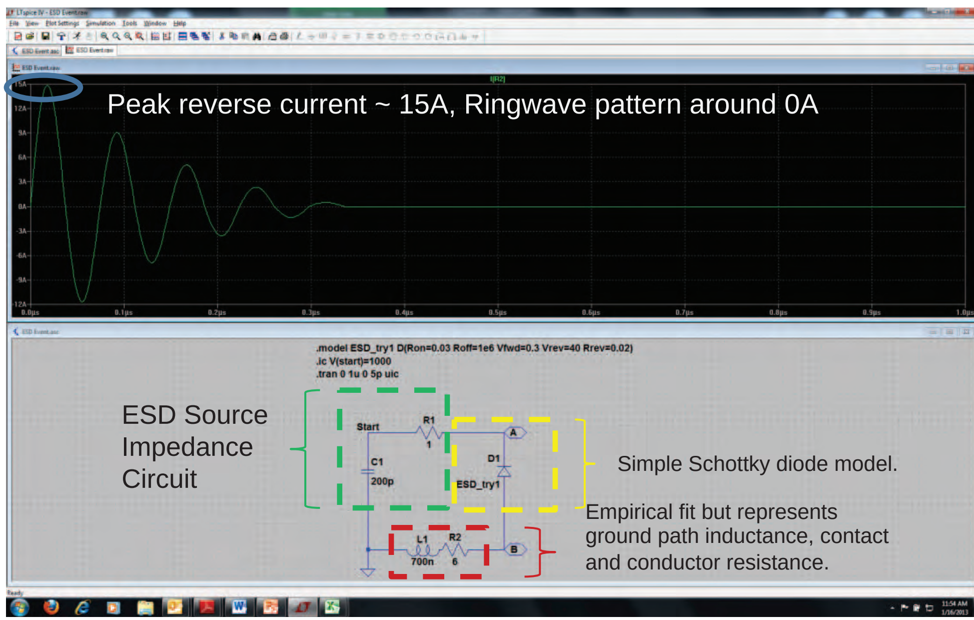
- Hard to measure voltage and current during actual test without affecting results.
- Contact repeatability issues also occur.
- So, validate a LTSpice model against real current waveforms and use model to improve understanding of surge differences.



LTSPICE Model Machine Model Impedance

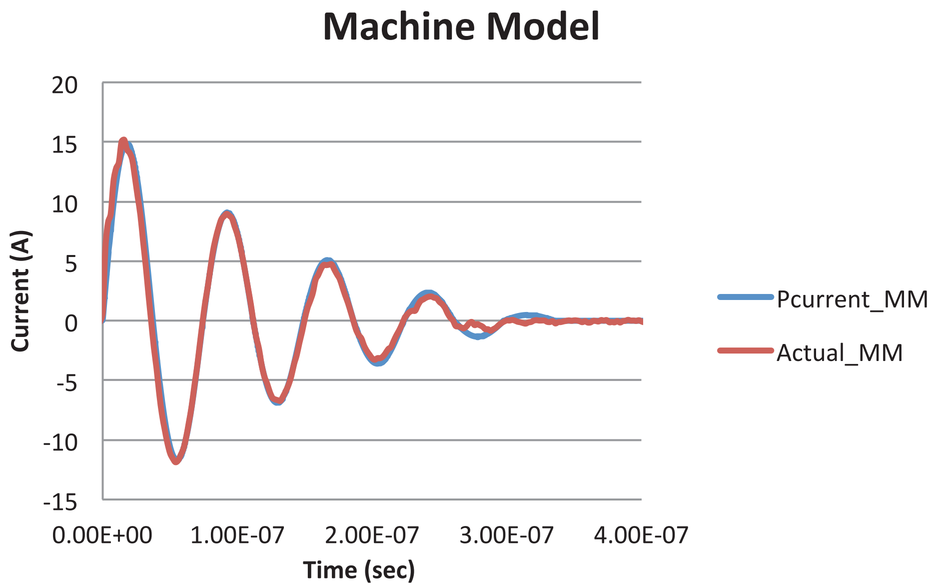
Schottky LTSPICE Diode Model

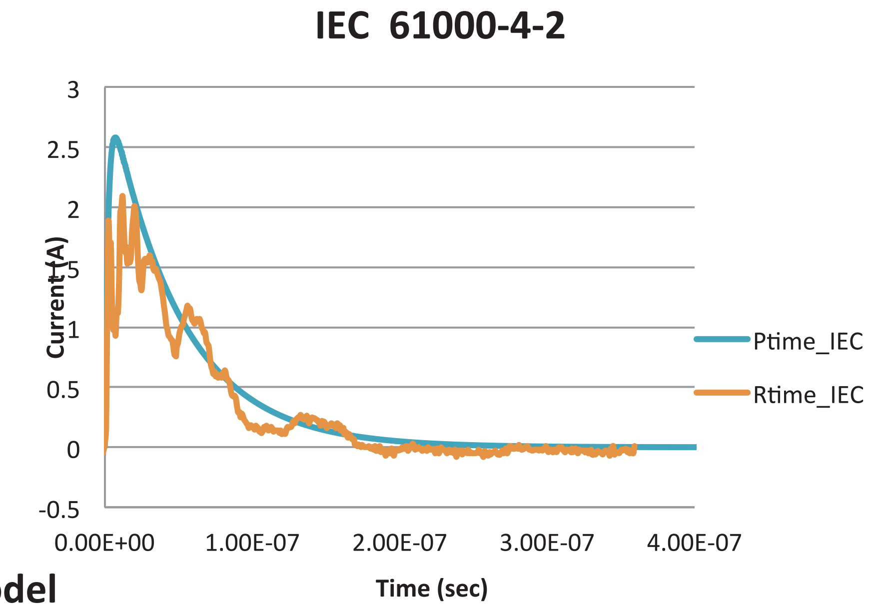


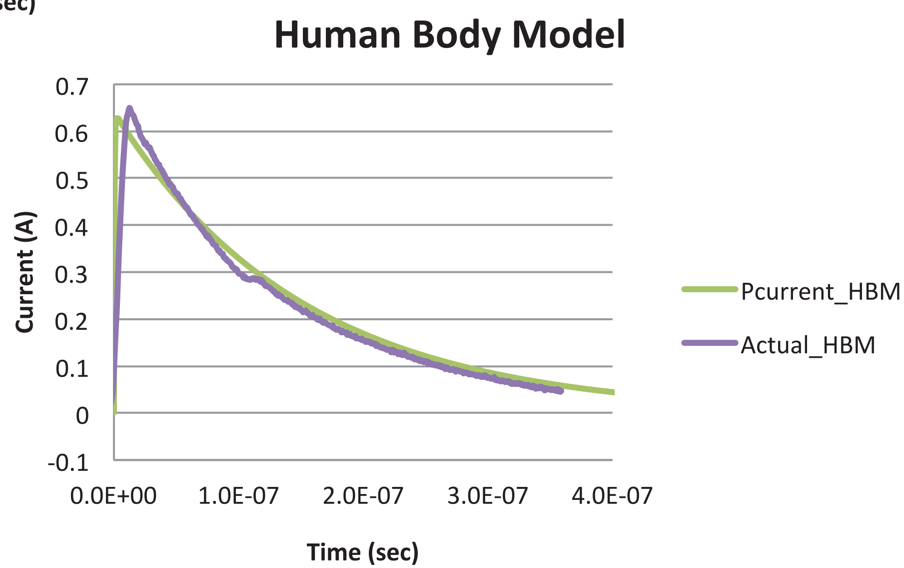


Key Consideration – This model diode is fully recoverable in the breakdown region regardless of current. Actual diodes are also fully recoverable in breakdown below a specific current threshold at a specific temperature.

Comparison to Actual

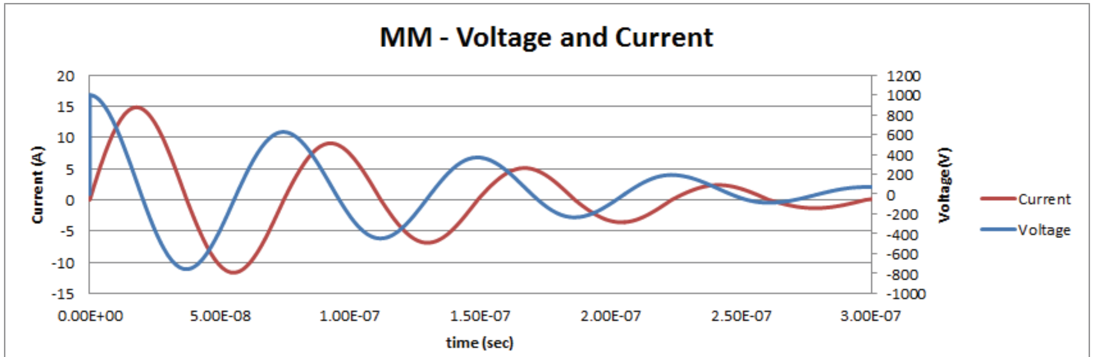




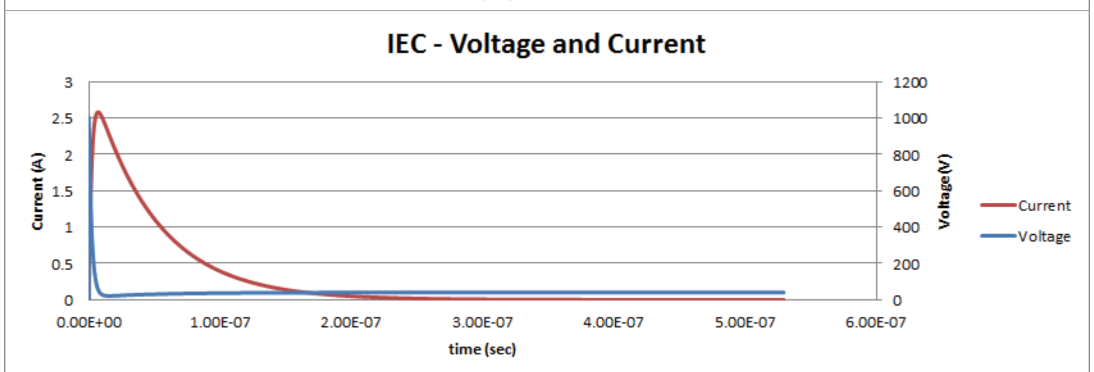


One model matches real current waveform quite well!

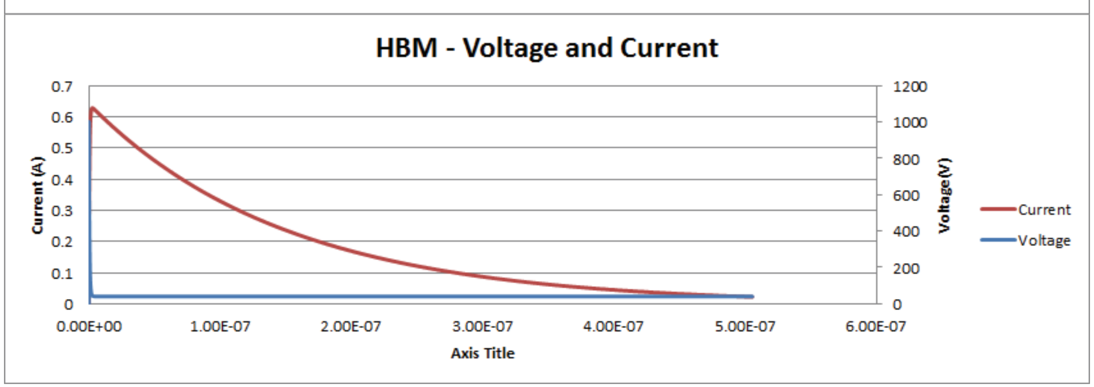
LTSPICE Voltage and Current



Numerically integrated surge energy ~0.4 mJ



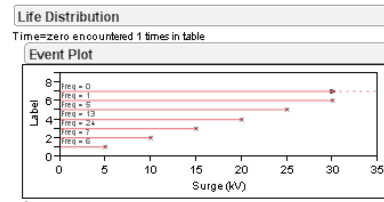
Numerically integrated surge energy ~7 μJ



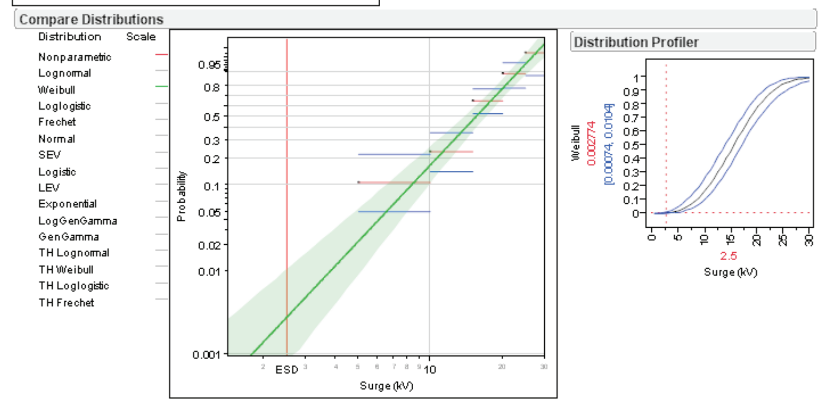
Numerically integrated surge energy ~4 μJ

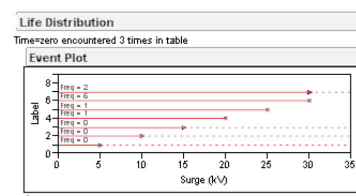
Arrived at ESD Testing Method

- 5kV steps from 5kV to 30kV using a simple multimeter check for short-circuit following surge application.
- Sample size of 10 diodes all having same date code.
- 10 positive surges applied to cathode side with 10 seconds between surges.
  - Literature suggests breakdown region on die is small so relaxation time required between surges.
- A Weibull curve used to fit data.
  - ➢ Where we have substituted surge voltage for time.
  - ➢ The CDF is thus interpreted to mean fraction of all units in the population which will fail by V peak voltage having a voltage and current waveform given by the IEC model.
  - ➢ Shaded region indicates a 95% confidence interval around the median line.

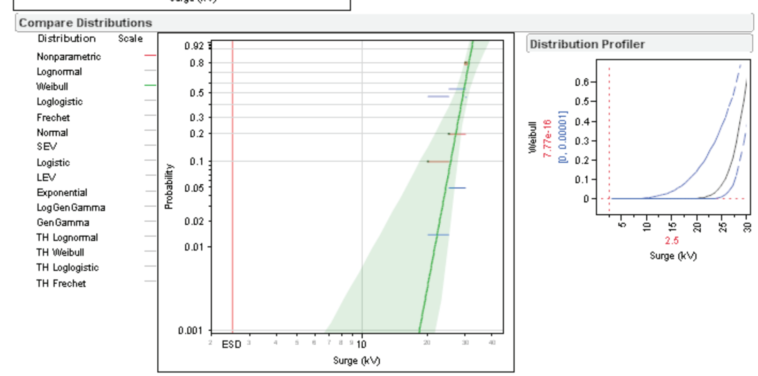


Group A, 56 samples tested, 2800 ppm expected fails at a 2.5kV peak ESD voltage.



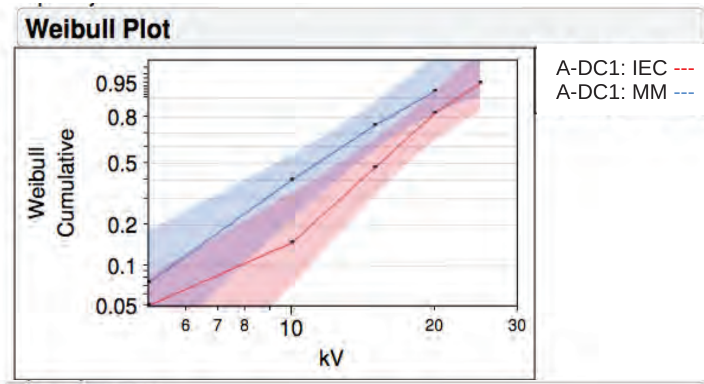


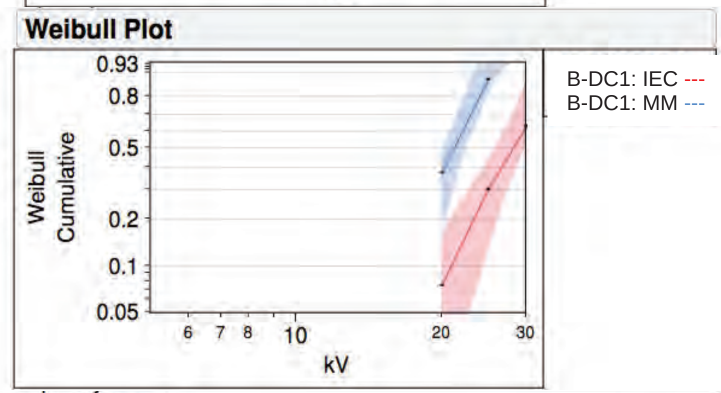
Group C, 10 samples, 0-100ppb expected fails at a 2.5kV ESD peak voltage.

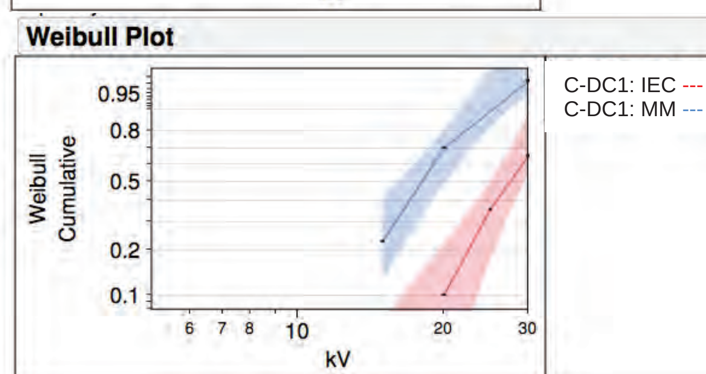


ESD Surge Testing

- Basis of ESD Test – IEC 61000-4-2
- Surge-to-Failure, Step-Stress Program. Considered following variables:
  - Impact to reverse leakage current at room temperature
    - No correlation below failure threshold.
  - Impact to reverse leakage current when diode is at 60C
    - No correlation below failure threshold.
  - Impact of positive surges against anode side of diode
    - No failures observed.
  - Impact of positive surges against cathode side
    - Resulted in failures.
  - Impact of sample size
    - Similarity of failure distributions exists with samples sizes from 10 to 60 at 95% confidence,
  - Impact of number of surges applied per stress step
    - Similarity of failure distributions exist with 5 to 50 surges at 95% confidence.
  - Compared results using IEC model with Machine Model
    - Failure distributions are similar in Weibull space, but shifted to lower voltages in the Machine Model.

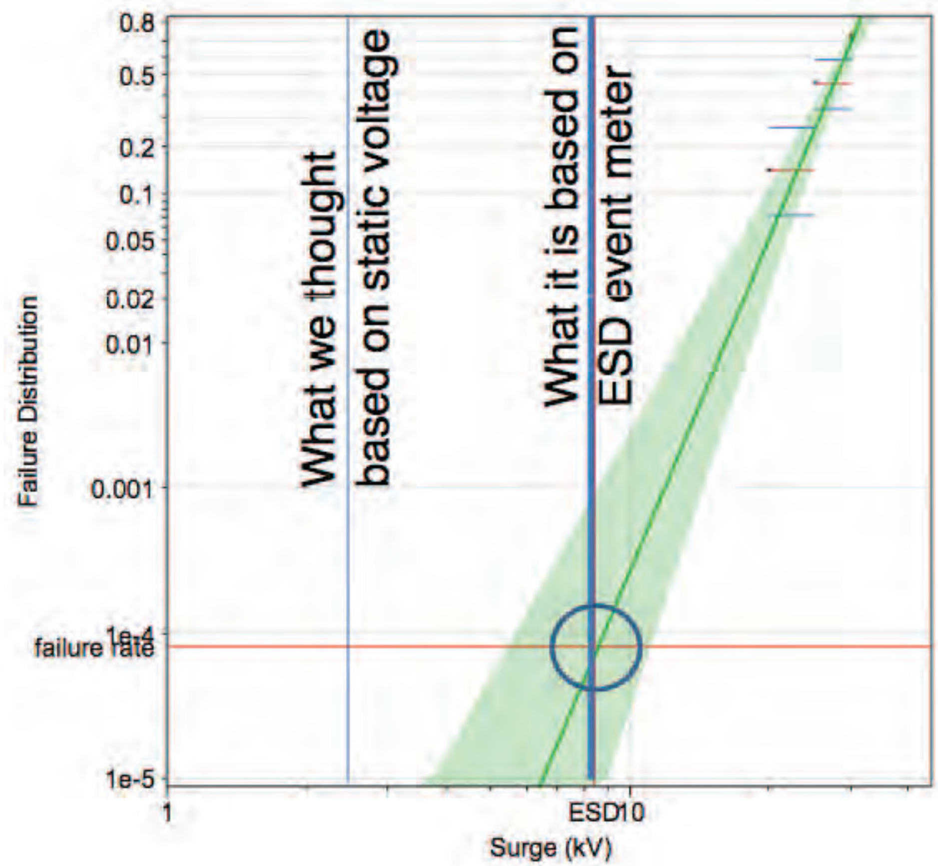






Some Confirmation of Technique

- Static voltage measurement indicated a 2500V risk in area of jbox installation.
- Tested a group of diodes using IEC model and selected one that SHOULD result in a 7.2ppb failure rate of at this level of ESD voltage.
- Actual failure rate in production found to be 82ppm!
- Changed in-house measurement from static voltage to actual ESD event detection.
- Measured 47 ESD events and mean found to be 8.2kV *NOT 2.5kV*.
- This mean correlated well with the observed production failure rate.



Conclusion and Next Steps

- ESD found to damage Schottky diodes.
- ESD events triggered when there is an interaction between charged devices during installation or testing although there appears to also be some operator interaction.
- Failure rates differ from diode-to-diode even when ratings are the same.
- A test procedure based IEC surge standard seems to be useful in characterizing diode ESD susceptibility.
- NEED other manufacturers to corroborate findings.
- PROPOSE a test method in IEC TC82, WG2 but without pass/ fail criteria.

Thank you!

On the occurrence of thermal runaway in Diode in the J-box

J-TG 4 activities of QA Forum

QA Task Force 4 ; Diode, Shading & Reverse Bias

Feb. 26-27, 2013 *@ Denver, USA*

Y. Uchida / JET (Japan Electrical & Environment Technology Laboratories)
Y. Konishi / ONAMBA CO.,LTD.
T. Okura / SOMA OPTICS, LTD.

J-TG4 Activity Report

J-TG4 activities had been reported in the following events ;

1. Dec.08, 2011 — 2nd. QA Forum Tokyo
2. Feb. 28, 2012 — NREL PV Module Reliability Work-shop
3. May 07, 2012 — WG2 STRESA meeting
4. Oct.01, 2012 — WG2 Oslo meeting
5. Nov.27, 2012 — 3rd. QA Forum Tokyo
6. **Feb.26,27, 2013 — NREL PV Module Reliability Work-shop**

Background

→ Trend of Bypass diode from P/N Si diode to SBD

■ This trend is because of the addition of “Bypass diode thermal test” in IEC 61215 Ed2. (2005-04),

①When applying current of Isc at 75℃, diode junction temperature shall not exceed max. rated Tj.

②When applying current of "1.25XIsc" at 75 ℃, the function of diode shall not be impaired.

On top of the above requirements, due to the pressure of the price reduction of diode and suppression of heat-up, the bypass diode has switched to the SBD with low Vf .

Test reports

Test① Continuous current test for J-box
①-1 for Diode-A
①-2 for J-box-A
Test② Intermittent current test for Diode
②-1 for Diode-A
②-2 for Diode-B

Reported at WG2 Oslo meeting.

Test③ Reverse bias test at high temperature (Thermal runaway test)

③-1 for J-box-A / with potting
③-2 for J-box-B-1 / without potting
for J-box-B-2 / without potting
③-3 for J-box-C / without potting

Contents of this report

1. **Thermal runaway test results of J-boxes**

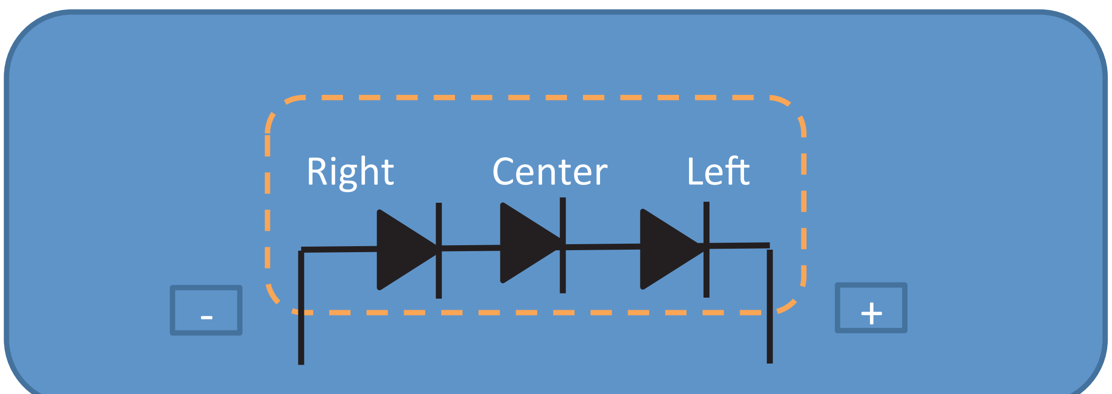
2. Tj measurement method for Bypass diode

J-boxes for Thermal-runaway tests


J-box-A


J-box-B


J-box-C



Summary of "Reverse bias test at high temperature" ;

Test ③-1 ; J-box-A / with potting (Test sequence : ①center→②right→ ③left)

■ Chamber temp. : 90℃

		Reverse bias / Vr			
		15V	20V	25V	30V
If / Forward current	9A	1. Center ○	2. Center ○	3. Center ○	
	11A	4. Center ○	5. Center ○	6. Center ×	
	12A	7. Right ○	8. Right×		
	13A	9. Left ×			

○ ; No thermal runaway
× ; Thermal runaway

The numbers mean a test sequence.

Summary of "Reverse bias test at high temperature" ;

Test ③-2 ; J-box-B-1 / without potting

■Chamber temp. : 75℃

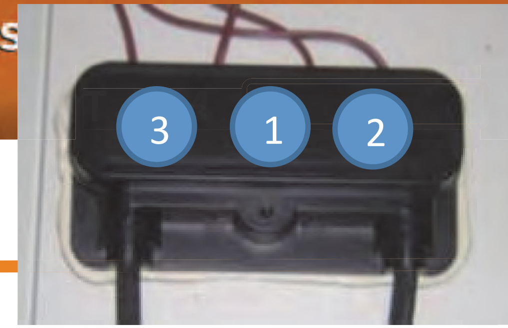
		Reverse bias / Vr			
		15V	20V	25V	30V
If / Forward current	8A	1. Center ○	3. Center ○		
	9A	2. Center ○	5. Center ○		
	11A	4. Center ○			
	12A				

○ ; No thermal runaway
× ; Thermal runaway

The numbers mean a test sequence.

■ Chamber temp. : 90℃

		15V	20V	25V	30V
If / Forward current	8A	6. Center ○	8. Center ○		
	9A	7. Center ○	10. Center ○		
	11A	9. Center ○	11. Center ×		
	12A				



Summary of "Reverse bias test at high temperature" ;

Test ③-2 ; J-box-B-2 #3 / without potting (Test sequence : ①center→②right→ ③left)

		Left diode		Center diode		Right diode	
VR; reverse voltage		15VR	20VR	15VR	20VR	15VR	20VR
■ Chamber temp. : 75C							
If	8A	Not done	Not done	1. ○	3. ○	1. ○	3. ○
	9A	Not done	Not done	2. ○	5. ○	2. ○	5. ○
	11A	Not done	Not done	4. ○	Not done	4. ○	Not done
■ Chamber temp. : 90C							
If	8A	Not done	Not done	6. ○	8. ○	6. ○	9. ○
	9A	Not done	1. ○	7. ○	—	7. ○	10. ○
	11A	2. ○	3. ×	9. ×	—	8. ○	11. ○
	12A	—	—	—	—	12. ○	13. ×

Summary of “Reverse bias test at high temperature” ;

Test ③-3 ; J-box-C / without potting

■Chamber temp. : 75℃

		Reverse bias / Vr			
		15V	20V	25V	30V
If / Forward current	8A	1. Center ○	3. Center ○		
	9A	2. Center ○	5. Center ○		
	11A	4. Center ○			
	12A				

○ ; No thermal runaway
× ; Thermal runaway

The numbers mean a test sequence.

■ Chamber temp. : 90℃

		15V	20V	25V	30V
If / Forward current	8A	6. Center ○	8. Center ○		
	9A	7. Center ○			
	11A	9. Center×			
	12A				

Temperature of each diode in J-box under the forward current

■ J-box-A-3 / Chamber temp. ; 75℃

If	Left diode Tj, ℃	Center diode Tj, ℃	Right diode Tj, ℃
9A	130.2	131.2	129.2

■ J-box-B-1 / Chamber temp. ; 75℃

If	Left diode Tj, ℃	Center diode Tj, ℃	Right diode Tj, ℃
9A	160.1	173.3	158.7
11A	178.7	192.7	176.8
12A	187.5	201.5	184.5
13A	195.5	212.1	193.7

■ J-box-B-1 / Chamber temp. ; 90℃

If	Left diode Tj, ℃	Center diode Tj, ℃	Right diode Tj, ℃
9A	171.0	182.6	169.8
11A	189.2	201.4	186.4
12A	197.2	211.3	194.3
13A	205.3	220.1	203.7

The temperature of the center diode is affected by the left and right diodes and becomes the highest.

Note ;
The Tj was obtained from the Vf value using Vf-Tj relation.

Results of the study -1

1. We were able to confirm the thermal runaway of the SBD during high-temperature reverse bias.

2. As for the thermal runaway, the timing of switching from forward to reverse is important.

3. We have confirmed that the conditions for the thermal runaway was different according to the type of J-box (ex. ; J-box shape and with or without the potting materials).
   → We are planning to perform the thermal runaway test for some more J-boxes with different diodes.

4. In case of typical J-box with 3 diodes in the box, the temperature of the center diode is affected by the left and right side diodes and becomes the highest.

Contents of this report

1. Thermal runaway test results of J-boxes

2. **Tj measurement method for Bypass diode**

T_{lead} method vs Vf-Tj method

From our experiment,

As for Diode Tj, the difference was confirmed in "Vf-Tj method" and "T_{lead} method".

→ with experimental data on the next page.

Test sample ; J-box-B-2

[Chamber temp. ; 75℃]

		Left diode		Center diode		Right diode	
		Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃
If	9A	158.1	160.1	165.0	173.3	143.1	158.7
	11A	175.2	178.7	183.4	192.7	156.9	176.8
	12A	183.5	187.5	192.4	201.5	164.0	184.5
	13A	192.0	195.5	201.2	212.1	170.7	193.7

[Chamber temp. ; 90℃]

		Left diode		Center diode		Right diode	
		Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃
If	9A	168.8	171	175.2	182.6	154.2	169.8
	11A	185.4	189.2	192.8	201.4	168.1	186.4
	12A	193.7	197.2	201.9	211.3	174.7	194.3
	13A	201.7	205.3	210.4	220.1	181.3	203.7

Note 1. : Tlead ; Tj by "Tlead method"
Tj = Tlead + (Rth × Vf × If), Rth= 2.5℃/W provided by diode maker

Note 2. : Vf-Tj ; Tj by "Vf-Tj method"
in accordance with "IEC61646 Ed.2 10.18 Btpass diode thermal test / Procedure 2"

Why always
Tlead < Vf-Tj ?

T_{lead} method

The correct Tj can not be obtained by Tlead method.

Because, the thermal resistance (Rth) could vary.

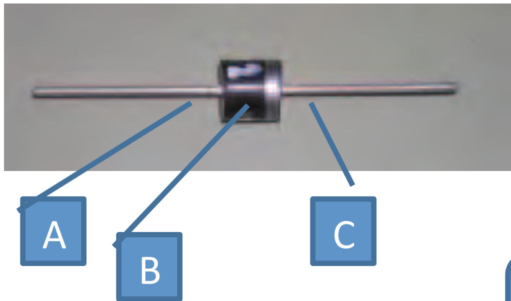
$$T_j = T_{lead} + (R_{th} \times I_f \times V_f)$$

The reason that thermal resistance varies is as follows;

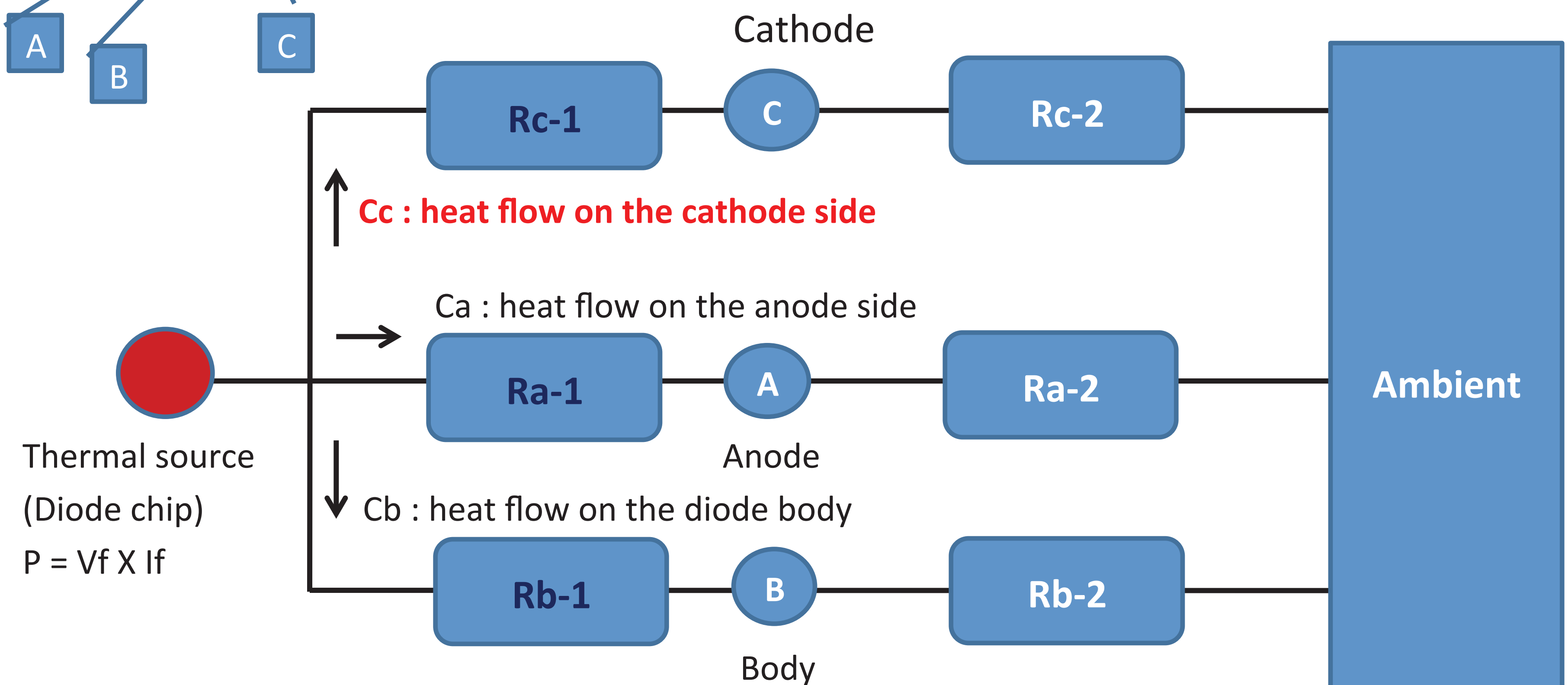
there is a difference in heat radiation conditions because diodes are installed in various J-box.

→ We are now measuring in order to obtain the support data.

Heat flow from Diode chip



$$Rc\text{-}1 < Ra\text{-}1 \ll Rb\text{-}1$$

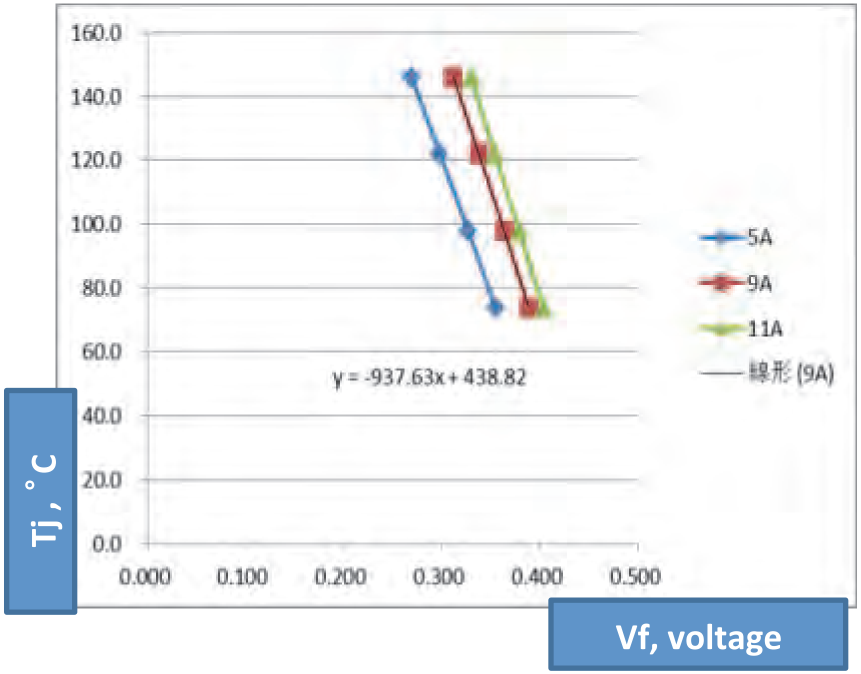


Heat flow varies with the radiation conditions !!!!!

Tj = Tlead + Vf×If × Cc × Rth (→ real Rth) → apparent Rth

Vf – Tj method

- **Once Vf-Tj relation is obtained, Tj is easily decided from the value of Vf. Vf-Tj relation can be acquired by measuring the temperature of the lead and the voltage across the diode in thermal equilibrium condition.**



Results of the study -2 (1/2)

From this experiment, the difference was confirmed in Vf-Tj method and Tlead method as for Tj of diode.

Regarding the thermal resistance (Rth) by Tlead method, Rth is provided by Diode maker.

When it is assembled into the J-box, an apparent Rth will vary because of the influence of wiring left and right side diodes, including Heat-sink.

$$T_j = T_{lead} + (R_{th} \times I_f \times V_f)$$

Results of the study -2 (2/2)

Therefore, we should use the Vf-Tj method in accordance with "paragraph 10.18 Bypass diode thermal test / procedure 2 specified in IEC61646".

In order to continue accumulating technical data for Tj of diodes, we would like to propose a Vf-Tj method.

Next activities

1. Establishment of a method of thermal design verification test for J-box, and preparation of a draft standard

2. Development and manufacturing of thermal runaway test equipment

3. Suggestions for improvement of Diode Tj measurement method

4. In order to discuss the rating system, we have to confirm the changes of the characteristics of reverse bias after long term reliability test.

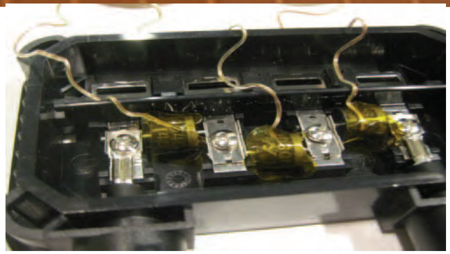
Thank you for your attention.

Acknowledgment ;
I would like to thank those who have helped us i.e. SHARP, Onamba, Nihon Inter Electronics, Sanken Electronic and SOMA Optics.

Posters

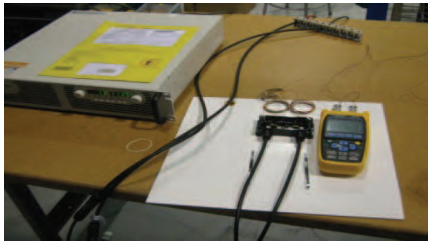
International PV Module Quality Assurance Forum

Task-4 Region US



Problem Description

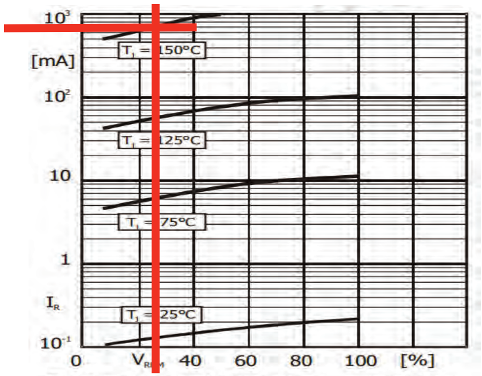
- By-pass diodes generally get "activated" during a shading occurrence in the field.
- For a 72-cell module with 3 by-pass diodes per module, the diodes are typically of the Schottky type and rated 40 to 45 V for maximum reverse voltage and 10 to 20 A for maximum forward current and maximum junction temperature of 150°C.
- Right after a shading occurrence and while the diode is still at high temperature, the diode goes into the normal mode where it sees the operating voltage of 24 cells or roughly 8 to 12 V and that induces a reverse leakage current that can exceed the diode reverse current rating at that temperature with the destruction of that diode most likely in the open mode, although shorted diodes have also been seen.
- We developed a very simple method to test diodes in a j-box or individually in the lab without the need for a sophisticated thermal chamber.



Simple Test Procedure

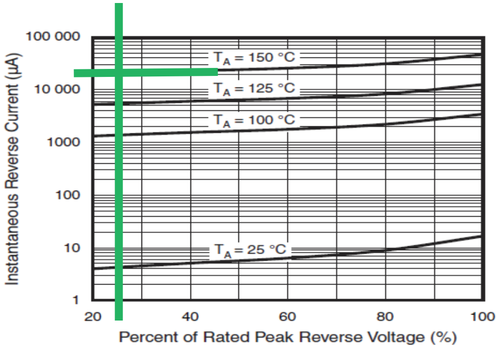
- 30 A 60 V power supply
- Thermo-couples and Fluke meter
- Connect diodes in forward mode and pass 12 to 15 A (note that the central diode always heats up faster)
- Wait until diodes temperature reaches 150°C
- Quickly reverse polarities and apply 10V per diode while reading the reverse current
- High current diodes fail quickly in a " run-away" mode; i.e. the hotter they get the more current they pass and so forth until the junction melts
- Lower current diodes cool down and stabilize safely at relatively low current.
- Tests were also done on individual diodes as well, outside the j-box with similar results

High Reverse Current Diode



- Vr = 10V or 25% or Vrmax
- Ir is then 700 mA at 150°C
- P reverse is 7 W
- Diode exceeds 200°C and fails within seconds in the open mode (most of the time)
- A dozen diodes were tested under these conditions and all failed open

Low Reverse Current Diode



Typical Reverse Leakage Characteristics

- Vr = 10V or 25% or Vrmax
- Ir is then 20 mA
- P reverse is 0.2 W
- Diode cools down to less than 100°C within seconds and further down
- No problem with this type of diode

Standards and Certification

- **Field failures of by-pass diodes are most concerning when the diode(s) fail open due to shading conditions as the upcoming shading incident will undermine the cell(s) involved and may lead to cell(s) failure and other related safety problems**
- **An official test procedure needs to be incorporated into the international standards (performance, reliability and safety) and pass/fail criteria included**
- **At a minimum, choose the diodes that have the appropriate reverse characteristics**

The thermal reliability study of bypass diodes in photovoltaic modules

Zhang, Z.[1,2], Wohlgemuth J.[1], Kurtz, S.[1]
National Renewable Energy Laboratory, Golden, Colorado, USA
State Key Lab of Photovoltaic Science and Technology, Trinasolar Co. Ltd., Changzhou, China

Introduction

Bypass diodes are a standard addition to PV (photovoltaic) modules. The bypass diodes' function is to eliminate the reverse bias hot-spot phenomena which can damage PV cells and even cause fire if the light hitting the surface of the PV cells in a module is not uniform. The design and qualification of a reliable bypass diode device is of primary importance for the solar module. To study the detail of the thermal design and relative long-term reliability of the bypass diodes used to limit the detrimental effects of module hot-spot susceptibility; this paper presents the result of high temperature durability and thermal cycling testing and analysis for the selected diodes. During both the high temperature durability and the thermal cycle testing, there were some diodes with obvious performance degradation or failure in J-box 1 with bad thermal design. Restricted heat dissipation causes the diode to operate at elevated temperatures which could lower its current handling capability and cause premature failure. Thermal cycle with forward biased current to the diode, is representative of hot spot conditions, can impose a strong thermal stress to diode, and may cause failure for bypass diodes in some PV module that may be able to pass the present criteria of IEC 61215.

Experiments

Test samples(shown in fig.1 and fig.2) :

- 3 types of junction boxes for testing
- J-boxes were attached on mini laminate modules
- 3 diodes per j-box
- Diode rated current > 10A
- Thermocouples were bonded to diode cases

Data monitoring

- Measure forward and reverse characteristics of diodes before each thermal durability test
- Monitor current and voltage data of diodes and/or power supply
- Monitor case temperature of each diode

Test Procedure

- Test 1
  - Put the samples in chamber with controlled temperature of 50, 60, 75°C
  - Add forward current of 10A to bypass diodes
  - Monitor the bypass diode case temperature and forward voltage drop and current
  - 1000 hours
- Test 2
  - Chamber temperature cycled from -40°C to 85°C
  - 3 hours per cycle
  - Dwell time at both 85°C & -40°C are 10~30 minutes
  - Add forward bias current of 10A to diodes when the chamber temperature is higher than 25°C
  - One power supply is used for one J-box (3 power supplies).
  - 100 cycles
- Test3
  - Chamber temperature cycled from -40°C to 85°C
  - 3 hours per cycle
  - Dwell time at both 85°C & -40°C are 10~30 minutes
  - Add reverse bias voltage of 12V to diodes when the chamber temperature is higher than 25°C.
  - One power supply is used for one diode(9 power supplies).
  - 100 cycles
- Next step
  - Chamber temperature at 75°C
  - One hour of reversed bias (12 V) plus one hour of forward bias(10A) per cycle
  - 20 cycles

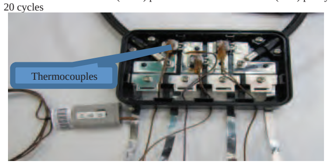


Fig. 1. Junction box sample for testing

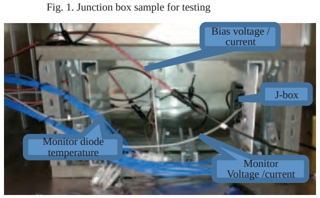


Fig. 2. Assembled testing samples in the chamber

Results

Test 1

High temperature endurance testing with forward biased current was applied to bypass diodes to assess diodes operating performance under long-term hot spot condition.

- Diodes temperature rise of 3 J-box during the testing(shown in fig.3 and fig.4) :
  - Box 1: Temperature rises of diodes 1-1 and 1-2 increased by 20°C . The highest diode case temperature reached 220°C when the chamber temperature was 60°C
  - Box 2: Temperature rises of diodes were very stable.
  - Box 3: Temperature rises of diodes 3-1, 3-2 and 3-3 increased slightly
  - Temperature rises of diodes decreased when ambient temperature increased.
  - Diode temperature rises of J-box 1 and 3 went up after restart testing.
- Diodes forward voltage of 3 J-box during the testing:
  - J-box 1: Voltages varied with testing time. Forward voltage of diodes 1-2 increased dramatically after restarted testing(Oct. 6), while voltage of diodes1-1, 1-3 decreased.
  - J-box 2: Voltages were stable
  - J-box 3: Voltages were stable
- No diode failed after the high temperature testing.

Note:

1.Temperature rise is the temperature difference between diode case and chamber
2.Diode 1-2, 2-2, 3-2 is the middle diodes of box 1, box 2 and box 3.
3.The temperature of middle one is highest in the box.

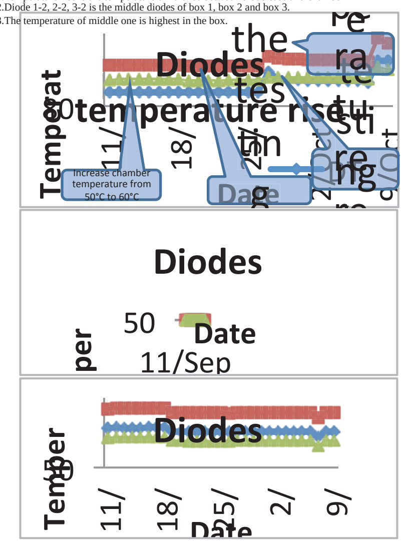


Fig. 3. Diode case temperature rise for 3 J-box during high temperature testing

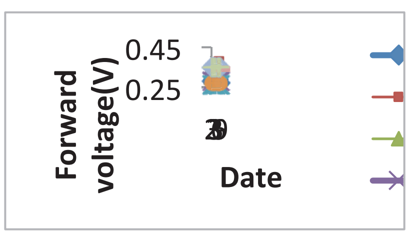


Fig. 4 Diodes forward voltage of 3 J-box during the high temperature testing

Test 2

Thermal cycle plus forward bias endurance testing was applied to bypass diodes to assess diodes reliability under thermal cycling caused by ambient temperature change combined with hot spot current flow.

Diodes case temperature during the testing :

- Box - 1: - 40 ~ 214°C
- Box - 2: - 40 ~ 158°C
- Box - 3: - 40 ~ 157°C

Diodes performance after the testing:

- Diodes forwards bias voltage of Box-1 increase dramatically after 40 cycles. Diodes of Box-1 totally failed after this testing.
- Reverse current(at reverse voltage of 10 - 16V) of diodes 3-2 (middle diode of box-3) and 2-2 increased by 10~20%.
- Diodes forward bias voltage of Box-2 remained steady
- Diodes forward bias voltage of Box-3 increased by 0.5V

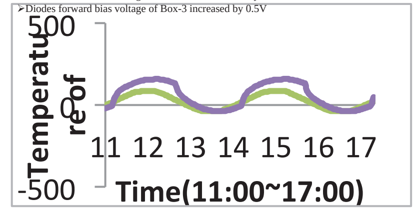


Fig. 5. Chamber temperature and diode case temperature of box 3 during diodes thermal cycle plus forward bias testing

Test 3

Thermal cycle plus reverse bias endurance testing was applied to bypass diodes to assess diodes reliability under thermal cycling caused by ambient temperature change without hot spot.

Diodes case temperature are very close to chamber temperature during the testing

Diodes performance after the testing:

- 12V reverse biased voltage was applied to diodes when the chamber temperature is higher than 25°C.
- Diode case temperature was close to chamber temperature.
- No failure or obvious degradation of diodes were observed during or after the test.

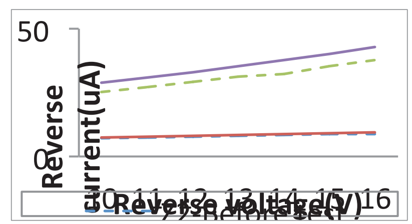


Fig. 6. Reverse characteristics of diodes 2-2(Q2) and diode 3-2(Z2) before and after diodes thermal cycle plus reverse bias testing

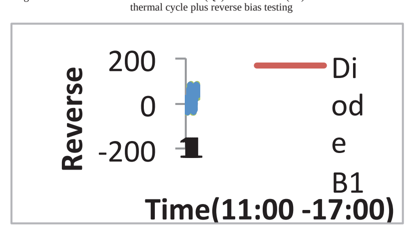


Fig. 7. Chamber temperature and diode case temperature of box 3 during diodes thermal cycle plus reverse bias testing

Discussion

To assess diodes thermal reliability of PV modules, three indoor tests were designed to simulate 3 types of diodes operating condition. The related test results were shown in above section.

High temperature endurance testing with forward biased current was applied to bypass diodes to assess diodes operating performance under hot spot condition. Mini modules with three types of junction boxes were put in chamber with controlled temperature. Forward biased current of 10A was added to bypass diodes; and the bypass diode case temperature and forward voltage drop and current were monitored during the testing. After 1000 hours' testing, though there is no abnormal appearance of diode were found and no appreciable changes in terms of reverse diode characteristics were detected, the temperature rise of worst diodes in one J-box increased by 25°C. The temperature rises of diodes in J-box 1 and 3 went up by 2-15°C and their forward voltage increased dramatically after cool down the diodes and restart testing, while that of J-box 2 was stable. Based on the test result above, we can find if the heat dissipation is not good, there is still some possibility of diodes degradation in PV modules in hot spot condition. When the diodes is forward biased with hot spot current flow, the forward current may make the diode hot enough for the dopants that create the N- and P-type areas in the diode to diffuse across the junction, wrecking the semi-conducting behavior that we rely on, and cause performance degradation.

Two types of thermal cycle testing were processed to assess the diodes' durability of thermal cycling stress caused by ambient temperature change with or without hot spot in PV modules. Three types of J-boxes were tested in chamber with cycling temperature range from -40°C to 85°C. For the first 100 cycles, forward biased current of 10A was applied to diodes when the chamber temperature is higher than 25°C. One of diodes totally failed with open circuit after the first 100 thermal cycles testing. The high temperature combined with thermal cycling will cause the diodes resistance increase and damage the PN junctions. For the second 100 cycles, -12V reverse biased voltage was added to diodes during the chamber temperature is higher than 25°C. The diodes case and junction temperatures were close to ambient temperature during the second 100 cycles test. And there was no failure or obvious degradation of diodes were observed during or after the test. The diodes performance of PV module is stable if there is no hot spot issue.

The diode performance is stable if the diode is reverse-biased with low diode temperature. However, the leakage currents doubles every 10°C as the temperature increase, and eventually the current may reach a level where the heat dissipation within the junction is high enough for the junction temperature to run away. For the field operating condition, the PV modules may encounter momentary shading caused by cloud or bird, etc. The diodes in the modules will work under the condition of high temperature with hot spot current flow firstly when the shading is on the modules. Then the diodes will be reverse-biased in high temperature condition after the shading is gone. For next step, the experiments need be designed to access the diode thermal reliability under simulated the field condition of momentary shading .

Conclusions

Based on the test result above, we can find if the heat dissipation is not good, there is still some possibility of diodes degradation or failure in PV modules under hot spot condition. Thermal cycle condition with forward biased current to diode, really representative of hot spot conditions, can impose a strong thermal fatigue stress to diode, and may cause failure for bypass diodes of some PV module that may be able to pass present criteria of IEC 61215.

Acknowledgements

The authors thank Peter Hacke and Kent Terwilliger of the National Renewable Energy Laboratory for offering help on the experiments. The author appreciate Vivek S. Gade of Jabil's Photovoltaic and Certification Test Laboratory and Paul Robusto of Intertek for insightful comment for the testing result analysis. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

Reference

1. Barreiro, C., et al. *PV by-pass diode performance in landscape and portrait modalities*. in *Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*. 2011.
2. Ben-Menahem, S. and S.C. Yang. *Online photovoltaic array hot-spot Bayesian diagnostics from streaming string-level electric data*. in *Photovoltaic Specialists Conference (PVSC), 2012 38th IEEE*. 2012.
3. Bower, W.I., M.A. Quintana, and J. Johnson, *Electrical and thermal finite element modeling of arc faults in photovoltaic bypass diodes*. 2012. p. Medium: ED; Size: 33 p.
4. Al-Rawi, N.A., M.M. Al-Kaisi, and D.J. Asfer, *Reliability of photovoltaic modules II. Interconnection and bypass diodes effects*. Solar Energy Materials and Solar Cells, 1994. **31**(4): p. 469-480.

US TG 4 activities of QA Forum

QA Task Force 4 ; Diode, Shading & Reverse Bias
Diode ESD Characterization

Contains no confidential information.

Kent Whitfield

with thanks to Solaria for their support of this work

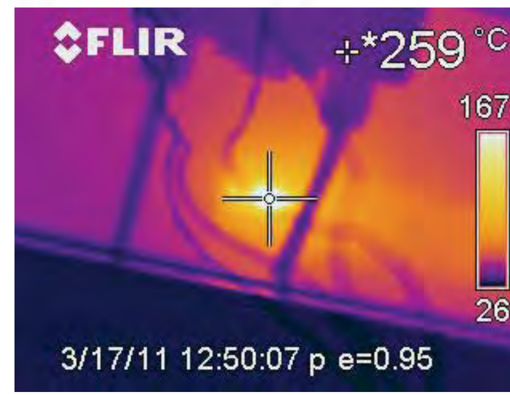
Overview of Presentation

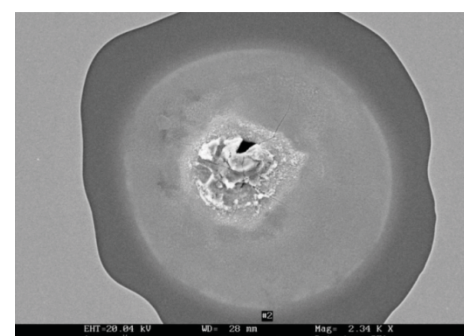
- ESD Surge Characterization of Schottky Diodes
  - Motivation – Why ESD characterization of diodes might be important
    - History
    - Case study
    - Observations from failed diodes
  - Methods to characterize a diode's ESD tolerance
    - Environment
    - Testing methods
    - Proposed procedure
    - Data analysis
    - Correlation to failures encountered
  - Next steps

A Completely Selective History

Diode Type	Maximum Allowable Junction Temperature	Derated Temperature for Long-Term Reliability
p-n	175°C	125°C
Schottky	125°C	75°C

- 1985: General diode reliability guidelines based primarily on operational temperature.
- 1993: 20k modules had a 50% failure rate over ten years.
  - 90% of the failures were from common causes that included lack of adequate bypass diode protection (hot spot failures).
- 2011: Task Group 4 reviewed testing standards and identified potential gaps:
  - Accuracy of diode technical data sheet.
  - Qualification tests that ensure reliability.
  - *Electrostatic Discharge (ESD) susceptibility.*





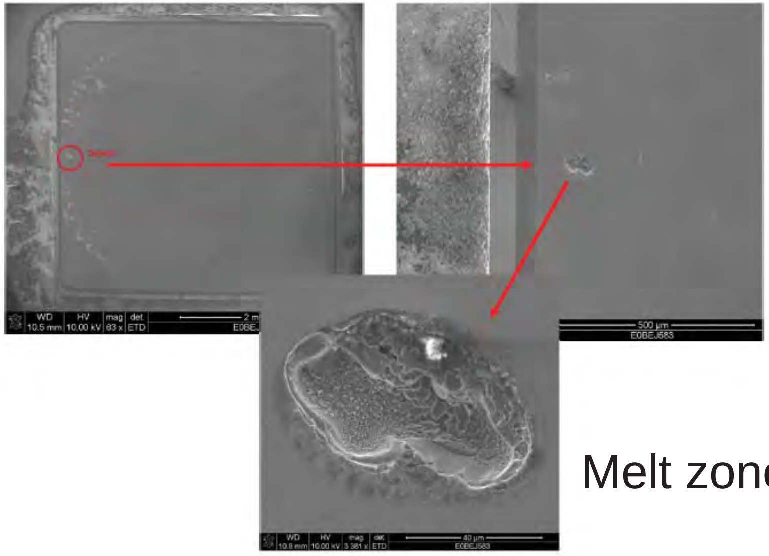
Case Study

- Field Failure Data: Anecdotal, mostly onesy-twosey, occasional large scale at *A* site. Suggests some batch/site-specific behavior.
- Undisputed: Schottky diodes are found to fail at a measurable rates in production – Final IV curve/EL.
  - 2011: Sudden onset of certification samples and production modules being found with shorted diodes.
  - No process or design change and some certification tests NOT related to diodes:
    - TC50, TC200, DH1000, Preconditioning???
  - Failure rate goes from 0.0% to 0.4% in one facility, but in another with ESDS 20.20 compliance, rates stays at 0.0%.

ESD ASSOCIATION 20.20 CERTIFIED

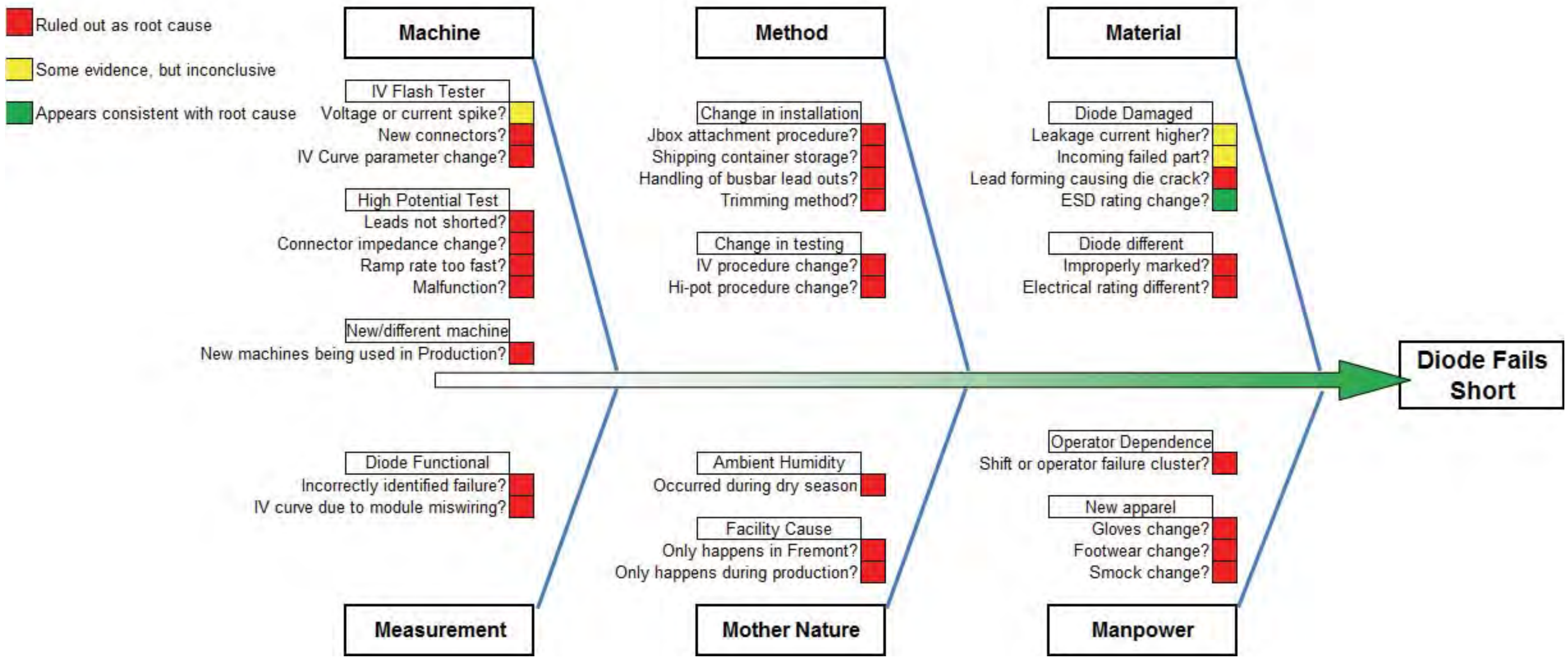
More Observations

- Decap and FA indicates all diodes of suffering from electrical overstress – but inconsistent from ESD alone due to presence of melted regions.
- Failed diodes happen to conform to a specific date code range.



Melt zone

Ye' Ol' Fishbone



- Evidence seems to point to ESD susceptibility change *in this case study only*.
- Bigger question is what is the susceptibility?

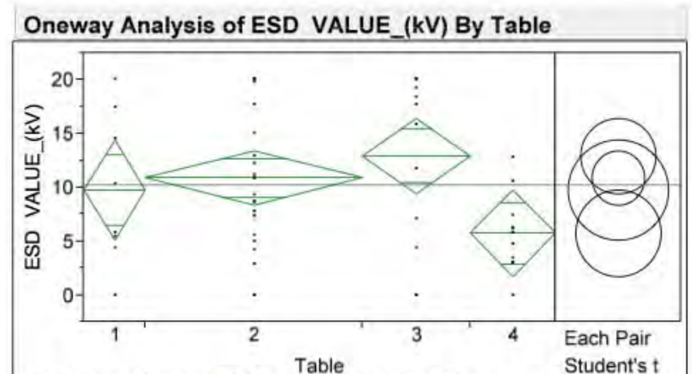
Characterization of Environment

- Electrostatic voltage in the facility.
  - Simple, low-cost test equipment and fast to characterize.
  - Cannot gauge charge transfer which is critical to the ESD failure mode.
- ESD event meter.
  - Simple, but higher-costing test equipment.
  - Can gauge peak voltage stress associated with standard charge transfer models.

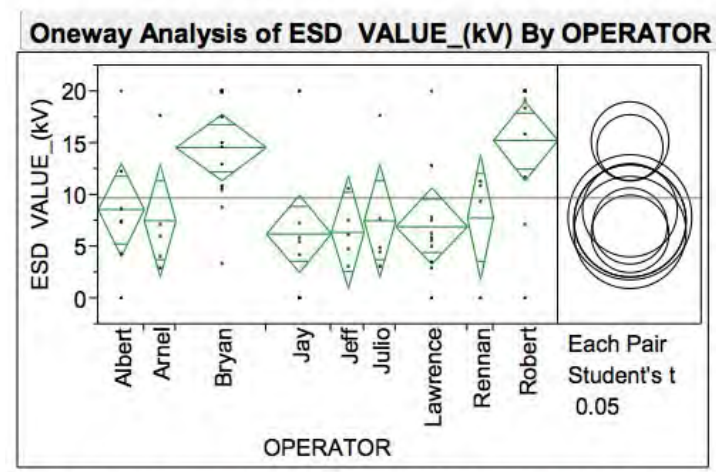
JBOX INSTALLATION STEP (measurement date 10 Oct 2011)	Measured Voltage (V)
Opening shipping container and measuring jbox potential while still in box	+1,260
Preparation table resting voltage	+90
Removal of Jbox from box and placement on table. Resulting jbox voltage.	+470
Placing two strips of double-sided 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

Knowns

- Schottky diodes more susceptible to ESD damage.
- ESD events may occur from
  - human contact only, or
  - In-house charged-device/ operator interaction such as jbox installation, connecting to test equipment (hi-pot, IV, EL), or
  - 3rd party charged device interaction, or
  - In field installation.



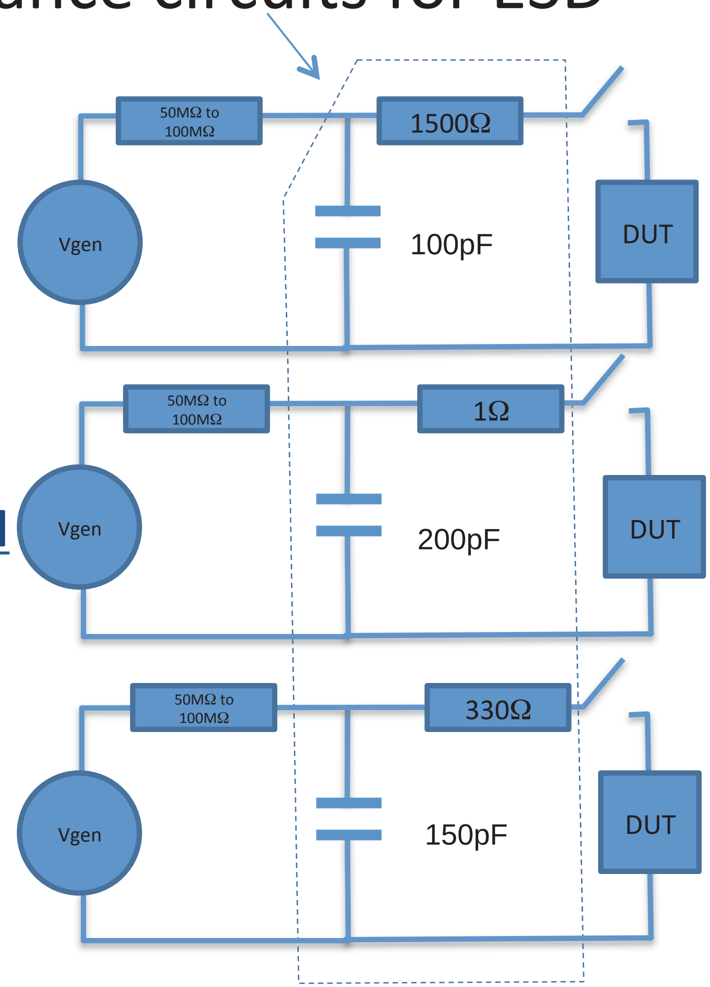
No significant difference in location



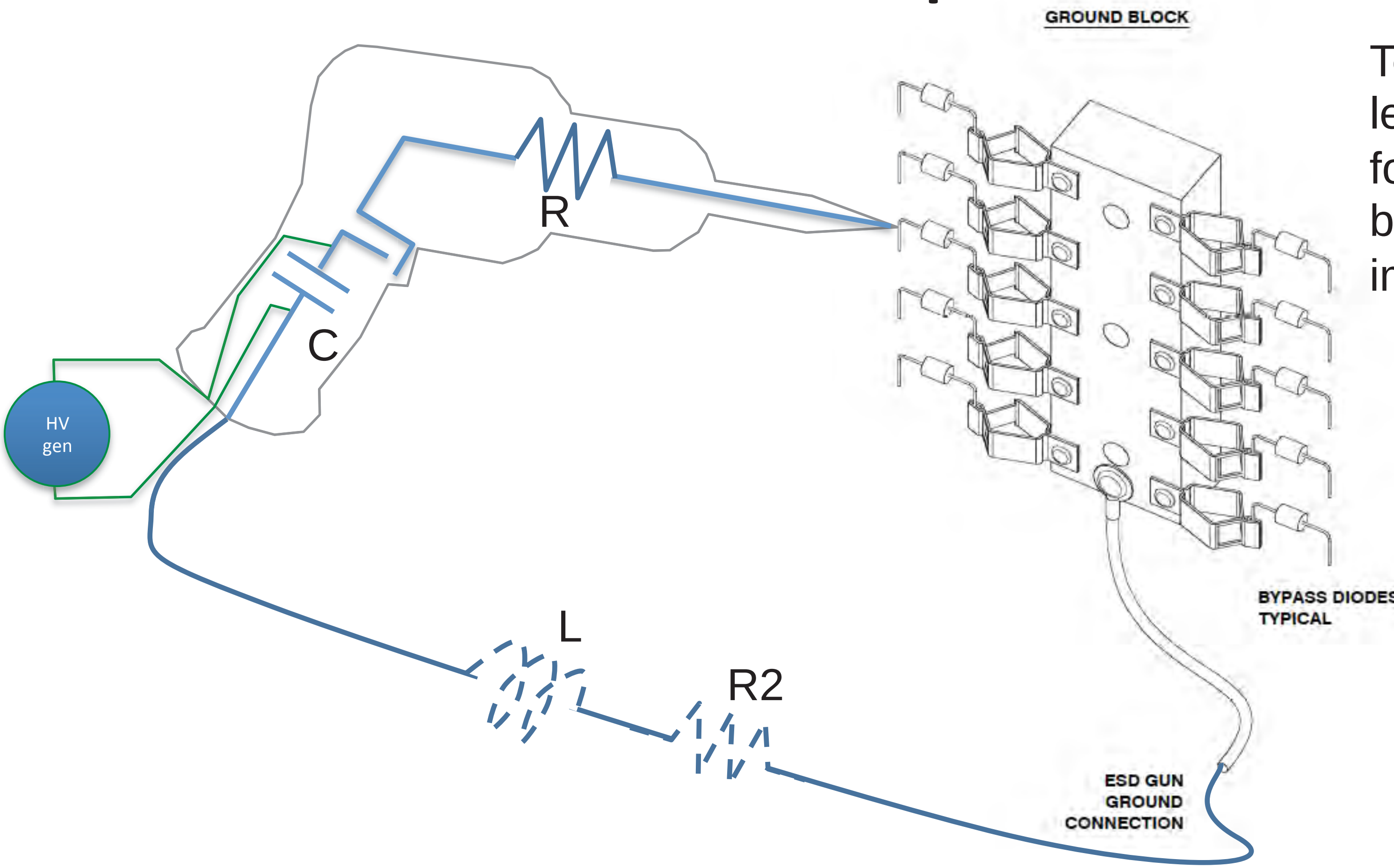
Some statistical difference between people

How to Characterize Susceptibility

- Most commonly used impedance circuits for ESD testing are:
  - Impedance Circuits:
    - ANSI/ESDA/JEDEC JS-001 – Human Body Model
      - Bare finger
    - JEDEC JESD22-A115C – Machine Model
      - Charged machine
    - IEC 61000-4-2 – ESD Immunity
      - Discharges from operators



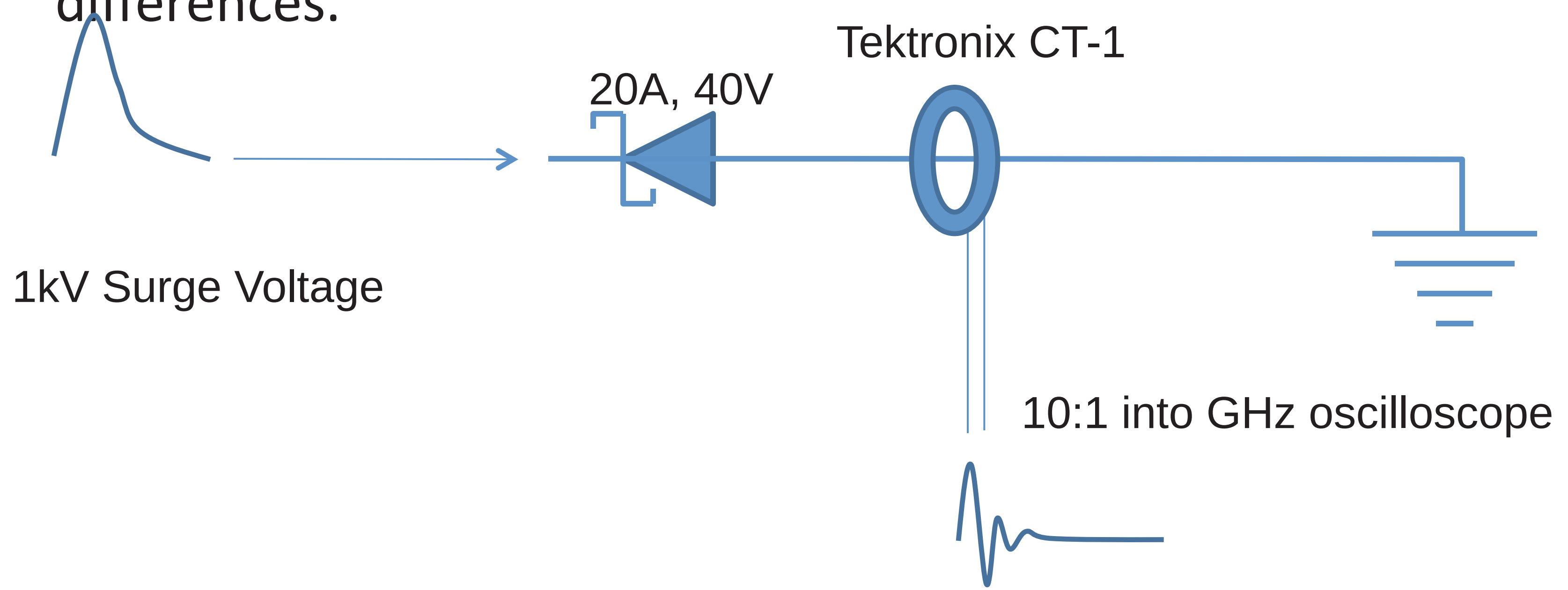
Set Up



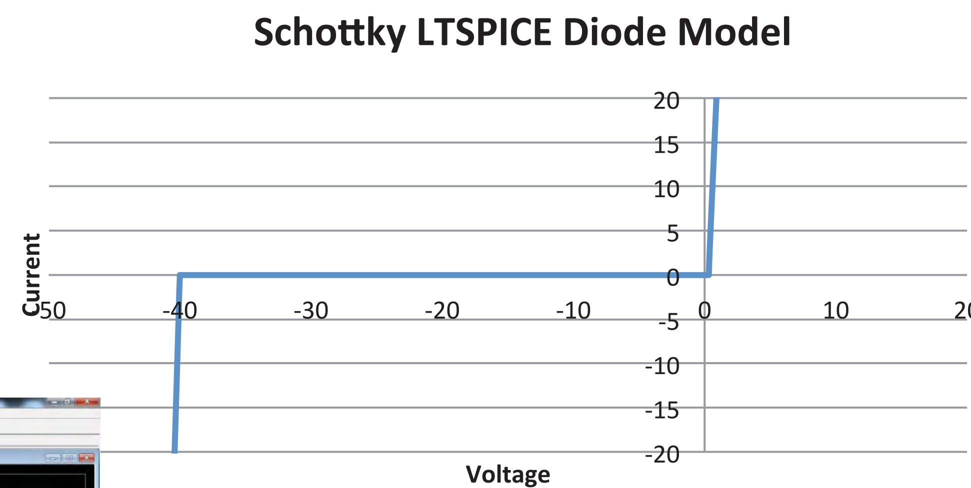
Testing with leads already formed for jbox believed to be important.

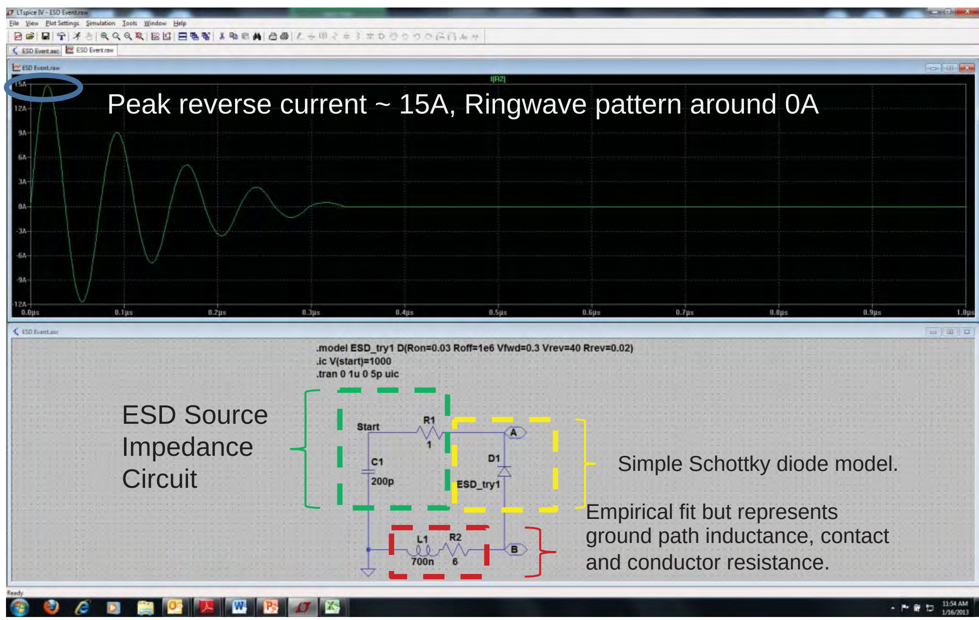
Differences in the Impedance Circuits

- Hard to measure voltage and current during actual test without affecting results.
- Contact repeatability issues also occur.
- So, validate a LTSpice model against real current waveforms and use model to improve understanding of surge differences.



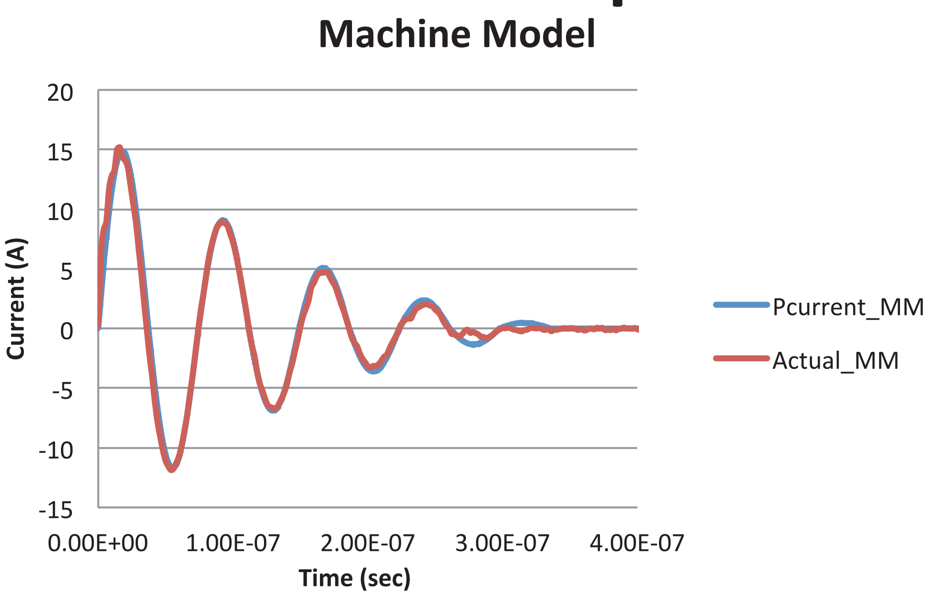
LTSPICE Model Machine Model Impedance

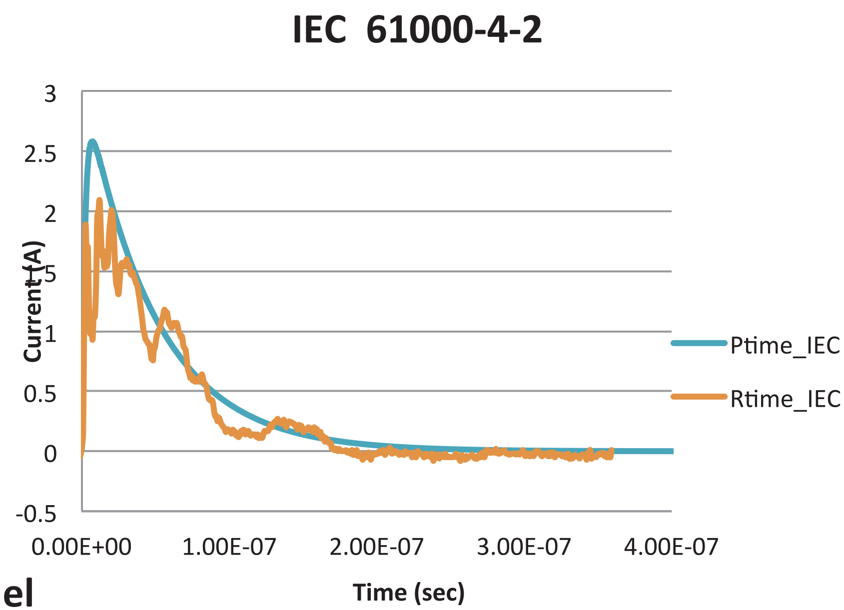


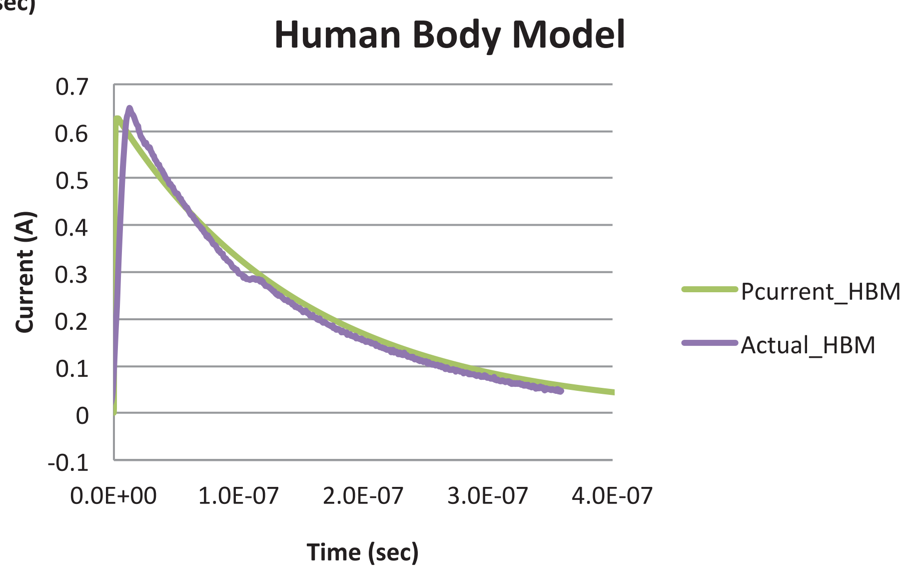


Key Consideration – This model diode is fully recoverable in the breakdown region regardless of current. Actual diodes are also fully recoverable in breakdown below a specific current threshold at a specific temperature.

Comparison to Actual

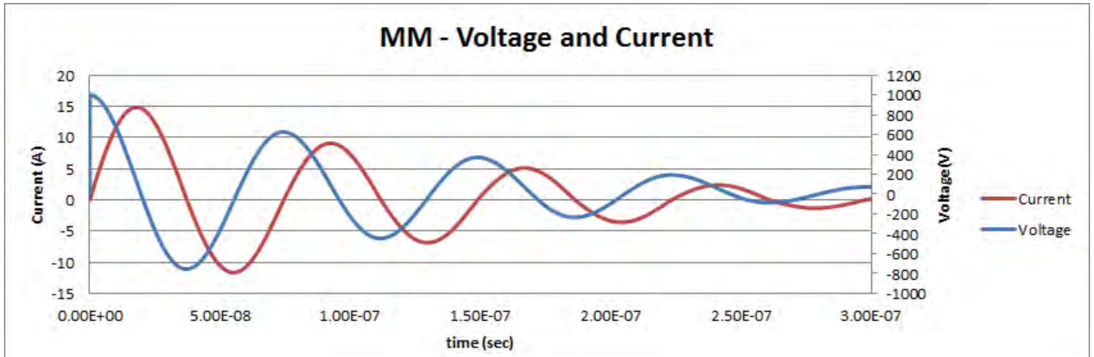




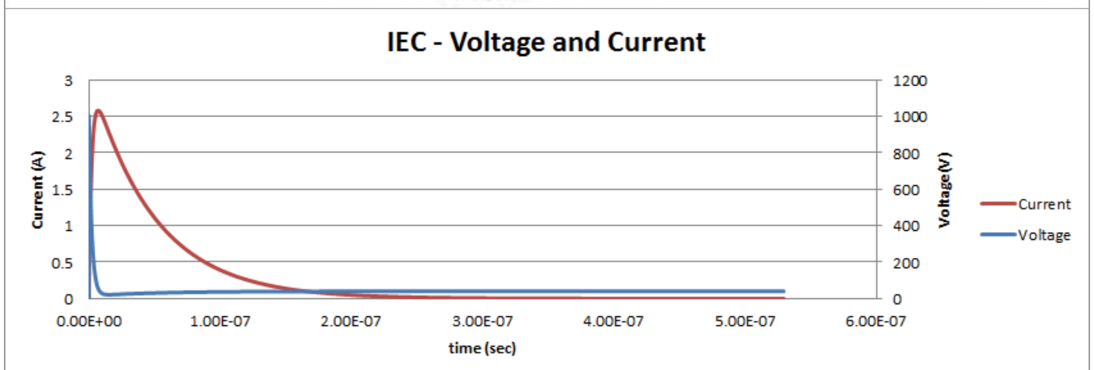


One model matches real current waveform quite well!

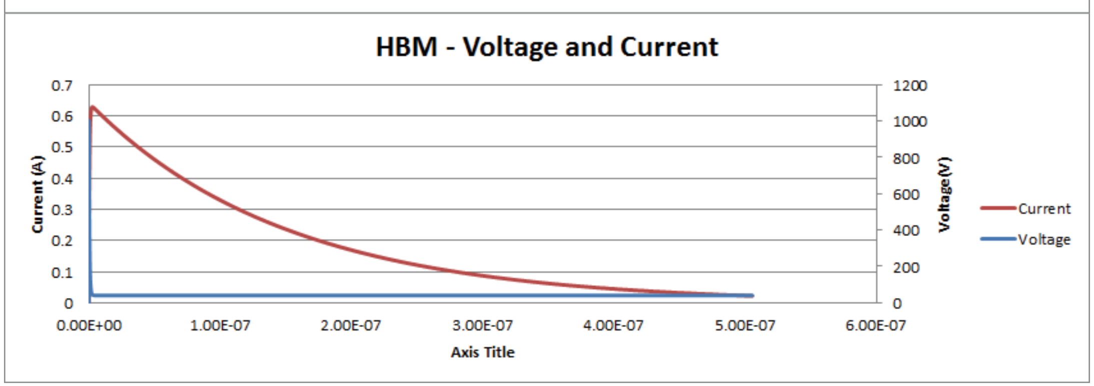
LTSPICE Voltage and Current



Numerically integrated surge energy ~0.4 mJ



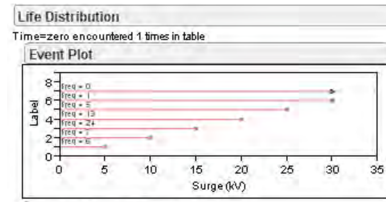
Numerically integrated surge energy ~7 μJ



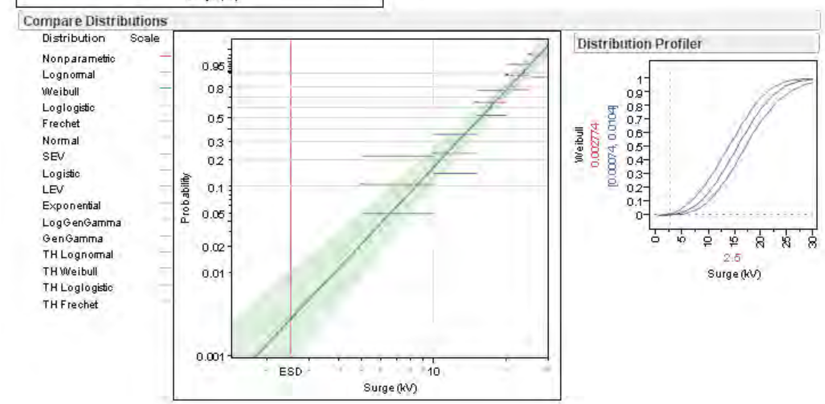
Numerically integrated surge energy ~4 μJ

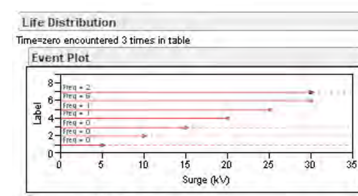
Arrived at ESD Testing Method

- 5kV steps from 5kV to 30kV using a simple multimeter check for short-circuit following surge application.
- Sample size of 10 diodes all having same date code.
- 10 positive surges applied to cathode side with 10 seconds between surges.
  - Literature suggests breakdown region on die is small so relaxation time required between surges.
- A Weibull curve used to fit data.
  - ➢ Where we have substituted surge voltage for time.
  - ➢ The CDF is thus interpreted to mean fraction of all units in the population which will fail by V peak voltage having a voltage and current waveform given by the IEC model.
  - ➢ Shaded region indicates a 95% confidence interval around the median line.

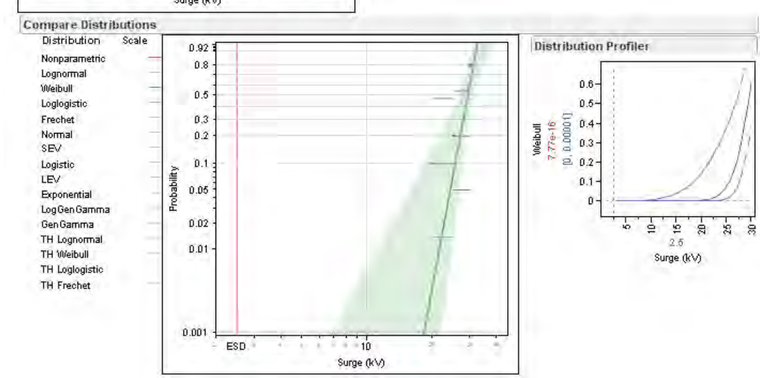


Group A, 56 samples tested, 2800 ppm expected fails at a 2.5kV peak ESD voltage.



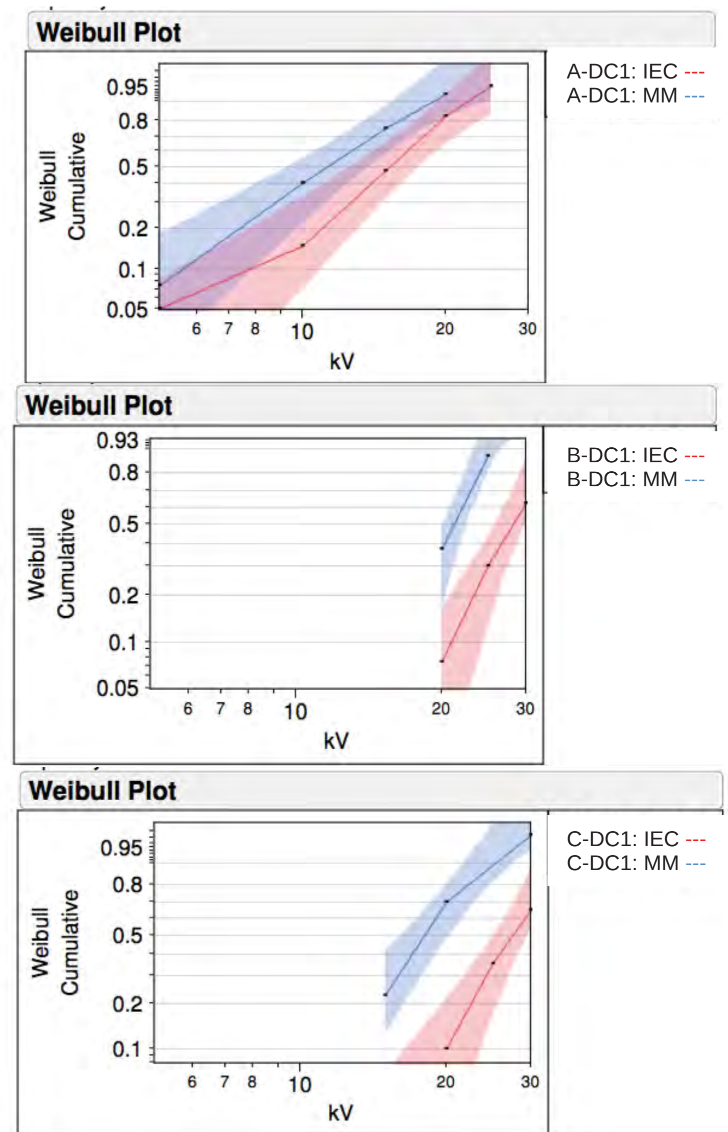


Group C, 10 samples, 0-100ppb expected fails at a 2.5kV ESD peak voltage.



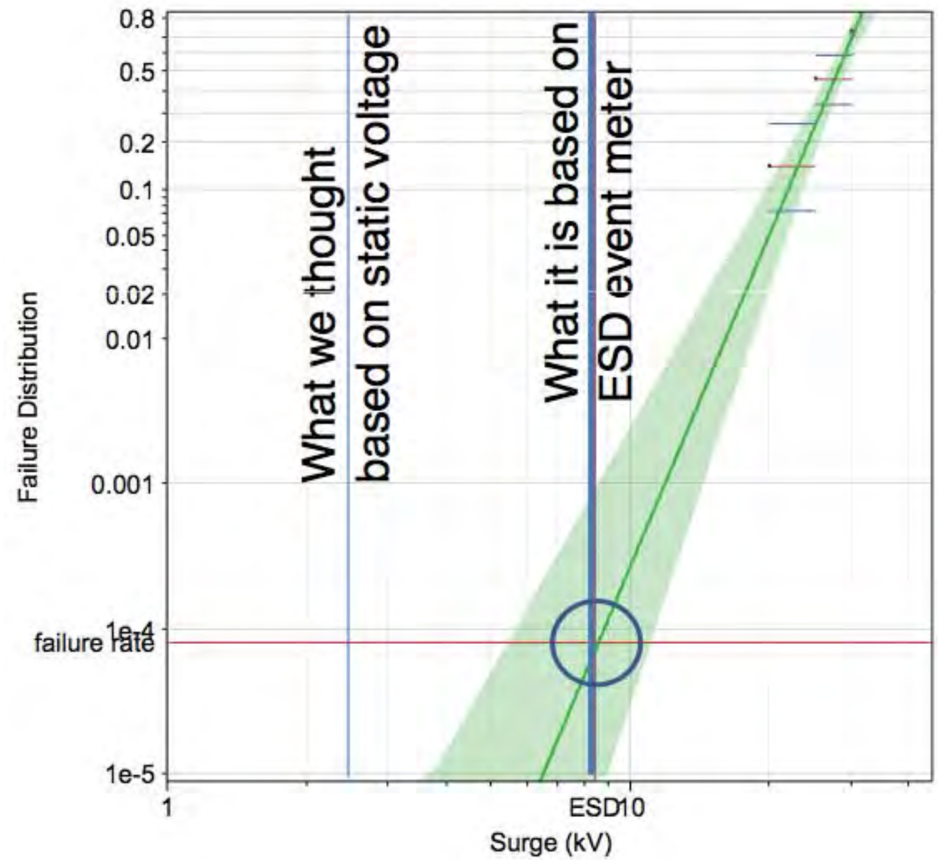
ESD Surge Testing

- Basis of ESD Test – IEC 61000-4-2
- Surge-to-Failure, Step-Stress Program. Considered following variables:
  - Impact to reverse leakage current at room temperature
    - No correlation below failure threshold.
  - Impact to reverse leakage current when diode is at 60C
    - No correlation below failure threshold.
  - Impact of positive surges against anode side of diode
    - No failures observed.
  - Impact of positive surges against cathode side
    - Resulted in failures.
  - Impact of sample size
    - Similarity of failure distributions exists with samples sizes from 10 to 60 at 95% confidence,
  - Impact of number of surges applied per stress step
    - Similarity of failure distributions exist with 5 to 50 surges at 95% confidence.
  - Compared results using IEC model with Machine Model
    - Failure distributions are similar in Weibull space, but shifted to lower voltages in the Machine Model.



Some Confirmation of Technique

- Static voltage measurement indicated a 2500V risk in area of jbox installation.
- Tested a group of diodes using IEC model and selected one that SHOULD result in a 7.2ppb failure rate of at this level of ESD voltage.
- Actual failure rate in production found to be 82ppm!
- Changed in-house measurement from static voltage to actual ESD event detection.
- Measured 47 ESD events and mean found to be 8.2kV *NOT 2.5kV*.
- This mean correlated well with the observed production failure rate.



Conclusion and Next Steps

- ESD found to damage Schottky diodes.
- ESD events triggered when there is an interaction between charged devices during installation or testing although there appears to also be some operator interaction.
- Failure rates differ from diode-to-diode even when ratings are the same.
- A test procedure based IEC surge standard seems to be useful in characterizing diode ESD susceptibility.
- NEED other manufacturers to corroborate findings.
- PROPOSE a test method in IEC TC82, WG2 but without pass/ fail criteria.

Thank you!

On the occurrence of thermal runaway in Diode in the J-box

J-TG 4 activities of QA Forum

QA Task Force 4 ; Diode, Shading & Reverse Bias

Feb. 26-27, 2013 ***@ Denver, USA***

Y. Uchida / JET (Japan Electrical & Environment Technology Laboratories)
Y. Konishi / ONAMBA CO.,LTD.
T. Okura / SOMA OPTICS, LTD.

J-TG4 Activity Report

J-TG4 activities had been reported in the following events ;

1. Dec.08, 2011 — 2nd. QA Forum Tokyo
2. Feb. 28, 2012 — NREL PV Module Reliability Work-shop
3. May 07, 2012 — WG2 STRESA meeting
4. Oct.01, 2012 — WG2 Oslo meeting
5. Nov.27, 2012 — 3rd. QA Forum Tokyo
6. **Feb.26,27, 2013 — NREL PV Module Reliability Work-shop**

Background

→ Trend of Bypass diode from P/N Si diode to SBD

■ This trend is because of the addition of “Bypass diode thermal test” in IEC 61215 Ed2. (2005-04),

①When applying current of Isc at 75℃, diode junction temperature shall not exceed max. rated Tj.

②When applying current of "1.25XIsc" at 75 ℃, the function of diode shall not be impaired.

↓

On top of the above requirements, due to the pressure of the price reduction of diode and suppression of heat-up, the bypass diode has switched to the SBD with low Vf .

Test reports

Test① Continuous current test for J-box
- ①-1 for Diode-A
- ①-2 for J-box-A

Test② Intermittent current test for Diode
- ②-1 for Diode-A
- ②-2 for Diode-B

Reported at WG2 Oslo meeting.

Test③ Reverse bias test at high temperature (Thermal runaway test)

- ③-1 for J-box-A / with potting
- ③-2 for J-box-B-1 / without potting
  for J-box-B-2 / without potting
- ③-3 for J-box-C / without potting

Contents of this report

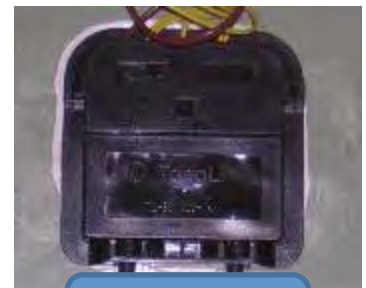
1. **Thermal runaway test results of J-boxes**

2. Tj measurement method for Bypass diode

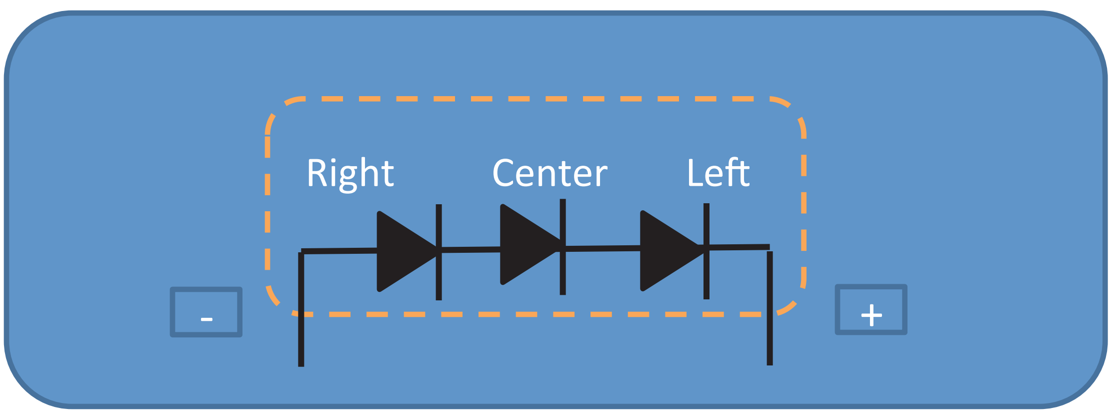
J-boxes for Thermal-runaway tests

J-box-A

J-box-B



J-box-C



Summary of "Reverse bias test at high temperature" ;

Test ③-1 ; J-box-A / with potting (Test sequence : ①center→②right→ ③left)

■ Chamber temp. : 90℃

		Reverse bias / Vr			
		15V	20V	25V	30V
If / Forward current	9A	1. Center ○	2. Center ○	3. Center ○	
	11A	4. Center ○	5. Center ○	6. Center ×	
	12A	7. Right ○	8. Right×		
	13A	9. Left ×			

○ ; No thermal runaway
× ; Thermal runaway

The numbers mean a test sequence.

Summary of "Reverse bias test at high temperature" ;

Test ③-2 ; J-box-B-1 / without potting

■Chamber temp. : 75℃

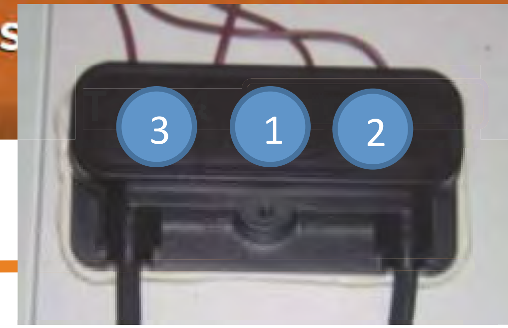
		Reverse bias / Vr			
		15V	20V	25V	30V
If / Forward current	8A	1. Center ○	3. Center ○		
	9A	2. Center ○	5. Center ○		
	11A	4. Center ○			
	12A				

○ ; No thermal runaway
× ; Thermal runaway

The numbers mean a test sequence.

■ Chamber temp. : 90℃

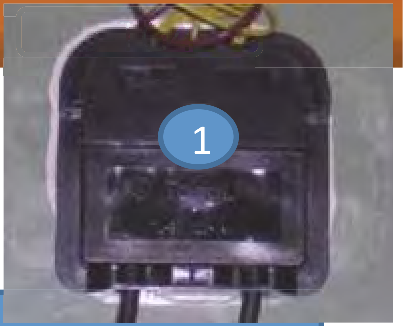
		15V	20V	25V	30V
If / Forward current	8A	6. Center ○	8. Center ○		
	9A	7. Center ○	10. Center ○		
	11A	9. Center ○	11. Center ×		
	12A				



Summary of "Reverse bias test at high temperature" ;

Test ③-2 ; J-box-B-2 #3 / without potting (Test sequence : ①center→②right→ ③left)

		Left diode		Center diode		Right diode	
VR; reverse voltage		15VR	20VR	15VR	20VR	15VR	20VR
■ Chamber temp. : 75C							
If	8A	Not done	Not done	1. ○	3. ○	1. ○	3. ○
	9A	Not done	Not done	2. ○	5. ○	2. ○	5. ○
	11A	Not done	Not done	4. ○	Not done	4. ○	Not done
■ Chamber temp. : 90C							
If	8A	Not done	Not done	6. ○	8. ○	6. ○	9. ○
	9A	Not done	1. ○	7. ○	—	7. ○	10. ○
	11A	2. ○	3. ×	9. ×	—	8. ○	11. ○
	12A	—	—	—	—	12. ○	13. ×



Summary of "Reverse bias test at high temperature" ;

Test ③-3 ; J-box-C / without potting

■Chamber temp. : 75℃

		Reverse bias / Vr			
		15V	20V	25V	30V
If / Forward current	8A	1. Center ○	3. Center ○		
	9A	2. Center ○	5. Center ○		
	11A	4. Center ○			
	12A				

○ ; No thermal runaway
× ; Thermal runaway

The numbers mean a test sequence.

■ Chamber temp. : 90℃

		15V	20V	25V	30V
If / Forward current	8A	6. Center ○	8. Center ○		
	9A	7. Center ○			
	11A	9. Center×			
	12A				

Temperature of each diode in J-box under the forward current

■ J-box-A-3 / Chamber temp. ; 75℃

If	Left diode Tj, ℃	Center diode Tj, ℃	Right diode Tj, ℃
9A	130.2	131.2	129.2

■ J-box-B-1 / Chamber temp. ; 75℃

If	Left diode Tj, ℃	Center diode Tj, ℃	Right diode Tj, ℃
9A	160.1	173.3	158.7
11A	178.7	192.7	176.8
12A	187.5	201.5	184.5
13A	195.5	212.1	193.7

■ J-box-B-1 / Chamber temp. ; 90℃

If	Left diode Tj, ℃	Center diode Tj, ℃	Right diode Tj, ℃
9A	171.0	182.6	169.8
11A	189.2	201.4	186.4
12A	197.2	211.3	194.3
13A	205.3	220.1	203.7

The temperature of the center diode is affected by the left and right diodes and becomes the highest.

Note ;
The Tj was obtained from the Vf value using Vf-Tj relation.

Results of the study -1

1. We were able to confirm the thermal runaway of the SBD during high-temperature reverse bias.

2. As for the thermal runaway, the timing of switching from forward to reverse is important.

3. We have confirmed that the conditions for the thermal runaway was different according to the type of J-box (ex. ; J-box shape and with or without the potting materials).

   → We are planning to perform the thermal runaway test for some more J-boxes with different diodes.

4. In case of typical J-box with 3 diodes in the box, the temperature of the center diode is affected by the left and right side diodes and becomes the highest.

Contents of this report

1. Thermal runaway test results of J-boxes

2. Tj measurement method for Bypass diode

T_{lead} method vs Vf-Tj method

From our experiment,

As for Diode Tj, the difference was confirmed in "Vf-Tj method" and "T_{lead} method".

→ with experimental data on the next page.

Test sample ; J-box-B-2

[Chamber temp. ; 75℃]

		Left diode		Center diode		Right diode	
		Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃
If	9A	158.1	160.1	165.0	173.3	143.1	158.7
	11A	175.2	178.7	183.4	192.7	156.9	176.8
	12A	183.5	187.5	192.4	201.5	164.0	184.5
	13A	192.0	195.5	201.2	212.1	170.7	193.7

[Chamber temp. ; 90℃]

		Left diode		Center diode		Right diode	
		Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃
If	9A	168.8	171	175.2	182.6	154.2	169.8
	11A	185.4	189.2	192.8	201.4	168.1	186.4
	12A	193.7	197.2	201.9	211.3	174.7	194.3
	13A	201.7	205.3	210.4	220.1	181.3	203.7

Note 1. : Tlead ; Tj by "Tlead method"
Tj = Tlead + (Rth × Vf × If), Rth= 2.5℃/W provided by diode maker

Note 2. : Vf-Tj ; Tj by "Vf-Tj method"
in accordance with "IEC61646 Ed.2 10.18 Btpass diode thermal test / Procedure 2"

Why always
Tlead < Vf-Tj ?

T_{lead} method

The correct Tj can not be obtained by Tlead method.

Because, the thermal resistance (Rth) could vary.

Tj = Tlead + (Rth ×If × Vf)

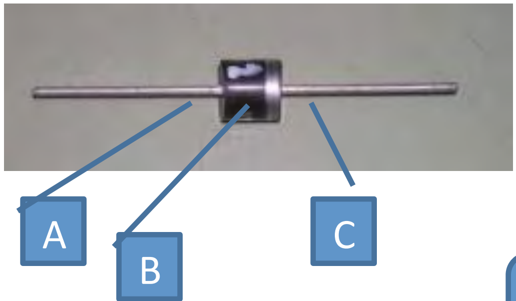
The reason that thermal resistance varies is as follows;

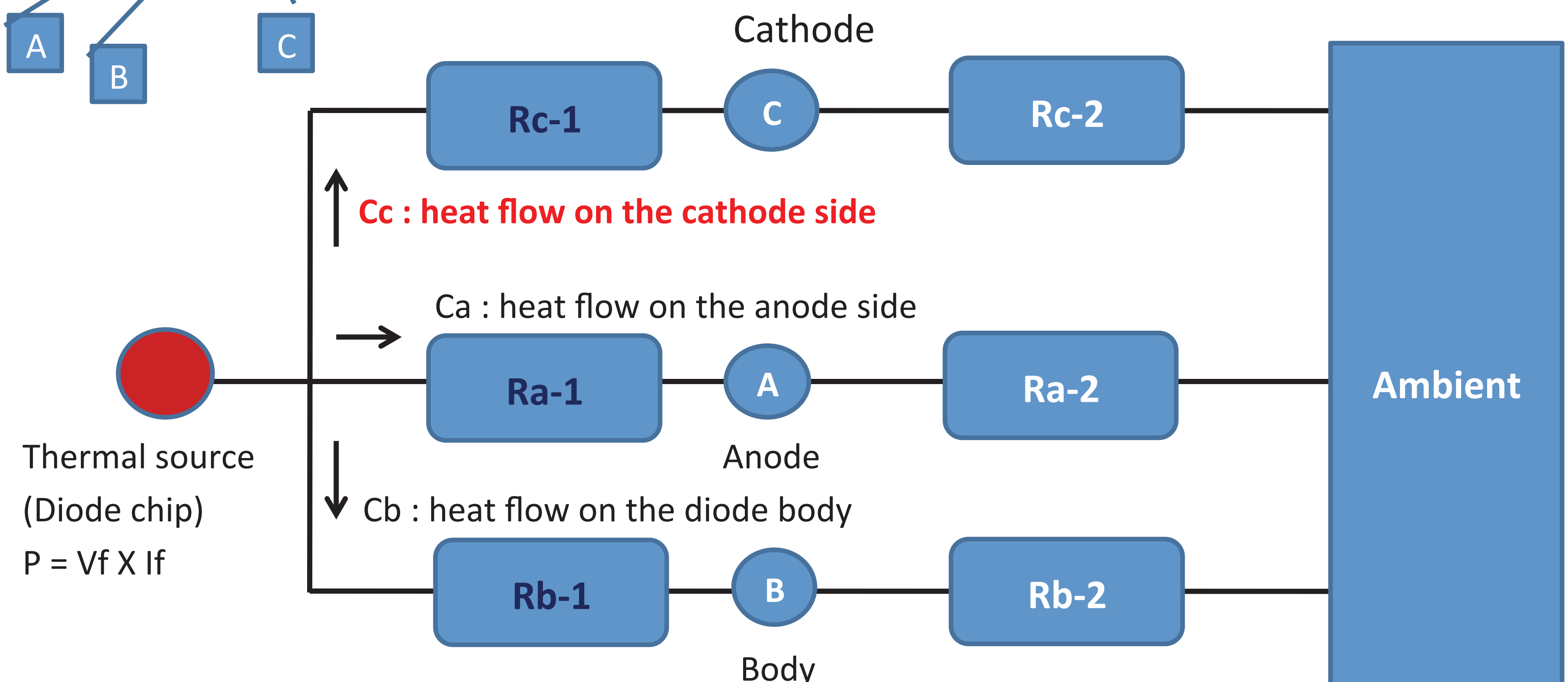
there is a difference in heat radiation conditions because diodes are installed in various J-box.

→ We are now measuring in order to obtain the support data.

Heat flow from Diode chip

Rc-1 < Ra-1 << Rb-1



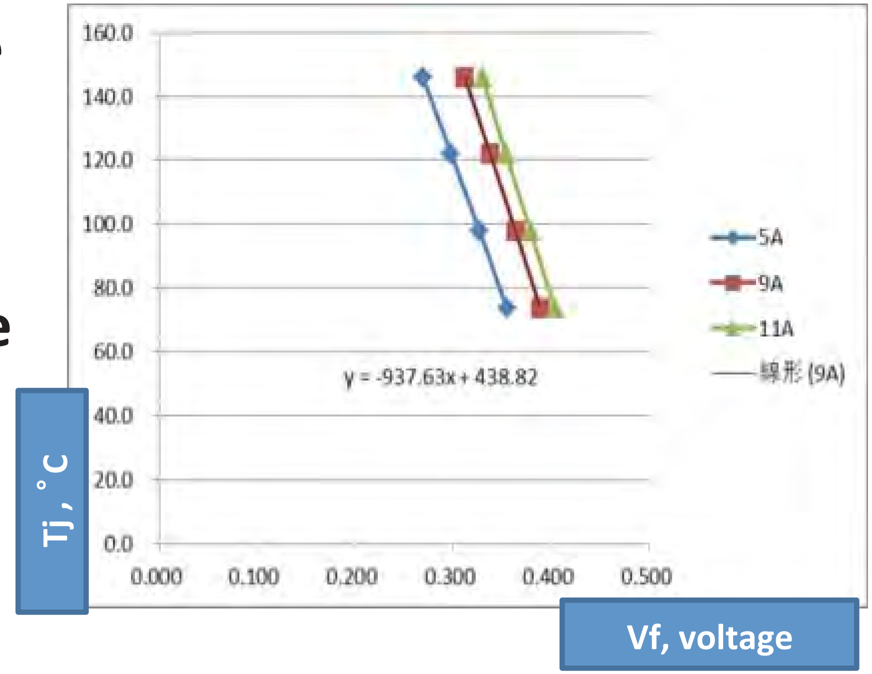


<u>**Heat flow varies with the radiation conditions !!!!!**</u>

$T_j = T_{lead} + V_f \times I_f \times C_c \times R_{th}$ (→ real Rth) → apparent Rth

Vf – Tj method

- **Once Vf-Tj relation is obtained, Tj is easily decided from the value of Vf.**
  Vf-Tj relation can be acquired by measuring the temperature of the lead and the voltage across the diode in thermal equilibrium condition.



Results of the study -2 (1/2)

From this experiment, the difference was confirmed in
Vf-Tj method and Tlead method as for Tj of diode.

Regarding the thermal resistance (Rth) by Tlead method, Rth is provided by Diode maker.

When it is assembled into the J-box, an apparent Rth will vary because of the influence of wiring left and right side diodes, including Heat-sink.

$$Tj = Tlead + (Rth \times If \times Vf)$$

Results of the study -2 (2/2)

Therefore, we should use the Vf-Tj method in accordance with "paragraph 10.18 Bypass diode thermal test / procedure 2 specified in IEC61646".

In order to continue accumulating technical data for Tj of diodes, we would like to propose a Vf-Tj method.

Next activities

1. Establishment of a method of thermal design verification test for J-box, and preparation of a draft standard

2. Development and manufacturing of thermal runaway test equipment

3. Suggestions for improvement of Diode Tj measurement method

4. In order to discuss the rating system, we have to confirm the changes of the characteristics of reverse bias after long term reliability test.

Thank you for your attention.

Acknowledgment ;
I would like to thank those who have helped us i.e. SHARP, Onamba, Nihon Inter Electronics, Sanken Electronic and SOMA Optics.

Posters

International PV Module Quality Assurance Forum

Task-4 Region US

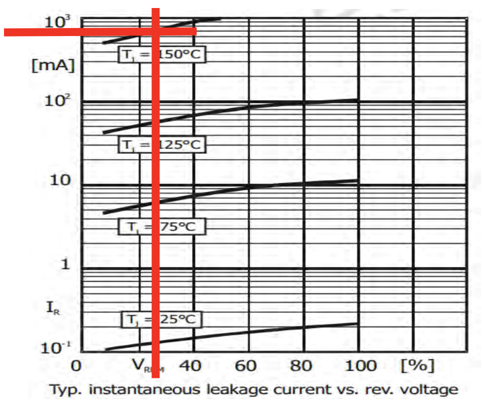
Problem Description

- By-pass diodes generally get "activated" during a shading occurrence in the field.
- For a 72-cell module with 3 by-pass diodes per module, the diodes are typically of the Schottky type and rated 40 to 45 V for maximum reverse voltage and 10 to 20 A for maximum forward current and maximum junction temperature of 150°C.
- Right after a shading occurrence and while the diode is still at high temperature, the diode goes into the normal mode where it sees the operating voltage of 24 cells or roughly 8 to 12 V and that induces a reverse leakage current that can exceed the diode reverse current rating at that temperature with the destruction of that diode most likely in the open mode, although shorted diodes have also been seen.
- We developed a very simple method to test diodes in a j-box or individually in the lab without the need for a sophisticated thermal chamber.

Simple Test Procedure

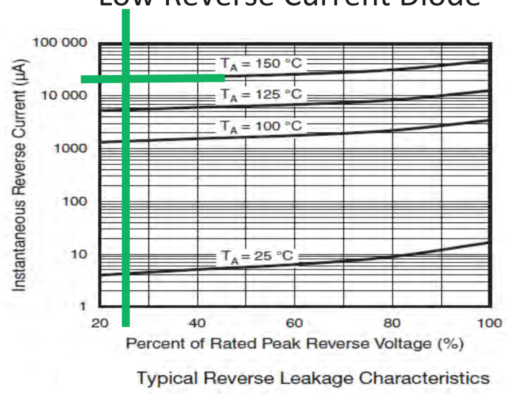
- 30 A 60 V power supply
- Thermo-couples and Fluke meter
- Connect diodes in forward mode and pass 12 to 15 A (note that the central diode always heats up faster)
- Wait until diodes temperature reaches 150°C
- Quickly reverse polarities and apply 10V per diode while reading the reverse current
- High current diodes fail quickly in a " run-away" mode; i.e. the hotter they get the more current they pass and so forth until the junction melts
- Lower current diodes cool down and stabilize safely at relatively low current.
- Tests were also done on individual diodes as well, outside the j-box with similar results

High Reverse Current Diode



- Vr = 10V or 25% or Vrmax
- Ir is then 700 mA at 150°C
- P reverse is 7 W
- Diode exceeds 200°C and fails within seconds in the open mode (most of the time)
- A dozen diodes were tested under these conditions and all failed open

Low Reverse Current Diode



- Vr = 10V or 25% or Vrmax
- Ir is then 20 mA
- P reverse is 0.2 W
- Diode cools down to less than 100°C within seconds and further down
- No problem with this type of diode

Standards and Certification

- **Field failures of by-pass diodes are most concerning when the diode(s) fail open due to shading conditions as the upcoming shading incident will undermine the cell(s) involved and may lead to cell(s) failure and other related safety problems**
- **An official test procedure needs to be incorporated into the international standards (performance, reliability and safety) and pass/fail criteria included**
- **At a minimum, choose the diodes that have the appropriate reverse characteristics**

The thermal reliability study of bypass diodes in photovoltaic modules

Zhang, Z.[1,2], Wohlgemuth J.[1], Kurtz, S.[1]
National Renewable Energy Laboratory, Golden, Colorado, USA
State Key Lab of Photovoltaic Science and Technology, Trinasolar Co. Ltd., Changzhou, China

Introduction

Bypass diodes are a standard addition to PV (photovoltaic) modules. The bypass diodes' function is to eliminate the reverse bias hot-spot phenomena which can damage PV cells and even cause fire if the light hitting the surface of the PV cells in a module is not uniform. The design and qualification of a reliable bypass diode device is of primary importance for the solar module. To study the detail of the thermal design and relative long-term reliability of the bypass diodes used to limit the detrimental effects of module hot-spot susceptibility; this paper presents the result of high temperature durability and thermal cycling testing and analysis for the selected diodes. During both the high temperature durability and the thermal cycle testing, there were some diodes with obvious performance degradation or failure in J-box 1 with bad thermal design. Restricted heat dissipation causes the diode to operate at elevated temperatures which could lower its current handling capability and cause premature failure. Thermal cycle with forward biased current to the diode, is representative of hot spot conditions, can impose a strong thermal stress to diode, and may cause failure for bypass diodes in some PV module that may be able to pass the present criteria of IEC 61215.

Experiments

Test samples(shown in fig.1 and fig.2) :

- 3 types of junction boxes for testing
- J-boxes were attached on mini laminate modules
- 3 diodes per j-box
- Diode rated current > 10A
- Thermocouples were bonded to diode cases

Data monitoring

- Measure forward and reverse characteristics of diodes before each thermal durability test
- Monitor current and voltage data of diodes and/or power supply
- Monitor case temperature of each diode

Test Procedure

- Test 1
  - Put the samples in chamber with controlled temperature of 50, 60, 75°C
  - Add forward current of 10A to bypass diodes
  - Monitor the bypass diode case temperature and forward voltage drop and current
  - 1000 hours
- Test 2
  - Chamber temperature cycled from -40°C to 85°C
  - 3 hours per cycle
  - Dwell time at both 85°C & -40°C are 10~30 minutes
  - Add forward bias current of 10A to diodes when the chamber temperature is higher than 25°C
  - One power supply is used for one J-box (3 power supplies).
  - 100 cycles
- Test3
  - Chamber temperature cycled from -40°C to 85°C
  - 3 hours per cycle
  - Dwell time at both 85°C & -40°C are 10~30 minutes
  - Add reverse bias voltage of 12V to diodes when the chamber temperature is higher than 25°C.
  - One power supply is used for one diode(9 power supplies).
  - 100 cycles
- Next step
  - Chamber temperature at 75°C
  - One hour of reversed bias (12 V) plus one hour of forward bias(10A) per cycle
  - 20 cycles

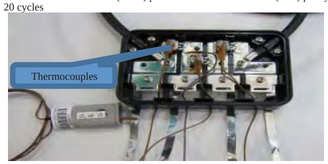


Fig. 1. Junction box sample for testing

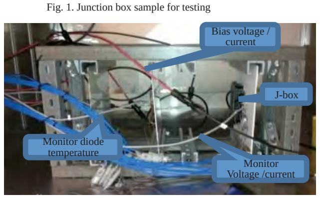


Fig. 2. Assembled testing samples in the chamber

Results

Test 1

High temperature endurance testing with forward biased current was applied to bypass diodes to assess diodes operating performance under long-term hot spot condition.

- Diodes temperature rise of 3 J-box during the testing(shown in fig.3 and fig.4) :
  - Box 1: Temperature rises of diodes 1-1 and 1-2 increased by 20°C . The highest diode case temperature reached 220°C when the chamber temperature was 60°C
  - Box 2: Temperature rises of diodes were very stable.
  - Box 3: Temperature rises of diodes 3-1, 3-2 and 3-3 increased slightly
  - Temperature rises of diodes decreased when ambient temperature increased.
  - Diode temperature rises of J-box 1 and 3 went up after restart testing.
- Diodes forward voltage of 3 J-box during the testing:
  - J-box 1: Voltages varied with testing time. Forward voltage of diodes 1-2 increased dramatically after restarted testing(Oct. 6), while voltage of diodes1-1, 1-3 decreased.
  - J-box 2: Voltages were stable
  - J-box 3: Voltages were stable
- No diode failed after the high temperature testing.

Note:
1.Temperature rise is the temperature difference between diode case and chamber
2.Diode 1-2, 2-2, 3-2 is the middle diodes of box 1, box 2 and box 3.
3.The temperature of middle one is highest in the box.

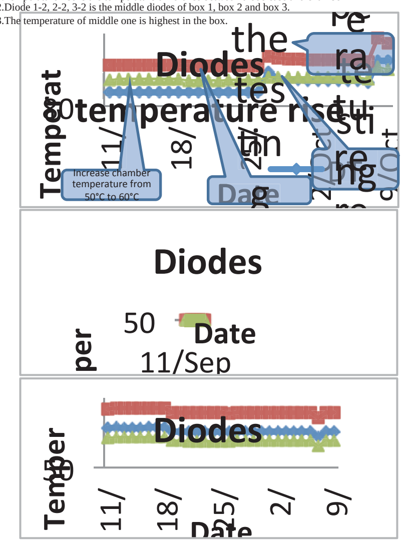


Fig. 3. Diode case temperature rise for 3 J-box during high temperature testing

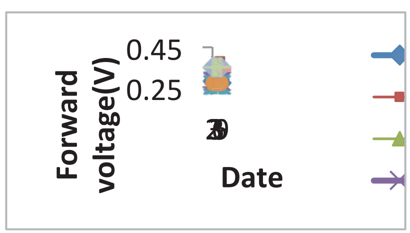


Fig. 4 Diodes forward voltage of 3 J-box during the high temperature testing

Test 2

Thermal cycle plus forward bias endurance testing was applied to bypass diodes to assess diodes reliability under thermal cycling caused by ambient temperature change combined with hot spot current flow.

Diodes case temperature during the testing :

- Box - 1: - 40 ~ 214°C
- Box - 2: - 40 ~ 158°C
- Box - 3: - 40 ~ 157°C

Diodes performance after the testing:

- Diodes forwards bias voltage of Box-1 increase dramatically after 40 cycles. Diodes of Box-1 totally failed after this testing.
- Reverse current(at reverse voltage of 10 - 16V) of diodes 3-2 (middle diode of box-3) and 2-2 increased by 10~20%.
- Diodes forward bias voltage of Box-2 remained steady
- Diodes forward bias voltage of Box-3 increased by 0.5V

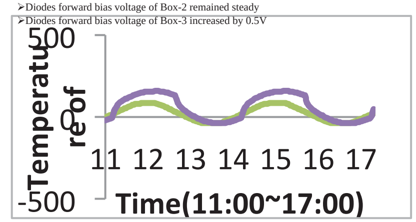


Fig. 5. Chamber temperature and diode case temperature of box 3 during diodes thermal cycle plus forward bias testing

Test 3

Thermal cycle plus reverse bias endurance testing was applied to bypass diodes to assess diodes reliability under thermal cycling caused by ambient temperature change without hot spot.

Diodes case temperature are very close to chamber temperature during the testing

Diodes performance after the testing:

- 12V reverse biased voltage was applied to diodes when the chamber temperature is higher than 25°C.
- Diode case temperature was close to chamber temperature.
- No failure or obvious degradation of diodes were observed during or after the test.

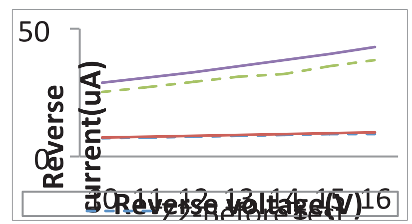


Fig. 6. Reverse characteristics of diodes 2-2(Q2) and diode 3-2(Z2) before and after diodes thermal cycle plus reverse bias testing

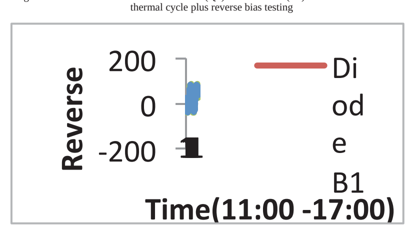


Fig. 7. Chamber temperature and diode case temperature of box 3 during diodes thermal cycle plus reverse bias testing

Discussion

To assess diodes thermal reliability of PV modules, three indoor tests were designed to simulate 3 types of diodes operating condition. The related test results were shown in above section.

High temperature endurance testing with forward biased current was applied to bypass diodes to assess diodes operating performance under hot spot condition. Mini modules with three types of junction boxes were put in chamber with controlled temperature. Forward biased current of 10A was added to bypass diodes; and the bypass diode case temperature and forward voltage drop and current were monitored during the testing. After 1000 hours' testing, though there is no abnormal appearance of diodes were found and no appreciable changes in terms of reverse diode characteristics were detected, the temperature rise of worst diodes in one J-box increased by 25°C. The temperature rises of diodes in J-box 1 and 3 went up by 2-15°C and their forward voltage increased dramatically after cool down the diodes and restart testing, while that of J-box 2 was stable. Based on the test result above, we can find if the heat dissipation is not good, there is still some possibility of diodes degradation in PV modules in hot spot condition. When the diodes is forward biased with hot spot current flow, the forward current may make the diode hot enough for the dopants that create the N- and P-type areas in the diode to diffuse across the junction, wrecking the semi-conducting behavior that we rely on, and cause performance degradation.

Two types of thermal cycle testing were processed to assess the diodes' durability of thermal cycling stress caused by ambient temperature change with or without hot spot in PV modules. Three types of J-boxes were tested in chamber with cycling temperature range from -40°C to 85°C. For the first 100 cycles, forward biased current of 10A was applied to diodes when the chamber temperature is higher than 25°C. One of diodes totally failed with open circuit after the first 100 thermal cycles testing. The high temperature combined with thermal cycling will cause the diodes resistance increase and damage the PN junctions. For the second 100 cycles, -12V reverse biased voltage was added to diodes during the chamber temperature is higher than 25°C. The diodes case and junction temperatures were close to ambient temperature during the second 100 cycles test. And there was no failure or obvious degradation of diodes were observed during or after the test. The diodes performance of PV module is stable if there is no hot spot issue.

The diode performance is stable if the diode is reverse-biased with low diode temperature. However, the leakage currents doubles every 10°C as the temperature increase, and eventually the current may reach a level where the heat dissipation within the junction is high enough for the junction temperature to run away. For the field operating condition, the PV modules may encounter momentary shading caused by cloud or bird, etc. The diodes in the modules will work under the condition of high temperature with forward bias current flow firstly when the shading is on the modules. Then the diodes will be reverse-biased in high temperature condition after the shading is gone. For next step, the experiments need be designed to access the diode thermal reliability under simulated the field condition of momentary shading .

