NREL
NATIONAL RENEWABLE ENERGY LABORATORY

2015 NREL Photovoltaic Module Reliability Workshops

Technical Monitor: Sarah Kurtz

February 24-27, 2015

Golden, Colorado

NREL/PR-5J00-68075

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.

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 or ani ations share at least one presentation (either oral or poster). This requirement greatly increases information sharing: If everyone shares a little information, everyone takes home a lot of information.

In 2015, the PVMRW was held in Golden, Colorado, February 24-27. Workshop participants shared more than 100 presentations and posters, covering topics such as reliability, quality assurance, inverters, system certification, and solar resources.

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SunShot
U.S. Department of Energy

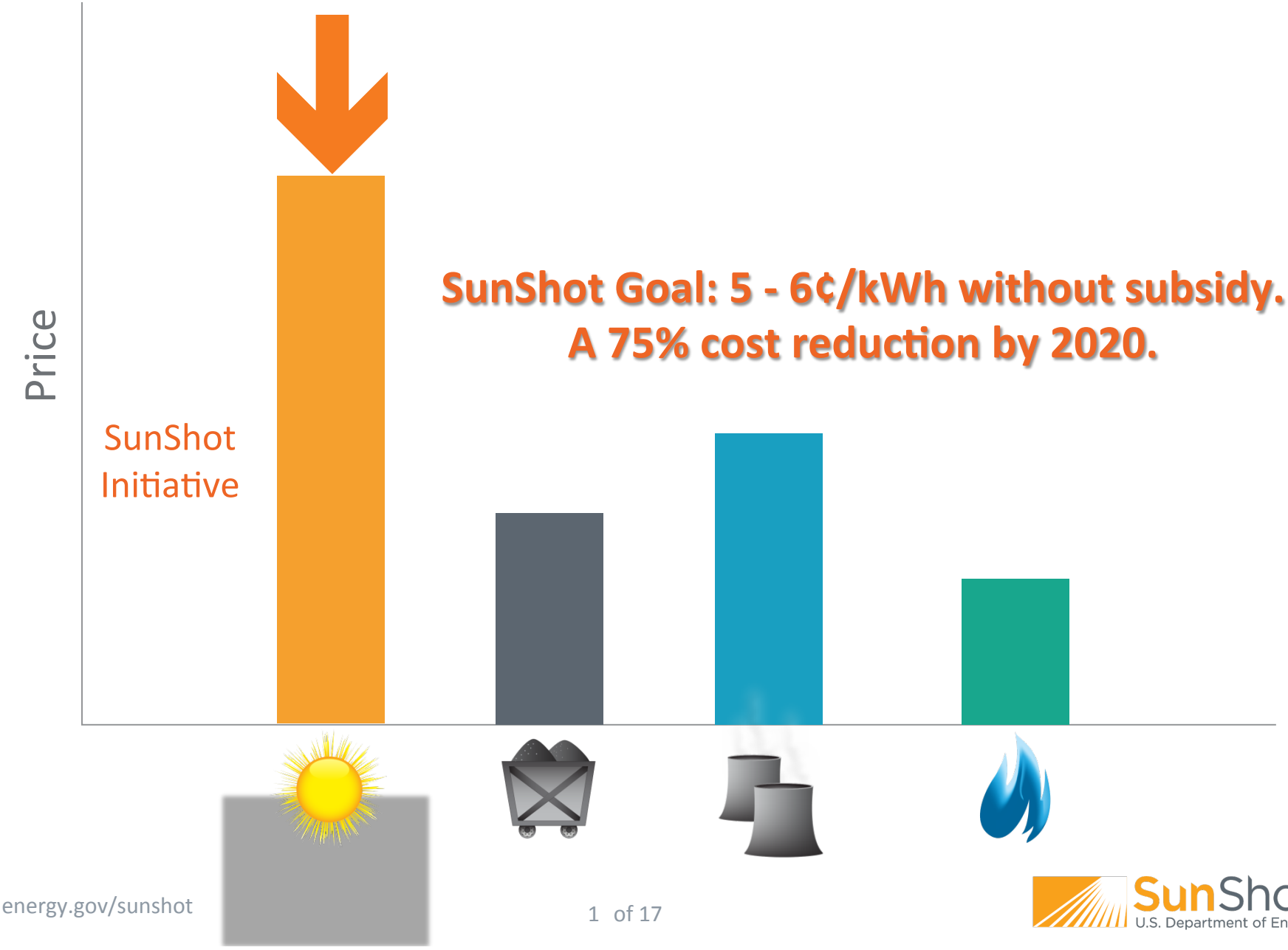
SunShot Initiative:
Lower cost via proven PV module reliability

Geoffrey S. Kinsey
Senior Scientist, Advanced R&D
Solar Energy Technologies Office

energy.gov/sunshot

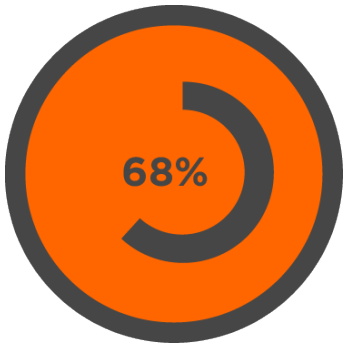
SunShot
U.S. Department of Energy

SunShot



SunShot Goal: 5 - 6¢/kWh without subsidy.
A 75% cost reduction by 2020.

SunShot Initiative – Solar Grid Parity by 2020

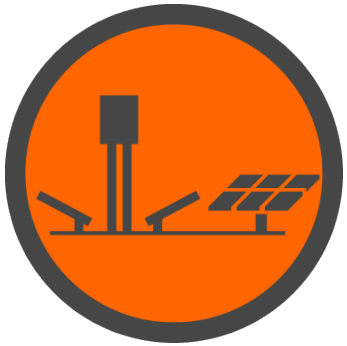


68% progress towards 2020 goals

SunShot Initiative – Solar Grid Parity by 2020

2010 2014 2020

MAJOR PROGRESS PRIORITY AREAS

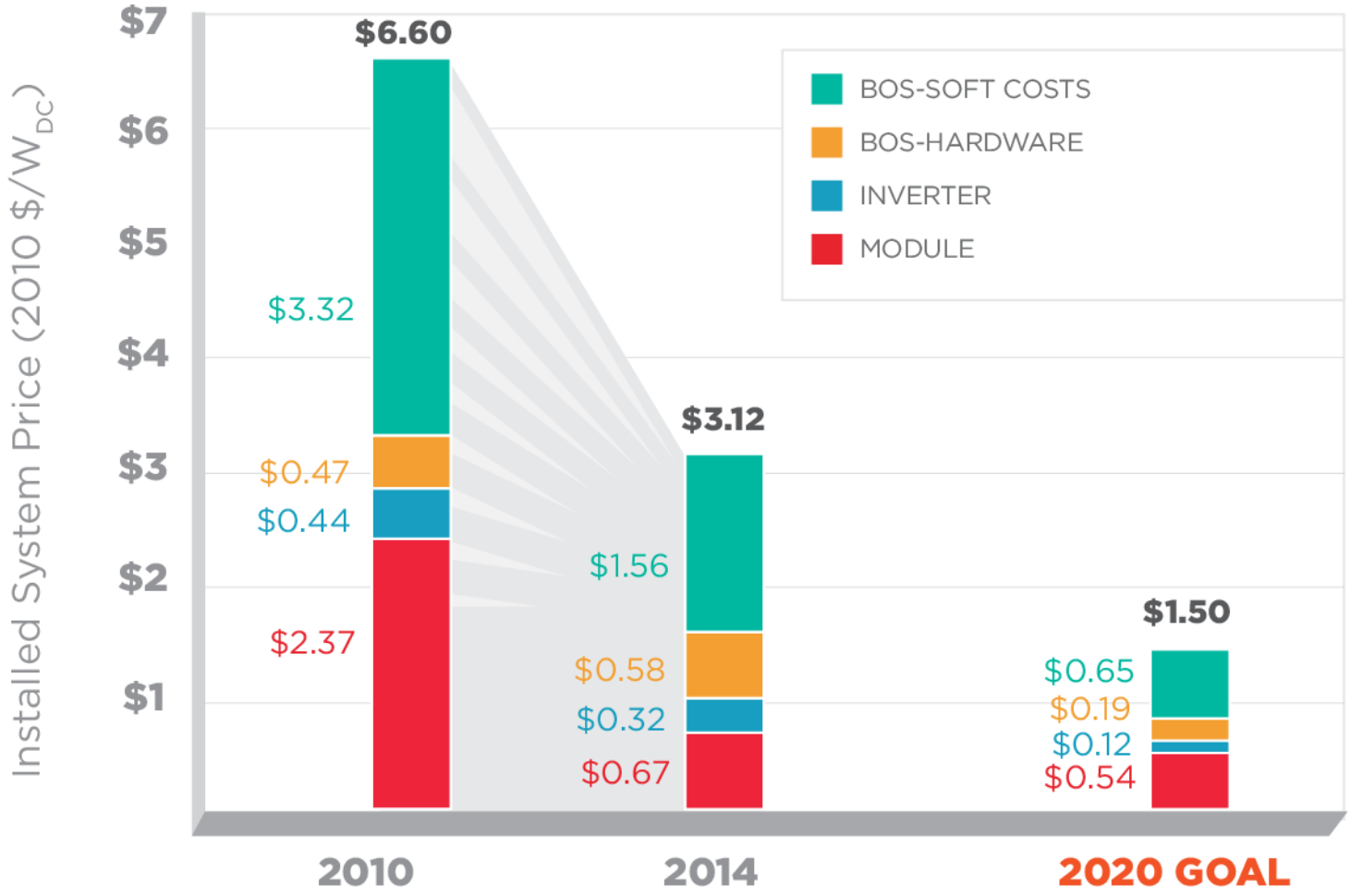


16GW of solar

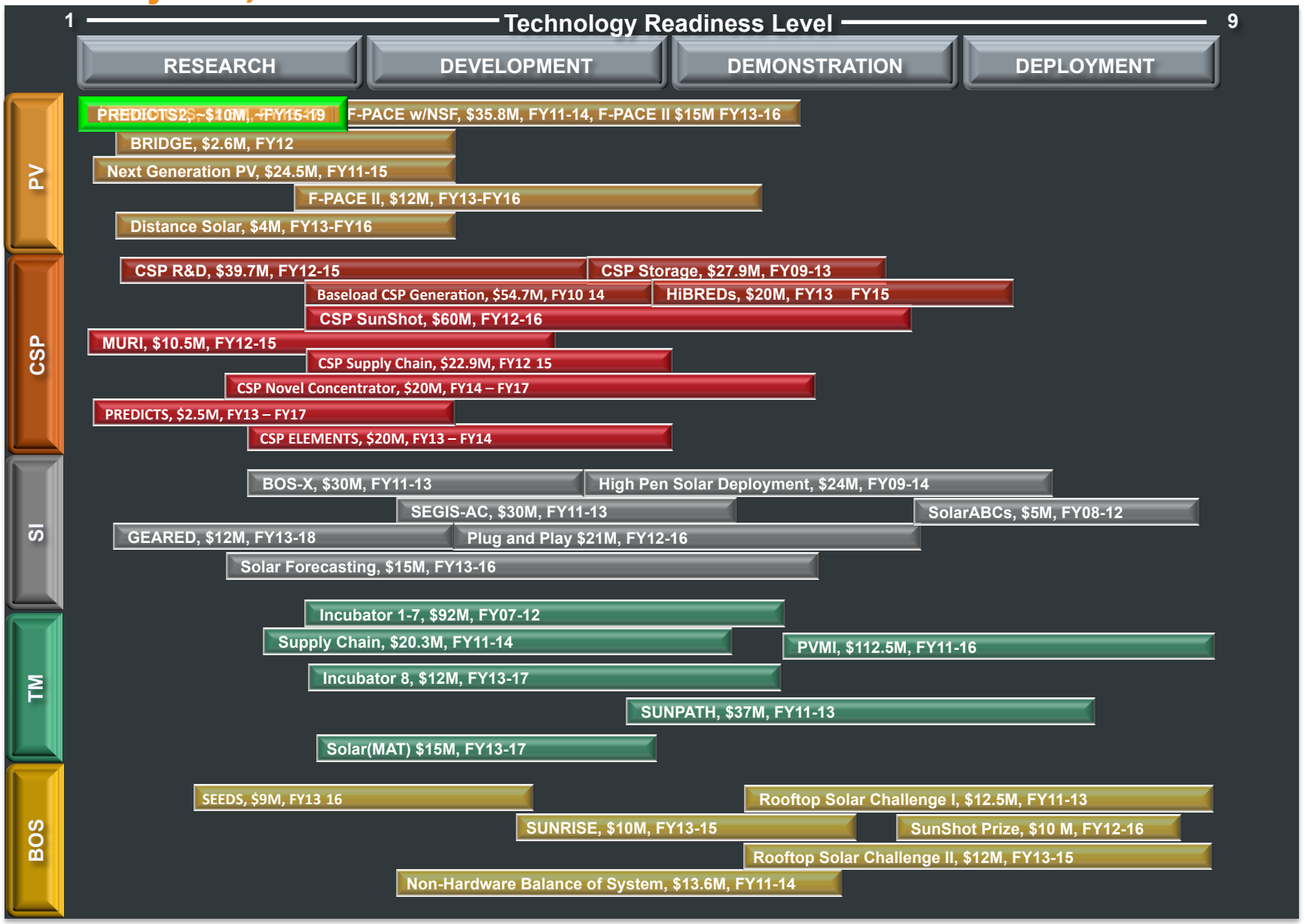
4.75GW of PV in 2013

13x growth rate from 2009

PV Residential-Scale System Pathway to SunShot

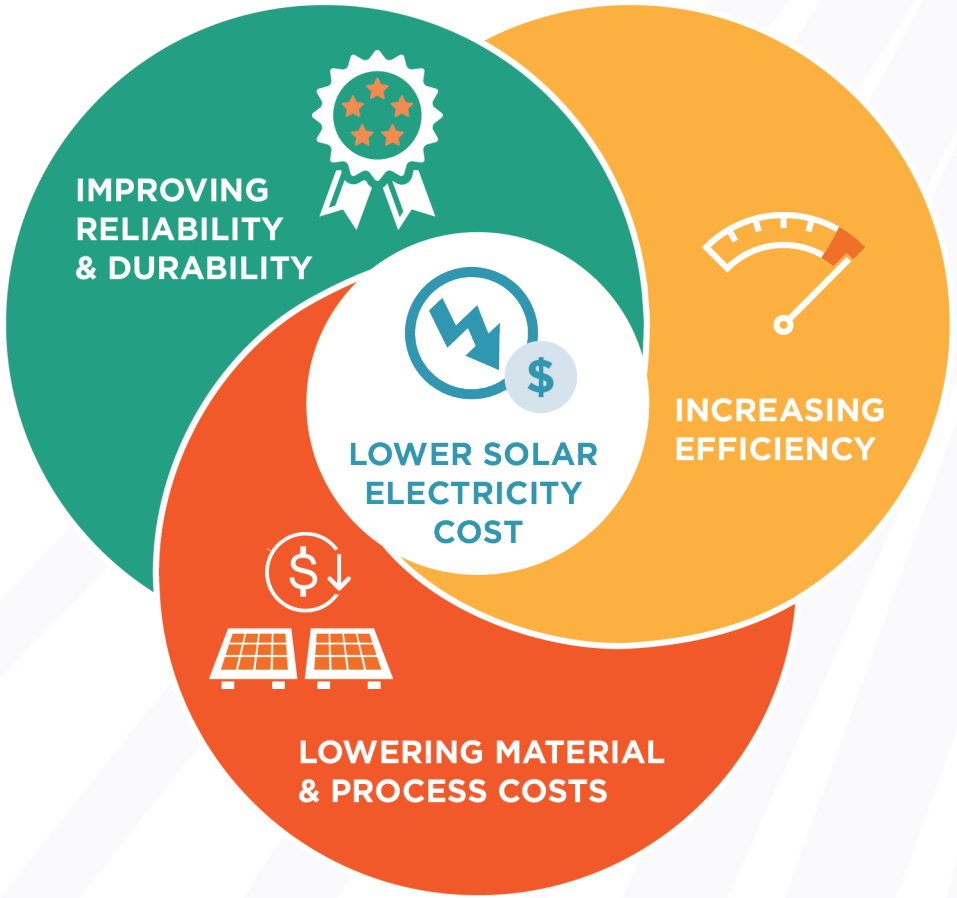


SETO Projects, FY08-16



Photovoltaics R&D

Dr. Rebecca Jones-Albertus, Program Manager



Reliability/durability/lifetime

Reliability/durability/lifetime at the National Labs

Increasing Prediction Accuracy and Confidence in PV System Performance

Characterizing Emerging Photovoltaic Technologies

PV Reliability: Prognostics and Health Management

Regional Test Centers

Quantifying Risk Through Bankability Reports/Standards

Emerging Technology Characterization

IEC PV Standards Activities

Advanced Measurement and Analysis of PV De-rate Factors

Predicting Service Life for PV Modules

Solar System Modeling Algorithms and Tools for Characterizing and Reducing Uncertainty

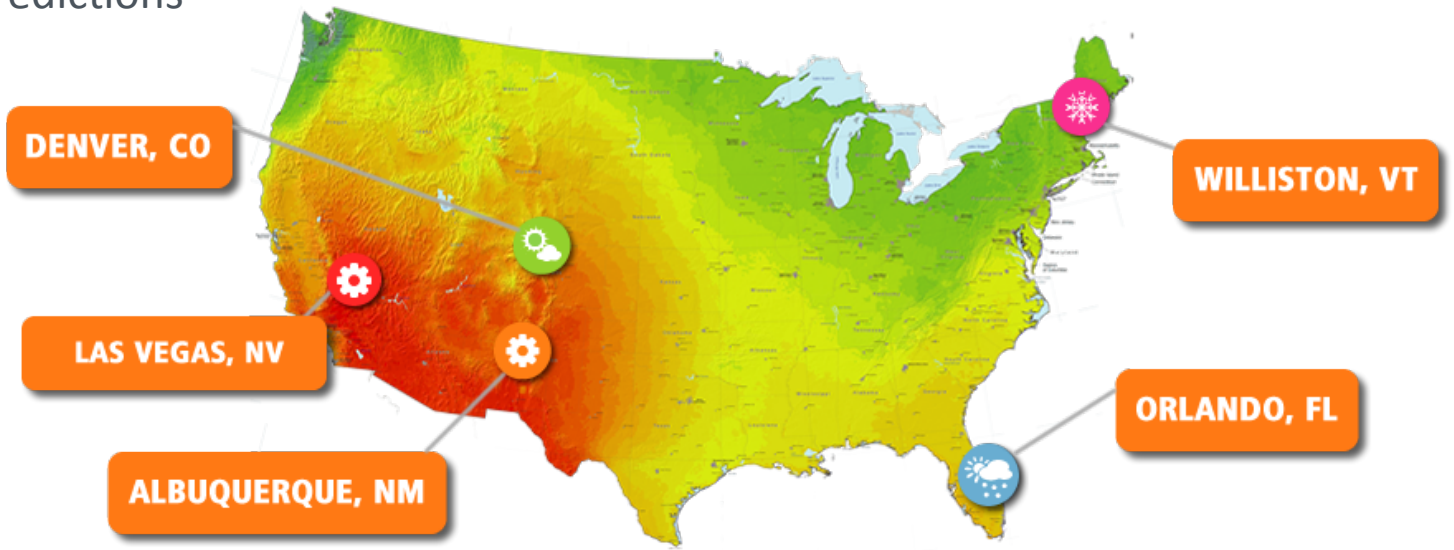
Mitigating Industry-Wide Risks through Data Collection and Assessment

FY 2014: $18.8 million

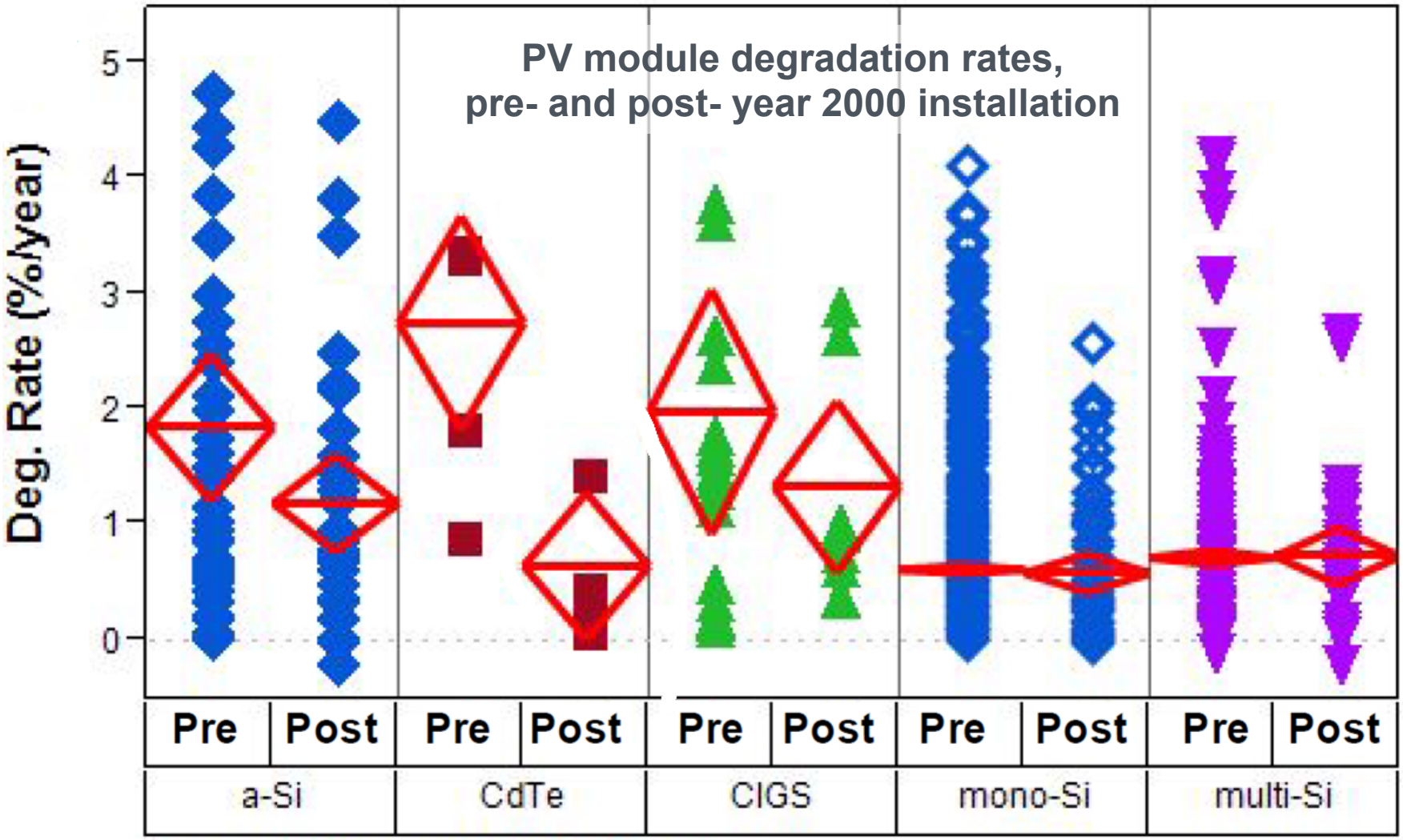
Regional Test Centers

Vision:

- Accelerate adoption of solar energy generation sources by helping U.S. PV manufacturers overcome the challenges on the path to commercialization
- Provide technical basis for bankability of PV systems
  - Installation size:
    - Module-level testing: 10-50kW per site
    - System-level testing: 50–300 kW per site
  - Validate in multiple climates, to compare performance and initial reliability against predictions

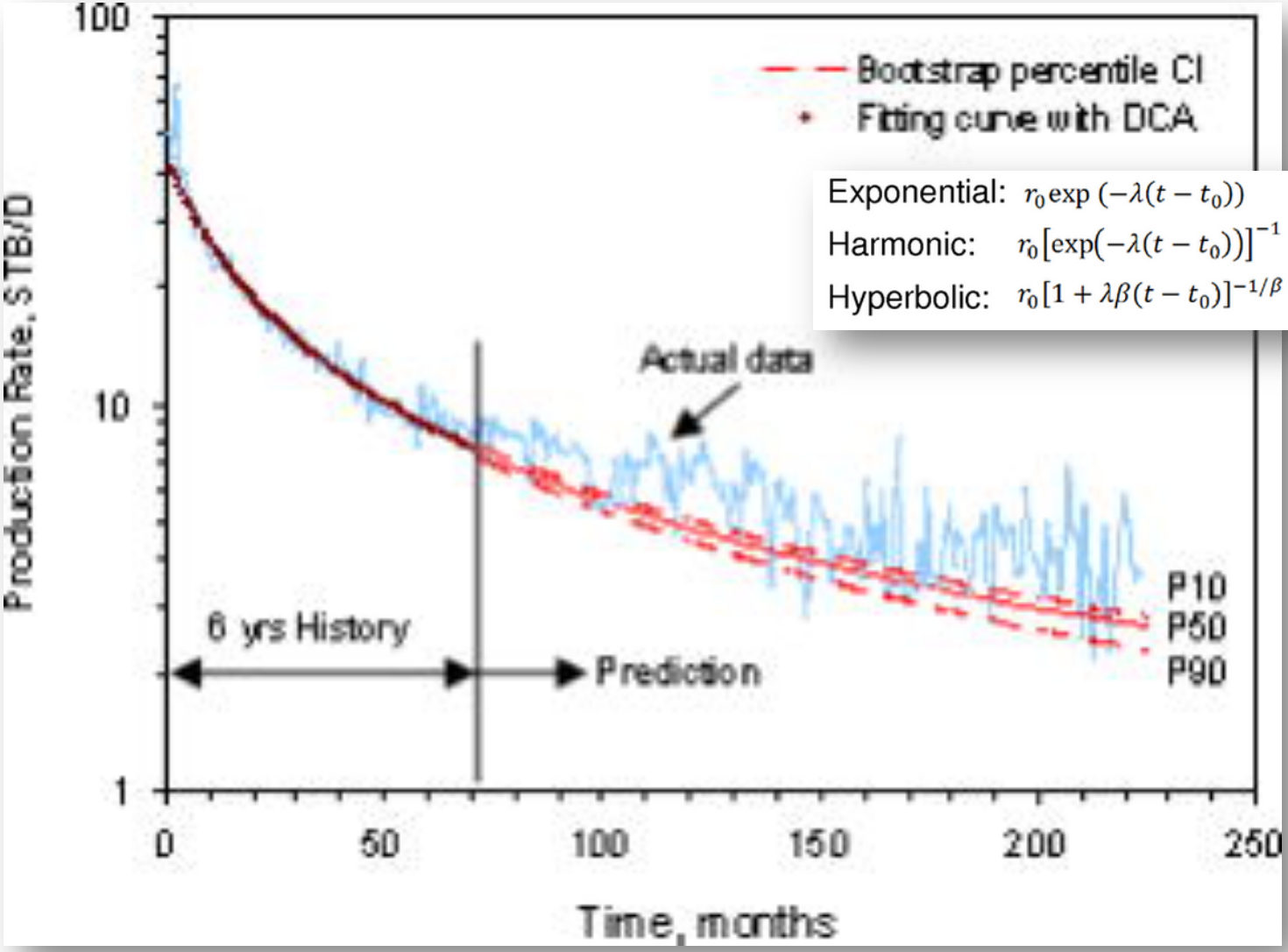


The challenge: degradation rates



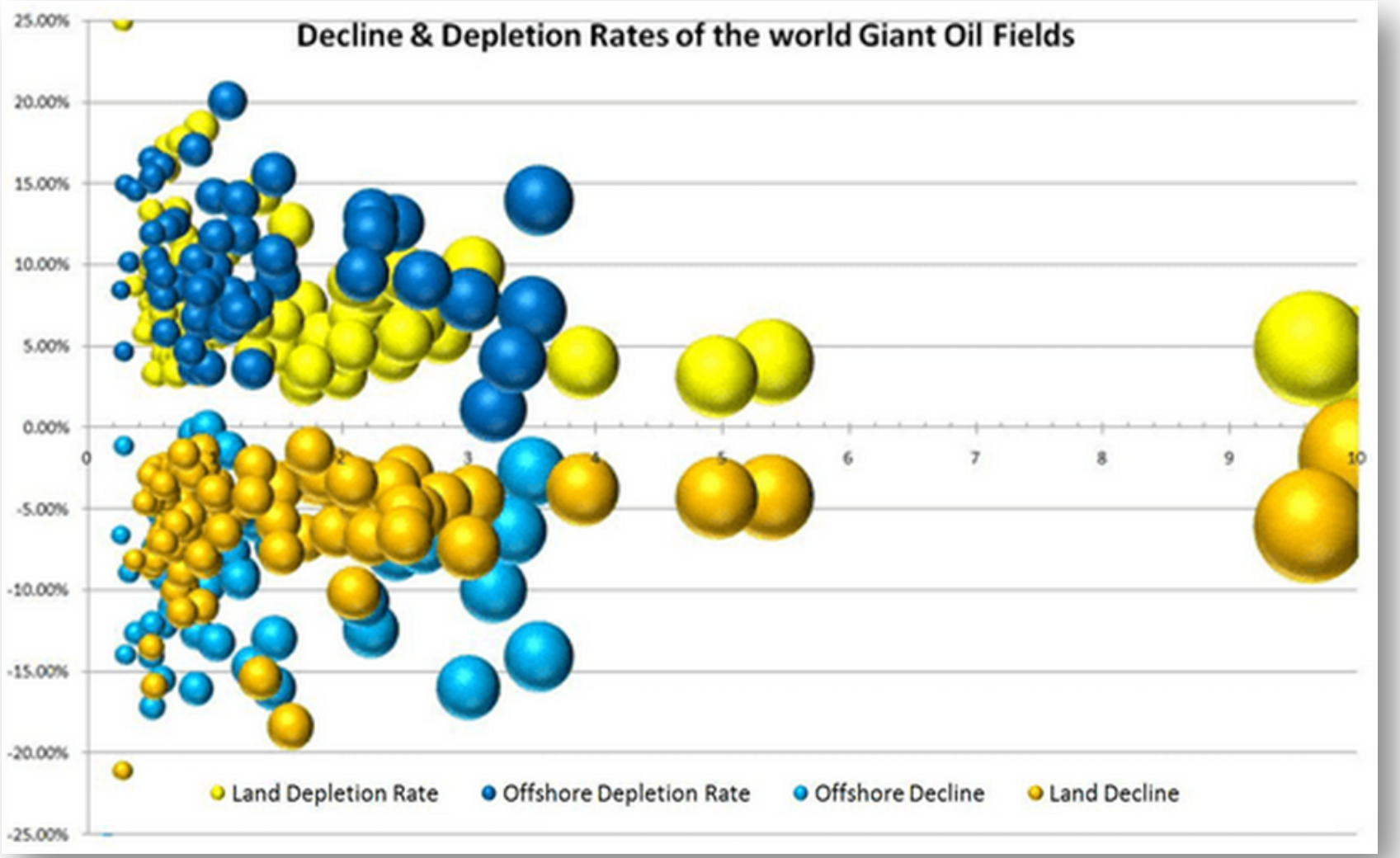
source: Jordan, D. C. and Kurtz, S. R. (2013), Photovoltaic Degradation Rates—an Analytical Review. Prog. Photovolt: Res. Appl., 21: 12–29. doi: 10.1002/pip.1182

Decline curve analysis: oil and gas wells



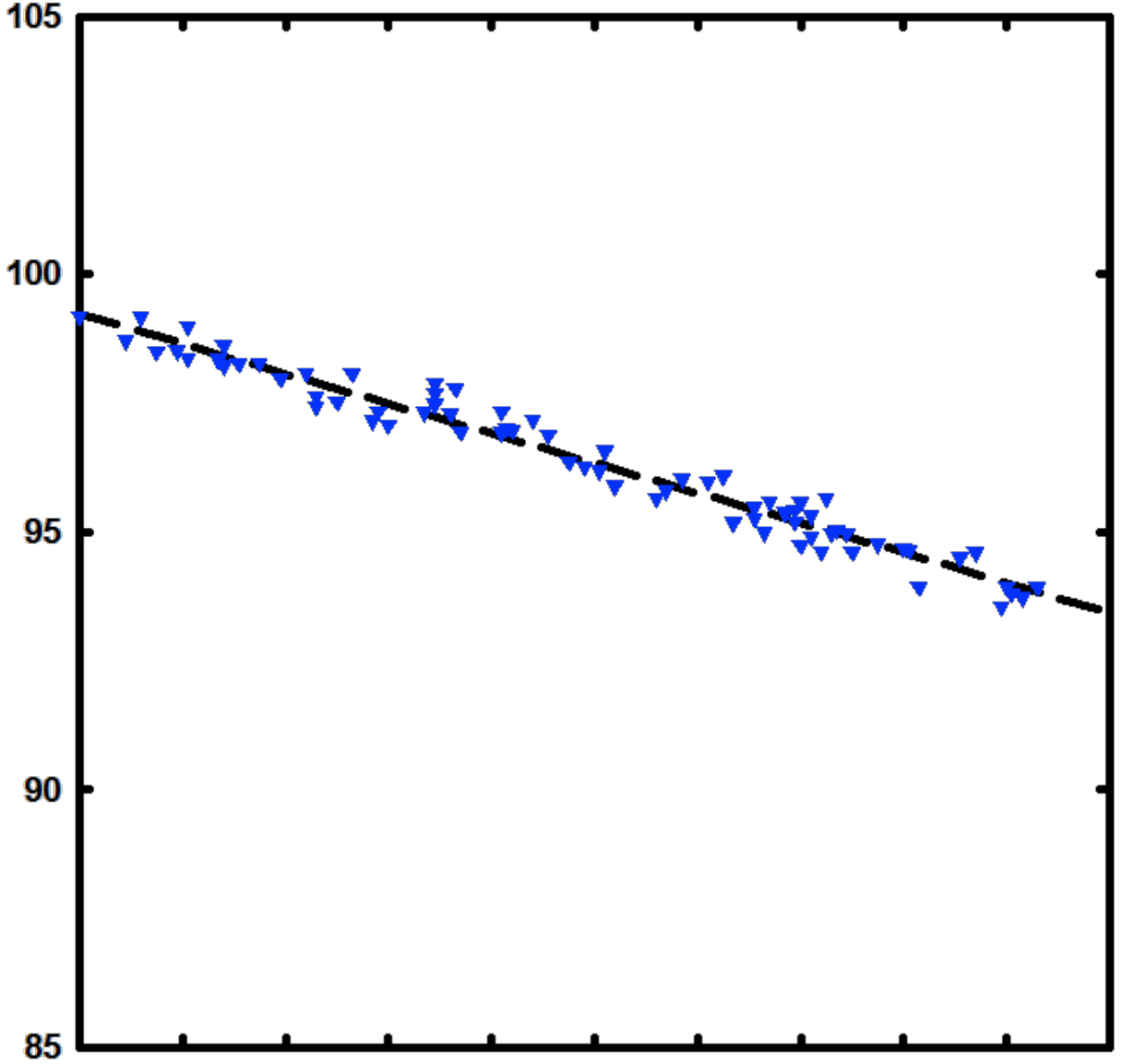
Source: Cheng Yueming, Lee W. John, McVay Duane A. Quantification of Uncertainty in Reserve Estimation From Decline Curve Analysis of Production Data for Unconventional Reservoirs J. Energy Resour. Technol. 130(4), 043201 (2008) (6 pages); doi:10.1115/1.3000096

Oil and gas industry falls back on linearity, too…

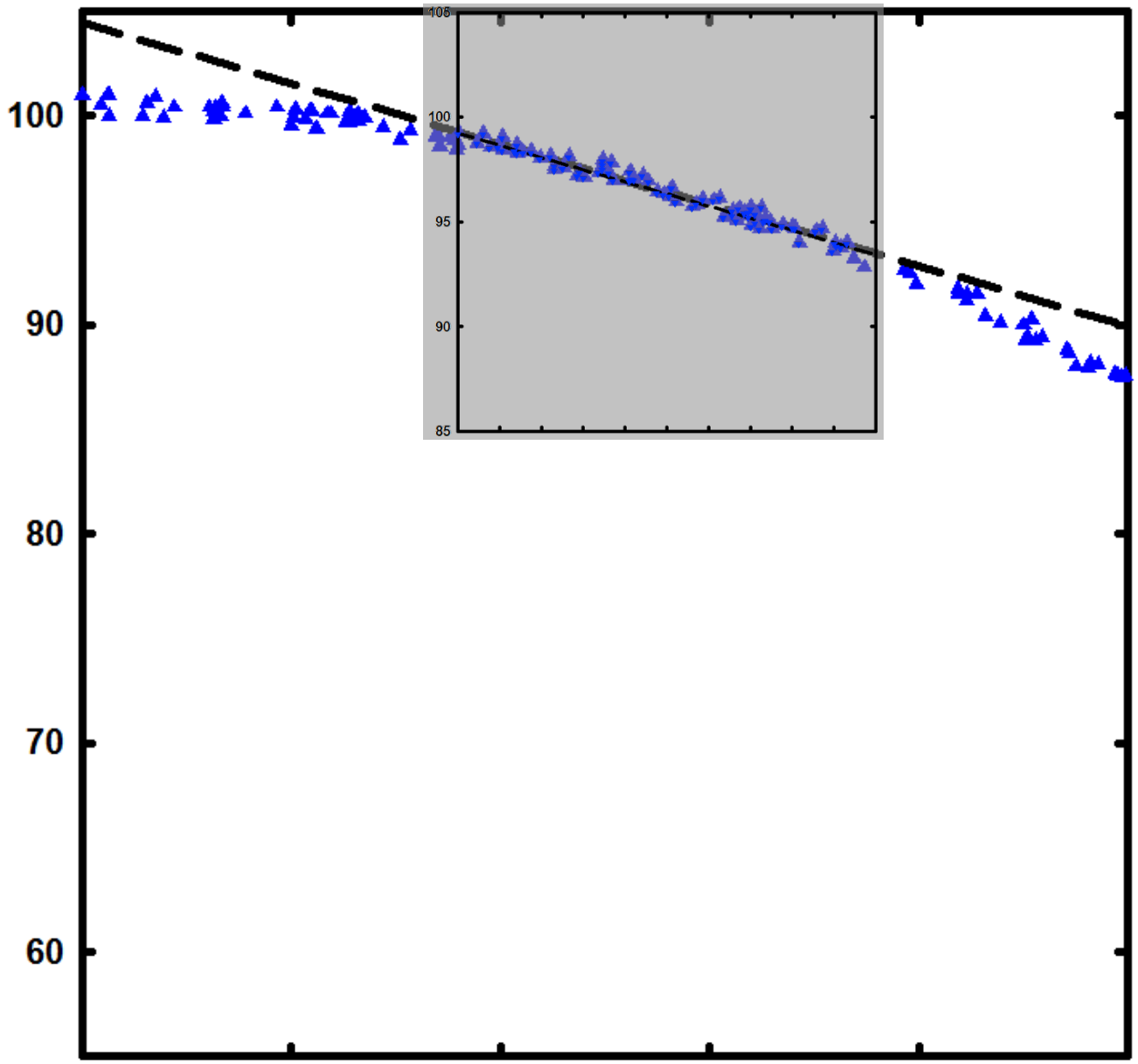


Source: M. Hook, Depletion and Decline Curve Analysis in Crude Oil Production, Licentiate Thesis, Uppsala University, 2009.

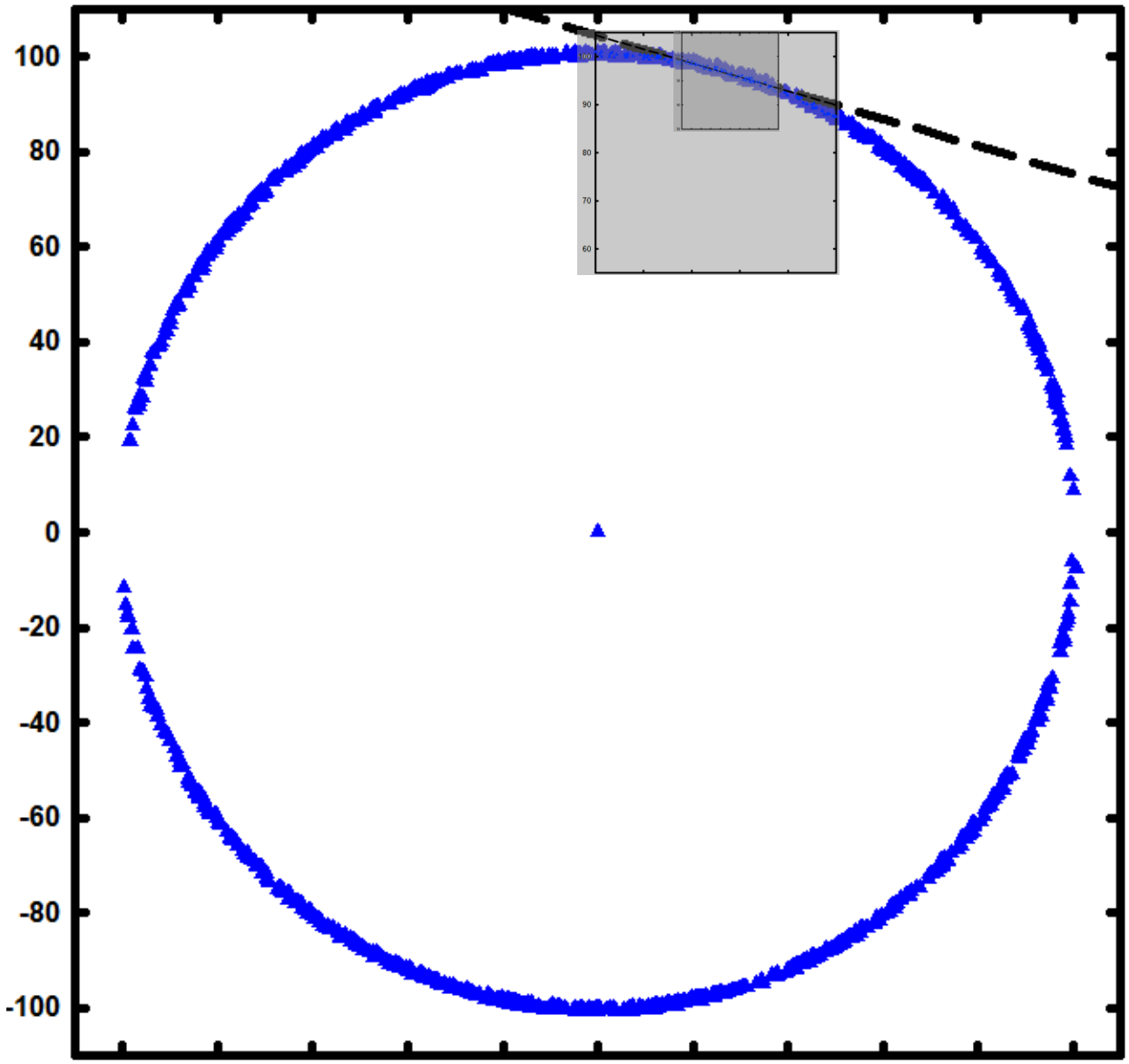
Linear degradation



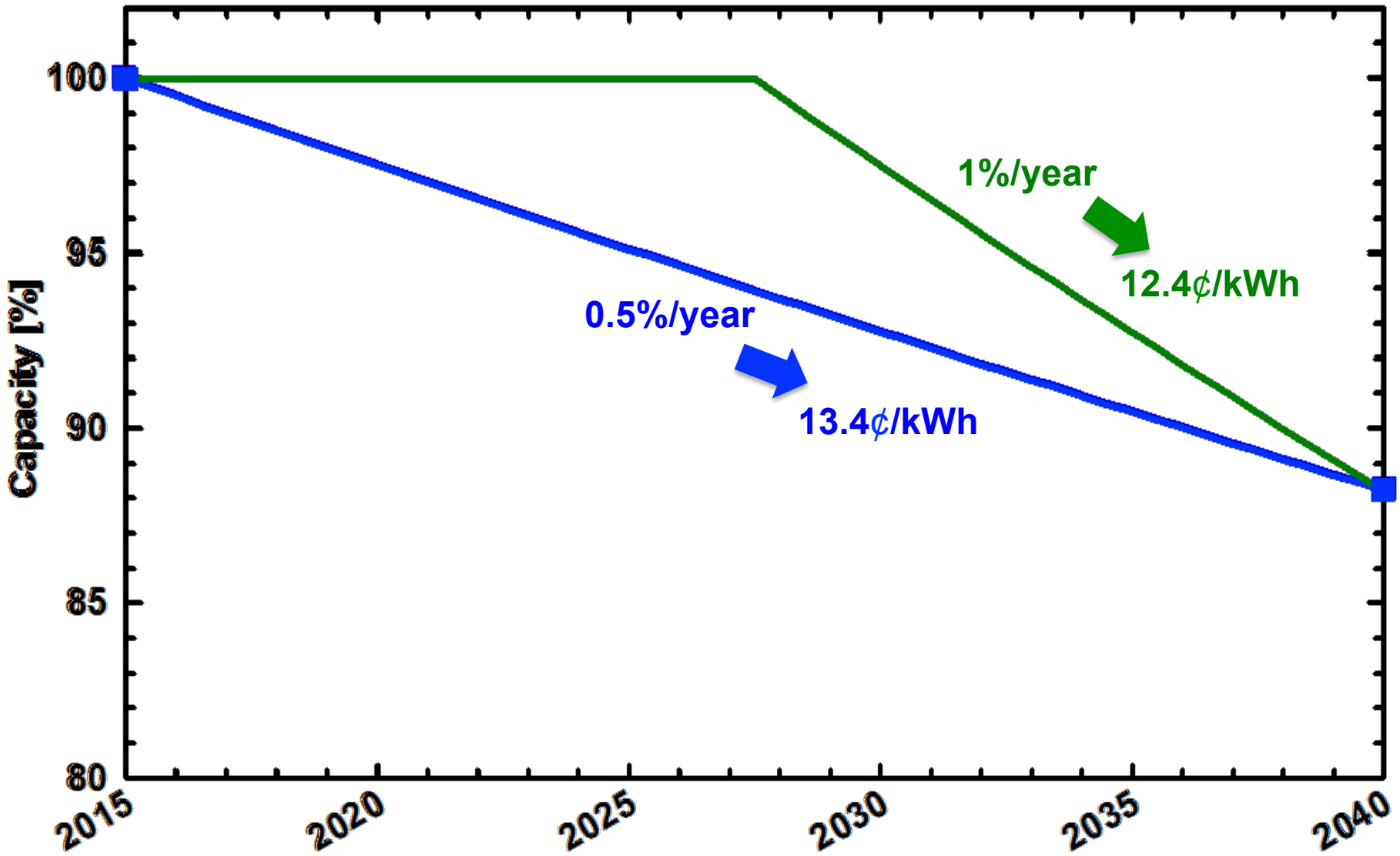
Linear degradation?



Linear degradation?



Impact on LCOE



Join our team!

Take on the SunShot challenge to make solar energy cost-competitive with traditional energy sources by 2020.

- Photovoltaics
- CSP
- Systems Integration
- Soft Costs
- Tech to Market

energy.gov/sunshot

SunShot
U.S. Department of Energy

RELIABILITY ON BANKABILITY

CONSERVATIVE, NOT NECESSARILY QUALITY

PV MODULE RELIABILITY WORKSHOP

FEBRUARY 2015

FEBRUARY 2015

NREL
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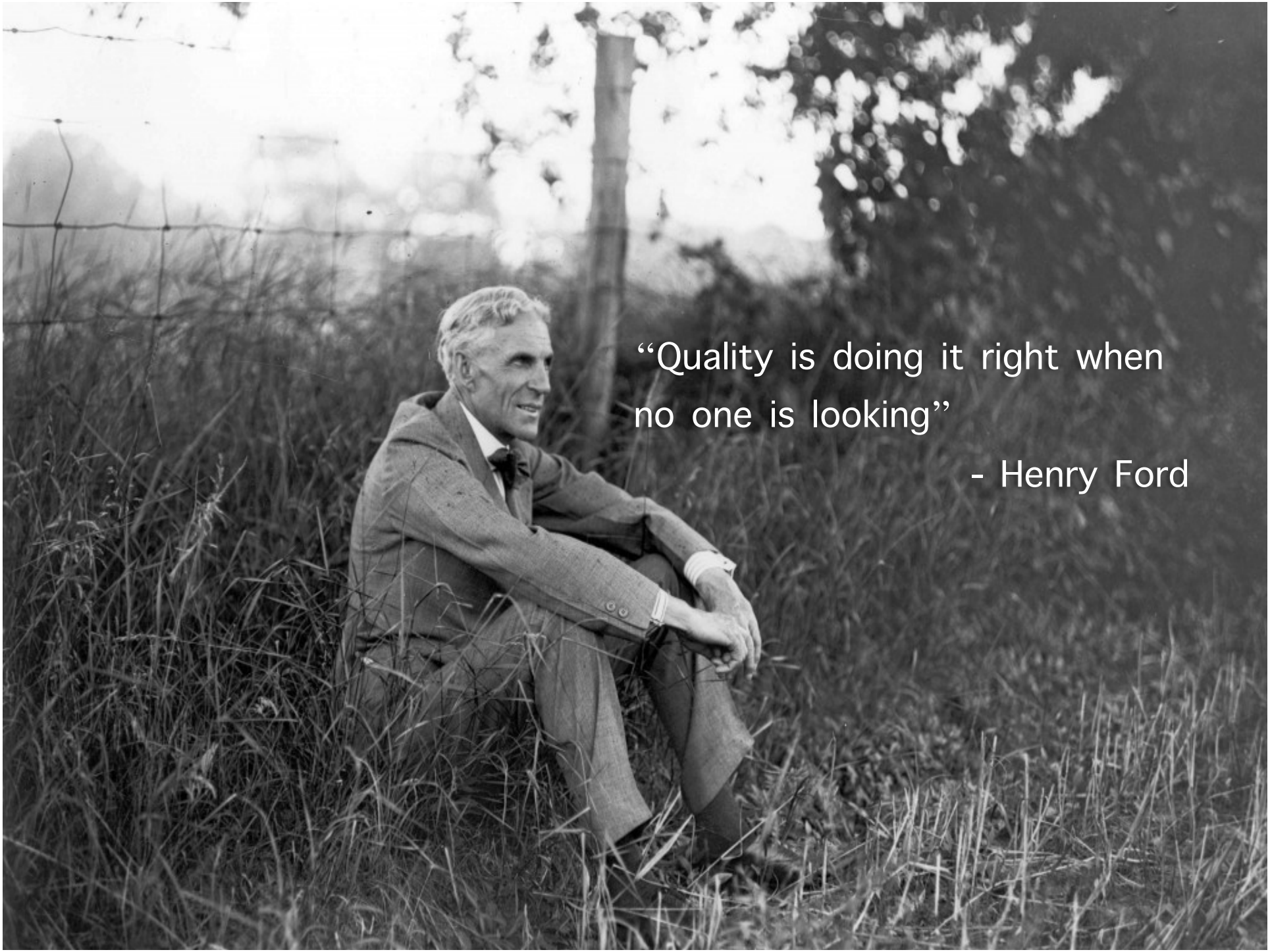

“Quality is doing it right when no one is looking”
- Henry Ford

WHY PROJECT FINANCE?

CASH REQUIRED

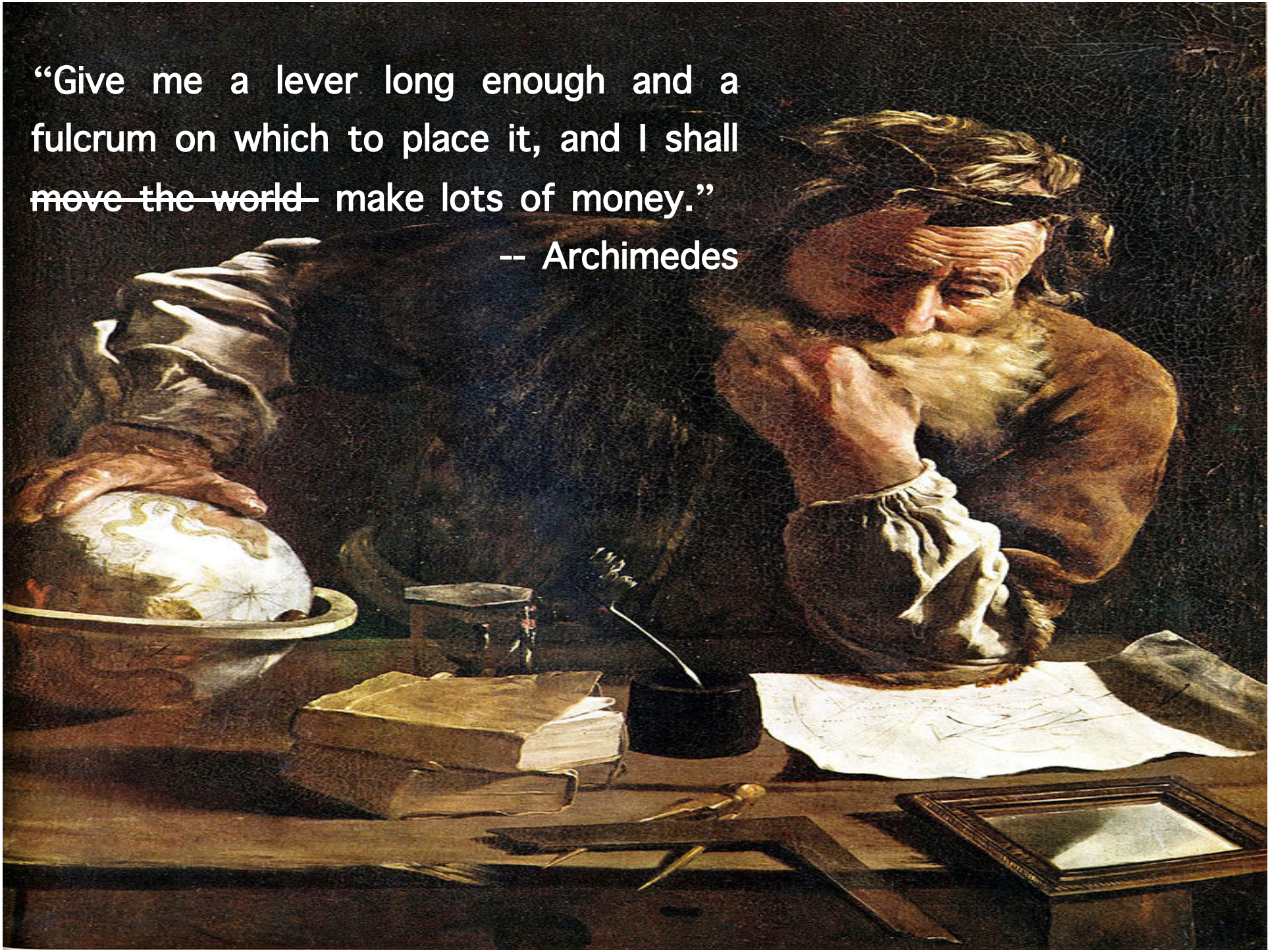
- LOW Capital
- INCREASE number of projects
- LOWER risk through portfolios

TERM

- Solar life-expectancy challenge for equity investors @ scale
- Spread equity across several projects

NON-RECOURSE

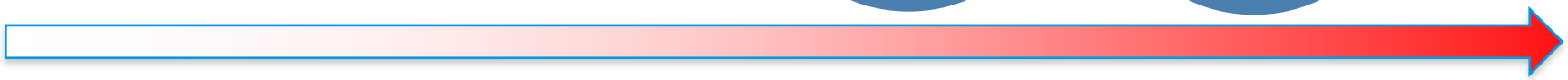
- Equity shares technical and economic risks
- LIMIT downside


“Give me a lever long enough and a fulcrum on which to place it, and I shall ~~move the world~~ make lots of money.”
-- Archimedes

POWER OF LEVERAGE

10 MW
$20 MILLION
20 YEARS
$0.17/KWH

7% DEBT
13 YEARS



ALL EQUITY

- ✓ CASH: $20million
- ✓ IRR: 12%
- ✓ 20-year NPV: ~$0

- ★ ALL risk on equity
- ★ REASONABLE returns
- ★ LARGE capital commitment

50/50

- ✓ CASH: $10million
- ✓ IRR: 15%
- ✓ 20-year NPV: $2.3 mln

- ★ LIMIT risk on equity
- ★ Medium capital commitment

20/80

- ✓ CASH: $4 million
- ✓ IRR: 20%
- ✓ 20-year NPV: $3.6 mln

- ★ LITTLE risk on equity
- ★ SMALL capital commitment
- ★ HIGH IRR
- ★ HIGH NPV

TECHNOLOGY VERSUS LEVERAGE

NOBEL WORK

- ⊙ *DOUBLE* ENERGY !!
- ⊙ TECHNOLOGY RISK: HIGH
- ⊙ LIMITED WARRANTY

- ✓ DEBT: DECLINED
- ✓ EQUITY IRR: 26%
- ✓ CASH: $20 million

- ★ HIGH Capital Commitment
- ★ BROADEN Geo-market
- ★ HIGH Risk (20 years)
- ★ SHRUNK Investor Pool

20/80

7% DEBT 13 YEARS

- ⊙ STANDARD PROJECT

- ✓ DEBT: STANDARD
- ✓ CASH: $4 million
- ✓ EQUITY IRR: 20%
- ✓ 20year NPV: $3.6 mln

- ★ HIGH returns
- ★ MEDIUM risk on equity
- ★ SMALL capital commitment

MODEST

7% DEBT 20 YEARS

- ⊙ STANDARD PROJECT
- ⊙ ACCEPTANCE OF WARRANTY

- ✓ DEBT: EXTENDED 20 YRS
- ✓ CASH: $4 million
- ✓ EQUITY IRR: 26%
- ✓ 20 year NPV: $4.6 mln

- ★ EXCEPTIONAL returns
- ★ INCREASED value
- ★ IDENTICAL capital
- ★ IDENTICAL technical risk

CERTAINTY

TECHNOLOGY

- ✓ MOST of revenue to service bank debt
- ✓ Technology needs to be consistently performing for life of bank debt
- ✓ Equity makes most money years AFTER debt is paid (year 15 on)
- ✓ Technology needs to be consistent reliable income – Toll Bridge

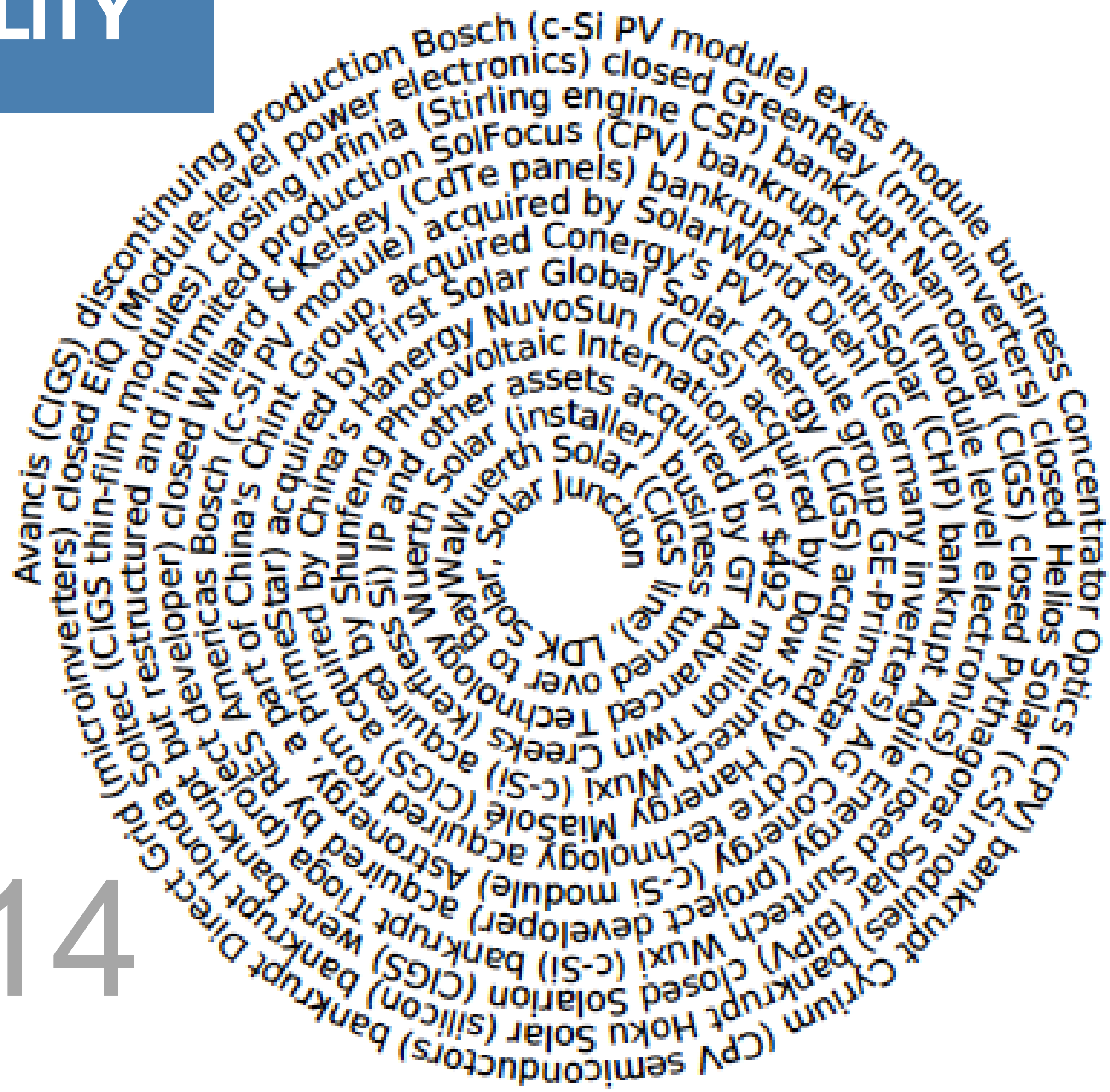
WARRANTY

- ✓ Problems with Technology fall to warranties
- ✓ FIRST, identifying a problem. Centralized architecture means identifying individual module claims is difficult
- ✓ SECOND, claiming a warranty has manufacture discrepancy
- ✓ THIRD, an awarded claim and a paid claim are not the same

BALANCE SHEET

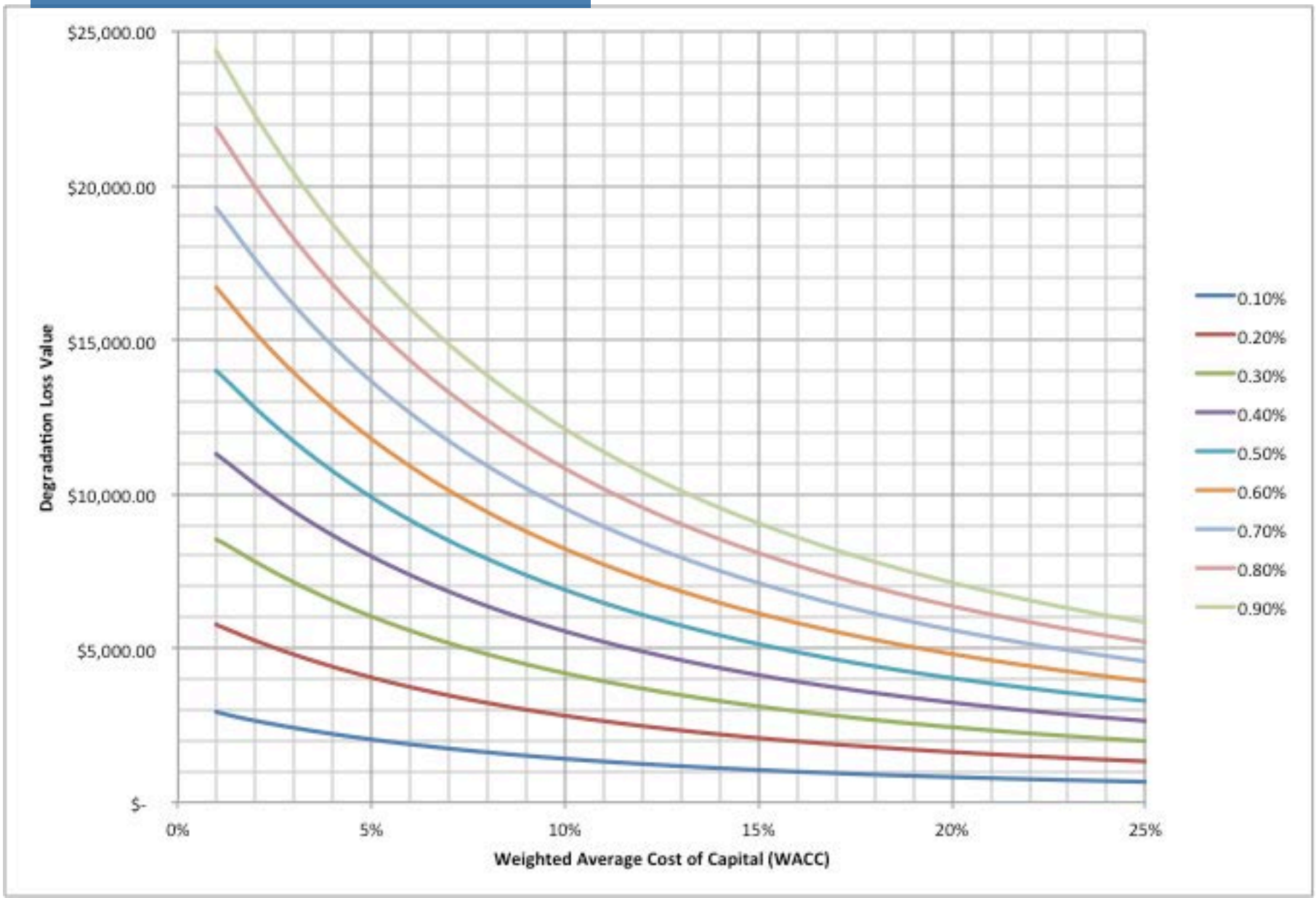
- ✓ Volatile manufactures
- ✓ Life-expectancy shrinking for large companies
- ✓ Cultural influence: Chinese industrial project debt

IN-STABILITY

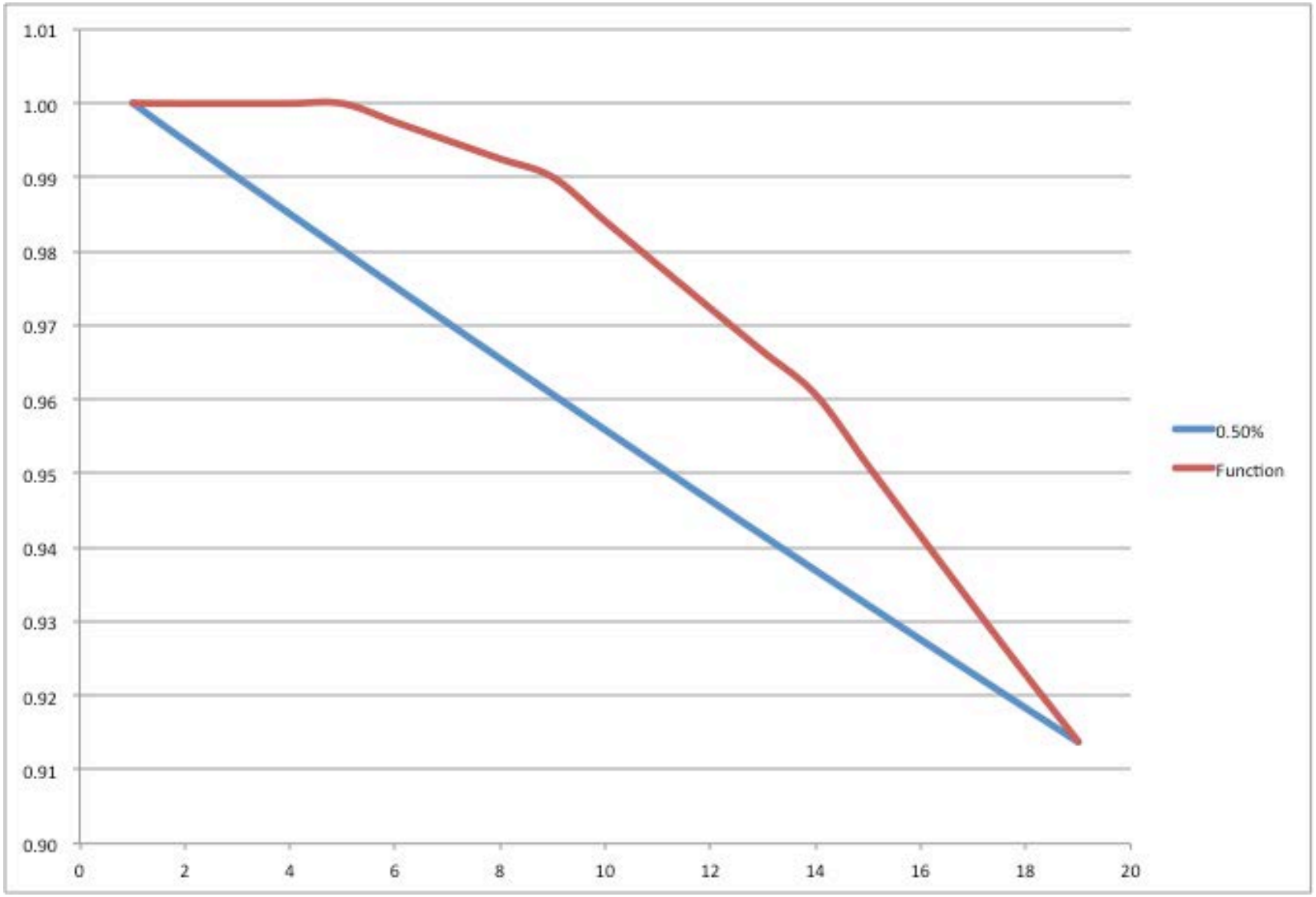


2014

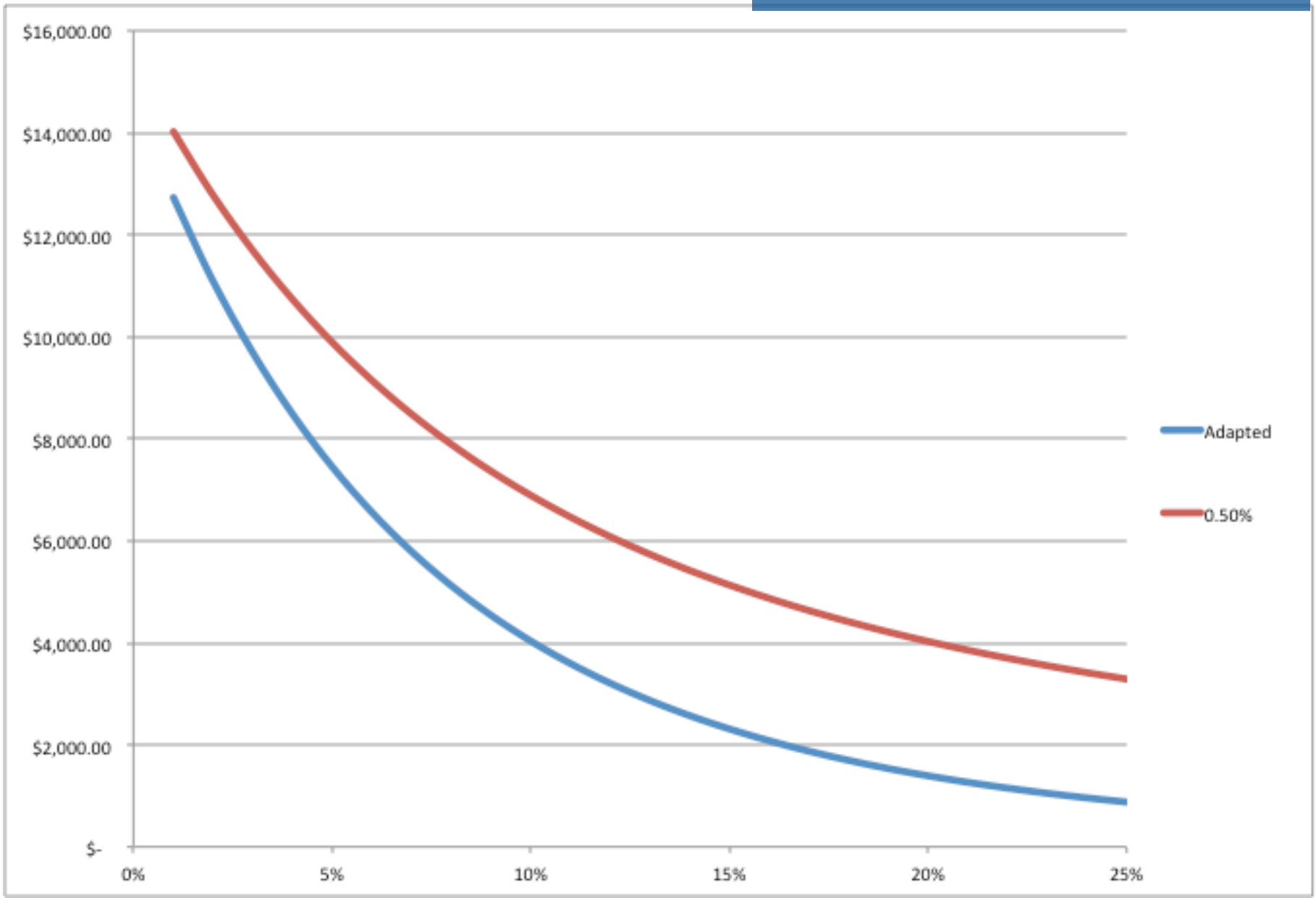
DEGRADATION



FUNCTION VS. COEFFICIENT



FUNCTION VS. COEFFICIENT



CONSERVATISM VERSUS QUALITY

SPONSOR

- ✓ A – B – C, A Always, B Be, C Closing
- ✓ Sponsors make NO money without funded project
- ✓ Development fee is at risk with no project
- ✓ COST

LENDER

- ✓ Acceptable portfolio performance possibly attributed to underestimation
- ✓ NEW technologies increase transaction costs from Independent Engineers
- ✓ Insufficient time for latent defects
- ✓ ‘TOP TIER’ eases credit committee discussion

OUTCOME

- ✓ Lender leads conservative stakeholder
- ✓ NEW technology upsets program
- ✓ Evolutionary changes “Just like the last one”
- ✓ Conservative performance estimation
- ✓ Warranties important but underlying technolgy

RESEARCH

SCIENCE TO COMMERCIAL VIABILITY

Hope is NOT lost.

Advances in applied science are critical for the successful adoption of solar in new markets, broaden investor pools, and lowering conservative assumptions

- Understand role of debt
- Parallel advances with finance
- Understand warranty implications and power of decades of leverage
- Reliability, quality, and consistency may have dramatic impact on economics
- NEW technology must have a commercialization plan including project finance.

Conclusions

ALIGNING 'CONSERVATIVE' & Quality

Knowledge of Quality
Over conservative assumptions

- Project Finance is here to STAY
- Stakeholders will tend to levered project structures which require consistent and reliable economics
- Projects will tend to use comfortable technology because of a sense of reliability and comfort
- Paradigms will be questioned with continual technology failures, companies dissolving, and manifesting latent defects
- Consistent independent standards will provide a platform for comparison of features and long-term reliability standards
- Quality requires stakeholders to be informed, create desire, and facilitate Demand.

Pitfalls of Accelerated Testing

William Q. Meeker[1]

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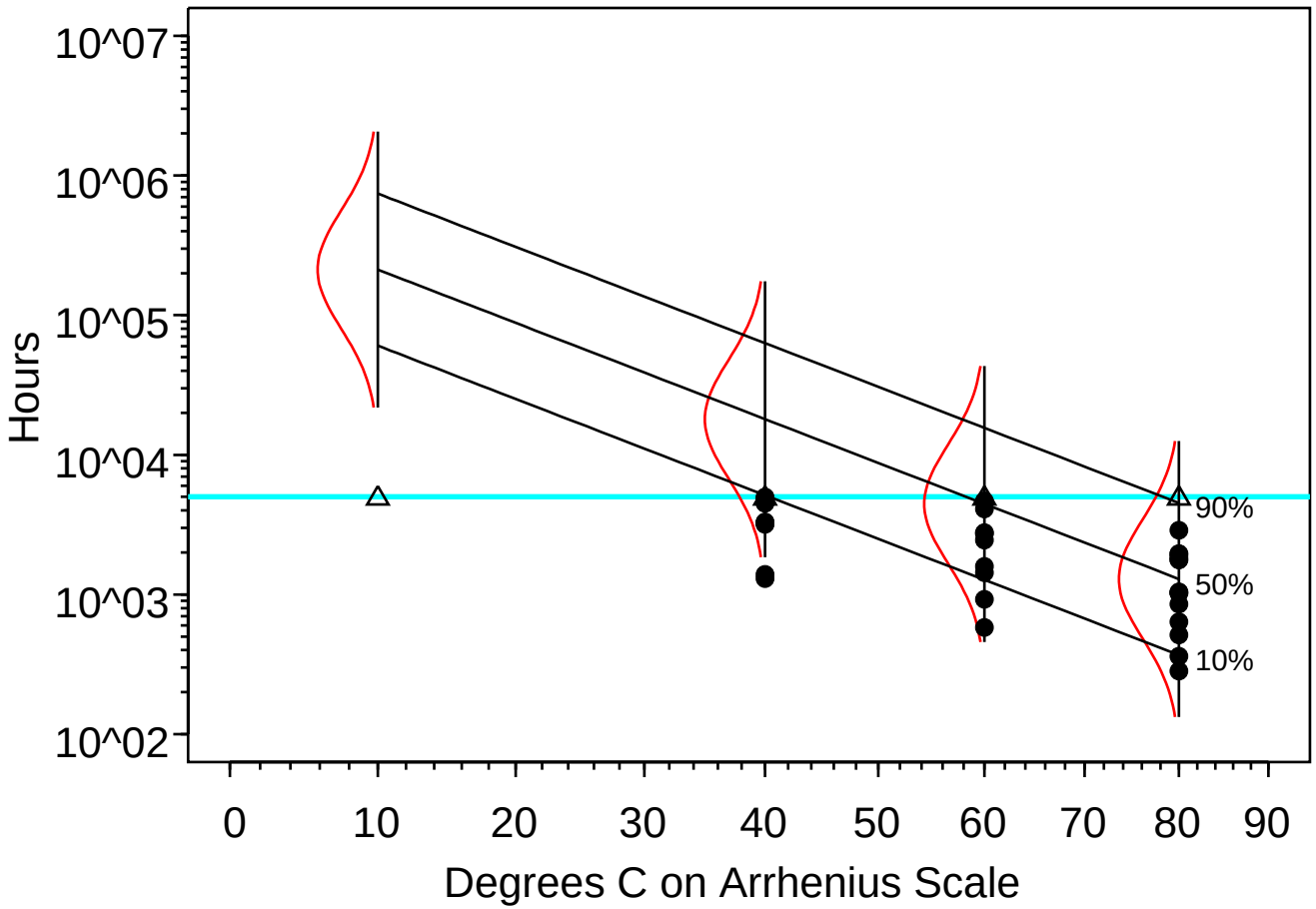
Overview

- Accelerated test overview
- Different kinds of pitfalls
- Examples illustrating particular pitfalls
  - GE Refrigerator Compressor: Faulty accelerated test almost caused GE Appliances to go out of business
  - Electronic component: Accelerated test did not detect a masked failure mode that caused a reliability disaster.
  - Appliance B: Industry-standard accelerated test led to incorrect predictions of field lifetime.
  - Insulating structure: Too much voltage stress caused extraneous failures and incorrectly optimistic lifetime predictions.
- Concluding Remarks

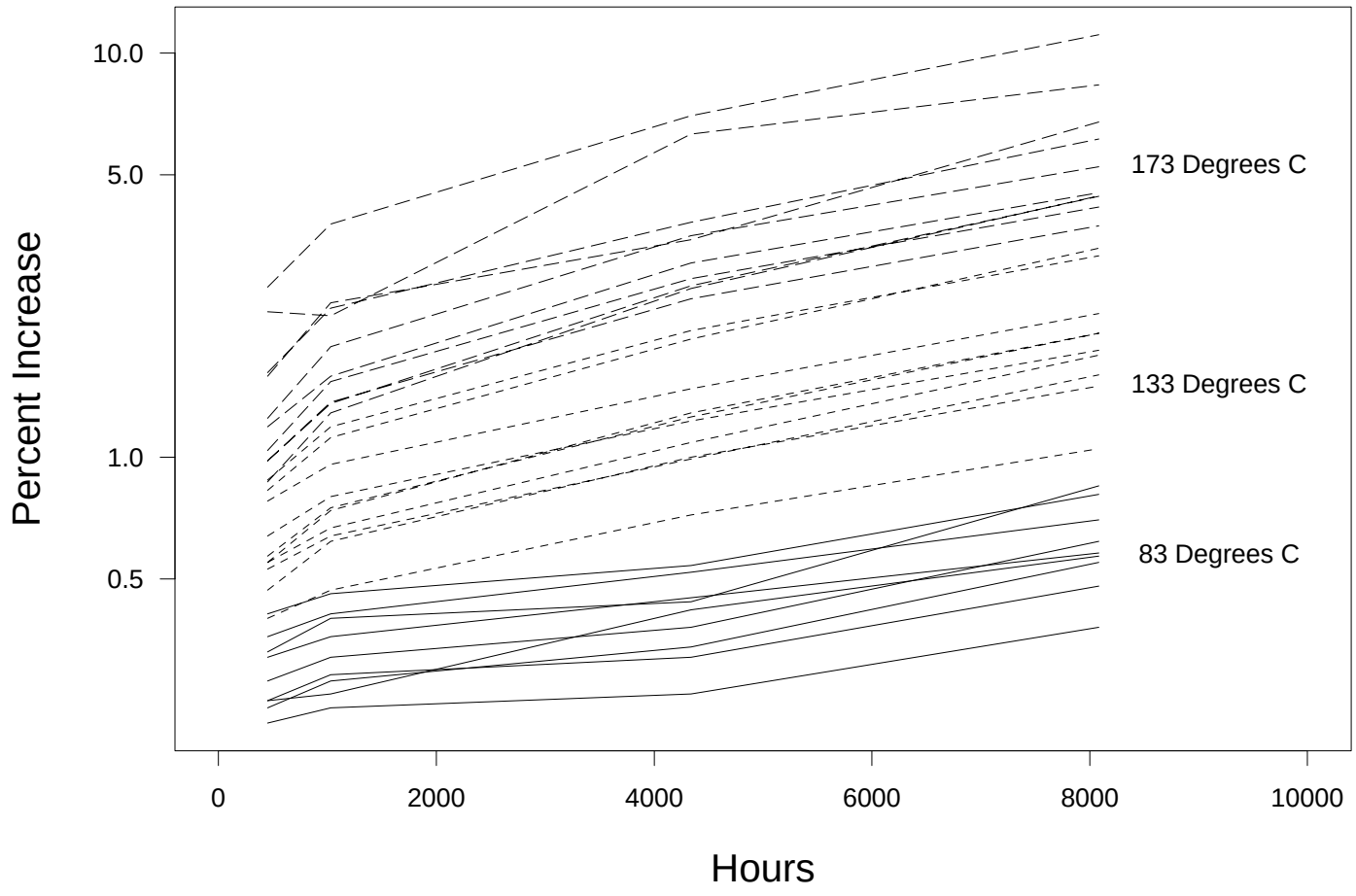
Types of Accelerated Tests

- There are three different kinds of accelerated tests, depending on what one is able to observe.
  - Accelerated life tests (ALT)
  - Accelerated repeated measures degradation tests (ARMDT)
  - Accelerated destructive degradation tests (ADDT)
- These different kinds of ATs have different data structures and thus **different** models and methods of analysis.

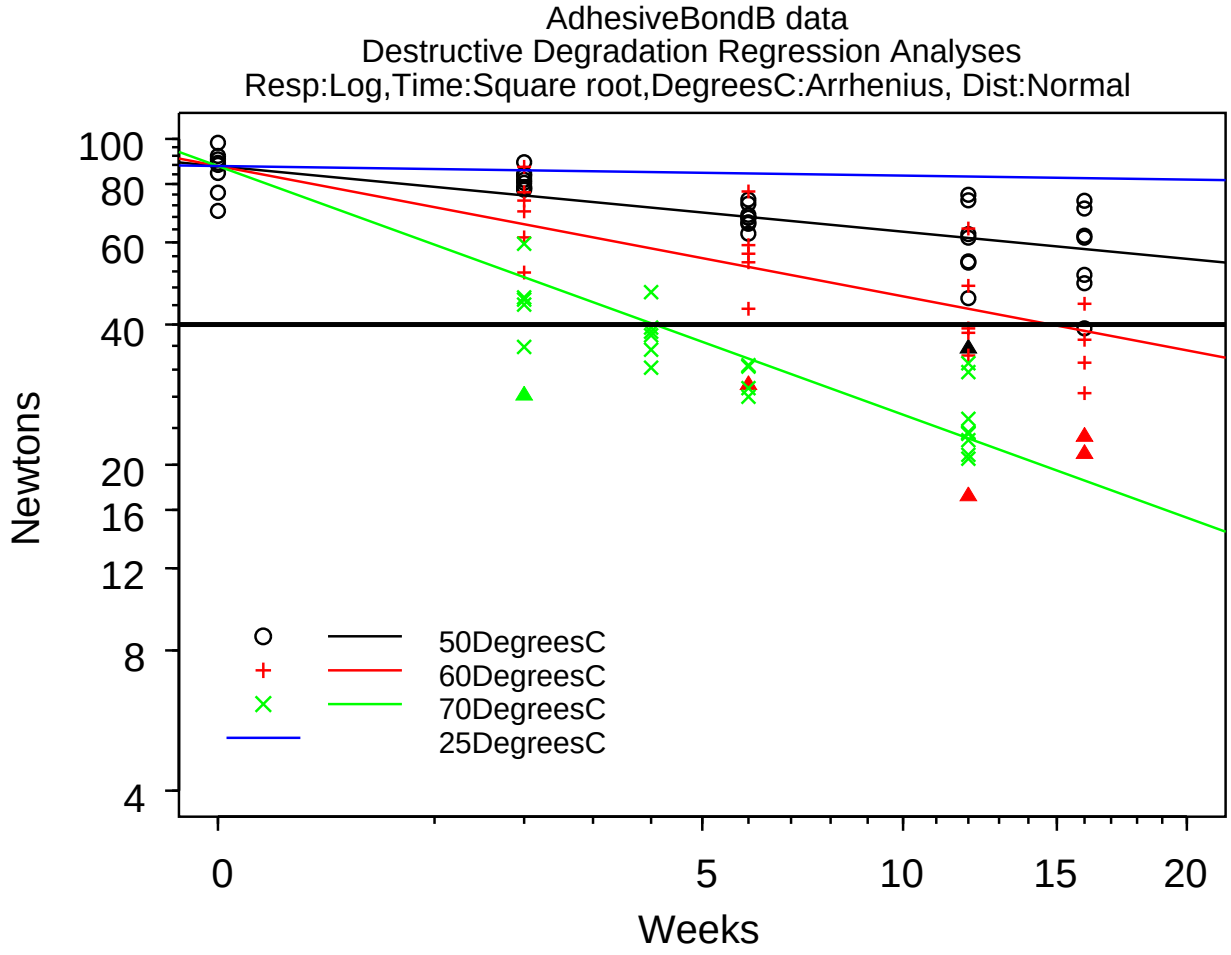
Typical Temperature-Accelerated Life Test



Accelerated Repeated Measures Degradation Test of Carbon-Film Resistors



Accelerated Destructive Degradation Test of an Adhesive



Methods of Acceleration

Three fundamentally different methods of accelerating a reliability test:

- Increase the use-rate of the product (e.g., test a toaster 200 times/day). Higher use rate reduces test time.
- Use elevated temperature or humidity to increase rate of failure-causing chemical/physical process.
- Increase stress (e.g., voltage or pressure) to make degrading units fail more quickly.

  Use a **physical/chemical** (preferable) or **empirical** model relating degradation or lifetime to **use** conditions.

Different Kinds of Pitfalls

Pitfalls are generally the result of **statistical misconceptions** or the **naive application** of accelerated test methods.

- In the recent JQT paper,

  Meeker, W. Q., Sarakakis, G., and Gerokostopoulos, A. (2013). More Pitfalls in Conducting and Interpreting the Results of Accelerated Tests. *The Journal of Quality Technology*, 45, 213-222.

  we categorized pitfalls according to

  - Pitfalls that occur during the **planning** of an accelerated test
  - Pitfalls that occur during the **execution** of an accelerated test
  - Pitfalls that occur during the **analysis and interpretation** of accelerated test data

GE Refrigerator Compressor Problem

WALL STREET JOURNAL MONDAY, MAY 7, 1990

(1)

Chilling Tale

GE Refrigerator Woes Illustrate the Hazards In Changing a Product

Firm Pushed Development Of Compressor Too Fast, Failed to Test Adequately

Missing: the 'Magical Balance'

GE Refrigerator Compressor Problem

- Early 1980s, GE was losing market share to competitors—Jack Welch was unhappy.
- 1983-1986 GE designed, tested, and began to produce a new higher efficiency, lower cost “rotary” compressor.
- Stopped accelerated testing after one year and no failures.
- One million + in service by 1987.
- First failure after 1.5 years; virtually all would have eventually failed early.
- GE replaced all compressors in refrigerators that it could find. Total cost was more than $450 Million.
- What went wrong?

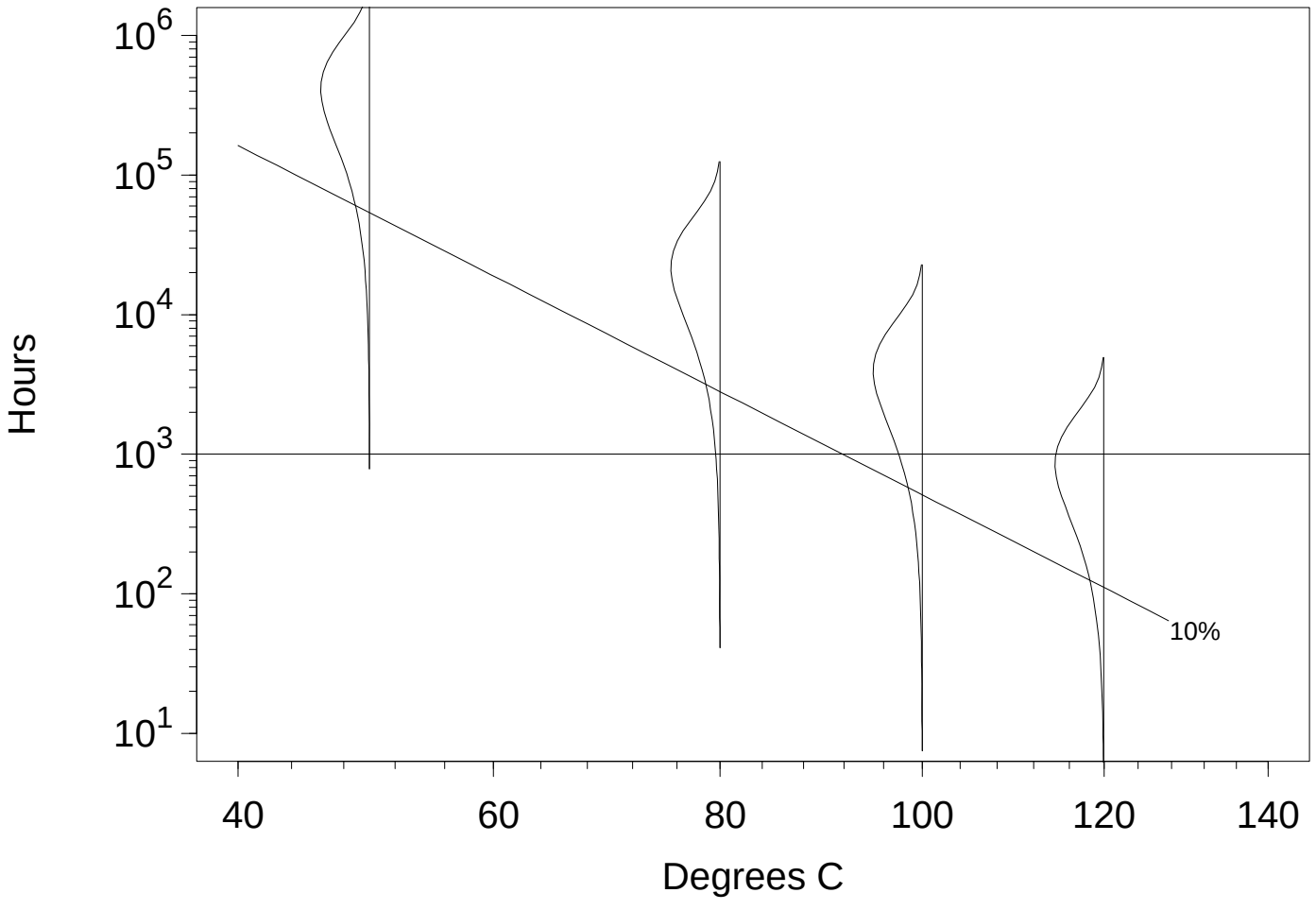
Pitfall I
Not Properly Using Information From Inspected Test Units

- Although there were no failures in the ALT, those who ran the test detected discoloration in the test units, indicating a lubrication issue.
- Test units were well on their way to failure.
- The bad news did not flow upward to higher management, as it should have.

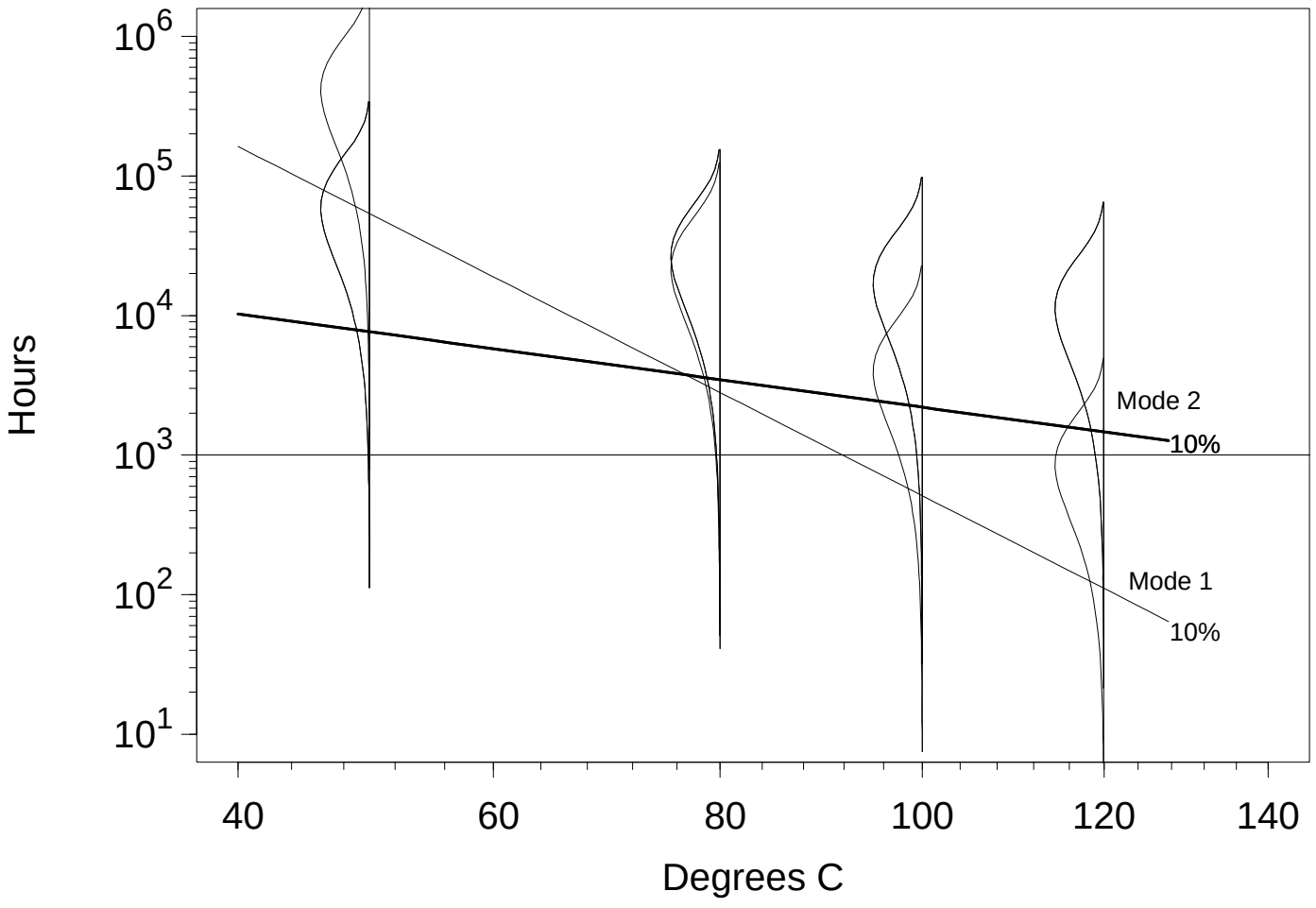
GE Refrigerator Compressor Reference

- O'Boyle, T. F. (1990). "Chilling Tale: GE Refrigerator Woes Illustrate the Hazards in Changing a Product." *Wall Street Journal* (Eastern edition). New York, N.Y.: May 7, 1990, page 1.

Temperature-Accelerated Life Test for an IC Device



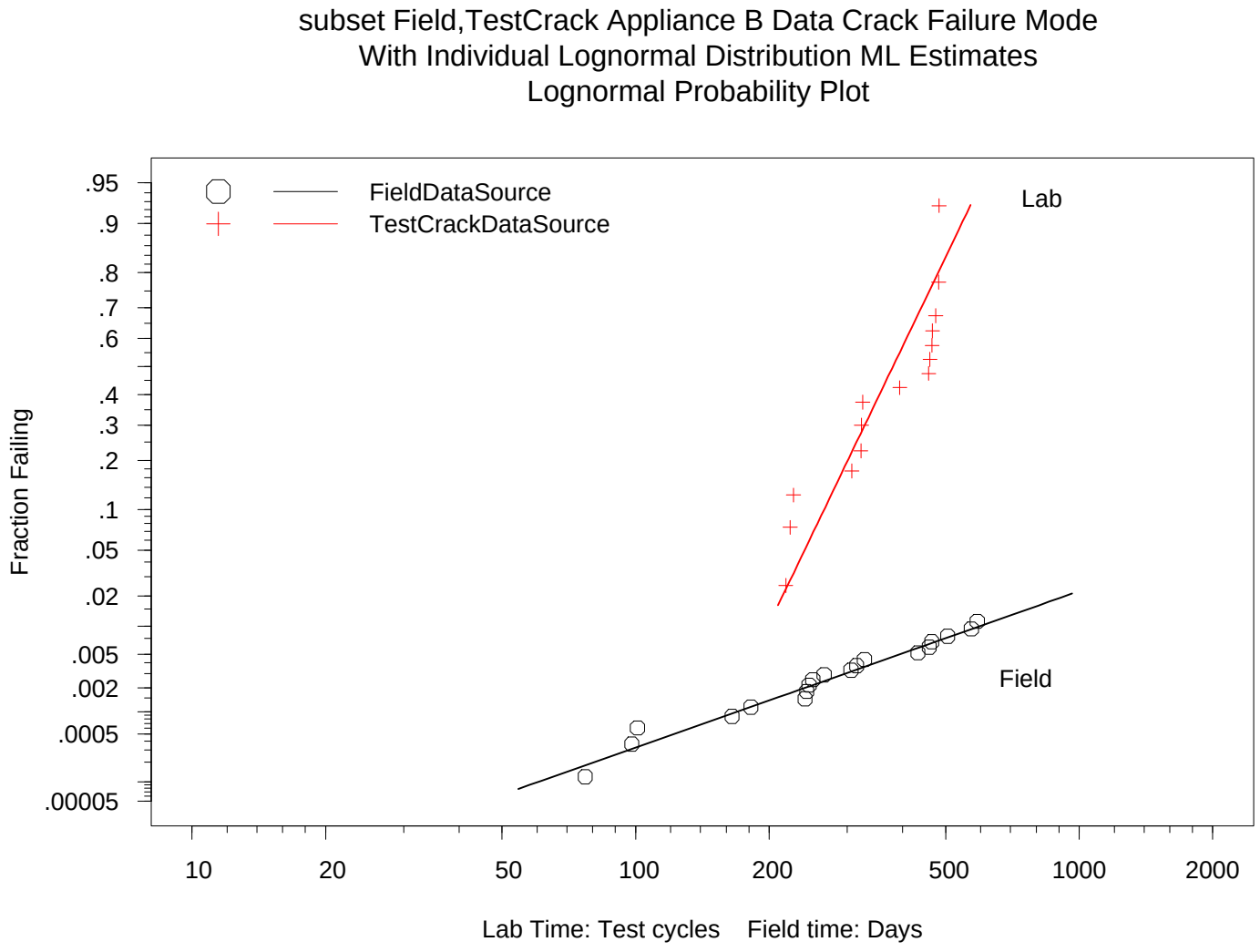
Lower Activation Energy Can Be Masked



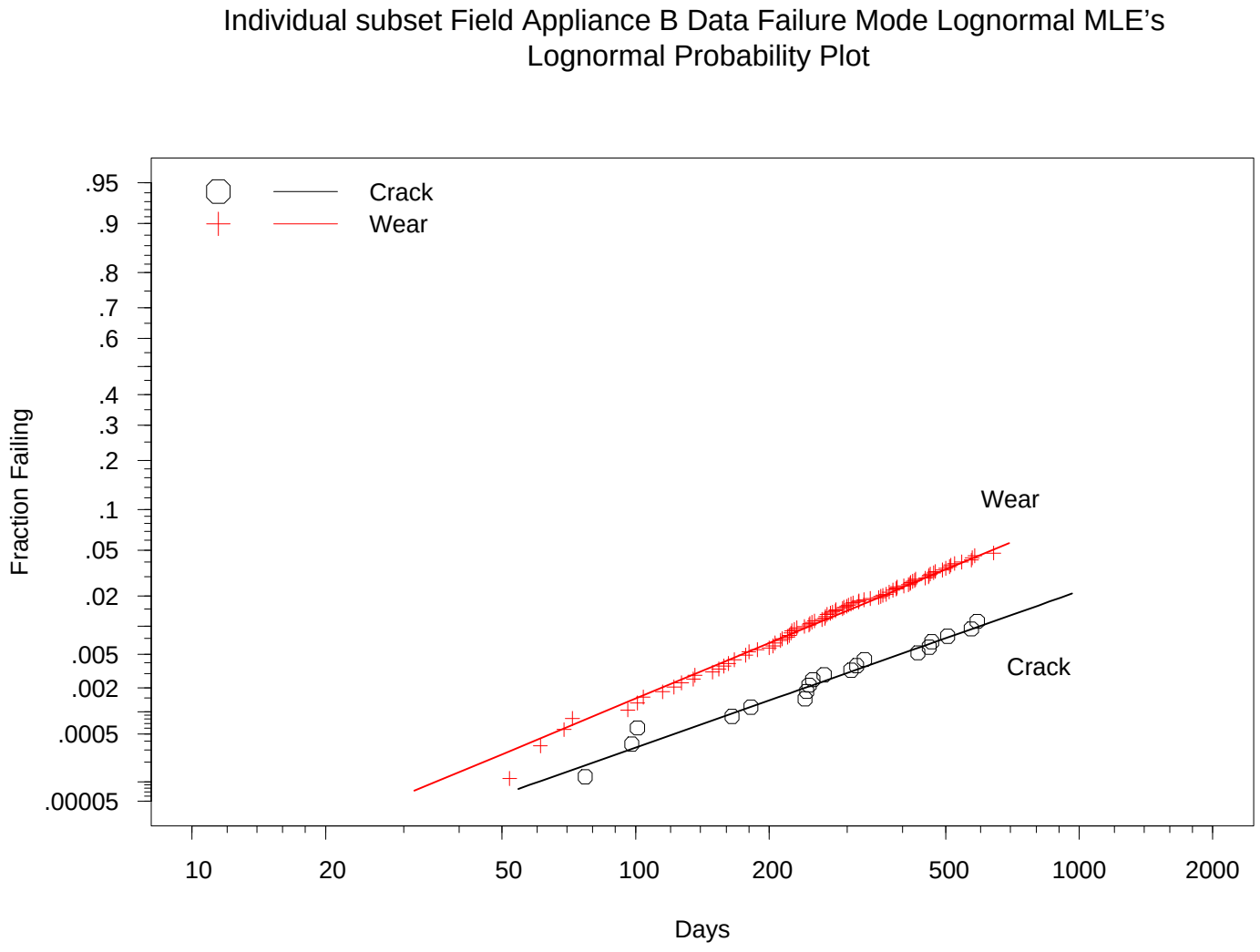
Pitfall 4
Masked Failure Mode

- Accelerated test may focus on one known failure mode, masking another!
- Masked failure modes may be the first one to show up in the field.
- Masked failure modes could dominate in the field.
- Suggestions:
  - Know (anticipate) different failure modes.
  - Limit acceleration and test at levels of accelerating variables such that each failure mode will be observed at two or more levels of the accelerating variable.
  - Identify failure modes of all failures.
  - Analyze failure modes separately.

Appliance B Comparison of **Laboratory** and **Field** Data for the **Crack** Failure Mode

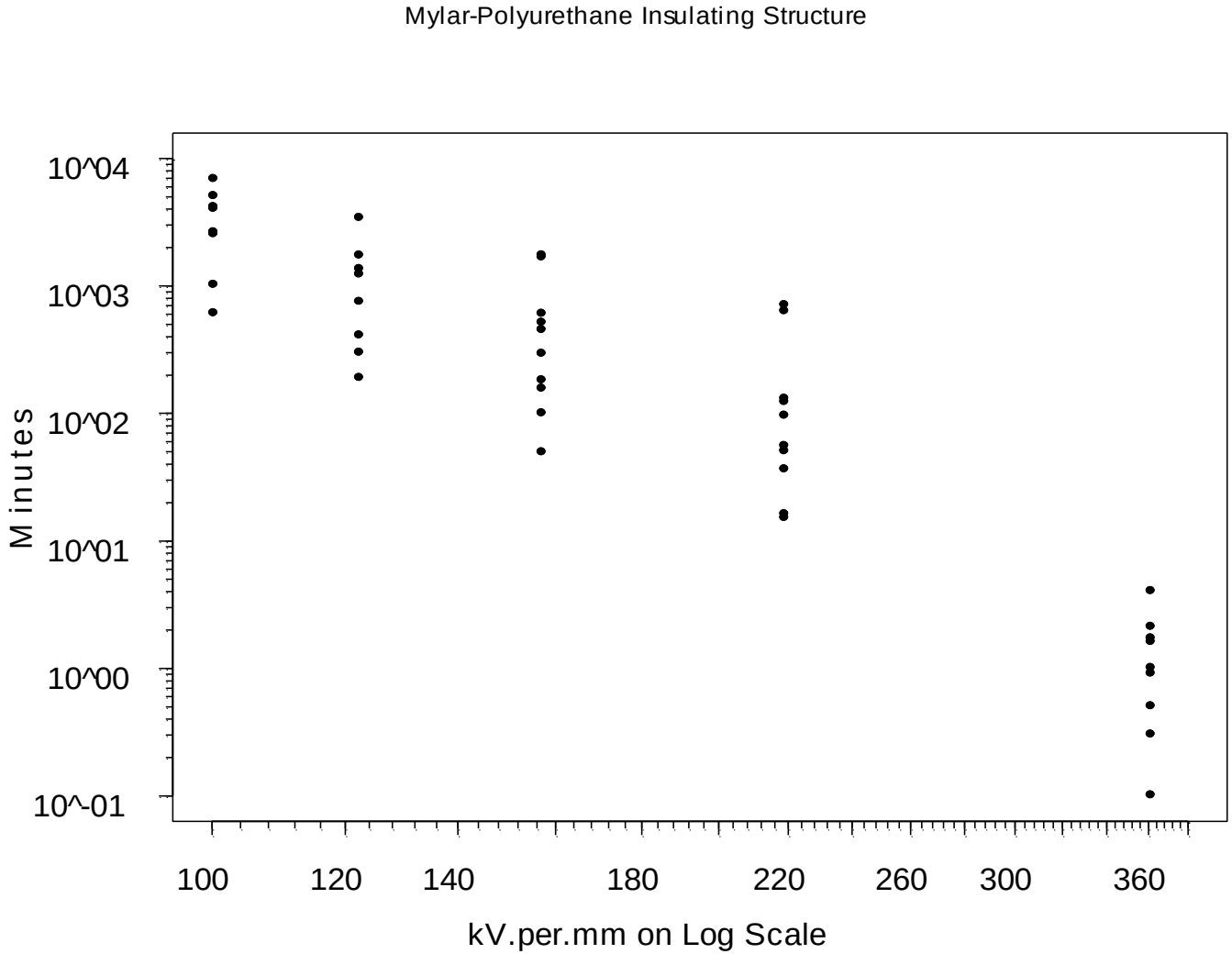


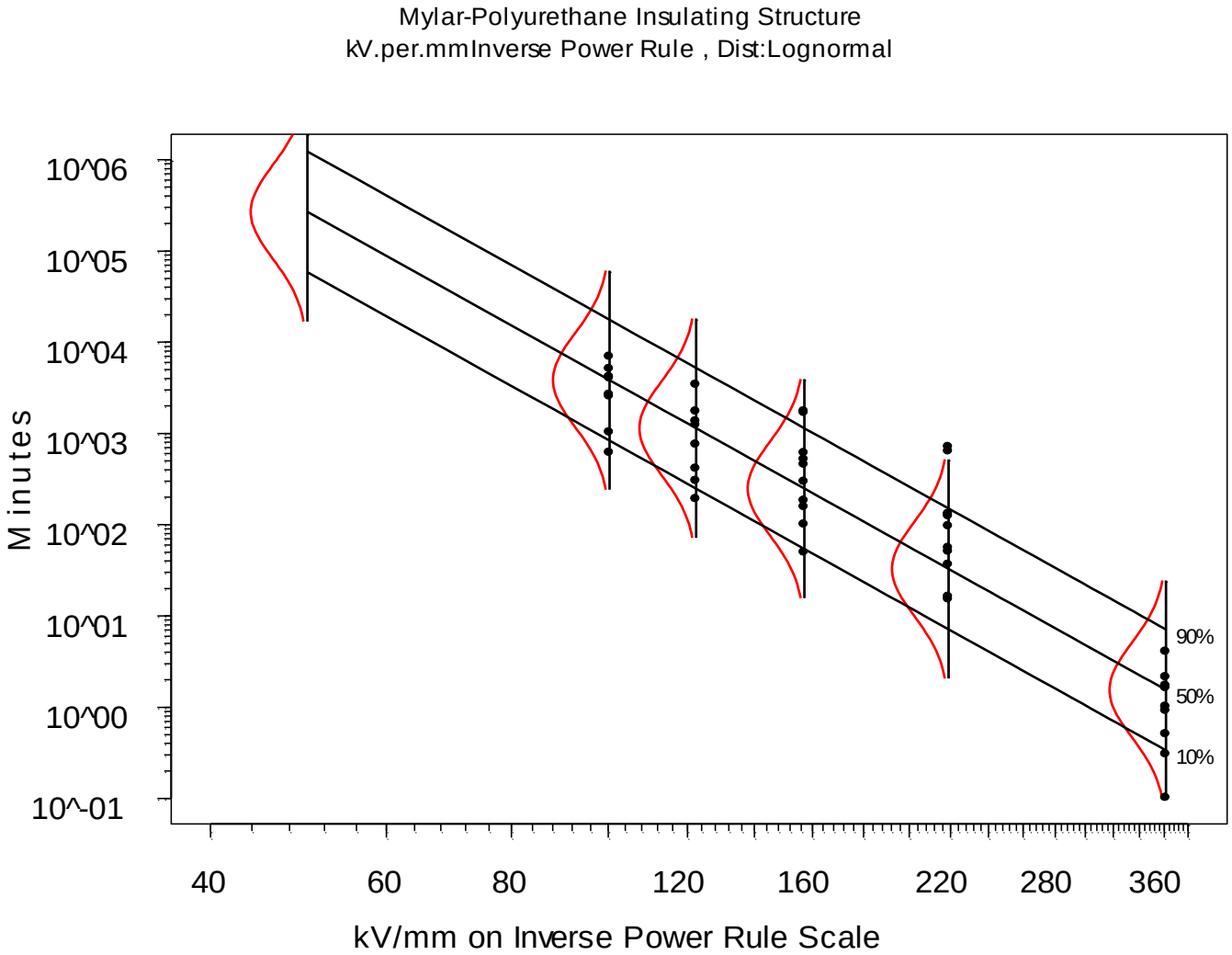
Appliance B Warranty-Return (Field) Data **Wear** and **Crack** Failure Modes



Pitfall Q
Not comparing failure modes in the field with failure modes in the laboratory

- Accelerated tests must generate failures in the same manner that they will be generated in actual use
- Often doing physical failure mode analysis is required
- When the mechanism is due to chemical change, analytical chemical measurements can be used to assure that AT and actual use have the same chemistry.


Mylar-Polyurethane Insulating Structure
Minutes
10^04
10^03
10^02
10^01
10^00
10^-01
100
120
140
180
220
260
300
360
kV.per.mm on Log Scale


Mylar-Polyurethane Insulating Structure
kV.per.mmInverse Power Rule , Dist:Lognormal
10^06
10^05
10^04
10^03
10^02
10^01
10^00
10^-01
Minutes
90%
50%
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160
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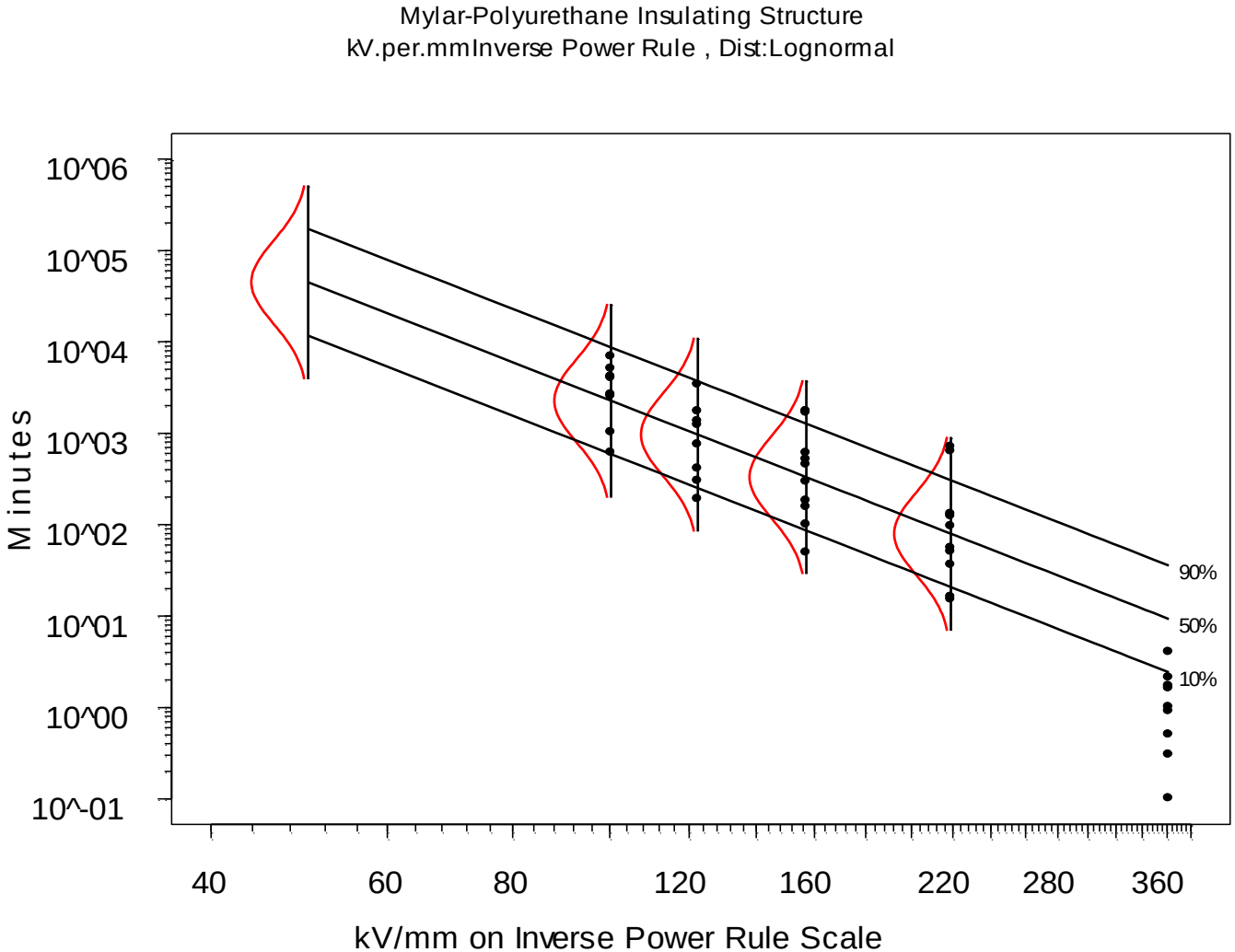
kV/mm on Inverse Power Rule Scale


Mylar-Polyurethane Insulating Structure
kV.per.mmInverse Power Rule , Dist:Lognormal
10^06
10^05
10^04
10^03
10^02
10^01
10^00
10^-01
Minutes
90%
50%
10%
40
60
80
120
160
220
280
360
kV/mm on Inverse Power Rule Scale

Pitfall E
Testing at High Levels of Accelerating Variables That Cause New Failure Modes

- Using too much acceleration, generating new failure modes, is one of the most common AT pitfalls
- Early failures from a new failure mode at high levels of the accelerating variable will cause incorrectly optimistic predictions of lifetime at the use conditions.
- Knowledge of failure mechanisms and physical failure mode analysis can help avoid problems.

Concluding Remarks

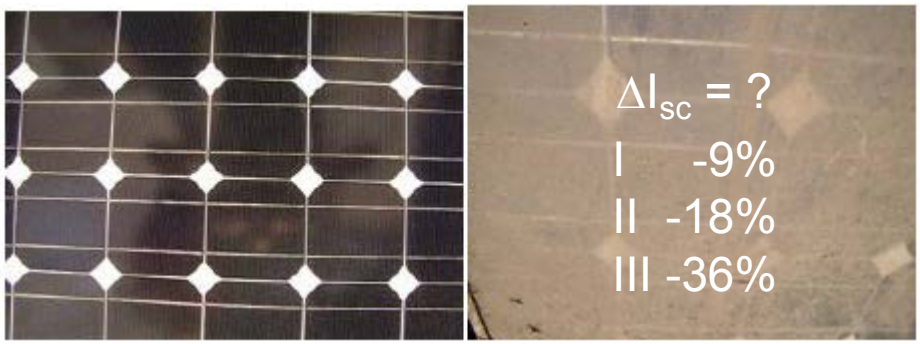
- Accelerated tests are an important part of product development processes and are often needed to achieve high reliability.
- Accelerated testing requires extrapolation in several dimensions. **Extrapolation is dangerous**.
- It is important, when possible, to understand the physics/chemistry behind failure mechanisms.
- Knowledge of the potential pitfalls can help in avoiding serious mistakes.

The End

Thank You

DAP-PL-4314.00

Impact & Consequences of Soiling and Cleaning of PV Modules



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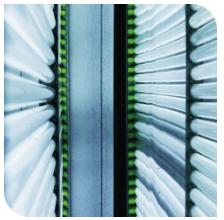
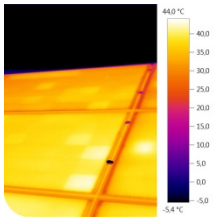
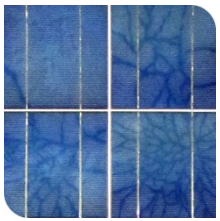
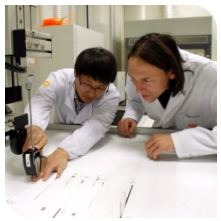
Photovoltaik Class A PID Institut Berlin No. 12012123









Business Units | Services

Customer

Quality

PV-Module Quality & Lab Services
(ISO 17025 accredited labs)

- Head of BU: Dipl.-Ing.(FH) Michael Schoppa
- Services: Supplier Qualification, In-depth Factory Inspections, Module Tests, Certification

Power plants

PV-Systems

- Head of BU: P. Eng. Steven Xuereb
- Services: Yield Optimization, Due Diligence, Plant Certification, Plant Analysis

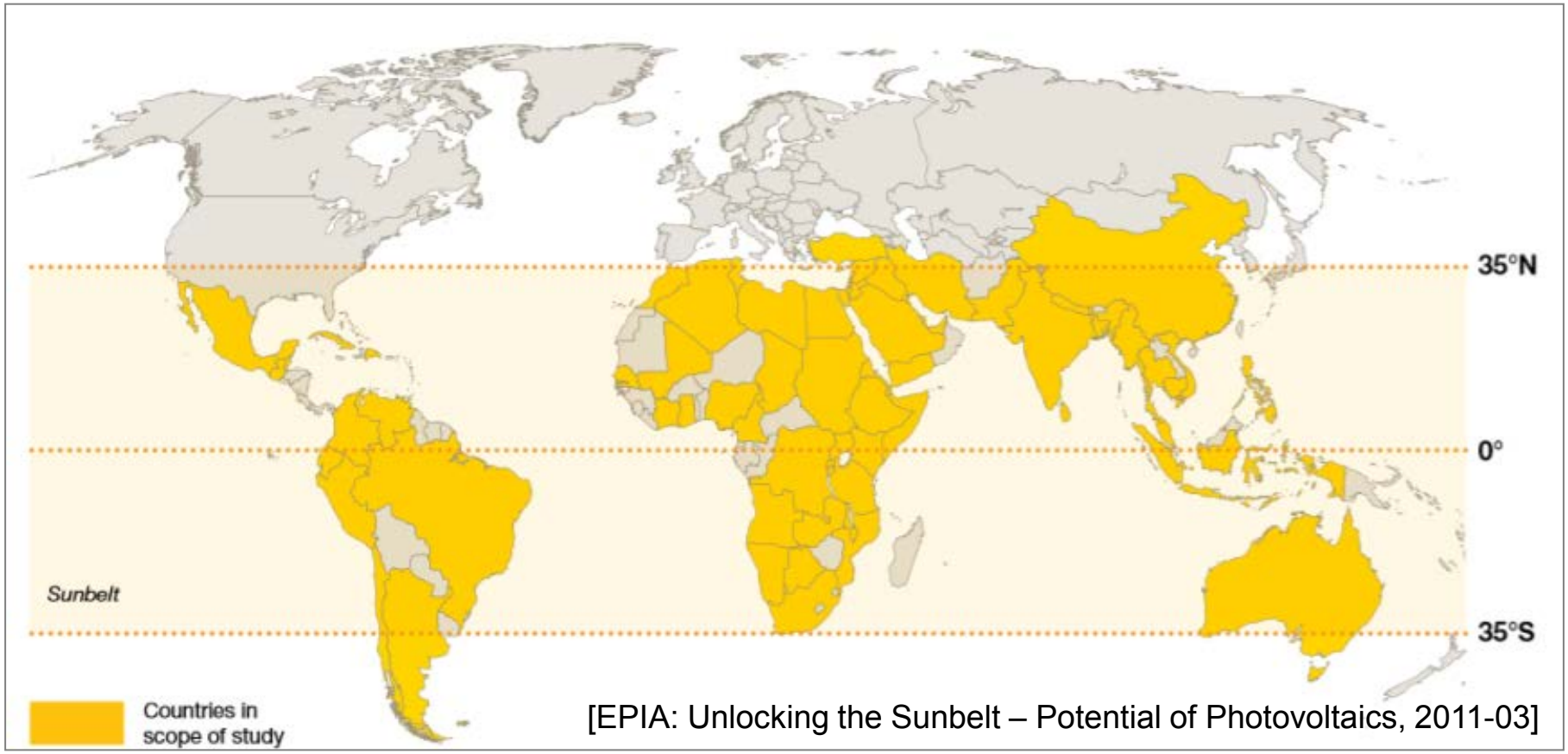
Technology

PV-Module Technology and R&D Services

- Head of BU: Dr. Juliane Berghold
- Services: Failure Analysis, Component Analysis, Expert Opinion, Funded Projects

Report

1) Motivation
Why turn soiling, cleaning and Abrasion into interest?

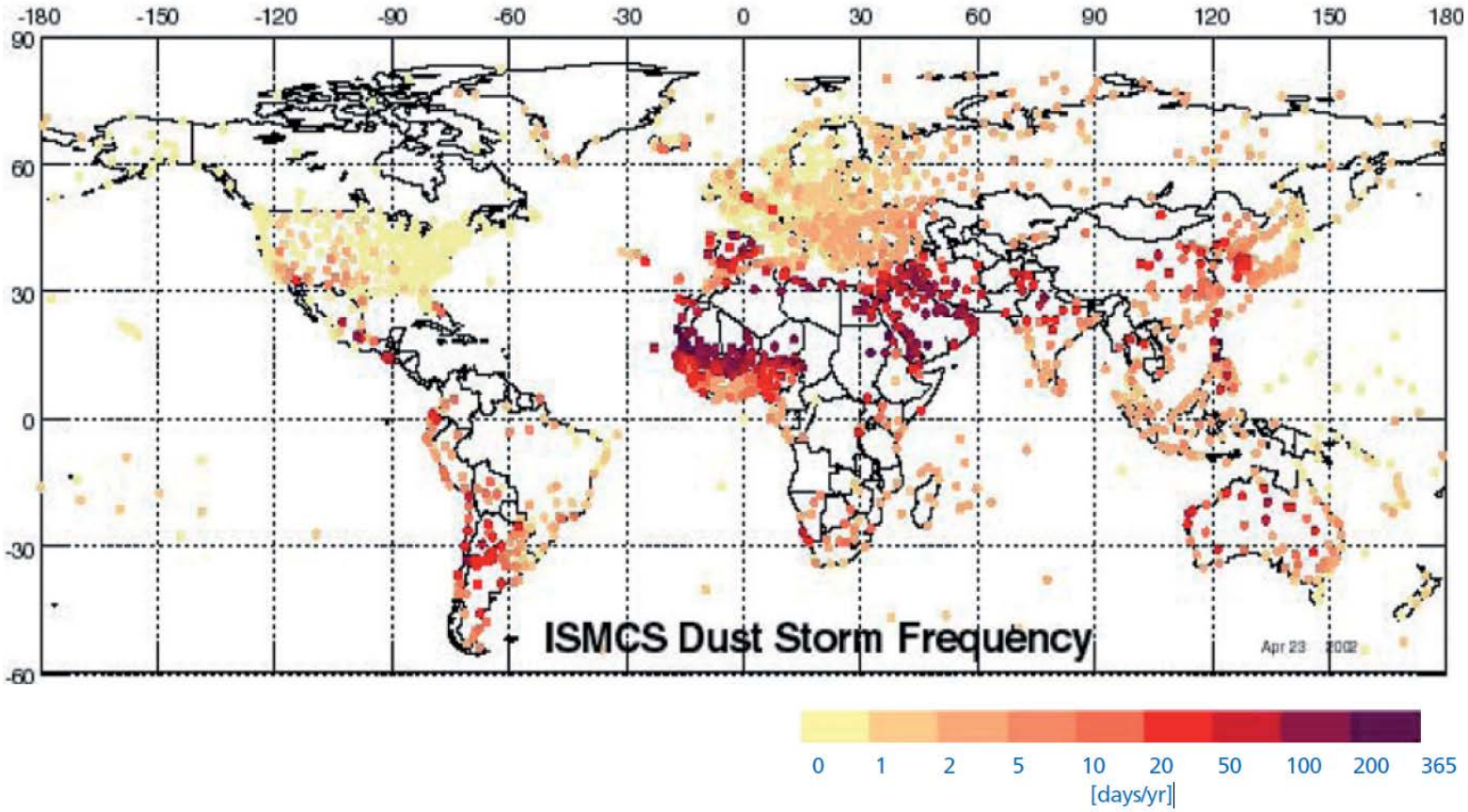


[EPIA: Unlocking the Sunbelt – Potential of Photovoltaics, 2011-03]

- 5 billion inhabitants in 66 Sunbelt countries representing 75% of the world's population

→ **deserts**, **pollution**, and **flat tilt angles** lead to **strong soiling impact** on PV modules

1) Motivation
Dust Storm frequency



[Tegen et al., "Relative Importance of climate and land use in determining present and duture global soil dust emission", Geophysical Research Letters 31, 2004]

- **Soiling and Abrasion impact is location dependent**

→ Mani contributed a usefull categorization of climatic zones and recommended cleaning schedules

[M. Mani et al. "Impact of dust on solar photovoltaic (PV) performance: Research status,challenges and recommendations", Renewable and Sustainable Energy Reviews 14 (2010) 3124–3131]

Overview

1) Motivation

2) Introduction

3) Soiling Test:

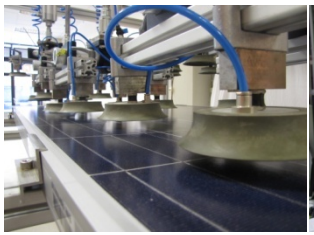
How one can **simulate soiling** and **determine self-cleaning properties.**

4) **Cleaning Impact** on modules

5) Abrasion Test:

How **coatings are effected by abrasion**.

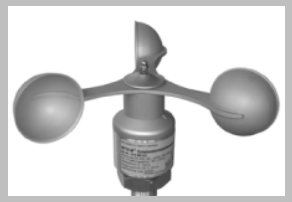
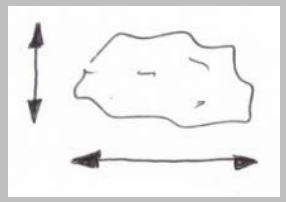
6) Summary



2) Introduction

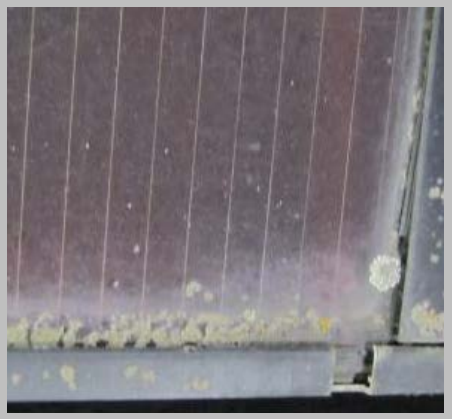
Environmental conditions of spec. location:

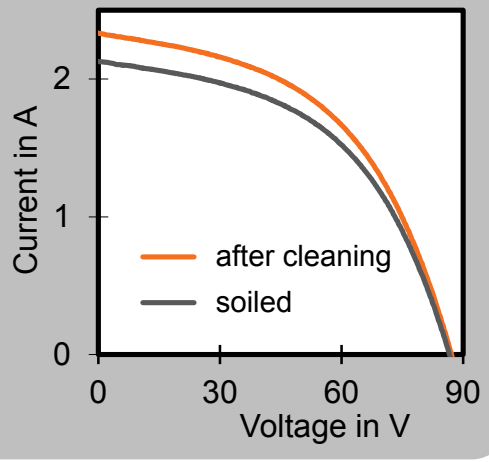
- wind speed / direction
- kind of dust
- moisture
- natural cleaning
- availability of water as cleaning resource

Power reduction:

- less significant e.g. in Germany
- 15 to 30% for moderate dust cond.
- losses up to 100% possible, if cementation





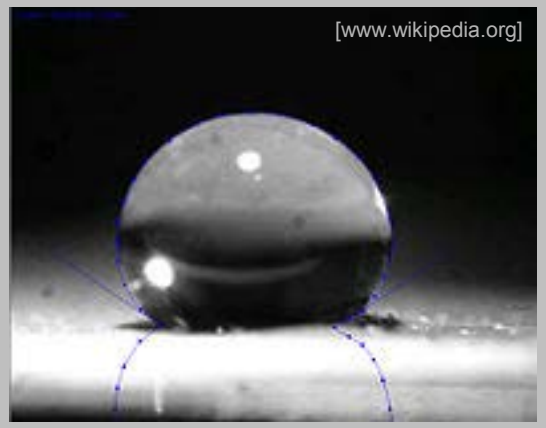
2) Introduction

Mitigation / corrective measures:

- water, air or mechanical cleaning
- manual or autom.

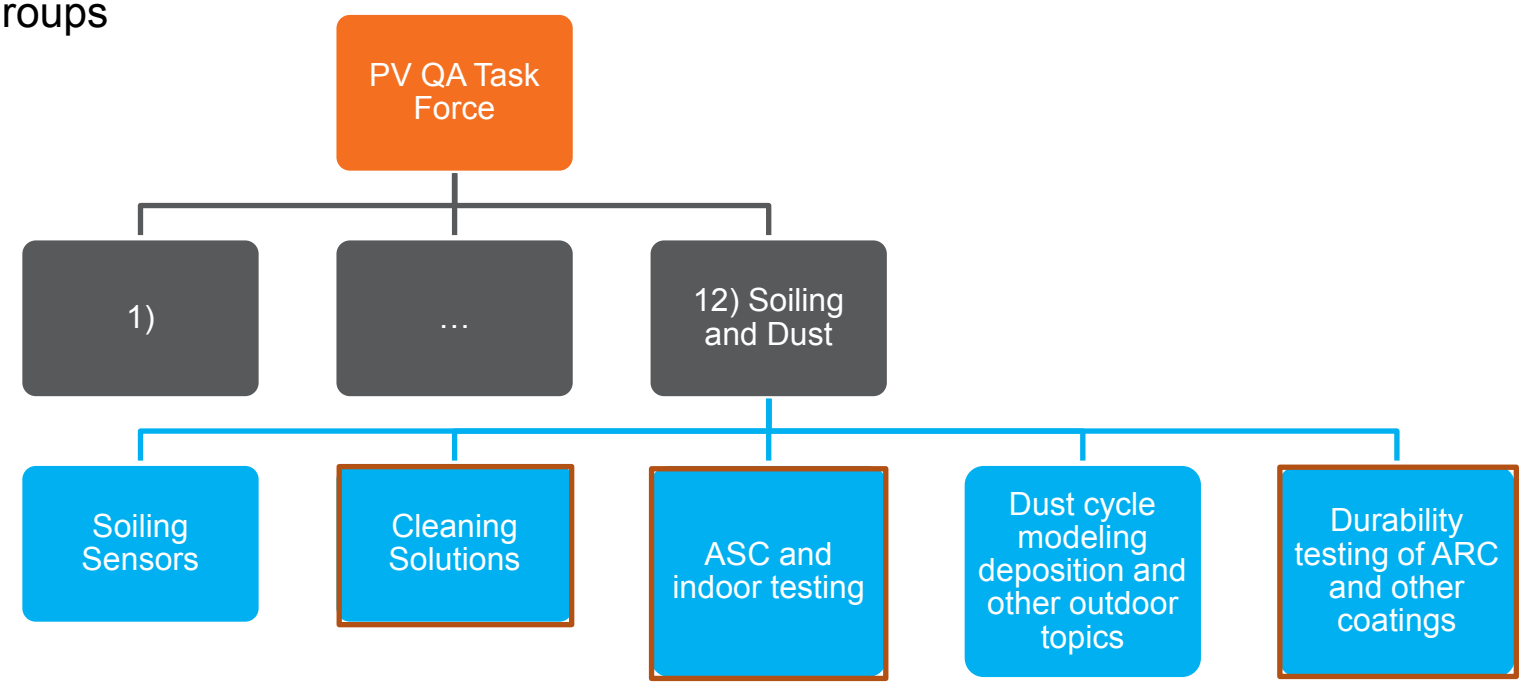
Mitigation / preventive appr.:

- ‘passive’ methods:
anti soiling coatings (ASC)
- ‘active’ methods:
repelling by charge



2) Introduction
Overview to PV QA Task Force 12) Soiling and Dust

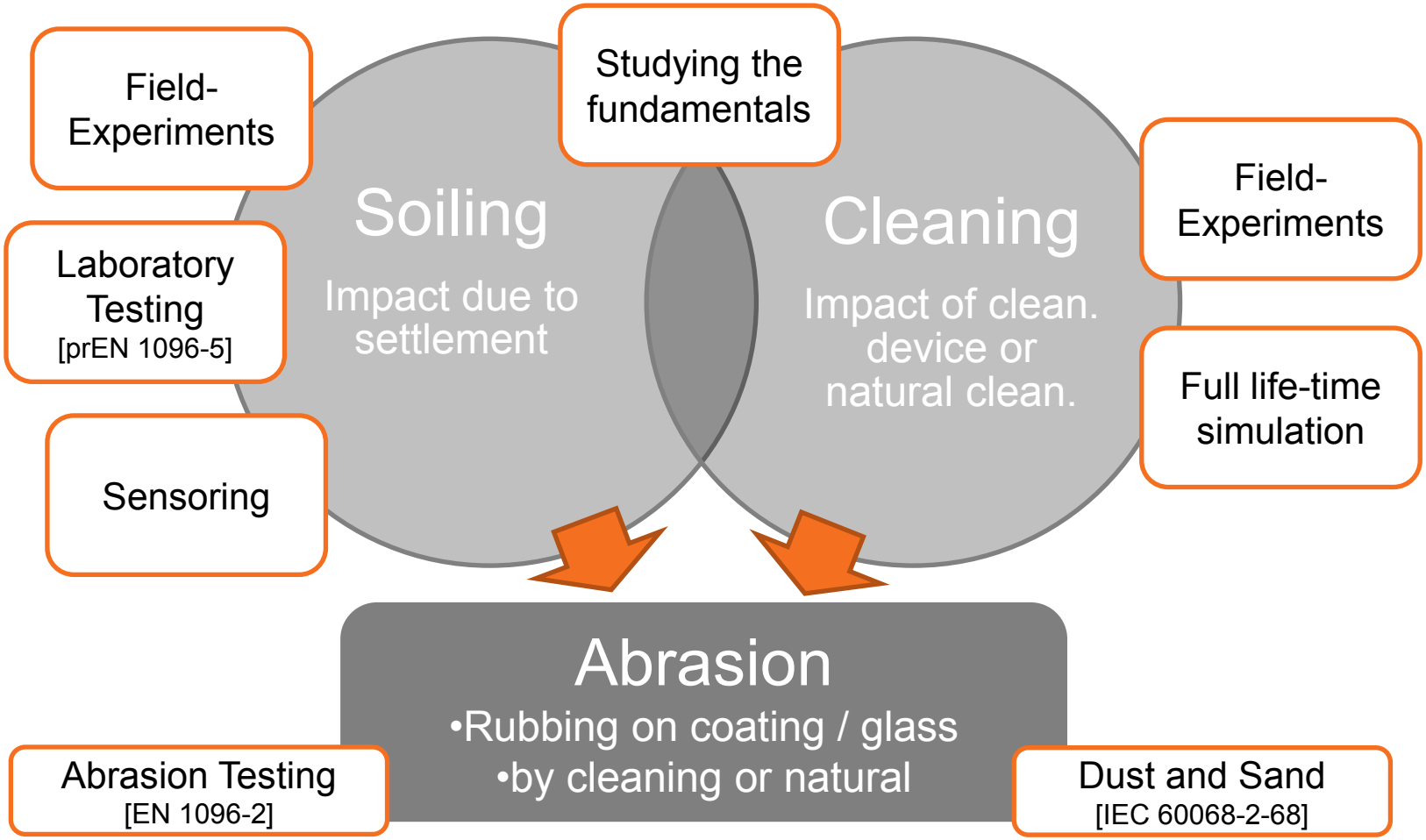
- PV QA Task Force was initiated at the International PV Module QA Forum 2011 in San Francisco
- Task group 12) Soiling and Dust
  - Leader of group Mike Van Isegheim (EDF) and Sarah Kurtz (NREL)
  - 5 subgroups



→ Look to the wiki-page:http://pvqataskforceqarating.pbworks.com

2) Introduction: Soiling, Cleaning and Abrasion [Sarver et al.]

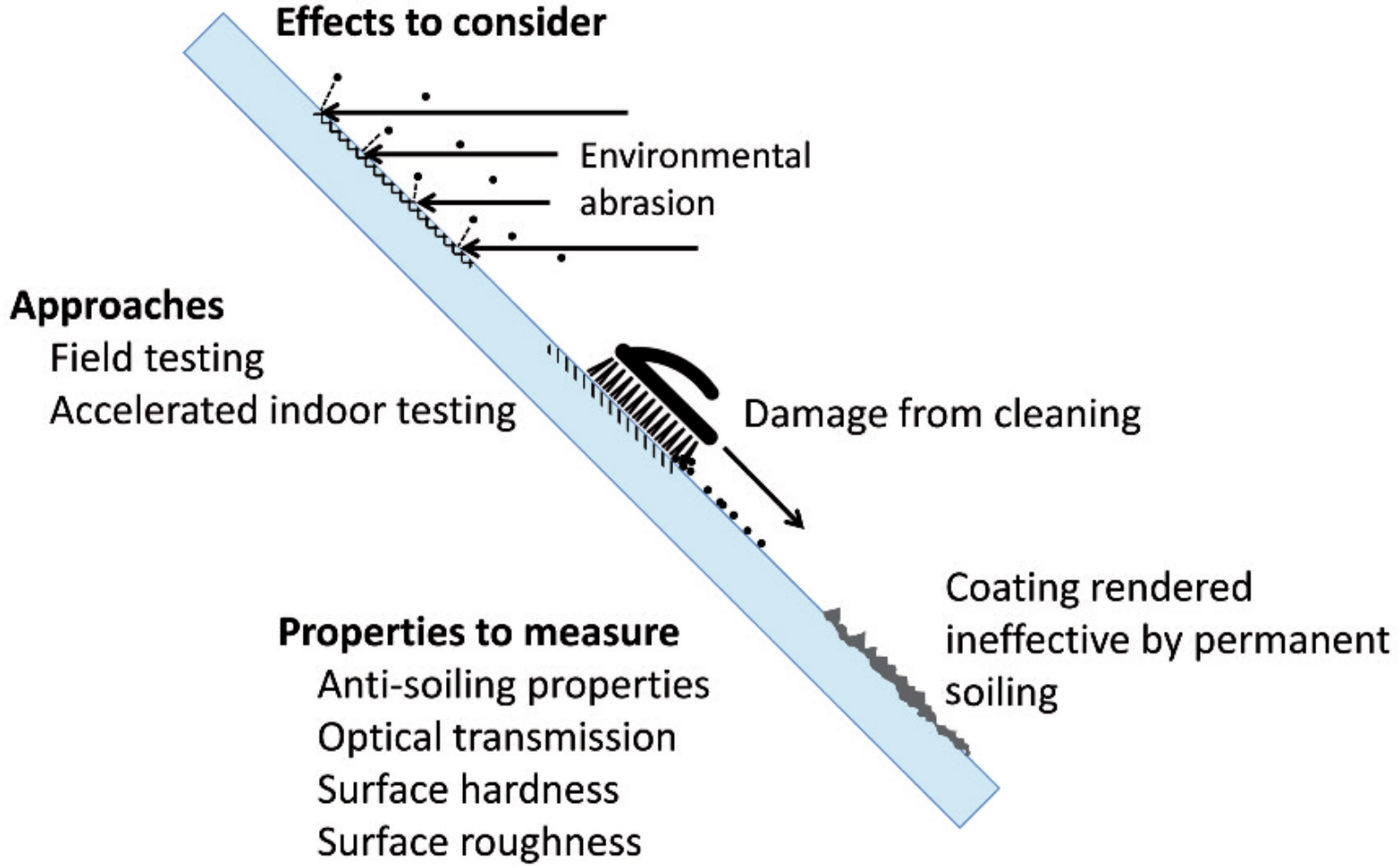
- Up till now no PV standard exists for soiling, Cleaning and abrasion



[T. Sarver et al. "A Comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches", Renewable and Sustainable Energy Reviews 22 (2013) 698-733]

→ Aim: Simulation of realistic soiling, cleaning and abrasion conditions

2) Introduction: Soiling, Cleaning and Abrasion

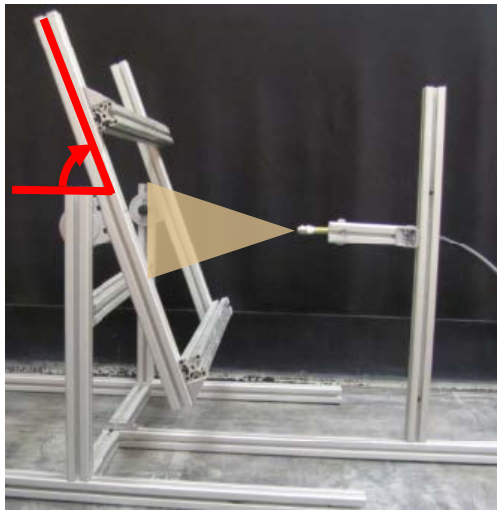


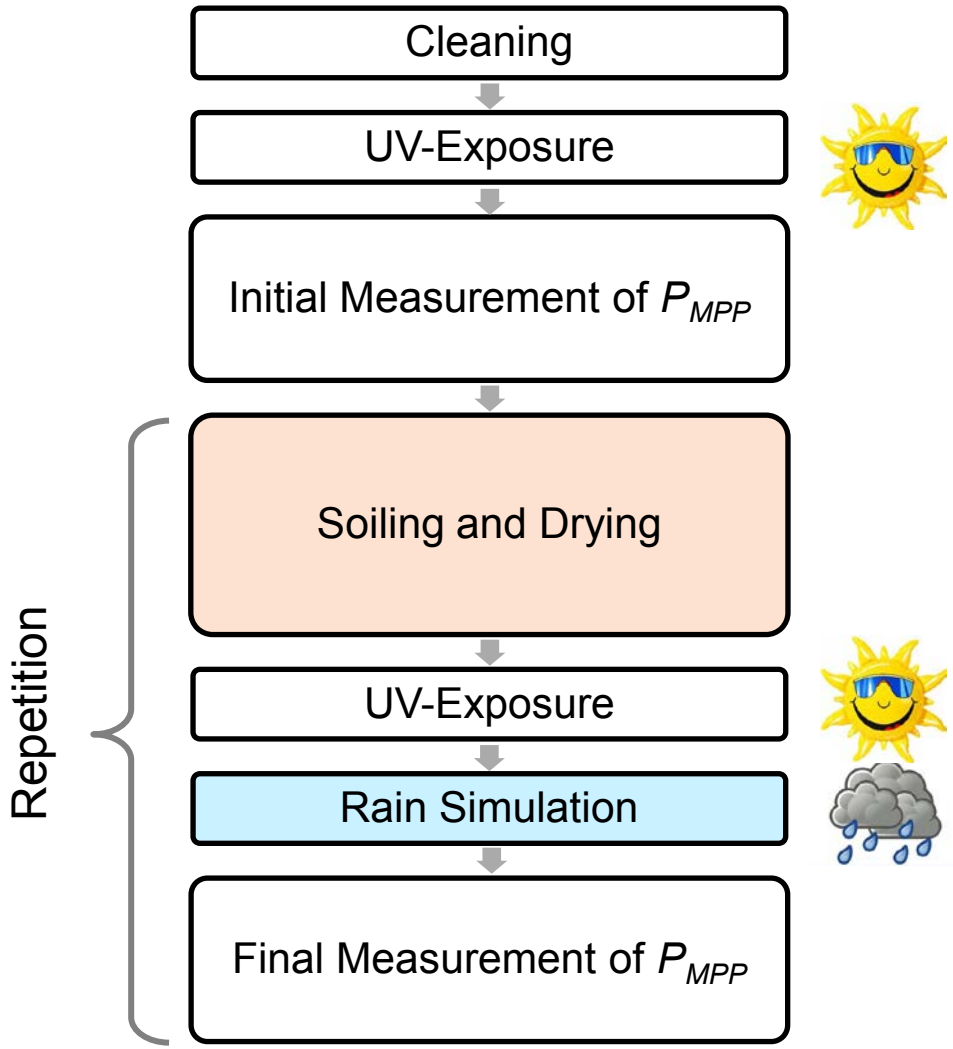
[M.Van Isegheim] et al., „The PVQAT Soiling Collaborative“, EU PVSEC 2014 Amsterdam, 5CV.2.25]

3) Soiling
3.1) Test Bench and Procedure

- We built up a soiling test acc. prEN 1096-5:2011
- Variable spray angle
- „Dirt solution“ acc. Standard

→ For evalutaion of the self-cleaning performances of coated glass surfaces





3) Soiling
3.2) Test Results of Self-Cleaning on Glasses

Evaluation of Procedure on Different Glasses:

- one-cell mini module with soiled glasses as filter infront of it measured in the flasher
- Error on repeatability of measurement 0.3%

Investigated Parameters:

surface structure of glass and tilt angle

Solar glass	ΔP_{MPP} in %	
	30°	10°
Float glass (flat)	-1.0	-1.9
Slightly structured glass	-1.3	-1.9
Prismatic glass	-1.5	-3.7

Results:

→ Prismatic glass soil most (especially under flat angles)

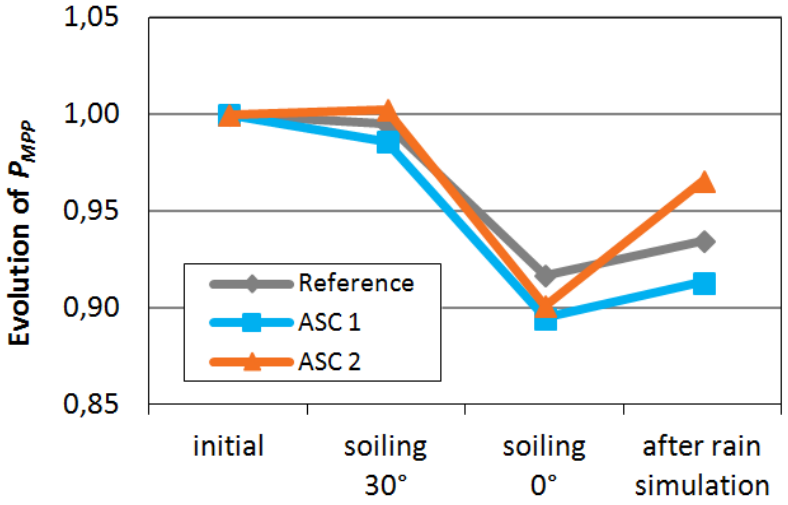
→ Structure of surface influence self cleaning property

→ Flat angles (10°) soil much more than standard angles (30°), two times in our case

3) Soiling
3.3) Results – Anti-Soiling-Coatings (ASC)

Comparison of Two Different Coatings on Standard mc-Modules vs. Reference

- ASC 1: Titanium dioxide
- ASC 2: Zinc/Silver dioxide

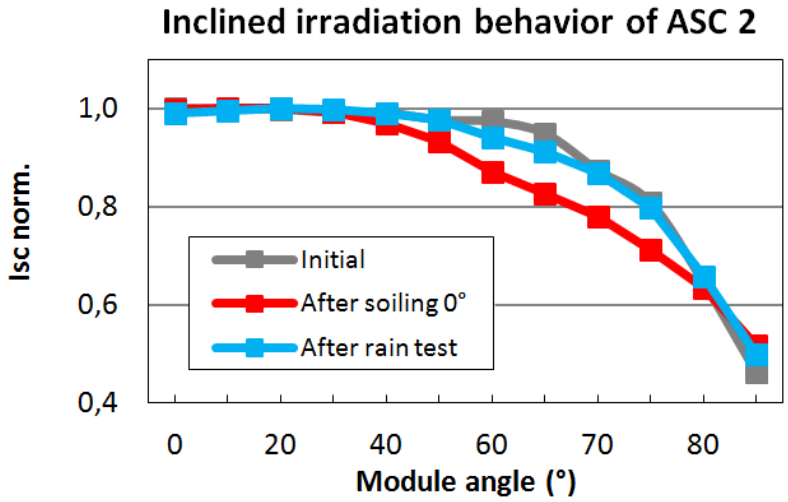


Results:

→ ASC 2: better self cleaning effect than ASC 1

→ resulting in higher yields

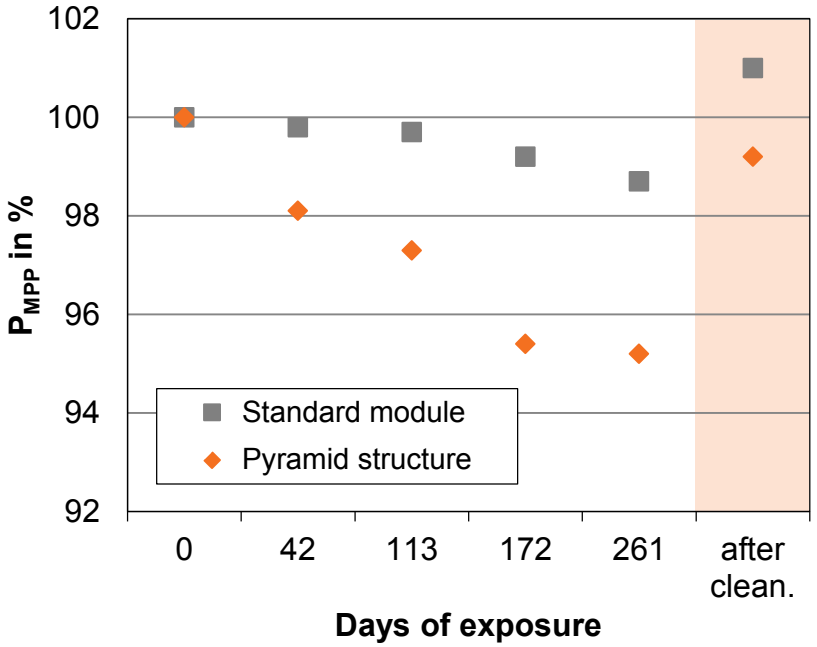
Specific Energy Yield			
	Reference	ASC 1	ASC 2
kWh/kWp	31.5	32.0	32.3
Dev. to Ref.		1.8	2.8



3) Soiling
3.4) Outdoor test results

Long-Time Test on Modules

- over 260 days from May ‘11 to April ’12
- Outdoor test facility PI-Berlin
- Module with pyramid structure vs. standard flat glass
- Pmpp determined under STC at laboratory flasher



Results:

→ Both modules soil, but the module with pyramide structure 4 times more

4) Cleaning
4.1) Kind of cleaning

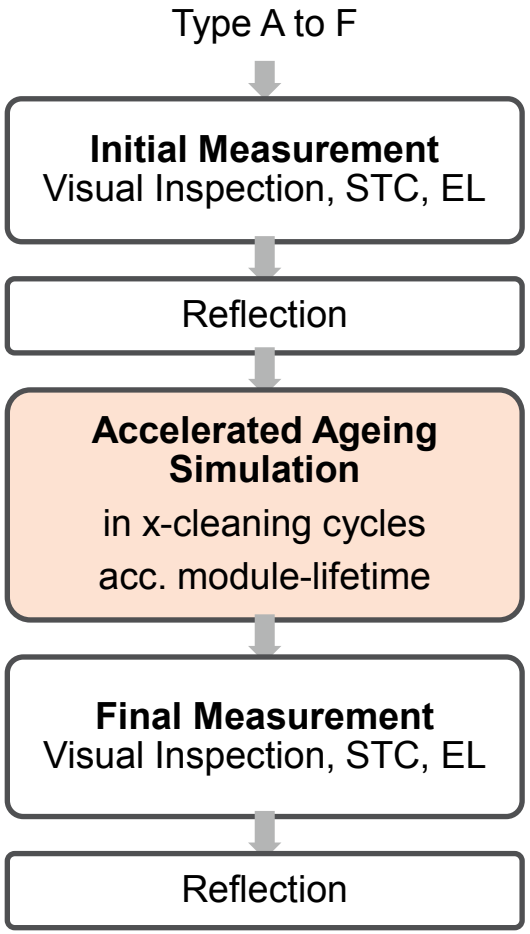
- Manual vs. Automated cleaning
- Many different solutions are available on the market

4) Cleaning
4.2) Evaluation of dust cleaning solutions

Evaluation of Dust Cleaning Solution:

- Testing of the impact of a **cleaning device** on the performance of PV modules
- **Full life-time simulation** according 'years of operation in field' and 'cleaning frequency'

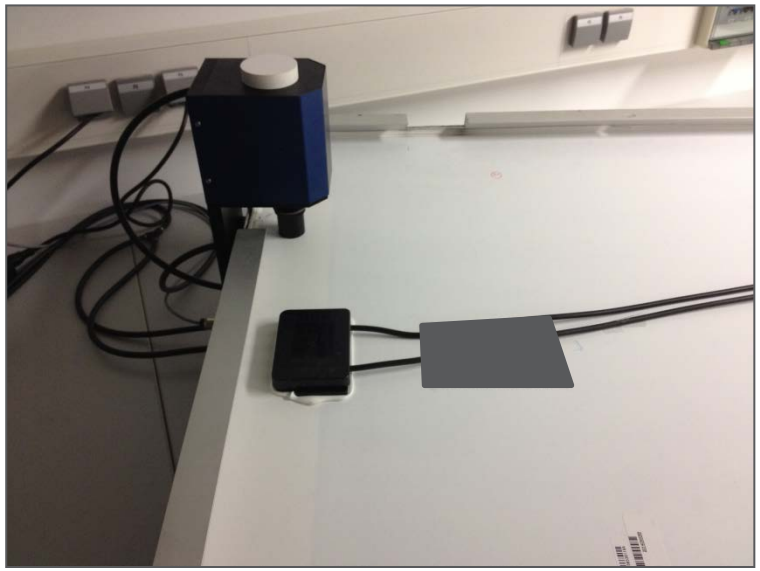
Investigation on Modules of well-known producers: Anonymous A to F



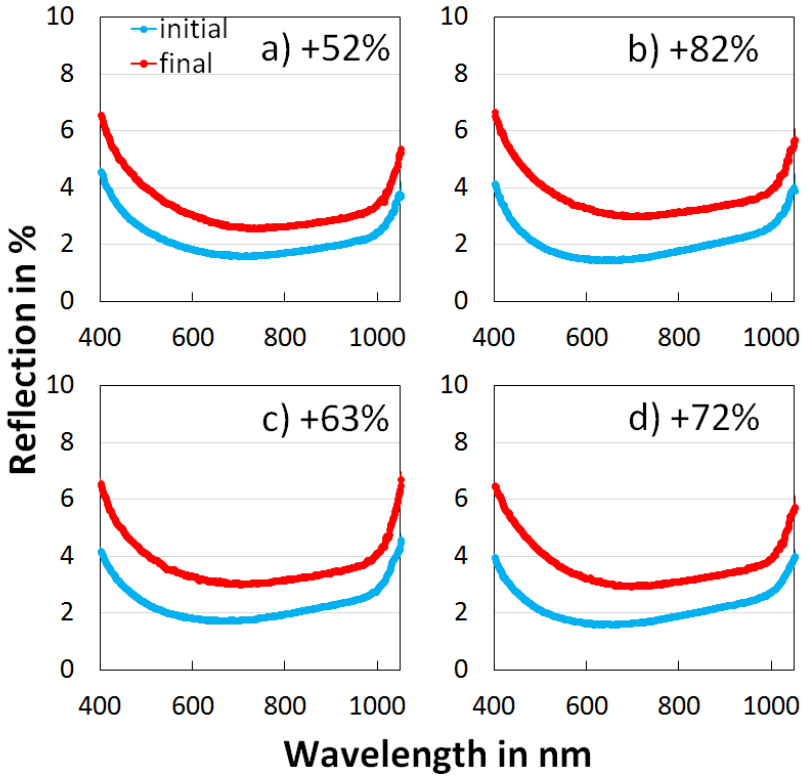
4) Cleaning
4.3) Reflection measurement

Device properties and measurement:

- 10mm measurement spot
- Range 400 – 900nm, uncertainty < 0.2
- Mean value out of 10 measurements per point, four points per module



→ Reflection results of module Type A



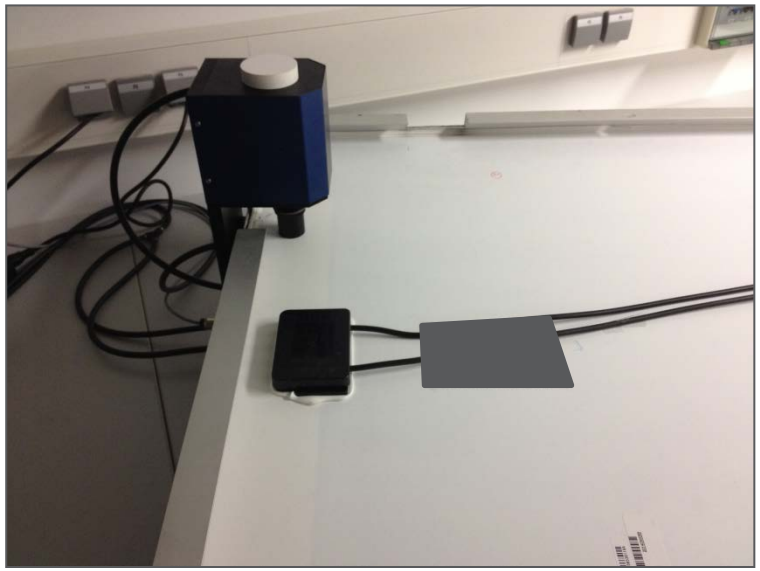
→ Homogeneous results

→ mean change of reflectance = 67% due to abbraded ARC

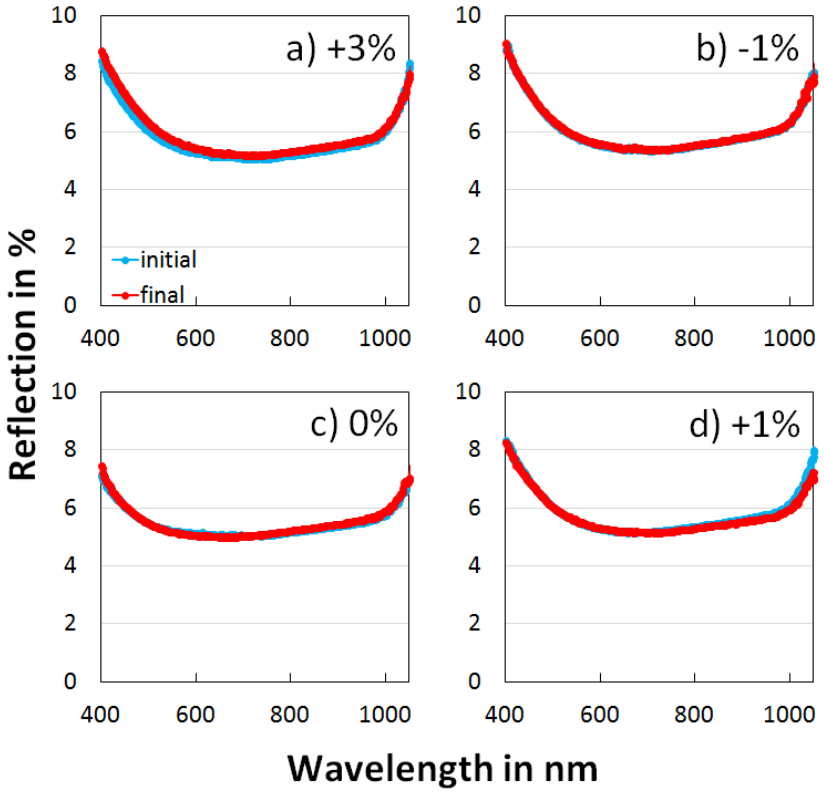
4) Cleaning
4.3) Reflection measurement

Device properties and measurement:

- 10mm measurement spot
- Range 400 – 900nm, uncertainty < 0.2
- Mean value out of 10 measurements per point, four points per module



→ Reflection results of module Type E



→ Homogeneous results, no ARC on glass

→ mean change of reflectance = 1%

4) Cleaning
4.4) Evaluation of dust cleaning solutions - Results

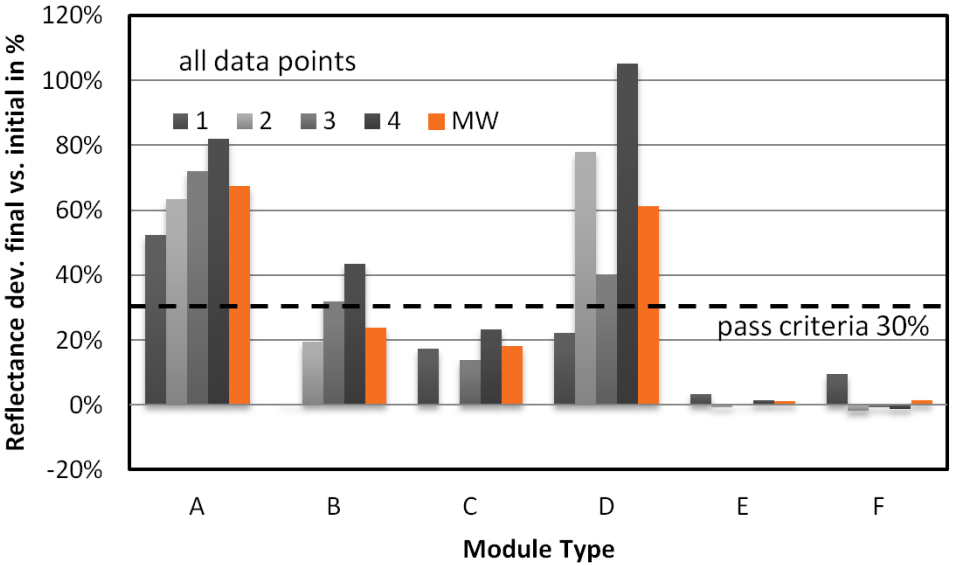
Results:

- No change in Power and Electroluminescence → means no mechanical impact on cells

→ Type A to D show change in the reflectance

→ Reflectance change is correlating with visible stripes on the front glass

→ Type E and F is completly stable



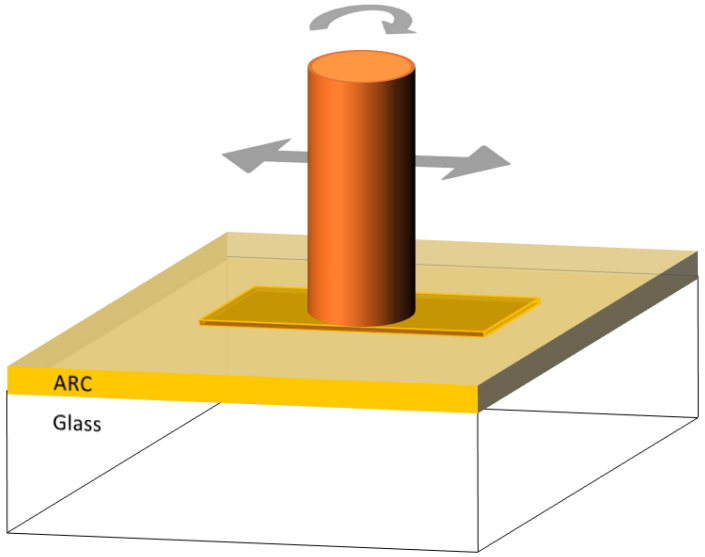
Conclusion:

→ No significant impact of the cleaning operation on the (STC-)performance but on some types a significant impact on the reflectance (influencing yield)

5) Abrasion
5.1) System and Methodology

Utilisation of an Abrasion Tester
acc. EN 1096-2

– Details can be found elsewhere [weber et al.]