Conclusions

Based on the test result above, we can find if the heat dissipation is not good, there is still some possibility of diodes degradation or failure in PV modules under hot spot condition. Thermal cycle condition with forward biased current to diode, really representative of hot spot conditions, can impose a strong thermal fatigue stress to diode, and may cause failure for bypass diodes of some PV module that may be able to pass present criteria of IEC 61215.

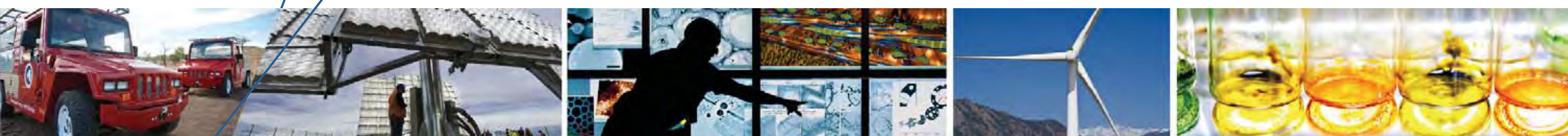
Acknowledgments

The authors thank Peter Hacke and Kent Terwilliger of the National Renewable Energy Laboratory for offering help on the experiments. The author appreciate Vivek S. Gade of Jabil's Photovoltaic and Certification Test Laboratory and Paul Robusto of Intertek for insightful comment for the testing result analysis. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

Reference

1. Barreiro, C., et al. *PV by-pass diode performance in landscape and portrait modalities*. in *Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*. 2011.
2. Ben-Menahem, S. and S.C. Yang. *Online photovoltaic array hot-spot Bayesian diagnostics from streaming string-level electric data*. in *Photovoltaic Specialists Conference (PVSC), 2012 38th IEEE*. 2012.
3. Bower, W.I., M.A. Quintana, and J. Johnson, *Electrical and thermal finite element modeling of arc faults in photovoltaic bypass diodes*. 2012. p. Medium: ED; Size: 33 p.
4. Al-Rawi, N.A., M.M. Al-Kaisi, and D.J. Asfer, *Reliability of photovoltaic modules II. Interconnection and bypass diodes effects*. Solar Energy Materials and Solar Cells, 1994. **31**(4): p. 469-480.

Group 3
Humidity, Temperature and Voltage



John Wohlgemuth

February 27, 2013

NREL PVMRW 2013

Introduction

- **Group 3 is chartered to develop accelerated stress tests that can be used as comparative predictors of module lifetime versus stresses associated with humidity, temperature and voltage.**
- **The tools we have to utilize are:**
  - **Outdoor test results**
  - **Accelerated stress tests results**
  - **Modeling**

Where we stand today

- The module qualification test sequence IEC 6121   (first published i   1993 contains a 1000 damp heat test (8   °C at 85% RH).
- This stress tes appears to do an excellent job of screening ou module designs an   materials that would fail in the field in short time periods.
- So Group 3 must look to find field failures that are no identified in the 100   hour damp heat test, bu are limiting the lifetime of PV modules.

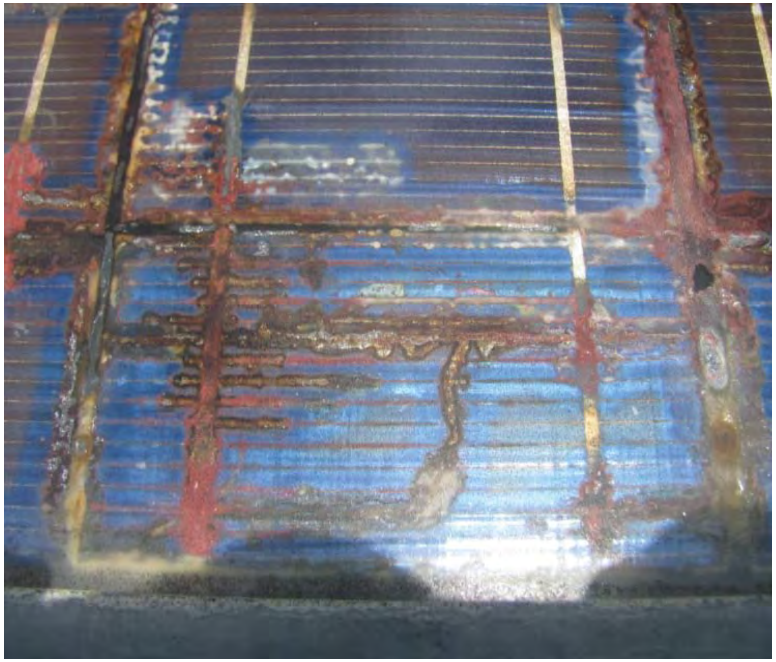
What has Group 3 been doing

- Making observations of field failures.
- PID Testing – Adding voltage to H and T
  - Have paper by Peter Lechner of ZSW
  - Have more posters on PID than any other subject
- Modeling to understand conditions within module
  - Mike Kempe will give paper on this work
  - This is critical because you can't understand accelerated stress test results if you don't understand the conditions during the test and the conditions that occur in the field
- Effectiveness of Qualification Test
- Look at results of testing beyond qualification

Field Results

So what do we say today in terms of wear out failures that are likely due to humidity?

- Most of the evidence of corrosion comes in conjunction with delamination
- Any of the metals (grid lines, interconnect ribbons, solder bonds) will likely corrode if exposed to liquid water.
- So even if our contacts can survive moisture in the encapsulant they are not likely to survive very long after failure of the encapsulation package.

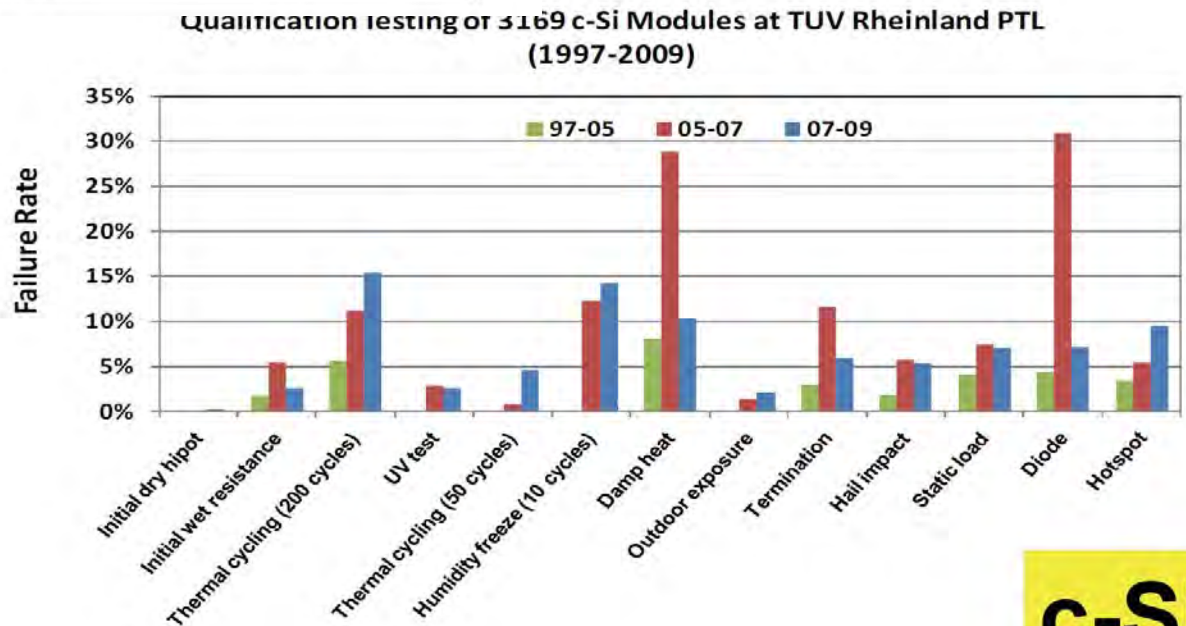


Field Results and Damp Heat Testing

Observed Field Failures

Types of Failures	% of Total Failures
Corrosion	45.3
Cell or Interconnect Break	40.7
Output Lead Problem	3.9
Junction Box Problem	3.6
Delamination	3.4
Overheated wires, diodes or terminal strip	1.5
Mechanical Damage	1.4
Defective Bypass Diodes	0.2

Wohlgemuth et.al. 20th EUPVSEC 2005



Tamizhmani 2010
PVMRW

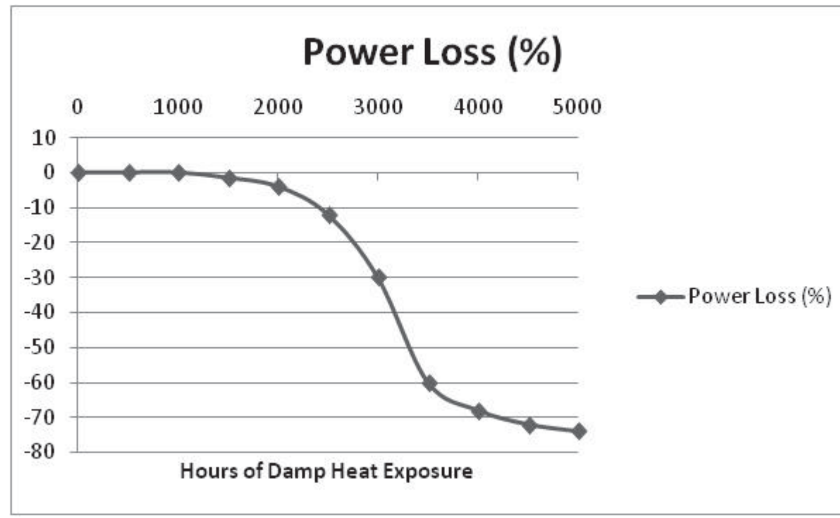
c-Si

Damp Heat Test Results

- **When damp heat test was first introduced it was the hardest test for most PV module manufacturers to pass.**
- **Even when you did pass damp heat the power loss was usuall approaching the 5% limit.**
- **When wet hi-pot test was added in 2005 many more module types failed after damp heat until they learned how to control the leakage current.**
- **As late as 2008 in 23rd EUPVSEC I reported on experiment where BP tested 10 different cry-Si modules (all of which carried IEC 61215 labels) from 9 different manufacturers from around the world to 1250 hours of damp heat, the standard test at BP Solar. 8 out of the 10 module types suffered more than 5% power loss in this experiment.**
- **Over the years the manufacturers learned how to reduce and eventually eliminate any power loss from 1000 hours of 85/85 testing.**
- **So it doesn't take extraordinary measures to get through 1000 or even 1250 hours at 85/85 with no measureable power loss.**

Extended Damp Heat Testing

- **So if 1000 hours of damp heat testing helped improve field performance maybe longer test times would provide a measure of longer term survival.**
- **See my results from 2005.**
- **Many other publications show similar results**
  - **Herrmann et. al. 37th IEEE PVSC 2011**
  - **Saint-Lary et. al. 27th EUPVSEC 2012**
- **This type of degradation occurs in cry-Si modules with EVA encapsulant and breathable polymeric backsheets.**

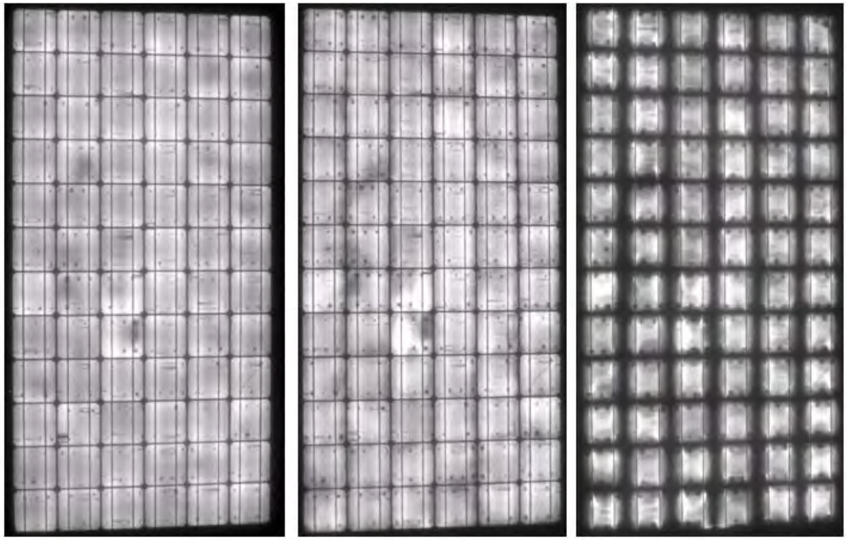


Wohlgemuth et.al. 20th EUPVSEC 2005

Degradation Signature

- **The dark area around the outside of each individual cell indicates that this area of each cell is no longer actively collecting carriers.**
- **This is due to moisture induced corrosion of the doped oxide that provides the electrical contact to the emitter of the silicon cell.**
- **Problem is, no one has reported seeing this degradation signature in PV modules from the field.**
- **This failure mode may never occur in the field or may take longer than present field exposure times (> 30 years).**

Electroluminescence pictures of a Cry-Si module after extended damp heat testing.



1000 hours 2000 hours 3000 hours

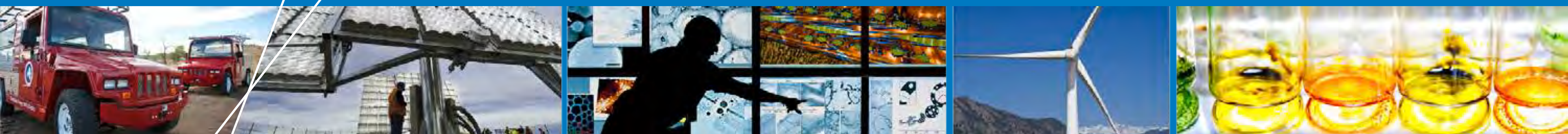
Saint-Lary et. al. 27th EUPVSEC 201

SUMMARY

- At present time we do not believe that damp heat testing beyond 1000 hours is justified.
- Looking for combined sets of stresses that can lead to delamination. Possibilities
  - UV and temperature
  - Dynamic mechanical loading/thermal cycling/humidity freeze.
- We are looking for:
  - Older arrays (>15 years) exposed in hot/humid environments to visit.
  - Reports on and samples of product returns that appear to be humidity and temperature related.

NATIONAL RENEWABLE ENERGY LABORATORY

Understanding the Temperature and Humidity Environment Inside a PV Module



2013 NREL PVMRW

Michael Kempe

Wednesday, February 27, 2013

NREL/PR-5200-58375

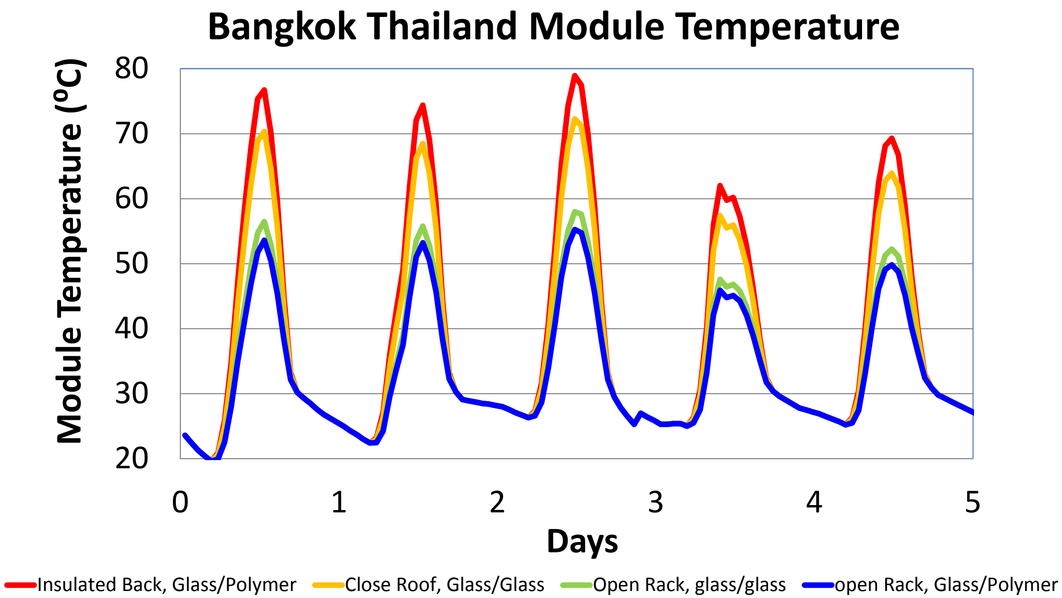
Introduction

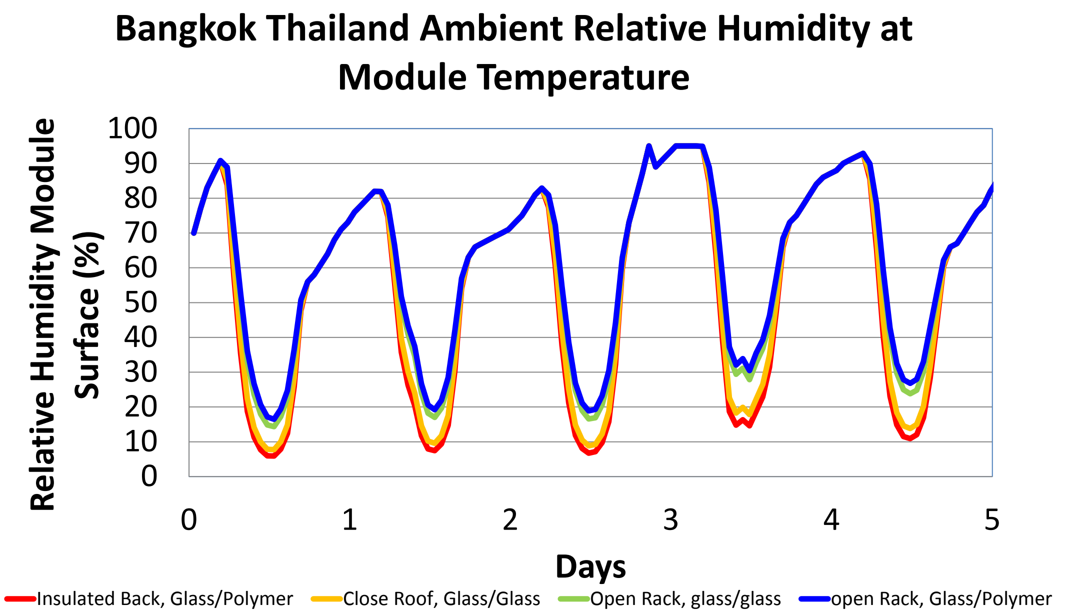
- Many degradation processes within a PV module are driven by moisture.
- The concentration of moisture in a module is a complex function of the use environment and the module construction.
- In accelerated stress testing one must know how water affects degradation to determine what temperature and humidity conditions to use.
- Here we show that by choosing humidity conditions that more closely match the use environment, one can minimize the uncertainty associated with moisture induced degradation modes.

Outline

- Describe moisture on the backside of a module.
- Look at the hydrolysis of a typical back-sheet made of PET as a case study for comparing 85 ^{o}C/85% RH to outdoor exposure.
- Examine the moisture and temperature environment on the front of a module as a worst case scenario.
- Show how good choices for RH testing will minimize uncertainty.

Representative Module Environment





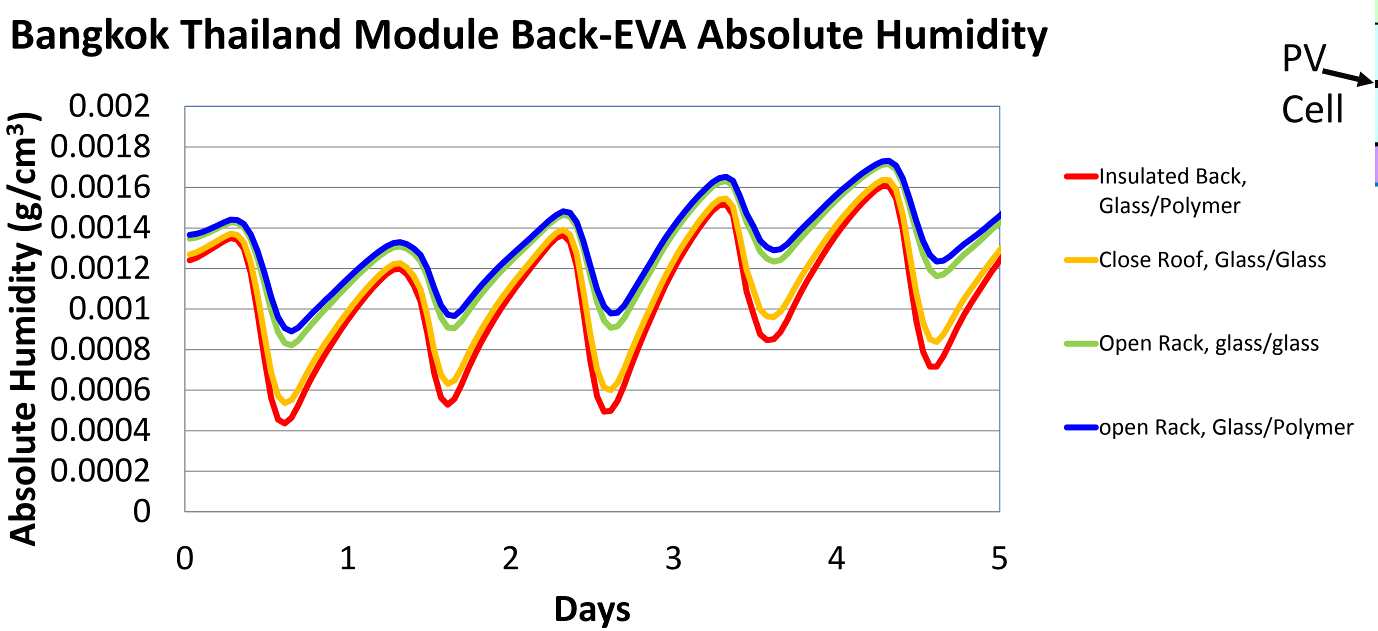
- **Use either IWEC or TMY-3 data for select environments.**
- **Use the model of King et al.* for module temperature.**
- **This produces *"representative"* data intended to generally duplicate a use environment**

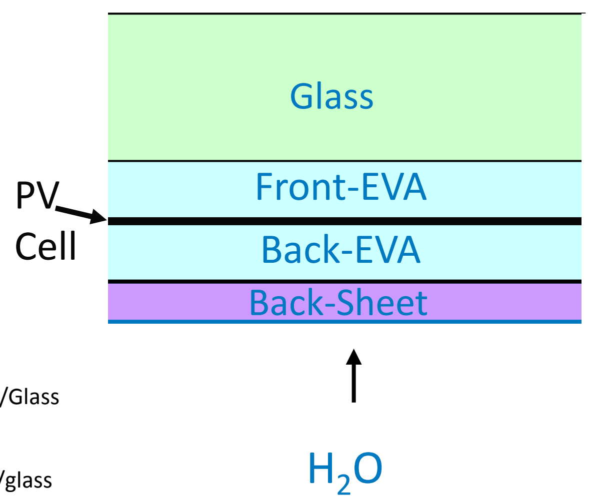
*D. L. King, W. E. Boyson, and J. A. Kratochvil, "Photovoltaic array performance model," SAND2004-3535, Sandia National Laboratories, Albuquerque, NM, 2004.

Moisture in the Back-EVA Layer

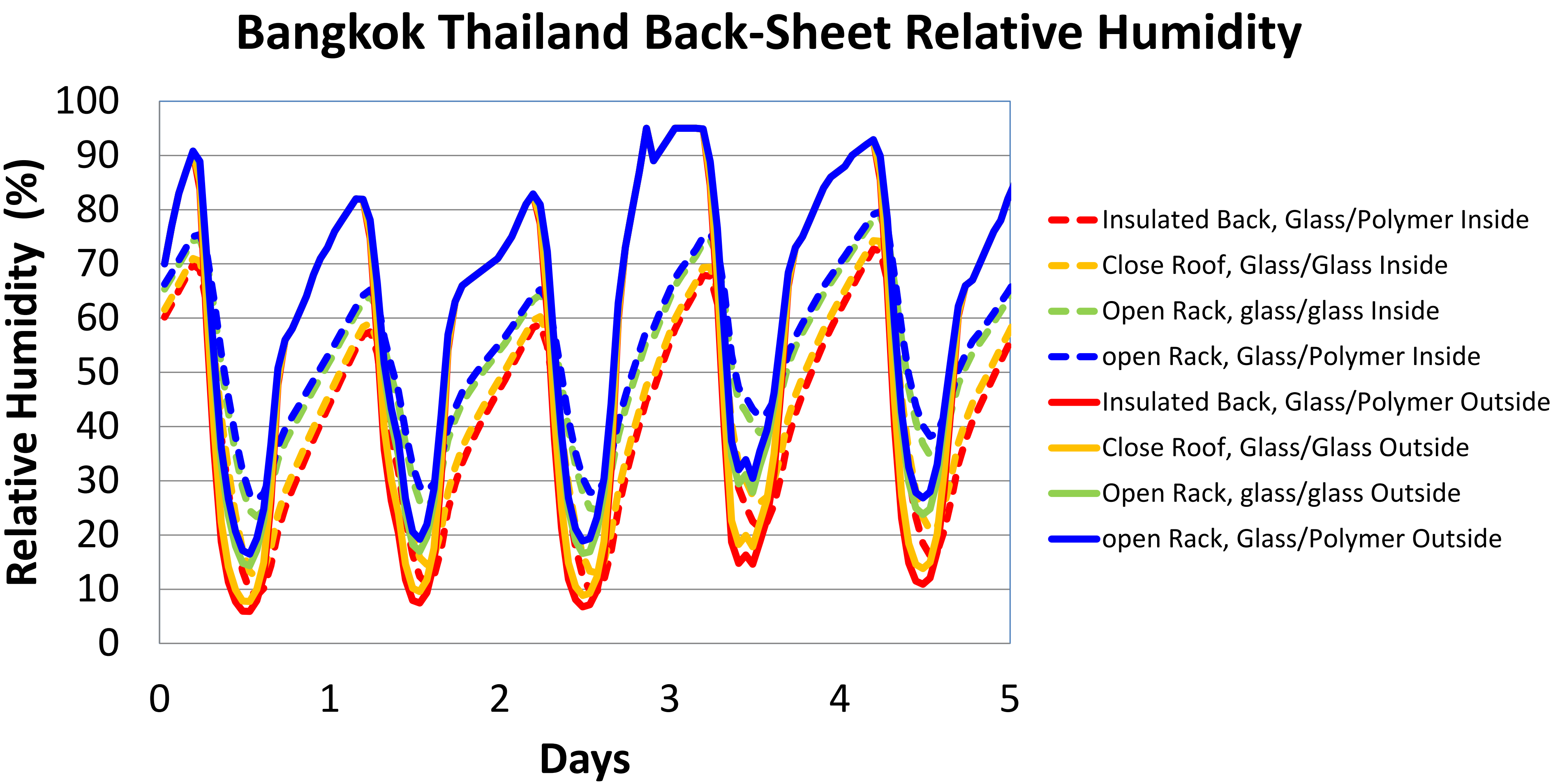
- **Assume diffusivity in EVA is much greater than in the back-sheet.**
- **Also assume transient moisture gradient in the back-sheet is unimportant.**

$$\frac{dC_E}{dt} = \frac{WVTR_{B,Sat}}{C_{E,Sat}l_E}\left(C_{E,Eq} - C_E\right)$$



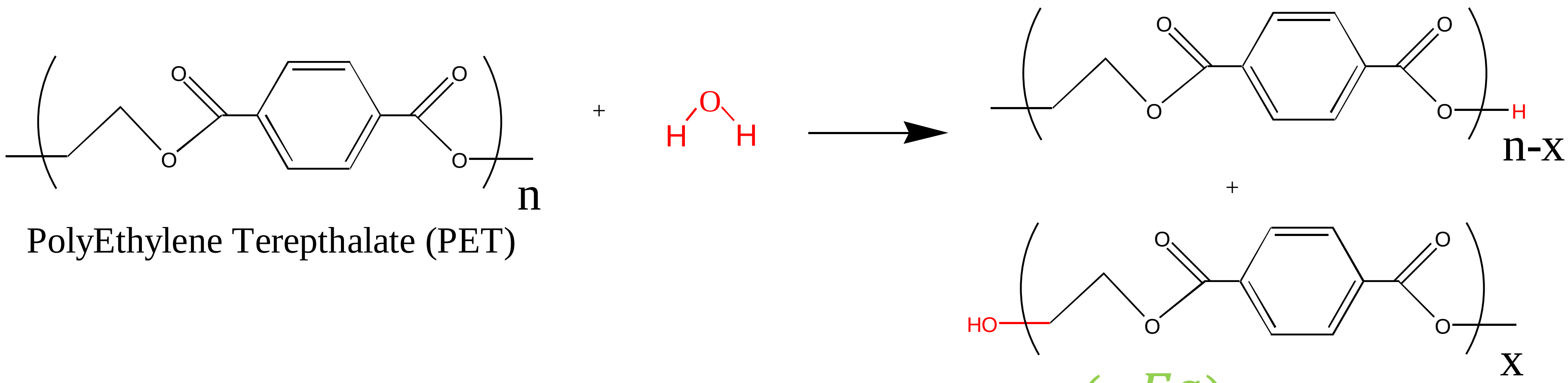


Back-Sheet Exposure



- **A PET based back-sheet will be exposed to humidity between that outside and inside the module.**

Pet Hydrolysis Kinetics



$$\log\left(\frac{C}{C-x}\right) = A \cdot t \cdot RH^2 \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

Ea=129.4 kJ/mol (1.340 eV), *A*=2.84·10^{10} 1/day, *RH* expressed as a percentage.

*PET becomes brittle (1/3 initial tensile strength) and "failed" when log(C/C-x)=~0.0024, or about 0.55% hydrolysis of ester bonds.

**Pickett et. al saw the activation energy vary between 125 and 151 kJ/mol with an average of 136±13 kJ/mol for four different PET grades.

*W. McMahon, H. A. Birdsall, G. R. Johnson, and C. T. Camilli, "Degradation Studies of Polyethylene Terephthalate," Journal of Chemical & Engineering Data, vol. 4, pp. 57-79, 1959.
**J. E. Pickett and D. J. Coyle, "Hydrolysis Kinetics of Condensation Polymers Under Humidity Aging Conditions," Submitted to the Journal of Polymer Degradation and Stability, 2013.

PET Hydrolysis Results

$$\log\left(\frac{c}{c-x}\right) = A \cdot t \cdot RH^2 \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

	Years to 0.55% degradation (i.e. Hydrolysis Service Life) (y)		1000 Hours 85°C/85% RH Years equivalent (y)		Relative Humidity at 85°C so that 1000 h equals 25 years exposure (%)		Temperature at 85% RH so that 1000 h equals 25 years exposure (°C)	
	Open Rack	Insulated Back	Open Rack	Insulated Back	Open Rack	Insulated Back	Open Rack	Insulated Back
Denver, Colorado	13,000	4,900	6,500	2,400	5.3	8.7	45	49
Munich, Germany	11,000	4,400	5,100	2,100	6.0	9.2	47	50
Albuquerque, New Mexico	9,000	3,200	4,400	1,500	6.4	11	48	52
Riyadh, Saudi Arabia	8,200	3,000	4,000	1,500	6.7	11	48	52
Phoenix, Arizona	3,400	1,300	1,700	630	10	17	54	58
Miami, Florida	1,100	510	530	250	19	27	62	65
Bangkok, Thailand	700	310	320	150	24	34	66	69

PET is predicted to "fail" after 2064 h of 85 °C and 85% RH.

Site Specific Equivalent T and RH

$$R = A \cdot RH^n e^{\left(-\frac{Ea}{kT}\right)}$$

$$RH_{weighted\ average} = RH_{WA} = \left[\frac{\sum RH^n e^{\left(-\frac{Ea}{kT}\right)}}{\sum e^{\left(-\frac{Ea}{kT}\right)}}\right]^{\frac{1}{n}}$$

This tells you what the relative humidity is at the temperatures where the most damage is done.

These terms cancel out

$$(RH_{WA})^n e^{\left(-\frac{Ea}{kT_{eq}}\right)} = \frac{\sum RH^n e^{\left(-\frac{Ea}{kT}\right)}}{N} = \left\{\left[\frac{\sum RH^n e^{\left(-\frac{Ea}{kT}\right)}}{\sum e^{\left(-\frac{Ea}{kT}\right)}}\right]^{\frac{1}{n}}\right\}^n e^{\left(-\frac{Ea}{kT_{eq}}\right)}$$

$$\therefore \frac{\sum e^{\left(-\frac{Ea}{kT}\right)}}{N} = e^{\left(-\frac{Ea}{kT_{eq}}\right)} \quad \therefore \quad T_{eq} = -\frac{K}{Ea} ln\left[\frac{\sum e^{\left(-\frac{Ea}{kT}\right)}}{N}\right]$$

The equivalent temperature (T_{eq}) gives the temperature at RH_{WA} for which constant conditions will produce a degradation rate equivalent to the yearly average.

PET Hydrolysis Equivalent T and RH

$$\log\left(\frac{C}{C-x}\right) = A \cdot t \cdot RH^2 \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

	Years to 0.55% degradation (i.e. Hydrolysis Service Life) (y)		1000 Hours 85°C/85% RH Years equivalent (y)		**Teq for Ea=129.3 kJ/mol (°C)**		**RH, at Teq for 2nd order Kinetics of PET (%)**	
	Open Rack	Insulated Back	Open Rack	Insulated Back	**Open Rack**	**Insulated Back**	**Open Rack**	**Insulated Back**
Denver, Colorado	13,000	4,900	6,500	2,400	**33**	**54**	**14**	**4.6**
Munich, Germany	11,000	4,400	5,100	2,100	**28**	**46**	**25**	**8.4**
Albuquerque, New Mexico	9,000	3,200	4,400	1,500	**37**	**58**	**13**	**4.2**
Riyadh, Saudi Arabia	8,200	3,000	4,000	1,500	**48**	**70**	**5.6**	**2.0**
Phoenix, Arizona	3,400	1,300	1,700	630	**46**	**68**	**9.8**	**3.3**
Miami, Florida	1,100	510	530	250	**37**	**54**	**36**	**14**
Bangkok, Thailand	700	310	320	150	**41**	**59**	**33**	**12**

What Are Relevant Activation Energies

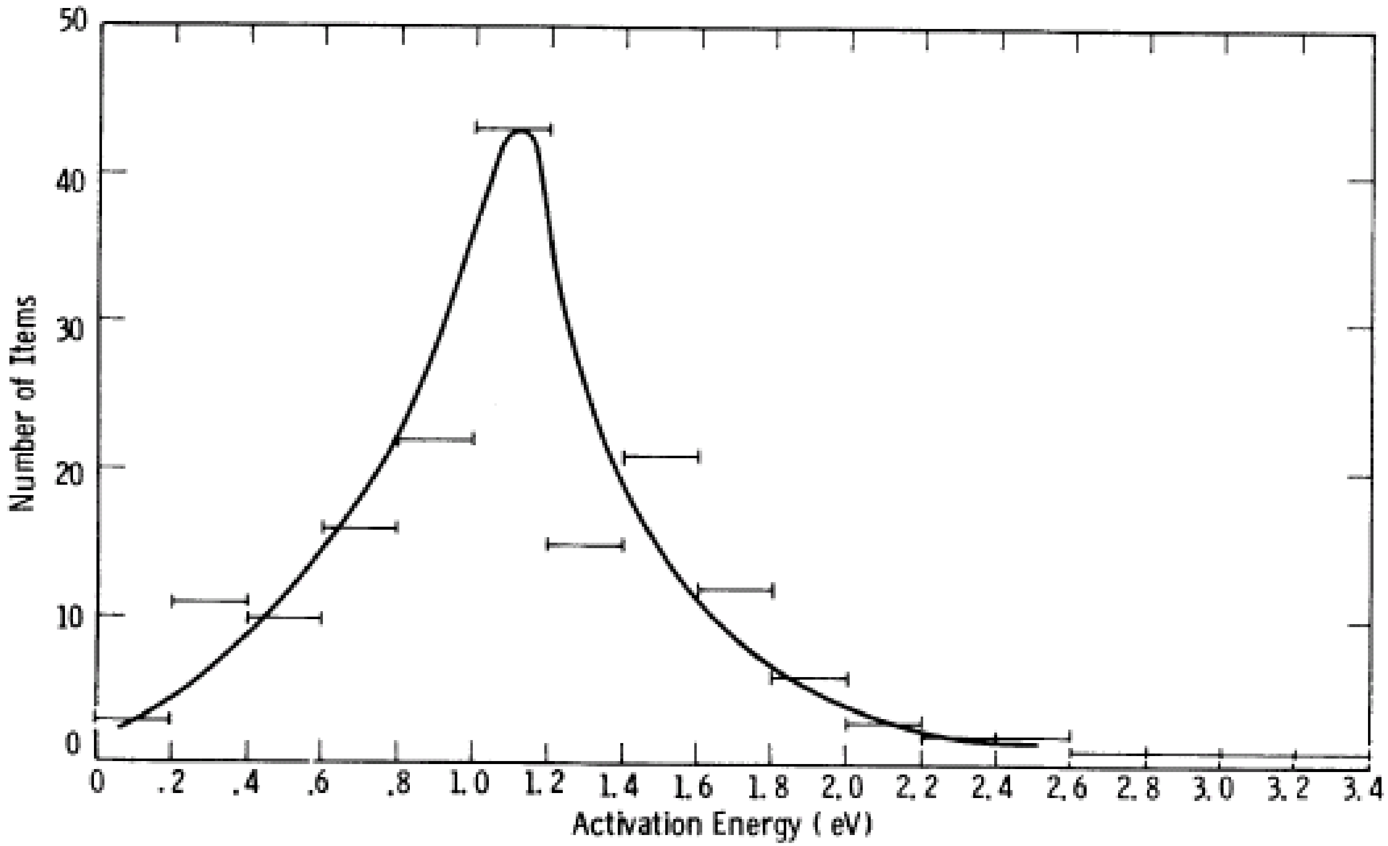


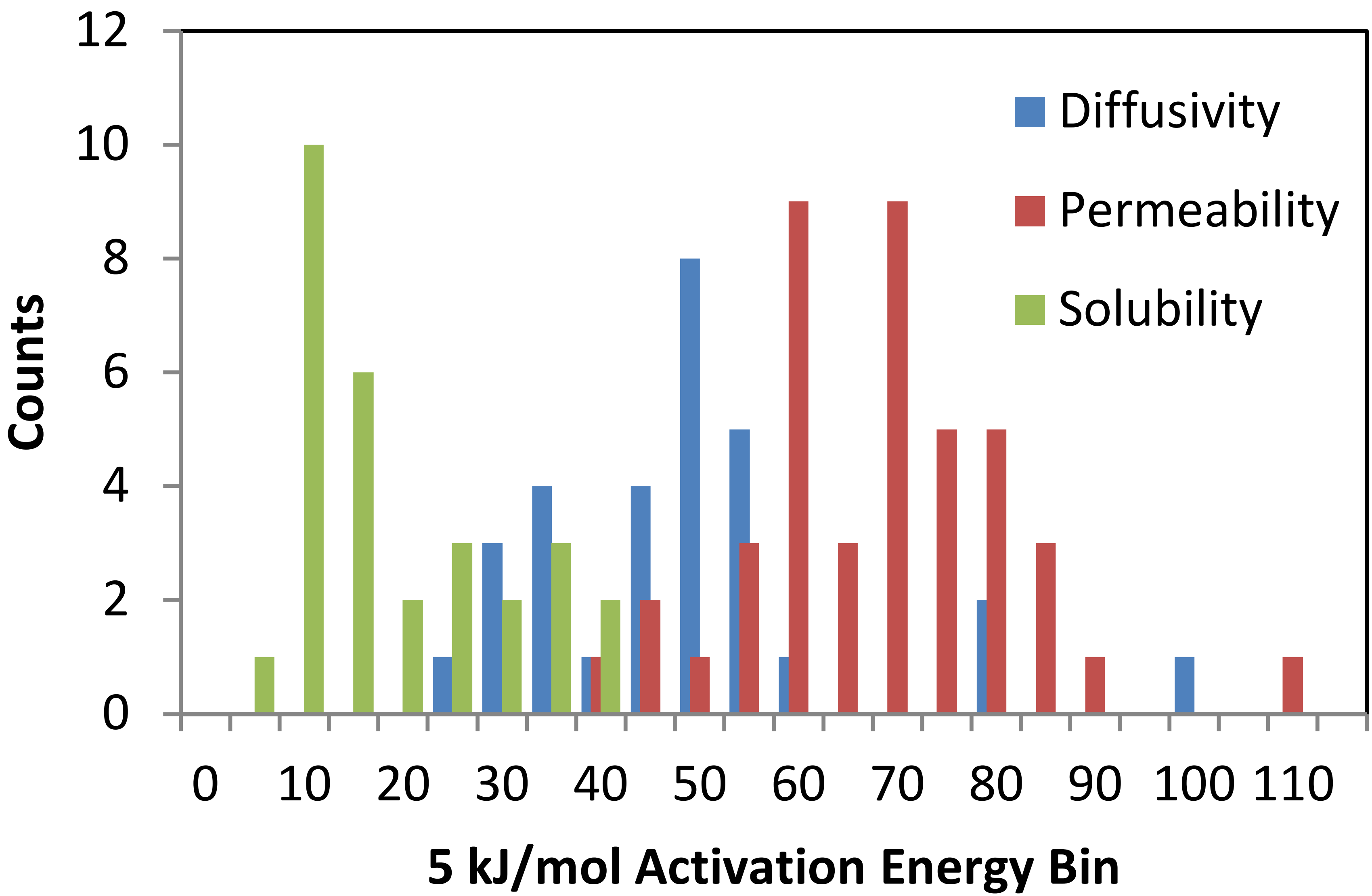
Fig. 3: Frequency distribution of activation energies of various components/materials (D. Cain - EPRI information)

Degradation activation energy from Dixon*. Based on RTI testing for properties such as:

Elongation at Break
Flexural strength
Tensile Strength
Shear Strength
Burst Strength
Weight Loss
Dielectric Strength
Imp. Strength

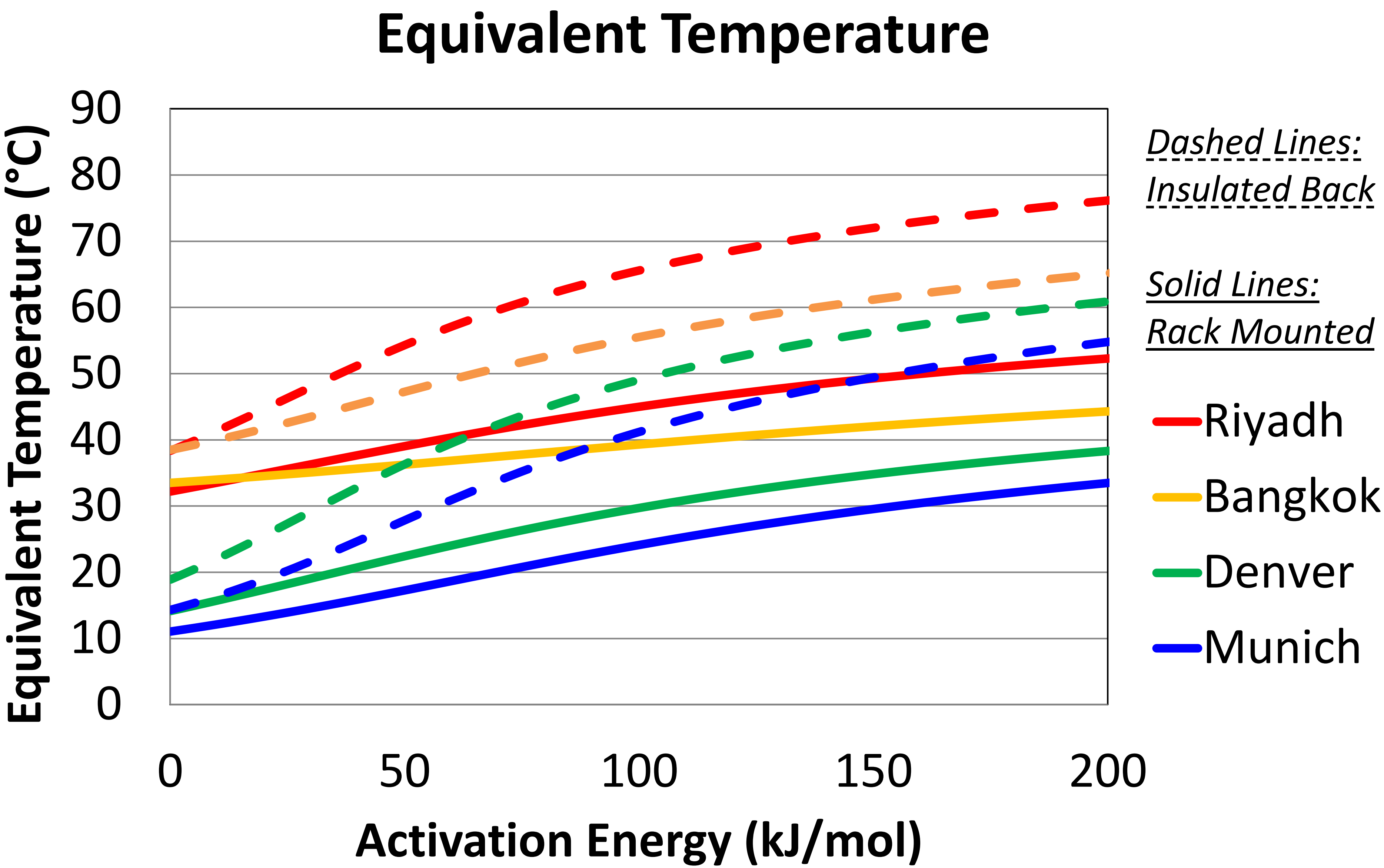
*R. R. Dixon, "Thermal Aging Predictions from an Arrhenus Plot with Only One Data Point," *Electrical Insulation, IEEE Transactions on,* vol. EI-15, pp. 331-334, 1980.

For Diffusion Controlled Processes

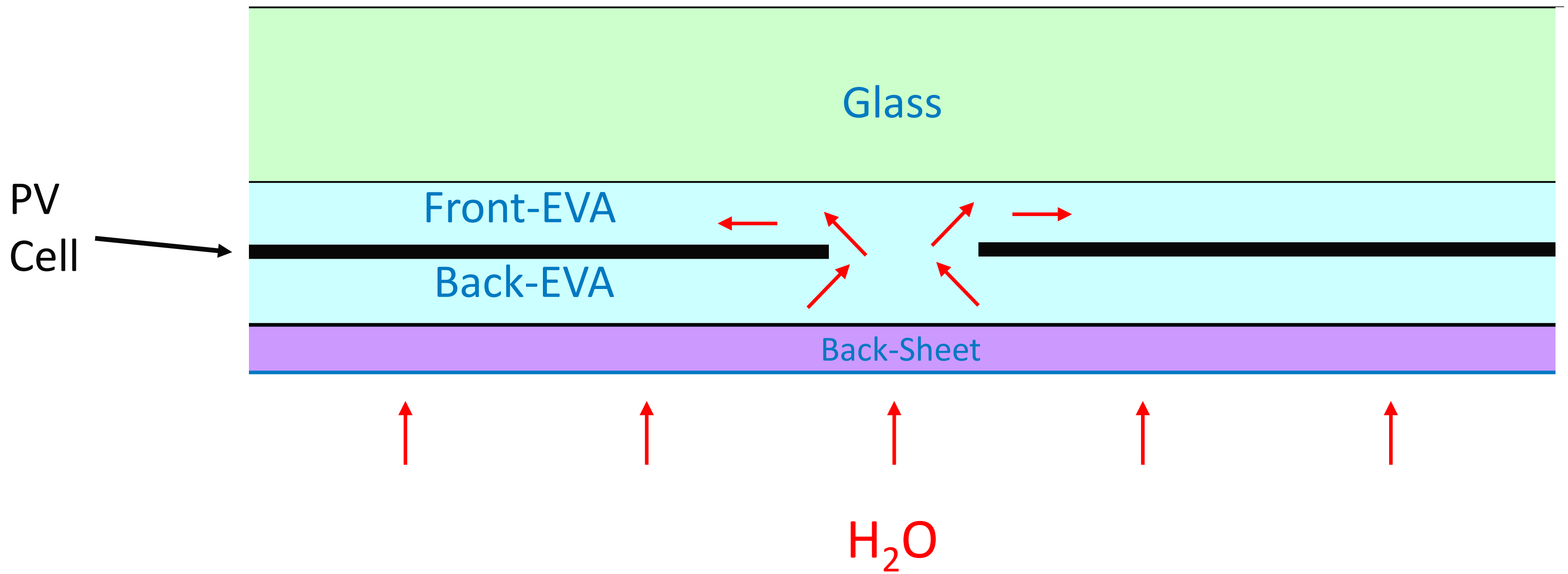


Histogram for moisture ingress activation energy for PV polymeric materials.

Thermal Stress by Location and Mounting



Modeling Moisture in the Front-EVA



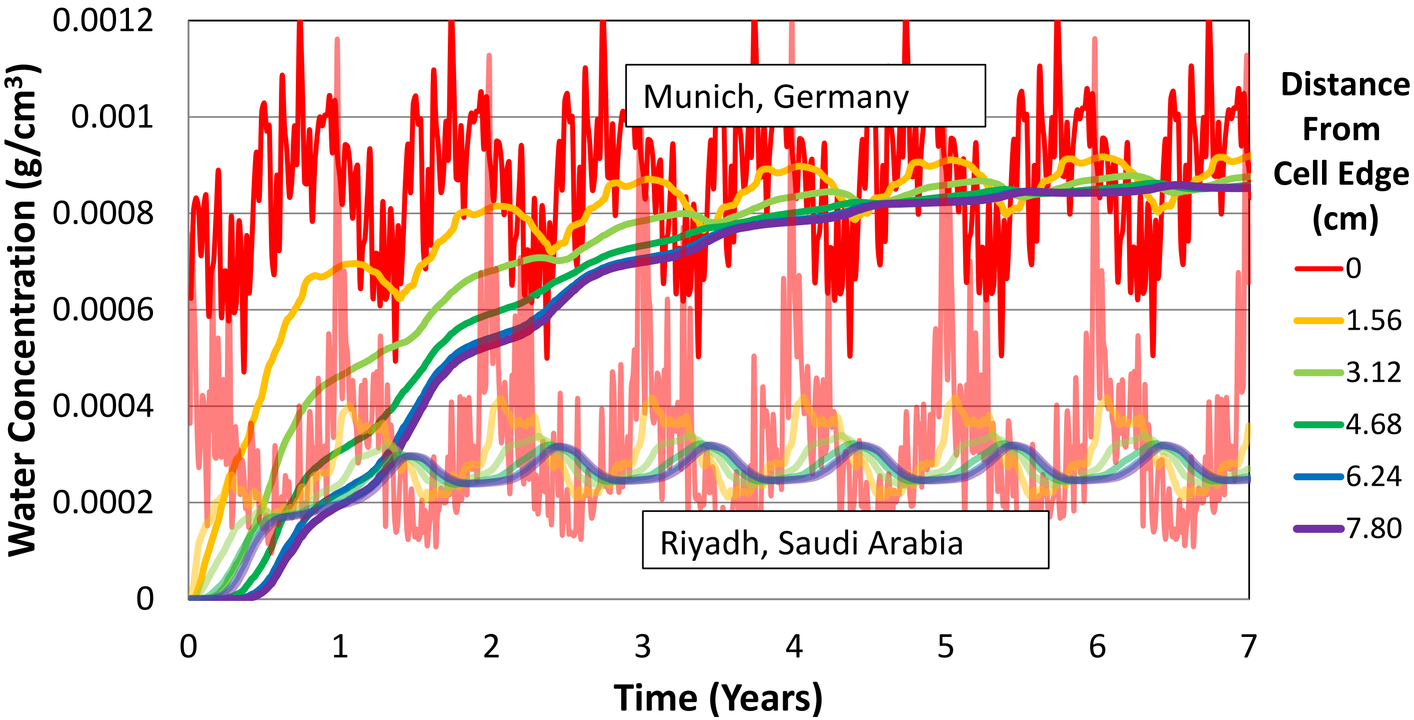
The Back-EVA equilibrates with a characteristic time of about a day.

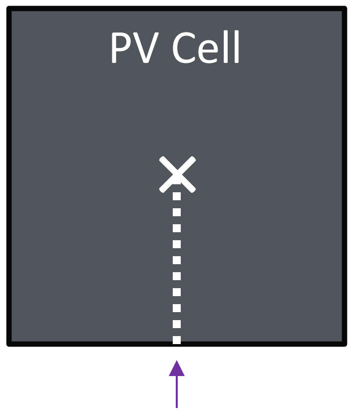
The Front-EVA equilibrates with halftimes of between a day and several years depending on the mounting configuration, location, and the position in front of the cell.

Uses the backside water concentration at the perimeter in a 2-D diffusion finite element algorithm. The cell size is 156+2 mm to account for water diffusing from the back to the front.

Front Encapsulant Water Content

Rack mounted, Glass/Polymer modules



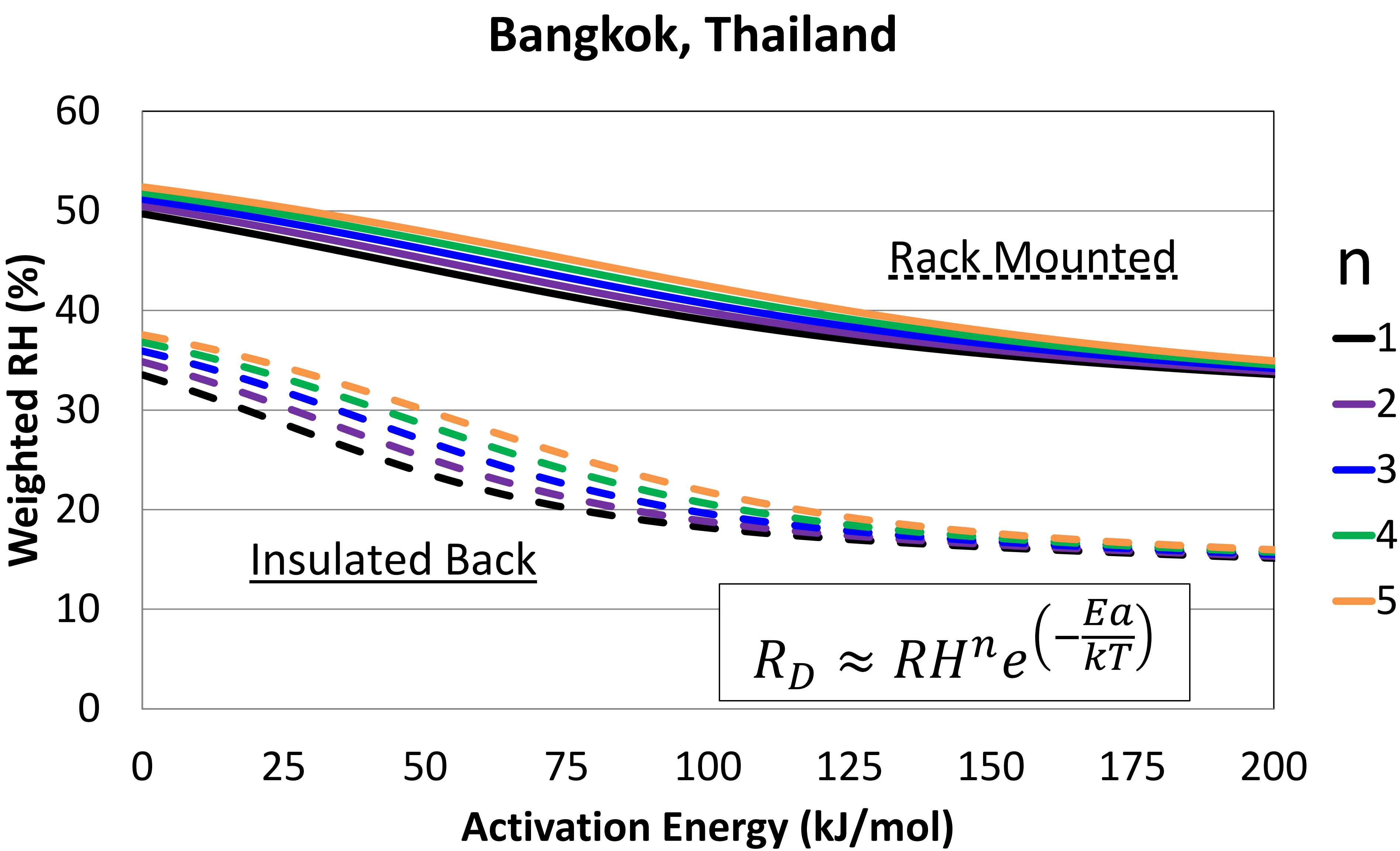


Profiles along this line are plotted.

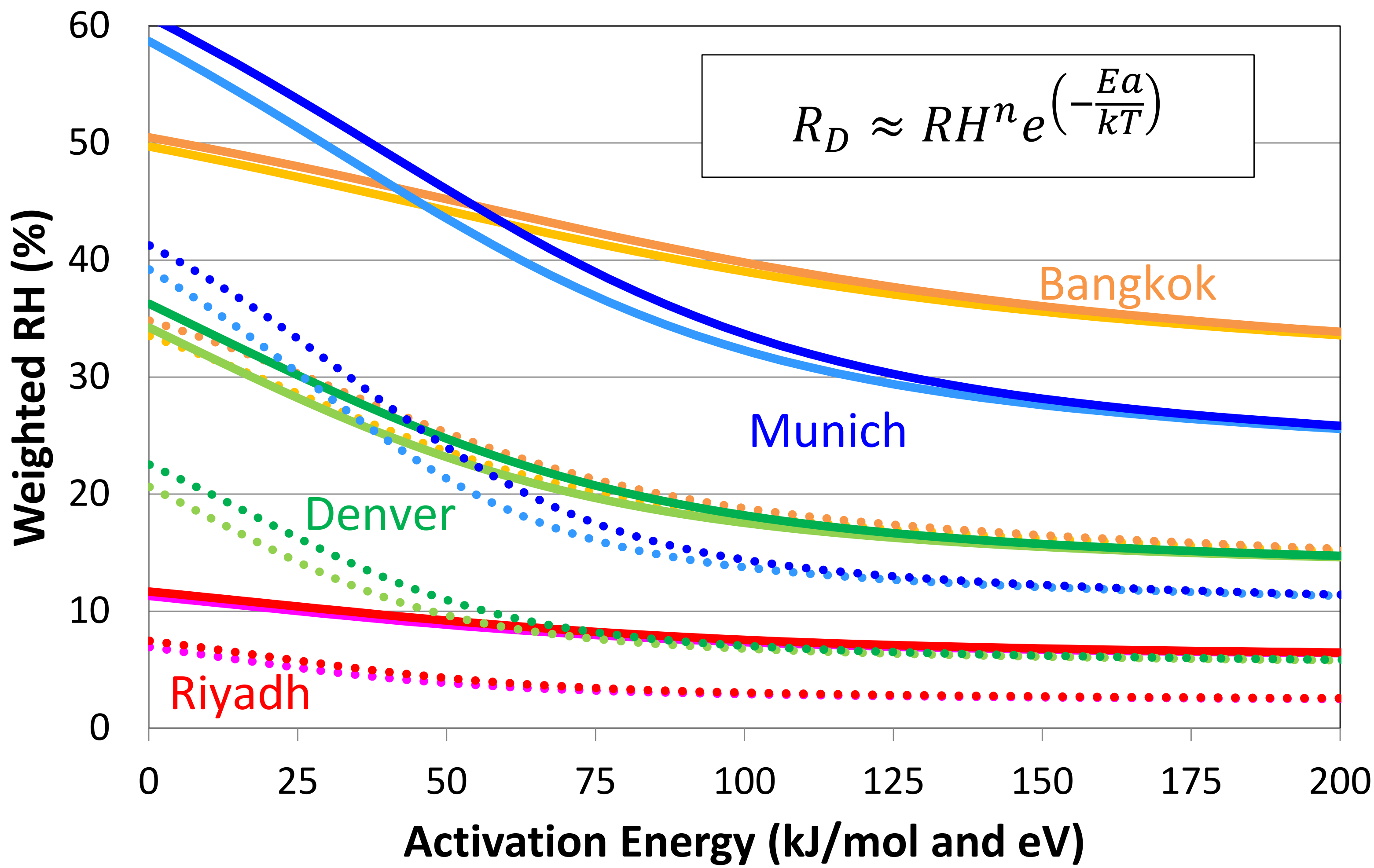
The front encapsulant traps in moisture seasonally making the center of the cell front the most hydrolytically damaging area.

The remainder of this presentation focuses on the center of the front side to evaluate the most stressful position in the module.

RH Not Very Dependent Kinetics or Ea



Small RH Dependence in All Climates



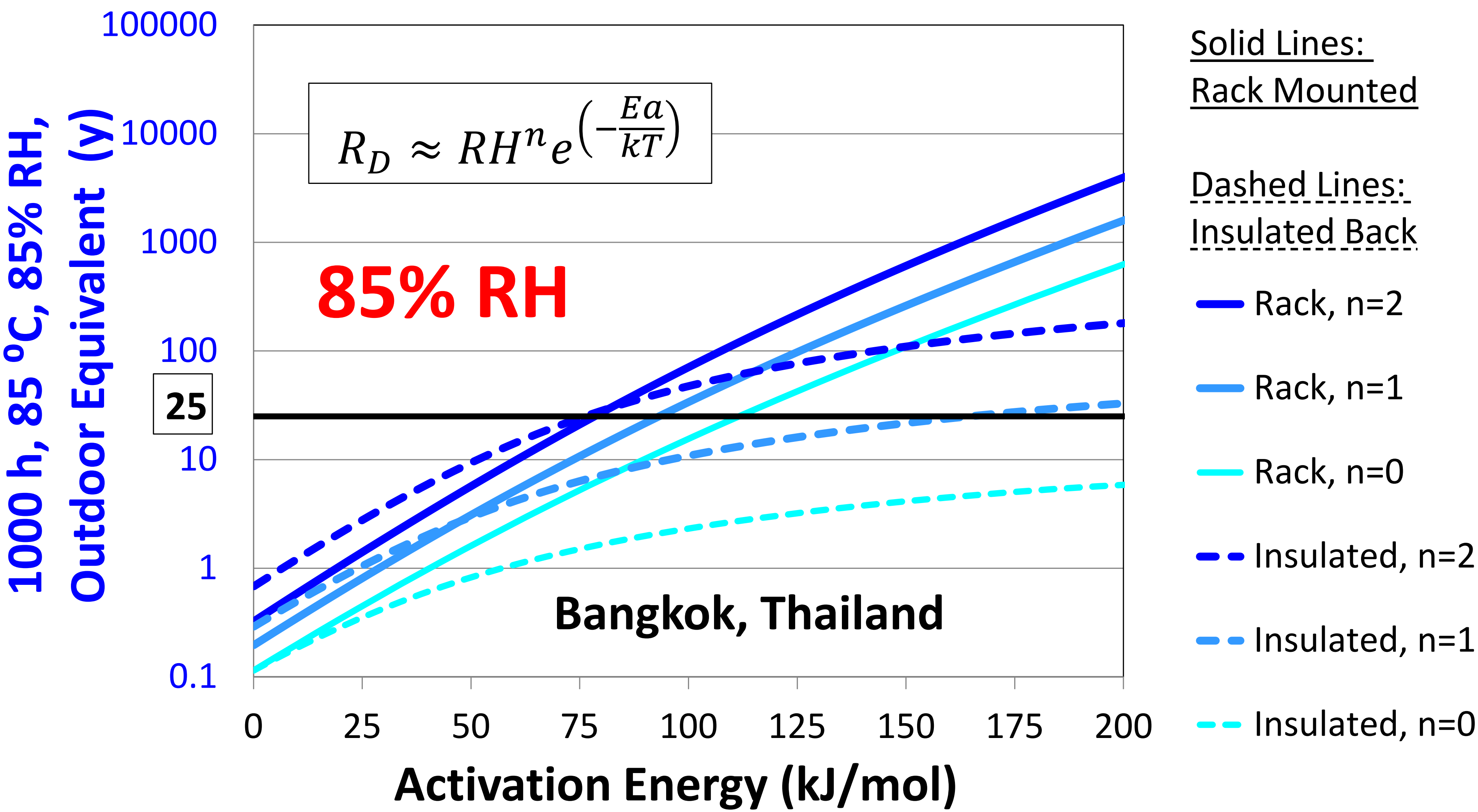
Solid Lines:
Rack Mounted

Dashed Lines:
Insulated Back

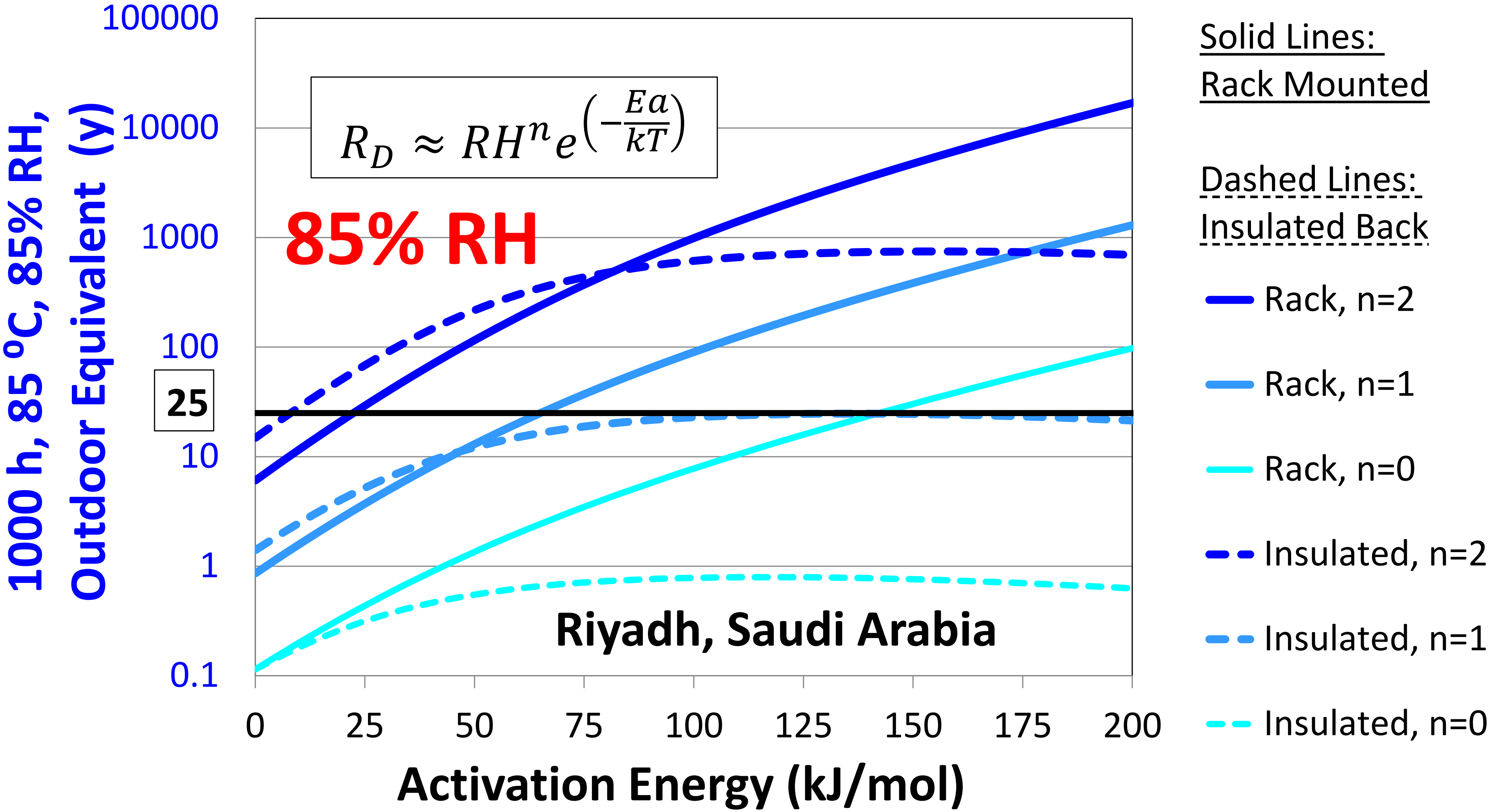
Darker Line:
n=2

Lighter Line:
n=1

85 ºC/85% RH Equivalent Time-Bangkok

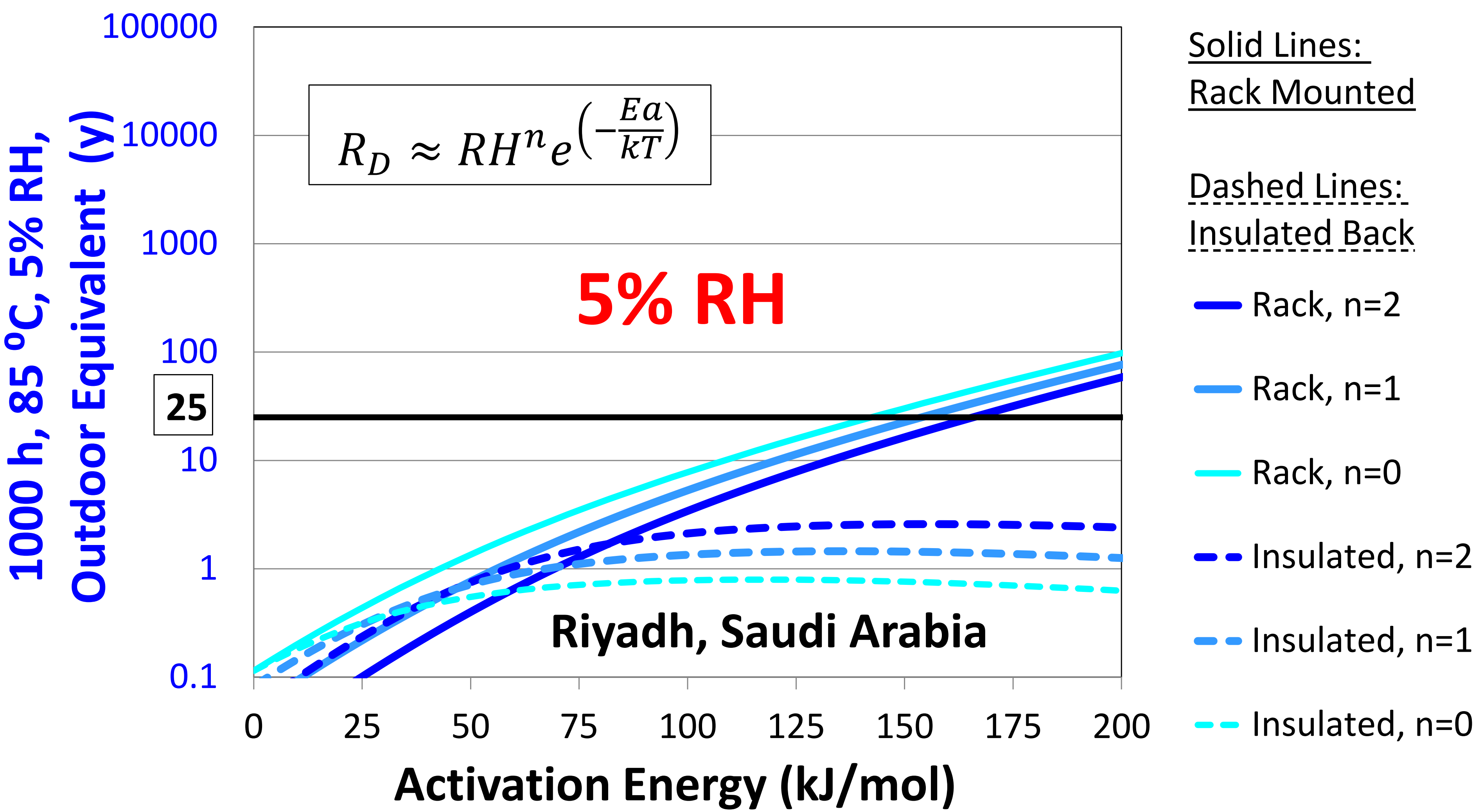


85 ^{o}C/85% RH Equivalent Time-Riyadh



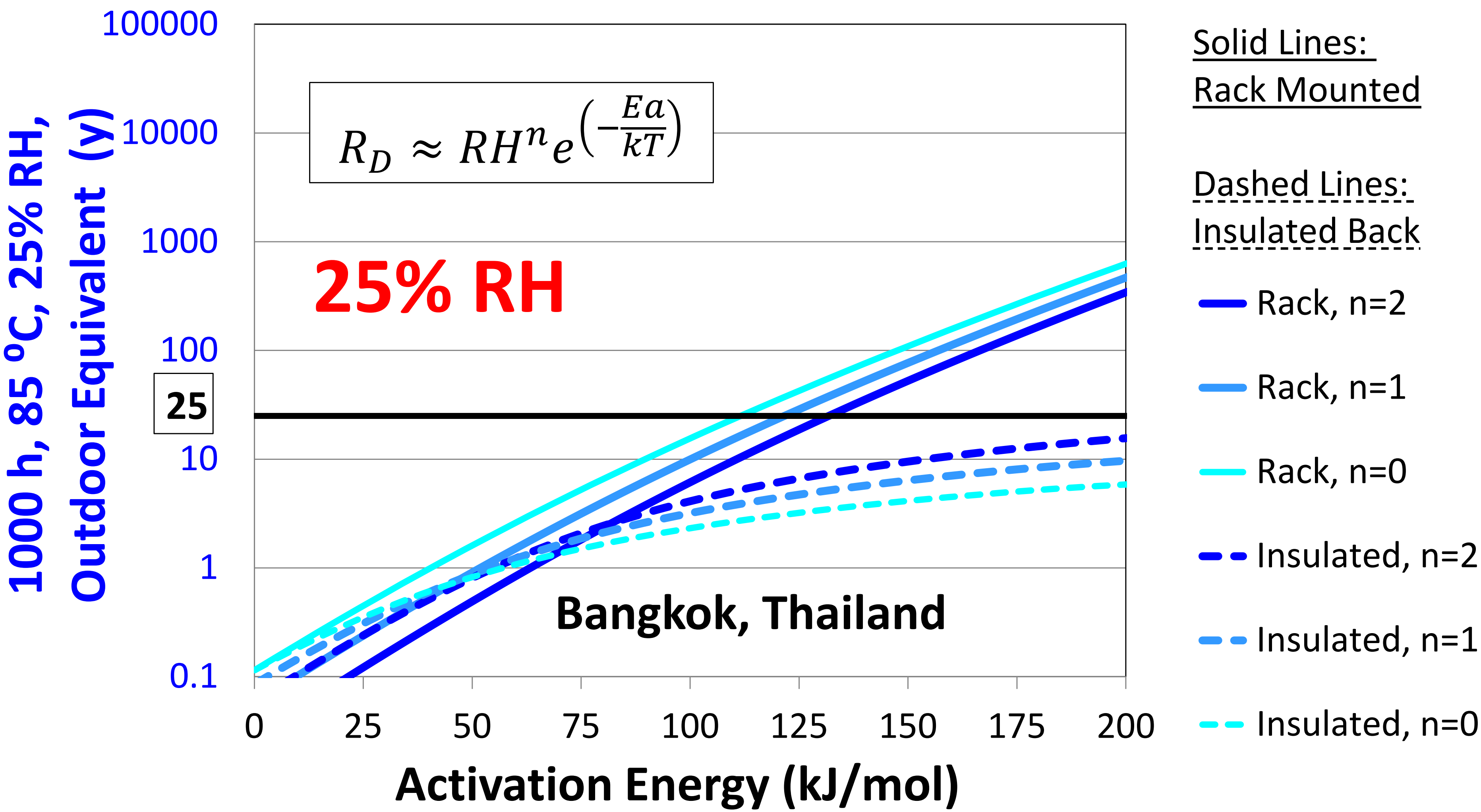
The unknown humidity dependence results in a 1000× uncertainty in the acceleration

Good RH Choice Reduces Uncertainty

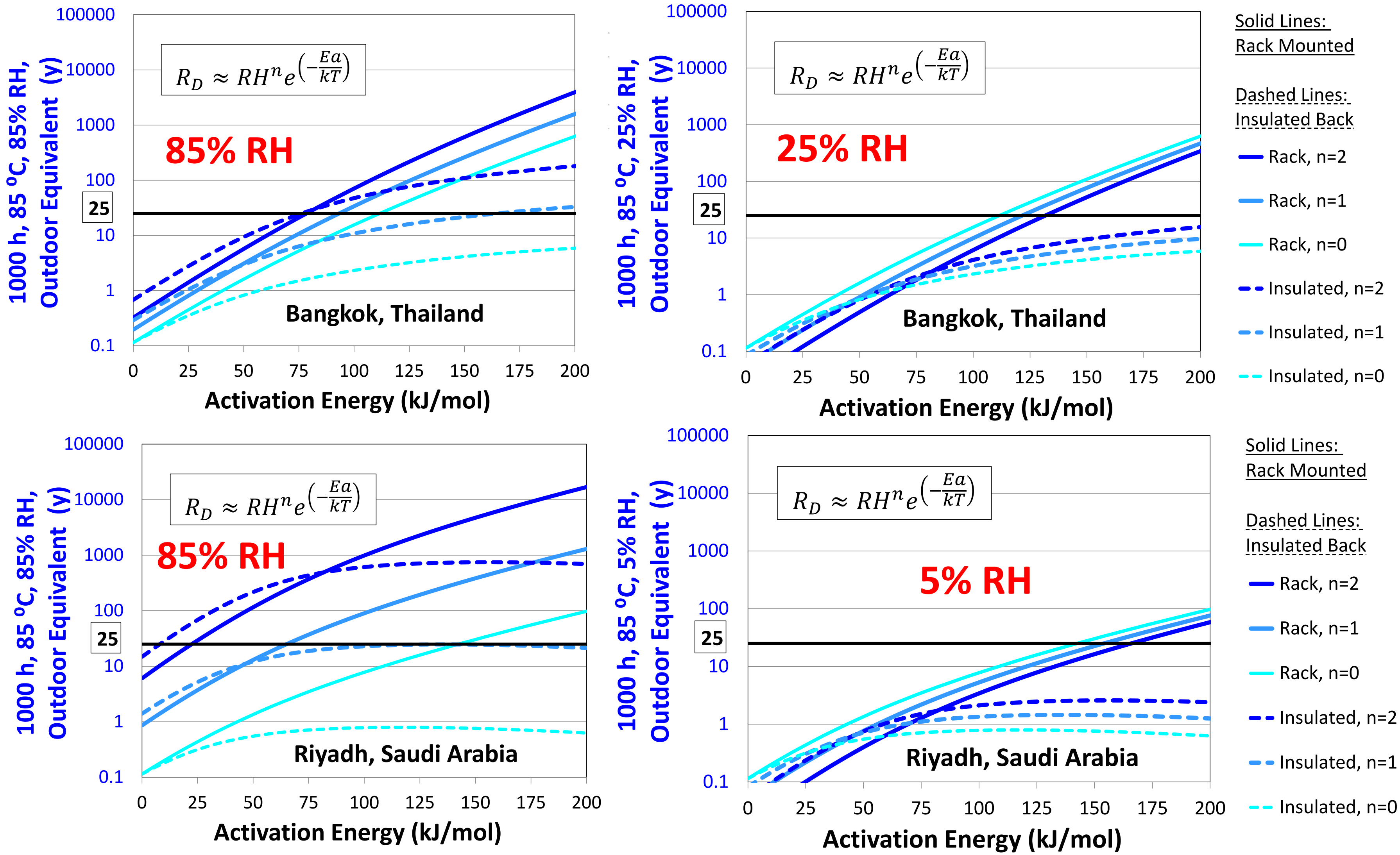


Testing using a chamber humidity of 5% vs. 85% significantly reduces the variability in the acceleration factor.

The Highest RH You Might Want is ~25%



Damp Heat vs. Low RH Stress Test



Without knowing the moisture induced degradation kinetics, it is better to use a low RH and accelerate processes principally by thermal acceleration.

Conclusions

- With respect to PET hydrolysis, 85 ^{o}C/85% RH, may be equivalent to hundreds or thousands of years.
- For thermal and/or moisture induced failure, the mounting configuration can be as important as the location.
- Care must be taken in accelerated stress testing to account for the variable relative acceleration of the different degradation modes.
- Choosing the right humidity level for accelerated stress testing can dramatically decrease the uncertainty in the results.

Acknowledgements

Sarah Kurtz

John Wohlgemuth

David Miller

Peter Hacke

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, Feb 26/27, 2013

PID Failure of c-Si and Thin-Film Modules and Possible Correlation with Leakage Currents

Peter Lechner

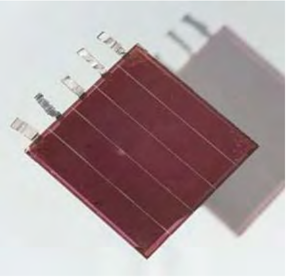
Zentrum für Sonnenenergie- und Wasserstoff-Forschung
Baden-Württemberg (ZSW)
Stuttgart, Germany

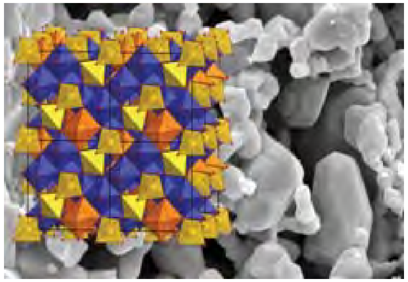
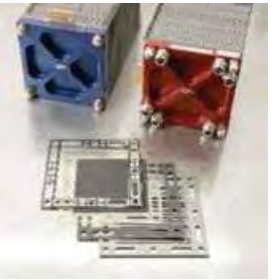
Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW)

ZSW is a non-profit foundation with 200 employees

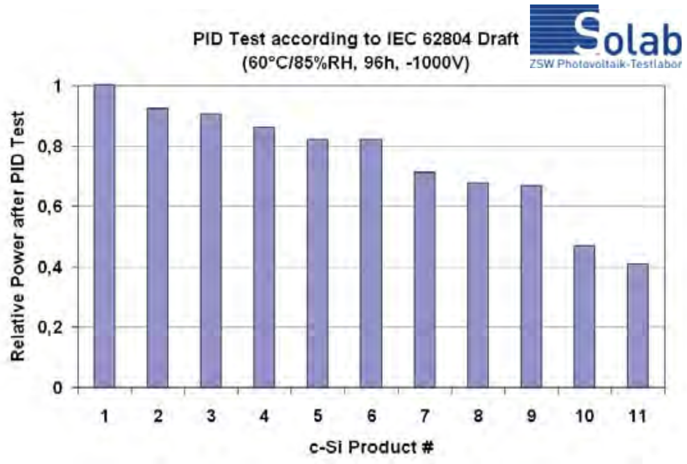
The focus is on
- Photovoltaics – Thin-Film Technology
- Fuel Cells and Hydrogen Technology
- Electrochemical Storage
- Renewable Fuels and Reformers
- System Analysis and Consulting

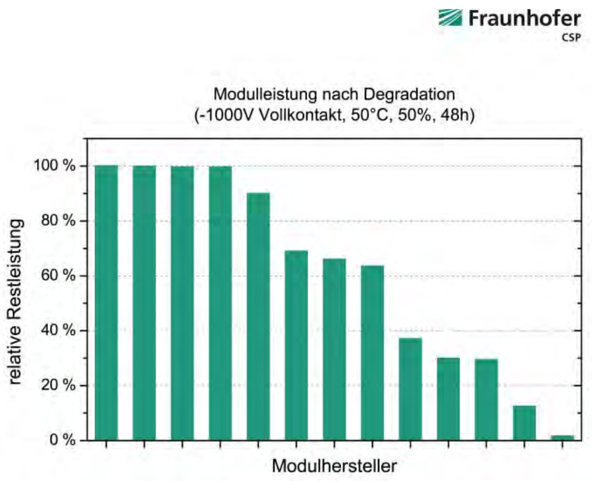
We work on the whole value chain:
From materials science to production and product development.




FAQs:





Source: Fraunhofer CSP, 2012

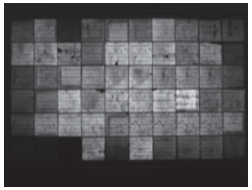
- Relation between different PID lab-tests and PID in the field?
- Is transferred charge a degradation indicator
  => time-to-failure estimation?
- Role of reversible effects?
- Thin-film tests to be based on the IEC Draft 62804 for c-Si?

Outline

- PID failure of c-Si and thin film
- Power degradation
- Evaluation of leakage currents from lab and field
- Does PID match with charge?
- Recovery effects

PID failure of c-Si and thin film modules

	c-Si	Si-TF (a-Si, µmorph) CdTe	CIGS
Degradation effect	Power loss	Power loss; Delamination	Power loss
Defect location	SixNy	TCO	CIGS
Trigger	Leak. Current	Leak. current; Moisture	Leak. current



Approach

Indoor (climate chamber)

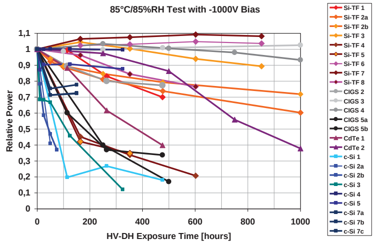
Leakage current (T-, RH-matrix)
Power loss (STC and low light)
Recovery

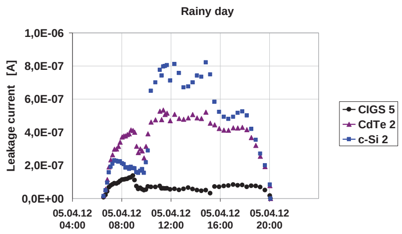
Bias -1000 V

Field (Widderstall)

Leakage current (5min sampling)
Power loss (flasher)

Bias up to -800V (PV- Generator)



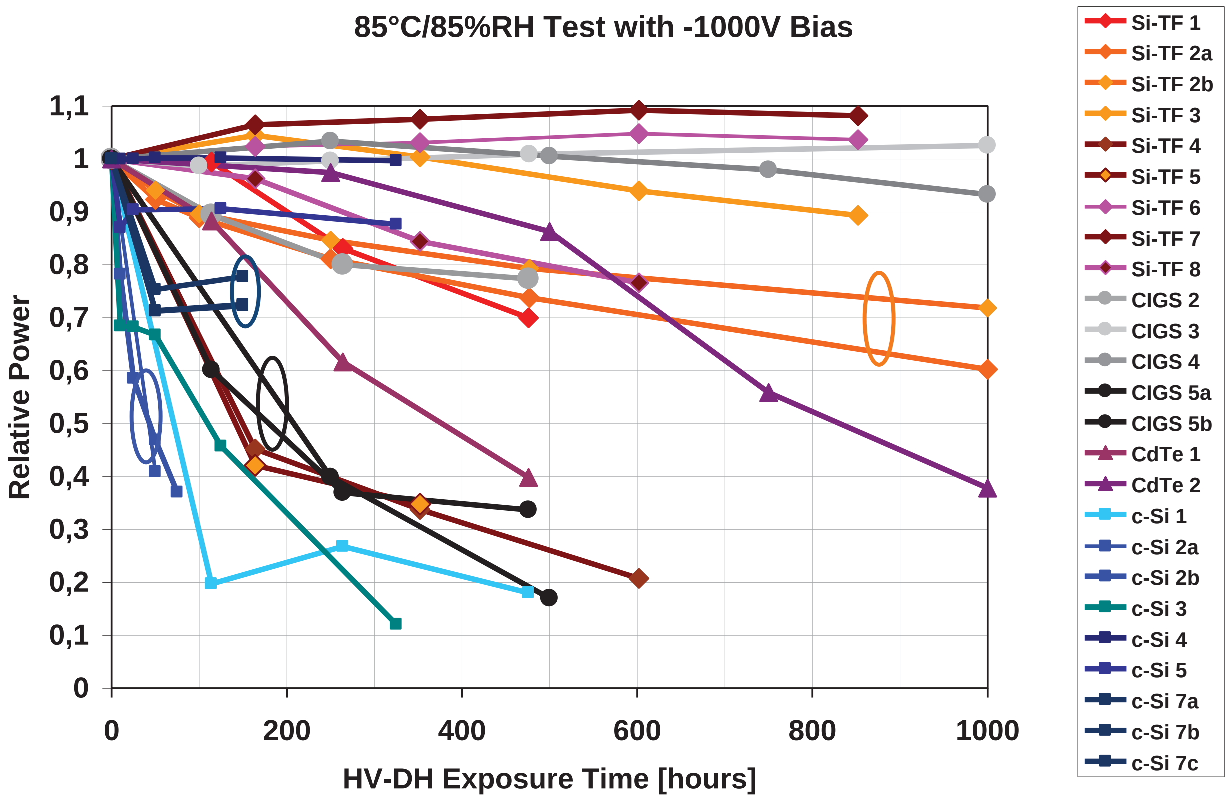


Time-to-PID-failure?

Outline

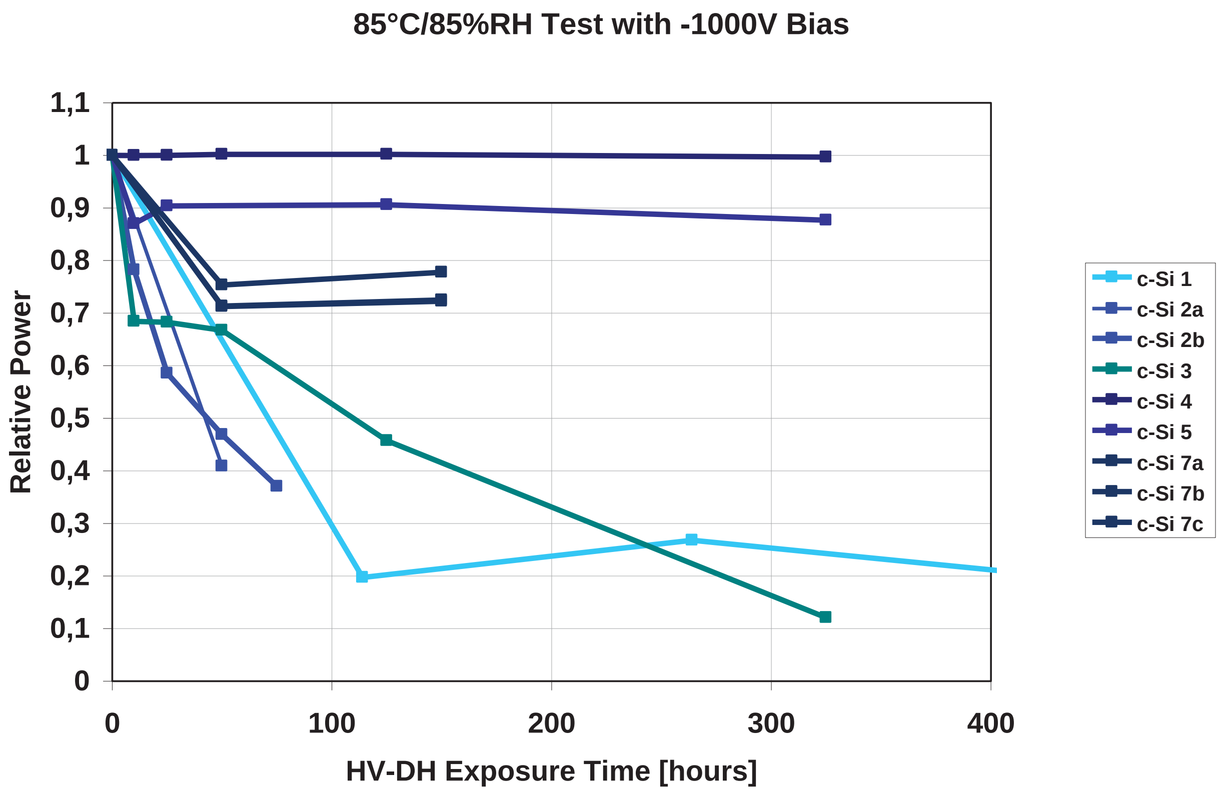
- PID-failure of c-Si and thin film
- **Power degradation**
- Evaluation of leakage currents from lab and field
- Does PID match with charge?
- Recovery effects

Module power after 85°C/85%-PID test: all technologies



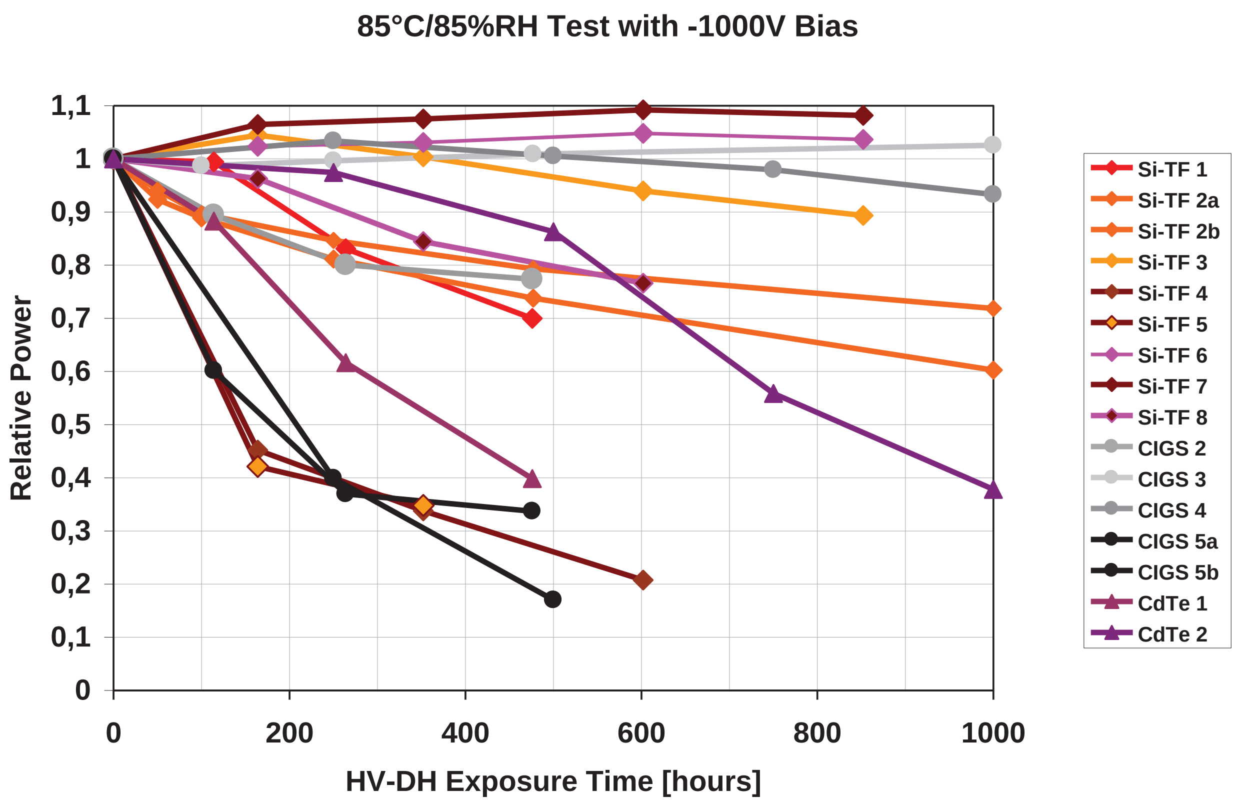
- Wide variation from stable to highly PID susceptible
- Reproducibility of PID failure is quite o.k.

Module power after 85°C/85%- PID test: c-Si only



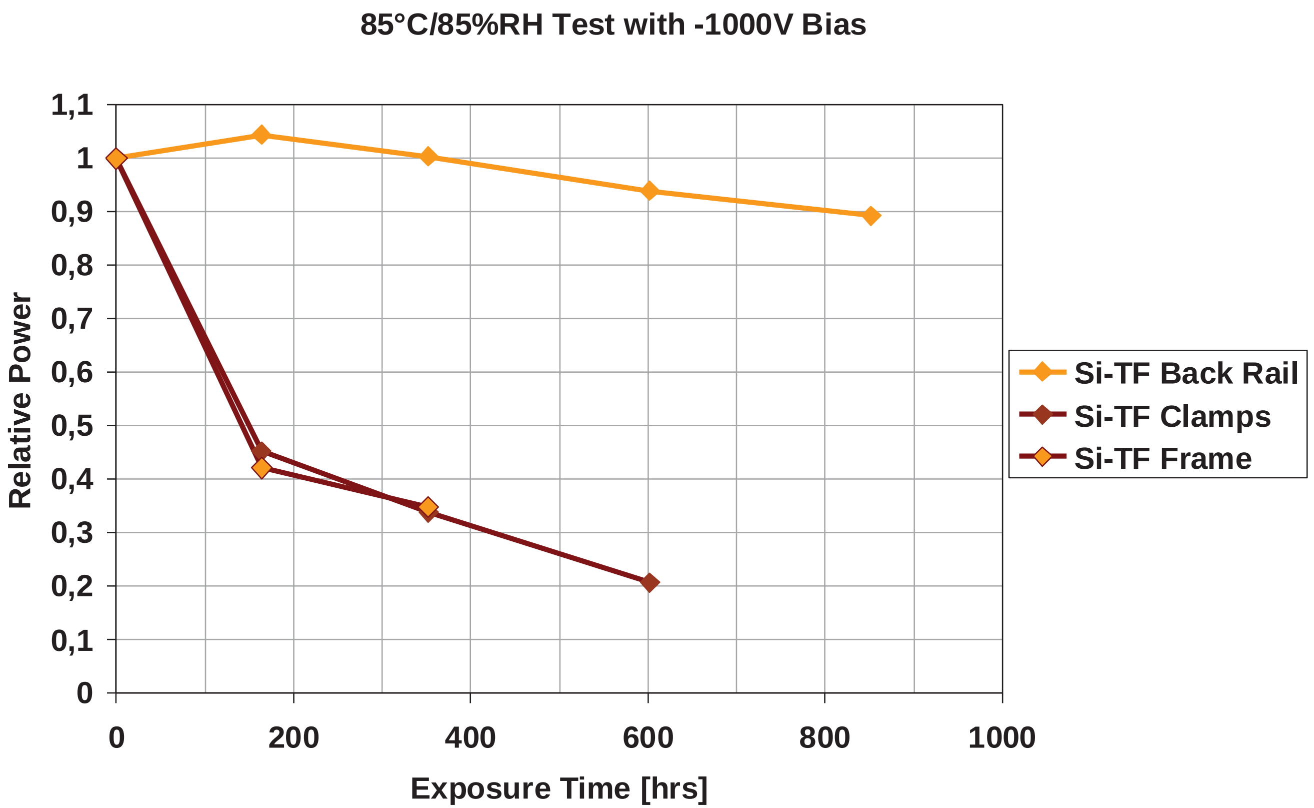
• **Shunting occurs (loss of FF, Rsh, very bad at weak light)**

Module power after 85°C/85%- PID test: TF only



- TCO corrosion occurs for some Si-TF and CdTe products
- Shunting occurs for some CIGS products; no visual defects
- For most of the PID-susceptible TF modules grounding is mandatory

Optimization of PID-resistivity by choice of mounting: Si-TF module

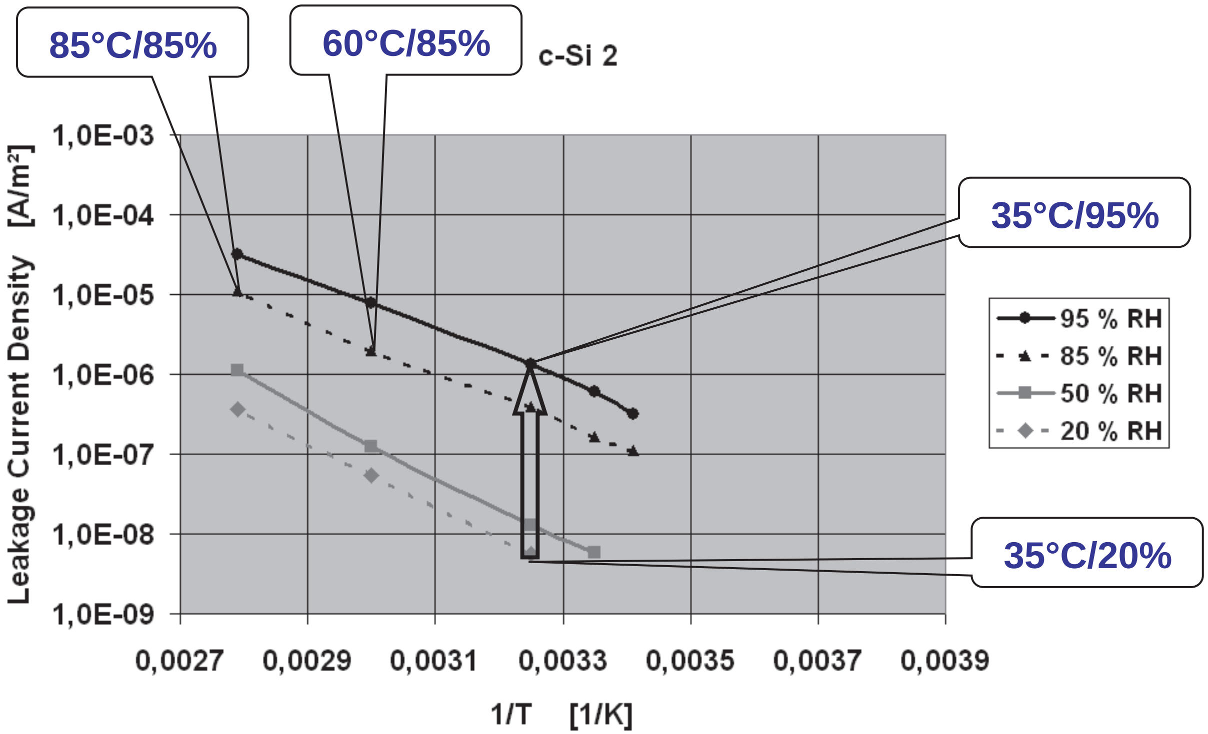


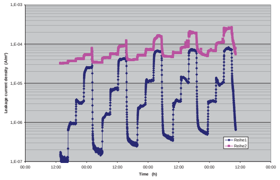
- **Back Rail mounting reduces susceptibility for TCO-corrosion**

Outline

- PID-failure of c-Si and thin film
- Power degradation
- **Evaluation of leakage currents from lab and field**
- Does PID match with charge?
- Recovery effects

Arrhenius plot of leakage currents from the lab:

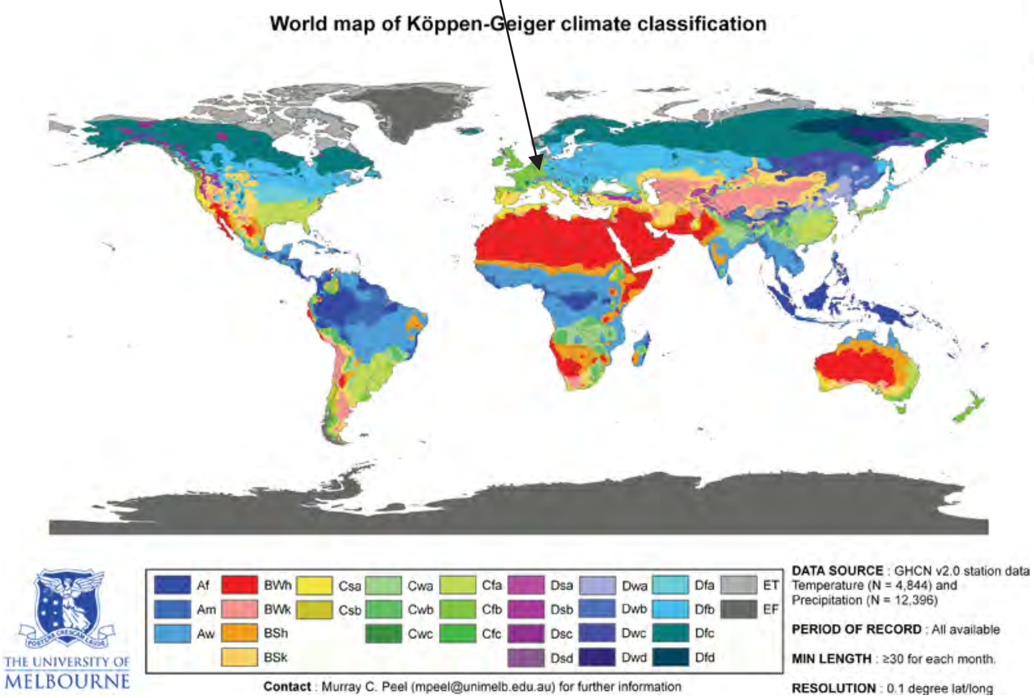


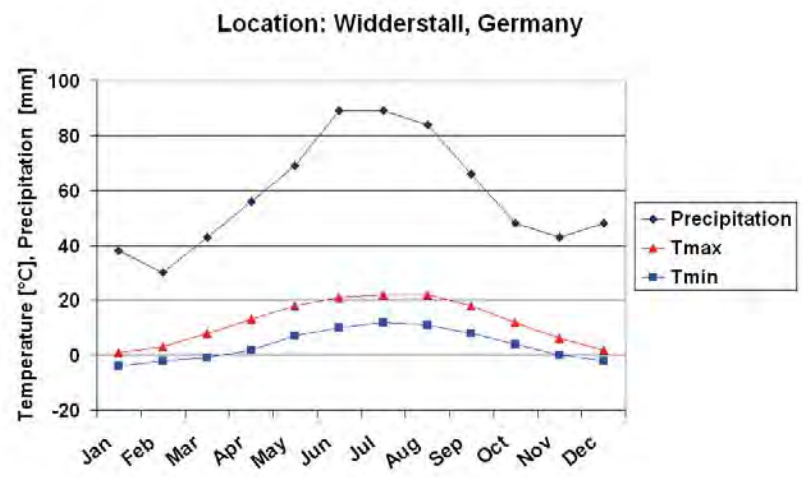


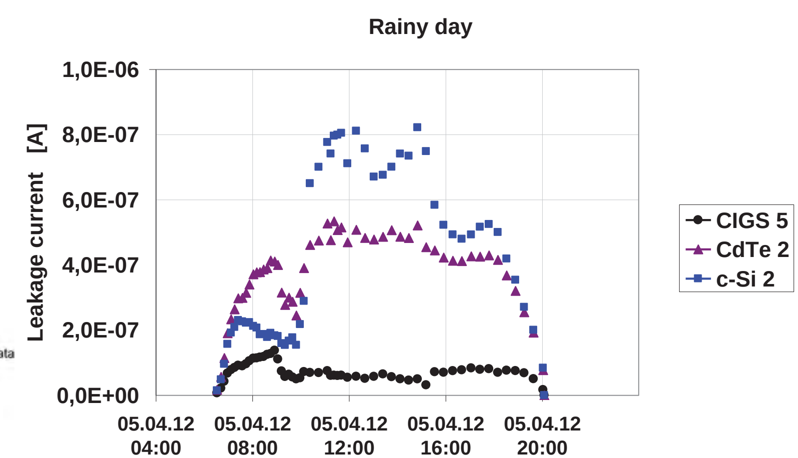
- Activation energy E_a typically between 0.6 and 0.8 eV
- Current is strongly dependent on humidity

Evaluation of leakage currents in the field

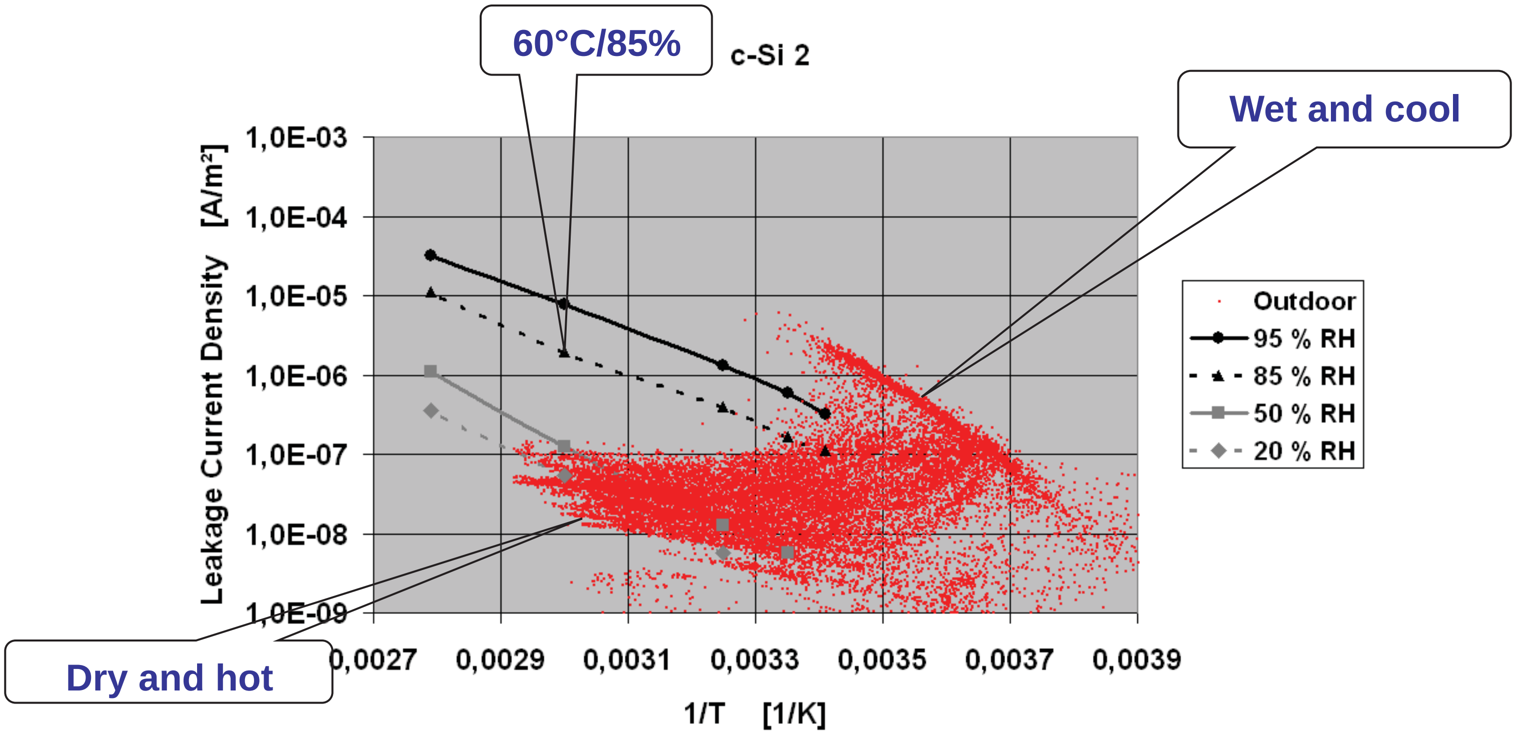
Location: Widderstall, Southern Germany
9.713°E, 48.537°N, 750m AMSL





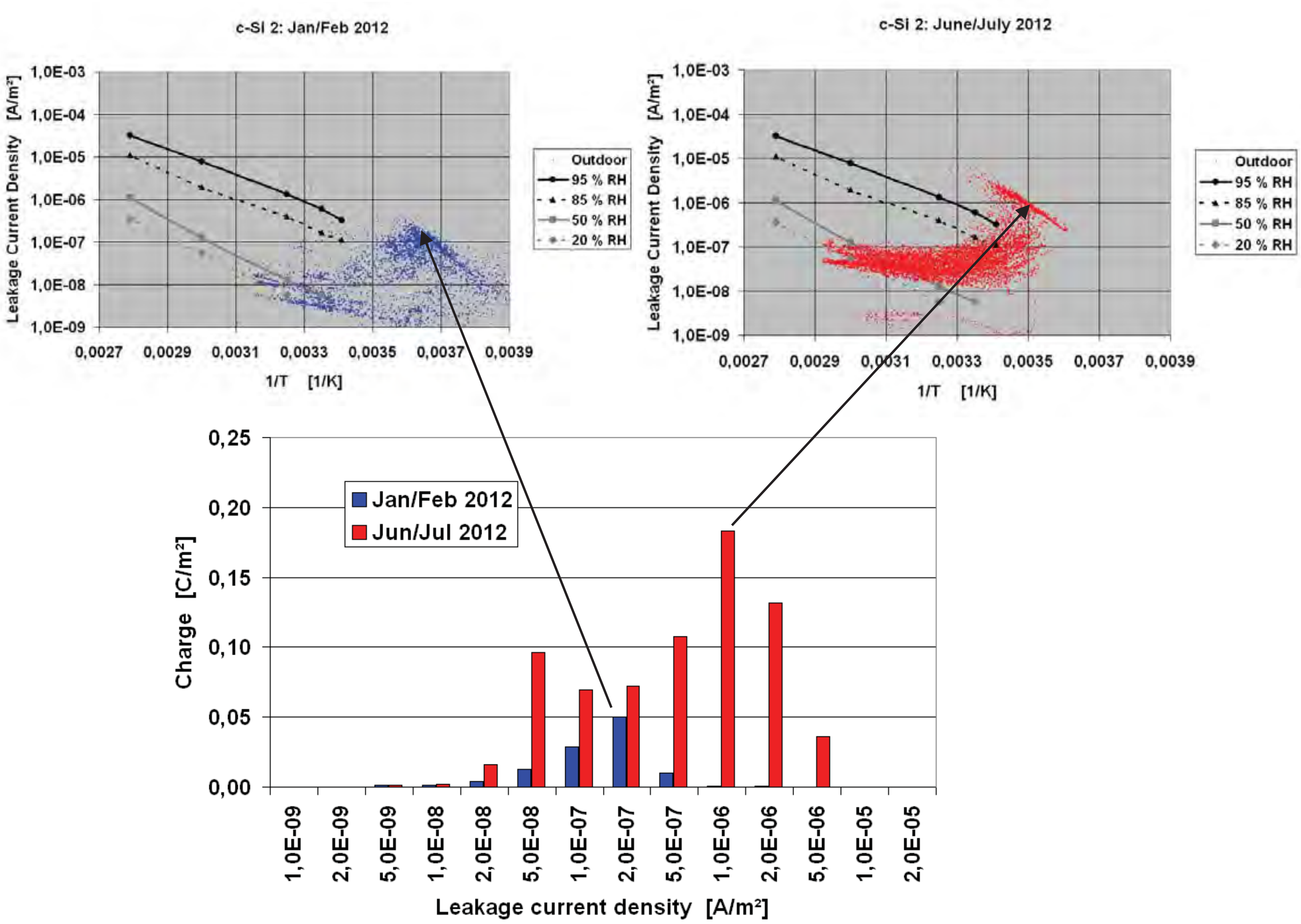


Superposition of chamber and field measurements Outdoor from Jan to Jul 2012



- High currents for wet and cool modules
- Low currents for dry and hot modules
- Moderate “acceleration” at 60°C/85% vs. “wet and cool”

Summer/winter distribution of leakage currents and charge



• **major contribution to transferred charge stems from wet/cool modules**

Outline

- PID-failure of c-Si and thin film
- Power degradation
- Evaluation of leakage currents from lab and field
- **Does PID match with charge?**
- Recovery effects

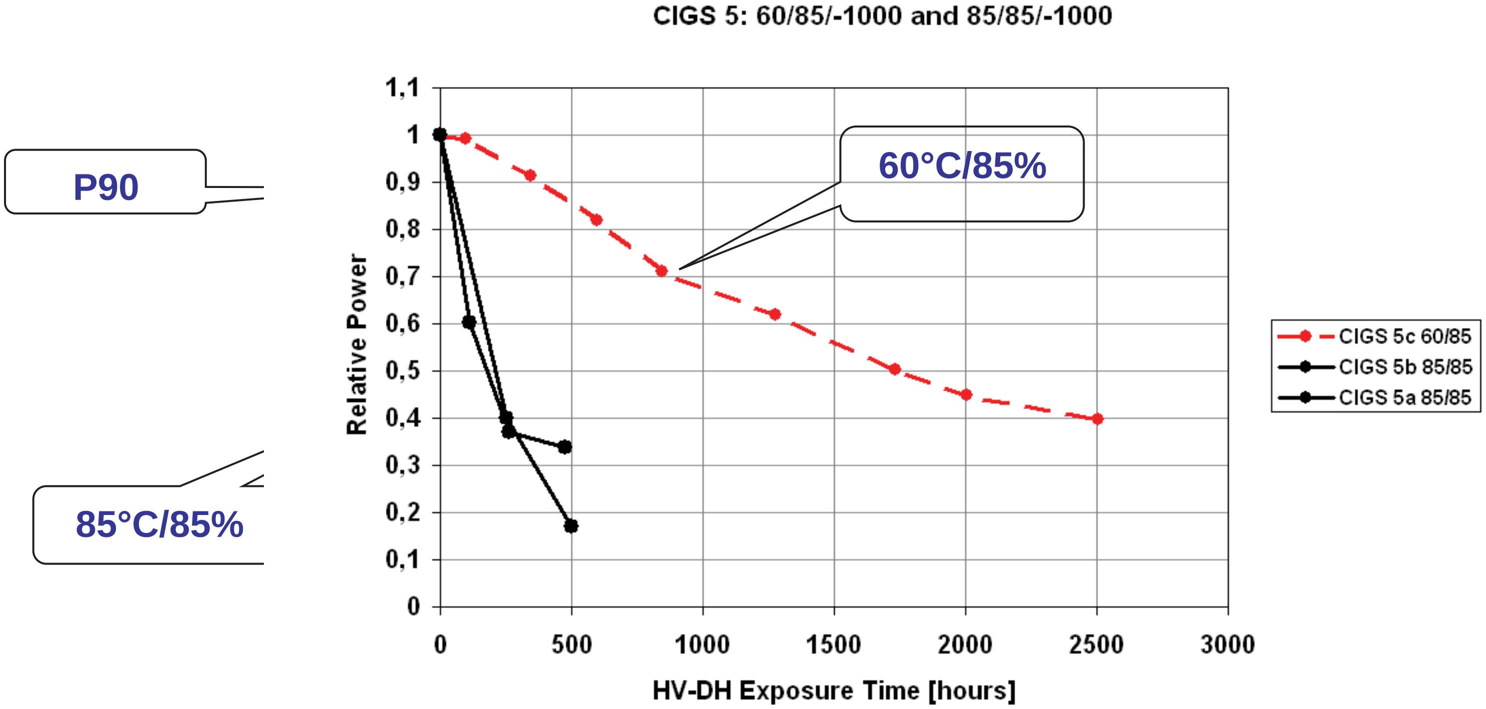
Estimation of time to 90% initial power (P90)

- If charge transfer would be the only PID-trigger -

Module type	Q from 85/85 for P90 [C/m²]	Qd from Outdoor [mC/m²]	Outdoor time)* to Q for P90 [yrs]
c-Si 2	0.6	7.5	0.2
Si-TF 2	33	32	2.8
CIGS 5	1.4	1.3	3.1
CdTe 2	23	6.1	10
CIGS 4	> 87	0.6	> 4*E2
CIGS 3	> 37	0.25	> 4*E2
Si-TF 6	> 300	1.4	> 5*E2

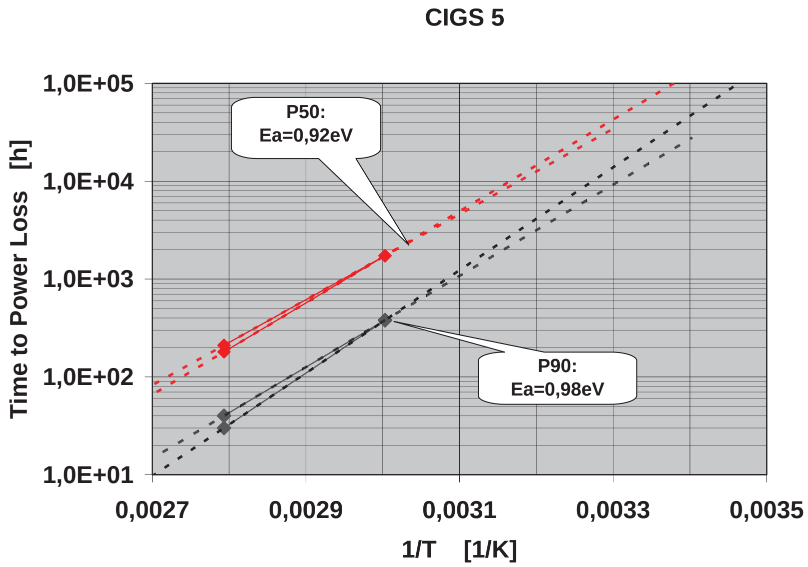
)* valid for location Widderstall, at about -800V Potential

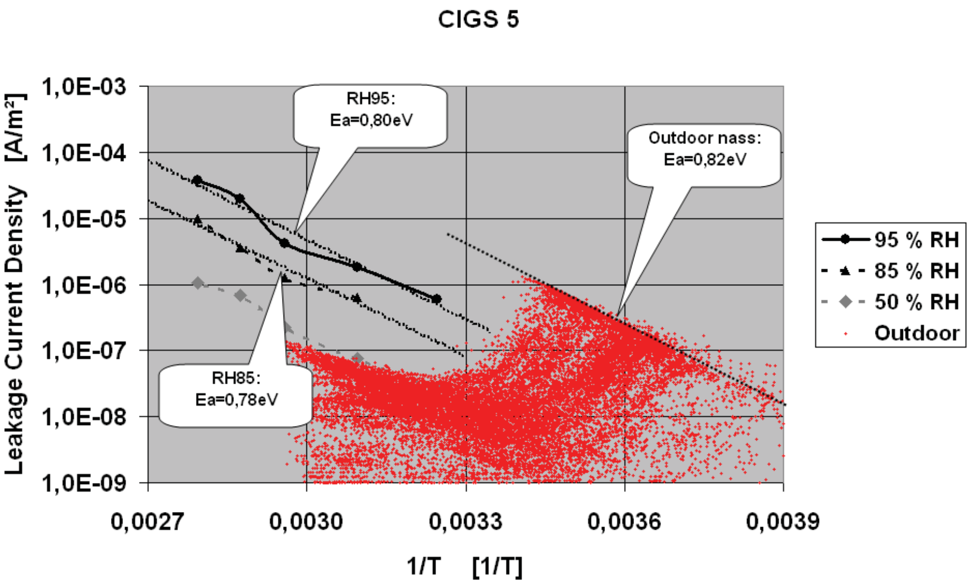
Does PID match with transferred charge?
Example: CIGS 5



Power loss vs. time

Activation energy for power loss and leakage currents CIGS 5



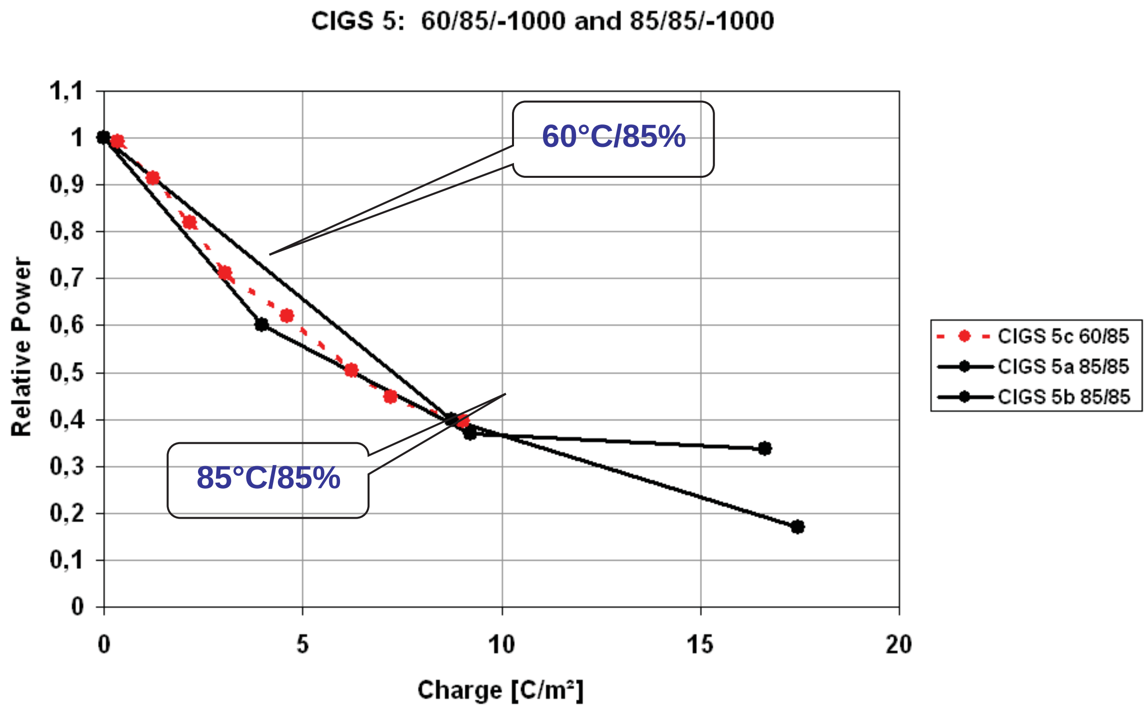


P-loss:
E_a = 0.92….0.98eV

Leakage current:
E_a = 0.78…0.82eV

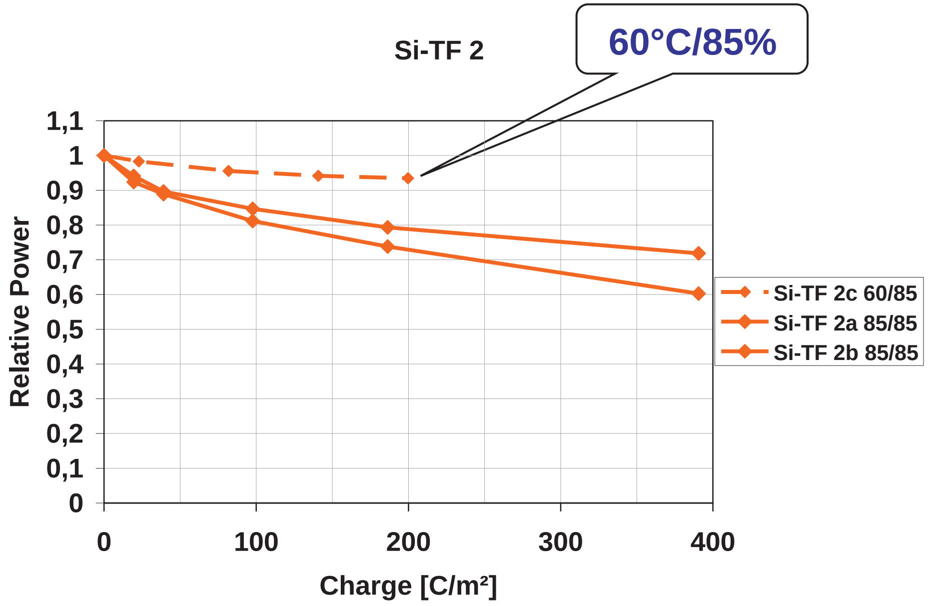
- E_a similar for P-losses and temperature activated leakage current

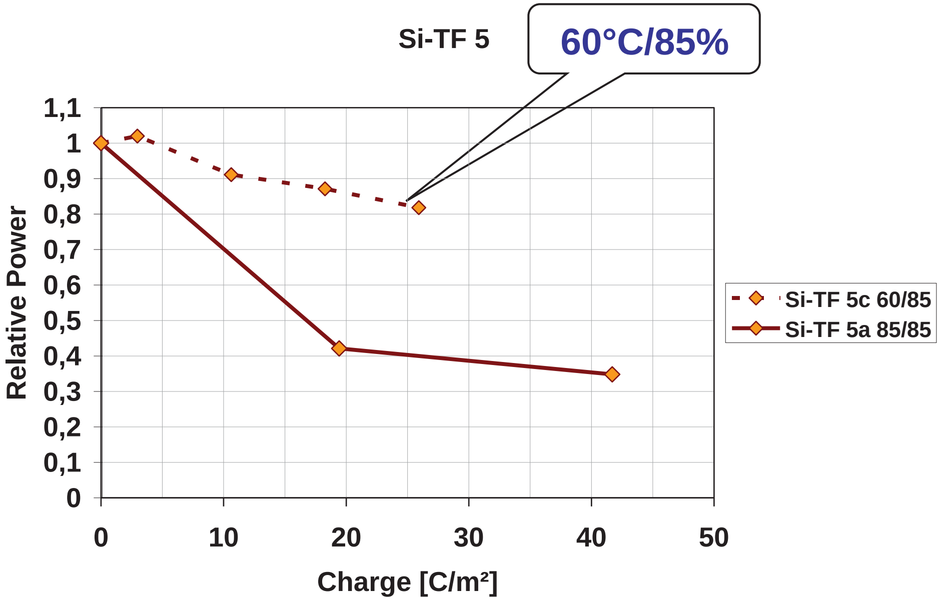
PID vs. charge
CIGS 5



- **Match of PID with transferred charge**
- **Field sample also seems to match with charge (not shown)**

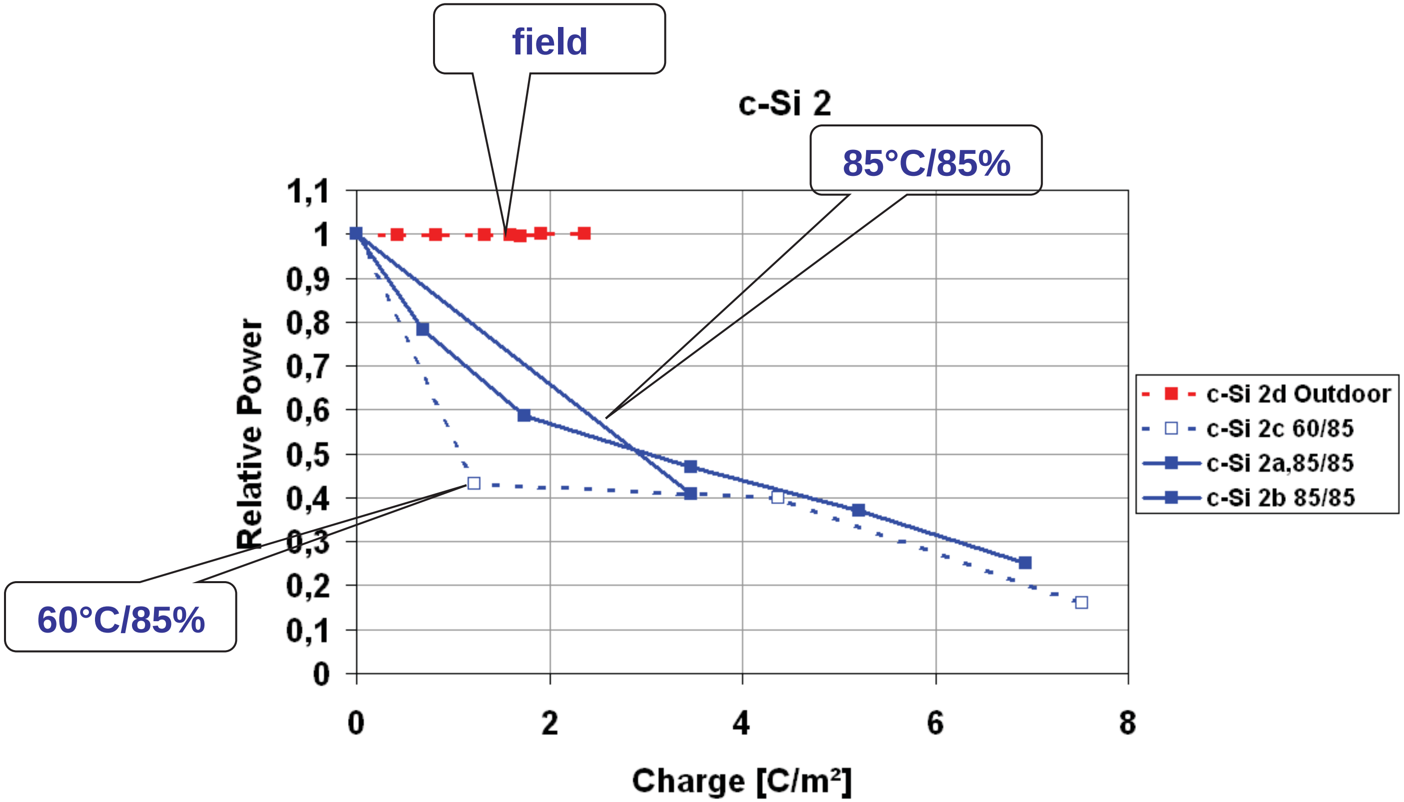
Does PID match with transferred charge?
(2) Si-TF





- No match of PID (TCO-corrosion) with transferred charge for Si-TF
- E_a = 1.1 to 1.2eV for power loss, much higher than E_a for leakage current
- Moisture ingression probably limiting at low temperature

Does PID match with the transferred charge?
(3) c-Si

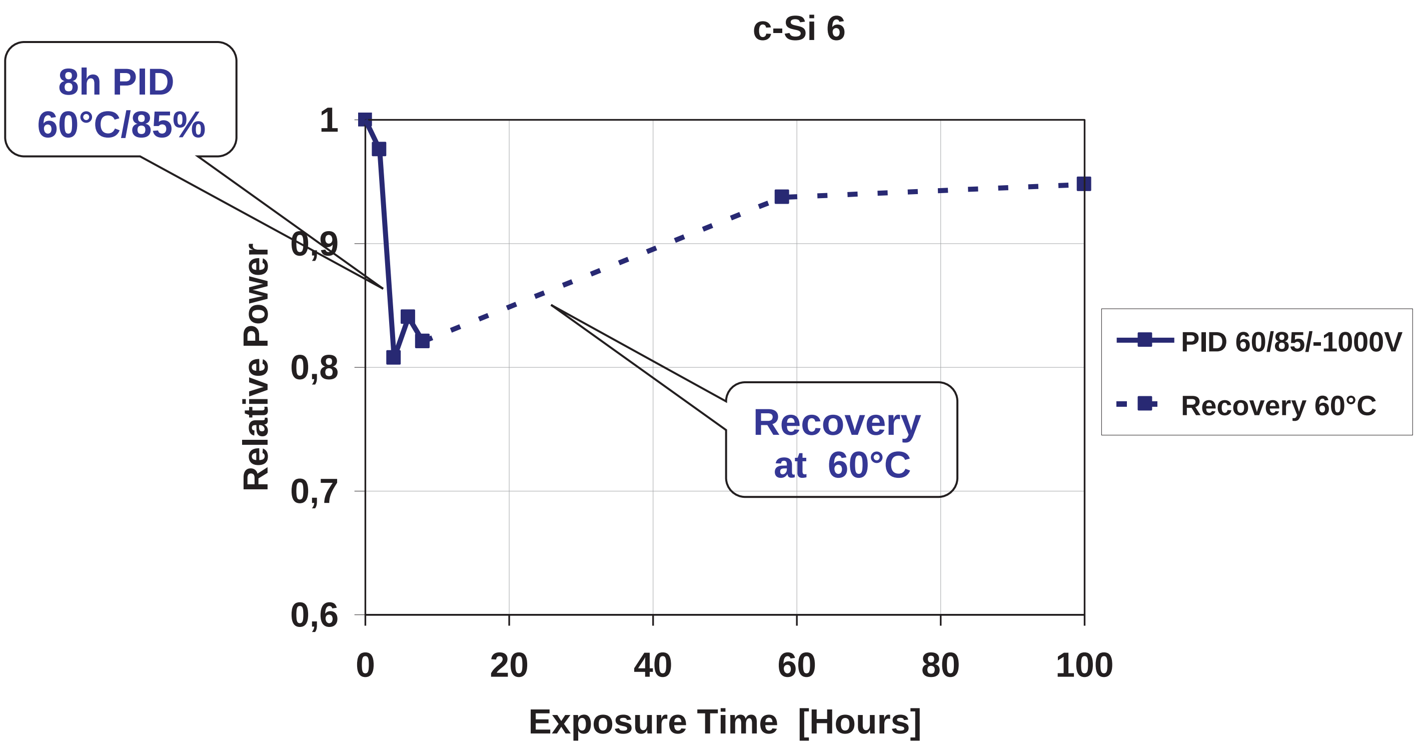


- Possible match of PID with charge for 60/85 and 85/85
- No PID after more than 1 year in the field
- Module type failed IEC62804 test

Outline

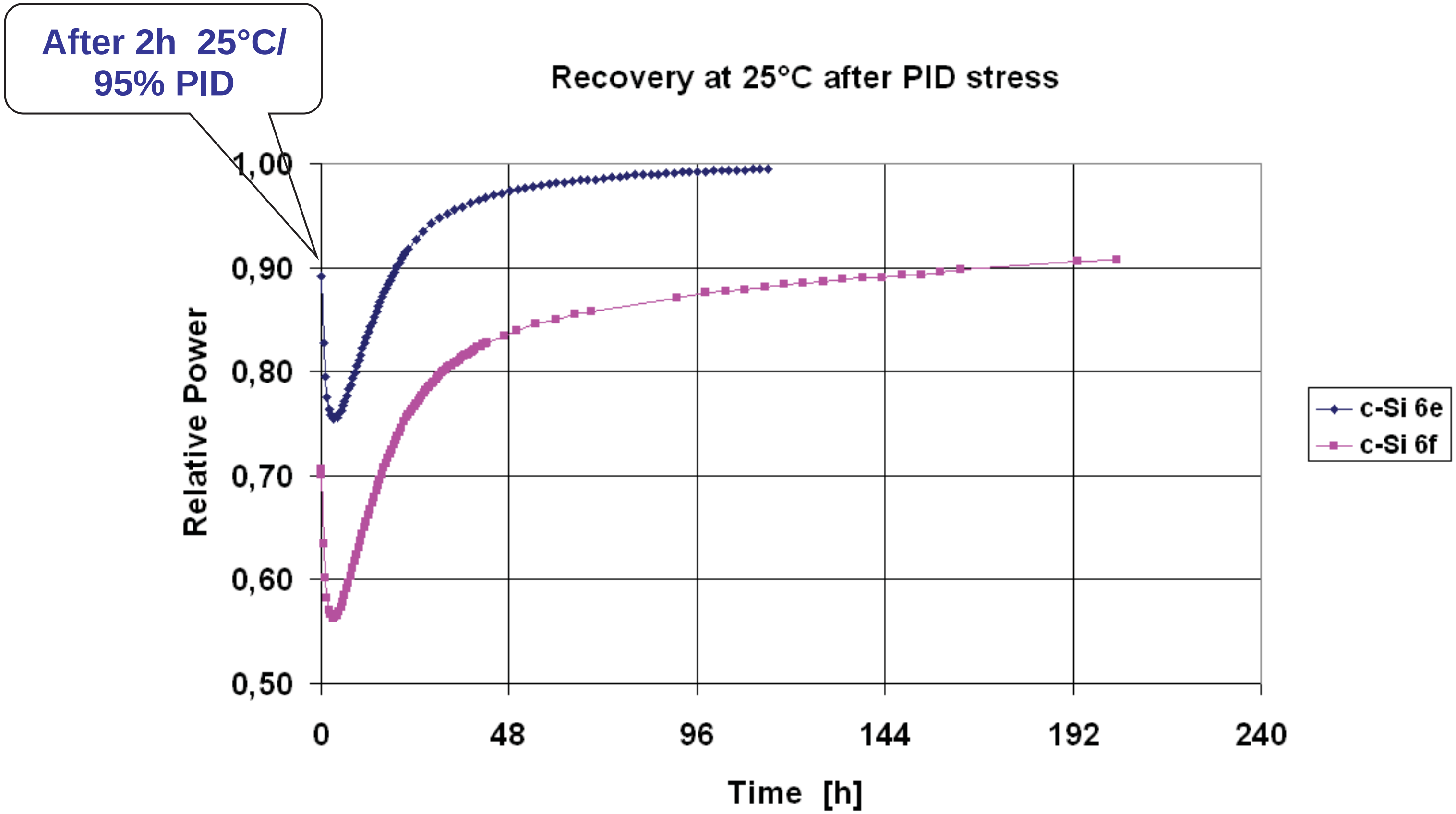
- PID-failure of c-Si and thin film
- Power degradation
- Evaluation of leakage currents from lab and field
- Does PID match with charge?
- **Recovery effects**

Thermal recovery of c-Si after PID stress



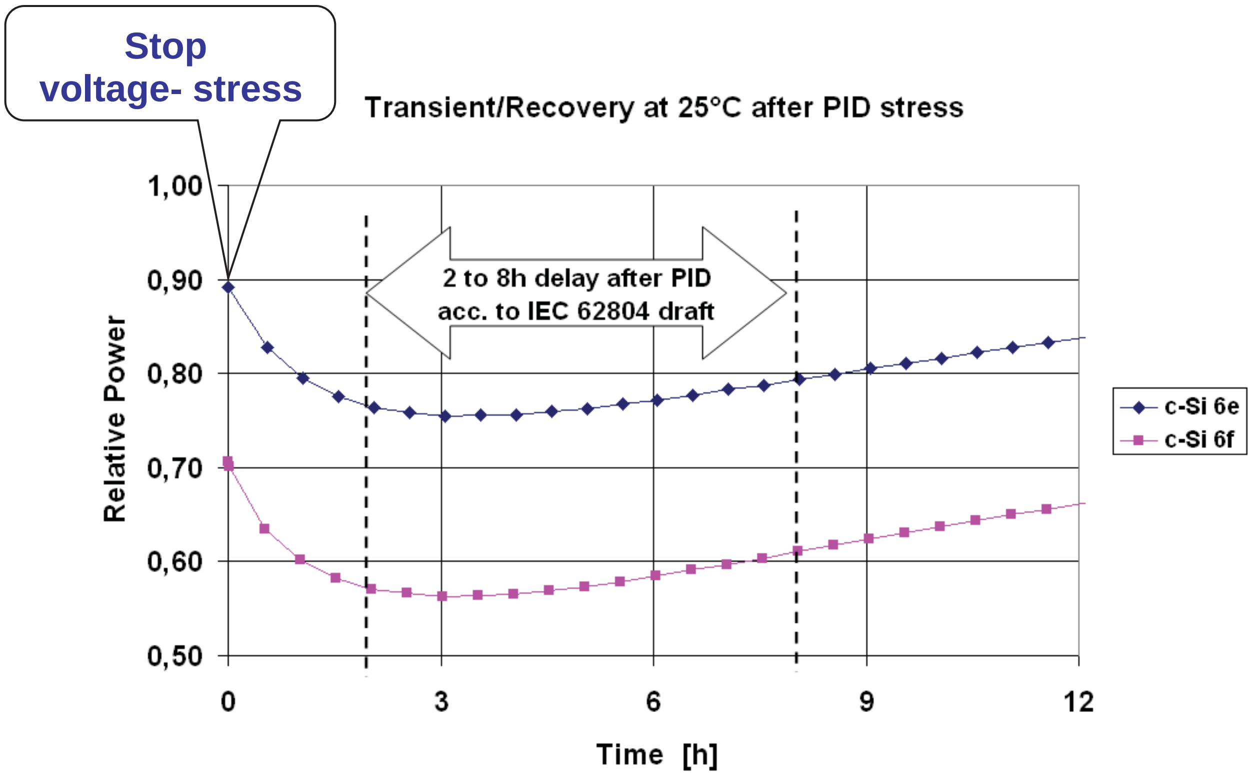
- Thermal recovery at low temperature is relevant for c-Si
- Is important for the field behaviour of c-Si:
  balance between periods of leakage current driven PID
  and temperature driven recovery

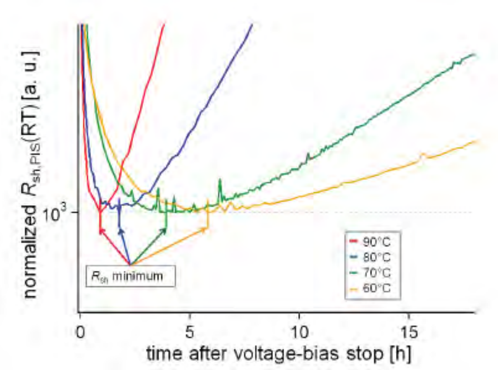
Thermal recovery of c-Si after PID stress (2)



- Relevant recovery even at 25°C possible
- Acceleration at higher T
- E_a is 0.7 to 0.8 eV

Thermal recovery of c-Si after PID stress (2)



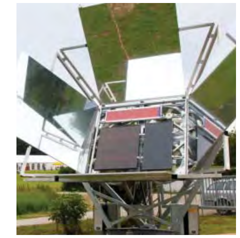


C. Taubitz, EUPVSEC, 2012

- After stop of PID: power degradation continues for hours
- Within the 2 to 8h period after stress (62804 draft): power is not stable

Conclusions and summary

- **Leakage currents are**
  - **- temperature activated with Ea 0.6 to 0.8eV and**
  - **- significantly driven by humidity**
- **CIGS: Correlation of PID (60/85 and 85/85) with transferred charge**
- **Si-TF: No correlation of lab-PID with transferred charge; moisture ingression might be limiting for TCO-corrosion**
- **c-Si: - Correlation with transferred charge definitively not true for PID in the field**
  - **- Thermal recovery from PID at low temperature can be relevant: needs to be addressed in the IEC Draft?**
  - **- Thermal recovery might reduce the “acceleration” of stress tests at high T**
  - **- Balance of leakage current driven degradation and thermal recovery controls PID for c-Si in the field**



Thank you for your attention

German BMU funding under 0325070B is acknowledged

Thanks to the ZSW colleagues supporting this work

www.zsw-bw.de

QA TG5: UV, temperature and humidity

http://pvqataskforceqarating.pbworks.com/ ⇒ goto 5. UV, temperature, and humidity

Wednesday, February 27, 11:00-11:15

Task-Force coordinated by:

Michael Köhl, Fraunhofer ISE, Germany
michael.koehl@ise.fraunhofer.de

Kusato Hirota, Toray Industries, Inc., Japan *
Kusato_Hirota@nts.toray.co.jp

Jasbir Bath, SEMA, USA*
jasbir_bath@yahoo.com

*Presented by David Miller, NREL, David.Miller@nrel.gov

Needs and Approaches

- Service life assessment needs to take UV-degradation seriously into account (up to 3000 kWh/m² in the desert for 25 years)
- Different suitable artificial UV radiation sources are available for ALT with varying spectral distribution of the irradiation
- Different spectral sensitivities of the tested materials have to be expected
- Are comparable tests in different labs possible ?
- Can we accelerate tests by increasing UV intensity?
- Can we accelerate tests by increasing the sample temperature?