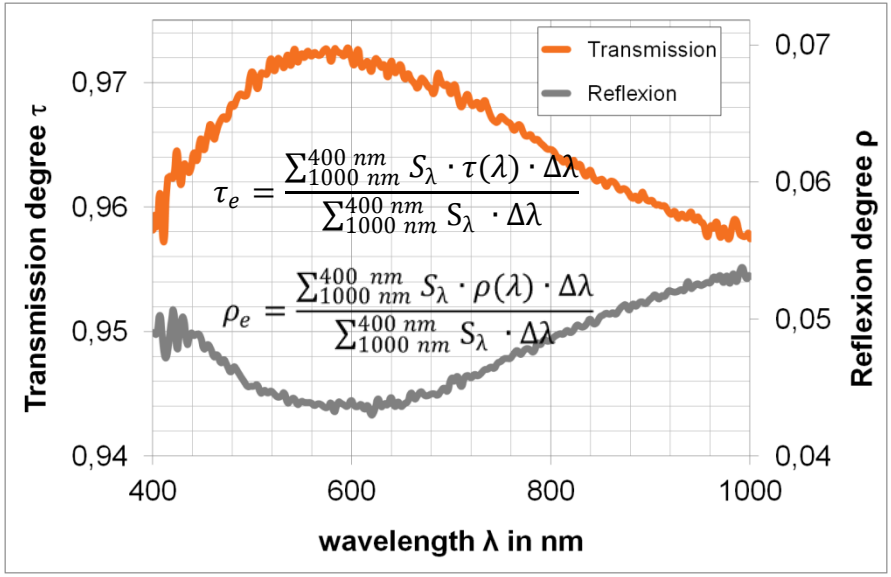
Spectral Transmission and Reflection Scans and Analysis

– acc. ISO 9050 incl. a distribution of AM1.5

Questions:

– Evaluation of test parameters

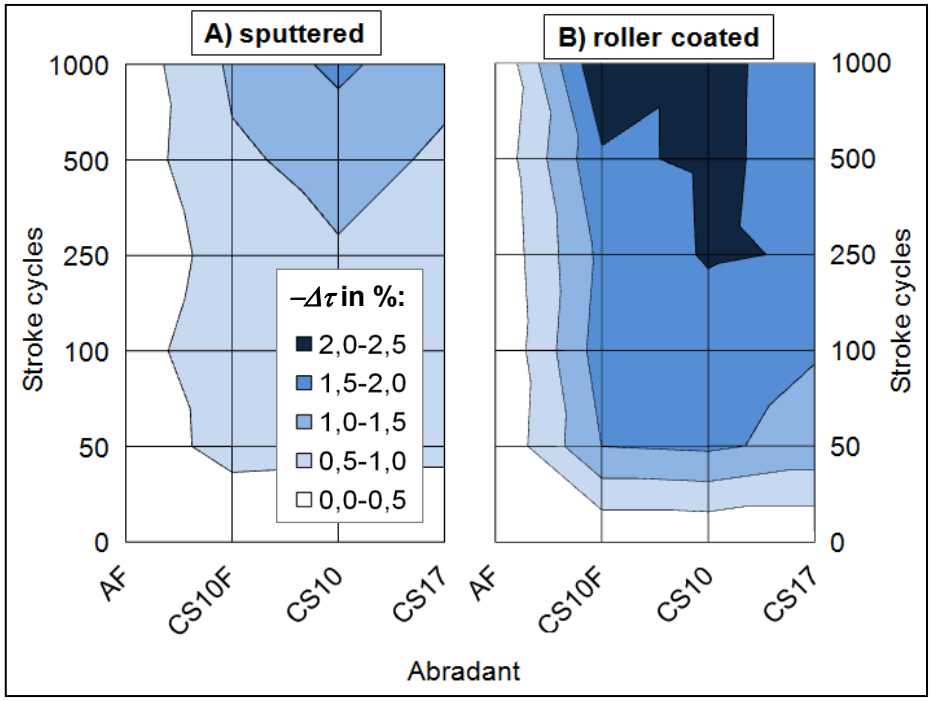
– Evaluation of different ARC's



5) Abrasion
5.2) Results comparing two ARC

Investigation on two different ARC‘s:

– change of transmission degree $\Delta\tau$ was determined



Results:

→ elastic soft (CS10) abradant show fastest results for investigated ARC‘s

→ **At Maximum abrasion for**

Sputtered: $\Delta\tau$ = -1.6 %

Roller-Coated: $\Delta\tau$ = -2.5 %

AF	CS10F	CS10	CS17
Abrasion felt	elastic extrem soft	elastic Soft	Elastic hard

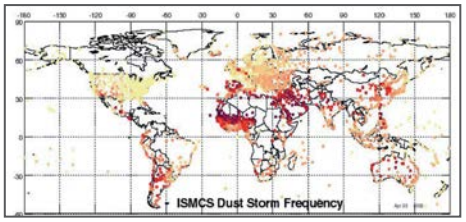
Conclusion:

→ The sputtered ARC (A) has a better abrasion resistance than the roller coated (B)

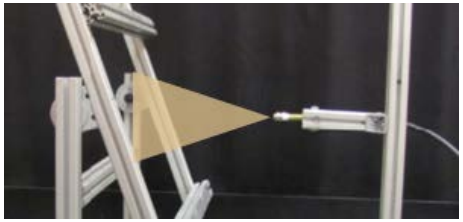
6. Summary and Conclusion

Future Fab: funded by
Bundesministerium für Bildung und Forschung
Bundesministerium für Wirtschaft und Energie

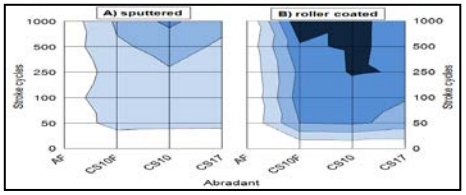
- **Soiling** strongly ***depends*** on the environmental condition of a ***specific location***
- Moreover **Soiling** ***depends*** on ***surface*** morphology and ***tilt*** angle



Soiling



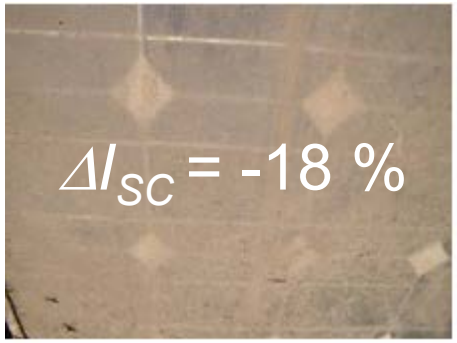
- The impact of a **cleaning device** can be determined by ***life-time simulation***
  - ***reflectance change*** indicate ***abrasion of coating***
  - coorelation to abrasion Tester will help to understand



- To ***investigate*** self-cleaning properties of surfaces a ***test method*** and ***test equipment*** was presented
- The **abrasion** on coatings by simulating soil or cleaning devices can be investigated with an ***abrasion test***

Abrasion

Cleaning



Thank You !

Recommended literature

[1] EPIA: Unlocking the Sunbelt – Potential of Photovoltaics, 2011-03

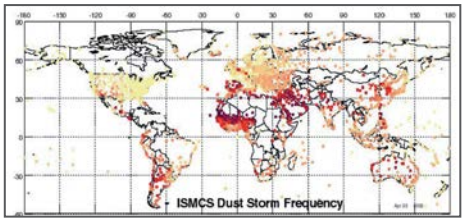
[2] Tegen et al.,“Relative Importance of climate and land use in determining present and duture global soil dust emission“, Geophysical Research Letters 31, 2004

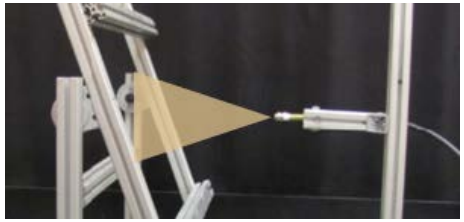
[3] M. Mani et al. “Impact of dust on solar photovoltaic (PV) performance: Research status,challenges and recommendations”, Renewable and Sustainable Energy Reviews 14 (2010) 3124–3131

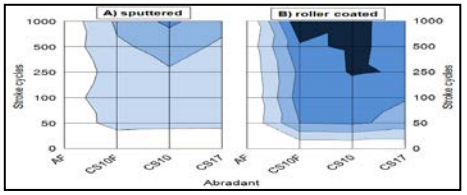
[4] T. Sarver et al. “A Comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches”, Renewable and Sustainable Energy Reviews 22 (2013) 698-733

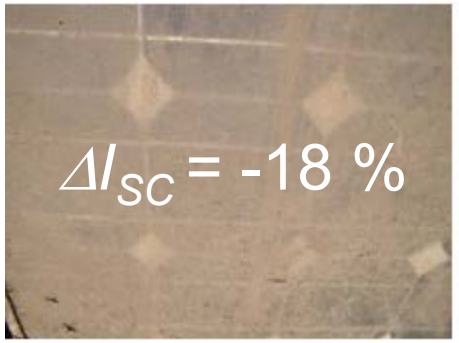
[5] Weber et al., “From the impact of harsh climates and environmental conditions on PV-Modules - Development of a Soiling and Abrasion Test”, EU PVSEC 2014 Amsterdam, 5DO.11.5

This presentation contains no confidential information









NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Review of observed degradation modes and mechanisms from fielded modules

Timothy J Silverman
John Wohlgemuth
David C. Miller
Michael Kempe
Peter McNutt

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.

Lifetime prediction requires field experience

Reliability tests need to address the correct modes and accelerate the correct mechanisms

We need to know what field failure looks like

Collecting field failures

Locations and climates

- Sacramento, California (warm temperate/summer dry/hot summer)
- Cocoa and Marin County, Florida (warm temperate/fully humid/hot summer)
- Springerville, Arizona (warm temperate/summer dry/warm summer)
- Tucson, Arizona (arid/steppe/hot arid)
- Toledo and Perrysburg, Ohio (snow/fully humid/hot summer)

Technologies

- mono-Si, poly-Si, HIT, EFG Si
- a-Si, CIGS, CdTe

Failure types

- Chemical breakdown
- Mechanical breakdown

Organizing observations

- Crystalline silicon modules
  - Chemical breakdown
    - Discoloration
    - Corrosion
  - Mechanical breakdown
    - Delamination
    - Interconnect failure
    - Cell cracking
- Thin-film modules
  - Chemical breakdown
    - Corrosion
  - Mechanical breakdown
    - Edge seal deformation
    - Interconnect failure

Crystalline silicon

Chemical breakdown

Discoloration

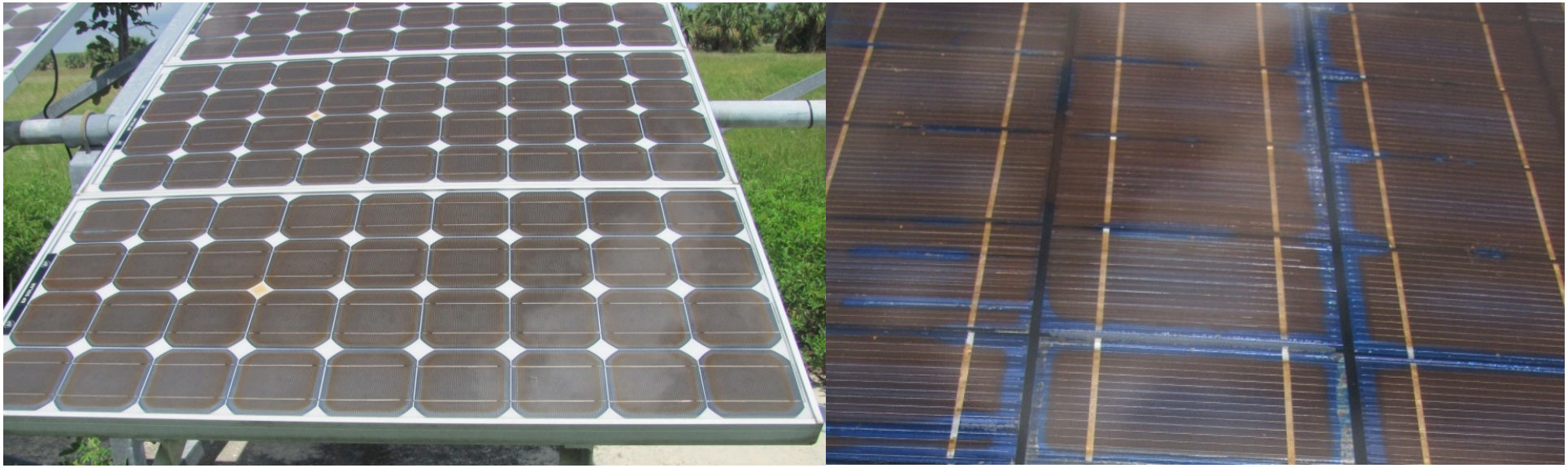
- Yellowing of encapsulant
- Driven by UV and heat

Corrosion

- Oxidation of metal components
- Driven by reaction with moisture and oxygen
- Often coincident with delamination

Crystalline silicon: Chemical breakdown

Discoloration

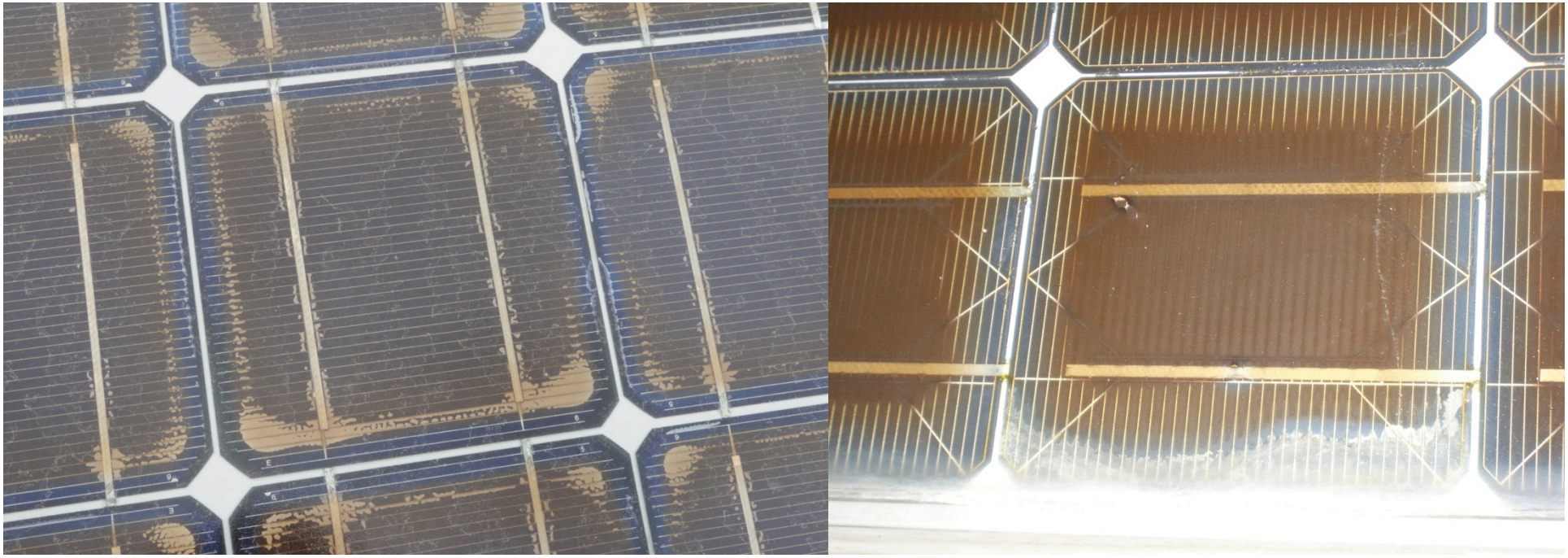


mono-Si (left) and EFG Si (right) after 23 years in Marin County, Florida (warm temperate/fully humid/hot summer)

Encapsulant can get very dark, reducing short-circuit current

Crystalline silicon: Chemical breakdown

Discoloration

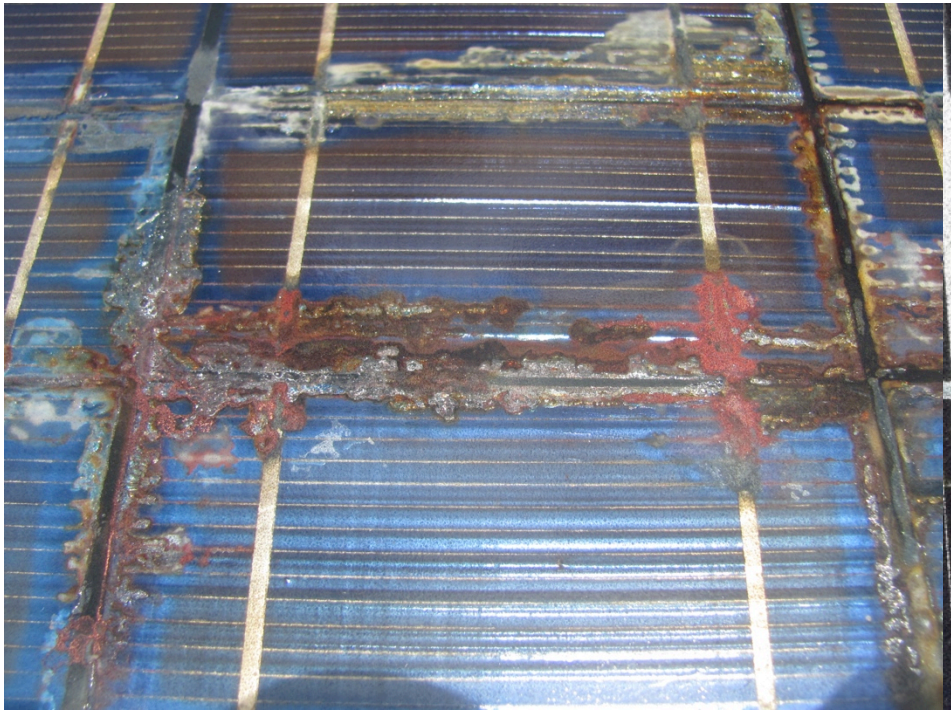


mono-Si after 18 years (left) and 27 years (right) in Sacramento (warm temperate/ summer dry/hot summer)

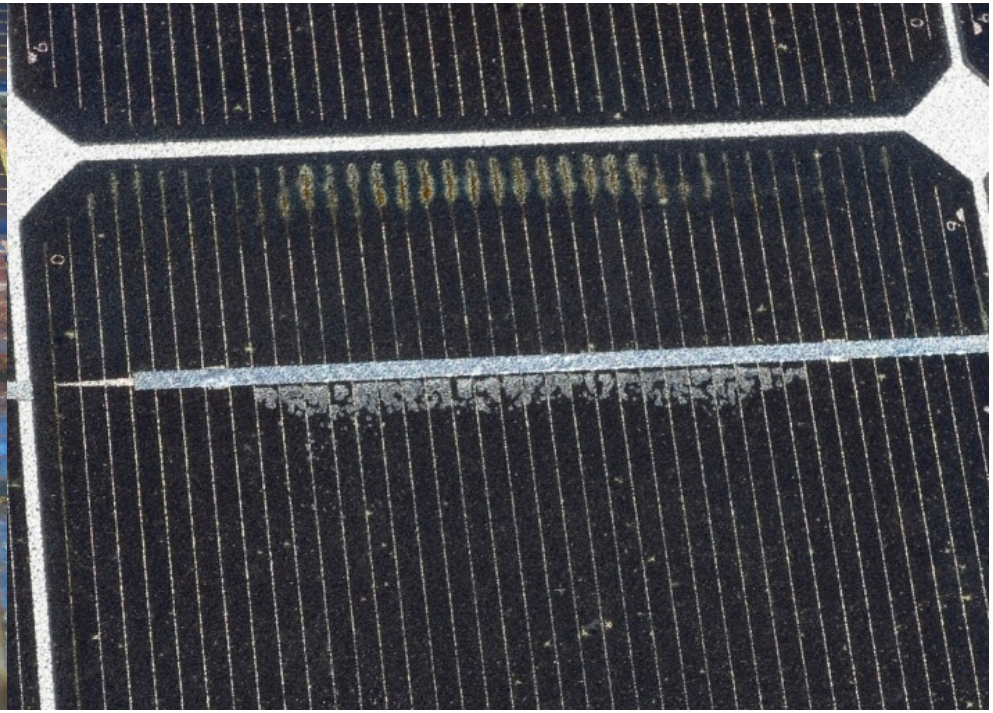
Delamination can accompany discoloration

Crystalline silicon: Chemical breakdown

Corrosion



EFG Si after 23 years in Marin County, Florida



mono-Si after 15 years in Cocoa, Florida

Delamination can let in moisture, causing corrosion, but some corrosion occurs without delamination

Mechanical breakdown

Delamination

- Caused by inadequate adhesion or loss of adhesion between layers
- Driven by moisture, mechanical stress and UV

Interconnect failure

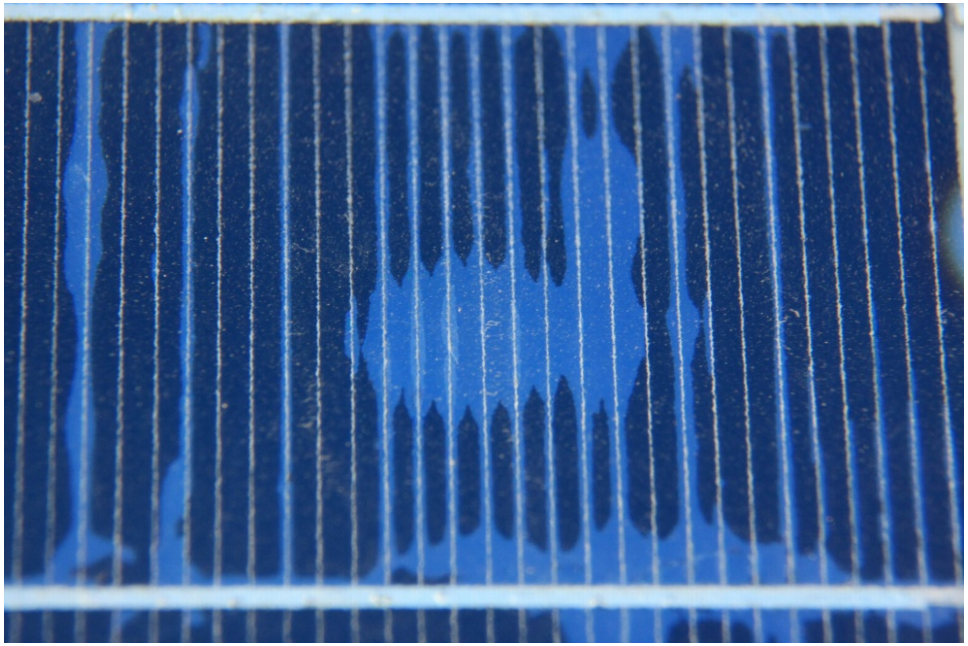
- Thermomechanical fatigue of ribbons or solder bonds
- Driven by thermal cycling

Cell cracking

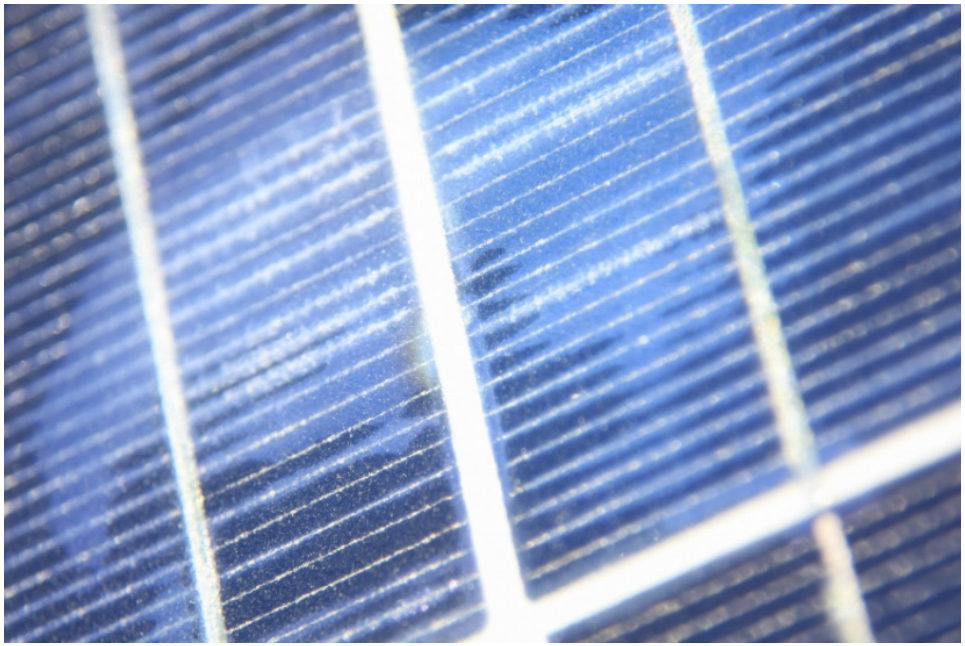
- Driven by one-time application of stress

Crystalline silicon: Mechanical breakdown

Delamination



EFG Si after 11 years in Springerville

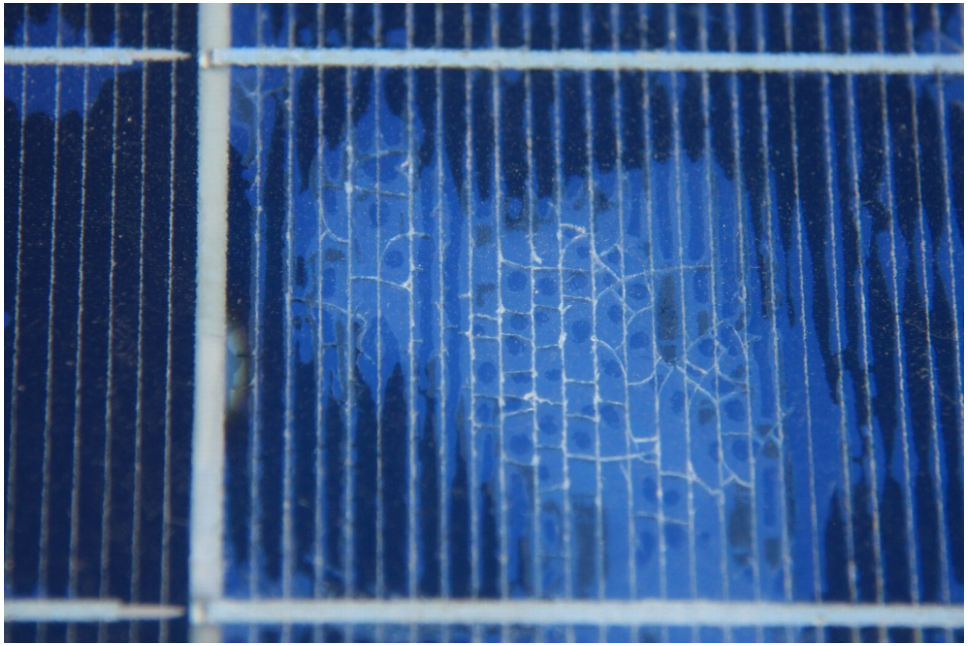


EFG Si after 13 years in Tucson

An ionomer encapsulant showed delamination along fingers at two sites

Crystalline silicon: Mechanical breakdown

Delamination



EFG Si after 11 years in Springerville

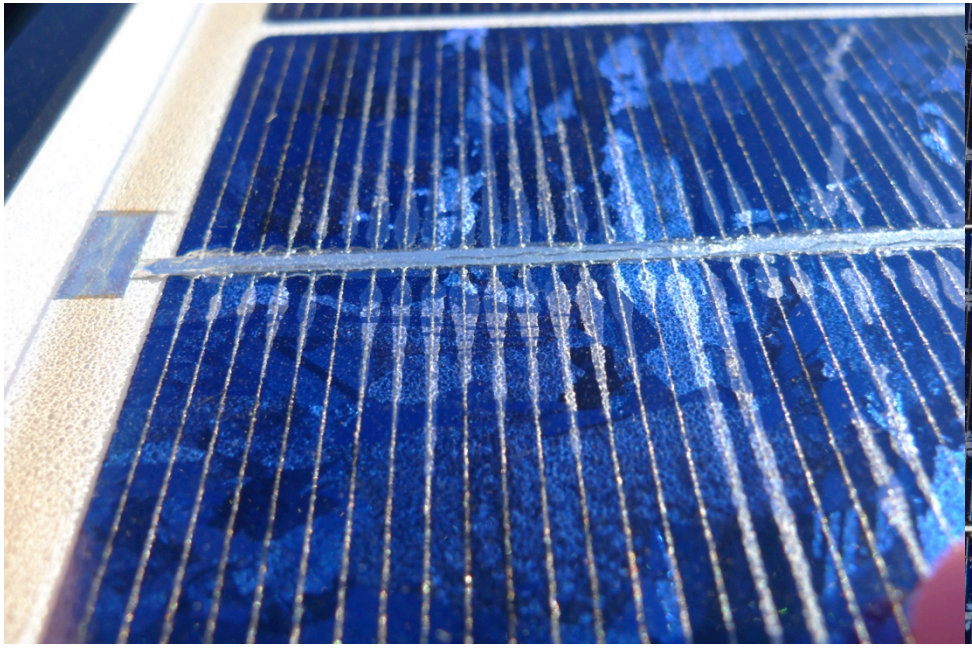
EFG Si after 13 years in Tucson

At the junction box, it showed cohesive failure, too

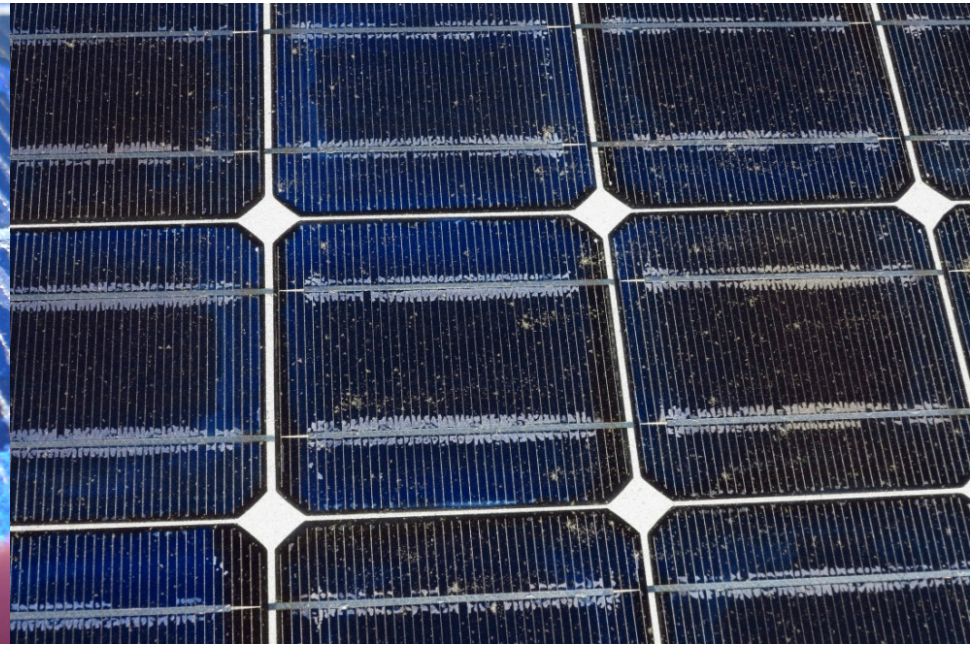
This was fixed with a reformulation of the ionomer

Crystalline silicon: Mechanical breakdown

Delamination



multi-Si after 10 years in Perrysburg, Ohio

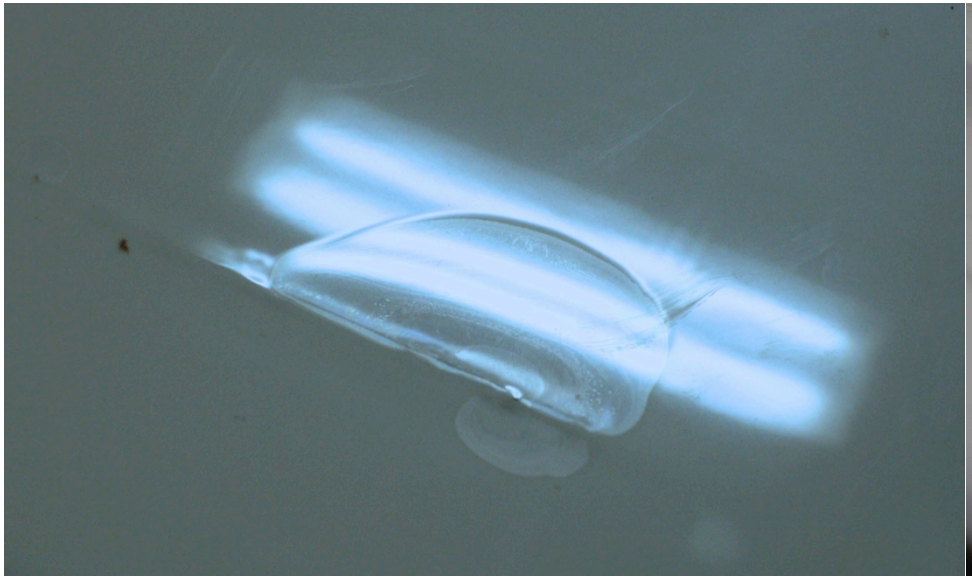


mono-Si after 15 years in Cocoa, Florida

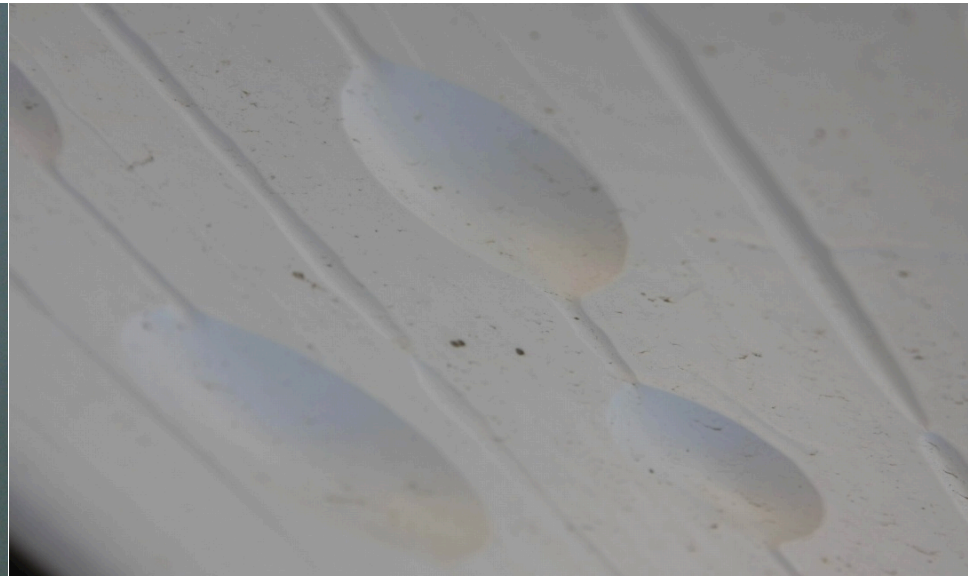
Delamination at the encapsulant-cell interface often follows ribbons and grid fingers

Crystalline silicon: Mechanical breakdown

Delamination



multi-Si after 10 years in Perrysburg

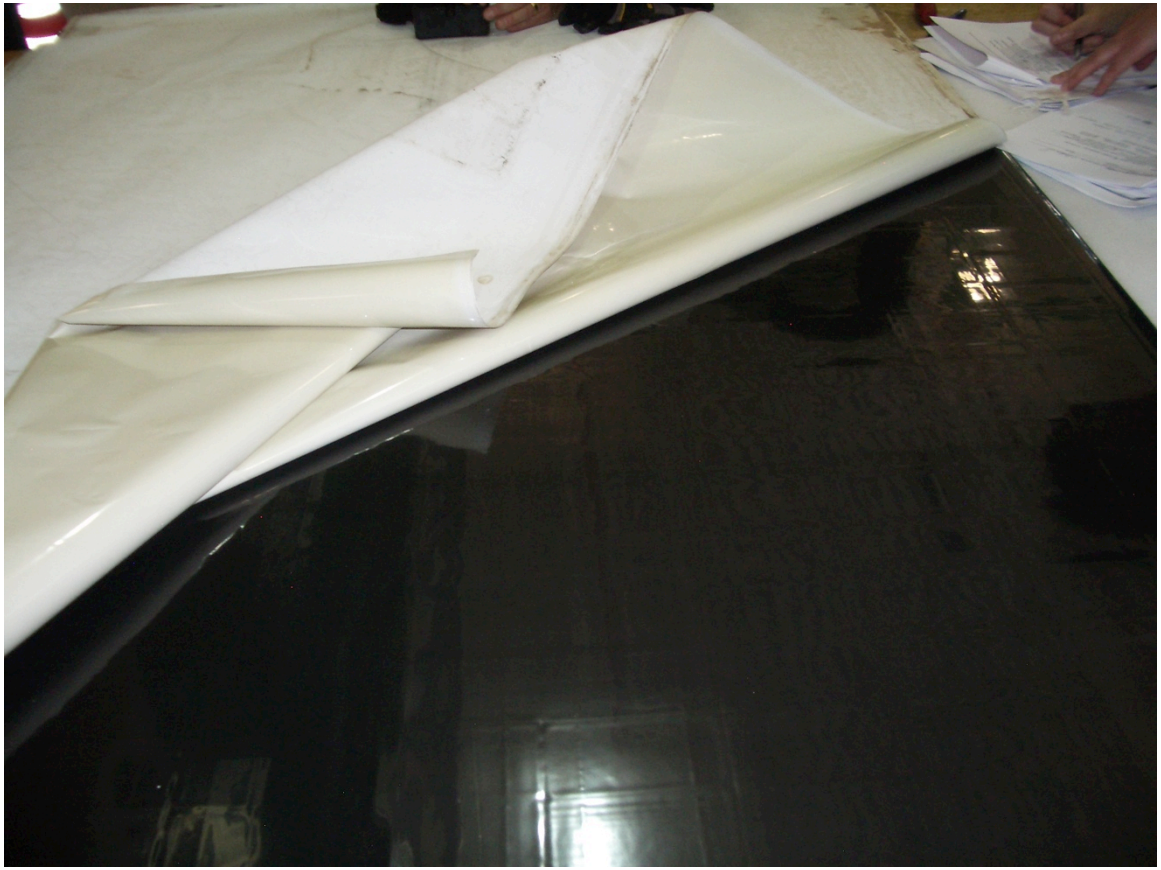


HIT after 10 years in Tucson
Al-containing backsheet traps outgassing

Backsheet layers can separate from each other or from the encapsulant

Crystalline silicon: Mechanical breakdown

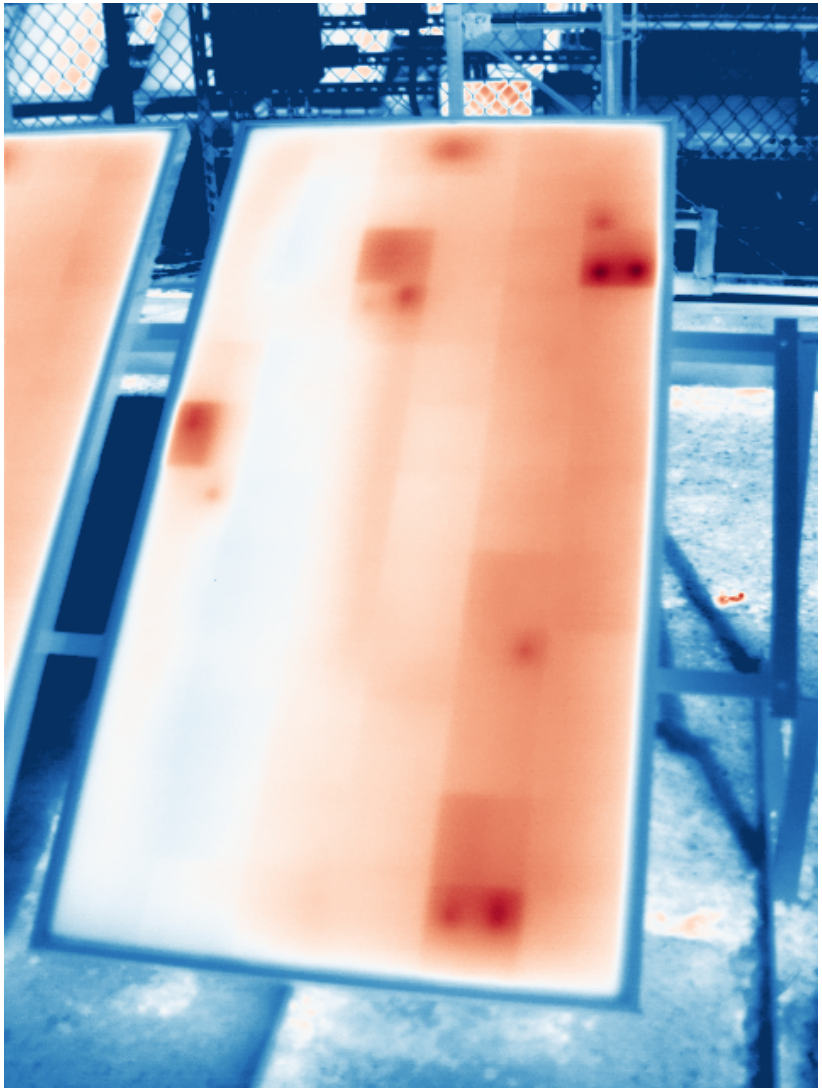
Delamination



EFG Si after 27 years in Sacramento

Or they can flee the module entirely

Interconnect degradation



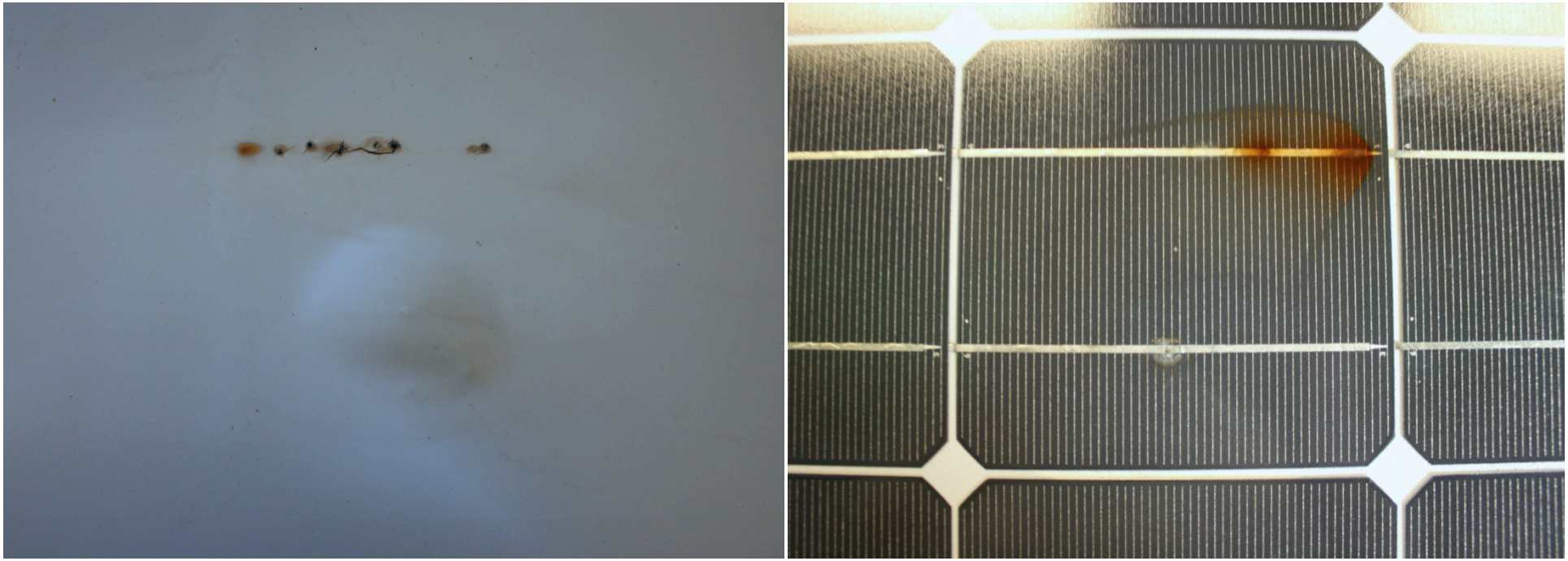
Broken solder bonds lead to high series resistance and loss of FF

They also result in highly localized dissipation of heat

mono-Si after
8 years in Tucson

Crystalline silicon: Mechanical breakdown

Interconnect degradation

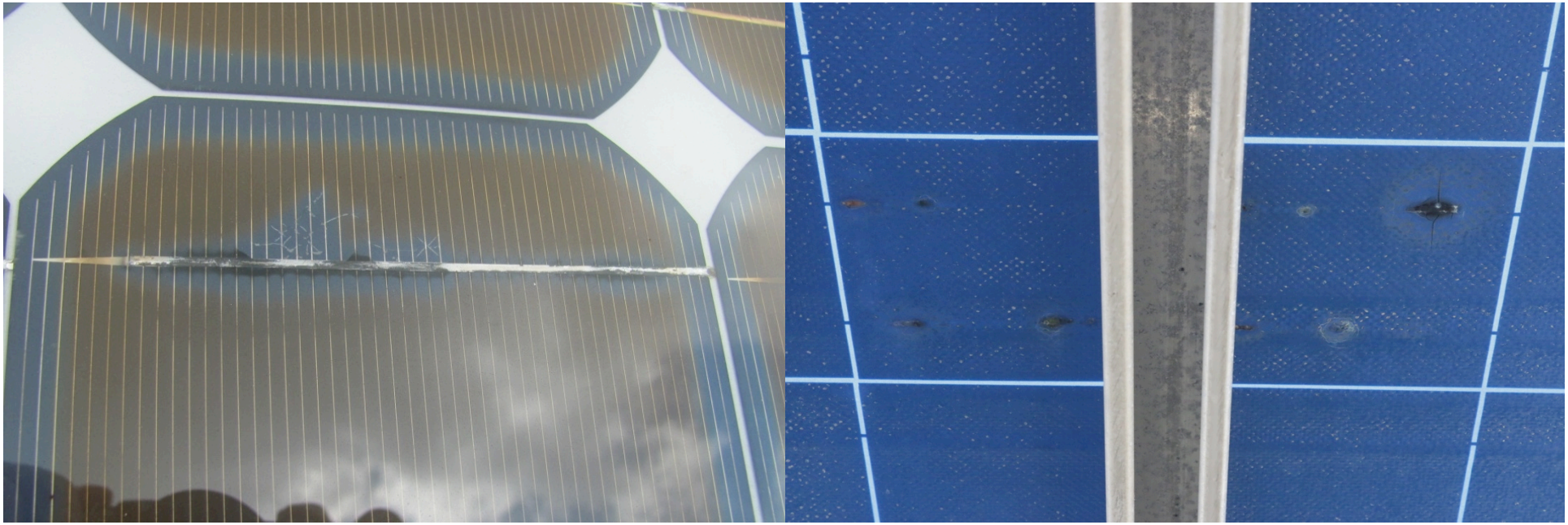


mono-Si after 10 years in Perrysburg, Ohio

Highly localized heating from broken solder bonds damages adjacent materials

Crystalline silicon: Mechanical breakdown

Interconnect degradation



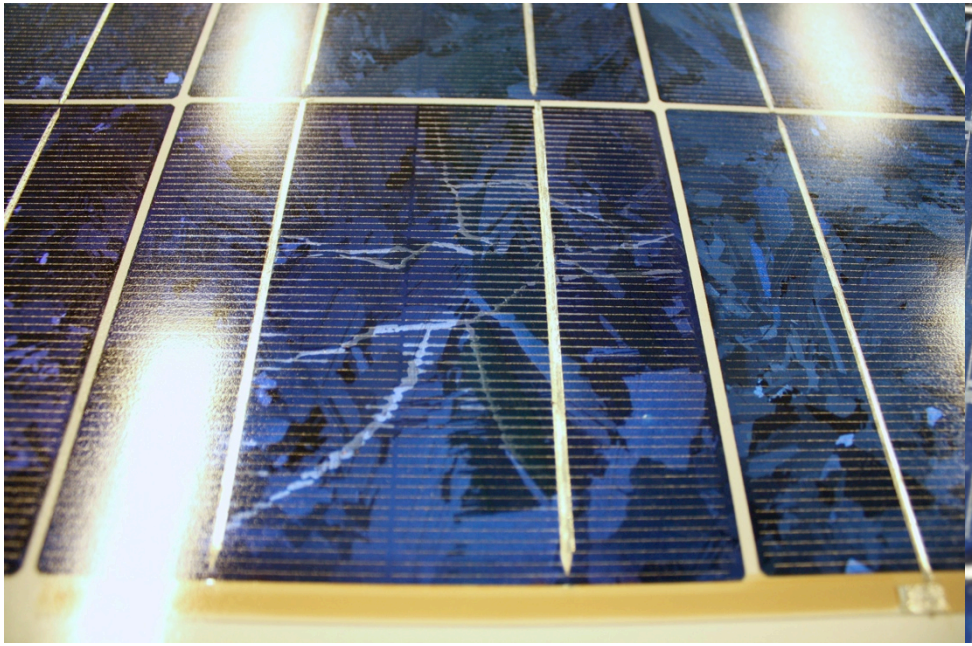
23 years in Marin County, Florida

16 years in Sacramento

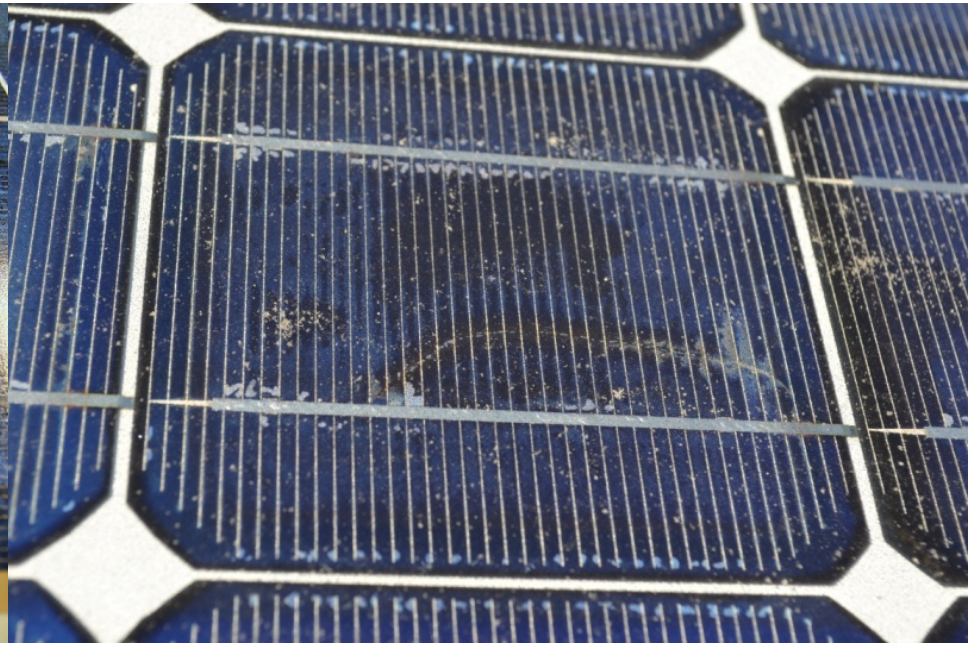
Highly localized heating from broken solder bonds damages adjacent materials

Crystalline silicon: Mechanical breakdown

Broken cells



multi-Si after 10 years in Perrysburg

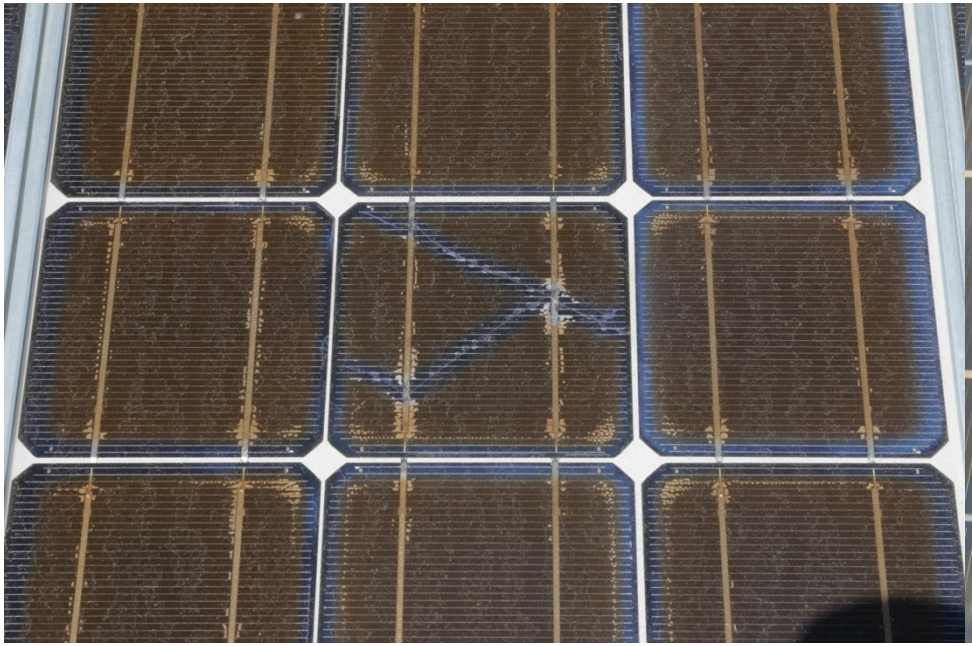


mono-Si after 15 years in Cocoa

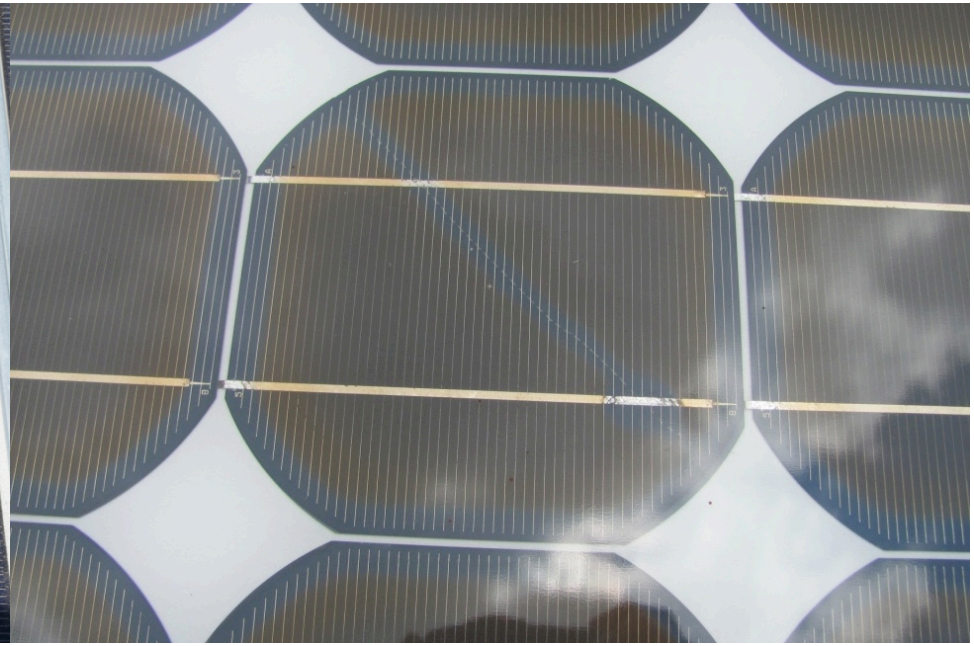
Broken cells can become visible when they permit delamination along cracks

Crystalline silicon: Mechanical breakdown

Broken cells



mono-Si after 18 years in Sacramento



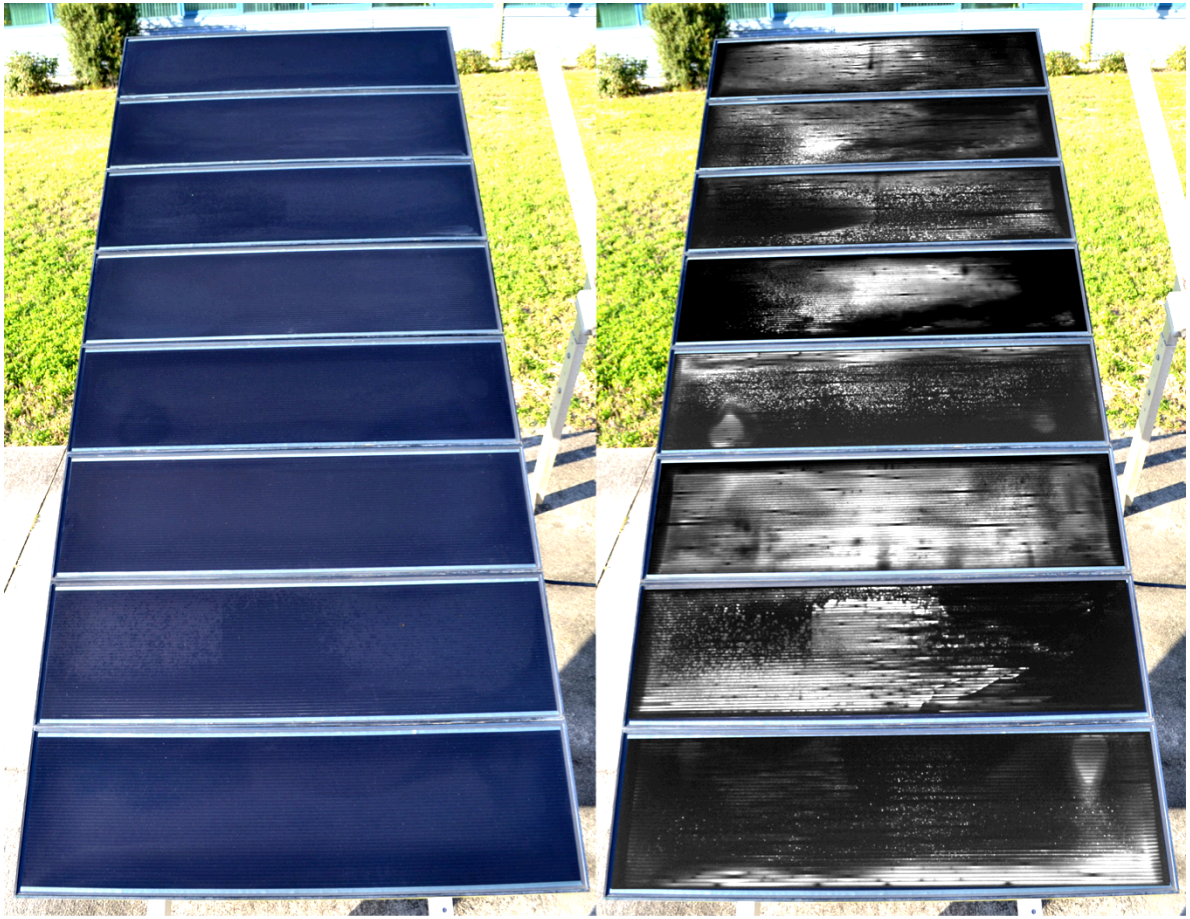
mono-Si after 23 years in Marin County, Florida

In modules with highly discolored encapsulant, the cracks permit photooxidative bleaching to occur

Chemical breakdown

- Corrosion
  - Decomposition of contact or absorber layers
  - Driven by moisture, heat and/or electric field

Corrosion



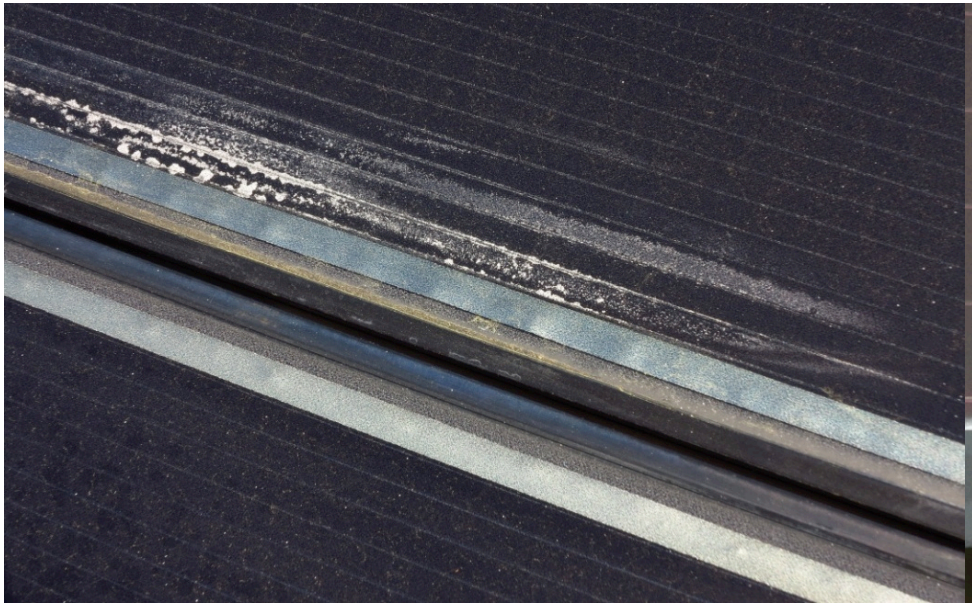
CIGS after 12 years in Cocoa (image courtesy FSEC)

TCO corrosion causes visible lightening and loss of emission in EL

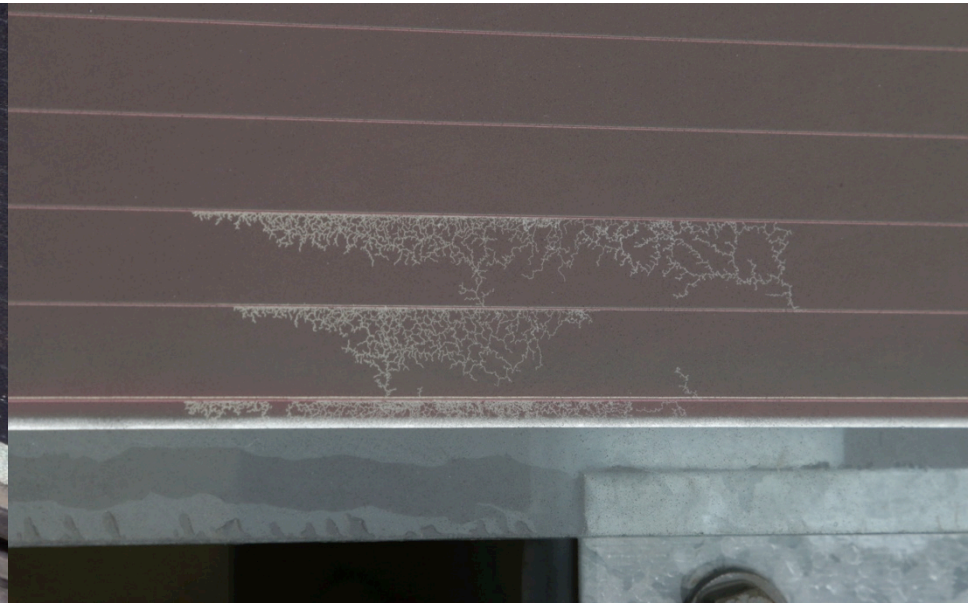
The increased series resistance is linked to loss of FF

Thin-film PV: Chemical breakdown

Corrosion



CIGS after 12 years in Cocoa



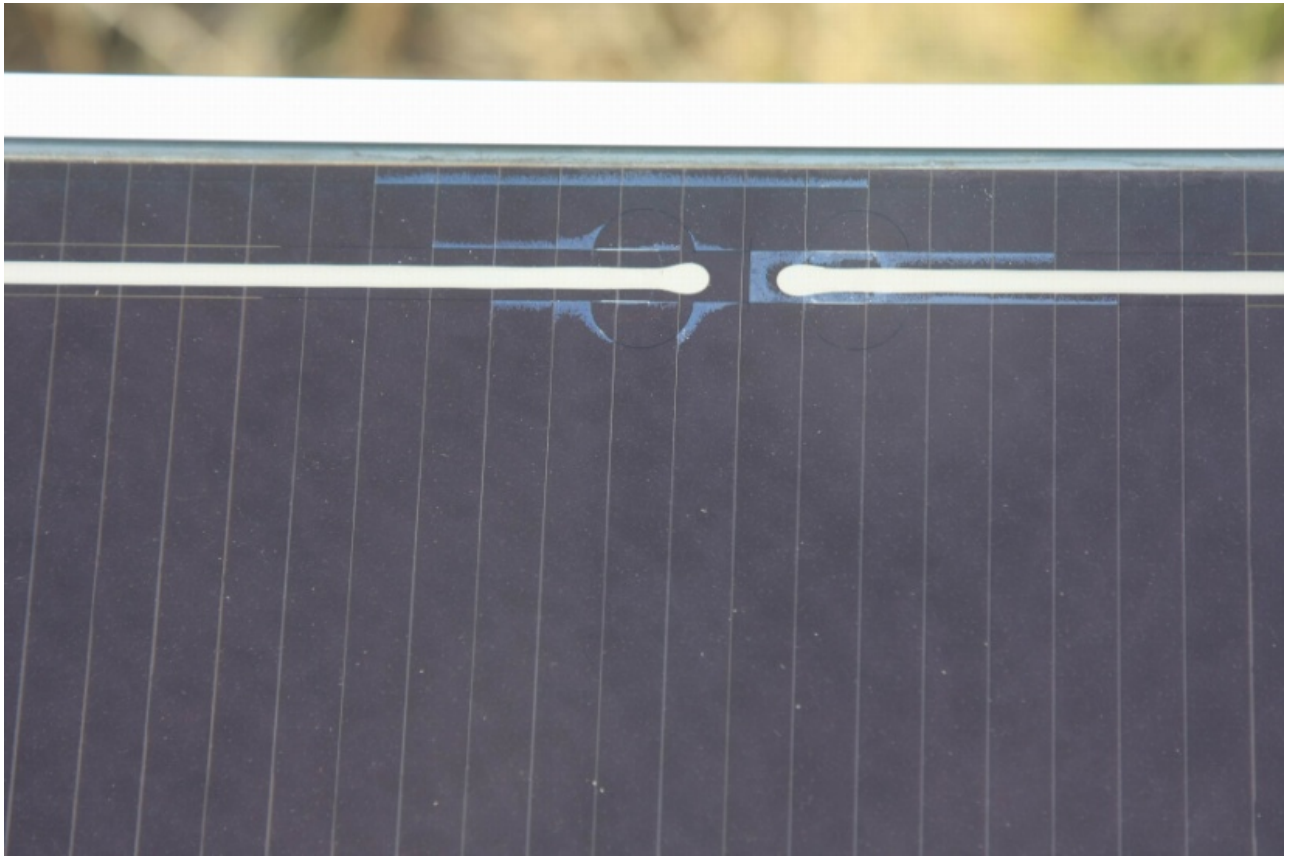
a-Si after 19 years in Sacramento

TCO/absorber corrosion can also interact with scribe lines

The dendritic form on the right is linked to voltage stress

Thin-film PV: Chemical breakdown

Corrosion



a-Si after 11–12 years in Springerville, Arizona

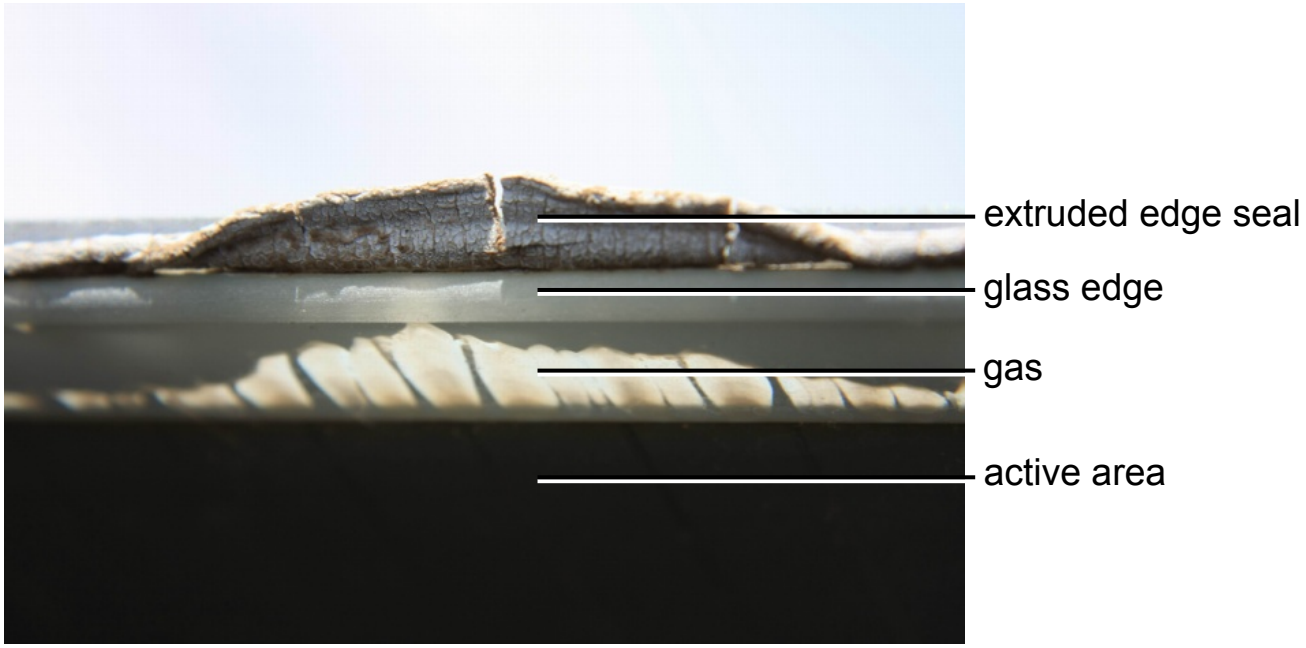
This TCO corrosion near the junction box appears to depend on polarity, suggesting an electric field mechanism

Mechanical breakdown

- Edge seal deformation
  - Caused by outgassing of packaging materials
- Interconnect failure
  - Actually a delamination caused by loss of adhesion
  - Driven by heat or thermal cycling

Thin-film PV: Mechanical breakdown

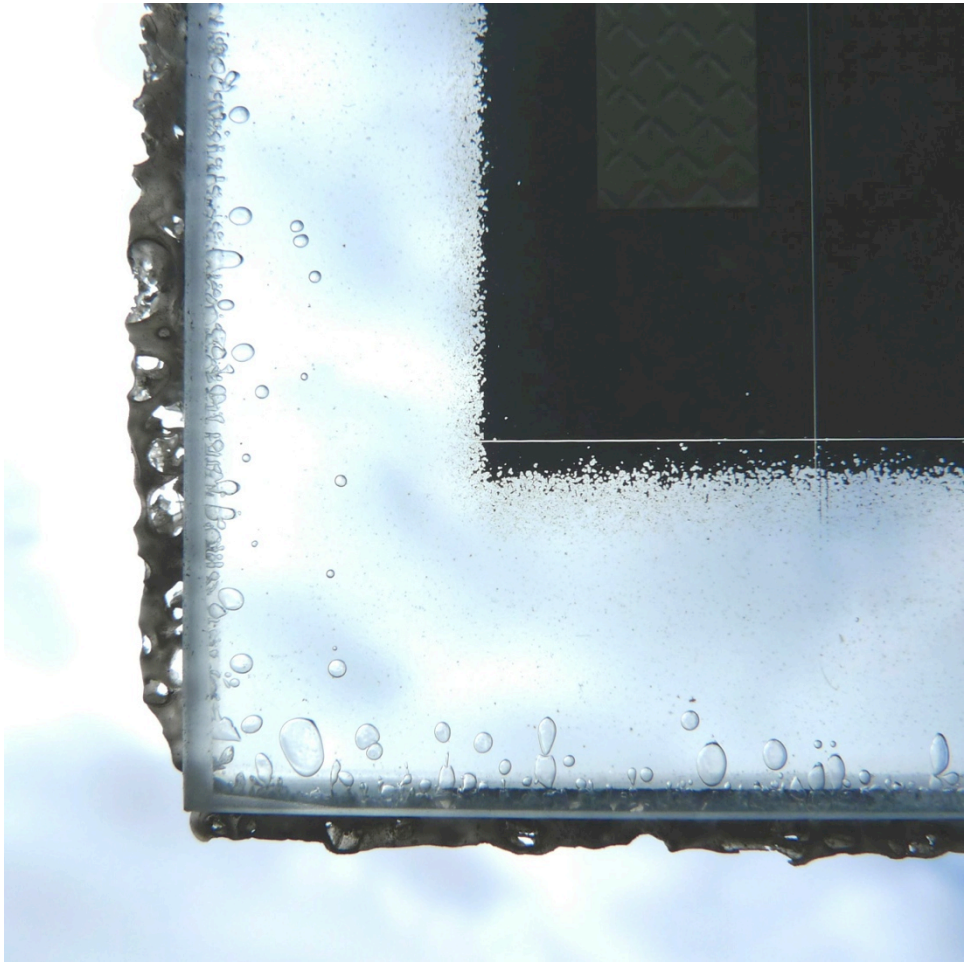
Seal deformation



CdTe after 9–11 years in Springerville, Arizona

Internal pressure can push edge seals outward

Not seal deformation



CdTe after 8 years in Toledo, Ohio

A band of seal or encapsulant material can be pushed out during production

This extrusion is not a field failure

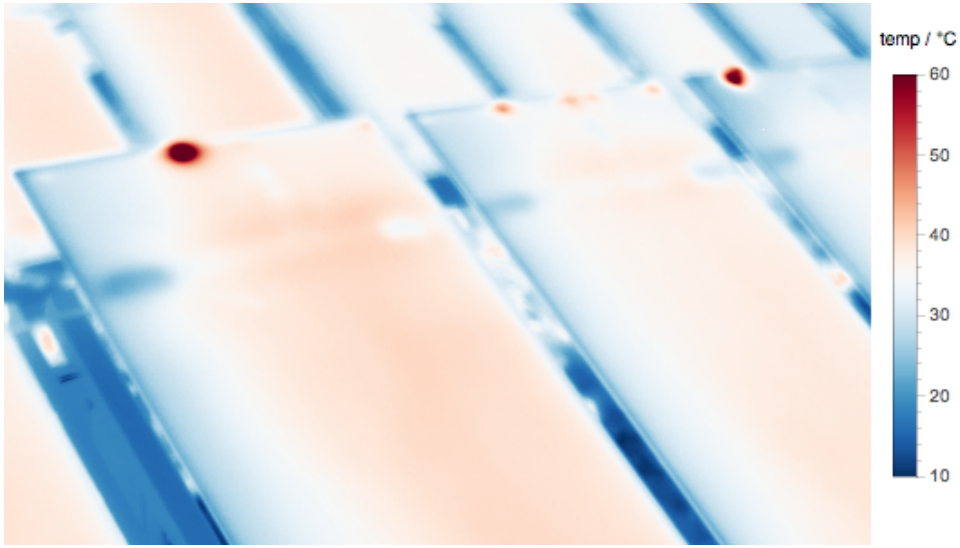
Interconnect degradation

8–11 years in Springerville, Arizona

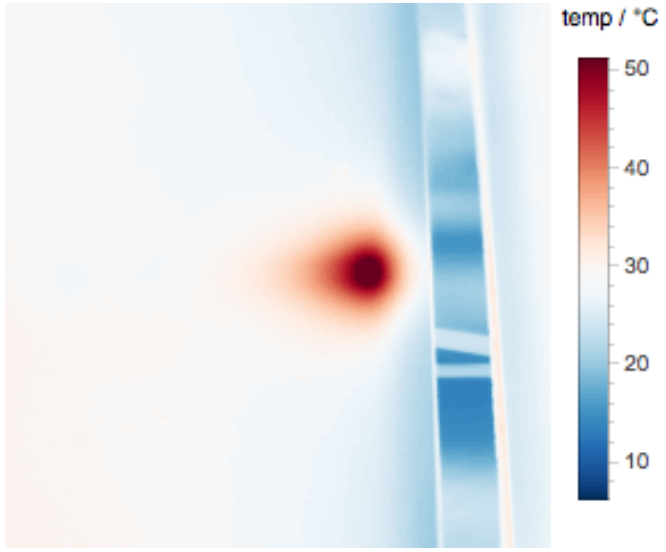
8 years in Toledo, Ohio

Delamination of the bus tape caused a partial failure of the interconnect

Interconnect degradation

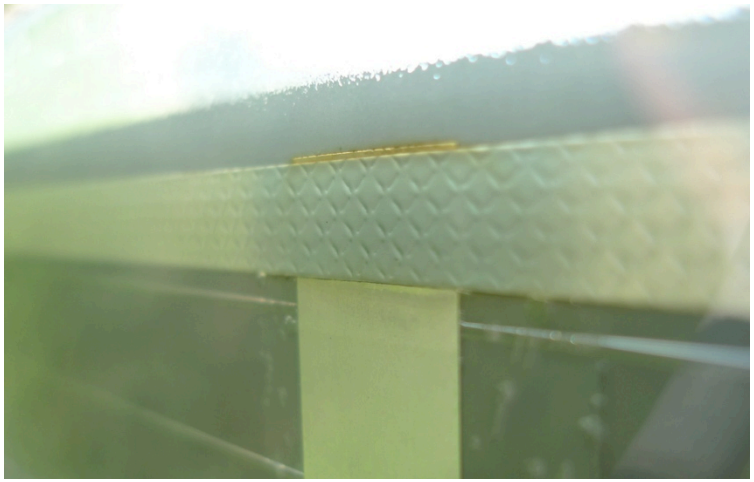


8–11 years in Springerville, Arizona



8 years in Toledo, Ohio

The delamination causes an increase in series resistance, leading to lost power and increased heat dissipation



Conclusion

Lifetime prediction requires field experience

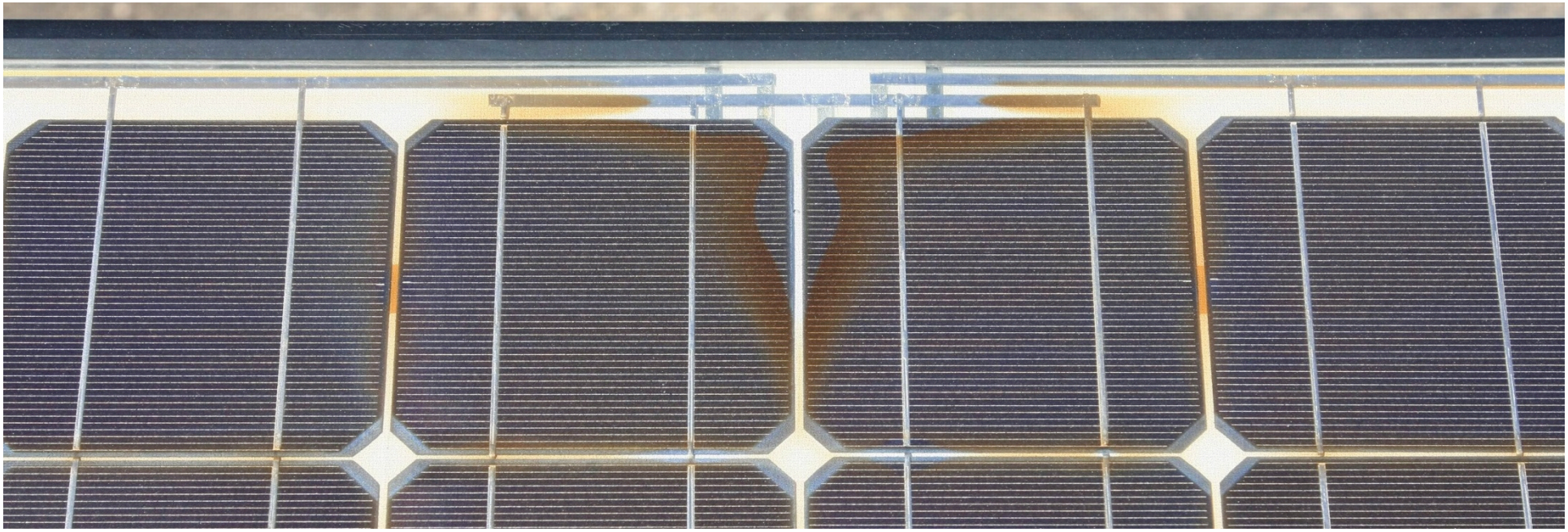
We displayed some of the chemical and mechanical breakdown modes we observed

- Discoloration
- Delamination
- Corrosion
- Interconnect degradation

Accelerated tests must address these failure modes

Crystalline silicon: Chemical breakdown

Discoloration



HIT after 10 years in Tucson (arid/steppe/hot arid)

Encapsulant and “beauty strips” turned brown near the junction box due to elevated temperature

Climate zones

Springerville
Arizona
Csb
warm temperate/summer dry/warm summer

Toledo
Ohio
Dfa
snow/fully humid/hot summer

Tucson
Arizona
BSh
arid/steppe/hot arid

Sacramento
California
Csa
warm temperate/summer dry/hot summer

Ocala (Marin County)
Florida
Cfa
warm temperate/fully humid/hot summer

Cocoa
Florida
Cfa
warm temperate/fully humid/hot summer

Denver
Colorado
BSk
arid/steppe/cold arid

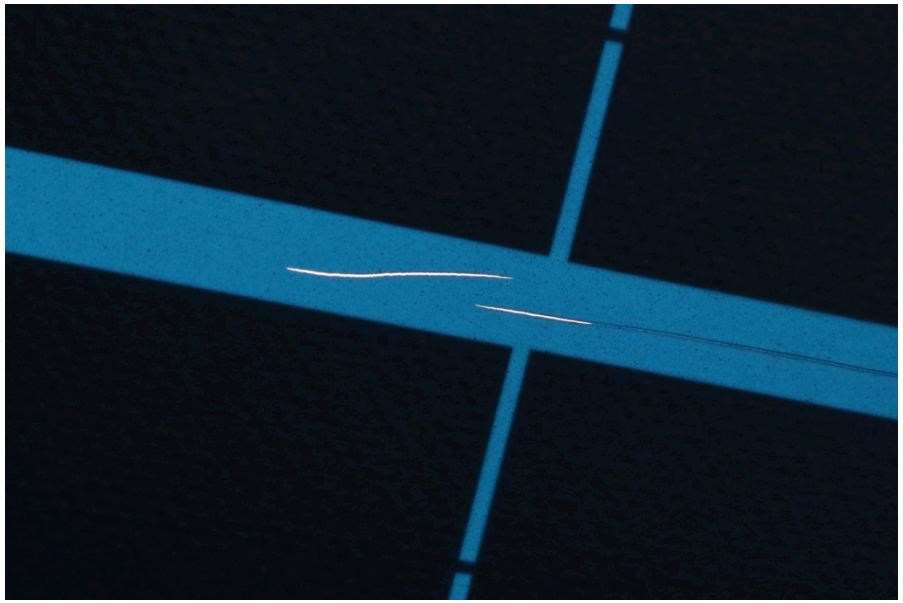
Crystalline silicon: Mechanical breakdown

Broken glass

16 years in Sacramento
<1% affected

11 years in Springerville, 2%, mostly just back glass broken

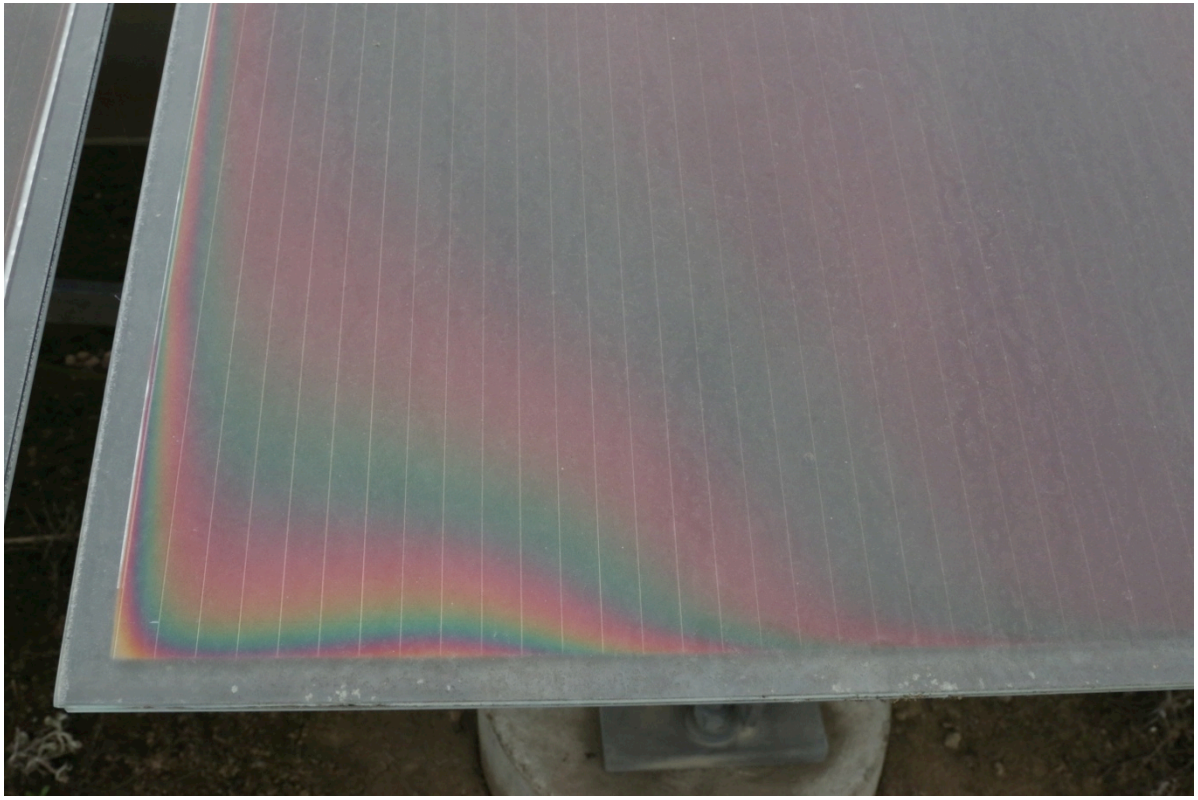
Broken backsheet



16 years in Sacramento

Thin-film PV: Chemical breakdown

Corrosion



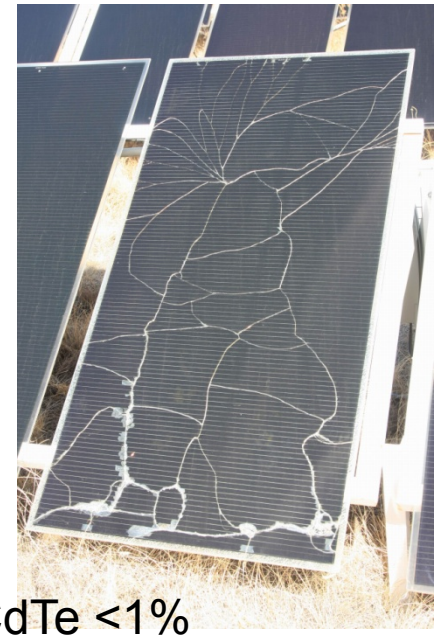
a-Si after 19 years in Sacramento

Local TCO corrosion can appear as interference fringes

Broken glass

Main idea

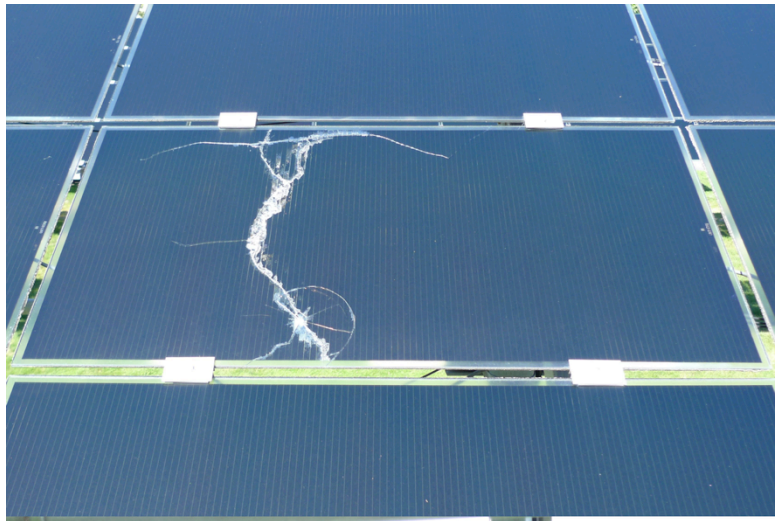
8–11 years in Springerville, Arizona
(warm temperate/summer dry, warm)



CdTe <1%

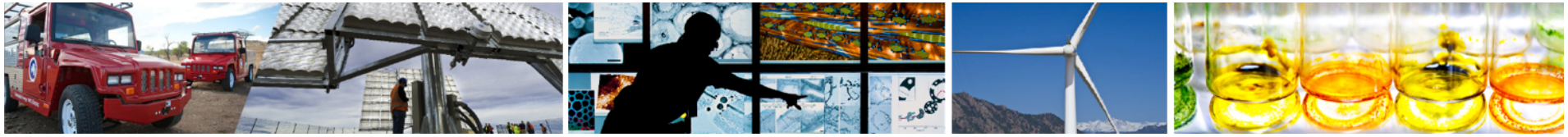
a-Si 5.5%

CdTe, 8 years in Toledo, Ohio
(snow/fully humid/hot summer)



1.4%

A Fracture Mechanics Based Approach for Adhesion Testing in the PV Module Laminate



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National Renewable Energy Laboratory

Reinhold H. Dauskardt
Stanford University

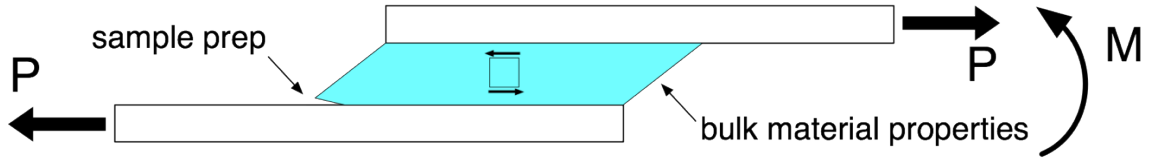
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

overview

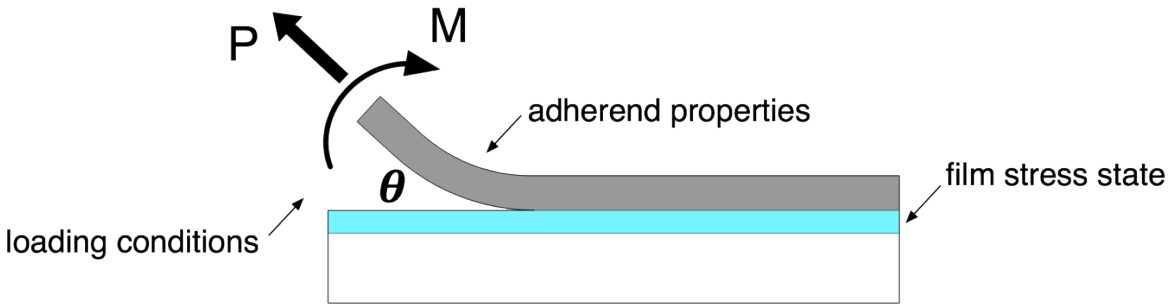
- Short review of common PV adhesion tests
- Introduction of the fracture mechanics based approach to adhesion testing
- Applications of this approach to PV laminate materials at both the coupon and module level
- Extension of these measurements for lifetime prediction of adhesive systems
- Review and Direction

limitations of common adhesion tests

lap shear



peel test



fracture mechanics

fracture toughness

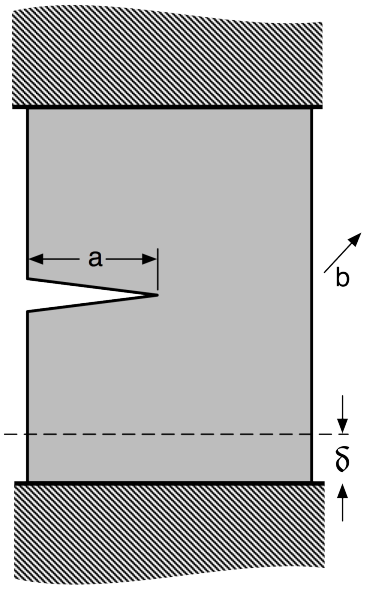
$$G_c = \frac{dW_s}{dA}$$

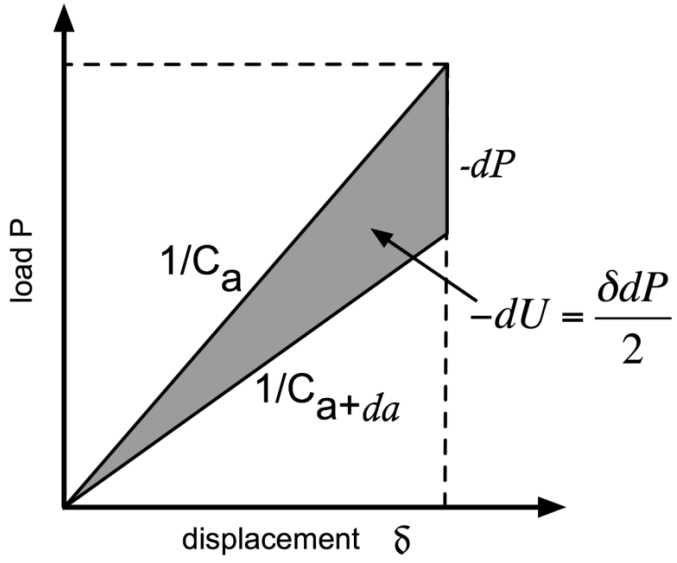
compliance

$$C = \frac{\delta}{P}$$

energy release rate
toughness
adhesion
debond energy

$$G = \frac{P^2}{2b}\frac{dC}{da}$$

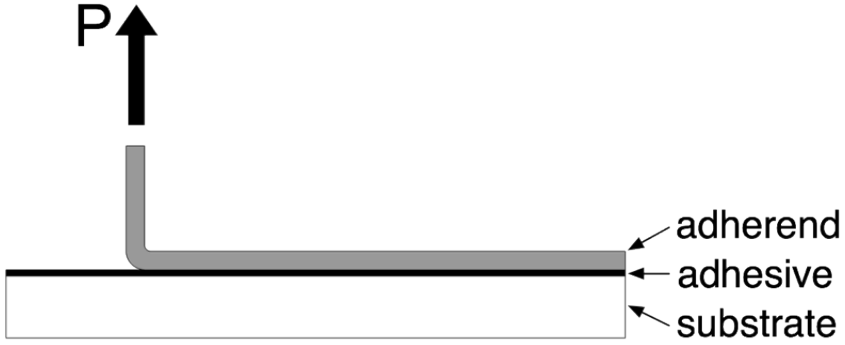




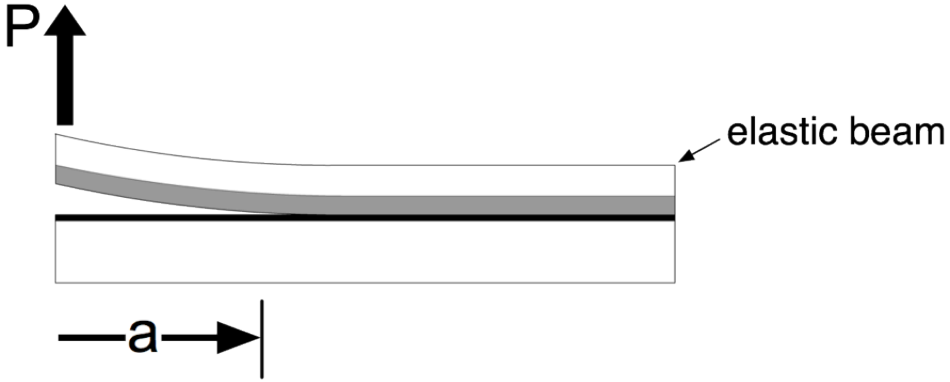
figures inspired by: T.L. Anderson, "Fracture Mechanics" CRC Press, Boca Raton, FL 1995

sample modification

peel test

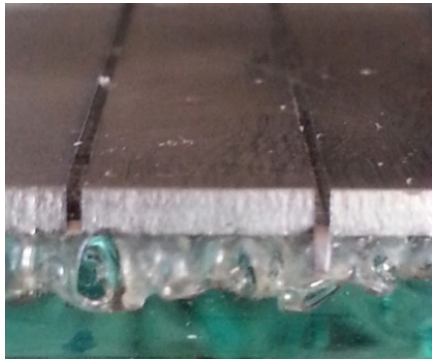


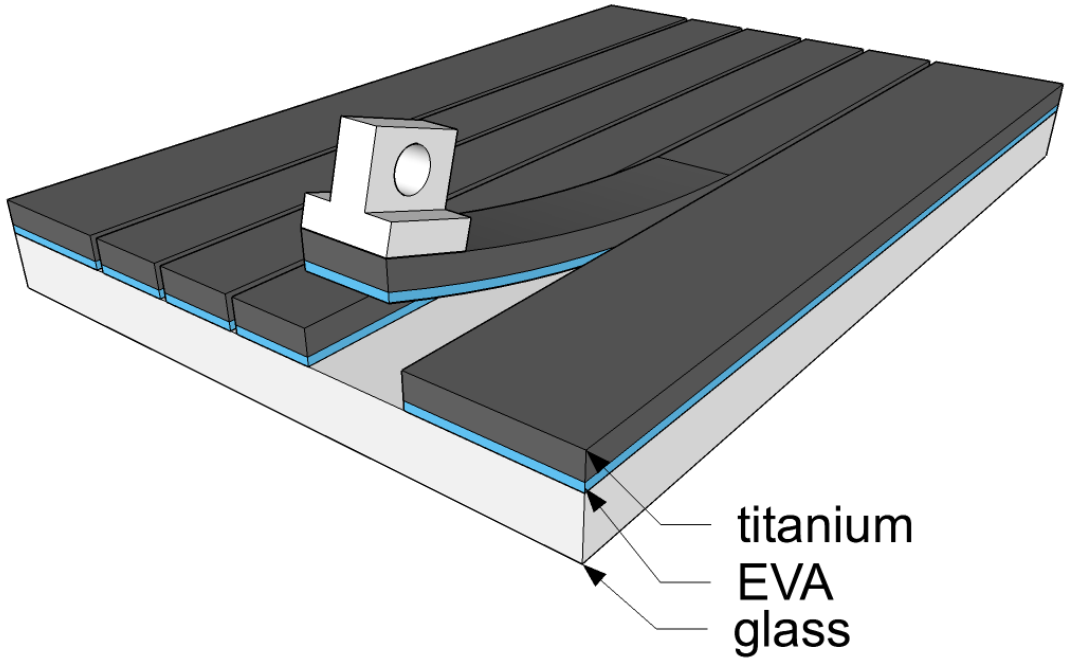
cantilever beam



single cantilever beam

glass/EVA





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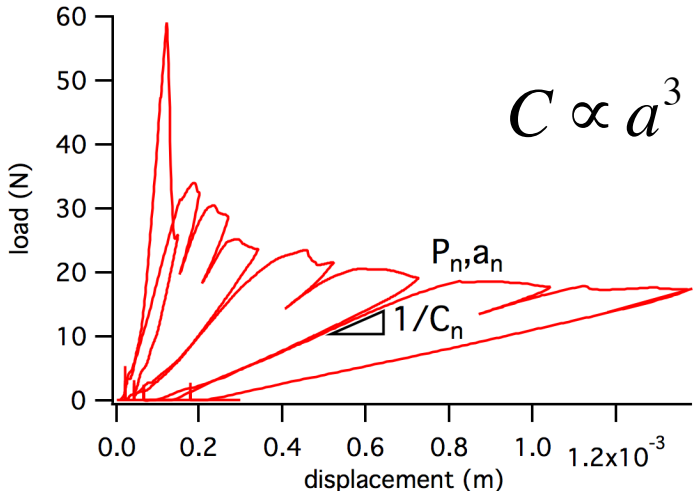
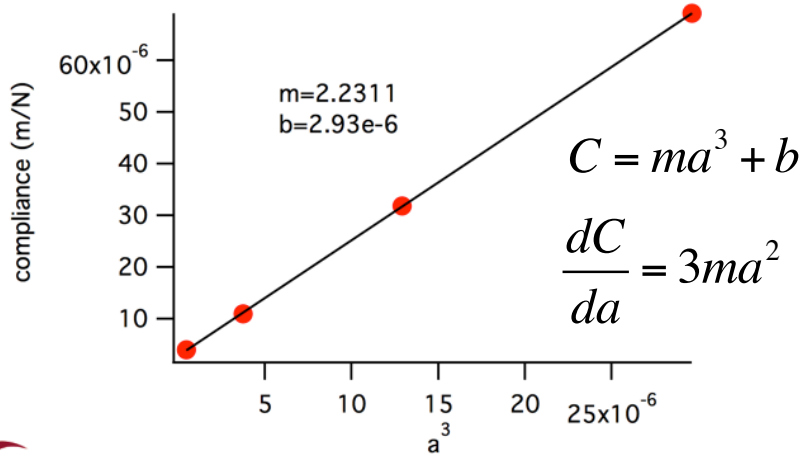
single cantilever beam

0% silane





- Load reversals to measure compliance with crack extension
- produce linear fit of compliance with crack extension
- Evaluate toughness at each crack length

$$G = \frac{P^2}{2b}\frac{dC}{da} = \boxed{\frac{P_n^2}{2b}3ma_n^2}$$

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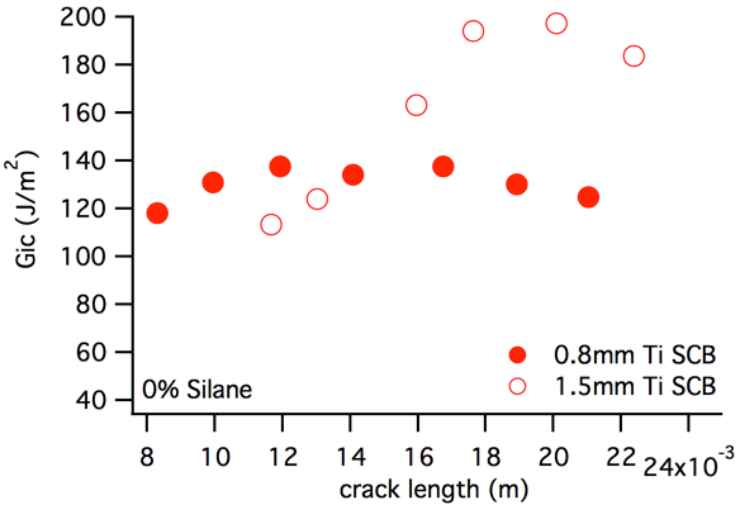
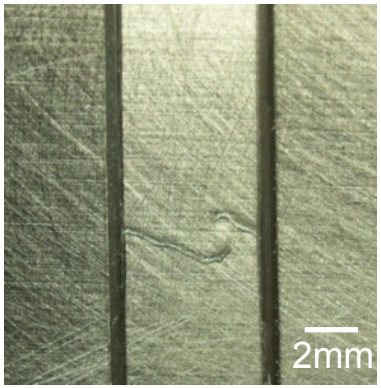
single cantilever beam, coupon level

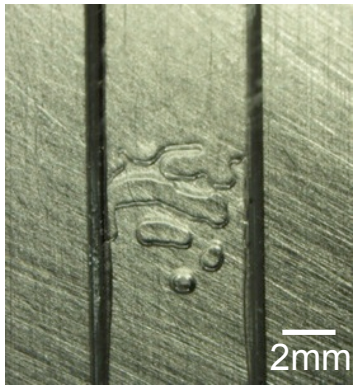
0% silane



Calculate fracture toughness for each crack extension



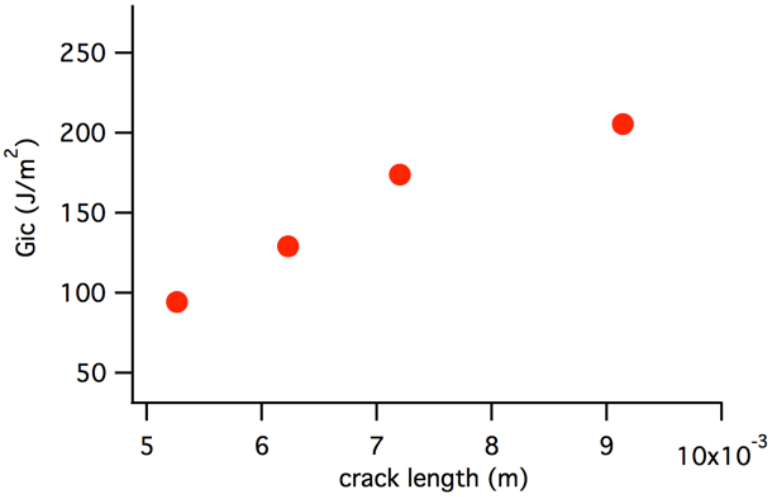
0.8 mm Ti beam

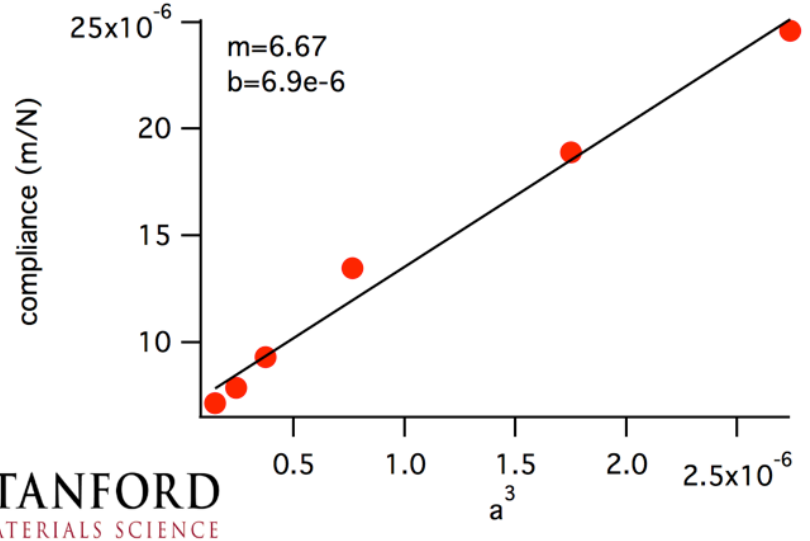


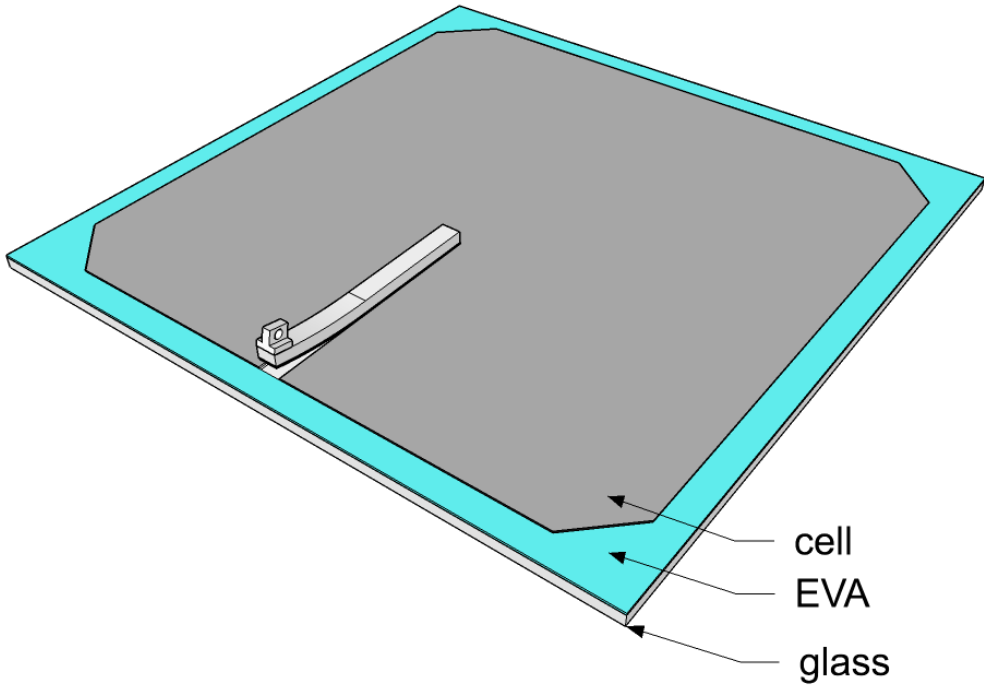
1.5 mm Ti beam

single cantilever beam, module level

0% silane







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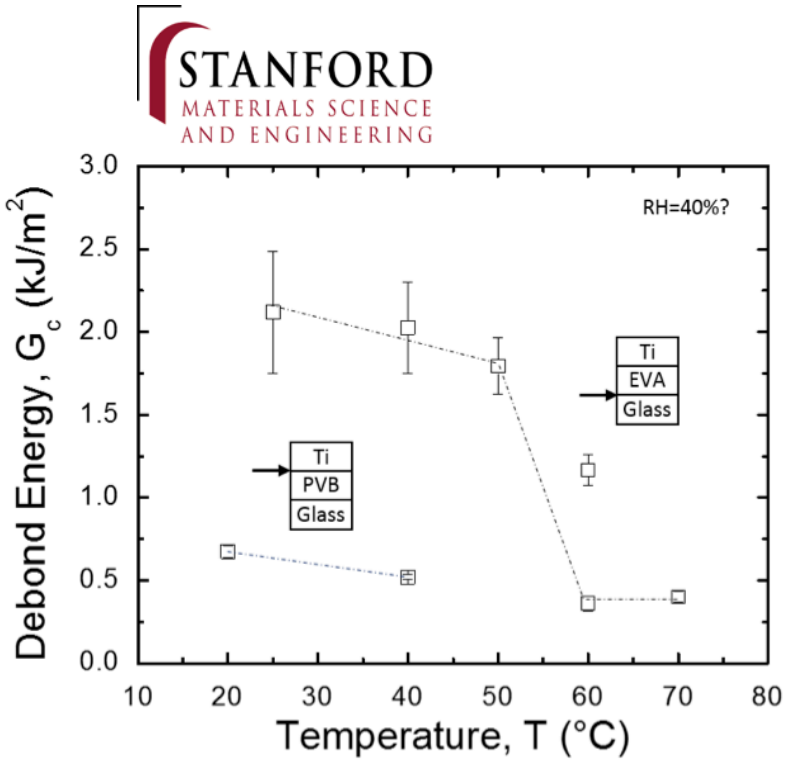
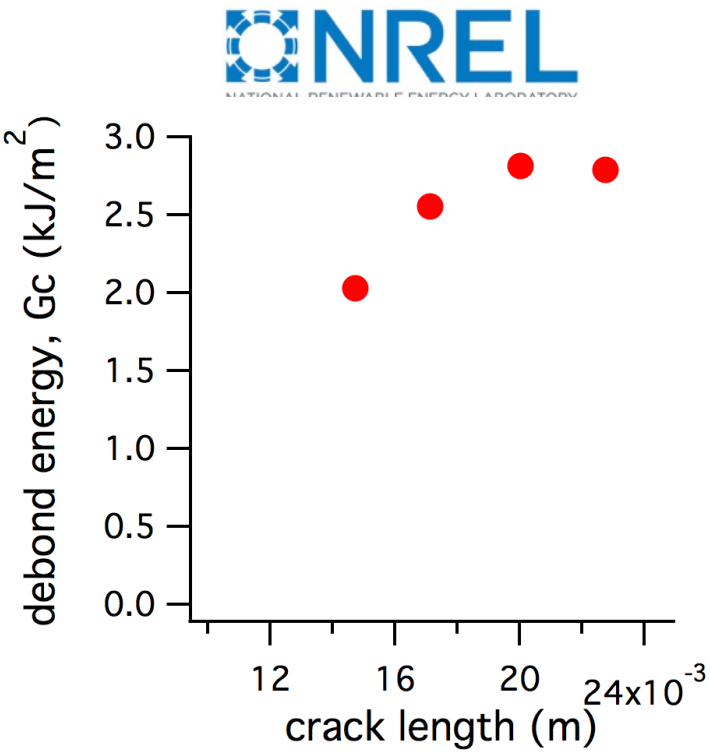
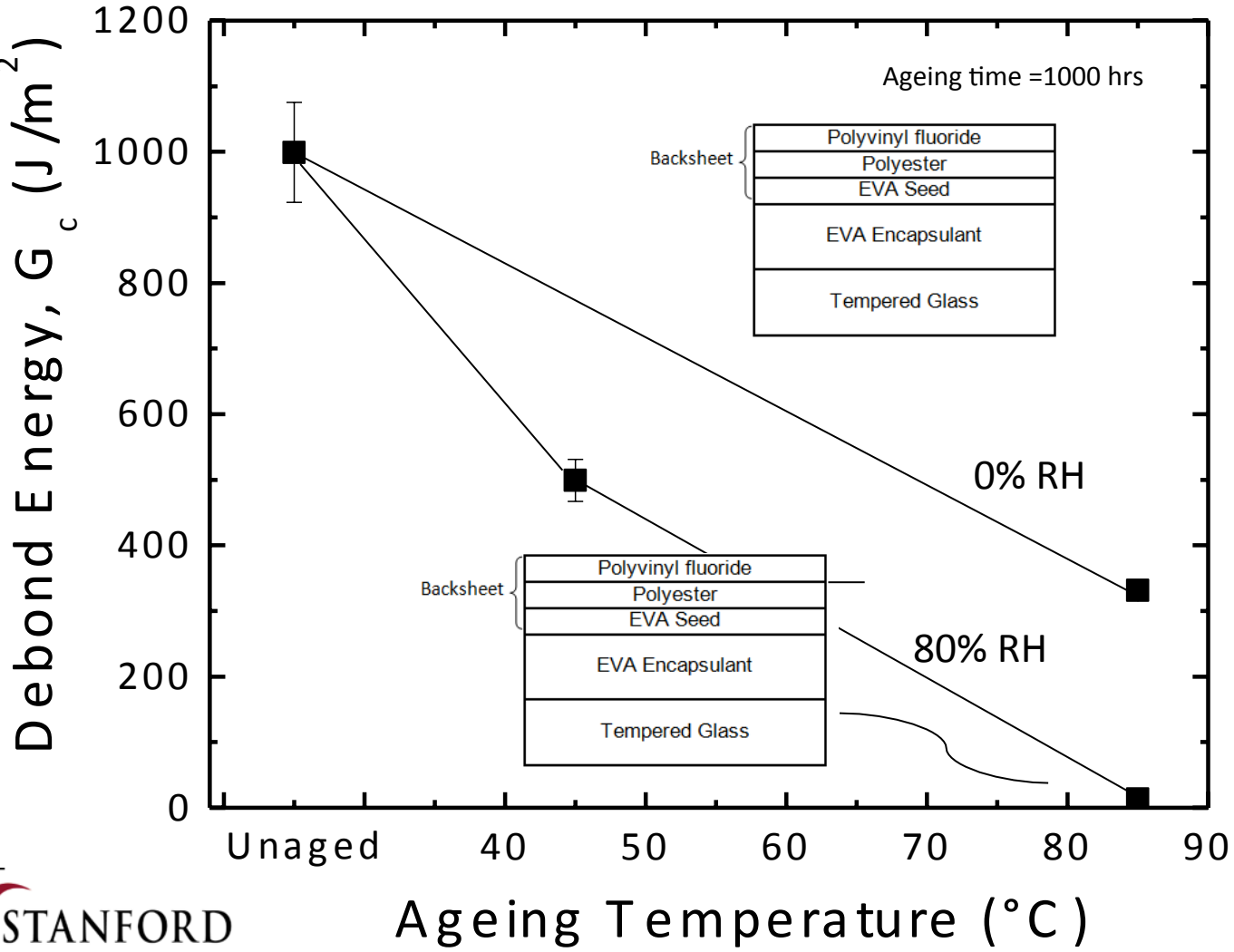
single cantilever beam, EVA

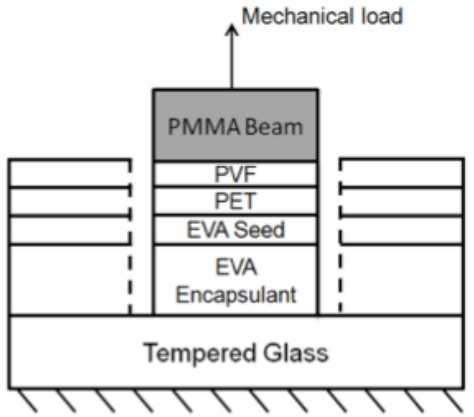


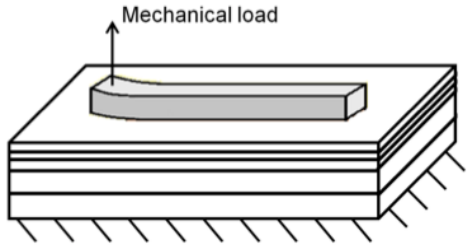


single cantilever beam, backsheet

Debond Energy decreased with aging temperature and RH







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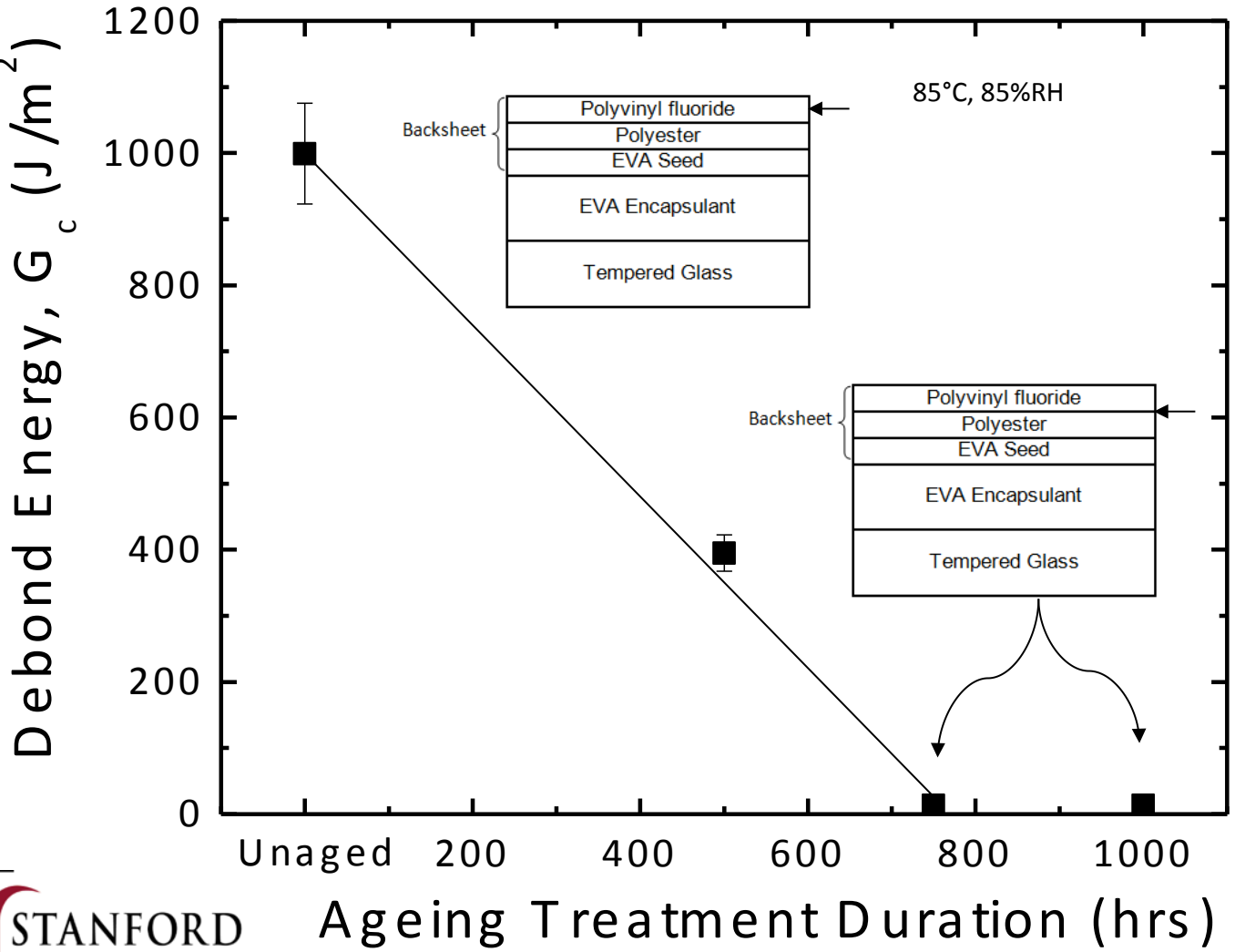
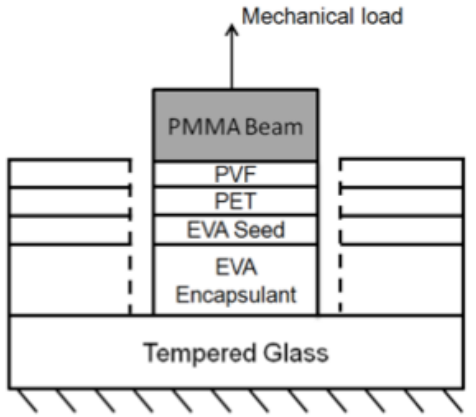
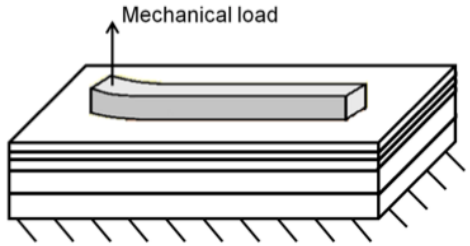
single cantilever beam, backsheet

Debond Energy decreased with aging duration







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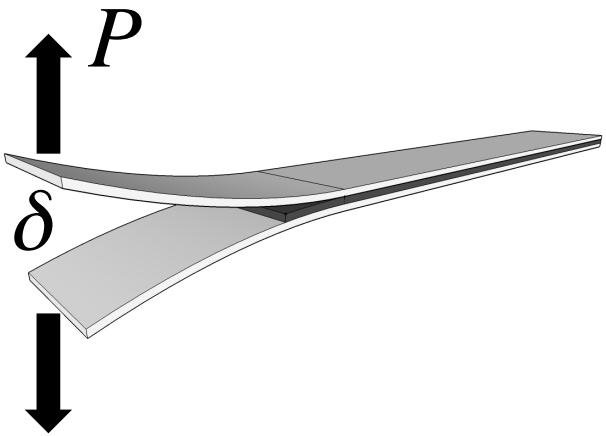
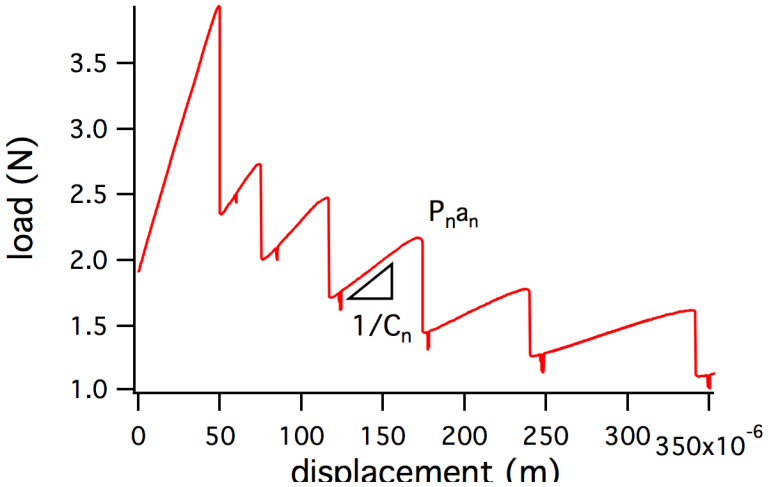
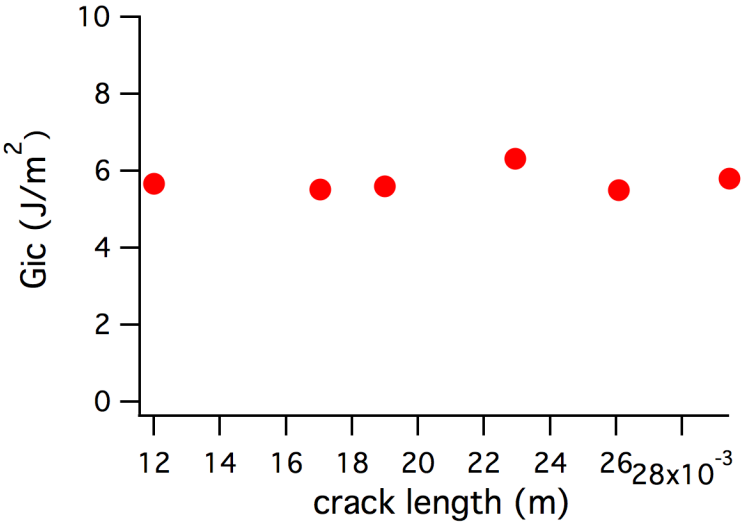
double cantilever beam (DCB)

thin metal film on glass







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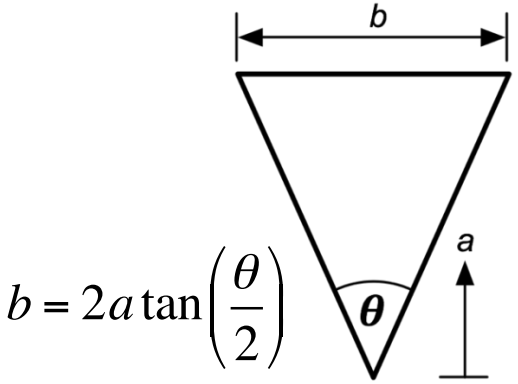
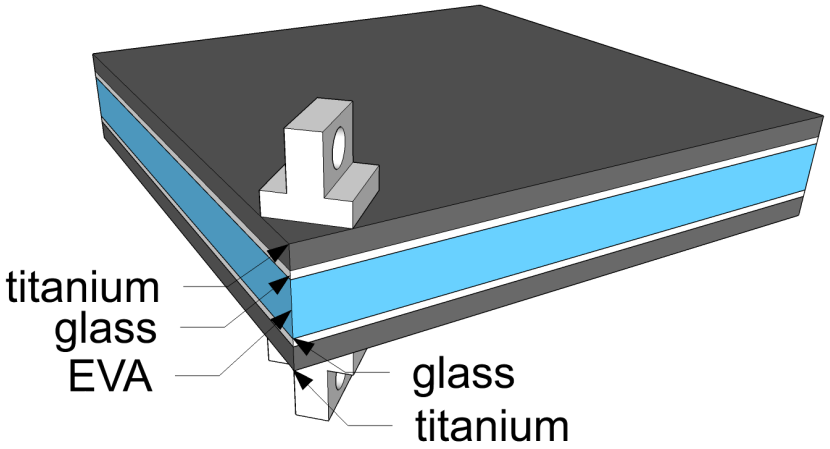
corner adhesion test

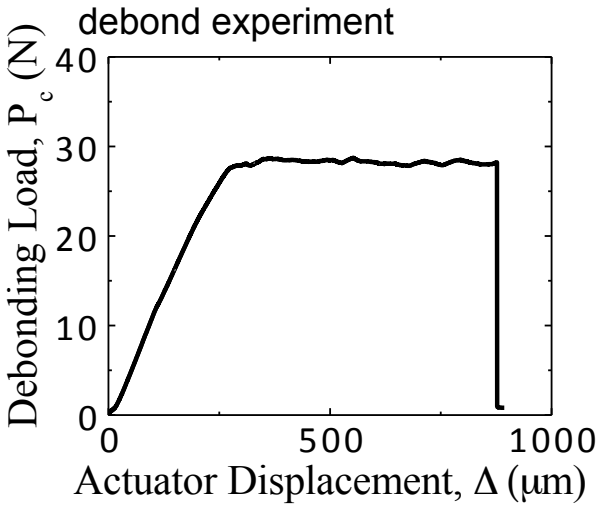
$$G = \frac{P^2}{2b}\frac{dC}{da}$$



$$b = 2a\tan\left(\frac{\theta}{2}\right)$$



$$G = \frac{12P_P^2}{E\left(2\tan\left(\frac{\theta}{2}\right)\right)^2 h^3}$$



- Compliance becomes independent of crack length
- Crack will extend at a constant, critical load

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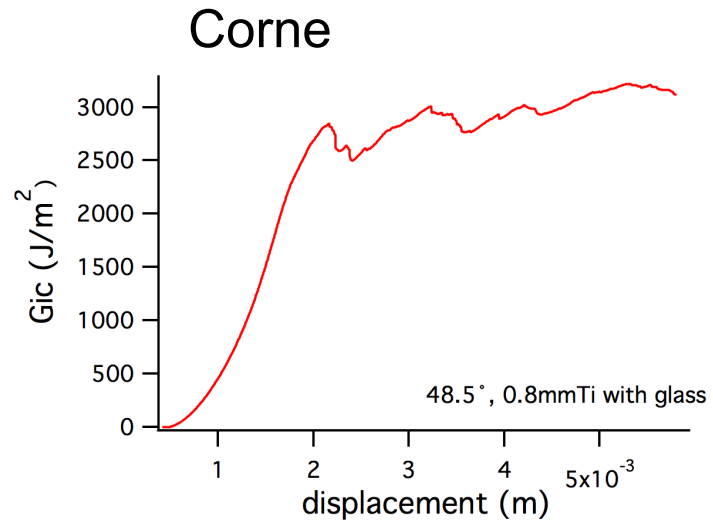
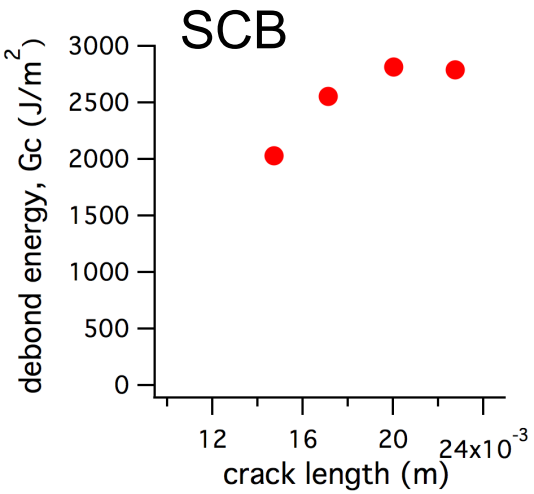
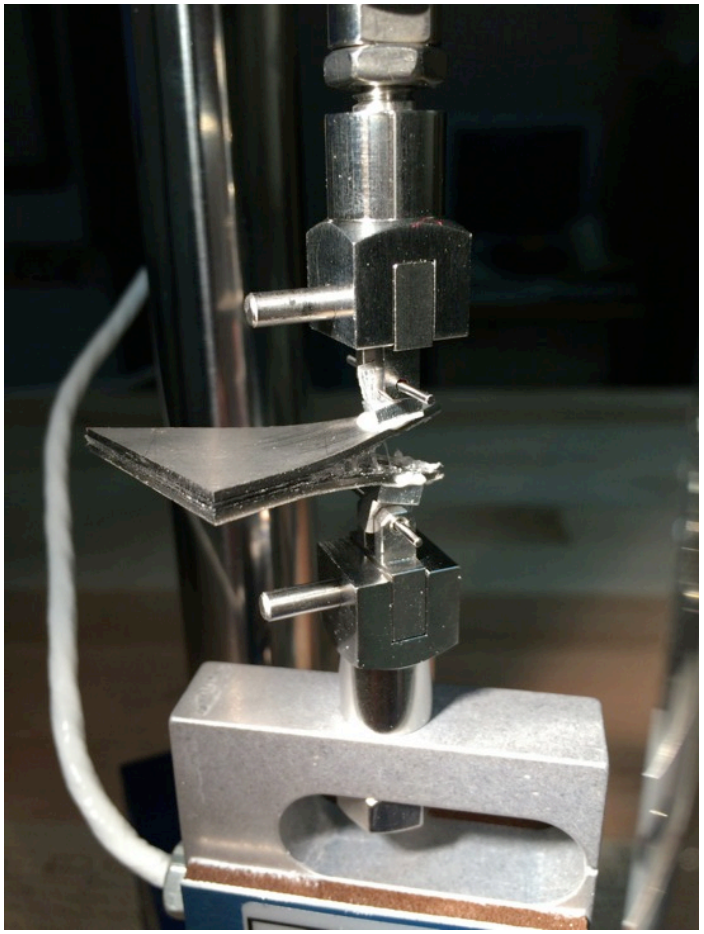
corner adhesion test, coupon level







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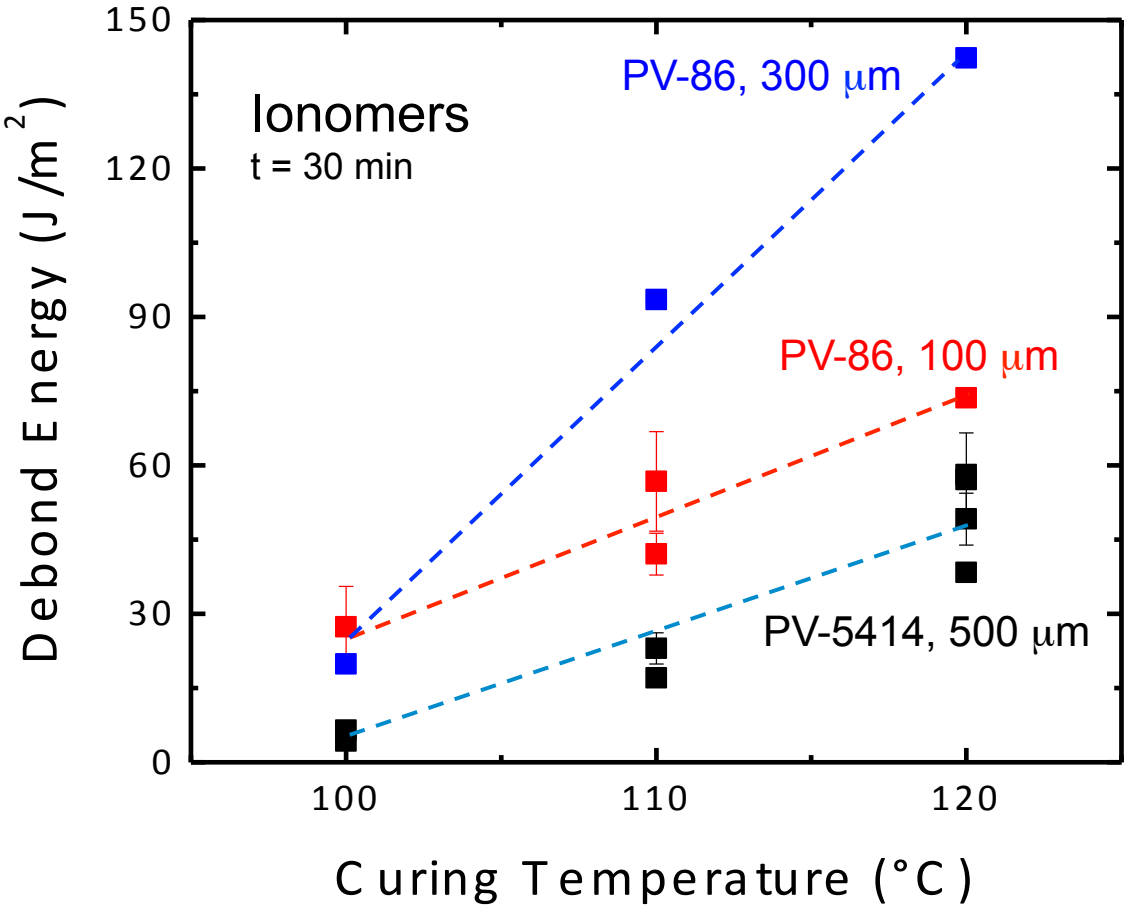
corner adhesion test, coupon level

Effect of Curing on Ionomer Bonding Strength



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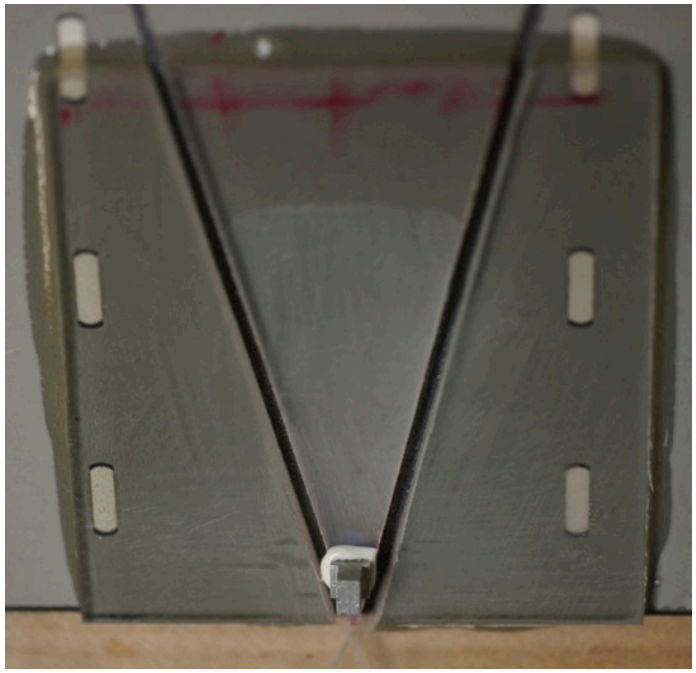
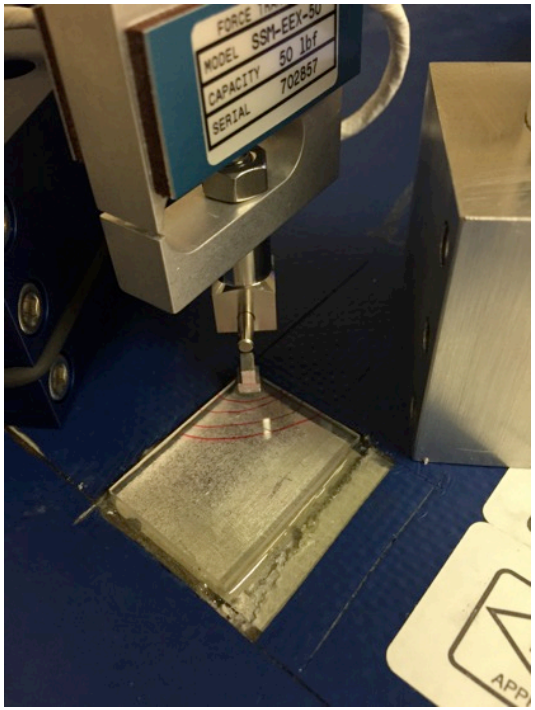
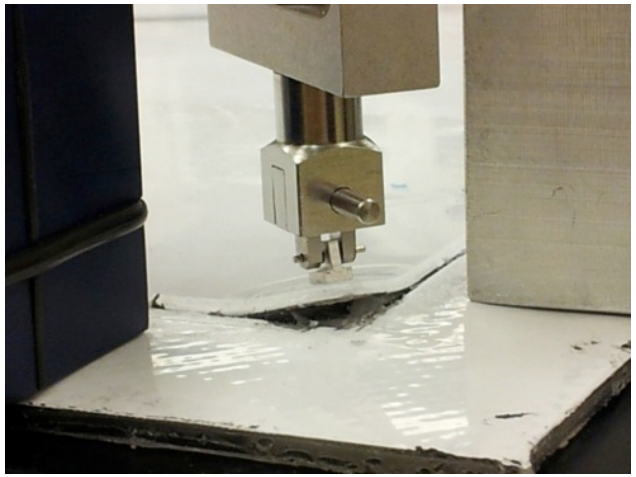
corner adhesion test, module level



corner adhesion test, module level



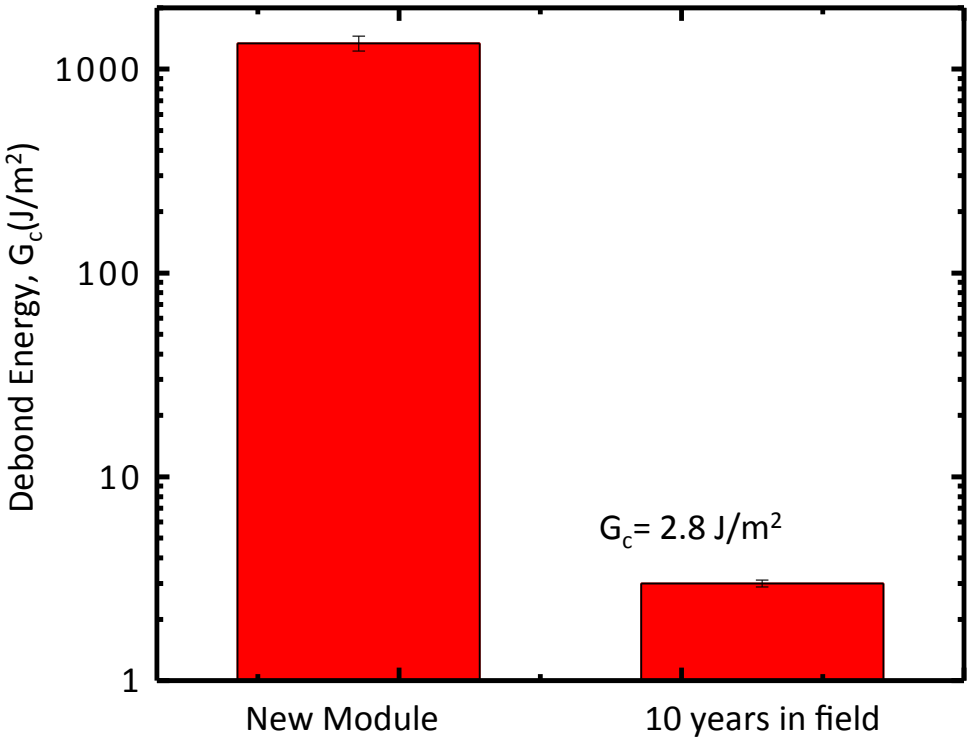
applied to module cell

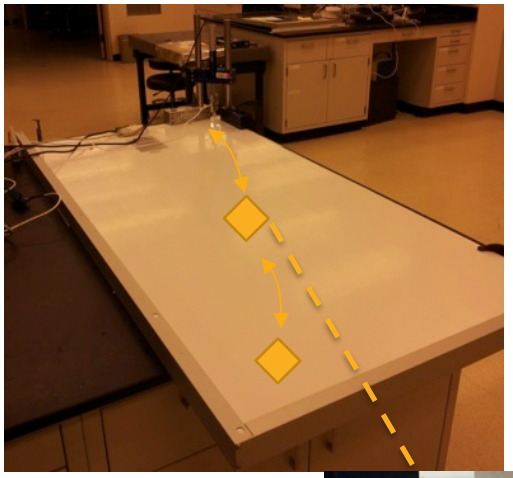


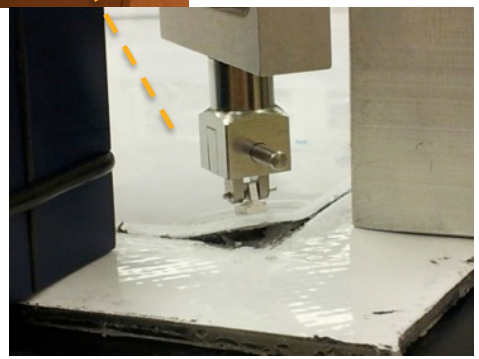
applied to module backsheet

corner adhesion test, module level

debond energy decreased 500-fold after 10 years in Florida







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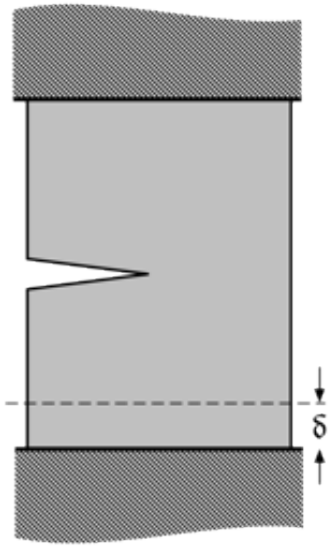
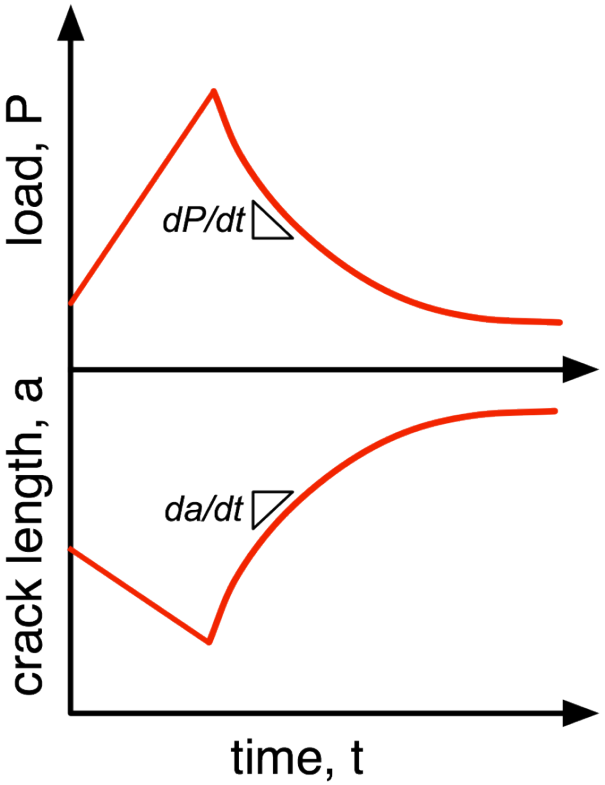
subcritical crack growth



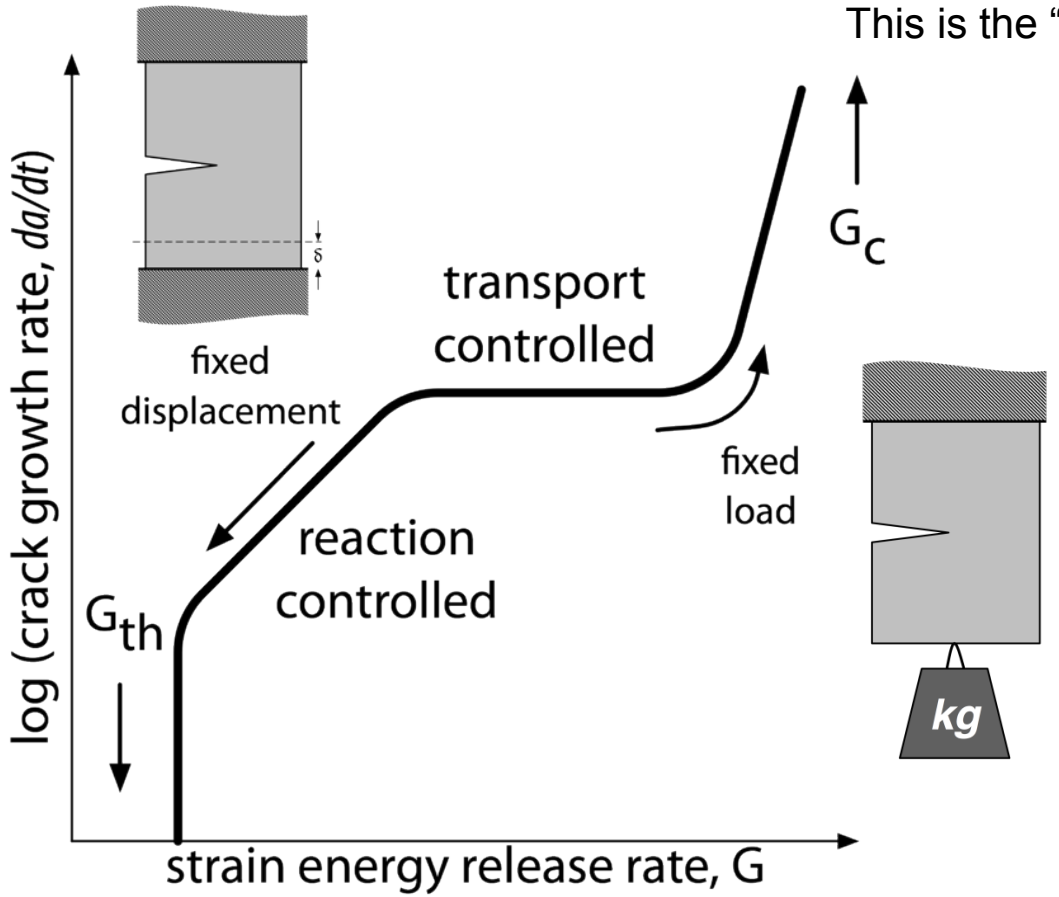


$$\frac{da}{dt} = -\left(\frac{dP}{dt}\right)\frac{ma^3 + b}{3Pma^2}$$

$$G_n = \frac{P(t_n)^2}{2b}3ma(t_n)^2$$

subcritical crack growth

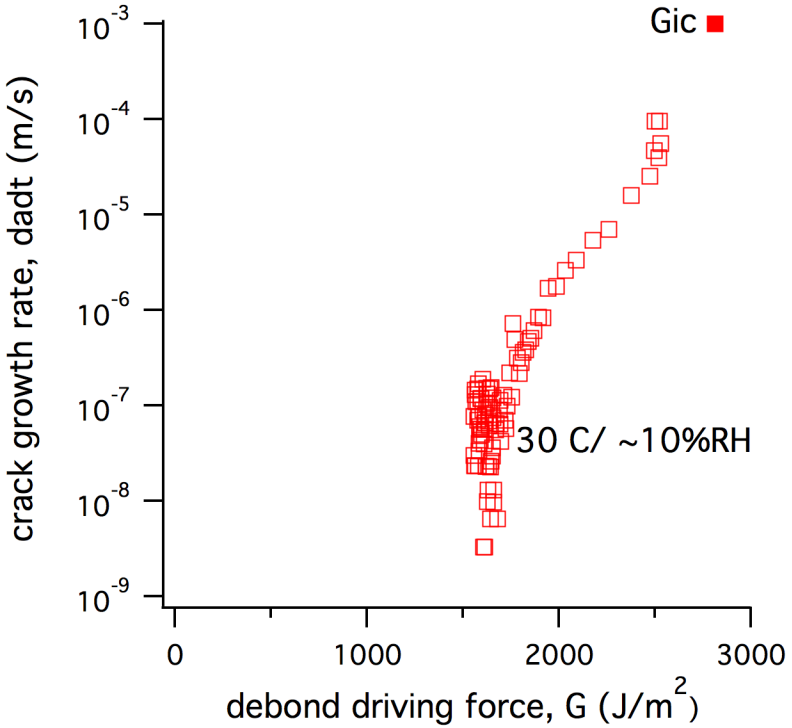
V-G plots



This is the “adhesive threshold”, or a stress at which cracks will not propagate. A reliable design will “live” here.