Present Activities

- Comparison of different light sources
- Test protocols for mini-modules in Japan
- Round Robin testing of encapsulants
- Round Robin testing of light sources and back-sheets
- Modelling the UV – irradiation locally and globally

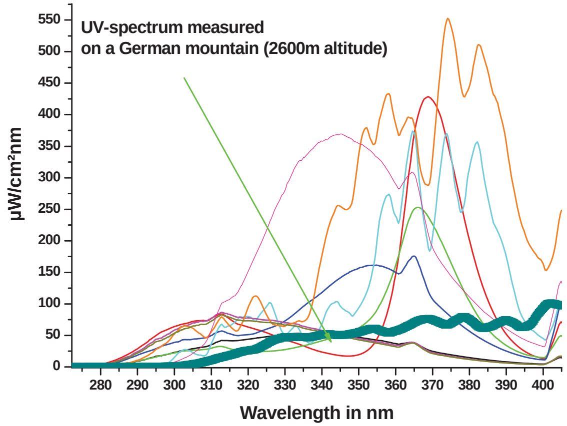
SOPHIA UV – Round Robin Light and Back-Sheets

- Aim:

Comparison of the effect of different UV- sources on glass/encapsulant/backsheet laminates with different materials

- Spectral distribution of different UV-light sources leads to different degradation on different materials

- Stronger UV testing needs better definition of the test conditions

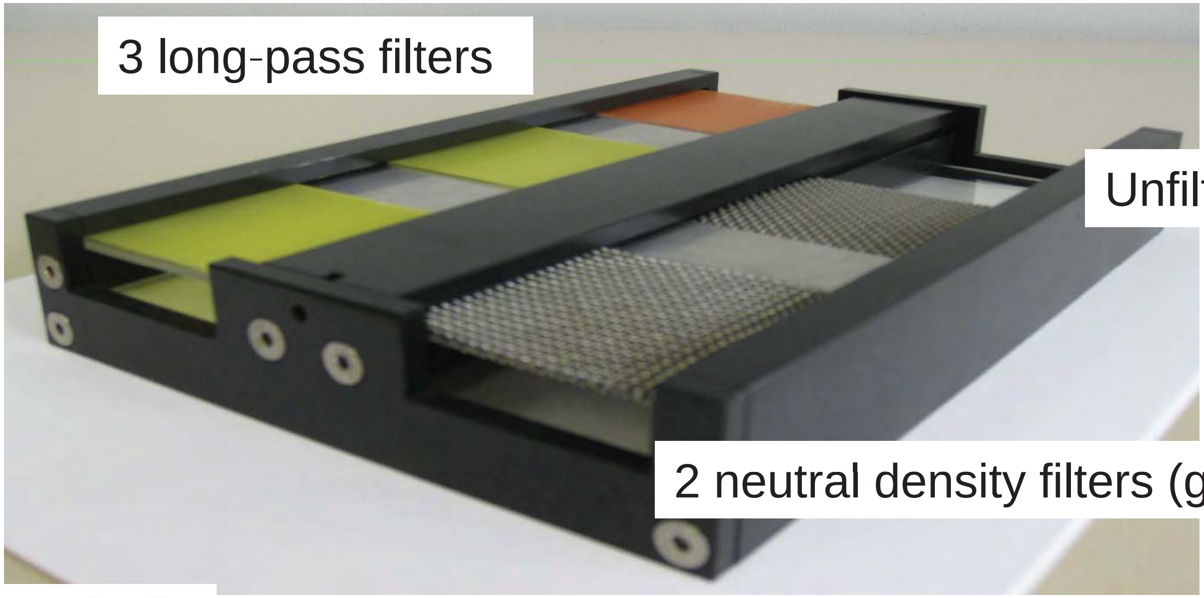


Spectra of radiation sources used in PV testing

Fraunhofer ISE

SOPHIA UV – Round Robin Samples

- Samples:
  - manufacturers provide different back-sheet types
  - ISE produces laminates (usual glass and EVA, 13x20 cm) and 300 sample holders (till end of February)



SOPHIA UV – Round Robin Procedure

European Research Infrastructure

- Time frame: September 2013
- Samples:
  - manufacturers provide different backsheet types
  - ISE produces laminates (usual glass and EVA, 13x20 cm)
  - direct radiation on the back side and on the front glazing
- Testing procedure:
  - 2 temperature levels: 60°C, 80°C (e.g.) (Assessment of sample temperatures)
  - Irradiation: integral UV dose: min. 120 kWh/m2
  - Light sources and (spectral distribution) characterised radiometrically (Fluorescence, Metal-halide, Xenon)
  - 3 longpass and 2 neutral density filters provided by ISE

UV – Round Robin Procedure

- Characterisation procedures after 0, 30, 60, 120 kWh (when available):
  - Spectral hemispherical reflectance (UV-VIS-NIR)
    Calculation of Yellowness Index or adequate degradation indicator
  - Raman / Micro-Raman spectroscopy
  - FTIR-ATR measurements for BS
    Calculation of carbonyl-index
  - Optical microscopy/AFM investigation for microcracks in BS
  - Fluorescence for encapsulants

  - And …..?

SOPHIA European Research Infrastructure

UV – Round Robin Participants

- Backsheet manufacturers
  - Krempel
  - Toray
  - Feron
  - Coveme
  - Dupont
  - Toppan printing
  - Dunmore
- Test labs
  - ISE
  - JRC
  - Fiti
  - ITRI
  - KTI
  - NREL
  - Ametek
- Encapsulant: UV transparent EVA
- Small number of TPSE (given adherence to back-sheet required)
- Glass: Interfloat

UV – Round Robin Procedure

- Results
  - Differences of degradation in different labs
  - Rough idea about spectral sensitivity of materials
  - Proven UV-stability
  - Acceleration possibilities by temperature increase
  - Base for new materials/modules standard

UV – Round Robin Schedule

- Preparation and Testing

  Purchasing of components (filters, etc) is finished

  Back-sheet materials are collected

  Production of Mini-modules and filter-holders in March 2013

  Distribution of samples to test labs beginning of April 2013

  Testing till August 2013 (at least 120 kW/m²)

  intermediadte telecons or meetings at NRELMRW, TC82 WG2 meeting)

- Final characterisation of the samples and evaluation of data by Fraunhofer ISE August - September 2013

- Final discussion of the results during PVSEC2013 or fall meeting of TC82 WG2

Overview of the QA TG5-Japan Activities

Objectives:

(1) Develop the procedure for a suitable UV weathering test using mini-modules.
Factors during the test: irradiation intensity, temperature, humidity
Experiment will help determine: test duration + characteristics to measure

(2) A combination test or a sequential test series (if appropriate).
UV weathering + Dynamic Mechanical load test
UV weathering + DH Test

Provisional schedule:

- 4 cell mini-module test 2000 cumulative hours: 2013 June
- Examination of UV weather resistant test of 1 cell module: 2013 October
- Examination of a compound or sequential test: 2013 October
- International proposal for a new comparative UV weathering test system and certification including the test of a full-size module, a mini module, and materials: 2014 May.

UV weathering test of 4-cells small size module

QA Task-5 Japan

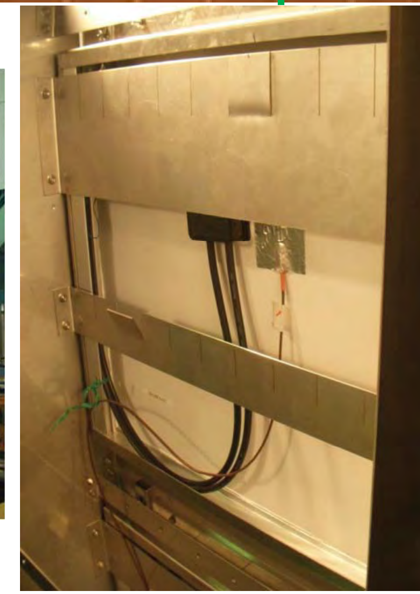
Irradiance ・・・ 90 W / m² （UV 300-400nm）
Nearly **2x UV** （ASTM G173 **Xenon Lamp**）

Chamber temp. ・・・・・ **65 ℃**
Chamber humidity. ・・・ No Control
（ typical **1 –10％RH**）

Test Modules ・・・ 4-cells, polycrystalline Si
Termination ・・・ Open circuit

Backsheet ・・・ Multilayer laminated PET

Encapusulant ・・・ EVA (all: fast cure)
EVA A ・・・ Within the shelf life
EVA B ・・・ Over the shelf life

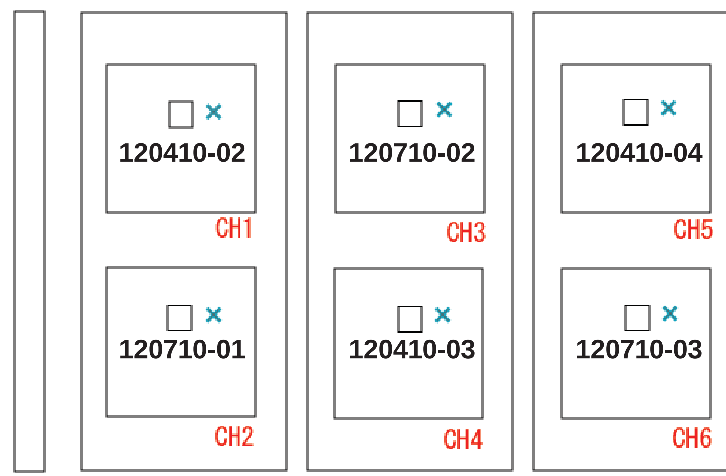


Sample ID and Test sequence

ID	EVA	UV330h 1stRUN	UV660h 2ndRUN	UV990 h 3rd RUN	UV1320 h 4th RUN
120410-01	A	Control module			
120410-02 (CH1)	A	Front side	→	→	Back side
120410-03 (CH4)	A	Front side	→	→	Back side
120410-04 (CH5)	A	Back side	Front side	→	→
120710-01 (CH2)	B	Front side	→	→	Back side
120710-02 (CH3)	B	Front side	→	→	Back side
120710-03 (CH6)	B	Back side	Front side	→	→

＊ The front or back side is irradiated

Module layout in the UV chamber

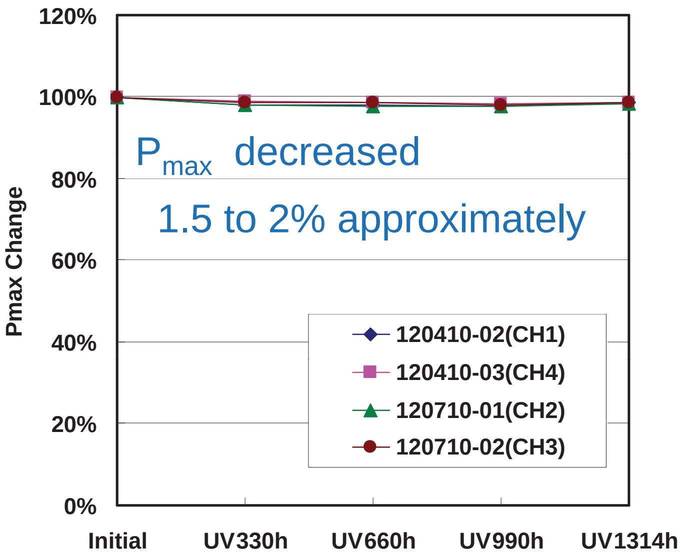


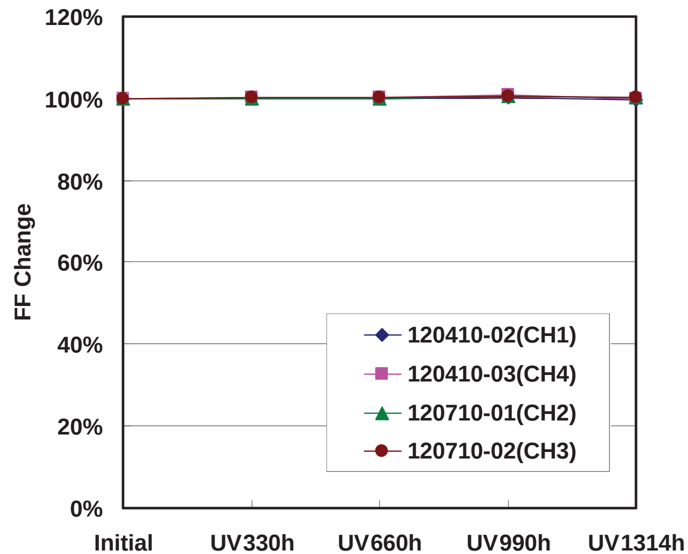
X: Thermocouple gage
□ : Junction BOX

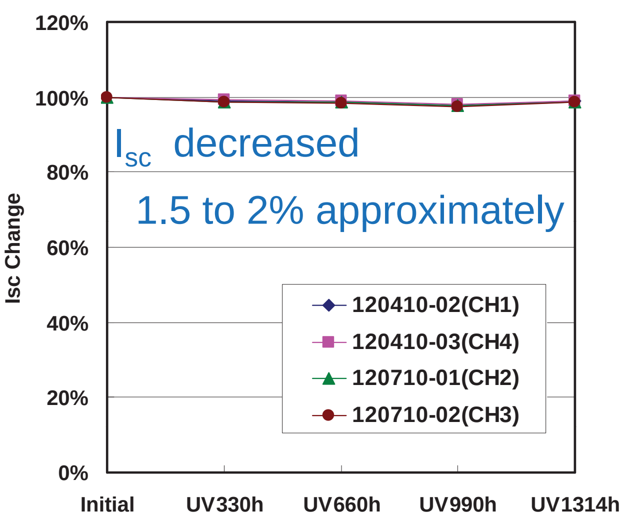
Output power performance

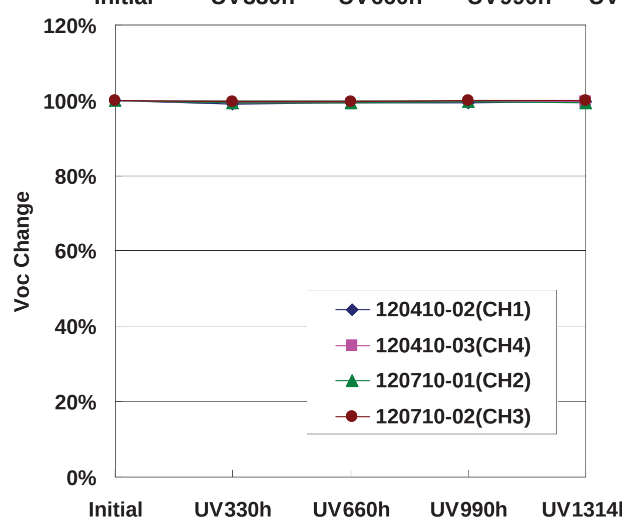
QA Task-5 Japan

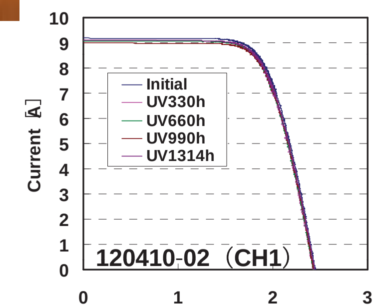
Irradiation on Front :990h + on Back :324h

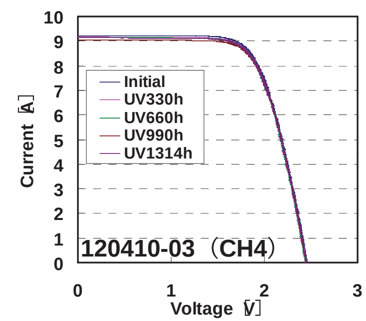


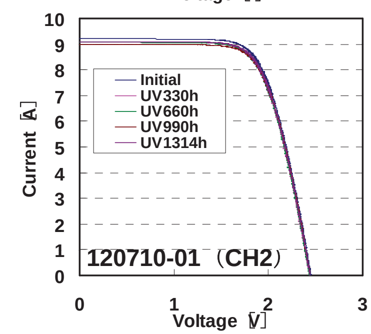


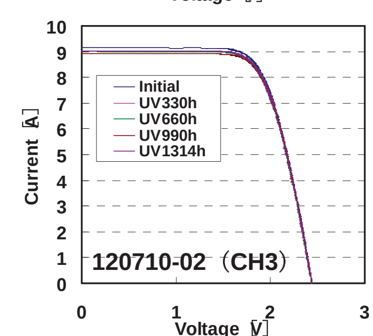












No major performance loss.

I_{sc}↓ with P_{max} ↓ is consistent with encapsulation discoloration.

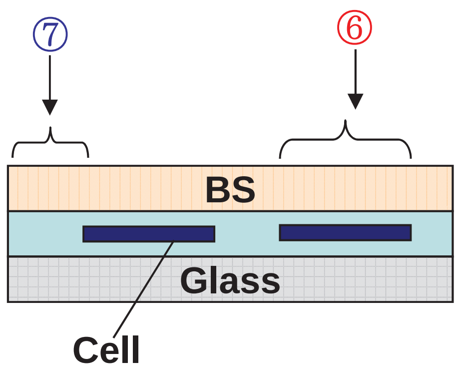
Discoloration of the Backsheet

QA Task-5 Japan

Measurement position

＊⑦ measured at 990hrs,1314 hrs only

Measurement position (Cross sectional view)



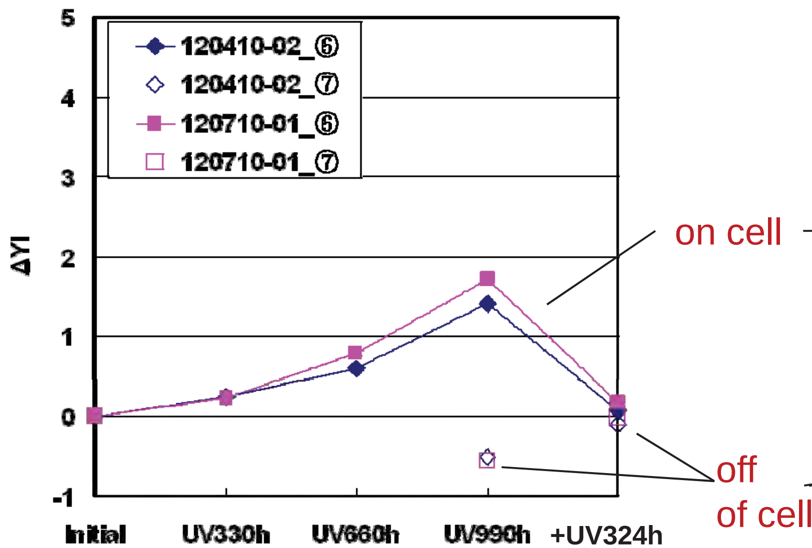
Slight yellowing of BS was observed.

Yellowing of BS differs on a cell vs. off of a cell.

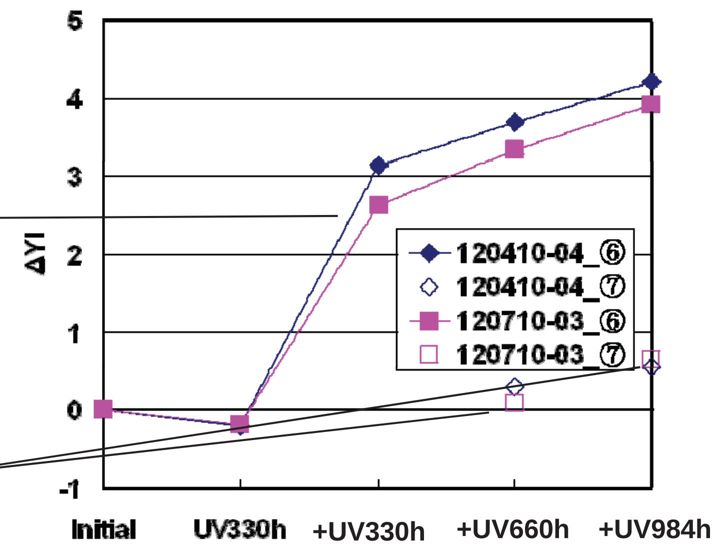
When UV light irradiation was carried out on the front side, after irradiation on back side, yellowing of the backsheet increased significantly.

→ Result: higher temperature on cell?

Test sequence Ⅰ:
Front side 990h → + Back side 324h



Test sequence Ⅱ:
Back side 330h → + Front side 984h



Motivation for the E_a Interlaboratory Experiment

•As in Kempe, “Group 3: Understanding the Temperature and Humidity Environment Inside a PV Module ”, knowing E_a is critical to prescribing and interpreting a <UV and temperature> mediated test.

•Unfortunately, E_a is not known for the common UV PV degradation modes.

$$k = A\left[\frac{T}{T_0}\right]^n e^{\left[\frac{-E_a}{RT}\right]}$$

The modified Arrhenius equation

Critical unknowns
<u>(Goals for the interlaboratory experiment)</u>:

1. Quantify E_a, so that applied test conditions can be interpreted.

2. Provide a sense of the range of E_a that may be present by examining “known bad”, “known good”, and “intermediate” material formulations.

3. Determine if there is significant coupling between relevant aging factors, *i.e.*, UV, temperature, and humidity.
What factors does TG5 need to consider?

4. Investigate the spectral requirements for light sources by comparing E_a for different sources, *i.e.*, Xe-arc, UVA 340.
Is visible light required in addition to UV light?

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Degradation Mechanisms for Crystalline Si PV

Failure/degradation mechanisms from the literature†:

- **Corrosion of AR coating on glass (Group3/Group 5)**
- **Corrosion of cells (Group 3/Group 5)**
- **Corrosion of electrical interconnects (Group 3/Group 5)**
- **Crazing of glass. Crazing/roughening of front surface (Group3/Group 5)**
- **Delamination of encapsulation (Group3/Group 5)**
- **Diode failure during "hot spots" (Group 4)**
- **Discoloration of encapsulation (Group 5)**
- **Embrittlement of back sheet (Group 5)**
- **Embrittlement of encapsulation (Group 5)**
- **Embrittlement of junction box material and wire insulation (Group 5)**
- **Fatigue of solder bonds (Group 2)**
- **Fatigue of interconnects [open circuits/arcing] (Group 2)**
- **Fracture of cells (Group 2)**
- **Fracture of glass/superstrate (Group 2)**
- **Ground faults (Group3/Group 5)**
- **Junction box and module connection failures (Group 2)**
- **Soiling of glass/superstrate (TBD)**
- **Structural failures (TBD)**

Study these

Literature*, site inspections, and industry feedback suggest these are most common

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

† based on Wohlgemuth, "PV Modules: Validating Reliability, Safety and Service Life", Intersolar 2012 Conf.

***e.g., D. C. Jordan and S. R. Kurtz, "Photovoltaic Degradation Rates—an Analytical Review", PIP, 21 (1), 2013, pp. 12-29.**

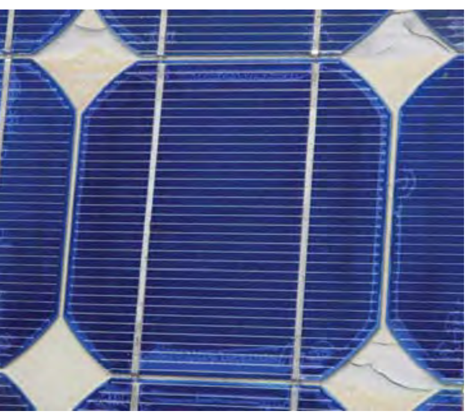
Details of the E_a Test Specimens

NREL NATIONAL RENEWABLE ENERGY LABORATORY

- (4) custom EVA formulations, (1) TPU product proposed for study.
- EVA to be extruded at NREL; specimens to be laminated at NREL.

Ingredient	Comment	Mass {g}	Mass {g}	Mass {g}	Mass {g}
Elvax PV1400	Dupont EVA resin, 33 wt% VAc	100	100	100	100
Dow Corning Z6030	Silane primer, gama-methacroyloxy propyl trimethoxysilane	0.5	0.5	0.5	0.5
Tinuvin 770	Hindered amine light stabilizer (HALS)	0.13	0.13	0.13	N/A
Tinuvin 123	Non-basic aminoether-hindered amine light stabilizer (NOR-HALS)	N/A	N/A	N/A	0.13
TBEC	Curing agent, OO-Tertbutyl-O-(2-ethyl-hexyl)-peroxycarbonate, 0.133kPa at 20C.	N/A	1.5	1.5	1.5
Lupersol 101	Curing agent, 2,5-Bis(tert-butylperoxy)-2,5-dimethylhexane	1.5	N/A	N/A	N/A
Naugard P	Phosphite anti-oxidant (AO)	0.25	0.25	N/A	N/A
Tinuvin 328	Benotriazole UV absorber (UVA)	N/A	N/A	N/A	0.3
Cyasorb 531	Benzophenone UV absorber	0.3	0.3	0.3	N/A
Comments		"Known bad", "slow cure"	"Intermediate", "fast cure"	"Intermediate", "fast cure"	"Known good"

- 50x50mm^2 quartz/encapsulation/quartz geometry for transmittance.



?

quartz/EVA/quartz specimen
Kempe et. al., Proc. PVSC 2009, 1826-1831.

?

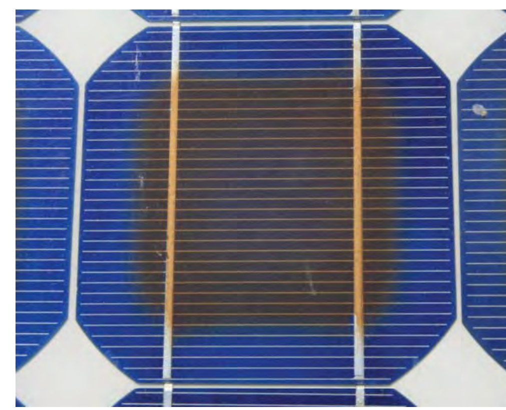


Photo of aged PV module
Miller, from APS-STAR site

- Details of adhesion experiment to be determined.

The E_a Interlaboratory Experiment Enables a Wider Range of Study

- Discoloration & adhesion will be studied in detail at different institutions using the same make & model of instrument (*i.e.*, Ci5000, QUV).
- This overcomes the difficulty of limitedly-available aging equipment.

- A standard condition (70°C in chamber) allows a broad variety of other instruments to also be compared.

LIGHT SOURCE, FILTER	Xe Arc (right-light/cira filter)						UVA 340 fluorescent (no filter)			UVA 340 fluorescent (no filter)			No light	field deployment (outdoors)
UV LIGHT INTENSITY	NOMINAL (92 W•m^{-2} for 300≤λ≤400)						NOMINAL (0.92 W•m^{-2}@ 340 nm)			NOMINAL (245.5 W•m^{-2} for 300≤λ≤400			0 W•m^{-2}	
CHAMBER RELATIVE HUMIDITY {%}	20 ("low")			50 ("high")		match for "very low" (~7%)	~7% ("very low")			50 ("high")			25	ambient
CHAMBER TEMEPRATURE {°C}	50	70	90	50	70	70	50	60	70	50	70	90	70	ambient
PARTICIPANT (INSTRUMENT MODEL)	3M (Ci5000)	3M (Ci5000)	3M (Ci5000)	ATLAS (Ci5000)	Mitsui(SX120)	NREL (Ci5000)	CWRU (QUV)	ATLAS (UVTEST)	QLAB (QUV)	Fraunhofer (custom)	Fraunhofer (custom)	Fraunhofer (custom)	NREL	ATLAS (EMMA in Phoenix)
		QLAB (QSUN XE3)			QLAB (QSUN XE3)	NREL (XR260)			NREL (UV suitcase)					CWRU (5x in Cleveland)
		ATLAS (SunTest XXL)							Fraunhofer (custom)					ATLAS (rack in Phoenix)
		Suga (SX75)							Suga (FDP)					ATLAS (rack in Miami
														NREL (rack in Golden)

Summary of participating laboratories and test conditions

- Rate of degradation will be compared against field data to allow site specific acceleration factors to be computed.
- Outdoor data should help verify validity of the test.

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

- Separate experiment at NIST (same EVA's) will determine action spectrum

Summary of QA TG5 (UV, T, RH)

- Goal develop UV & temperature facilitated test protocol(s) that may be used to assess materials, components, and modules relative to a 25 year field deployment.

Round-robin (under Sophia project)

- Emphasis on backsheet materials
- Examination of source (spectral) dependence

Mini-module round-robin (QA Task-5 Japan)

- Examining backsheet and encapsulation
- Apply a combination or series of aging plus dynamic mechanical or DH tests?

E_a interlaboratory study

- Examining discoloration and delamination of encapsulation
- Quantify coupled and (irradiation) source dependent effects

Upcoming talks in QA TG5 session:

- David Burns and Kurt Scott, “Light Sources for Reproducing the Effects of Sunlight in the Natural Weathering of PV Materials, Components and Modules”

  (light sources, indoor weathering equipment, spectral effects on materials)
- Charlie Reid, Jayesh Bokria, and Joseph Woods, “Accelerated UV Aging and Correlation with Outdoor Exposure of EVA Based PV Encapsulants”

  (results of a field study)

Goal and Activities for QA TG5 (UV, T, RH)

•IEC qualification tests (61215, 61646, 61730-2) presently prescribe up to 137 days equivalent (IEC 60904-3 AM 1.5) UV-B dose
•Goal develop UV & temperature facilitated test protocol(s) that may be used to assess materials, components, and modules relative to a 25 year field deployment.

Core Activities:
1: (weathering and climates… location dependent information)
    e.g., known benchmark locations… Miami, FL; Phoenix, AZ
2: (standards from other fields of work)
    summary exists from Kurt Scott *et. al.*
3: (test conditions)
4-1 (collect information about observed failure mechanism)
    e.g., the literature, site inspections
4-2 (find appropriate models for ALT procedures)
5: (suitable UV sources)
    summary exists from David Burns *et. al.*
6: (proposal for accelerated service testing)
7: (laboratory verification of acceleration of proposed test standard/failure mechanism)
    Japan mini-module study, Sophia round-robin, E_a interlaboratory study

Light Sources for Reproducing the Effects of Sunlight in the Natural Weathering of PV Materials and Systems

3M Weathering Resource Center

David M. Burns 3M Weathering Resource Center

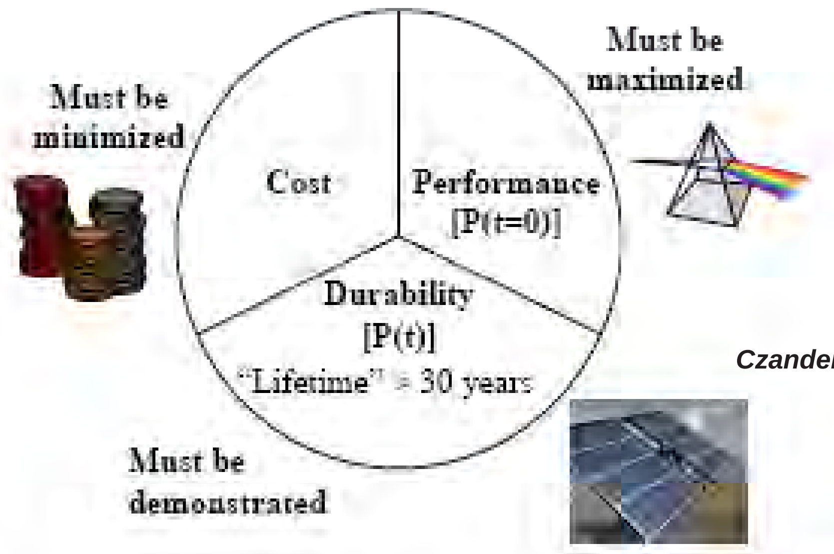
Kurt Scott ATLAS MATERIAL TESTING SOLUTIONS

3M Weathering Resource Center

Light Sources for Reproducing the Effects of Sunlight in the Natural Weathering of PV Materials and Systems

1. PV Challenge and PVMQA
2. Weathering Fundamentals
3. Light Sources for Weathering
    1. In-Scope & Out of Scope
    2. Reference Sources
    3. Commercial Sources – Advantage/Disadvantages
        1. Fluorescent Ultraviolet Lamps
        2. Filtered Xenon Arc
        3. Metal Halide
    4. Research Sources
4. General Conclusions and Caveats

1. The Photovoltaic Challenge



Czanderna & Jorgensen, NREL (1999)

The product requirement triad of cost, performance, and durability (lifetime).

"…the worldwide investment in PV installations is approaching $100 billion/yr. **Those financing this market growth want to be able to predict the *risk of failure of PV products* and are asking for more quantitative tests**."

NREL/AIST/EC/SEMI 2011 http://www.nrel.gov/docs/fy11osti/50651.pdf

…use local weather data ... creation of standards … assess a module's ability to withstand regional stresses … define a minimum durability … durability standards that lead to the desired durability … …comparative information about the durability …**quantitative PV lifetime predictions**…

Int'l PVMQA is all about creating a standard approach to evaluate the

Weatherability
(the capability … to resist the deteriorating effects of weather exposure; for example, sun, heat, rain and high and low humidity.)

&

Durability
(the capability …to maintain serviceability over not less than a specified time.)

&

Service Life Prediction
(an estimate of the mean functional life of a material under defined in-service conditions based on modeling of Time-to-Failure as a function of weathering stresses calculated using location specific climate data as inputs)

[see ASTM Technical Committee E06 on Performance of Buildings and G03 on Weathering & Durability]

of photovoltaic module designs under the range of natural weathering conditions encountered in service.

2. Weathering Fundamentals

Weathering Science – the interdisciplinary field of applied photochemistry, materials science, chemical kinetics and climatology concerned with understanding the effect that exposure in the natural environment has on the degradation and lifetime of materials and constructions.

Weathering – photo-induced changes resulting from exposure to the radiant energy present in sunlight in combination with heat, including temperature cycling, and water in its various states, predominately as humidity, dew and rain.

Weathering Test – a defined exposure procedure for degrading a material or construction by weathering. The result of a weathering test is expressed in terms of time to a specified property change ($t_{\Delta P(x)}$), Time-to-Failure ($t_{F(x)}$) or degradation rate (dP(x)/dt), where x denotes the property monitored.

Predictive Weathering Test - a weathering test that induces the same degradation along the same pathways and to the same end state as that produced by outdoor weathering. Discussion: Predictive weathering tests are the only tests valid for service life prediction.

ASTM Technical Committees
E44 on Solar, Geothermal and Other Alternative Energy Sources
G03 Weathering and Durability

Weathering Fundamentals

The elusive quest:
A single weathering test that accurately predicts in-service lifetime.

Outdoor weathering test – an exposure test conducted in the natural environment using the sun as the source of radiation and subject to the natural variation in the environment (***solar irradiance***).

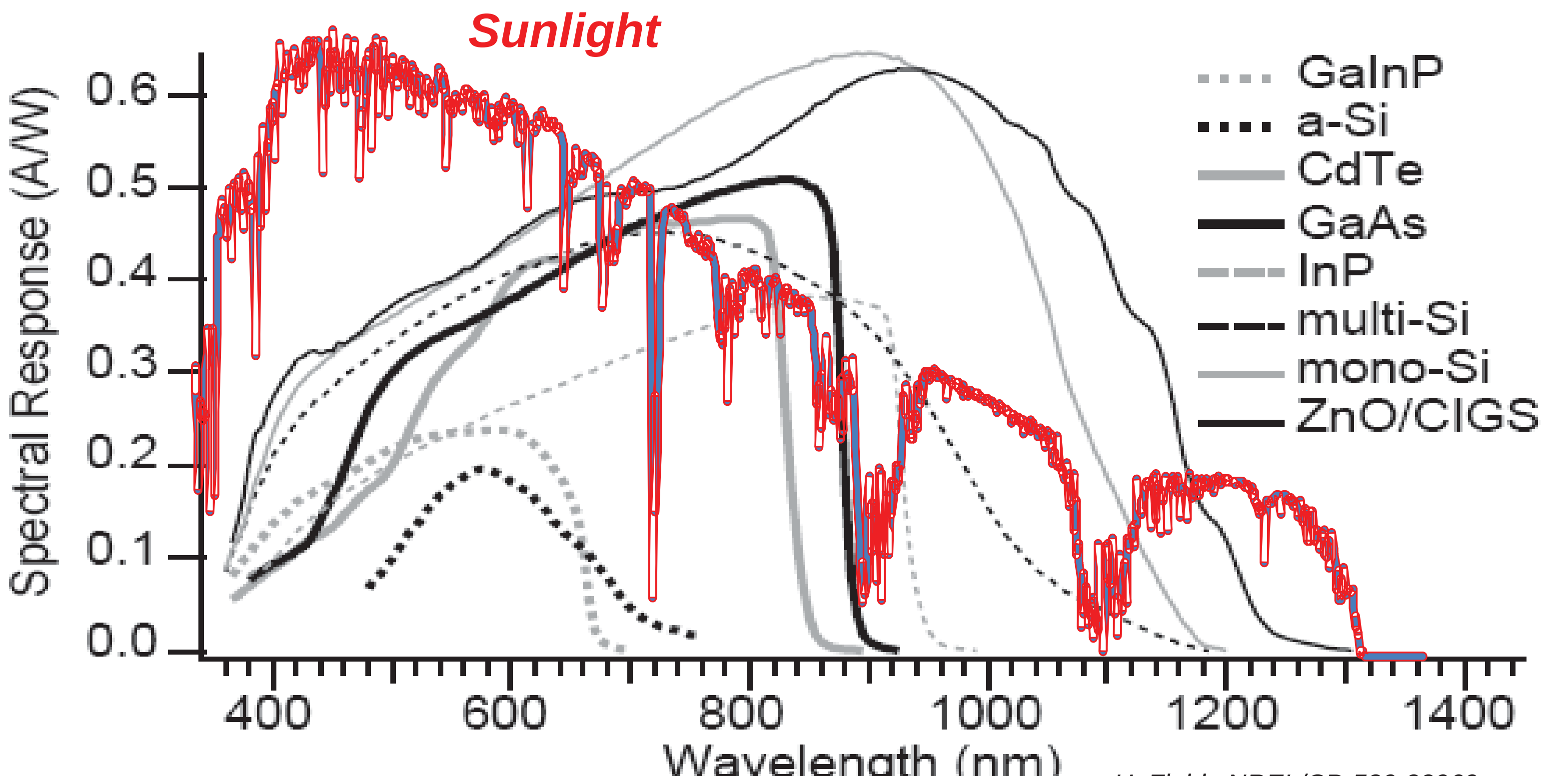
Artificial weathering test - an exposure test conducted in a laboratory weathering device using an engineered source to simulate sunlight and a controlled environment (***simulated solar irradiance***)

Accelerated weathering test - an exposure test that applies stress at levels higher than those encountered in-service in order to induce degradation within a shortened ('accelerated') time frame.

The reality:
Results of a set of predictive weathering tests allow one to calculate lifetime (service life prediction) and quantify the relative the risk of future failure under specific idealized in-service conditions.

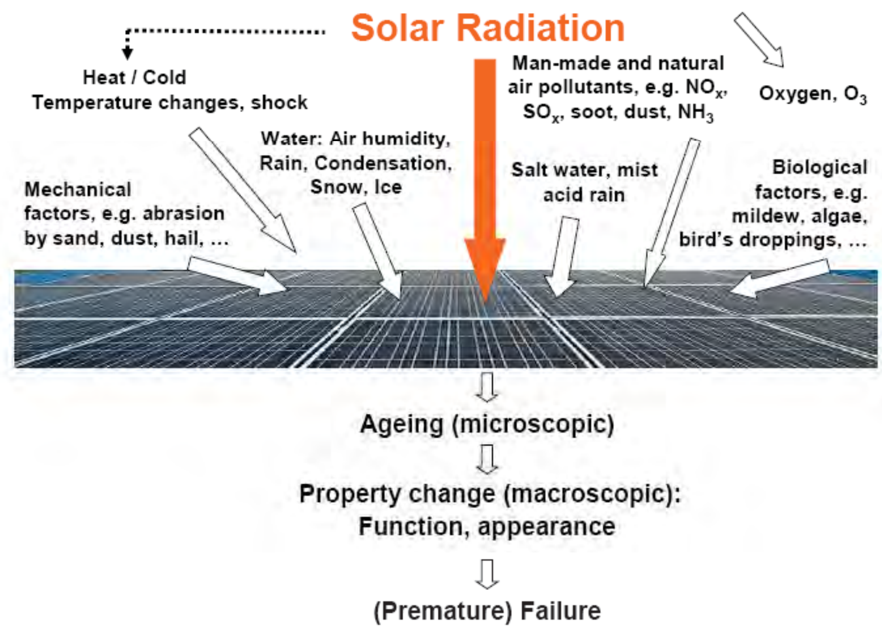
Weathering Fundamentals

"UV" is not the entire story, especially in PV …. Long wavelength solar irradiance (> 380 nm) is mandatory for photovoltaic energy conversion. Short wavelength visible light is also known to contribute to polymer photodegradation during long term exposure via multiple reaction pathways. Using only part of the solar spectrum may excite only some of the degradation processes. Whether "UV" (<380 nm) plays the controlling role must be experimentally validated and not simply assumed *a priori.*



H. Field,, NREL/CP-530-22969

3.1 In Scope / Out of Scope



IN Scope

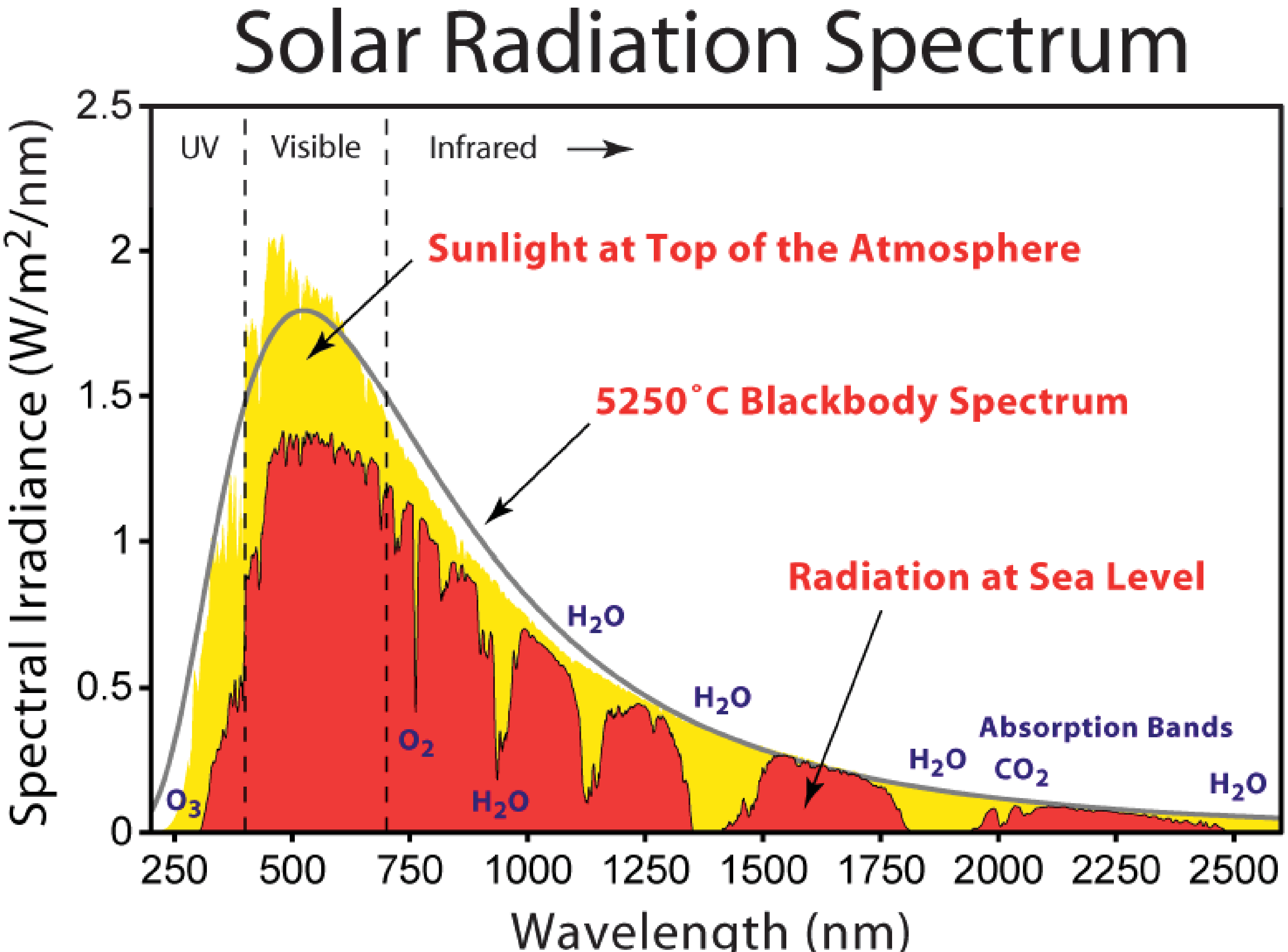
1. Standard sources
2. Commercial sources
   (i.e., broadly available, multiple suppliers)
3. Specialty research sources
   (select Government / Independent Labs)

OUT of Scope

1. Specific commercial equipment
2. Cost
   ($ Equip + $ Operation + $ Maintenance +$ Calibration)

$$\text{Value to Solar in mitigating Financial Risk} \approx \frac{\text{Test Relevance x Test Reliability}}{\text{Cost}}$$

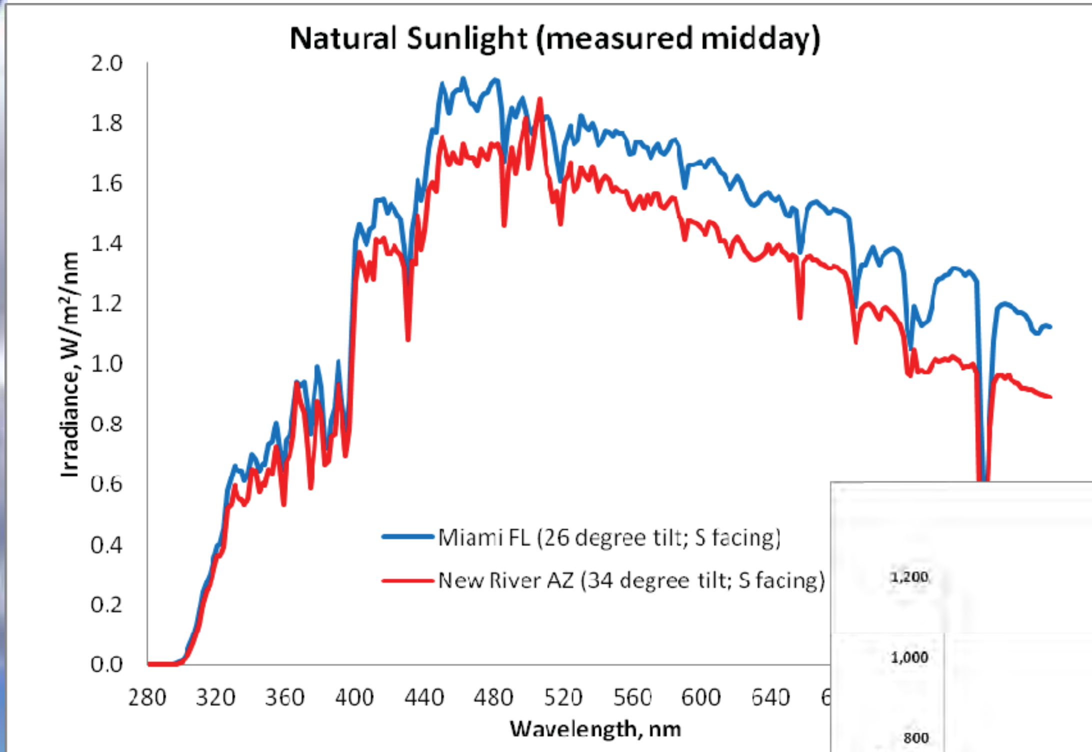
2. Reference Sources – Sunlight, the Ultimate Reference



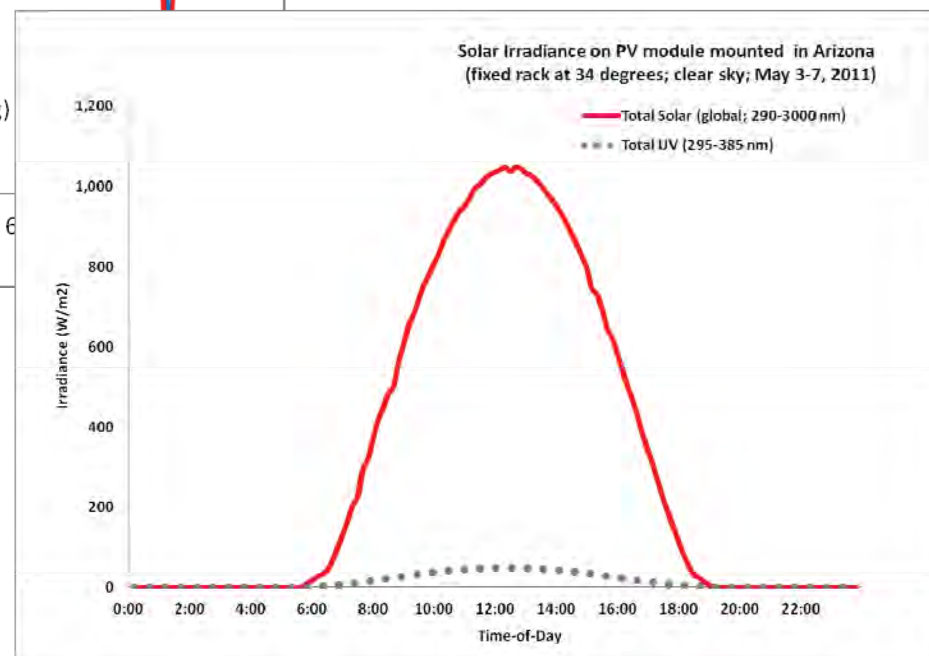
http://upload.wikimedia.org/wikipedia/commons/4/4c/Solar_Spectrum.png

3M Weathering Resource Center

Sunlight varies - both in spectral distribution and intensity



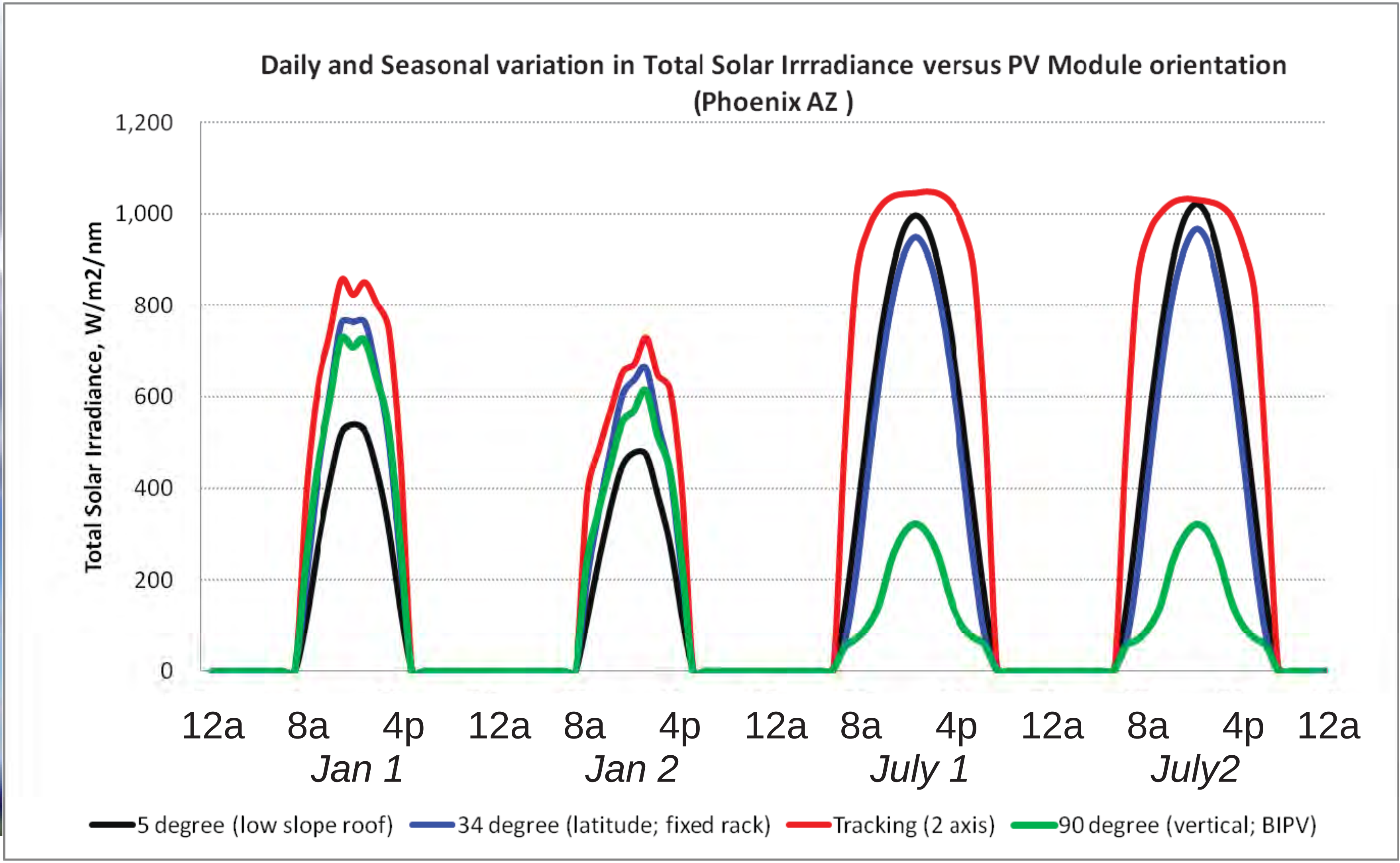
Place to Place



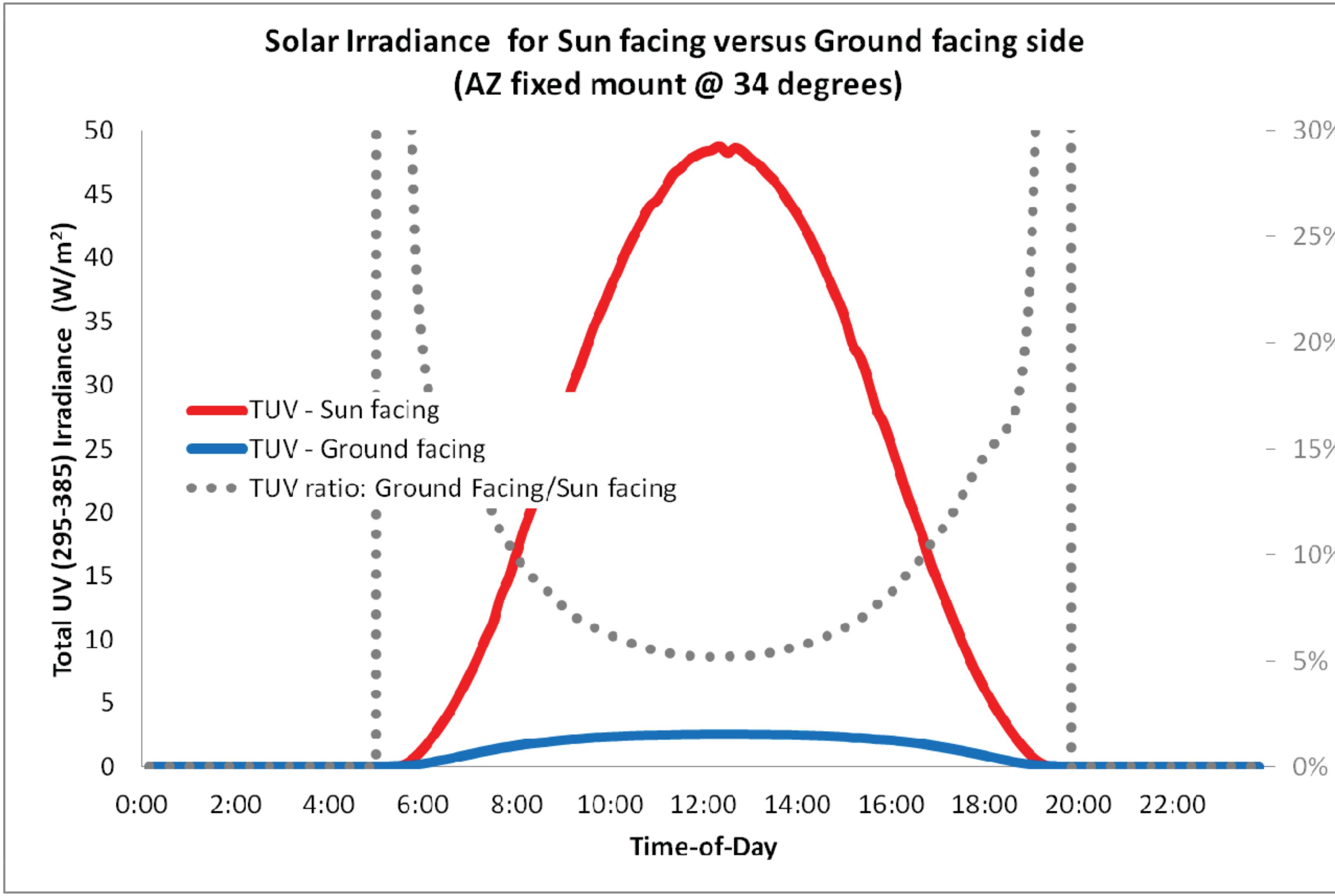
Hour by Hour

Sunlight varies – Day-to-Day, Seasonally and by module orientation

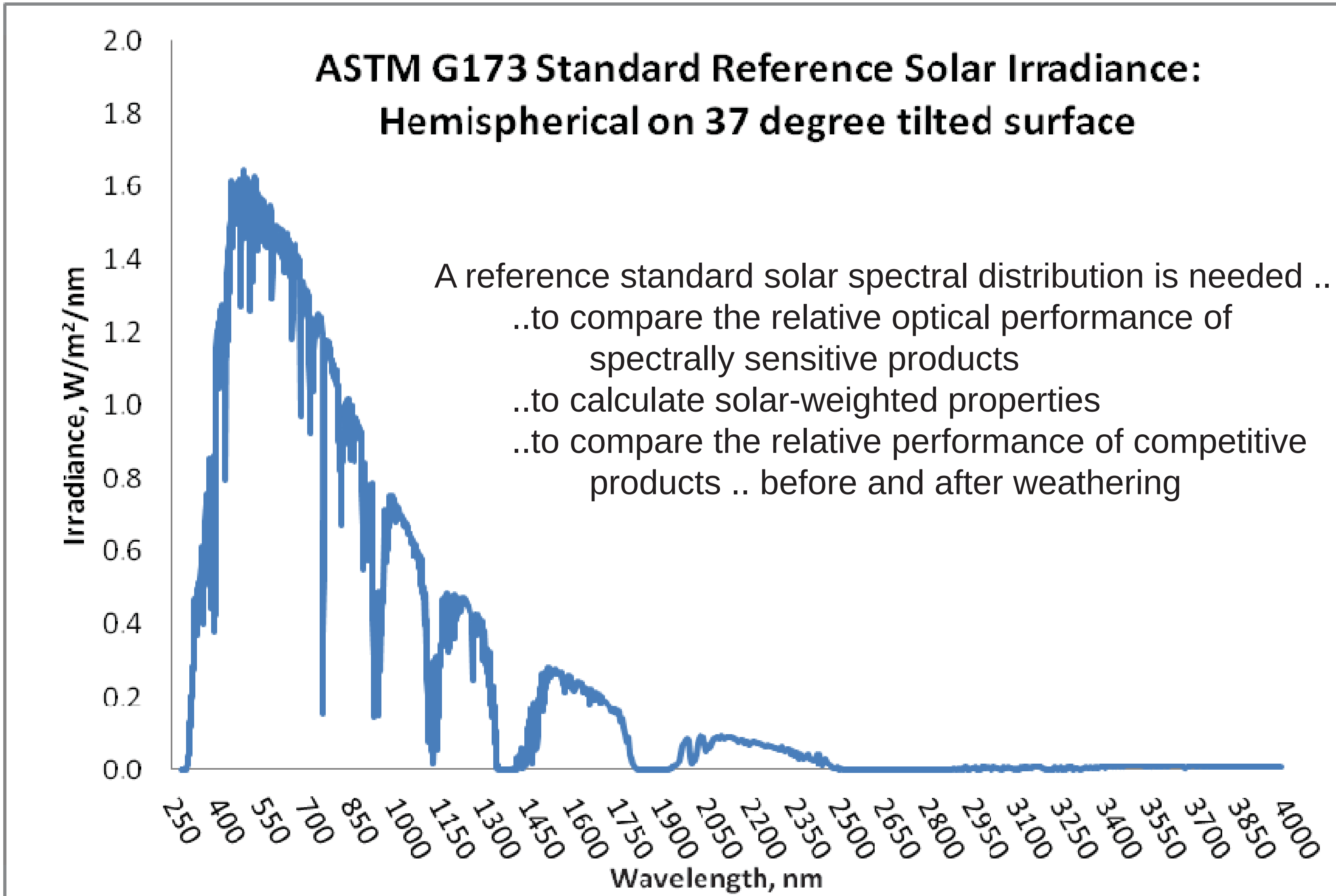
(roof, rack, track, BIPV)



Sunlight varies – Frontside and Backside



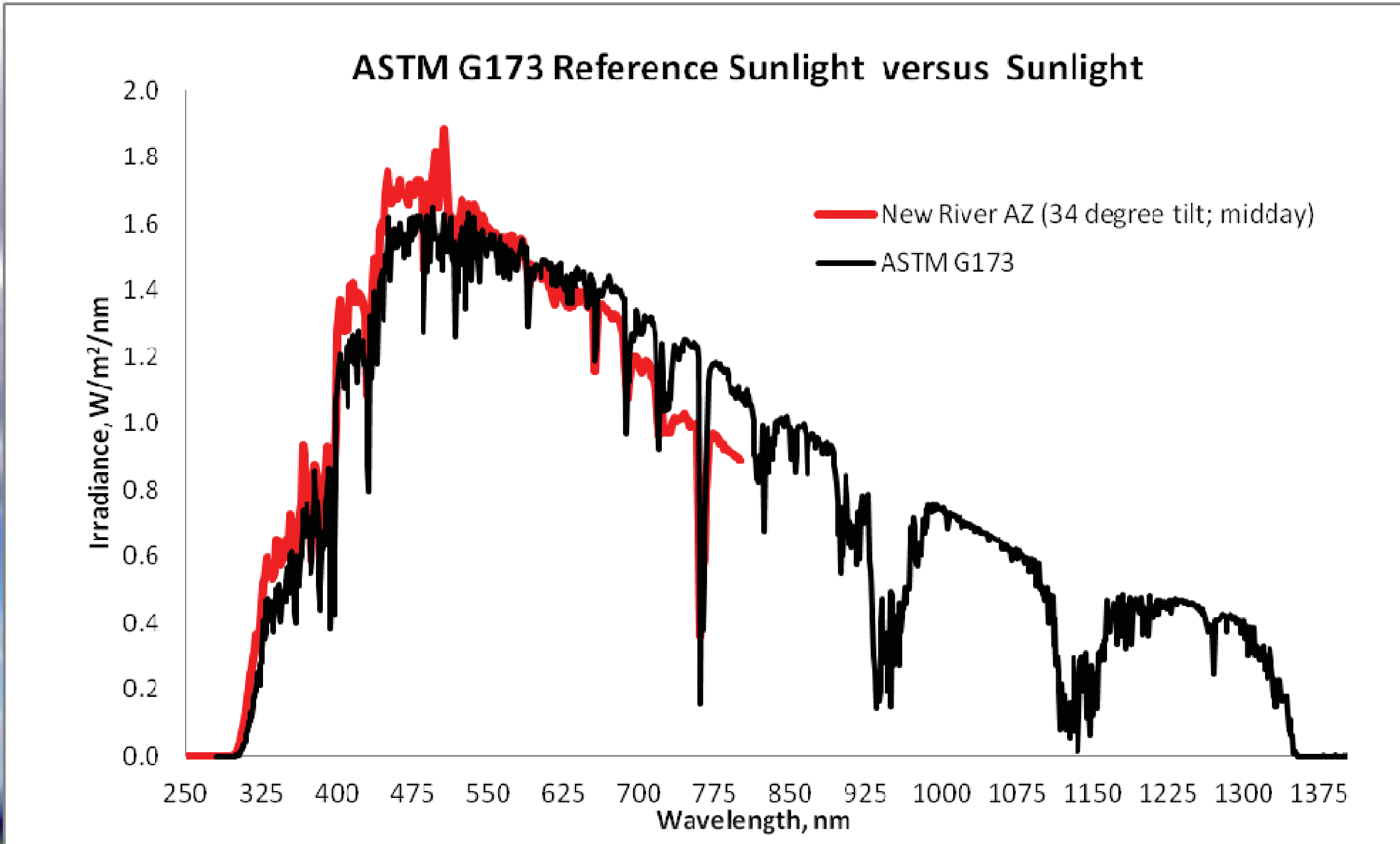
Standardized Reference Sources



A reference standard solar spectral distribution is needed ..
- ..to compare the relative optical performance of spectrally sensitive products
- ..to calculate solar-weighted properties
- ..to compare the relative performance of competitive products .. before and after weathering

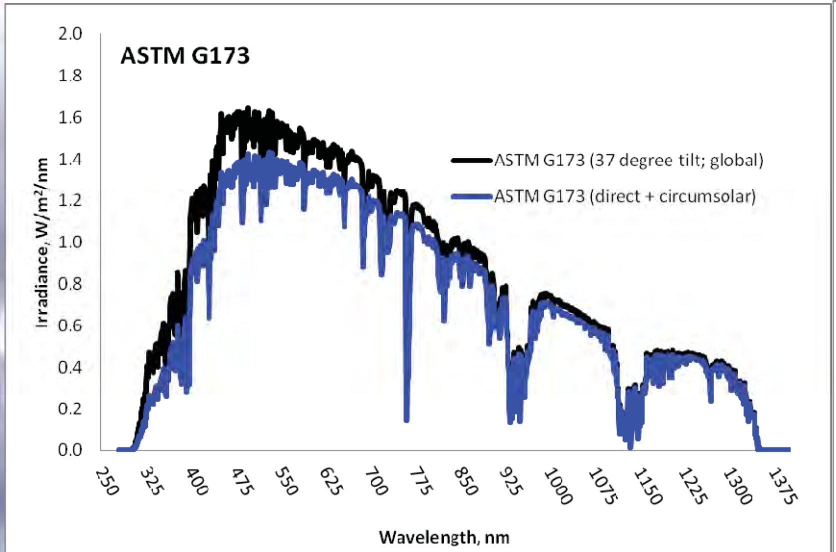
3M Weathering Resource Center

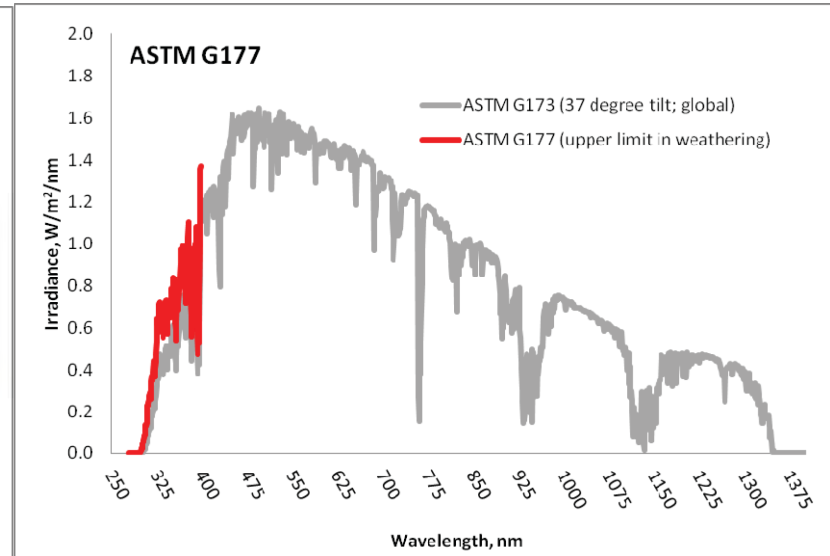
ASTM G173 – A realistic representation

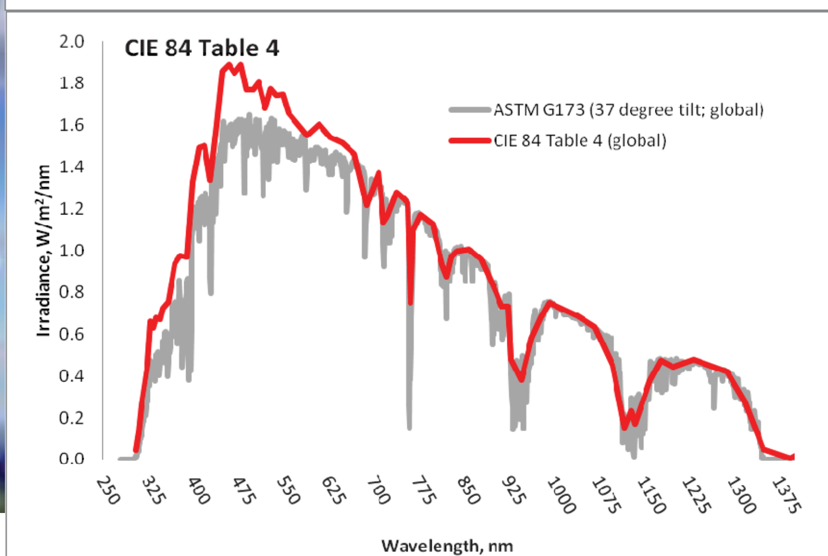


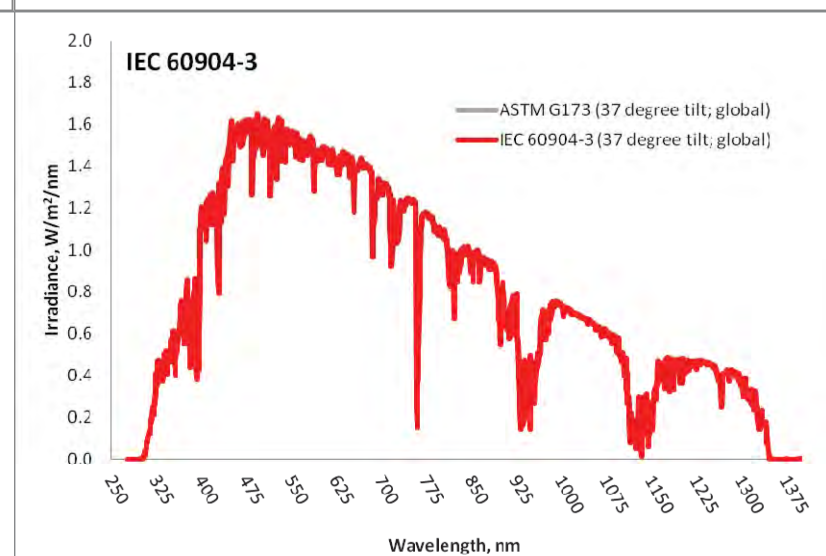
Standard Sunlight – More than one:

ASTM G173, ASTM G177, CIE 85 Table 4, IEC 60904-3



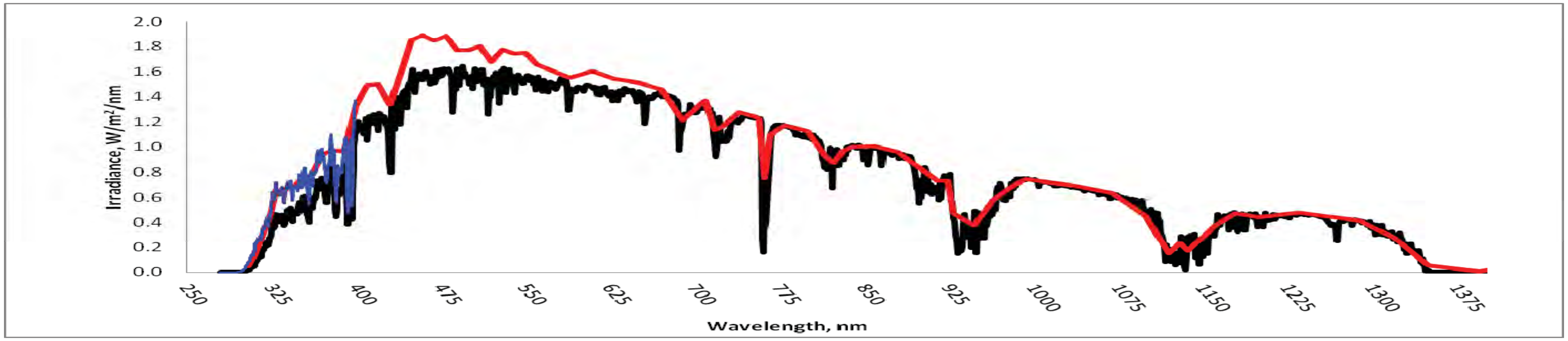






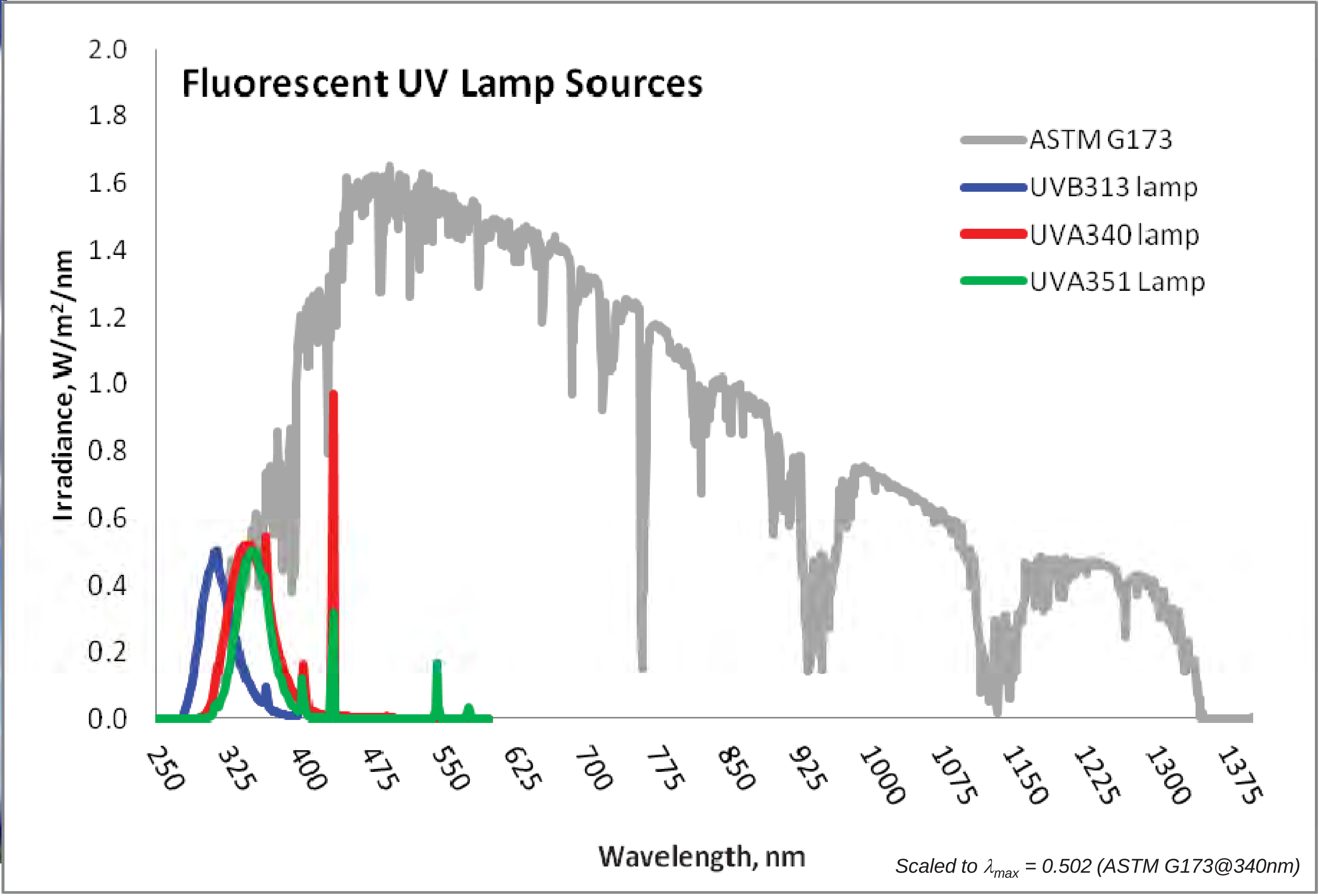
Standard Sunlight – More than one:

ASTM G173, ASTM G177, CIE 85 Table 4, IEC 60904-3

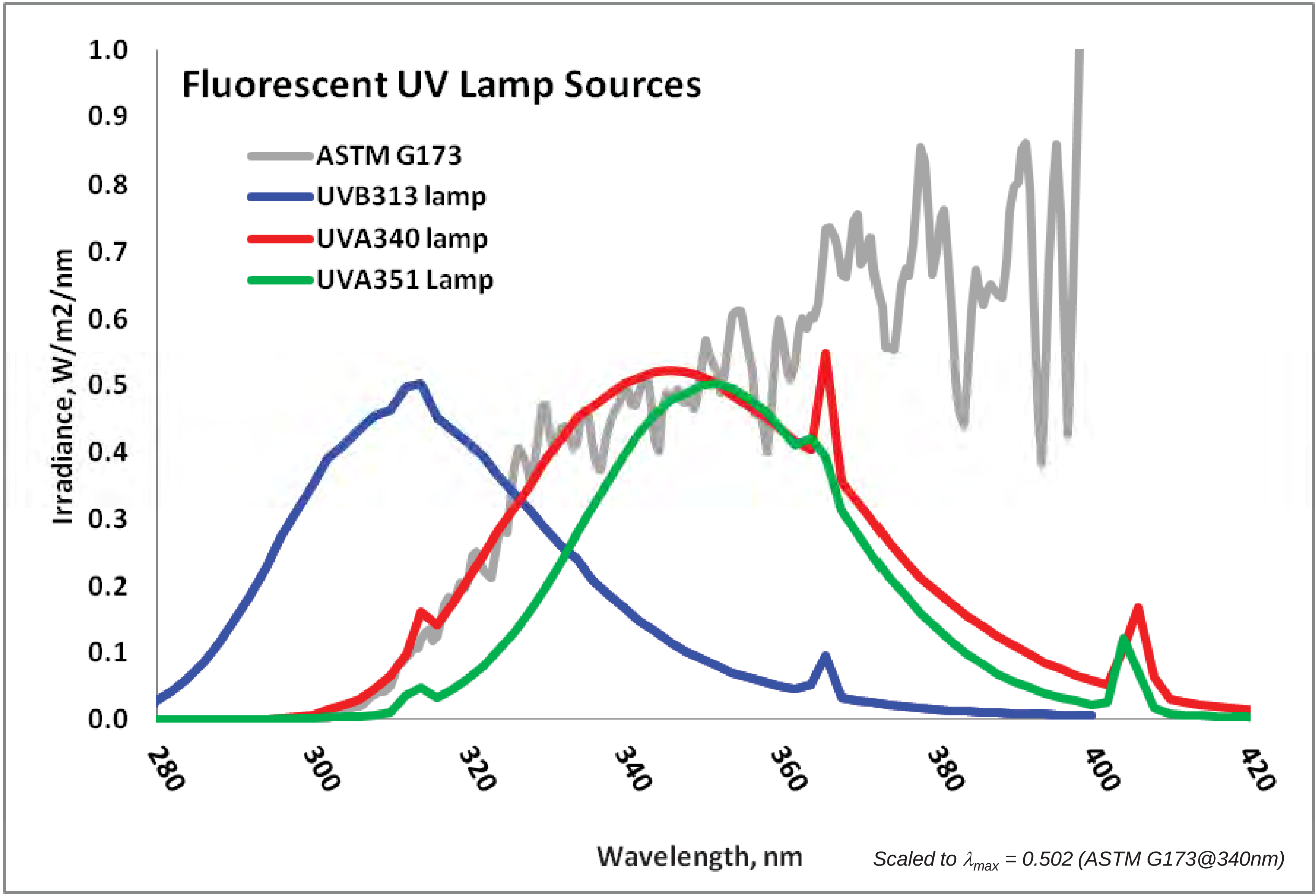


						Global Irradiance			
ID	Derivation	Air Mass	Refernce location	Wavelength Range	340 nm	300-400 nm	TUV (295-385 nm)	290-800 nm	Total Solar (280-4000 nm)
				nm	$W/m^2/nm$	W/m^2	W/m^2	W/m^2	W/m^2
	Scope: "reference…to compare the relative performance … relate the performance rating of PV devices…classify solar simulators…								
CIE 84 tbl 4	SOLTRAN	1.00	Horizontal	305-2450	0.68	68	63	669	--
ASTM G173	SMARTS 2.9.2	1.50	37° N	280-4000	0.50	46	35	590	1000.1
IEC 60904-3	SMARTS 2.9.2	1.50	37° N	280-4000	0.50	46	35	587	1000.0
	Scope: "...reference for the upper limit of ultraviolet radiation in the outdoor weathering of materials … guide against which manufactured ultraviolet light sources may be judged "								
ASTM G177	SMARTS 2.9.2	1.05	37° N	280-400	0.73	64	51	--	--
	Sample of the Real World for relative comparison								
New River AZ	Measured	--	34° N	---	0.65	58	46	600	--
Miami FL	Measured		26° N		0.70	52	65	679	--

3.3.1 Commercial Fluorescent Ultraviolet Lamp Sources



Fluorescent Ultraviolet Lamp Sources - scaled



3M Weathering Resource Center

UVB313

Advantages

1. Simple construction
2. Very short λ (high energy) radiation produces fast degradation;
3. Irradiance controllable (but not common practice)
4. Good spectral reproducibility lamp to lamp

Disadvantages

1. Does NOT match solar cut-on;
2. Degradation does NOT reproduces the effects of sunlight (see Nicholas, Gerlock, Fisher&Ketola, Pickett, …)

(ASTM G154: NOTE 8—Fluorescent UVB lamps ….emit significant amounts of radiation below 300 nm…that may result in aging processes <u>not occurring outdoors</u>. Use of this lamp is not recommended for sunlight simulation.)

UVA340

Advantages

1. Simple construction
2. Readily scalable to large exposure area;
3. Good match to solar cut-on;
4. Good spectral distribution match out to ~ 360 nm;
5. Irradiance controllable (up to~ 1.6 $W/m^2/nm$ @340 nm; ~2X peak solar)
6. Good spectral reproducibility lamp to lamp

Disadvantages

1. Poor spectral match >360 nm (Actives only degradation processes initiated by λ <360 nm);
2. No significant radiation >400 nm (Lacks radiation to fully engage photoactive component) ;
3. Limited dynamic range : ~0.7 – 1.6 $W/m^2/nm$ @340 nm;

UVA351*

Advantages

1. Simple construction
2. Simulates sunlight through ordinary window glass

Disadvantages

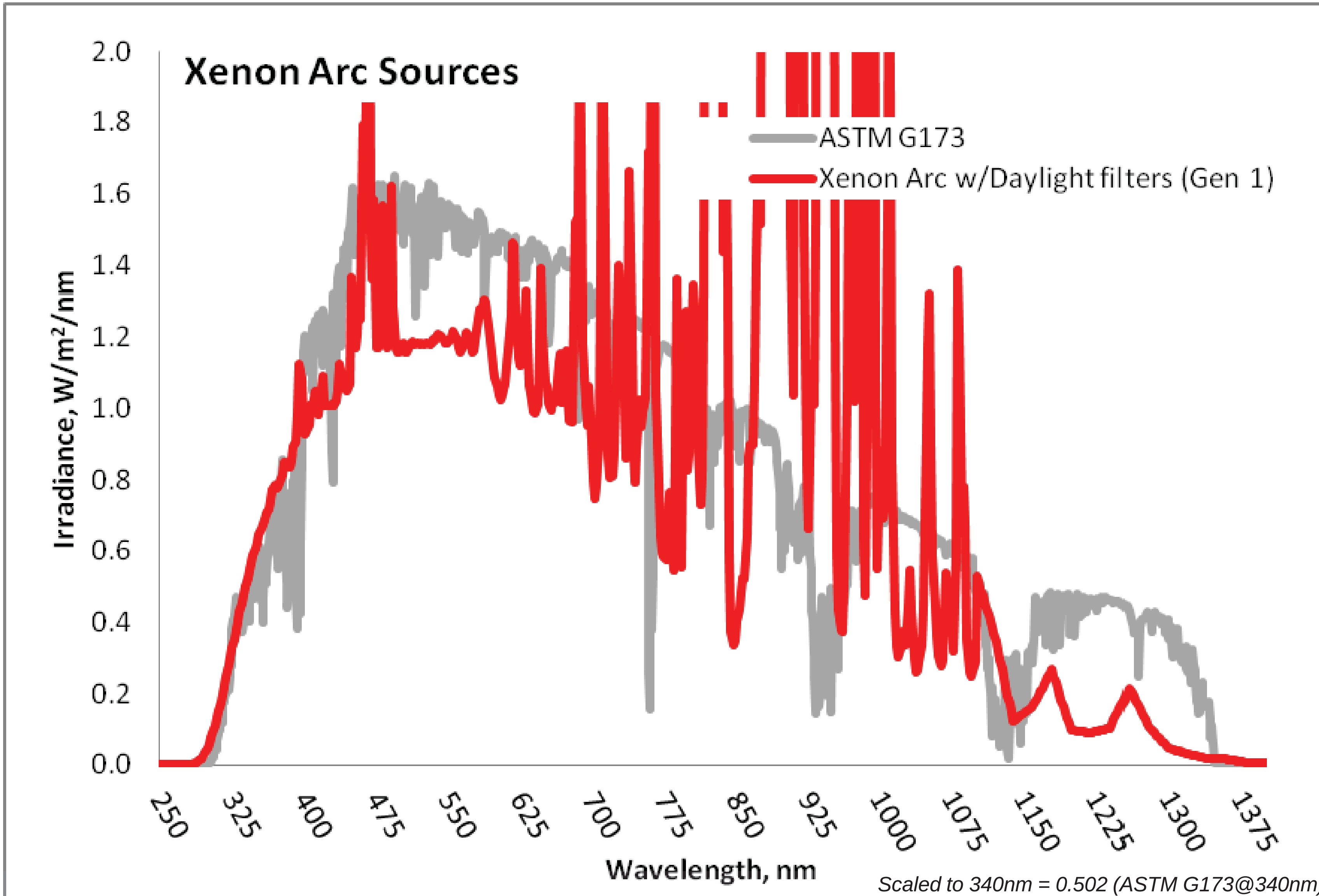
1. Poor simulation of sunlight through solar glass

Note on Mixing lamps : ASTM G154: NOTE 3—Do not mix different types of lamps. Mixing different types of lamps in a fluorescent UV light apparatus may produce major inconsistencies in the light falling on the samples, unless the apparatus has been specifically designed to ensure a uniform spectral distribution.

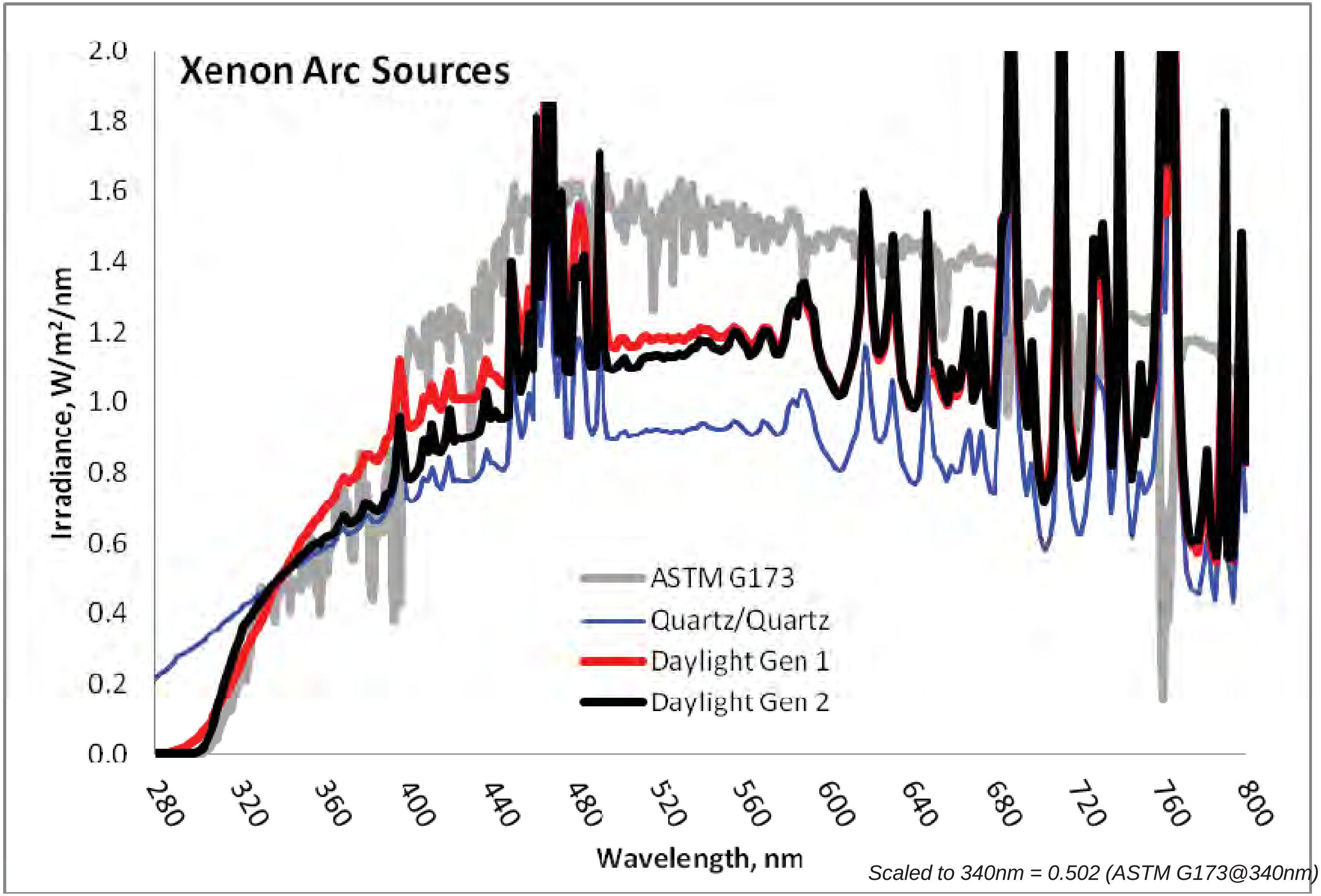
Overall Advantage –Scalable & Relatively simple to operate and maintain

Overall Disadvantage – Limited dynamic range with no radiation >400nm

3.3.2 Commercial Filtered Xenon Arc Sources

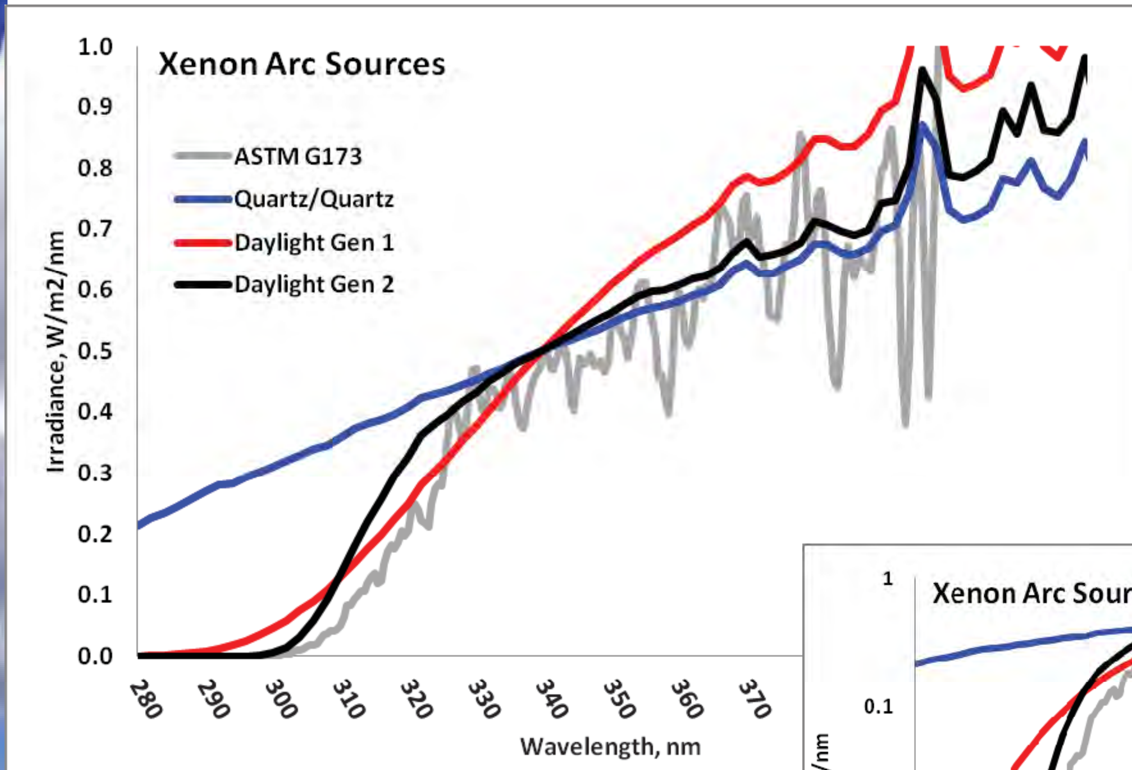


Filtered Xenon Arc Sources for Simulating Sunlight

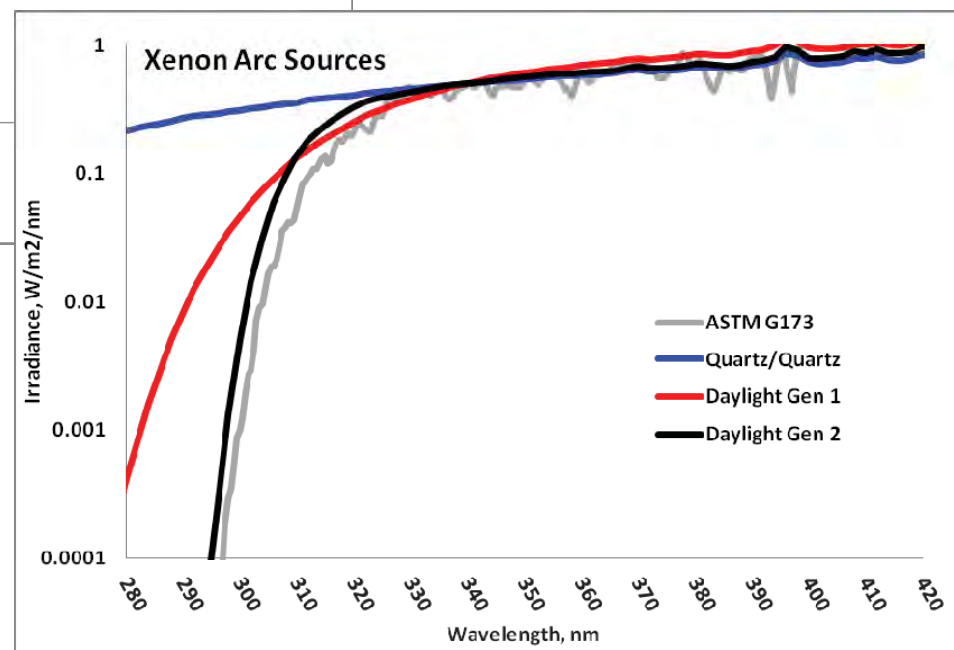


3M Weathering Resource Center

Daylight filters for Xenon Arc Sources to replicate the Solar Cut-on



"Extra" high energy radiation makes a difference in correlating accelerated with outdoor results, especially when doing service life prediction



Filtered Xenon Arc Sources

Advantages

1. Simple construction - xenon gas in sealed quartz
2. Can optimize spectra using various filter sets - 2nd generation Daylight filters provide very good match to solar cut-on are available for most all xenon devices
3. Full spectrum source from solar cut-on through the infra-red
4. Irradiance control with large dynamic (~0.2 to 1.7 W/m^2@340nm) without significant changes in spectral distribution that is essential for reciprocity studies
5. Good spectral reproducibility lamp to lamp

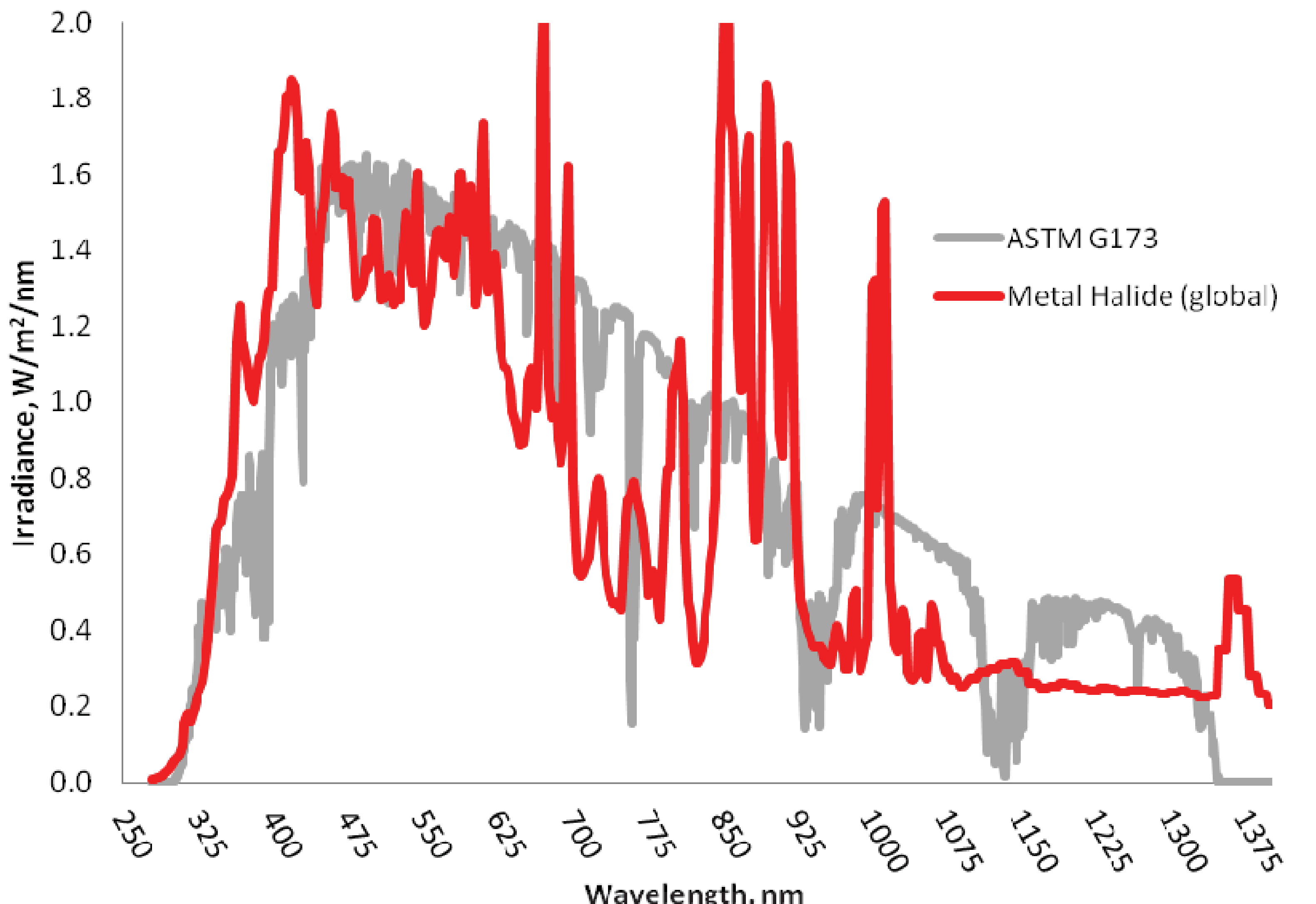
Disadvantages

1. Complexity of equipment - requires active cooling of source with air or water jacket
2. High IR relative to sunlight from ~ 850-1050 nm – could increase radiant heating relative to sunlight; can mitigate with IR filters
3. Not readily scalable to large sizes (full module size)

Overall Advantage – Full spectrum with good match to solar cut-on and large dynamic range

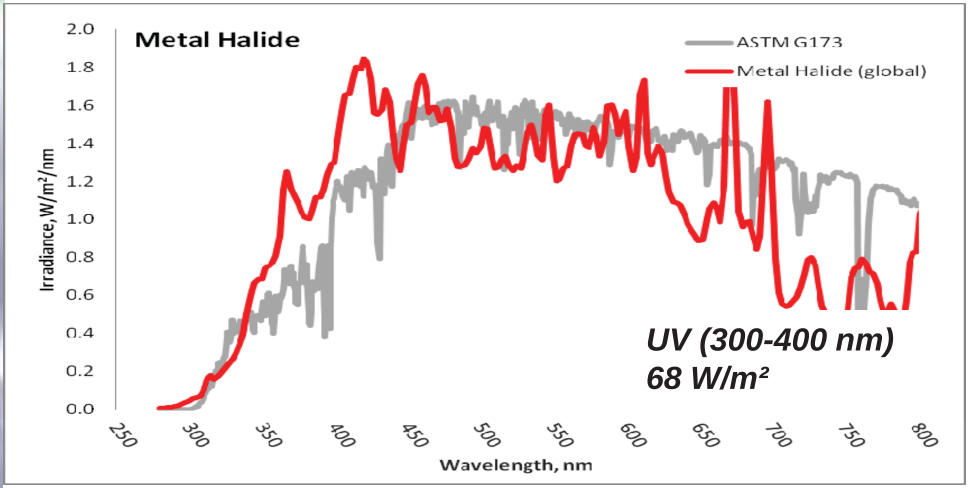
Overall Disadvantage – Scalability and operational complexity

3.3.3 Commercial Metal Halide Sources



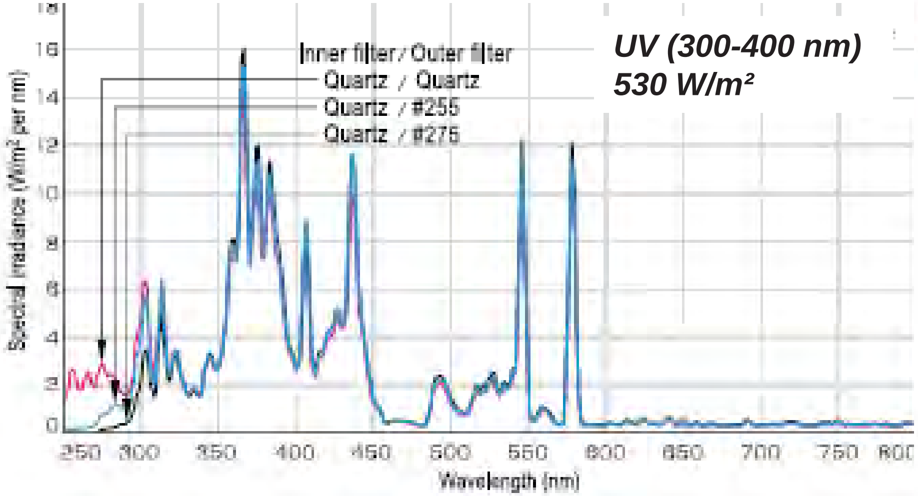
Scaled to 340nm = 0.502 (ASTM G173@340nm)

Metal Halide – All are NOT created equal

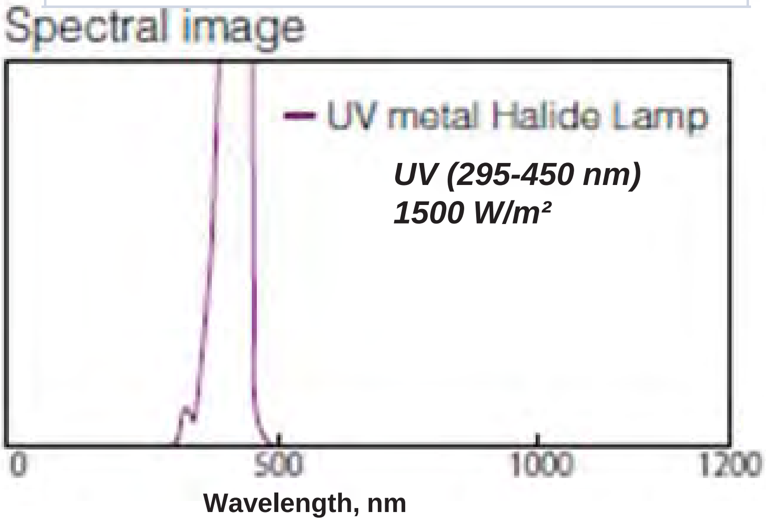


ID	300-400 nm	TUV (295-385 nm)
	W/m²	W/m²
ASTM G173	46.4	35.4
ASTM G177*	64.2	50.5
New River AZ*	57.7	45.7
Miami FL*	64.7	51.6

* SMARTS2 extended; * single random measurement midday



http://www.sugatest.co.jp/english/download/pdf/weather_20110401.pdf



http://www.eye.co.jp/optics/photovoltaic/pv03.html

Metal Halide Sources

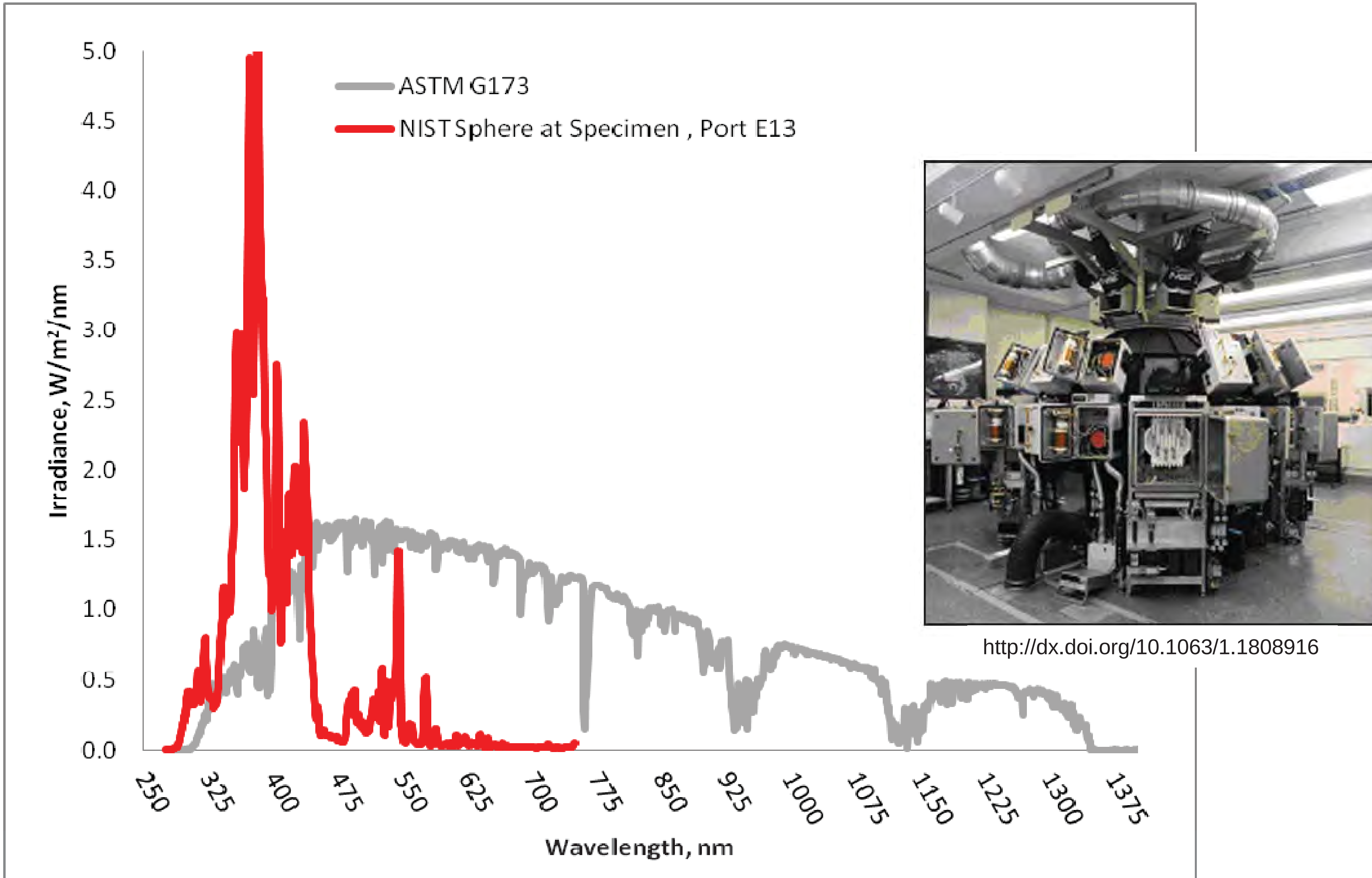
Advantages
1. Readily scalable to large exposure areas (full module)
2. Extremely high irradiances achievable
3. Does not produce excessive long wavelength IR
4. Does not require active cooling

Disadvantages
1. Metal Halide sources have not been standardized for weathering applications resulting in an extremely wide range of spectral distributions
2. Match to sunlight not readily controlled in UV region
3. Variable spectral reproducibility lamp to lamp
4. Spectrum shifts with power, so irradiance control is by varying distance

Overall Advantage –Scalable & extremely high irradiance achievable
Overall Disadvantage – Highly variable supplier to supplier with poor dynamic range

4. Research Sources

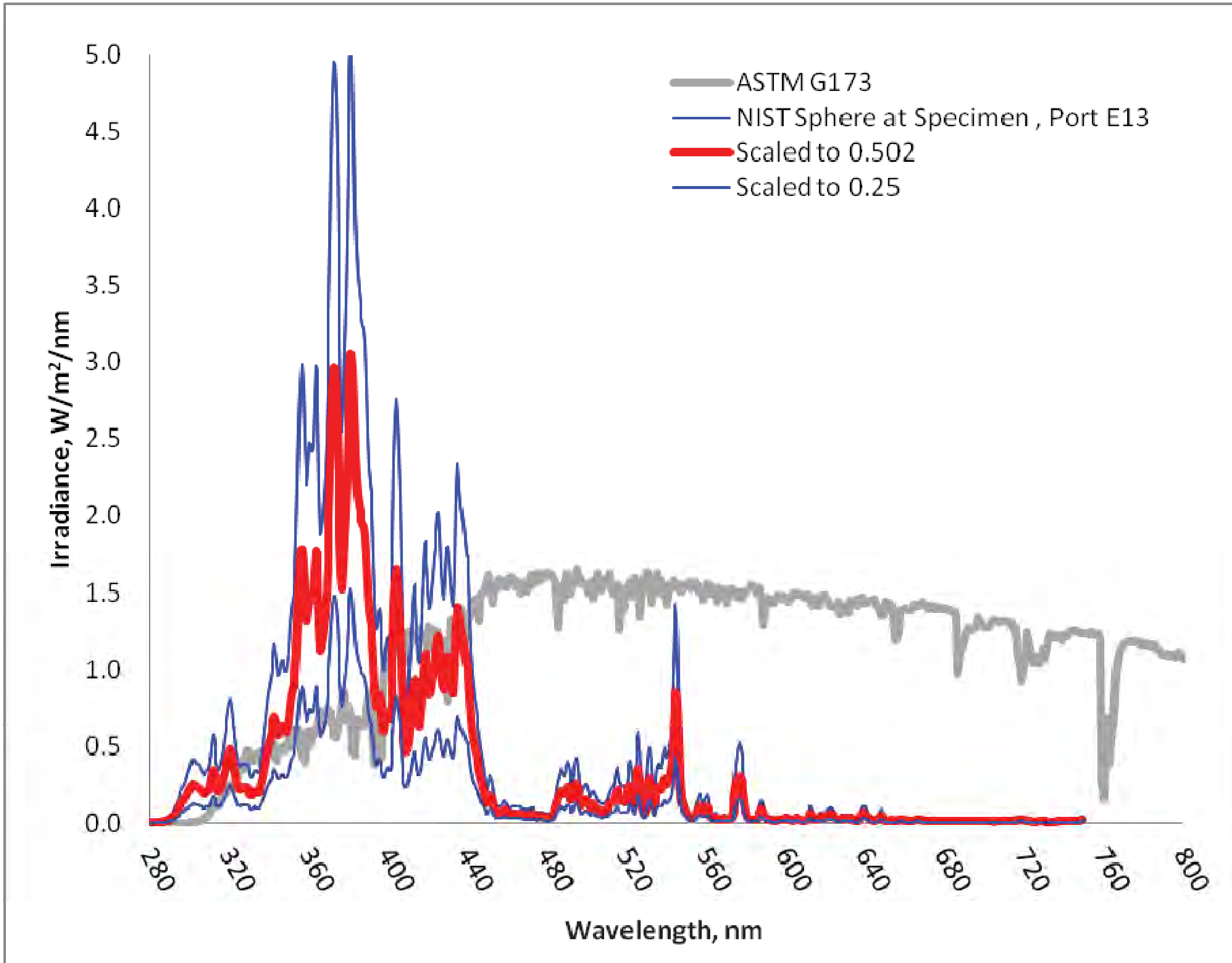
NIST SPHERE – Representative irradiance at the Specimen



http://dx.doi.org/10.1063/1.1808916

Research Sources

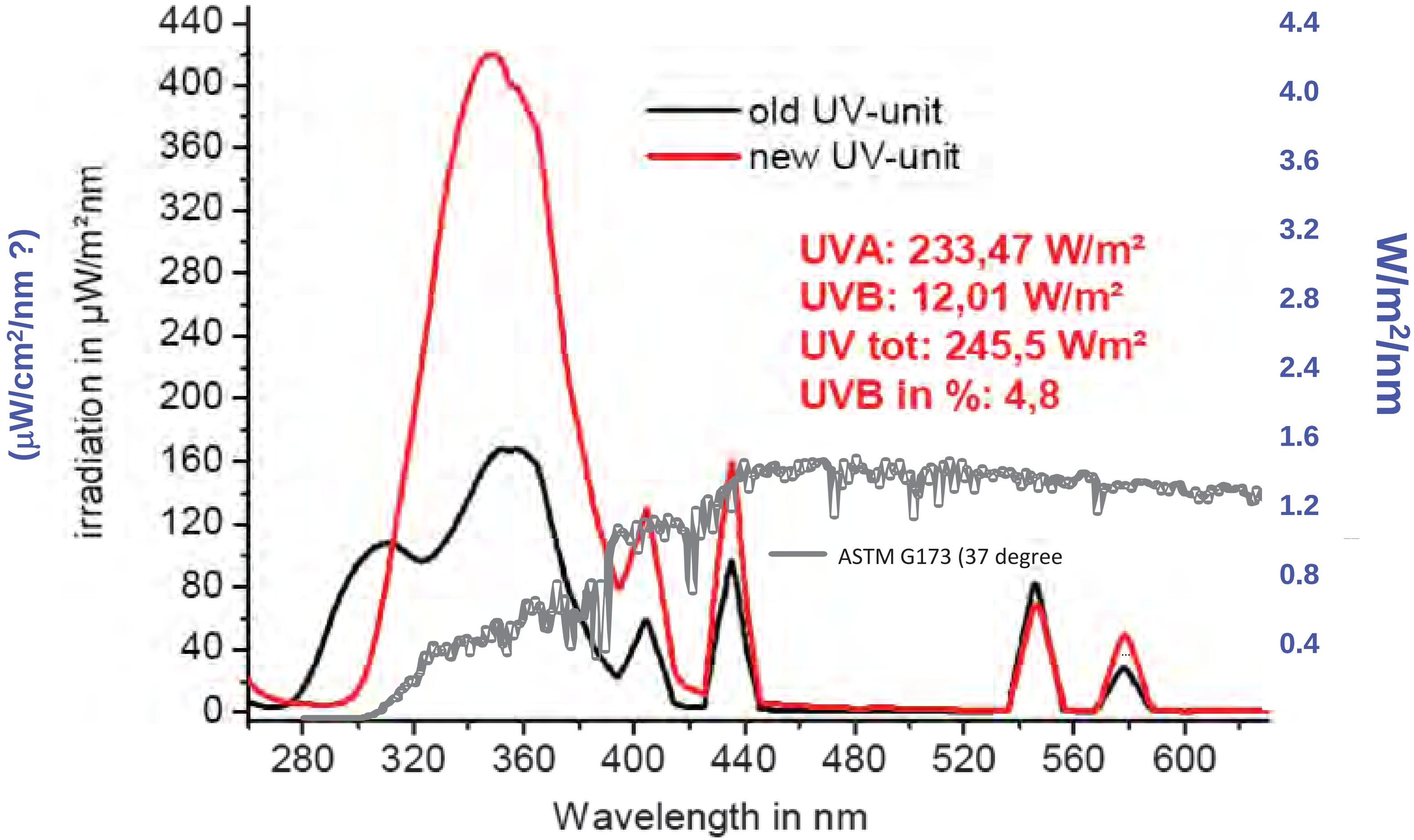
NIST SPHERE – Designed for flexibility



3M Weathering Resource Center

Research Sources

Fraunhofer Institute UV light source for PV-module testing



Spectral distribution of different set-ups with fluorescent UV light-sources. The red line is the spectrum of the newly developed source.

Proc. of SPIE Vol. 7412 741202-1

Research Sources

NIST SPHERE

Advantages

1. Very high irradiances achievable
2. Specifically designed for basic research - extreme flexibility

Disadvantages

1. Lacks long wavelength radiation
2. Very small specimen size
3. Little radiation >450 nm (Lacks radiation to fully engage photoactive component)

Fraunhofer Institute UV light source for PV-module testing

Advantages

1. Good match to solar cut-on
2. Very high irradiances achievable
3. Readily scalable to large exposure areas (full module)

Disadvantages

1. Specialty lamps
2. Little radiation >450 nm (Lacks radiation to fully engage photoactive component)

3M Weathering Resource Center

Light Sources for Reproducing the Effects of Sunlight in the Natural Weathering of PV Materials and Systems

General Conclusions / Caveats

- Weathering tests using artificial sources are tools for gaining insight into the photo-induced degradation of PV materials and constructions.

- There is a wide range of sources available
    - differing significantly in spectral distribution and
    - capable of producing a broad range of irradiance levels.

Therefore, one can expect these sources to induce different effects depending upon the responsively of the materials under test.

- Whether a source is useful for quantitative service life prediction depends upon how well it induces the same degradation along the same pathways and to the same end state as that produced by outdoor weathering.

- Caveat Emptor – PV engineers need to consider the objective of their testing (design screening, degradation understanding, lifetime estimation, quality assurance, other)
    - what can it tell you
    - what can it not tell you

3M Weathering Resource Center

Light Sources for Reproducing the Effects of Sunlight in the Natural Weathering of PV Materials and Systems

QUESTIONS

David M. Burns 3M Weathering Resource Center

Kurt Scott ATLAS MATERIAL TESTING SOLUTIONS

Accelerated Light Aging of PV Encapsulants: Correlation of Xenon Arc and Mirror Accelerated Outdoor Aging from 1993-1997

Charles Reid, Ph.D.

Jayesh Bokria, Ph.D.

Joseph Woods

NREL Reliability Conference, Golden, CO

February 27, 2013

“Rule of Thumb” for Xe Arc and PV

“1 Week in Xe Arc is Equivalent to 1 Year Field Exposure” [1]

Is this valid?

Where did this come from?

What are the assumptions behind this relationship?

[1] Earliest printed citation is 2005

R. Tucker, “Results to Date: Development of a Low-Temperature, Super Fas-Cure Encapsulant”, Paper 5BV.4.8, 20th European Photovoltaic Solar Energy Conference, June 2005, Barcelona, Spain

Introduction

This presentation describes the origin of this “rule of thumb”

This relationship was derived by STR.

- Incorporated using information published in reports from the NREL administered PVMaT phase 3 project.
- This relationship is very specific to a certain set of test conditions and a certain EVA grades.

The relationship may, or may not, be accurate when extrapolated to other conditions or other materials.

… but… This is a starting point for development of accelerated methods

Data Reference: (DOE PVMaT 3 project)
“Advanced EVA-Based Encapsulants, Final Report January 1993-June 1997”
W.W. Holley and S.C. Argo, Specialized Technology Resources, Inc.
September 1998
NREL/SR-520-25296
(US Dept of Energy contract No. DE-AC36-83CH10093)

This reference will be called “**Holley/1998**” with in this document

Introduction

Goals of PVMaT 3:

- Why do encapsulants turn yellow or brown?
- What is the mechanism?
- What test methods can be used to simulate this?

Key Conclusions (Holley/1998)

- Color formation is due to creation of chromophores created by mixture of polymer additives exposed to UV and heat
- Glass type (cerium, non-cerium) was a complicating factor
- Accelerated UV and Temperature can replicate field observations for EVA browning of the older formulations

Materials:

Holley/1998 describes several different commercial and pre-commercial EVA based encapsulant products. Only one encapsulant material will be considered for the purpose of deriving the correlation between xenon arc and natural weathering:

EVA Encapsulant = STR PHOTOCAP® A9918P

(this product is the original standard cure EVA commercially introduced in 1979, and is still commercially available from STR Solar.)

Two different glass grades are used for this correlation work. Both grades are non-cerium, low iron glass intended for use in solar photovoltaic applications.

AFG Solite®
PPG Starphire®

AFG Solite is still commercially available from AGC and is in commercial use. PPG Starphire is also commercially in use for solar industry.

Test Coupons

The test coupons describe in Holley/1998 are as follows:

Glass-Encapsulant-Glass

Coupons have dimension of 68 x 70 mm (2.7 x 2.75 inch).
Coupons were vacuum/thermal laminated and cured.
Target gel content for these coupons was above 75% (toluene soak 60°C test method)

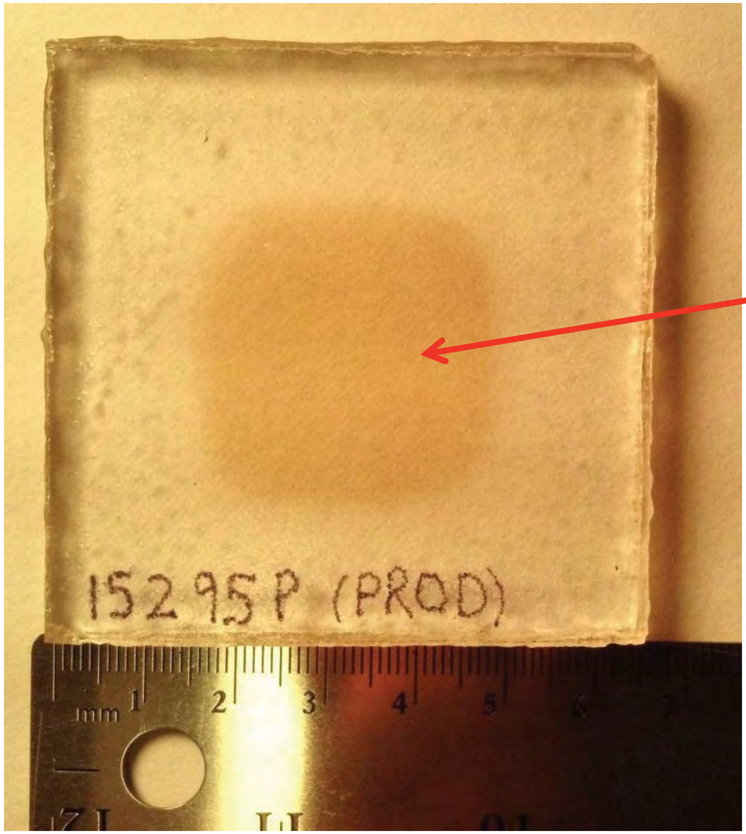
This coupon was selected in order to better simulate the encapsulant between the front face of the PV cell and the cover glass.

In all cases, some bleaching occurred around the perimeter of the coupon. This is due to oxidative bleaching of the EVA yellowing/browning, a mechanism that is well understood and described in other papers.

Yellowness index was measured in the center of the coupon to minimize the influence of oxidative bleaching.

Test Coupons

Picture of Xe Arc Aged Coupon: Glass-EVA-Glass, 70 x 70 mm



Yellowness Index ~ 35
Measurement made in center

Background is white.
Color correction issues with camera

Note – edges are not sealed.

Xenon Arc Exposure

Instrument used: Atlas Ci35A, installed circa 1992-1993
Test conditions:
- Bulb filters = quartz inner / Type S-glass borosilicate outer
- Irradiance controlled at 340 nm, to 0.55 W/m^2
- Temperature = 100°C
- Humidity >95%

Holley/1998 report does not state if the temperature is black body panel or air temperature. It is reasonable to presume that this is the black body panel temperature

Holley/1998 report does not provide details about the humidity control.

This same instrument is still in use at STR Inc in East Windsor, Connecticut, USA.
Atlas Ci5000 also in use

Test conditions used today by STR for this and other xenon arc instruments are:
- 0.55 W/m^2 at 340 nm (quartz / type S boro filters)
- 90°C black body panel,
- 70°C air temperature, and
- 50% relative humidity.

Outdoor Testing: Equatorial Mount Mirror Acceleration

Equatorial mount mirror acceleration (EMMA®) was performed by DEST Labs in Phoenix, Arizona, in mid 1990's. This laboratory is now owned by Atlas Material Testing Technology.

EMMA is a ground mounted mirror and fresnel lens based accelerated aging protocol. EMMA is designed to achieve about 4X UV acceleration and 7-8X visible light acceleration. The method also accelerates temperature and holds the test specimens at a higher temperature than ambient conditions.

Additional information can be found at:
http://atlas-mts.com/services/natural-weathering-testing/accelerated-weathering/emmaqua

Image from Atlas Material Testing Technology

The EMMA used in mid 1990's did not have temperature control and humidity/ water spray was not used.

The data reported in Holley/1998 are from dry aged, accelerated irradiance and elevated temperature.

Results: Xenon Arc Exposure

XAW exposed yellowness index data for EVA encapsulant coupons are shown in Table 7 of **Holley/ 1998**
(image at right).

Total exposure time 24 weeks
Tests performed ~1993-1994

Use the values reported for "A9918/Starphire (Control)"

Table 7 - Average Change in Yellowness Index of Cured Glass/EVA/Glass Laminates With Weather-O-Meter Aging (1)

Sample Construction (2)	4 weeks	Change in Yellowness Index 8 weeks	12 weeks	24 weeks
"Standard Cure" Encapsulants				
X9903P/Starphire	2.4	2.1	1.6	2.0
X9933P/Starphire	2.8	4.3	5.3	4.3
X9923P/Starphire	1.8	2.0	--	1.0
A9918P/Starphire (Control)	6.3	16.0	29.9	58.8 (4)
A9918P/Solatex II or Airphire	5.6	6.8	8.0	12.6
"Fast Cure" Encapsulants				
X15303P/Starphire	2.1	1.9	0.9 (3)	2.0
15295P/Starphire (Control)	0.8	2.6	6.1	48.9
15295/Solite (Control)	1.7	2.7	5.8	31.2
15295P/Solatex II	1.3	1.8	2.2	4.8

(1) Ci35A xenon-arc Weather-O-Meter, 100° C, 0.55 watts/square meter at 340 nm

(2) Glass/EVA/Glass laminates with Starphire on the back side

(3) Data taken by different technician

(4) Solite glass superstrate

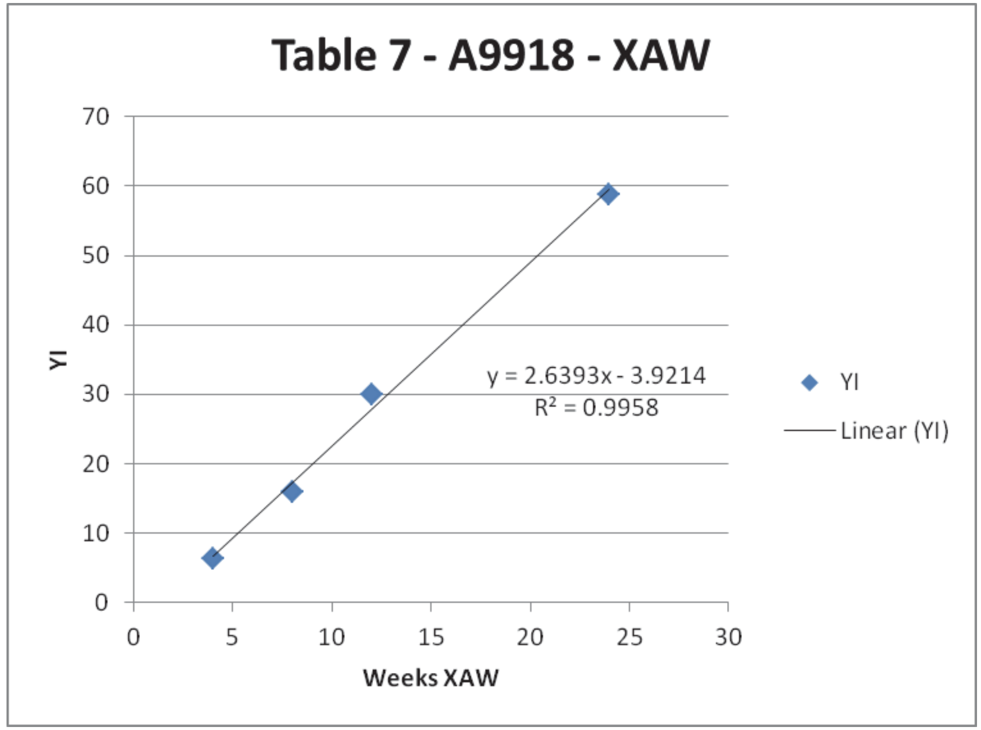
Results: Xenon Arc Exposure

Sample:
EVA = STR A9918P
Glass = PPG Starphire

Yellowness index increases monotonically with increased xenon arc exposure. Rate of increase is approximately:

2.6 YI / week-XAW

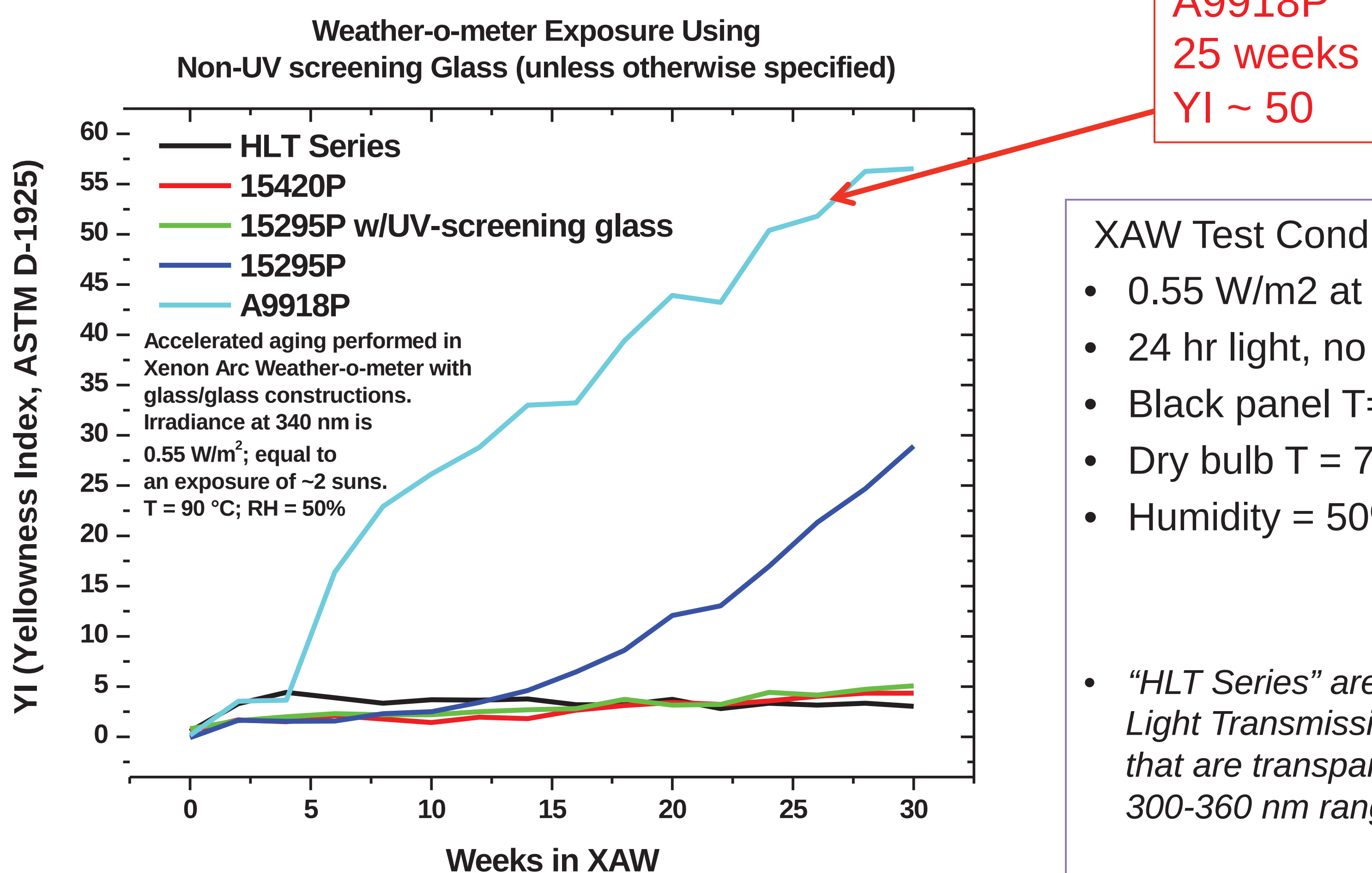
Holley/1998



Xenon Arc Exposure – 2010 Results

Xenon arc is used as a screening tool for new compositions.

A9918 is used as the "control" for new studies.



XAW Test Conditions:

- 0.55 W/m2 at 340 nm.
- 24 hr light, no dark cycle
- Black panel T= 90°C
- Dry bulb T = 70°C
- Humidity = 50%

- *"HLT Series" are new High Light Transmission grades that are transparent over 300-360 nm range.*

Results: Outdoor EMMA exposure

Specialized Technology Resources, Inc.

EMMA exposed yellowness index data for EVA encapsulant coupons are shown in Table 4 of **Holley/1998** (image at right).

Total exposure time = 60 weeks.

Total irradiance = 78 GJ/m^2

Use the values reported for "Starphire/A9918"

Table 4: Average Yellowness Index (2) of Cured Laminates After EMMA(1)

Samples	Construction of Lam	week 0	week 4	week 12	week 36	week 40	week 48	week 61	week 65	week 69	difference 0 to 69 W
1, 2	Solite/A9918P	-1.3	0.5	1.6	13.8	21.1	30.3	34.1	34.5	34.7	36
3, 4	Solatex II/A9918P	-1.2	0.0	-0.0	1.0	1.3	1.3	0.6	0.6	0.8	2.0
5, 6	Starphire/A9918P	-1.6	-0.7	1.1	15.7	23.2	30.7	32.7	33.1	34.0	35.6
7, 8	Tefzel/A9918P	-0.1	-0.6	-0.9	-0.9	-0.9	-0.9	-1.1	-1.3	-1.1	--
9, 10	Solite/15295P	-2.6	-1.4	-1.0	-0.7	-0.0	2.3	3.9	4.2	4.8	7.4
11, 12	Solatex II/15295P	-2.3	-1.9	-2.0	-1.5	-2.1	-1.5	-1.8	-2.0	-1.8	0.5
							Difference 0 to 40				
new	Starphire/X9903P	-1.4	-1.7	-1.7	-	-1.5	--				

(1) EMMA Aging by DSET Laboratories, Phoenix, nominal 5 suns in U.V. region

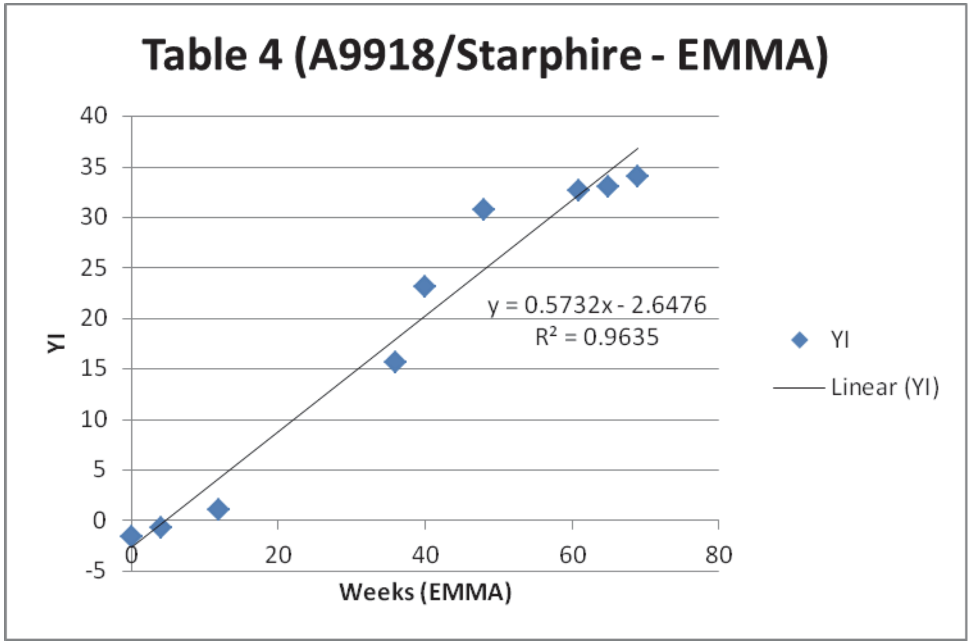
Results: EMMA exposure

Sample:
EVA = STR A9918P
Glass = PPG Starphire

Yellowness index increases monotonically with increased xenon arc exposure. Rate of increase is approximately:

0.57 YI / week-EMMA

Holley/1998



XAW vs EMMA Correlation

EMMA: 5X acceleration of UV exposure
1 week EMMA = 5 weeks Arizona

$$\frac{\textbf{10.4 week EMMA}}{\textbf{1 year Arizona}} \bullet \frac{\textbf{0.57 YI Units}}{\textbf{1 week EMMA}} \bullet \frac{\textbf{1 week XAW}}{\textbf{2.6 YI Units}} \cong \frac{\textbf{2.3 week XAW}}{\textbf{1 year Arizona}}$$

Further Simplification:

Solar irradiance in Arizona is about 2X that of higher latitude moderate climates, such as Germany and North East USA. Thus, the relationship has been simplified to be:

1 week XAW ~ 1 year Outdoor exposure.

CAVEATS:
Relationship is based upon yellowing of STR PHOTOCAP A9918P with Glass-EVA-Glass coupons.
Interaction effects between encapsulant and PV cells are neglected.
The relationship uses both EMMA and Xenon arc, both of which have accelerated irradiance and elevated temperatures.

XAW vs EMMA Correlation

“2 week Xenon Arc ~ 1 year Outdoor AZ exposure”

This is a simple correlation based on EVA browning phenomenon of 1st Generation EVA encapsulants.

Xenon arc is a key test to ensure new encapsulant products do not exhibit this type of browning.

How is Xe Arc Used Today?

Encapsulation Formulation Development

- This is a routine component test, Glass-Encapsulant-Glass
- Different polymers
- Different additives
- Process changes, etc.

Properties Tested with Xenon Arc Coupons

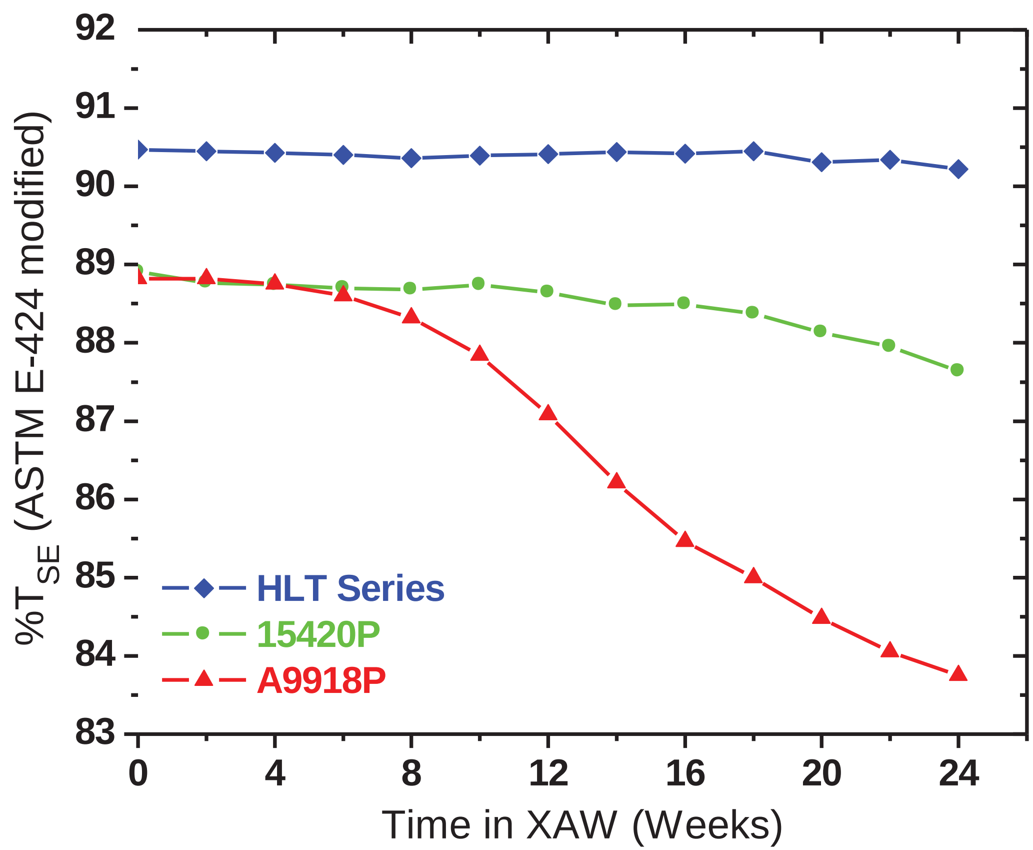
- Color formation
- %Transmission and shifts in UV absorbance
- Glass adhesion stability
- I-V curves for PV cells
- Component corrosion

Interaction Effects:

- Encapsulant interacts with all other components in a PV module

Xenon Arc and %T Measurements

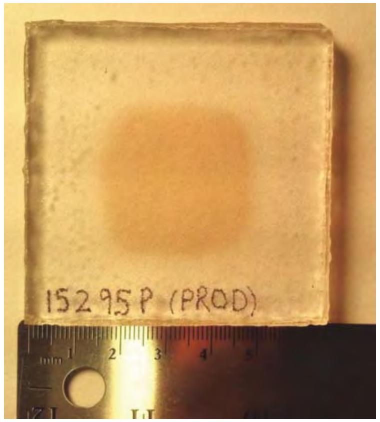
- Solar-energy Weighted %T ($\%T_{SE}$)
  - Practical characterization of %T with UV-Vis Spectrometer
  - %T value integrated over a specific wavelength range (350-1200 nm)
  - Method modified from ASTM E-424 (2007)



3.2 mm Solite glass only = 90.8 %Tse

Is EVA-Browning Understood?

Specialized Technology Resources, Inc.



For EVA Alone as a Component – Yes:

- Component test of encapsulant and glass is well studied and understood.
- Tests described here are used for development of new encapsulant formulations.
- Browning due to additive interactions

For EVA in Contact with Other Components – Yes & No

- Color formation can vary depending upon the PV cell
- Encapsulant and backsheet interactions can cause color
- PID: ion migration through encapsulant to the PV device
- Snail Trails: appears to be silver migration from the fingers into the encapsulant, which interacts with the additive system

Xenon Arc Method Can Be Used to Study Interactions of PV Components for Degradation by UV, T, and humidity

Conclusions

"2 week Xenon Arc ~ 1 year Outdoor AZ exposure"

- This statement is derived from coupon testing done during PVMaT-3 in mid 1990's
- It is reasonably accurate for EVA-browning/yellowing accelerated by UV and Temperature
- This statement cannot be extrapolated to other PV module components or interaction between components

The Xenon Arc Method Can Be Used To Study Combined Stress Acceleration of Components and Interactions

Gen-1 EVA Encapsulants are Good "Standards" for New Method Developemnt to Ensure Browning is Observed

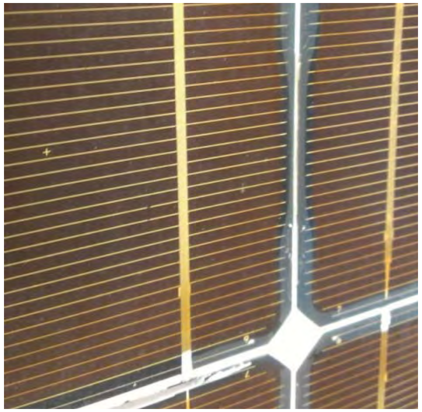
Americas	Europe	Asia
Specialized Technology Resources, Inc. 18 Craftsman Road East Windsor, CT 06088 USA Phone: +1 860-763-7014 ext: 2560 Email: sales@strsolar.com	Specialized Technology Resources, España Parque Tecnologico de Asturias, parcela 36 33428 Llanera, Asturias SPAIN Phone: +34 985 73 23 33 Email: sales@strsolar.com	Specialized Technology Resources, Malaysia Plot D20, Jalan Tanjung A/3 Port of Tanjung Pelepas 81560 – Gelang Patah, Johor MALAYSIA Phone: +607 507 3185 ext:113 Email: sales@strsolar.com

WWW.STRSOLAR.COM

Extra Slides – Modules from the PVMat-3 Project

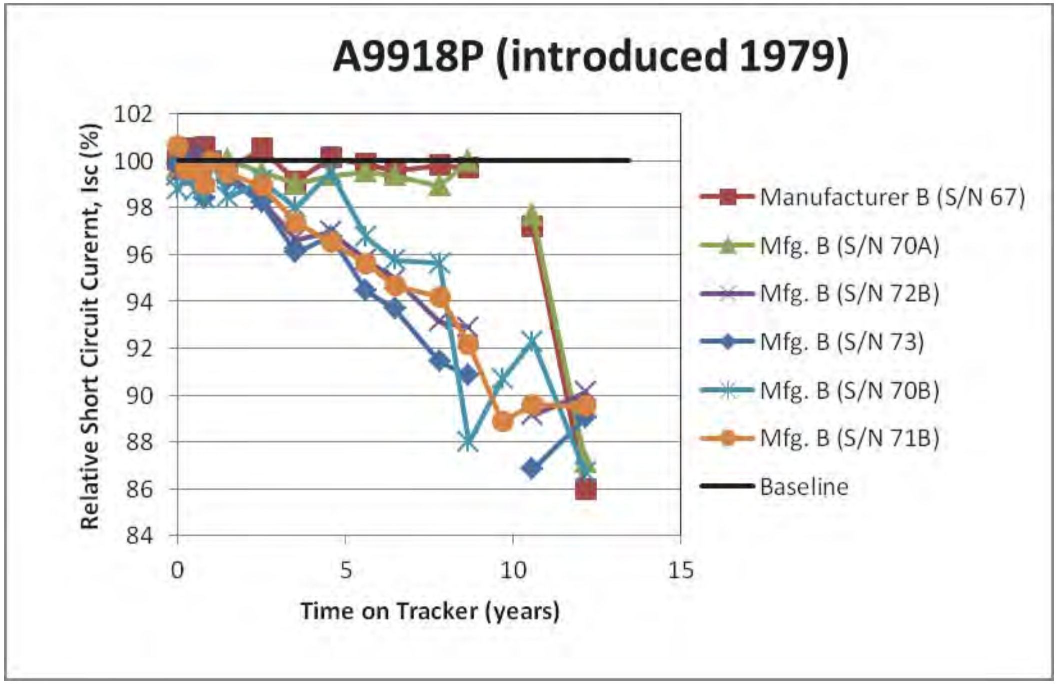
PVMaT-3 Project Modules
Encapsulant A9918P (browning/yellowing)

Slight browning
(panels w/ cerium-based glass)



Cell browning &
cell edge delam to EVA
(panels w/ starphire glass)

Non-Cerium glass:
Isc has dropped ~15%.
Pmax has dropped ~ 50% (interconnect issues)



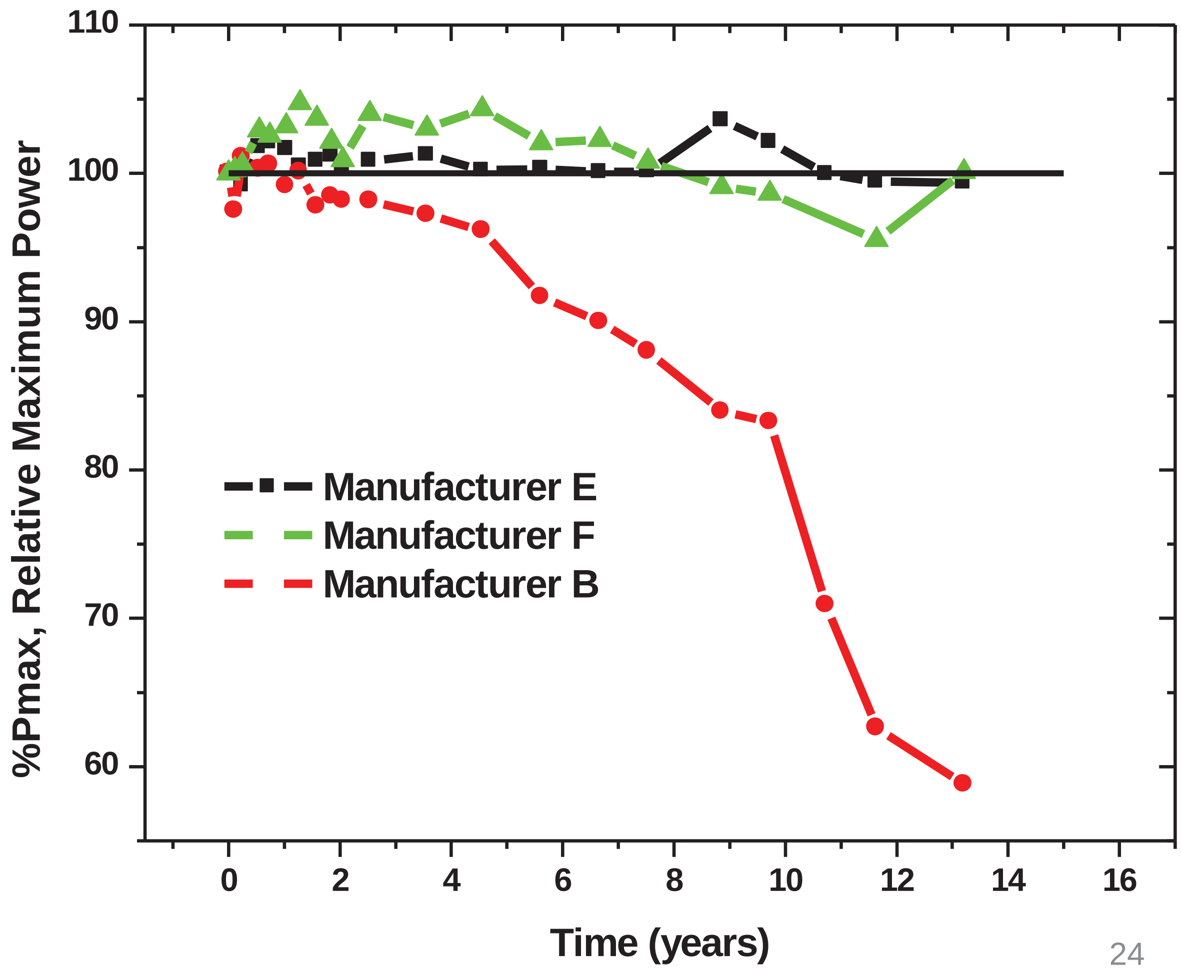
PVMaT-3 Project Modules Encapsulant X15303 (15420P)

Modules made in 1996-97, fielded until 2012, tested by ASU-PRL in situ. Modules are now at STR for diagnostic testing.

Relative Maximum Power (Pmax)

- **Mfg-E = 99.4%**
- **Mfg-F = 100.1%**
- **Mfg-B = 58.8%**

Mfg B modules have corrosion on solder junctions at end of strings. Isc is 95% of original value.



A SYSTEM DEGRADATION STUDY OF 445 SYSTEMS USING YEAR-OVER-YEAR PERFORMANCE INDEX ANALYSIS

Mike Anderson, Zoe Defreitas, Ernest F. Hasselbrink, Jr.
SunPower Corporation, San Jose, Calif., USA

INTRODUCTION

Year-Over-Year Performance Index Change Analysis is a powerful and practical technique for assessing the median degradation of a large fleet of systems

- **ROBUST:** Insensitive to noise and absolute accuracy errors, uses minimal data manipulation and filtering
- **PRACTICAL:** Requires only AC inverter data and essential met data
- **RELEVANT:** Uses data from a live, real-world fleet

A system level degradation study of 445 systems representing 3.2 million module-years of monitored data has been performed using this technique:

- 266 systems (86MW) using SunPower modules as old as 5.5 years ? show median degradation rate = -0.32% ± 0.05% (95% confidence) ? per year
- 179 systems (42MW) using non-SunPower modules (conventional ? front-contact) as old as 11.5 years show median degradation rate = ? -1.25% ± 0.05% (95% confidence) per year?

MOTIVATION

- Degradation rates are generally low, but they still affect project ? economics significantly

? – 0.25%/yr on a $2B project has NPV impact of ~$50M?

PROBLEM STATEMENT

- Solar Investors and Consumers need proof of low degradation.?
  – Small changes are expensive to measure accurately
- Need <1% measurement error ?
- But small-scale experiments do not address Investor concerns:?

? – Well-controlled experiment may not represent real-world experience?
– Extensive data processing and manipulation
? – Noise and Statistical relevance, possible "hand-picked" modules?

SOLUTION STRATEGY

Obtain a massive dataset from installed fleet, use statistics to get high-accuracy median degradation rate.

YEAR-OVER-YEAR PERFORMANCE INDEX ANALYSIS METHOD

1. Minimal filtering – remove obviously spurious data

? – 400 W/m² < Irradiance < 2000 W/m²
– -40°C < Ambient temperature < 65°C
? – 0 (m/s) < Wind Speed < 50 (m/s)?
? – Communication Errors (Flat-lined data)?

Exception made for wind-speed. Bad wind-speed sensors are very common – removing this data would have significantly reduced dataset and sensitivity is low. Wind-speed was replaced with a nominal 2m/s value; this ? approximation has a negligible effect on relative degradation calculations.

2. Compute expected power from weather data + performance model

? – We used PVSim, SunPower's publicly available, state-of-the-art PV ? system simulator, based on Sandia performance model

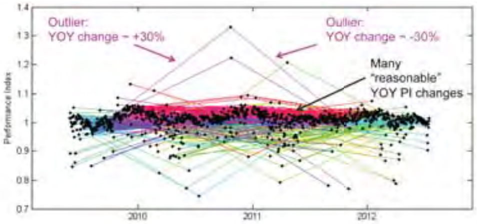
3.Compute Performance Index

P.I. = (Output) / (Expected Output) for each day

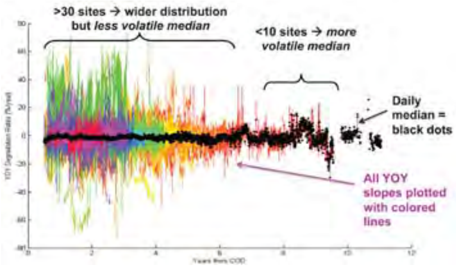
– If performance model were perfectly accurate except for degradation, then P.I. would start at unity but gradually decrease due to degradation

4. Calculate YOY change in PI: $\Delta PI_{n+365/2} = PI_{n+365} - PI_n$

? – This is a central-difference estimate of the local slope d(PI)/dt)?
– Example shown below – colored lines connect YOY PI values.
– Some of the slopes are outliers … but there are thousands of measurements per inverter

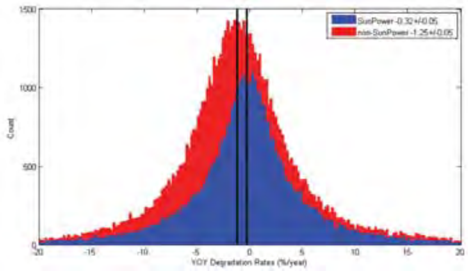


5. Obtain median degradation rate from distribution

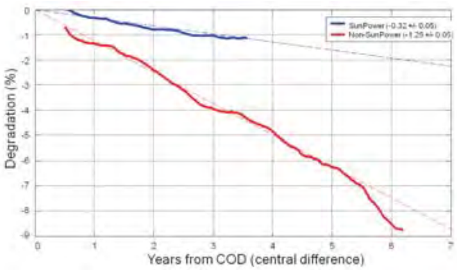


RESULTS AND DISCUSSION

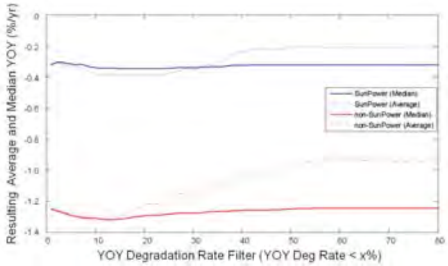
(1) Behavior with system age can be obtained by calculating median)? YOY slopes for all fleet data grouped by system age



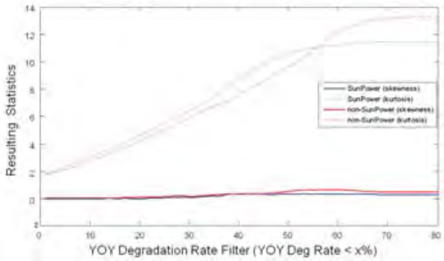
… and these Daily median YOY slopes can be integrated to yield imputed degradation curve:



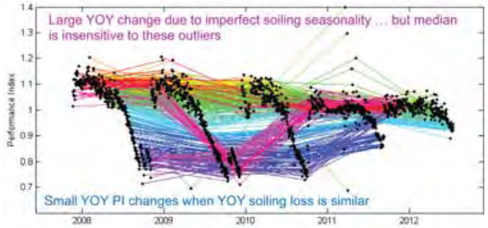
2) Median appears stable even when filtering "outlier" degradation)? rates. Average is not as stable.



3) Skewness is near zero, and stable to filtering of outliers?
(4) Kurtosis, as expected, is affected by outlier filtering?



5) What happens at heavy seasonal-soiling sites?
Soiling is not captured in the performance model. However, YOY approach is still accurate to the degree that soiling is seasonally repeatable.



CONCLUSION

Year-Over-Year Performance Index Change Analysis is a powerful and practical technique for assessing the median degradation of a large fleet of systems

- **ROBUST:** Insensitive to noise and absolute accuracy errors, and soiling
  ? – Median is stable to filtering of "outliers", skewness is near zero?
- **PRACTICAL:** Requires only AC inverter data and essential met data
  – No need for module removal, cleaning and flash testing, or curve)? tracing
- **RELEVANT:** Uses data from a live, real-world fleet
  – Module manufacturers can prove their real-world track record

A system level degradation study of 445 systems representing 3.2 million module-years of monitored data has been performed:

- 266 systems (86MW) using SunPower modules as old as 5.5 years ? show median degradation rate = -0.32% ± 0.05% (95% confidence) ? per year
- 179 systems (42MW) using non-SunPower modules (conventional ? front-contact) as old as 11.5 years show median degradation rate = -1.25% ± 0.05% (95% confidence) per year?

SUNPOWER

SunPower Corporation
77 Rio Robles
San Jose, CA 95134

LPVO Laboratory of Photovoltaics and Optoelectronics

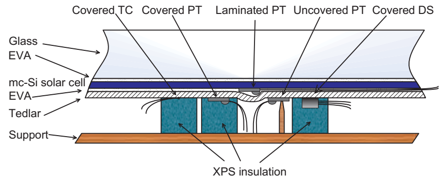
Accuracy of Outdoor PV Module Temperature Monitoring Applications

Marko Jankovec, Jože Stepan, Marko Topič
University of Ljubljana, Faculty of Electrical Engineering, Tržaška cesta 25, SI-1000 Ljubljana, Slovenia
University of Ljubljana Faculty of Electrical Engineering

Objectives

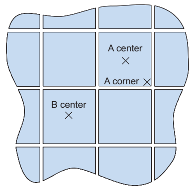
- To evaluate and compare different types of temperature sensors for long term outdoor monitoring of PV modules.
- To evaluate the difference between temperature measurement at the backsheet of PV module, back surface of cells and calculation from V_{OC} (EN60904-5)
- To evaluate the feasability of digital temperature sensors DS18B20 for long term PV temperature monitoring .

Experiment



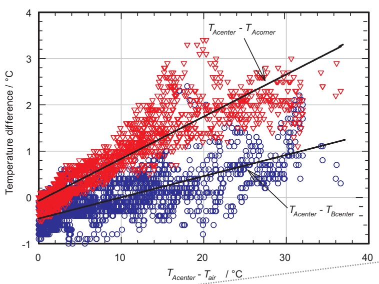
Sensor	Type	Class	Uncertainty T = [0, 85 °C]
PT	Pt1000	1/3 B+	± 0.25 °C (k = 2)
TC	K-thermocouple	2	± 3.2 °C (k = 2)
DS	DS18B20	-	± 0.5 °C (k = 3)

- Locations of laminated PT sensors behind two cells in the middle area of the PV module and a photo of temperature sensors arrangement at the back side of PV module.

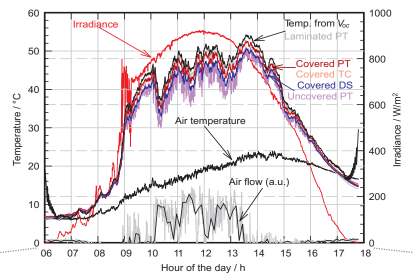


Results

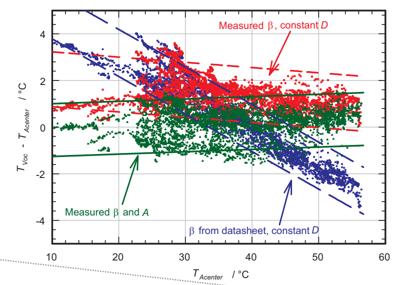
- Additional heating of cells due to isolation at the back of cell A is less than 1 °C.

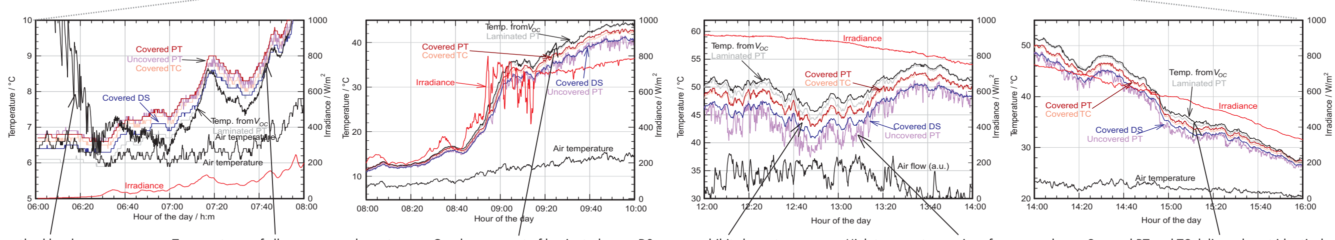


- Temperature, irradiance and wind data for a typical clear sky day.



- Temperature from V_{oc} (EN 60904-5) compared to laminated PT in center of cell A.





V_{oc} method has low accuracy at low irradiances.

Temperatures of all sensors are close at low irradiance and low air temperature.

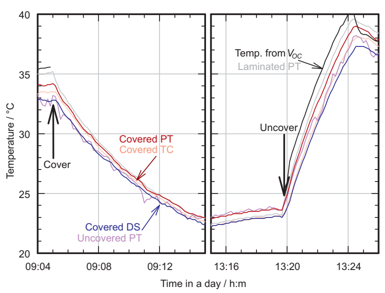
Good agreement of laminated PT and V_{oc} method.

DS sensor exhibits lowest temperature despite insulation.

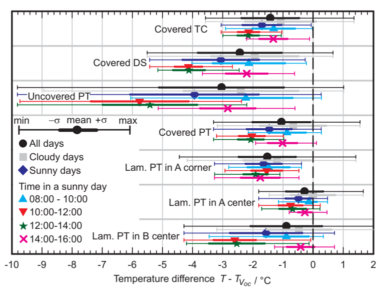
High temperature noise of uncovered PT due to air flow at the back side.

Covered PT and TC deliver almost identical results, but lower than laminated PT.

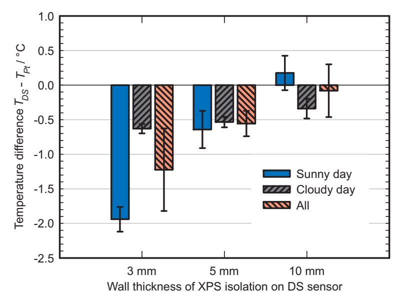
- Test by shading the PV module shows adeqate time response of all sensors.



- Temperature deviations of each sensor according to temperature from V_{oc}.



- DS sensor with different XPS isolations compared to covered PT at the back side.



Conclusion

- Temperature calcualted from V_{OC} give very accurate results at irradiances above 200 W/m^2 if parameters of PV module at STC conditions are known.
- Among sensors attached at the back side, covered PT and TC sensors delivers the best results in range of 1-2 °C of lower temperature in average.
- DS sensors exhibit similar results to PT if they are properly isolated and are more suitable for simultaneous temperature acquisition at many locations.
- XPS insulation of sensors at the back side cause a slight temperature raise of the cell area around, however less than 1 °C in average.

[M. Jankovec and M. Topic, "Intercomparison of Temperature Sensors for Outdoor Monitoring of PV Modules", Journal of Solar Energy Engineering, in print, 2013.]

PV Module Reliability Workshop 2013, Golden, 26-27 Feb 2013

marko.jankovec@fe.uni-lj.si

Laboratory Testing at STC: Necessary but Not Sufficient (

Real World System Testing Picks Up Where Lab Testing Falls Short

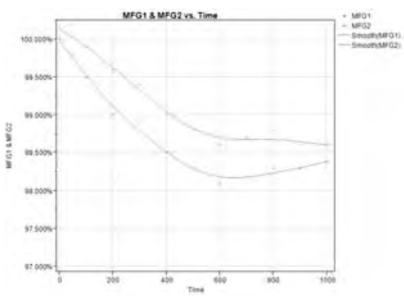
MPropst, NAOlsson, CRichardson; pearllaboratories, 2649 Mulberry Unit 15, Fort Collins CO 80524

Abstract

- Historically performance evaluations have been performed at standard test conditions (STC). A number of pitfalls may skew accelerated lab test results when evaluating performance at STC. Skewed results may over-estimate or under-estimate real world performance often leading manufacturers astray. A comprehensive look at module performance in real world conditions is required to compliment the lab test results. For example, metastabilities in thin film technologies are inherent in the measurements and can result in incorrect conclusions. Parametric values like temperature coefficients and low light performance may not be stable and can degrade more rapidly than measurements at STC will show. These parameters play a big part in the economics of solar installations due to loss in overall energy yield. Accelerated lab testing is necessary in providing some assurances in stability and durability but field performance is the critical and complimentary piece of testing required to accurately predict performance of installations. In this study we present a detailed analysis comparing and contrasting results between accelerated lab testing and outdoor performance testing. This study highlights the shortfalls of STC only performance assessments.

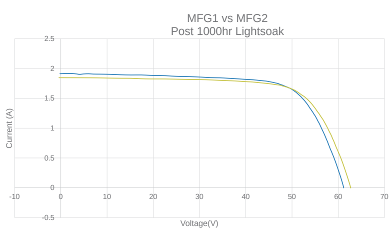
Indoor Light Soak

- MFG1 and MFG2 were subjected to 1000hrs of indoor 1 sun continuous light soak. Modules were pulled from soak and tested at STC every 100hrs.

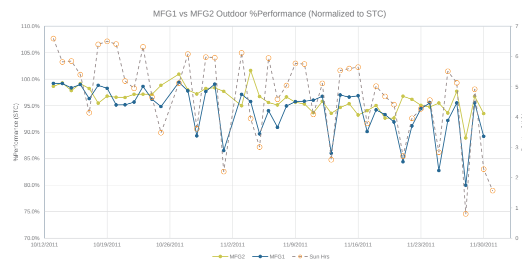


Observations

- MFG1 and MFG2 show very little degradation after 1000hrs of light soak
- MFG1 has begun to recover to match MF2
- IV curves appear nearly identical under STC



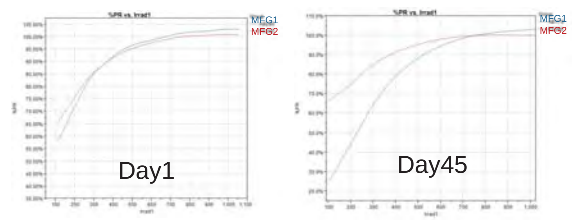
- MFG1 and MFG2 were installed outdoors in identical 5kW systems
- Additionally, 4 modules of each were installed on individual channel MPP trackers and IV curves were swept every 5 minutes.
- Energy yield appeared very similar, noticeable differences occurring on lowlight days



- Using module temperature and Irradiance, each value was corrected to STC and normalized to sticker giving a %Performance (STC) value.
- The days total sun hours in kWh are plotted on the secondary axis to highlight lowlight vs full sun days.
- MFG1 shows significantly poorer performance when days are cloudy or higher percentage of lowlight hours

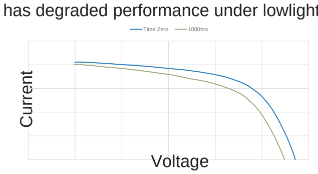
Performance vs Irradiance

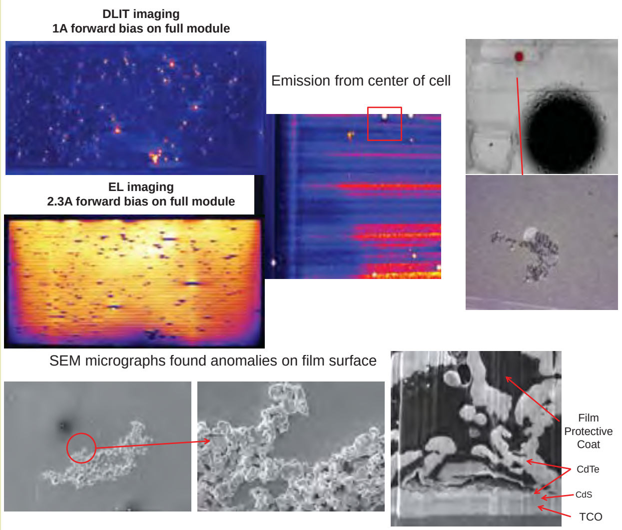
- Initial performance vs irradiance was very good for both MFG1 and MFG2
- Post 45 days performance vs irradiance has degraded at lowlight in MFG1



IV Analysis

- A more in depth analysis of the IV curves after 1000hrs of indoor light soak shows a significant difference when tested off of STC
- Using neutral density filters to assess the curves at varying IRR levels reveals MFG1 has degraded performance under lowlight conditions





- This defect was traced back to the CdTe source form factor which resulted in "spitting" during sublimation.

Conclusions

- Very different conclusions can be drawn about the equivalence of these two thin film manufacturers when looking at laboratory STC testing and actual outdoor performance.
- This particular type of Rsh defect degrades over time and manifests itself in lowlight performance first.

- The PVSYST PAN files for these 2 manufacturers show identical dark Rsh and exponential relationships because at time zero they do match.
- Adjusting the PAN files to account for the degraded Rsh values reveals a significant loss in energy yield each year.
- Above shows the %energy lost when MFG2 is modeled using a 50% Rsh relationship and MFG3 is modeled using a 25% Rsh relationship.

`




The Impact of PV Module Reliability on Plant Lifetimes Exceeding 25 Years

2013 PV Module Reliability Workshop

Larry McClung, P.Eng. and Matt Dorogi, Ph.D.
February 26, 2013

NATIONAL SECURITY • ENERGY & ENVIRONMENT • HEALTH • CYBERSECURITY

SAIC®

Overview of Presentation

.

- Impact of potential induced degradation (PID)
- Correlation between early-life LTD rates and end-of-life failure rates

- Strategies for extending the life older plants
  - Diagnostics for detecting failed modules
  - Strategies for re-paneling PV plants
  - Performance and safety of re-paneled plants
  - Balance of system (BOS) equipment
  - Changes in O&M costs

SAIC®

Introduction to SAIC

- Since the 1980s we have worked with clients around the world to evaluate the viability of energy development
- We have advised clients on more than 1,000 power, infrastructure, and industrial projects in roughly 75 countries and territories
- Expertise in all conventional and renewable power technologies, including solar, hydro, wind, geothermal, and biofuels
- SAIC was ranked as the top independent engineering firm for renewable energy by the trade magazine *Infrastructure Journal*
- Our energy-focused consulting practice is backed by the full strength of SAIC – a diversified, 41,000-employee, Fortune 500 company

Role of the Independent Engineer (IE) in Project Finance

- Evaluate technical risks and mitigants
  - Pure technical risks (e.g., module performance and reliability)
  - Commercial risks from technical contracts (e.g., EPC, O&M)
- Review or develop projected operating results (performance, cost, etc.)
- Liaison between the sponsor and lenders/investors
  - A successful IE will be viewed by all parties as a trusted advisor, striking the right balance between the interests of all parties and showing how those interests are aligned %

SAIC®

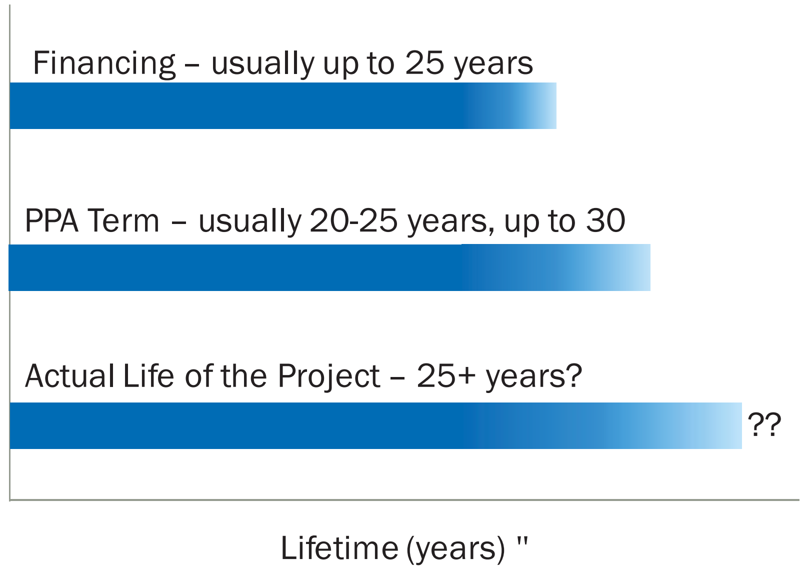
The IE's Interest in PV Module Reliability

- Fundamental questions all financial institutions are asking, directly or indirectly:
  - How much revenue will the project generate, and how much could that change year-to-year
    - Energy production and degradation, resource variability, uncertainty
  - How much will the project cost to operate
    - O&M costs including repair or replacement of major equipment
- Inverters can be repaired, modules can only be replaced
  - How many modules will need to be replaced and when? Why do we think so?
  - What if we can't find compatible modules?
    - Reshuffling of strings/blocks etc.

SAIC®

Push for > 25 year project "useful life"

- Several drivers
  - 25+ year term financing is rare, but not unheard of
  - Sale leaseback financing even for 25 years requires a "useful life" of > 25 years for IRS purposes
  - <u>Revenues from out years drive equity returns</u>
- What do we know?
  - PV modules won't spontaneously combust on Day 1 of Year 26
  - Project could/should have useful life beyond the warranty period, but modules <u>will</u> eventually start to fail at an increasing rate
- How do we consider this from the perspective of an investor?

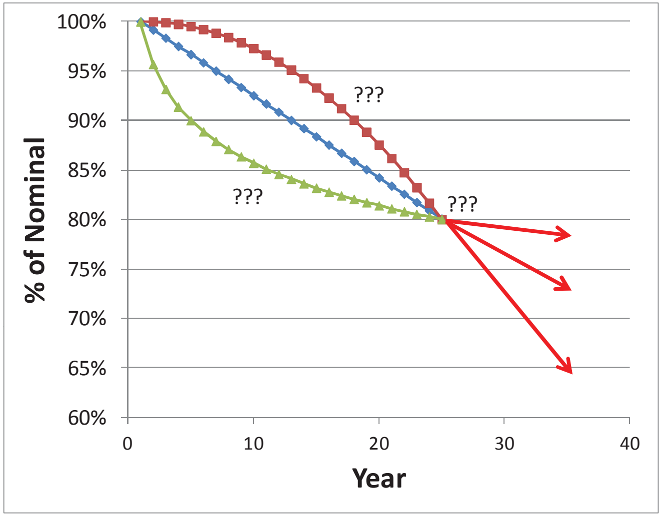


PV Module Life and Long-Term Degradation: Summary of Current Knowledge and Issues

How long will PV modules operate reliably?
What constitutes "failure"?

Useful Life of Modern PV Modules

- Useful life of 25 years supported by accelerated life tests (ALT) of modules, materials tests and field survival of pre-1990 modules
- Little consensus on life beyond 25 years
- Limited field data on multi-decade degradation rates
  - Do degradation rates continue linearly, level off or accelerate?



- What causes end-of-life?
  - Early life failures largely due to poor manufacturing; may not relate to end-of-life failure mechanisms
  - Do old modules just fade away, or do sudden failure mechanisms dominate?
  - Can we identify potential end-of-life failure mechanisms that are simply due to age?
    - Package breakdown, followed by corrosion

Multi-Decade Rates of Long Term Degradation

are inconclusive on key issues:

- Rate of LTD (% per year)
- Linearity of LTD rates over time
  - Do LTD rates accelerate or do modules stabilize?
- Influence of climate on LTD rates
- Applicability of data from old modules to current production

SAIC®

Impact of potential induced degradation (PID)

- Reversible PID
  - Certain PID effects can be reversed if the % proper mitigation is implemented %
  - No impact to LTD?
- Non-reversible PID
  - Na+ diffusion from glass to cell
  - Contribution to LTD?

Courtesy of Department of Energy / National Renewable Energy Laboratory

Courtesy of DOE/NREL

Strategies for Extending the Life of Older PV Plants

What Options Will be Available to Plant Owners %
for Extending Plant Life Well Beyond 25 Years? %

What Defines a "Failed" PV Module?

In this context, module failure is defined in <u>business</u> terms, not purely <u>technical</u> terms

foundations and racking)

- That leaves PV modules as the *de facto* component that limits useful life
- "Failed" modules then are those <u>that produce so little power that it is uneconomical to continue to operate the plant</u>, if all modules performed equally poorly
  - Whether this occurs through a catastrophic component or material failure or ongoing long-term degradation (LTD) is not essential

SAIC®

Safety Concerns as a Failure Mode

- Can safety issues cause a plant to be uneconomical to continue operation, even though power production is unaffected?
- Potentially yes. For example:
  - O&M costs may increase due to an increase in the hazard level workers are exposed to %
  - Insurance costs may increase, or insurance may be refused
  - Payments related to injured workers
- Are there any scenarios where hazard could increase simply due to module aging?
  - Back sheet deterioration, breaking down voltage isolation
  - Failure of junction box means of attachment, exposing live conductors
  - Breakdown of insulation on module pigtails
- Safety concerns will likely increase with higher DC voltages becoming more common

Safety concerns can cause or contribute to ongoing operations becoming uneconomical

Diagnostics for Detecting Failed Modules

- Low cost, effective diagnostics will be required
- Options: spot tests or mining operating data
  - Mining operating data likely lowest cost, but also likely requires “smart” combiners (or module-level data from optimizers or micro-inverters)
  - Alternative may be spot measurements of current, voltage or full IV-trace inside combiner boxes
  - Test for activated bypass diodes? IR imaging?
  - Plant-wide IR imaging of modules (fly over)
  - Other tests?

Courtesy of tenKsolar, Inc.

If re-paneling, detailed measurements are possible, once modules are removed.

Expected Performance of Older Arrays

- Examples in table show 5 cases; all have 20% power loss from "as new"
- All will produce same AC power
  - Inverter voltage thresholds may cause some differentiation
- On DC side LTD is primarily a loss of current; failure is primarily a loss of voltage
  - Therefore relatively easy to distinguish Case A from Case E
  - Less certainty in distinguishing among Cases B, C & D
- The real world is more complex than this example

Example cases of 20% power loss in a string of 20 modules

Header	Degradation	Failed Modules
Case A	20%	0
Case B	15%	1
Case C	10%	2
Case D	5%	3
Case E	0%	4

True ability to distinguish more readily comes from historical performance data. Each of these five cases could be readily differentiated from historical data trends.

SAIC®

Potential Re-Paneling Strategies

Components Replaced	By Strings or Tables	By Inverters	New DC Field
PV modules	●	●	●
Module fasteners	○	●	●
String wiring	○	●	●
Combiner boxes	○	○	●
Racking		○	●
Foundations		○	●
Inverters		○	○
Underground cabling			○
	• Lowest cost • Requires similar modules • Large mismatch errors	• No mismatch • Permits updated electrical • Increased safety	• Required if foundation integrity suspect • Use of adjacent land?

● Replace ○ Optional

SAIC®

Performance of Re-Paneled Plants

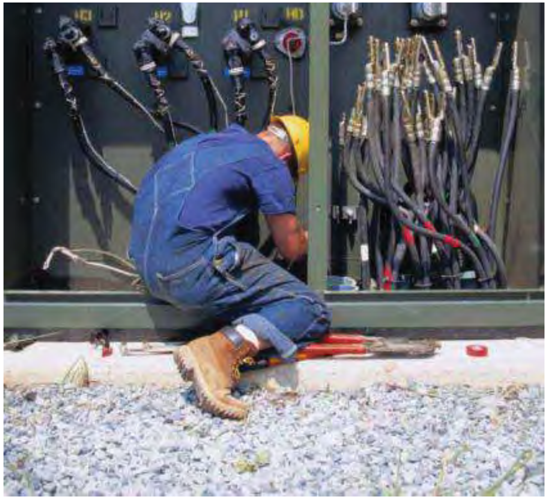
– **Structural review of foundations and racking likely required before long-term re-use permissible**

Courtesy of Department of Energy / National Renewable Energy Laboratory

Courtesy of DOE/NREL

O&M Costs

- How much will they rise, and when?
  - As IE we look for bottoms-up analysis, some thought behind what O&M expenses will increase and when/why
  - Lenders/investors will look for a robust project that can withstand some uncertainty around future O&M costs
- Is it worth it?
  - Post-PPA revenues are uncertain at best even if module performance/reliability is known
  - Difficult question for project developers/owners to answer



SAIC®

Re-Paneling Conclusion

- We conclude that re-paneling will often include replacement of all above ground equipment in the DC field, with the possible exception of the foundations, because:
  - Modules may not be mechanically or electrically compatible, after two-plus decades of innovation
  - Old racking and fasteners may lack the integrity to last another 25+ years
  - Safety concerns may mandate the replacement of all wiring exposed to the weather
  - Concerns of lessened performance if only partial array replacement undertaken
- However, renewal may take place over 2 – 5 years, to spread costs and maintain revenue
  - Owners of larger portfolios may be able to plan staged renewals funded from operations, avoiding the need for capital investment
- Possible exceptions
  - Plant shutdown expected within a few years
    - Unable to extend property lease, unable to negotiate post-PPA power agreement, etc.
  - Future plants have more robust structural design when new, with all components except modules (and string wiring) designed for 50+ year useful life

Developers should <u>consider</u> designing foundations for very long life

Areas for Further Discussion and Research

1. %What will the LTD rate of crystalline modules be in years 25 – 40?
2. %What mechanisms can cause sudden end-of-life?
   - Can we quantify seriousness via HALT?
3. %Do differences in the ability of new modules to withstand extended HALT provide a reliable indication of differences in useful life, or merely differences in early life failure rates?
4. Will safety concerns (e.g. environmental breakdown of dielectrics) play a bigger factor than degraded performance in decisions to continue operating older PV plants? %
5. %If cumulative heat exposure is a major contributor to LTD and/or sudden failures, will module useful life be:
   - Longest in locations with moderate insolation?
   - Somewhat shorter in locations with high insolation?
   - Shorter still in tracking systems?

SAIC®

Thank You

Larry McClung, P.Eng., Senior Engineer
60 Queen Street, Suite 1516 | Ottawa, Ontario K1P 5Y7
Tel: 613.683.3283 | Email: larry.mcclung@saic.com

Matt Dorogi, Ph. D., Senior Project Manager
550 Cochituate Road, West Wing | Framingham, Massachusetts 01701-4654
Tel: 508.935.1649 | Email: matthew.j.dorogi@saic.com

Teresa W. Zhang, Ph.D., Renewable Energy Engineer
1000 Broadway, Suite 675 | Oakland, California94607
Tel: 510.466.7128 | Email: teresa.w.zhang@saic.com

Kevin R. Lang, Ph. D., Director, Solar Generation
1801 California Street, Suite 2800 | Denver, Colorado 80202
Tel: 303.299.5221 | Email: kevin.r.lang@saic.com

SAIC®

An Unanticipated System Vulnerability: Rodent Attack

R. B. "Dutch" Uselton, P.E. (TX), FASHRAE
Mechanical Engineer, Fellow, Applied Research Group
Lennox Industries Inc.
February 25, 2013

ABSTRACT

The PV industry strives to deliver solar power systems that are reliable and effective for a minimum of 25 years. These systems are virtually maintenance-free because they have to be. The return on investment of a PV system is compromised when unanticipated maintenance and repair costs arise. A largely unanticipated system failure mode is starting to show up: electrical failure due to rodents chewing through the insulation of system wiring. This presentation briefly describes occurrences of the failure mode, the current mitigation strategies and possible options for reducing the frequency of this issue.

INTRODUCTION

The dc wires connecting solar modules in a sting inverter system and the dc and ac wires for connecting solar modules with microinverters are not intended to be installed in conduit. Instead, they are ruggedized and simply strapped to the supporting structure of the array. They are vulnerable to squirrels and other rodents that decide to gnaw on the insulation. While it seems odd that rodents would chew on electrical insulation, a quick internet search reveals that this is indeed happening to car wiring and also house wiring. Other than parking the car in a garage, for cars, there isn't a good solution and the repair bills are reported to be high. For house wiring, the damage is usually in the attic and the advice given is to trap and remove the animal and seal openings used by the rodent to get into the attic. It is believed that there are a number of house fires each year attributable to this problem.

In researching this subject we also learned that squirrels will gnaw on materials in order to keep their teeth sharp:

> "It turns out that aluminum wire has an attractive consistency for gnawing," says Stephen Spruell, Southwire Senior Product Engineer. "And the bare aluminum neutrals on overhead service drop cables are a convenient target. We've seen this gnawing problem primarily on service drop cables in areas that are heavily wooded."[1]

A major utility in the southeast began a program to replace bare aluminum neutral service entrance conductors with hard-drawn copper ones. Research showed that squirrels did not find the copper suitable for sharpening their teeth. The solar PV industry mainly uses copper for electrical conductors (aluminum PV wire is available). If cost pressures cause a shift to aluminum conductors, this could very well exacerbate the current problems caused by rodents.

Here are a few photos documenting the occurrence of rodent damage to solar PV wiring systems. Most photos are courtesy of John Wiles[2] and his photo archive.

Photo #1 DC wires damaged by rodents (J. Wiles)

Photo #2 Rat thought to have been electrocuted while chewing on PV module wiring (J. Wiles)

Photo #3 Chewing damage to an AC wiring cable of a PV system (J. Wiles)

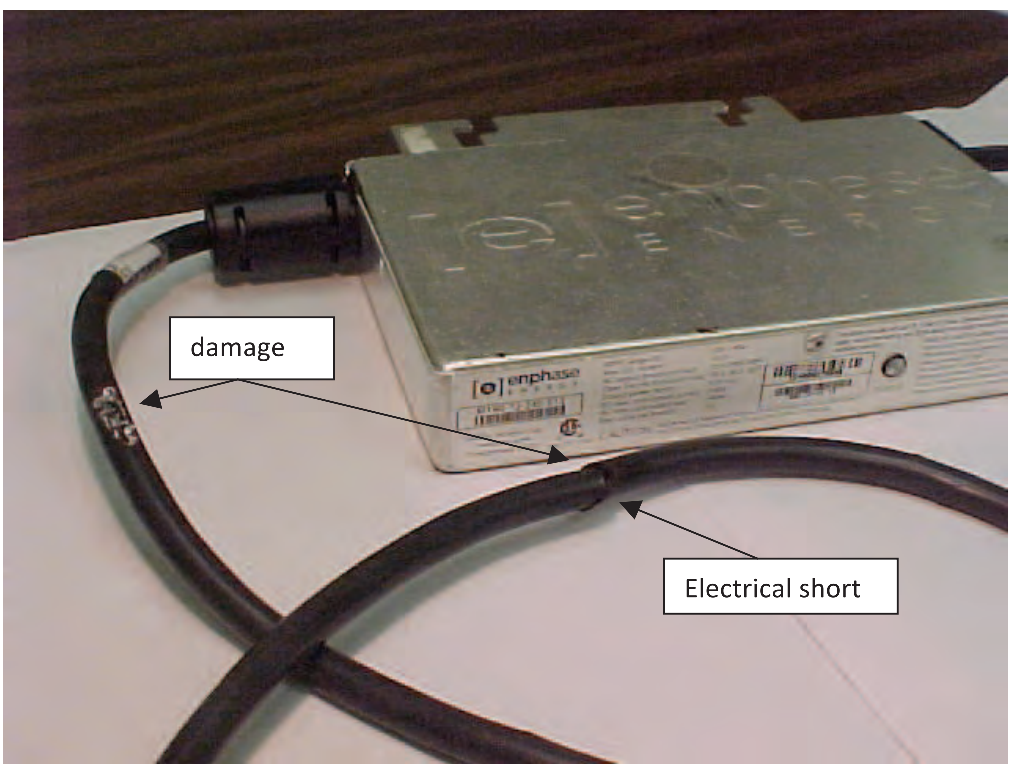


Photo #4 Enphase microinverter AC cable - electrical short from rodent damage (R. Uselton)

Photo #5 Chewing damage to a DC male connector (J. Wiles)

Photo #6 After fire caused by squirrel family gnawing on dc conductors (N. Soleil)

Insulating materials used in at least some (and probably most) of the available wiring systems seem to attract damage by rodents. This includes AC and DC wiring and even the electrical insulation used on some connectors.

Our conclusion is that the problem of rodents damaging electrical wiring is more general than just affecting solar PV installations on the roofs of houses. There could be mitigation techniques that can be borrowed from other industries.

CURRENT BEST PRACTICE

A recent SolarPro article[3] included a page, entitled "Protecting PV Array Conductors from Pests", as part of a larger article on "Array Wire Management". The one recommendation for protecting conductors is to install screening (hardware cloth, etc.) around the perimeter of the array and to put any wires going outside of the perimeter into metallic conduit. This is bound to be an improvement in protection of the wires and additionally discourages nesting of animals under the array. There are several drawbacks to this protection method: additional installation labor involved, debris will tend to build up at the guards and, when some repair or maintenance needs to be done, there is extra work to remove and re-install the screening.

The article mentions two companies with products intended to facilitate rodent-proofing a solar array with guarding. The products are Heyco's SunScreener and Spiffy Solar's Spiffy Clip System (see weblinks on last page).

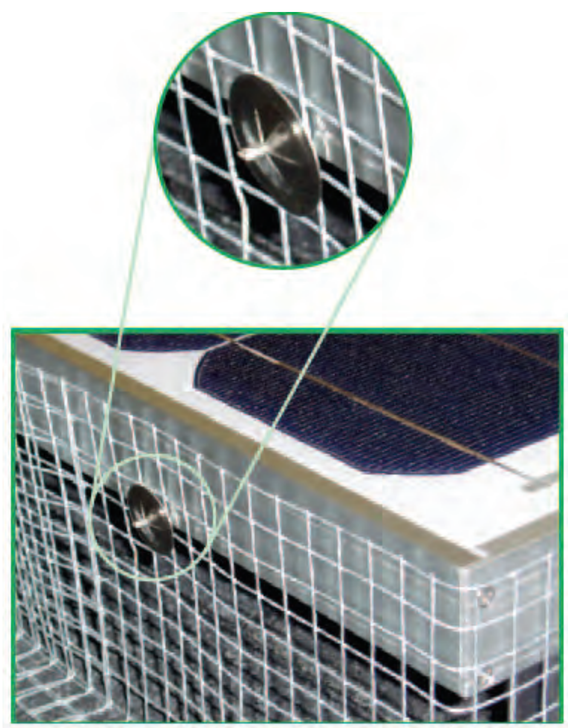


Photo #7 Heyco's SunScreener retaining clips to secure hardware cloth to perimeter of PV array

Photo #8 Wire mesh and clips offered by Spiffy Solar

OTHER SOLUTIONS WITH POTENTIAL

There are a few companies promoting integrated wiring systems. In the figure below, a PVAC module has the connectors for the AC trunk cable integrated within the frame of the solar module. There is no DC wiring and the AC connections from module to module are automatically made when the module is installed next to the adjacent one. The attachment system takes care of module and microinverter grounding.

If the manufacturer would take the additional step of placing a hardware cloth barrier covering the wiring on the back of each assembly, then the field labor to install guarding would be eliminated. This should be an attractive selling feature… if it were offered.

Photo #9 Westinghouse Solar PVAC Instant Connect™ Module

It stands to reason that other industries have been facing the issue of rodents damaging wire insulation so we did some searching through patents and scientific and trade journals. Our feeling was that there ought to be a practical way to make electrical cable either resistant or repellent to rodents. A few interesting leads did turn up in this search.

A Siemens patent[4] presents a cable that is shaped so as to be impossible for rodents to bite. The cable is extruded in a compressed diamond shape and the two sharp points of the diamond have metal embedded at the tips. The bluff shape of the cable is too large for the rodent's mouth and the tips are protected by the metal strips. It is not clear that this design has made it to production. It would be significantly more expensive than the cable it replaces.

FIG 1

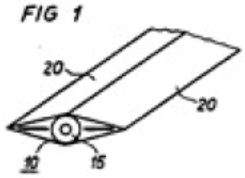


FIG 2

Figures 1 and 2 Two views of a German invention from the early 1980's assigned to Siemens AG

Another German patent[5] discloses a communications cable with a combination of two metallic sheathings to protect against rodent bites. This 1982 patent was assigned to AEG KABEL AG.

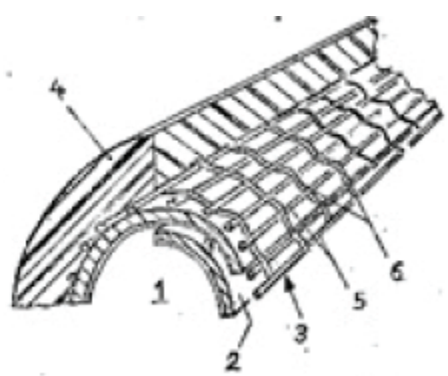


Figure 3 Cable having metallic shielding surrounding the cable core and consists of at least two layers

A 1970 US patent assigned to Phillips Petroleum (3,503,800A) describes the use of a repellent to deter rodents from damaging cables. The abstract reads:

> "Materials subject to physical damage and rodent attack, particularly buried electrical cables, are protected by surrounding same with structurally stable foam having rodent repellent dispersed throughout."

We were able to find the names of a number of companies that supply specialty rodent repellent concentrates and "masterbatchs" for compounding rodent repellent jacketing for electric cable. Here is an example of a PolyOne Corp. press release from 2010.

> "DÜSSELDORF – October 27, 2010 – PolyOne Corporation (NYSE: POL), a premier global provider of specialized polymer materials, services and solutions, today announced plans to incorporate C-Tech Corporation's non-toxic rodent and termite repellent additives to their offering. These new repellent additives will be marketed under the PolyOne OnCap™ concentrate brand."

Another company is Aversion Technologies. Their product family, RodRepel, is described below:

> "The long-linked polymer can be added to rubber or plastic to prevent animals from chewing through cables, composite fencing and other products. RodRepel contains a synthetic purine that mimics predator urine as well as a compound extracted from hot peppers."

Other companies that have advertised similar additives are: Burlington Scientific (maybe bankrupt now), Momentum International, and Evonik Industries.

Some of the chemicals that are used to repel rodents are:

- Capsaicin ($C_{18}H_{27}NO_3$, natural ingredient in hot peppers)
- Piperine (an isomer of Capsaicin)
- Polyolefinic Polyvinylchloride
- Cycloheximide
- N, N-dialkyl-sulfenyl dithiocarbamate
- Mercaptan
- Versatic acid zinc
- Phenitrothion, and
- Terpenoid.

It is clear that the chemical suppliers are steering away from poisons and looking for repellent materials that will not require special disposal procedures for cable at the end-of-useful-life.

In addition we learned that Southwire, a major wire manufacturer in the US, does have its own additive formulations for deterring rodent damage. This feature can be provided when the volume of material is large enough to justify the special compounding.

We know that some manufacturers have qualified their formulations using third-party testing laboratories but we have not been able to find any published data on effectiveness. This does present a barrier to adoption of rodent repellent additives for cable insulation.

NEXT STEPS

The ideal solution to the problem of rodents damaging residential PV wiring would be to identify and use rodent repellent additives in the insulation of the electrical conductors (the ones that do not ordinarily get placed in conduit). There are several open questions about this potential solution.

1. Are any (or many) of the above repellent compounds effective at repelling squirrels, rats and mice?
2. How long can a relatively benign repellent additive be expected to work in our extreme environment of heat, moisture, UV radiation, ozone, etc.?
3. Can these repellent materials be incorporated in a way that allows the installer to do his work without special precautions?
4. Would solar PV wiring that is rodent repellent be a clear winner? Would the additional cost be several times less than the cost of parts and labor for field-installed guarding?

An research program, perhaps organized by NREL, to answer these questions would be of help to the industry.

FOOTNOTES

1. T&D Update (A Southwire Newsletter), ”Service Drop Cables with a SCRAMessenger Keep Squirrels at Bay”, Southwire Corporation, 2005

2. John C. Wiles, Senior Research Engineer, Southwest Technology Development Institute, New Mexico State University, 3705 Research Drive, Las Cruces, NM 88003-8001
575-646-6105 575-646-3841 (FAX)

3. Kane, Stephen, “Protecting PV Array Conductors from Pests”, page 42, SolarPro Magazine, Issue 6.2, February/March 2013

4. German Patent DE3110008A1, 1982, Siemens AG

5. German Patent DE19823234730, 1982, AEG KABEL AG

WEBLINKS

Weblink for Southwest Technology Development Institute and John Wiles:

http://www.nmsu.edu/~tdi/Photovoltaics/Codes-Stds/Codes-Stds.html

Weblink for Heyco:

http://www.heyco.com/alternative_energy_products/product.cfm?product=SunScreener&section=Alternative_Energy_Products

Weblink for Spiffy Solar:

http://www.spiffysolar.com/

Weblink for Westinghouse Solar:

http://www.westinghousesolar.com/index.php/products/72-ac235-instant-connect

Weblink for Southwire:

http://www.southwire.com/

Salvage Values Determines Reliability of Used Photovoltaics

Joseph McCabe, P.E.

ABSTRACT

Tracking salvage values can help to represent the reliability of a particular technology, the manufacturer and model of PV modules. There exists a secondary market for used modules and new modules from bankrupt companies. This presentation examines data from historic utility salvage sales and a bankruptcy auction. Reliability perspectives are presented. From 2005 to 2012, large volume of used PV modules sold at salvage for a variety of pricing dependent upon age, 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.

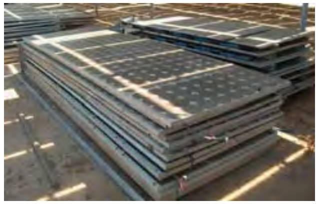


Photo 1: 2006 Stacked single crystal silicon salvaged PV.

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. 1 MW 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. Graph 1 shows these trends overtime.

New Abound Solar CdTe Modules sold between $0.77 and $0.38/watt during the 2012 bankruptcy auction (see Photo 2 & 3). 50 modules per crate sold at different prices due to higher wattage and larger quantity of crates.

Winning Bids from 7 Years of Surplus Photovoltaic Sales at SMUD

	2005		2006		2007		2008		2009		2010		2012	
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	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	a-Si	$0.21
2	a-Si	$0.46	a-Si	$0.31	Single	$0.66	a-Si	$0.50	a-Si	$0.06	a-Si	$0.13	a-Si	$0.25
3	a-Si	$0.46	a-Si	$0.20	Single	$0.77	a-Si	$0.97	a-Si	$0.04	a-Si	$0.07	a-Si	$0.22
4	Poly	$0.98	a-Si	$0.22	Single	$0.82	Poly	$0.44	a-Si	$0.06	Poly	$0.23	Single	$0.27
5	Poly	$0.75	a-Si	$0.24	Single	$0.73	Poly	$1.15	a-Si	$0.04	Single	$0.13	Single	$0.20
6	Single	$0.51	Single	$0.66	Single	$0.82	Single	$0.54	a-Si	$0.04	Single	$0.13	Single	$0.27
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		$0.20
Max		$0.98		$1.26		$0.82		$1.15		$0.48		$0.33		$0.27
Total kW	150		69		177		136		212		160		75	

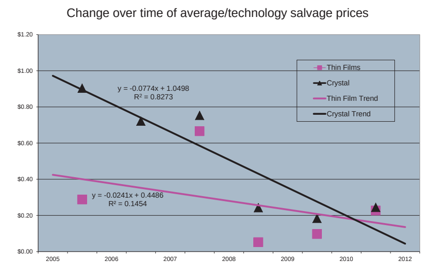
Table 1: 2005 – 2012 Salvage Values for various technologies; 1 MW total original capacity.

RESALE MARKETS

Used modules are bought and sold in a number of ways. They can be installed into non-incentivized systems like off grid markets. They are often sold in resale channels like on E-Bay, Craigslist or classified section of Home Power Magazine.

Individual modules could be sold into existing systems where a component has broken. If an existing PV system has a problem with an individual module, replacing that module could have a very high system level value.

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 are available around the world including a PV ReCycling.



Graph 1: Trends for salvage sales, 2005 to 2012.)

Photo 2 & 3: Crate of 50 new Abound CdTe ($0.77 to $0.38/W) & 800 to 2000 lbs. of broken CdTe. Were 140,000 of these CdTe modules locally landfilled?

ENERGY, 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 W/m^2.

SMUD salvage sales illustrates a-Si on breakable float glass has considerable less salvage value than single or poly silicon technologies using tempered glass. 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 5, reducing the resale value dramatically.

PHOTOS OF SALVAGED PV MODULES

Photo 4 & 5: 1995 Solec SP-102's piled up in 2010, EVA discoloration, lowered price, but didn't effect performance.

Photo 5 & 6: Well stacked float glass a-Si for bid in 2009.

PHOTOS OF SALVAGED PV MODULES

Photo 7: Well cared for and stacked modules obtain best salvage price.

Photo 8: Panorama of poorly handled float glass a-Si for bid 2005.

2011 Salvage Operation

In 2011 we examined the 144 Solec SP-102's 24 volt modules shown in photo #4 for the actual resale value. Operating modules produced approximately 85 watts in full sun, consistent with a 1%/year degradation. Performance was field measured with a 100 watt variable resistor providing voltage open circuit, short circuit current and a good approximation of voltage and current at max power in full sunlight. Good modules with junction boxes sold on a roadside in Grass Valley CA (see Photo 9) 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 (see Photo 10), delamination, serious browning of EVA (see Photo 5), 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 would be taken out of service with immediate installation in a new location.

Photo 9 & 10: Selling PV in CA, Broken and good quality modules.

CONCLUSION

There is a healthy resale market for PV modules that should be recognized in project level economic calculations. The salvage price is a market reflection of the reliability. 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. Live auction might provide higher salvage values as in the Abound Solar experience. 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. Recycling is an important industry issue.

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 – 2012 http://www.smud.org

NREL PVRW 2010 BP Solar presentation pvrw2010_wohlgemuth.pdf

October 2012 Abound Solar Bankruptcy auction.

energyideas@gmail.com

Understanding Differences in Induced Stresses to Improve Variation in Light Soak Response

Jim Sorensen, Katie Hoepfl, Kevin Neibel

Introduction

Understanding the impact of induced environmental conditions on fully encapsulated PV modules is critical for modeling and predicting stimulus response and performance under field conditions. Significant differences in results have been noticed in light soak tests conducted with equipment from different manufacturers beyond the differences resulting from testing modules of varying construction. Through specially constructed thin-film modules, the semiconductor temperature was mapped through various back-of-module setpoint temperatures, at various irradiance levels. Using this approach, the p-n junction temperature was modeled. The equipment setpoints were adjusted to match estimated p-n junction temperature, and test results confirmed.

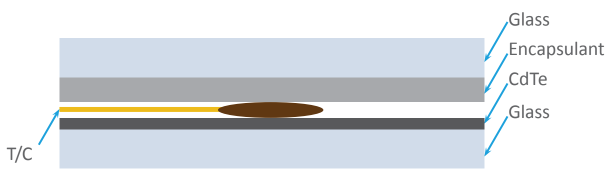


Figure 1: Side view of placement of thermocouple in module stack.

To investigate this issue, we developed a tool to measure the critical temperature and map it across VLS types. The tool we developed was a standard First Solar module with K-type thermocouples laminated inside.

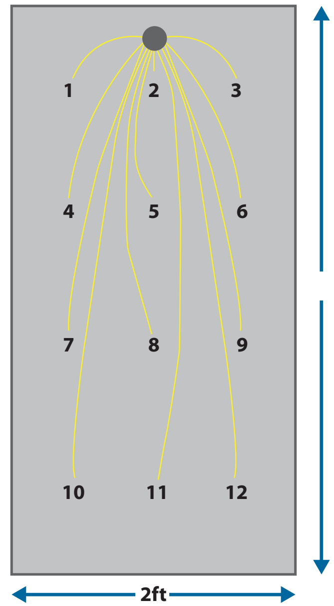


Figure 2: Diagram of T/C placement throughout module.

Results

As a result of extensive temperature mapping between units based on setpoint temperature, irradiance and other factors, a guide was developed to determine equivalent conditions between manufacturer A and manufacturer B. (Figure 5) Once conditions were matched, light soak test results were also well matched. (Figure 6)

This study has highlighted that this issue is relevant throughout the entire industry. As a collective, we need to understand the effective induced stresses to appropriately analyze stress test results.

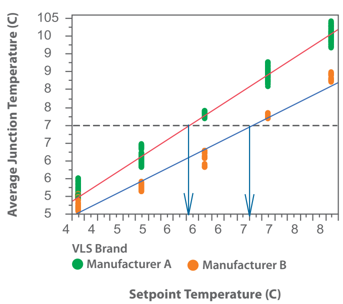


Figure 5: A guide has been developed for use within the company to determine proper setpoint temperatures to obtain accurate critical temperatures.

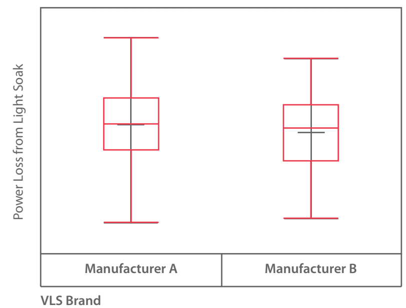


Figure 6: Test results showed critical conditions are now well matched.

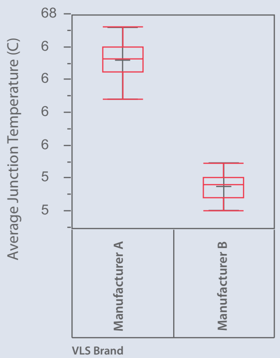


Figure 3: Identical conditions between VLS manufacturer A & manufacturer B, produced very different critical temperatures.

An initial survey in manufacturer A and B showed very different critical temperatures at identical setpoint conditions (irradiance & temperature). **This difference produced a 25% difference in results.**

The distribution of temperatures throughout the module was also quite different. Manufacturer A had a much larger standard deviation than the other.

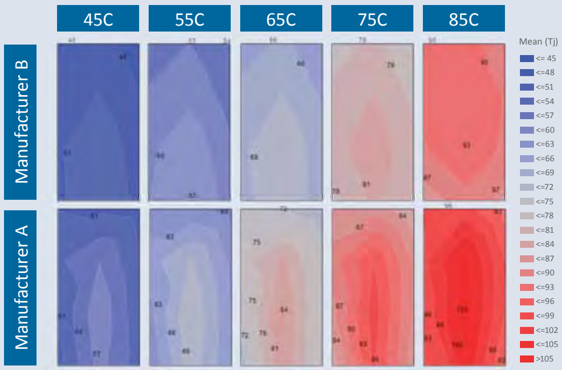
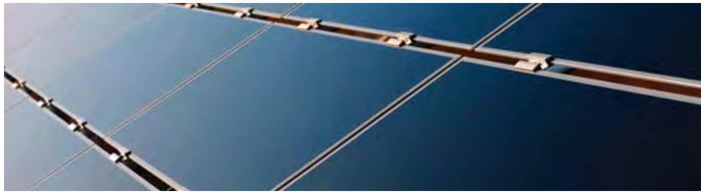


Figure 4: Contour Plots of temperature distribution throughout the module at five setpoint temperatures in both VLS types.

Conclusion

With this poster, First Solar aims to share its understanding that not all stress equipment induce stress in a similar fashion. **Equipment characterization is necessary to ensure predictable and accurate modeling.** Specified conditions need to be standardized in terms of critical temperature. Testing standards should define test conditions similarly (ambient temperature, backsheet temperature, junction temperature, etc.)



Effects of metastabilities on CIGS photovoltaic modules

D. Pic, B. Bertrand, V. Bermudez, L. Parissi and P. Calzi !

Nexcis Photovoltaic technology, 190 avenue Célestin Coq, 13790 Rousset, France !

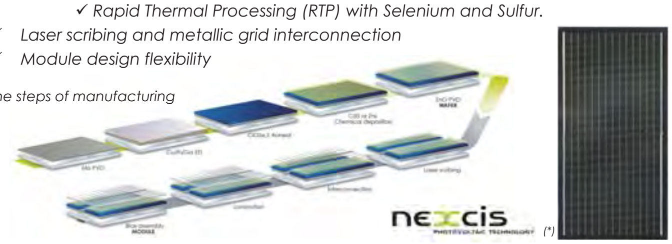
✓ *In this work, we have characterized metastabilities behavior on our CIGSe thin film module obtained by Electrodeposition and RTP process steps. We have carried out an understanding study of the driving force of the mechanisms which rules the different observed phases during storage, light exposition and annealing. The aim of this study is to obtain a better understanding of this phenomenon and hence a better evaluation of its impact on Panel Reliability and for qualification tests provided by IEC 61646 norm.*

✓ *Chalcopyrite CuIn$_x$Ga$_{1-x}$(S,Se)$_2$ solar cell by 2-step process:*
- ✓ *Electrodeposition CuInGa on Molybdenum-covered glass (ED)*
- ✓ *Rapid Thermal Processing (RTP) with Selenium and Sulfur.*

✓ *Laser scribing and metallic grid interconnection*

✓ *Module design flexibility*

The steps of manufacturing



Characterization tools and methods

✓ *All experiments are performed with 30x60 cm² prototype modules (*).*

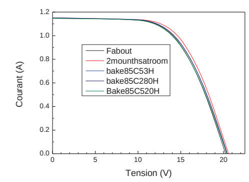
✓ *We use a calibrated flash solar simulator class AAA to obtain optoelectronic parameters. Before measurement, modules are stabilized at 25°C ± 1°C.*

✓ *Bakes are performed with a standard oven stabilized at 85°C ± 2°C.*

✓ *Illumination ageing study is performed in a dedicated chamber maintained at 30°C ± 2°C (Xenon lamp class C in term of spectral mismatch and time stability).*

✓ *We observe a gain after storage in fab room under ambient illumination. (+3/+4%).*

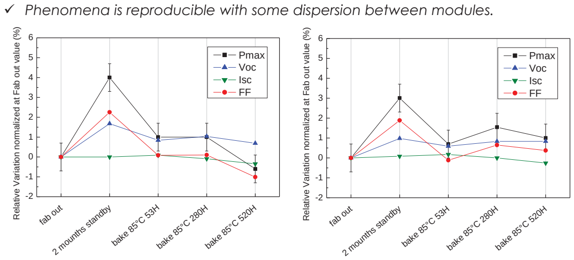
✓ *After a bake at 85°C in the dark, this gain is recovered.*



Storage time in fab room under ambient illumination : *2 months*

Bake temperature : *85°C*
Sampling : *53H, 280H, 520H*

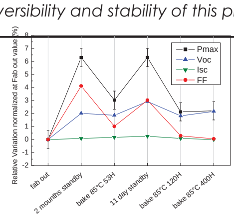
✓ *Phenomena is reproducible with some dispersion between modules.*



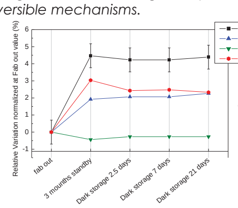
✓ *Similar phenomena have been reported in the literature for CIGS technology [1],[2].*

✓ *In order to understand metastabilities origin, we have performed a set of experiments to dissociate dark, light and temperature effects.*

1) Reversibility and stability of this phenomenon



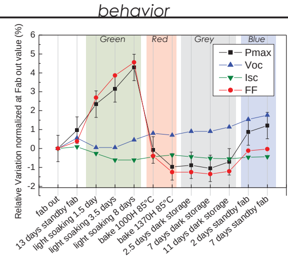
✓ *The metastabilities gain under illumination (for various intensities) and the metastabilities recovery in dark storage conditions at high temperature (85°C) are both reversible mechanisms.*



Dark Storage at 25°C

✓ *The metastabilities gain obtained remains stable during the time in dark storage conditions at room temperature (25°C ± 5°C).*

2) The driving forces of the associated electrical behavior



The performed tests show that :

✓ *Metastabilities gain is accelerated at standard illumination conditions (1000W/m²) (green area).*

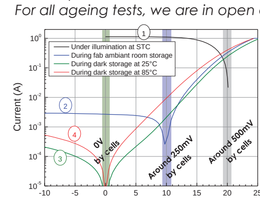
✓ *Metastabilities recovery is accelerated in temperature if we compare dark storage at 20-30°C (grey area) and 85°C (red area).*

✓ *Metastabilities gain is generated under low illumination conditions too (<10W/m²) (blue area).*

✓ *The recovery phenomena is also observed at 60°C.*

3) Study of Storage conditions characteristics

✓ *Respective electrical field conditions comparison. For all ageing tests, we are in open circuit condition (I= 0A).*



Studied conditions description :
1) *IV under illumination*
2) *IV in fab ambiant room storage*
3) *IV in dark storage at 25°C*
4) *IV in dark storage at 85°C*

✓ *For illumination condition(black IV curve 1) and fab ambient room storage condition (blue IV curve 2), the thermodynamic equilibrium is modified by generated electron flux which can be responsible of the metastabilities gain.*

✓ *In the case of dark storage at 25°C (green IV curve 3), 60°C and 85°C (red IV curve 4), electron flux is negligible. The metastabilities recovery mechanisms is highly activated in temperature (diffusion mechanisms?).*

✓ *Perspectives :*
- ✓ *Extraction of the activation energy of metastabilities recovery mechanisms.*
- ✓ *Bias soaking study to better characterize metastabilities gain mechanisms.*

Conclusions

✓ *All these studies allow a better understanding of the metastabilities phenomena linked to our panel. To realize reliability evaluation and qualification tests, we have to deal with these aspects.*

✓ *Light soaking is a well known phenomenon for CIGSe technology.*

✓ *Metastabilities defects have to be controlled to properly address reliability issues.*

✓ *Bias soaking effects and recovery thermal activation have to be investigated to continue this work.*

[1] Light Soaking Effects on PV Modules Overview and Literature Review , M. Gostein and L. Dunn Atonometrics, NREL PV Module Reliability Workshop, February 2011

[2] Analysis of Alternate Methods to Obtain Stabilized Power Performance of CdTe and CIGS PV Modules J.A. del Cueto and Al. NREL, NREL PV Module Reliability Workshop, February 2011

Contacts :

david.pic@nexcis.fr
bertrand.bertrand@nexcis.fr
veronica.bermudez@nexcis.fr

Partial Shading in Monolithic Thin Film PV Modules: Analysis and Design

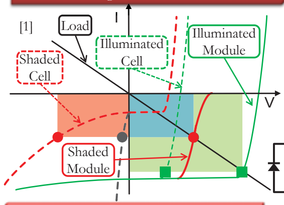
Sourabh Dongaonkar (sourabh@purdue.edu) and Muhammad A. Alam (alam@purdue.edu)
School of Electrical and Computer Engineering, Purdue University

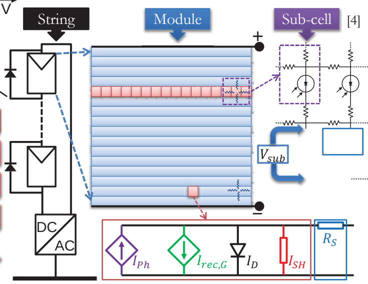
Network for Photovoltaic Technology

1 Partial Shading in TFPV Modules

Partial shading can induce reverse stress

Shadow stress is important reliability concern

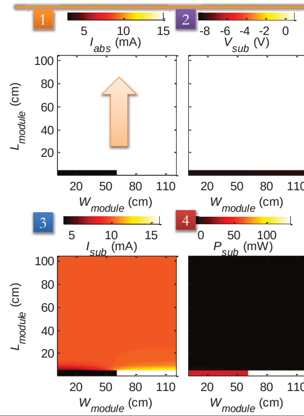




Unique challenges for TFPV modules

- No integrated bypass diode
- Size and shape of individual cells
- 2D connectivity plays important role
- Full SPICE simulation must be used

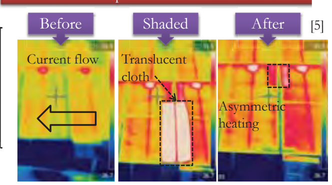
2 Asymmetric shadow stress



Simulation of typical ($104 \times 120cm^2$) a-Si:H module shadow area ($5 \times 60cm^2$) at bottom left

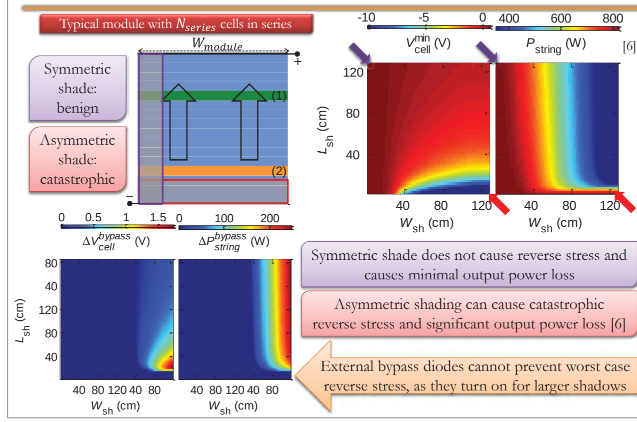
1. Color plot of absorption current, showing left half of 5 bottom cells shaded
2. Sub-cell voltage across shaded cells becomes negative uniformly across the width
3. Sub-cell current in unshaded region must *increase* to maintain current continuity
4. Entire width of shaded cells dissipates power, but unshaded half is at higher stress [5]

Experimental validation



3 Effect of shadow geometry

Typical module with N_{series} cells in series

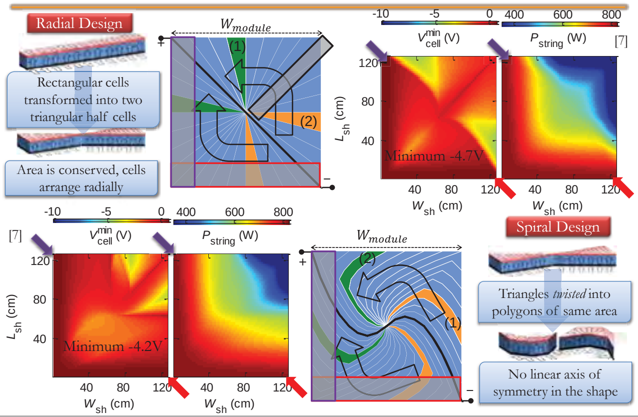


Symmetric shade does not cause reverse stress and causes minimal output power loss

Asymmetric shading can cause catastrophic reverse stress and significant output power loss [6]

External bypass diodes cannot prevent worst case reverse stress, as they turn on for larger shadows

4 Shade Tolerant TFPV Modules



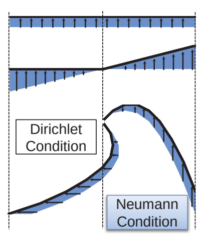
5 Shade Tolerant Module Efficiency

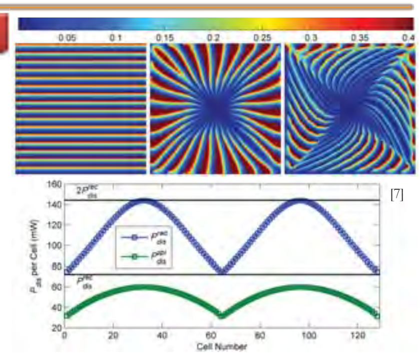
Sheet resistance loss in non-rectangular geometries

$$\nabla^2_{xy}\phi = -J_{phR} \; .$$

$$= \sigma \vec{\mathcal{E}}_{xy} = \vec{\mathcal{E}}_{xy}/R_{\square}$$

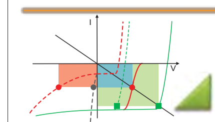
$$P_{dis} = \int \vec{J} \; .$$





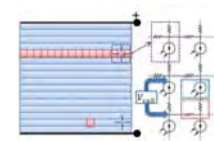
Change in cell geometry can reduce overall sheet resistance loss as well as provide shade tolerance

6 Summary and Conclusions



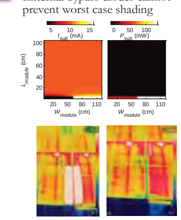
Partial shade effects in TFPV modules

- Unique challenges for monolithic TFPV modules
- Cell and shadow geometry must be considered
- Full 2D simulations required for prediction



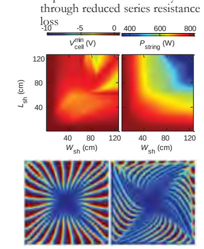
Asymmetric shadow stress

- Unshaded portions of TFPV cells can be under higher stress
- Shadow geometry and orientation have a huge impact of shadow stress
- External bypass diodes cannot prevent worst case shading



Shade tolerant design

- Geometry can be used as a design parameter to avoid shadow performance
- Radial and spiral designs improve shade tolerance as well as power output
- Shaping the cells can also lead to improved module efficiency through reduced series resistance loss



References

[1] S. Dongaonkar, Y. Karthik, D. Wang, M. Frei, S. Mahapatra, and M. A. Alam, "Identification, Characterization and Implications of Shadow Degradation in Thin Film Solar Cells," in Reliability Physics Symposium (IRPS), 2011 IEEE International, 2011, pp. 5E.4.1 – 5E.4.5.
[2] F. Martínez-Moreno, J. Muñoz, and E. Lorenzo, "Experimental model to estimate shading losses on PV arrays," Solar Energy Materials and Solar Cells, vol. 94, no. 12, pp. 2298–2303, Dec. 2010.
[3] A. Woyte, J. Nijs, and R. Belmans, "Partial shadowing of photovoltaic arrays with different system configurations: literature review and field test results," Solar Energy, vol. 74, no. 3, pp. 217–233, Mar. 2003.
[4] S. Dongaonkar and M. A. Alam, "End-to-End Modeling for Variability and Reliability Analysis of Thin Film PV," in 2012 IEEE International Reliability Physics Symposium (IRPS 2012), 2012, pp. 4A.4.1 – 4A.4.6.
[5] S. Dongaonkar, C. Deline, and M. A. Alam, "Performance and Reliability Implications of Two Dimensional Shading in Monolithic Thin Film Photovoltaic Modules," (Under Review).
[6] S. Dongaonkar and M. A. Alam, "A Shade Tolerant Panel Design for Thin Film Photovoltaics," in 38th IEEE Photovoltaic Specialists Conference (PVSC 2012), 2012, pp. 002416–002420.
[7] S. Dongaonkar, and M. A. Alam, "Geometrical Design of Thin Film PV Modules for Improved Shade Tolerance and Performance", Progress in Photovoltaics (Under Review).

PURDUE UNIVERSITY

Preliminary Analysis of Modules * Deployed at PV-USA for 18-24 Years *

Author and Project Lead: Alex Pineda. Support Team: Mike Silva, Alejandra Hernandez, Anthony Molina, Carlos Molina, Erik Brambila, Matthew Donovan, John Watts, Chad Southard, Rajeev Singh, and Jenya Meydbray

ABSTRACT

Modern photovoltaic (PV) module manufacturers offer a 25 year warranty. It benefits the PV industry to have a present state maximum power (P_{mp}), mismatch, and degradation analysis performed of modules exposed to real world conditions for long periods of time. In an effort to acquire such data, a sample set of modules and sub strings from PV-USA (ARCO, Solarex, AstroPower, and Advanced Photovoltaic Systems (APS)) arrays are analyzed. The technologies of these PV arrays are polycrystalline-Si, thin-film bifacial polycrystalline, polycrystalline film, and amorphous-Si, respectively. Data is collected at PV-USA using a Solmetric PVA-600 PV Analyzer and sensor kit, provided by PV Evolution Labs (PVEL), as well PVEL's Electroluminescence and Wet HiPot testing equipment.

Photovoltaics for Utility Scale Applications (PV-USA) Site, located in Davis, CA.

Field Tests at PV-USA

IV Curve Trace:

$P_{mp\ meas}$: Translated to 1000 W/m² @ 25 °C
WNTY: Time Scaled Module's Age wrt 25 yrs. No Tol.
Pass: IFF $P_{mp\ trans}$ > =P_o(1-0.008*Age), For Age <= 25 yrs.

Lab Test at PVEL

Wet HiPot:

Trip > 4 mA. *Sparks.

Lab Test at PVEL

Electroluminescence:

ARCO

Array Module: ARCO
Technology: Polycrystalline-Si
Installation Date: Jan. 1989

Array Module: ARCO
Tech: Polycrystalline-Si
Install Date: Jan. 1989
Age at Test: 23 Yr. 7 Mo

Nameplate

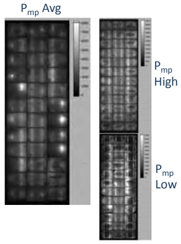
P_{mp}	I_{sc}	V_{oc}
60 W	4.0 A	24.4 V

Sample size: 50 Modules
Strings: 10
Modules/String: 5 in Parallel

$P_{mp\ avg}$ Degr. [%]	Avg Degr [%/Yr]	WNTY. Pass [%]
34.0	1.4	0

String [#]	Mismatch [%]	Avg M smatch [%]
1	1.3	6.0
2	1.6	
3	4.7	
4	6.7	
5	6.5	
6	2.9	
7	5.0	
8	5.6	
9	4.4	
10	21.3	

Leak Current [mA]	Pass/ Fa
0.003	Pass
Trip	Fail
Trip*	Fail
0.003	Pass
Trip*	Fail
Trip	Fail



Solarex

Array Module: Solarex
Technology: Thin-Film Bifacial Polycrystalline
Installation Date: Oct. 1990

Array Module: Solarex
Tech: TF Bifacial Polycrystalline
Install Date: Oct. 1990
Age at Test: 21 Yr. 10 Mo

Nameplate

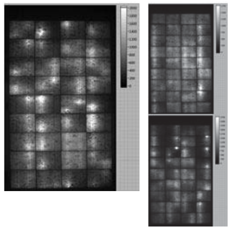
P_{mp}	I_{sc}	V_{oc}
57 W	3.75 A	20.8 V

Sample size: 30 Modules
Strings: 10
Modules/String: 3 in Series

$P_{mp\ avg}$ Degr. [%]	Avg Degr [%/Yr]	WNTY. Pass [%]
32.6	1.5	10.0

String [#]	Mismatch [%]	Avg M smatch [%]
1	11.2	3.7
2	15.8	
3	-0.4	
4	0.6	
5	0.6	
6	0.7	
7	1.1	
8	2.6	
9	1.8	
10	3.1	

Leak Current [mA]	Pass/ Fa
0.003	Pass
0.003	Pass
Trip	Fail
0.003	Pass
Trip	Fail
Trip	Fail



APS

Array Module: APS
Technology: Amorphous-Si
Installation Date: Sept. 1992

Array Module: APS
Tech: Amorphous-Si
Install Date: Sept. 1992
Age at Test: 19 Yr. 11 Mo

Nameplate

P_{mp}	I_{sc}	V_{oc}
50 W	1.8 A	55.5 V

Sample size: 100 Modules
Strings: 10
Modules/String: 10 in Series

$P_{mp\ avg}$ Degr. [%]	Avg Degr [%/Yr]	WNTY. Pass [%]
21.4	1.1	9.0

String [#]	Mismatch [%]	Avg M smatch [%]
1	0.4	6.0
2	-0.4	
3	0.6	
4	7.4	
5	13.9	
6	8.1	
7	6.1	
8	9.3	
9	6.7	
10	7.6	

Leak Current [mA]	Pass/ Fa
0.009	Pass
0.013	Pass
0.011	Pass
0.010	Pass
0.011	Pass
0.008	Pass

AstroPower

Array Module: AstroPower
Technology: Polycrystalline Film
Installation Date: Nov. 1994

Array Module: AstroPower
Tech: Polycrystalline Film
Install Date: Nov. 1994
Age at Test: 17 Yr. 9 Mo

Nameplate:

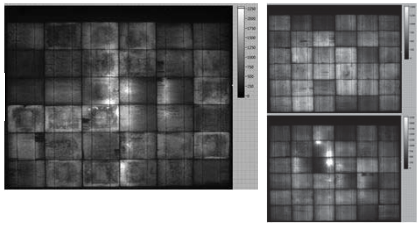
P_{mp}	I_{sc}	V_{oc}
72.3 W	4.73 A	19.1 V

Sample size: 30 Modules
Strings: 10
Modules/String: 3 in Series

$P_{mp\ avg}$ Degr. [%]	Avg Degr [%/Yr]	WNTY. Pass [%]
12.7	0.6	75.9

String [#]	Mismatch [%]	Avg M smatch [%]
1	2.4	0.6
2	1.0	
3	-5.4	
4	0.7	
5	-0.5	
6	2.4	
7	3.2	
8	3.6	
9	-2.3	
10	N/A (1 Bad Module)	

Leak Current [mA]	Pass/ Fa
Trip	Fail
0.004	Pass
0.005	Pass
Trip	Fail
0.004	Pass
0.004	Pass



Impact and Detection of Pyranometer Failure on PV Performance

D.C. Jordan, B. Sekulic, S.R. Kurtz

National Renewable Energy Laboratory, Golden, CO 80401, USA

1 Introduction

Long-term PV Performance

1. Financially:
Cash flow !
Uncertainty directly related to risk !

2. Technically:
Lifetime prediction !
Product improvement !

Pyranometers often used to measure Plane-of-array irradiance (POA)

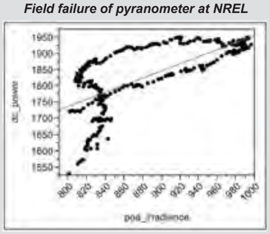
Pyranometers are recommended to be calibrated 1-2 years

Better understand one failure mechanism we observed in the field

Find analytical signal for early-fault detection

2 Catastrophic Failure

Field failure of pyranometer at NREL

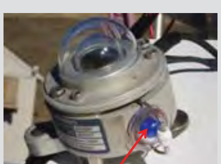


Catastrophic field failure: Seal of SiO2 cartridge failed
–> moisture penetrated inside

If failure not catastrophic but seal slowly disintegrates
Could be a long time until failure is recognized!

3 Pyranometer with High Humidity '

ASTM E104-85 (1996) Standard:
Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions

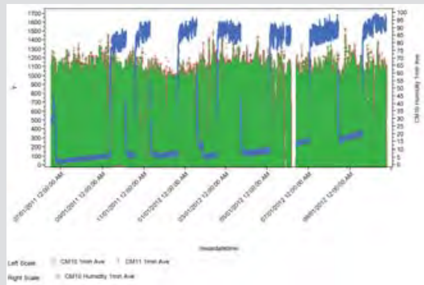


Cartridge filled with desiccant SiO2
Low humidity

Cartridge filled with saturated NaCl
High humidity

Saturated NaCl maintains relative constant humidity in closed-spaced environment

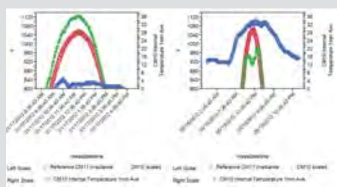
4 CM10 Pyranometer



By swapping salt and desiccant, periods of high & low humidity are alternated so as not to destroy pyranometer

Use both data for PV system degradation rate determination

5 Sunny – High Humidity



Sunny Day - Winter *Sunny Day - Summer*

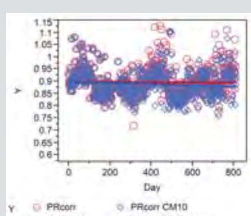
Some droplets on outer dome

Condensation film on inner dome

On sunny days, high humidity leads to condensation that diminishes signal

Effect clearly visible on sunny days & high temperature

6 Performance Impact '



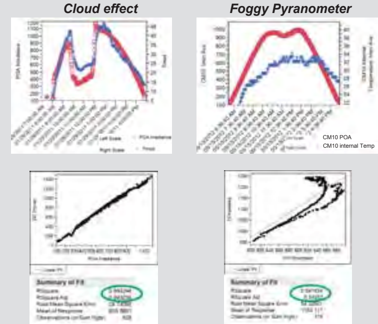
Pyranom.	R_d (%/year)	Uncertainty (%/year)
Regular	-0.18	0.38
High humidity	-1.15	0.36

CM10 pyranometer (high humidity) drifted about 1%/year

Significant performance impact if problem is not detected

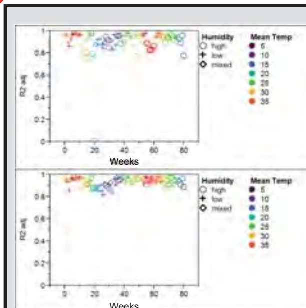
7 Detection Method

Cloud effect *Foggy Pyranometer*



Careful tracking of R^2 of DC Power vs. POA

8 Detection Results



Using CM10 irradiance, High humidity: circles

Using system POA irradiance

Humidity is indicated for comparison sake

R^2 adj = R^2 adusted for different number of data points per interval

R^2 adj drops significantly during pyranometer problem

9 Conclusion

Accurate PV performance often depends on accurate irradiance measurements

Pyranometer with high humidity inside was used to simulate slow failure

More than 1 year of data have been collected

Pyranometer has drifted by about 1%/year

At sufficient high temperature condensation forms on inside of dome that skews data

An analytical method based on the fit of DC Power vs. POA irradiance in weekly intervals was used to detect the faulty pyranometer.

This work was supported by the U.S. Department of Energy under Contract No. DE- - -

NREL PV Module Reliability Workshop, Golden CO, Feb.26-Feb.27, 2013

Manufacturing Metrology for c-Si Module Reliability/Durability

Marianne P. Rodgers ♦ Ashwani Kaul ♦ Kristopher O. Davis ♦ Neelkanth G. Dhere ♦ Hubert Seigneur ♦ Andrew C. Rudack ♦ Winston V. Schoenfeld
University of Central Florida – Florida Solar Energy Center ♦ 1679 Clearlake Rd ♦ Cocoa ♦ Florida 32922

Introduction

- Many degradation modes develop during or as a result of processing steps for the manufacturing of photovoltaic (PV) modules
- It is desirable to identify metrology that can be performed during manufacturing to predict failures or unacceptable degradation for PV modules in the field
- c-Si U.S. PVMC aims to perform a literature review of the effects of module manufacturing steps on module reliability and durability
- The goals of this work are to:
  - ◊ Provide a comprehensive review of the current state of manufacturing metrology for improved PV reliability and durability
  - ◊ Identify failure modes and degradation mechanisms induced during manufacturing
  - ◊ Determine in-line and off-line measurement/characterization techniques
  - ◊ Create a master list of metrology techniques
  - ◊ Perform a gap analysis and identify where improvements can be made
  - ◊ Assess trends and new challenges for advanced materials and device concepts

Table 1. Processes and production areas carried out during PV module manufacturing

	Feed stock and Wafering	Cell Manufacturing	Module Manufacturing
Process / Production Area	Polysilicon Production	Wet Chemical Processes (e.g. saw damage removal, texturing, PSG removal, edge isolation)	Stringing and Tabbing
	Ingot/Brick Production	Emitter Formation (e.g. in-line P doping, $POCl_3$)	
	Wafer Production	ARC / Passivation Deposition	Lamination
		Screen-Printing and Co-Firing	

References

[1] DC Miller, et al., Progress in Photovoltaics: Research and Applications, (2012) n/a.
[2] J Schlothauer, et al., Sol Energy Mater Sol Cells, 102 (2012) 75.
[3] P Sánchez-Friera, et al., Progress in Photovoltaics: Research and Applications, 19 (2011) 658.
[4] K Matsuda, et al., Jpn J Appl Phys, Part 1, 51 (2012) 10NF07.
[5] M Sander, et al., Photovoltaic Specialists Conference (PVSC), 35th IEEE 20-25 June 2010.
[6] GR Mon, et al. Electrical Insulation, IEEE Transactions on, EI-20 (1985) 989.

Lamination

- In modules polymers are used as:
  - ◊ Encapsulants
  - ◊ Edge-seals
  - ◊ Structural sealants
  - ◊ Back and front covers
- Laminate creep/loss may cause:
  - ◊ Internal component motion/fracture
  - ◊ Reduced electrical insulation
  - ◊ Delamination at interfaces
  - ◊ Increased moisture ingress
  - ◊ Loss of structural integrity
  - ◊ Loss of connectivity (open circuits)
  - ◊ Exposed wires
  - ◊ Compromised electronic grounding
  - ◊ Electrical arcing
  - ◊ Falling components

Inhomogeneities

- Contamination control and module hermeticity during field deployment is important[1]
  - ◊ Contamination causes discoloration resulting in thermal-runaway
  - ◊ Contamination induced cracking of the silicone
- A white or milky pattern is observed in many modules at the cell perimeter and interconnection ribbons[2-4]
  - ◊ Indicates non-uniformity of lamination/curing

Mechanical Degradation

- Expansion induced by temperature changes in PV modules constrained by the adjoining layers results in thermomechanical stresses
  - ◊ Cracking of harder silicones during cold weather is attributed to thermal misfit[1]
- Information about stress inside the laminate can be obtained from a PV module geometry scan[5]

Loss of Insulation / Moisture Ingress

- As the conductance of the insulation increases with time, the leakage currents may eventually be unacceptably high[6]
  - ◊ This mode of failure is associated with influx of water, with effects of elevated temperature or ultraviolet irradiation
- A good dielectric:
  - ◊ Absorbs little water - even at elevated temperature/humidity combinations
  - ◊ Exhibits a low ionic concentration and mobility in the presence of water

Impact of Processing Steps on Lamination

- c-Si PV cells and modules
  - ◊ Fabricated by a leading PV manufacturer during 1985-89
  - ◊ p-type silicon wafers
  - ◊ Used a phosphorous-rich diffusion glass layer as a P source by P diffusion during p-n junction formation
  - ◊ After diffusion, the P-rich diffusion glass layer was not removed from the cell surface
- The modules were field deployed in:
  - i) A hot & dry climate for <8 years
  - Ii) A hot & humid climate for <9 yrs
  - iii) An extremely harsh hot & humid environment: high insolation, cyclones, high levels of atmospheric salt & sea-water flooding for ~4 yrs
- The modules were returned because of delamination that ranged from some to several to all in the array

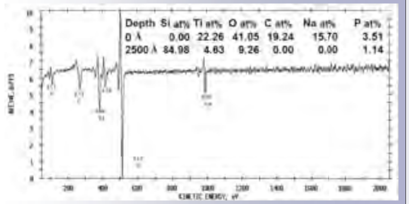


Figure 1. Auger electron spectroscopy (AES) survey (hot and dry). The inset shows atomic concentrations of the elements

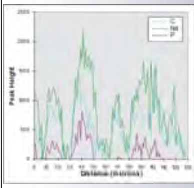


Figure 2. AES line scan for C, Na, and P (hot and humid)

Figure 3. SEM image of corroded grid line in the harsh coastal climate

- The loss of adhesional strength, measured by rotational torque also ranged from some to severe to most
- The problem was traced to the P-rich diffusion glass layer that was left on the cells
  - ◊ Eliminated after modification of the process by removing the diffusion glass

Acknowledgements

Funding for the c-Si U.S. PVMC was provided as part of the PVMI Sunshot Initiative

Development of a Visual Inspection Checklist for Evaluation of Fielded PV Module Condition

Corinne E. Packard[1, 2*], John H. Wohlgemuth[1], Sarah R. Kurtz[1]
[1]National Center for Photovoltaics, National Renewable Energy Laboratory, Golden, CO USA
[2]Department of Metallurgical and Materials Engineering, Colorado School of Mines, Golden, CO USA
*Corresponding Author: cpackard@mines.edu

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.

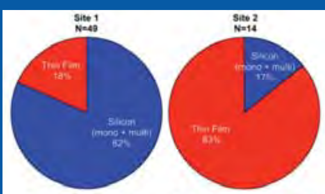


Figure 1. Composition of module sets at Site 1 and Site 2 used for early testing of the inspection checklist.

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*.

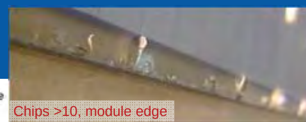
*O. S. Sastry, *et al.*, "Degradation in performance ratio and yields of exposed modules under arid conditions," in *26th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, Germany, 2011.

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-AC36-08GO28308 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.

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.
Presented at the PV Module Reliability Workshop, 28 February - 2 March 2012, Golden, Colorado • NREL/PO-5200-54568

Highly Reliable Redundant Solar Topology

Introduction

The conventional serially connected solar topology is prone to system failure impacting energy production and prompting costly repairs.

A highly reliable solar topology can be achieved by uncoupling the individual photovoltaic elements down to the most basic level, and providing alternate current paths through the system (from cell-to-grid).

1. Problem Statement

In conventional photovoltaic (PV) solar arrays, serially interconnected solar modules are strung together to increase the voltage from module-to-module, limited to 600VDC in North America and 1000VDC in Europe (480 VDC and 800 VDC with required safety margin).

Scaled down inverters termed "micro-inverters" have been introduced for smaller systems where the inverter is attached to each module, but retain many of the topological features of the large central inverters. DC optimizers have also been introduced for attachment at the module, for allowing an improvement in string balancing between panels to reduce the inherent mismatch losses between panels.

One of the most notable issues facing each of these solar topology is the single-point-of-failure nature of these entire systems. Failure of any component in a string, including cells, cell connectors, module wiring, combiner boxes, inverters, etc., results in an immediate failure and requires field service to repair and restart the lost array portion or in many cases the entire array. While micro-inverters and DC optimizers help to minimize the interdependencies of the string components, they are often limited in their operating range and introduce additional electrical components with their own single-point-of-failure dependencies and field service requirements.

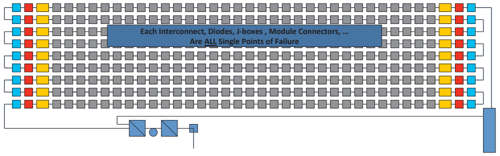


Figure 1. Conventional Solar Serial Topology

2. Highly Reliable Solar Topology

An alternate topology, where there are no single-point-of-failure dependencies within the entire system results in increased efficiency and reliability. This highly fault-tolerant topology is much more consistent with other highly distributed commercial applications, such as in information storage, telecommunications, and the power distribution grid, where failures are tolerated without significant performance impacts, and repairs are managed on extended and planned maintenance schedules. Solar modules used in a redundant topology do not have cells wired serially, but rather use a combination of serial and parallel connections within the module and a proprietary interconnection method to a DC bus. It should be noted that all the components in the system are standard "off-the-shelf" components, they are just configured in a unique package.

Due to the lower voltage at each cell interconnected panel, in order to generate a current and voltage sufficient for conversion to AC energy, a solar charge controller is integrated into each redundant and interconnected module to produce a regulated 48V nominal voltage. In the charge controller is a set of redundant DC converters where the number of available DC converters exceeds the number required to produce full power from the module.

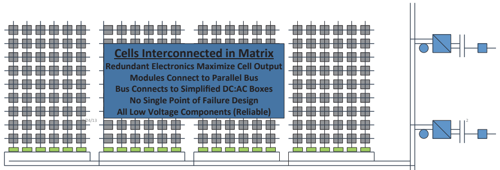


Figure 2. Redundant array of solar modules with interconnected cells.

The deep electronics integration level and the cell wiring method, means any failure in a cell, interconnection, or electronic component does not result in a superordinate decrease in the power production capability of the module as current can flow from any cell to any DC converter (the DC converters are not dedicated to specific groups of cells). No bypass diodes are required in the module to achieve this. The module DC bus interconnects the modules in parallel across the system, and is fed into groups of parallel, 5KW inverters to convert the DC bus voltage into three-phase AC voltage.

The inverters are also connected in a redundant manner. In the event of an inverter failure, the power from a group of modules that would normally be lost with a conventional inverter can flow to adjacent inverters in the redundant system of Fig. 2. Some peak shaving may occur in the remaining operational inverters; however, because of the solar daily power profile the impact of this limit on the total annual energy production is minimal. Any required repairs to the inverters can be on a greatly extended and fixed schedule.

3. Economic Model

Taking the known reliabilities of each system component and levels of redundancy and modeling the resulting system Annualized Failure Rate (AFR) and applying service costs and times to repair, it is possible to project the relative financial impact of common implementation of solar topologies. As is demonstrated the redundant topology greatly reduces the impact of losses due to individual component failure.

In the example given, 1 MW DC nominal solar array is modeled.