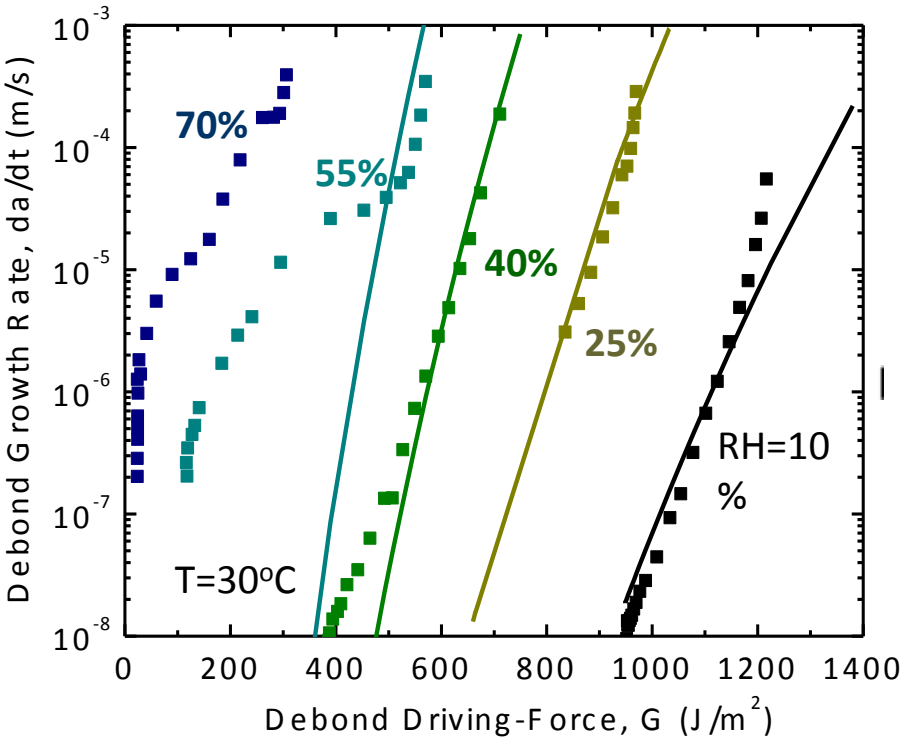
subcritical crack growth, SCB

Glass/ EVA

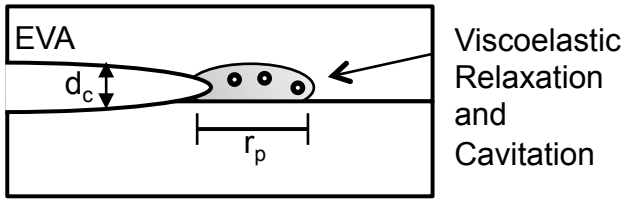


subcritical crack growth, SCB

Glass/ EVA debond growth kinetics



debond growth of EVA encapsulant interfaces is controlled by the viscoelastic processes that are affected by water through the plasticization of the debond tip

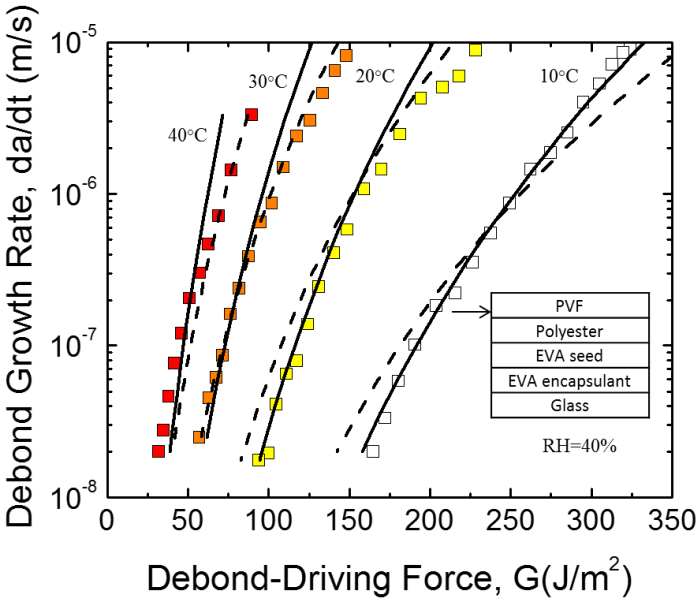


$$\frac{da}{dt} = \frac{\pi}{8} \frac{\delta_c}{\varepsilon_y \left(\delta_c \varepsilon_y E_1\right)^{1/n}} G^{1/n} 10^{\frac{C_a\left(T+\gamma RH-T_{g-dry}\right)}{C_b+\left(T+\gamma RH-T_{g-dry}\right)}}$$

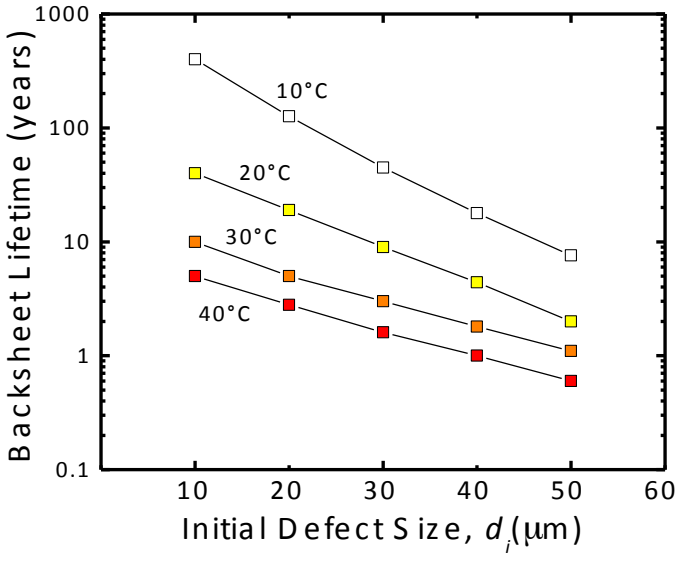
STANFORD MATERIALS SCIENCE AND ENGINEERING

subcritical crack growth, SCB

Backsheet debond kinetics and lifetime prediction



$$\int_{a_i}^{a_f} da = \int_0^t \frac{da}{dt} dt$$



$$\frac{da}{dt} = kG^{1/n} 10^{\frac{C_a\left(T+\gamma RH-T_{g-dry}\right)}{C_b+\left(T+\gamma RH-T_{g-dry}\right)}}$$

STANFORD
MATERIALS SCIENCE
AND ENGINEERING

direction

- Ongoing NREL scientific work is focused on applying the FM method to characterization for all PV adhesives
- We will develop protocols for applying this technique to all relevant material systems
- This work will provide the scientific basis for incorporating these techniques into future revisions of international standards

limitations of common adhesion tests

Sample Properties

- Stiffness
- Electrical Resistance
- *Strength*

Material Properties

- Elastic Modulus
- Electrical Resistivity
- *Toughness*

review

- FM based adhesion tests measure a quantitative material property
- Methods can be applied at both the coupon and module level and to all interfaces of the PV laminate
- Tests may be developed to be straight forward using common mechanical test equipment
- Subcritical measurements allow modeling of adhesive degradation mechanisms and ultimately provide a lifetime prediction tool

NREL PV Module Reliability Workshop (Feb 24, 2015)

Adhesion - Considerations, Testing and Interpretation

Presenter

Scott R. Meyer: Senior Specialist-Product and Application Development Engineer;

3M headquarters in St. Paul, MN, USA; Chemical Engineer B.S. degree from Iowa State University, 1985; 28 years at 3M Company in various divisions; experience with PSA tapes, epoxies, urethanes and fluoroelastomers; ~20 years of Experience with Adhesives; 6 years of tapes and adhesives experience related to the solar industry.

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Topics:

1. Adhesion and Testing
    - Failure Modes
    - Types of Forces
    - Types of testing

2. Material & Adhesive Characteristics
    - Perform differently – Difficult to compare materials

3. Many Variables Impact Test Results and Performance
    - Material types
    - Time & Temperature
    - Environmental
    - Aging (outside scope of this discussion)

4. Rigid PV Module Application
    - Relevant Forces & Testing

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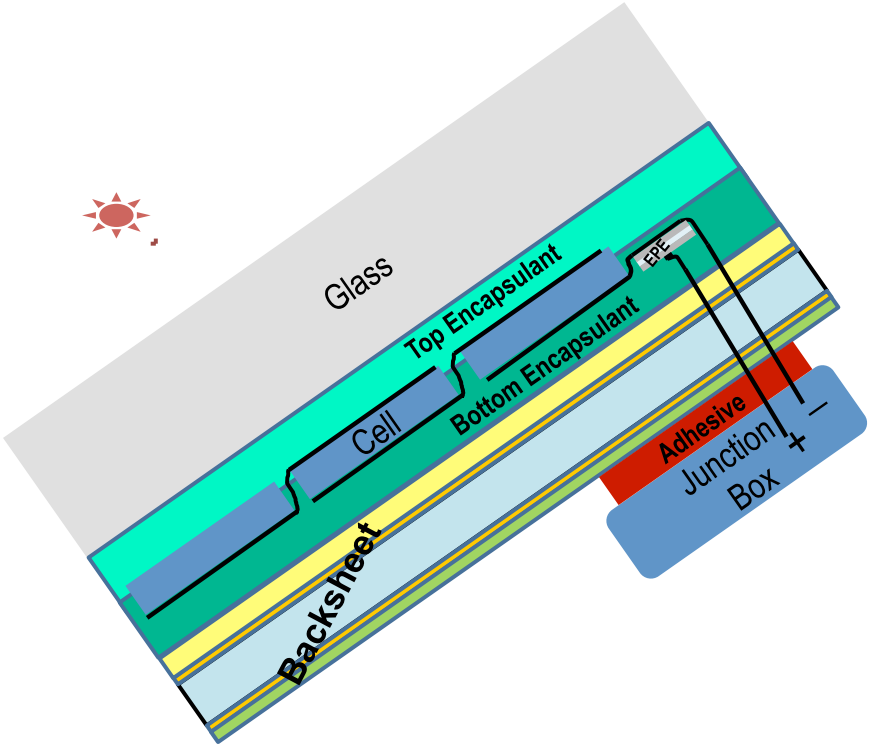
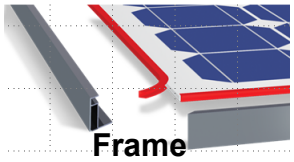
Why is Adhesion Important In PV Modules?

Many Adhesion Areas in a Module Can Fail



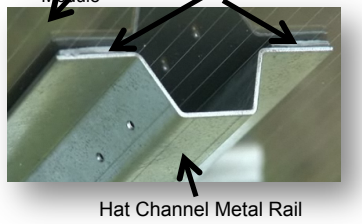


Bulk (with-in a material)

- Each material has its own bulk characteristics
- Some materials (e.g. Backsheets, EPEs) have layers within the material that may have additional Interfacial adhesion issues as well as different bulk characteristics

Interfaces

- Front Glass to Encapsulant
- Encapsulant to Cells and Ribbons
- Encapsulant to Backsheet or Backside Glass
- J.Box to Backsheet
- Rails to Backsheets or Backside Glass
- Frames to Backsheets or Backside Glass
- Edge Seals – Glass/Glass Thin Film



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Adhesion

- Molecular attraction that holds material together (Single material or multiple layers)
- Does it stick together? Is it resistant to de-bonding?

Modes of Failure (De-bonding)

- Cohesive Failure (CO) – Bulk layer
- Adhesion Failure (AF) - Interface between layers

Is CO failure required or is a high force to failure sufficient?

Not Always easy to identify failure mode

- Mixed failure modes (Some CO & some AF)
- Thin bulk layer surface failure (Can be difficult to see)

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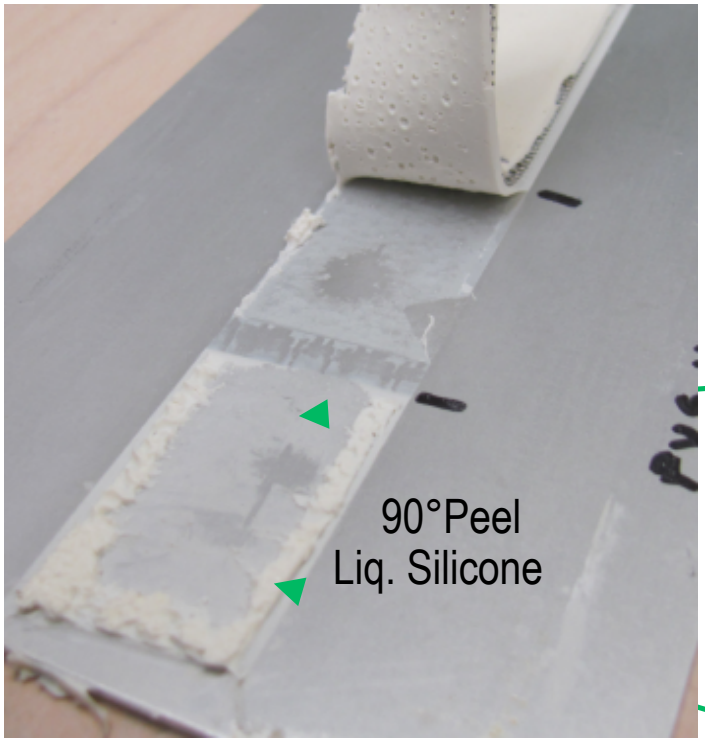
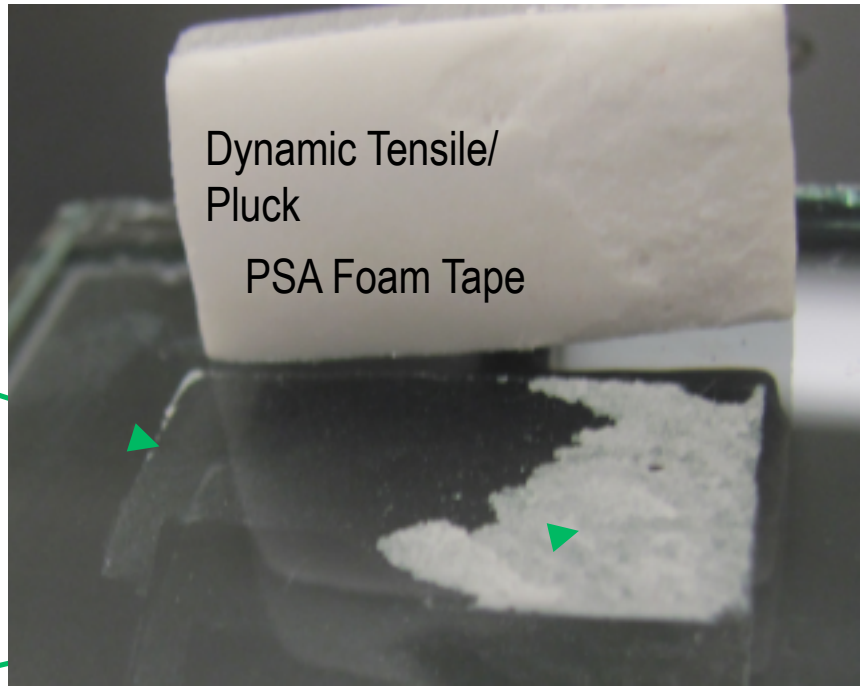
Can Be Difficult To Say If Cohesive (CO) or Adhesion (AF) Failure Some Times



Thin Cohesive

Cohesive



- Not To Hard -But Some May Say Mostly AF
- But Really Thin CO Film

- Difficult – Most would Say Mostly Mixed with 35% CO and 65% AF to Glass
- But Really CO – 35% CO & 65% Thin CO Film

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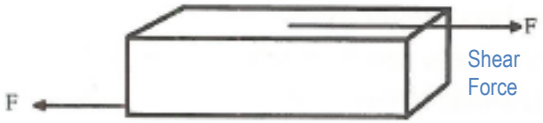
Types of Forces

1. Shear



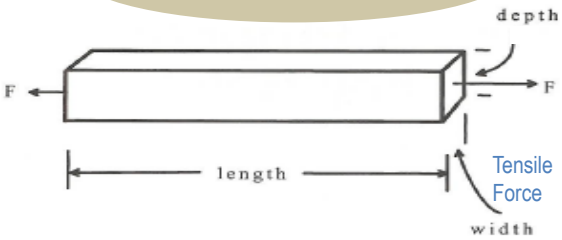
Stress=Force/Area

Force is Parallel to Bond area

Shear Force

Area

2. Tensile/Pluck



Stress=Force/Area

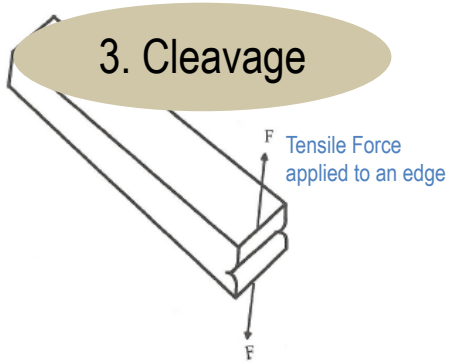
Force is Perpendicular to Bond area

Tensile Force

Area

Force

3. Cleavage



Force/Width = Energy/Area

Fracture Mechanics
Fracture Energy to propagate a crack

Tensile Force applied perpendicular to an edge

More complex to understand what cleavage results mean.

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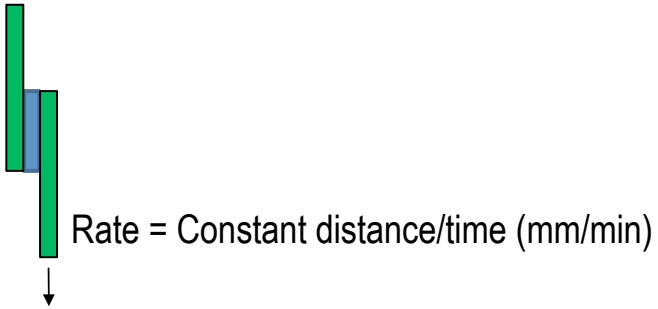
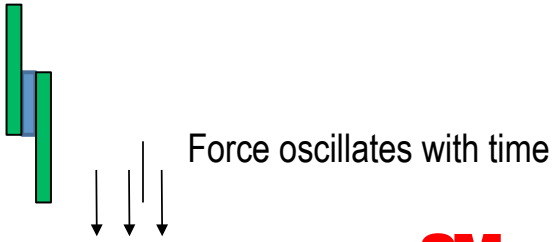
Force Applied In Different Test Modes

a. Constant Rate - Displacement (or Force)



b. Constant - Force (or Displacement)

c. Cyclic – Displacement or Force goes up and down



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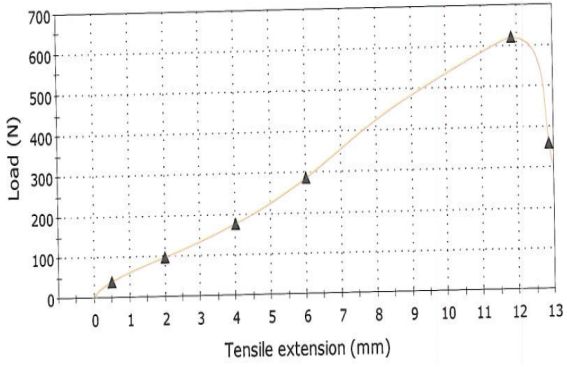
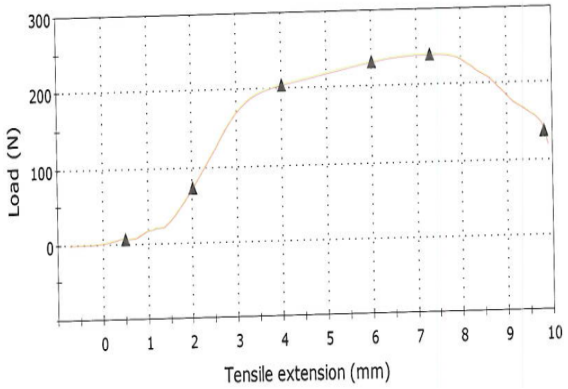
Constant Rate Displacement Lab Test Examples

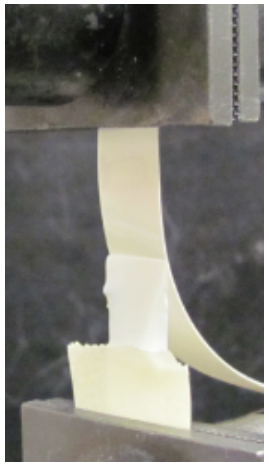
Overlap Shear

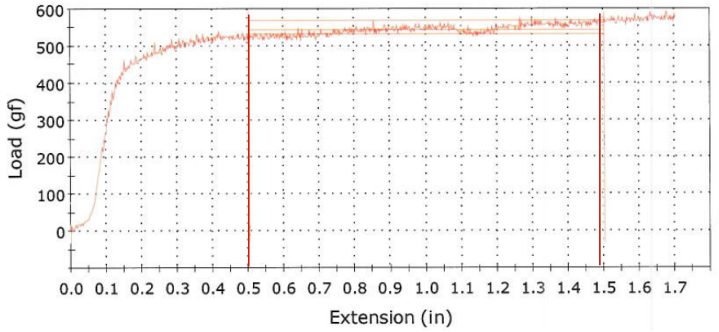


T Block Tensile/pluck



Peel





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Comments on Peel Testing

- Peel is a special class of a cleavage test
- Easy to run
- Complex with regards to understanding what it means relative to performance in an application; Fracture Energy
- **Many variables impact results – Difficult to compare materials unless identical:**
  - Configurations of Peel Test (e.g. 90°,180°,T-Peel, various fixtures, …….)
  - Pull speed (Rate)
  - Temperature
  - Humidity
  - Dwell time
  - Adhesive (Material Characteristics, thickness)
  - Substrates (Material Characteristics, thickness)
  - **Backing (Material Characteristics, thickness) - Can have large Impact**

$$G_a = P/b\,(1+\varepsilon_a-\cos\theta)-h\int_0^{\varepsilon_a}\sigma\cdot d\varepsilon-G_{db}$$

fracture energy | Total work done | Energy used to stretch peeling arm material | Energy dissipated in plastic bending of peeling arm

Williams and Kauzlaurich, *Strain*, **47**(5), 439-448, 2011

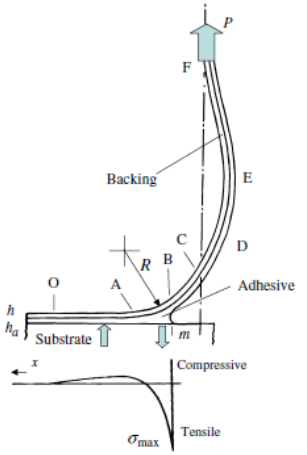

Figure 1: Fixed arm peeling with $\theta = 90°$. The backing of thickness h is attached to the rigid substrate by an adhesive layer of thickness h_a. The peel force P is equilibrated by a distribution of normal stress conveyed by the adhesive to the substrate which is tensile at the point of separation but is compressive at larger values of coordinate x. Dimension R represents the root radius

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Effect of Backing Thickness in Conventional Peel Test

Williams and Kauzlaurich, *Strain*, **47**(5), 439-448, 2011

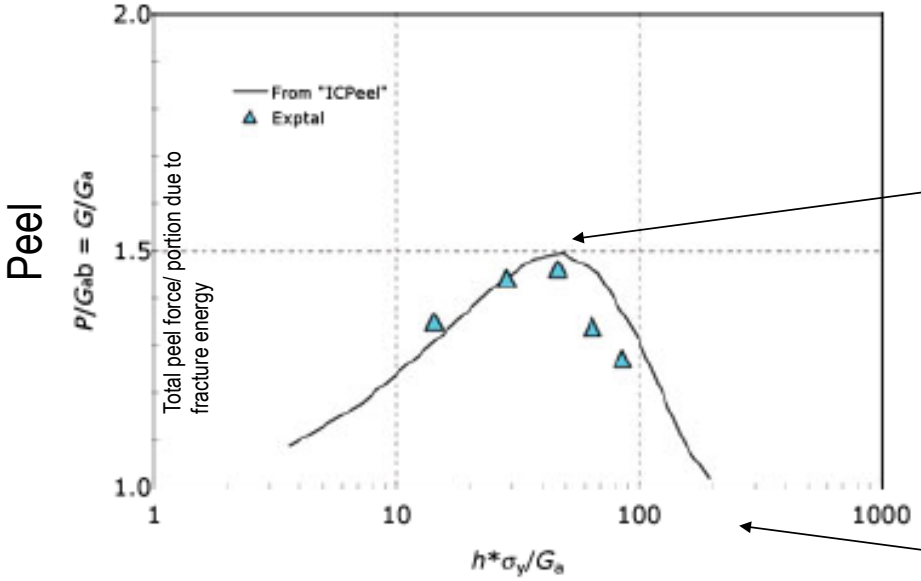

Figure 14: Plot of ratio of total peel energy to de-adhesion energy G/G_a to $h\sigma_y/G_a$ for Mylar backing and 200MP adhesive. Solid line form *ICPeel*

Peel can be 50% higher due to backing effects

- Same adhesive
- Same backing except thickness

Backing thickness range: 75 to 350 µm

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Comments on Peel Testing (Continued)

- Peel may not be the best test to use to simulate the forces of PV module applications
- Be cautious in the interpretation of peel data; conclusions can be misleading

Only thing worse than no data is “bad” or misleading data !

When to use peel:

1. Understanding the impact of dwell on adhesion build – How much time should you give something to reach its best interfacial adhesion?
2. QC tests during manufacturing of an adhesive or identical construction - Are things changing?
3. If application is in a peel mode

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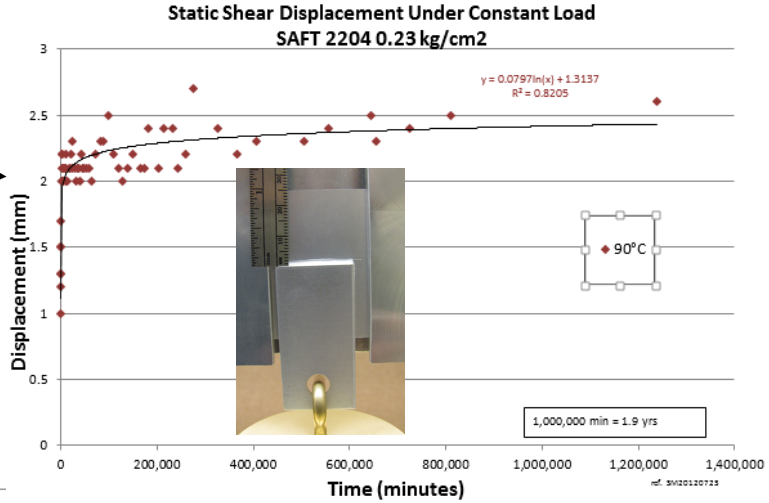
Example Of Constant Load Lab Tests

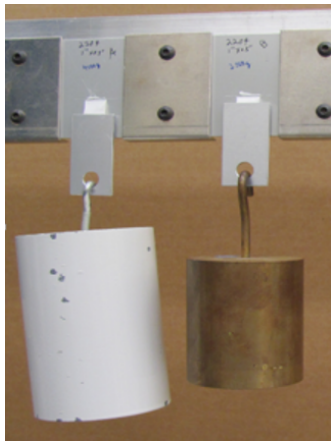
One Condition

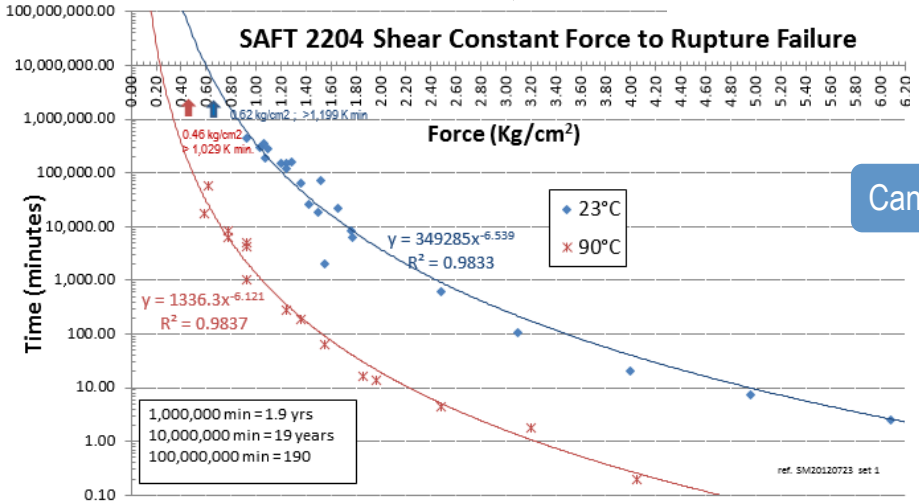
- Pass/Fail
- Measure Displacement as a f(time).



Multiple Conditions

- *Constant Force To Rupture* (CFTR) Failure Analysis
  - Creates projections on expected failure point
  - Time Temperature Superposition





Can be Done in Shear or Tensile

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Adhesive Types

Adhesive State Changes – During Bonding

- Curing Liquids
  - forms bond in liquid (unreacted) state; Crosslinks during cure
  - e.g. epoxies, reactive polyurethanes
  - Some may become glassy (e.g. structural epoxy & acrylics)
- Hot Melt Adhesives (thermoplastics)
  - melt crystals to form bond; solidifies on cooling to give strength
  - Can have crosslinking (e.g. encapsulants)
  - e.g. polyamides, thermoplastic polyurethanes, polyolefins

No Change in Adhesive State – During Bonding

- Pressure Sensitive Adhesives (PSA)
  - forms bond with contact time and pressure
  - relies on viscoelasticity to provide resistance to debonding

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Many Variables Impact Adhesion Performance

- Environmental Aging
  - No Change
  - Crosslinking
  - Degradation (Breaking Molecular Bonds)
- Dwell Time
  - Time to each optimal performance - Surface wet out & chemical reactions
  - Be careful, Dwell can cause issues when comparing if not allowed to reach optimal performance
- Adhesive, Substrate, & Backing
  - Bulk Characteristics
  - Surface Chemistry
  - Thickness
- Rate and Temperature
  - Different for different material classes

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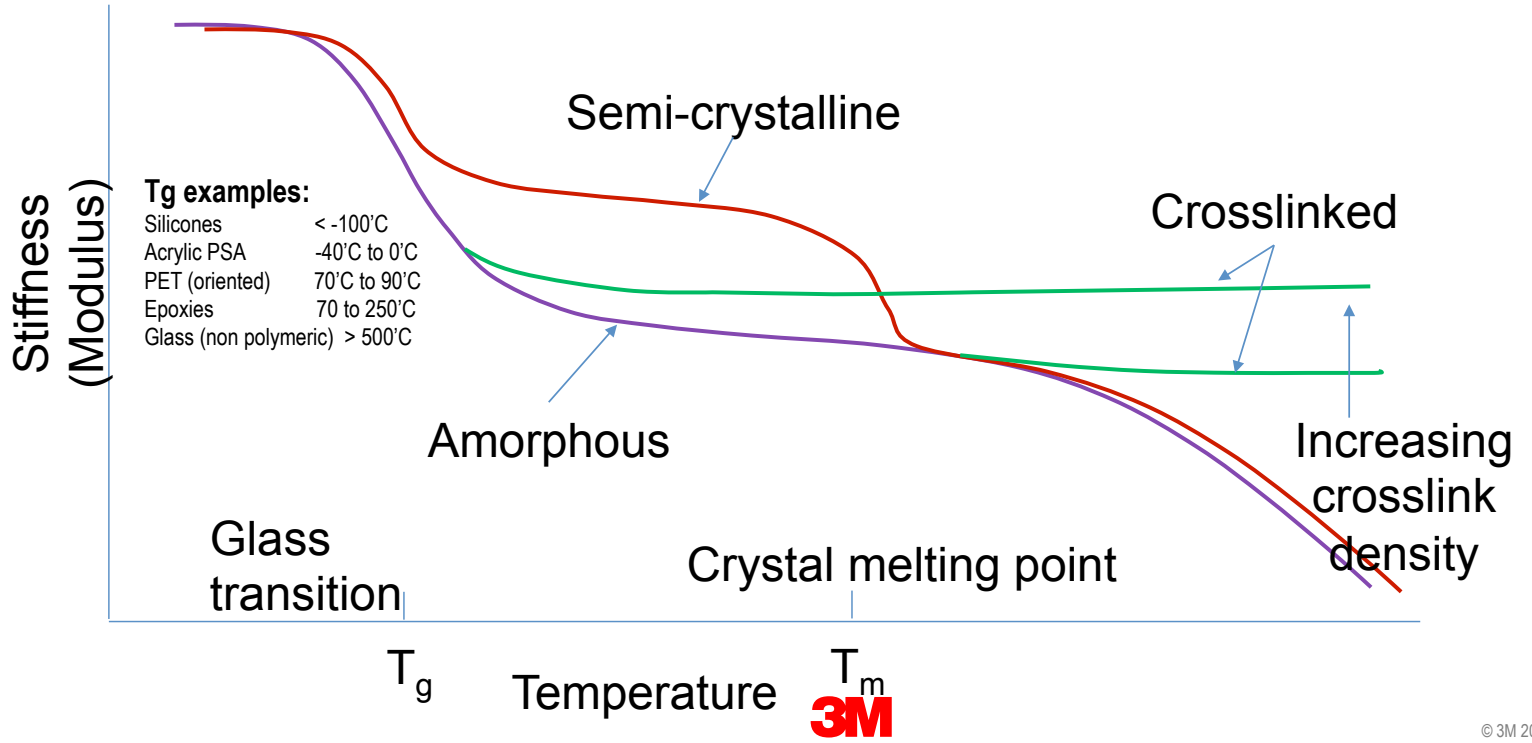
Adhesive and Substrate Properties

Stiffness Dependence on Temperature for Polymers

- Stiffness is impacted by Temperature
- Stiffness is also impacted by Rate (Speed)

Tm examples:

Silicones	Amorphous
Acrylic PSA	Amorphous
PET (oriented)	260'C
EVA (40%-9%)	50'C to 100'C
Glass	Amorphous



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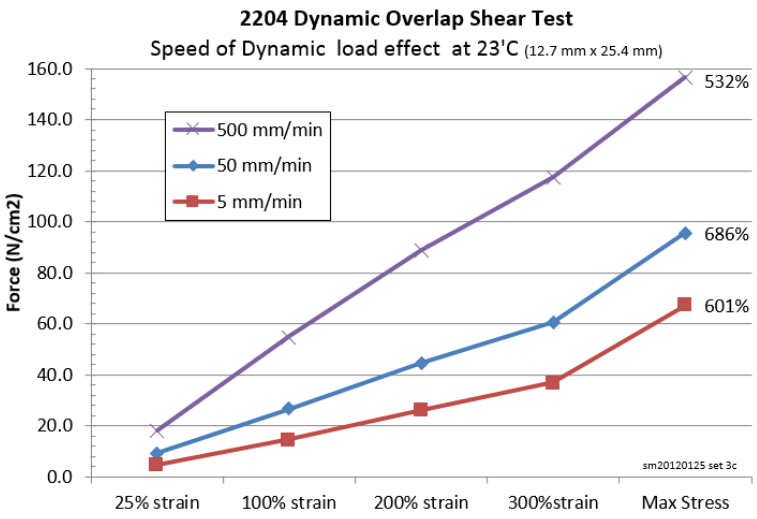
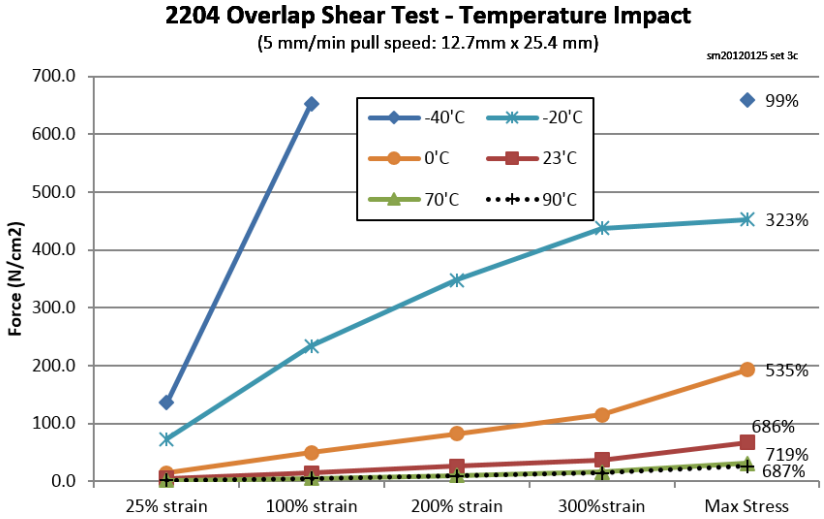
Temperature & Test Rate - Significant Impact On An Adhesive

- Some material are influenced more by this than others…..e.g.silicone versus acrylic PSA
- Need to ask what is important in the application

Effect of Rate on Adhesive Strength



Effect of Temperature on Adh. Strength



Technique that can be used to relate time & temperature
– time temperature super-positioning (hot is like slow; cold is like fast) → Master curve

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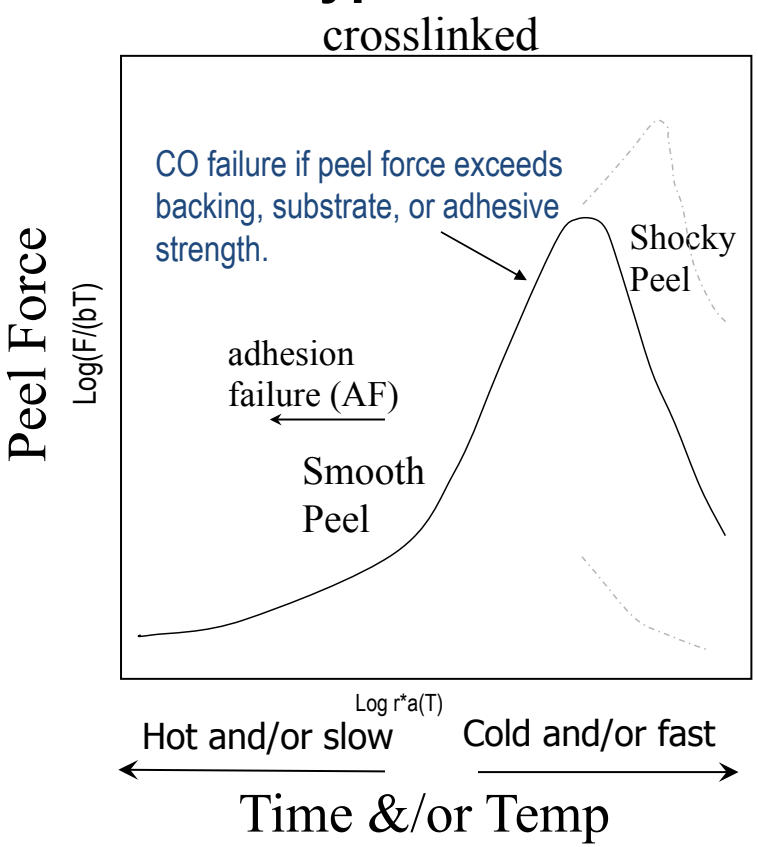
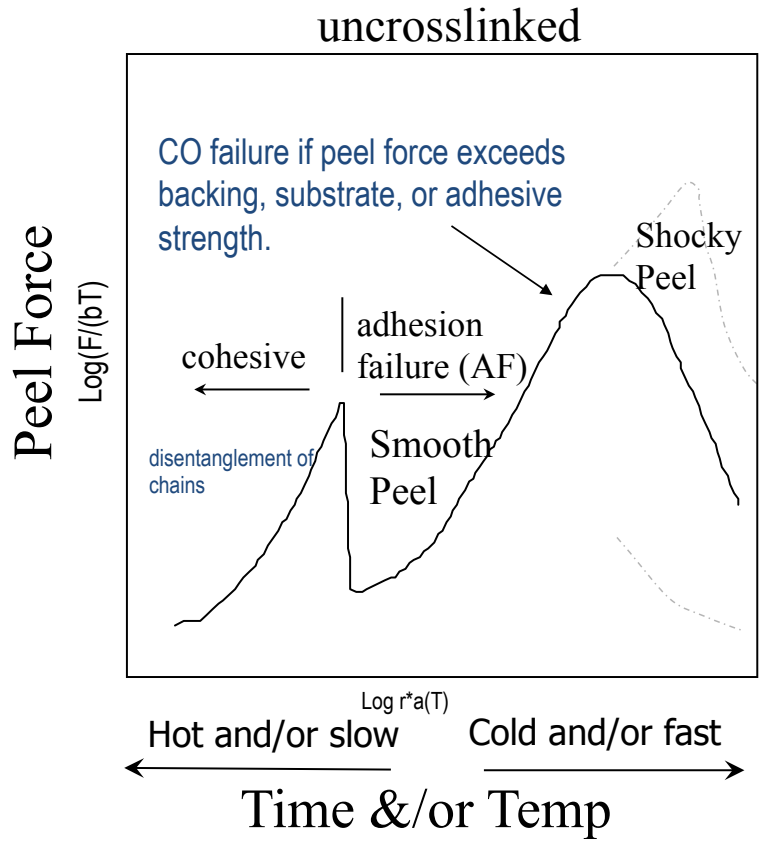
Typical Rate & Temperature Impact On Peel





What is the temperature and rate that should be used to represent the application?

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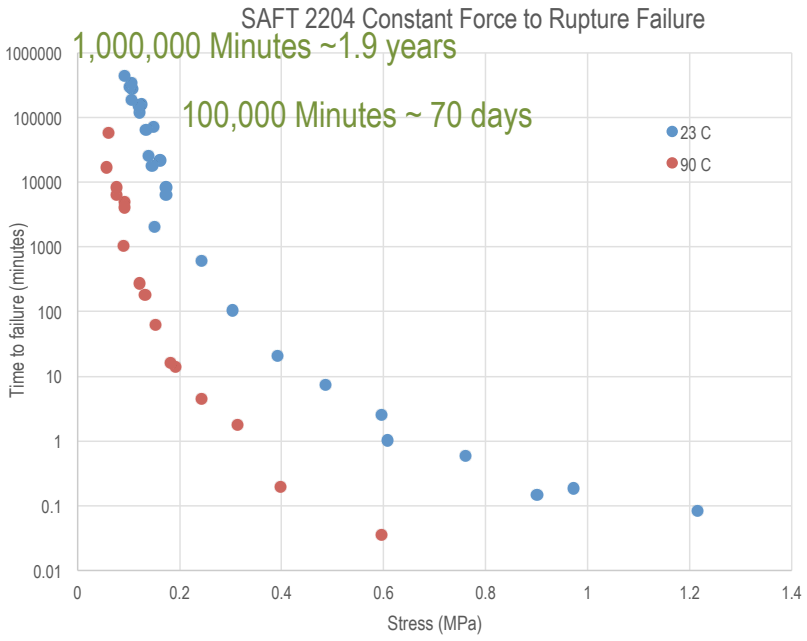
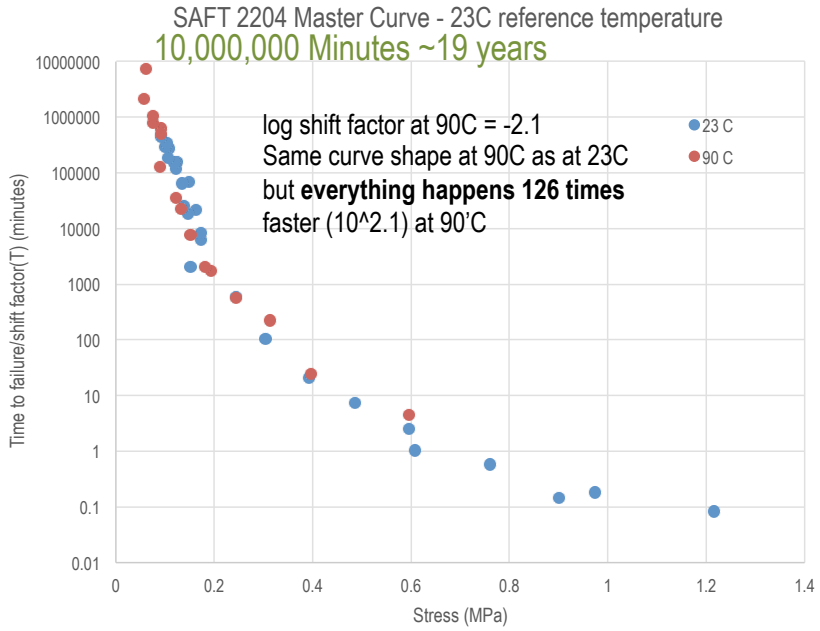
Time Temperature Super-postitioning Shear CFTR Example

Time and temperature dependence - failure times in constant shear load of 2204 foam tape

Time-temperature superposition





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Time Temperature Super-posititioning – When It Doesn't Work

When does time-temperature superposition not work?

- Semi-crystalline materials
  - Not work with materials that are Crystalline - melting of crystal phase produces softening that will not be seen below T_m regardless of time scale of test
- Multi-phase materials
  - different phases have different sensitivity to temperature
- Temperature causes irreversible changes/degradation of material

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Each Application is Unique - Need to ask the following

- **What are the critical forces that can cause failure?**
  - Type - Shear, Tensile, Cleavage
  - Mode - Constant Load, Constant Rate, cyclic
  - Limit - maximum forces requirement

- **What are reasonable tests that can be run to help get a perspective on performance?**
  - Usually have to make compromises to do the best you can on a small scale
  - Need to validate &/or correlation with field results

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PV Example - Rail Bonding Adhesives In Rigid PV Modules

What are the type of forces on this adhesive?

What are test methods that simulate the forces?

			Type of Lab Test						
			Tensile/Pluck			Shear			Cleavage
			Constant Rate Displacement		Constant Load	Constant Rate Displacement		Constant Load	peel
			Slow	Fast		Slow	Fast		
application characteristics	***Forces***	importance							
Ability to handle stress from an adhesion perspective Does It stick?	***gravity***	***9***				1		9	
	wind gusts	***9***		9	1		9	1	
	Installation/Handling	***9***		9	1		9	1	1
	Thermal variations (CTE mismatch)	***3***				3			3
	Snow Loads	***3***				1 (cold)		9 (cold)	
	IEC& UL Mechanical Load Test				9				

- **Fast Tensile/Pluck**
- **Fast Shear**
- **Constant Load Shear**

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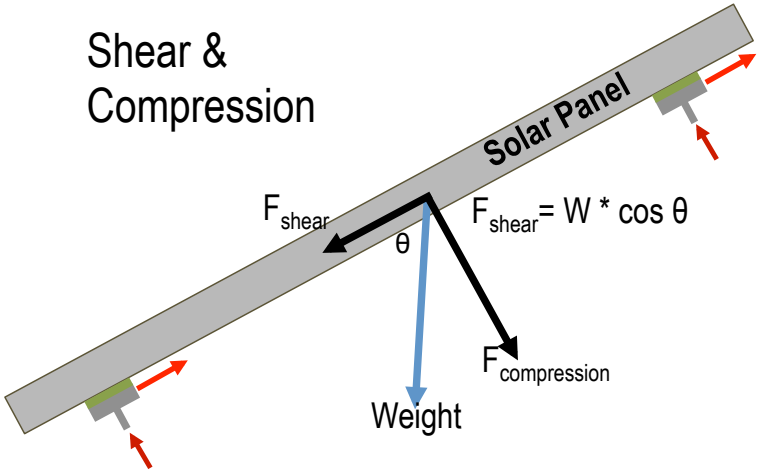
Example of Forces on Rail Bonding Adhesives In Rigid PV Modules

- **Gravity**
  Panel Weight – Above Ambient Temperatures
  Long time Scale – 25+ years
  Snow Load – Cold Temperatures

What are the type of forces on this adhesive?

Shear & Compression



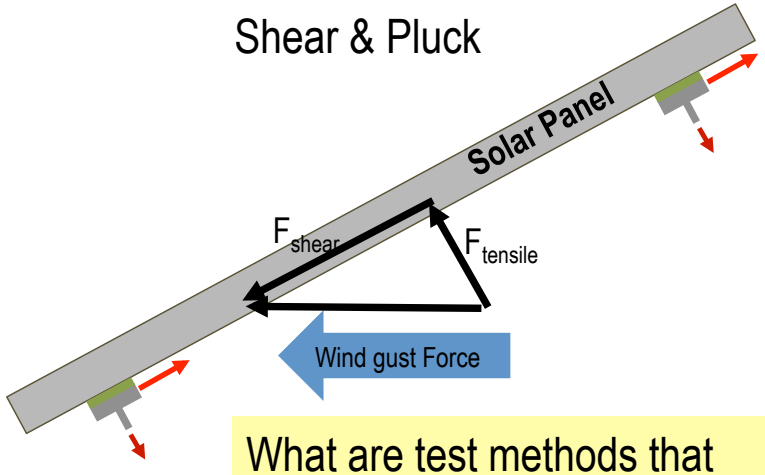
What are test methods that simulate the forces?

Shear & Compression

- **Wind Gusts**
  (Building codes use 3 second wind gusts)

What are the type of forces on this adhesive?

Shear & Pluck



What are test methods that simulate the forces?

Shear & Pluck

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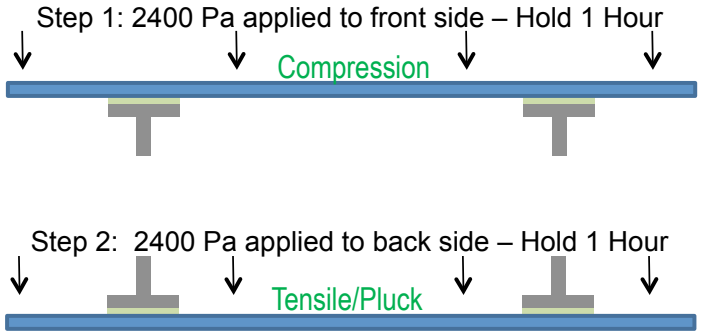
Mechanical Load Test - IEC & UL Standard



<u>Repeat steps 1 & 2 three times.</u>
If want heavy snow load approval, replace last front loading with 5400 Pa.

Concerns

- **1 hr load is not representative of a wind gust.**
  - Building codes – 3 second wind Gusts
- **Not representative of snow load because testing:**
  - Does not include shear
  - Is done at room temperature

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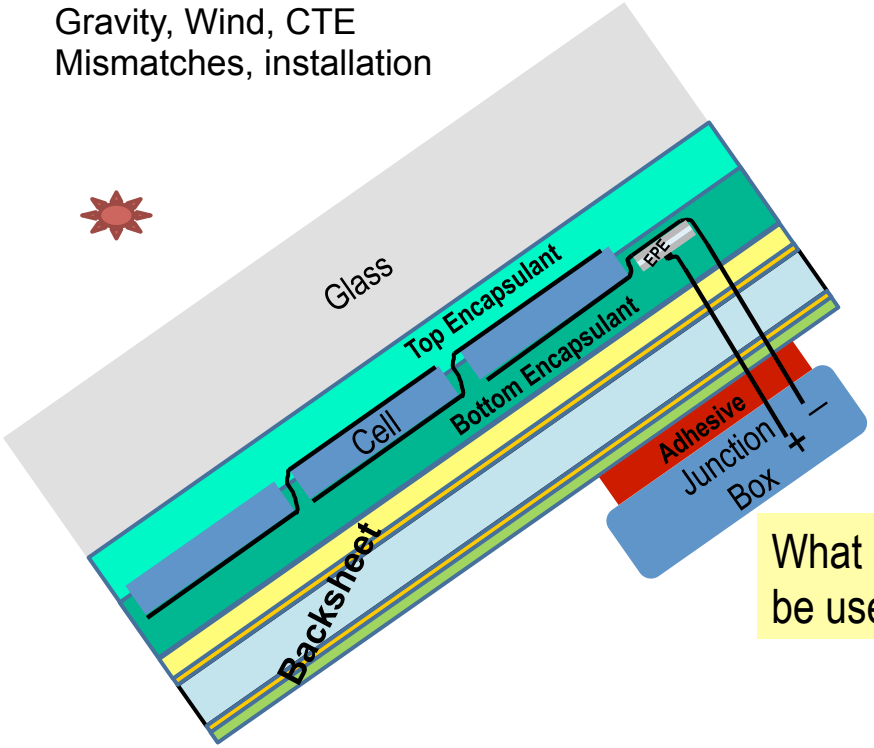
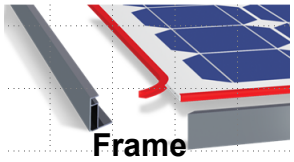
Solar Panel Stack Up – Adhesion Areas in a Module

What are the forces acting on the layers in the module?

Gravity, Wind, CTE Mismatches, installation



Interfacial



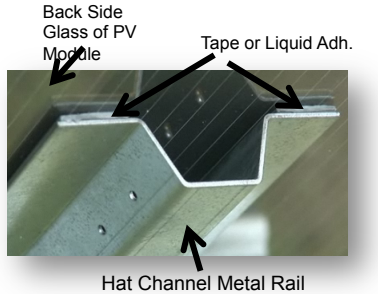
- Front Glass to Encapsulant
- Encapsulant to Cells and Ribbons
- Encapsulant to Backsheet or Backside Glass
- J.Box to Backsheet
- Rails to Backsheets or Backside Glass
- Frames to Backsheets or Backside Glass
- Edge Seals – Glass/Glass Thin Film

Bulk

- Each material has its own bulk characteristics
- Some materials (e.g. Backsheets, EPEs) have layers within the material that may have additional Interfacial adhesion issues as well as different bulk characteristics

What are test methods that can be used to simulate forces?

Shear, Tensile, Cleavage



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Key Points:

1. Peel
   - Easy to run but complex with regards to understanding what it means relative to performance in an application.
   - Influenced by many variables. (Backing, substrate, angle, stretching,……)
   - May not be the best test to use to simulate the forces of PV module applications

2. Understand application stresses & simulate stress as best as possible to get most relevant information.

3. Various adh. & materials perform differently - makes it difficult to compare application performance.

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Backup Slides

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Time & Temperature Have A Significant Impact Failure Mode

Peeling PET film from rubber at differen

Gent and Petrich, Proc. Roy. Soci. A., **310**, 433 (1969)

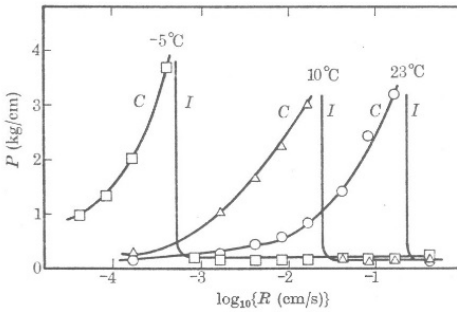


FIGURE 2. Average peel force P against rate of peel R for polymer
C and I denote cohesive and interfacial failure mo

Peel Force

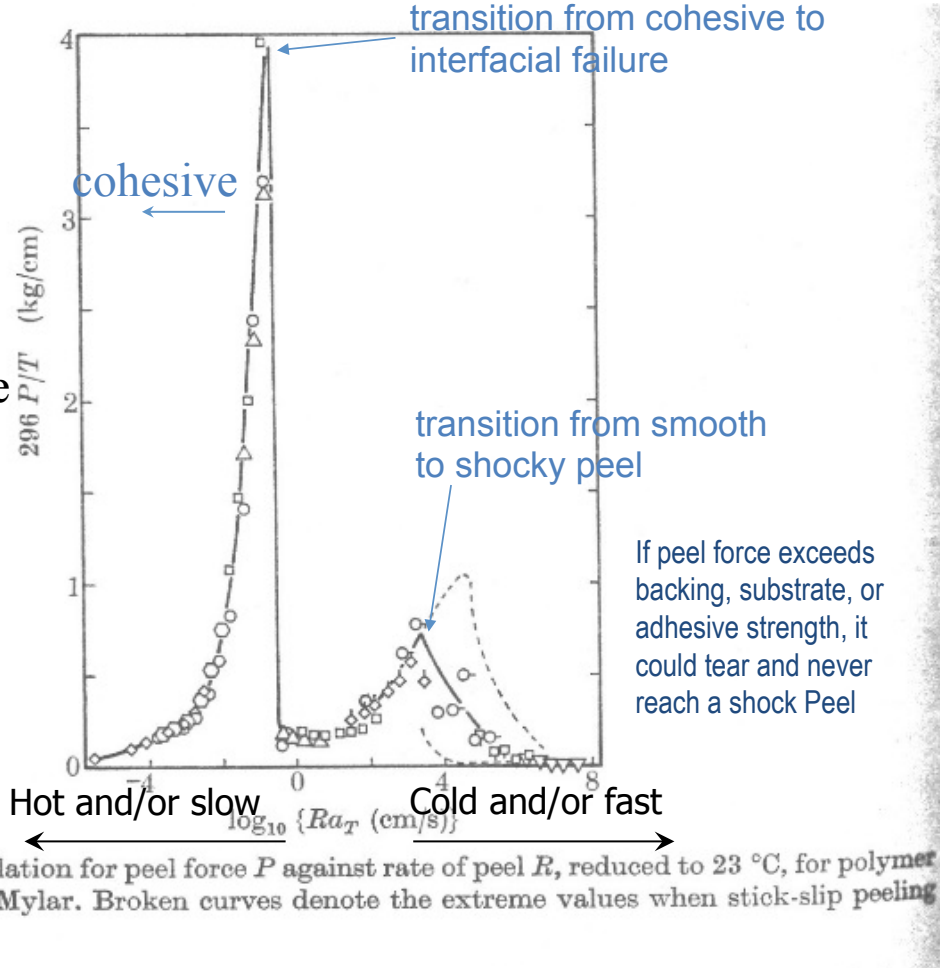
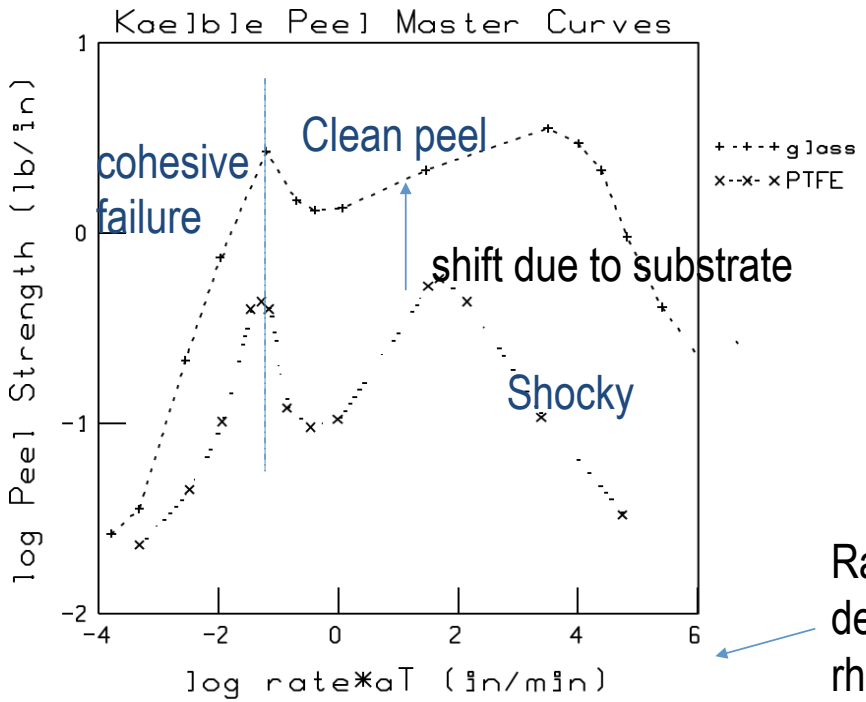


FIGURE 3. Master relation for peel force P against rate of peel R, reduced to 23 °C, for polymer A adhering to Mylar. Broken curves denote the extreme values when stick-slip peeling occurred.

Substrate Type Can Have A Significant Impact Failure Mode

Interaction of interfacial forces and material properties



Rate and temperature dependence comes from rheological properties of the adhesive and backing

Cold and/or fast

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ARIZONA STATE UNIVERSITY
PHOTOVOLTAIC RELIABILITY LABORATORY

IRA A. FULTON SCHOOLS OF engineering
ARIZONA STATE UNIVERSITY

Performance and Reliability Evaluation of CPV Systems

Mani G. TamizhMani
ASU-Photovoltaic Reliability Laboratory

Presentation Objective

To provide objective field evidence why accurate **LONG-TERM tracking** and **NON-ADJUSTABLE misalignment** issues are extremely critical for the success of high concentration CPV systems.

Outline

- System Description
- Performance and Reliability Results
- Key findings
- Conclusions

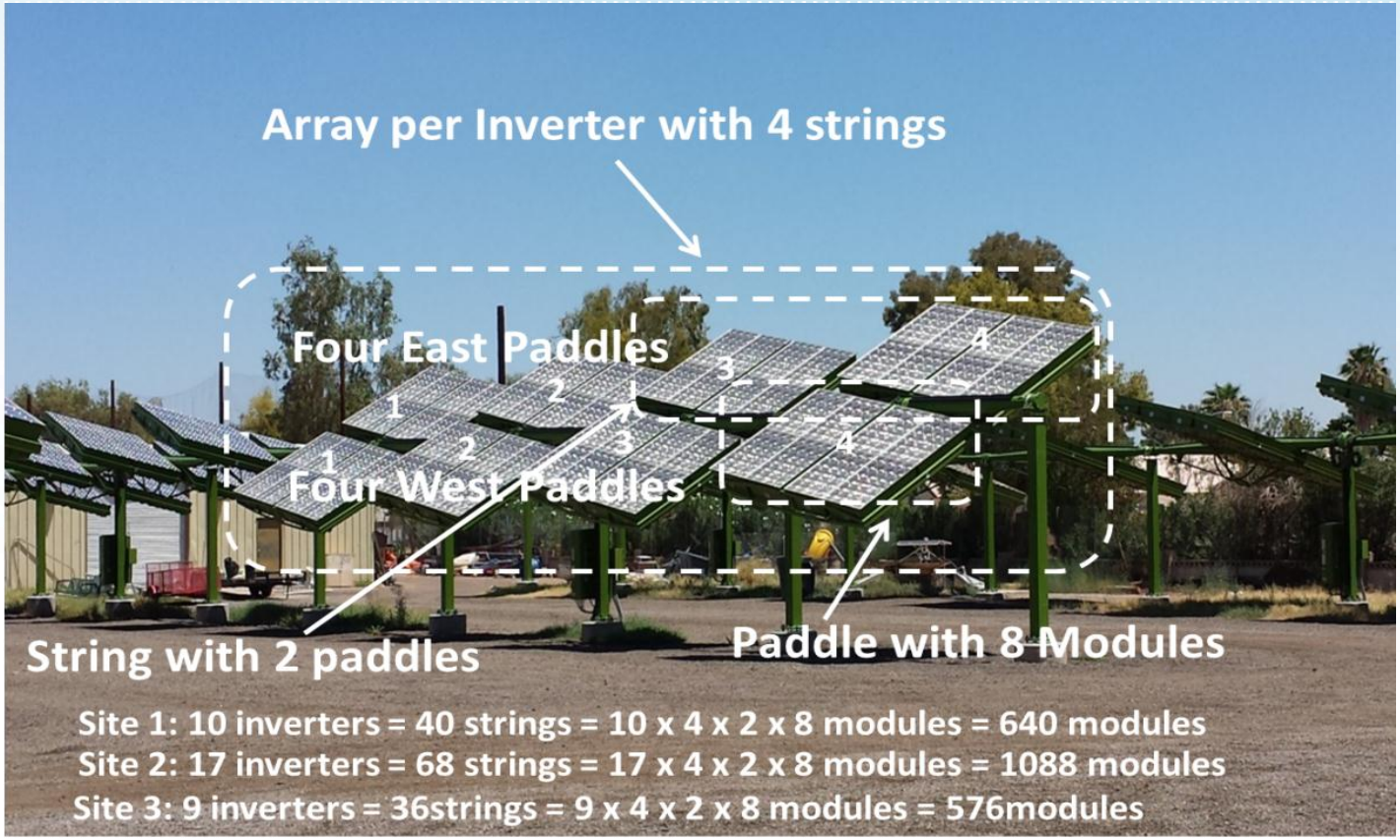
System Description

Site	Size (kW_{DC})	Age (y)
Plant 1	160	2.25
Plant 2	272	2
Plant 3	144	1

Concentration 1300x (tracking resolution 0.1°)

Module Rating 900 W/m² DNI, 25°C Cell T

Rated P_{max} 250 W



Controller software adjusts the tracking of:

- Array
- Strings in an array
- Paddles in a string

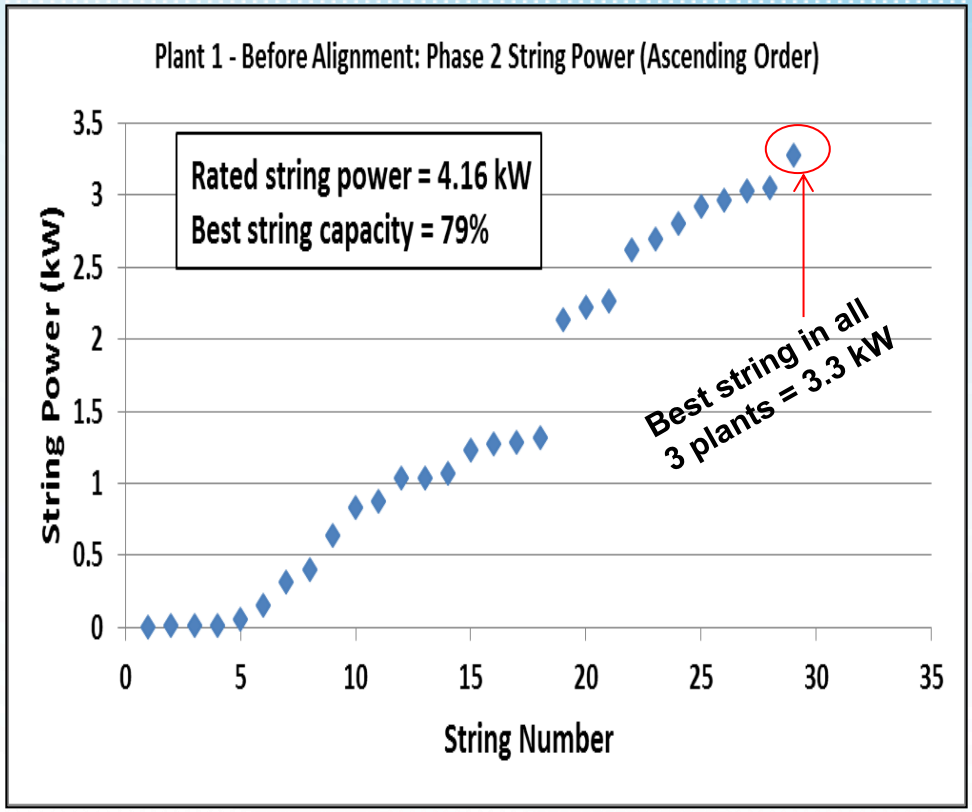
…..but not of:

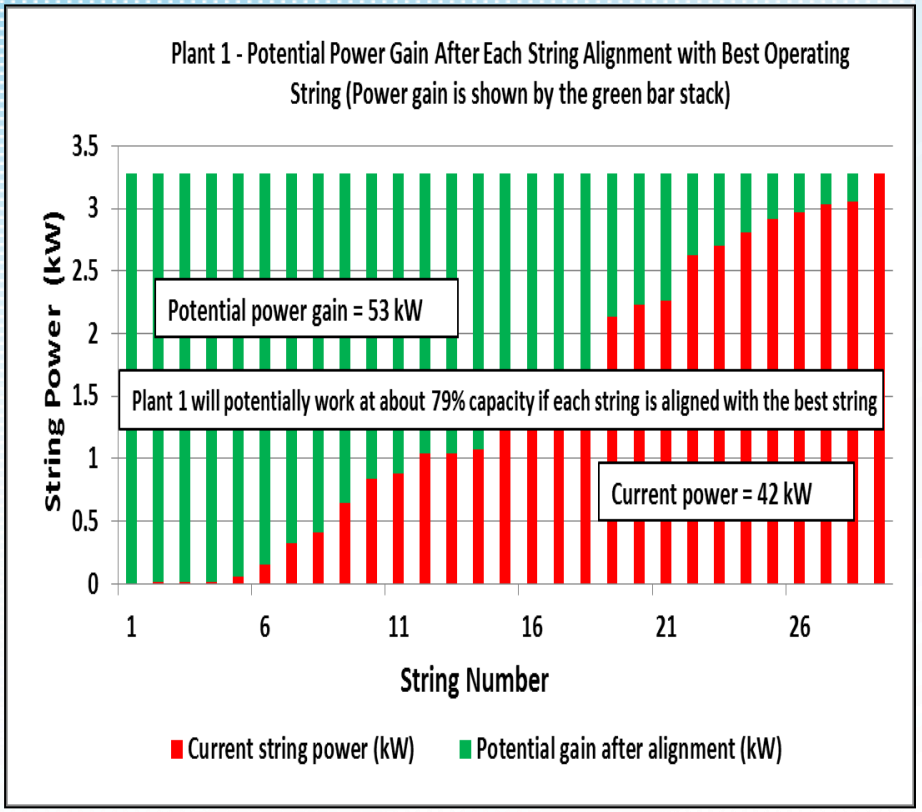
- Modules in a paddle
- Optics in a module
- Receivers/cells in a module

Note: I-V curves were translated with a voltage temperature coefficient of -99.1 mV/°C (-0.12%/°C) and a current temperature coefficient of 2.34 mA/°C (0%/°C) assuming heat-sink temperature is equal to cell temperature.

Performance and Reliability Results

Plant 1



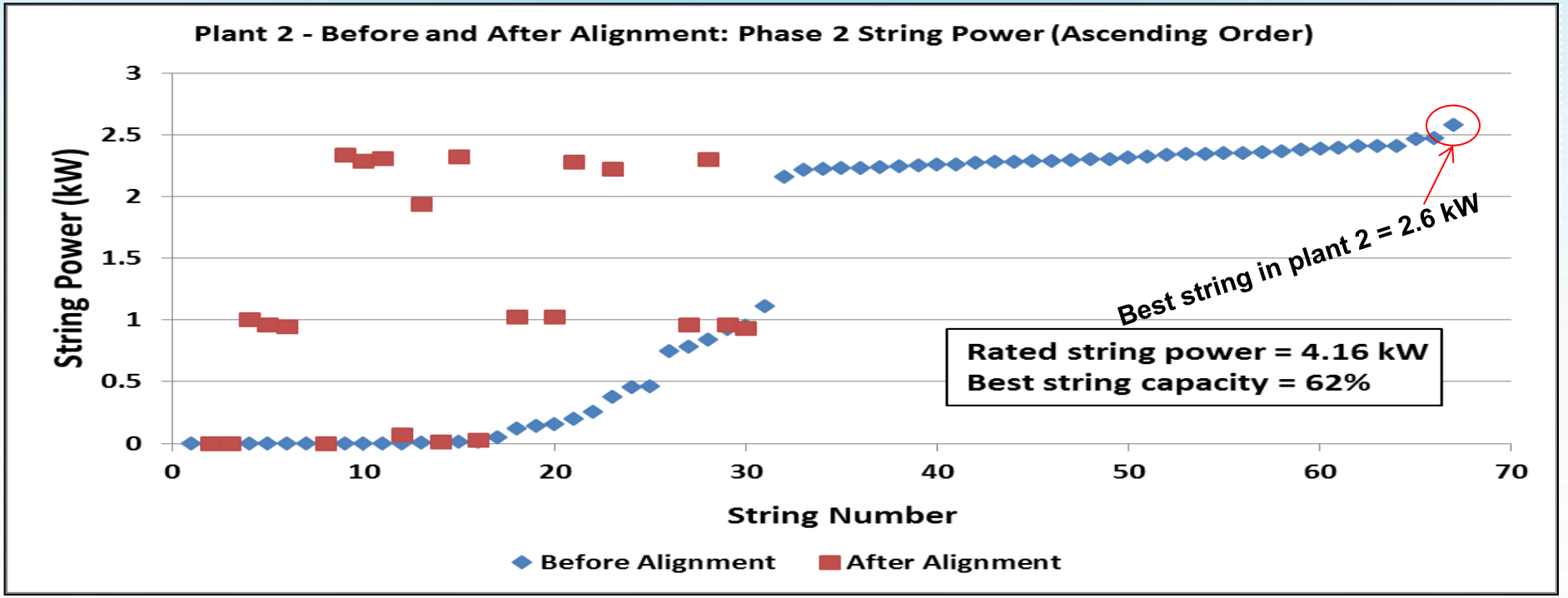


Best string capacity = 79%
Non-adjustable HARDWARE issue = 21% loss
(Intrinsic issue)

Potential gain if each string is adjusted to best string performance using tracker controller SOFTWARE and adjustable hardware
(Extrinsic issue)

Note: Intrinsic issue is probably caused by the misalignment and/or degradation of optics and/or receivers/cells due to thermal cycling stresses which cannot be fixed in the field.

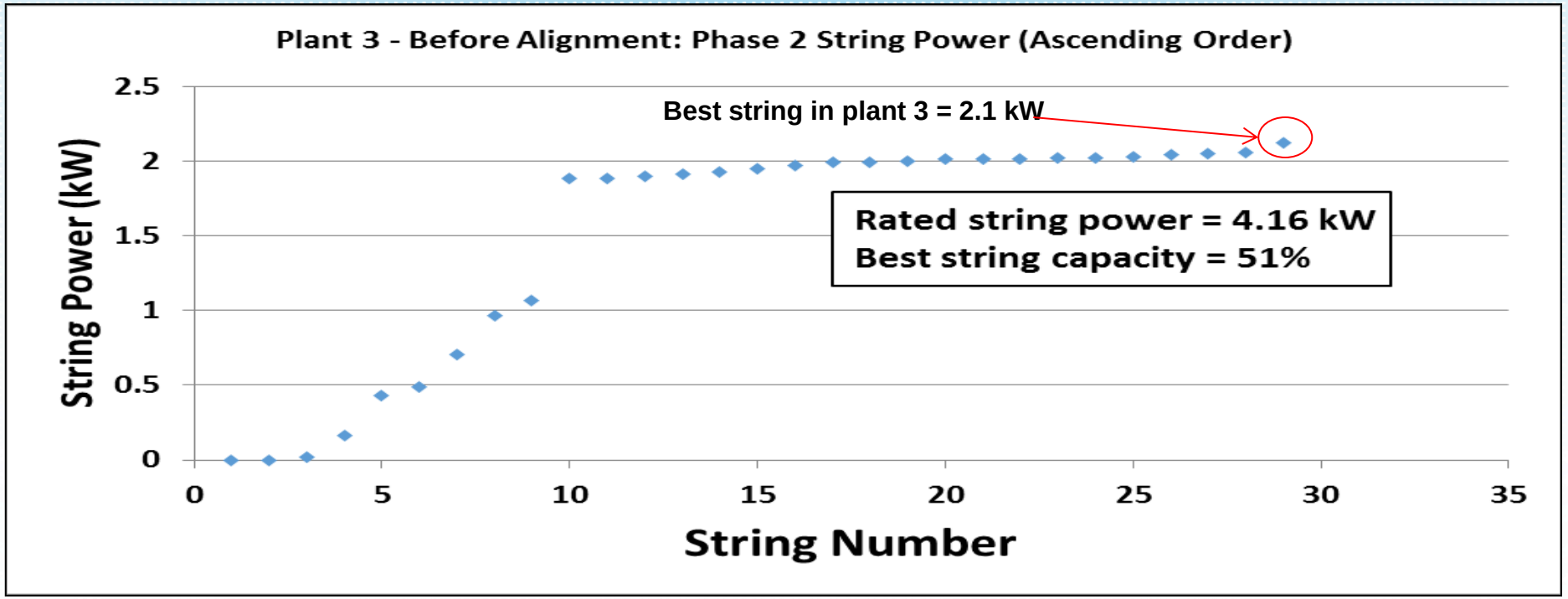
Plant 2



Best string capacity = 62% (has potential to be improved to 79% - see previous slide)

Important note: After manual alignment of strings and paddles (not modules or receivers) using a sundial and pyrheliometer, a few of the bad strings gained power but not to the full 100% capacity. The 100% non-recovery issue could be due to combination of two reasons: intrinsic issue (see previous slide) and inaccuracy in our manual alignment using unsophisticated mechanical sundial and 5° full view angle based pyrheliometer which are not sufficient for these 1300X CPV designs..