Micro-Inverter with 270W PV modules	Base Reliability	Units / String	Redundancy	AFR
Silicon Cells	0.999999	60	1	99.9940%
Module Components	0.999900	1	1	99.9900%
Bypass Diodes	0.999990	3	1	99.9970%
Module-Inverter Connections	0.999990	4	1	99.9960%
Inverter	0.997000	1	1	99.7000%
AC Interconnections	0.999990	2	1	99.9980%
AFR / String Unit				0.3249%
# of "Strings"		3704		
Yearly Repairs		12		$12,035
Impact of Failures (Assume Fixed in One Year)				$455
Total Annual Cost				$12,490

4 kW String Inverters	Base Reliability	Units / String	Redundancy	AFR
Silicon Cells	0.999999	900	1	98.8000%
Module Components	0.999900	15	1	98.0000%
Bypass Diodes	0.999990	45	1	99.4000%
Module Interconnections	0.999990	32	1	99.5800%
Inverter	0.980000	1	1	98.0000%
AC Interconnections	0.999990	2	1	99.9980%
AFR / String Unit				6.0798%
# of "Strings"		267		
Yearly Repairs		6.17		$6,174
Impact of Failures (Assume Fixed in One Year)				$2,800
Total Annual Cost				$8,974

Redundant Topology	Base Reliability	Units / String	Redundancy	AFR
Silicon Cells	0.999999	1000	3	100.0000%
Module Components	0.999900	20	3	100.0000%
Module Electronics	0.999000	10	2	99.9990%
Module-Inverter Connections	0.999990	4	1	99.9960%
Low Voltage 5KW Inverter	0.980000	1	2	99.9600%
AC Interconnections	0.999990	2	1	99.9980%
AFR / String Unit				0.0470%
# of "Strings"		200		
Yearly Repairs (One Repair / Five Years)		0.1		$93.99
Impact of Failures (Repair Required / Five Years)				$399.48
Total Annual Cost				$493.47

Conclusion

Utilizing off the shelf proven conventional solar and power electronics materials, but connected in a novel redundant topology reduces the financial impact to solar arrays of component failures.

Contact

Tim Johnson
tenKsolar
tjohnson@tenKsolar.com
612-845-0776

ABENGOA

Innovative technology solutions for sustainability

Abengoa Solar Visual Inspection Tool

A. Delgado, K. Kiriluk, P. Banda, J.A. Perez,
Abengoa Solar PV Inc., Lakewood, CO 80215 (

Abengoa Solar operates multiple plants, consisting of flat mono- and multi-crystalline silicone modules, with one or two axis tracking. These modules consist not only of different technologies, but also different manufacturers, designs, layouts, etc. However, it is a fact that PV modules exhibit degradation such as burns, delamination, encapsulant yellowing, corrosion of bus-bars and interconnectors, broken glass, etc.

Currently, visual inspection of the PV plants is conducted manually and not always as exhaustively as it should be, demanding long hours of dedicated work. In this context, it is essential to have access to a quick, cheap, and effective way to analyze the different defects that appear over time.

Abengoa's Photovoltaic R&D Department has developed, in association with the University of Seville, a tool that allows the operator to perform an exhaustive visual inspection of the modules of a PV solar plant, making manual analysis more efficient. This analysis can also be performed automatically, almost without requiring the intervention of human operators. The development of this tool was initiated because, in spite of module manufacturer's guarantee, a great number of defects tend to appear in PV plants over time due to their exposure to sunlight and other atmospheric agents. This negatively affects their energy production.

Four steps are needed prior to the use of the tool:

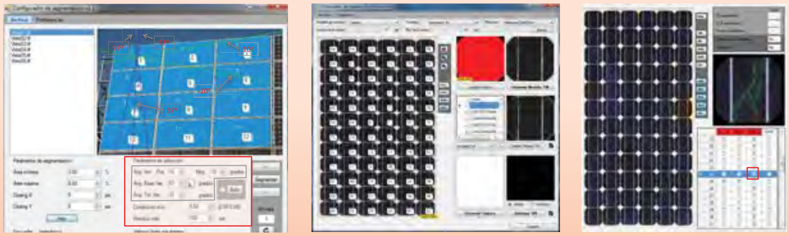
(1) Taking pictures of all the modules that need to be inspected

(2) Define plant configuration for segmentation of the images (separating the original images into multiple single-module images)

(3) Thresholds definitions (to define the severity at which a defect will be taken into account when running the automatic mode)

(4) Tool training (to "teach" the tool from reference defect images)

Steps (1) and (2) are necessary for both the manual and the automatic mode.
Steps (3) and (4) are necessary for the automatic mode.



* Examples of the segmentation (left), threshold definition (center), and prior training (right)

The layout of the tool is the same in both manual and automatic mode. The main window is divided in different sections.

(1) Tracker/structure (center-left) and module (center-right) visualization

(2) Defects filter window (left), where different defects can be selected from a list. Checked defects will be detected in automatic mode, or showed during a review

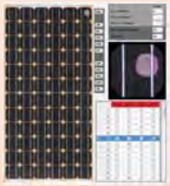
(3) Tree window (down-left), with a summary of the defects found, organized by plant, tracker, etc.

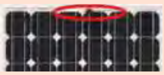
(4) Defects list and statistics: List of defects found in the module seen in present image and statistics of the number of defects found during the inspection

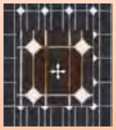
(5) Control panel (center-down): a set of buttons to select the module to display or select the "play" mode during review

The list of defects that can be tagged or detected automatically include:

- Broken glass
- Yellowing
- Delamination
- Bubbles
- Bus-bars and interconnectors corrosion
- Burns
- "Worms" (or lambda figures)







Fraunhofer
CSP

FRAUNHOFER CENTER FOR SILICION PHOTOVOLTAICS CSP

CHARACTERIZATION OF DYNAMIC LOADS ON SOLAR MODULES WITH RESPECT TO FRACTURE OF SOLAR CELLS

Sascha Dietrich, Matthias Pander, Martin Sander, Matthias Ebert &

Fraunhofer - Center for Silicon-Photovoltaics CSP
Walter-Huelse-Straße 1, 06120 Halle (Saale)
Telefon +49 (0) 345/5589-408
sascha.dietrich@csp.fraunhofer.de

SPONSORED BY THE Federal Ministry of Education and Research

INVENTED IN GERMANY

SOLARVALLEY Mitteldeutschland

Motivation

- Cracks in solar cells are identified as a key issue in module reliability concerning stability of performance as well as product safety [1].
- Large scale cracks are initiated by mechanical loading (wind, snow, transport, handling).
- Wind loads usually come with a static portion of the load superposed by dynamic portion (vibration) [2].
- Frequencies up to 14 Hz and an amplitude of 1.6 mm [2] leads to a deflection ramp of ~5200 mm/min. *
- Polymeric encapsulant transfers strain from glass to solar cell [3]. *

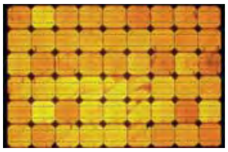


Fig. 1: EL image of cracks in solar cells

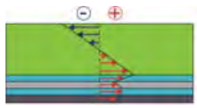


Fig. 2: Strain gradient across laminate cross section

Material Modeling

- Polymers show temperature and strain rate dependent stiffness *
- visco-elastic modeling of polymer material required (i.e. frequency sweeps in DMA) *
- development of Prony-series and translating in generalized Maxwell * model *
- utilization of time-temperature-superposition *

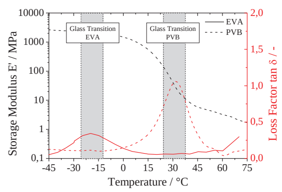


Fig. 3: Dynamic-Mechanical-Analysis of an EVA and PVB at 1 Hz

Finite-Element-Model Approach

- superposition of mechanical stress field from each simulation step

Soldering	Lamination	Temperature Change	Mechanical Load
183 °C → 20 °C	140 °C → 25 °C	25 °C → 75 °C 25 °C → -35 °C +	4-Point-Bending +

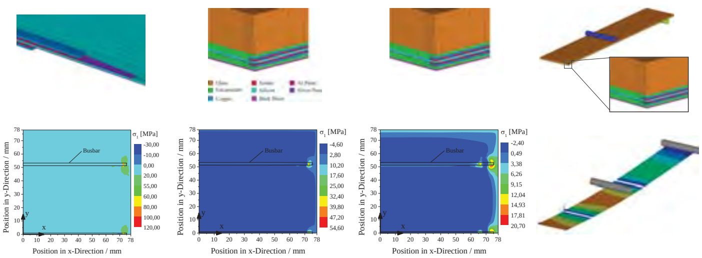


Fig. 4: 1st Principal Stress in top side of silicon at several temperature steps and 4-point-bending
top: Finite- Element- Model; bottom: 1st principal stress plots in top side of silicon

Results – Superposition of Loads

1st Principal Stress &

Probability of Failure P_f

$$P_f = 1 - exp\left[-A_e\left(\frac{\sigma_{max}}{\sigma_0}\right)^m\right]$$

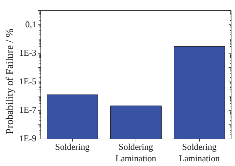


Fig. 5: Superposition of soldering, lamination and 4-point-bending

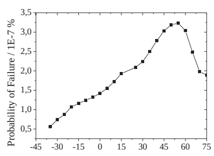


Fig. 6: Probability of failure during of a solar cell during cooling / heating of module laminate (for EVA)

Results – 4-Point-Bending &

- reduction of P_f after lamination (Fig. 5) due to increased pressure load across cell (Fig. 4)
- PVB shows higher stiffness level and larger dependency on time (Fig. 6)
- visco-elastic behavior of encapsulant characterizes the load on solar cells (Fig.7) *
- generally at low temperatures strain rate dependency decreases (Fig. 8)
  - but: glass transition increases damping (i.e. see loss factor for EVA) *

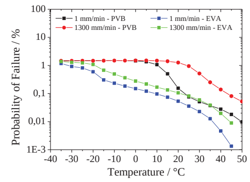


Fig. 6: Development of probability of failure over temperature

Discussion

- time-temperature superposition important for definition test conditions at room temperature (Fig. 8) *
- example EVA *
  - influence of load ramp similar in the range between -15C and +30C with mirror axis at +10C
  - adjustment of magnitude of load required (see Fig. 6 and 8) *
- example PVB
  - glass transition in the range of RT
  - temperature during testing should be carefully controlled *
  - testing at RT with high load ramp can simulate load on cells at low * temperatures (Fig. 6 and 8) *

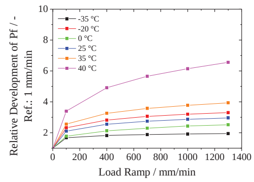


Fig. 7: Relative development of probability of failure over load ramp (for EVA) *

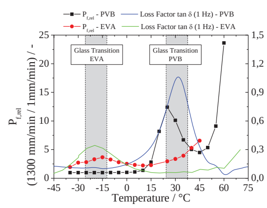


Fig. 8: Relative difference of probability of failure between 1 mm/min and 1300 mm/min * over temperature for EVA and PVB

Results – Modules

- IEC CD 62782 "Dynamic Mechanical Load Testing"
  - 1000 Pa
  - 7 sec dwell time at elevated load
  - 1 – 3 cycles/minute
  - room temperature
- number of cycles / min crucial to applied load on cells *

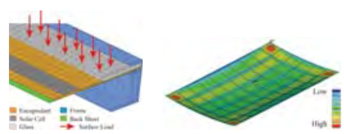


Fig. 9: left: Finite-Element-Model for complete solar modules with distributed surface load; right: 1st Principal Stress in solar cells *

Cycles [min⁻¹]	Dwell Time [sec]	Time [sec/1000 Pa]	Ramp [Pa/sec]	Ramp [N/sec]	Ramp [mm/min]	P_f Relative Change + [-]
0.02	7	746.5	1.34	2.14*1	1*2	1.00 / 0.65
1.00	7	11.50	87	139*1	70*2	1.53 / 1.00
3.00	7	1.50	666	1067*1	533*2	1.81 / 1.18
3.66	7	0.60	1671	2674*1	1300*2	1.95 / 1.28
4.00	7	0.25	4000	6400*1	2834*2	2.08 / 1.37

*1 Module size 1.6 m²
*2 Example from FE-Simulation for 1.6 m² Module (1000 Pa)
Simulations carried out for EVA at 20 °C

Bibliography &

[1] J. Wohlgemuth et al., "Long term reliability of PV modules" Proc. 20th EU-PVSEC, 2010 *

[2] M. Assmus et al., "Experimental investigation of the mechanical behavior of photovoltaic modules at defined inflow conditions" J. of Photonics for Energy Vol. 2, 2012

[3] S. Dietrich et al., "Interdependency of mechanical failure rate of encapsulated solar cells and module design parameters", Proc. SPIE Optics & Photonics, 2012

Statistical and Domain Analytics Applied to PV Module Lifetime and Degradation Science

Laura S. Bruckman[1], Nicholas R. Wheeler[1], Junheng Ma[2], Ethan Wang[3], Carl Wang[3], Ivan Chou[4], Jiayang Sun[2] and Roger H. French[1]
[1]SDLE Center & Dep. of Material Science, [2]Department of Epidemiology and Biostatistics, Case Western Reserve University, Cleveland OH 44106
[3]Underwriters Laboratories, Taiwan [4]Delsolar Co., Taiwan

1 Abstract

A better understanding of the degradation modes and rates for photovoltaic PV modules is necessary to optimize and extend the lifetime of modules. Lifetime and degradation science (L&DS) is used to better understand degradation modes, mechanisms and rates of materials, components and systems in order to predict lifetime of PV modules. Statistical analysis was used to explore the relationship of various module performance and degradation pathways. A PV module lifetime and degradation science (PVM L&DS) model is an essential component to predict lifetime and mitigate degradation of PV modules. Previously published accelerated testing data from Underwriter Labs on PV modules with TPE backsheets which included eight modules were exposed to 4000 hours of damp heat (85% relative humidity at 85°C) and eight exposed to 4000 hours of ultraviolet light (80 W/m^2 of TUV at 60°C) . There were 15 different variables that related to experiments on system performance, degradation mechanisms, component metrics and time. Modules were analyzed for three system performance metrics (fill factor, peak power and wet installation). In addition, 11 unit experiments, six of which are directly related to degradation mechanisms and five of which are component performance experiments, were performed. The results from these experiments were statistically analyzed to identify variable transformations, statistically significant relationships and to develop a PVM L&DS model using structural equation modeling. The statistically signification relationships and significant model coefficients were then combined with domain analytics incorporating materials science, chemistry and physics expertise to produce a system of equations that model system performance based on unit degradation processes at the materials, component and system level. This exemplifies the development of a methodology to determine lifetime and degradation pathways present in modules and their effects on module performance over lifetime.

2 Introduction

Lifetime and degradation science (L&DS) can be used to help understand degradation modes, mechanisms and rates for PV materials, components and systems their overall contribution to power loss in PV modules. This understanding can help companies to mitigate degradation from the major contributor to power loss and not focus on modes that are related to small amounts of power loss [1] (Figure 1). Domain and statistical analytics are used to develop a PV module L&DS (PVM L&DS) model that can predict service lifetime and guide new technology insertion.

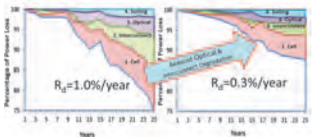


Figure 1: A simulated example of possible contributors to power loss in different modules.

3 UL Data

The data used for the statistically modeling was published by E. Wang et. al.. [2] Twenty commercially available polycrystalline 60-cell solar PV modules made with TPE backsheets were fabricated at the same time by DelSolar.[3] Eight PV modules were subjected to damp heat (DH) aging and eight modules were exposed to UV and two modules were not exposed and used as control samples.There were no explicit variations in the PV modules used by using the same PV modules under two exposures conditions for the statistical analysis. Damp heat exposure consisted of 85°C ambient temperature and 85% relative humidity and is described in the test 10.13 of IEC 61215 Ed.2..[4] The UV exposure was similar to test 10.10 of IEC 61215 Ed.2, [4] for UV preconditioning but with higher light intensity, approximately 80 W/m^2 UV irradiance plus an additional 15% of the total irradiance at the back of the PV modules. The module temperature was controlled at 60°C, but the relative humidity was uncontrolled.Fifteen experiments were measured on the harvested modules (Figure 3(a) and Figure 3(b)) and several measured variables were performed on each module (Figure 2).

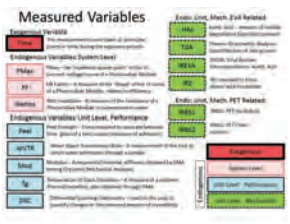


Figure 2: Measured variables used in the model development

Figure 3: (a): Example of a harvested module (left) (b): Modules harvested at each time point for analysis and destructive testing (right)

4 PVM L&DS Model Development

The PVM L&DS model will be iteratively developed with both real-world and accelerated testing information. This model will be guided by domain knowledge from literature and statistics. Better informed study protocols can be elucidated from the statistics and improved domain knowledge will be available. The model development continually checks with domain knowledge to ensure the validity of the models from knowledge of chemistry and physics and will be guided by good statistics (Figure 4).

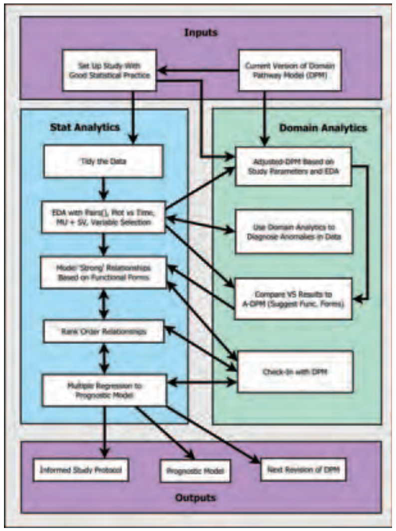


Figure 4: Iterative PVM L&DS model development

5 Domain Analytics

An initial domain pathway diagram was developed from literature that includes both real-world and accelerated testing insights [5, 6, 7, 8, 9, 10] (Figure 5(a)). Modes that were not analyzed in this study are considered latent variables appear as ovals in Figure 5(b). The final domain pathway model used to inform the statistical analysis is shown in Figure 5(c), which includes only measured variables from the UL study.

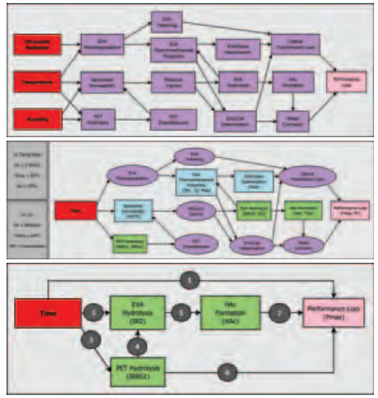


Figure 5: (a):Literature informed degradation pathway model (top) (b): Pathway model showing the latent (not measured) variables as ovals (middle) (c): Possible pathway model that includes the measured variables in this study (bottom)

6 Statistical Analytics

For a statistically valid model, only n-2 variables can be included in a model where n is the number of coincident observations; therefore, only 6 variables including time were used in the stepwise variable selection using the AIC statistic as the criterion value as statistical significant for variables to one another. In order to include more variables in the model, there needed to be more coincident samples by increasing sampling rate or exposure time. [11] Statistical analysis was performed with R and RStudio. [12]

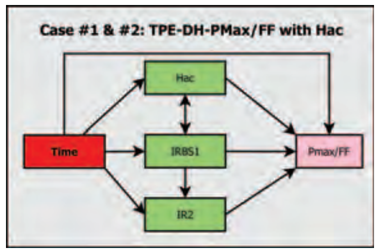


Figure 6: Statistical pathway diagram for the damp heat exposure modules for Pmax and FF system responses including the HAc variable.

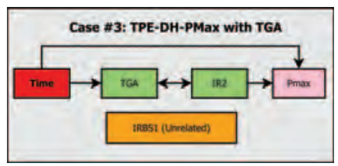


Figure 7: Statistical pathway diagram for the damp heat exposure modules for the Pmax system response including TGA

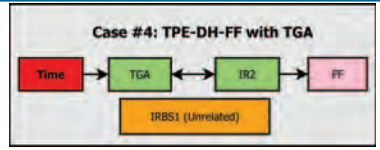


Figure 8: Statistical pathway diagram for the damp heat exposure modules for the FF system response including TGA

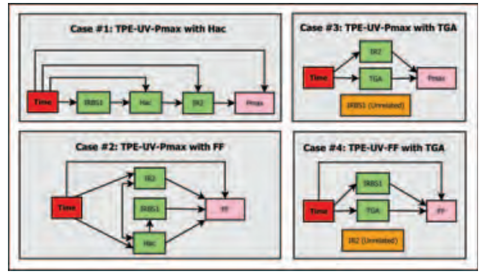


Figure 9: Statistical pathway diagram for the modified UV preconditioning exposures: for Pmax including the HAc variable (top left), for FF including the HAc variable (top right), for Pmax including the TGA variable (bottom left), for FF including the TGA variable (bottom right)

7 Conclusion

A PV module lifetime and degradation science modeling approach is being developed as an essential component to predict lifetime and mitigate degradation of PV modules. Through the combination of domain analytics and statistical analytics, a degradation pathway model can be developed that encompasses both domain knowledge of degradation modes and mechanisms and statistical measures of relationships and rates. The results from diverse experiments can be statistically analyzed to identify statistically significant relationships between the variables and develop and improve the PVM L&DS model of the system. The model is then further refined by combining these statistical insights with domain analytics incorporating materials science, chemistry and physics expertise to produce a system of equations that model system performance based on unit degradation processes at the material, component and system levels. This process exemplifies the development of a methodology to determine lifetime and degradation pathways present in modules and their effects on module performance over lifetime.

8 Acknowledgments

The authors acknowledge funding from Underwriter Laboratories. Research was performed at the SDLE Center at Case Western Reserve University, funded through the Ohio Third Frontier, Wright Project Program Award Tech 12-004.

References

[1] M. P. Murray, L. S. Bruckman, and R. H. French, "Photodegradation in a stress and response framework: Poly(methyl methacrylate) for solar mirrors and lens," *Journal of Photonics for Energy*, vol. 2, no. 1, pp. 022 004–022 004, 2012. [Online]. Available: + http://dx.doi.org/10.1117/1.JPE.2.022004

[2] E. Wang, H. E. Yang, J. Yen, S. Chi, and C. Wang, "Failure modes of evaluation of pv module via materials degradation approach," in *PV Asia Pacific Expor and Conference, 2012*. Elsevier Science Direct, in press.

[3] DelSolar Co., Ltd. Headquarters 6 Kebei 2nd Road, Shunan Science Park, Zhunan Township, Miaoli Country 35053, Taiwan, R. O. C.

[4] IEC 61215, "IEC Standard 61215 second edition-Crystalline silicon terrestrial photovoltaic (PV) modules-design qualification and type approval," ASTM International, 2005, IEC 61215:2005(E).

[5] F. Pern, "Factors that affect the EVA encapsulant discoloration rate upon accelerated exposure," in *Photovoltaic Energy Conversion, 1994., Conference Record of the Twenty Fourth. IEEE Photovoltaic Specialists Conference - 1994, 1994 IEEE First World Conference on*, vol. 1, Dec 1994, pp. 897 –900 vol.1.

[6] F. Pern and S. Glick, "Photothermal stability of encapsulated Si solar cells and encapsulation materials upon accelerated exposures," *Solar Energy Materials and Solar Cells*, vol. 61, no. 2, pp. 153–188, 2000.

[7] D. King, W. Boyson, and J. Kratochvill, "Photovoltaic array performance model. Sandia National Laboratories, Albuquerque, New Mexico, 87185-0752," 2004.

[8] D. L. King, M. A. Quintana, J. A. Kratochvil, D. E. Ellibee, and B. R. Hansen, "Photovoltaic module performance and durability following long-term field exposure," *Progress in Photovoltaics: Research and Applications*, vol. 8, no. 2, pp. 241–256, 2000. [Online]. Available: http://dx.doi.org/10.1002/(SICI)1099-159X(200003/04)8:2¡241::AID-PIP290¿3.0.CO;2-D

[9] W. Gambogi, "Comparative performance of backsheets for photovoltaic modules," in *25th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC), 2010.*

[10] J. Del Cueto and T. McMahon, "Analysis of leakage currents in photovoltaic modules under high-voltage bias in the field," *Progress in Photovoltaics: Research and Applications*, vol. 10, no. 1, pp. 15–28, 2002.

[11] R. Kline, *Principles and practice of structural equation modeling.* Guilford Press, 2010.

[12] R Development Core Team, *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria, 2008, ISBN 3-900051-07-0. [Online]. Available: http://www.R-project.org

Evaluation of hail grain production methods

results of a Round Robin in Switzerland and Austria

Thomas Friesen '
Institute for Applied Sustainability to the Built Environment (ISAAC) - University for Applied Sciences of Southern Switzerland (SUPSI) '
Campus Trevano, CH - 6952 Canobbio; Phone: +41 58 666 62 51, Fax: +41 58 666 63 49 '
www.supsi.ch/isaac, thomas.friesen@supsi.ch '

INTRODUCTION

For the qualification of PV modules in accordance to the IEC 61215 and IEC 61646 standards the hail resistance test is mandatory. Chapter 10.17 of the standard describes the launching equipment and the measurement instrumentation, but has some lacks in the definition of the hail grain quality. In fact laboratories in Switzerland and Austria found different results in testing hail impact resistance in particular for building materials. Supposition is, that the differences were mainly due to the ice quality of the hail grain. In this work a round robin was performed between three institutes in Switzerland and one in Austria, which test building materials, thermal collectors and PV modules, to determine the quality of the hail grains.

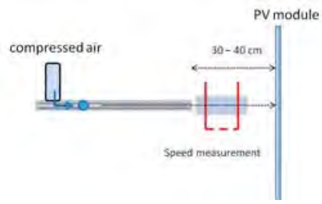
LAUNCHING SYSTEM

The launching system for the hail grain is composed of a launching tube and a device to measured the speed of the hail grain. For IEC standard the ice temperature should be –4°C ± 2%, for Switzerland –20°C.

Speed 23 m/sec ± 5%

Weight 7,53 g ± 2 %

Diameter 25 mm ± 2 %



PRODUCTION METHODS

Hailstones are produced with three different methods with diameters 25, 30, 35, 40 and 50 mm

- in silicon rubber molds
- In aluminum molds
- Melting out from a

CHARACTERIZATION AND MEASUREMENT METHODS

DROP TEST

To evaluate the quality of the hailstone a drop test was developed.
The hailstone was dropped on a POM-C block of 12.5 kg. The fracture probability in dependence of the height should give an indication on the quality of the hail grain.

LOAD CELL

The impact energy of the hailstone on the PV module was measured with a load cell.

PLASTICINE METHOD

To evaluate the impart energy of the hailstone a plasticine support with a Al plate (0.5 and 0.8 mm thickness) was prepared. The depth of the impression give the impact energy

RESULTS

IMPACT ENERGY MEASURED WITH LOAD CELL AND PLASTICINE METHOD

1. The measurement of the impact energy with the load cell and the plasticine method are comparable and both are suitable.
2. The best results in terms of reproducibility are achieved with the hail grains obtained with the melting method due to the clear appearance which allows the detection of defects as cracks, bubbles etc. The reproducibility of the impact energy was for all diameters better then 4%. The impact energy of the hail grains produced with the silicon and Al molds varied about 13 %.

DROP TEST

This test is not suitable for the evaluation of the quality of the hail grain due to slow impact energy and no correlation between impact energy and drop height.

INFLUENCE OF THE ICE TEMPERATURE ON THE IMPACT ENERGY

The impact energy of hail grains at – 4°C and – 20°C (30—40 and 50 mm diameter) was measured with the load cell. The impact energy of the hail grains stored at –2°C to –4° C is lower then the hail grains stored at –20°C (36% for the 30 mm, 31% for 40 mm and 34 % for the 50 mm diameter)

CONCLUSIONS

- The production method of and quality the hail grains is as important as the launching device and the measurement instruments
- The impact energy depends on ice temperature, it is lower for hail grains stored at higher temperature
- Ice balls obtained with the melting method give results with the smallest spread of impact energy due to the better evaluation of the quality of the ice
- Measurement results obtained with the load cell and the plasticine are comparable

ROUND ROBIN PARTNERS:

Assiciation of Public Building Insurance Companies
Bundesgasse, 20
CH— 3011 Bern

Institut für Solartechnik SPF
Hochschule für Technik HSR
Oberseestrasse, 10
CH—8640 Rapperswil

EMPA—Swiss Federal Laboratories for Material Science
Uberlandstrasse, 129
CH—8600 Dübendorf

IGS—Institute for Tested Safety
Petzholdstrasse, 45
A—4017 Linz

ACKNOWLEDGEMENTS: Mauro Bernasocchi, Flavio Serrano for the execution of the test in the **SWISS PV module test centre** *

Hail impact testing on crystalline Si modules with flexible packaging %

Mike Brown[1], Mike W. Rowell[2], Steve J. Coughlin[2], Duncan W.J. Harwood[2],
[1]Westpak, 83 Great Oaks Blvd, San Jose, CA 95119 !
[2]D2Solar, 2369 Bering Drive, San Jose, CA 95131 !

INTRODUCTION %

Semi-flexible packaging of silicon solar cells has potential applications in BIPV and consumer electronics. One of the more difficult reliability requirements for modules without a glass superstrate is hail impact robustness. Here, we investigate the effect of hail impact testing on standard silicon solar cells in non-traditional packaging. We test a variety of constructions without glass superstrates and show the effect of adding additional protective polymer layers. In addition, the effect of the backstop of the test apparatus is explored in anticipation of realistic BIPV installations.

MODULE CONSTRUCTION

For each configuration, a single cell module using a conventional front contact cell was used as the test configuration with a combination of superstrates, encapsulant layers and substrates as shown in Table 1.

The four factors to be explored for hail impact resistance were:

1. Superstrate hardness/rigidity (ETFE versus glass)
2. Substrate hardness/rigidity (Polymer backsheet versus glass)
3. Encapsulant thickness for improved cushioning (0.5mm or 2.0mm (4x) EVA)
4. Influence of mounting surface (rigid backing versus neoprene)

Part #	Superstrate	Front encapsulant thickness (mm)	Rear encapsulant thickness (mm)	Substrate	Hail Test backstop
01	Glass	0.5	0.5	TPT	NA
02	ETFE	0.5	0.5	Glass	
03		2	0.5		
04		0.5	2		
05		2	2		
06	ETFE	0.5	0.5	TAPE	Hard
14					Soft
07		2	0.5		Hard
15					Soft
08		0.5	2		Hard
16					Soft
09		2	2		Hard
17					Soft
10	ETFE	0.5	0.5	TPT	Hard
11		2	0.5		
12		0.5	2		
13		2	2		

Table 1: Sample configuration matrix

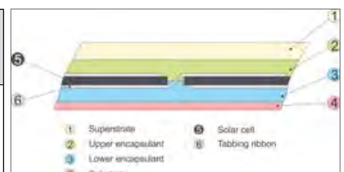


Figure 1: Layers in sample construction !

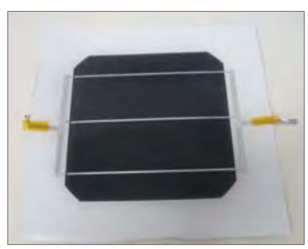


Figure 2: Sample 15 prior to testing !

TEST SETUP

Each sample was characterized by IV testing and EL imaging prior to hail testing. Hail impact testing was conducted using a hail launching apparatus compliant with IEC 61215/61646 Clause 10.17. The launcher was used to propel 25mm diameter hail stones at a velocity of 23 m/s. Each sample tested was struck with a single hail stone at the center of the cell. Samples were mounted against either 5mm fiberglass board representing a rigid structural backing (Figure 5) or 3mm neoprene layer over a 5mm fiberglass board representing a soft or compliant structural backing (Figure 6).

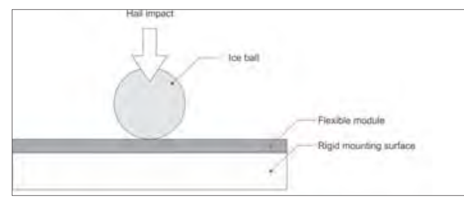


Figure 3: Impact deformation of sample struck against rigid mounting surface !

Figure 5: Rigid backing test setup !

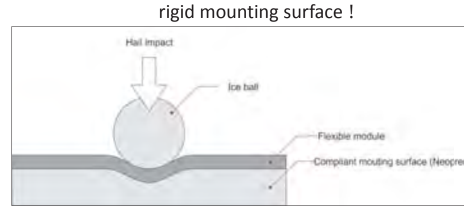


Figure 4: Impact deformation of samples struck against soft backing surface !

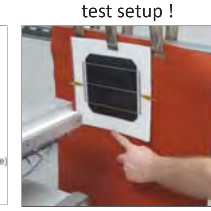


Figure 6: Soft backing test setup !

RESULTS

Changes in sample efficiency grouped by variable are plotted in Figure 7. EL images of the samples post-hail impact are shown in Figure 9. Samples with glass substrates showed the best resistance to damage caused by hail impact. Flexible samples constructed with 1.0mm total encapsulant thickness saw a 41% average decrease in power output; cells with 2.5mm or 4.0mm of total encapsulant saw a 21% average decrease in power output. Of the samples with 2.5mm of total encapsulant the samples with 2.0mm front layers and 0.5mm back layers had an average power decrease of 24%, where the samples with 0.5mm front layers and 2.0mm back layers had an average power decrease of 17%.

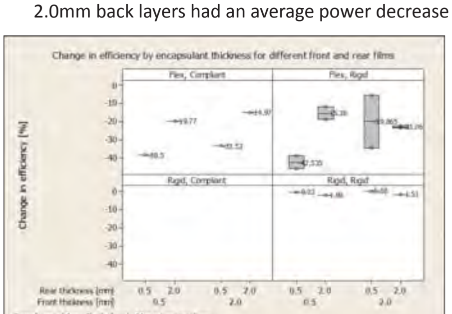


Figure 7: Pre and post hail efficiency data, grouped by total package thickness and impact backing !

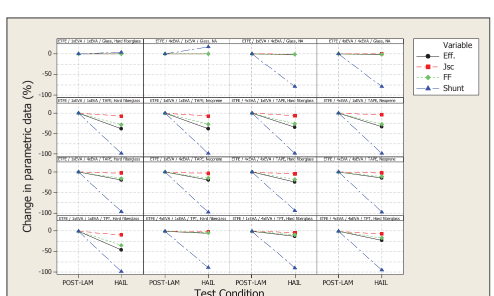


Figure 8: Pre and post hail performance data

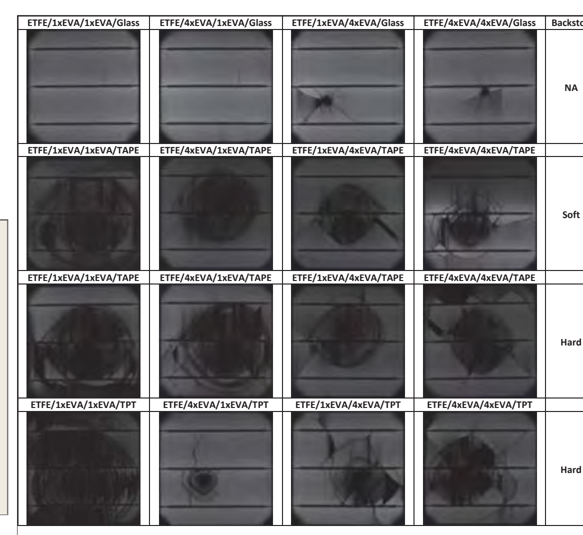


Figure 9: Post hail impact EL images

CONCLUSIONS

For semi-flexible modules, hail impact resistance may be improved by using a rigid substrate with minimal encapsulant behind the cell to minimize cell flexure. For flexible modules, increasing the encapsulant thicknesses particularly behind the cell can mitigate some of the damage caused by impact.

Based upon this study hail and mechanical impact resistance will prove to be a reliability challenge for c-Si modules with flexible packaging.

Development of a Rating System for a Comparative Accelerated Test Standard

Sarah Kurtz, representing discussions with Task Group #6 and seeking your input!

NREL PV Module Reliability Workshop
Feb. 26, 2013

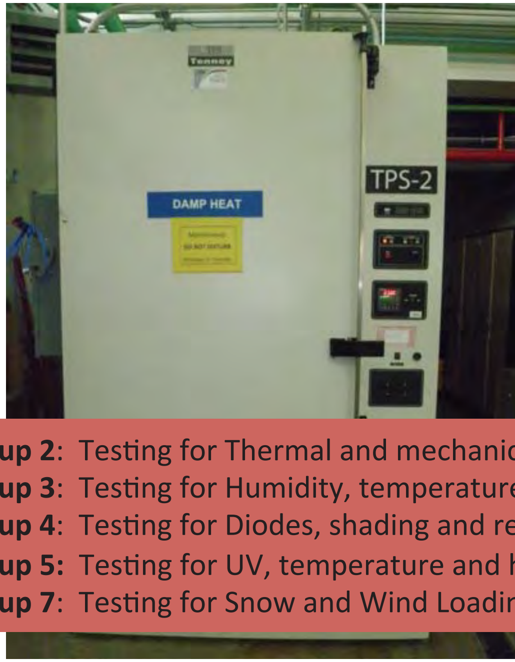
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Objective: Develop a Useful Rating System

- Identify field failures that could be reduced by improved accelerated testing
- Analyze how to group types of accelerated tests to best correlate with field performance
- Propose how to structure a useful Rating System
- Propose how to communicate the results of the Rating System

Need for Rating System

Task Groups develop accelerated tests to predict experience in the field



Task Group 2: Testing for Thermal and mechanical fatigue
Task Group 3: Testing for Humidity, temperature, and voltage
Task Group 4: Testing for Diodes, shading and reverse bias
Task Group 5: Testing for UV, temperature and humidity
Task Group 7: Testing for Snow and Wind Loading

How do we communicate the results?

Rating System

Types of Accelerated Tests – This work focuses on Comparative tests, even though we would prefer Lifetime testing

	Qualification	Comparative	Lifetime
Purpose	Minimum design requirement	Comparison of products	Substantiation of warranty
Quantification	Pass/fail	Relative	Absolute
Mechanisms studied	Infant mortality	Wear out	Wear out
Climate or application	No differentiation	Differentiated	Differentiated

What failures are seen in the field?

Observation	Sample size
Laminate internal electrical circuit 36% of failures (~2% of modules failed after 8 yr); glass 33%; j-box and cables 12%; cells 10%; encapsulant, backsheet 8%	21 manufacturers; ~60% of fleet of > 1.5 GW
16% of systems required replacement of some or all modules because of a variety of failures, with many showing breaks in the electrical circuitry	483 systems
3% developed hot spot after < 7 years; 47% had non-working diodes	1232-module system
External wiring, shattered, failed	~70,000 modules
Early degradation linked to optical transmission losses (through glass and encapsulant) and light-induced degradation; Later degradation from increased series resistance is more dramatic	204 modules from 20 manufacturers
Encapsulant discoloration 66%; delamination 60%; corrosion 26%; glass breakage 23%; j-box 20%; broken cells 15%*	~2000 reports
200 thermal cycles corresponded to ~10 y in the field	?

A.L. Rosenthal, M.G. Thomas, and S.J. Durand "A Ten Year Review of Performance of Photovoltaic Systems". Proc. 23rd IEEE PVSC, pp. 1289-1291.
D. Degraaff, R. Lacerda, and Campeau "Degradation Mechanisms in Si Module Technologies Observed in the Field", PV Module Reliability Workshop, 2011
K. Kato "PVRessQ!: a research activity on reliability of PV systems from a user's viewpoint in Japan". Proc. SPIE, San Diego
K. Kato ""PVRessQ!" PV Module Failures Observed in the Field", PV Module Reliability Workshop, Golden, CO2012
A. Skoczek, et al "The Results of Performance Measurements of Field-aged Crystalline Silicon Photovoltaic Modules", Prog. in PV, 17, 2009, pp. 227-240.
D.C. Jordan, J.H. Wohlgemuth, and S.R. Kurtz "Technology and Climate Trends in PV Module Degradation". Proc. 27th Eu PVSEC, Frankfurt, Germany
J.H. Wohlgemuth, et al. "Using Accelerated Tests and Field Data to Predict Module Reliability and Lifetime". Proc. 23rd Eu PVSEC, Valencia, Spain, 4EP1.2.
J.H. Wohlgemuth, D.W. Cunningham, A.M. Nguyen, and J. Miller "Long Term Reliability of PV Modules". Proc. 20th Eu PVSEC, Barcelona, Spain, pp. 1942.

Rating System – First address wear out that is slipping past the qualification tests

1. In response to:

- Broken interconnections, solder bonds, diodes

Add:

- Additional thermal cycling or mechanical stress, plus bypass diode/shading testing

2. In response to:

- Encapsulant discoloration and/or delamination

Add:

- Additional UV stress

Rating System – Additional testing

	New Tests Will Require Additional Stress					Targeted Meaning of Rating	
Failure types, loosely grouped	Thermal cycling & diode testing	UV	High Temperature	High humidity	Proposed labels	★	★★★★★
Infant mortality	-	-	-	-	**Qualification test**	-	-
Interconnects, discoloration, delamination	✔	✔	-	-	Hot-cold	Better than qualification test	30 y in location/appl. w worst thermal cycling
Heat-induced failures	✔	✔	✔	-	Hot-dry	Better than qualification test	30 y in location/appl. w worst heat-induced degradation
Humidity-induced failures	-	✔	✔	✔	Hot-humid	Better than qualification test	30 y for location/appl. w worst heat-induced degradation

The two primary extremes that have not yet been addressed are:

Heat

Humidity

So add additional stress for these, indicated by ✔

Note: Wind is also a priority in some locations

Principles for creating tests/rating system

- Must be predictive
  - (correlate with field experience)
- Must be relevant
  - (predict 10-40 y, not 1 y or 300 y)
- Must be communicated in useful ways
  - (both simple and detailed for different audiences)
- We'll do our best and communicate uncertainty
  - (when we don't know, we'll communicate that we guessed)
- Must be designed so we learn from the results
  - (application of the standard will help improve standard)
- Must be cost and time effective
  - (manufacturers must bring the product to market)
- Must define who is responsible/accountable
  - (customers need confidence in information)

Rating System Proposal – Communicate four ways:

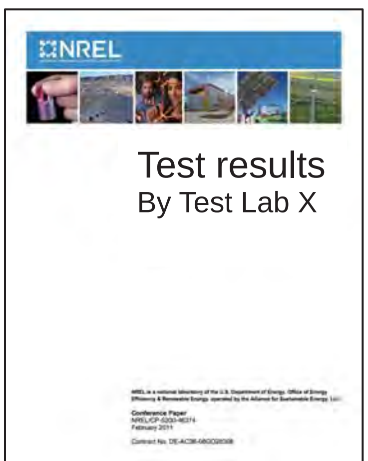
1. Nameplate:

Pmax	205 W
Durability rating:	
Hot-cold	★★★
Hot-dry	★ ★
Hot-humid	not rated
Snow/wind	2400 Pa
Salt spray etc.	

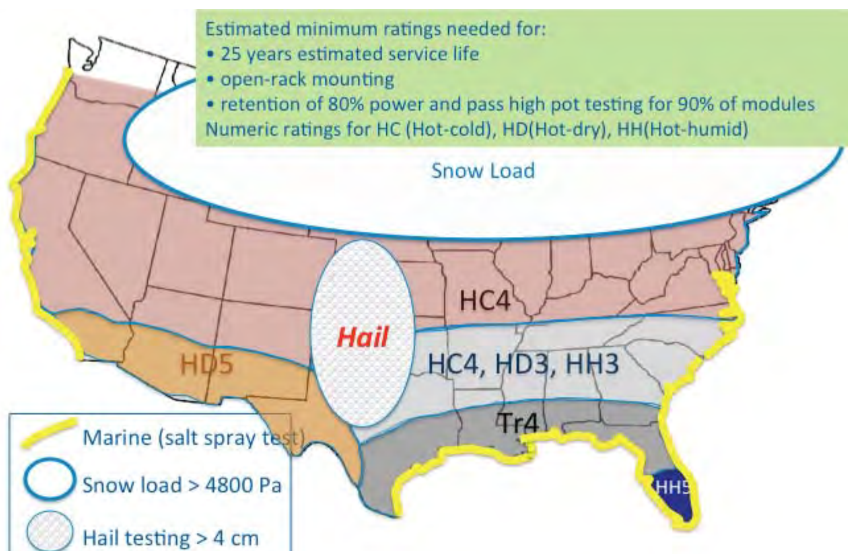
A high level summary on the nameplate will allow researchers to correlate tested rating with field experience 20 y from now.

2. Report:

Standards



A detailed report can be used by engineers to more closely compare specific products



3. Interpretive maps:

Publications/Guides

4. Climate charts that link climates with stresses (see next slide):

Climate charts – similar to the interpretative maps: define relationship between climate zones and stress testing needed in these.

Chart can define:

- 25 years estimated service life
- retention of 80% power and safe operation of 90% of modules

Use environment	"Hot-dry"	"Hot-humid"	"Hot-cold"	Snow load
Cfa/open rack	★	★	★★★★	2400 Pa
Geneva/open rack	★★	★	★★★★★	5600 Pa
Tropical/rooftop	B	A	C	n.a.
Choose your favorite use environment	?	?	?	

Communicate meaning of tests for all climate zones, locations, and applications

Other challenges

Different module constructions will have different acceleration factors. Good science tells us that the test must vary with module construction, but manufacturers will complain if they have to bake longer or shake harder.

The stresses are applied in different combinations and different sequences. We need to simplify a complex problem! Can we simplify and still be meaningful?

Conclusions

- A Rating System is necessary for the success of the QA Task Force
- Building consensus on:
  - Principles: tests must be meaningful/useful
  - Assessing today's most common wear out mechanisms and those expected in hotter and wetter climates defines our current opportunity to strengthen the standards
  - Must find simple way of summarizing *test results* to standardize communication of a complicated picture
  - *Meaning of test results* should be communicated in maps and publications

Compressive shear test to accurately measure adhesion of PV encapsulants

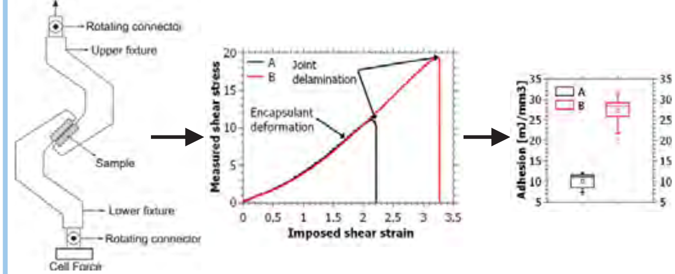
Author: F. Galliano, V. Chapuis, C. Schlumpf, C. Ballif, L.-E.Perret-Aebi*
Ecole Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), 3
Photovoltaics and thin-film electronics laboratory, Breguet 2, CH-2000 Neuchâtel, Switzerland 3
**now at: PV-center, CSEM Centre Suisse d'Electronique et de Microtechnique SA, Jaquet-Droz 1, Case postale, 2002 Neuchâtel, Switzerland* 3
e-mail:federico.galliano@epfl.ch 3

Motivations and goals

- **Good adhesion of PV encapsulants to glass or other module materials is needed to guarantee long lifetime**
- **Deep understanding of the adhesion test is needed to ensure reliable data collection**

Compressive Shear Test

Test geometry → Response curve → Curve integration



V. Chapuis and al., Prog. Photovolt: Res. Appl. (2012), DOI: 10.1002/pip.2270

Advantages

- Simple induced stress state
- Delamination mode controlled
- High reproducibility
- Stored elastic energy used as an indicator of adhesion

Drawbacks

- Limited to encapsulant bonded to rigid substrates in a subtrate/encapsulant/substrate configuration
- May lead to cohesion failure if the encapsulant is too soft

Understanding adhesion

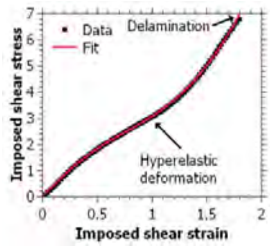
Mechanics of joint response

EVA has a hyperelastic behavior

$$S_{ss} = \frac{dW}{d\gamma} = \frac{\gamma}{\gamma^2+3}\sum_{r=1}^{2} 3^{1-\alpha_r}\mu_r(\gamma^2+3)^{\alpha_r} \quad [1]$$

Stored elastic energy in the encapsulant represents the delamination energy

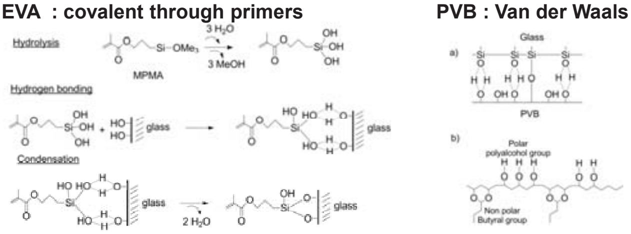
$$E^{el} = \int \tau(\gamma)\,d\gamma$$



[1] : O. Lopez-Pamies, C.R. Mécaniques 338, pp.3-11, 2010

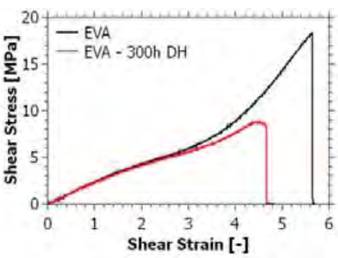
Chemistry of adhesion

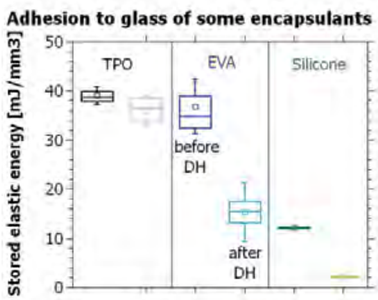
EVA : covalent through primers **PVB : Van der Waals**



Different examples of encapsulant/glass adhesion mechanisms

Comparison of different encapsulants and aging effect

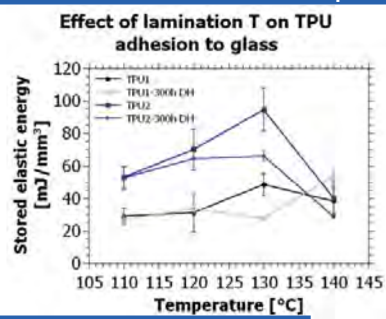




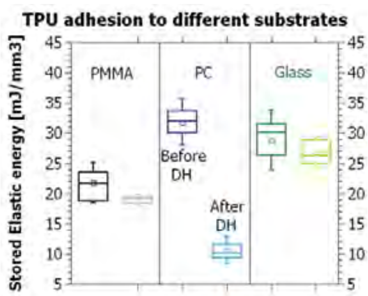
Observations:

- (Adhesion of different encapsulants to glass after Damp Heat (300h) on evidences different behaviours:
  - TPO and EVA same initial adhesion due to similar chemical structure and adhesion promoters but lower moisture diffusion barrier of EVA leading to more important drop after DH aging
  - Silicone has much lower adhesion in initial conditions and tend to be extremely low after DH aging
  - TPU shows an extremely high adhesion to glass even at lamination temperatures as low as 110°C
  - TPU adhesion to other rigid and transparent substrates such as PMMA is stable after aging

Comparison of different lamination temperatures



Comparison of different substrates



Conclusions)

- (***Compressive shear test allows reproducible and reliable adhesion measurement for PV encapsulants bonded to rigid substrates***
- (***Testing different encapsulants allows a clear ranking in adhesion before and after aging (i.e. on glass TPO>EVA>Silicone)***
- (***Process tuning to optimize adhesion is straightforward (i.e. glass/TPU adhesion optimization)***

A Multi-Perspective Approach to PV Module * Reliability and Degradation *

Alessandra Colli*, John P. Looney C
*Tel: +1-631-344-2666, E-mail: acolli@bnl.govC

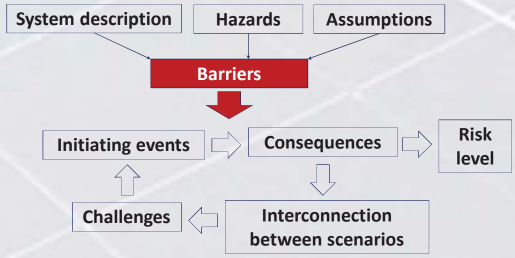
U.S. DEPARTMENT OF ENERGY

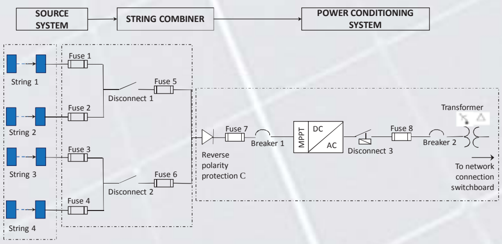
BROOKHAVEN NATIONAL LABORATORY

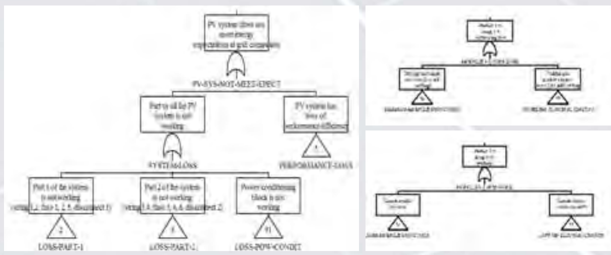
PV modules use different energy conversion materials that vary in composition, properties and structure. The module macro-structure is a complex system where mechanical, electro-chemical, electrical and structural interactions are taking place at micro- and nano-scale level. These effects can lead the PV technology to undergo unexpected changes in behavior not predictable by material studies under standard test conditions. Based on the methodological discussions in the area of system engineering and risk analysis, complex systems are approached by using a practical philosophy called holism, where the system is a working concert of all its part and the environment where it is located. Using such an approach to study degradation and reliability of PV modules means understanding that the synergy of different accelerating factors has a more powerful impact than the sum of the single factors if considered alone. Reliability and degradation studies have the main purpose to outline the acceptable level of defects in PV modules so to define marginal costs for O&M and reduce the lifelong costs of PV plants. The analysis should differentiate diverse failures (intrinsic, extrinsic) and different stages of the module lifetime: early life (pay-back), useful life, and wear-out. To achieve this purpose it is important to adopt proven as well as innovative reliability modeling approaches, and to understand those mechanisms of failure still not clear concerning behavior, cause, activating energy and accelerating factors.

The use of probabilistic risk analysis (PRA) for photovoltaic systems

PRA groups various tasks: design modeling, system analysis, identification of basic events and initiating events, event sequence analysis conducted on the basis of fault trees (FTs) and event trees (ETs), and finally the evaluation of the consequences and the quantification of risk. The main PRA analysis flow is shown at the right. To simulate the correct interactions leading to the fault propagation, the appropriate knowledge of failure modes, causes and effects for each system component is achieved through FMEA. Below, the considered PV system scheme, some example fault trees, and the initiating events (IEs). FTs support failure propagation analysis.



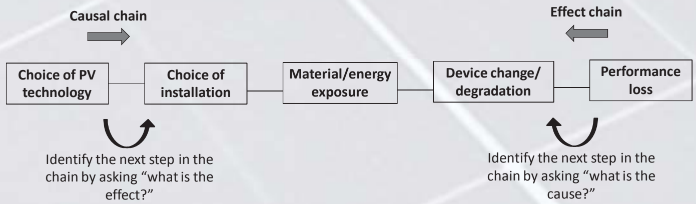




Internal IE	
Loss of grid electricity (AC)	IE_INT_LOSSGRD
Grid electricity transient fluctuations	IE_INT_GRDFLCT
Overvoltage	IE_INT_OVERVLT
Loss of electrical connection of module strings (DC)	IE_INT_LOSSDC
Structural damage to rack	IE_INT_DMGRACK
Leakage (of transformer coolant)	IE_INT_LEAKOIL
Internal fire	IE_INT_FIRE
External IE	
Flood	IE_EXT_FLOOD
Earthquake	IE_EXT_ERTQUAKE
Extreme wind load	IE_EXT_EXRMWIND
Extreme snow load	IE_EXT_EXRMSNOW
Sand storm	IE_EXT_SNDSTRM
Animals	IE_EXT_ANIMAL
Lightning	IE_EXT_LIGHTN
Sabotage (terrorism)	IE_EXT_SABOTG
Adversary action (vandalism)	IE_EXT_ADVACT
Airplane crash	IE_EXT_AIRCRSH
Explosion (considered for transformer, inverter)	IE_EXT_EXPLSN
External fire	IE_EXT_FIRE
Mechanical shock	IE_EXT_MECHSHCK
High humidity	IE_EXT_HUMID
High chemical air contamination	IE_EXT_CHEM
Soil/dust/pollen	IE_EXT_DUST
Shadows on modules	IE_EXT_SHADOW

Investigating reliability from the system to the cell material

- Integration of bottom-up and top-down approach.
- A causal/effect chain (right), with the support of appropriate indicators, can guide the initial steps of the investigation.
- Need of reliability models capable to link the effects at system level with construction defects, impurities and atomic/molecular interactions into the PV device material.
- Models and investigations based on holistic system considerations.



Understanding failure mechanisms

The packaging structure of PV modules and their working environment (geographical location, meteorological conditions and system integration) create a multivariate operational framework. Once degradation effects and failures are identified in modules and cells, the next step leads to decode their physics and mechanisms. Innovative techniques associated with tests to simulate more realistically the degradation and the environmental conditions are introduced to study cell and module reliability, along with ex-situ, in-situ and in-operando analysis using enhanced material investigation techniques (such as those soon available at BNL's NSLS II). Reliability and degradation data (failure rates, frequencies, probability distributions) are needed, along with the knowledge of the associated causes leading to faults and degradation.
Understanding failure mechanisms is not only based on material analysis under single or multivariate conditions, but also requires the introduction of new visions, models and investigations approaches, as so far adopted to investigate complex systems in the nuclear, space, aviation, chemical process and semiconductor manufacturing industry.

Outdoor operation
NSERC grid-connected operation, and degradation of different modules, prototypes and small sample structures in the Northeast environment.

PV devices laboratory to characterize cells/samples and detect small defect areas (QE, IV measurements, LBIC)

NSERC laboratory *

Indoor accelerated tests and module characterization *

Ex-situ, in-situ, and in-operando material investigations involving CFN and NSLS

Analysis of material composition, defects, electro-chemical, electrical and structural interactions to understand degradation mechanisms.

BNL is managed for the U.S. Department of Energy by Brookhaven Science Associates, a company founded by Stony Brook University and Battelle *

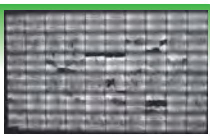
Quantum Efficiency Measurement Artifacts of Solar Cell Modules

Aaron Korostyshevsky, Anna Fox, Eric Straily, Orri Jonsson, and Halden Field
PV Measurements, Inc., 5757 Central Avenue Suite B, Boulder, CO 80301, USA

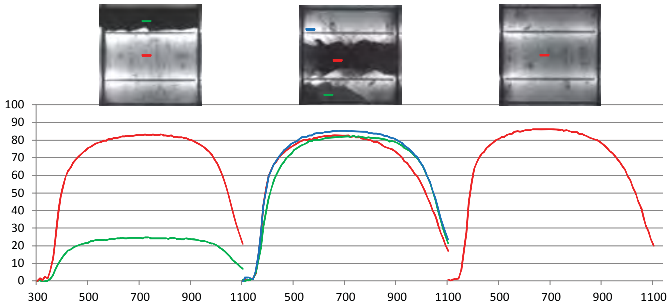
Abstract

In this study, we examine the process, analysis, and artifacts of quantum efficiency (QE) measurements of solar cells within a module. Experience with measuring QE of multi-junction cells lends some insight regarding the use of light and voltage biasing, but the QE of a module presents some unique differences. The most significant of these is that a much larger number of devices in series is available to negatively influence the measurement condition via shunting. Some cases are identified where an absolute QE measurement is not obtainable due to severe degradation. We can use this measurement technique in conjunction with other types of data to study cell failure modes in a module that has been subjected to a variety of stress tests.

Control Module

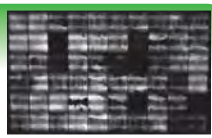


No PID or thermal cycling stress

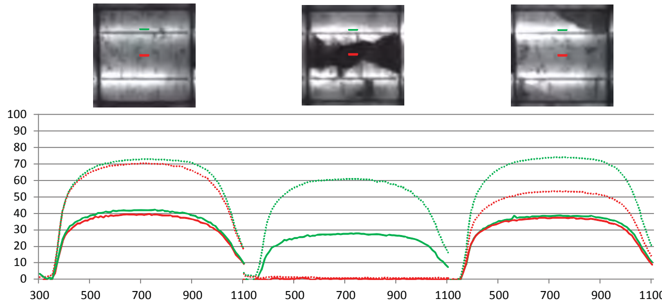


- All measurements performed through the string using light and voltage bias.
- Integrated current is within 1 % of nameplate Isc when measured on high performing areas.

Stressed Module



70 % loss of power after PID and thermal cycling stress



- Dotted lines show measurements by direct contact through the back sheet.
- Solid lines show measurements through the string using light and voltage bias.

Summary

- Correlation is observed between QE and EL data for identifying high- and low-performing areas.
- QE measurements of cells in a module highly dependent on levels of degradation in both the DUT and the remainder of the string.
- Half of the available light bias intensity is sufficient to maximize the QE level in non-degraded panels. Full bias light is not sufficient to measure severely degraded panels.

solar test laboratory

Failure Rates from Certification Testing to UL and IEC Standards for Flat Plate PV Modules

Larry Pratt*, Nicholas Riedel*, Martin Plass, and Michael Yamasaki
CFV Solar Test Laboratory, Inc., Albuquerque, NM

Purpose

The purpose of this analysis is to report the most common failure modes identified during certification projects for flat plate PV modules tested at the CFV Solar Test Laboratory from April 2011 to December 2012. Our statistics are compared to similar findings reported by Fraunhofer ISE and TÜV Rheinland Photovoltaic Testing Laboratory so as to identify the most common failure modes occurring in PV module certification testing.

The CFV Facility


AAA+ Flash Simulator


Mechanical Load Tester


CFV's Outdoor Test Site


Large Climate Chamber


Large UV Chamber (5x sun)

CFV Solar Test Laboratory is a state-of-the-art PV test center accredited to ISO17025. Since April 2011, CFV has been conducting module certification testing for its partners CSA and VDE. 54 certification projects have been completed (24 Mono-Si, 25 Poly-Si, 2 A-Si/C-Si Tandem, 1 CIGS, 1 CPV, and 1 Spherical C-Si) using CFV's indoor and outdoor testing equipment. CFV's projects have included all environmental tests per UL1703, IEC61215, and IEC61646 and their respective pre- and post-characterization steps.

Results

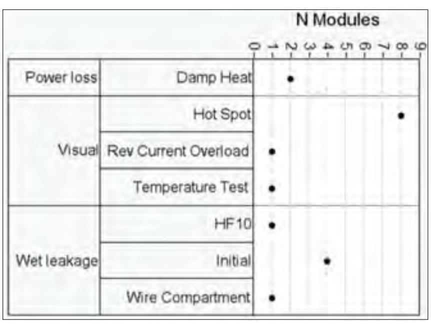
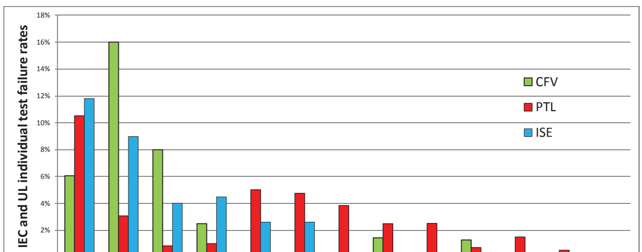


Figure 1: Number of certification modules failing at CFV for different failure modes and effects.



	Damp Heat	Hot Spot	Other	HF 10	TC 200	MLT	Diode	Wire Box	Out Door	Initial	Hail	TC 50	UV
CFV	6.1%	16.0%	8.0%	2.5%	0.0%	0.0%	0.0%	1.4%	0.0%	1.3%	0.0%	0.0%	0.0%
PTL	10.5%	3.1%	0.8%	1.0%	5.0%	4.8%	3.8%	2.5%	2.5%	0.7%	1.5%	0.5%	0.0%
ISE	11.8%	9.0%	4.0%	4.5%	2.6%	2.6%	NA	0.1%	NA	NA	0.2%	NA	NA

Figure 2: CFV, PTL, and ISE failure rates for characterization tests by environmental stress

Notes:
- CFV data is for projects performed between April 2011 and December 2012.
- PTL data reported is from 1997 to 2005.
- ISE data reported is from 2006 to 2009.

Conclusions

1. Three labs show similar failure rates for common failure modes: Damp Heat, Humidity Freeze, TC 200, and the Mechanical Load Test.
2. The failure rates for the hot-spot test differ considerably among the three labs. This is possibly due to differences in procedures or standard followed. CFV and ISE follow the procedure outlined in Rev 3 of IEC for identifying the lowest shunt resistance cell.
3. In the interest of standardized testing, some normalization around the hot-spot test should be considered.
4. No UV failures specifically reported by any lab, which is not surprising due to the low dosage of UV exposure received by modules during this test (the equivalent of roughly 30-90 days of outdoor exposure).

References

- Ferrara, C. (2012, January). *What can we learn from testing and certification?*. PV Rollout Conference , Boston, Massachusetts.
- IEC 61215:2005. Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval.
- IEC 61646 Rev 2 2008. Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval.
- Li, B., Arrends, T., Kuitche, J., Shisler, W., Yi, K., & Tamizhmani, G. (2008, September). *IEC and IEEE design qualifications: An analysis of test results acquired over nine years*. 21st European Photovoltaic Solar Energy Conference, Dresden, Germany.
- UL 1703. Standard for Safety for Flat-Plate Photovoltaic Modules and Panels, Third Edition.

JOINTLY OWNED BY: CSA INTERNATIONAL · Fraunhofer ISE · Fraunhofer USA · VDE INSTITUTE

High-Efficiency GaAs Thin-Film Solar Cell Reliability

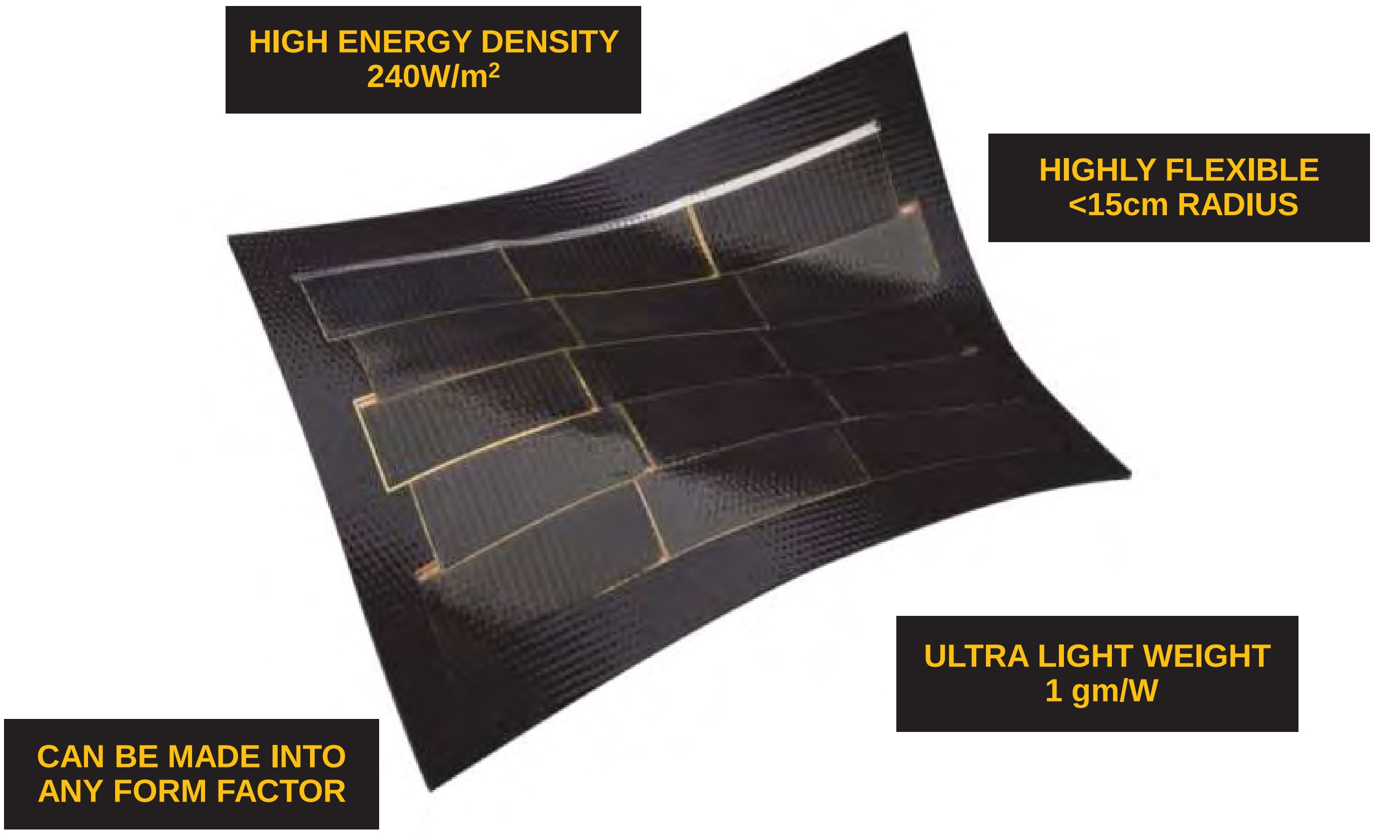
NREL PV Module Reliability Workshop, Feb. 26-27, 2013

Erhong Li and Prasad Chaparala

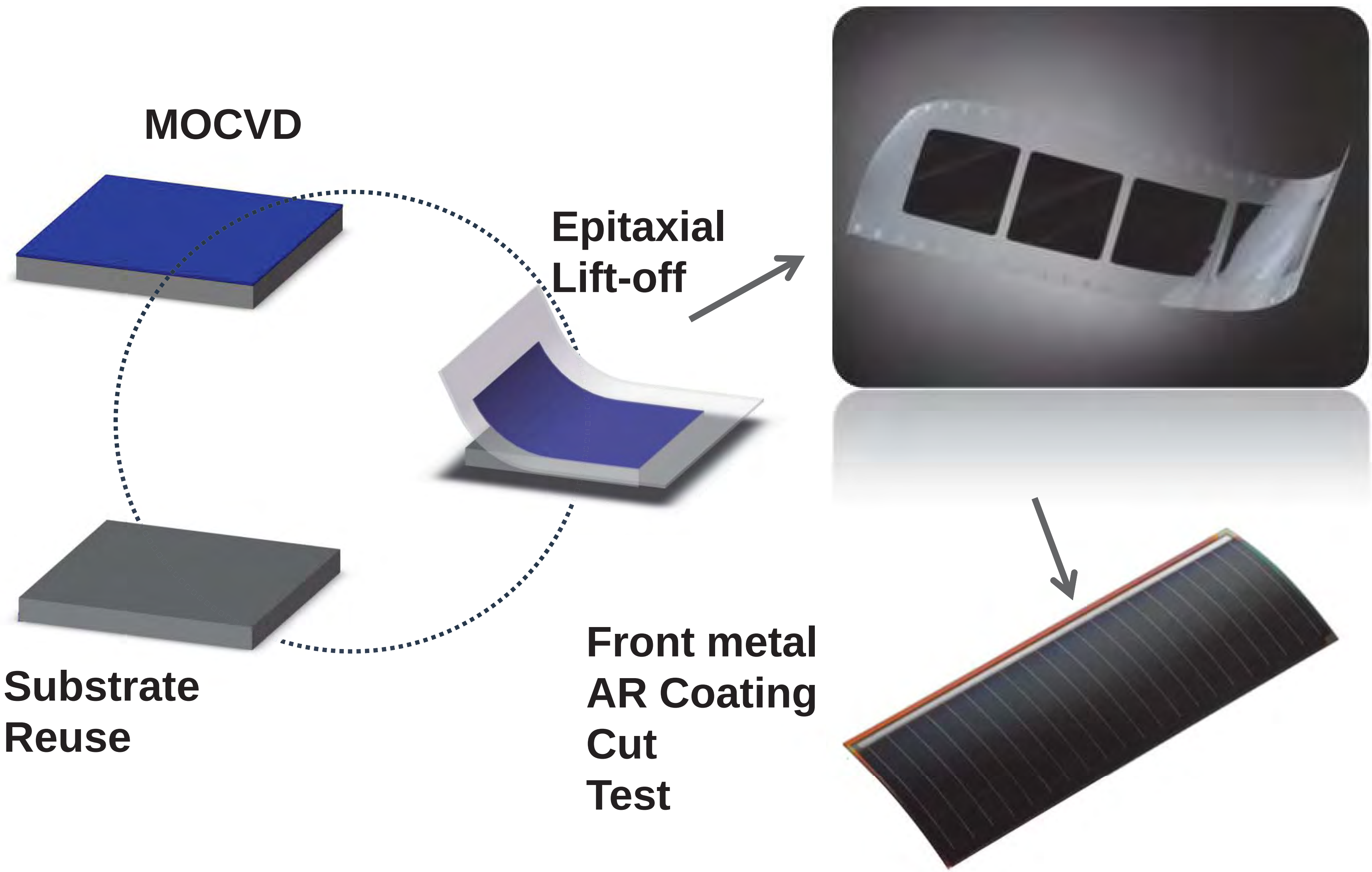
Alta Devices, Inc.

Alta Devices Flexible Solar Technology

- World-record efficiencies
  - Single junction cell/module: 28.8% / 24.1%
  - Dual junction cell: 30.8%

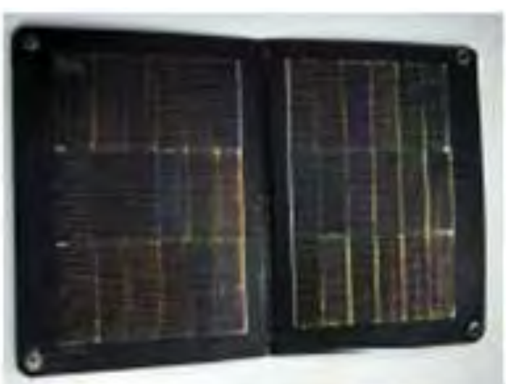


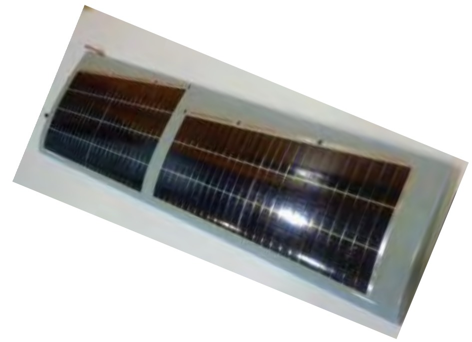
How Alta's Flexible Cells Are Formed



Mobile Power Applications

Remote
Power



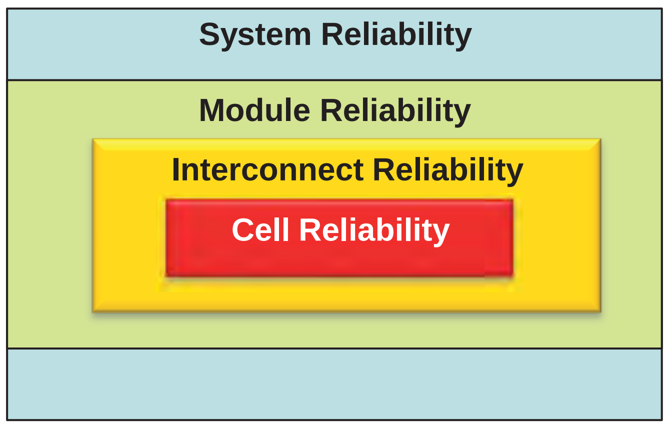


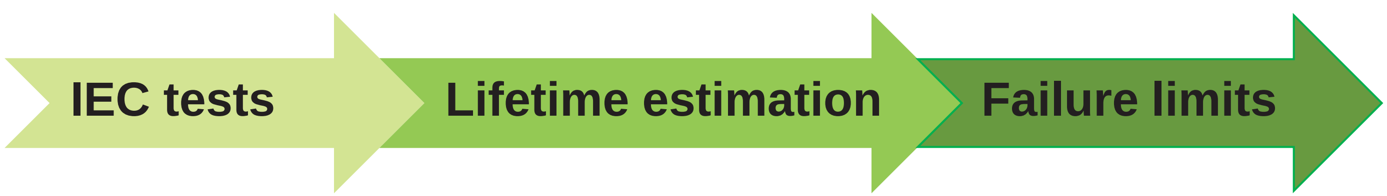
UAVs / Aerospace

Portable
Electronics

Built-in Reliability Methodology

- In-depth reliability characterization, beyond certification & specs
  - Know when, where and why it fails
- Built-in reliability mindset
  - Reliability - integral part of development
  - Cell-level accelerated testing for fast feed-back





Reliability Tests

- Technology Reliability Characterization
  - Accelerated tests on bare solar cells (un-encapsulated)
  - IEC tests on glass mini-modules (150 cm^2)

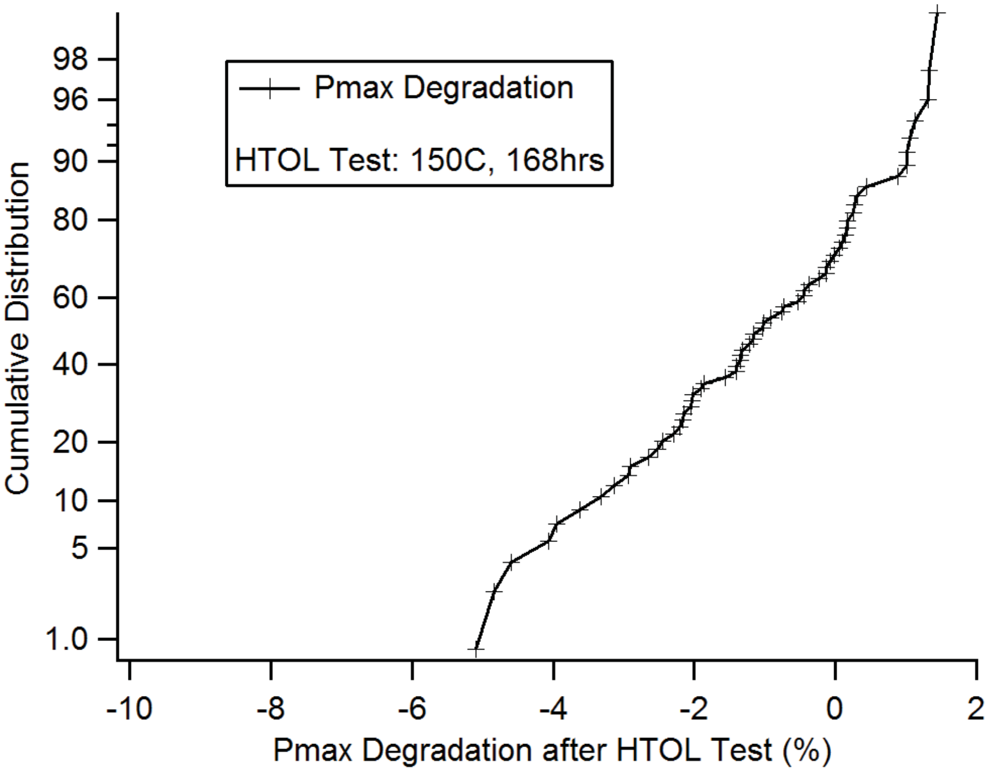
- Reliability Tests

Sample	HTOL	LTSL	Damp Heat	Thermal Cycling	Humidity Freeze
Cells	150C 168hrs	-60C 168hrs	85C/85%RH 168hrs	-40C/85C 200 cys	NA
Modules	110C 1000hrs	NA	IEC61646	IEC61646	IEC61646

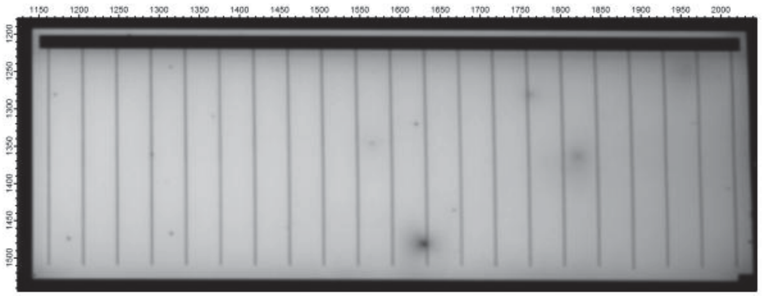
- Failure Criterion
  - Pmax Degradation(%) = (Pmax@Tx-Pmax@T0)/Pmax@T0*100

Cell Level Reliability – High Temperature Test

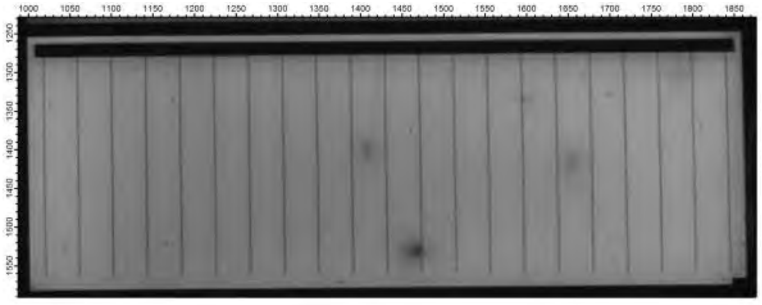
- Cells tested @150C for 168hrs
- Pmax degradation < 6%



PL @0hr

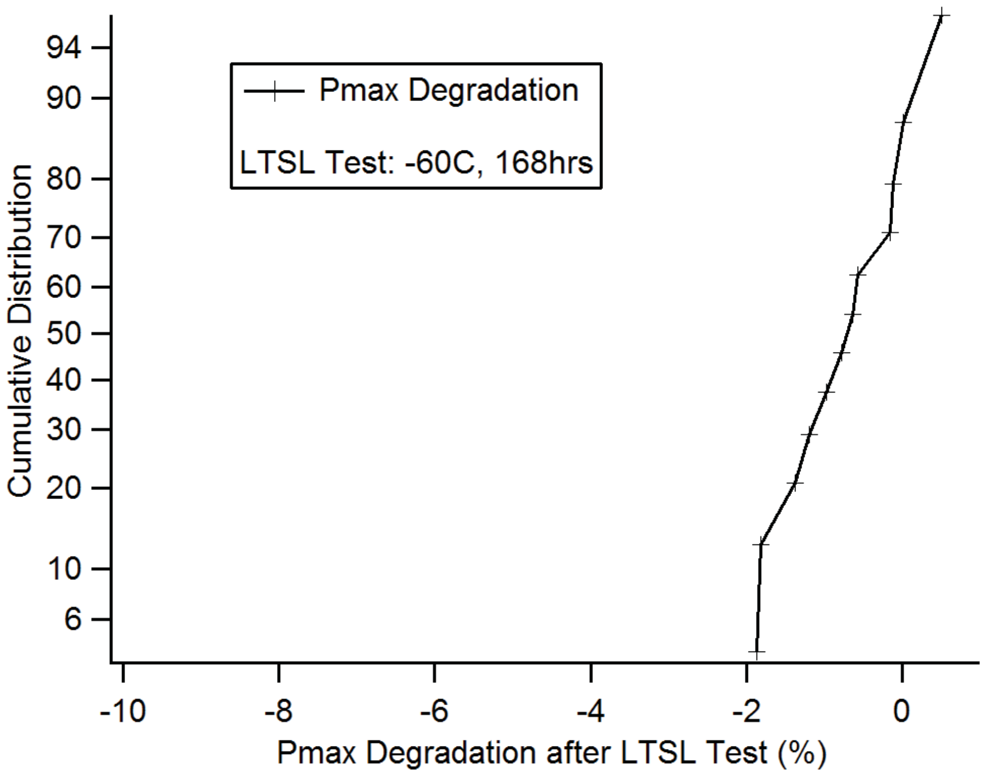


PL @168hrs

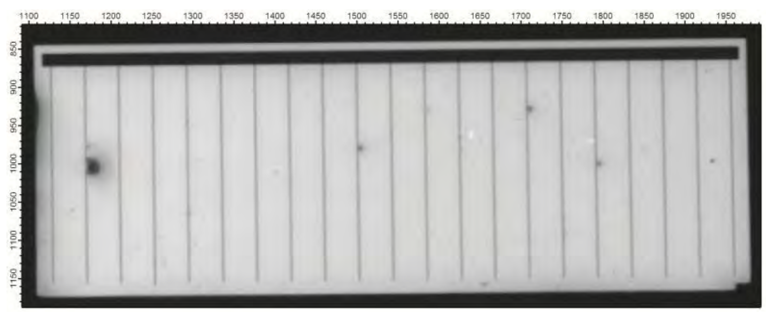


Cell Level Reliability – Low Temperature Test

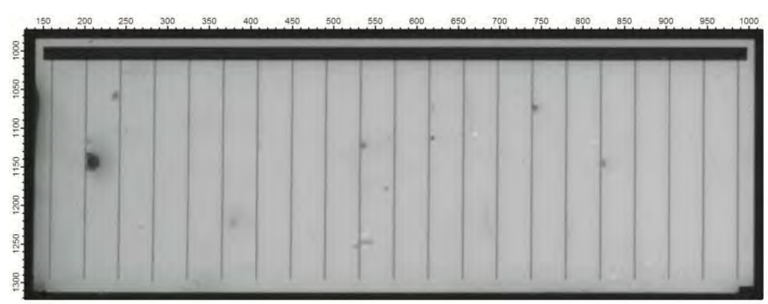
- Cells tested @-60C for 168hrs
- Pmax degradation < 2%



PL @0hr

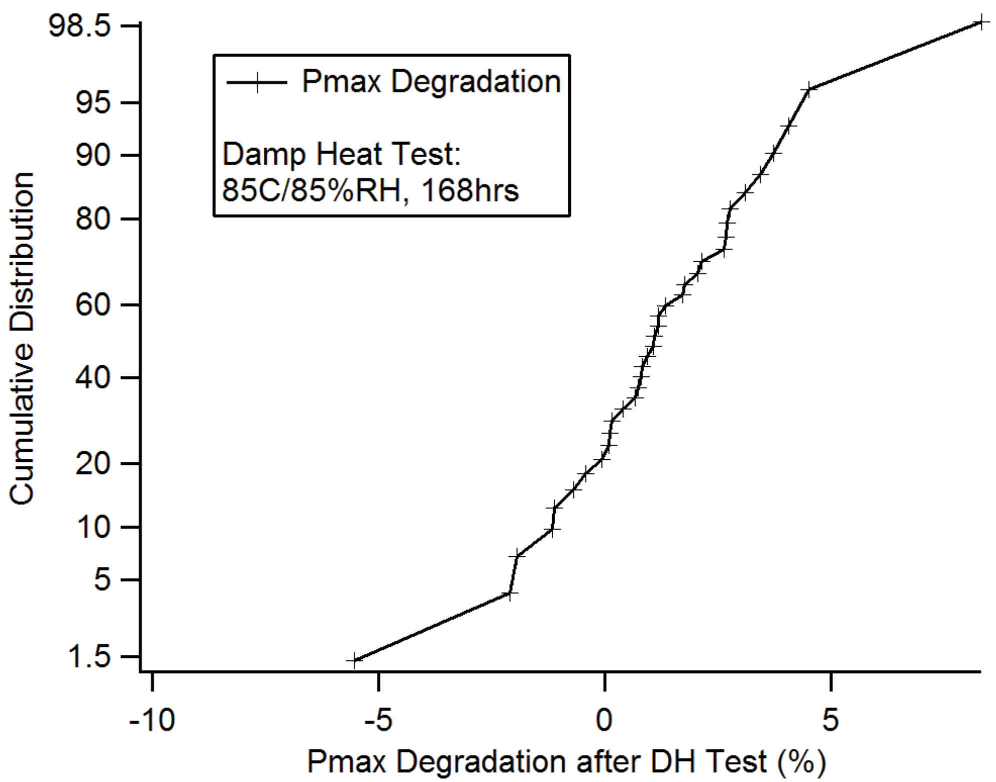


PL @168hrs

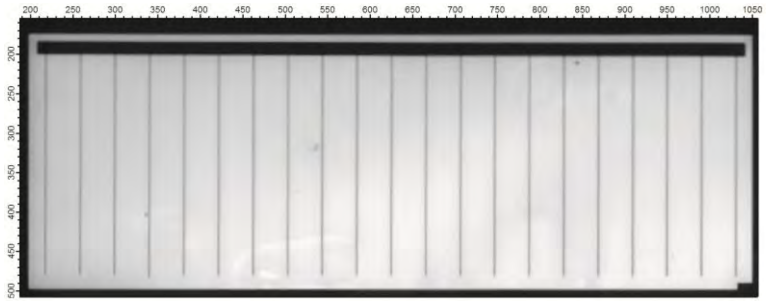


Cell Level Reliability - Damp Heat Test

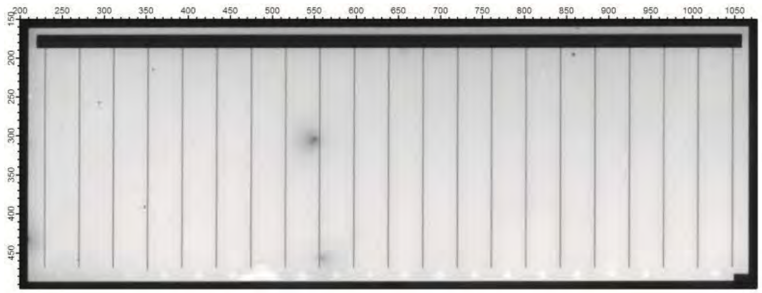
- Cells tested @ 85C/85%RH for 168hrs
- Pmax degradation < 6%



PL @0hr

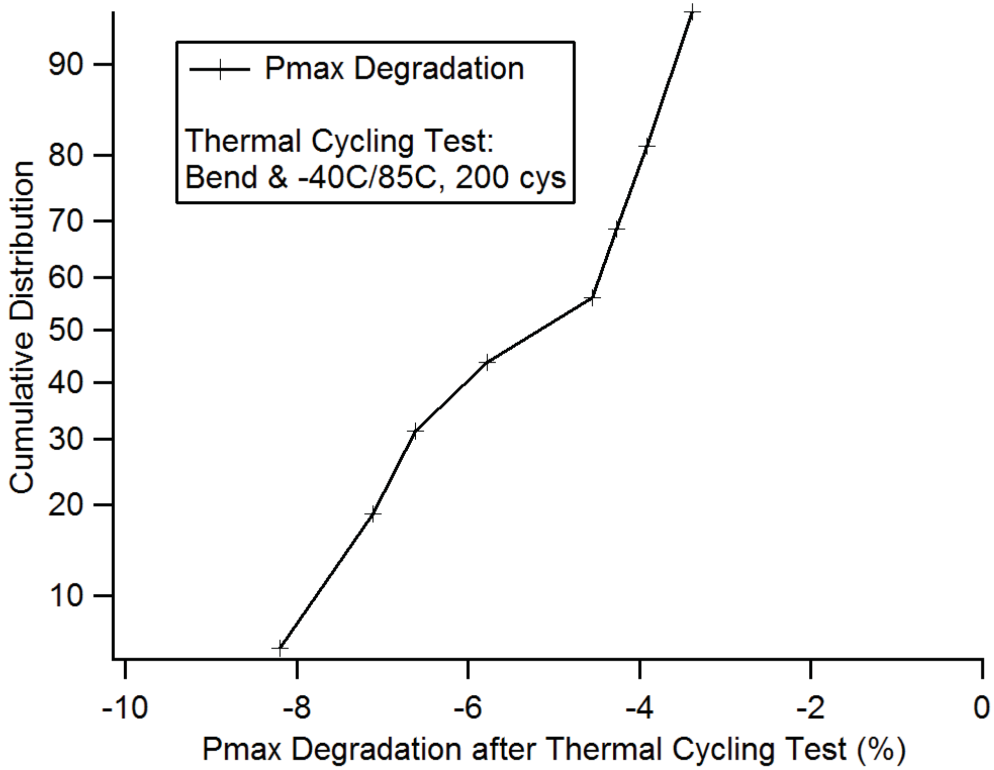


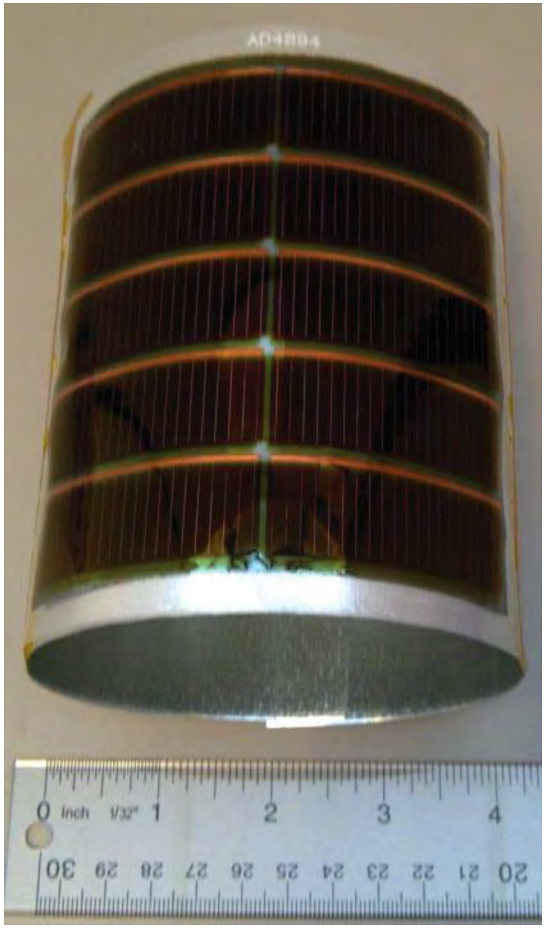
PL @168hrs



Cell Level Reliability - Thermal Cycling Test

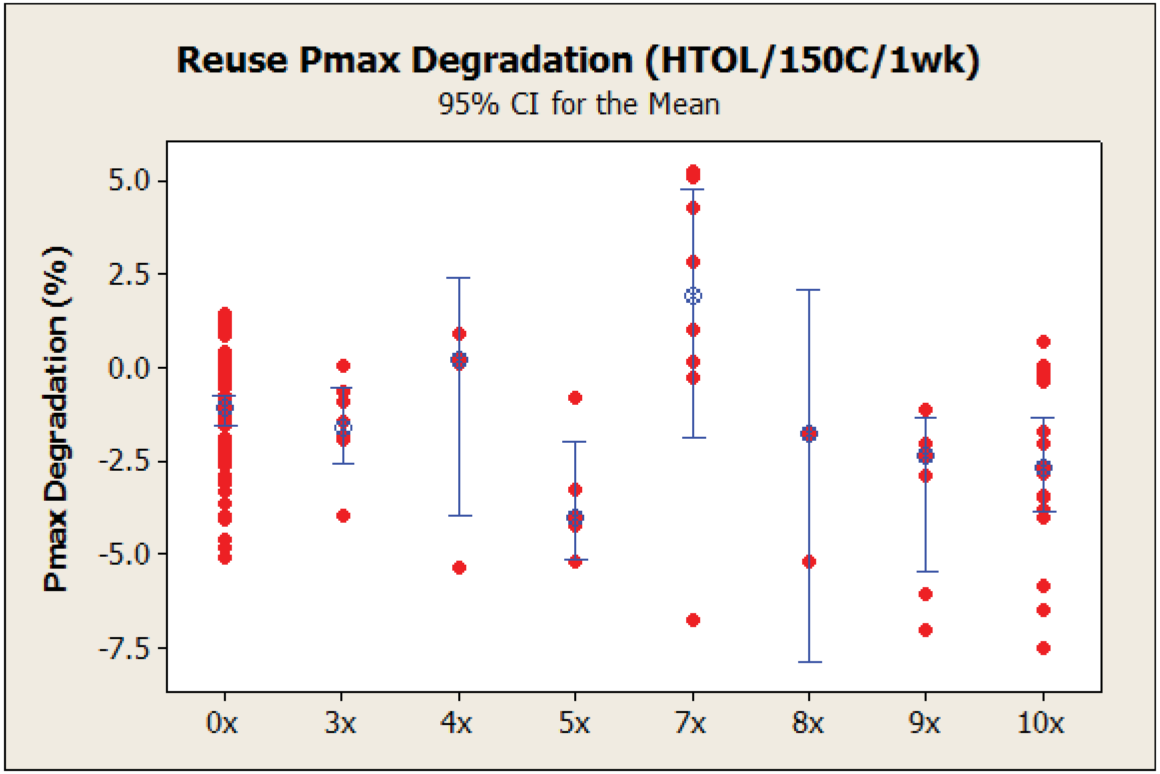
- Thermal cycling under 2” bend radius (-40C/85C, IEC profile, 200 cycles)
- Pmax degradation < 10%





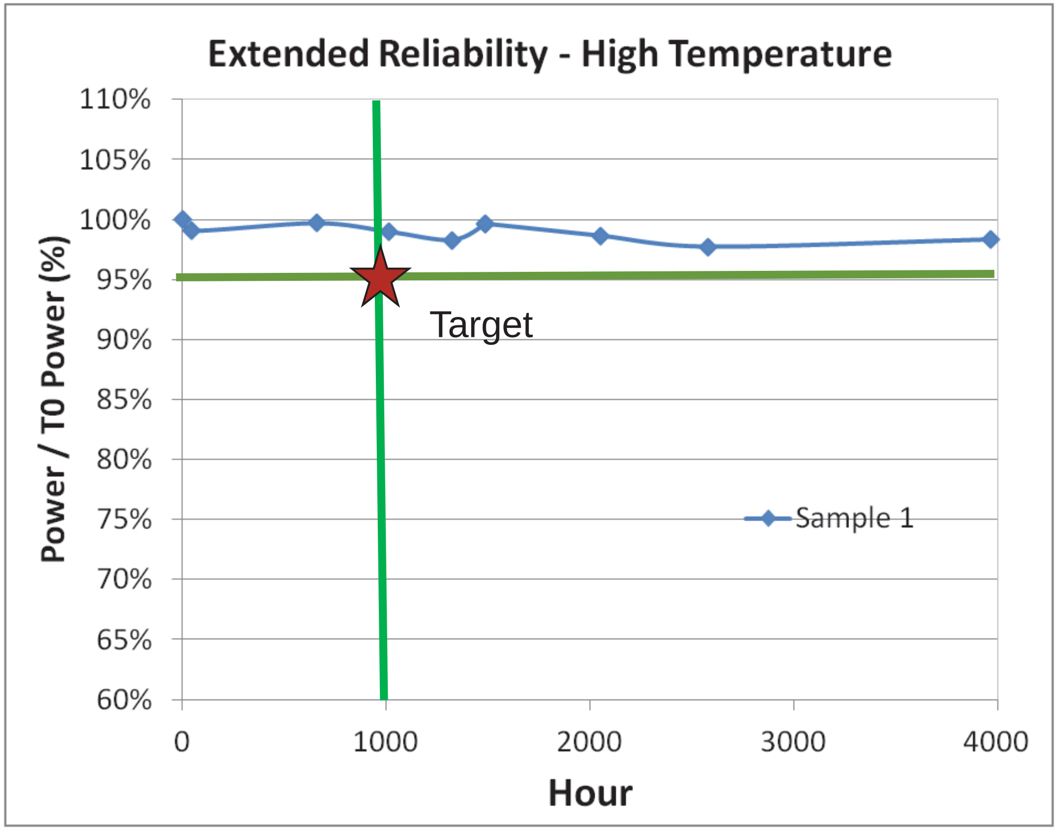
Reliability of Cells from Multiple Substrate Reuses

- Substrate reuse is one of the key process steps to lower cost for GaAs thin-film solar technology
- Cells tested @150C for 168hrs
- No intrinsic degradation mechanism was found on material up to 10-time substrate reuse

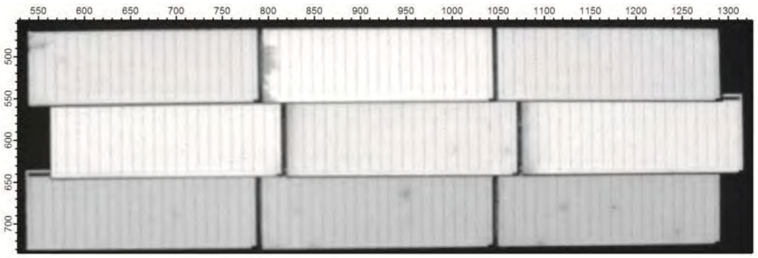


Module Level Reliability – High Temperature Test

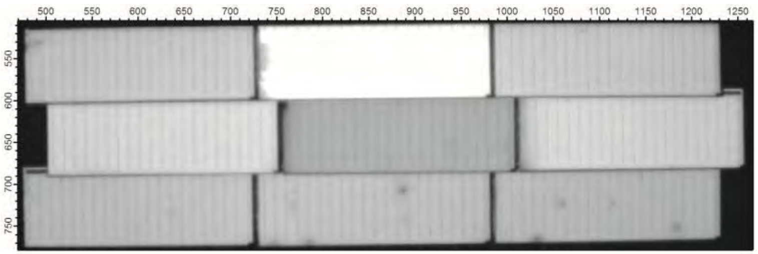
- Module tested @110C, 1000hrs
- Pmax degradation < 5%



PL @0hr

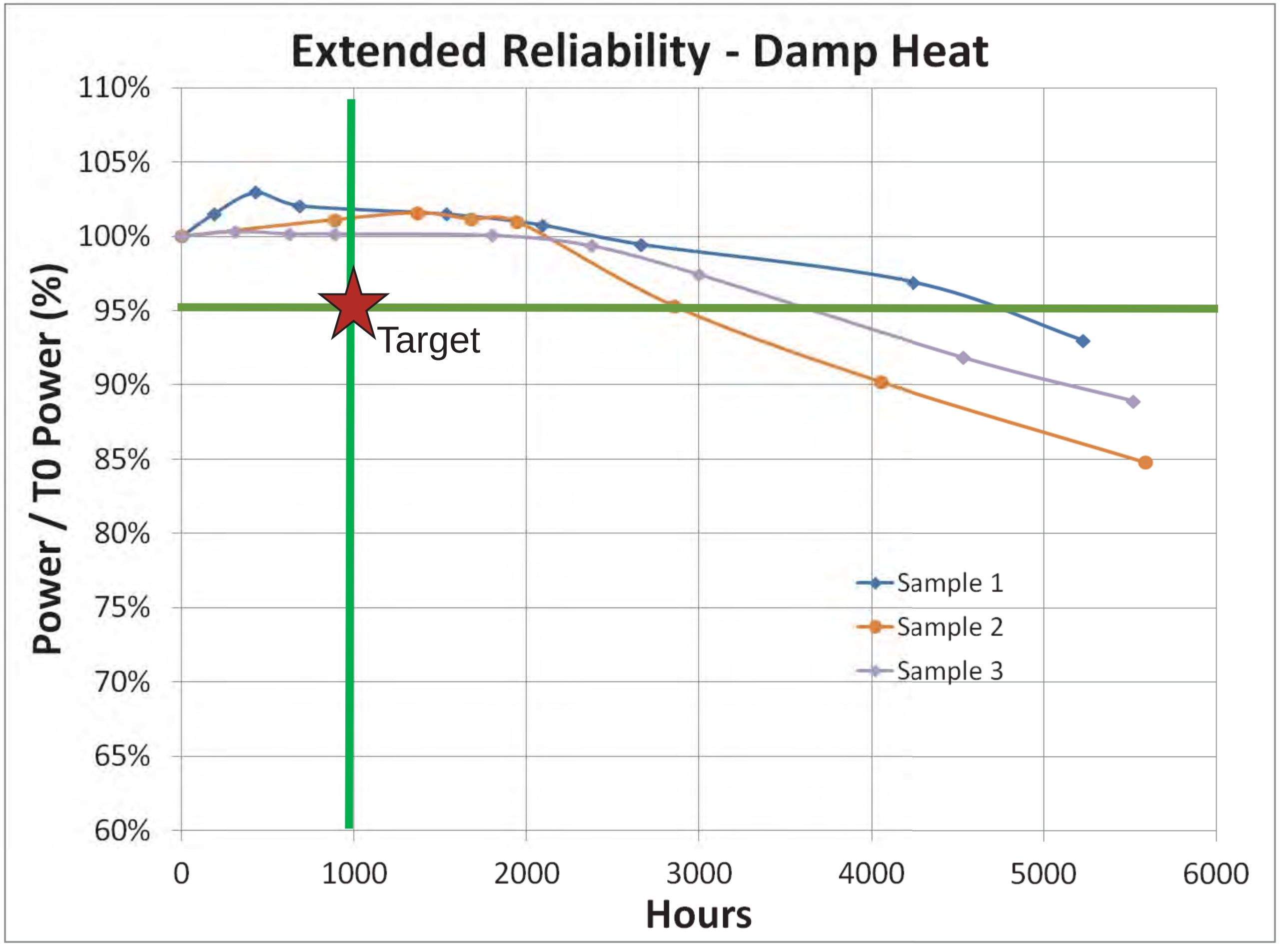


PL @4000hrs



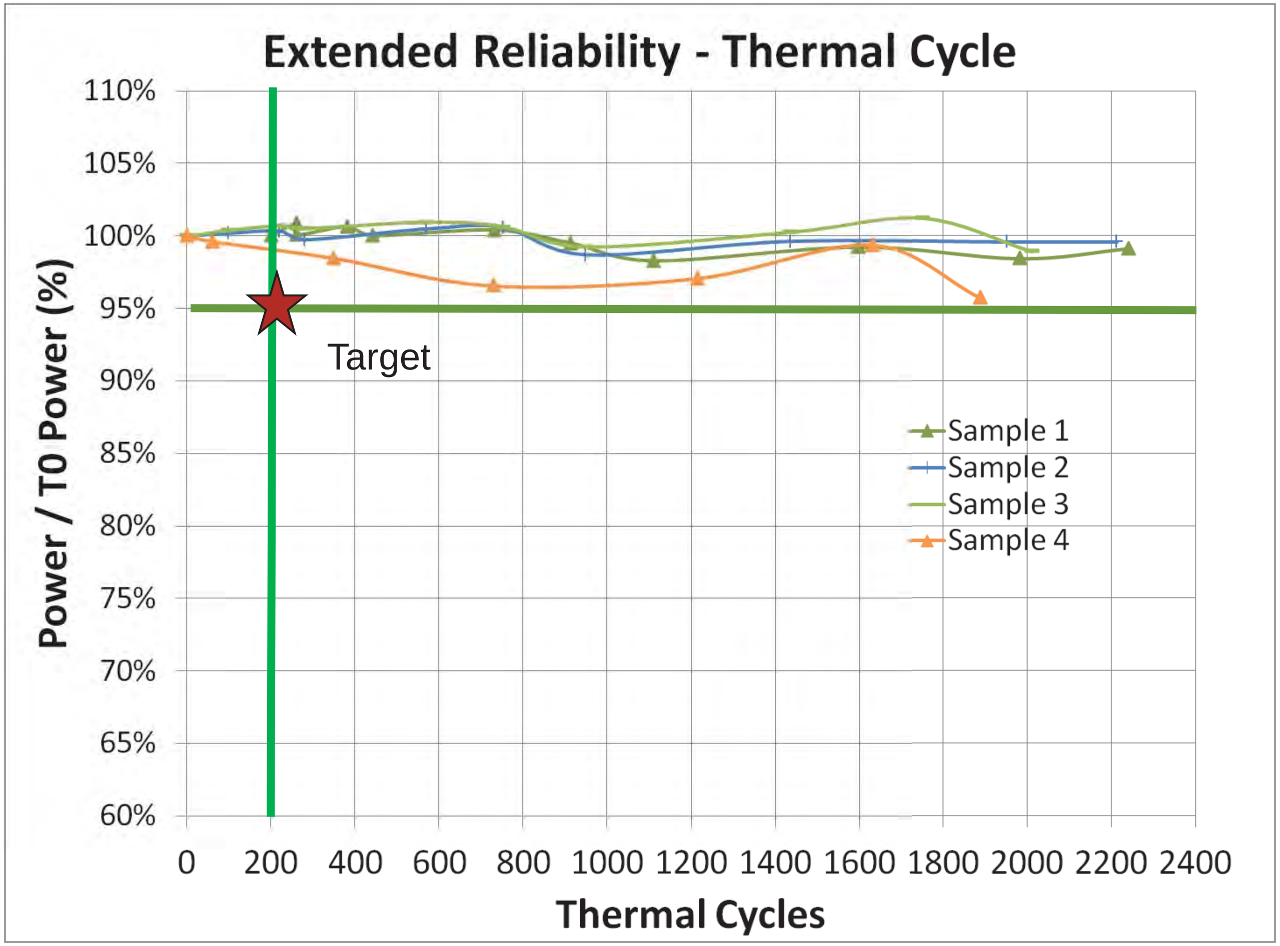
Module Level Reliability – Damp Heat Test

- Pmax degradation < 5% at 1000hrs
- Results exceed IEC test requirements



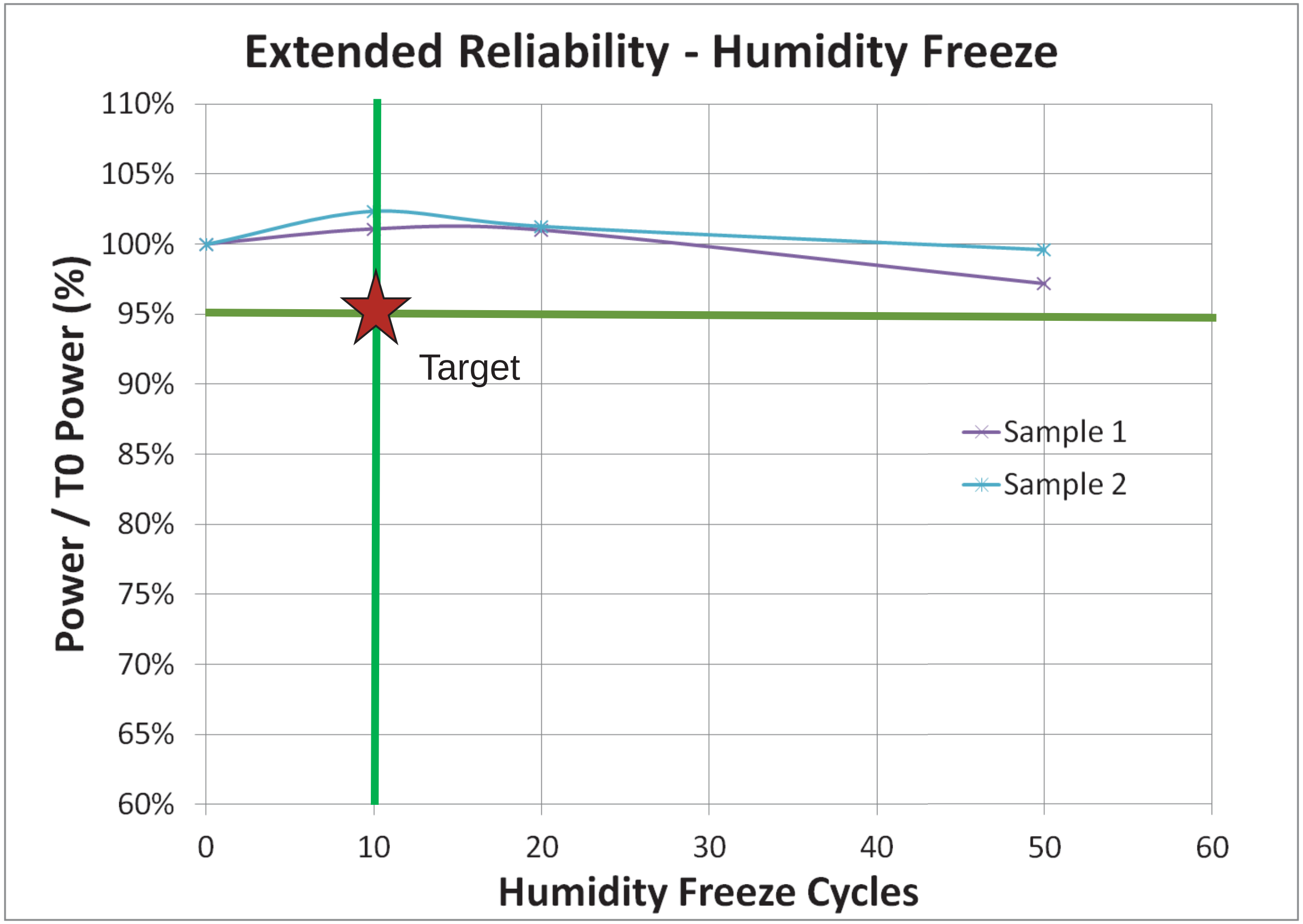
Module Level Reliability – Thermal Cycling Test

- Pmax degradation < 5% at 200cys
- Results exceed IEC test requirements



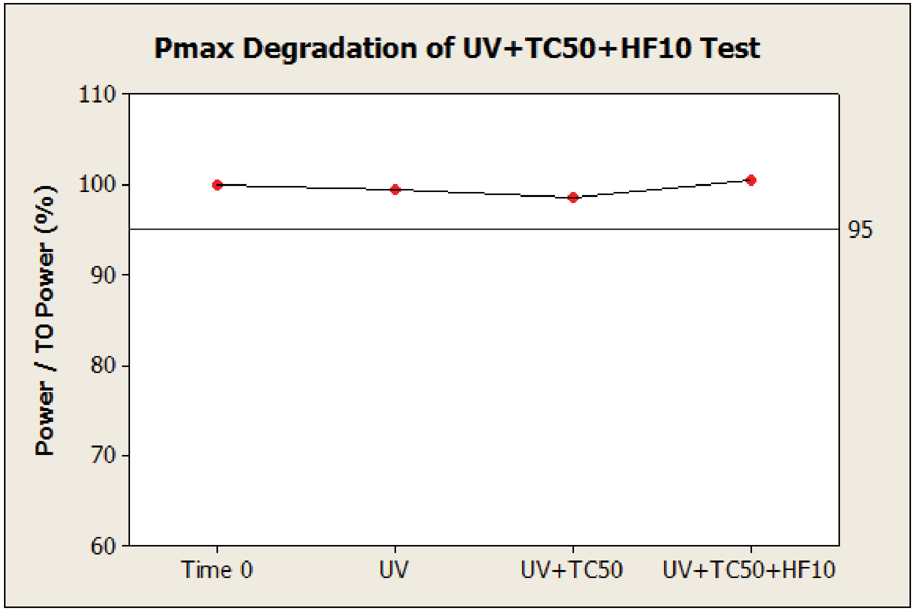
Module Level Reliability – Humidity Freeze Test

- Pmax degradation < 5% at 10cys
- Results exceed IEC test requirements

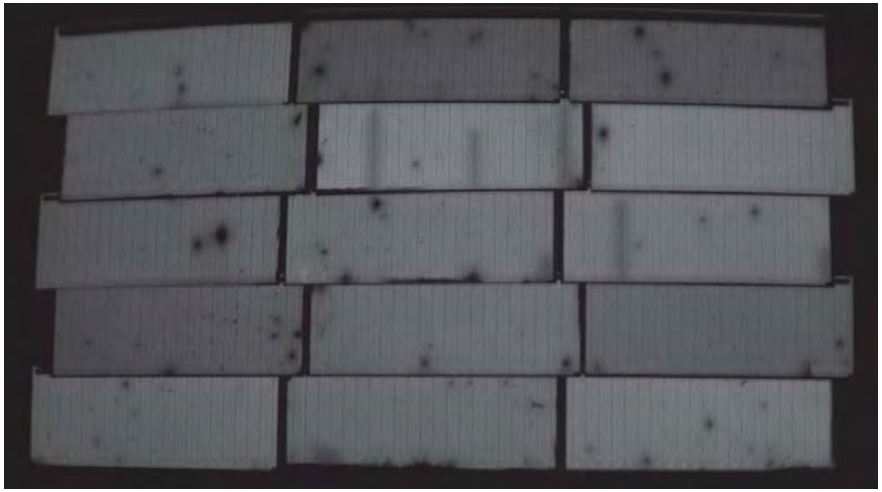


Module Level Reliability – UV + TC + HF

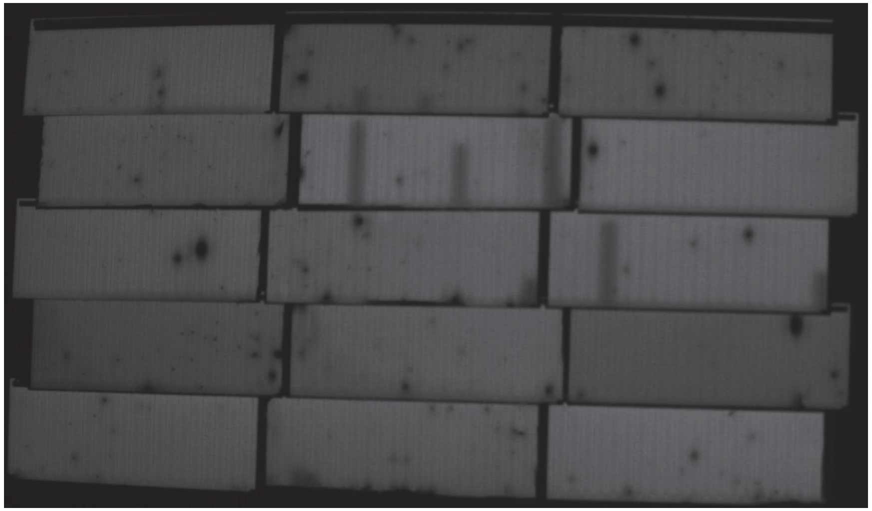
- Pmax degradation < 5%
- Modules passed UV sequence test
  - UV (15kWh/m^2)
  - TC50
  - HF10



EL @0hr



EL @UV+TC50+HF10



Conclusion

- Thin-film solar cells from GaAs reuse substrate show no intrinsic degradation after reliability tests

- Broad range of cell-level and module-level reliability tests demonstrate that Alta Devices GaAs thin-film solar technology from Epitaxial Lift-off (ELO) process exceeds lifetime requirements for PV applications

Acknowledgement

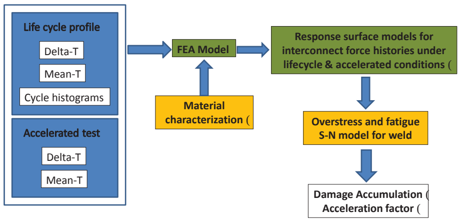
- Thanks to Chris Ling, Sharon Myers and Chris France for support
- Thanks to the Device/EPI/Process/Integration/Matrix team to provide materials for this reliability study

PV MODULE INTRACONNECT THERMOMECHANICAL DURABILITY DAMAGE PREDICTION MODEL

Ryan Gaston*, N. Ramesh
The Dow Chemical Company

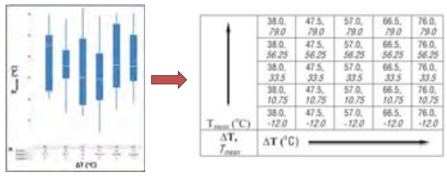
J. Akman, A. Dasgupta, C. Choi, S. Mukherjee, D. Das
University of Maryland - CALCE

Outline of Methodology

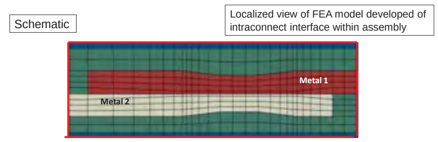


Thermal Cycle Design Space

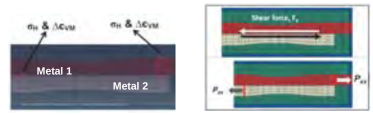
- Continuous temperature readings taken at various geographic locations
- 3 parameter Rainflow algorithm used to reduce raw data to significant cycles
- Temperature data quantified in terms of cyclic T_{mean} and ΔT
- Design space generated to describe life cycle profiles
- Accelerated profile: -40ºC to 90ºC



FEA Model - Intraconnect

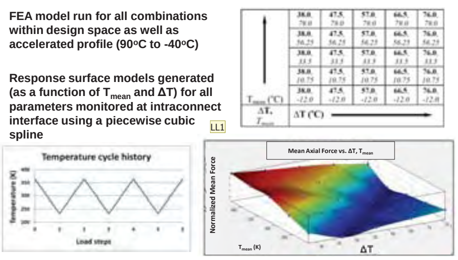


- Shear, peel, and axial forces estimated using FEA
- Parameters monitored at intraconnect interface (below)



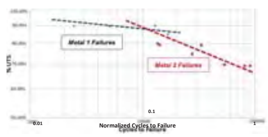
Response Surface Models

- FEA model run for all combinations within design space as well as accelerated profile (90ºC to -40ºC)
- Response surface models generated (as a function of T_{mean} and ΔT) for all parameters monitored at intraconnect interface using a piecewise cubic spline



Mechanical Failure Modes

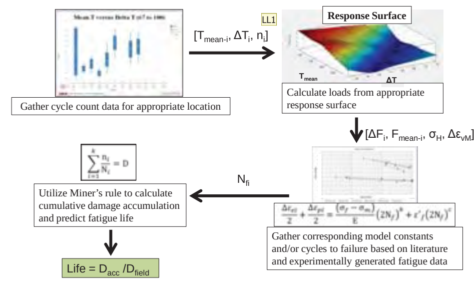
Failure Model 1 (FM1)	Failure Mode 2 (FM2)	Failure Mode 3 (FM3)
Room Temperature Max Load: 90% of P_{ult} Normalized N_f: 0.0683 Failure Site: **Metal 1**	Room Temperature Max Load: 70% of P_{ult} Normalized N_f: 1 Failure Site: **Metal 2**	Room Temperature Max Load: 90% of P_{ult} Normalized N_f: 0.00825 Failure Site: **Interconnect Region**



Competing fatigue curves seen for different failure modes (

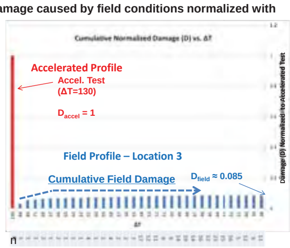
NOTE: Plot generated while testing was in progress and does not contain all fatigue data

Damage Accumulation: Approach



FM1: Damage Modeling

- Plot shows a cumulative damage caused by field conditions normalized with respect to accelerated test
  - Majority of damage accumulated from the first few largest ΔT values
  - Cycles with smaller ΔTs that have a higher cycle count in the field (i.e. higher **n value**) still contribute less damage cumulatively than a small number of the highest ΔT cycles



FM1: Acceleration Factor

$$\frac{\Delta\varepsilon_{el}}{2} + \frac{\Delta\varepsilon_{pl}}{2} = \frac{(\sigma_f - \sigma_m)}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

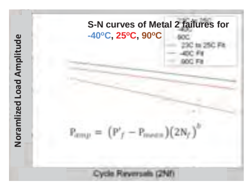
- Sensitivity study of model coefficients σ_f' and ε_f' (i.e. fatigue curve intercept)
- Values chosen based on values for σ_f' and ε_f' in literature
- N_f values changed by as much as a factor of 2 for most severe field conditions

Combinations	
σ_f' (MPa)	ε_f'
135	0.10
139	0.13
142	0.14

	Location 1	Location 2	Location 3
AF	5.7-6.1x	2.7-2.9x	11.7-12.9x

FM2: Damage Modeling

- S-N curves generated for metal 2 failure
- The fatigue strength coefficient (P'_f) is modeled using a power-law dependence on temperature and the fatigue exponent b is modeled using a log-linear dependence on temperature
- This allows for fatigue constants to be estimated at any T_{mean} in the field environment.



P_{amp} Load Amplitude
P'_f Fatigue strength coefficient
P_{mean} Mean Load
N_f Cycles to Failure
b Fatigue exponent

FM2: Acceleration Factor

Linear damage superposition (Miner's rule) used to calculated damage accumulation:

1. FEA & Response Surface Models used to extract stress/strain histories at interconnect
2. N_f values calculated using extracted data and fatigue model(s) for all field conditions at each location
3. Cumulative damage index calculated from field conditions (D_{field})
4. Acceleration factor (AF) calculated by comparing damage index ratio of single accelerated cycle 'D_{acc}' to all field cycles 'D_{field}'
5. Repeatable for any field location where cycle history is known

$$D = \sum \frac{n}{N_f} \qquad AF = \frac{D_{acc}}{D_{field}}$$

	Location 1	Location 2	Location 3
AF	~13x	~5x	~21x

Summary

- A method for determining the durability of a PV module intraconnect was established
- The life prediction approach consisted of four parts:
  1) collection and qualification of temperature history data from life cycle environments
  2) experimental characterization of intraconnect fatigue data
  3) thermal cycle modeling using 2D and 3D FEA
  4) damage accumulation modeling to assess product durability
- A 3 parameter Rainflow algorithm was used to reduce module temperature data to significant cycles of Tmean and ΔT
- FEA models were developed and used to generate response surface models as a function of Tmean and ΔT over a 2D design space
- Damage was calculated using the Coffin-Manson relation with model constants from both literature and fatigue test coupons
- AF values were generated comparing relative damage index between field environments and an accelerated thermal cycle profile (90C to -40C)

2013 NREL PV Module Reliability Workshop (PVMRW)
February 26-27th, 2013 Golden, Colorado

Acknowledgements: Victor Juarez, Keith Kauffmann, Bhawesh Kumar, David Langmaid, Hua Liu, Minoru Sakuma, Jay Tudor

The thermal reliability study of bypass diodes in photovoltaic modules

Zhang, Z.[1, 2], Wohlgemuth J.[1], Kurtz, S.[1]
National Renewable Energy Laboratory, Golden, Colorado, USA
State Key Lab of Photovoltaic Science and Technology, Trinasolar Co. Ltd., Changzhou, China

Introduction

Bypass diodes are a standard addition to PV (photovoltaic) modules. The bypass diodes' function is to eliminate the reverse bias hot-spot phenomena which can damage PV cells and even cause fire if the light hitting the surface of the PV cells in a module is not uniform. The design and qualification of a reliable bypass diode device is of primary importance for the solar module. To study the detail of the thermal design and relative long-term reliability of the bypass diodes used to limit the detrimental effects of module hot-spot susceptibility; this paper presents the result of high temperature durability and thermal cycling testing and analysis for the selected diodes. During both the high temperature durability and the thermal cycle testing, there were some diodes with obvious performance degradation or failure in J-box 1 with bad thermal design. Restricted heat dissipation causes the diode to operate at elevated temperatures which could lower its current handling capability and cause premature failure. Thermal cycle with forward biased current to the diode, is representative of hot spot conditions, can impose a strong thermal stress to diode, and may cause failure for bypass diodes in some PV module that may be able to pass the present criteria of IEC 61215.

Experiments

Test samples(shown in fig.1 and fig.2) :

- 3 types of junction boxes for testing
- J-boxes were attached on mini laminate modules
- 3 diodes per j-box
- Diode rated current > 10A
- Thermocouples were bonded to diode cases

Data monitoring

- Measure forward and reverse characteristics of diodes before each thermal durability test
- Monitor current and voltage data of diodes and/or power supply
- Monitor case temperature of each diode

Test Procedure

- Test 1
  - Put the samples in chamber with controlled temperature of 50, 60, 75°C
  - Add forward current of 10A to bypass diodes
  - Monitor the bypass diode case temperature and forward voltage drop and current
  - 1000 hours
- Test 2
  - Chamber temperature cycled from -40° C to 85° C
  - 3 hours per cycle
  - Dwell time at both 85° C & -40° C are 10~30 minutes
  - Add forward bias current of 10A to diodes when the chamber temperature is higher than 25° C
  - One power supply is used for one J-box (3 power supplies).
  - 100 cycles
- Test3
  - Chamber temperature cycled from -40° C to 85° C
  - 3 hours per cycle
  - Dwell time at both 85° C & -40° C are 10~30 minutes
  - Add reverse bias voltage of 12V to diodes when the chamber temperature is higher than 25° C.
  - One power supply is used for one diode(9 power supplies).
  - 100 cycles
- Next step
  - Chamber temperature at 75°C
  - One hour of reversed bias (12 V) plus one hour of forward bias(10A) per cycle
  - 20 cycles

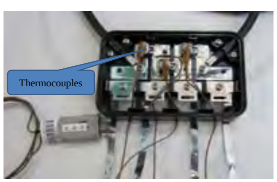


Fig. 1. Junction box sample for testing

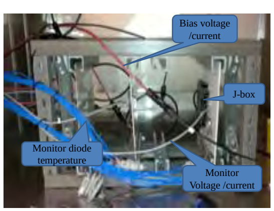


Fig. 2. Assembled testing samples in the chamber

Results

Test 1

High temperature endurance testing with forward biased current was applied to bypass diodes to assess diodes operating performance under long-term hot spot condition.

- Diodes temperature rise of 3 J-box during the testing(shown in fig.3 and fig.4) :
  - Box 1: Temperature rises of diodes 1-1 and 1-2 increased by 20°C . The highest diode case temperature reached 220°C when the chamber temperature was 60°C
  - Box 2: Temperature rises of diodes were very stable.
  - Box 3: Temperature rises of diodes 3-1, 3-2 and 3-3 increased slightly
  - Temperature rises of diodes decreased when ambient temperature increased.
  - Diode temperature rises of J-box 1 and 3 went up after restart testing.
- Diodes forward voltage of 3 J-box during the testing:
  - J-box 1: Voltages varied with testing time. Forward voltage of diodes 1-2 increased dramatically after restarted testing(Oct. 6), while voltage of diodes1-1, 1-3 decreased.
  - J-box 2: Voltages were stable
  - J-box 3: Voltages were stable
- No diode failed after the high temperature testing.

Note:

1. Temperature rise is the temperature difference between diode case and chamber
2. Diode 1-2, 2-2, 3-2 is the middle diodes of box 1, box 2 and box 3.
3. The temperature of middle one is highest in the box.

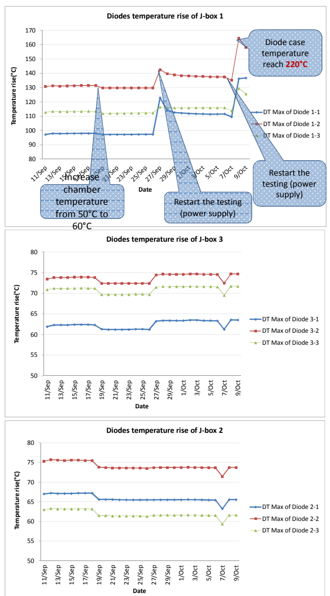


Fig. 3. Diode case temperature rise for 3 J-box during high temperature testing

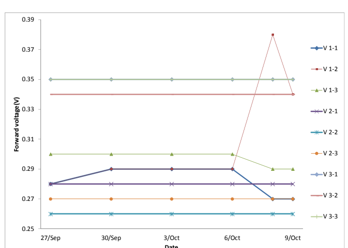


Fig. 4 Diodes forward voltage of 3 J-box during the high temperature testing

Test 2

Thermal cycle plus forward bias endurance testing was applied to bypass diodes to assess diodes reliability under thermal cycling caused by ambient temperature change combined with hot spot current flow.

Diodes case temperature during the testing :

- Box - 1: - 40 ~ 214°C
- Box - 2: - 40 ~ 158°C
- Box - 3: - 40 ~ 157°C

Diodes performance after the testing:

- Diodes forwards bias voltage of Box-1 increase dramatically after 40 cycles. Diodes of Box-1 totally failed after this testing.
- Reverse current(at reverse voltage of 10 - 16V) of diodes 3-2 (middle diode of box-3) and 2-2 increased by 10~20%.
- Diodes forward bias voltage of Box-2 remained steady
- Diodes forward bias voltage of Box-3 increased by 0.5V

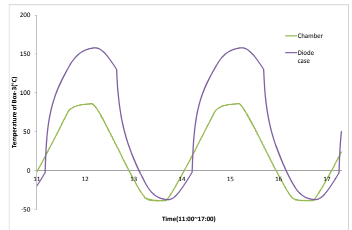


Fig. 5. Chamber temperature and diode case temperature of box 3 during diodes thermal cycle plus forward bias testing

Test 3

Thermal cycle plus reverse bias endurance testing was applied to bypass diodes to assess diodes reliability under thermal cycling caused by ambient temperature change without hot spot.

Diodes case temperature are very close to chamber temperature during the testing

Diodes performance after the testing:

- 12V reverse biased voltage was applied to diodes when the chamber temperature is higher than 25°C.
- Diode case temperature was close to chamber temperature.
- No failure or obvious degradation of diodes were observed during or after the test.

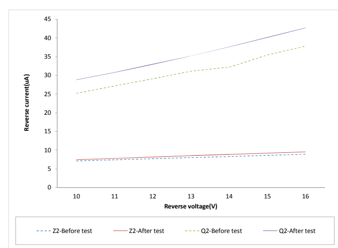


Fig. 6. Reverse characteristics of diodes 2-2(Q2) and diode 3-2(Z2) before and after diodes thermal cycle plus reverse bias testing

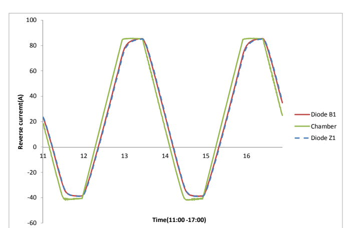


Fig. 7. Chamber temperature and diode case temperature of box 3 during diodes thermal cycle plus reverse bias testing

Discussion

To assess diodes thermal reliability of PV modules, three indoor tests were designed to simulate 3 types of diodes operating condition. The related test results were shown in above section.

High temperature endurance testing with forward biased current was applied to bypass diodes to assess diodes operating performance under hot spot condition. Mini modules with three types of junction boxes were put in chamber with controlled temperature. Forward biased current of 10A was added to bypass diodes; and the bypass diode case temperature and forward voltage drop and current were monitored during the testing. After 1000 hours' testing, though there is no abnormal appearance of diode were found and no appreciable changes in terms of reverse diode characteristics were detected, the temperature rise of worst diodes in one J-box increased by 25° C. The temperature rises of diodes in J-box 1 and 3 went up by 2-15° C and their forward voltage increased dramatically after cool down the diodes and restart testing, while that of J-box 2 was stable. Based on the test result above, we can find if the heat dissipation is not good, there is still some possibility of diodes degradation in PV modules in hot spot condition. When the diodes is forward biased with hot spot current flow, the forward current may make the diode hot enough for the dopants that create the N- and P-type areas in the diode to diffuse across the junction, wrecking the semi-conducting behavior that we rely on, and cause performance degradation.

Two types of thermal cycle testing were processed to assess the diodes' durability of thermal cycling stress caused by ambient temperature change with or without hot spot in PV modules. Three types of J-boxes were tested in chamber with cycling temperature range from -40° C to 85° C. For the first 100 cycles, forward biased current of 10A was applied to diodes when the chamber temperature is higher than 25° C. One of diodes totally failed with open circuit after the first 100 thermal cycles testing. The high temperature combined with thermal cycling will cause the diodes resistance increase and damage the PN junctions. For the second 100 cycles, -12V reverse biased voltage was added to diodes during the chamber temperature is higher than 25° C. The diodes case and junction temperatures were close to ambient temperature during the second 100 cycles test. And there was no failure or obvious degradation of diodes were observed during or after the test. The diodes performance of PV module is stable if there is no hot spot issue.

The diode performance is stable if the diode is reverse-biased with low diode temperature. However, the leakage current doubles every 10° C as the temperature increase, and eventually the current may reach a level where the heat dissipation within the junction is high enough for the junction temperature to run away. For the field operating condition, the PV modules may encounter momentary shading caused by cloud or bird, etc. The diodes in the modules will work under the condition of high temperature with hot spot current flow firstly when the shading is on the modules. Then the diodes will be reverse-biased in high temperature condition after the shading is gone. For next step, the experiments need be designed to access the diode thermal reliability under simulated the field condition of momentary shading .

Conclusions

Based on the test result above, we can find if the heat dissipation is not good, there is still some possibility of diodes degradation or failure in PV modules under hot spot condition. Thermal cycle condition with forward biased current to diode, really representative of hot spot conditions, can impose a strong thermal fatigue stress to diode, and may cause failure for bypass diodes of some PV module that may be able to pass present criteria of IEC 61215.

Acknowledgments

The authors thank Peter Hacke and Kent Terwilliger of the National Renewable Energy Laboratory for offering help on the experiments. The author appreciate Vivek S. Gade of Jabil's Photovoltaic and Certification Test Laboratory and Paul Robusto of Intertek for insightful comment for the testing result analysis. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

Reference

1. Barreiro, C., et al. *PV by-pass diode performance in landscape and portrait modalities*. in *Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*. 2011.
2. Ben-Menahem, S. and S.C. Yang. *Online photovoltaic array hot-spot Bayesian diagnostics from streaming string-level electric data*. in *Photovoltaic Specialists Conference (PVSC), 2012 38th IEEE*. 2012.
3. Bower, W.I., M.A. Quintana, and J. Johnson, *Electrical and thermal finite element modeling of arc faults in photovoltaic bypass diodes*. 2012. p. Medium: ED; Size: 33 p.
4. Al-Rawi, N.A., M.M. Al-Kaisi, and D.J. Asfer, *Reliability of photovoltaic modules II. Interconnection and bypass diodes effects*. Solar Energy Materials and Solar Cells, 1994. **31**(4): p. 469-480.

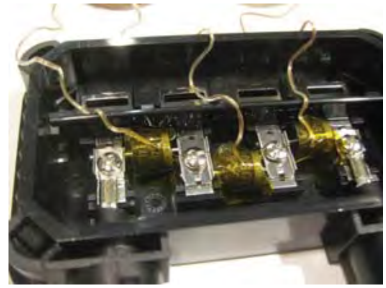
High Temperature Reverse By-Pass Diodes Bias and Failures

Jean Posbic, Eugene Rhee and Dinesh Amin
NREL PVMRW – February 2013

MEMC SunEdison

Problem Description

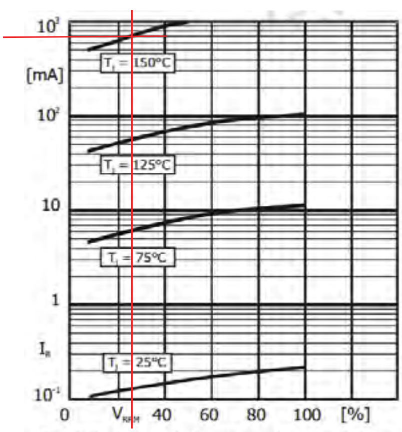
- By-pass diodes generally get "activated" during a shading occurrence in the field.
- For a 72-cell module with 3 by-pass diodes per module, the diodes are typically of the Schottky type and rated 40 to 45 V for maximum reverse voltage and 10 to 20 A for maximum forward current and maximum junction temperature of 150°C.
- Right after a shading occurrence and while the diode is still at high temperature, the diode goes into the normal mode where it sees the operating voltage of 24 cells or roughly 8 to 12 V and that induces a reverse leakage current that can exceed the diode reverse current rating at that temperature with the destruction of that diode most likely in the open mode, although shorted diodes have also been seen.
- We developed a very simple method to test diodes in a j-box or individually in the lab without the need for a sophisticated thermal chamber.



Simple Test Procedure

- 30 A 60 V power supply
- Thermo-couples and Fluke meter
- Connect diodes in forward mode and pass 12 to 15 A (note that the central diode always heats up faster)
- Wait until diodes temperature reaches 150°C
- Quickly reverse polarities and apply 10V per diode while reading the reverse current
- High current diodes fail quickly in a " run-away" mode; i.e. the hotter they get the more current they pass and so forth until the junction melts
- Lower current diodes cool down and stabilize safely at relatively low current.
- Tests were also done on individual diodes as well, outside the j-box with similar results

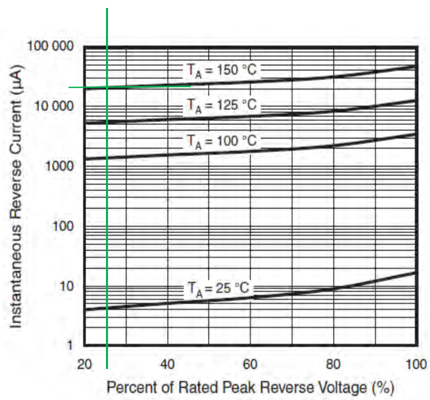
High Reverse Current Diode



Typ. instantaneous leakage current vs. rev. voltage

- Vr = 10V or 25% or Vrmax
- Ir is then 700 mA at 150°C
- P reverse is 7 W
- Diode exceeds 200°C and fails within seconds in the open mode (most of the time)
- A dozen diodes were tested under these conditions and all failed open

Low Reverse Current Diode



Typical Reverse Leakage Characteristics

- Vr = 10V or 25% or Vrmax
- Ir is then 20 mA
- P reverse is 0.2 W
- Diode cools down to less than 100°C within seconds and further down
- No problem with this type of diode

Standards and Certification

- **Field failures of by-pass diodes are most concerning when the diode(s) fail open due to shading conditions as the upcoming shading incident will undermine the cell(s) involved and may lead to cell(s) failure and other related safety problems**
- **An official test procedure needs to be incorporated into the international standards (performance, reliability and safety) and pass/fail criteria included**
- **At a minimum, choose the diodes that have the appropriate reverse characteristics**

International Electrotechnical Commission
Technical Committee 82 on Photovoltaics

PV Standards.
What IEC TC82 is Doing for You

By George Kelly, TC82 Secretary
solarexpert13@gmail.com
February 26, 2013

TC 82 Working Groups

WG1: Glossary

Task: To prepare a glossary of terms relevant to PV.

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 photovoltaic system design and maintenance.

WG6: Balance-of-system components

Task: To develop international standards for BOS components for PV systems.

WG 7: Concentrator modules

Task: To develop international standards for photovoltaic concentrators and receivers.

WG 8: Solar cells and wafers (new group to be formed in 2013)

Task: To develop international standards for photovoltaic cells and wafers.

JWG 21/TC 82 Batteries

Task: To draw up standard requirements 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 Standards

Standards published by TC 82 can be found on at this link:
http://www.iec.ch/dyn/www/f?p=103:23:0::::FSP_ORG_ID,FSP_LANG_ID:1276,25

Or go to www.iec.ch and search for TC 82 dashboard.

Select IEC - **TC 82 Dashboard** > Scope and click on Projects/Publications. The TC 82 Work Program will be listed. Click on **Publications** to view all standards that have been published to date.

The following pages list some of the New Work Item Proposals and projects for improvement of existing standards that are presently underway. Figures in red indicate expected publication dates.

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

IEC 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 2013

IEC 62759-1 Ed. 1.0 Transportation testing of photovoltaic (PV) modules - Part 1: Transportation and shipping of PV module stacks 2013

IEC 62782 Ed. 1.0 Dynamic mechanical load testing for photovoltaic (PV) modules 2014

TC 82
WG2 (cont.)

IEC 62775 Ed. 1.0 Cross-linking degree test method for Ethylene-Vinyl Acetate applied in photovoltaic modules - Differential Scanning Calorimetry (DSC) 2014

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 2014

TC 82
WG2 (cont.)

IEC 62790 Ed. 1.0 Junction boxes for photovoltaic modules - Safety requirements and tests 2014

IEC 62852 Ed. 1.0 Connectors for DC-application in photovoltaic systems - Safety requirements and tests 2014

PNW 82-685 Ed. 1.0 System voltage durability test for crystalline silicon modules - Qualification and type approval 2013

PNW 82-689 Ed. 1.0 Test method for total haze and spectral distribution of haze of transparent conductive coated glass for solar cells 2014

PNW 82-690 Ed. 1.0 Edge protecting materials for laminated solar glass modules 2014

PNW 82-691 Ed. 1.0 Test method for transmittance and reflectance of transparent conductive coated glass for solar cells 2014

NWIP Comparative testing of PV modules to differentiate performance in multiple climates and applications – Part 1: Overall test sequence and method of communication 2014

TC 82
WG3 and WG6

Working Group 3

IEC 61829 Ed. 2.0 Crystalline silicon photovoltaic (PV) array - On-site measurement of I-V characteristics 2013

IEC/TS 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

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 2014

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 2015

TC 82
WG7 and WG8

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

Working Group 8

New WG to be formed during 2013 – **seeking a volunteer** to be the Convenor

TC 82
Joint Working Groups

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] 2013

Solar America Board for Codes and Standards – 2013 Progress Update

Larry Sherwood, Solar ABCs Project Administrator

Fire Classification Rating Testing of Standoff-mounted Photovoltaic Modules and Systems

(Publication due in Summer 2013)

Can the presence of a rooftop PV system contribute to the intensity or spread of a structural fire? This is the reason for the fire classification rating of PV modules and systems and was the subject of a series of laboratory tests that will be reported in this report. These tests were designed specifically to evaluate how PV and roof material interact as a system during exposure to fire and burning material.

From a safety perspective, the goal is that the installation of a standoff-mounted PV system does not degrade the fire class rating of the roof assembly. Tests conducted at the UL Fire Test Laboratory show that the fire class rating of the PV module (performed to UL 1703) is not a predictor of the whether or not the fire class rating of the PV module and roof assembly as a system is changed from the fire classification rating of the roof assembly. Thus the stakeholders and investigation team decided to pursue the development of a new fire classification test for the PV module and roof assembly as a system. UL conducted many additional tests to develop and validate this new fire classification rating test.

The proposed new fire classification test procedure is a significant change from the current PV module fire classification test procedure. In the new procedure, the module is tested mounted over representative roof covering systems and the performance of the entire system is the basis for the fire classification rating of the PV module with mounting system. In this way, the new PV fire classification test is a measure of impact of the photovoltaic installation on the fire classification rating of the roof covering system and provides a more logical rating than the old PV rating test. This new test procedure is current ly in the review and approval process with the UL 1703 Standard Technical Panel.

A Literature Review and Analysis on Accelerated Lifetime Testing of Photovoltaic Modules

(Mani) GovindaSamy TamizhMani, Joseph Kuitche, Arizona State University
(Publication due Spring 2013)

One of the major technical barriers for photovoltaic (PV) diffusion and to access project financing is the technology risk: concern that a technology will underperform (durability issue) or become obsolete prematurely (reliability issue). The purpose of accelerated testing (AT) is to assess the reliability and durability of products by inducing failures and degradation in a short period of time using accelerated test conditions much more severe than the actual field operating conditions while replicating the actual field failure mechanisms. This report provides a background literature review and analysis on the field failures, degradation and the available accelerated testing methodologies. Based on this review report and the other published literature, the research teams may develop accelerated testing protocols which could potentially be converted into an accelerated comparative testing and/or lifetime testing protocol/standard by one or more standards developing organizations or international/national industry organizations. In order to generate this report, a large number of published papers related to PV module reliability and durability were collected and systematically analyzed.

Additional Reports due by Summer 2013

- Examination of Ground-Fault Blind Spot with Recommendations for Mitigation
- PV Blind Spot Electrical Simulations
- Maintenance and Inspection Guidebook
- Validation of IEC 61853, Part 2
- Validating PV Module Durability Tests
- PV Generation: Temporary Overvoltage Impact and Recommendations
- PV Module Grounding: Addendum Report on Corrosion Testing

Photovoltaic Module Grounding: Issues and Recommendations

Greg Ball, BEW Engineering
Timothy Zgonena, Christopher Flueckiger, Underwriters Laboratories Inc.

This report provides the PV industry with practical guidelines and procedures for module grounding in the overall context of system grounding.

General recommendations for ensuring proper grounds based on field experience and feedback received throughout the course of this study:

•Follow through with proposed changes to the existing standards to improve the method and quality of ground connections.
•Elicit additional industry feedback from the accelerated aging test study to determine if and how these or similar tests might be incorporated into standard testing.
•Be aware of and make use of the new and expanded set of channels for listing module grounding equipment.
•Be aware of the principles of module frame grounding, the type of faults that may occur, and the implications for safety and ground system design.

- Follow the specific design and installation recommendations enumerated in this report, such as using proper materials and components, following manufacturer instructions, using torque wrenches to ensure proper tightening of connections, and avoiding connections of dissimilar metals that lead to corrosion, among many others.

Photovoltaic System Grounding

John C. Wiles, Jr., Southwest Technology Development Institute, New Mexico State University

This report provides the PV industry with practical guidelines and procedures to ensure reliable PV system grounding as well as the ongoing safety of these systems.

The report explains what grounding is and defines different types of grounding. It also describes existing *National Electrical Code® (NEC®)* grounding requirements in some detail, explains the basics of grounding PV equipment and systems, and notes the U.S. organizations responsible for developing and publishing grounding and safety standards.

In addition, the report discusses grounding requirements for equipment such as microinverters and AC PV modules, and clarifies the differences between PV system and conventional electrical power systems (utility, generator, or battery sourced) grounding requirements. Finally, it includes an explanation of utility and *NEC* grounding requirements.

A Proposed Standard for: Nameplate, Datasheet, and Sampling Requirements of Photovoltaic Modules

Govindasamy TamizhMani, Joseph Kuitche, Arizona State University
Alex Mikonowicz, PowerMark Corporation

Solar ABCs recommends that the following requirements be included in required standards for PV modules:

•After accounting for the light induced degradation, the measured average power shall be equal to or higher than the nominal nameplate power rating at STC and no individual module power shall be more than 3% below nominal.
•At least one module closest to the nominal rated power shall be measured at the other four rating conditions given in IEC 61853-1 standard (NOCT, LIC, HTC, and LTC).
•Nameplates and datasheets shall contain at least the minimum information specified in the Solar ABCs standard.
•The number of samples used to calculate the measured average power shall be determined using the method identified in the Solar ABCs standard.

Selected Reports - All Reports Available from www.SolarABCs.org

U.S. DOE contract number DE-FC36-09GO17034/A001

The US TAG

"What is it?"

"Why should I care?"

“**What is It?**”

The term **TAG** stands for “**Technical Action Group**”

It is a group of experts from businesses, Government, Financial Interests, Universities, Research Laboratories from around the world that have a common interest in the betterment of a need or philosophy.

“Why should I care?”

The need to be involved or “care” is because the Group originates, refines, determines performance, acceptance, applicability, and heavily influences standards that are established to unify the behavior of the idea or in this case a “**product**” called **Photovoltaic’s**.

Within the US, the Photovoltaic Technical Action Group or TAG is assigned to the American National Standards Institute called **ANSI**, headquartered in Washington DC and New York City, who act as the official voice of the

US interests within the International Electrotechnical Commission (**IEC**) which is part of the International Standards Organization (**ISO**) headquartered in Geneva Switzerland. In the case of Photovoltaic's the TAG is part of an IEC Technical Committee number 82.(**TC 82**)

"What does being a member of the US TAG do for me or my company?"

Joining the US TAG allows you to initiate new items to be considered for standardization or the creation of standards. More importantly it allows you to review and input to standards under consideration and contribute to their technical accuracy and applicability.

“What are my Responsibilities?”

Your responsibilities as a TAG member are to read and consider new proposals for standards, read and provide improvements for standards in the process of achieving acceptance within the IEC TC 82 and eventually the World community.

“What is the Cost to be a member?”

At present, the cost of joining the US TAG is $295.00 dues that are paid to ANSI as part of their operating cost. (Unlike other countries, the US Standards organizations are funded through the collection of dues and are not directly supported by the Government.)

"How do I join the US TAG?"

You may join the US TAG by contacting one or all of the following people, and express your interest with a short description of your expertise, and provide your "official", total contact information. George, Howard, and I will inform Mr. Kevin Sullivan of ANSI to send you a $295.00 invoice. Upon payment of the invoice you will receive a user name and a temporary password to be able to use any of the website materials

Our contact information is:

Alex Mikonowicz, US TAG TA or Manager
AlexMikonowicz@Powermark.org
George Kelly, TC 82 Secretary and US TAG Secretary.
solarexpert13@gmail.com
Howard Barikmo, assistant US TAG Secretary.
hbarikmo@gmail.com

All of us will be happy to assist you.

Infrared Thermography (IRT) Working Group

Scott McWilliams

U.S. Photovoltaic Manufacturing Consortium (PVMC)

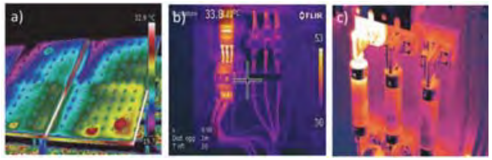
Infrared Thermography

Infrared Thermography (IRT) has been demonstrated as a tool that can be effectively used to improve the installation, maintenance and reliability of Photovoltaic (PV) arrays. IRT has multiple applications for testing components in a PV system:

- Modules
  - hot spot detection
  - shading events
  - cleaning cycles
- Power electronics
  - inverters
  - power optimizers
- Connector verification
- Predictive Maintenance (PdM)

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM

PVMC ™



Photos courtesy FLIR Commercial Systems B.V.

IRT applications exist for PV modules (a), wiring (b) and electronics (c)

Program Focus

PVMC's IRT working group will develop:

- Applications
- Standards
- Best known methods (BKM)
- IRT curriculum/training

specifically tailored towards Photovoltaic systems.

www.uspvmc.org

IRT Working Group

A Working Group has been formed as part of the PVMC's Balance of Systems (BOS) and Power Electronics program.

Potential working group members are being actively recruited, and will include:

- IR camera manufacturers
- Module manufacturers
- Power electronics manufacturers
- BOS supply chain
- System integrators/installers
- Utility maintenance personnel

For further information about joining the PVMC IRT working group, please contact:

Scott McWilliams
(518) 649-1047
scott.mcwilliams@uspvmc.org

PVMC is funded by the DOE under agreement number DE-EE0004947

Connector Issues in Reliability*

Juris Kalejs, Jeff Gadomski and Zach Nobel
American Capital Energy, Lowell, MA 01854

Abstract: We have extended our studies on wiring failures in the field reported at this workshop last year to more extensive examination of connector issues. New aspects of connector deficiencies are being reported in our PV field installations after relatively short outdoor exposure of 2-4 years. We examine factors which may be responsible for these failures and existing standards for their use. We find that there is a general lack of guidelines on connector design in wiring terminations both for module connections and at the Junction box inserts, or for handling during installations.

Examples of wiring failures after 2-4 years field exposure

1. Melted connector joint in wiring connecting two modules

2. Connector failures at junction box

3. Gap of 2-3 mm opens up between mating connectors without any obvious external damage, external stress or fracture in latches

Connector failure manifestations

- **Failures are caused by field conditions which combine extreme variable excursions:**
  - **mechanical forces**
  - **temperature excursions**
  - **applied voltage**
- **Types of failures may exploit poor design:**
  - **overheating in pin joint likely caused by misalignments, poor contacts**
  - **broken latches**
  - **separation of two mating parts without obvious mechanical damage or heating**
- **Connector design impact is not obvious in failures**

Potential issues/causes in connector failures:

- Pin misalignments, metal-to-metal pressure contact mechanism failures
- Pin O-ring weathering
- Inadequate stress safety factors in latch design
- Dirt/dust ingress in latch and pin areas during shipping, warehousing and installation; some connector manufacturers recommend capping of pins, but module manufacturers do not pass on options
- Lack of uniform installation procedures to protect against stress on wiring and latches in the field
- Mixing of compatible connector parts from different manufacturers

Major questions to be answered:

Are failures a result of:
- fundamental design flaws,
- inadequate certification testing, which may test for module but not electrical component durability
- systematic deficiencies in manufacturing/assembly practices, or
- lack of proper handling or installation methodology

Conclusion: There appears to be a critical gap in connector qualification, durability testing and installation procedure guidelines

* Email: jkalejs@americancapitalenergy.com ; Does not contain confidential information

Summary of 3rd International PV Module Quality Assurance Forum

Hiroko Saito (PVTEC) &
Masaaki Yamamichi (AIST) &

1

International Pre meeting & Welcome Dinner

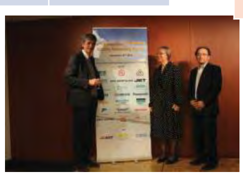
November 26th

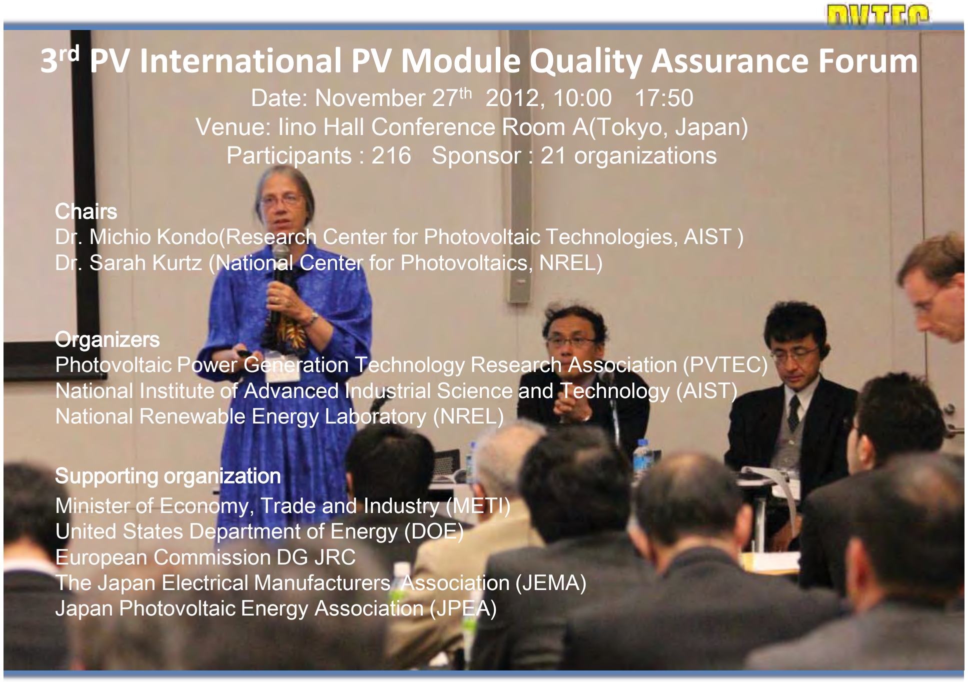
International Pre Meeting

Task Group	Attendees
Task Group 1	13
TG2,3,5 Joint	26
Task Group 4	9
Task Group 8	6
Total	54

Welcome Dinner

Category	Attendees
Invited Guest	5
Sponsor	36
TG member	3
Organizer(PVTEC)	5
Total	48





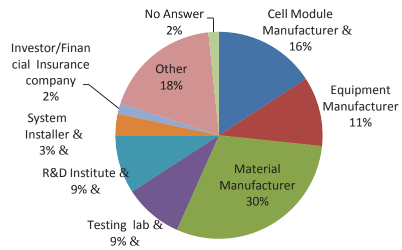
PVTEC
Photovoltaic Power Generation Technology Research Association

Program Agenda

10:00	Opening remarks	Dr. Michio Kondo(AIST) / Dr. Sarah Kurtz(NREL)
10:10	Welcome Speach	Ryoji Doi (METI)/Jeffrey Miller(DOE/US Embassy)/Dr. Hiromu Takatsuka(PVTEC)
10:40	**Session I. Special Talk**	
10:40	Quality Requirement for PV Systems	Dr.Heinz Ossenbrink(EU_DG_JRC)
11:10	The True PowerTM – Advanced Combination of extended indoor & outdoor testing of PV modules & system across various climate zones	Dr.Thomas Reindl(SERIS)
11:40	Outline of newly started Japanese FIT program	Keisuke Murakami(METI)
12:10	**Session II JIS Q8901 and Bankability**	
12:10	JIS Q8901 and its certification	Katsuaki Shibata(JET)
12:30	"Bankability" of PV project	Teiko Kudo (SMBC)
12:50	Q&A	
13:00	Lunch Break	
14:00	**Session III Technical session**	
14:00	PID and correlation with field experience	Dr. Juliane Berghold (PI-Berlin)
14;20	PID Testing—	Dr. Tadanori Tanahashi(Espec)
14:40	PV Module Quality Assurance	Dr. Neelkanth Dhere(FSEC)
15:00	Discussion	
15:20	Coffee Break	
15:40	**Session IV Task Group update**	
15:40	Update of QA Forum efforts and its future perspective	Dr. Sarah Kurtz(NREL)
16:00	Update of TG1-5 & 8	Japan TG leaders
17:00	Open discussion	All
17:40	Closing Remarks	Dr. Michio Kondo(AIST)

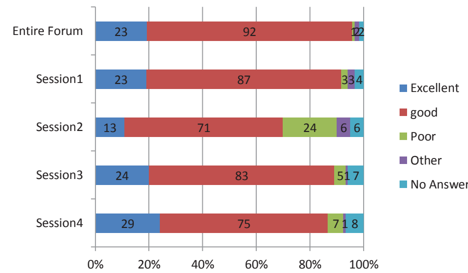
Attendee Survey - 1 –

120 returns



1.Categry of organization

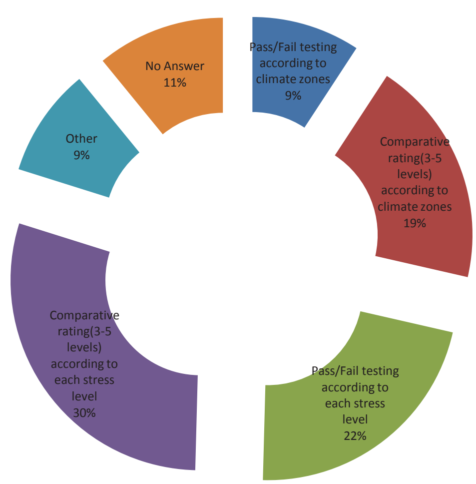
2.Evaluation of each session



Attendee Survey - 2 -

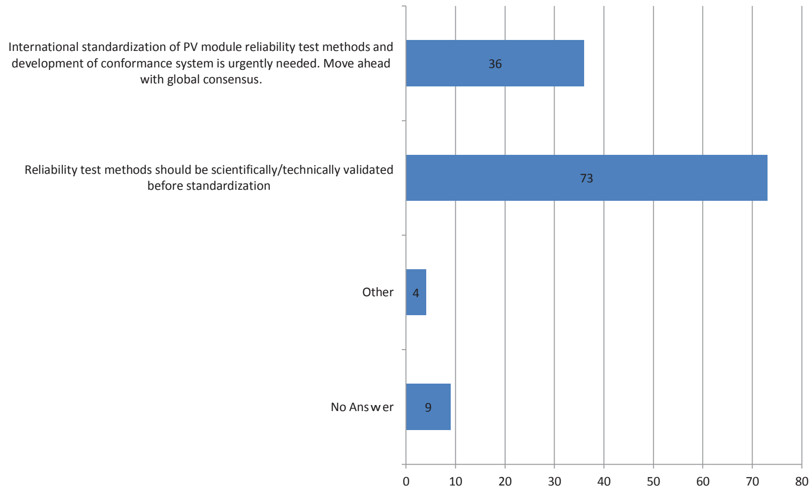
3. Which of the following testing/rating system is more preferable?

Pass/Fail testing according to climate zones	11
Comparative rating(3-5 levels) according to climate zones	23
Pass/Fail testing according to each stress level	26
Comparative rating(3-5 levels) according to each stress level	35
Other	11
No Answer	13



Attendee Survey - 3 -

3. Comment on International standardization for PV module reliability test methods and development of relevant conformance system.



Discussion Summary – 1 -

□TG1・JISQ8901 Terrestrial photovoltaic (PV) modules-Requirement for PV reliability assurance system(Design, Production and Product Warranty)

JIS*: Japanese Industrial Standards

English version available at

http://www.webstore.jsa.or.jp/webstore/Com/FlowControl.jsp?lang=en&bunsyoId=JIS+Q+8901%3A2012&dantaiCd=JIS&status=1&pageNo=0

- More clear definition of "functional life time" and measures to assess its validity desired.
- Consistency with IEC / ISO standard is a future challenge.

□Tests for PV module reliability(Efforts of TG2-5)

- Indoor test results should align with actual field failure mode. Applying more stress itself does not make sense.
- Collection of field data from different climate zones/application is required to develop climate zone/application specific test methods.
- Acceleration factor of each test
- 61215/62646 with some minor modification could be used to assess PV module reliability in many climate zones. If so, it could be a fast and cost effective solution.
- Reliability should cover not only module power output performance but also safety.

Discussion Summary – 2 -

☐ PV Module Rating system

- Major module manufacturers may be driven to make a single product which satisfy requirements for all climate zones/application, resulting in higher cost.
  - ✓ mass-production benefits
  - ✓ difficulty to forecast each regional demand, risk of excessive inventory
  - ✓ efficient R&D, Certification cost/time
  - ✓ product performance warranty, uncertainty of final destination of the product
- PV is still new industry. Every company is trying to differentiate their products for successful market development. Rating information will help their efforts
- Rating will provide module makers with good information in developing their & product portfolio strategy, e.g. many different types modules for each climate & zones, focus on some specific market, single product to fit all, and, etc.
- Currently proposed rating system is tentative one and should be revised by further feedback from users including investors and finance institution.
- Rating by climate zone is preferable, however, 61215+(steroid) can be considered as a realistic first step
- Incentives may be offered for High rating (High quality) product e.g. lower & insurance rate &
- Vote for support of rating system by show of hands ….Favor 74 vs. Against 44

PVTEC (Photovoltaic Power Generation Technology Research Association)

✓Established at 1990 '

✓67 member organization (as of march 1st of 2013) '

Asahi Glass Co.,Ltd.	Denki Kagaku Kogyo Kabusiki Kaisha	Hitachi Chemical Co.,Ltd.	Kyodo Printing Co.,Ltd.	Nitto Denko Corporation	Sumitomo Bakelite Co.,Ltd.	Toshiba Mitsubishi-Electric Industrial Systems-Corporation
Asahi Kasei Corporation	Dexerials Corporation	Iwasaki Electric	Lasertec Corporation	NPC Incorporated	Sumitomo Seika Chemical Co.,Ltd	
C. .I. Kasei Co.,Ltd.	DIC Corporation	Japan Electrical Safety & Environment Technology Laboratories(JET) TG4 Leader	Lintec Corporation	Okura Industrial Co.,Ltd.	Tanaka Holdings Co.,Ltd.	Toyo Alminum K.K.
Central Research Institute of Electric Power Industry	Dow Corning Toray Co.,Ltd.	JX Nippon Oil & Energy Corporation	Mitsubishi Chemical Corporation	Onamba Co.,L t d	Teijin DuPont Films Japa Limited	Toyo Ink SC Holdings Co.,Ltd.
Choshu Industries Co.,Ltd.	Du Pont Kabushiki Kaisha	Kaneka Corporation	Mitsubishi Heavy Industries, Ltd.	Panasonic	The National Institute of Advanced Industrial Science and Technology (AIST) TG3 Leader	TOYOBO Co.,Ltd.
Dai Nippon Printing Co.,Ltd.	Du Pont-Mitsui Polychemicals Co.,Ltd.	Kikusui Electronic Corp.	Mitsubishi Plastics Inc.	SAES Getters SPA	Three Bond Co., Ltd.	UL Japan Inc.
Daicel Corporation	EKO Instruments Co.,Ltd.	Kobelco Research [illegible]c.	Mitsubishi Rayon Co.,Ltd.	Saga Prefecture	Tokyo Electron Ltd.	ULVAC Inc.
Daido Steel Co.,Ltd	ESPEC Corp. TG2 Leader	Komatsu NTC Ltd.	Mitsui Chemicals Inc.	Sekisui Chemical Co.,Ltd.	Toppan Printings Co.,Ltd.	Yocasol Inc.
Daikan Chemical Co.,Ltd.	Fuji Electric Co.,Ltd.	Kuraray Co.,Ltd.	Nippon Sheet Glass Co.,Ltd.	Sharp Corporation TG1 Leader	Toray Engineering Co.,Ltd.	
Daikin Industries Ltd.	Fujifilm Corporation	Kyocera Corporation	Nissan Chemical Industries Co.,Ltd.	Shin-ei Electronic Measuring Co.,Ltd.	Toray Industies Inc. TG5 Leader	

More than 20years history established broad network in Japan.
PVTEC is providing platform for QA taskgroup activities.

Degradation Study of the Peel Strength of Mini-Modules under Damp Heat Condition

Dan Wu, Jiang Zhu, Tom Betts, Ralph Gottschalg*

Centre for Renewable Energy Systems Technology (CREST), School of Electronic, Electrical and Systems Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK

Abstract This paper presents the degradation study results of adhesion strength between backsheet and encapsulant for a commercial mini-module. A concept of environmental dose is established to quantify the cumulative stress suffered by PV module. A degradation model for the adhesion strength is developed and the activation energy is obtained. Outdoor prediction example is given based on environmental data in Loughborough and Denver.

1

Experiment

Accelerated tests were conducted in environmental chamber at four different damp heat conditions.

T \ RH	85%	65%
95ºC	X	
85ºC	X	X
65ºC	X	

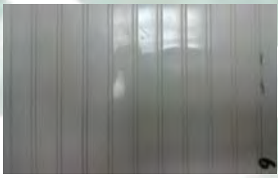


Fig. 1: Mini PV module after laser cutting. 100mm x 120mm, frameless P-Si

The backsheet of PV module is cut by laser into several strips (See **Fig. 1**). Laser is a quick and precise cutting method with accurate control of cutting depth. Each of the strips is peeled off using a specific peel test machine before and after certain time intervals during ageing (See **Fig. 2**). The peel angle is 90º and the peel speed is 50mm/min. Visual detection is also conducted after removal from chamber each time.

Fig. 2: Peel test

2

Degradation Results

Several types of defects are observed after visual inspection. The most severe ones are shown in **Fig. 3**.

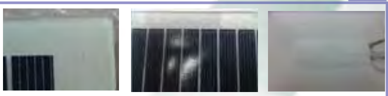


Fig. 3. Visual detection resutls with bubble near electrode (left), moistrue ingress (middle) and edge/ corner delamination (right)

Adhesion strength results are plotted in **Fig. 4** together with the standard deviation of the results for each sample (**Fig. 5**). The strength can be modelled by following equation:

$$S = S_0\, e^{-\left(\frac{t}{t_{del}}\right)^{\beta}}$$

Where S is adhesion strength at time t, S_0 is the strength without degradation, β and t_{del} are assumed to be function of stress levels having an influence on degradation slope which need to be further investigated to understand the degradation behaviour.

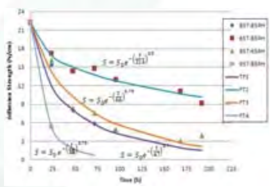


Fig. 4: Adhesion strength vs. time at different damp-heat conditions.

Both T and RH are accelerators of the degradation. The rate of T acceleration is faster than that of RH.

Acceleration factors around 3-6 in testing time is achieved for the other three conditions compared with that at 65ºC T and 85% RH.

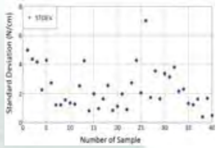


Fig. 5: Standard deviation for each module with ten strips

3

Kinetic Stress Model

An empirical kinetic model is developed by assuming that the rate of adhesion degradation is proportional to moisture concentration at the interface of backsheet / encapsulant and the reaction rate constant is Arrhenius dependent. It can be expressed as following:

$$\frac{\Delta S}{\Delta t} = R_D \propto f\,(RH)\, e^{-\frac{E_a}{RT}}$$

Where f (RH) is a function of relative humidity; Ea is activation energy, R is gas constant (8.314J/K·mol) and T is absolute temperature in kelvin.

For the first step, f(RH) is assumed to be proportional to RH in the air:

$$\frac{\Delta S}{\Delta t} = R_D \propto RH \cdot e^{-\frac{E_a}{RT}}$$

A concept of "stress dose" is developed for the quantification of accumulative stresses (**Fig. 6**) which is actually the right part of the above formula.

Ea need to be obtained which determines the acceleration factor.

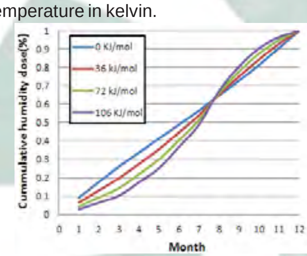


Fig. 6. Relative humidity dose in Loughborough with different Ea values

4

Arrhenius behaviour and Ea

A linear relationship can be obtained by taking natural logarithm of R_D and $\frac{1}{T}$.

$$\ln R_D = -\frac{E_a}{R}\frac{1}{T} + \ln(k \cdot RH)$$

Ln R_D vs. $\frac{1}{T}$ plot is shown in **Fig. 7.** at constant RH of 85% but varying T of 95ºC, 85ºC and 65ºC. A linear line is observable, allowing Ea to be calculated:

$$-\frac{E_a}{R} = \text{slop} = -6202.4$$

$$E_a \cong 51\ KJ/mol$$

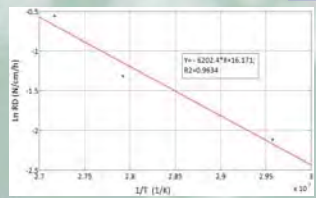


Fig. 7: The relationship between Ln R_D and the reverse of temperature

A linear relationship is obtained by plotting the changes of adhesion strength and temperature dose ($e^{-\frac{E_a}{RT}} \cdot \Delta t$) (**Fig. 8**). This proved the linear proportional dependent of R_D on RH.

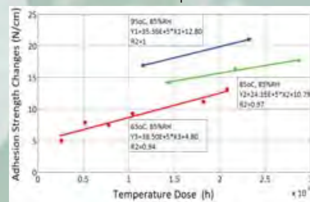


Fig. 8: Changes of adhesion strength vs. temperature dose

5

Outdoor & Indoor Prediction

Outdoor exposure time to achieve equivalent indoor degradation can be calculated as following:

$$\Delta t_{out} = \frac{RH_{in}\exp(-\frac{E_a}{R\,T_{in}})}{RH_{out\_eff} \cdot \exp(-\frac{E_a}{R\,T_{out\_eff}})}\ \Delta t_{in}$$

Effective T and RH for outdoor is obtained (example in **Fig. 9**):

$$\sum (RH_{out}\ e^{-\frac{E_a}{RT_{out\_eff}}}) = \sum RH_{out} \cdot e^{-\frac{E_a}{R\,T_{out}}}$$

$$\sum RH_{out\_eff} \cdot e^{-\frac{E_a}{R\,T_{out}}} = \sum RH_{out} \cdot e^{-\frac{E_a}{R\,T_{out}}}$$

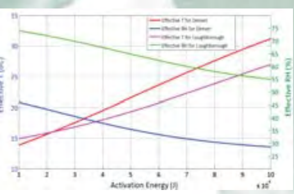


Fig. 9: Effective temperature and relative humidity in Denver and Loughborough

The subscript of out and out_eff represent measured and effective value for T & RH.

Module T need to be transformed from ambient temperature Tamb:

$$T_{mod} = T_{amb} + \frac{(NOCT-20)\times G}{800}$$

NOCT is Nominal Operating Cell Temperature. 47º is taken in this study.

Different Ea:

Exponential increase of outdoor time (**Fig. 10**). (no other stresses induced degradation is assumed)

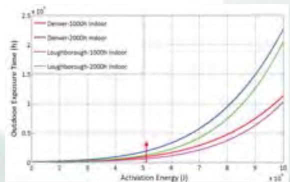


Fig. 10: Corresponding outdoor exposure time at Denver and Loughborough for an indoor exposure of 85ºC and 85%RH

6

Conclusions and Future Work

Peel test at different stress levels are conducted for commercial mini-modules. An example of the result is shown in **Fig. 11**.

A kinetic model for adhesion strength degradation between backsheet and encapsulant of PV module is established with an Arrhenius temperature acceleration and linear proportion of relative humidity.

Activation energy is obtained for the mini-module enabling outdoor prediction.

Future work will focus on analysing the effects of relative humidity on degradation model and how the moisture degrade the strength. More testing conditions are needed to improve accuracy of the fitting results. Delamination prediction will be conducted with cooperation of the University of Nottingham in UK.

As peel test is influenced by factors like mechanical property of polymer, geometry of strips, peel speed, peel angle etc. The mechanics of peeling are also going to be investigated.

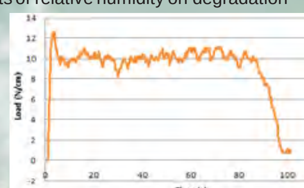


Fig. 11: A peel test result

CREST

***Corresponding author: Dan Wu**
Tel.: +44 1509 635318, Fax: +44 1509 635301,
Email: D.Wu@lboro.ac.uk

Loughborough University

Encapsulant based solution to Potential Induced Degradation of Photovoltaic Modules *

Kumar Nanjundiah, John Naumovitz, Michael White, Nichole Nickel, Tom Burns

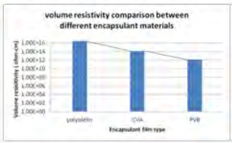
The Dow Chemical Company

1605 Joseph Drive, Midland, MI 48642, USA

Introduction

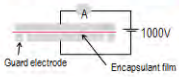
In solar power installations, modules made of individual solar cells are connected in series to achieve desired supply voltage. The module frames are also grounded to prevent electrical shock hazards. The large potential created by this architecture between the ends and ground has been shown to cause small leakage currents across the insulators protecting the cells. This leakage current over time has been associated with reduced power output from the system. This phenomenon has been called potential induced degradation (PID). Accordingly, materials used as the insulators protecting the cells become extremely important in designing PID resistant modules. In this study, electrical properties of encapsulants (insulators) made from ethylene vinyl acetate (EVA) and polyolefins (ENLIGHT™) are evaluated and compared. Accelerated testing of PID on single and multiple cell modules made with different encapsulant films at elevated temperatures are related to the electrical properties of the films. ENLIGHT™ films show orders of magnitude higher volume resistivity compared to EVA films. It is also seen that the resistivity over broad temperature range is essential to minimize the effect of PID.

Electrical properties



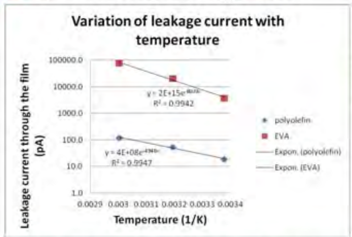
Sample	Encapsulant Film Thickness (micron)	WVTR @ 38°C
ENLIGHT™ Polyolefin Encapsulant Film	457	3.3
EVA-based Encapsulant Film	457	34
PVB-based Encapsulant Film	457	84

PO films show two orders lower leakage current compared to EVA films



Sample	Temp. Tested, C	ELECTRICAL Volume Resistivity (ohm cm)	Leakage Current (picoamp)
PO	23	2.64E+16	19
	40	9.47E+15	52
	60	4.12E+15	121
EVA	23	1.32E+14	3795
	40	2.48E+13	20243
	60	6.45E+12	77635

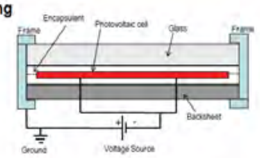
Arrhenius factor for Leakage Current



Arrhenius factor
EVA – 0.7 eV
Polyolefin – 0.42 eV

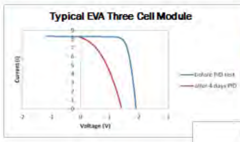
The slope is 1.5X higher for EVA suggesting EVA film is more prone to current leakage than PO film through the encapsulant with increase in temperature

PID Testing

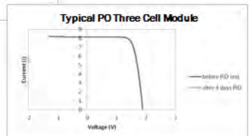


- Prepare single cell modules with MC 4 connectors and junction boxes
- Flash them to get baseline power, IV data and get electroluminescence image of the module
- Place them in the oven at 60C and 85% RH and apply -1000V to the cells with respect to the frame
- Age for 96 hours with voltage applied
- Flash the modules to check for loss of power and do EL measurements to look for failures

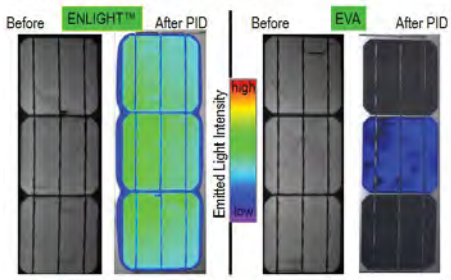
PID Test Results



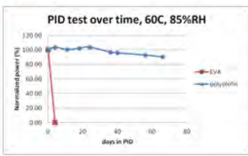
Module	Power loss after PID
EVA based	> 60%
PO based	< 1%



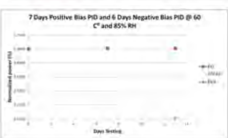
Electroluminescence Measurements

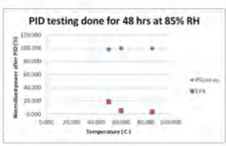


PID continued..



PID testing over 2 months shows ~10% power drop for Polyolefin with EVA based modules showing >90% power drop in 4 days





PID continued..

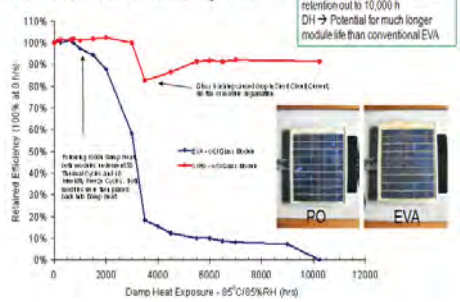
Even with PID resistant cells – severe conditions can lead to power drop

Encapsulant film	7 days under water @RT	85C, under water, 7 days	85 C, dry, 7 days
ENLIGHT™ PO	-0.9%	-0.7%	-1.8%
EVA	-2.3%	12.0%	7.5%

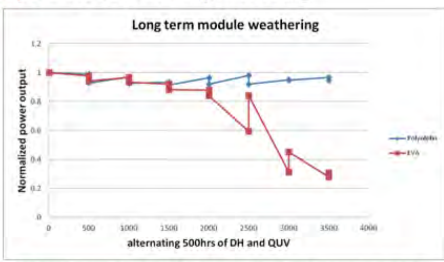
Negative sign means power gain compared to before PID test

Extended Module Reliability Data

PO module still shows 90% power retention out to 10,000 h DH → Potential for much longer module life than conventional EVA

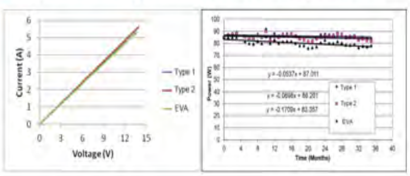


Exposure to QUV and Damp Heat testing



PO based module retains power during alternative cycling of damp heat and UV exposure over 7000hrs of total exposure

Long-term Durability of Modules with Dow Encapsulant films



Module type →	Dow Prototype 1	Dow Prototype 2	EVA
Degradation Rate (%/ year)	0.74	0.97	2.46

The power of EVA modules drop 2X compared to the PO film modules

Summary

- PID has been shown to be a significant issue in crystalline silicon modules in the field
- There have been solutions suggested to the solve the issue by changing the coating on solar cells or changing the grounding configuration
- In this work, we present an approach by using polyolefin based encapsulant in place of EVA which does not lead to any change in the type of cells used or the installation process
- It was found that electrical insulation resistance and lower water vapor transmission are required to prevent ion migration and PID
- The ENLIGHT™ Polyolefin encapsulant film provides two orders higher volume resistivity and one order lower water vapor transmission rate which in turns helps modules resist PID.

2013 Photovoltaic Module Reliability Workshop
NREL, Golden, CO
February 26–27, 2013

Study on PID resistance of HIT® PV modules

Tasuku Ishiguro[1], Hiroshi Kanno[1], Mikio Taguchi[1]
Shingo Okamoto[2]
[1] Energy Research Center, Energy Company, SANYO Electric Co., Ltd.
[2] Solar Business Unit, Energy Company, SANYO Electric Co., Ltd.
Phone: +81-78-993-1018, Fax: +81-78-993-1096, e-mail: ishiguro.tasuku@jp.panasonic.com

Motivation

1. For increasing request in reliability, it is important to demonstrate that high-efficiency HIT module shows high PID resistance as originally designed.
2. For customer benefit, we aim for increasing high efficiency and reliability at the same time to maximize the lifetime power generation.

Conclusion

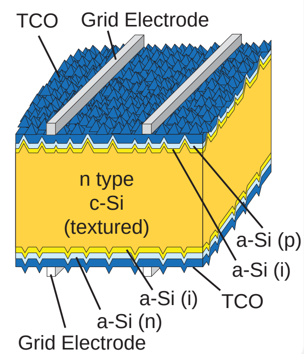
1. All HIT PV modules have exhibited no sign of degradation under several PID tests.
2. Surface layer of HIT cell is TCO without insulating layer which does not cause accumulation of charges.
3. No incidences of PID have been reported from the European, U.S. or Japanese markets.

These facts confirm the high quality and high reliability of HIT modules.

Maximizing the advantages of the HIT structure

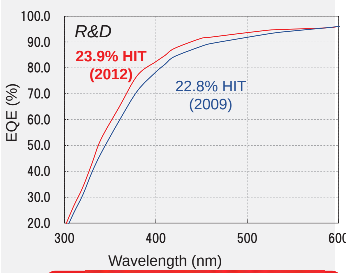
Panasonic HIT®

Heterojunction with Intrinsic Thin layer



(1) Improved optical confinement

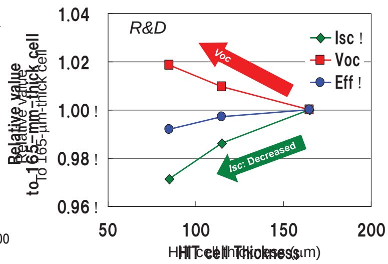
- Optimized textured structure
- High mobility TCO layer
- Wide gap a-Si layer



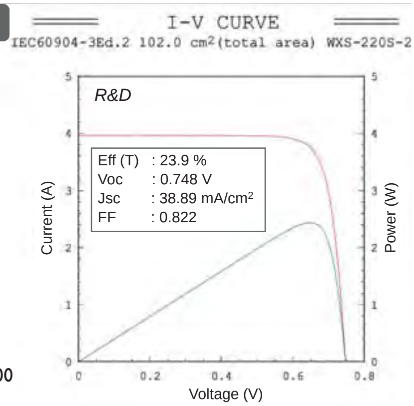
Improved Q.E. at shorter wavelengths

(2) Improved heterostructure

- Clean Si surface
- Low damage, high quality a-Si deposition



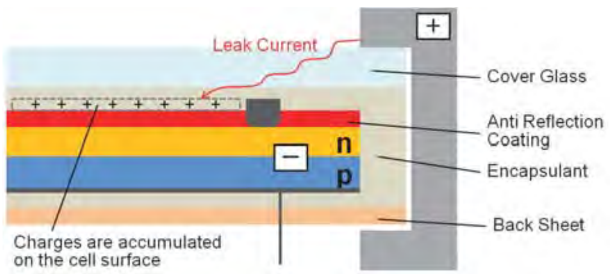
Increased Voc can compensate for the drop in Isc



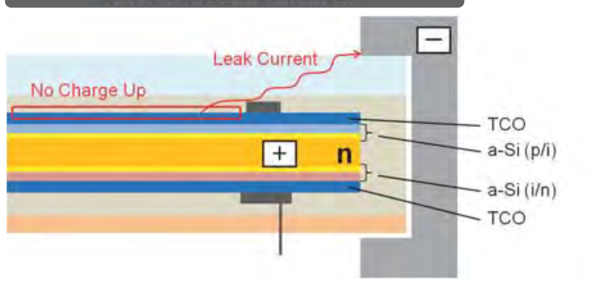
23.9% efficiency with 98-µm thickness

PID resistance of HIT structure

Conventional c-Si PV module structure

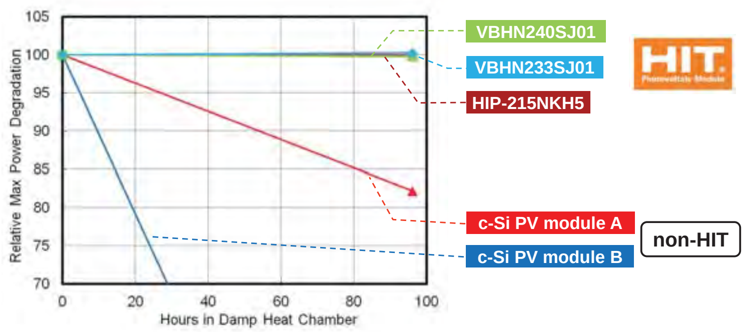


HIT PV module structure



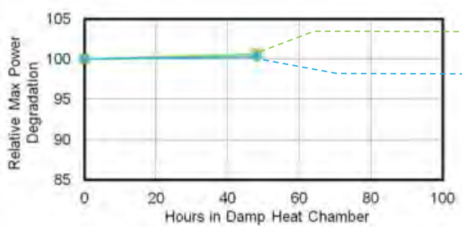
Results of PID test by Chemitox Inc.

60℃ 85%RH +1000V



Results of PID test by Fraunhofer CSP

50℃ 50%RH +1000V, -1000V



P1FC8KZ00028 (+1000V)
P1FC8KZ00015 (-1000V)

All HIT solar modules exhibited no sign of degradation

Conventional c-Si module structure

(1)Front surface is covered with insulating anti-reflection coating.
(2)Positive/negative charges are accumulated on the cell surface, that result in the power degradation.

HIT structure

(1)Both surfaces are transparent conductive oxide (TCO) layers.
(2)There is no insulating layer that accumulates electric charges under high-voltage biased condition.

PID resistance of HIT PV modules is confirmed.

EXPERIENCES ON PID TESTING OF PV MODULES IN 2012

Sascha Dietrich, Jens Froebel, Matthias Ebert, Joerg Bagdahn

Fraunhofer - Center for Silicon-Photovoltaics CSP
Walter-Huelse-Straße 1, 06120 Halle (Saale)
Telefon +49 (0) 345/5589-408
sascha.dietrich@csp.fraunhofer.de

Motivation

- High voltage stress conditions are identified as a crucial degradation problem for solar cells
- Degradation usually happens quickly (months), large scale and with high magnitude in terms of performance loss
- Na^+ migration through encapsulant and SiN due to potential between the cell and the frame + glass found as root cause
- Type approval test for modules required (IEC NWIP 62804)

Fig. 1: High voltage stress degradation (PID) along module string in floating ground configuration [1]

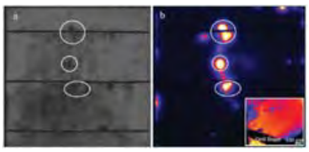


Fig. 2: Shunted regions on solar cell EL-image (left), LIT image (right) [2]

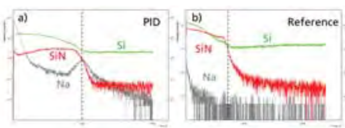


Fig. 3: Na accumulation at SiN / Si interface PID cell (left), reference cell (right) [2]

High Voltage Stress Testing (HVST)

Condition	Setup 1	Setup 2	Setup 3
Relative Humidity	50 %	85 %	50 %
Temperature	50 °C	60 °C	25 °C
Al-foil	yes	no	yes
Test Duration	48 h	96 h	168 h
No. of Modules Tested	77	11	7

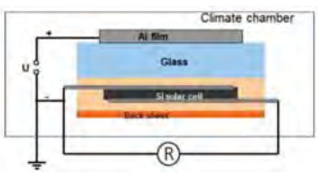


Fig. 4: Scheme of experimental setup 1

Fig. 5: Experimental setup 1 at Fraunhofer CSP with Al-foil covered PVC sheets

Results

- 46 % of modules failed the 5 % loss criteria (Fig. 6)
- scattering of power loss per module type can be very largely (Fig. 7)
  → statistical scattering of PID sensitive cells

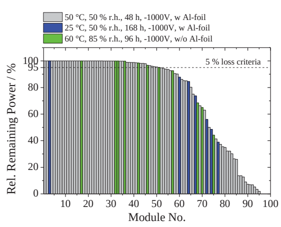


Fig. 6: Remaining power summarized for all tested modules (95 tested modules)

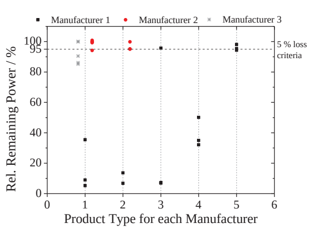


Fig. 7: Rel. remaining power per product type of several manufacturers (test setup 1)

Results

- test setup guides degradation pattern (Fig. 8)
- without Al-foil: strong concentration along the perimeter of the module
- with Al-foil: homogeneous electrode across module surface
- A few degraded cells may lead to high degradation (Fig. 9)
  - cells may be arbitrarily distributed across the module
- cloudy EL-image (local shunting) of a cell typically beginning of degradation

Discussion:

- statistical significance of HVST should be discussed
  → needle in a haystack may be crucial to the result
- low current EL appropriate for qualitative statistical evaluation of progress of degradation

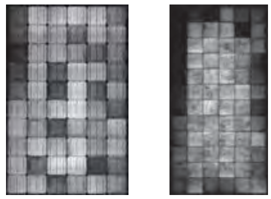


Fig. 8: Typical degradation pattern for different test approaches;
left: setup 1; right: setup2

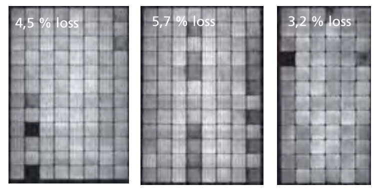


Fig. 9: Example where a few degraded cells with arbitrary distribution lead to rel. high performance los (8 A)

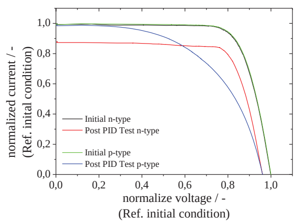


Fig. 10: Typical IV-curves for degraded n-type and p-type modules at -1000 V

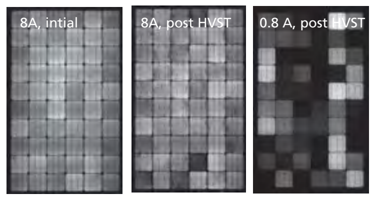


Fig. 11: Local shunting of solar cells leads to cloudy EL image of cells (here: power loss 15 %)

Recovery

- n-type cells show PID effect at negative bias with different degradation characteristic compared to p-type cells
- fast recovery after testing

Discussion:

- How to deal with this type of behavior in terms of testing?
- Definition of time frame for characterization after HVST?
  - e.g. Minimum waiting time before measurement
- Does it come with fast degradation during HVST?

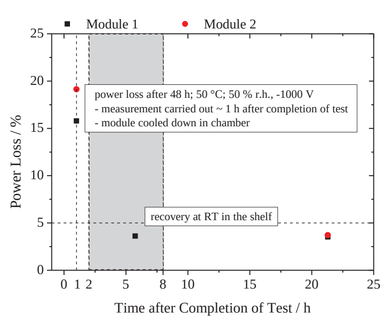


Fig. 12: PID effect on modules with n-type cells + fast recovery at room temperature after completion of the test (same manufacturer)

Bibliography

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

[2] V. Naumann, C. Hagendorf, S. Grosser, M. Werner, J. Bagdahn „Micro Structural Root Cause Analysis of Potential Induced Degradation in c-Si Solar Cells" Energy Procedia, 27, 1 – 6 (2012)

The use of humidity sensors to develop BIPV packaging solutions

rodney.rice@tatasteel.com tim.wilderspin@tatasteel.com

Tata Steel, PV Accelerator, Shotton Works. Wales. CH5 2NH

Background

As a manufacturer of coated steel and cladding systems, rather than photovoltaic cells, an approach that allowed the development of encapsulation systems somewhat independent of cell technology was required.

A selection of indicators, from simple colour-change capsules to electronic sensors to measure relative humidity levels have been reported elsewhere, and humidity sensors are already utilised in the measurement of water vapour transmission rates for encapsulants (ISO 15106).

Subsequently, we have routinely utilised humidity sensors as a proxy to working cells in order to screen a wide range of encapsulants, films and sealants in addition to coated steel cladding systems and lamination process settings.

Procedure

Firstly, individual humidity sensors (Honeywell 4000 series) were calibrated by recording sensor voltage and ambient relative humidity (RH) in both the dry (<5%RH) and wet (c.55% RH) laboratories. A linear relationship between output voltage and RH is stated in the technical literature of the sensors.

Samples were then prepared in the dry laboratory for consistency. A sample size of 100x100mm was chosen, as sufficiently meaningful for larger modules, albeit with a greater ratio of perimeter to surface area. Colorcoat Prisma® (coated steel) was used as the backsheet in all cases, together with various polymer barrier film frontsheets and differing butyl edge seals. The 10mm butyl perimeter seal was sealed using a heated press at 30psi and 140°C for 30 seconds.

Later experiments also included an encapsulant as part of a more complete solution.

Damp heat testing was conducted in line with conventional protocols (85°C/85%RH) in a Design Environmental Alpha 190-40H chamber, with samples measured periodically.

Results

After some early sample failures associated with poor workmanship, a series of experiments were undertaken, focussing on particular material sets. As confidence in the test procedure grew, exposure times were extended beyond the basic test standards.

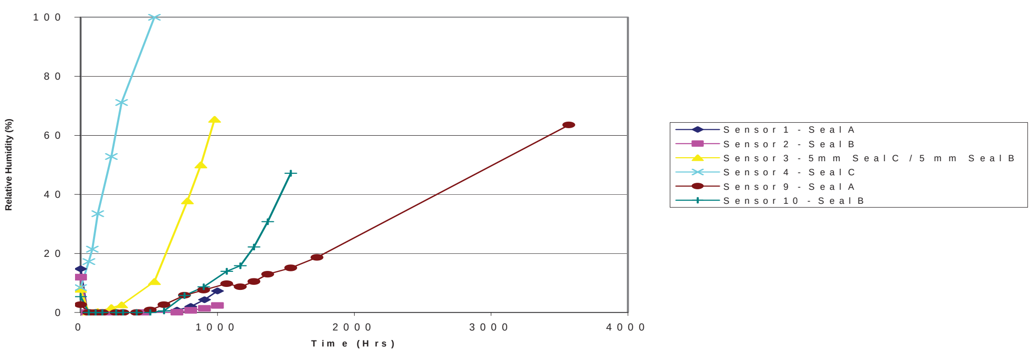


Chart 1: Both Seals A & B contained high levels of desiccant, resulting in very low RH levels within the package after 1000hours. Seal C contained no desiccant, and very quickly became saturated, even if used in combination with another material (as a potential reduced-cost option). Even after >3000hours exposure, RH levels for Seal A only just began to exceed ambient conditions. As these samples were prepared without encapsulant, performance of a more complete solution could be expected to be even better.

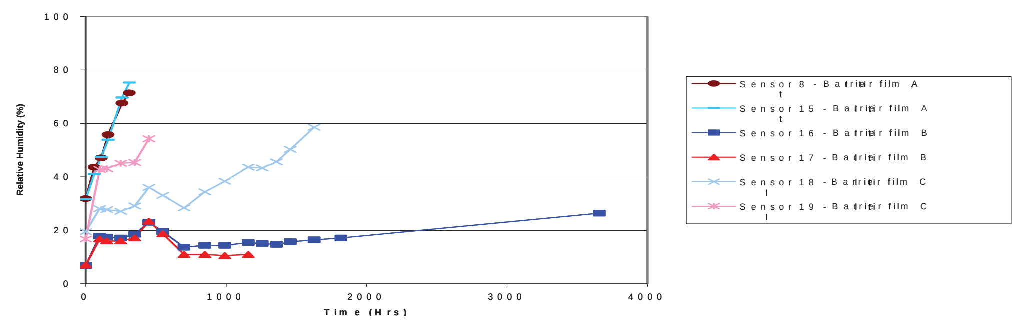


Chart 2: Barrier film Samples A, B & C were prepared with identical encapsulant and seal materials. The samples were chosen as representative of differing price/performance points. After only 1000hours there is a clear distinction between the samples, with Sample B significantly outperforming the others. Even approaching 4000hours (to date), the RH levels were still substantially below ambient.

Conclusions

i) Humidity sensors have been successfully utilised in the screening of encapsulant systems

ii) Quantitative results can be generated without the need to fully appreciate different cell technology characteristics

iii) The approach is being extended to compare material combinations and the influence of process conditions

TATA STEEL

The acceleration of degradation by HAST and Air- HAST in c-Si PV modules

Soh Suzuki[1], Tadanori Tanahashi[1], Takuya Doi[2] and Atsushi Masuda[2]
[1]ESPEC, Japan, [2]National Institute of Advanced Industrial Science and Technology (AIST), Japan

INTRODUCTION

Background : The damp heat test (DHT) in IEC 61215 is defined as 85 °C /85% RH condition for 1,000 h, as the high hygrothermal test. However, it has been suggested that DHT under these conditions cannot assure the long-term reliability of c-Si PV modules.

Purpose : In order to propose the novel hygrothermal test-condition, we attempt to clarify the effect of higher hygrothermal stresses (HAST and Air-HAST) on the degradation of mini c-Si PV modules, along with the extended DHT.

Air-HAST is the test procedure which is carried out in the high temperature humanized atmosphere with air, although the air is completely exhausted in ordinary HAST condition.

Table 1. Partial pressure of test conditions.

	Tem-perature (℃)	Humidity (%)	Water vapor (MPa abs.)	Total pressure (MPa abs.)	Air (MPa abs.)
R.T.	25	60	0.0016	0.1013	0.0997
DH	85	85	0.0495	0.1010	0.0518
HAST	105	100	0.1208	0.1208	0
	120	100	0.1985	0.1985	0
Air-HAST*	110	85	0.1216	0.2498	0.1282

*Each value in Air-HAST is obtained by theoretical calculations.

EXPERIMENTS

Table 2. Specification of samples.

Material	Specification	Supplier
Cell	Multicrystalline Si cell (156 mm × 156 mm)	Q Cells
Glass	Semi-tempered glass	AGC
Encapsulant	EVA (Fast Cure)	SANVIC
Interconnector	A-SPS (Leaded, Ag)	Hitachi Cable
Back sheet	TPT	Nondisclosure

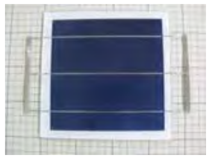


Fig. 1. Photograph of single-cell module.

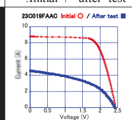
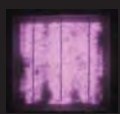
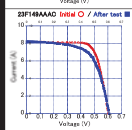
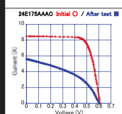
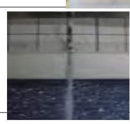
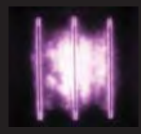
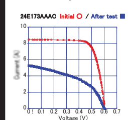
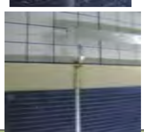
Table 3. Test conditions.

Test condition	Temperature/ humidity	Test time
Damp heat test	85 ℃ / 85%	4000 h
HAST	105 ℃ / 100%	1000 h
	110 ℃/85%	800 h
	120 ℃ / 100%	400 h
Air-HAST	110 ℃ / 85%	800 h

HAST (Highly-Accelerated Temperature and Humidity Stress Test)

RESULTS & DISCUSSION

Table 4. Comparison of characteristics after each environmental test.

Test conditions	EL	I-V (-:Initial / - after test)	Appearance	Remarks
Damp heat test 85 ℃/85% 4000 h				Dark region in EL image appears from the cell edge. Degradation occurs after DH 3000 h. P_{max} was reduced by 60%. Change to brown in interconnector, BS and EVA.
HAST 120 ℃/100% 400 h				Dark region in EL image appears from the cell edge. P_{max} was reduced by 16%. Peeling of the outside sheet of BS. Stress is possibly too strong. It may be different degradation mode from DH.
HAST 110 ℃/85% 800h				Dark region in EL image appears from the cell edge. P_{max} was reduced by 56% in I-V . Change to brown in BS. No change to brown in interconnector and EVA.
Air-HAST 110 ℃/85% 800 h				Dark region in EL image appears from the cell edge. P_{max} was reduced by 70% in I-V . Change to brown in interconnector, BS and EVA. It is possible to correlate with DH. It is possible to accelerate DH by 5 times.

1. Pmax was decreased by less than 5% and 40% in DHT condition for 1,000 and 4000 h, respectively.
2. The HAST condition (120 °C/100% RH) is extremely high-stress condition with the particular failure-modes, unlike in the cases of other conditions.
3. For 800 h at these conditions, the reduction levels of Pmax were 50~60% and 60~80% at HAST condition (110 °C/85%) and Air-HAST condition, respectively. In addition, the expansion levels of dark area in EL imaging were similar. It is suggested that the air in surrounding atmosphere of PV module (probably oxygen) induced the additional degradation .
4. By comparing the appearance of modules after Air-HAST for 800 h, HAST (110 ℃/85%) for 800 h and DHT for 4000 h it was found that the color is changed to brown for interconnector and EVA in the same manner for DHT and Air-HAST. The color was also changed to brown for BS at HAST (110 ℃/85%) but no change in color occurred for interconnector and EVA.
5. From the results of dark I-V measurement, it is also revealed that the change of I-V parameter induced by these hygrothermal stresses are not so much the decreasing of shunt resistance (Rsh) as the increasing of series resistance (Rs).

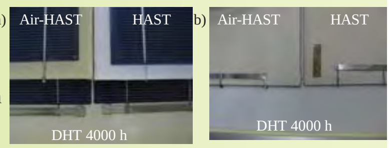


Fig. 2. Appearance of modules after Air-HAST and HAST.
a) Front side. b) Back side.

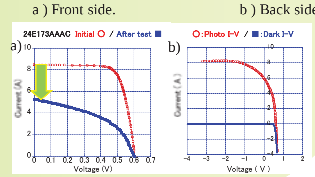


Fig. 3. I-V a) First quadrant. b) Photo I-V and dark I-V.

SUMMARY

In this study, we show that the highest hygrothermal condition which is able to accelerate the degradation without different failure-modes from those of DHT is 110 °C /85% RH (Air-HAST). We have to elucidate the effect of air on the degradation of PV modules in the further investigation.

Contact Person : Soh Suzuki (so-suzuki@espec.co.jp)

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).

Sensitivities of I-V Parameters in c-Si PV Modules to Hygrothermal Stress

Soh Suzuki [1], Eiichiro Obana [1], Takuya Doi [2], Atsushi Masuda [2], and Tadanori Tanahashi [1]

[1] ESPEC CORP., Japan, [2] National Institute of Advanced Industrial Science and Technology (AIST), Japan

Introduction & Procedures

Backgrounds

Hygrothermal Stress Test in IEC 61215: 10.13 Damp Heat Test

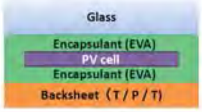
"To determine the ability of the module to withstand the effects of long-term penetration of humidity"

Long-term penetration of humidity (moisture Ingress) induced the power-loss of PV modules by corrosion, delamination, loss of elasticity / adhesion in polymer materials, discoloration, and other failure modes.

To accelerate this testing, we attempt to clarify the failure mechanisms of c-Si PV modules using the recent module components, under the several hygrothermal-stress conditions.

c-Si PV Mini-Module

Mini-Module Architecture



No Frame / No Edge Seal
= practically "No Guard" to Moisture Ingress

Mini-Module (1 cell)

Experimented Hygrothermal Conditions

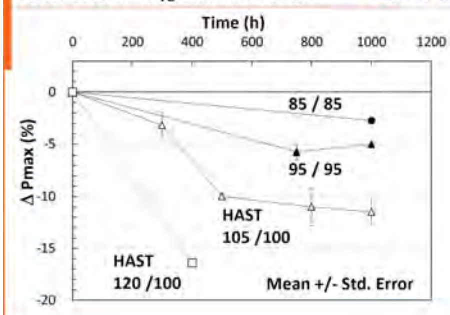
Conditions	Temp. (°C)	Humidity (% RH)	Equipment
Damp Heat (85/85)	85	85	ESPEC: PL-2KP
Damp Heat (95/95)	95	95	ESPEC: PL-2KP
HAST (105/100)	105	100 (Unsaturated)	ESPEC: EHS-221
HAST (120/100)	120	100 (Unsaturated)	ESPEC: EHS-221

Equipment:
http://www.espec.co.jp/english/products/products01.html
http://www.espec.com/na/applications/solar/

Summary

1. Along with the elevation of hygrothermal stress, Pmax of c-Si PV mini-module was decreased [Panel 1].
2. The reduction of Pmax with elevation of the hygrothermal stress almost correlated with that of FF, but not those of Voc and Isc [Panel 3]. Especially, the extreme reduction of Isc (which was observed in the long- term damp heat test) was not detected in our experimental conditions (up to 1,000 h) [Panel 2].
3. By the breakdown of FF reduction to the changes of shunt resistance (Rsh) and series resistance (Rs) [Panel 4], it is confirmed that, in the whole stress conditions, the sensitivity of Rsh-LP (Rsh like parameter = Ipm/Isc) to the change of hygrothermal stress was about 2.5-folds against that of Rs-LP (Rs like parameter = Vpm/Voc) [Panel 5, 6, 7].
However, in the low-stress conditions, the reduction of Rs-LP was about 2.5-folds against that of Rsh-LP [Panel 5, 6, 7]. The reduction of Rs-LP in the high-stress conditions was maintained virtually constant, although Rsh-LP was decreased with the applied stresses [Panel 5,6, 7]. These results suggest that the failure modes differ between in the low- and high-stress conditions [Panel 8].
4. HAST (120 °C/100% RH) induced the drastic failure which was not observed in the other conditions [Panel 9,10].

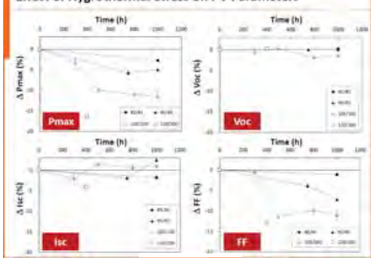
Panel 1 Power Loss with Hygrothermal Stress



Experimental Results

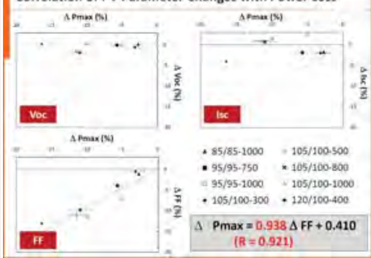
Panel 2

Effect of Hygrothermal Stress on I-V Parameters



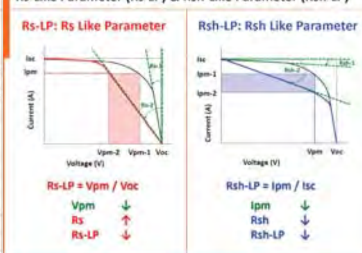
Panel 3

Correlation of I-V Parameter Changes with Power Loss



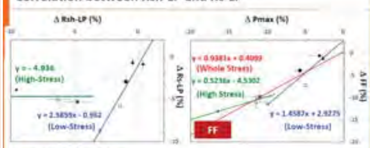
Panel 4

Rs-Like Parameter (Rs-LP) & Rsh-Like Parameter (Rsh-LP)



Panel 5

Correlation between Rsh-LP and Rs-LP

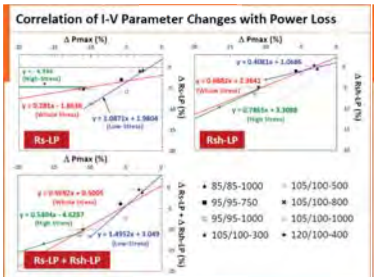


Low-Stress Condition:
(85/85-1000, 95/95-750, 95/95-1000, 105/100-300, 105/100-500)
The reduction of Rs-LP was about 2.5-folds against that of Rsh-LP.

High-Stress Condition:
(105/100-800, 105/100-1000, 120/100-400)
The reduction of Rs-LP was maintained virtually constant.

Panel 6

Correlation of I-V Parameter Changes with Power Loss



Panel 7

Correlation of I-V Parameter Changes with Power Loss (Δ Pmax)

Stress Condition	Independent Variables	Slope	Intercept	Correlation Coeff. (R)
Whole	Δ FF	0.938	0.410	0.921
	Δ Rs-LP	0.281	-1.864	0.504
	Δ Rsh-LP	0.688	2.364	0.970
	Δ Rs-LP + Δ Rsh-LP	0.969	0.501	0.923
Low-Stress	Δ FF	1.459	2.928	0.925
	Δ Rs-LP	1.087	1.980	0.912
	Δ Rsh-LP	0.408	1.069	0.932
	Δ Rs-LP + Δ Rsh-LP	1.500	3.049	0.926
High-Stress	Δ FF	0.524	-4.530	0.958
	Δ Rs-LP	0 (-0.246)	-4.936 (-7.938)	(0.996)
	Δ Rsh-LP	0.787	3.309	0.972
	Δ Rs-LP + Δ Rsh-LP	0.540	-4.629	0.955

Panel 8

Correlation of I-V Parameter Changes with Power Loss (Δ Pmax)

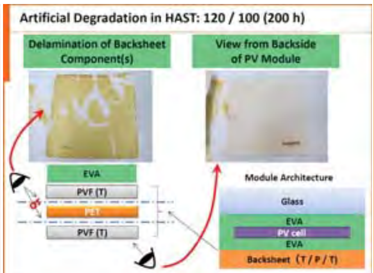
Whole Stress Condition:
The sensitivity of Rsh-LP to the change of hygrothermal stress was about 2.5-folds against that of Rs-LP.
However, ΔRs-LP did not correlated with Δ Pmax.

Low-Stress Condition:
Δ Pmax was dominantly decreased by the reduction of Δ Rs-LP.
Δ Rsh-LP also contributed to the reduction of Pmax (about 30%).
By the partitioning of stress conditions, Δ Rs-LP and Δ Rsh-LP sufficiently correlated with Δ Pmax.

High-Stress Condition:
Δ Pmax was dominantly decreased by the reduction of Δ Rsh-LP.
Δ Rs-LP did not contribute to the reduction of Pmax, although the reduction of Pmax depended on the reduction of Δ Rsh-LP.
The combination of Δ Rs-LP and Δ Rsh-LP also completely correlated with Δ Pmax.

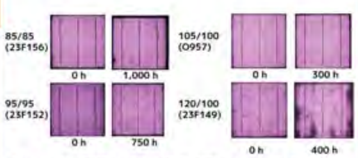
Panel 9

Artificial Degradation in HAST: 120 / 100 (200 h)



Panel 10

EL Image

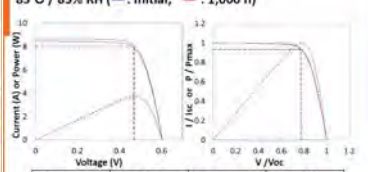


Except in the HAST condition (120 / 100), the defect in EL images was not detected in all cases.

Appendix 1

I-V Characteristics in PV Mini-Module

85°C / 85% RH (— : Initial, — : 1,000 h)

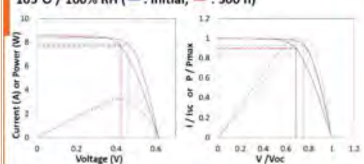


Δ Pmax	- 2.70 %	Δ Vpm	- 1.04 %
Δ Voc	0.19 %	Δ Ipm	- 1.69 %
Δ Isc	- 2.27 %	Δ Rs-LP	- 1.22 %
Δ FF	- 0.64 %	Δ Rsh-LP	0.59%

Appendix 2

I-V Characteristics in PV Mini-Module

105°C / 100% RH (— : Initial, — : 500 h)

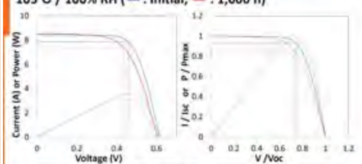


Δ Pmax	-10.35 %	Δ Vpm	- 8.54 %
Δ Voc	0.25 %	Δ Ipm	- 2.07 %
Δ Isc	1.54 %	Δ Rs-LP	- 8.69 %
Δ FF	-11.94 %	Δ Rsh-LP	- 3.56 %

Appendix 3

I-V Characteristics in PV Modules

105°C / 100% RH (— : Initial, — : 1,000 h)



Δ Pmax	- 10.53 %	Δ Vpm	- 4.69 %
Δ Voc	- 1.73 %	Δ Ipm	- 6.13 %
Δ Isc	0.87 %	Δ Rs-LP	- 3.01%
Δ FF	- 9.74 %	Δ Rsh-LP	- 6.94 %

Contact Person: Tadanori Tanahashi (t-tanahashi@espec.co.jp)

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).

Initial results of IEC 62804 *draft* round robin testing

Peter Hacke and Kent Terwilliger
NREL, USA
Simon Koch, Thomas Weber, and Juliane Berghold
PI-Berlin, DE
Stephan Hoffmann and Michael Koehl
Fraunhofer ISE, DE
Sascha Dietrich and Matthias Ebert
Fraunhofer CSP, DE
Gerhard Mathiak
TÜV Rheinland, DE

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.

Abstract

Two out of three planned crystalline silicon module designs were distributed in five replicas each to five laboratories for testing according to the IEC 62804 (draft) system voltage durability qualification test for crystalline silicon modules. The stress tests were performed in environmental chambers at 60°C, 85% relative humidity, 96 h, and with module nameplate system voltage applied to the cells (two modules in each polarity and one control). Pass/fail results, means, and standard deviations of degradation of the modules tested as a function of module design and test laboratory are presented and discussed. Preliminary results from the module designs tested so far indicate the test protocol is able to discern susceptibility to potential-induced degradation with acceptable consistency from lab to lab. Influence of possible variations in the severity of the test between labs has so far not been distinguishable.

Introduction

- **Testing was performed according to IEC 62804 draft "SYSTEM VOLTAGE DURABILITY QUALIFICATION TEST FOR CRYSTALLINE SILICON MODULES." The motivation was to:**
  - **See if the specified sample size (2 modules per polarity) is adequate considering variations that might exist in shipping modules**
  - **See if possible lab to lab variation in stress levels overly influences results**

- **Modules were chosen to be near the pass/fail limit vis-à-vis the 60°C/85%RH/-1000 V 96h stress condition to attempt to get useful statistics (without 'censoring'). Said another way, we *could* have chosen modules that do not degrade at all, and modules that degrade an extreme amount, and shown how well the test differentiates the two, but such results would be less useful.**

Experiment

- **Highlights of round-robin test procedure based on IEC 62804 *draft*:**
  - Modules leads shorted and connected to high voltage, module frames grounded
  - Neither *in-situ* nor *ex-situ* I-V measurements are performed on the module over the course of the 96 h test
  - Leakage current from the active layer/cells to ground may optionally be measured during the testing (most labs did not report)
  - Open market modules chosen (but not necessarily currently shipping), not specially designed modules
  - Electroluminescence measurements are carried out before and after the test
  - Modules are tested in both polarities (2 each), although testing labs may instead choose to use the modules destined for the known stable polarity for outdoor tests
- **Stress conditions**
  - Chamber air temperature 60 °C ± 2°C
  - Chamber relative humidity 85 % ± 5 % RH
  - Test duration 96 h
  - Voltage: module nameplate rated system voltage (1000 V), 2 for each polarity, 1 module supplied for control, voltage applied during ramps
  - Pass criterion: both modules of a tested polarity must show < 5% power degradation and pass IEC 61215 ed. 2 visual inspection criteria

Experiment

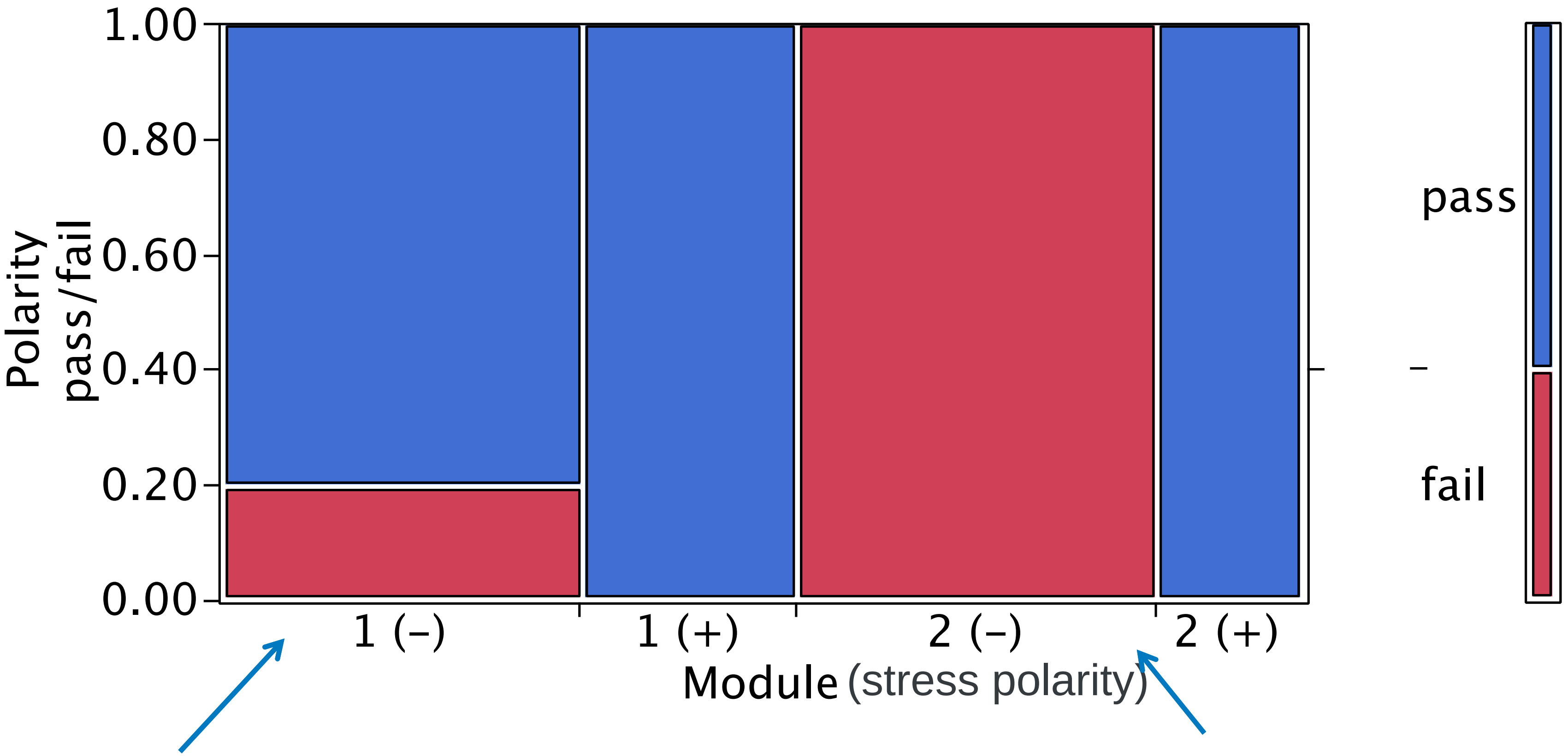
- **Module designs 1 and 2 made with conventional front junction $n^+/p/p^+$ cells, Al frames, and polymeric backsheets were selected:**
- **Module 1**
  - 230 W class mc-Si module design (60 15.6 cm x 15.6 cm cell)
  - Manufactured from 2011 onward
  - Based on previously published reports of PID tests under different conditions, the module was expected to show a small PID signal with some scatter in results, but generally less that 5% degradation
- **Module 2**
  - a 170 W class mc-Si module design (72 12.5 cm x 12.5 cm cells)
  - Manufactured in 2008 or 2009
  - Expected to show PID based on data obtained at NREL under different conditions, but significant scatter in the data was expected due to poorer process control and increased variability in the cells made during this period and as evidenced in prior EL imaging.
- **Module 3, in test**

Participants

Lab #	Lab name
1	NREL
2	Fraunhofer ISE
3	TÜV Rheinland
4	Fraunhofer CSP
5	PI Berlin

Overview of pass/fail results of two different module designs tested at 5 labs

Pass/fail condition: If 1 or 2 modules tested in a polarity fail (Pmax drop > 5%), that design is considered failed in that polarity at the given test lab

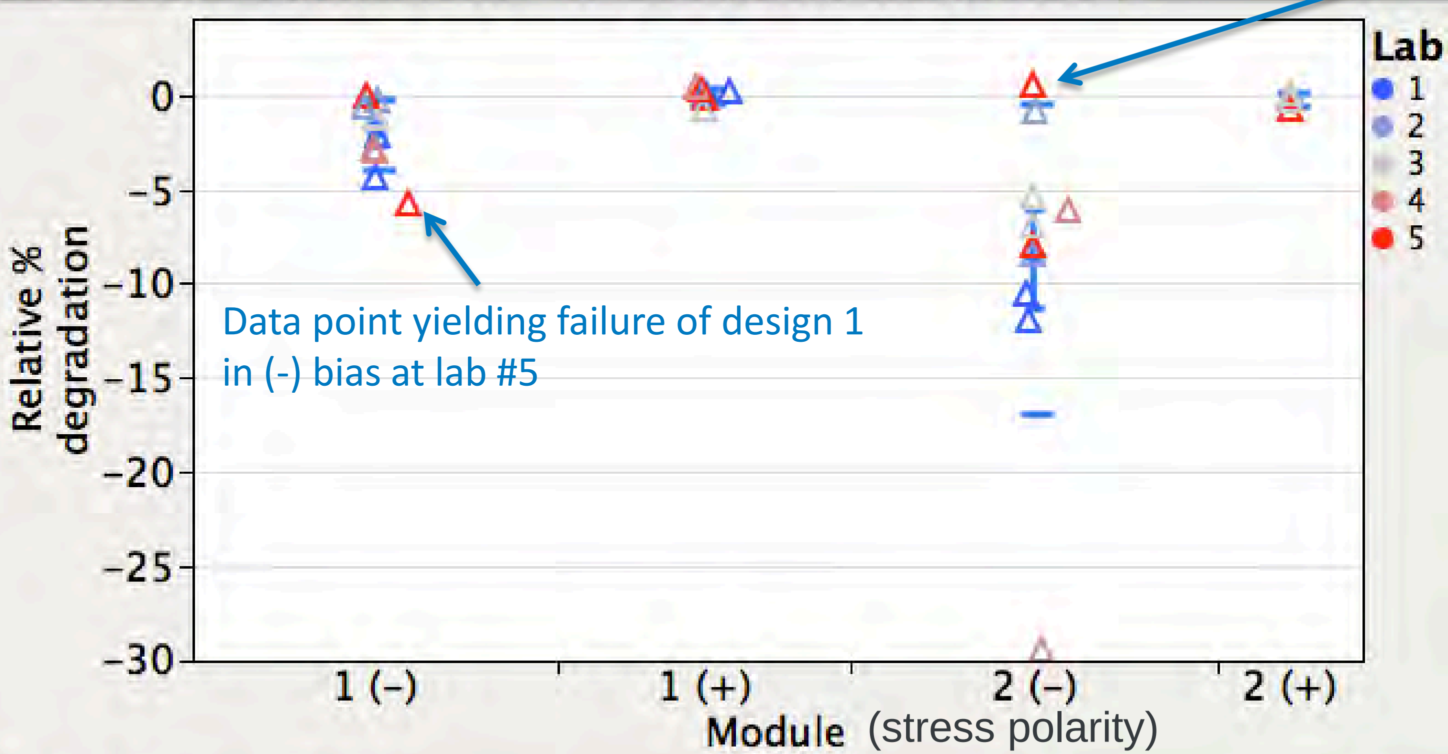


Module design 1 failed in the (-) polarity test at one of the five labs when one of the two replicas tested there failed.

Module design 2 failed in the (-) polarity test at all five labs when at least one of the two modules tested failed at each lab.

Considering stress in (-) bias, module design 1 shows both smaller mean degradation and standard deviation of degradation than design 2

Oneway Analysis of Relative % degradation By Module



Missing Rows 10

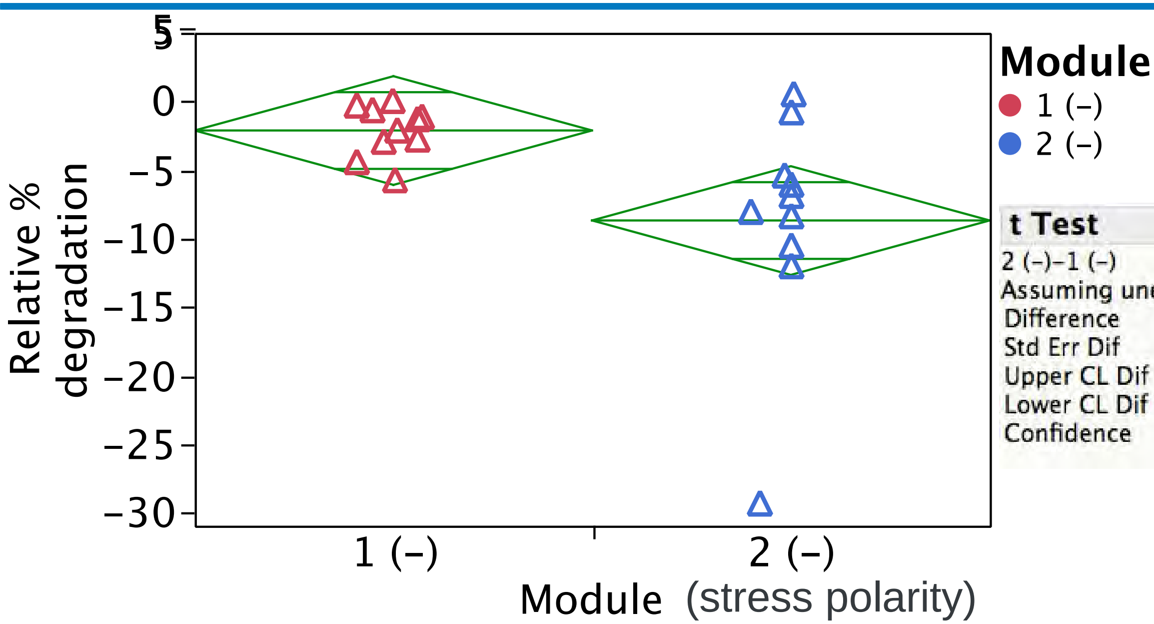
Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
1 (-)	10	-2.1240	1.87072	0.5916	-3.46	-0.786
1 (+)	8	-0.1021	0.43217	0.1528	-0.46	0.259
2 (-)	10	-8.6960	8.22389	2.6006	-14.58	-2.813
2 (+)	4	-0.2900	0.31602	0.1580	-0.79	0.213

What is the probability of both those 2 modules that degraded less than 5% arriving at one lab, and thus passing the stress test in the (-) polarity at that one lab?

There are 45 different combinations when the number of samples is 10 with 2 samples in each combination. The probability of those two passing modules ending up at one lab is 1/45 (2.22%).

Results are controlled by module design, no conclusive proof that results are controlled by lab

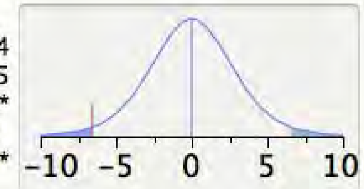


t Test

2 (–)-1 (–)

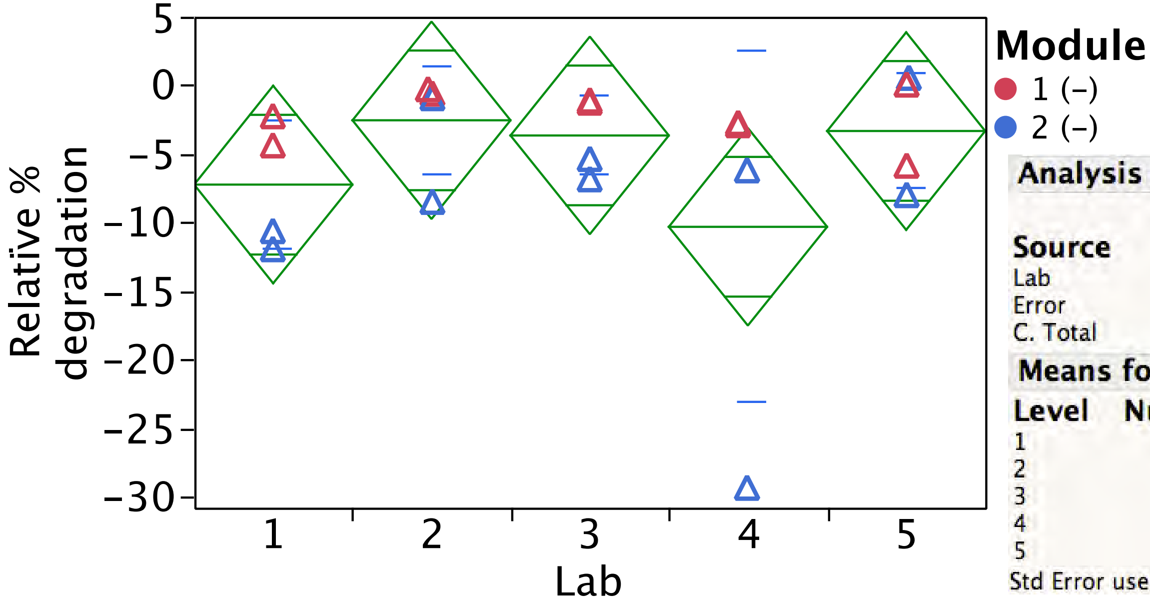
Assuming unequal variances

Difference	-6.572	t Ratio	-2.46414
Std Err Dif	2.667	DF	9.928915
Upper CL Dif	-0.624	Prob > |t|	0.0336*
Lower CL Dif	-12.520	Prob > t	0.9832
Confidence	0.95	Prob < t	0.0168*



Bayesian Variance Component Estimates

Random Effect	Var Component	Pct of Total
Lab	6.1232337	14.557
Module[Lab]	9.0064708	21.411
Residual	26.934157	64.032
Total	42.063861	100.000



Analysis of Variance

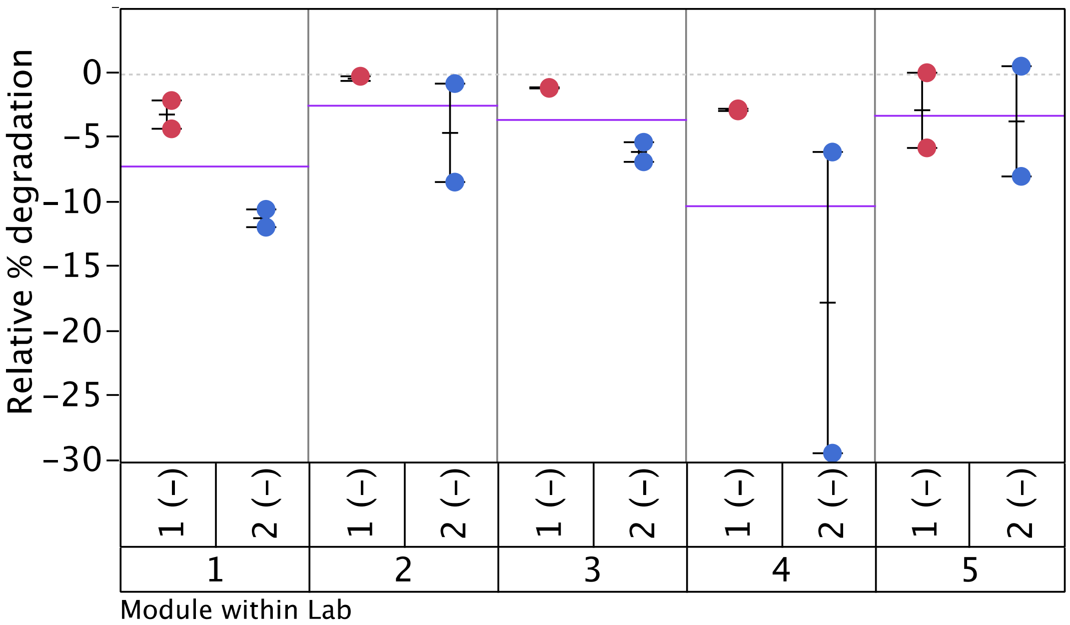
Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Lab	4	171.71495	42.9287	0.9408	0.4672
Error	15	684.42845	45.6286		
C. Total	19	856.14340			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
1	4	-7.233	3.3774	-14.43	-0.034
2	4	-2.545	3.3774	-9.74	4.654
3	4	-3.645	3.3774	-10.84	3.554
4	4	-10.303	3.3774	-17.50	-3.104
5	4	-3.325	3.3774	-10.52	3.874

Std Error uses a pooled estimate of error variance

What extent did the possible varying severity of the test labs influence outcomes?



Module degradation [(-) bias only] viewed as a function of lab to determine if any labs are more severe than others.

The analysis shows that the choice of lab is the least influential component of the variation, the type of module is the next important factor, but variation of the modules within a given module type (residual) is the most influential.

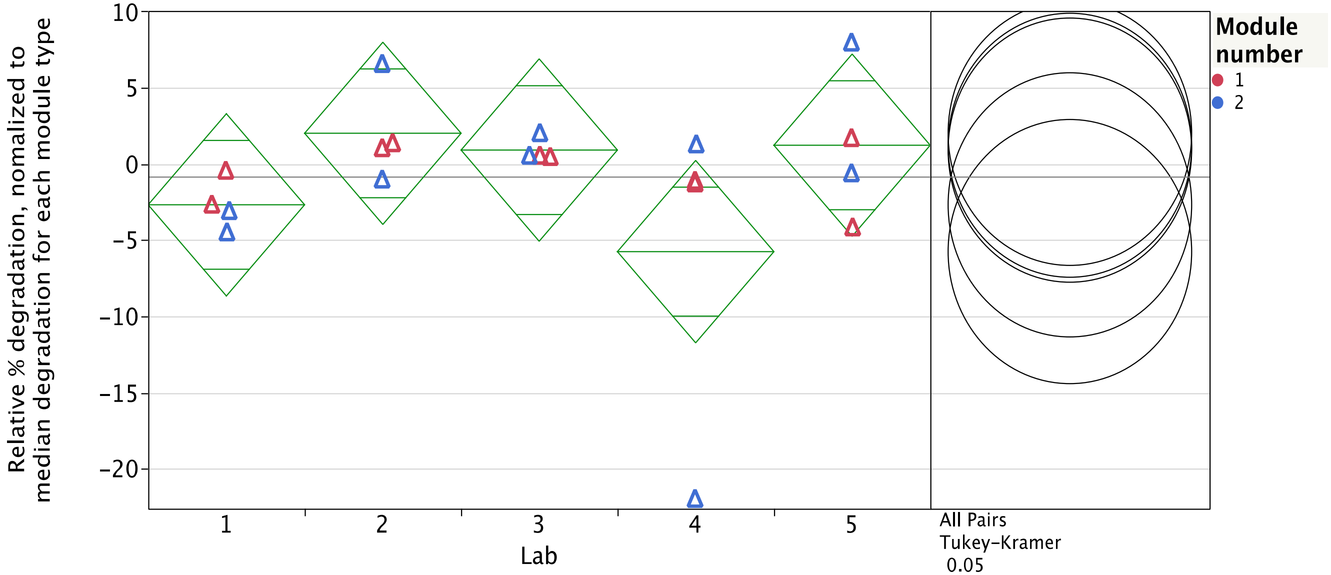
Bayesian Variance Component Estimates

Random Effect	Var Component	Pct of Total
Lab	6.1232337	14.557
Module[Lab]	9.0064708	21.411
Residual	26.934157	64.032
Total	42.063861	100.000

Variance Components

Component	Var Component	% of Total
Lab	6.123234	14.6
Module[Lab]	9.006471	21.4
Within	26.934157	64.0
Total	42.063861	100.0

Examination of lab to lab variability



Level		Mean
2	A	2.012500
5	A	1.232500
3	A	0.912500
1	A	-2.675000
4	A	-5.745000

Levels not connected by same letter are significantly different.

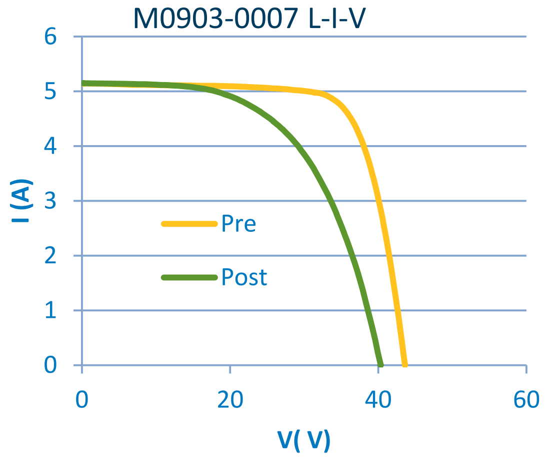
Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
2	4	7.757500	3.965387	-4.4873	20.00232	0.3319
5	4	6.977500	3.965387	-5.2673	19.22232	0.4303
3	4	6.657500	3.965387	-5.5873	18.90232	0.4745
2	1	4.687500	3.965387	-7.5573	16.93232	0.7611
5	1	3.907500	3.965387	-8.3373	16.15232	0.8577
3	1	3.587500	3.965387	-8.6573	15.83232	0.8907
1	4	3.070000	3.965387	-9.1748	15.31482	0.9342
2	3	1.100000	3.965387	-11.1448	13.34482	0.9985
2	5	0.780000	3.965387	-11.4648	13.02482	0.9996
5	3	0.320000	3.965387	-11.9248	12.56482	1.0000

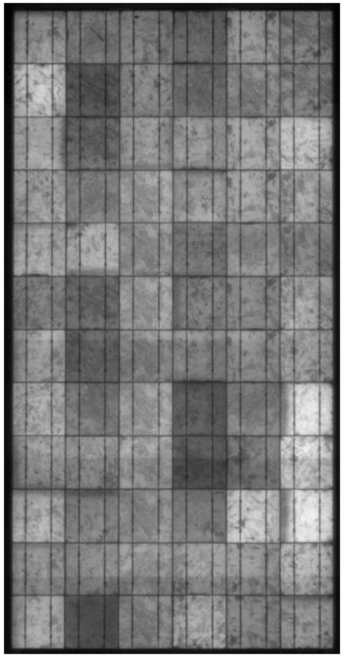
Subtracting median degradation for each module type also failed to show a statistically significant difference between labs

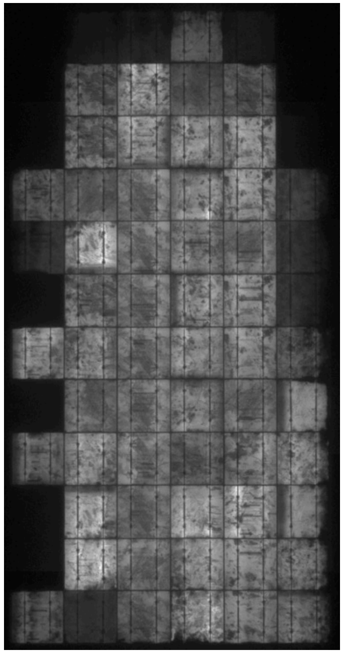
Results of a module design 2 from lab 4

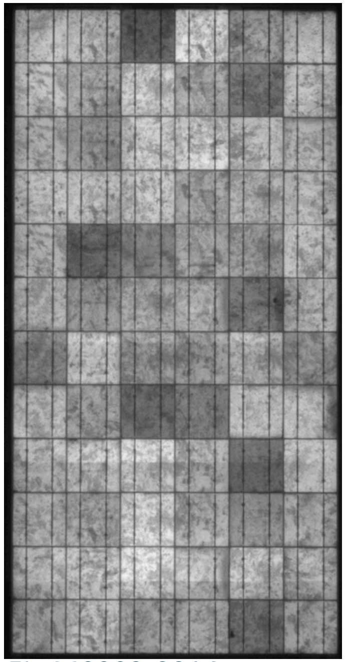
NREL ID	Round	Sequence	Voc (V)	Isc (A)	FF (%)	Vmax (V)	Imax (A)	Pmax (W)	Pmax change (%)
M0903-0007	0	-1000V	43.59	5.14	74.03	34.97	4.74	165.80	
M0903-0007	96hr	-1000V	40.32	5.15	56.41	28.2	4.15	117.13	-29.36
M0903-0014	0	-1000V	43.57	5.17	73.14	34.64	4.76	164.92	
M0903-0014	96hr	-1000V	43.43	5.19	68.71	34.42	4.5	154.82	-6.12

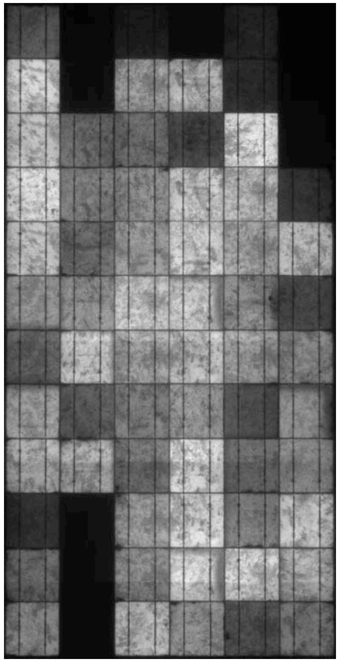


Potential-induced degradation in the most degraded module design


EL: M0903-0007, pre


EL: M0903-0007, post


EL: M0903-0014, pre


EL: M0914-0014, post

Images/Data:
Sascha Dietrich
Fraunhofer CSP

Conclusions

- **2 module designs completed testing at 5 labs for system voltage durability**
- **The test was able to statistically significantly discern the two module designs for potential-induced degradation**
- **Extent of variability measured for each module design was in line with expectations based on previous experience**
- **Potential-induced degradation was observed in the modules by electroluminescence**
- **lab to lab variability was the least influential variable**
- **The test (per IEC 62804 draft) appears successful with respect to the scope of this round robin with results of two of the three modules analyzed**

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory

Breakthrough time and mechanical properties of edge sealing in different environmental conditions

A. Bonucci, J. Gigli, P. Gallina [a], Andy Hayden[b]

[a]SAES Getters SpA, Viale Italia 77, 20020 Lainate (Italy) - [b]SAES Getters USA Inc, 1122 E Cheyenne Mountain Blvd, Colorado Springs CO80906, USA

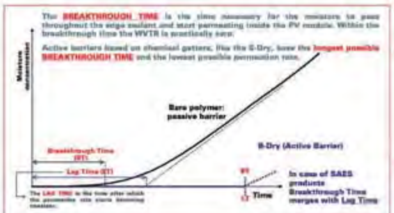
Background and Objectives

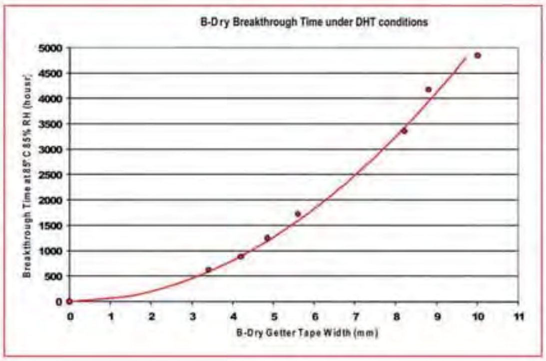
Long term stability, reliability and operational lifetime of PV modules are essential for their commercial success. Since environmental conditions strongly affect both performance and yield of modules based on thin film technologies like CdTe, CIGS and a-Si, proper encapsulation architecture is important to obtain the desired long term outdoor stability. SAES Getters has focused its efforts on eliminating or minimizing moisture ingress along the edges of the module which is believed to be the main cause of degradation .

B-Dry®

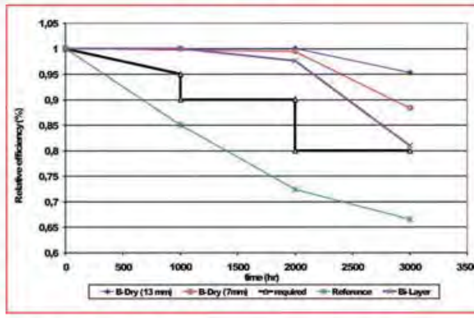
Thin film photovoltaic panels with B-Dry edge sealant passed complete IEC 61646 and IEC 61730

B-Dry edge sealant as an Active Barrier





Damp Heat stability at 85°C 85%RH on CIGS, performed at ZSW



A. Bonucci , S. Rondena , A. Gallitognotta , P. Gallina, O. Salomon, W. Wischmann, S. Hiss, Solar Energy Materials & Solar Cells 98 (2012) 398–403

Features and Results

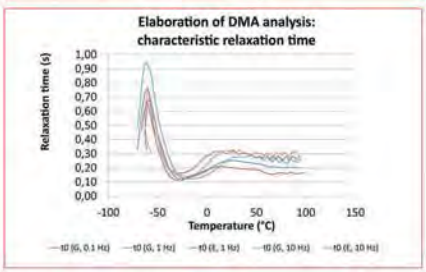
B-Dry edge sealant

B-Dry black thermoplastic edge sealant tape:
Thickness: 0.5 mm to 1.3 mm
Width: 7 mm to 12 mm.

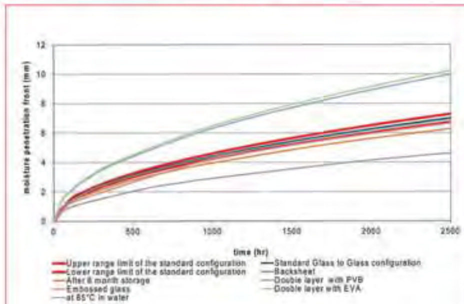
Electrical Isolation

Dielectric Strength	kV/mm	35
Volume Resistivity	ohm*cm	10^{16}

Viscoelastic Properties

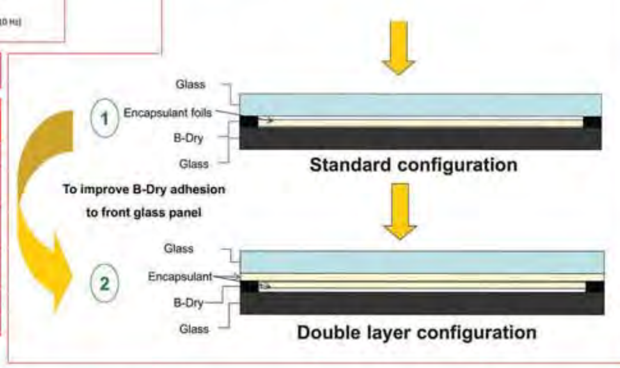


Moisture penetration front at 85°C 85%RH in different configurations



Adhesion Strength to Glass: dependance on the deformation rate

	lap shear (MPa)@50mm/min (UNI EN ISO 523-3)	lap shear (MPa)@1.31mm/min (D1002)	Ageing
as received	0.44 ± 0.04	0.26 ± 0.006	
after DH test 1000 hours @85°C 85%RH	0.41 ± 0.06	0.34 ± 0.025	IEC 61646
after DH test 2000 hours @85°C 85%RH	0.54 ± 0.09		IEC 61646
After UV aging	0.40 ± 0.03		Xenotest Miami (30 days)
UV/TC50/HF		0.28 ± 0.012	IEC 61646
TC200		0.26 ± 0.006	IEC 61646



Conclusions

- B-Dry shows a superior moisture barrier property
- B-Dry ensures very good damp heat stability
- B-Dry ensures lifetime even in hard weather conditions
- B-Dry ensures high electrical isolation

www.saesgetters.com

saes group

making innovation happen, together

Potential induced degradation (PID) tests for commercially available PV modules

Takuya DOI[*1], Kohji MASUDA[*2], Hiroshi KATO[*2], Yasunori UCHIDA[*2], Katsuaki SHIBATA[*2], Shinji KAWAI[*3], Yutaka FUKUMOTO[*3], Fujio TAMAI[*3], Atsushi MASUDA[*1] and Michio KONDO[*4]

*1 National Institute of Advanced Industrial Science and Technology (AIST-Kyushu), 807-1 Shuku-machi, Tosu, Saga 841-0052, Japan; *2 Japan Electrical Safety & Environment Technology Laboratories (JET), 1-12-28 Motomiya, Tsurumi-ku, Yokohama, Kanagawa 230-0004, Japan; *3 Industrial Technology Center of SAGA, 114 Oaza-Yaemizo, Nabeshimamachi, Saga-shi, Saga 849-0932, Japan; *4 National Institute of Advanced Industrial Science and Technology (AIST-Tsukuba), 1-1-1 Umezono, Tsukuba Central 2, Tsukuba, Ibaraki 305-8568, Japan

INTRODUCTION

As it causes large output power decrease in short term, potential induced degradation (PID) inflicts large loss on users [1]. Some methods to reproduce PID phenomena were reported [2,3]. We applied two PID test methods, that is, so-called chamber method [2] and water film method [3], to various PV modules made by domestic and overseas PV module makers, purchased from markets.

EXPERIMENTS AND METHODS

In the chamber method, PID tests were conducted with 15 PV module types (Table 1, type A to O), the number of sample N=2, respectively, under the condition described in the IEC 62804 draft (November, 2012), that is, 60 ºC, 85%RH, 96 h.

In the water film method, the test procedure is as follows: PV module was installed horizontally so that its front side faces upward in the air-conditioned room kept at 25 ºC. Front surface was covered with water film, then it was covered with plastic film to prevent water evaporation. Wiring for applying voltage is the same way described in the IEC 62804 draft. Test duration is 7 days. In this method, 6 PV module types (Table 1, type A,B,C,E,F,G) were tested with the number of sample N=3, respectively.

RESULTS

Figure 1 shows the results of the chamber methods. The value of each module's power was normalized by the value of the control module of the same module type, respectively. Remarkable power decrease was observed in 3 module types (C, F, J). Furthermore, though the power decrease was small in the module type B and G, they failed to pass the criteria of IEC 62804 draft. The results of the water film methods are shown in Fig. 2.

The value of each module's power was normalized by the initial value of the individual module, respectively. Remarkable power decrease was observed in 2 module types (C, F). As for module type B, it was classified as fail as one sample decreased by more than 20%.

Table 1 Test modules.

module type	cell type	module type	cell type
A	mc-Si	I	mc-Si
B	mc-Si	J	mc-Si
C	mc-Si	K	mc-Si
D	Thin film	L	Thin film
E	mc-Si	M	mc-Si
F	sc-Si	N	mc-Si
G	mc-Si	O	mc-Si
H	sc-Si		

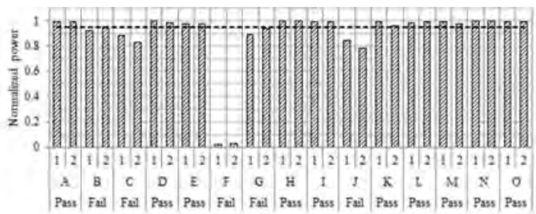


Fig. 1 Normalized power after the test by chamber method.

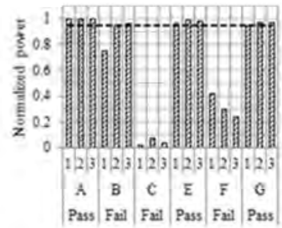


Fig. 2 Normalized power after the test by water film method.

DISCUSSION

In Fig. 3, in order to compare the results of two test methods, the average values of normalized module's power after chamber method test were plotted against those after the water film method test. In this figure, the broken line shows perfect correlation between two test methods. The retention of power after PID tests could be classified into four types; (1) Hardly decreased in both methods (module type A and E), (2) Decreased a little in the test of at least one method (module type B and G), (3) Perfectly lost of power generation function in the water film method (module type C) and (4) Perfectly lost of power generation function in the chamber method (module type F).

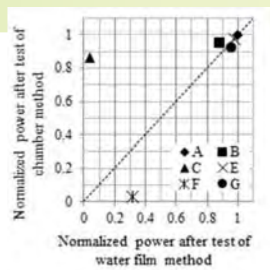


Fig. 3 Comparison between the chamber method and the water film method.

CONCLUSION

From these results, it was found that water film method not always gave more stress than chamber method because one module type showed larger degradation with chamber method than with water film method. Another important finding was that some module types show different PID degradation behavior by different test methods.

ACKNOWLEDGMENTS

This joint project was cooperated by Photovoltaic Power Generation Technology Research Association (PVTEC), National Institute of Advanced Industrial Science and Technology (AIST), Industrial Technology Center of SAGA (SAGA-ITC) and Japan Electrical Safety & Environment Technology Laboratories (JET) under "Asia-Pacific Industrial Science & Technology and International Standardization Cooperation Program" conducted by METI. We acknowledge to Dr. Tadanori Tanahashi of Espec Corp. for discussion of experimental results.

REFERENCES

[1] Pingel S *et al.*, "Potential induced degradation of solar cells and panels", 35th IEEE PVSC (2010–6), 2817–2822, Honolulu, Hawaii.
[2] Hacke P *et al.*, "System voltage potential-induced degradation mechanisms in PV modules and methods for test", 37th IEEE PVSC (2011–6), 19–24, Seattle, Washington.
[3] Koch S *et al.*, "Polarization effects and tests for crystalline silicon cells", 26th EUPVSEC and Exhibition, (2011–9), 1726–1731, Hamburg, Germany.

High PID resistant cross-linked encapsulant based on polyolefin SOLAR ASCE™

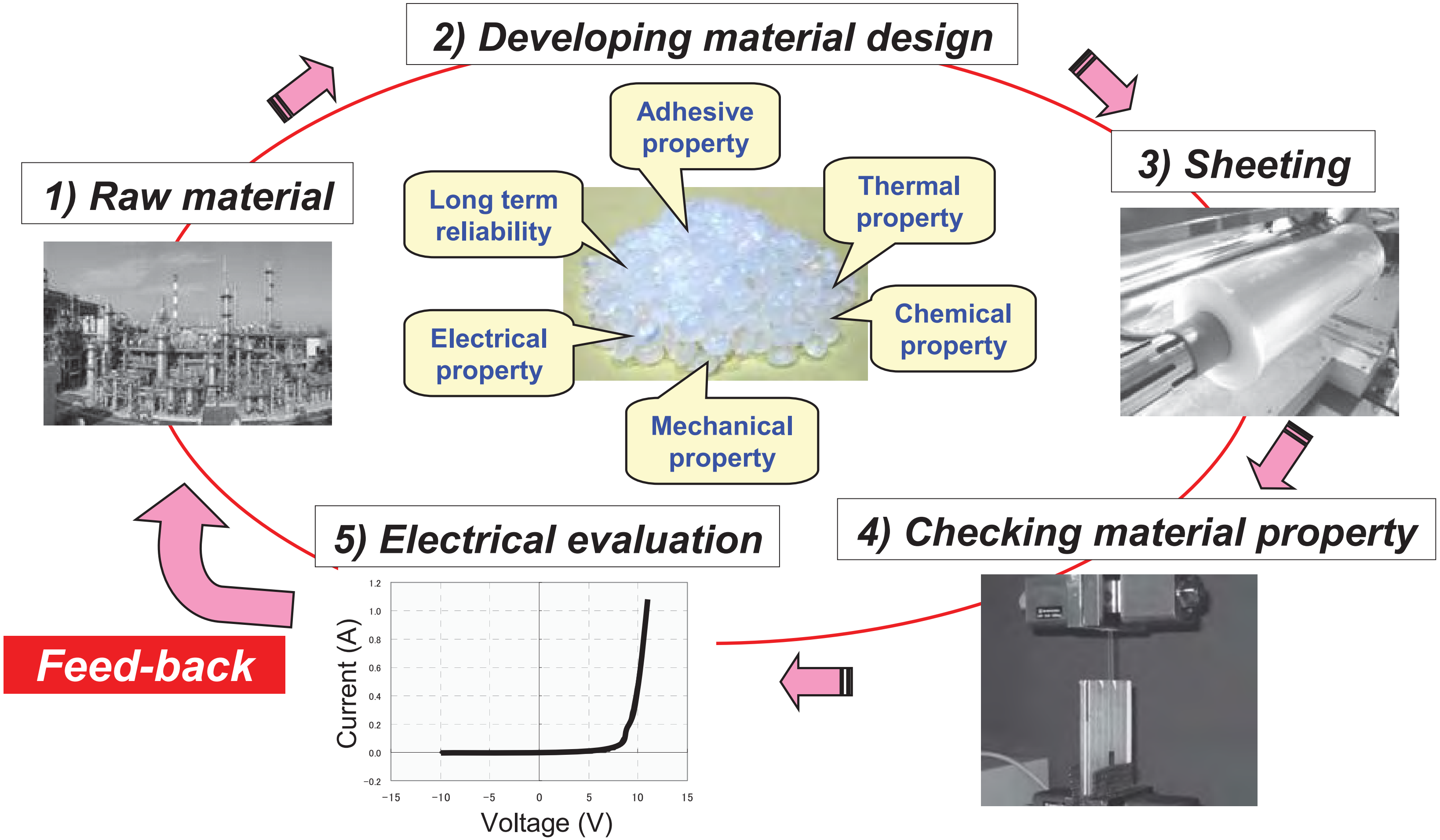
[1]H.Zenkoh,[1]J.Tokuhiro,[1]T.Murofushi, [1]M.Odoi
[1,2] T.Shioda

[1]Mitsui Chemicals Tohcello, Inc.
[2]Mitsui Chemicals, Inc.