Plant 3



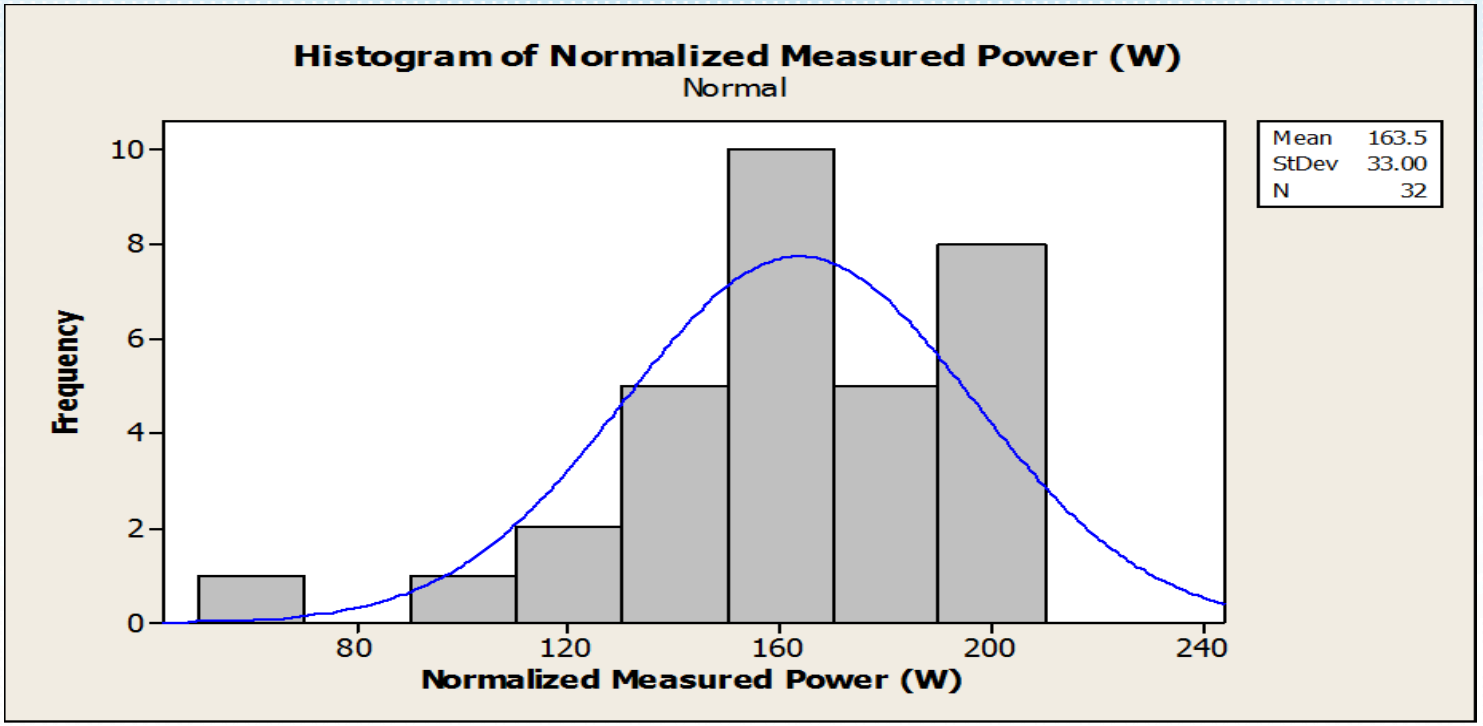
Best string capacity = 51% (has potential to be improved to 79% - see slide 7)

P_{max} of Individual Modules

(32 modules individually tested; modules are from the best array based on inverter kWh data)

Module Rating **900 W/m² DNI, 25°C Cell T**

Rated P_{max} **250 W**



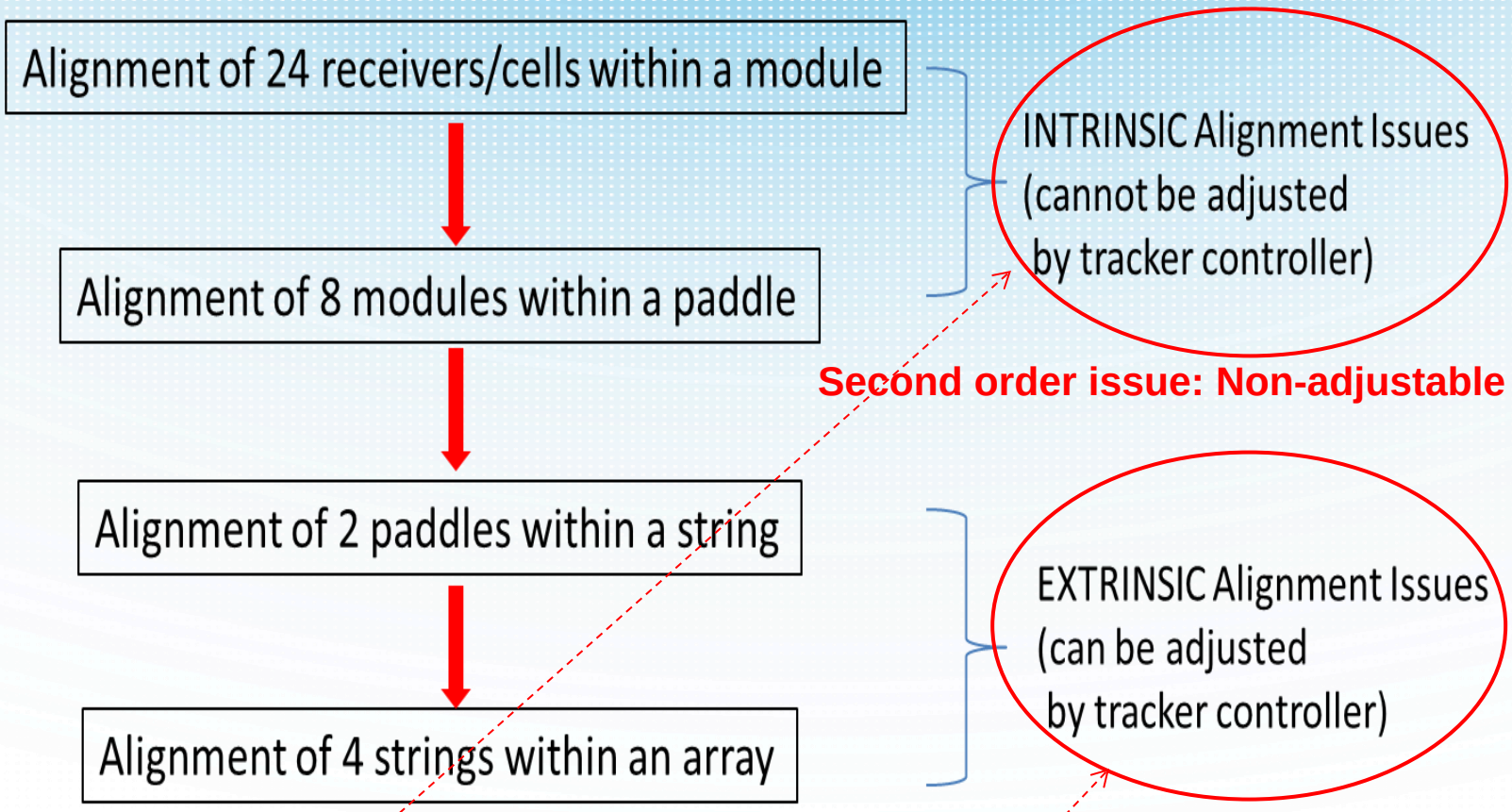
Best module capacity = 79%; Non-adjustable HARDWARE issue = 21% loss (Intrinsic issue)

Note: Intrinsic issue is probably caused by the misalignment and/or degradation of optics and/or receivers/cells due to thermal cycling stresses which cannot be fixed in the field.

Key Findings

- Best string and best module are operating at about 79% of rated capacity.
- 7 out of 36 arrays in all three power plants are not producing any power at all
  - Indicated a severe off-axis tracking issues on 7 arrays
- The best performing array operates at 70% of the rated capacity; all working arrays (29 out of 36) are underperforming at less than 70% of the rated capacity
  - Indicated that the strings, paddles and/or modules are having serious misalignment issues
- On an average, all operating and non-operating arrays (36 arrays) are working at **41% of rated capacity (Just less than 2 years old!)**
  - Indicated that the strings, paddles and/or modules (optics and receivers) are having serious misalignment issues

Conclusions



Second order issue: Non-adjustable hardware

First order issue: Complex software

Presentation Objective

To provide objective field evidence why accurate **LONG-TERM tracking** and **NON-ADJUSTABLE misalignment** issues are extremely critical for the success of high concentration CPV systems.

Thanks for your attention!

Contact:
Mani G. TamizhMani
manit@asu.edu

Prototyping and Validation of Two Low-Cost Inline CPV Module Efficiency Characterization Methods

Michael Sinclair, Stephen Caelers, Pascal Dufour,
Stefan Myrskog, John Paul Morgan

morgansolar

February 24th 2015

Presentation at PV Module Reliability Workshop

Golden, Colorado

The Problem

- Quantifying CPV performance is challenging!
  - Requires a collimated solar simulator (CSS) to test to Concentrator Standard Test Conditions (CSTC)
  - High CAPEX and high operating costs
  - Hard to maintain calibration
  - Requires highly trained operators and technicians
  - Repeatability σ = 2.8% (current system at MSI)

Is there another way?

The Solution

- Prototype new tools for low cost in-line efficiency estimation
- Use standard automation equipment to reduce complexity and minimize sources of variation
- These alternative techniques will estimate optical efficiency (I_{sc}) for individual optics
  - Module P_{mp} can be calculated based on an average cell model (Future work!)

The Solution

- Key Question:
  - How accurate does the estimate need to be?

Agenda

1. Laser Solar Simulator
   i. Approach
   ii. Experimental Set-Up
   iii. System Performance
   iv. Results

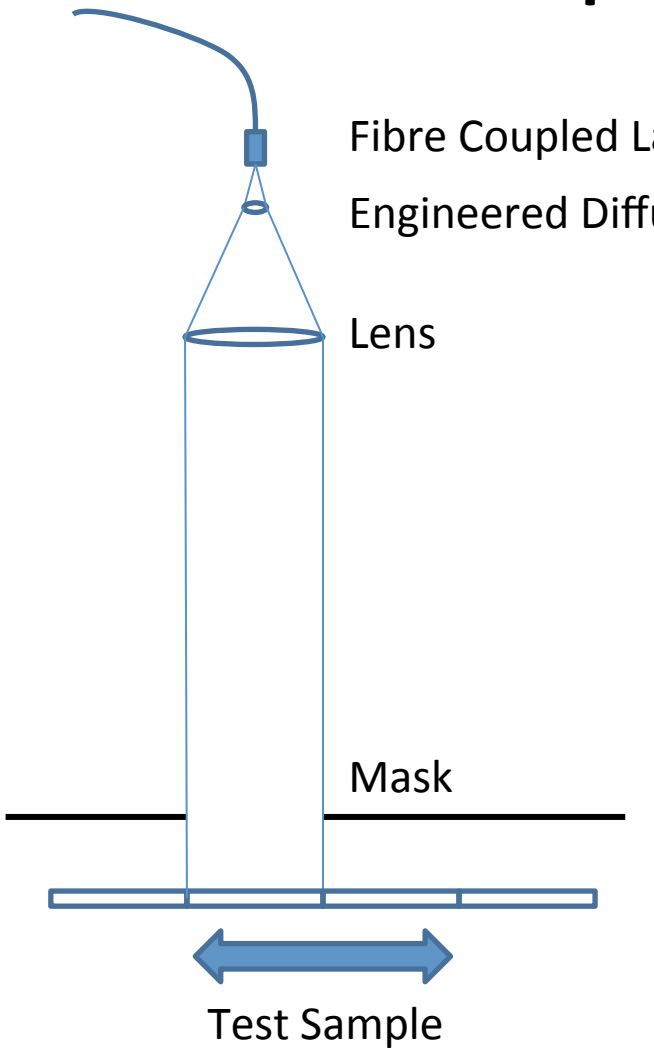
2. Electroluminescence Imaging
   i. Approach
   ii. Experimental Set-Up
   iii. System Performance
   iv. Results

3. Conclusions

LSS: Approach

1. The output beam from a fibre-coupled laser system is collimated over the area of one optic
2. A two-axis translation stage shuttles the sample under the collimated beam
3. I_{sc} is directly measured for each individual optic

LSS: Experimental Set-Up



- The sample translates under a stationary imaging system
- Not shown: Laser source, 2-axis translation stage, LabVIEW GUI

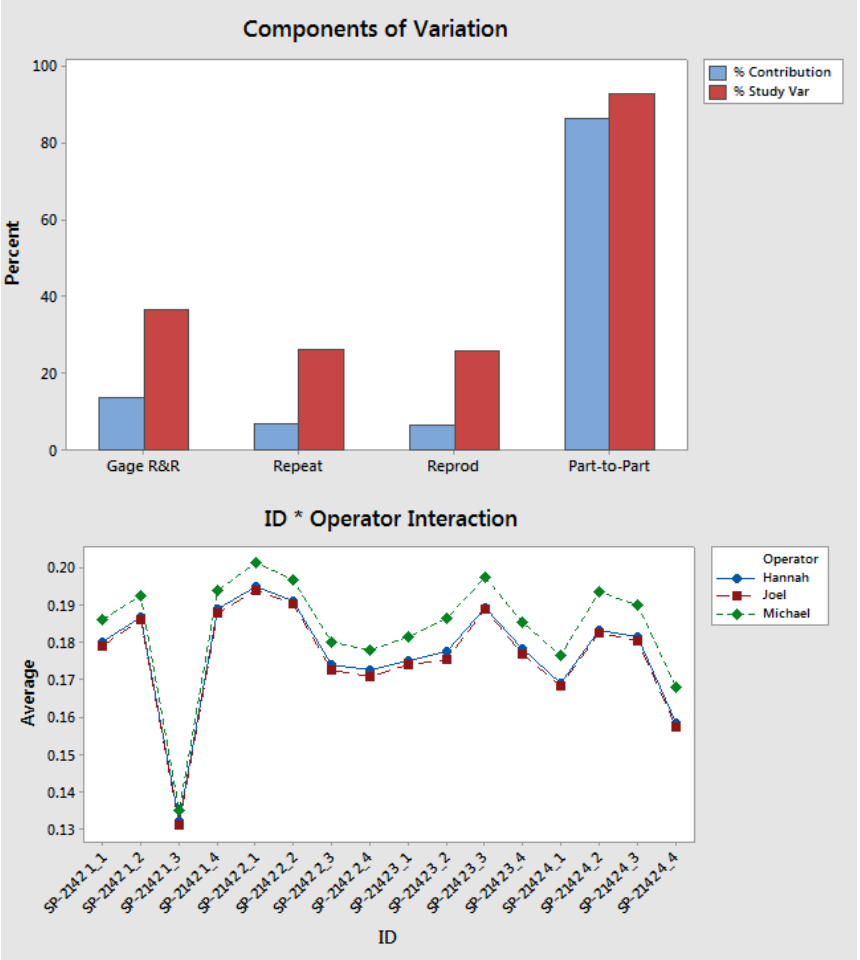
LSS: System Performance

- Collimation: ±0.5°
- Irradiation Non-Uniformity: ±5%
- Fast results: less than 2 seconds per optic

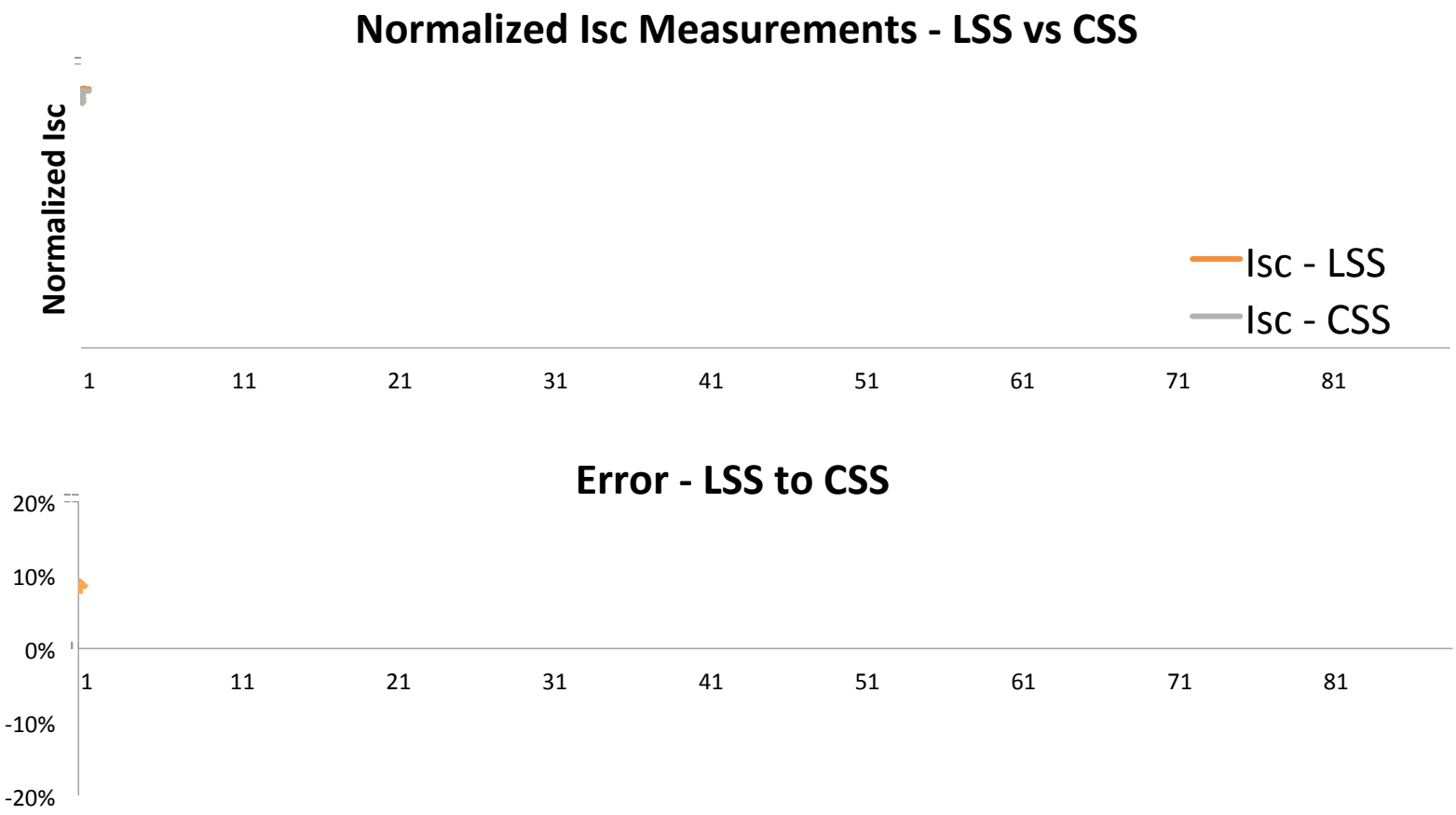
LSS: System Performance

- Gauge R&R results:
  - Not great!
  - Repeatability σ = 3.4%

Source	% Contribution (of VarComp)
Total Gage R&R	13.49%
Repeatability	6.88%
Reproducibility	6.61%
Part-to-Part	86.51%
Total Variation	100%



LSS: Results



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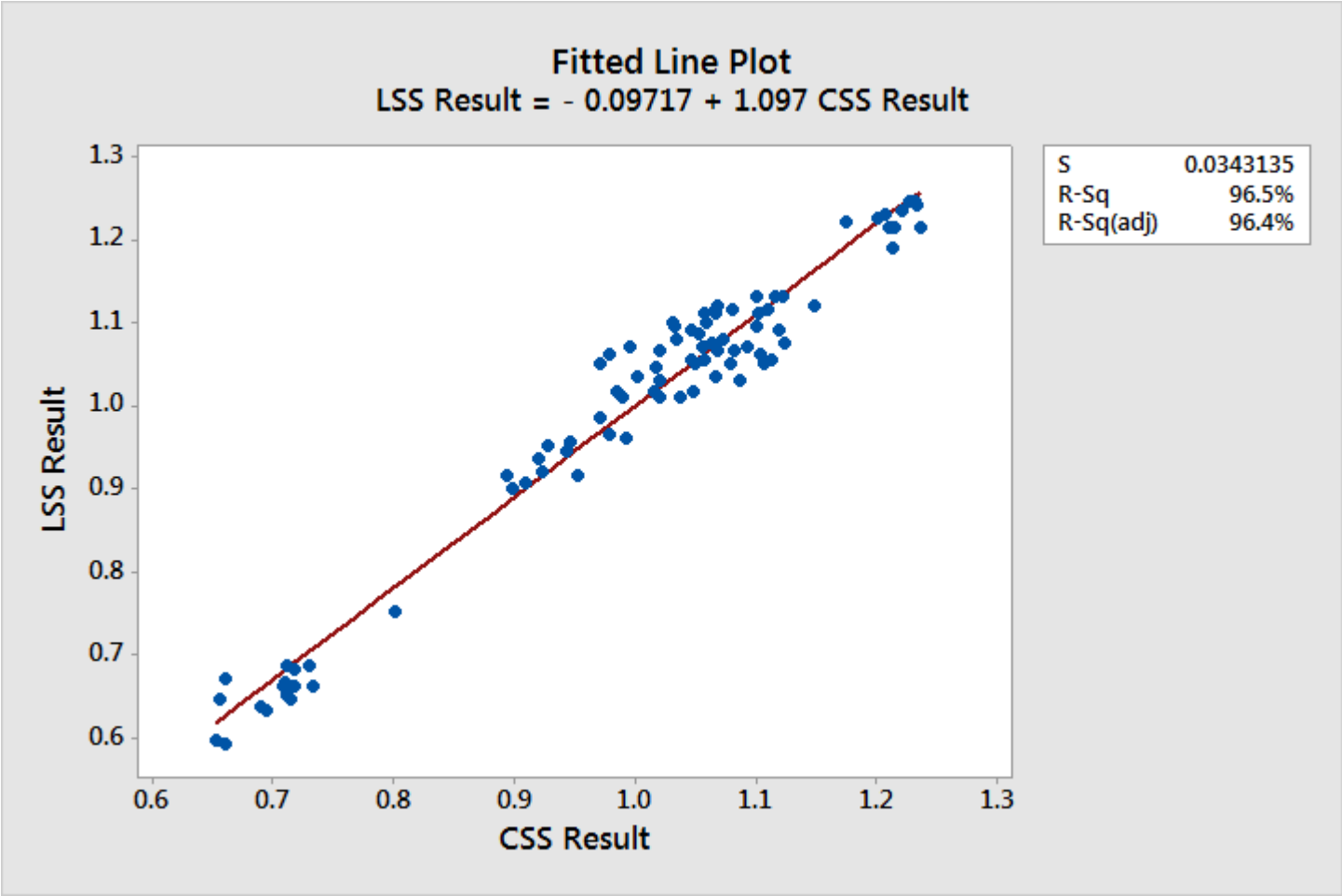
LSS: Results


Fitted Line Plot
LSS Result = - 0.09717 + 1.097 CSS Result
S 0.0343135
R-Sq 96.5%
R-Sq(adj) 96.4%
LSS Result
CSS Result
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3

Agenda

1. Laser Solar Simulator
   i. Approach
   ii. Experimental Set-Up
   iii. Performance
   iv. Results

2. Electroluminescence Imaging
   i. Approach
   ii. Experimental Set-Up
   iii. Performance
   iv. Results

3. Conclusions

EL: Approach

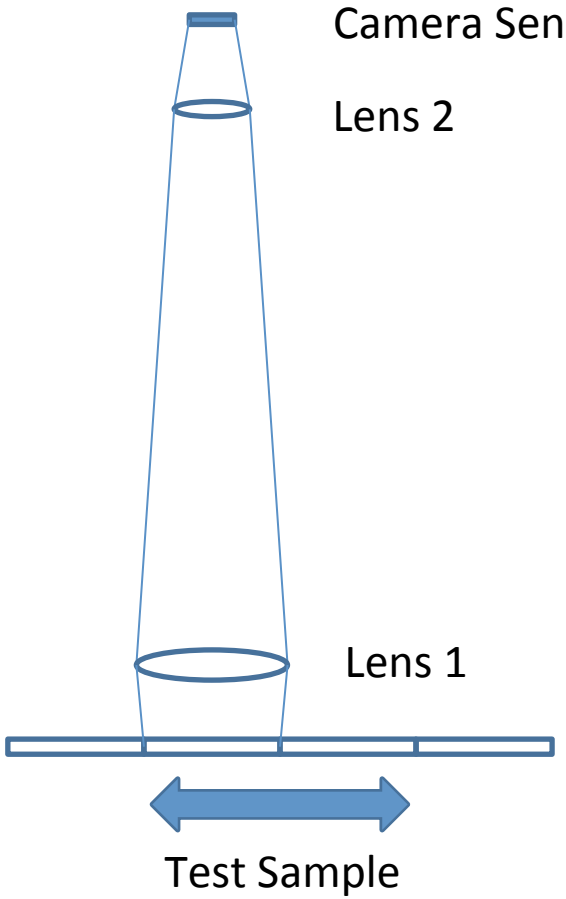
- Electroluminescence (EL) imaging is widely used in PV manufacturing for defect detection

- Reversible Systems
  - Solar cell -> LED
  - Concentrator -> Collimator

EL: Approach

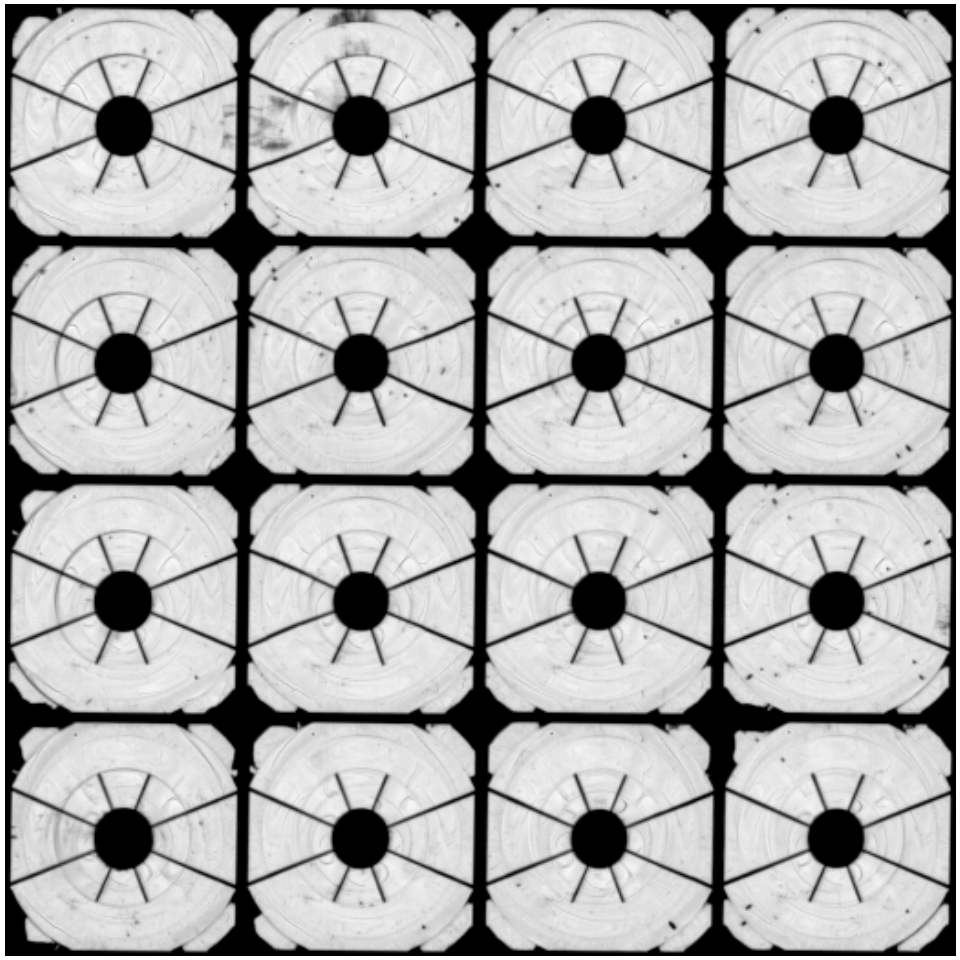
1. Constant current is applied to the test module leads
2. The collimated output beam is imaged by the test system
3. Individual optic images are processed to make I_{sc} estimate

EL: Experimental Set-Up



- The sample translates under a stationary imaging system
- Not shown: power supply, 2-axis translation stage, LabVIEW GUI

EL: Approach



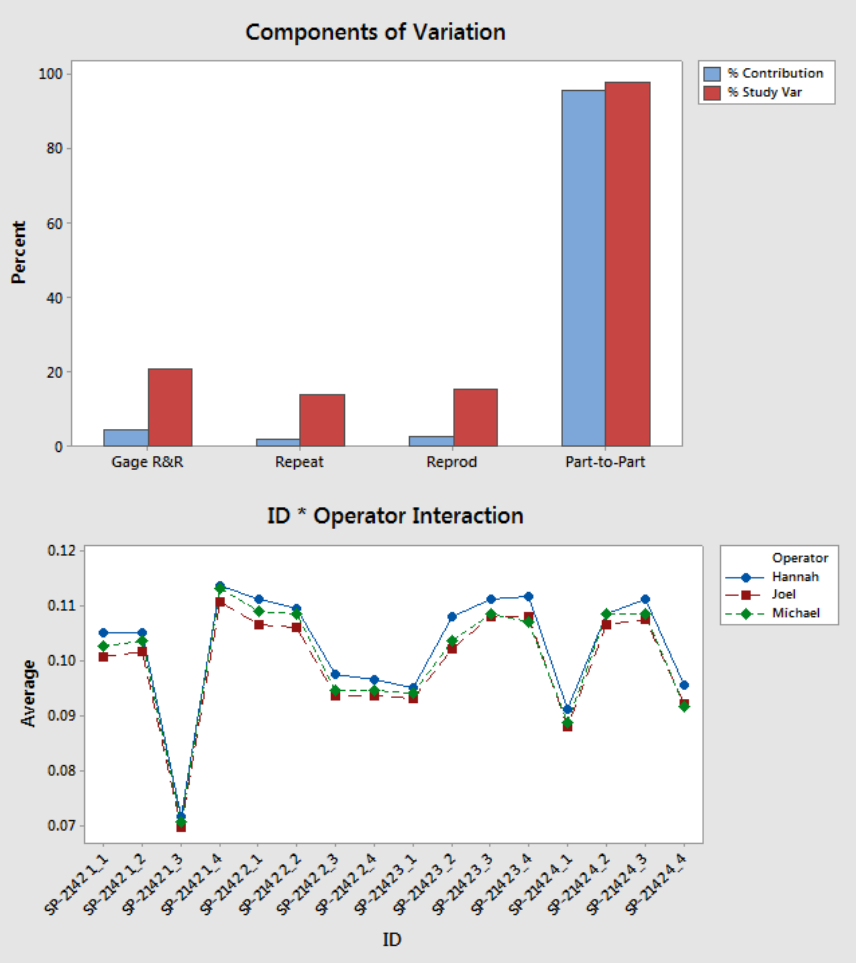
EL: System Performance

- We developed a lab-scale system which provides:
  - Fast feedback –> less than 5 seconds per optic
  - High resolution –> 40 µm
  - Meaningful test images
  - Proof-of-concept for a production test system

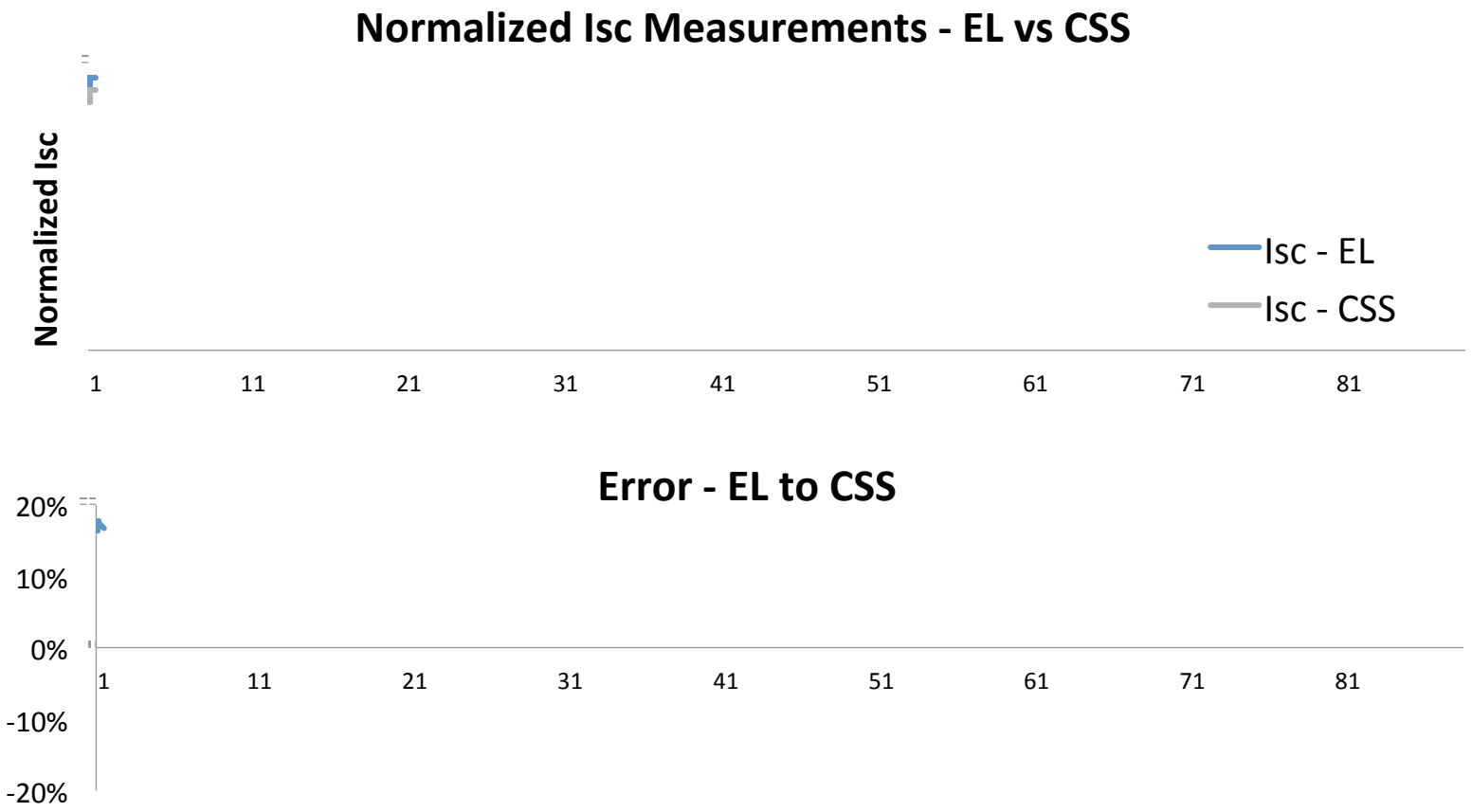
EL: System Performance

- Gauge R&R results:
  - Good!
  - Repeatability σ = 2.3%

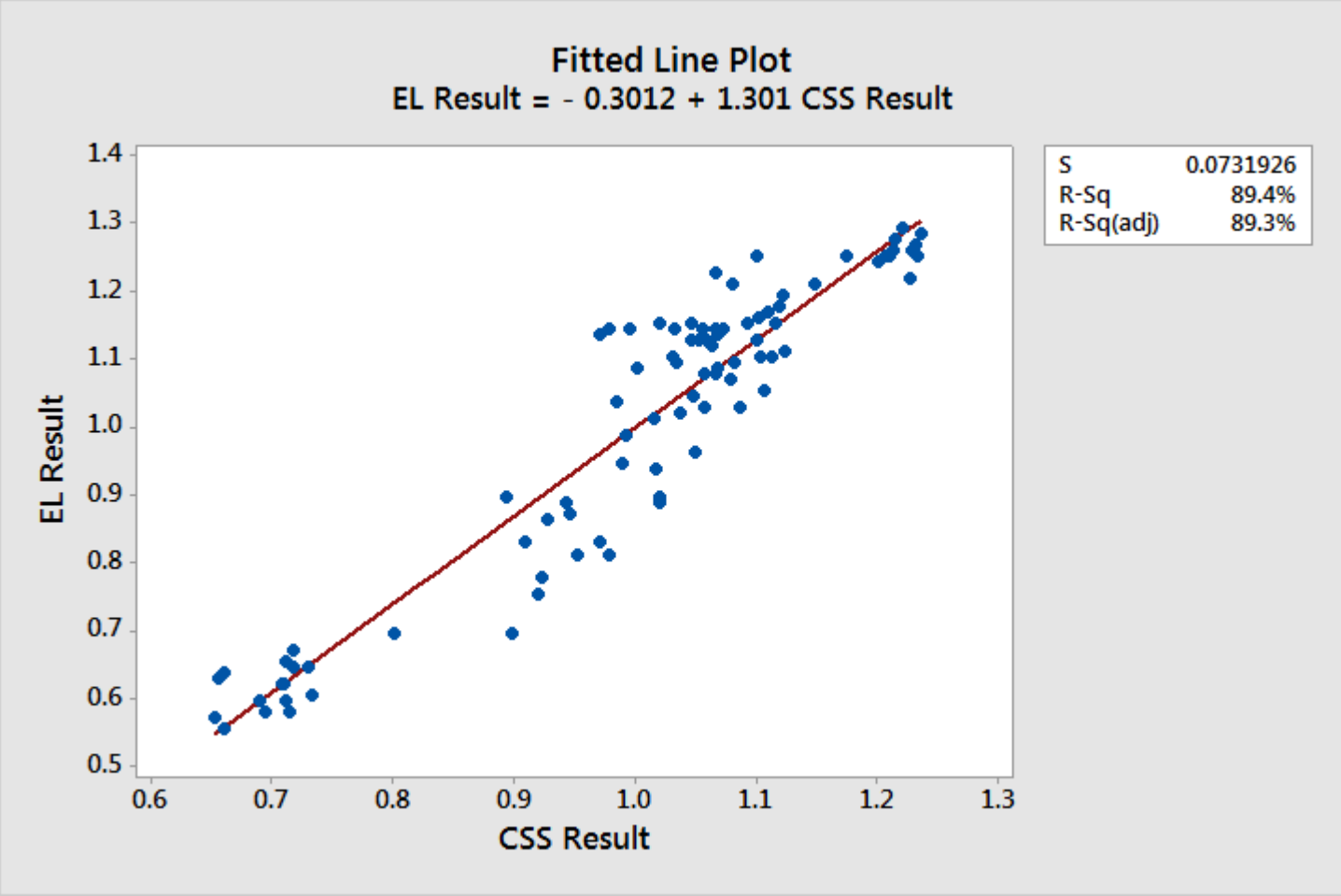
Source	% Contribution (of VarComp)
Total Gage R&R	4.33%
Repeatability	1.94%
Reproducibility	2.39%
Part-to-Part	95.67%
Total Variation	100%



EL: Results


Normalized Isc Measurements - EL vs CSS
Normalized Isc
Isc - EL
Isc - CSS
1
11
21
31
41
51
61
71
81
Error - EL to CSS
20%
10%
0%
-10%
-20%
1
11
21
31
41
51
61
71
81

EL: Results



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Review

- Two low-cost efficiency estimation tools are in development

	CCS	LSS	EL
Repeatability (σ)	2.8%	3.4%	2.3%
Accuracy to CSS (σ)	-	3.4%	7.3%

- Further improvements are required to improve estimation accuracy

Conclusions

- Alternative solutions for quantifying CPV module performance at CSTC can be considered
  - Careful calibration of test results to CSTC is essential
  - Additional quality systems requirements can be designed to facilitate low-cost testing methodologies

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Thank You!
morgansolar

February 24, 2015

Semprius' Approach to Flash Testing

Steven Seel & Brent Fisher

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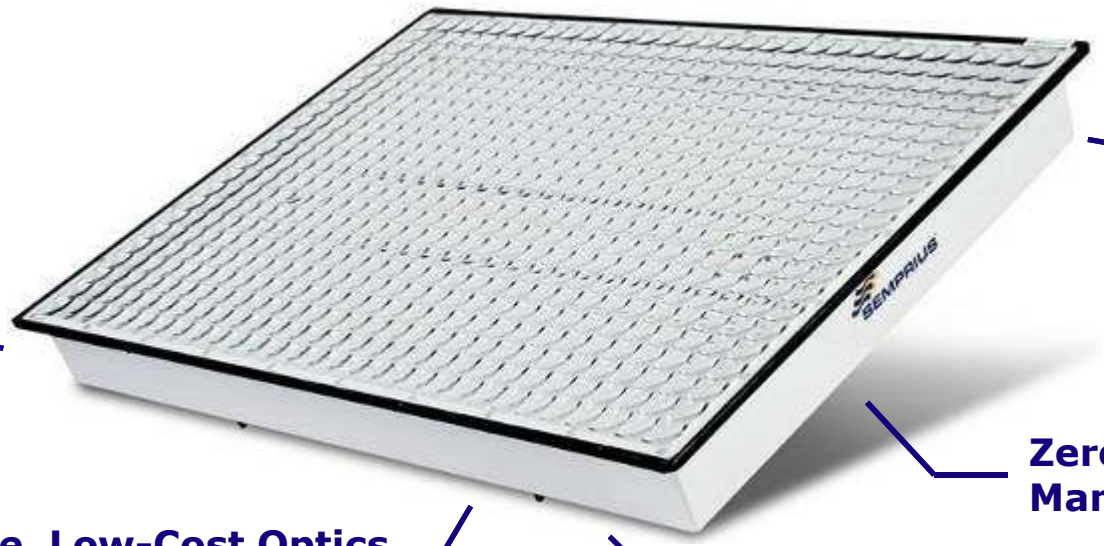
Semprius Design Advantages

World's Highest Efficiency
- 35.6% efficiency
- Near-term path to 42%

High Efficiency, Low-Cost Microcells
- 600 x 600 microns
- >41% triple junction cells
- Substrate reuse cuts cost in half



Lightweight
(7.3kg)

Thin
(68 mm)

Zero Cost Thermal Management

High-Performance, Low-Cost Optics
- 1,100 → 1600X concentration
- Wide angle of acceptance
- Uniform energy flux on cell

Standard Manufacturing Processes

High Efficiency – Low Cost – High Reliability

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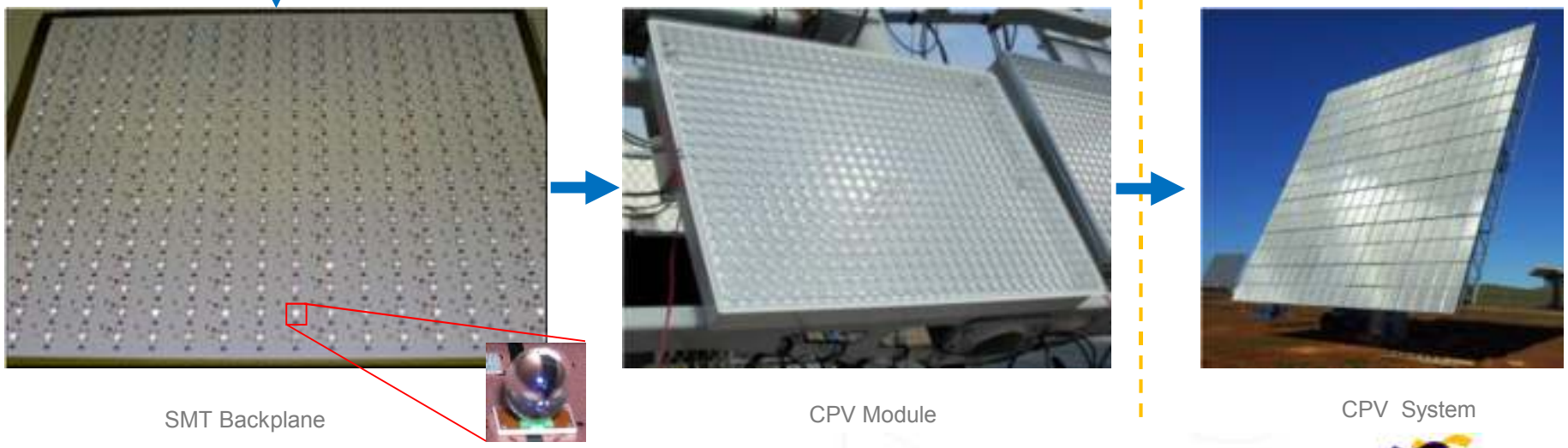
Overview of Semprius CPV Approach



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SEMPRIUS

100% Quality Control Testing

- Solar cells
  - Printed solar cell within 10um of nominal position
  - NIR inspection for voids in cell attach
  - Automated visual inspection for defects
- Solar cell on interposer
  - Dark & Light IV
  - Electroluminescence image inspection for defects
  - Thermal transient testing to evaluate die attach
- Backplane
  - Dark-IV testing (shunt & series resistance)
  - Reverse bias for by-pass diode check
- Module
  - Electroluminescence image inspection for defects
  - Leak test of seal integrity (pressure decay)
  - Hipot (3600V for 1sec) & wet hipot on sampling basis
  - **Flash test**

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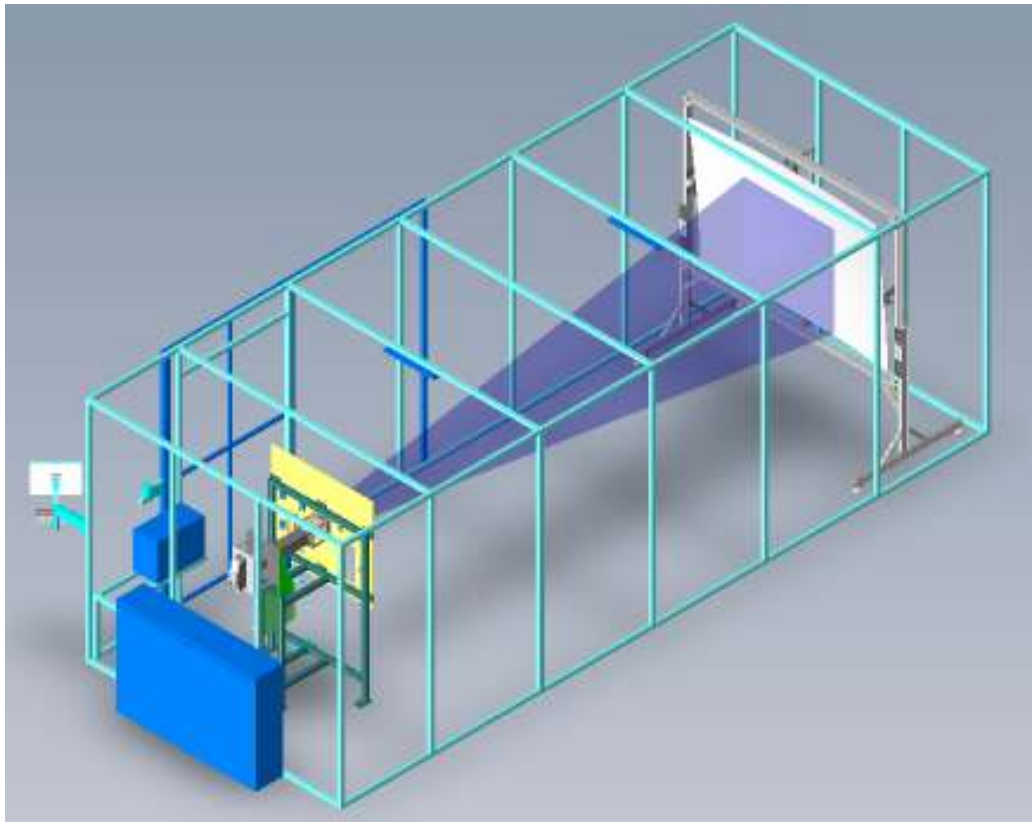
Semprius Flash Test System



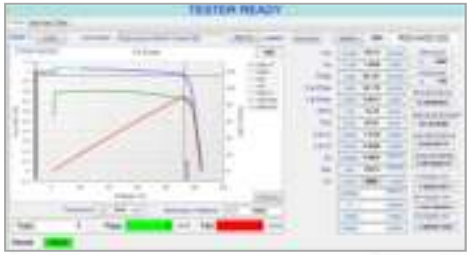
- ABB rating (ASTM E927-05) for spectral match, spatial uniformity, and temporal stability
- Xenon flash bulb capable of nearly 1000 W/m^2 in test plane (Si detector)
- Collimation better than 0.4 degrees
- Custom spectral filter to match AM1.5D spectrum
- 3 isotype cells, silicon reference cell, and triple-junction mini-module

Flash

Reflect

Illuminate

Measure



Label

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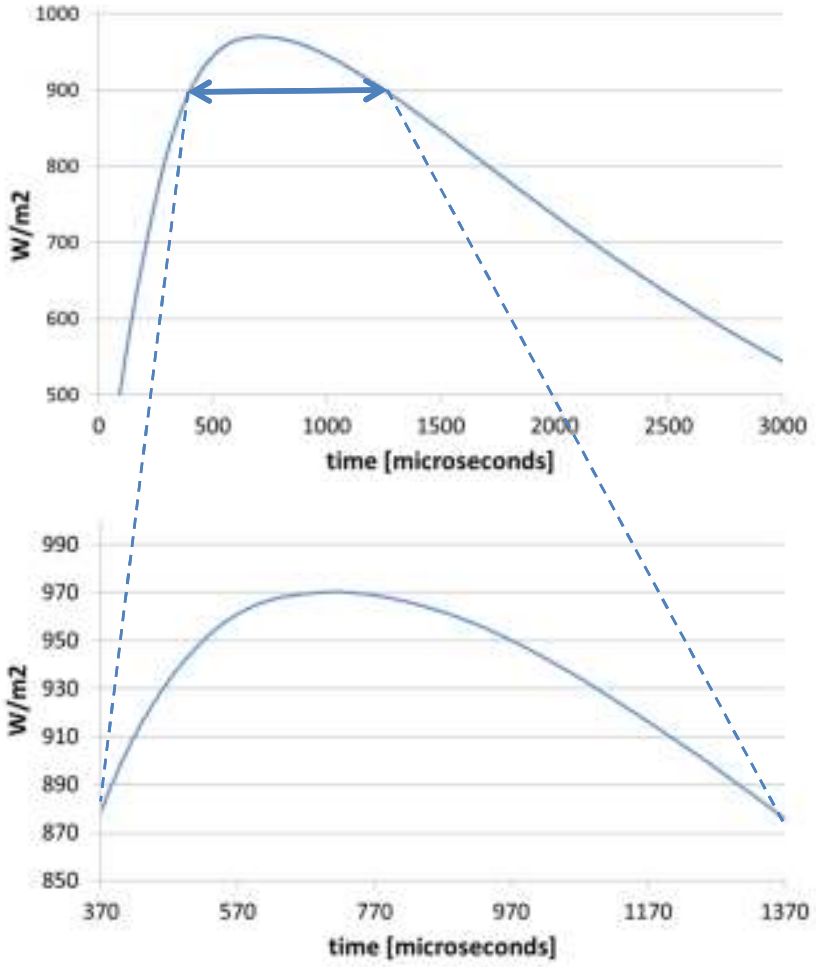
Temporal Stability

Flash Pulse Duration



- Flash duration of several milliseconds
- 200-point LIV curve acquired in 1.0 msec
- Temporal stability of < ± 5% (Class B)

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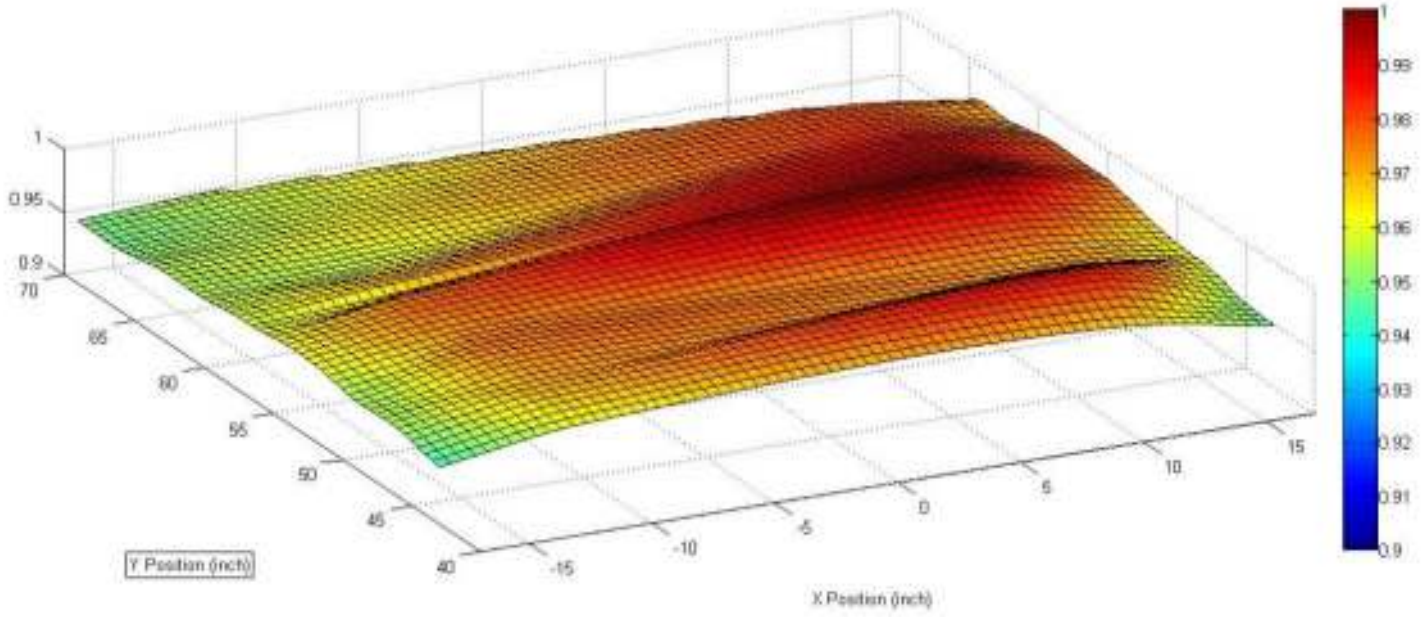
Spatial Uniformity

- 40 measurements with Si detector over 1m^2 area
- 2.8% non-uniformity, defined as (max - min)/(max + min)/2
- Class A uniformity defined as <2% non-uniformity (ASTM E927-05)



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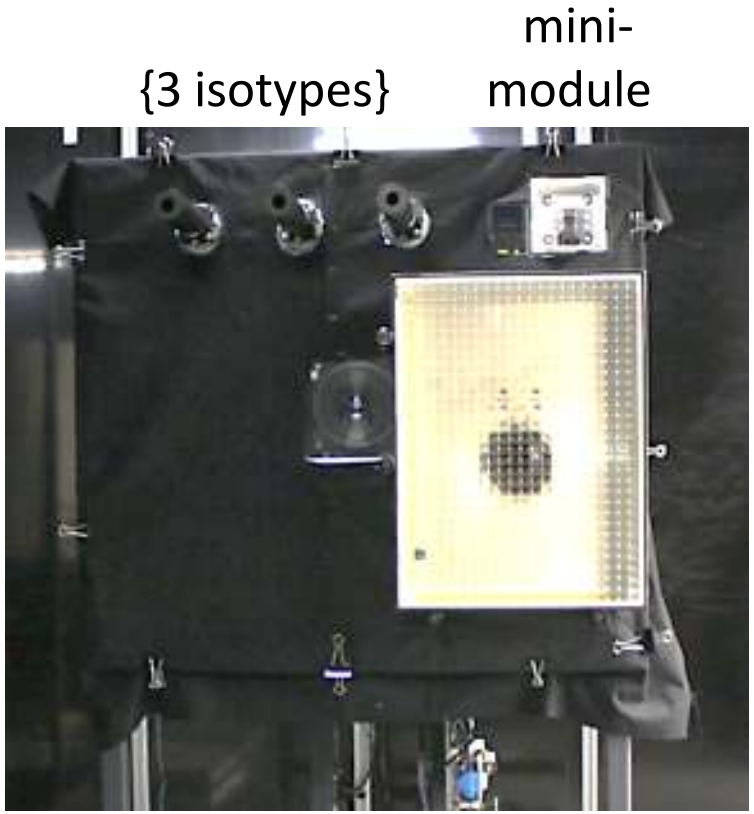
Spectral Match

- Custom filter designed so spectral matching ratios (SMR) for triple-junction cell emulate AM1.5D spectrum
- 3 isotype cells (grown by epi supplier and calibrated at NREL) allow SMR measurements during flash
- Minimodule measured during flash to correct for spectral response by normalizing measured module current



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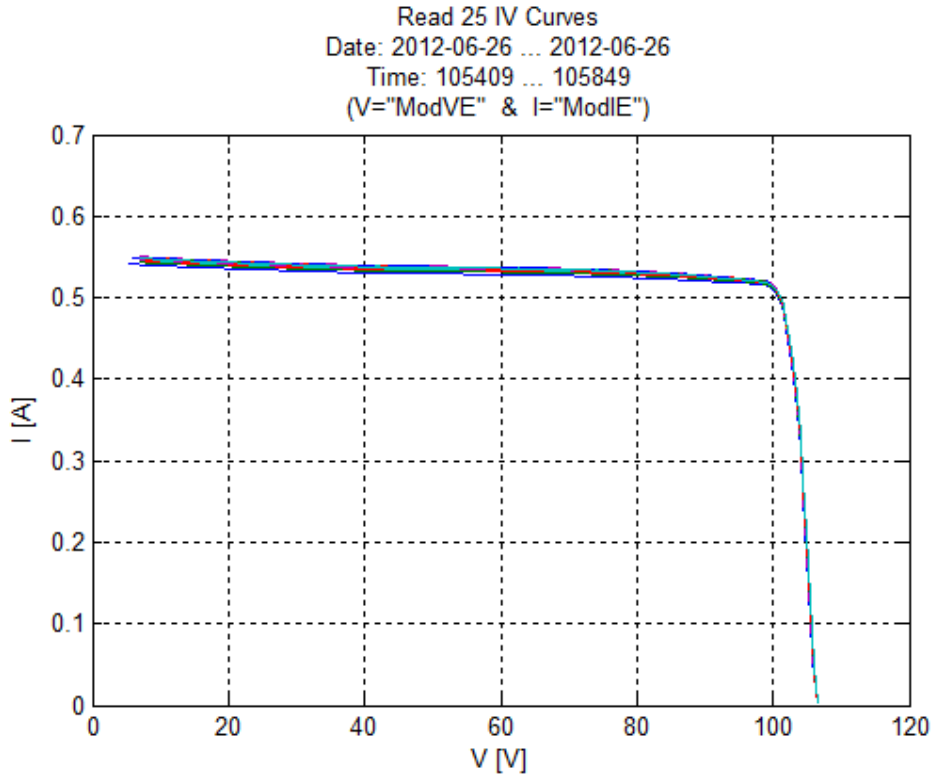
Flash Repeatability (without removing module)

- 10-sec interval between flashes
- Repeated 25X in a row
- Demonstrates recovery time of flash bulb system
- Demonstrates repeatability of data acquisition during 1ms window of flash



Metric	STDEV (%)
Voc	0.04%
Isc	0.39%
Vmp	0.05%
Imp	0.21%
Pmax	0.22%
Fill Factor	0.22%

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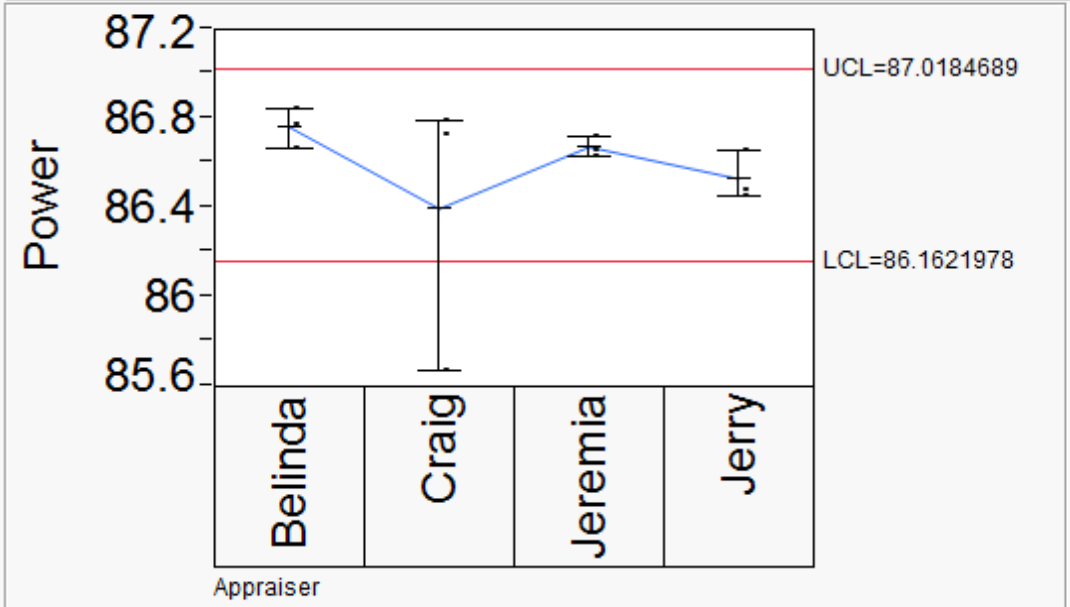
Variability of Flash Power by Appraiser (with removing module)

Variability Chart for Power



Variability Summary for Power

	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%	Minimum	Maximum	Observations
Power	86.59033	0.312271	0.090145	86.39193	86.78874	85.669	86.846	12
Appraiser[Belinda]	86.762	0.090598	0.052307	86.53694	86.98706	86.666	86.846	3
Appraiser[Craig]	86.39633	0.630701	0.364136	84.82958	87.96308	85.669	86.792	3
Appraiser[Jeremia]	86.673	0.046184	0.026665	86.55827	86.78773	86.634	86.724	3
Appraiser[Jerry]	86.53	0.108761	0.062793	86.25982	86.80018	86.457	86.655	3

Flash test repeatability better than ± 0.5W (~0.5%)

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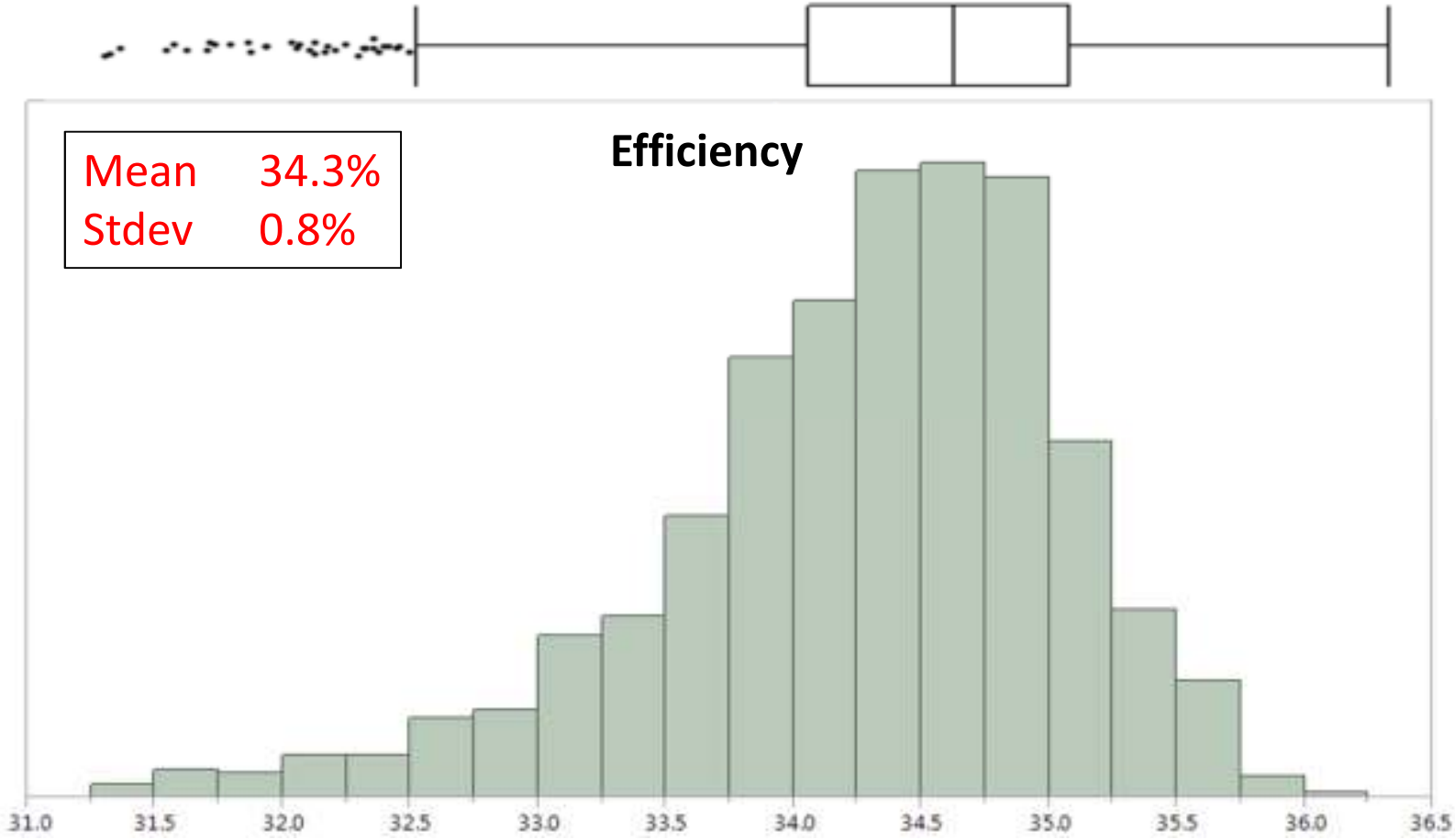
Reference Module Over Time (SPC of Tool)

Beside Pmax, also monitor flash intensity, Voc, Isc, SMR ratio on daily basis

© 2015 Semprius

Flash Test Results

- 1000 modules produced in Jan & Feb 2015



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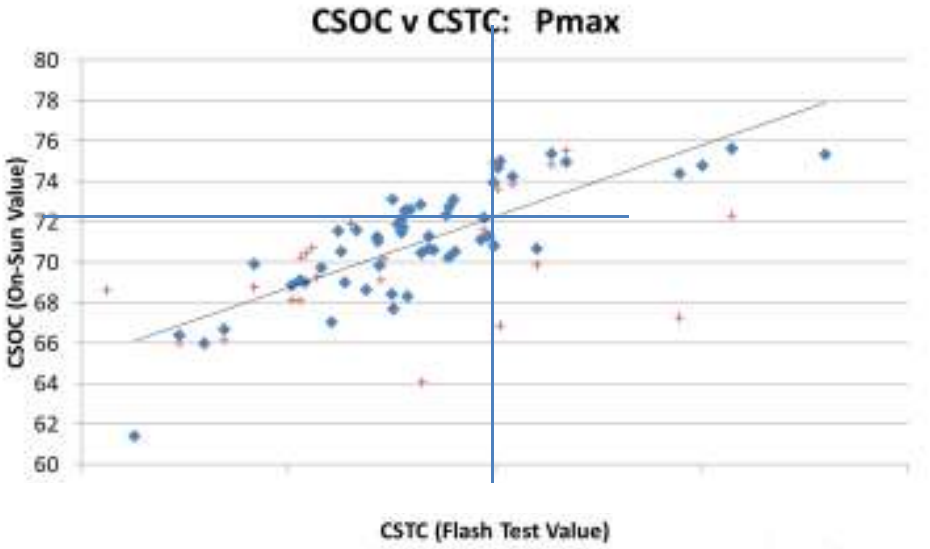
CSTC to CSOC correlation

- Concentrator standard test & standard operating conditions

Condition	Irradiance (W/m^2)	Temperature (C)	Spectrum	Wind Speed (m/s)
CSTC	1000	25C cell	AM1.5D	0
CSOC	900	20C ambient	AM1.5D	2.0

- Reference modules measured at Fraunhofer & UPM (Spain) to correlate on-sun performance to flash test results

- At Semprius, 75 modules flash tested then placed on-sun to compare performance



<5% uncertainty in CSTC to CSOC correlation at 2-sigma level

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Additional Flash Test Projects

- Zero voltage ramp testing
  - Monitor module current vs isotype cell currents during entire flash duration (during which spectrum shifts) to determine which subcell limiting
  - Enables characterization of Air-Mass dependence of module response
- Module angle-of-acceptance testing
  - Tip-tilt stage allow full AOA map in 15 minutes
  - Further development will allow full AOA map in single shot
- Flash test performance vs temperature
  - Heating/cooling to simulate on-sun performance vs temperature
  - Check for impact of pitch variation, focal length, etc.
- Future considerations
  - Automation: horizontal module orientation to allow conveyorized flash testing
  - More powerful light source and larger mirror for larger modules
  - 4J & 5J solar cells
    - More sensitive to spectral matching to AM1.5D
    - Custom light source & filter required but can't sacrifice light intensity

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Thank You!

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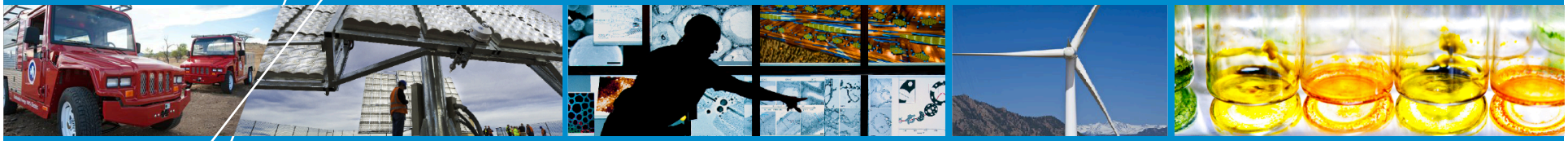
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Overview of IEC Testing for PID



Peter Hacke

National Renewable Energy Laboratory (NREL)

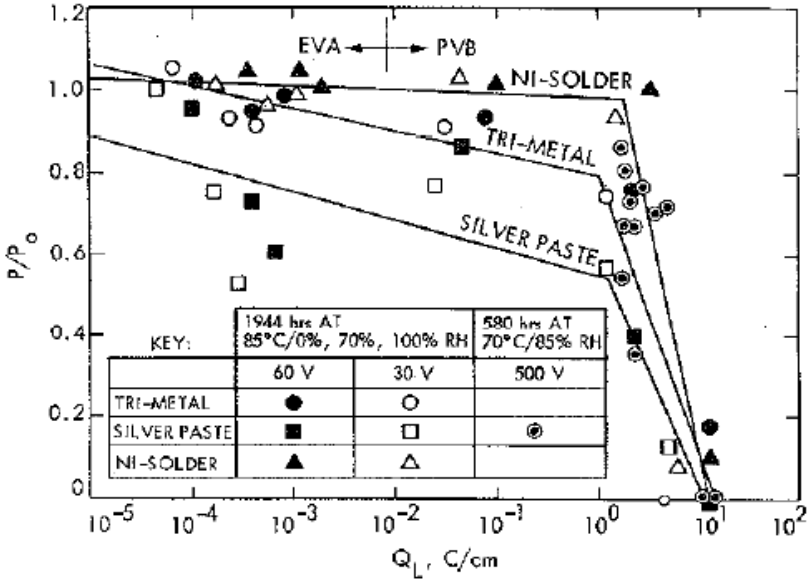
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

- **Introduction of mechanisms**
- **IEC 62804 – overview/history of PID test method**
- **Present status of test types**
  - Chamber test
  - Foil test
- **Future of IEC testing for system voltage stress**
  - Basic level testing (such as for qualification testing)
  - Climate-specific, lifetime predictions
- **Understanding of stress factor interactions**
  - Multi factor cyclic/combined stress testing

Introduction/background

- Mon, Ross/JPL 1970s and 1980s
  Degradation with ionic current coulombs transferred (c-Si, a-Si)

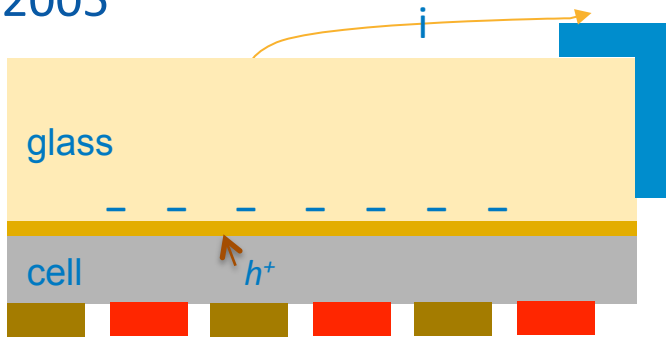


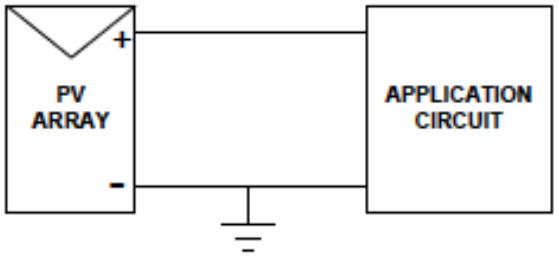
JPL- Mon, Ross (1985)

- Wohlgemuth/BP Solar (2000) showed TCO corrosion
- Osterwald/NREL (2003) showed corrosion occurs in the SnO_2:F transparent conductor layers in a-Si and CdTe modules; mitigated by:
  - Lowering humidity
  - Reduction of voltage potential between the frame and the active layer
  - More resistive packaging: changing from soda lime to borosilicate glass,
  - Moving the frame from the glass edge to adhesive bonding on the module rear

Introduction/background

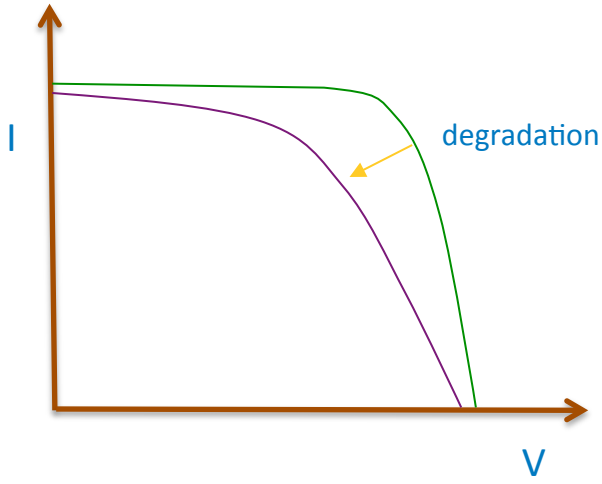
SunPower reports 'surface polarization' in n-base Si modules (field and test) in 2005





Swanson et al, Asian PVSEC (2005)

- Positive bias string leads to leakage current through glass to ground, leaving negative charge on cell surface, degrading effectiveness of the n^+ front surface field of the n^+/n structure
- Minority carriers (holes) recombine at front surface, leading to degraded cell performance



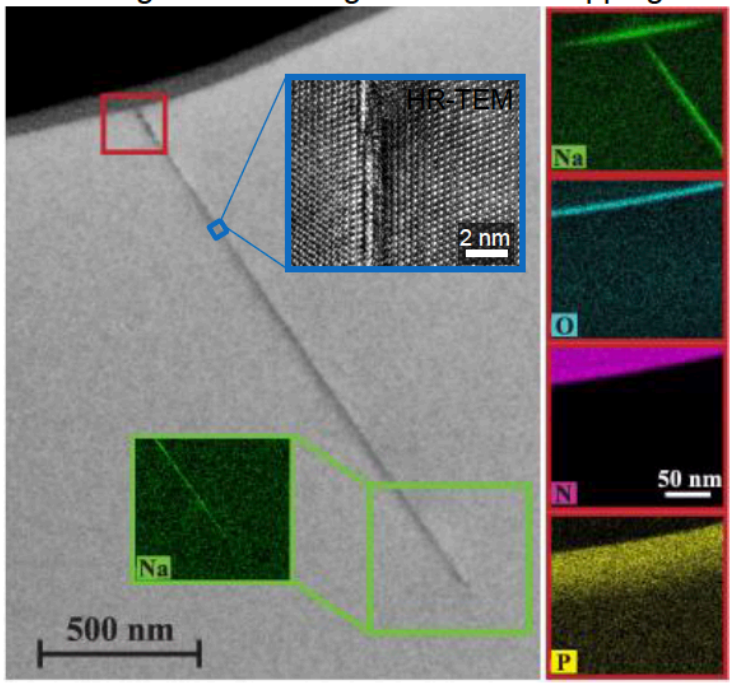
- SunPower ***also*** reports system voltage degradation in p-base Si modules (2005)
- Evergreen – field degradation (2008), SOLON – field degradation and testing (2010), NREL – testing(2010)

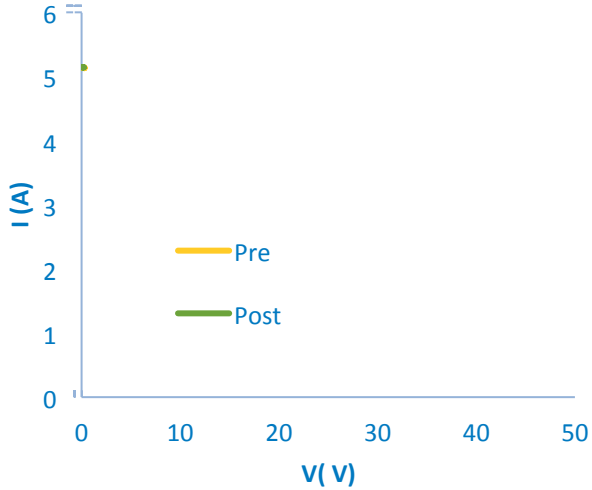
Introduction: Physical nature of PID n+/p Si cells

Negative system voltage strings

1. Positive Na ions electromotively attracted through encapsulant to silicon cell
2. Na diffusion to junction through stacking faults, $f(T, |\mathrm{Na}|)$

TEM image of a stacking fault + EDX mapping:





V. Naumann (Sol.Mat. 2014)

- PID-shunt = 2D crystal defect ("stacking fault") in Si, decorated with Na [1]

Stacking faults

- Associated with the crystal growth
- Can be created and annihilated with high temperature diffusions and oxidation

IEC 62804 TS– Overview of scope

- **Screening test to evaluate c-Si PV modules to the effects high voltage stress including potential-induced degradation (PID) and polarization**
- **Glass surfaces, silicon cells having passivating dielectric layers, for degradation mechanisms involving mobile ions**
- **Measures short term effects**
  - Does not deal with encapsulation failure that in turn leads to rapid moisture ingress and electrochemical corrosion.