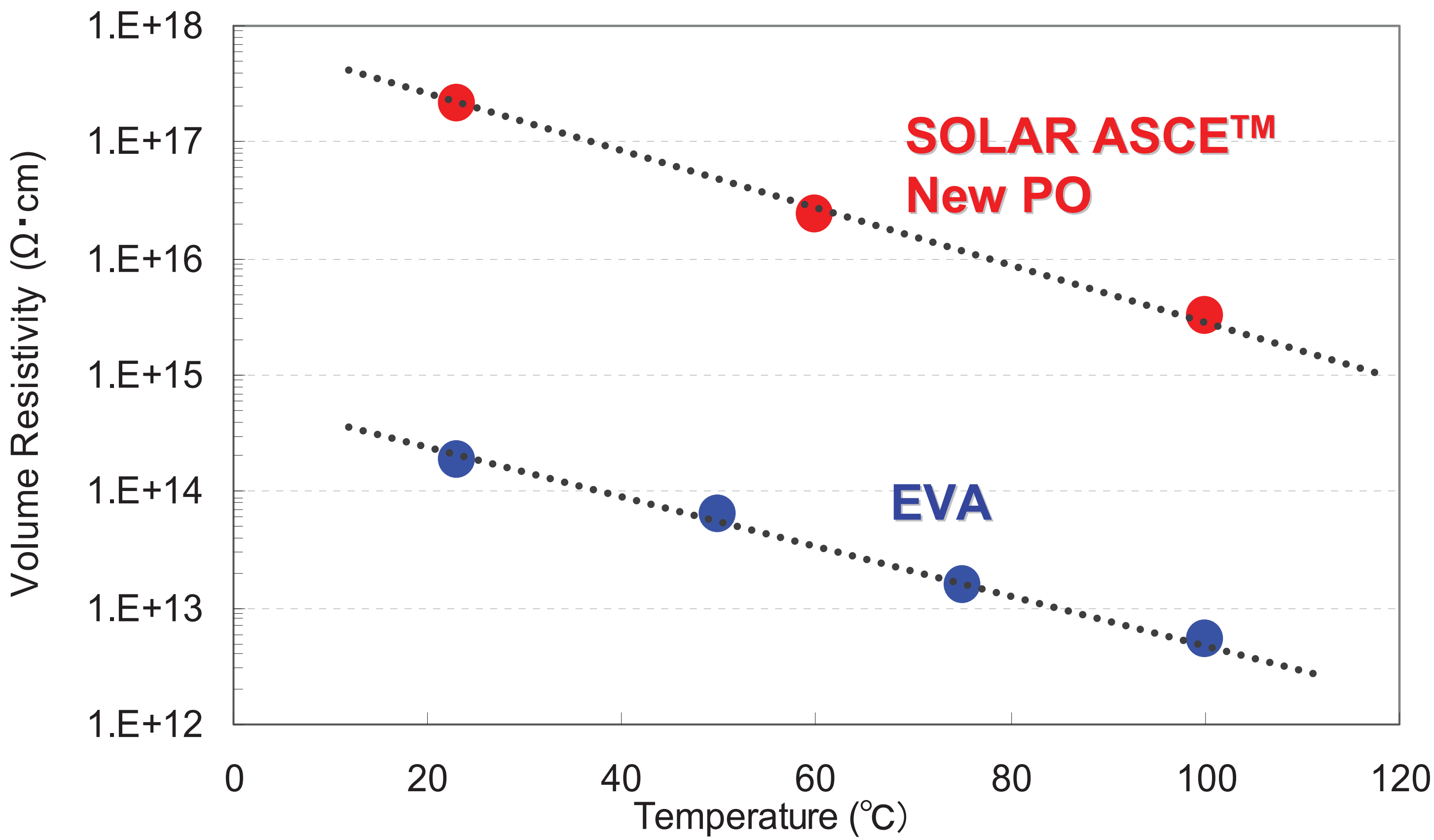
Motivation %

- ✓ In PV modules, cross-linked EVA encapsulant is commonly used because it has its transparency, thermal creep resistance, proven long term reliability on the field exposure over 20 years
- ✓ To address PID issue, high insulation encapsulant is one of the solutions
- ✓ Thermoplastic polyolefin encapsulant show better insulation property than EVA, but there are some concern about thermal creep resistance
- ✓ We have developed new polyolefin encapsulant "SOLAR ASCE™", which is based on high electrical resistivity polyolefin resin and is cross-linked during % lamination like EVA encapsulant %

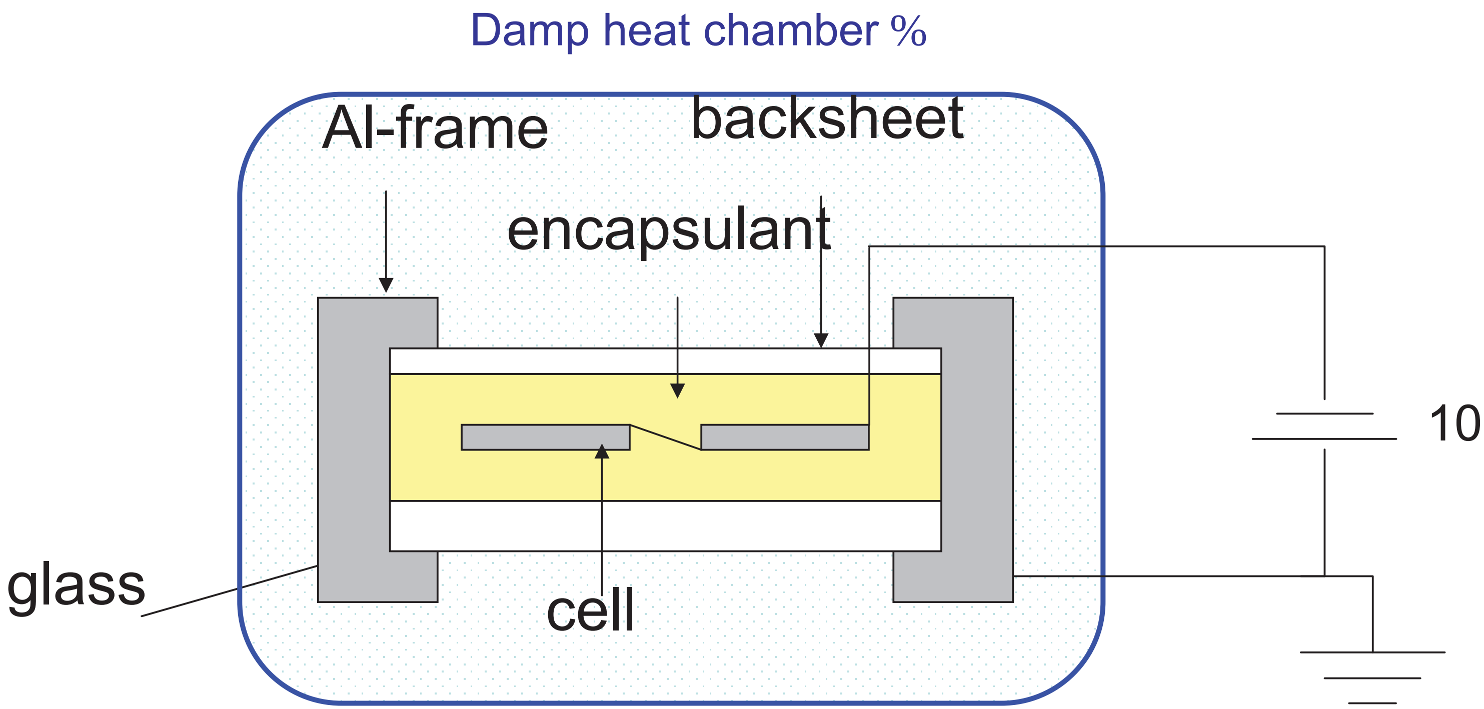
Scheme of designing New PO encapsulant



Volume Resistivity %



PID acceleration tests method %



Test conditions

Cell :single cell or full module

Exposure time : 96h - 240hr

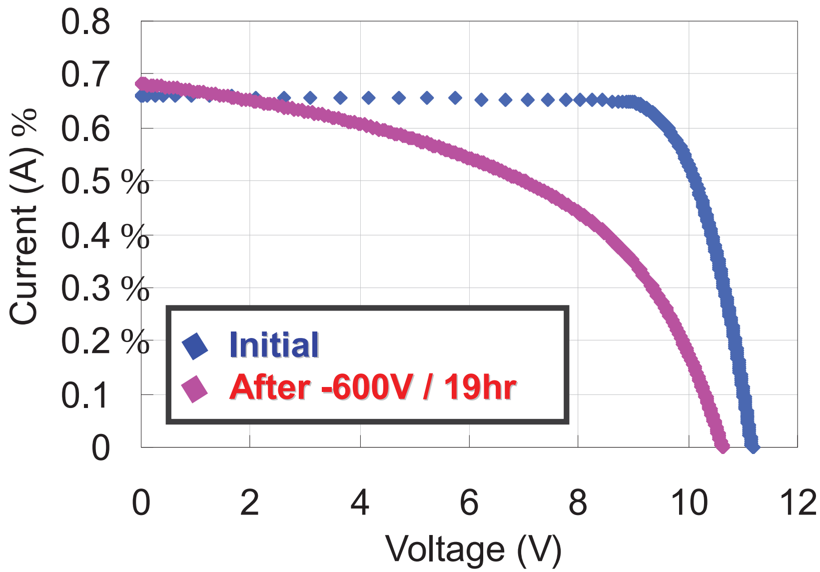
Voltage : -600V or -1000V

Temp. : 60^0C85% or 85^0C85%

Cell selection by PID test with conventional EVA

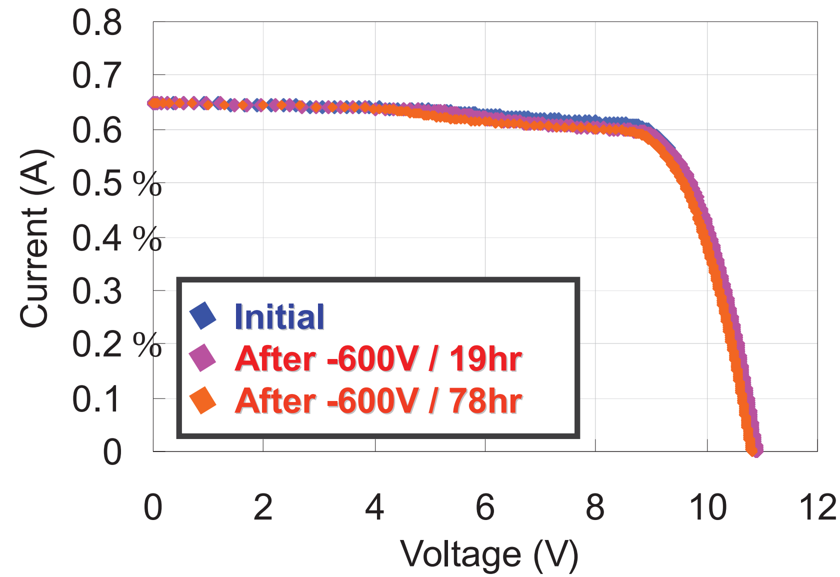
EVA with PID-prone cell (60oC85%RH,-600V)

Power loss : 40%



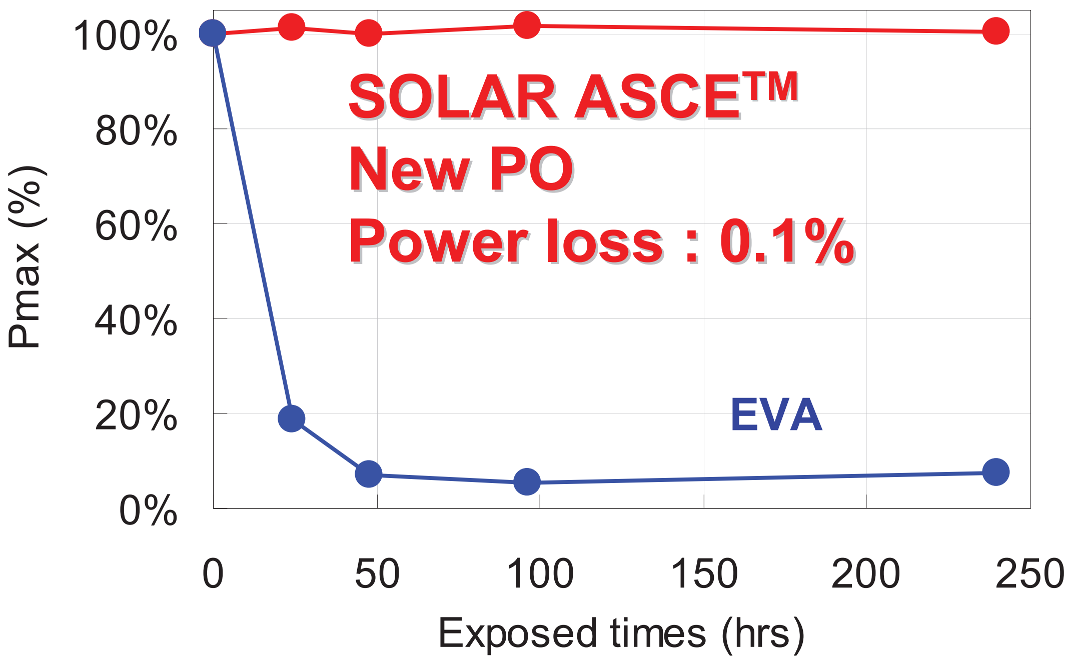
EVA with PID-durable cell ($60^{o}C85\%RH,-600V$)

Power loss : 2%



We have chose PID prone cells to evaluate SOLAR ASCE™

PID durability of New PO %



<u>PID test condition</u>

• Module

1Cell, 6inch multi-crystalline

(PID sensitive sell)

• 85^{o}C85% -1000V

<u>Measurement of Pmax</u>

Irradiance : 1000W/m2

PID durability of New PO %

<u>60 cells full module PID test with various encapsulant</u> %

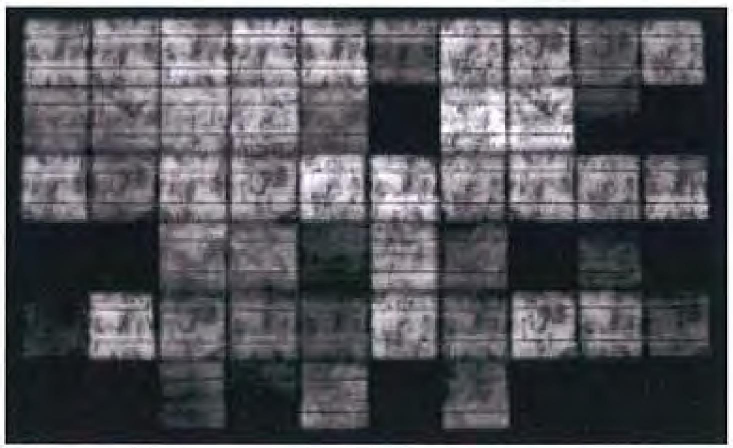
PID condition	SOLAR ASCE™ New PO	EVA
60°C85% -1000V 96hr	-1%	-75%
85°C85% -1000V 48hr	-1%	-80%

<u>PID test module</u> %
60Cells (6x10cells) %

SOLAR ASCE™
REAL PID FREE

Cell quality effect on PID %

Electroluminescence image of
PID occurred module

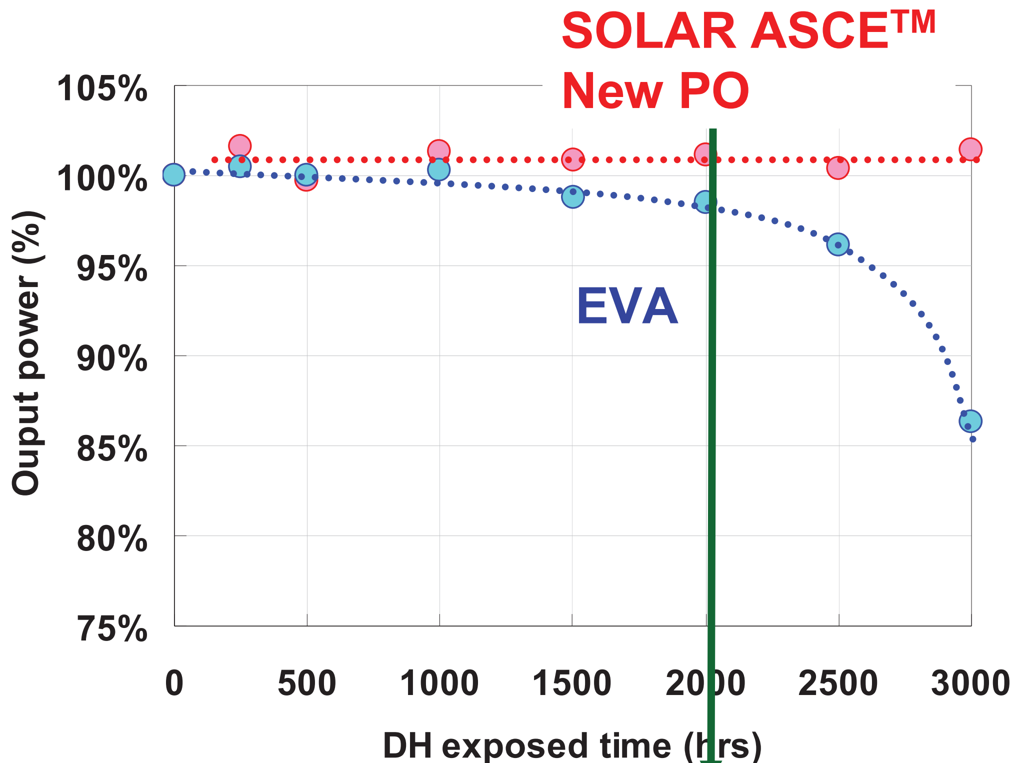


Reflective Index of AR-coating affects PID degradation

The data above was published at SOLON SE

Damp heat durability of New PO %

<u>*DH test of 36cells full module*</u> &



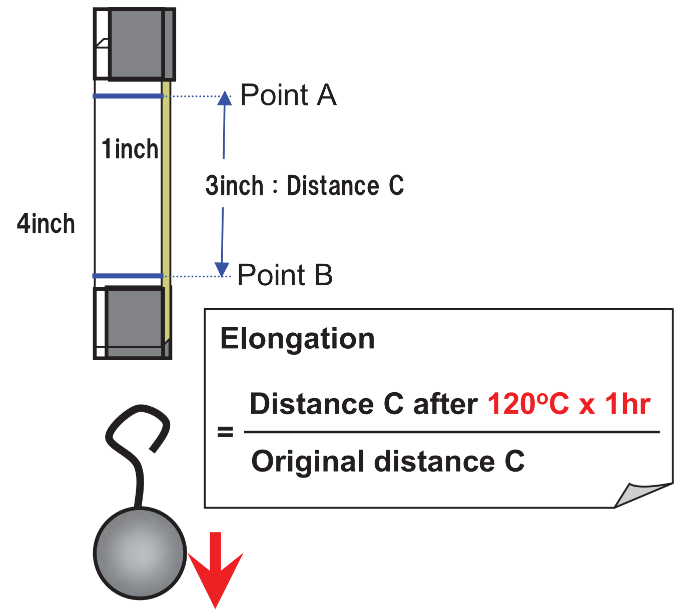
2000 hr: %generally recognized as the equivalent to 20 years in the field

**** Mono-Crystalline module (36Cell,1200mm ×527mm)***

Thermal creep stability %

Elongation of encapsulant at 120°C

		3000Pa	100Pa
SOLAR ASCE™ New PO	Cured	13%	0%
EVA	Cured	17%	0%
Thermoplastic PO encapsulant	Non-Cure	217%	12%



3000 or 100 Pa x 120°C x 1hr %

Thermal Creep property is improved by curing

Summary %

- ✓ PID failure occurs on high temperature, high humidity and high negative voltage on modules
- ✓ PID failure depends on Cell quality, especially reflective index of AR-coating
- ✓ Our New PO encapsulant ,SOLAR ASCE™, shows prominent PID improvement effect and expanding diversity of cell choices
- ✓ Cross-linking of New PO improve thermal creep stability just as good as cross-linked EVA encapsulant

PID-free c-Si PV module using novel chemically-tempered glass

Mika Kambe[1], Kojiro Hara[2], Michio Kondo[2]
1 Asahi Glass Co. Ltd.
2 National Institute of Advanced Industrial Science and Technology (AIST)

We have developed a PID free c-Si PV module using novel glass that is chemically tempered by substitution of Na ions by K ions in the surface region (AGC Leoflex^{TM}). Leoflex^{TM} is aluminosilicate glass and chemically tempered. Chemically tempered glass is widely used for smart-phones.
It is found that the absence of Na ions in the surface region drastically suppress the PID even using the same cells which shows severe degradation with conventional soda-lime glass.
After 96 hours application of -1000 V to the cell, the module with conventional cell shows degradation in the power by more than 90% and only 10% of the power remains, while the module with chemically tempered glass shows no degradation keeping more than 99.5% of the power.
Na migration into Si wafer is suppressed by using chemically tempered glass.

Experimental

Fabrication of 4-cell modules

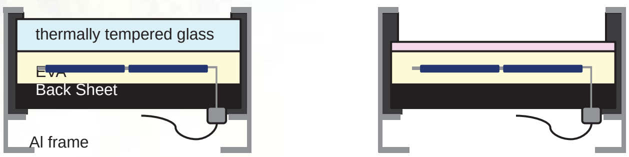


Fig. 1. Schematic diagrams of cross-section view of two kinds of 4-cell modules, with thermally tempered glass (left) and with chemically tempered glass "Leoflex^{TM}".

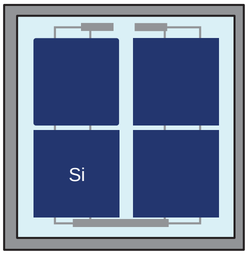


Fig. 2. Schematic diagram of top view of 4-cell modules.

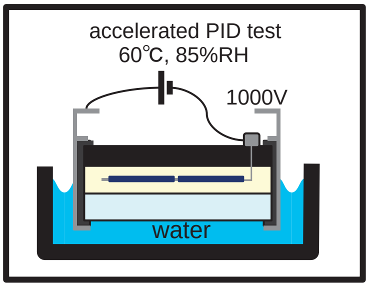


Fig. 3. Schematic diagram of accelerated PID test conditions.

Chemically tempered glass

Glass is submerged in a bath containing a potassium nitrate. Sodium ions in the glass surface are exchanged with potassium ions from the solution.

Na_2O in glass surface : >10 wt% → ~ 3 wt%
resistivity of glass : 1 → x 100

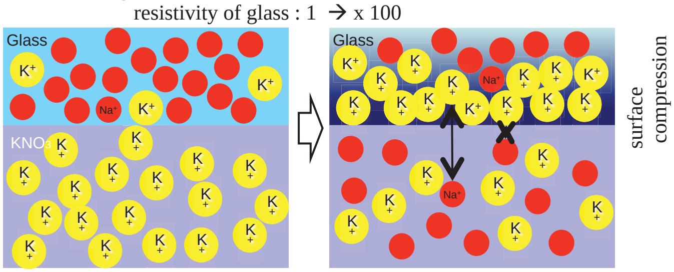


Fig. 7. Schematic diagrams of glass and potassium nitrate bath, before (left) and after (right) chemically tempering.

Chemically tempered glass as a photovoltaic module cover glass is commercially available now, as "Leoflex^{TM}" by Asahi Glass.
The Leoflex^{TM} is aluminosilicate glass and its composition is specially designed for good chemical-tempering characteristics.

Results

Modules with chemically tempered glass show no degradation keeping more than 99.5% of the power.

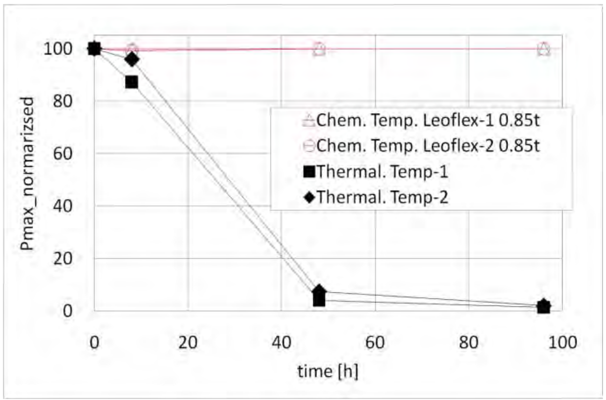
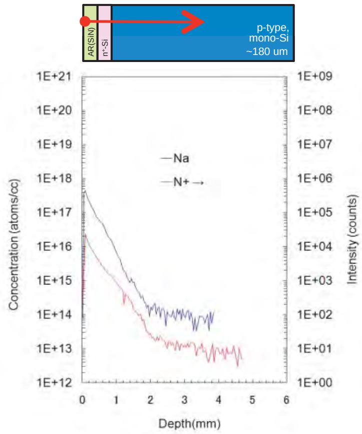
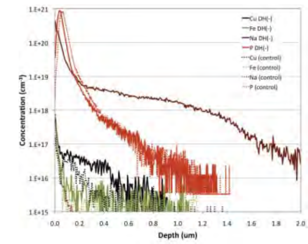


Fig. 4. Normalized performance of four 4-poly-Si modules, with thermally tempered glass and with chemically tempered glass "Leoflex^{TM}", in 60^{o}C/85% RH, -1000 V applied to the active layer for 96 h. Two modules were prepared and operated PID test for each type of the module.

SIMS





[ref] Fig. 6. SIMS analysis of a cell in a module that has undergone 1000 h of 85^{o}C/85% RH with –600 V applied to the active layer. Significant Na accumulation and up to an order of magnitude higher is seen near the surface. *P. Hacke et al. WCPEC-5 (2010, Spain), 3760.*

Fig. 5. Na and N depth profiles of a p-type mono-Si wafer in a module with chemically tempered glass that has undergone 48 h of 60^{o}C/85% RH with –1000 V (dipped in water) applied to the active layer. Na migration into Si wafer is suppressed by using chemically tempered glass compared to Fig. 6. Resolution of depth is not high enough because surface of the Si wafer is rough.

Literature Review of the Effects of UV ! Exposure on PV Modules !

Lawrence Dunn, Michael Gostein and Bill Stueve !
Atonometrics, Inc. !
Austin, Texas 78757 !
www.atonometrics.com !

Prepared for NREL PV Module Reliability Workshop !
February 16-17, 2013 !

lawrence.dunn@atonometrics.com
michael.gostein@atonometrics.com
bill.stueve@atonometrics.com

Abstract !

- Understanding the factors affecting the outdoor degradation and eventual failure of PV modules is crucial to the success of the PV industry. A significant factor responsible for PV module degradation is exposure to the UV component of solar radiation.
- We present here a literature review of the effects of prolonged UV exposure of PV modules, with a particular emphasis on UV exposure testing using artificial light sources, including fluorescent, Xenon, and metal halide lamps.
- We review known degradation mechanisms which have been shown to arise from UV exposure of PV modules, and examine the dependence of those degradation mechanisms on UV exposure.

UV Exposure and IEC Preconditioning Tests !

- The PV module qualification tests (*e.g.*, IEC 61215 [1] and IEC 61646 [2]) are not meant to simulate outdoor UV exposure for extended periods of time.
- The "UV Preconditioning" sections of the IEC standards mentioned above typically require 15 kWh/m^2 of total UVA+UVB exposure (280 nm - 400 nm), and at least 5 kWh/m^2 of UVB exposure (280 nm – 320 nm). The IEC standards require that the UV light source used emit light with a UVB content between 3% and 10%.
- The standard AM 1.5 spectrum [3] contains 46.1 W/m^2 between 280 nm and 400 nm, and 1.52 W/m^2 between 280 nm and 320 nm.
  - ~5% of the AM 1.5 Spectrum is UVA+UVB, and ~0.15% is UVB.
  - **15 kWh/m^2 (between 280 nm and 400 nm) corresponds to 13.5 days under the AM 1.5 spectrum.**
  - **5 kWh/m^2 (between 280 nm and 400 nm) corresponds to 137 days (~4.5 months) under the AM 1.5 spectrum**
- Annual total UV exposure in the Negev Desert is on the order of 120 kWh/m^2 [4]. 25 years of outdoor exposure in this environment is equivalent to approximately 3000 kWh/m^2.
  - The proscribed total UV dose in the IEC preconditioning tests of **15 kWh/m^2 simulates 2-4 months (conservatively) of real world operation** [5].
- **IEC UV Preconditioning tests provide no information on module lifetime.**

Encapsulant Issues !

EVA Browning !

- The browning of EVA ! encapsulant used in PV modules with outdoor exposure has been observed ! since at least the late 1980s at the Carrisa Planes PV installation [6]–[9]. !
- Later observations and studies appeared in the mid-1990s [10], [11], although at this time the agent responsible for EVA browning had not been identified. It is interesting that even in 1994 the authors of Ref. [10] noted that Cerium Oxide-containing glass (which blocks UV radiation below 350 nm) prevented EVA discoloration in indoor tests.

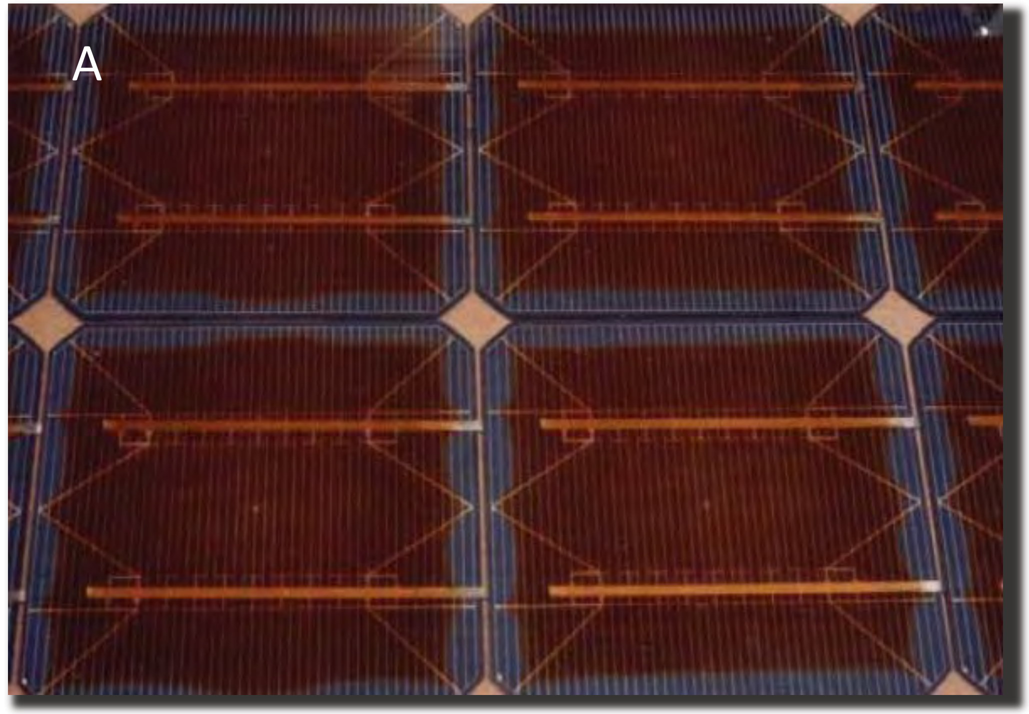
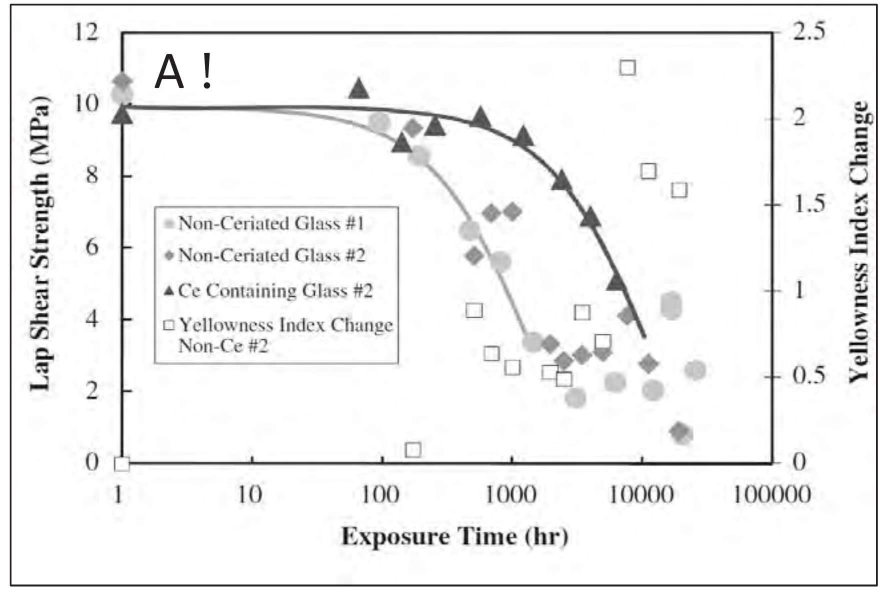


Figure A taken from Ref. [8].

EVA Browning

- Formulations of EVA that undergo yellowing/browning has also been shown to produce acetic acid, with UV exposure which corrodes solder bonds and electrical contacts [12]–[14]. This also corresponds to increased leakage current through the encapsulant [15].
- EVA adhesion and shear strength also studied, both shown to decrease significantly with EVA degradation [12], [16];
- By 1996-1997 it had been found that that EVA discoloration could be mediated through different EVA formulations (*i.e.*, the use of different additives), and by UV blocking glass [6], [13], [16]–[18].



Lap Shear Strength and Yellowness Index of EVA after exposure to 60 °C/60% Relative Humiditiy, and 2.5 UV Suns.

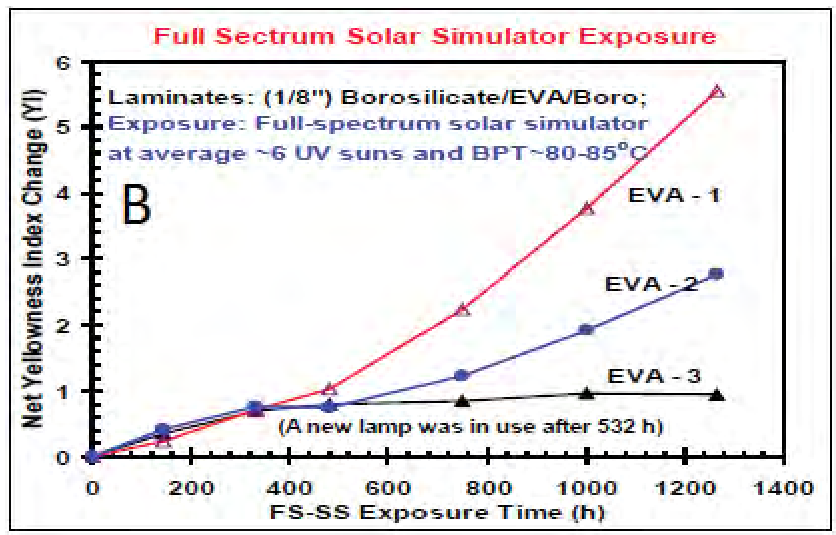
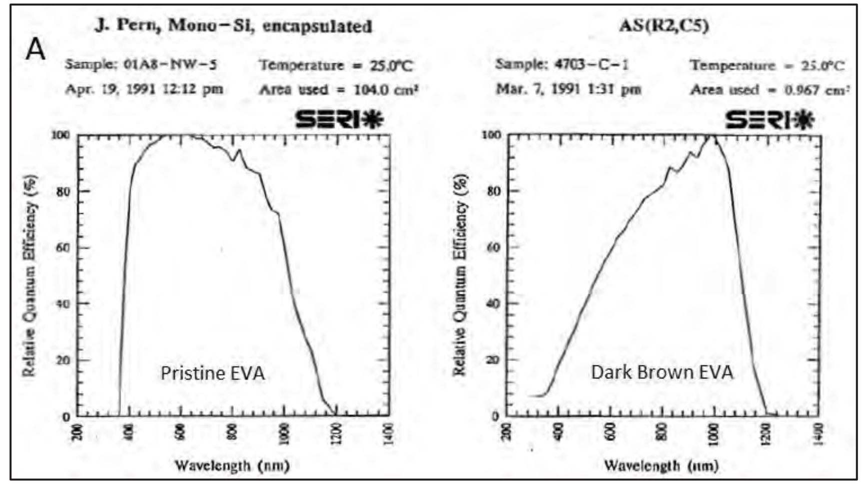
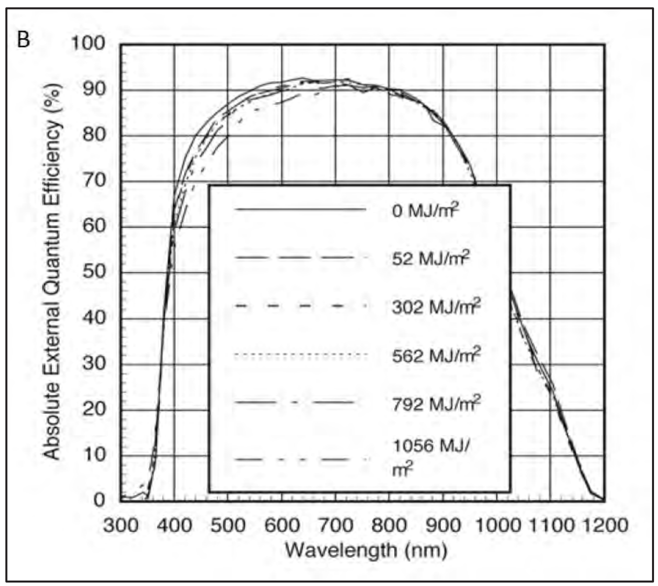


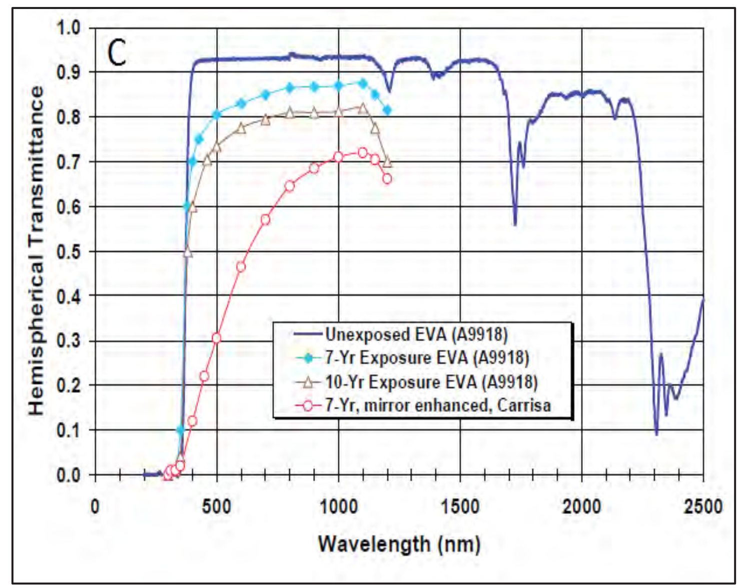
Fig. A taken from Ref [16]. *Fig. B taken from Ref. [8].*

Optical Losses due to EVA Browning

- Browning of EVA can cause a significant change in the perceived optical transmission of c-Si cells [8], [19], [20].
- Performance Losses initially attributed optical losses at the from EVA browning at the Carrisa Planes Site have later attributed to Fill Factor Losses due to solder-bond degradation and inadequate use of bypass diodes [21].
- Fig. A taken from Ref. [8], Fig. B taken from Ref. [22], and Fig. C taken from Ref. [19].







Encapsulant Adhesion & Delamination !

- Encapsulant delamination with prolonged outdoor exposure of PV modules is a well-known phenomenon [19], [23]–[26]. However, separating the effects of UV exposure and moisture on encapsulant delamination is not trivial.
- In 2003 Jorgensen *et al.* measured the "Peel Strength" of EVA layers vacuum laminated to various backsheet materials after exposure to a Xenon UV source at intensities of ~1 sun [27]. The results of the study are shown in the table below.
- Kempe has also quantified the effect of UV exposure on EVA adhesion via Lap Shear studies. See, *e.g.*, Ref. [16], and Fig. A on Slide 6.

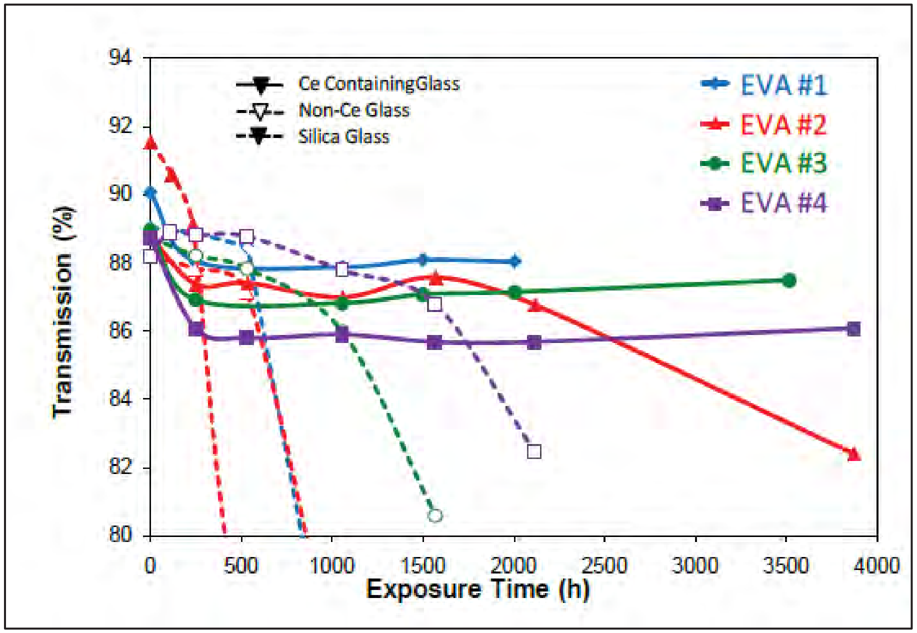
Peel strength (N/mm) at the EVA/coating interface as a function of exposure time in an Atlas Ci4000 Xenon Weather-Ometer (light intensity ~1 sun, 65°C, and 10% RH).

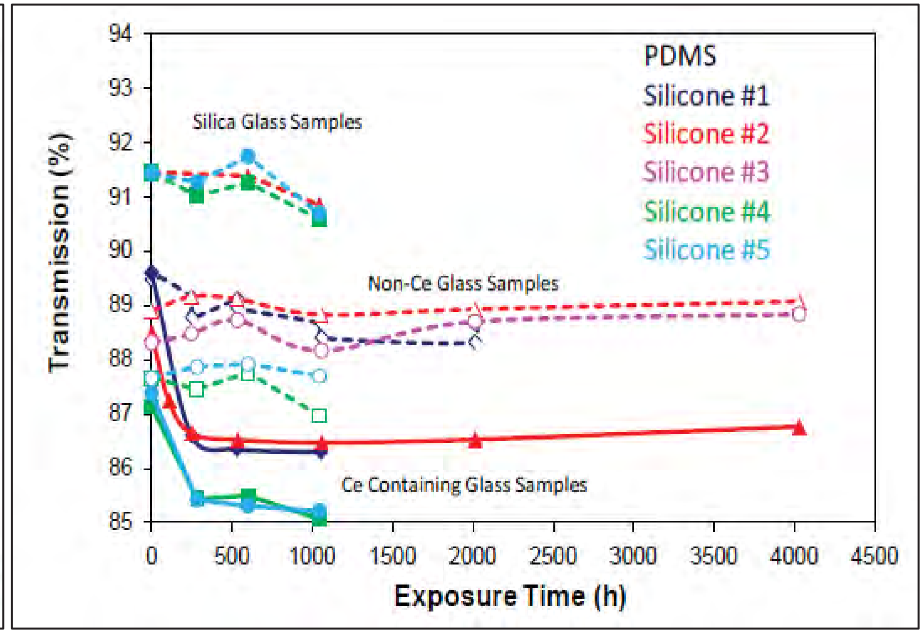
Backsheet	Time of Ci4000 Exposure (h)			
	0	**400**	**800**	**1200**
AKT Coated PET	11.4	13.0	7.2	6.4
NREL Coated PET	11.4	12.1	6.9	4.2
Uncoated PET	0.5	0.5	0.5	
TPE	7.5	7.0	0.5	
TAT	0.5	0.6	1.5	

Image of cell with delaminated encapsulant taken from Ref. [26]

EVA Alternatives

- Silicone has been shown to be more stable with UV exposure than EVA [15], [16], [28]
- Silicone encapsulants has been shown to have better optical transmission than EVA encapsulants. [29]–[31], resulting in one study in a 0.5% to 1.5% relative increase in PV module efficiency, mostly due to an increase in transmission below 400 nm [31].
- At least one study has examined the decrease in light transmittance and PV module efficiency for silicone-encapsulated PV modules with UV light exposure under an AM0 spectrum [32]. The authors found a ~15% decrease in PV module efficiency after a ~15 year UV dose.



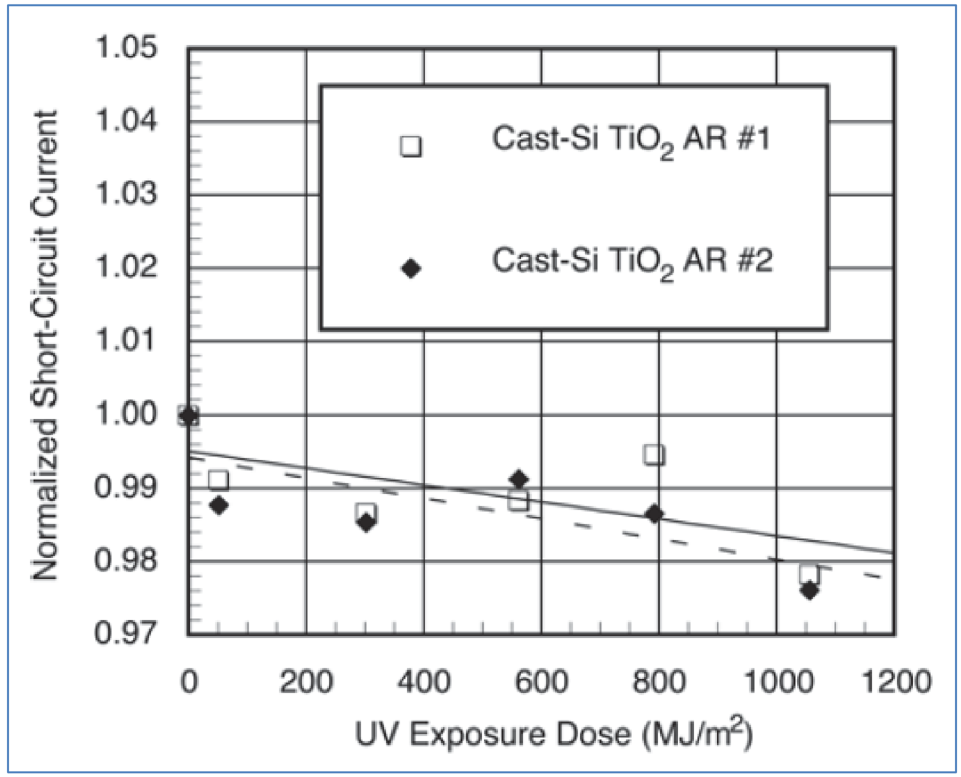


Figures taken from Ref. [28].

Intrinsic c-Si Degradation with UV Exposure !

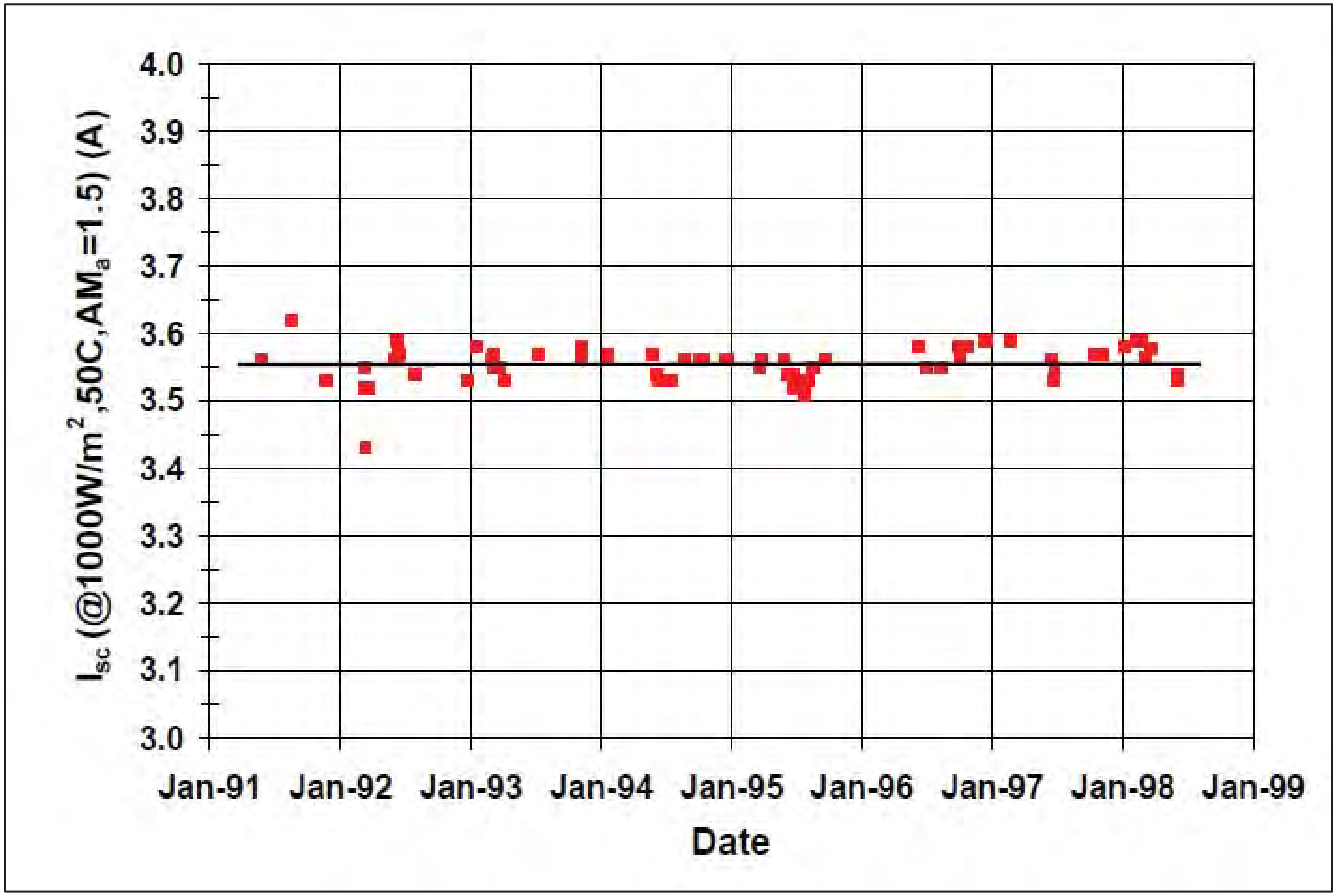
Intrinsic c-Si Isc Degradation with UV Exposure

- In 2003, Osterwald *et al.* published the results of a 5-year study of commercial c-Si PV modules in which the authors found a linear relationship between slow Isc degradation rates (-0.2%/year tob-0.5% year) and UV radiation dose [33]. The authors did not attribute the decrease in Isc to EVA browning, noting an example of one module with an 8% drop in Isc and no obvious change in encapsulant appearance.
- Osterwald *et al.*'s initial 2003 study was followed up by a 2005 study of EVA encapsulated and unencapsulated Si cell Isc degradation rates with UV exposure [22].
- The authors observed a 2% drop in Isc with a UV dose of 1056 MJ/m^2 (~3.8 years of outdoor exposure) in unencapsulated cells [22].
- The degradation rate with UV exposure of unencapsulated cells of varying types (*e.g.*, cast c-Si vs. Cz c-Si, with and without TiO_2, etc.) varied by a factor of ~2.7X [22].
- Unencapsulated cells kept in an oven as a control showed no change in Isc.
- Fig. shown from Ref. [22] for unencapsulated cells.



Intrinsic c-Si Isc Degradation with UV Exposure！

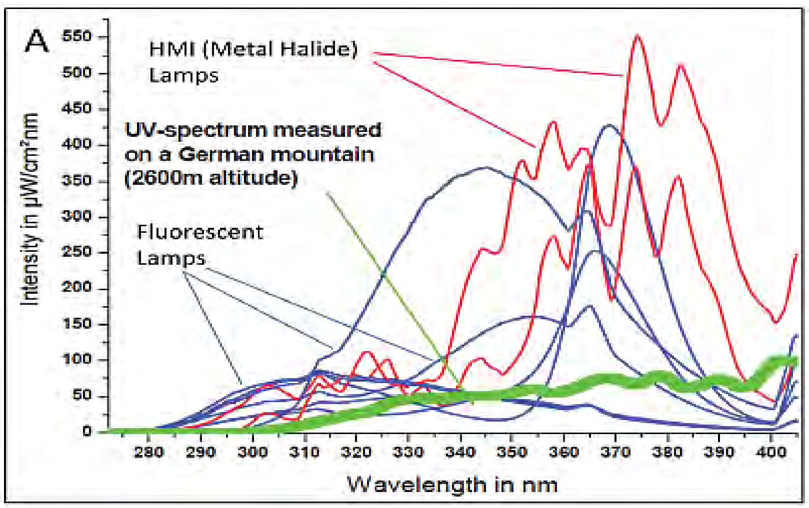
- King *et al.*, were able to show the use of Ce-Doped glass and a browning-resistant EVA formulation resulted in a stable PV module Isc after 7 years of outdoor exposure in Albuquerque [19]. Figure shown below taken from Ref. [19].



Simulating Outdoor UV Exposure !

Artificial Light Sources !

- Several artificial light sources that have been used for indoor UV exposure, including Xenon Arc Lamps [10], [12]–[14], [16]–[18], [28], [30], [34]–[37], [27], [38]–[40], Metal Halide Arc-Lamps [22], [34], [35], [41], and UV fluorescent lamps [4], [29], [35], [37], [39], [42]–[45].
- At least one study found differences in transmission spectra of EVA encapsulant aged in natural sunlight for 17 years and EVA encapsulant aged at high UV irradiances [34]. Another study used Raman Spectroscopy to compare outdoor aging of PV Modules with indoor exposure from fluorescent lamps [42].
- One major challenge is accurate spectral and irradiance measurements of UV irradiance.
- Fraunhofer ISE has performed an inter-comparison of UV sources and irradiance measurement sensors from accredited laboratories and major PV module manufacturer test centers, and errors as large as 120% in the calibrations of irradiance sensors [41].



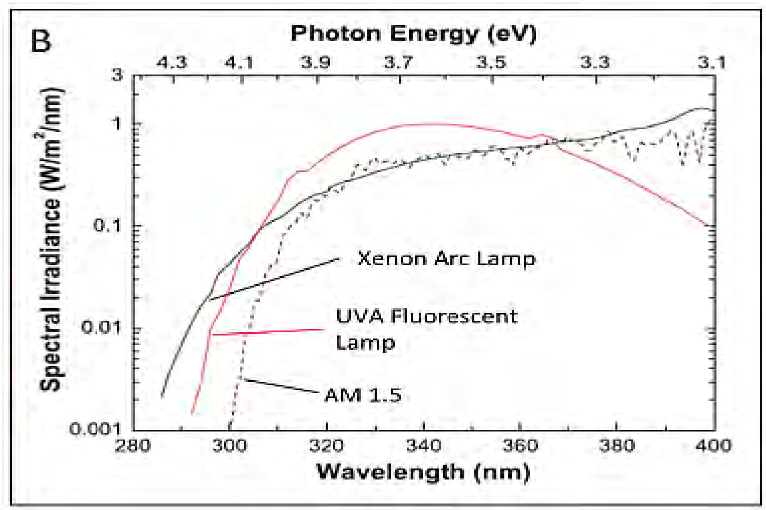


Fig. A taken from Ref. [41]. *Fig. B taken from Ref.* [29].

Atonometrics UV Exposure System !

References !

[1] “IEC 61215 ed2.0 - Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval.” IEC, 2005.
[2] “IEC 61646 ed2.0 - Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval.” IEC, 2008.
[3] ASTM International, West Conshohocken, PA, “ASTM Standard G173, 2008, ‘Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surfaces’.”
[4] M. Koehl, D. Philipp, N. Lenck, and M. Zundel, “Development and application of a UV light source for PV-module testing,” 2009, pp. 741202–741202–7.
[5] M. Köhl, “The challenges of testing the UV-impact on PV-modules,” Golden, Colorado, 2012.
[6] F. J. Pern, “Ethylene-vinyl acetate (EVA) encapsulants for photovoltaic modules: Degradation and discoloration mechanisms and formulation modifications for improved photostability,” *Die Angewandte Makromolekulare Chemie*, vol. 252, no. 1, pp. 195–216, Dec. 1997.
[7] H. J. Wenger, J. Schaefer, A. Rosenthal, B. Hammond, and L. Schlueter, “Decline of the Carrisa Plains PV power plant: the impact of concentrating sunlight on flat plates,” in *Conference Record of the 22nd IEEE Photovoltaic Specialists Conference*, Las Vegas, NV, 1991, pp. 586–592.
[8] J. Pern, “Module Encapsulation Materials, Processing and Testing,” Shanghai, China, 2008.
[9] D. C. Jordan and S. R. Kurtz, “Photovoltaic Degradation Rates-an Analytical Review,” *Progress in Photovoltaics: Research and Applications*, vol. 21, no. 1, pp. 12–29, Jan. 2013.
[10] W. H. Holley, S. C. Agro, J. P. Galica, L. A. Thoma, R. S. Yorgensen, M. Ezrin, P. Klemchuk, and G. Lavigne, “Investigation into the causes of browning in EVA encapsulated flat plate PV modules,” in *Conference Record of the 24th IEEE Photovoltaic Specialists Conference*, Waikoloa, HI, 1994, vol. 1, pp. 893–896.
[11] D. Berman, S. Biryukov, and D. Faiman, “EVA laminate browning after 5 years in a grid-connected, mirror-assisted, photovoltaic system in the Negev desert: effect on module efficiency,” *Solar Energy Materials and Solar Cells*, vol. 36, no. 4, pp. 421–432, Apr. 1995.
[12] M. D. Kempe, G. J. Jorgensen, K. M. Terwilliger, T. J. McMahon, C. E. Kennedy, and T. T. Borek, “Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices,” *Solar Energy Materials and Solar Cells*, vol. 91, no. 4, pp. 315–329, Feb. 2007.
[13] P. Klemchuk, M. Ezrin, G. Lavigne, W. Holley, J. Galica, and S. Agro, “Investigation of the degradation and stabilization of EVA-based encapsulant in field-aged solar energy modules,” *Polymer Degradation and Stability*, vol. 55, no. 3, pp. 347–365, Mar. 1997.
[14] F. J. Pern and A. W. Czanderna, “EVA degradation mechanisms simulating those in PV modules,” 1992, vol. 268, pp. 445–452.
[15] M. Kempe, M. Reese, A. Dameron, and T. Moricone, “Types of Encapsulant Materials and Physical Differences Between Them,” Golden, Colorado, 2010.
[16] M. D. Kempe, “Ultraviolet light test and evaluation methods for encapsulants of photovoltaic modules,” *Solar Energy Materials and Solar Cells*, vol. 94, no. 2, pp. 246–253, Feb. 2010.
[17] W. H. Holley, S. C. Agro, J. P. Galica, and R. S. Yorgensen, “UV stability and module testing of nonbrowning experimental PV encapsulants,” in *Conference Record of the 25th IEEE Photovoltaic Specialists Conference*, Washington, DC, 1996, pp. 1259–1262.

[18] M. D. Kempe, T. Moricone, and M. Kilkenny, “Effects of cerium removal from glass on photovoltaic module performance and stability,” 2009, p. 74120Q–74120Q–12.
[19] D. L. King, M. A. Quintana, J. A. Kratochvil, D. E. Ellibee, and B. R. Hansen, “Photovoltaic module performance and durability following long-term field exposure,” presented at the National center for photovoltaics (NCPV) 15th program review meeting, Denver, CO, 1999, pp. 565–571.
[20] A. Parretta, M. Bombace, G. Graditi, and R. Schioppo, “Optical degradation of long-term, field-aged c-Si photovoltaic modules,” *Solar Energy Materials and Solar Cells*, vol. 86, no. 3, pp. 349–364, Mar. 2005.
[21] W. J. H. and P. R. C., “Reliability of EVA modules,” in *Conference Record of the 23rd IEEE PV Specialists Conference*, Louisville, KY, 1993, pp. 1090– 1094.
[22] C. R. Osterwald, J. Pruett, and T. Moriarty, “Crystalline silicon short-circuit current degradation study: initial results,” in *Conference Record of the 31st IEEE Photovoltaic Specialists Conference*, Lake Buena Vista, FL, 2005, pp. 1335–1338.
[23] A. Skoczek, T. Sample, and E. D. Dunlop, “The Results of Performance Measurements of Field-aged Crystalline Silicon Photovoltaic Modules,” *Prog. Photovolt: Res. Appl.*, vol. 17, pp. 227–240.
[24] E. D. Dunlop and D. Halton, “The performance of crystalline silicon photovoltaic solar modules after 22 years of continuous outdoor exposure,” *Progress in Photovoltaics: Research and Applications*, vol. 14, no. 1, pp. 53–64, Jan. 2006.
[25] M. A. Quintana, D. L. King, T. J. McMahon, and C. R. Osterwald, “Commonly observed degradation in field-aged photovoltaic modules,” in *Conference Record of the 29th IEEE Photovoltaic Specialists Conference*, New Orleans, LA, 2002, pp. 1436–1439.
[26] C. E. Chamberlin, M. A. Rocheleau, M. W. Marshall, A. M. Reis, N. T. Coleman, and P. A. Lehman, “Comparison of PV module performance before and after 11 and 20 years of field exposure,” in *Conference Record of the 37th IEEE Photovoltaic Specialists Conference*, Seattle, WA, 2011, pp. 000101–000105.
[27] G. Jorgensen, K. Terwilliger, S. Glick, J. Pern, and T. McMahon, “Materials Testing for PV Module Encapsulation,” presented at the National Center for Photovoltaics and Solar Program Review Meeting, Denver, CO, 2003.
[28] M. D. Kempe, M. Kilkenny, T. J. Moricone, and J. Z. Zhang, “Accelerated stress testing of hydrocarbon-based encapsulants for medium-concentration CPV applications,” in *Conference Record of the 34th IEEE Photovoltaic Specialists Conference*, Philadelphia, PA, 2009, pp. 001826–001831.
[29] K. R. McIntosh, N. E. Powell, A. W. Norris, J. N. Cotsell, and B. M. Ketola, “The effect of damp-heat and UV aging tests on the optical properties of silicone and EVA encapsulants,” *Progress in Photovoltaics: Research and Applications*, vol. 19, no. 3, pp. 294–300, May 2011.
[30] K. R. McIntosh, J. N. Cotsell, J. S. Cumpston, A. W. Norris, N. E. Powell, and B. M. Ketola, “The effect of accelerated aging tests on the optical properties of silicone and EVA encapsulants,” in *Proceedings of the 24th European PVSEC*, Hamburg, Germany, 2009.
[31] K. R. McIntosh, J. N. Cotsell, A. W. Norris, N. E. Powell, and B. M. Ketola, “An optical comparison of silicone and EVA encapsulants under various spectra,” in *Conference Record of the 35th IEEE Photovoltaic Specialists Conference*, Honolulu, HI, 2010, pp. 000269–000274.

[32] C. G. Zimmermann, "Time dependent degradation of photovoltaic modules by ultraviolet light," *Applied Physics Letters*, vol. 92, no. 24, p. 241110, 2008.
[33] C. R. Osterwald, "Degradation in weathered crystalline-silicon PV modules apparently caused by UV radiation," in *Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion*, Osaka, Japan, 2003, vol. 3, pp. 2911–2915.
[34] T. Shioda, "UV accelerated test condition based on analysis of field-exposed PV modules," Gaithersburg, MD, Oct-2011.
[35] C. R. Osterwald and T. J. McMahon, "History of accelerated and qualification testing of terrestrial photovoltaic modules: A literature review," *Prog. Photovolt: Res. Appl.*, vol. 17, no. 1, pp. 11–33, Jan. 2009.
[36] M. D. Kempe, "Accelerated UV Test Methods for Encapsulants of Photovoltaic Modules," presented at the 33rd IEEE Photovoltaic Specialists Conference, San Diego, CA, 2008.
[37] G. J. Jorgensen and T. J. McMahon, "Accelerated and outdoor aging effects on photovoltaic module interfacial adhesion properties," *Progress in Photovoltaics: Research and Applications*, vol. 16, no. 6, pp. 519–527, Sep. 2008.
[38] G. D. Barber, G. J. Jorgensen, K. Terwilliger, S. H. Glick, J. Pern, and T. J. McMahon, "New barrier coating materials for PV module backsheets," in *Conference Record of the 29th IEEE Photovoltaic Specialists Conference*, New Orleans, LA, 2002, pp. 1541–1544.
[39] C. R. Osterwald, J. Pruett, D. R. Myers, S. Rummel, A. Anderberg, L. Ottoson, and T. Basso, "Real-Time and Accelerated Solar Weathering of Commercial PV Modules," presented at the NCPV Program Review Meeting, Lakewood, CO, 2001.
[40] V. Saly, M. Ruzinsky, and P. Redi, "Indoor study and ageing tests of solar cells and encapsulations of experimental modules," presented at the 24th International Spring Seminar on Electronics Technology: Concurrent Engineering in Electronic Packaging, Calimanesti-Caciulata, Romania, 2001, pp. 59–62.
[41] D. Philipp, K.-A. Weiss, and M. Koehl, "Inter-laboratory comparison of UV-light sources for accelerated durability testing of PV modules," in *Proc. SPIE 8112, Reliability of Photovoltaic Cells, Modules, Components, and Systems IV, 81120G*, 2011, vol. 8112, p. 81120G–81120G–5.
[42] C. Peike, T. Kaltenbach, K. A. Weiß, and M. Koehl, "Indoor vs. outdoor aging: polymer degradation in PV modules investigated by Raman spectroscopy," 2012, p. 84720V–84720V–8.
[43] J. Mori, "Light source for PV modules test," 19-Jan-2012.
[44] T. Sample, A. Skoczek, M. Field, M. Köhl, D. Geyer, and W. Herrmann, "Accelerated Ageing of Seven Different Thin-Film Module Types by Sequential Exposure to Damp Heat or Damp Heat with either Additional Applied Voltage or Ultraviolet Light," in *Conference Record of the 24th European Photovoltaic Solar Energy Conference*, Hamburg, Germany, 2009, pp. 3241 – 3247.
[45] "A Choice of Lamps for the QUV," Q-Lab Corporation, Technical Bulletin LU-8160, 2006.

Use of Standard Fluorescent UV Weathering Lamps to Perform UV Conditioning Tests Prescribed in IEC Qualification Standards

Sean Fowler
Q-Lab Corporation
sfowler@q-lab.com

Q-LAB

Scope

IEC qualification tests require UV Conditioning exposures. Precisely how to meet these requirements has caused some confusion in the marketplace. Sources of confusion include:

- Different exposure requirements in each qualification standard
- Lack of readily available single light source to meet two of the standards
- Lack of specifics or references to other standards for guidance

ASTM Committee E44 intends to address these concerns by creating a standard on meeting the UV conditioning requirements of the IEC qualification standards.

WK38365: Standard Practice for Ultraviolet Conditioning of Photovoltaic Panels or Mini-Modules Using a Fluorescent Ultraviolet (UV) Lamp Apparatus

UV Conditioning Test Requirements

- IEC 61215 (Crystalline Si Modules Qualification)
  - 60°C module temperature
  - 15 kWh/m^2 280nm-385nm
  - 5 kWh/m^2 (minimum) 280nm-320nm
  - Consecutive exposures to UVA-340 and UVB-313 lamps
- IEC 61345 (UV Test of PV Modules)
  - 60°C module temperature
  - 15 kWh/m^2 320nm-400nm
  - 7.5 kWh/m^2 (minimum) 280nm-320nm
  - Consecutive exposures to UVA-340 and UVB-313 lamps
  - At end of initial exposure, expose back side of modules for an additional 10% of time
- IEC 61646 (Thin Film Modules Qualification)
  - 60°C module temperature
  - 15 kWh/m^2 280nm-400nm
  - .45-1.5 kWh/m^2 (minimum) 280nm-320nm
  - UVA-340 lamps only

Proposal: ASTM WK38365

- Perform UV conditioning tests according to method and apparatus described in ASTM G154-12: Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials

Apparatus

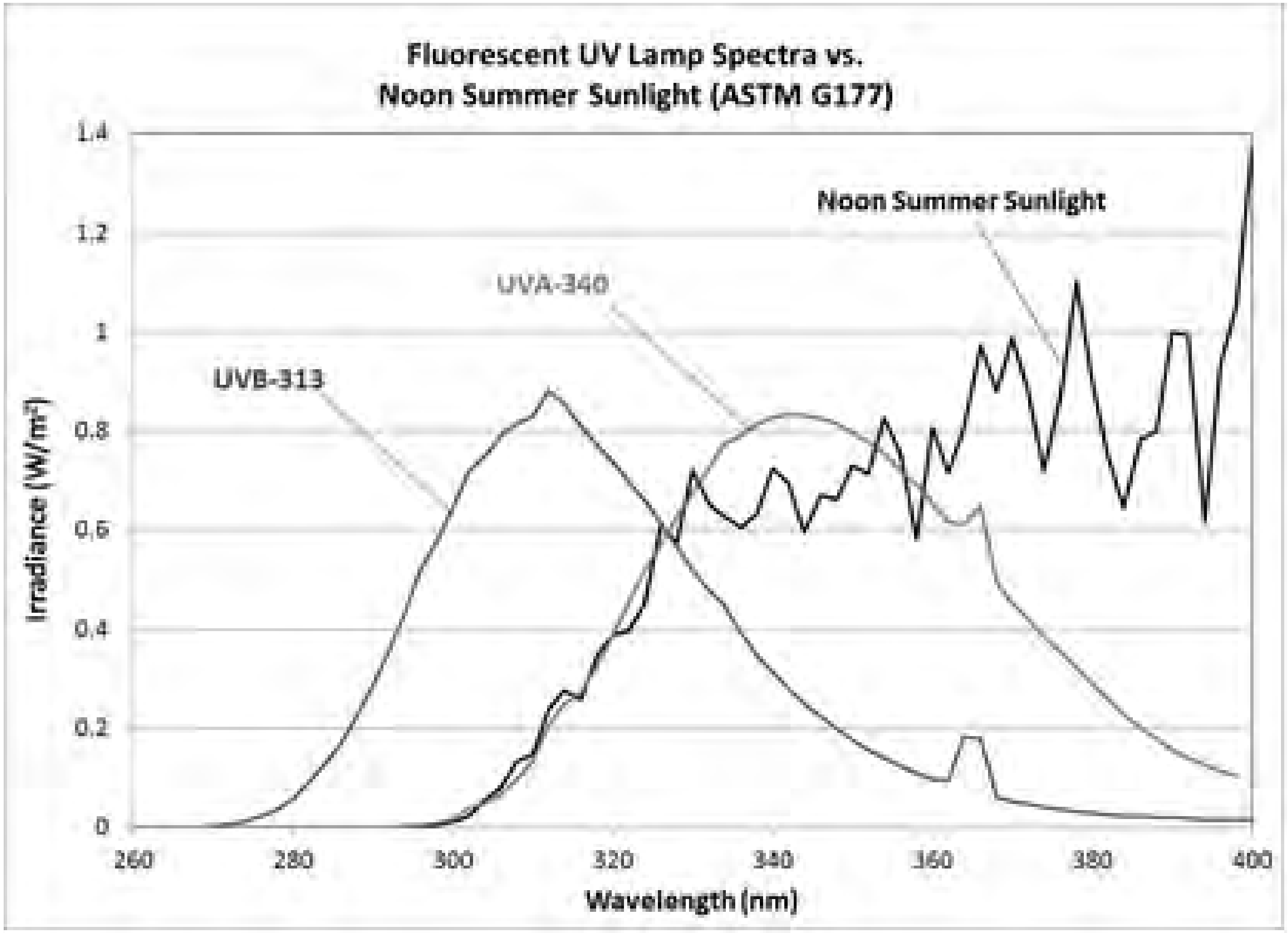
- Fluorescent Ultraviolet Lamp Apparatus (ASTM G154)

QUV Accelerated Weathering Tester from Q-Lab

UVTest Fluorescent/UV Instrument from Atlas

- UVA-340 lamps
- UVB-313 lamps
- Optional moisture (condensation, spray)

Common Fluorescent UV Lamps



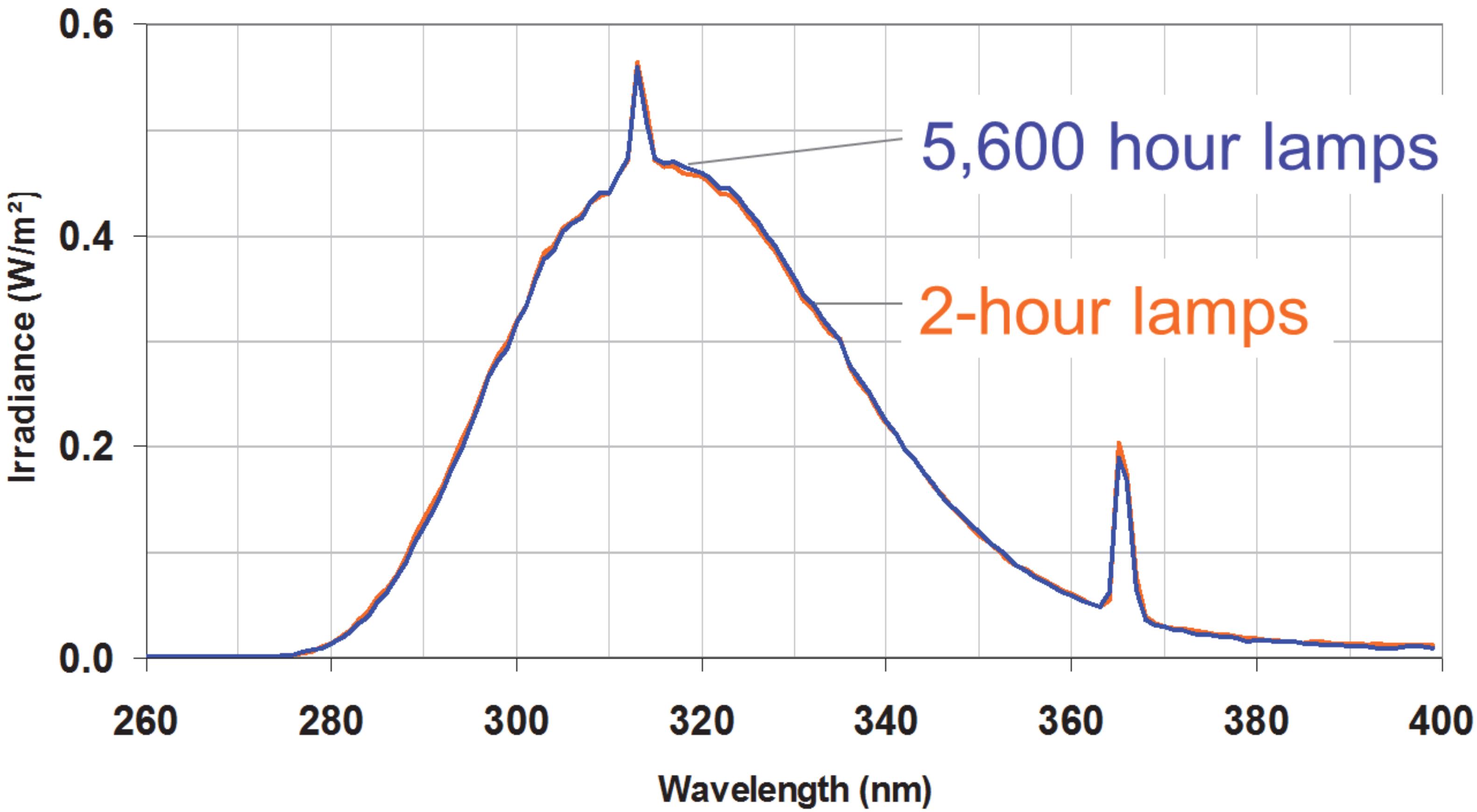
UVA-340 Lamps

Spectral Bandpass Wavelength λ in nm	Minimum Percent	Benchmark AM1.5 Solar Radiation Percent	Benchmark AM1 Solar Radiation Percent	Maximum Percent
λ <290				0.01
290 ≤ λ ≤ 320	5.9	3.5	5.8	9.3
320 < λ ≤ 360	60.9	38.0	40.0	65.5
360 < λ ≤ 400	26.5	58.5	54.2	32.8

UVB-313 Lamps

Spectral Bandpass Wavelength λ in nm	Minimum Percent	Benchmark AM1.5 Solar Radiation Percent	Benchmark AM1 Solar Radiation Percent	Maximum Percent
λ <290	1.3			5.4
290 ≤ λ ≤ 320	47.8	3.5	5.8	65.9
320 < λ ≤ 360	26.9	38.0	40.0	43.9
360 < λ ≤ 400	1.7	58.5	54.2	7.2

Lamp Aging with Controlled Power Source



Test performed in a QUV with SOLAR EYE
Irradiance Control

Irradiance Measurement/Control

- G154 Instruments generally use narrow band irradiance measurement and control and irradiance is measured in Watts per square meter
  - 340 nm for UVA type lamps, 310 nm for UVB type lamps

    Example: 0.89 W/m^2 @ 340 nm

  - Necessary to convert to wide band values:

$$\int_{\lambda=lower\ limit}^{upper\ limit} irradiance\ (W/m^2)$$

Where *lower limit* = 280 nm or 320 nm AND *upper limit* = 320 nm or 385 nm or 400 nm

Depending on the particular IEC method

IEC 61215

$$\int_{\lambda=280}^{385} \textit{irradiance}\ (W/m^2) \times \textit{Time (hours)} = 15\ \text{kW•hr}$$

AND

$$\int_{\lambda=280}^{320} \textit{irradiance}\ (W/m^2) \times \textit{Time (hours)} = 5\ \text{kW•hr}$$

IEC 61345

$$\int_{\lambda=280}^{320} \textit{irradiance}\ (W/m^2) \times \textit{Time (hours)} = 7.5\ \text{kW•hr}$$

AND

$$\int_{\lambda=320}^{400} \textit{irradiance}\ (W/m^2) \times \textit{Time (hours)} = 15\ \text{kW•hr}$$

IEC 61646

$$\int_{\lambda=280}^{400} \textit{irradiance}\ (W/m^2) \times \textit{Time (hours)} = 15\ \text{kW•hr}$$

AND

$$\int_{\lambda=280}^{320} \textit{irradiance}\ (W/m^2) \times \textit{Time (hours)} = 0.45\text{-}1.5\ \text{kW•hr}$$

Integration Factors to convert single wavelength irradiance measurements into wide band measurements

Wavelength Range	UVA-340 (340 nm)	UVB-313 (310 nm)
280-400 nm	54.5	46.3
280-320 nm	4.3	27.2
321-400 nm	50.2	19.2
280-385 nm	52.0	46.0

$Irradiance_{narrow\ band}$ (W/m^2) x Integration Factor x Time(hours) = Energy Dosage (Watt-hours

<u>IEC 61215, C-Si UV Conditioning</u>

[0.87 W/m^2 @ 340 nm] x 52.0 x 168 hours = 7.6 kW•hr (280-385 nm)
[0.87 W/m^2 @ 340 nm] x 4.3 x 168 hours = 0.6 kW•hr (280-320 nm)

[0.96 W/m^2 @ 310 nm] x 46.0 x 168 hours = 7.4 kW•hr (280-385 nm)
[0.96 W/m^2 @ 310 nm] x 27.2 x 168 hours = 4.4 kW•hr (280-320 nm)

Total: 15 kW•hr (280-385 nm) AND 5kW•hr (280-320 nm)

IEC 61646, Thin Film UV Conditioning

[1.15W/m^2 @ 340 nm] x   54.5 x 240 hours = 15.0 kW•hr (280-400 nm)
[1.15 W/m^2 @ 340 nm] x   4.3 x 240 hours = 1.2 kW•hr (280-320 nm)

IEC 61345, UV Test of PV Modules

[0.86 W/m^2 @ 340 nm] x   50.2 x 240 hours = 10.4 kW•hr (320-400 nm)
[0.86 W/m^2 @ 340 nm] x   4.3 x 240 hours = 0.9 kW•hr (280-320 nm)

[1.02 W/m^2 @ 310 nm] x   19.2 x 240 hours = 4.7 kW•hr (320-400 nm)
[1.02 W/m^2 @ 310 nm] x   27.2 x 240 hours = 6.6 kW•hr (280-320 nm)

Total: 15 kW•hr (320-400 nm) AND 7.5kW•hr (280-320 nm)

Accelerated Laboratory Tests Using Simultaneous UV, Temperature and Moisture for PV Encapsulants, Frontsheets and Backsheets

NIST
Polymeric Materials Group
Engineering Laboratory

Xiaohong Gu, Chiao-Chi Lin, Yongyan Pang, Kathryn Connolly, and Joannie Chin*

INTRODUCTION

The use of simultaneous multiple stresses (temperature, moisture, UV radiation) for the accelerated laboratory testing is critical to the development of reliable laboratory test methods that correlate to field test.

In this study, the NIST SPHERE *(Simulated Photodegradation via High Energy Radiant Exposure)* was used for accelerated laboratory testing of PV encapsulants, including ethylene vinyl acetate (EVA), fronsheet fluoropolymers, and polyvinyl fluoride /polyester/EVA (PVF/PET/EVA) backsheet materials. The outdoor exposure was also carried out in Gaithersburg, Maryland. Multiscale chemical, optical, mechanical and morphological measurements were performed to follow changes during accelerated laboratory 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 simutaneous UV, temperature and moisture on degradation mechanism of PV materials/modules)
- **Outdoor Exposure** (with monitored weather parameters)
- Cumulative Damage Prediction Model
- Failure Mode Analysis

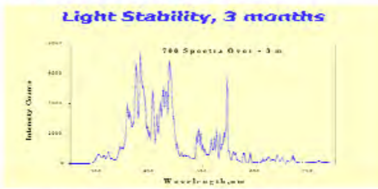
➢ **To develop reliable accelerated laboratory test methods that correlate to field test.**

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 6626052*

EXPERIMENTAL

Materials

(A) EVA

Laminated EVA

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

(B) Frontsheet fluoropolymers

(C) PVF/PET/EVA backsheets

SPHERE Exposure

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

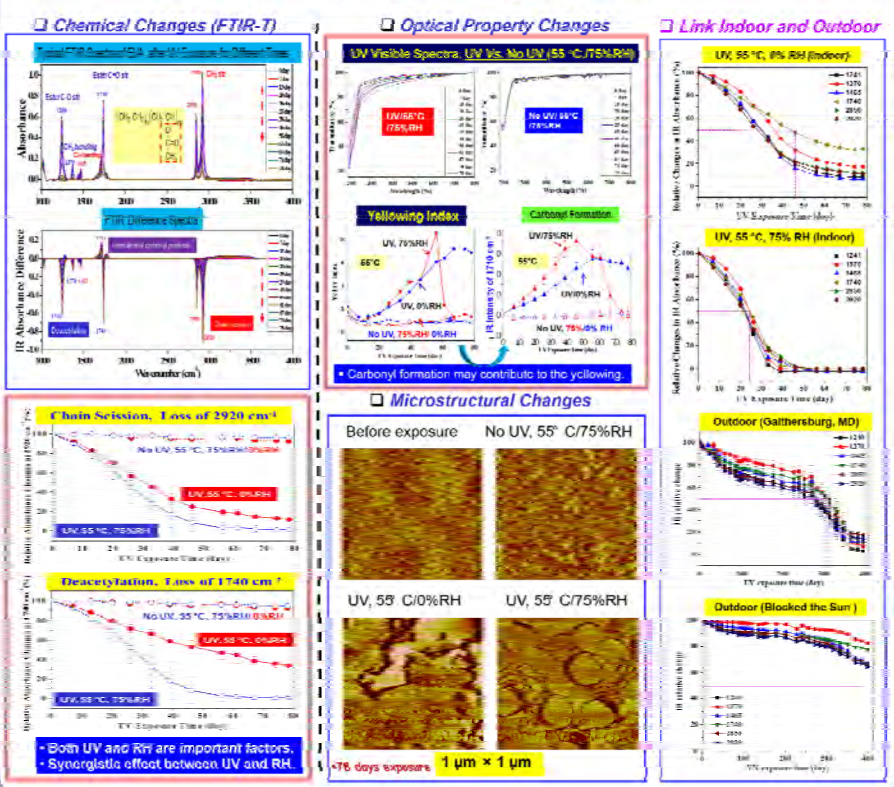
- UV Irrdiance *(200 W/m², 295-480 nm)*
- Different Temperatures *(25-85 °C)*
- Different RHs *(0-75%)*

Outdoor Exposure

Gaithersburg, MD

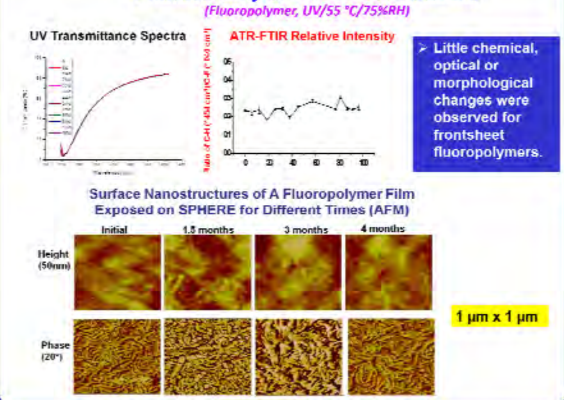
RESULTS FROM LABORATORY EXPOSURE

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



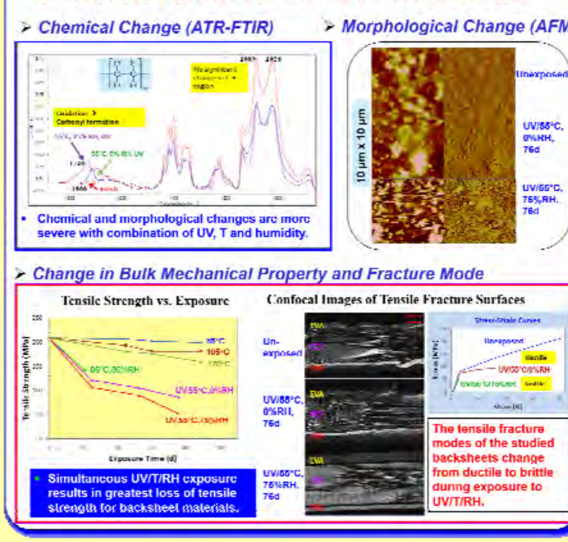
Photostability of Frontsheet Materials

(Fluoropolymer, UV/55 °C/75%RH)



➢ Little chemical, optical or morphological changes were observed for frontsheet fluoropolymers.

Simultaneous UV/T/RH on PVF/PET/EVA Backsheets



- Chemical and morphological changes are more severe with combination of UV, T and humidity.
- Simultaneous UV/T/RH exposure results in greatest loss of tensile strength for backsheet materials.
- The tensile fracture modes of the studied backsheets change from ductile to brittle during exposure to UV/T/RH.

SUMMARY

➢ UV radiation was the most important factor for degradation of all studied materials. A RH/UV synergistic effect was observed for EVA and backsheet materials.

➢ A fundamental understanding of degradation mechanism under simultaneous multiple stresses is important to develop reliable standardized accelerated tests for PV materials.

NREL PVRWS 2013 %

2013 Feb. 27 %

TORAY

Innova ı

Test Procedure for UV Weathering % Resistance of Backsheet %

Kusato Hirota, Michiko Tanaka, Takao Amioka, Miki Terada %

Toray Industries, Inc. %
Environment & Energy Development Center, %
1-1, Oe 1-chome, Otsu, Shiga 520-2141 JAPAN %

Technical Background and Object %

TORAY
Innova

Based on the past discussion of weathering sub-group, WG2 material group consider the followings about the test procedure of Backsheet.

"Polymeric materials that are exposed to direct sunlight but are protected by glass, or other transparent medium ,may be tested with an equivalent layer of that medium attenuating the UV light exposure during the test".

The preparation of samples and test procedure are proposed in this presentation. Moreover, preliminary exam results of UV weathering resistance of backsheet are illustrated.

Apparatus and Procedure %

'TORAY'
Innova ı

Apparatus:

Xenon weathering tester. Modified ISO 4892-2 (discussed in Weathering group)
- Irradiance of UV were increased from that of IEC61730-1 A2 to increase accretion ratio.
- Dark cycles were employed to consider dark chemical reaction.

Test conditions and sequences:

Condition 1 (108min.) => Condition 2 (18min) :120min (2 hrs)
=> Condition 1 (108min.) => Condition 2 (18min) :120min (2 hrs)
=> Condition 3(120 min) :120min (2 hrs)
=> repeat above test cycle
Front : 2000 hrs , Back :1000hrs (Duration will be discussed in material group)

Condition 1:
Irrad .E(300-400 nm) = **88.0 W/m2** , Filter type (SPD) DL filter
CHTemp 65 degC, RH = 50%RH, BPTemp = 89degC

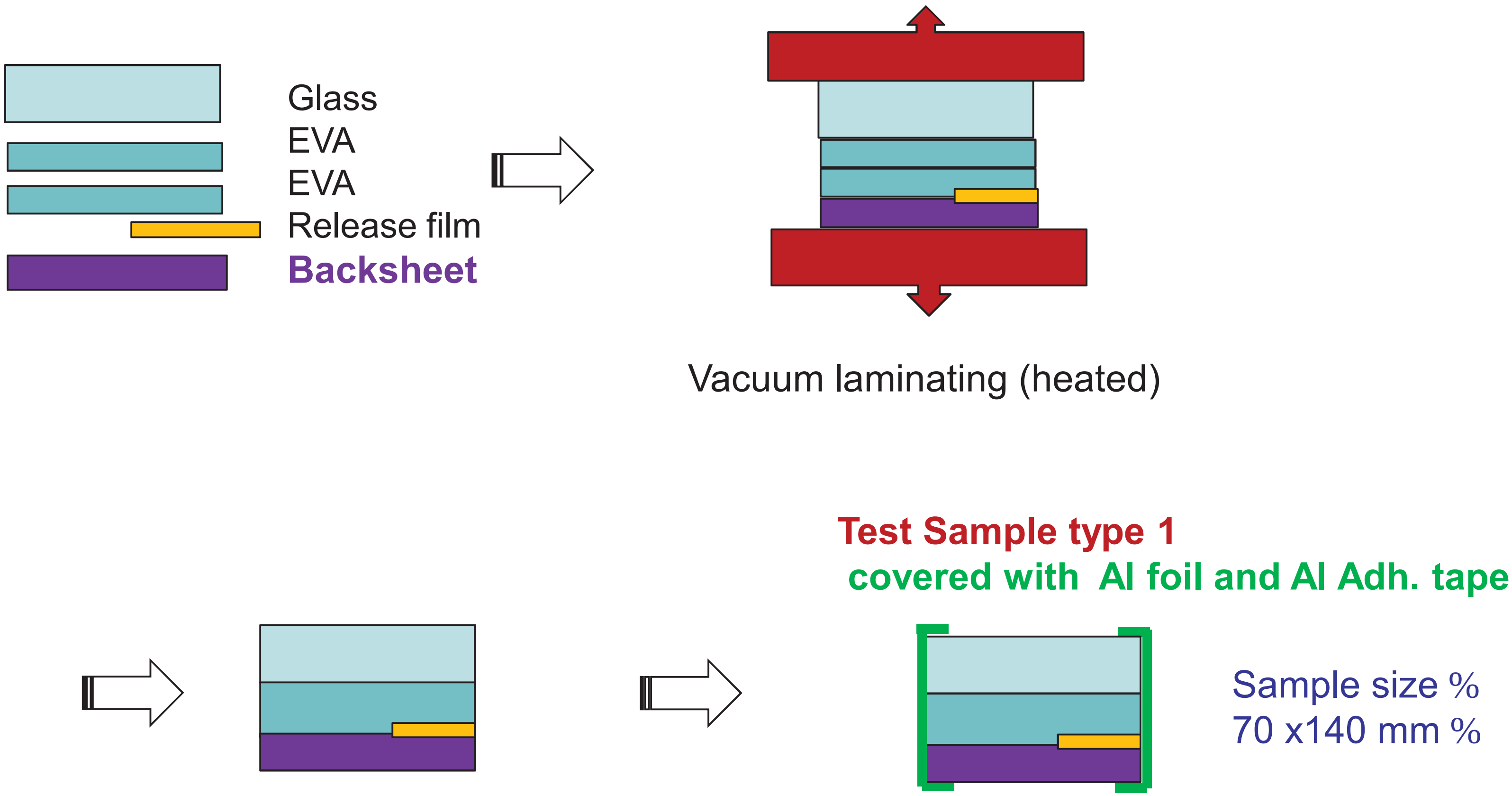
Condition 2:
Irrad .E(300-400 nm) = **88.0 W/m2** , Filter type (SPD) DL filter
Water Spry CHTemp 65 degC, RH is NC , BPTemp is NC.

Condition 3:
Dark CHTemp 65 degC, RH = 50%RH

NOTE: IEC61730-1 A2 Ed.1 describes UV test condition as following;
ANSI/UL 746C or ISO 4892-2. Test condition defined by Xenon cycle 1 at 0,35 W/m2/nm or **41 W/m2 (in the wavelength range from 300 nm to 400 nm)**, test duration 1 000 h; equivalent pass/fail-criteria as in UL 746C shall be applied.

Sample preparation and setup (1) %

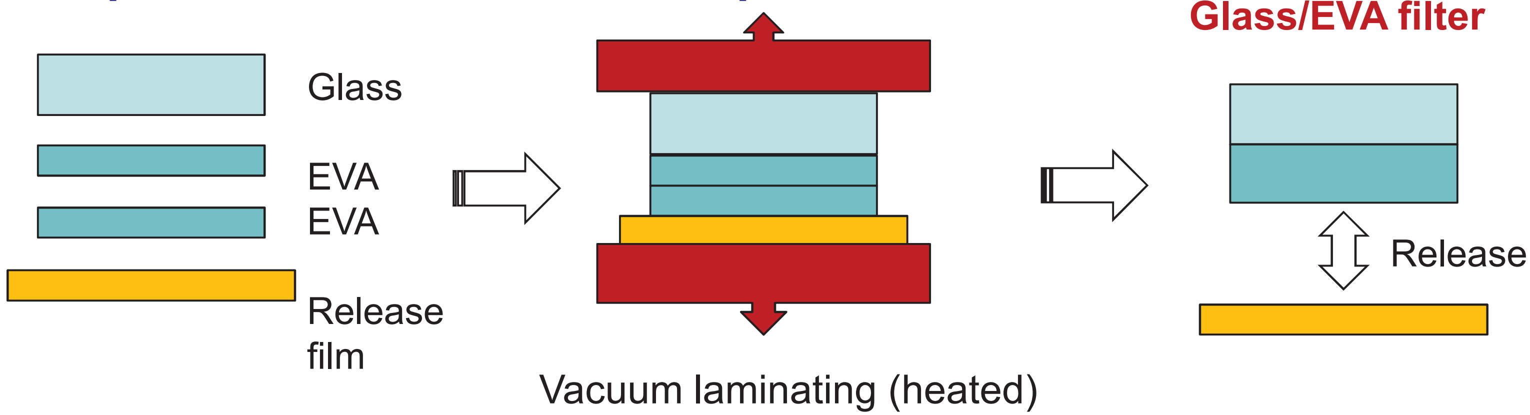
1. Preparation of test sample for peal-strength after UV weathering test %



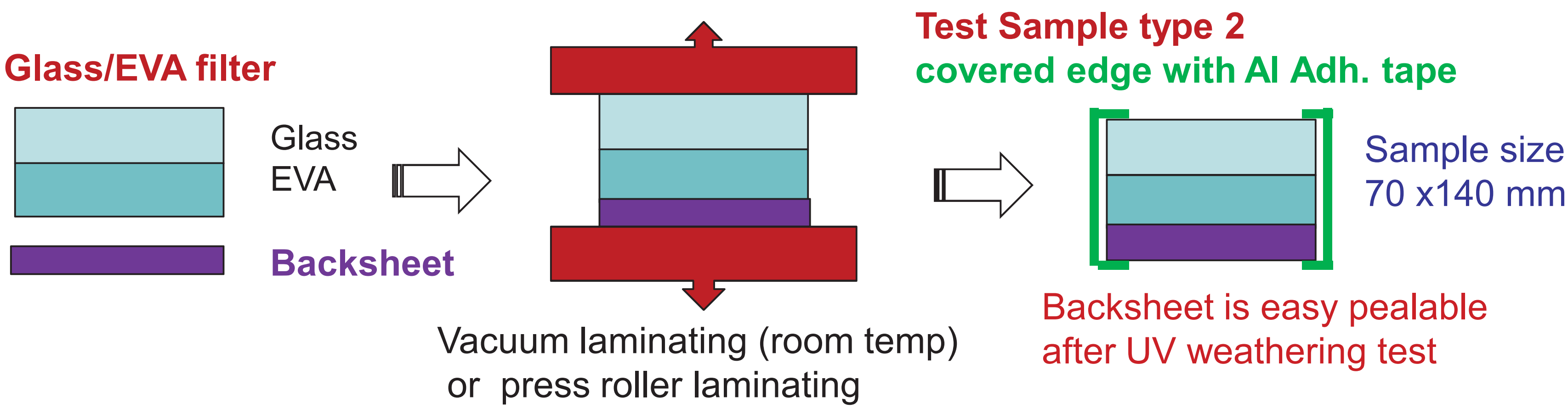
Note; %
It is preferable to cover the edge of the samples with aluminum adhesive tape to prevent water % penetrating. %
Because the regular size sample holder is 150mm in long side, it is difficult to hold glass sample using % 3.2mm t and150mm length.

Sample preparation and setup (2) %

2. Preparation of Glass/EVA filter parts %



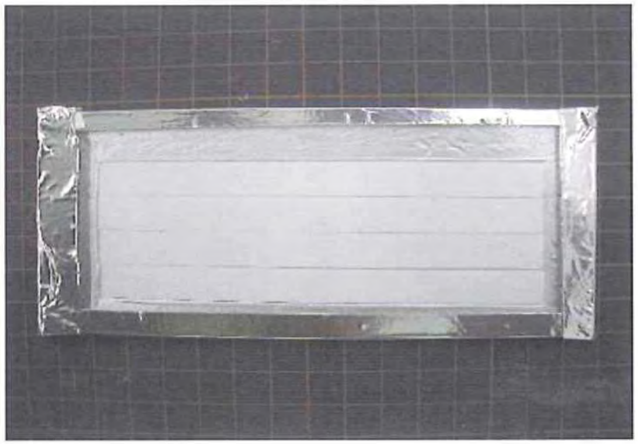
3. Preparation of test sample for breaking strength after UV weathering test



Note;
It is important to remove air gap between glass and backsheet at the following points of view.
(a) Remove light reflection at the interface of Glass-Air and Air- Backsheet.
(b) Avoid degradation of the polymer by ozone or active oxygen caused by UV light.

Test sample and sample holder %

Sample (back view)



Sample size
70 x140 mm

Sample backsheet was pre-cured in the shape of 10mm width in this experiment.

Note. 15mm width is required in ISO standard measurement

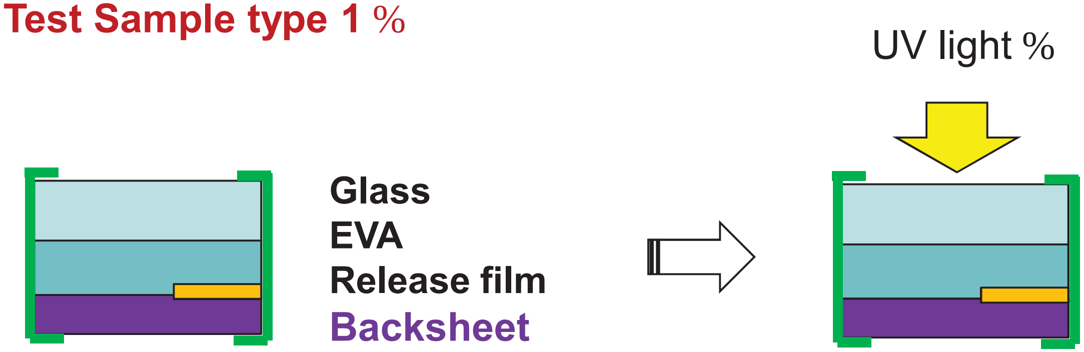
Sample holder of UV test chamber

Procedure of UV Weathering Test %

TORAY
Innova

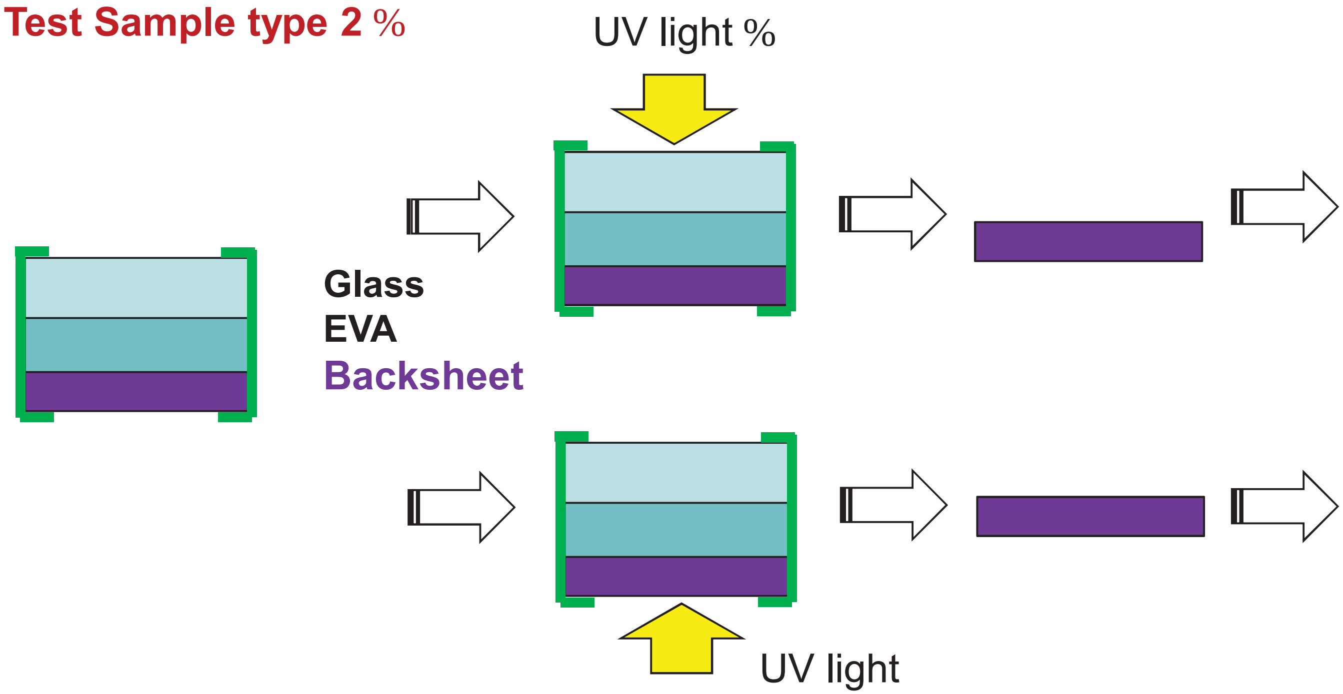
Measurement (for requirement)

Test Sample type 1 %



(a) **Bond strengths between encapsulant and Backsheet 180° peel %**
(NEW proposal % from TORAY) %

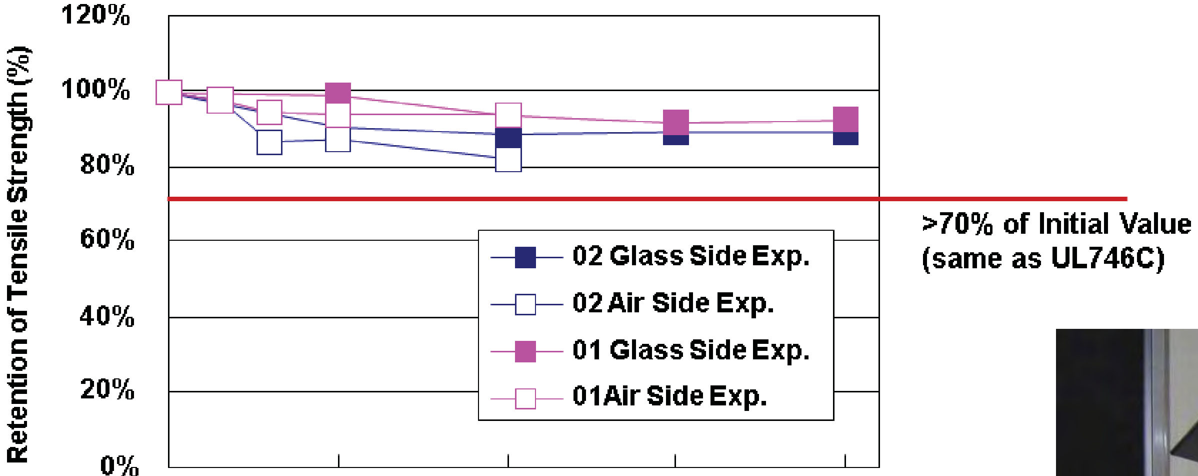
Test Sample type 2 %

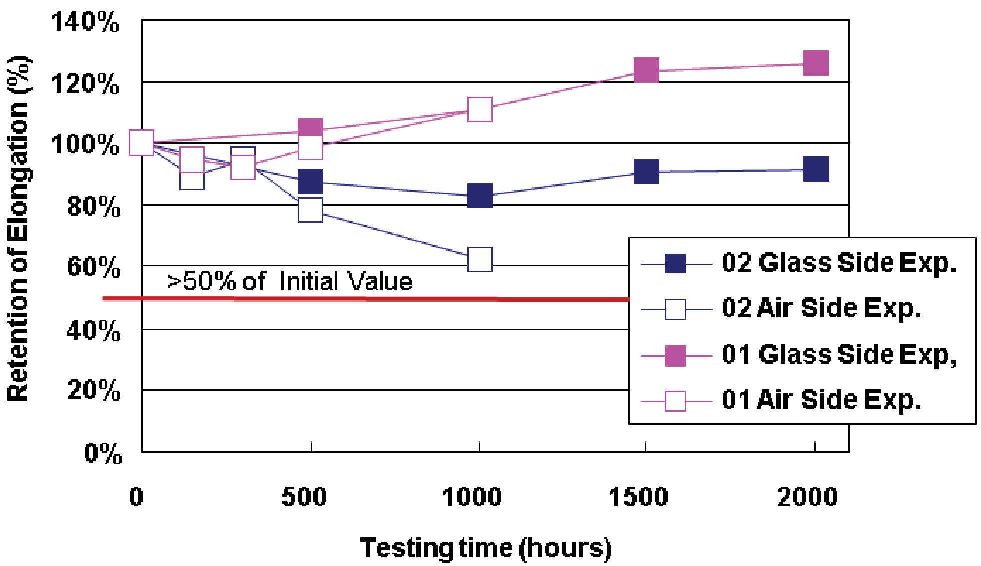


(b) Tensile strength / elongation
(c) Yellowing (Front view)
(d) Reflection

(b) Tensile strength / elongation
(c) Yellowing (Back view)

Measurement result : Tensile strength, Elongation

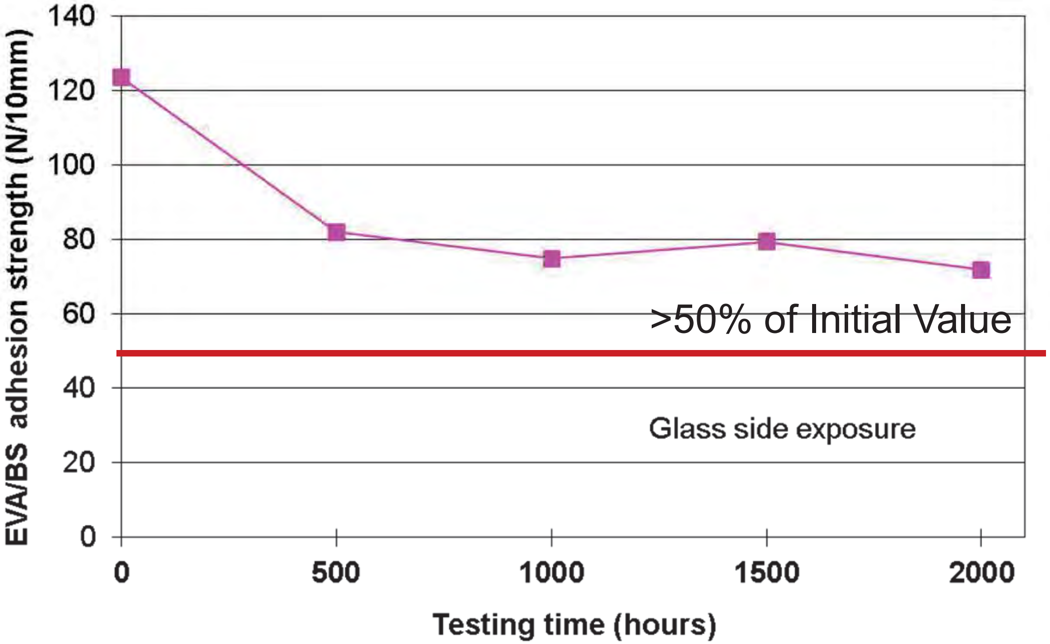




Note: 2000 hrs. test = 117.3kW hrs. UV(300-400nm)

Measurement result : %
Bond Strength between EVA and Backsheet %

'TORAY'
Innova ı



Measurement result :
Yellowing of EVA and Backsheet

'TORAY'
Innovation by Chemistry

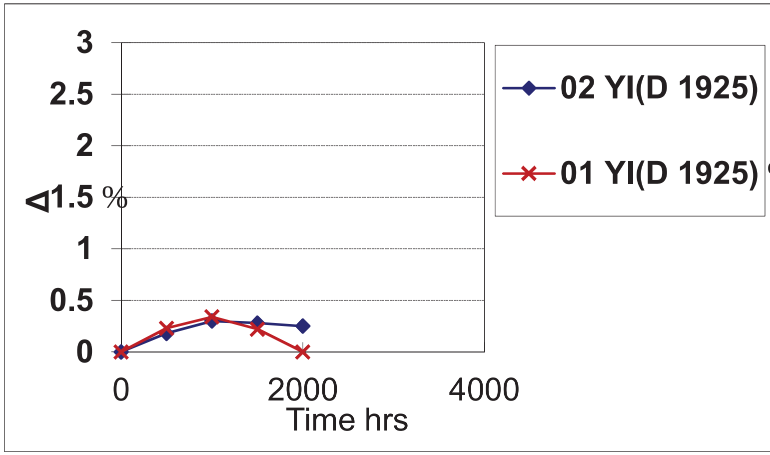


Fig1.　Glass side Exp.　(Sample type 1)
YI of front face of BS , through the glass

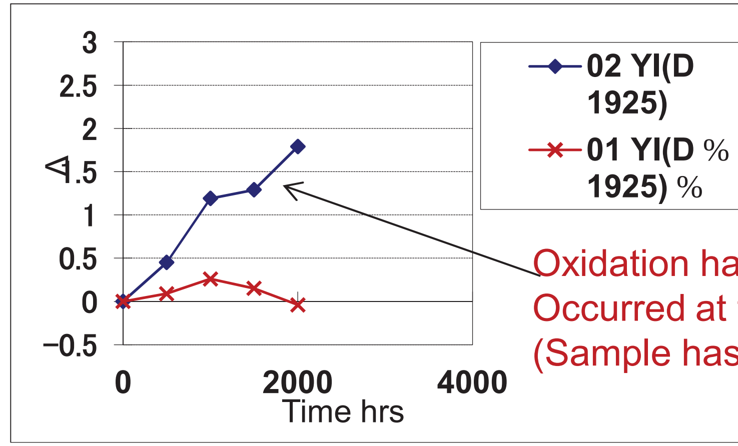


Fig2.　Glass side Exp. .　(Sample type 2 with air gap)
YI of of front face of BS after separate BS from glass

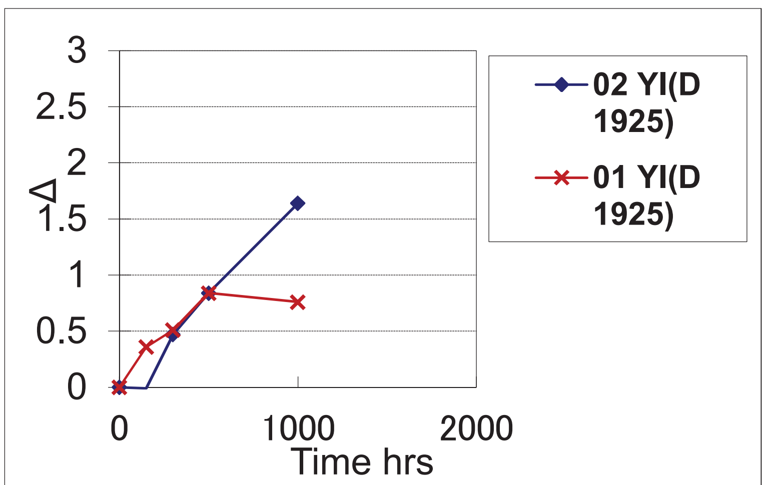
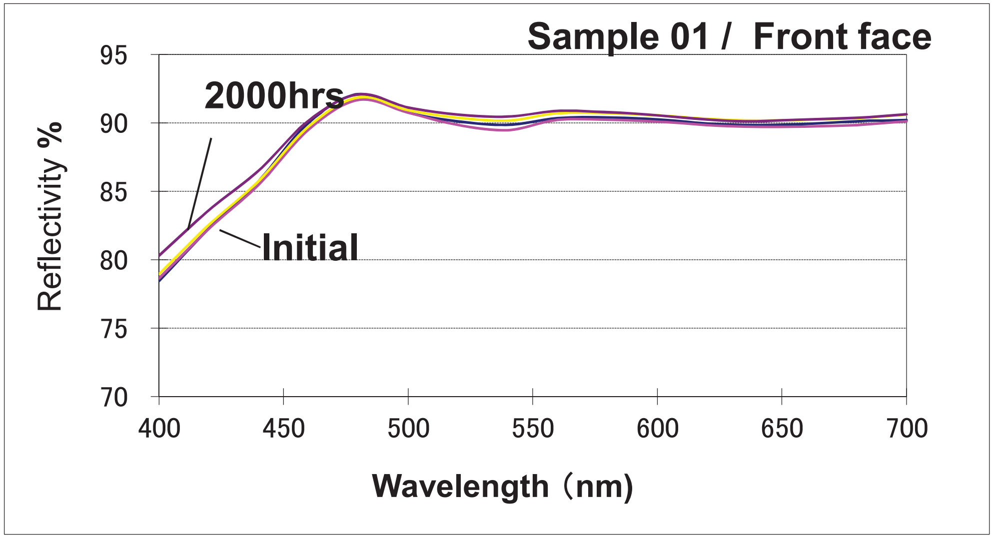


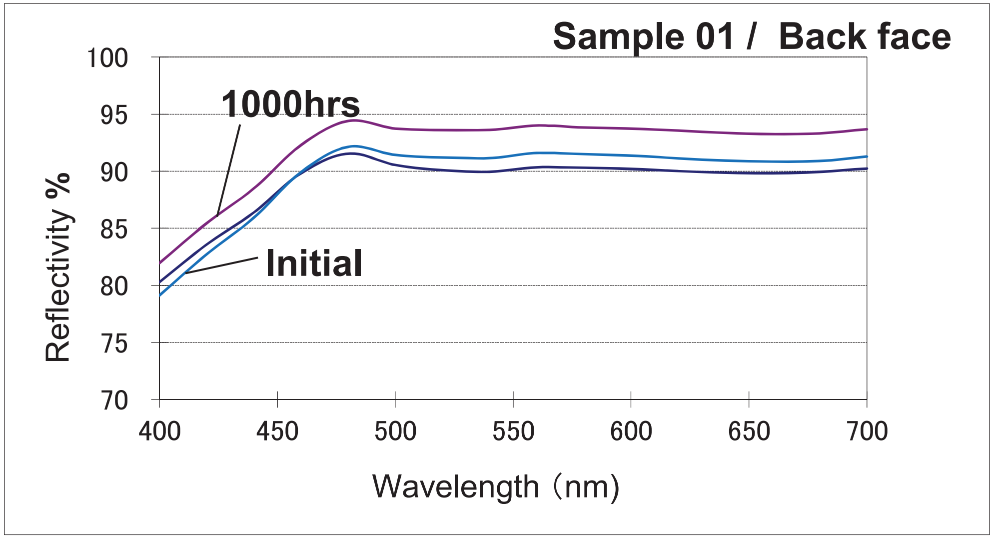
Fig3.　Back side Exp.
YI of back face of BS

Reflectance after UV Weathering test %



Note
Exp. Through the glass

2000 hrs. test
= 117.3kW hrs. UV(300-400nm)



Note
Exp. directly

1000 hrs. test
= 58.7 kW hrs. UV(300-400nm)

Conclusion and proposal %

'TORAY'
Innova ı

Procedure of sample preparation for UV weathering test of backsheet are proposed.

(a) Backsheet can be temporarily fixed on Glass/Encapsulant component % without air gap, using a conventional laminating machine. %

(b) Bond Strength between EVA and Backsheet after UV weathering test % can be measured by 180 degree peal test method. %

To be shortened test time, we may consider that increase in the irradiance to 2-SUN (90W/m2 ,300-400nm) is permitted in IEC standard.

It is necessary to further discussion at WG2 (& FS,BS sub group, Weathering sub-group) to determine the test conditions and duration in detail.

Weathering Performance of PV Backsheets

A. Lefebvre, G. O'Brien, D. Althouse, B. Douglas, G. Moeller, D. Garcia, T. Fine, A. Bonnet

2013 PV Module Reliability Workshop

February 26-27, 2012

ARKEMA
INNOVATIVE CHEMISTRY

Introduction

- **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.**
  - IEC 61215 UV preconditioning test: Preconditions modules – but does not measure durability. Total UV exposure (15 kWh/m2 280-385 nm) is less than 3 months direct exposure in Miami, FL.

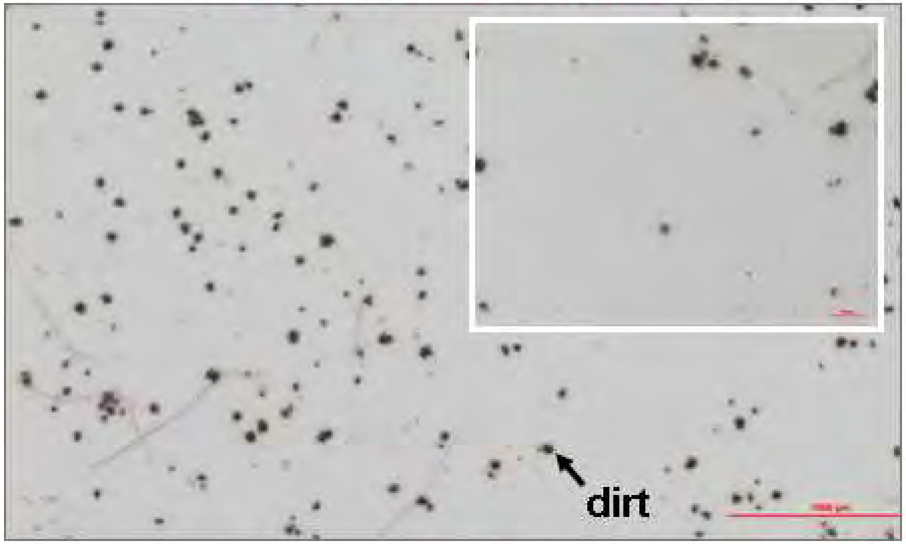
- **Long PV module lifetimes are supported by using materials with proven, long term weatherability.**
  - A weathering durability test is needed for UL and IEC standards

Weathering Study Details

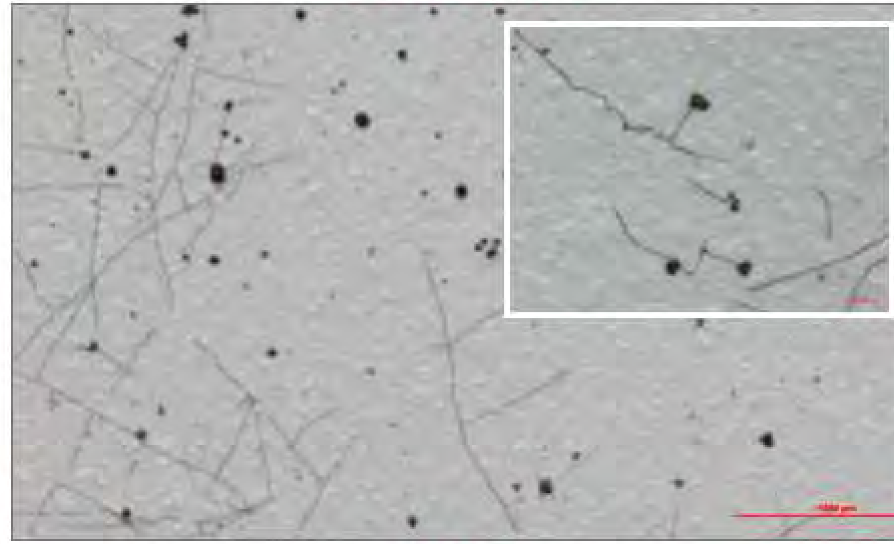
- **Arkema initiated a study to examine effects of FL outdoor exposure on backsheets.**
  - Photo-degradation monitored by gloss retention, optical and SEM microscopy, chalking evaluation, and FTIR spectroscopy.
  - Compare results with accelerated weathering using QUV A.
- **Florida Outdoor Testing Conditions:**
  - Samples located in Miami, FL.
  - Direct Exposure samples oriented south facing at 45 degrees angle facing the sun.
  - Indirect Exposure samples oriented north facing at 45 degree angle facing the ground.
- **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/m2 or 4.91 MJ/m2 in 24 hrs.
  - Backsheets are facing the lamp.
  - 1300 hrs exposure has equivalent UV radiation to 12 months in Florida.
  - In the Field - Backsheet exposure is a percentage of direct exposure (25% - 10%) .
- **Backsheet Materials Tested:**
  - KPE® Backsheet – Kynar® Film/ PET /EVA 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

Optical Images after 2 yr. FL Direct Exposure

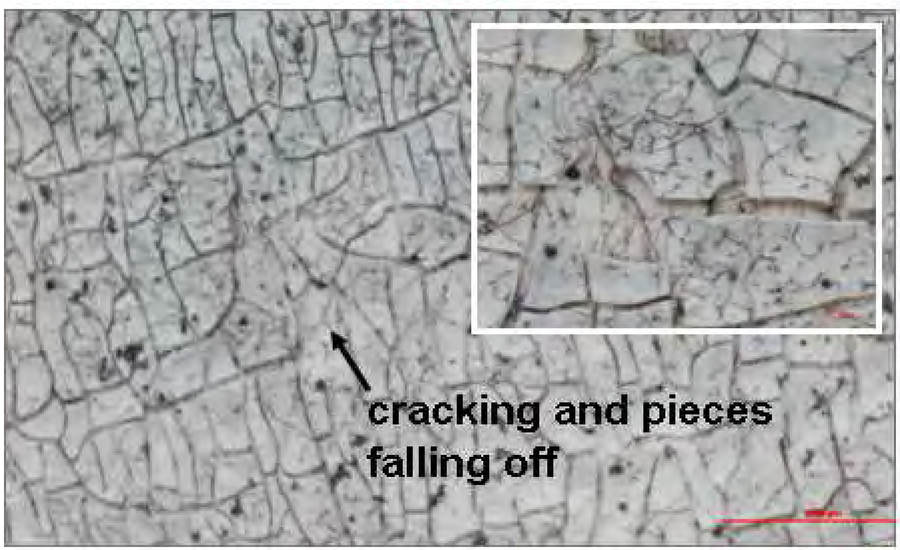
KPE ® Backsheet



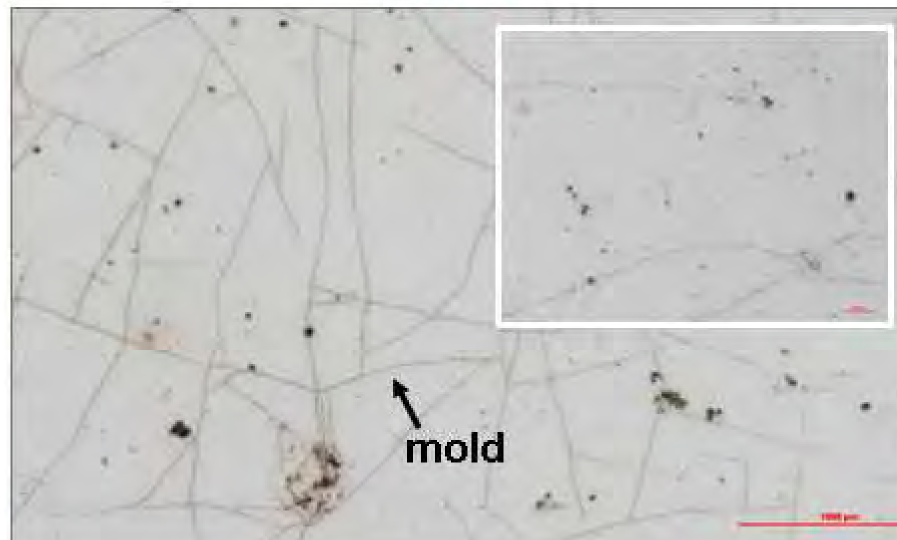
PVF, Gen 1



AAA



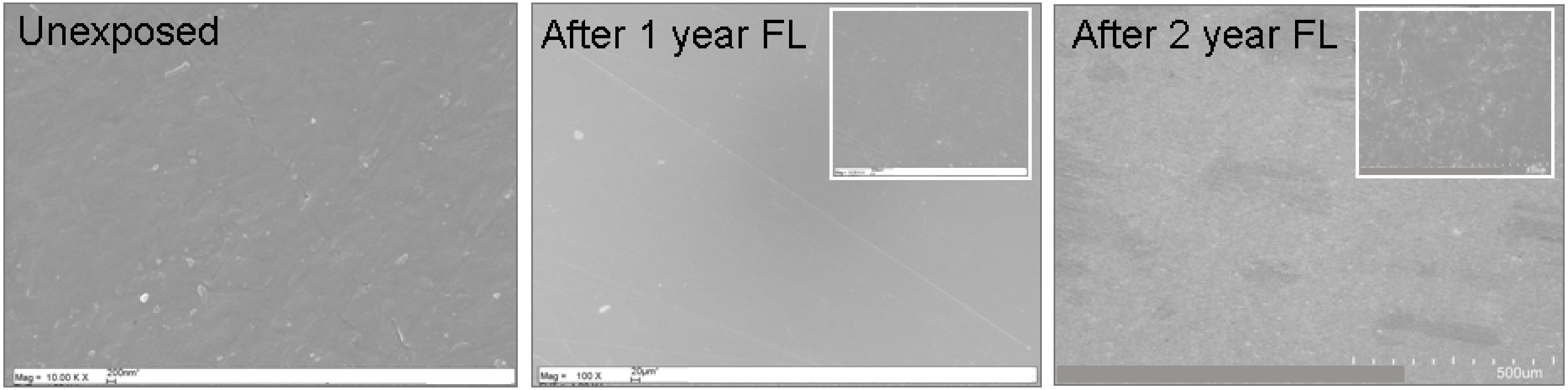
PPE



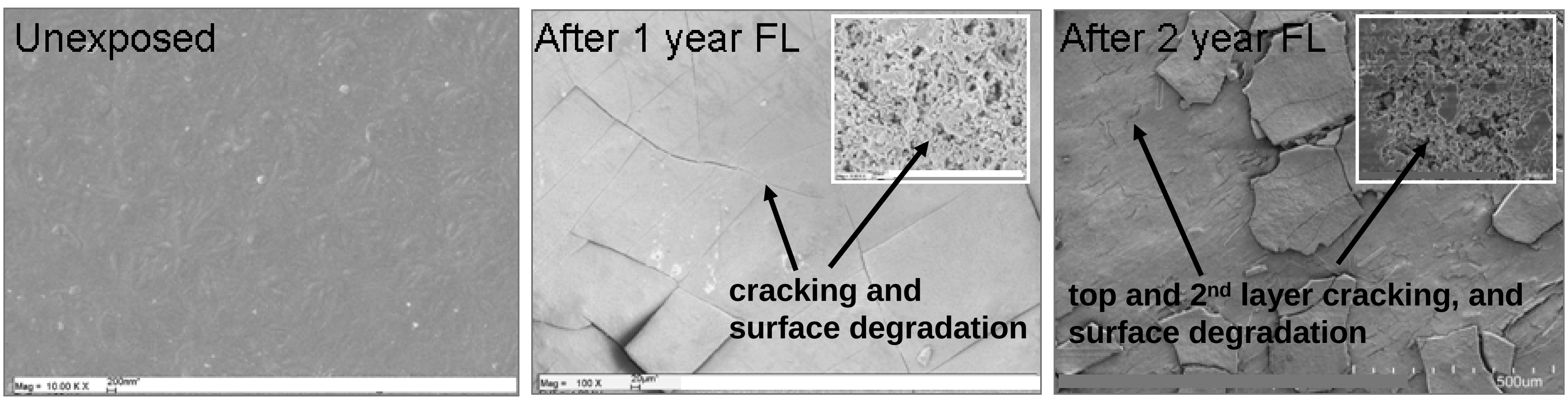
Images obtained on unwashed samples: show dirt specks, mold growth, and cracking.

SEM Images of Unexposed and Florida Direct Exposure

KPE® Backsheet



AAA

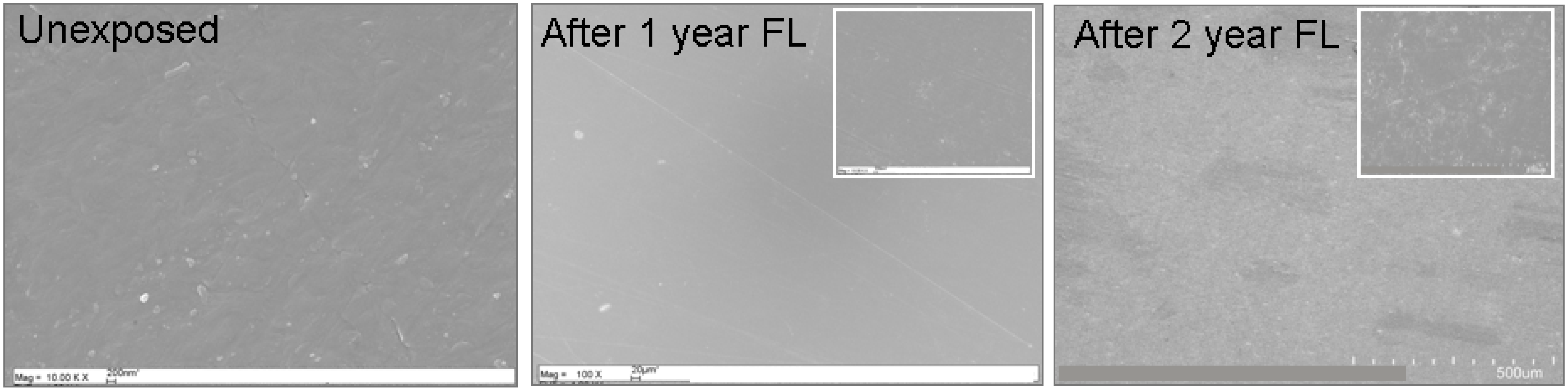


•Samples washed prior to imaging. AAA lost a significant amount of its top layer when the sample was rinsed gently with DI water. KPE® Backsheet shows no chalking.

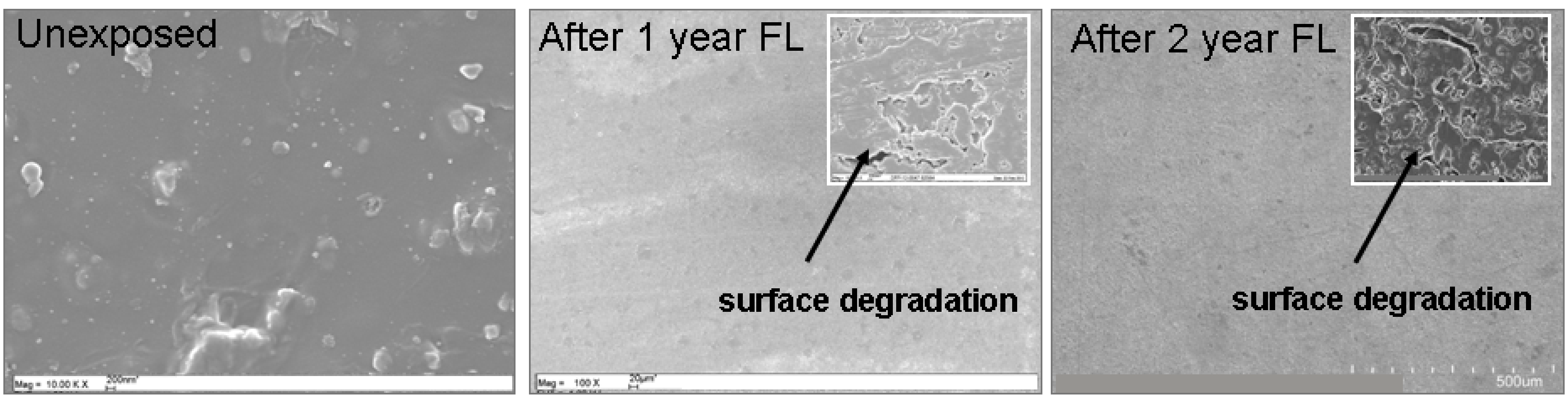
KYNAR® BY ARKEMA

SEM Images of Unexposed and Florida Direct Exposure

KPE® Backsheet

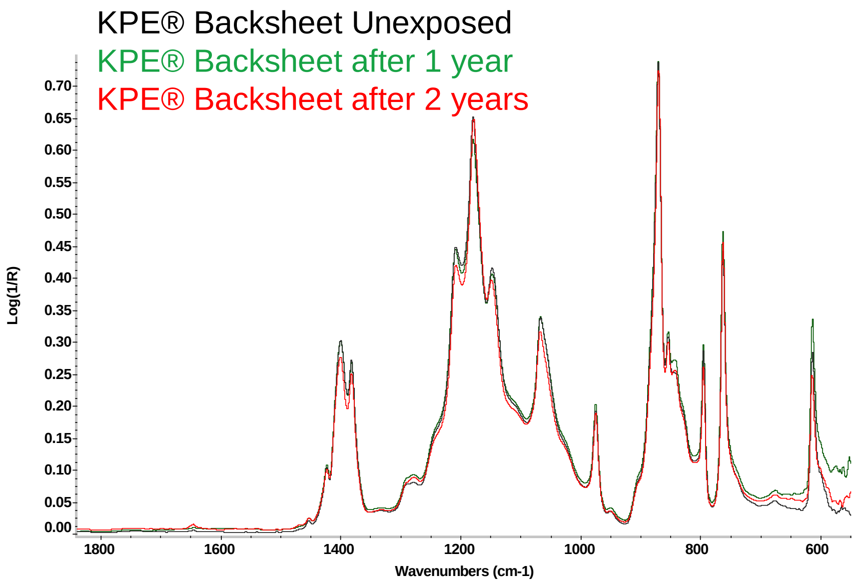


PPE

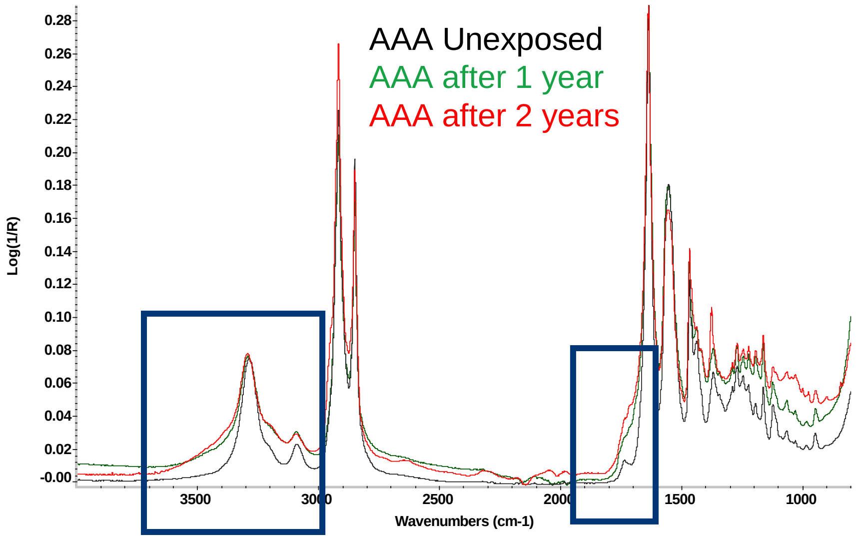


•Samples washed prior to imaging.

FTIR Spectra of Backsheets after Direct FL Exposure

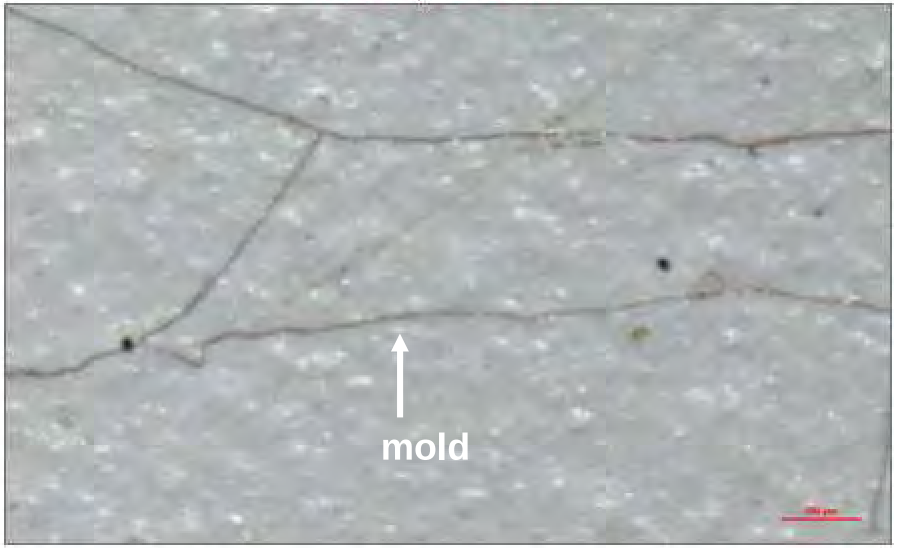


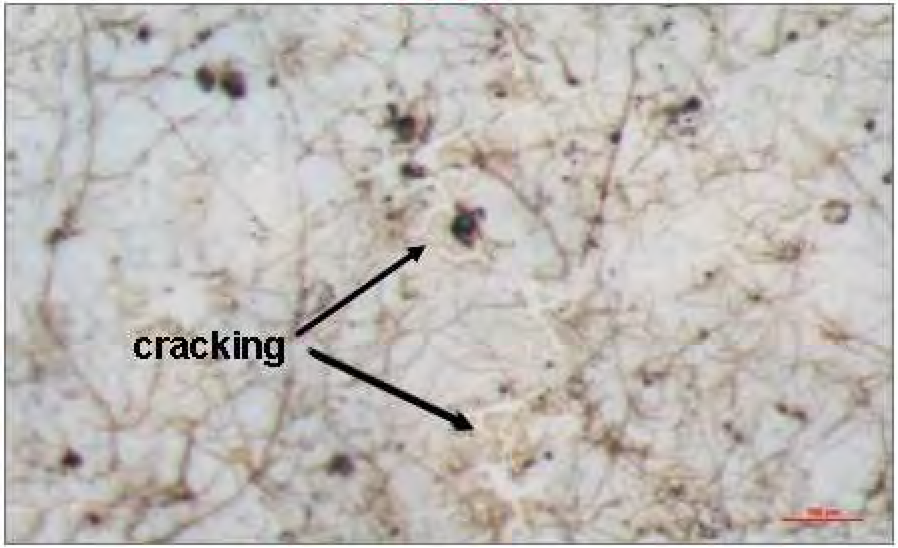
- No spectral changes KPE® Backsheet surface.
- No sign of degradation.

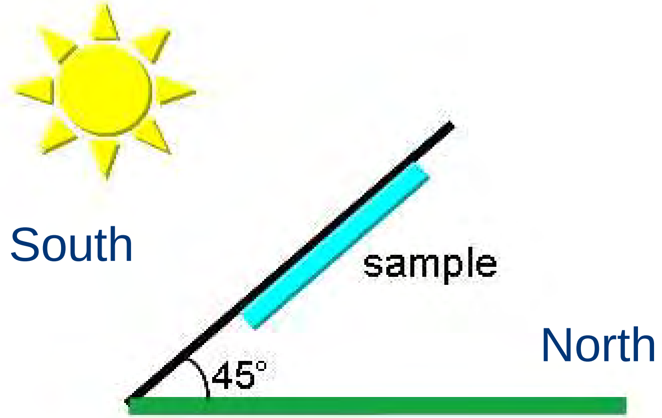


- AAA shows significant degradation by oxidation of polymer.
- NH/OH and –C=O spectral regions indicates increasing OH.

Optical Images after 2 yr. Florida Indirect Exposure



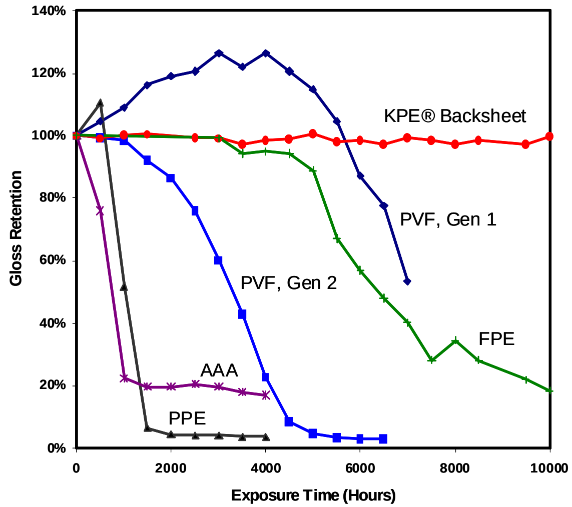




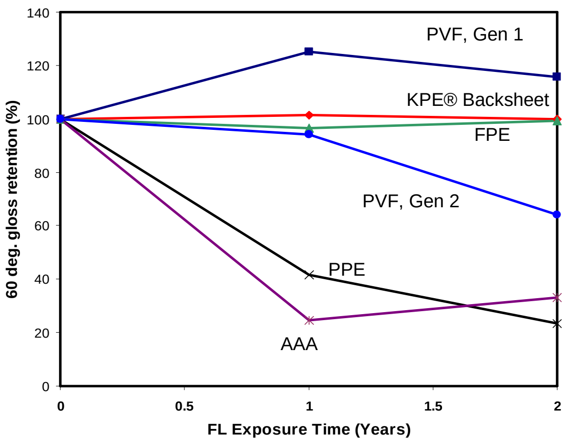
Images obtained on unwashed samples: show dirt specks, mold growth, and cracking.

Surface Degradation of Backsheets

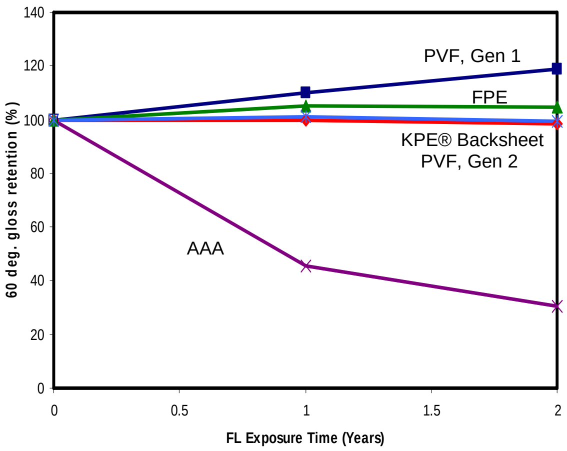
QUVA Accelerated Weathering



Florida - Direct Exposure



Florida - Indirect Exposure



- 1300 hrs. QUV A exposure has equivalent UV radiation to 1 year direct exposure in FL.
- Indirect exposure, typical for backsheets, is a percentage of direct exposure.
- The same decreasing gloss retention trends observed in QUV A are being measured in both direct and indirect FL exposures just at slower rates due to decreased amount of UV radiation.
- In a few years, we expect the plots of gloss retention versus exposure time for the three different types of exposures to look the same.

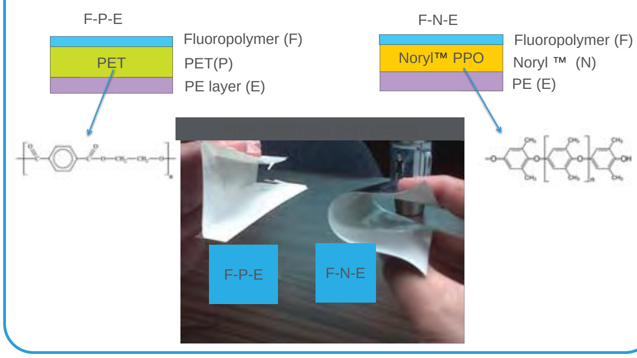
Conclusions

- **Short term outdoor exposure shows significant UV degradation of both AAA and PPE backsheets (after only 1 year of FL exposure).**
- **Fluoropolymer based backsheets show little to no change after 2 years FL exposure.**
- **AAA backsheet shows surface cracking and mold growth after only 1 year FL exposure. PPE shows surface erosion and gloss loss in only 1 year of FL exposure. After 2 years the AAA has cracks through the outside layer.**
- **Gloss retention in outdoor tests correlates well with gloss retention in accelerated QUV A testing protocol. Both show rapid gloss loss for both AAA and PPE backsheets.**
- **Better UV Exposure test (than IEC) is needed to test products for durability over 25+ year product lifetime**
  - 5000 hrs QUV A at 1.55 Irrad. approximately equals 25 years in FL at 15% of direct irradiance.

IMPROVED RELIABILITY OF PV MODULES WITH LEXAN™ (PC) SHEET - FRONT SHEET NORYL™ (PPE) SHEET - BACK SHEET

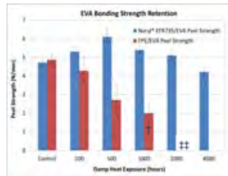
NORYL™ Sheet for back sheet application   LEXAN™ sheet for front sheet application

HYDROTHERMAL RESISTANCE OF PET AND NORYL™ FILM AS CORE LAYER OF BACKSHEET



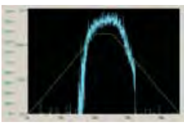
PROPERTIES COMPARISON OF PET AND NORYL™ BASED BACKSHEET

Property		Units	FPE	FNE
Outer layer gauge		micron	30	30
Corelayer gauge		micron	177	250
Primer layer gauge		micron	100	140
Adhesive layer gauge		micron	15	30
Total gauge		micron	~320	~450
WVTR (at 38°C, 100%RH)		g/m^2-24h	2.4	2.4
Partial Discharge Voltage (with / without E layer)		V	1045 / --	1310/1040
Shrinkage (MD/TD, 150°C/ 30min)		%/%	1.0 / 0.3	0.2 / 0.1
Tensile (Initial)	Strength	MPa	105	37
	Elongation	%	247	65
Tensile (After 72hr PCT)	Strength	MPa	PET cracks!	33
	Elongation	%	4	17
Intra-layer bonding after 72hr PCT			PET cracks & delaminated	No delamination
EVA Bonding (Initial)		N/mm	>7	>7



†: Failure "jumps" from EVA interface to intralayer surface
‡‡: Not suitable for testing due to PET cracking

ELECTRICAL INSULATION AND FLAME RETARDATION FOR SAFETY



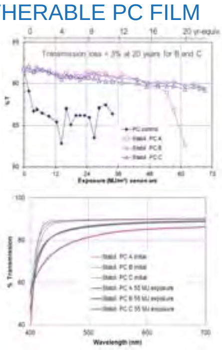
Film Sample	Gauge (mil)	Partial discharge voltage (V)	UL94 Flame Rating
PV grade PET	10	850~ 900	HB or worse
Noryl™ EFR735	10	1020	V0

WHY POLYCARBONATE AS PV FRONT SHEET?

- **Lighter weight and flexibility v.s. glass**
- **Compared to thin fluoropolymer film:**
  - **Superior toughness**
  - **Flame retardation desired for BIPV**
  - **Low cost**

HIGHLY WEATHERABLE PC FILM

- Unprotected PC yellows & loses transmission in 1-2 years outdoors
- Highly weatherable PC demonstrates UV life capacity >20 year (equivalent Florida year)

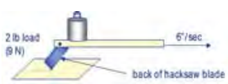


PUNCTURE & CUT RESISTANCE TEST OF PC FILM

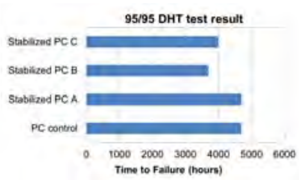
Energy	Penetration	
inch-lb	ETFE	PC
20	pass	pass
40	pass	pass
60	pass	pass
80	fail	pass

5 mil films are tested for both ETFE and PC

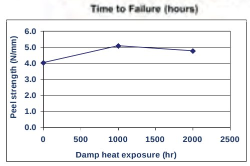
sample	load (pounds)				
	2	3	4	5	6
2 mil ETFE/ EVA-glass	OK	cut			
5 mil ETFE/ EVA encapsulant	OK	OK	OK	cut	
2.5 mil PC/ EVA encapsulant	OK	OK	cut		
5 mil PC / TPU encapsulant backing	OK	OK	OK	OK	cut
12 mil stabilized PC film	OK	OK	OK	OK	OK



DAMP HEAT RESISTANCE AND EVA BONDING

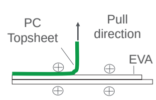


Note: after 95°C/95%RH exposure; bend film around ¼" mandrel (pass/fail)



85°C/85% RH exposure

90 deg peel test



SUMMARY

- Demonstrated superior hydrostability of Noryl* film compared to PET, with DH resistance > 4000 hours
- FNE backsheet outperforms FPE in hydrothermal resistance, shrinkage and electrical insulation
- Highly weatherable PC sheet as PV front cover can last >20 years outdoors, enabling flexible and durable PV modules
- Stabilized PC has puncture & cut resistance superior to fluoropolymers

™ Trademark of SABIC

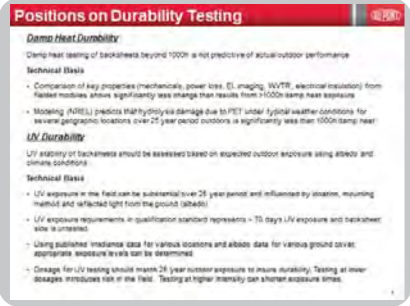
Jian Zhou[1], James Pickett[2], Scott Davis[1], Shreyas Chakravarti[1], Michael J. Davis[1]
Affiliations: 1. SABIC 2. GE Global Research

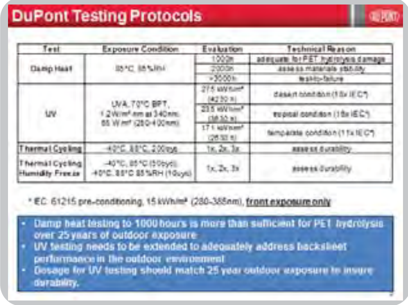
CHEMISTRY THAT MATTERS™

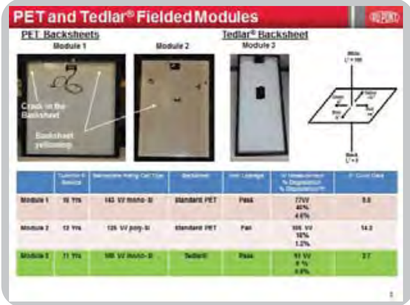
A Comparison of Key PV Backsheet and Module Properties from Fielded Module Exposures and Accelerated Test Conditions

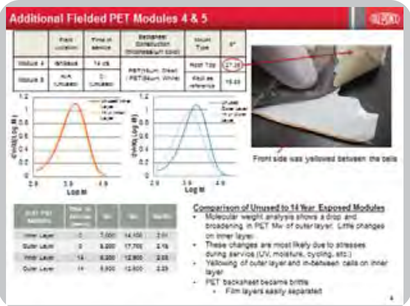
W. Gambogi[1], O. Fu[2], Y. Heta[3], K. Hashimoto[3], J. Kopchick[1], T. Felder[1], S. MacMaster[1], A. Bradley[1], B. Hamzavytehrany[1], V. Felix[1], T. Aoki[3], T. J. Trout[1] and T. Sample[4], (1) DuPont Photovoltaic Solutions , Wilmington, Delaware, (2) DuPont Photovoltaic Solutions, Shanghai, China, (3) DuPont K.K., Utsunomiya, Japan, (4) European Commission Joint Research Centre, Ispra, Italy

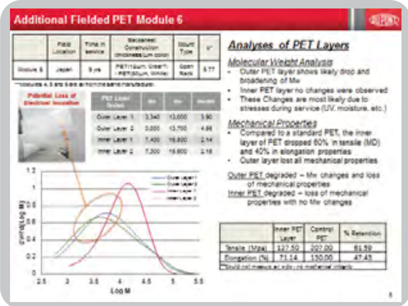
2013 NREL PV Module Reliability Workshop, Golden, CO

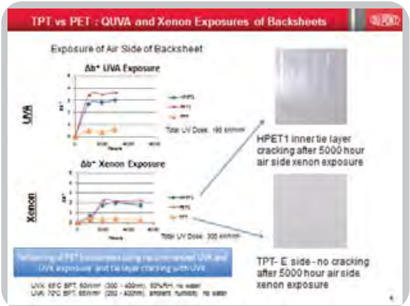


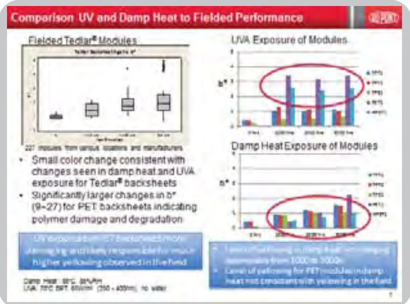


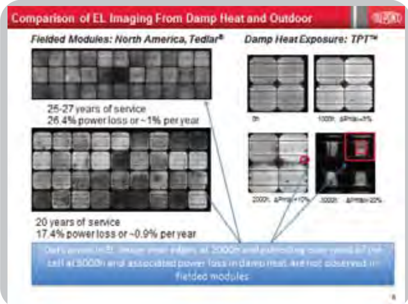


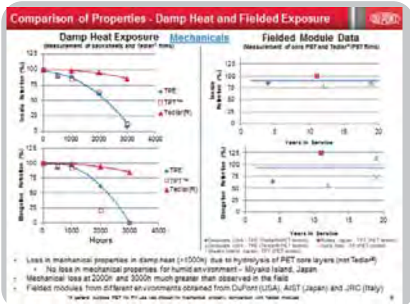


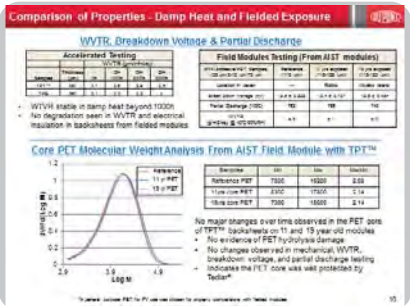


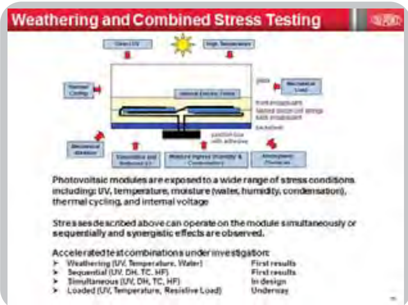


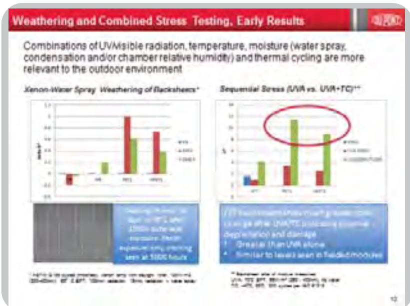


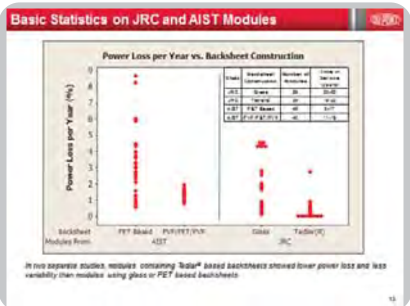


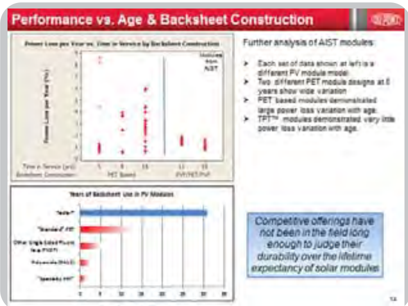












This poster contains no confidential information. *

Special thanks to JRC (European Commission Joint Research Centre) and AIST (The National Institute of Advanced Industrial Science and Technology) for use of their fielded modules.

3M Ultra-Barrier Solar Film

Demonstrating Reliability of 3M Ultra-Barrier Film for Flexible PV Applications

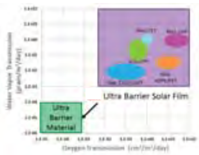
Alan Nachtigal, Tracie Berniard, Bill Murray, Mark Roehrig, Charlene Schubert, Joseph Spagnola, Mark Weigel

3M Ultra-Barrier Solar Film Product Overview

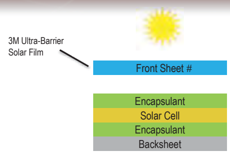
Revolutionary Product
- Over 45 U.S. patents and patent-pending applications on barrier constructions, materials, and processes
- Engineered for flexible Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe) and Organic Photovoltaic (OPV) solar modules

Features
- Optical transmission >89% (average 400nm-1400nm)
- Water vapor transmission rate = $5x10^{-4}$ $g/m^2/day$ @ 23°C / 85%RH
- Excellent UV stability
- Flexible

Key Highlights
- UL Certified Component
- Partial discharge 1,000V

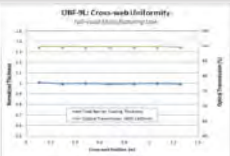


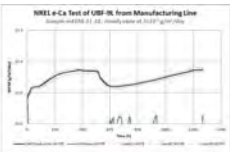
3M Ultra-Barrier Solar Film Application



Light weight → 1/8th compared with glass-on-glass
Lower Balance of System costs → less labor and reduced mechanical racking
Higher packing density → Significantly more kW per shipping container
Large area modules → Lower relative "fixed" module costs
Lower manufacturing costs → Fully automated roll-to-roll processing

Scale-up to Production





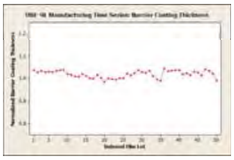
3M Ultra-Barrier Manufacturing
- New production line start-up in 2012
- Located in the United States

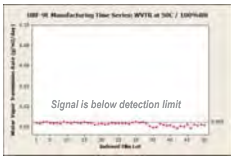
Widths
- Currently producing at up to 1.2 meters
- Available in wider widths depending on market requirements

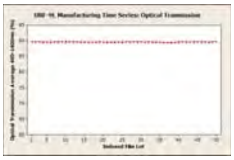
Manufacturing Highlights
- Full-scale product matches or exceeds performance of narrow-width product in 3M reliability and qualification testing
- NREL e-Calcium testing as low as $5x10^{-6}$ $g/m^2/day$ at 45°C / 85%RH

Production Data

Manufacturing Process Capability
- Barrier coating thickness
- Optical transmission
- Total film thickness
- Water vapor transmission rate #





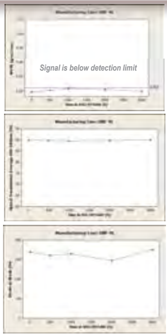


Reliability and Qualification Testing

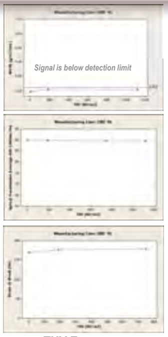
Qualification Testing
- 3000h+ damp heat (85°C / 85%RH)
- >1000 MJ/m2 Total UV Dose*
- Humidity freeze
- Thermal shock
- ...above exposures in combination

Film Responses
- Optical transmission
- Mechanical strength
- Water vapor transmission rate
- Color
- Haze

*Total UV Dose (TUV) is the time integrated energy over the range 295-385nm



Damp Heat Exposure %

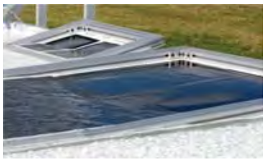


TUV Exposure

Reliability and Qualification Testing

Florida %

Colorado %



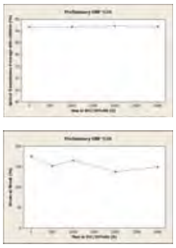
Water Submersion %

Reliability Testing
- Multi-year study with indoor and outdoor exposures
- Accelerated indoor weathering chambers with varied irradiance, relative humidity, and temperature levels
- Active modules and film-only specimens
- Multiple sizes, aspect ratios and film lots

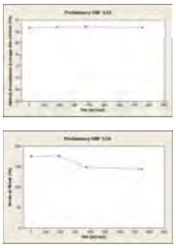
Lifetime Prediction
- Correlating measurements from film-only exposures to module-level performance #

Aggressive Conditions
- Test films to failure to speed development #
- Highly accelerated stress test (120°C / 100%RH)
- Water submersion testing

2nd Generation 3M Ultra-Barrier Film UBF-510

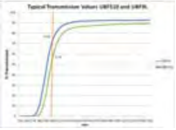


Damp Heat Exposure %



TUV Exposure %

3M UBF-510 Key Highlights
- Improved adhesion to a broader range of encapsulant and edge seal materials
- Higher light transmission
- Lower Cost



Improved Optical Transmission %

Summary

3M Ultra-Barrier Solar Film
- Water vapor transmission rates as low as $5x10^{-6}$ $g/m^2/day$ at 45°C / 85%RH for production material
- Film performance for 1.2 meter wide film meets or exceeds narrow-width material in qualification testing
- 3M has extensive qualification and reliability test sequences to validate film performance
- 2nd Generation UBF-510 film with improved module performance to launch Q3 2013

SunShot U.S. Department of Energy

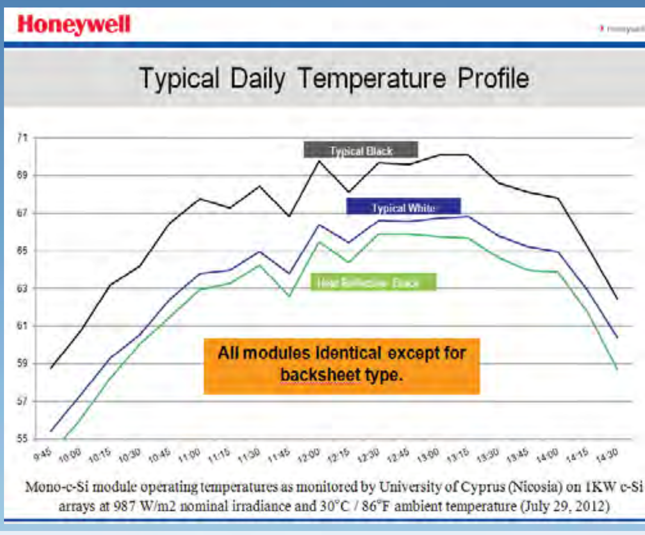
Acknowledgement: "This material is based upon work supported by the Department of Energy under Award DE-EE004739."

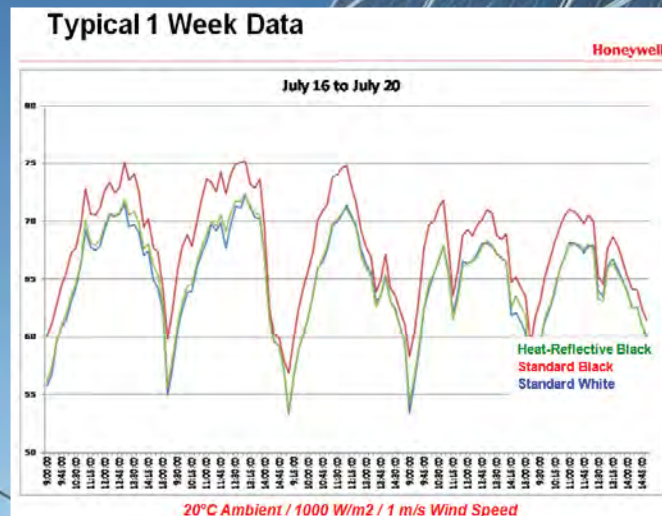
Disclaimer: "This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

3M Technology Advancing Every Company
3M Products Enhancing Every Home
3M Innovation Improving Every Life

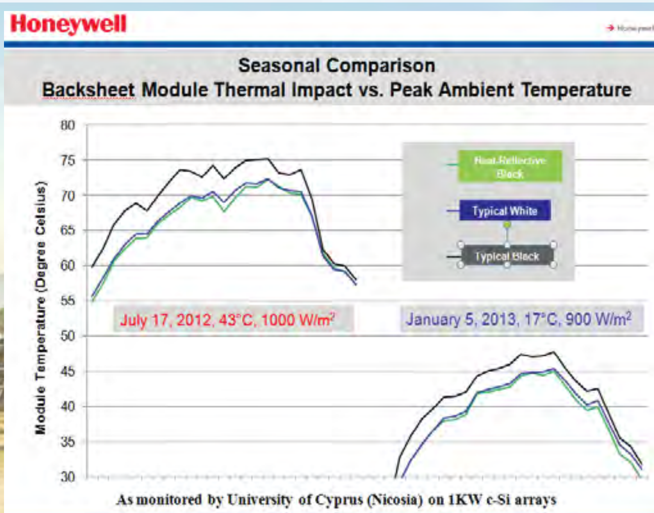
Reducing c-Si Module Operating Temperature via PV Packaging Components

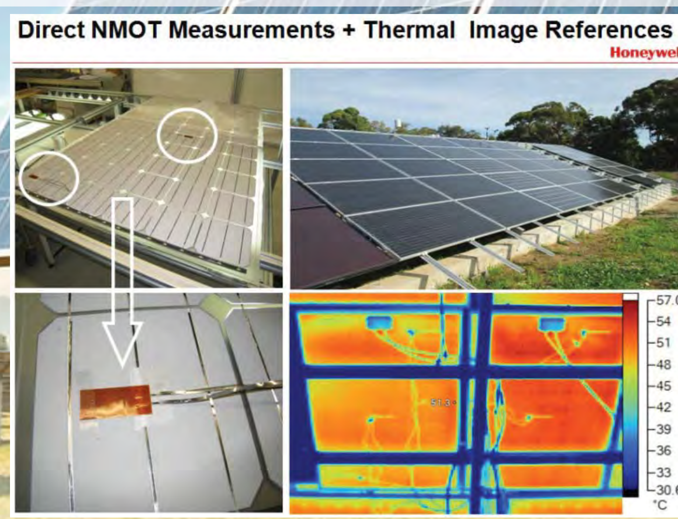
Purpose of Work: In theory, reducing average module operating temperatures should reduce the long term rate of degradation of module components, especially for polymer based materials, and lead to improved module reliability. As opposed to the recent common practice of “cost out among most PV module producers, another approach is suggested where small changes in packaging materials could lower c Si module operating temperatures by 2 to 10 degrees Centigrade. One such example is presented and potentially has additional benefits.





Typical daily and weekly comparisons of 3 independent grid-connected module arrays illustrating that the backsheet employed can impact NMOT. Note that the module with the “heat-reflective” black backsheet displays average operating temperatures closer to those of a typical white module.





Modules with heat-reflective backsheets still maintain lower NMOT despite seasonal variations in ambient temperatures.

Data via embedded probes cross-referenced to IR images confirms lower temperature of modules equipped with heat-reflective backsheets.

Conclusion: Module packaging can influence NMOT. Lower NMOT’s theoretically should improve module reliability. In BIPV / BAPV applications, where dark modules are often used, lower NMOT’s can theoretically also result in higher system power and reduced impact on building envelope.

Honeywell

Acceleration factors for damp-heat and HAST with high voltage stress

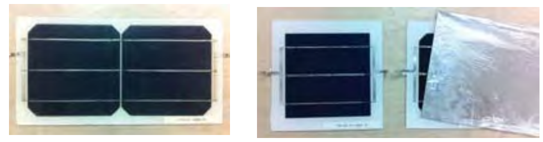
Mike W. Rowell, Steve J. Coughlin, Duncan W.J. Harwood,
D2Solar, 2369 Bering Drive, San Jose, CA 95131

Introduction

Damp heat (DH) testing can take up to 4000 hours before failure. HAST can accelerate degradation 10-20x over DH, speeding screening tests and product development. Here, we determine the acceleration factor (AF) and show that the failure modes in DH and HAST are similar for common glass module constructions. We also look at potential induced degradation (PID) in both DH and HAST conditions and determine the failure modes and AF's.

Module construction

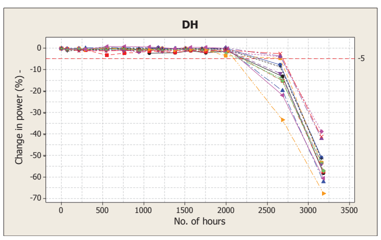
Module construction was made with representative industry standard materials (SnPb ribbon, EVA encapsulant, low iron glass and TPE backsheet). The commercially available multi-crystalline and mono-crystalline cells were from a tier 1 manufacturer with nameplate efficiencies of 19% and 17.6%, respectively. Mini-modules for DH and HAST testing were a 1x2 construction and mini-modules for PID-DH and PID-HAST testing were a 1x1 construction. In PID-DH and PID-HAST, a sheet of aluminum foil pressed against the front glass was used for the grounding.

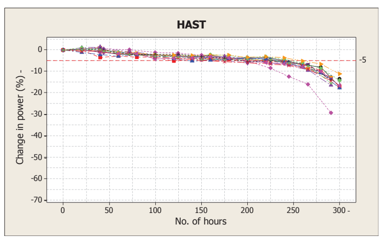


DAMP-HEAT (DH), HAST

Efficiency degradation:

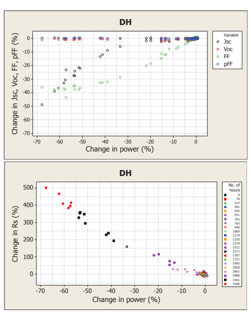
For quality control purposes, multiple groups of modules with identical construction are run through DH (85C/85%RH) and HAST (120C/100%RH) with periodic testing. The time to failure (TTF), taken as the time of 5% loss in power, for DH modules was ~2400 hours and for HAST ~210 hours, giving an acceleration factor of approximately 11.

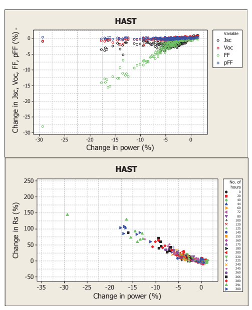


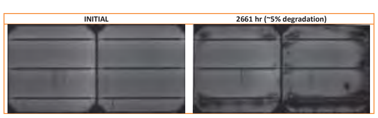


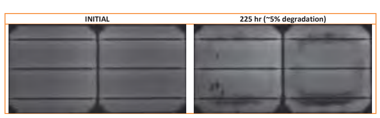
Failure modes

The predominant failure mode observed in both HAST and DH was an increase in series resistance (Rs) leading to a drop in fill factor (FF) and eventually a loss in current (Jsc). Similar signatures for both tests are also visible in electroluminescence images shown below. The mechanism is likely corrosion from acetic acid and moisture which eventually leads to an increase in contact resistance between the front grid and emitter.[1,2]





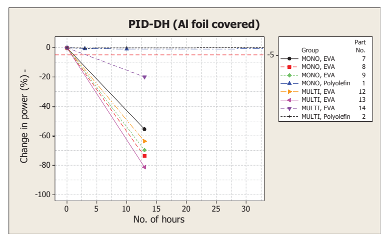


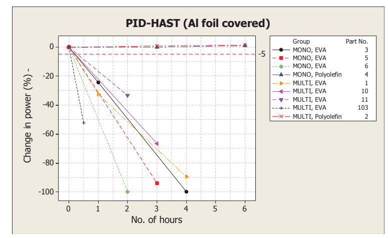


PID-DH, PID-HAST

Efficiency degradation:

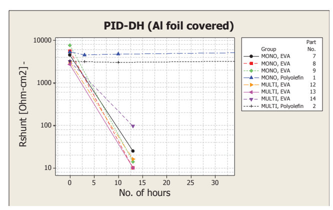
Potential induced degradation (PID) testing was performed in both DH (85C/85%RH) and HAST (120C/100%RH) conditions. In both cases, voltage biasing (-1kV) was performed with the front surface covered in Al foil in order to accelerate the test and reduce the dependence on the glass front surface conductivity which differs significantly between the two chamber conditions. In all cases with EVA, failure was quite rapid and TTF was determined by extrapolating back to a 5% power loss. Parts with polyolefin encapsulant were also tested and showed no degradation (up to 300hrs PID-DH and 7 hrs PID-HAST)

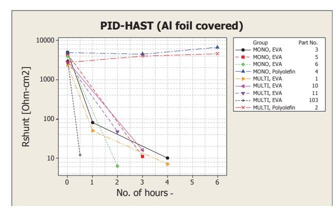


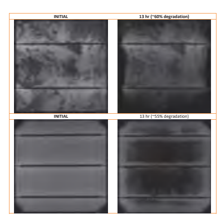


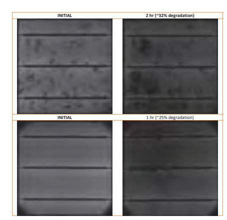
Failure modes

The predominant failure mode observed in both PID-HAST and PID-DH was a decrease in shunt resistance (Rshunt) leading to a drop in fill factor (FF). In both cases, electroluminescence images, shown below for representative samples, show the dark spotting of shunted areas typical of PID.

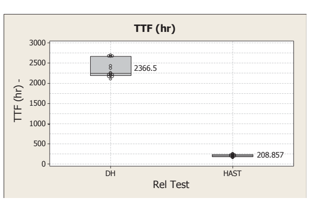






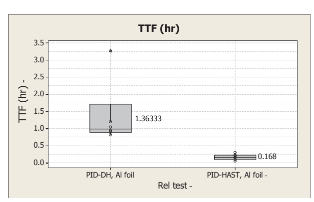


Acceleration factors



$$AF = \frac{MTTF_{DH}}{MTTF_{HAST}} = 11$$

Acceleration factors



$$AF = \frac{MTTF_{PID-DH}}{MTTF_{PID-HAST}} = 8$$

The acceleration factors (AF) here are simply computed as the ratio of the mean time to failure (MTTF) for the two tests. In the case of the PID tests, parts failed too rapidly to capture a measurement near a 5% power loss, and therefor there is significant uncertainty determining the TTF. Clearly, however, there is a significant acceleration of the dominant degradation mechanism.

Conclusions

We have shown that the dominant failure mechanisms for both damp heat and high voltage stress in damp heat can be accelerated by approximately an order of magnitude under HAST conditions. It should be underscored that these findings are only for conventional modules with conventional cells.

References

1. Ketola, Barry, and Ann Norris. "Degradation Mechanism Investigation of Extended Damp Heat Aged PV Modules."
2. Hacke, Peter, et al. "Test-to-failure of crystalline silicon modules." *35th IEEE PVSC* (2010): 244-250.

COMPARING ACCELERATED TESTING AND OUTDOOR EXPOSURE

Michael Köhl

Fraunhofer Institute for Solar Energy Systems ISE

3rd PV Rollout Conference Workshops – 2013

requirements for bankable pv modules

and pv power plants

Metro Atlanta Chamber, USA - February 25th, 2013

www.ise.fraunhofer.de

hofer

Challenges <

The durability is very good for most of the actual premium c-Si modules on the market (less than 1% loss in performance per year)

But new materials and designs have to be developed in order to decrease costs

- Accelerated service life tests are needed for optimisation of the durability and convincing investors

- The longer the desired lifetime, the higher the needed acceleration factor, the bigger the unsecurity of the tests

- The tests should be based on **real stress in the field**, because usually the materials and their degradation processes are not known

Stress-factors at operation of PV-modules

Moisture causes hydrolysis and corrosion (Acetic acid from EVA)

Electrical potentials introduce leakage currents and reduction of cell efficiency

UV – irradiation causes destruction of polymeric components: "

Photo-degradation "

Temperature cycling, static oder dynamic **mechanical loads** lead to: "

Cell-breakage, inter-connecture breakage, delamination

Salt, heat (high temperatures)

Example for development of Accelerated Life Testing < based on real stresses during operation of PV-modules <

Moisture causes hydrolysis and corrosion

Electrical potentials introduce leakage currents and reduction of cell efficiency

UV – irradiation causes destruction of polymeric components:

Photo-degradation

Temperature cycling, static oder dynamic mechanical loads lead to tensions :

Cell-breakage, inter-connecture breakage, delamination

Salt, heat (high temperatures)

1 Monitoring climatic conditions

Ambient climate and sample temperatures as 1min averaged time series

Corrosivity, salt concentration as yearly or monthly dose

City or reference: %

Freiburg Germany %

Arid

Sede Boqer

Israel

Alpine

Zugspitze

Germany

Tropical

Serpang

Indonesia

(operated by TÜV Rheinland

Maritime

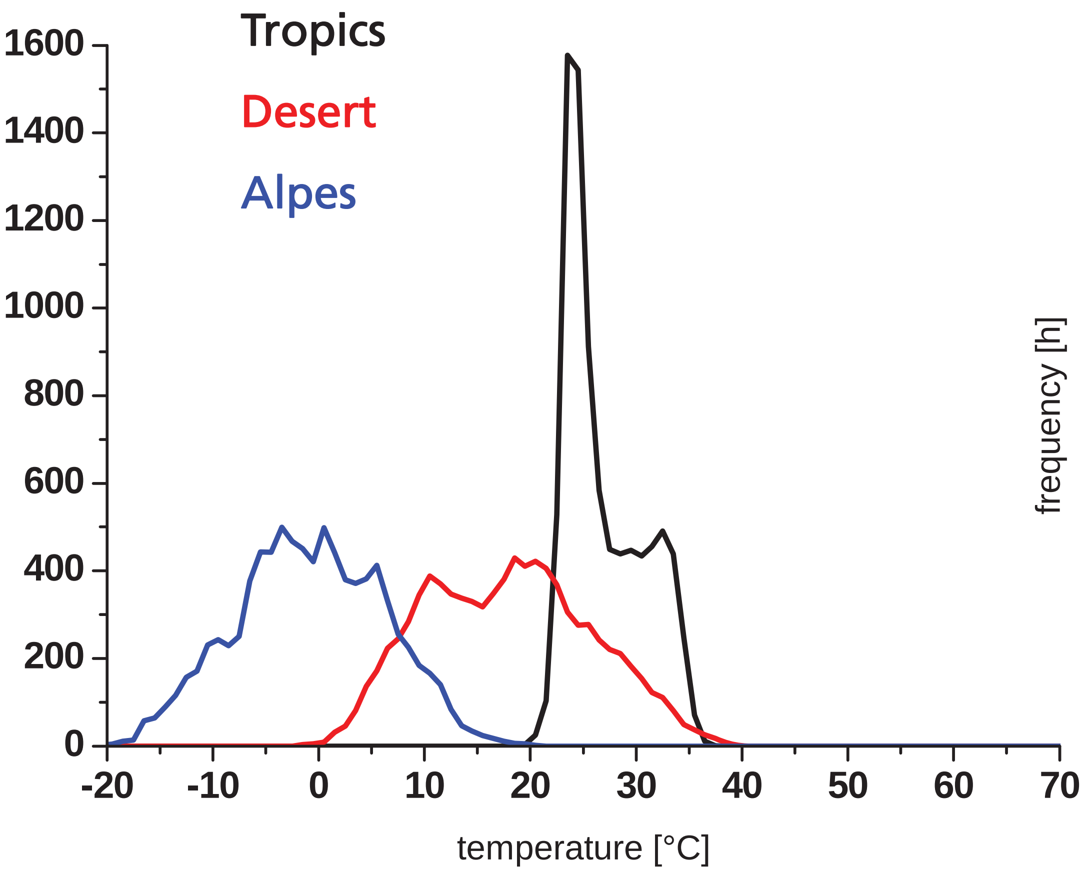
Pozo Izquierdo

Gran Canaria

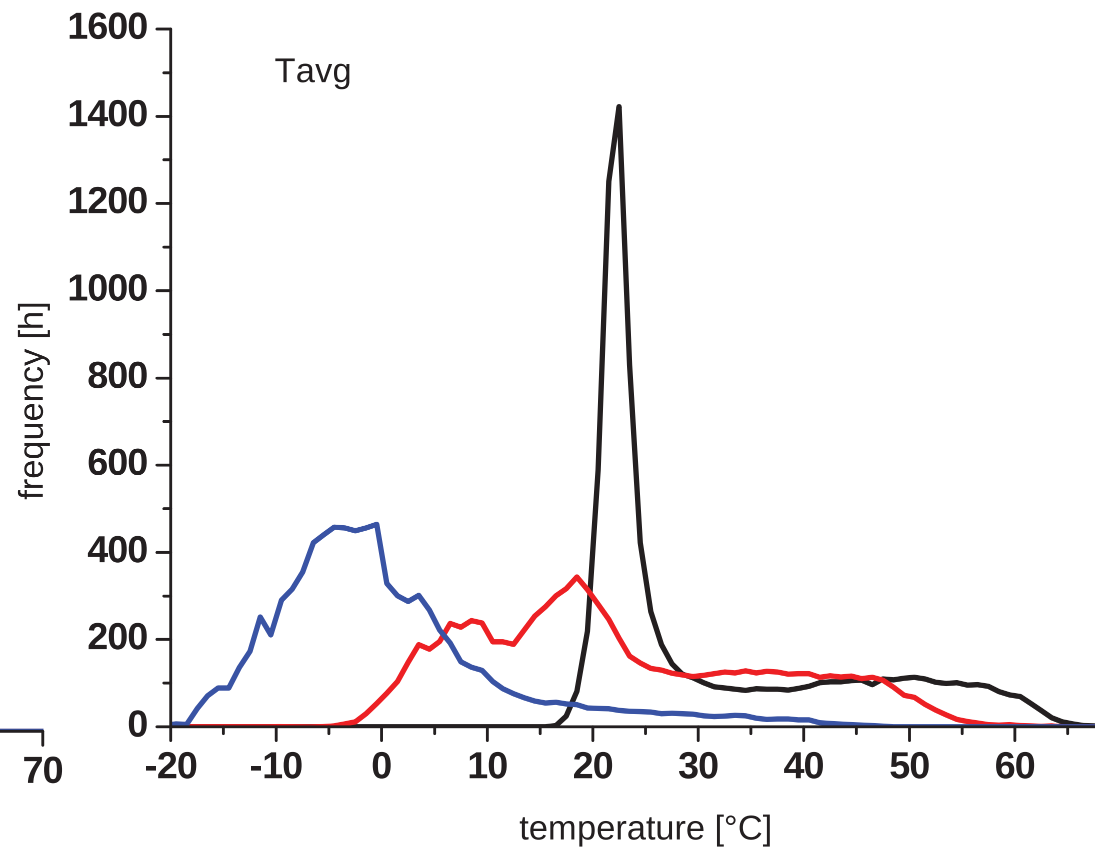
Module temperature monitoring during outdoor exposure

Macro – climate => Micro – climate

Ambient temperature



Average module temperature (c-Si)



3 Modeling micro-climatic stress factors

Physical modeling of module temperature for each of the different module types using David Faiman's approach (could be King, Fuentes……as well)

Macro – climate => Micro – climate

Irradiation, wind, ambient temperature => T_{mod}

Neglected: IR-radiation exchange and natural convection

$$T_{\mathrm{mod}} \quad T_{amb} + \frac{H}{U_0 + U_1 \cdot v}$$

T_{mod} module temperature

T_{amb} ambient temperature

v wind velocity

H solar radiation

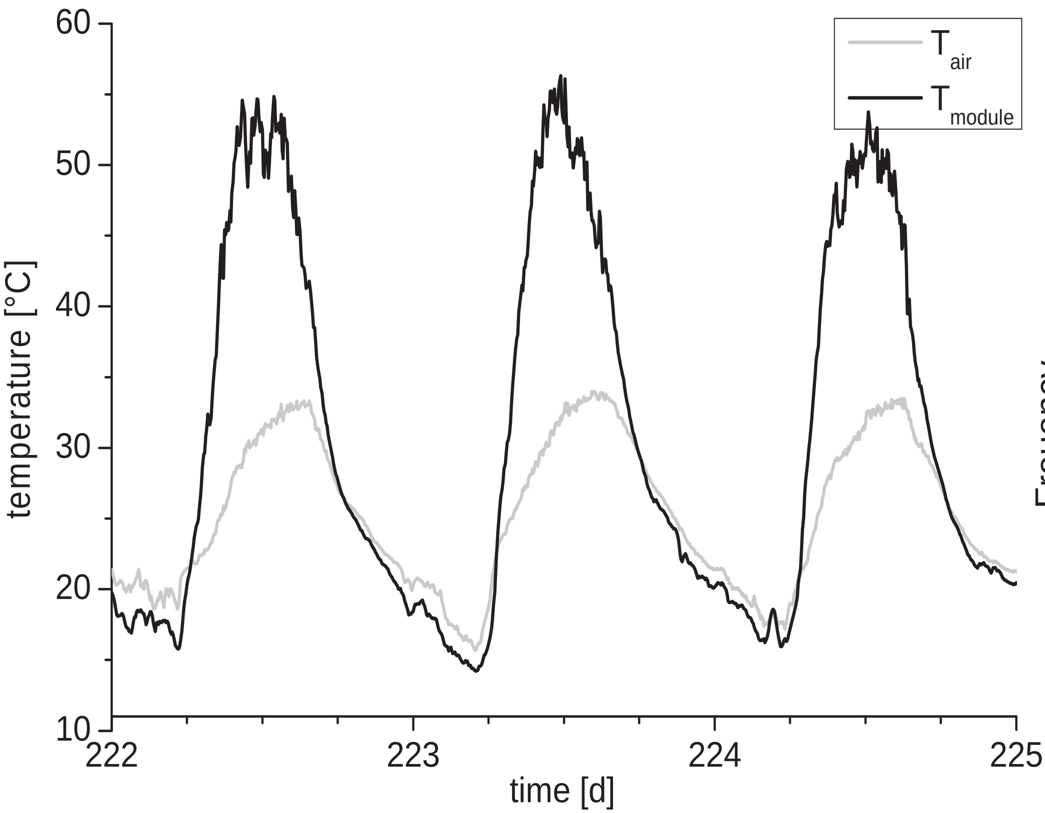
	U1	U0
a-Si 1	10,7	25,7
a-Si 3	5,8	25,8
a-Si 4	4,3	26,1
CIS 1	3,1	23,0
CIS 2	4,1	25,0
CdTe	5,4	23,4
c-Si	6,2	30,0

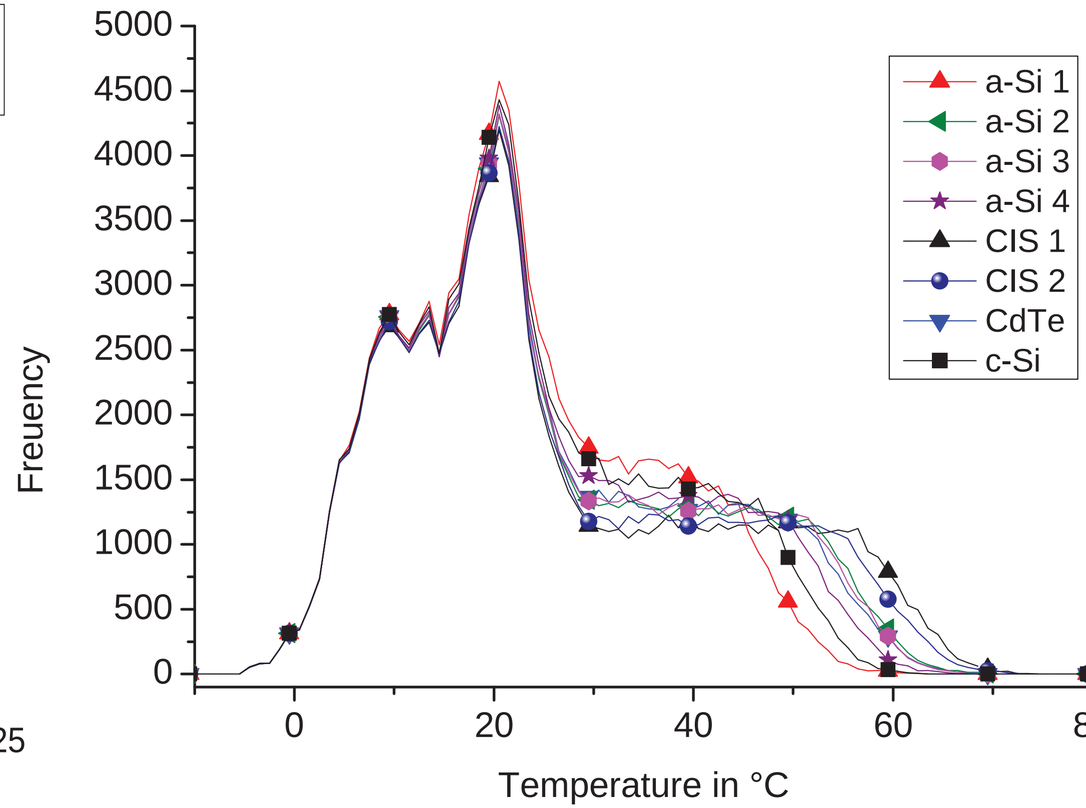
The parameters U are module-specific but location independent "

M.Koehl et.al.: Modelling of the nominal operating cell temperature based on outdoor weathering, Sol. Energy Mat. Sol. Cells (2011)

3 Modeling micro-climatic stress factors

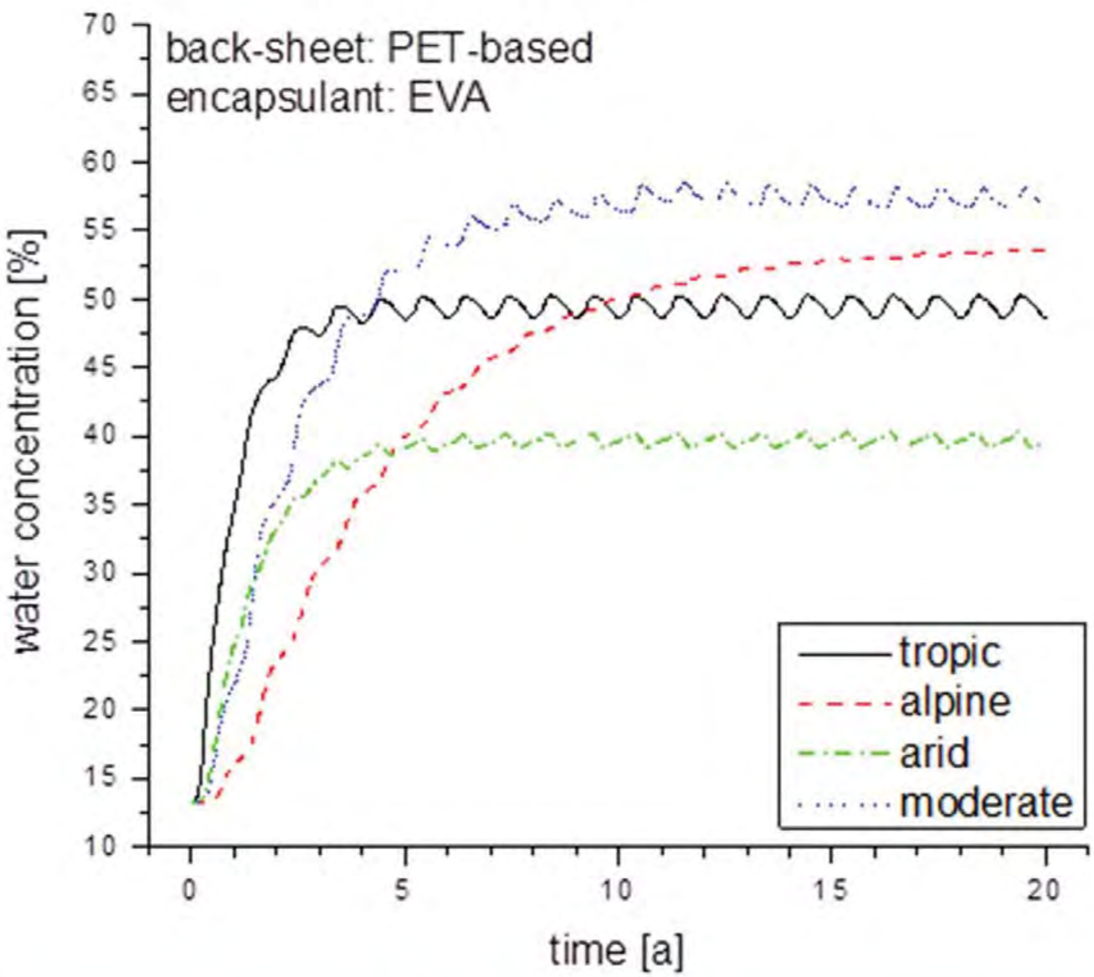
Module-temperature as time-series based on ambient climate data and as histograms (one year)

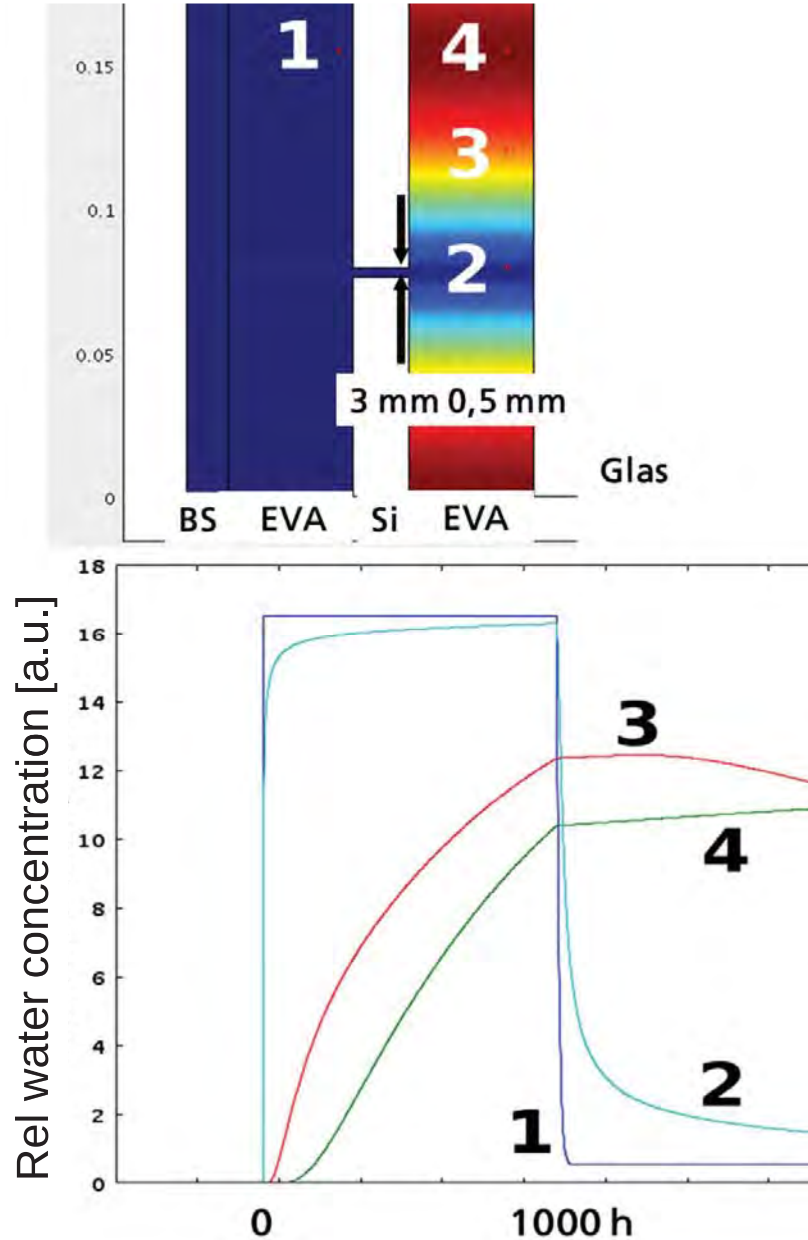




3 Modeling micro-climatic stress factors

Simulation of module humidity by FEM



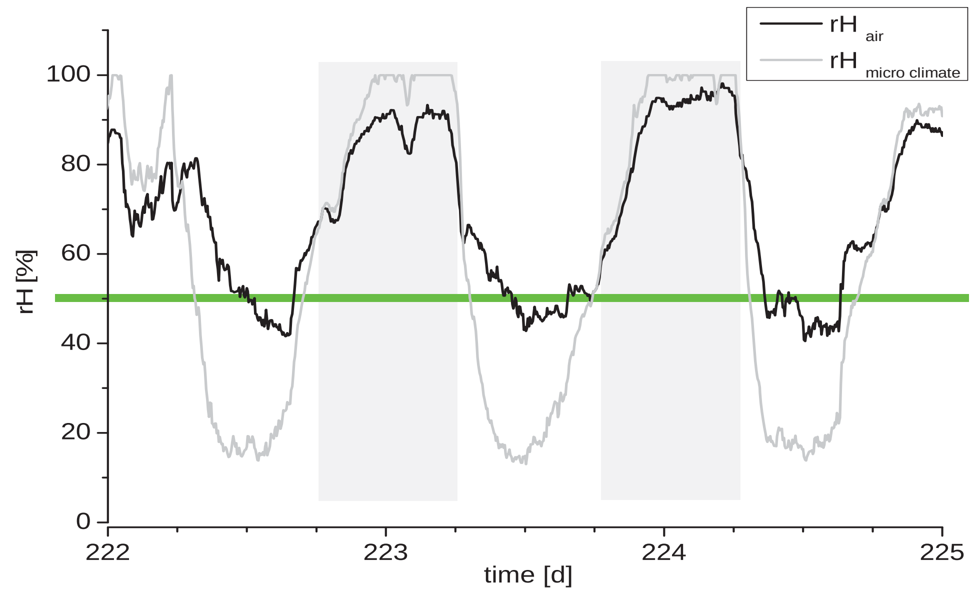


Damp-heat testing 85%rh @ 85°C

J. Wirth, Diplomarbeit. Diploma Thesis, University of Freiburg, 20

3 Modeling micro-climatic stress factors

Phenomenological modelling of moisture impact

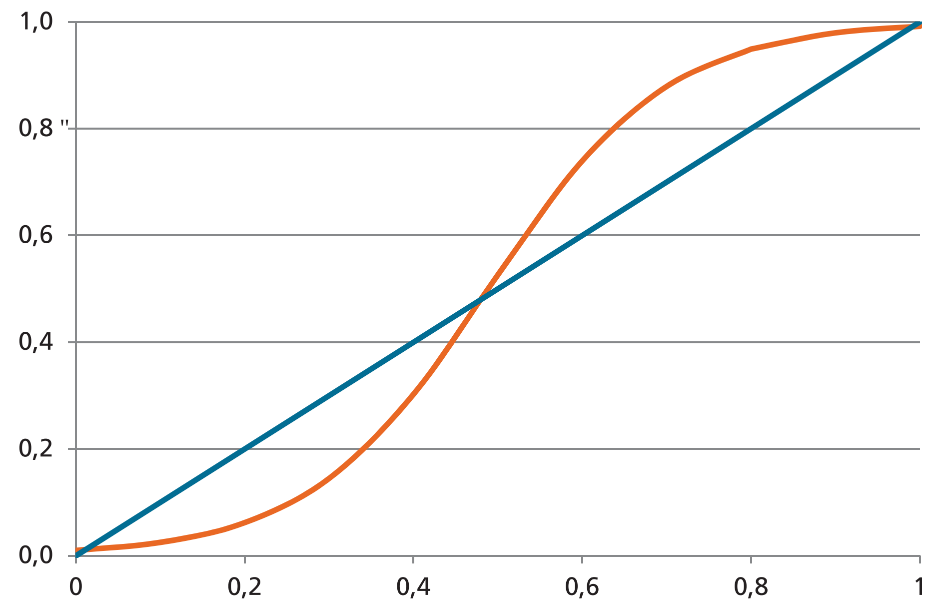


1.) Humidity at the module surface:

$$rh\,(T_{mod}) = rh\,(T_{amb}) * P_{sat}\,(T_{mod}) \,/\, P_{sat}\,(T_{amb})$$

2.) Put more weight on high moisture levels:

$$rh_{eff} = 1 \,/\, (1 + 100 \cdot \exp(-9.4 \cdot rh))$$



3.) Humidity level at test conditions (85%rh):

$$\Delta t_i = \Delta t_i \cdot rh_{eff} \,/\, 0.85$$

M. Koehl et al. / Solar Energy Materials & Solar Cells 99 (2012) 282–291

4 Time-transformation functions for major degradation processes

4.) Process kinetics depend on module temperature (Time Transformation Function):

$$t_{test} = \text{Lifetime (years)} \cdot \Sigma_i \{\Delta t_i(rh_{eff}, T_{mod,i}) \cdot \exp[-(E_a / R)\cdot(1/T_{test} - 1/T_{mod,i})]\}$$

E_a = activation energy for the rate dominating degradation process

5 Modeling corresponding ALT – conditions for micro-climatic stress factors

Testing time at 85%rh/85°C for 25 years lifetime

Example:

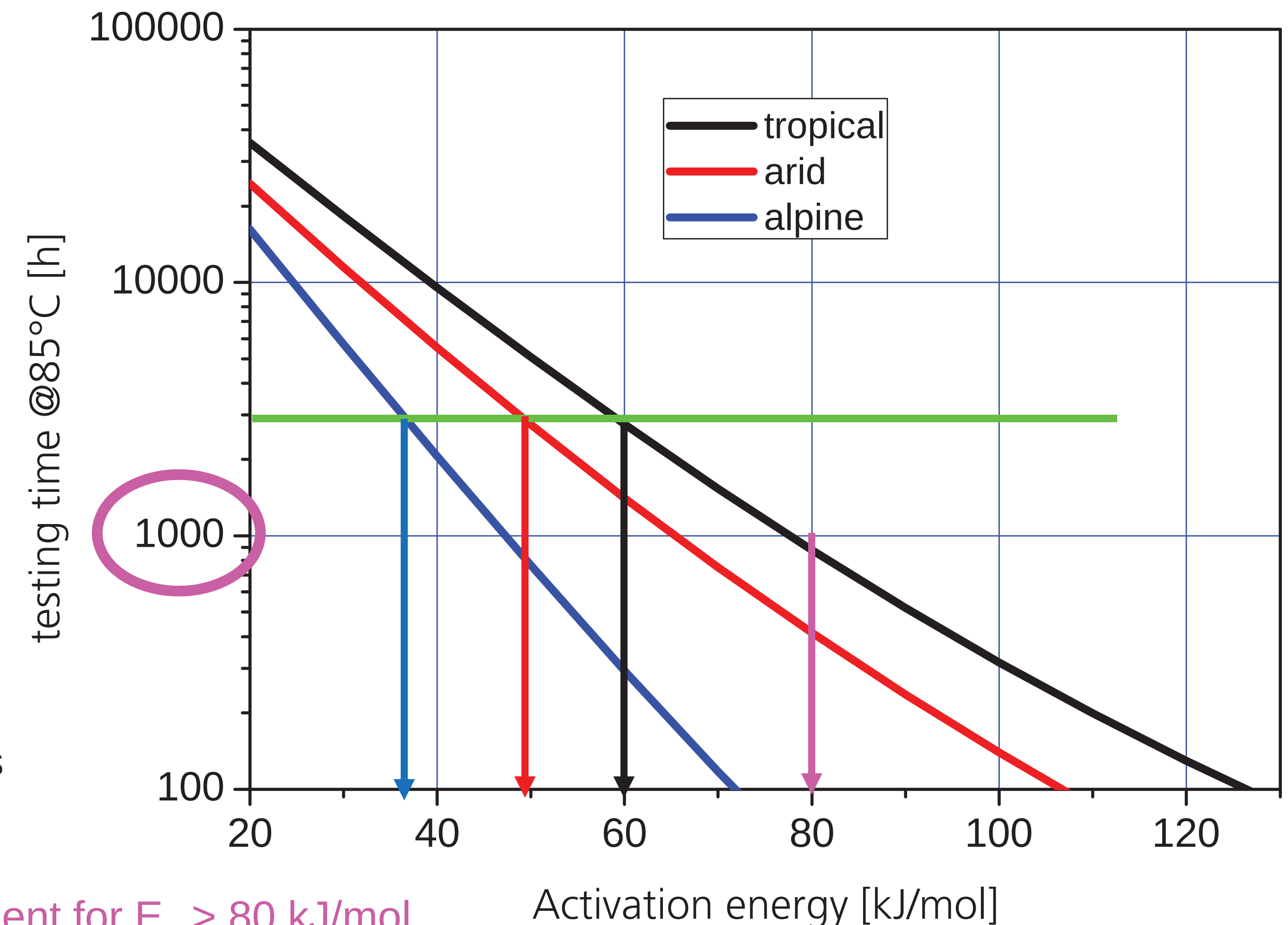
Time to failure @ 85°C/85%rh:

3000h

E_a > 35 kJ/mol for alpine climates

E_a > 50 kJ/mol for arid climates

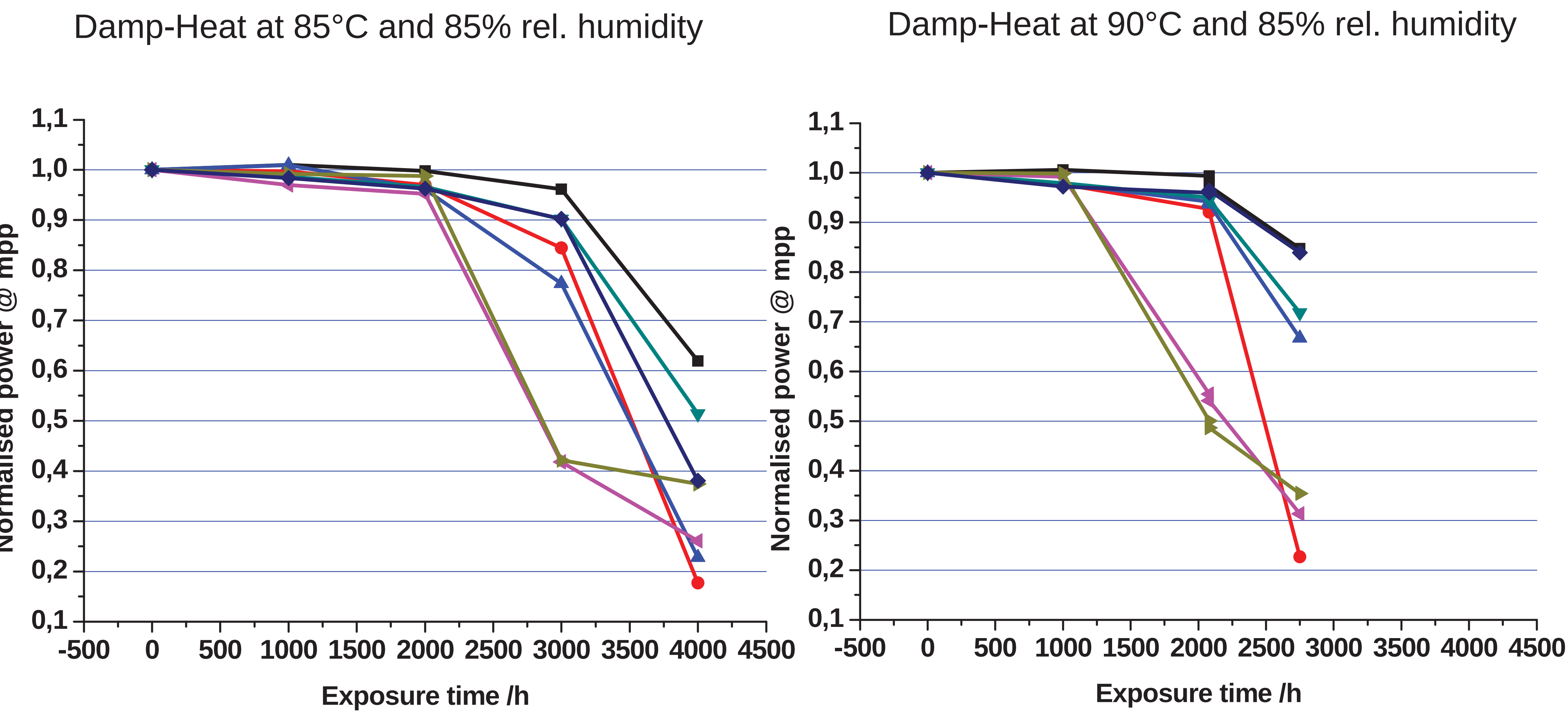
E_a > 60 kJ/mol for tropical climates



Type approval test would be sufficient for E_a > 80 kJ/mol

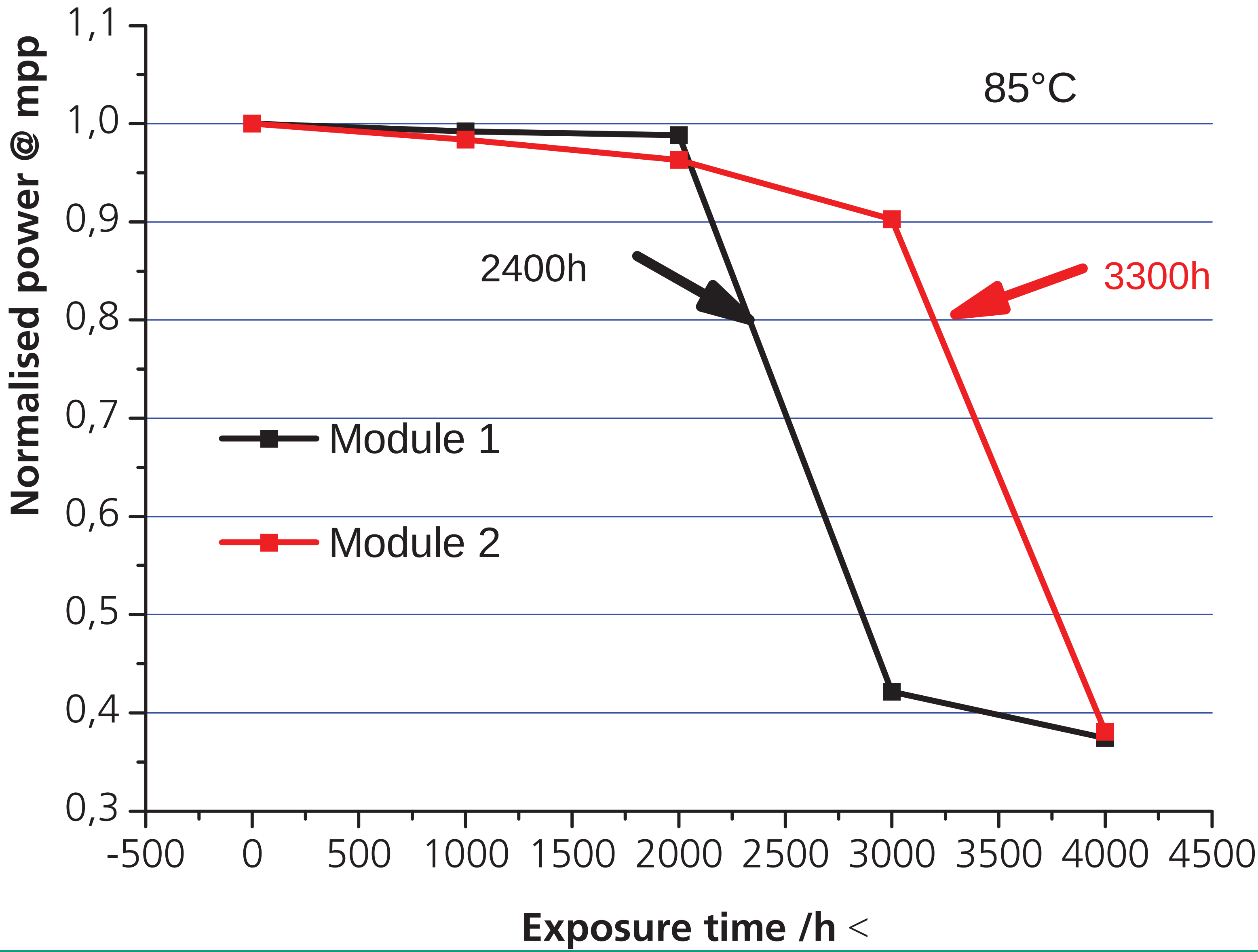
6 Evaluation of the parameters for time-transformation functions by ALT

Testing of c-Si modules from 7 different manufacturers

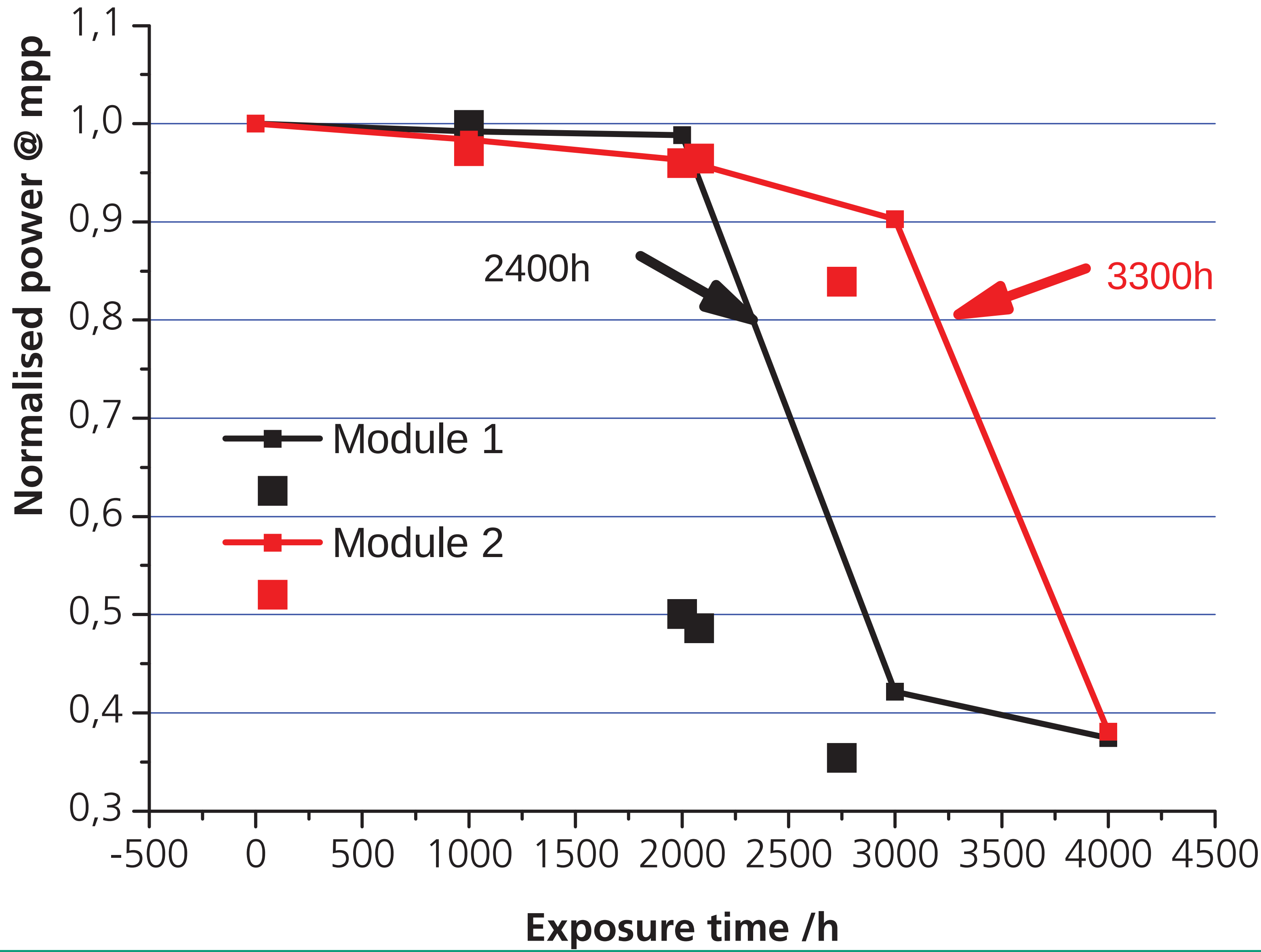


6 Evaluation of the parameters for time-transformation functions by ALT

Damp-heat testing at 85%rh@85°C, module 1 und module 2 "

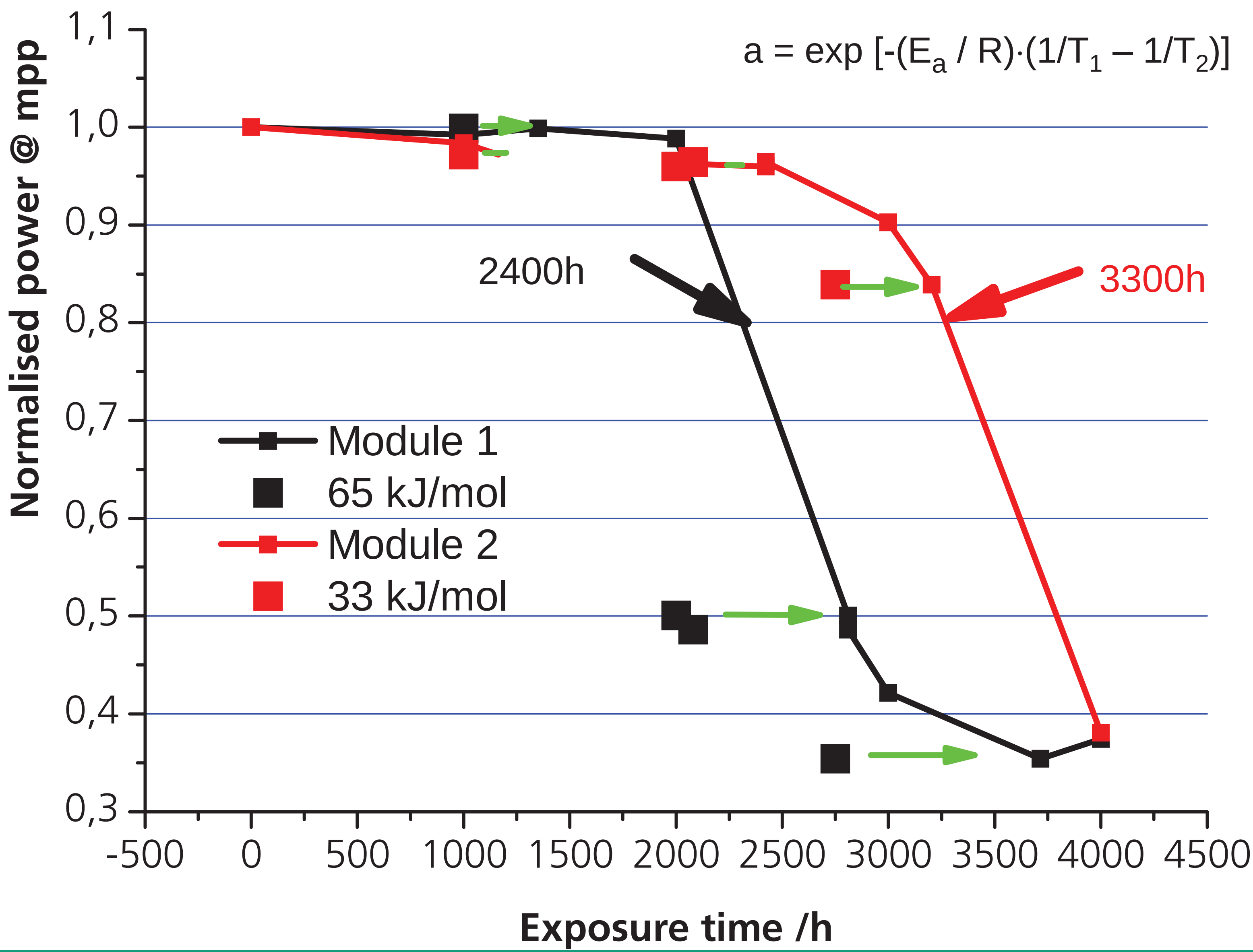


Damp-heat testing at 85%rh@85°C and @90°C, module 1 und module 2 "



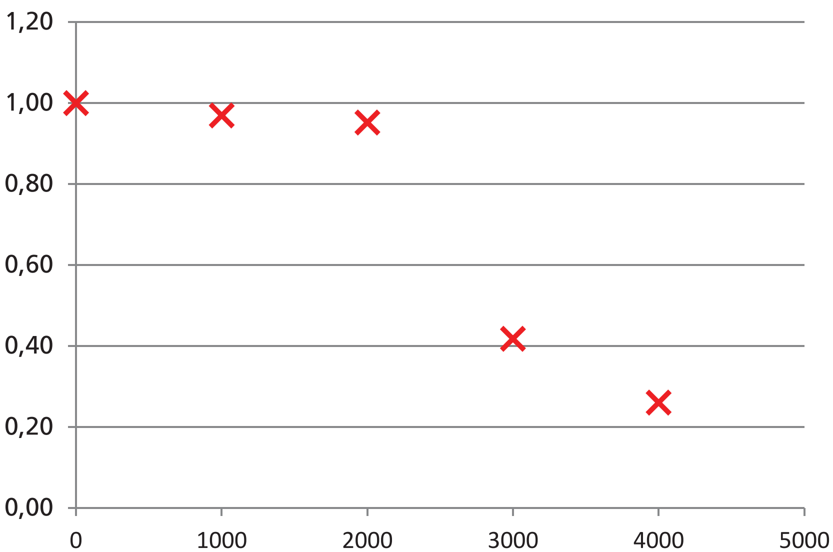
6 Evaluation of the parameters for time-transformation functions by ALT

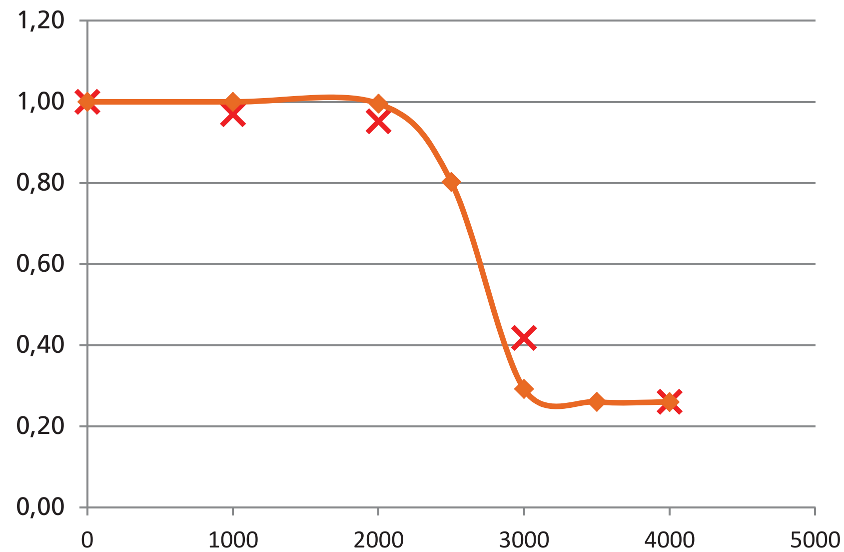
Damp-heat testing at 85%rh@85°C and @90°C, module 1 und module 2 "



6 Evaluation of the parameters for time-transformation functions by ALT

$$\Delta P = G/(1+ (G/0.01-1)\ \exp(-(t-tind\ (T))*k(T))\ )$$



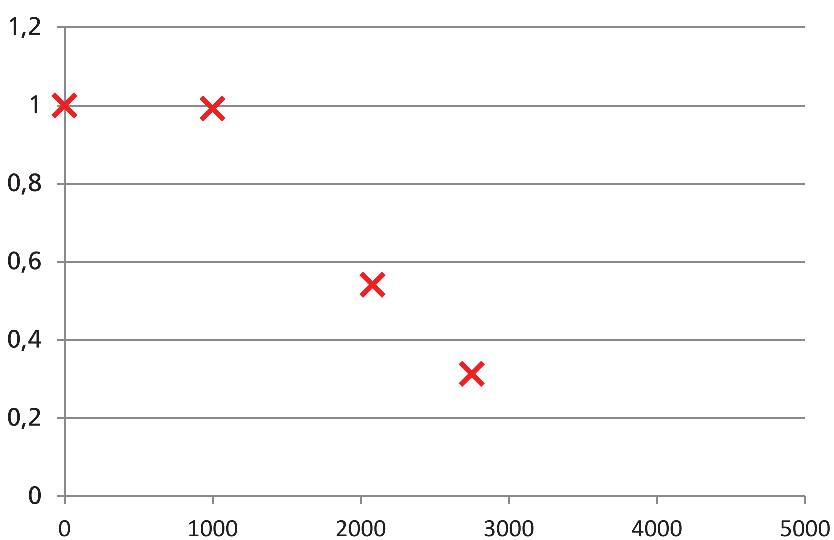


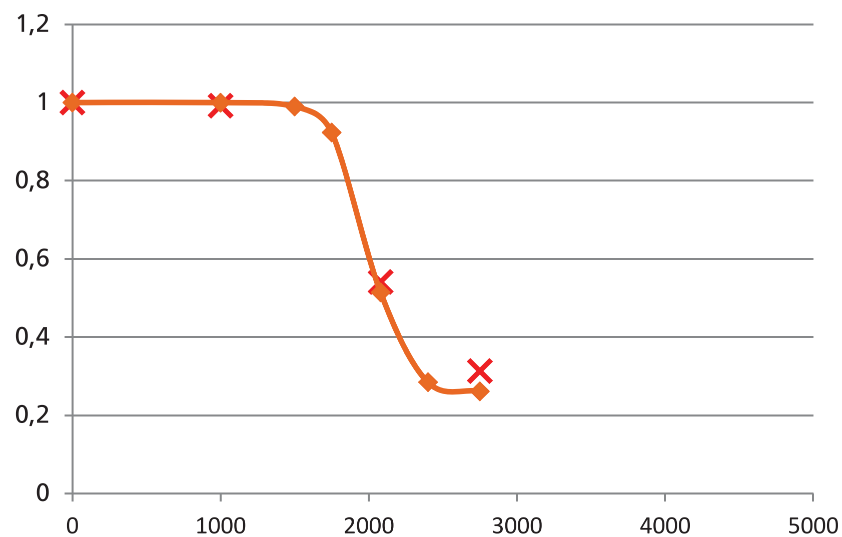
T=85°C

Tind=2100h

K=0,0082/h

G=0,26



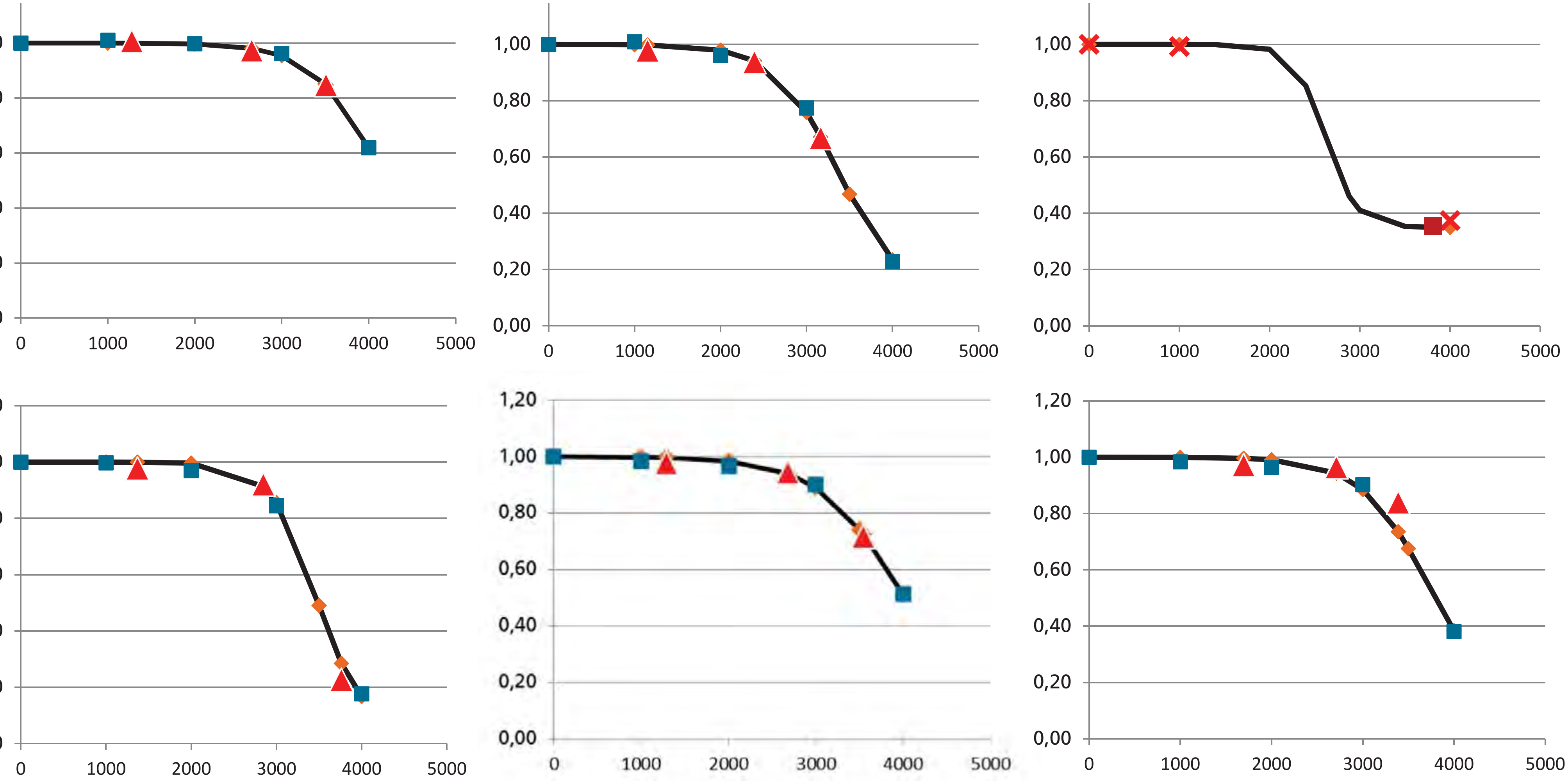


T=90°C

Tind=1500h

K=0,0115/h

G=0,26



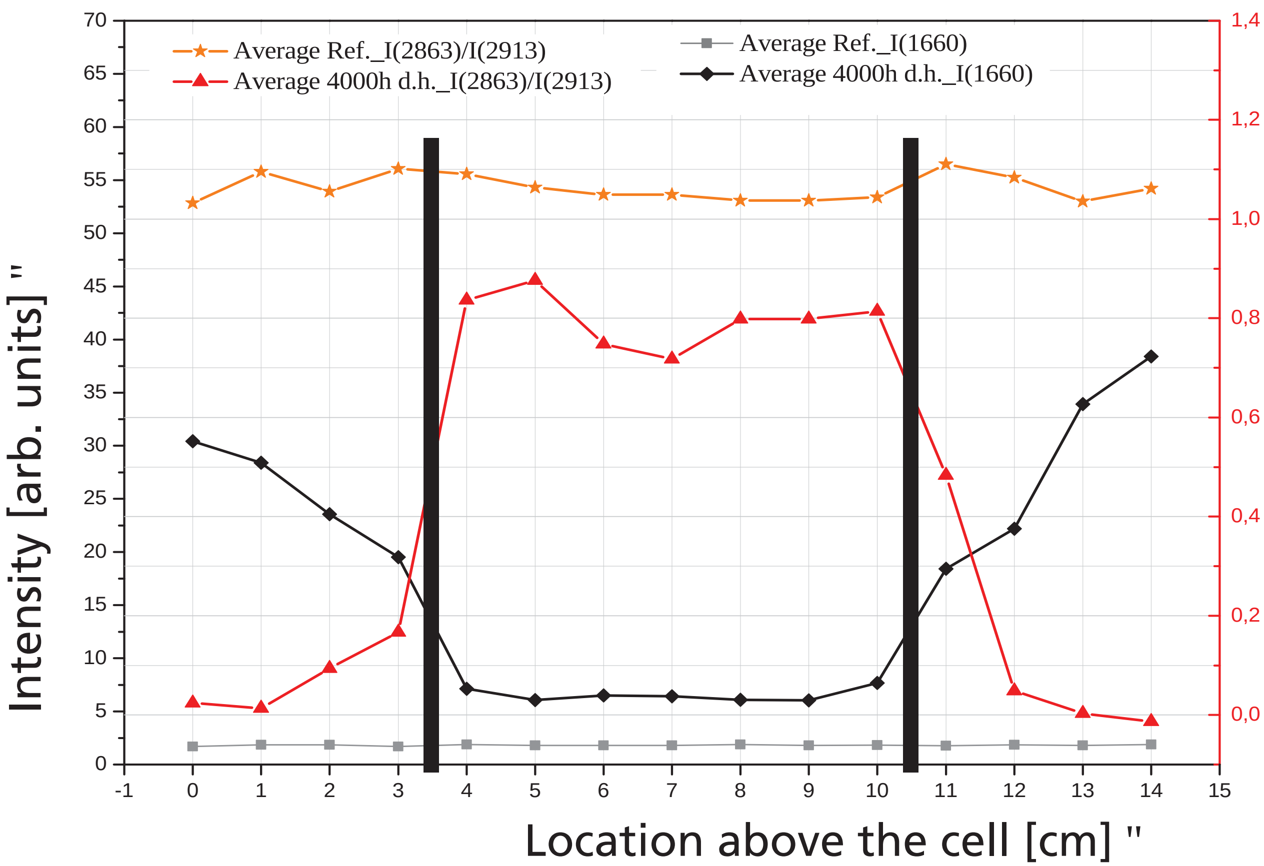
time (@85°C) [h]	2412	2576	2821	3047	3160	3227	3548
ivation energy [kJ/mol]	70	73	30	68	26	55	53
nate class	A	A	C	A	C	B	B

Qualification for different stress levels or climate zones allows diversification of PV-modules

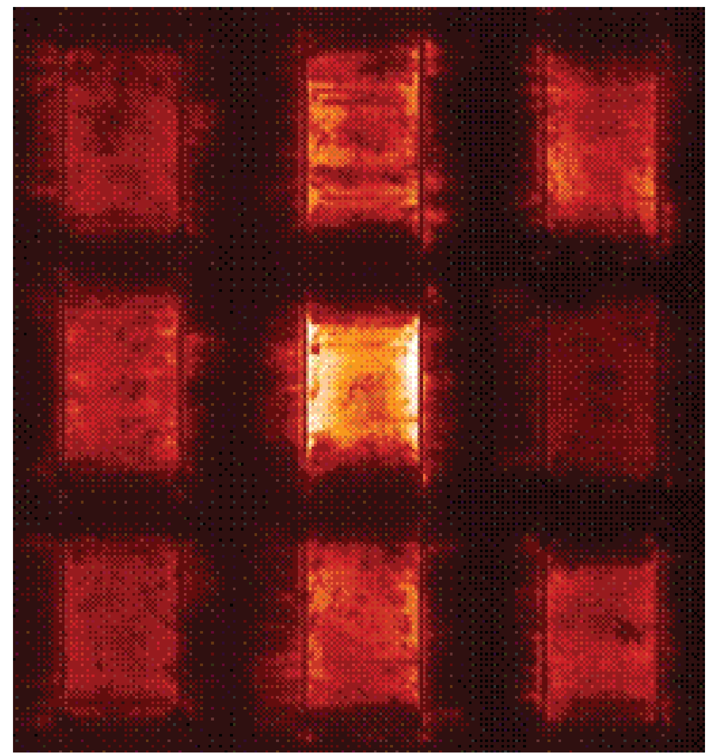
Degradation of the modules

Polymer Analysis by Raman-Spectroscopie

Comparison of the Vinyl-Band (red) and the fluorescence-background (black) unaged and after 4000h damp-heat-testing



Elektroluminescence-picture of the degraded cells



C. Peike et.al.: Non-destructive degradation analysis of encapsulants in PV modules by Raman Spectroscopy, Sol. En. Mat. Sol. Cells (2011)

6 Evaluation of the service life time for different climates

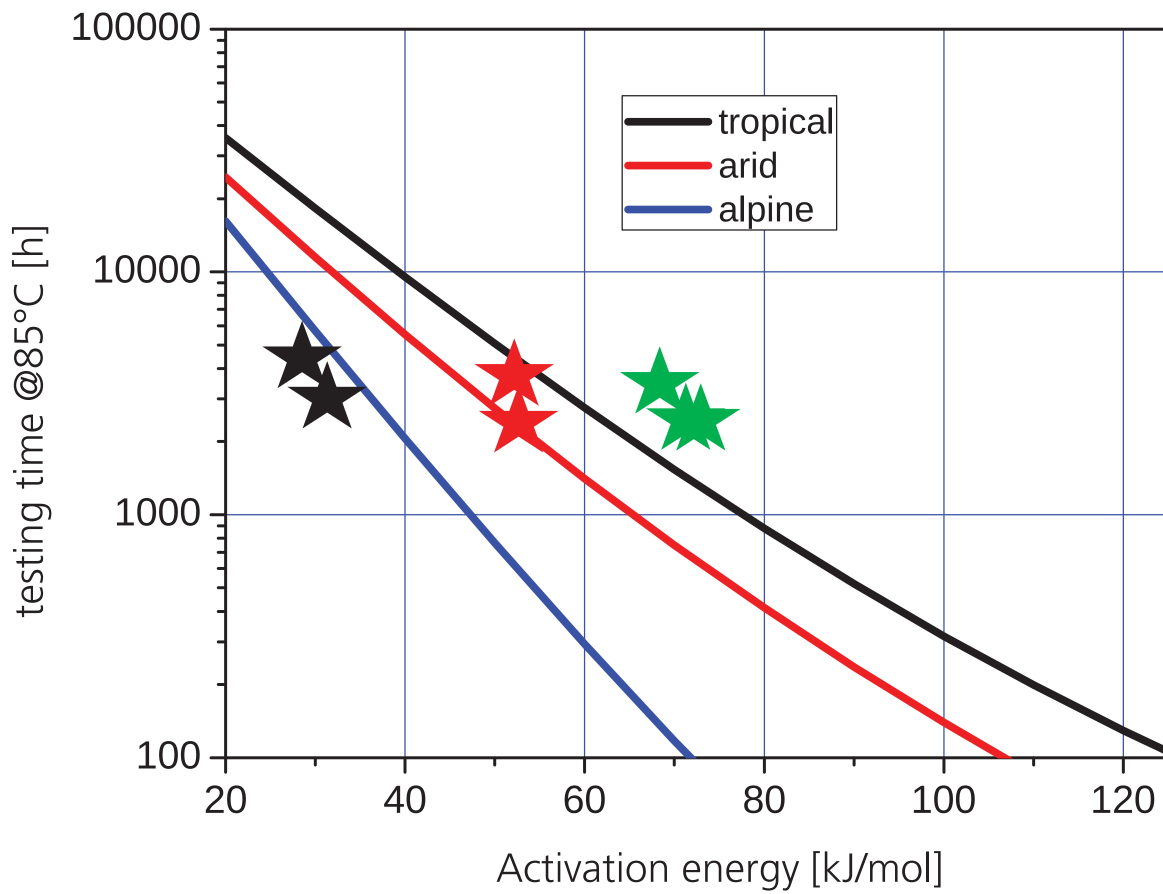
Testing time at 85%rh/85°C for 25 years lifetime

Climate classes:

A: **Most severe moisture stress**

B: **Moderate moisture stress**

C: **Low moisture stress**



Assumptions:

The measured stress levels are representative

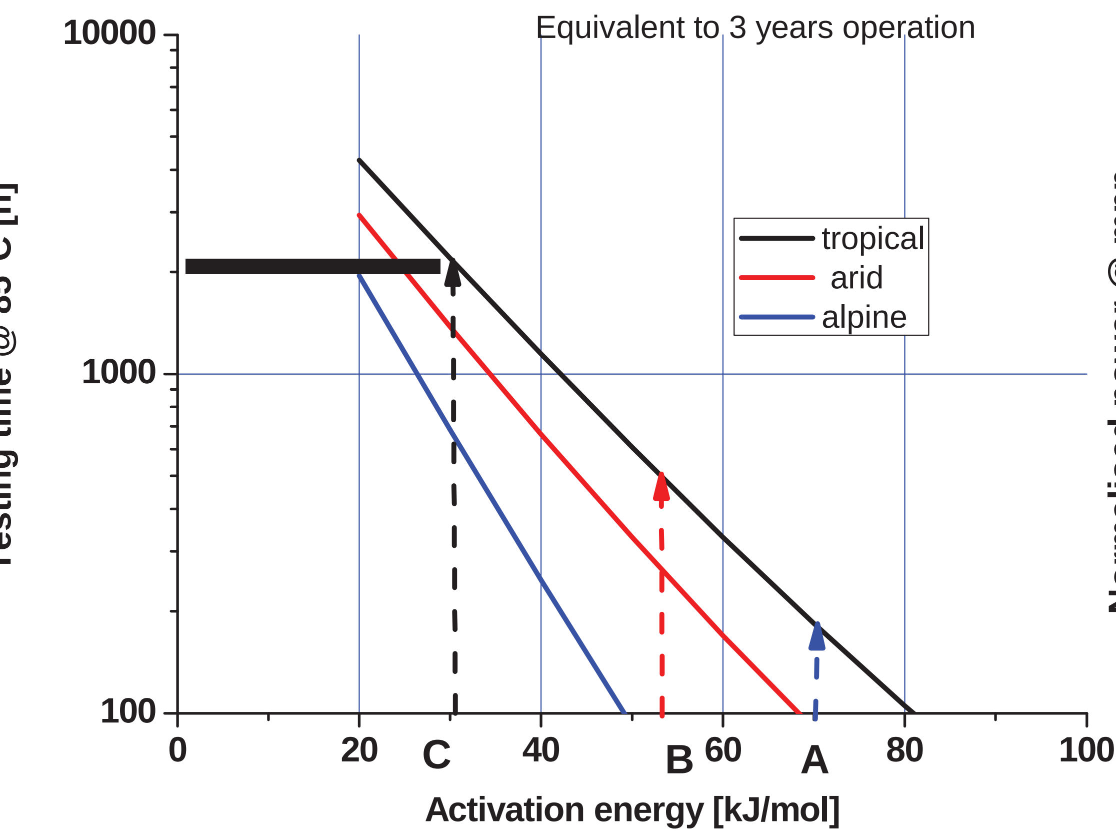
The model for the kinetics is valid

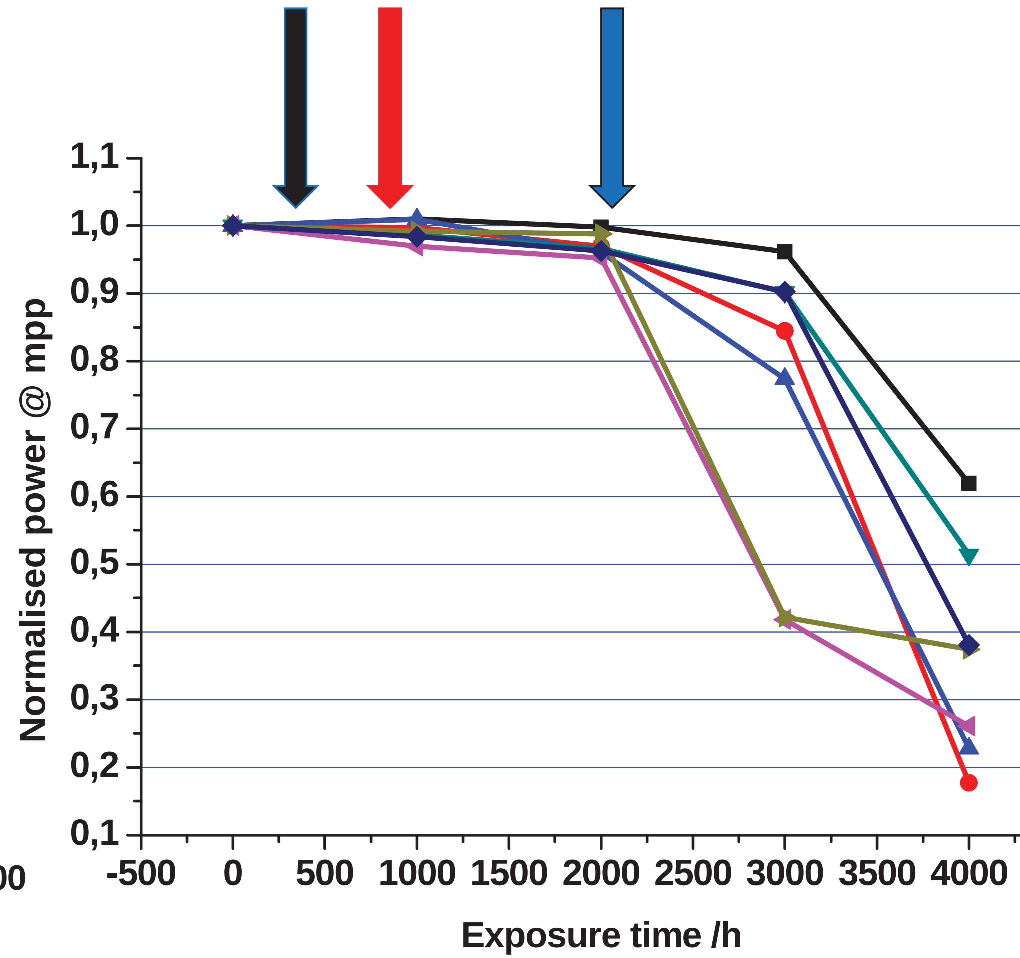
The constant load D/H test reflects reality

7 Modeling expected degradation for validation by outdoor exposure

Power reduction after 3 years outdoor exposure < 3%

Exposure time has to be doubled





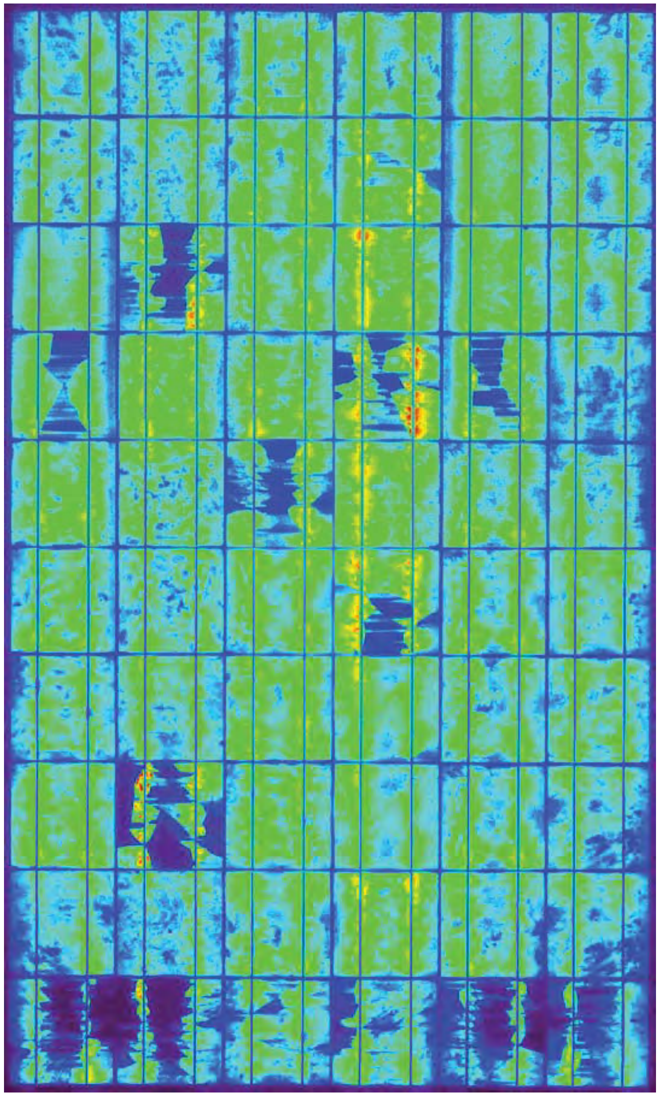
7 Degradation effects during outdoor exposure

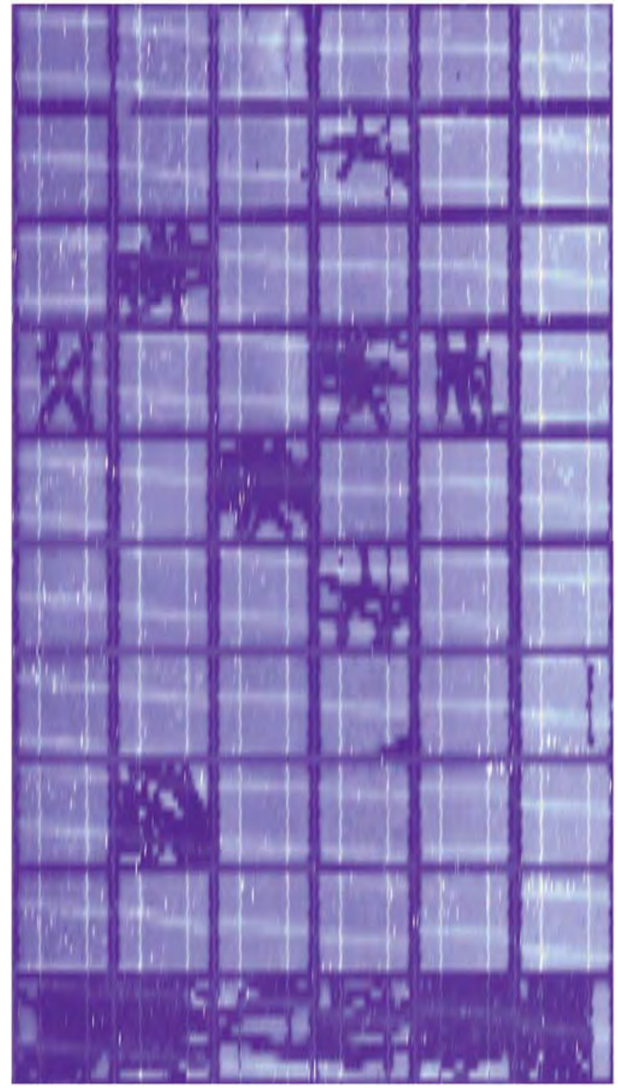
Changes of the electrical performance at the outdoor exposure site

Test site	Tropical	Arid	Urban	Alpine	Average
Module 1	-1,5%	-0,6%	-0,9%	-1,1%	-1,0%
2	-0,1%	-1,1%	-0,8%	-4,7%	-1,7%
3	-1,0%	-0,1%	-0,5%	1,3%	-0,1%
4	-3,2%	-0,1%	1,7%	-6,6%	-2,1%
5	-0,1%	-2,2%	-1,8%	-0,8%	-1,2%
Average	-1,2%	-0,8%	-0,5%	-2,4%	-1,2%

After 3 years operation hardly out of the error bars

7 Degradation effects during outdoor exposure

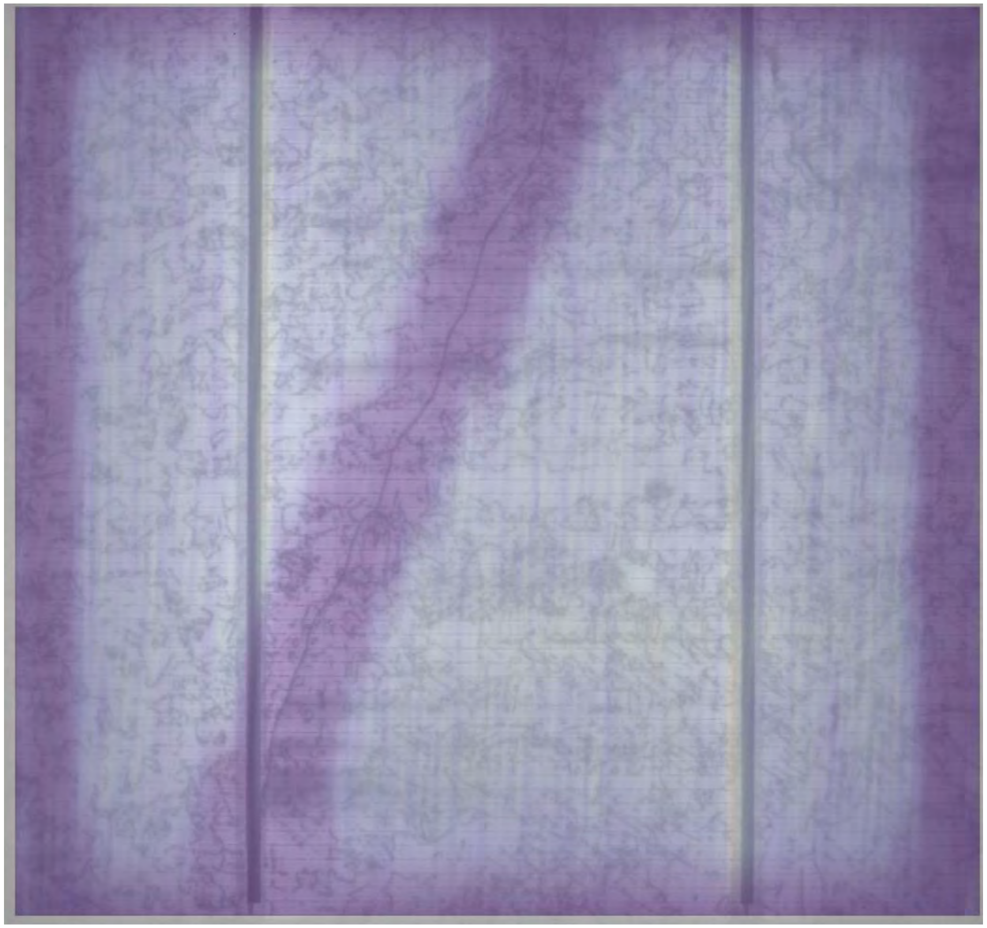




After 3 years on the alpes

Degradation of module materials - UV-induced fluorescence <

2 a alpine outdoor exposure

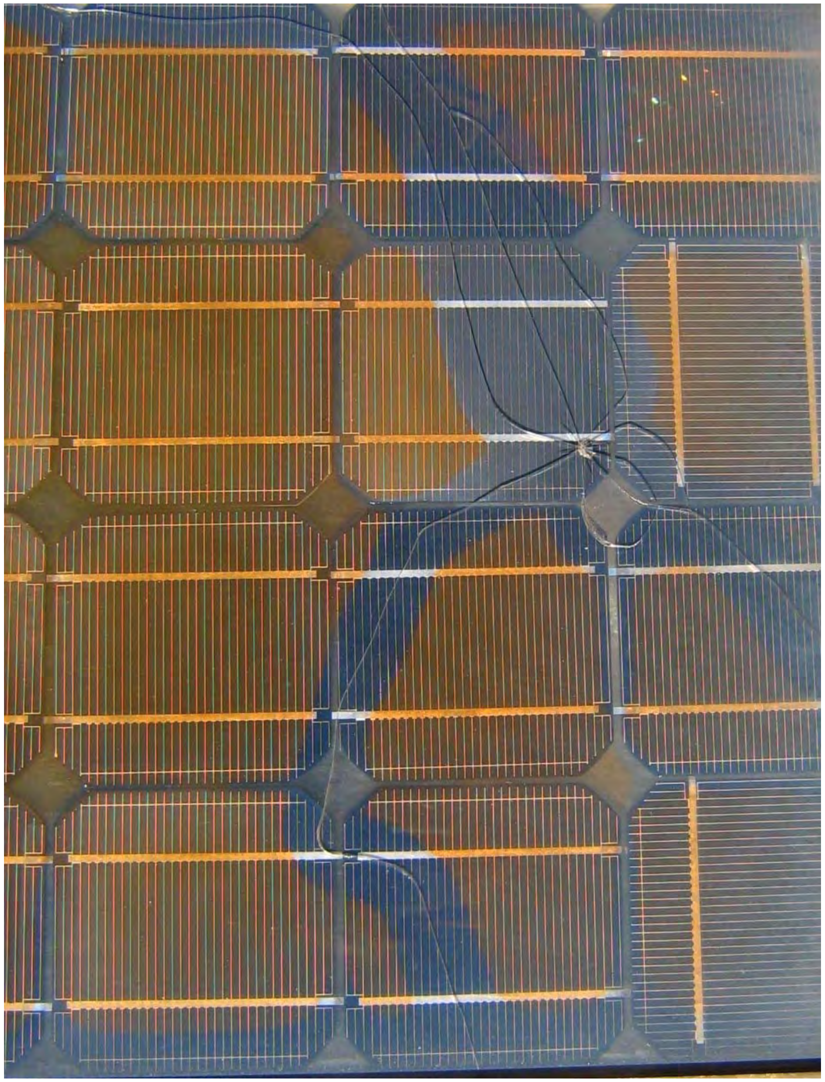


2 a desert outdoor exposure

Combination of electroluminescence and fluorescence

J. Schlothauer, et al., Fluorescence imaging: a powerful tool for the investigation of polymer degradation in PV modules, *Photovoltaics International* journal, November 2010

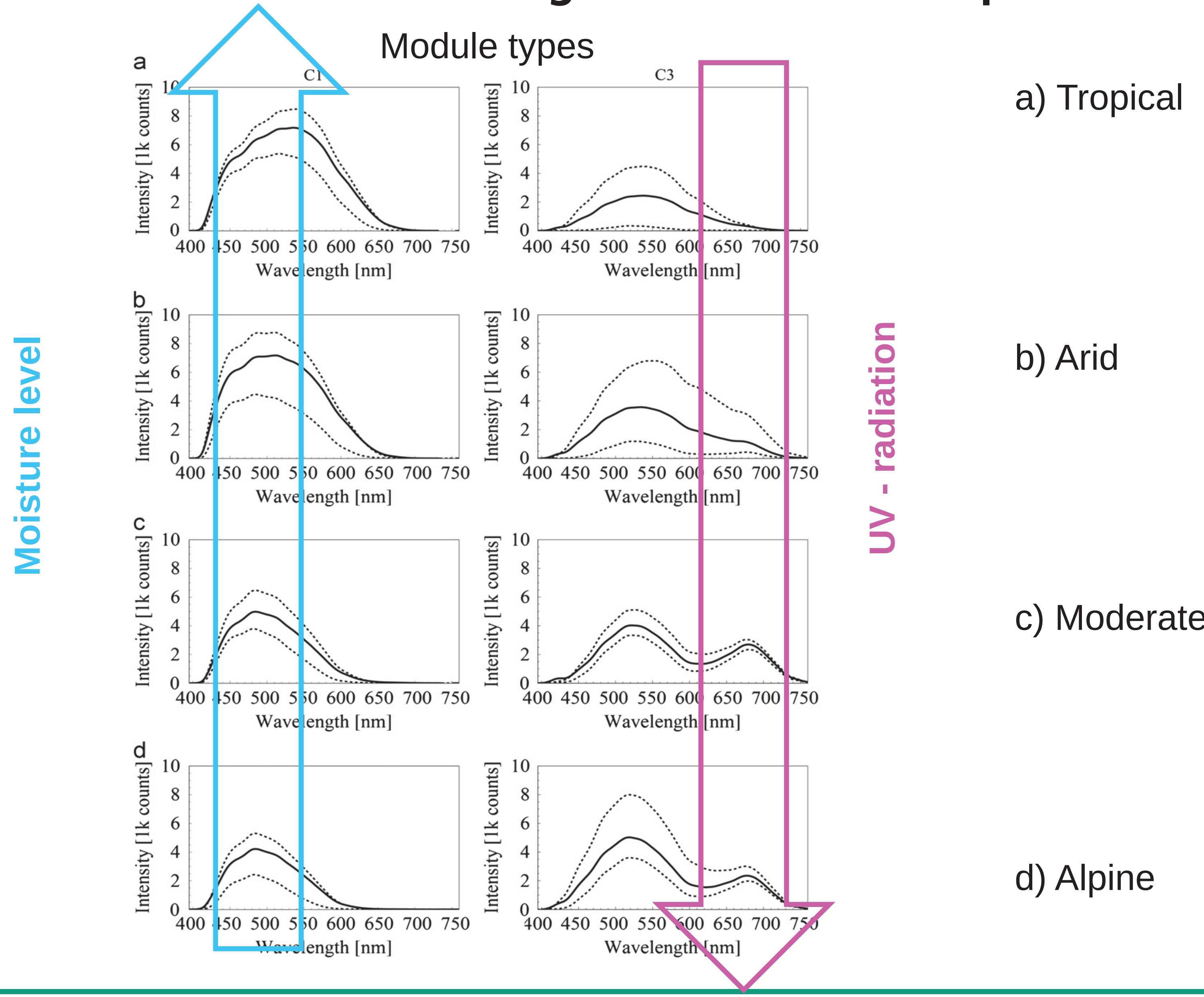
Browning and photo-bleaching - UV-induced fluorescence <



2 a desert outdoor exposure

Combination of electroluminescence and fluorescen

Effect of outdoor weathering on fluorescence spectra



J. Schlothauer, et al., Degradation of the encapsulant polymer in outdoor weathered photovoltaic modules: Spatially resolved inspection..., Solar Energy Materials&Solar Cells 102 (2012) 75–85

Methodology for design of Accelerated Service Life Testing "

1 Monitoring climatic conditions

2 Monitoring micro-climatic stress factors

3 Modeling micro-climatic stress factors

4 Time-transformation functions for major degradation processes

5 Modeling corresponding ALT – conditions for micro-climatic stress factors

6 Evaluation of sample-dependent parameters for time-transformation functions

7 Modeling of expected degradation for outdoor exposure and validation of the tests

Conclusions

Accelerated Damp-heat service life tests have been proposed

- Based on monitored climatic data
- Modelled micro-climatic stress conditions
- Modelled kinetic of the degradation processes

but final validation was not achieved yet

Conclusions and outlook

Accelerated Damp-heat service life tests have been proposed

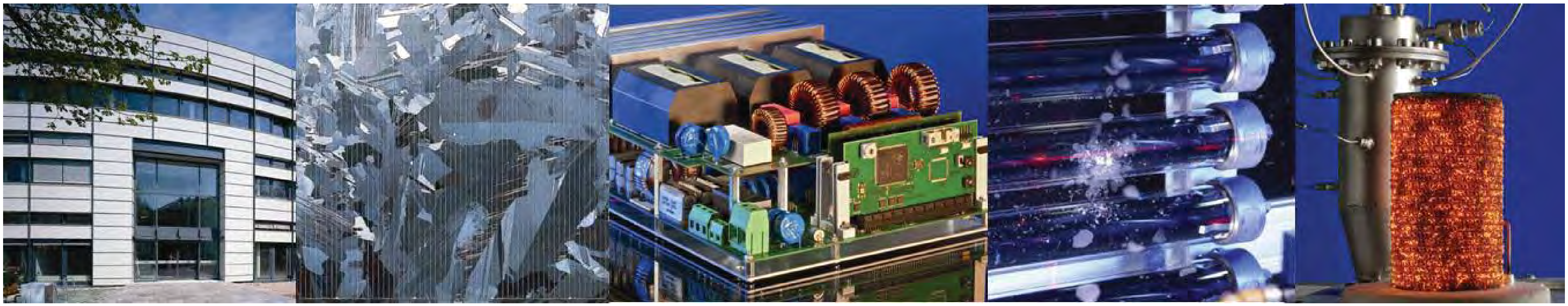
- Based on monitored climatic data
- Modelled micro-climatic stress conditions
- Modelled kinetic of the degradation processes

but final validation was not achieved yet

Tests for other stress factors (UV, temperature cycling, potential induced degradation etc) and their combinations are under development

Global stress mapping will allow qualification of diversified, specialised products for different climatic zones

Thank you for your Attention! <



Fraunhofer Institute for Solar Energy Systems ISE

Michael Köhl

www.ise.fraunhofer.de

michael.koehl@ise.fraunhofer.de