IEC 62804 – Brief history

- Concept for a system voltage durability test proposed Fall 2010 WG2 meeting
  - Contained damp heat with voltage bias stress test
  - WG2 membership needed time to study the matter
- New work item proposal published Dec. 2011
  - "System voltage durability test for crystalline silicon modules - Qualification and type approval"
- *Two* votes at WG2 meetings moved the document to a test method; reasons held by some include:
  - Not enough understanding to standardize pass/fail criteria
  - Module makers needed to be convinced it was necessary
  - Better to include pass/fail criteria in IEC 61215
- Fall 2013/Spring 2014:
  - Added Al foil test parallel to the environmental chamber test
    - Simple test, but not able to evaluate module designs with frame/mounting-based mitigation
  - Changed to a test method (IEC technical specification)
- IEC 62804 TS: Test methods for detection of potential-induced degradation of crystalline silicon photovoltaic (PV) modules
  - Draft approved by national committee voting on 2015-01-09
  - Final submission, adjusting language and other minor items*, very soon*

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~~Qualification test~~

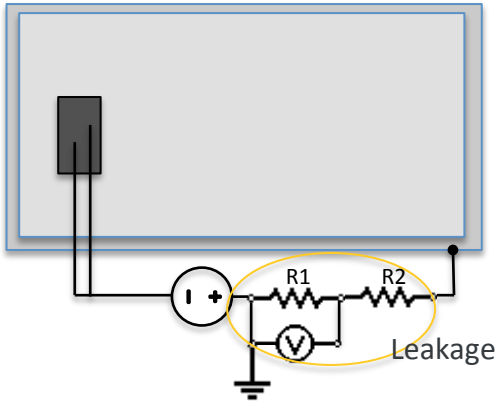
Test method

Damp heat and foil methods – setup

Damp Heat

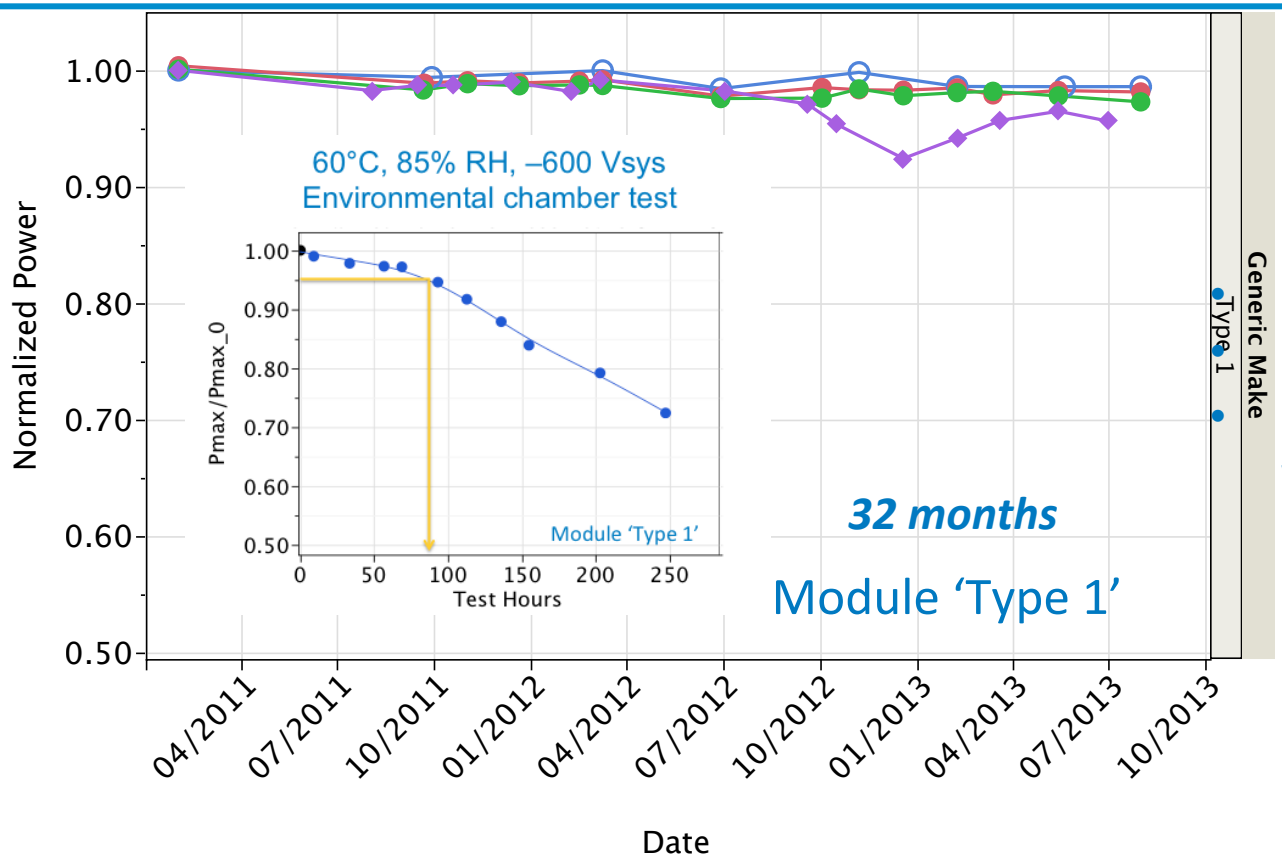
Foil

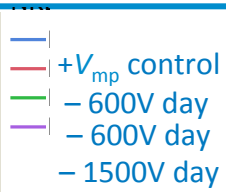
Bagdahn, Fraunhofer CSP
PV Japan, 5-7 Oct 2012



Leakage current metering

Origin of damp heat stress test





7 module types (31 modules)

5% P/F test works so far with Florida–fielded replicas

P. Hacke *et. al.*
28th PVSEC (2013)

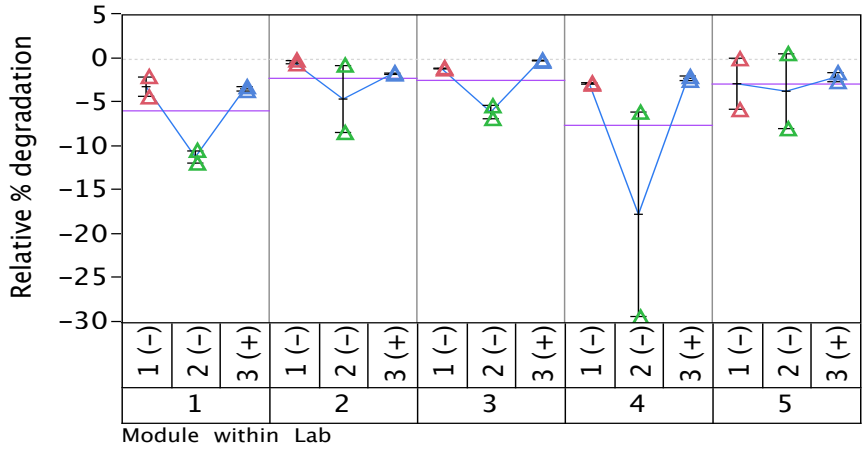
Take note: For reproducibility, not qual testing "test method IEC 62804 TS" changes:

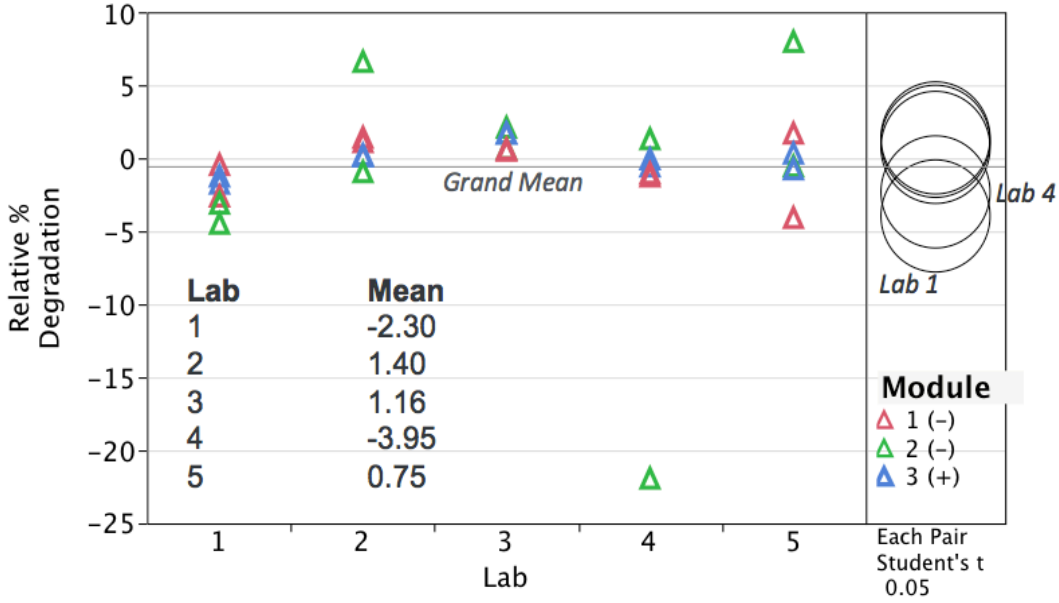
- Startup sequence to eliminate excess humidity on module
- Tolerances for relative humidity tightened

Results is a weakened 60°C 85% RH stress test.

Recalibration of relationship required with new startup sequence

Reproducibility/repeatability– damp heat stress test





P. Hacke et al, JPV (2015)

Older (CD) profile: 60°C/85% RH, Vsys

3 module types

2 replicas/polarity

5 labs

NREL

PI-Berlin

Fraunhofer ISE

TUV Rheinland

Fraunhofer CSP

- Subtracting median degradation for each module type
- Failed to show a statistical significance in difference between labs.
- Data shows sufficient reproducibility for qualification test

Move to test method:

Startup sequence changed to mitigate non-equilibrium excess moisture on modules during startup

- Expected improved reproducibility
- Weakens test significantly

Conditions for damp heat stress test

These severities represent the minimal stress levels for detection of PID.

- Module temperature: 60 °C ± 2 °C;
- Chamber relative humidity: 85 % ± 3 % relative humidity;
- Dwell: 96 h
- Voltage: module rated system voltage and polarities.

Note : Suggested common temperatures to use for the detection of PID for further acceleration: 65 °C and 85 °C.

Origin of foil test

- Joint press release of:
  Fraunhofer ISE,
  Photovoltaic Institute Berlin
  TÜV Rheinland,
  VDE,
  Q-Cells,
  Schott Solar
  Solon

"First Test Conditions for Potential Induced Degradation (PID) of Solar Modules Developed", September 5, 2011

- Too early to establish a general industry guideline or an international standard.
- An easy method avoiding any need of expensive equipment to check solar modules of their PID reliability.

  Koch et al, 26th PVSEC (2011)

Conditions for foil test

These severities represent the minimal stress levels for detection of PID.

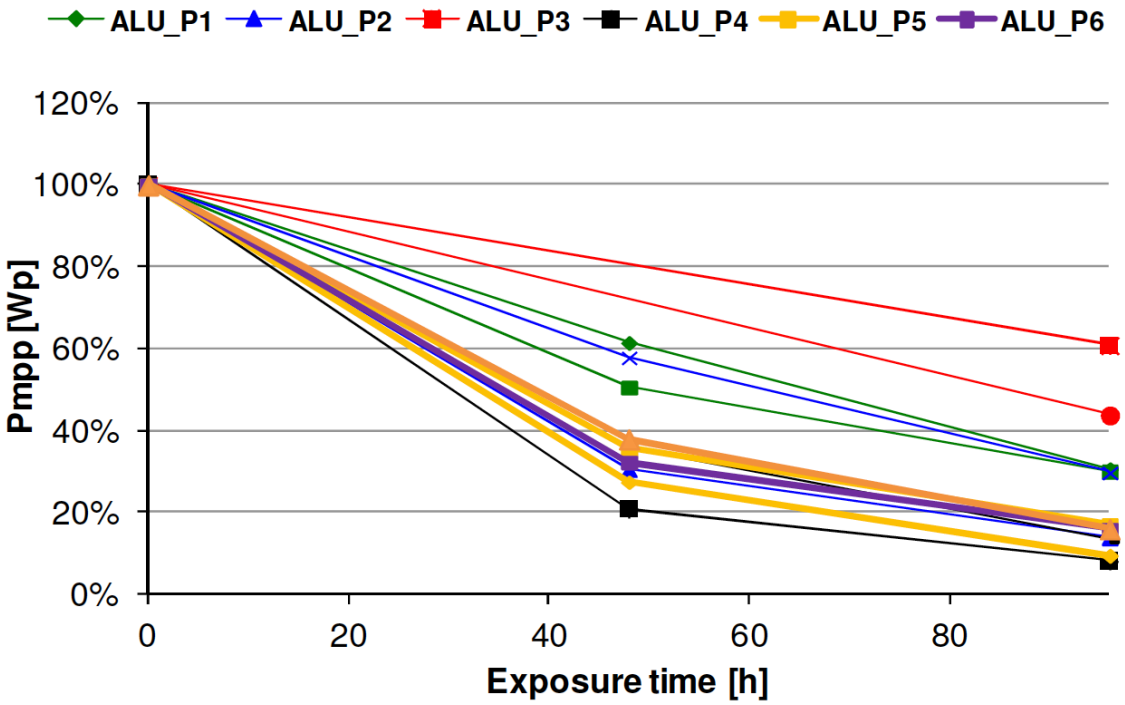
- Module temperature: 25 °C 1 °C
- Relative humidity: less than 60 %;
- Test duration: 168 h
- Voltage: module rated system voltage and polarities.

Note : Suggested common temperatures to use for the detection of PID with further acceleration: 50 °C and 60 °C.

Reproducibility/Repeatability – foil test

- PID test results from six test labs testing to the test procedure for 25°C/Al/-1000V/96
  - 1 'sensitive' module type
  - 2 replicas/lab

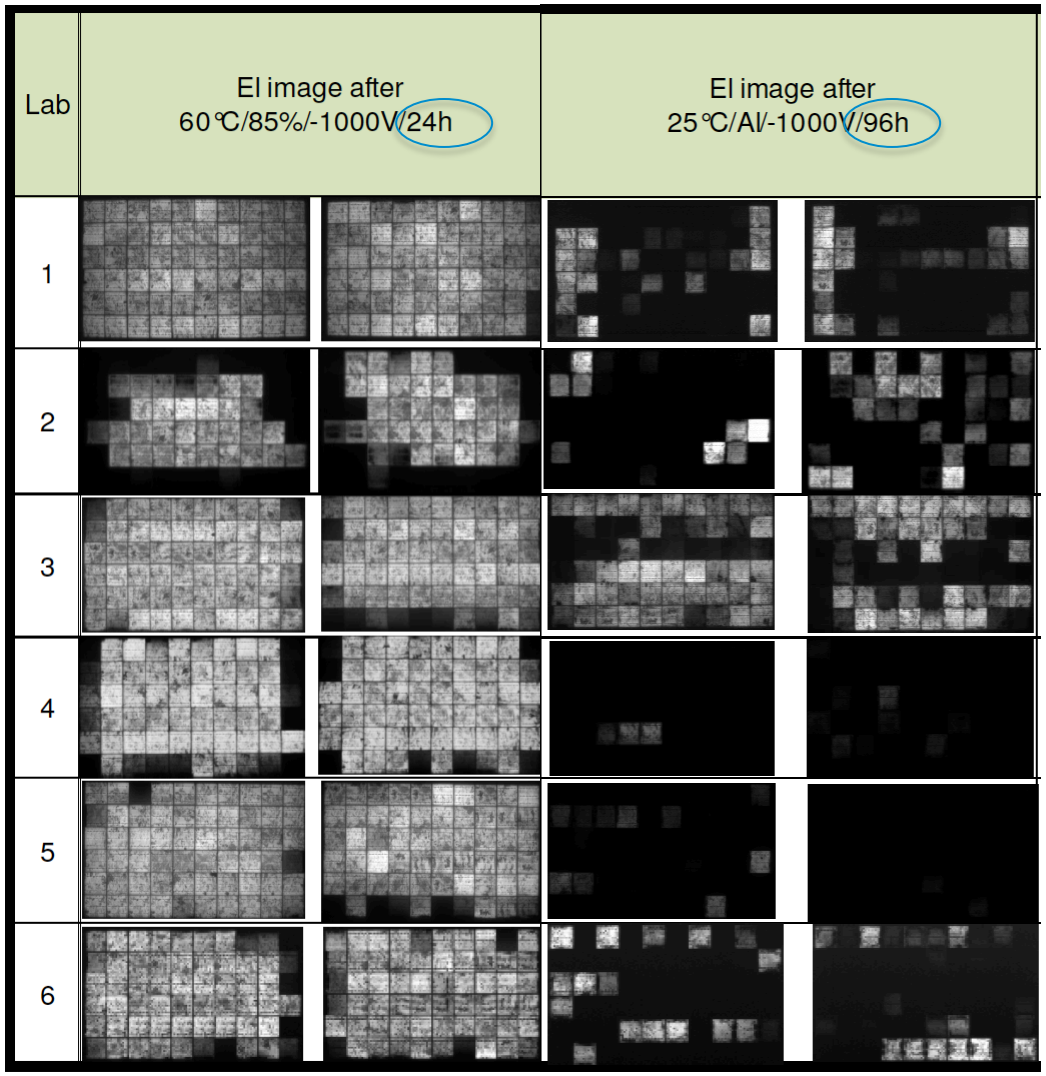
PI Berlin
NREL
Fraunhofer ISE
TÜV Rheinland
SGS
UL
SOLON



Partner	PID in % after 25°C/Al/1000V/96 h	
	Module 1	Module 2
1	69	70
2	86	70
3	39	56
4	92	87
5	83	91
6	84	84

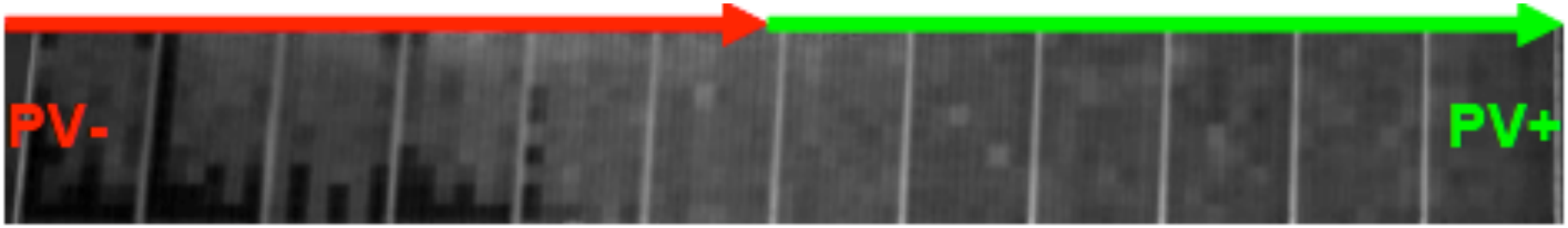
Berghold et al, 28th PVSEC (2013)

EL images of chamber & foil tested modules

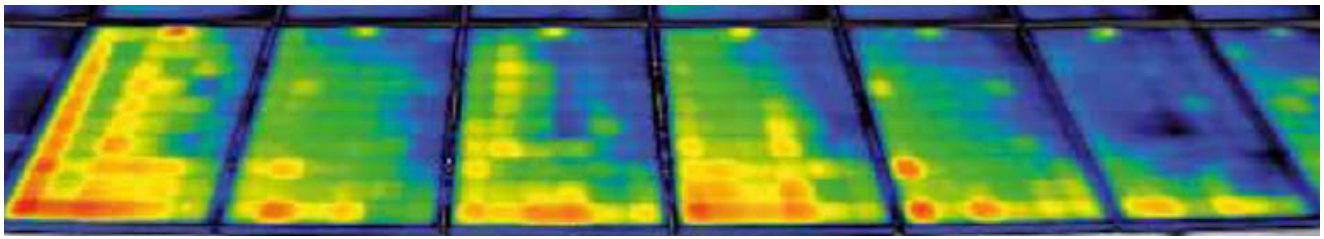


Berghold et al, 28th PVSEC (2013)

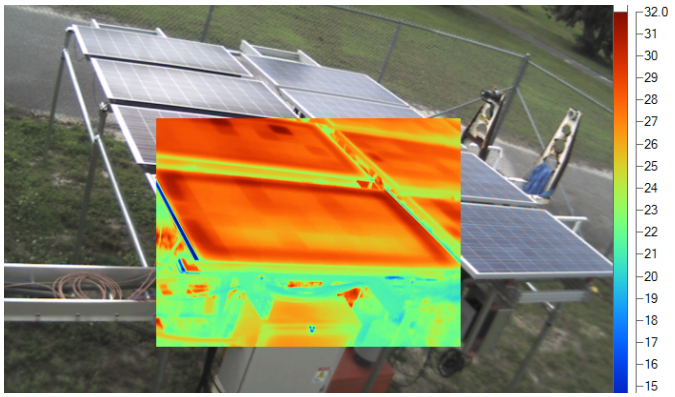
Imaging of PID c-Si modules in the field



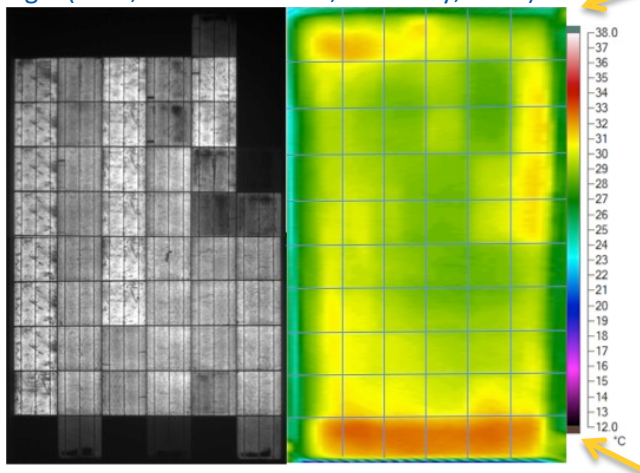
S. Pingel, O. Frank, M. Winkler, S. Daryan, T. Geipel, H. Hoehne and J. Berghold SOLON SE, Presented at 35th IEEE PVSC, 2010



B. Weinreich, Proc. 28th Symposium Photovoltaische Solarenergie (OTTI, Bad Staffelstein, Germany, 2013)



4-Edge frame, -1000 V, 3 years, Florida Schneller/Hacke



2-edge frame

2-Edge frame (top/bottom), -1000 V, 3 years, Florida Schneller/Hacke

Modules typically are more stressed at the frame edges

Future of IEC testing for system voltage stress

- **Test method development**
  - ***c-Si exists in IEC 62804 TS ed. 1***
- **Qualification testing (basic level)**
- **Climate-specific**
- **Lifetime prediction (higher stress levels Combined/cyclic stresses)**

Integration needed into some of the above:

Heterostructures

Thin film

Understanding of new technologies

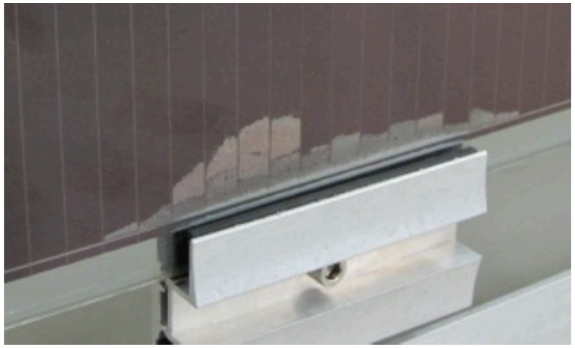
Understanding of interactions

factors: light, humidity ingress, stress: multi-mechanism…

mechanisms: delamination, corrosion…

Test method/ Qualification testing (basic level)

- **Experience required to agree upon qualification test level determination for PID**
  - Accelerated test/outdoor comparisons in various environments
  - Modeling
- **Inclusion of thin film; not just new materials, but new mechanisms**
  - Philosophical question about what levels of stress will be acceptable
    - Na interactions with active/absorber layer degrading efficiency
    - Na migration, humidity →TCO corrosion
  - Columbic relationships may be possible with TF (P. Lechner, T. Weber)



P. Lechner, 2013 PVMRW

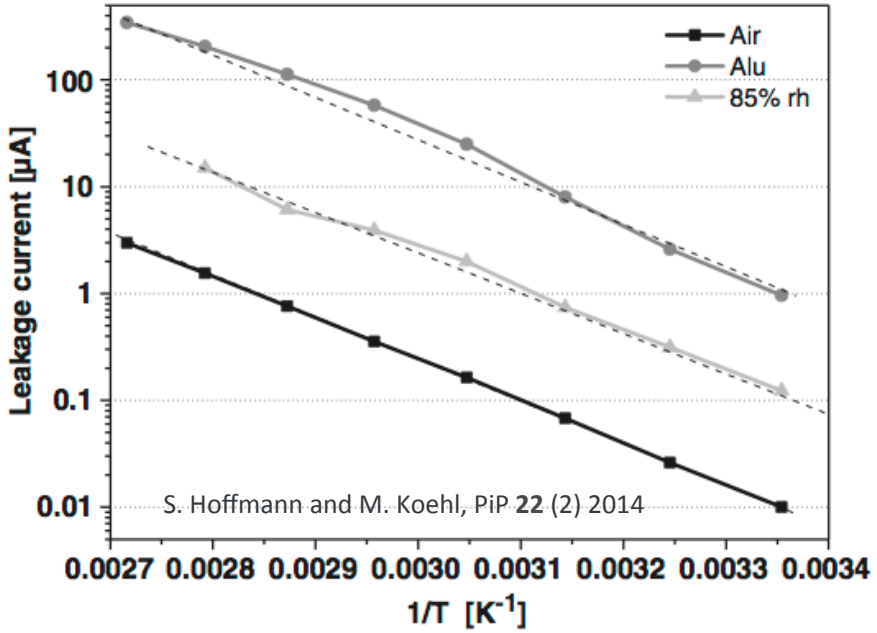
Understanding of interactions

Factors affecting degradation:

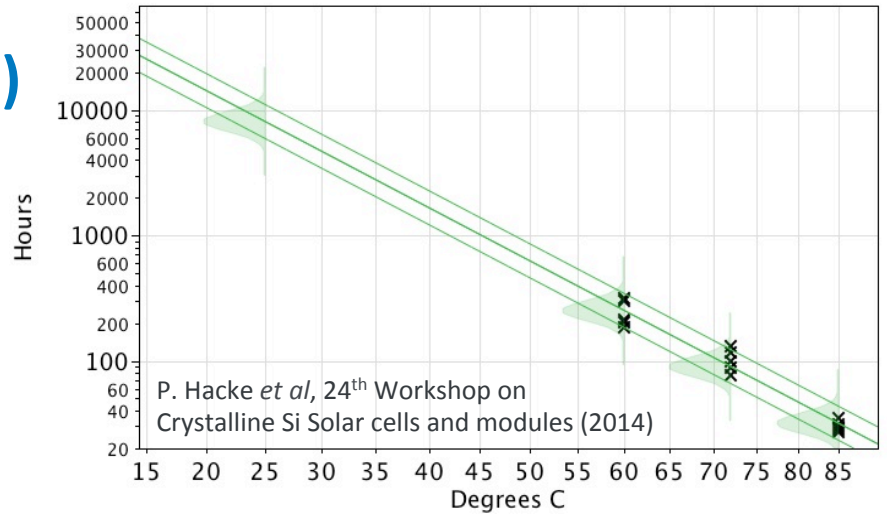
- Temperature
- Relative humidity
- Voltage
- PID Stress history/ effective stress
- Light
- Thermal-activated recovery
- Charge build-up over SiN
- Encapsulant resistivity
- Soiling
- Mounting
- …

Factors for degradation: T

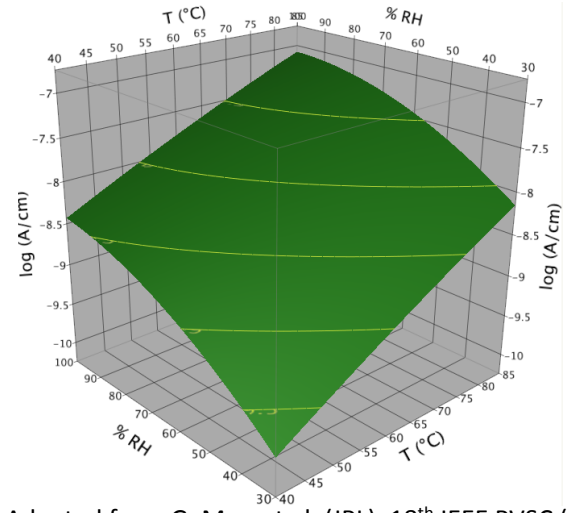
- **Leakage current dependency**
  - Activation energy same; independent of contacting scheme 75kJ/mol; 0.78 eV
    - Low RH (room)
    - Aluminum Foil on Surface
    - 85% RH



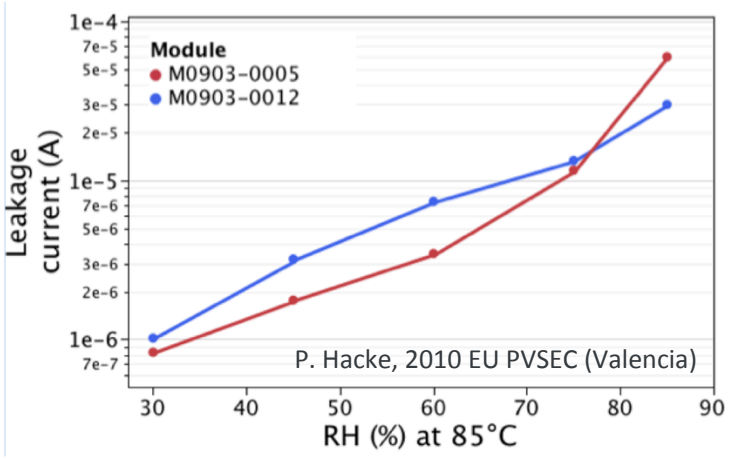
- **PID rate (to 1% P_{max} degradation)**
  - 82 kJ/mol; 0.85 eV

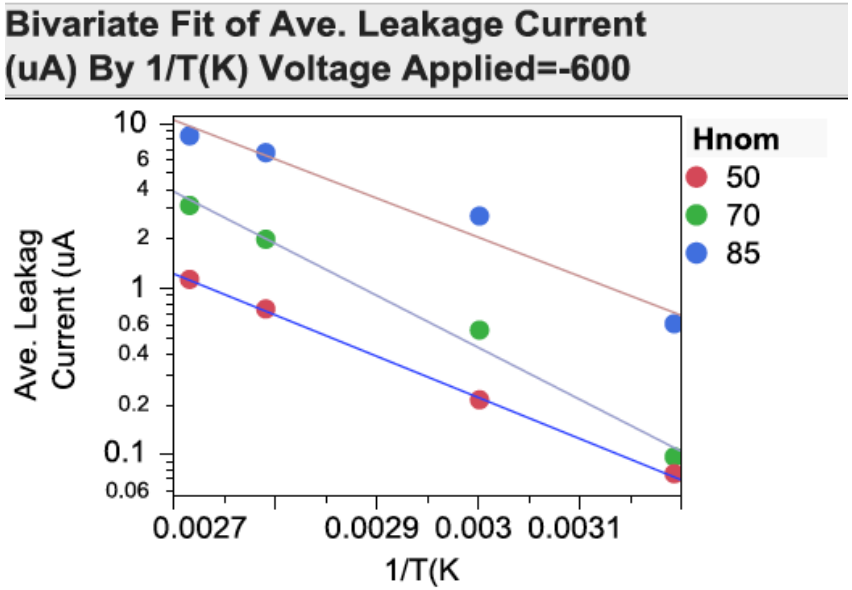


Factors for degradation: Relative humidity



Adapted from G. Mon et al, (JPL), 18th IEEE PVSC (1985)





Kent Whitfield, 2014 NREL PV Module reliability workshop

$$LC = A \cdot e^{n \cdot RH} \cdot e^{\frac{-Ea}{k \cdot T}} \cdot f(V) \text{ and } f(V) \propto V$$

$$LC(\mu A) = 2200(\mu A / V) \cdot V_{sys}(V)/2 \cdot e^{0.06/\%\cdot RH_{module}(\%)} \cdot e^{\frac{-0.5eV}{k \cdot T_{module}}}$$

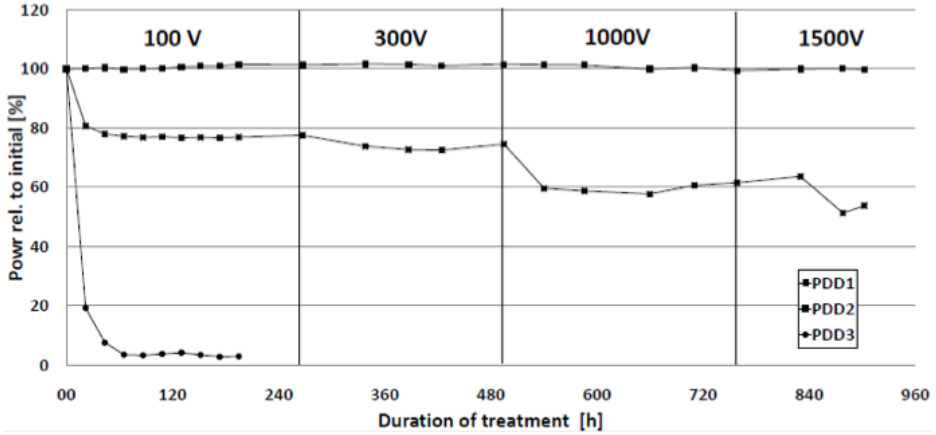
- Exponential model fit

- **Leakage current can be reasonably described considering RH and T**
  - Has been iterated over various climates assuming you can determine module T and atmospheric RH→ module RH

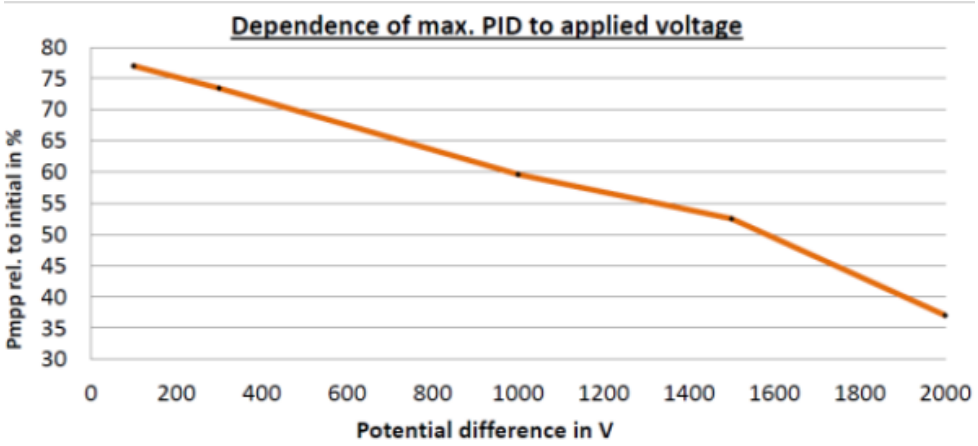
Factors for degradation: Voltage

- Leakage current generally seen to be linear with voltage both in chambers and outdoors (V=IR)
- Maximum stabilized degradation has been linked with applied voltage

S. Koch et al, 26th EU PVSEC (2011)

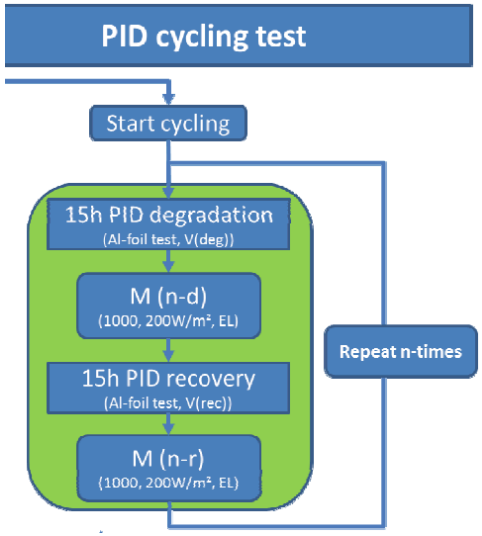


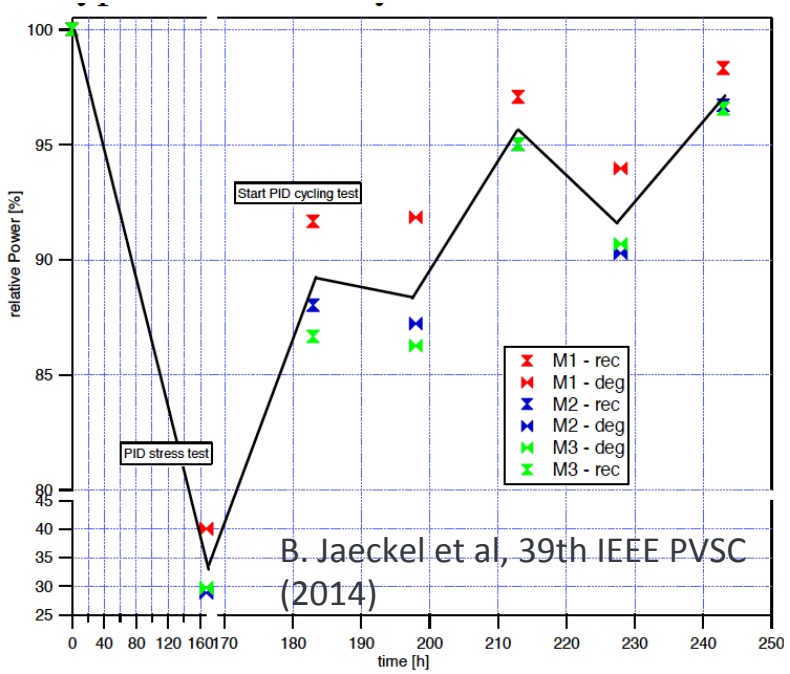
S. Koch et al, 27th EU PVSEC (2012)



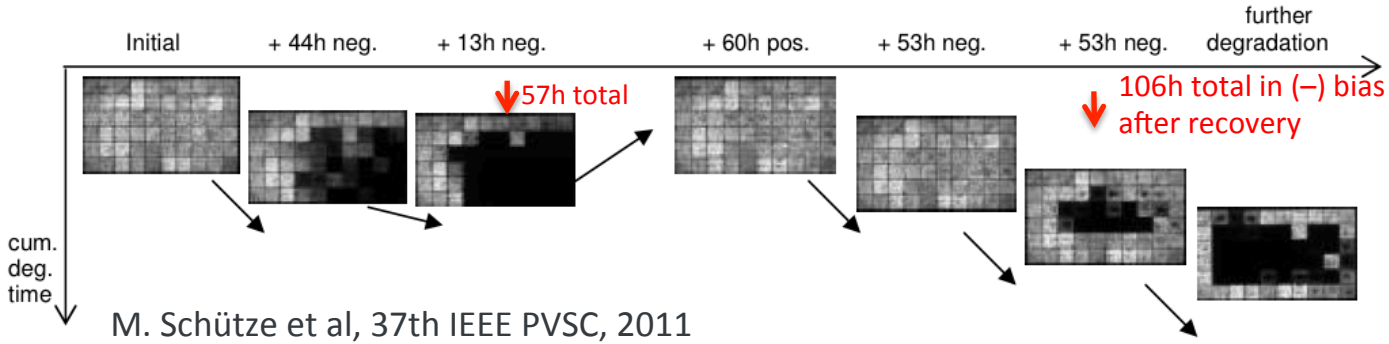
Mitigating Factor: previous PID stress history

- **PID experience followed by recovery, can reduce sensitivity to further PID stress, or even lead to stability**

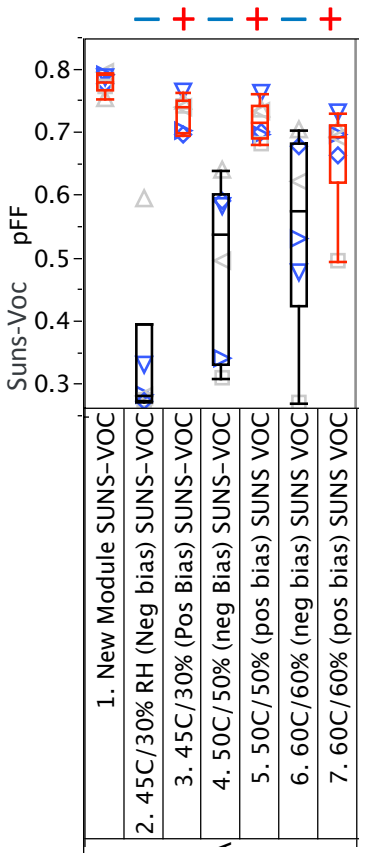




B. Jaeckel et al, 39th IEEE PVSC (2014)

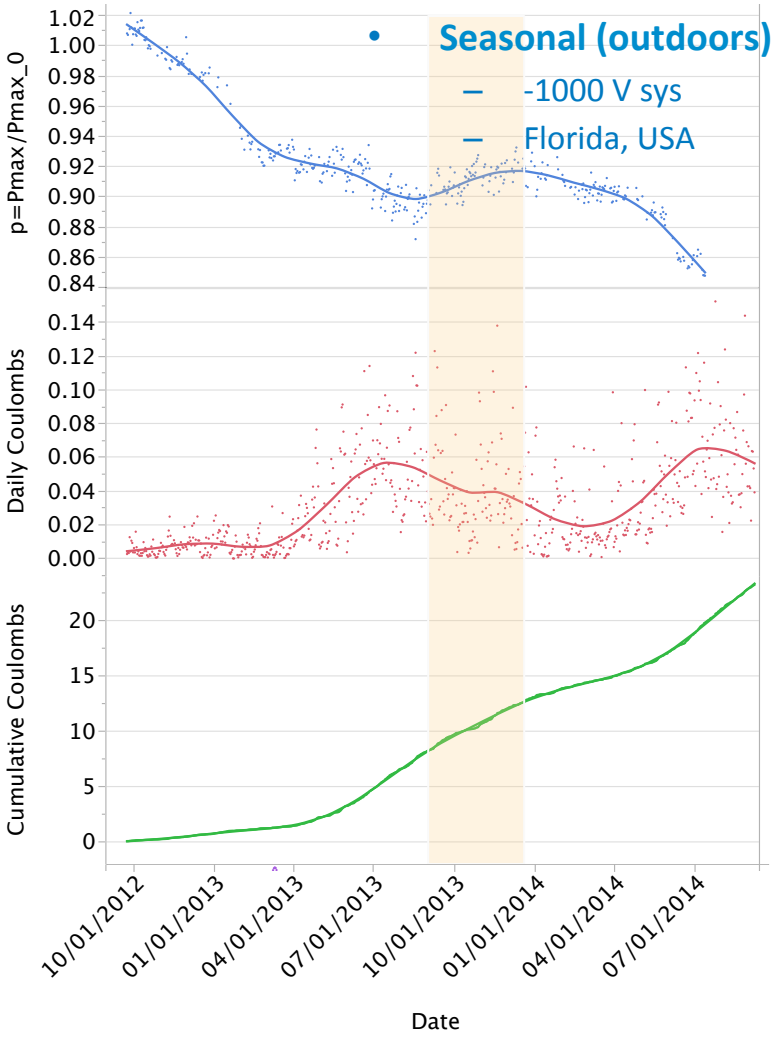


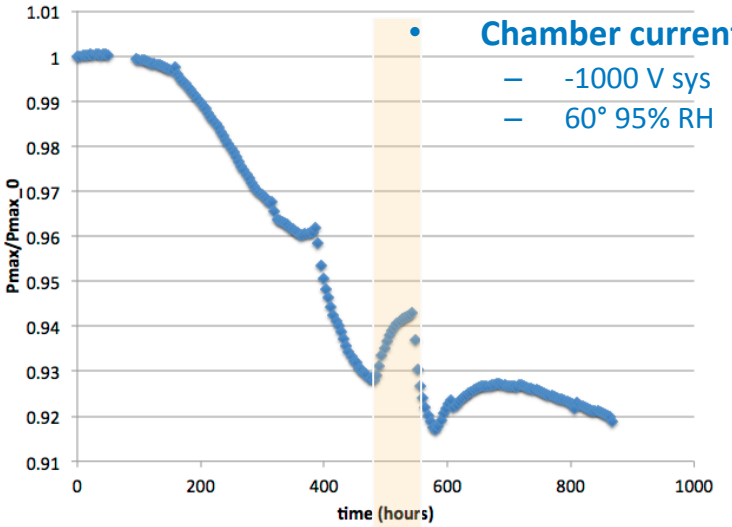
M. Schütze et al, 37th IEEE PVSC, 2011

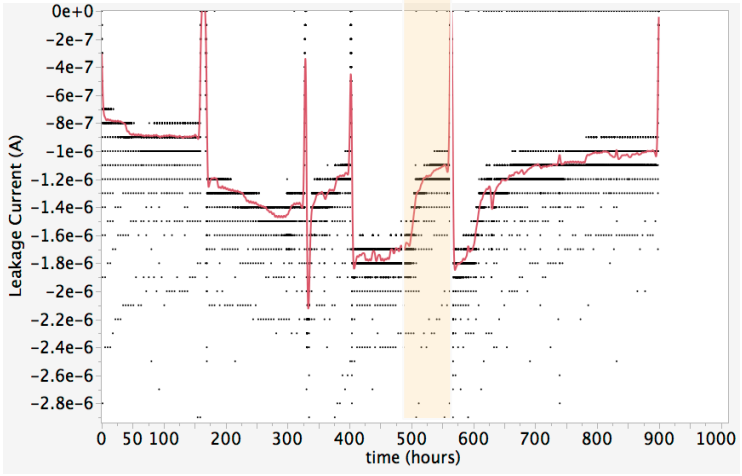


Hacke et. al, 37th IEEE PVSC (2011)

Mitigating Factor: Effective stress decrease

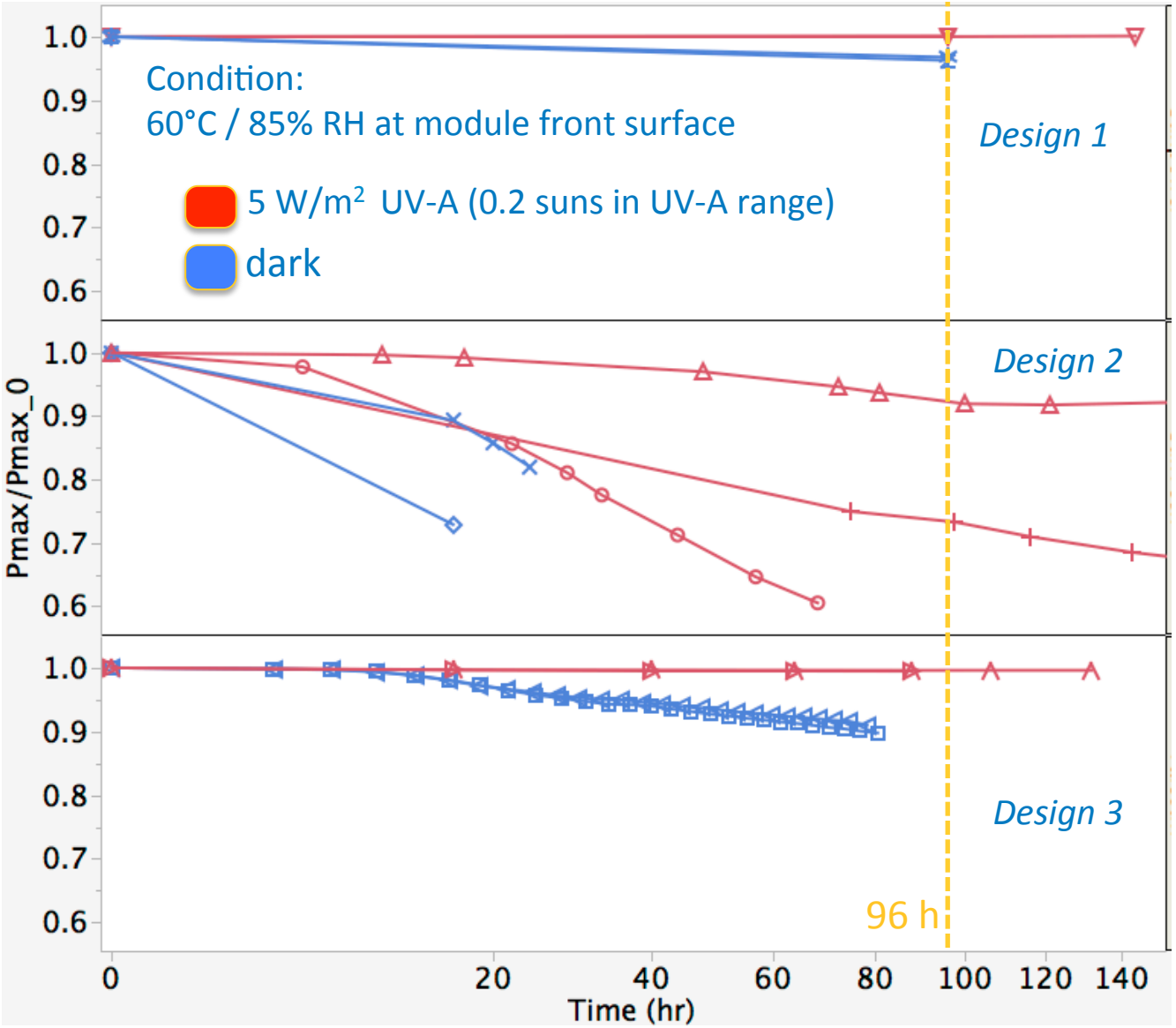






- **Recovery seen with stress magnitude decrease**

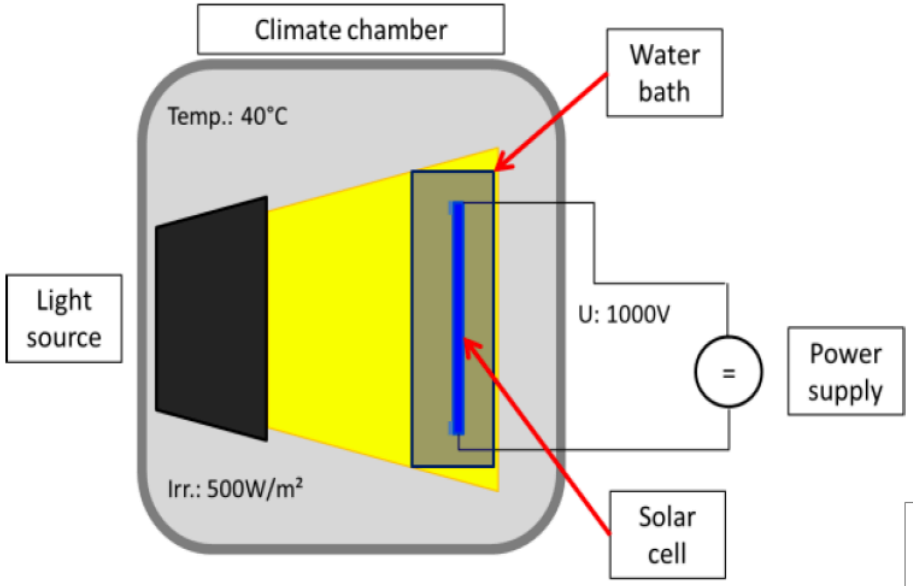
Mitigating Factor: Light



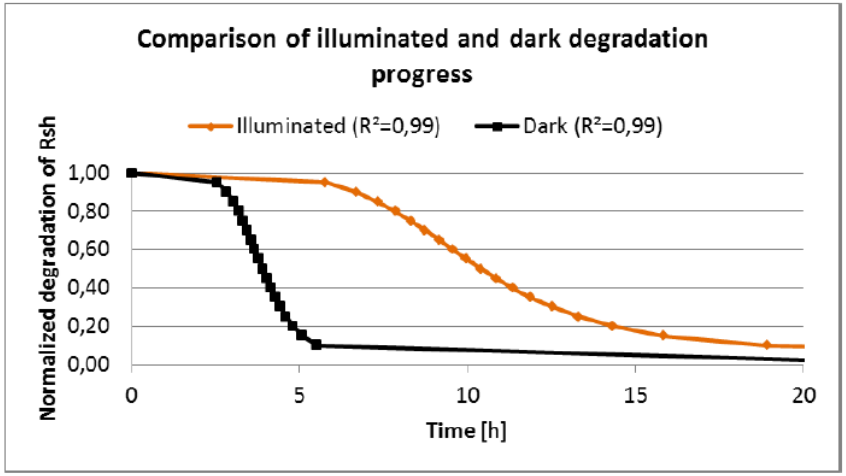
- T Chamber decreased and RH increased to maintain 60°C/85% RH on surface.
- Leakage current with UV at or above dark condition: leakage current not mitigated

P. Hacke, 2014 NREL PV Module Reliability Workshop

Mitigating Factor: Light (continued)



- The PID is decelerated by irradiation
- The degradation phase is 2.4 times longer



- It seems that the degradation is slowed down by a higher SiN_x conductivity (further investigations have to be done)

S. Koch, 2014 NREL PV Module Reliability Workshop

Mitigating factor: thermal activated recovery

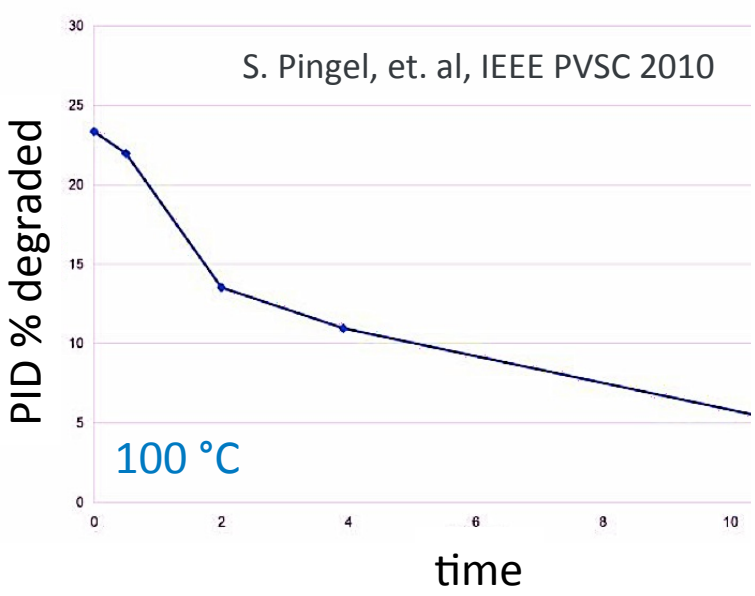
- **Removal or reduction of stress**
  - Drying of module
  - Removal of voltage potential (*ie, at night*)
- **Significant recover is frequently seen**
  - Out-diffusion of Na from stacking fault
    - Na in stacking fault apparently not energetically favorable
- **Much less recovery in extreme cases of degradation**

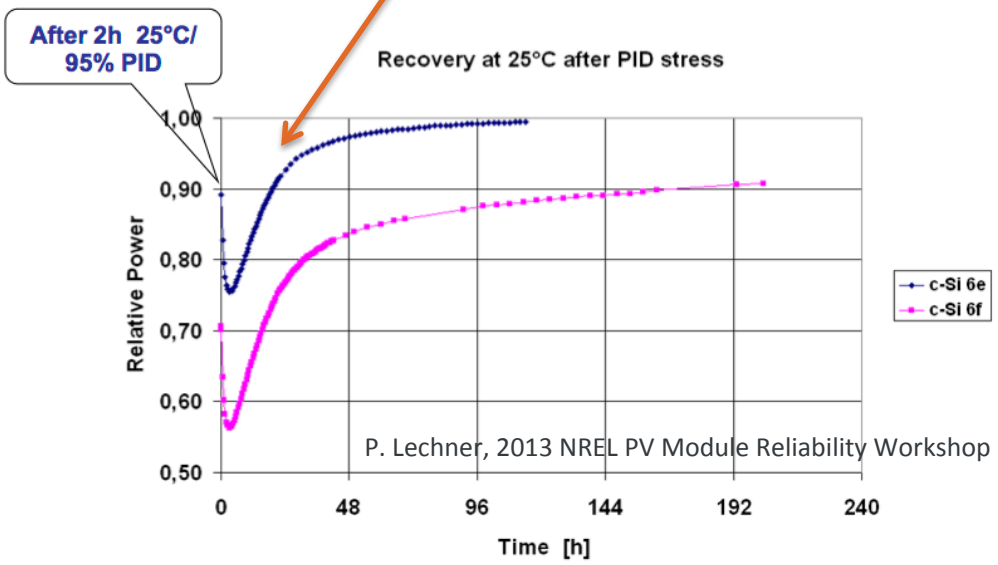
PID Ionic charge motion

Electromotive (in EVA & SiN)

+

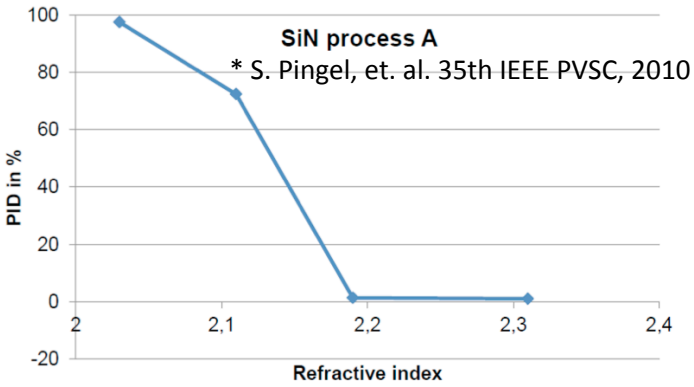
Diffusion (in oxide & silicon)

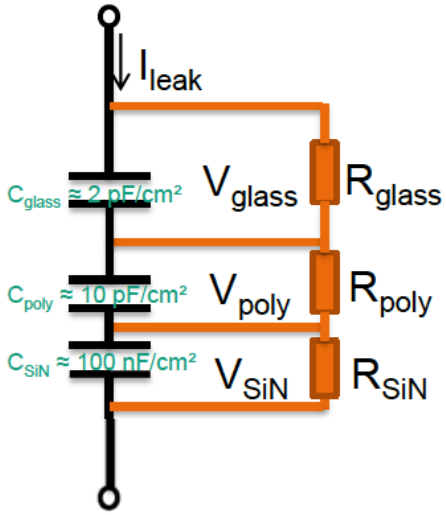




- **Relevant recovery even at 25°C possible**
- **Acceleration at higher T**
- **E_a is 0.7 to 0.8 eV**

Factor: Charge build up over SiNx





SiN_x layer	refractive index	Si/N ratio	electronic conductivity	PID sensitivity
SiN1	1.93	low	low	high
SiN2	2.32	high	high	low

$$V_{SiN} = \frac{R_{SiN}}{R_{glass} + R_{poly} + R_{SiN}} V_{ext}$$

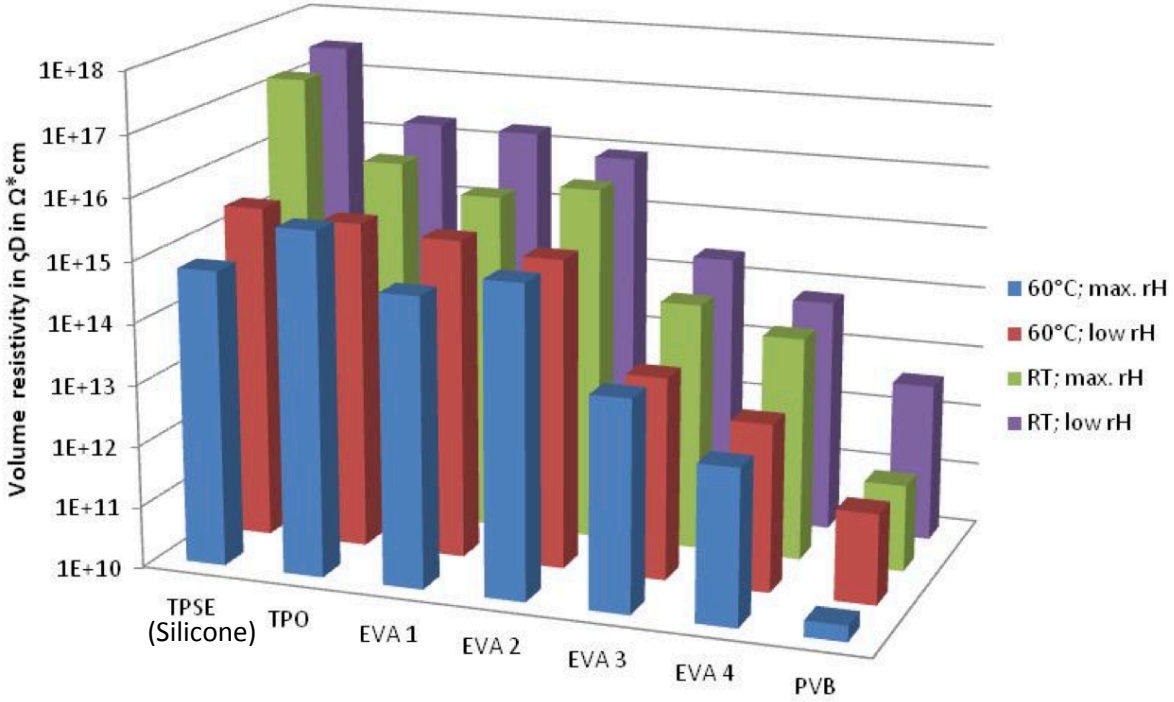
$$V_{SiN} = \frac{R_{SiN}}{R_{glass} + R_{poly} + R_{SiN}} V_{ext}$$

V. Naumann, 2014 NREL PV Module Reliability Workshop

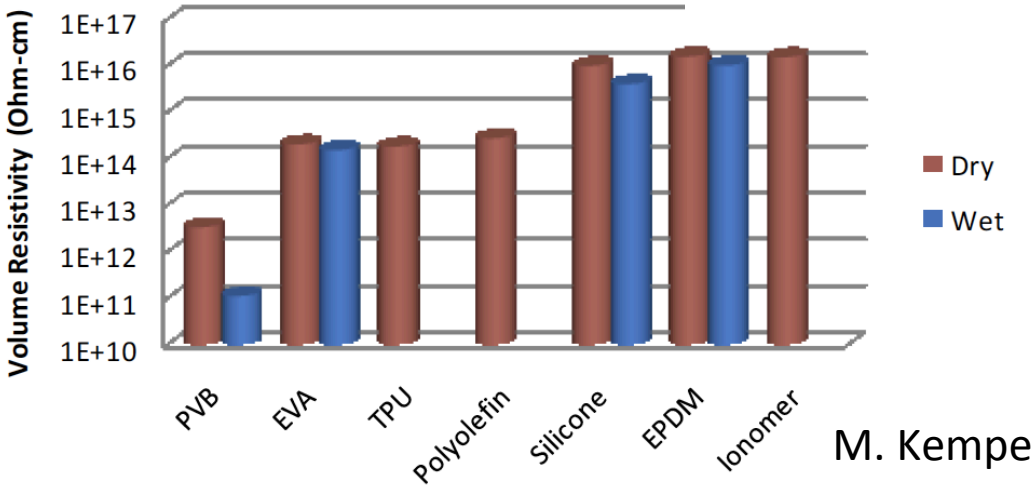
- Index of SiNx refraction, closely linked to Si:Si bonding, SiNx conductivity, and ability to dissipate charge.
- Reducing voltage potential over SiNx (ie electromotive driving force for ions) can be achieve by decreasing R_{SiNx} or increasing R_{glass}+ $R_{polymer}$

Factor: Encapsulant resistivity

- **Ionic conductivity of encapsulants**
  - Temperature
  - ***Humidity Ingress***
  - Quality (solute for mobile ions)
    - Impurities
    - Dangling bonds/polymerization



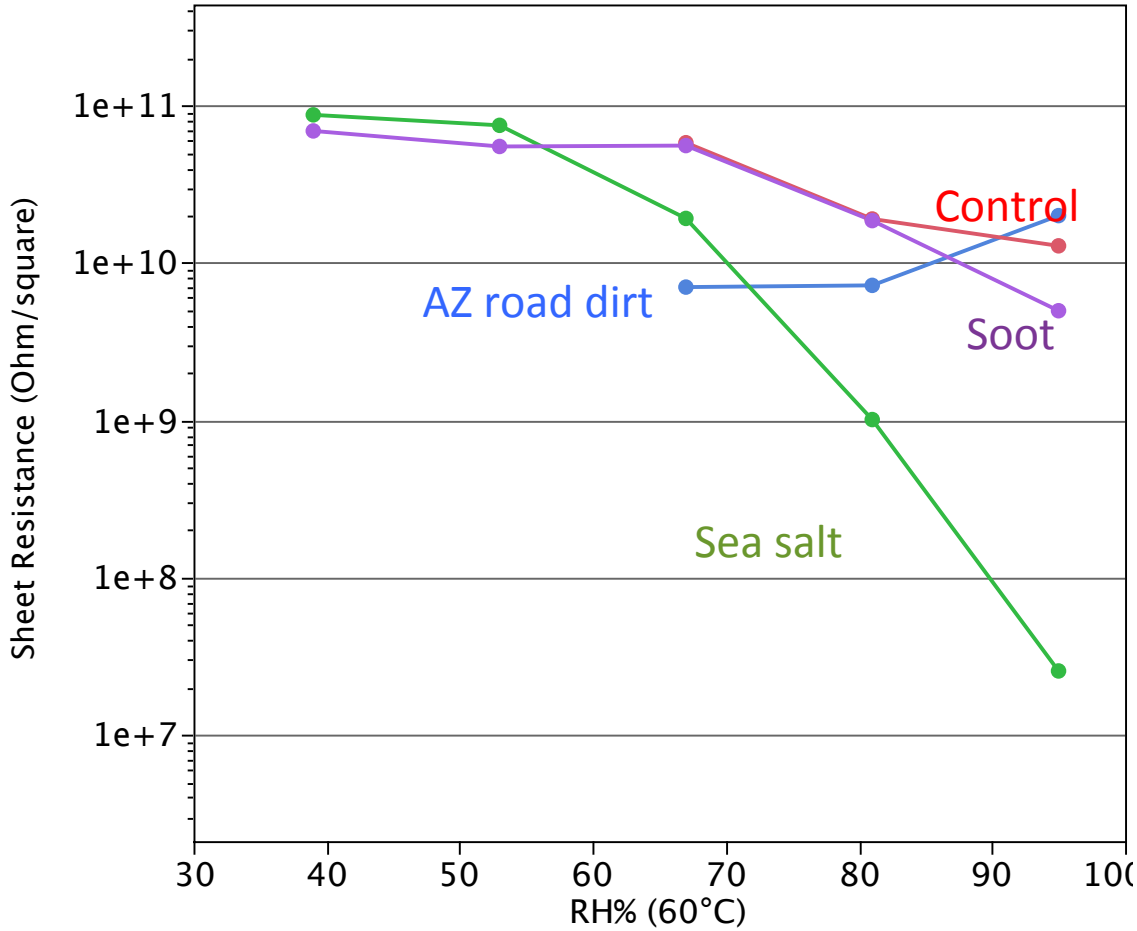
Berghold et. al IEEE PVSC (2014)



M. Kempe

Soiling

Sheet resistance as a function of soil type and relative humidity

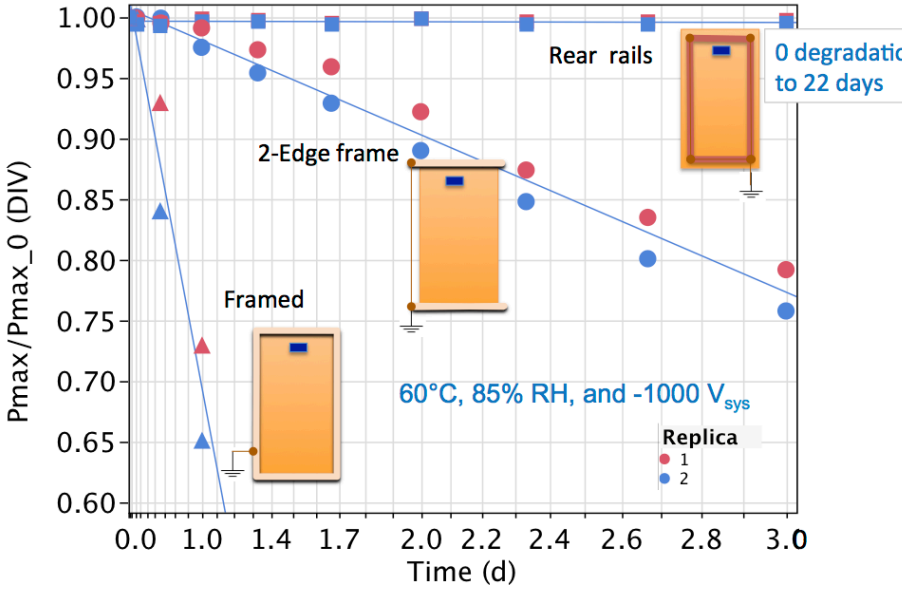


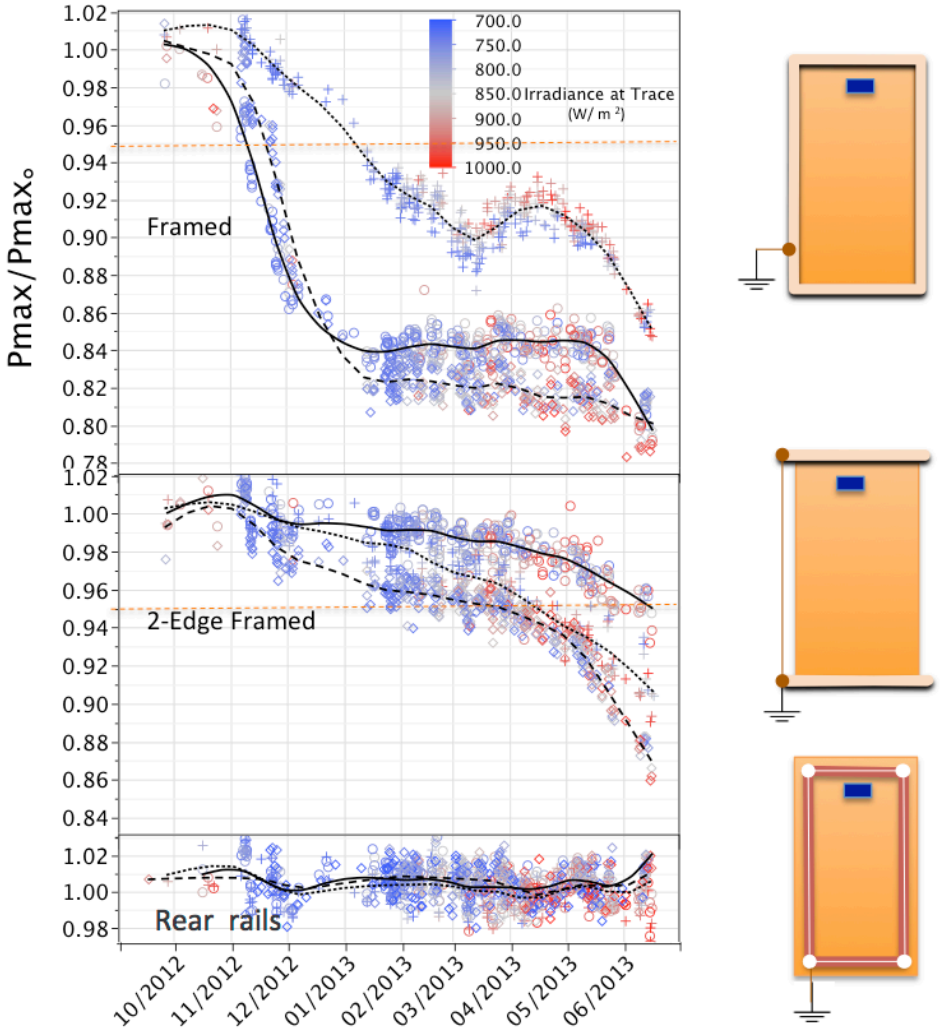
NREL-Hacke/Sandia-Burton,
Preliminary results
To be published

- Sea salt yields greatest decrease in glass surface face sheet resistance with RH
- AZ road dirt showed an important decrease, but less humidity dependence
- Decreased resistance over the glass face→ higher conductivity to ground → accelerated PID

Mitigating Factor: Mounting

- **Full metal frames *vs*. 2 edge frames *vs*. rear fiberglass rails**



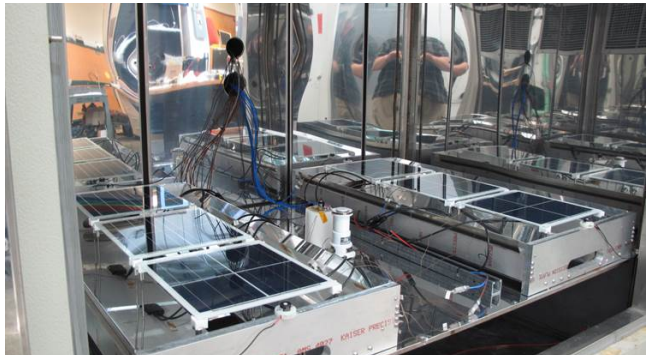


- **Minimizing conduction to ground via framing mitigates PID**
- **Module dimensional effects can also matter**
  - Distance from frame to active cell
  - Mounting angle
  - Grounded/ungrounded mounts

P. Hacke, et. al. 28 EU-PVSEC (2013)

Understanding of interactions

- Temperature
- Relative humidity
- Voltage
- PID Stress history/ effective stress
- Light
- Thermal-activated recovery
- Charge build-up over SiN
- Encapsulant resistivity
- Soiling
- Mounting
- …



Combined and cyclic stress testing including multiple stress factors required for clarifying multiple, inter-related mechanisms

Future of IEC testing for system voltage stress

- **Test method development**
  - ***c-Si exists in IEC 62804 TS ed.1***
- **Qualification testing (basic level)**
  - ***Field experience***
  - ***Validated modeling***
  - ***Few factors (ie. T, RH, V)***
- **Climate-specific**
  - ***Field experience***
  - ***Validated modeling***
  - ***Few factors (ie. T, RH, V, soil)***
- **Lifetime prediction**
  - ***Combined/cyclic stress testing***
  - ***Consideration of long term system voltage effects such as delamination, electrochemical corrosion.***

No hard walls between the categories above

To be integrated to some of the above:

Heterostructures

Thin film

Understanding of new technologies

Understanding of interactions

Thank you for your attention

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A PID model ensuring 25 years of service life

PVMRW 2015, Feb 24th, 2015, Golden, Colorado
Max B. Koentopp, Christian Taubitz, Matthias Schütze, Marcel Kröber

Q CELLS

CONTENTS

I Introduction

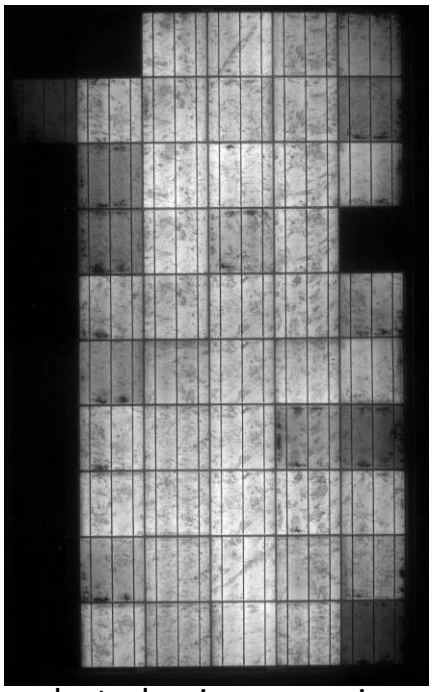
II PID-s modeling:
How do we ensure a 25 year service life with respect to PID-s ?

- need to have reproducible tests
- need to understand progression of PID-s in the field
  → **PID-s model**
- need to derive parameters for tests
- need to establish process control in production

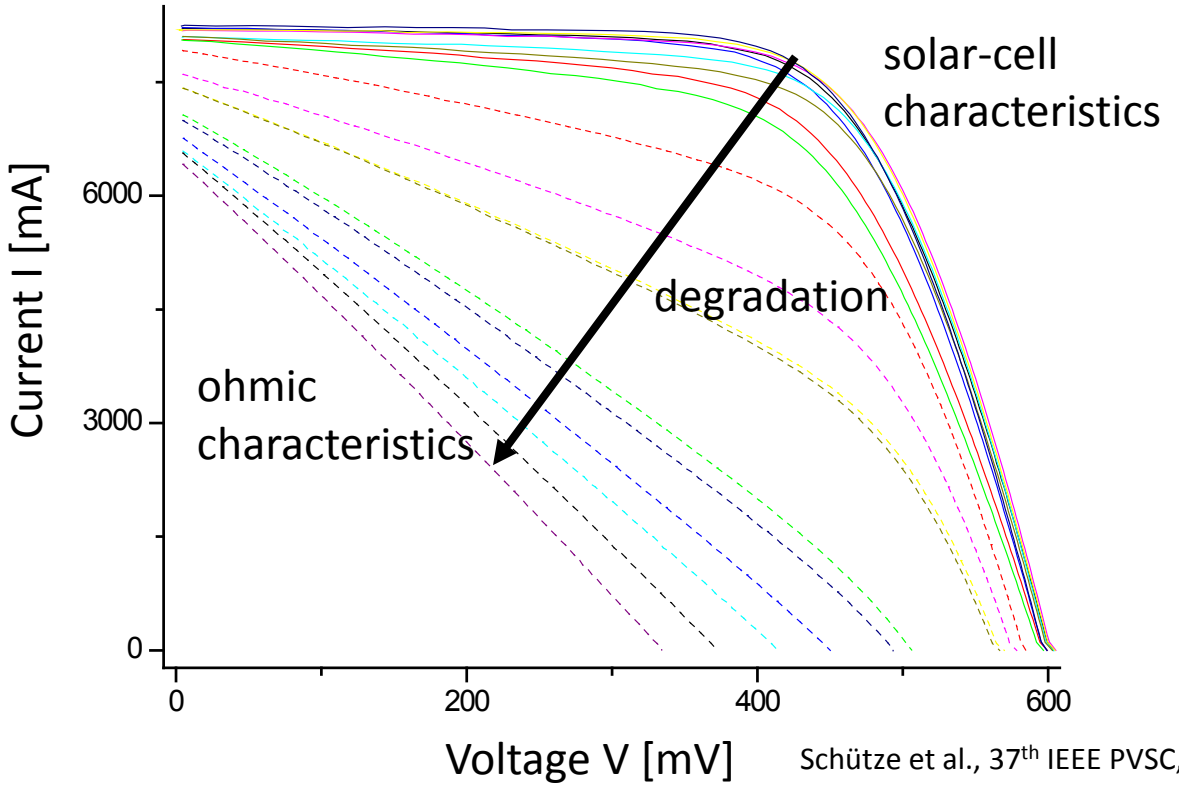
III Conclusion and Outlook

INTRODUCTION

PID-s CHARACTERISTICS



electroluminescence image



Schütze et al., 37th IEEE PVSC, 2011

PID-s → Potential induced degradation by shunting of solar cell

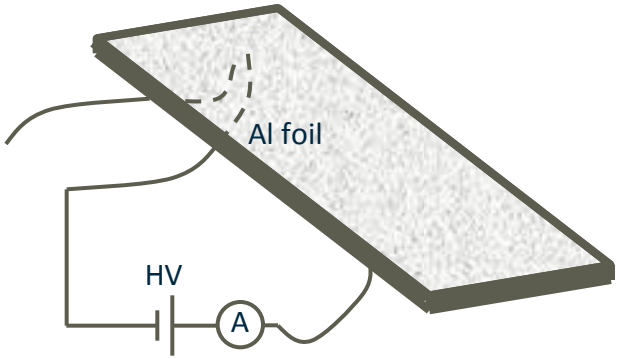
PID-s MODELING FOR 25 YEARS SERVICE LIFE

How do we ensure a 25 year service life with respect to PID-s ?

- need to have reproducible tests
- need to understand progression of PID-s in the field
  → PID-s model
- need to derive parameters for tests
- need to establish process control in production

LABORATORY PID TEST METHODS

Al foil test



temperature: 25 °C
voltage: -1 kV
contacting: Al-foil

climate chamber test (DH)

temperature: 60 °C
voltage: -1 kV
contacting: indirect via humidity

→ reproducible, but continuous PID stress

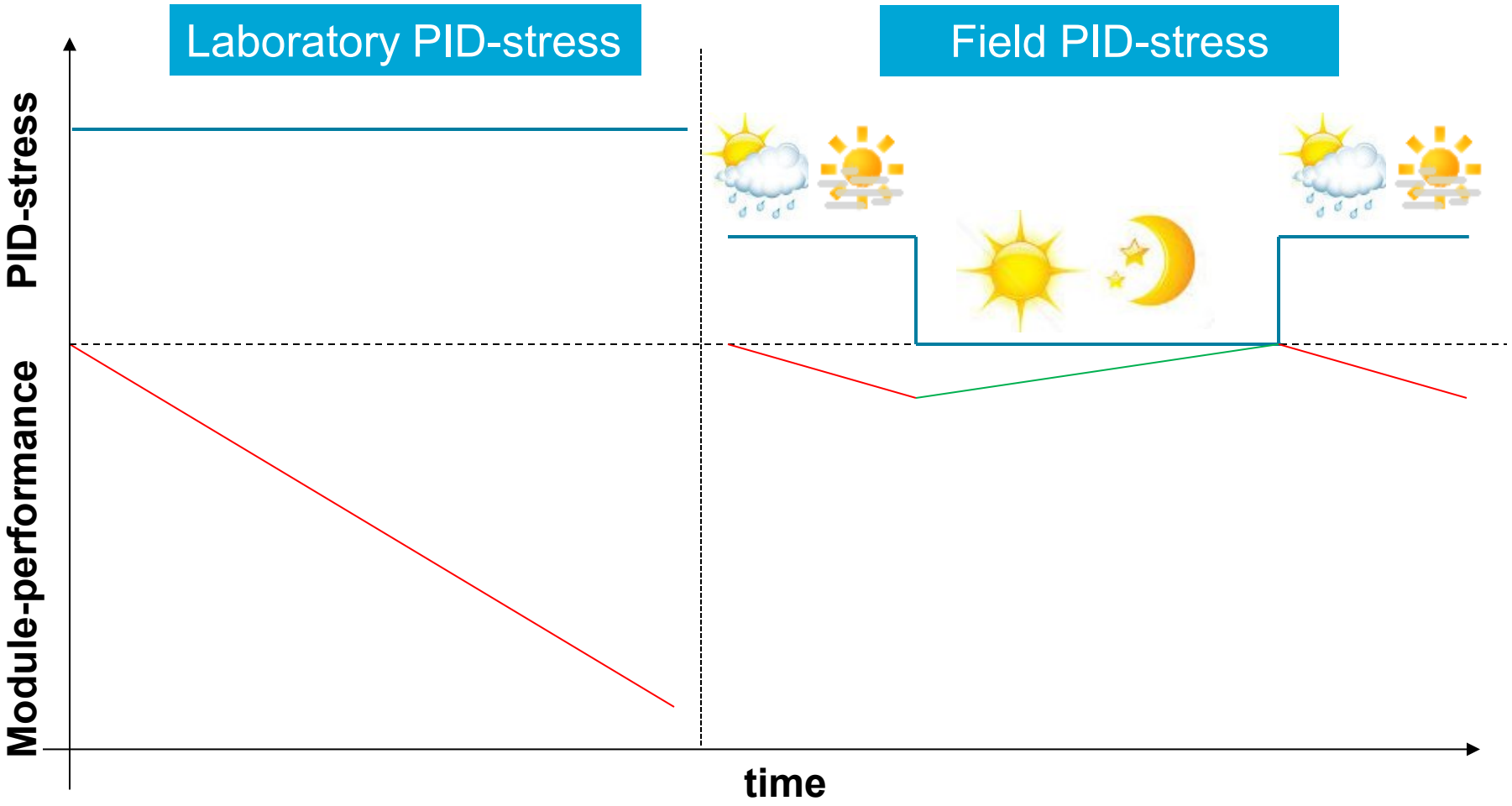
PID-s MODELING FOR 25 YEARS SERVICE LIFE

How do we ensure a 25 year service life with respect to PID-s ?

- need to have reproducible tests ✓
- need to understand progression of PID-s in the field
  → PID-s model
- need to derive parameters for tests
- need to establish process control in production

PROGRESSION OF PID-s

LABORATORY ENVIRONMENT VS FIELD CONDITIONS



common PID-tests represent only one part of PID-s kinetics in the field

MODELLING PID-s

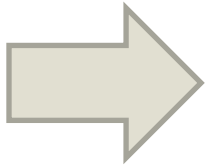
Environmental data

MODELLING PID-s

Environmental data

Measured

- irradiation
- ambient temperature
- relative humidity
- rain data



Computed

- module temperature
- humidity at module surface

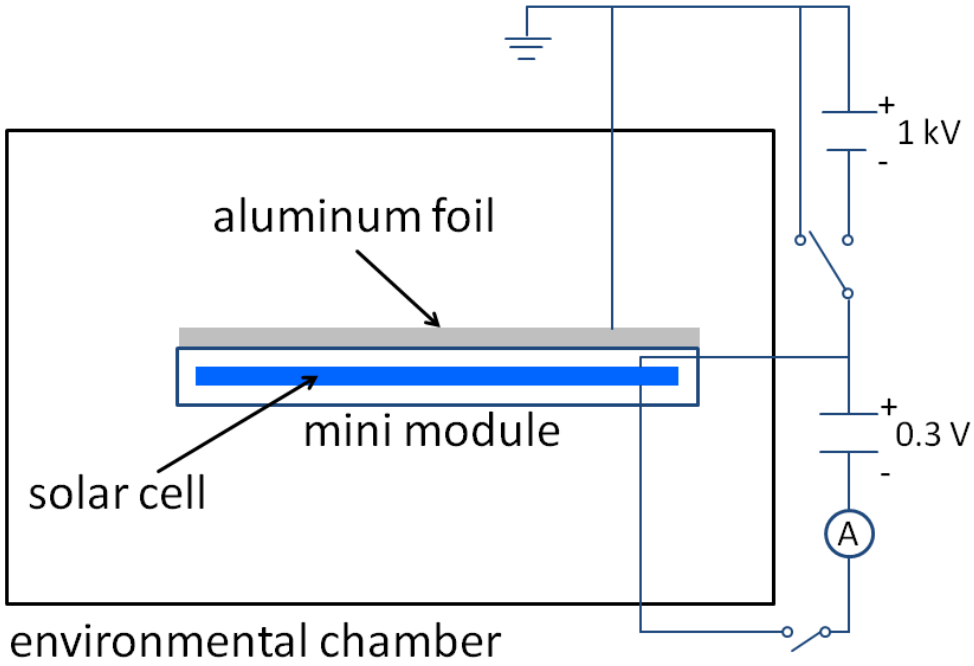
MODELLING PID-s

Environmental data

R_{sh}-kinetics from lab measurements

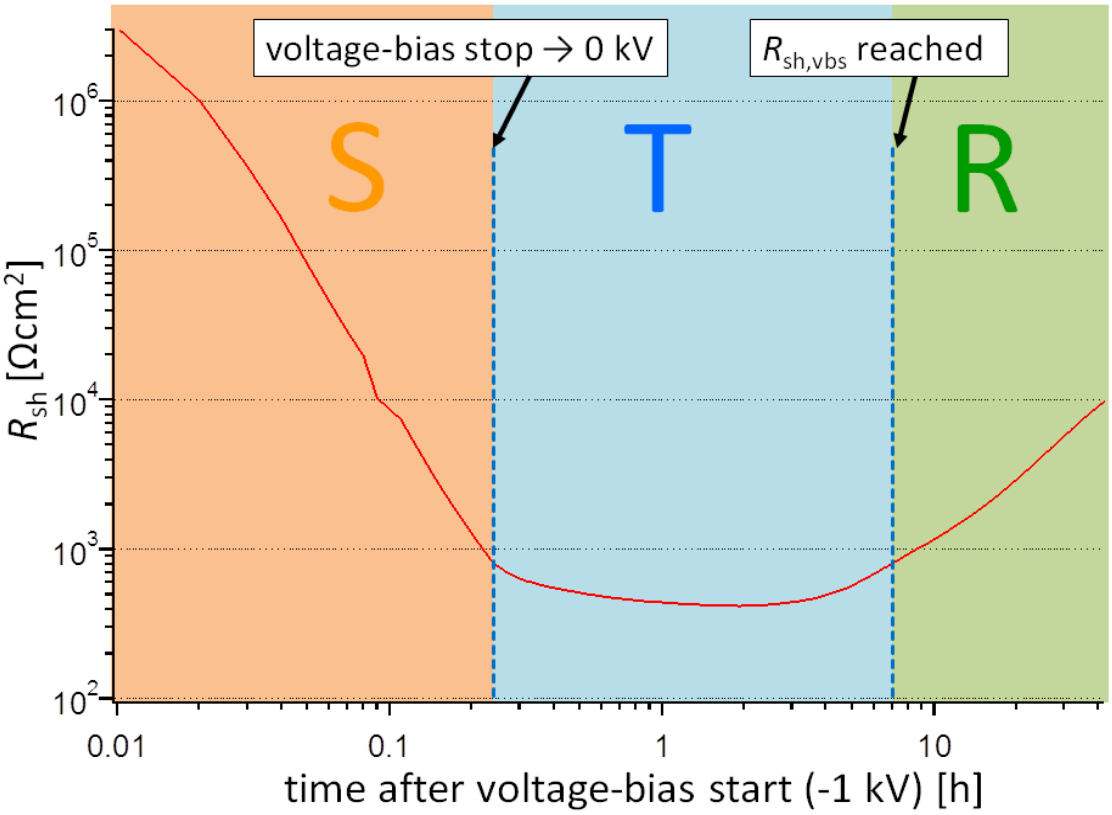
MODELLING PID-s

Measurement of shunt resistance (R_{sh})



MODELLING PID-s

R_{sh}-kinetics

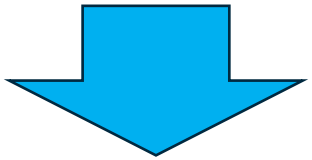


Taubitz et al.,
27th EU PVSEC, 2012

→ shunting (S)-, transition (T)- and regeneration (R)-phase

MODELLING PID-s

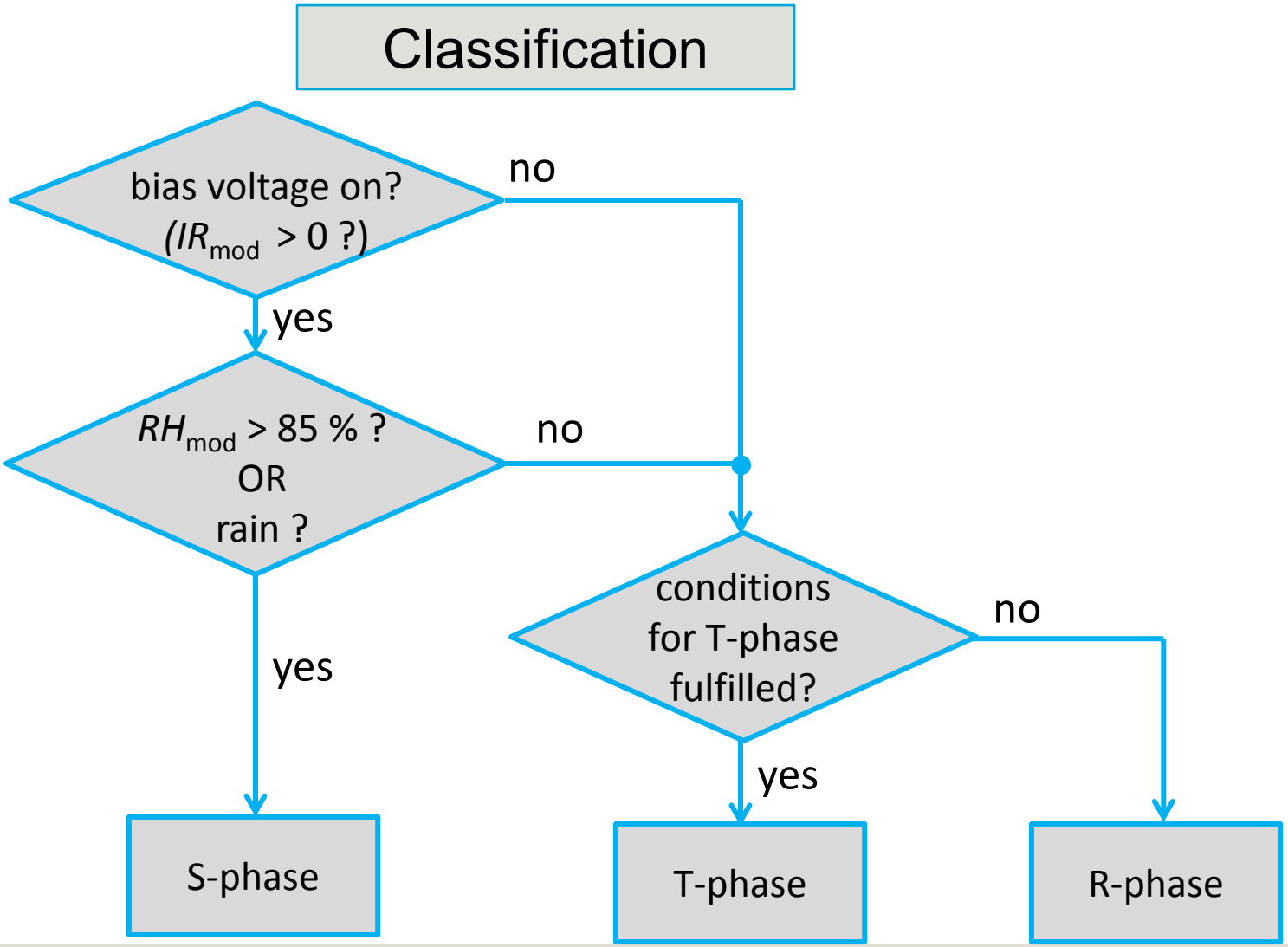
Environmental data



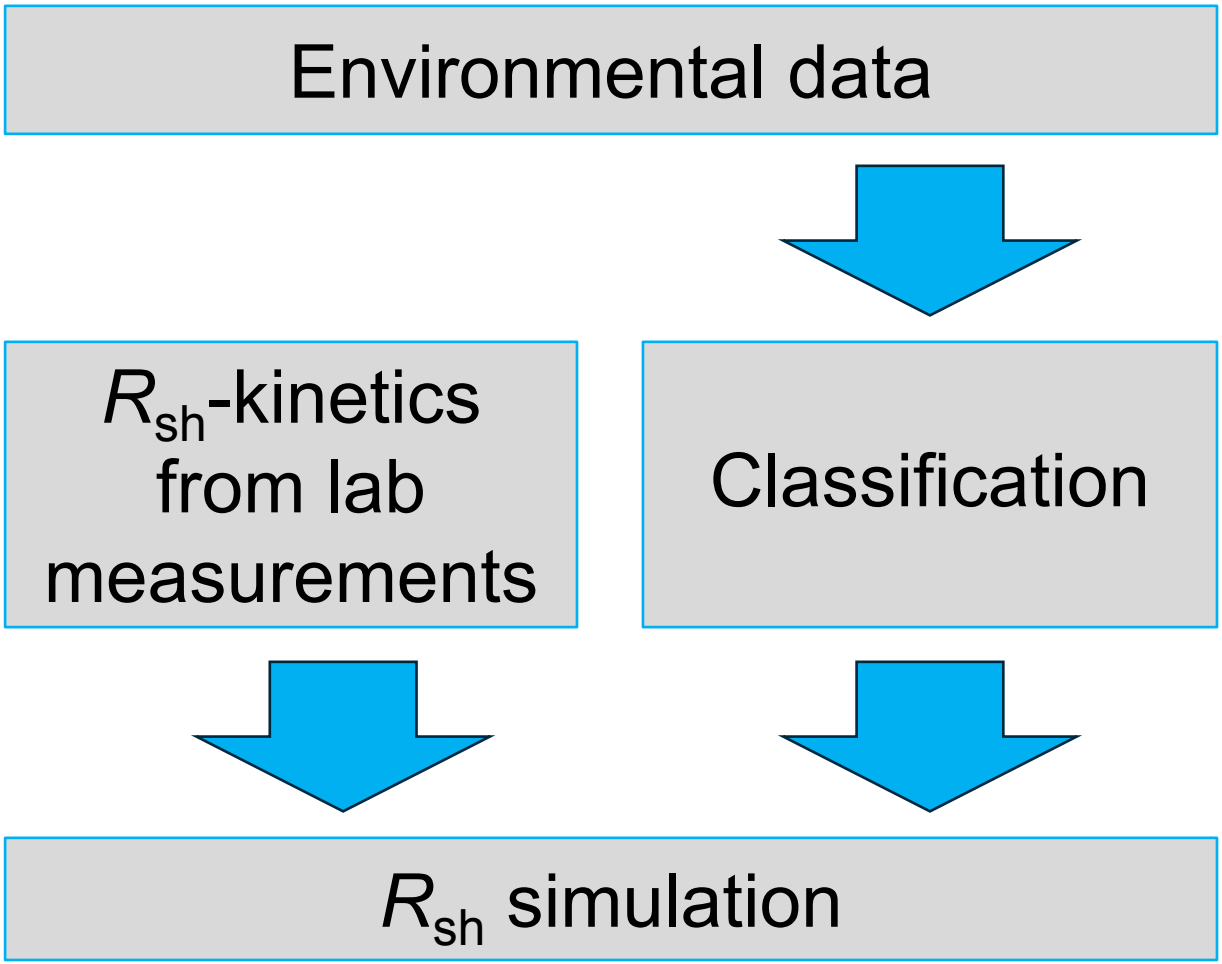
R_{sh}-kinetics from lab measurements

Classification

MODELLING PID-s

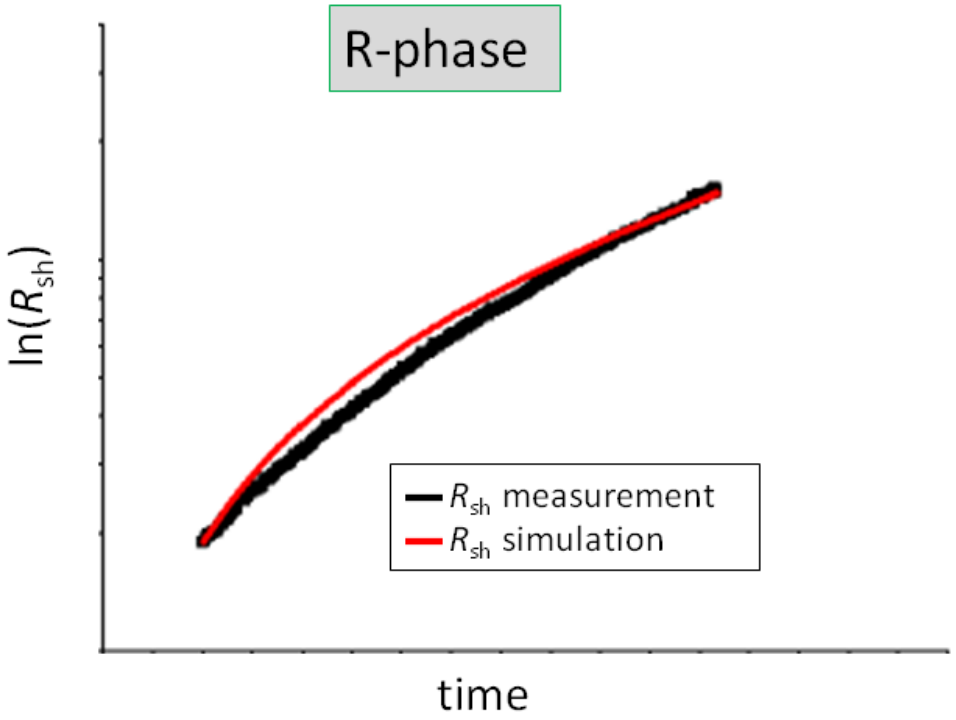


MODELLING PID-s



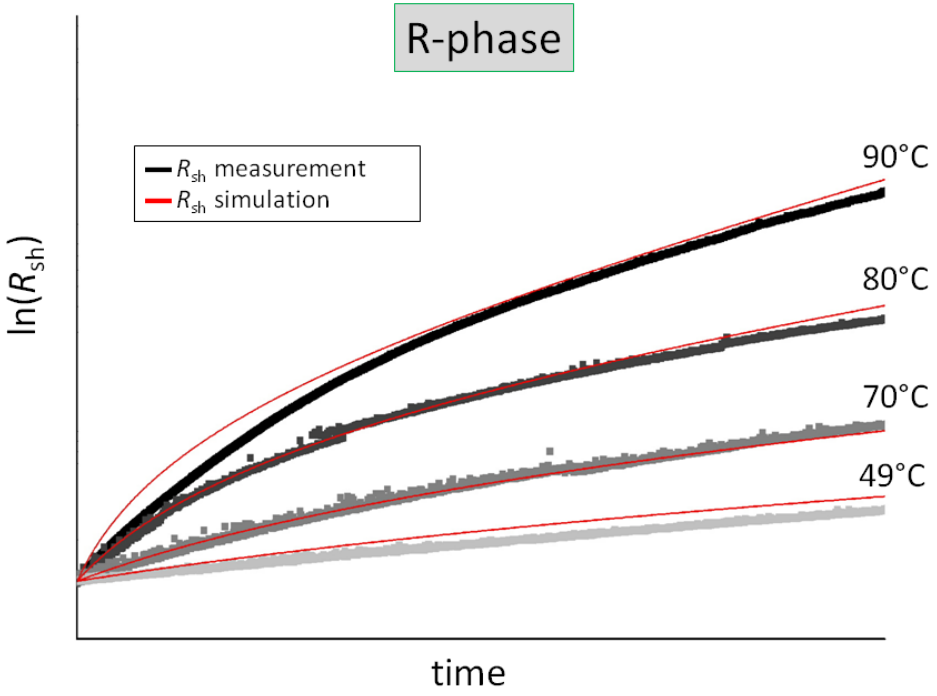
MODELLING PID-s

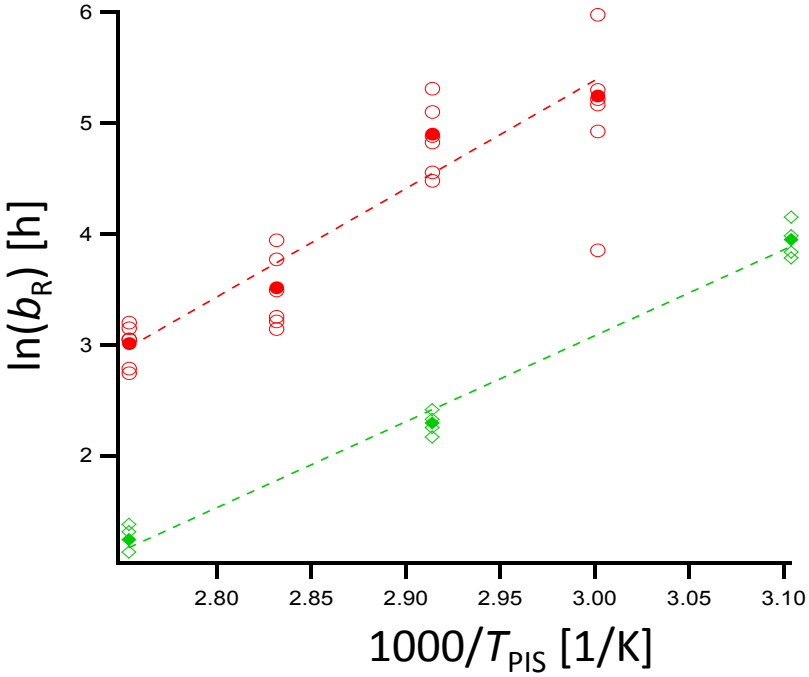
R_{sh} simulation



MODELLING PID-s

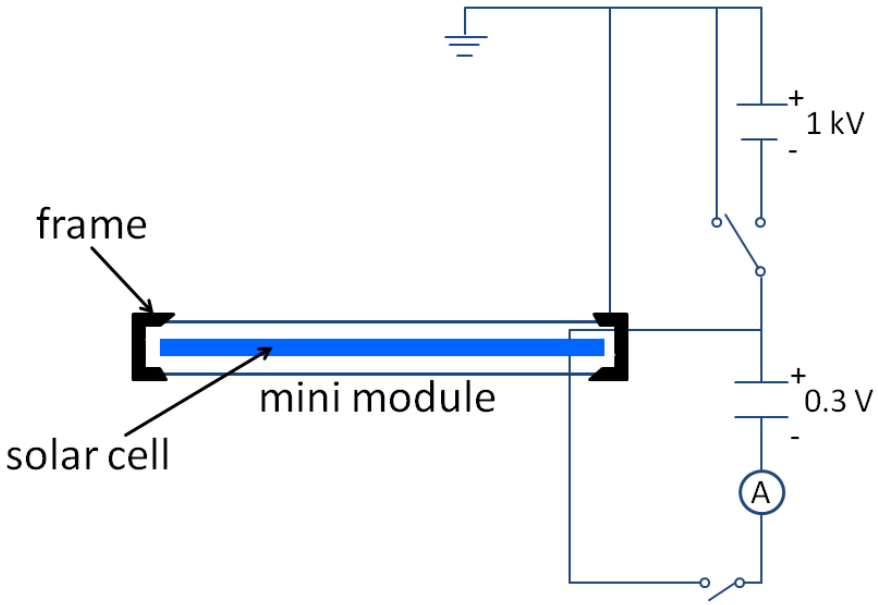
R_{sh} simulation





COMPARISON TO OUTDOOR MEASUREMENTS

Measurement of shunt resistance (R_{sh})



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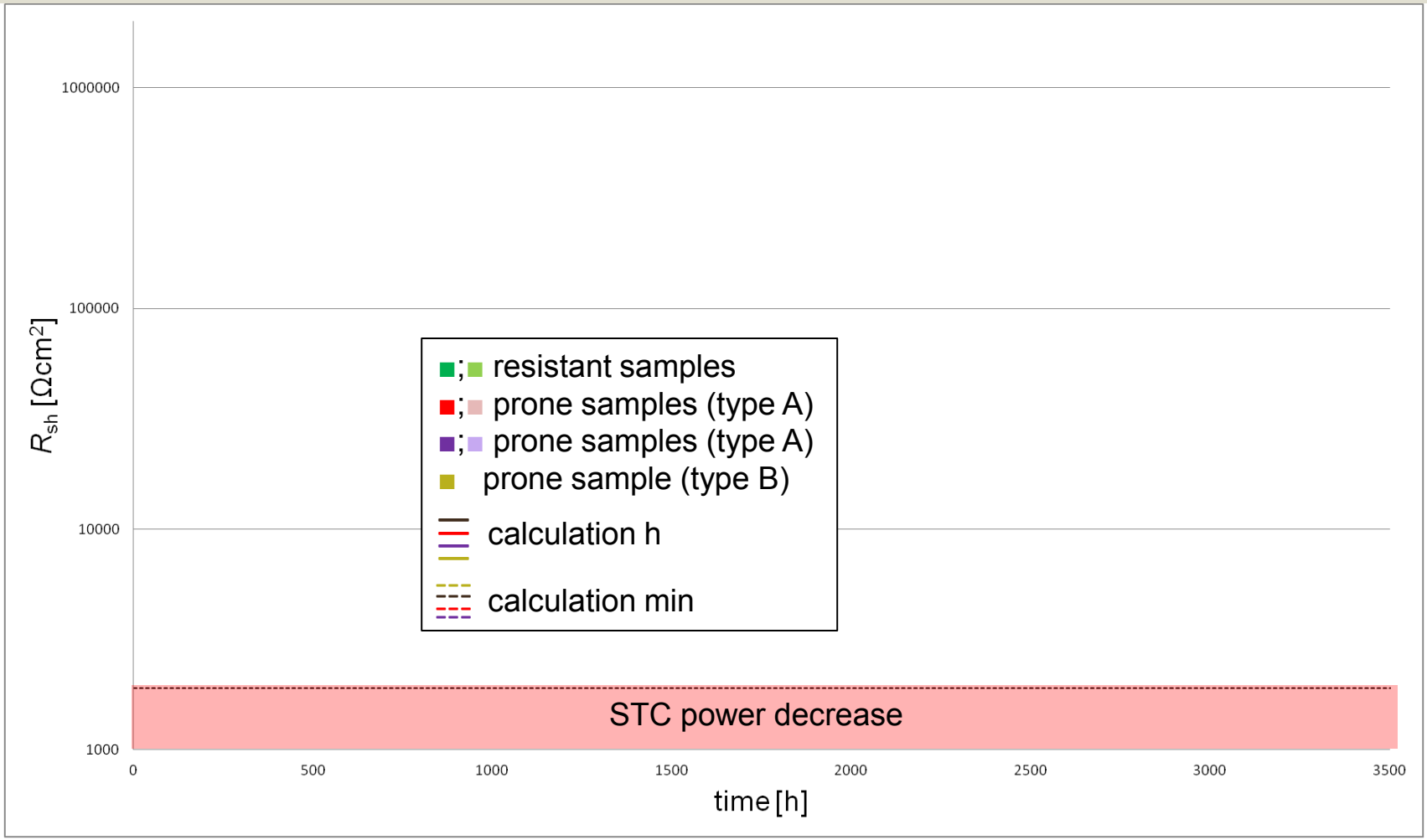

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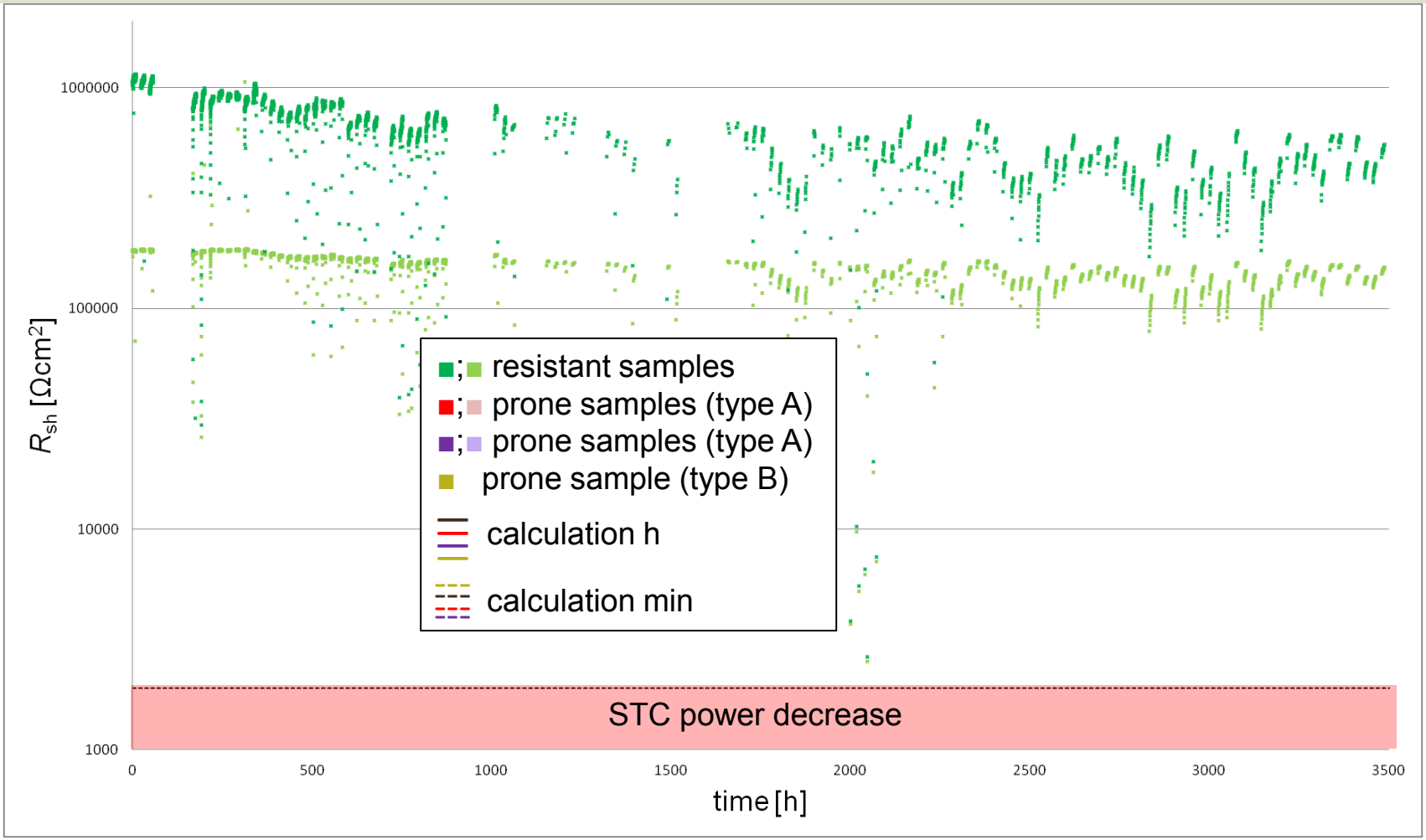

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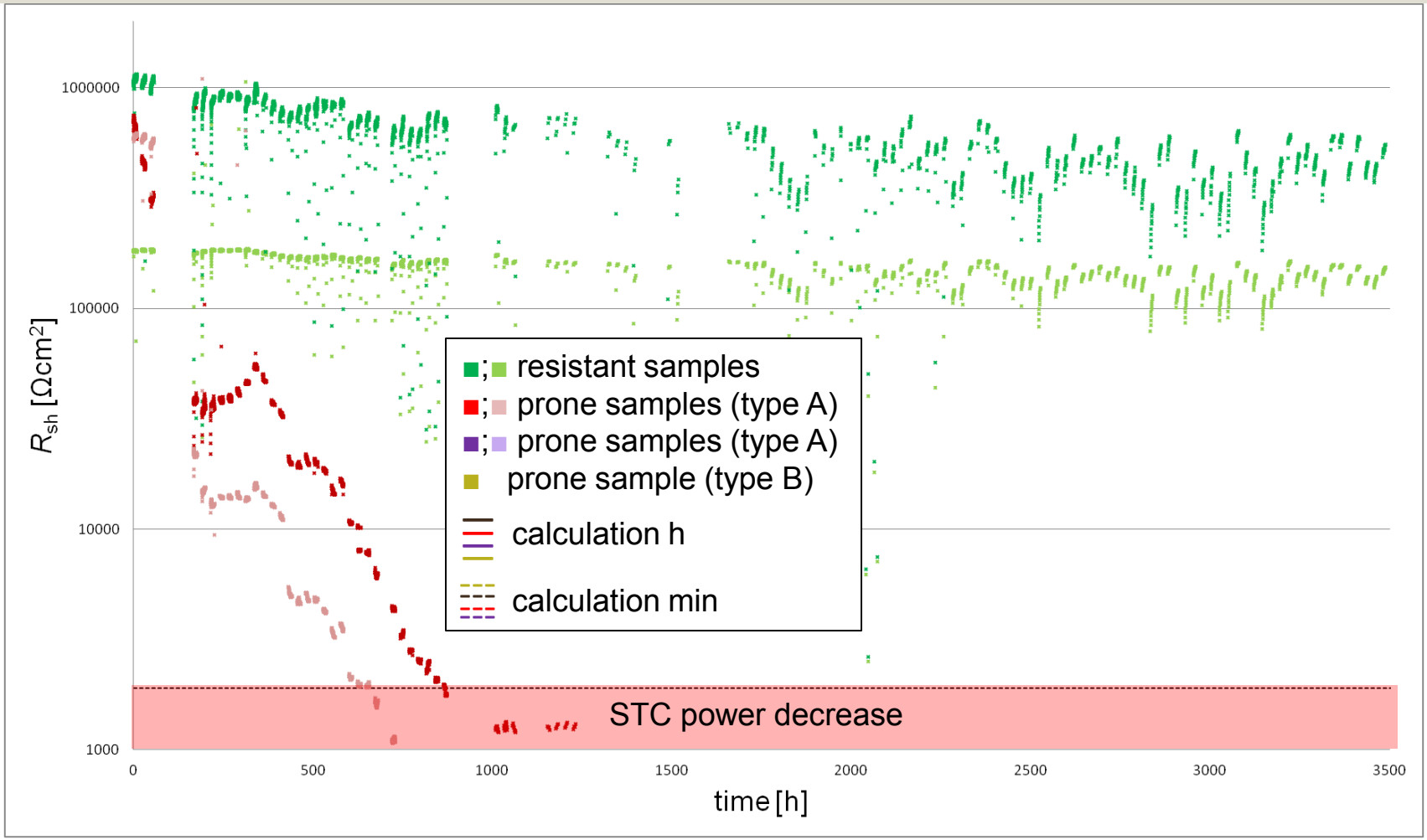

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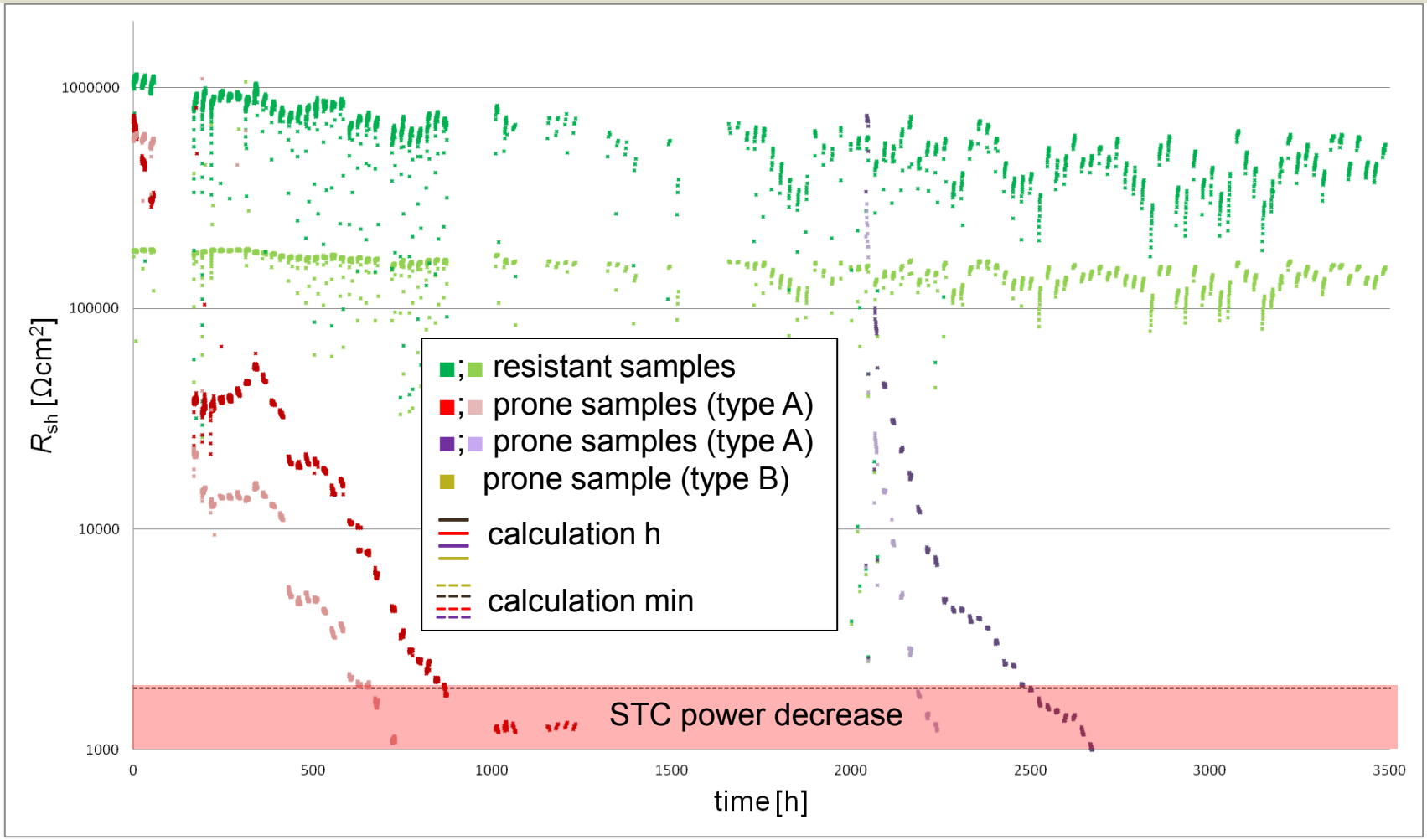

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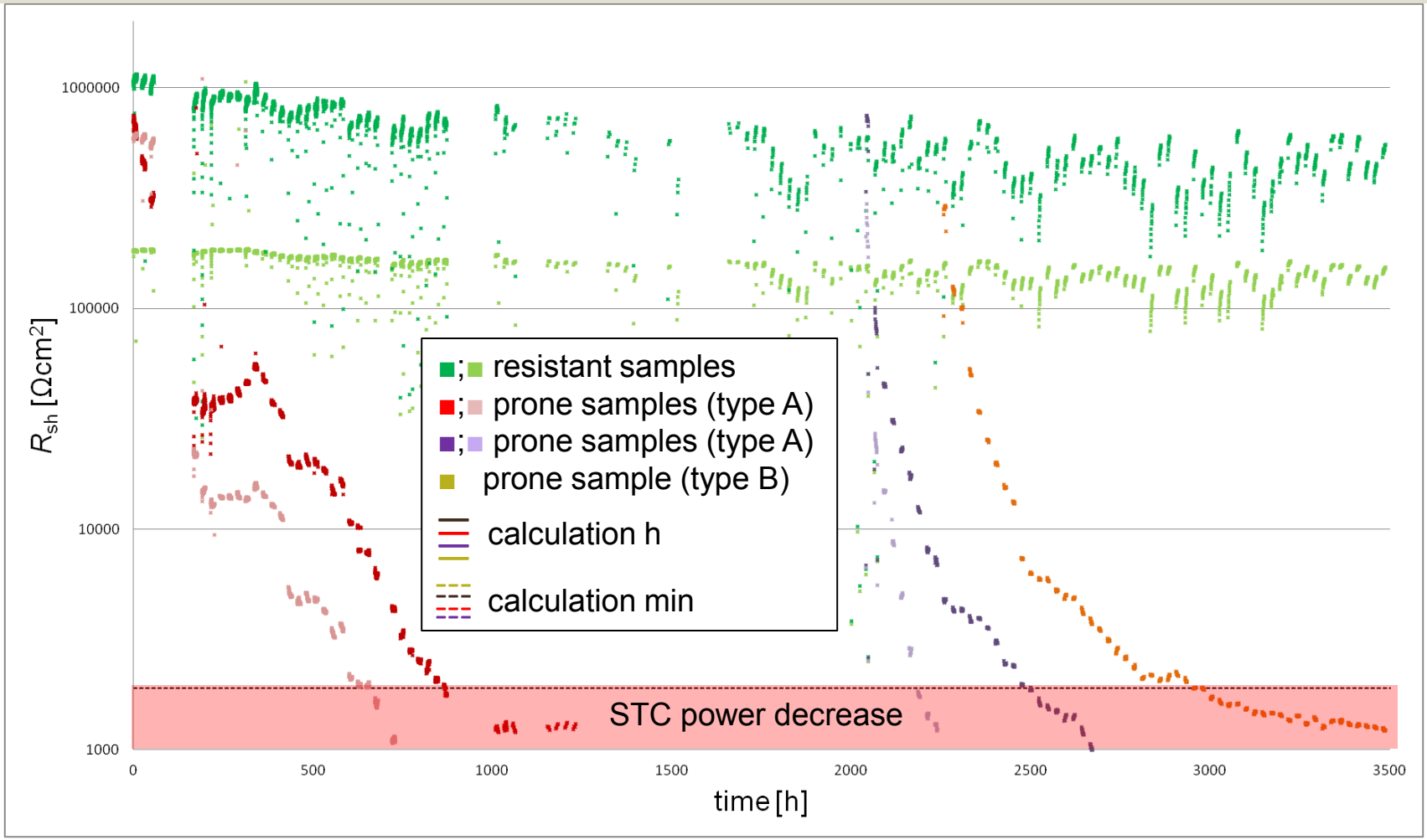

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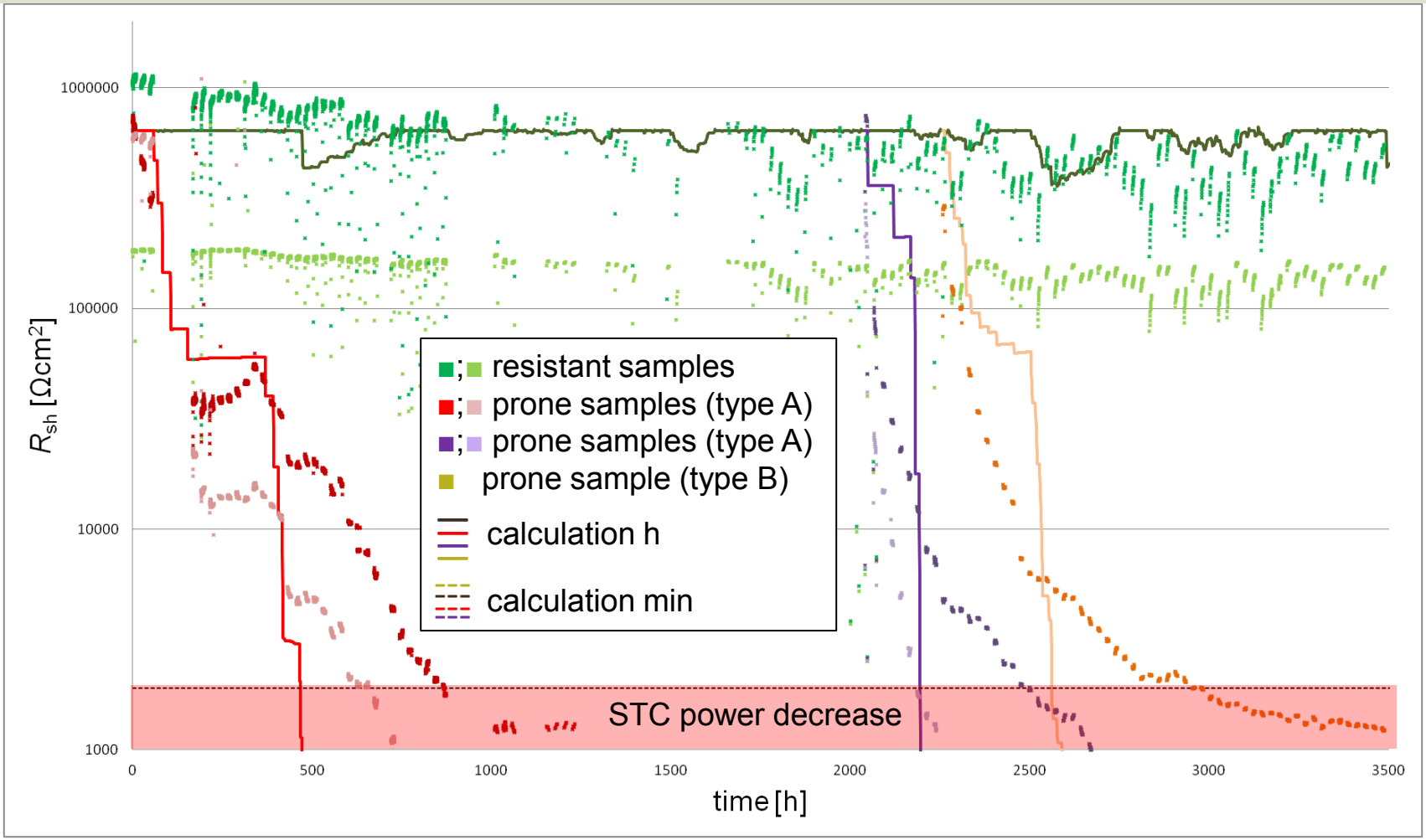

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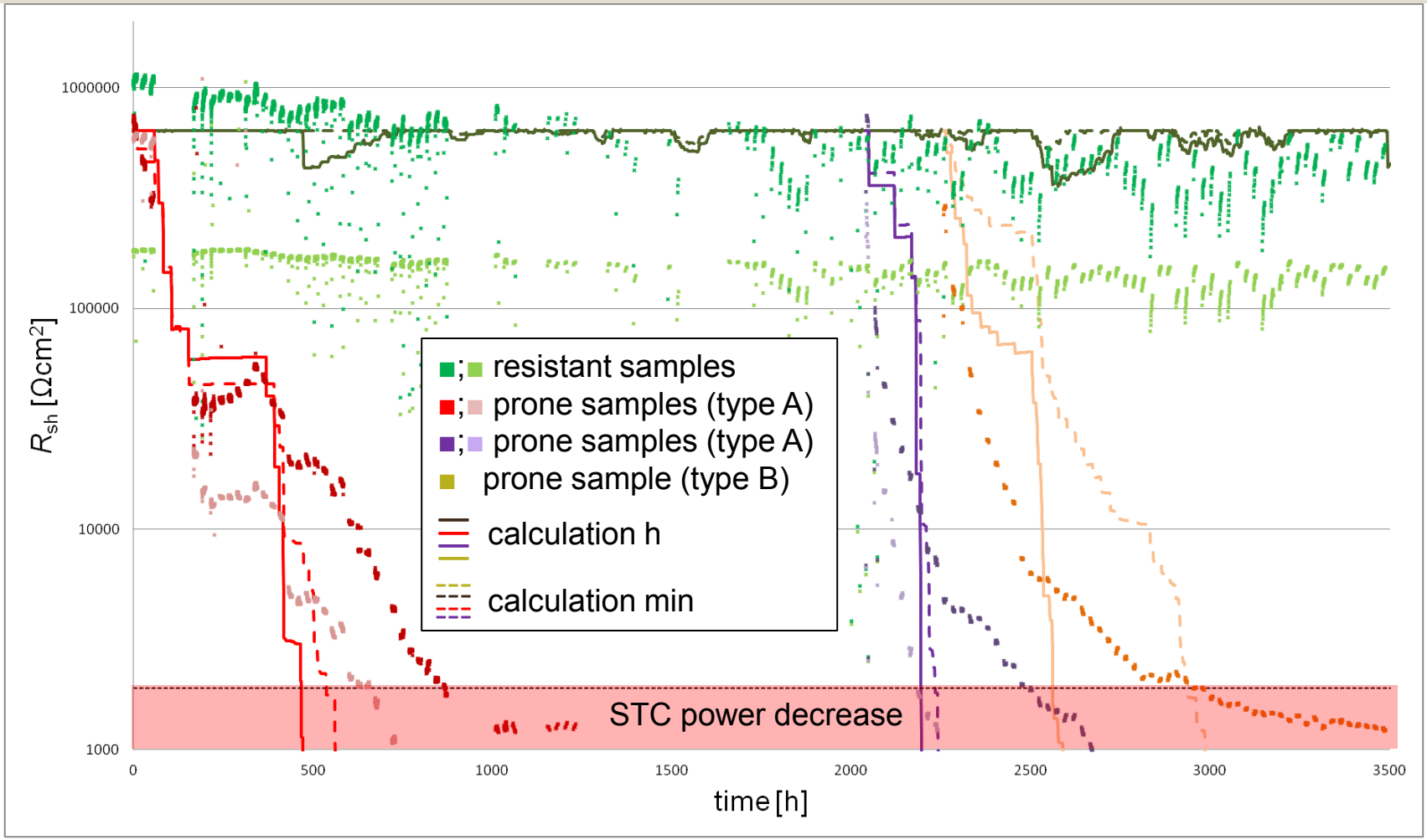


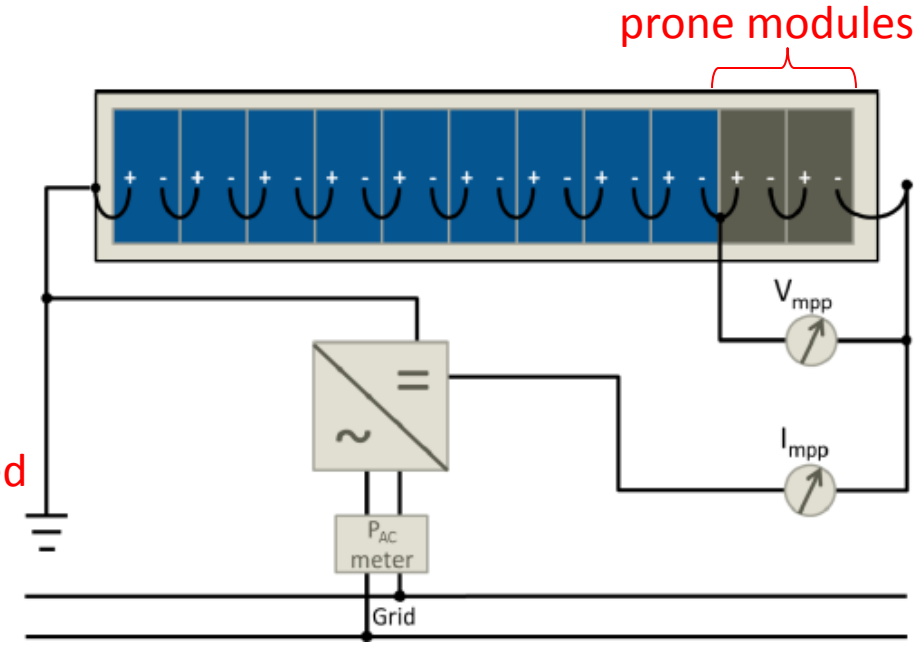
→ good qualitative agreement

COMPARISON TO OUTDOOR MEASUREMENTS

Results for full size modules:

"Valletta" test site (Thalheim, Germany)

test setup



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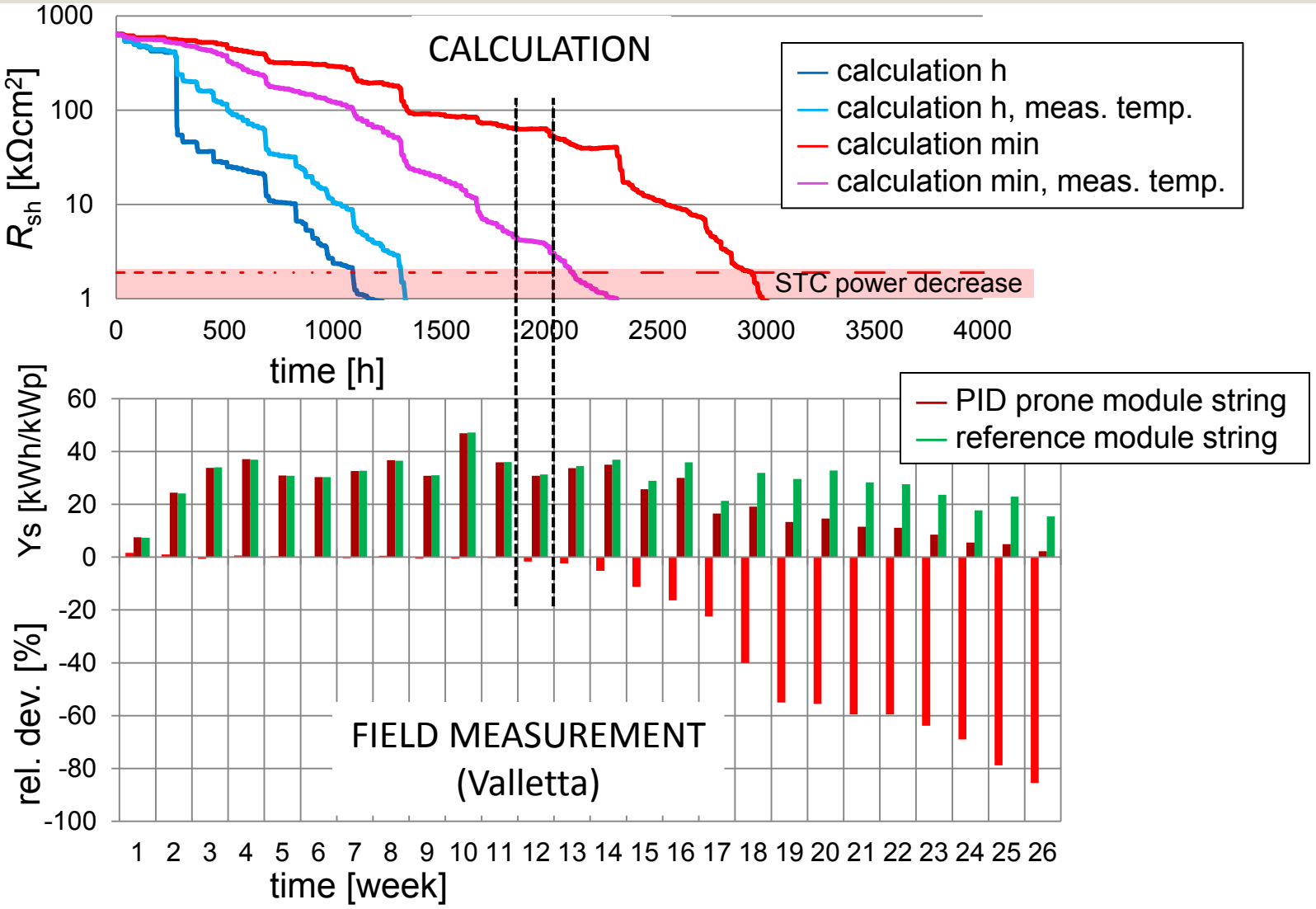
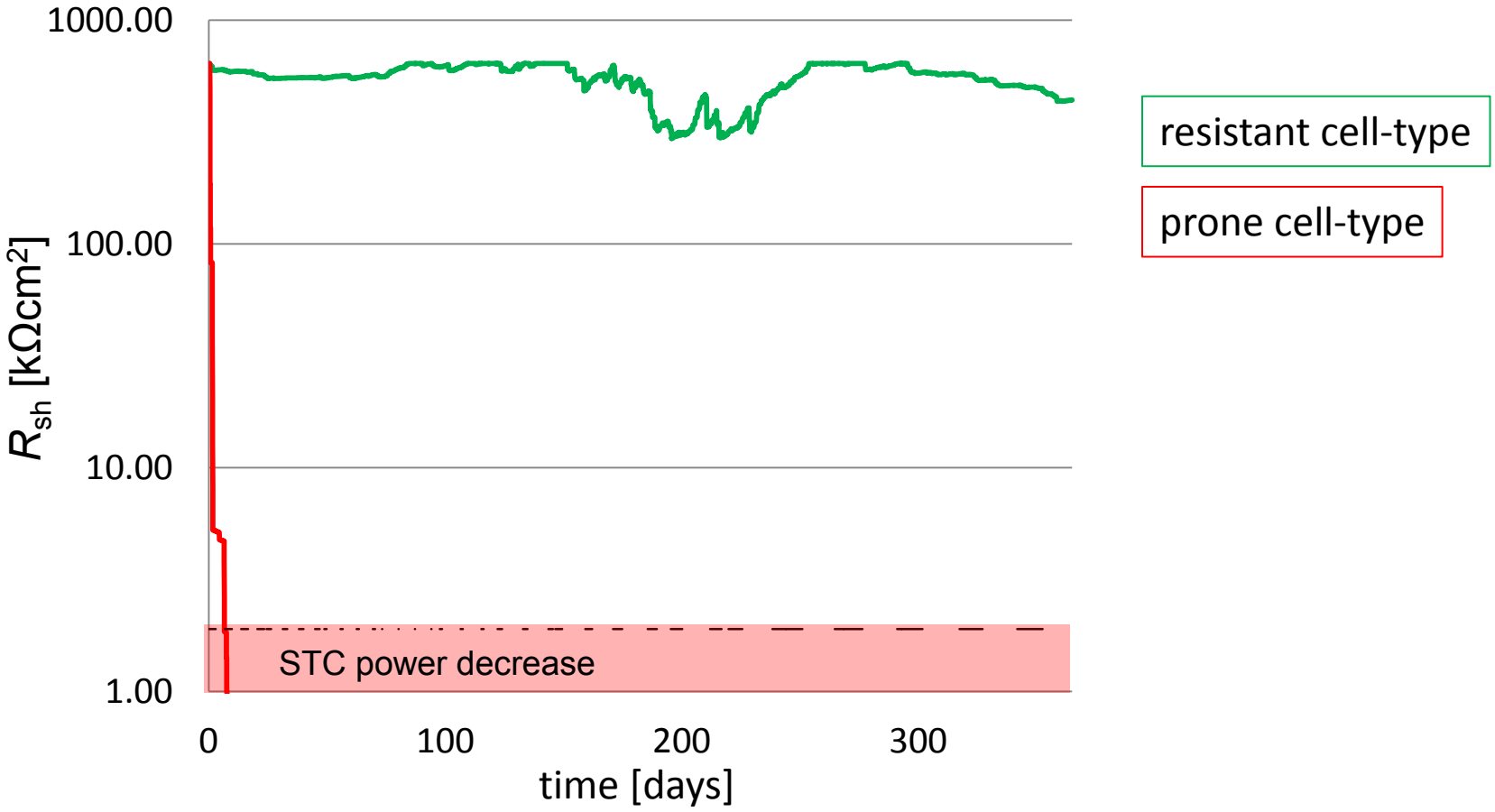


PID-s MODELING FOR 25 YEARS SERVICE LIFE

How do we ensure a 25 year service life with respect to PID-s ?

- Need to have reproducible tests ✓
- Need to understand progression of PID-s in the field → PID-s model ✓
- Need to derive parameters for tests
- Need to establish process control

LONG TERM PREDICTION POSSIBLE



→ parameters necessary for 25 years service life can be derived

Thalheim, Germany weather data of 2012 used

PID-s MODELING FOR 25 YEARS SERVICE LIFE

How do we ensure a 25 year service life with respect to PID-s ?

- need to have reproducible tests ✓
- need to understand progression of PID-s in the field → PID-s model ✓
- need to derive parameters for tests ✓
- need to establish process control in production

PROCESS CONTROL: PRODUCTION MONITORING

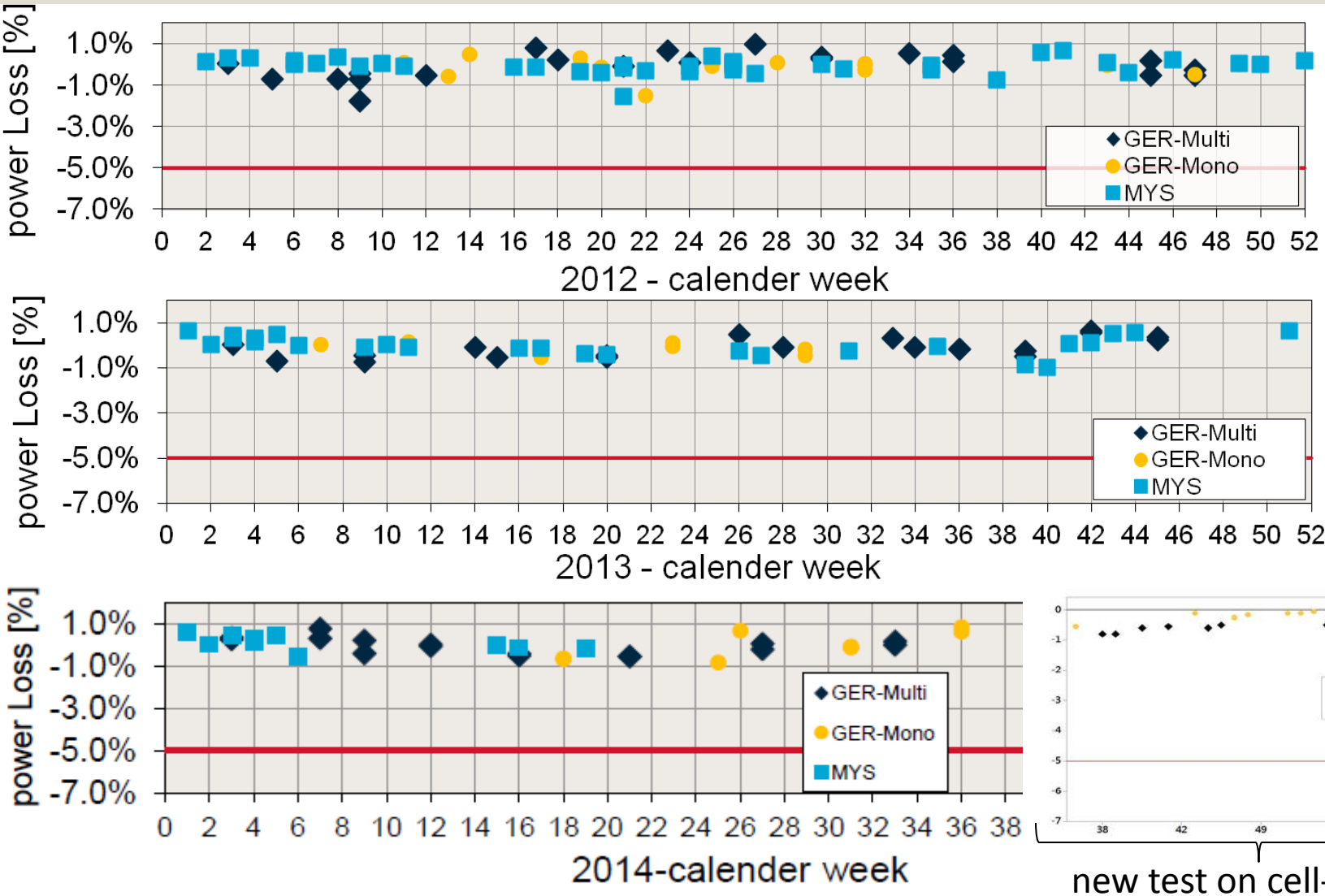
module level monitoring (Al-foil test, 168h)

- weekly sampling: random cells from production are tested on module level
- monthly sampling: random modules from every conversion site

cell level testing (PID cell tester, 24h)

- weekly sampling: PID-test on cell level (feedback < 48h) → fast reaction possible

PROCESS CONTROL: MONITORING DATA CELL PRODUCTION



PID-s MODELING FOR 25 YEARS SERVICE LIFE

How do we ensure a 25 year service life with respect to PID-s ?

- Need to have reproducible tests √
- Need to understand progression of PID-s in the field → PID-s model √
- Need to derive parameters for tests √
- Need to establish process control √

CONTENTS

I Introduction

II PID-s modeling:
How do we ensure a 25 year service life with respect to PID-s ?

- need to have reproducible tests
- need to understand progression of PID-s in the field
  → **PID-s model**
- need to derive parameters for tests
- need to establish process control in production

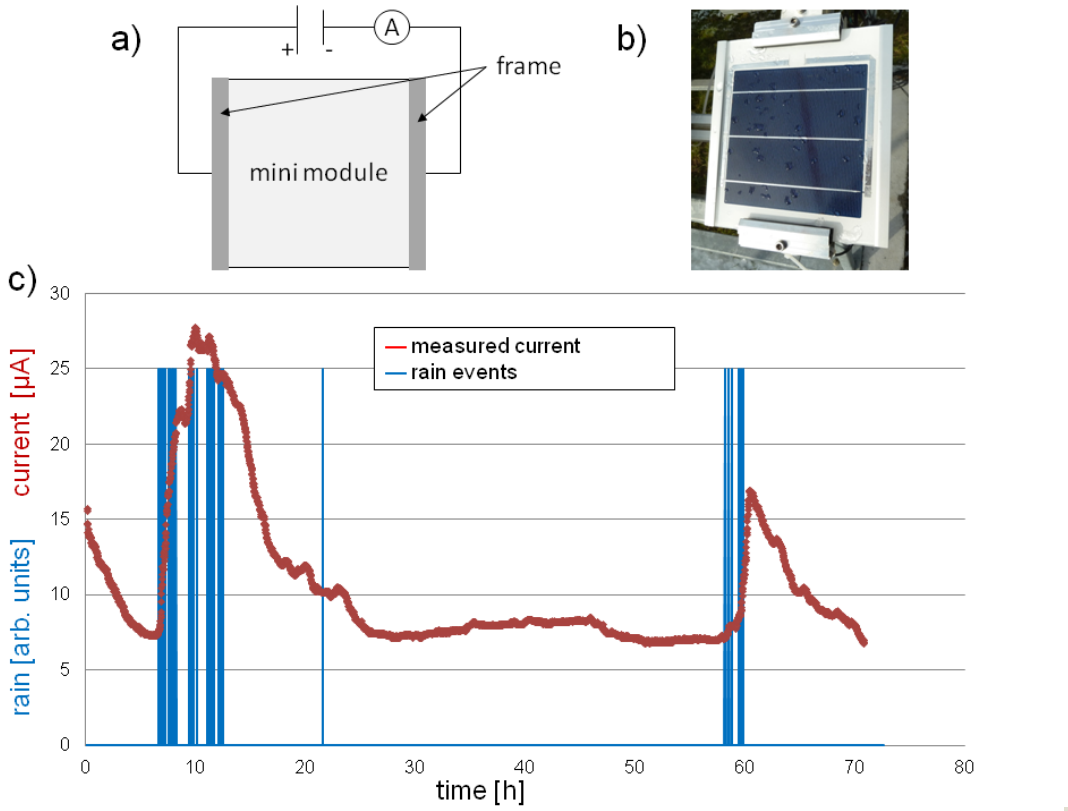
III Conclusion and Outlook

CONCLUSION

- reproducible PID tests are available (Al-foil, climate chamber)
- laboratory PID-tests represent only part of PID-s kinetics in field
- studying regeneration properties is essential
- PID-s model based on laboratory tests and meteorological data can describe long term progression
→allows for prediction of time of PID-s onset in specific location
- good qualitative agreement with outdoor measurements
- continuous production monitoring is essential

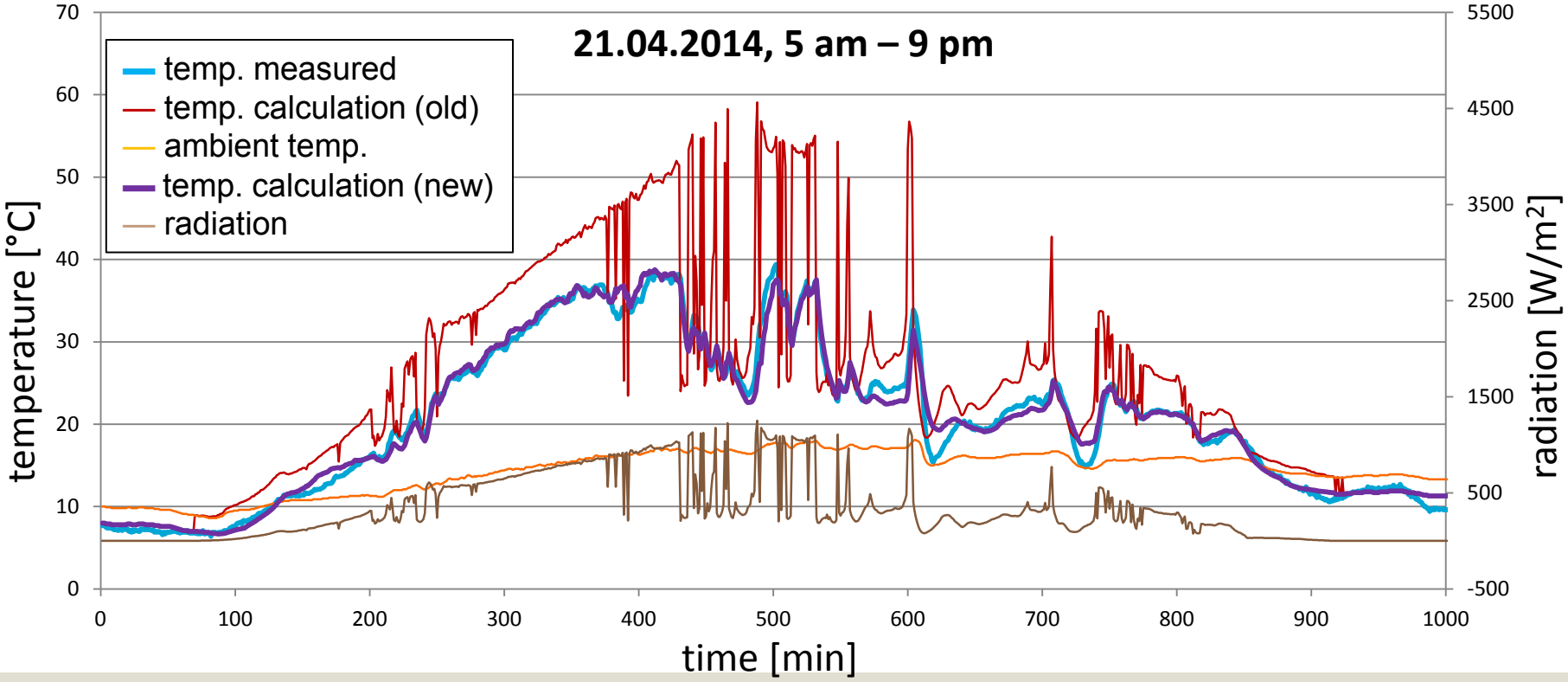
OUTLOOK

- new PID test sites in different climates planned
- improvement of model calculations:
  - detailed investigation of interplay between meteorological conditions and PID-s



OUTLOOK

- new PID test sites in Malaysia and USA planed
- improvement of model calculations:
  - detailed investigation of interplay between meteorological conditions and PID-s
  - revision of model equations



Thank you

Golden, 24.02.2015

Max B. Koentopp, Christian Taubitz, Matthias Schütze, Marcel Kröber

ACKNOWLEDGEMENT

This work was partly supported within the Spitzencluster Solarvalley project *xμ-Clip* (FKZ 03SF0452) by the German Federal Ministry of Research and Technology.

Thanks to co-authors:

Christian Taubitz
Matthias Schütze
Marcel Kröber

SOLARVALLEY Mitteldeutschland

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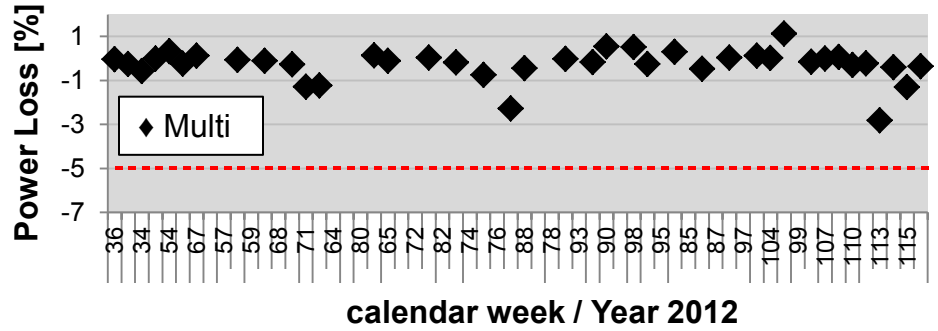
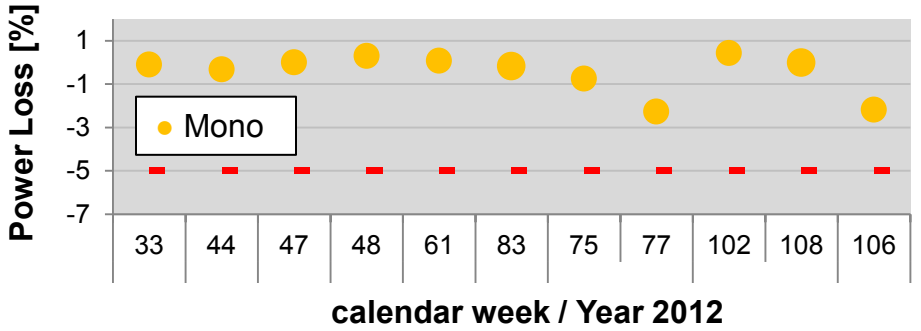
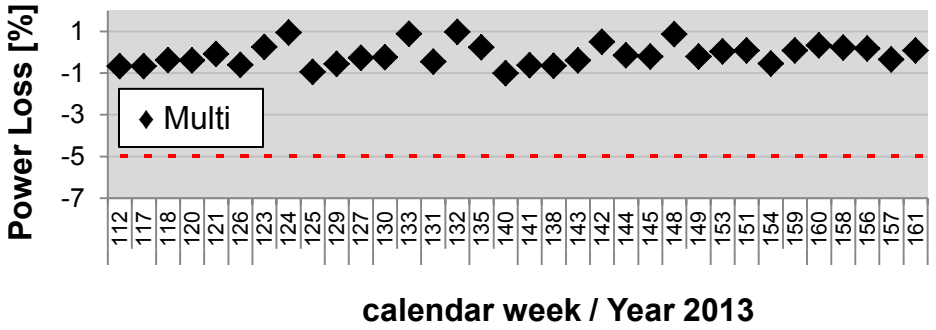
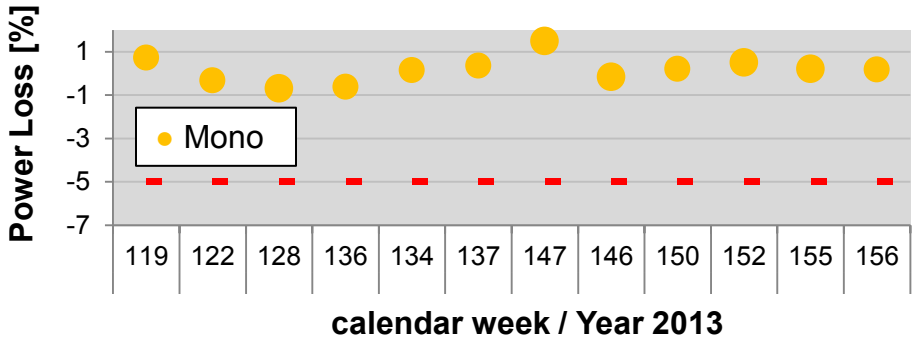
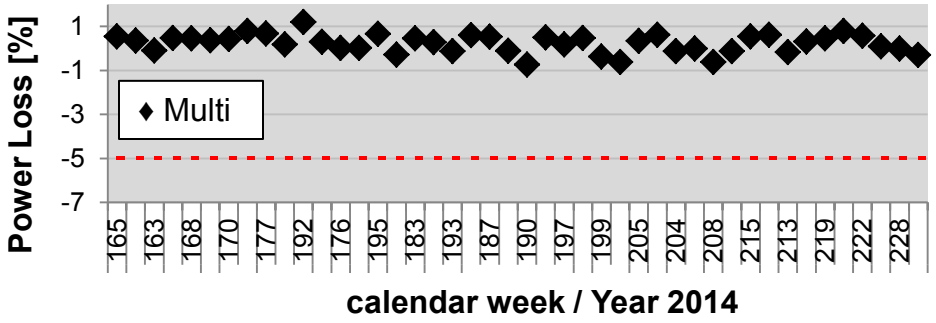
PROCESS CONTROL: MONITORING DATA MODULE PRODUCTION

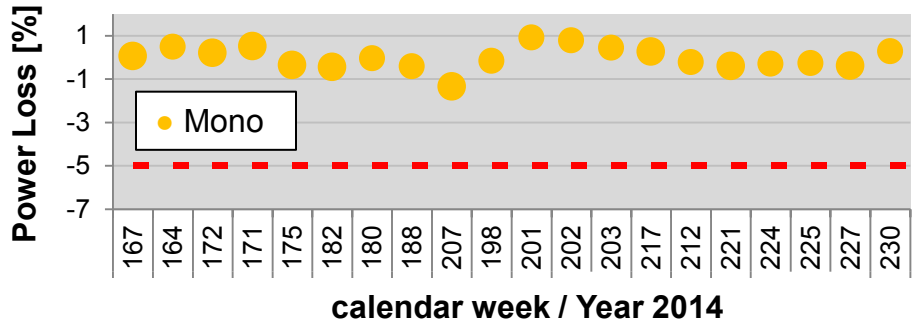






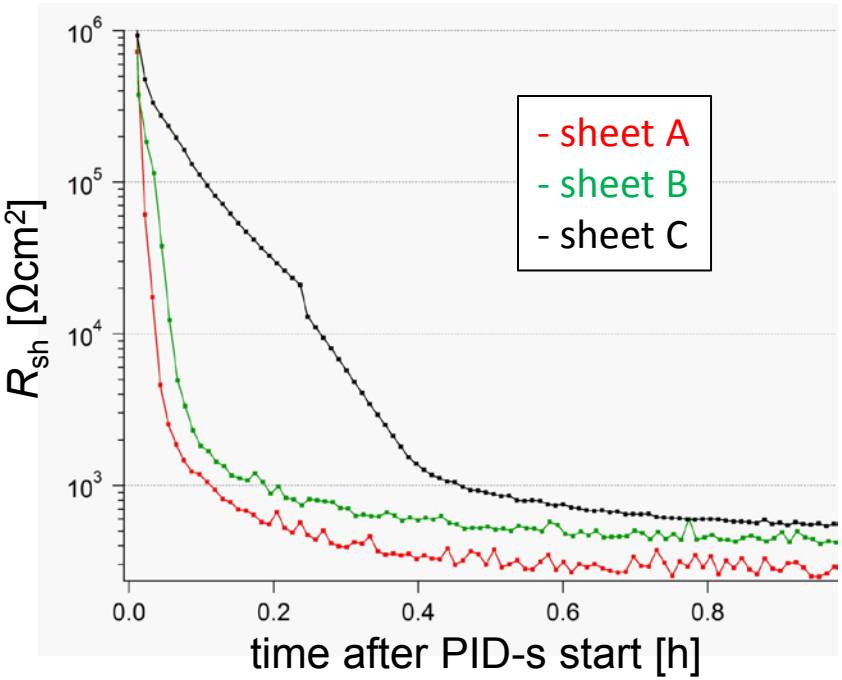


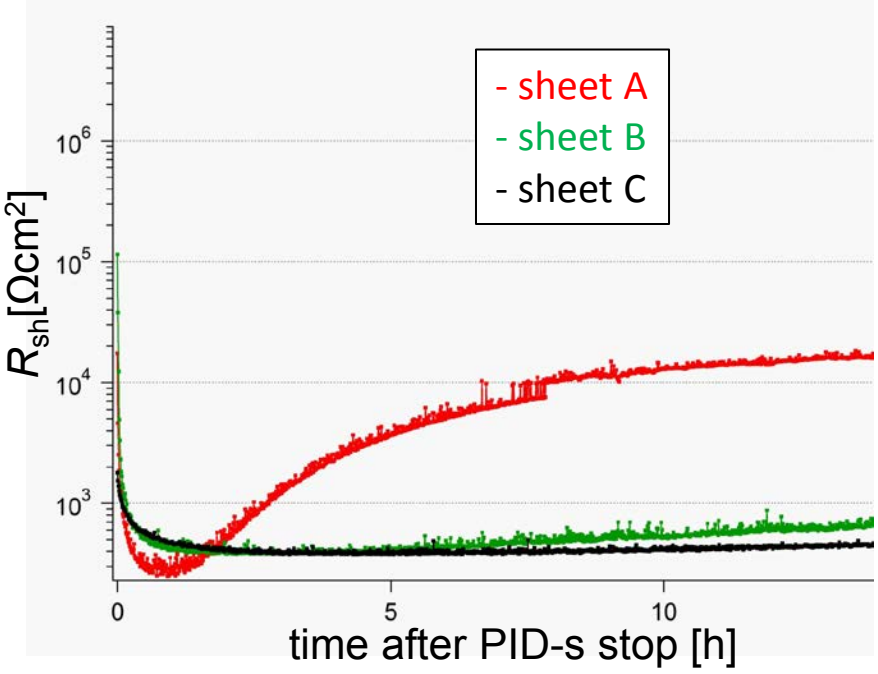




ENCAPSULANT INFLUENCE ON PID-s

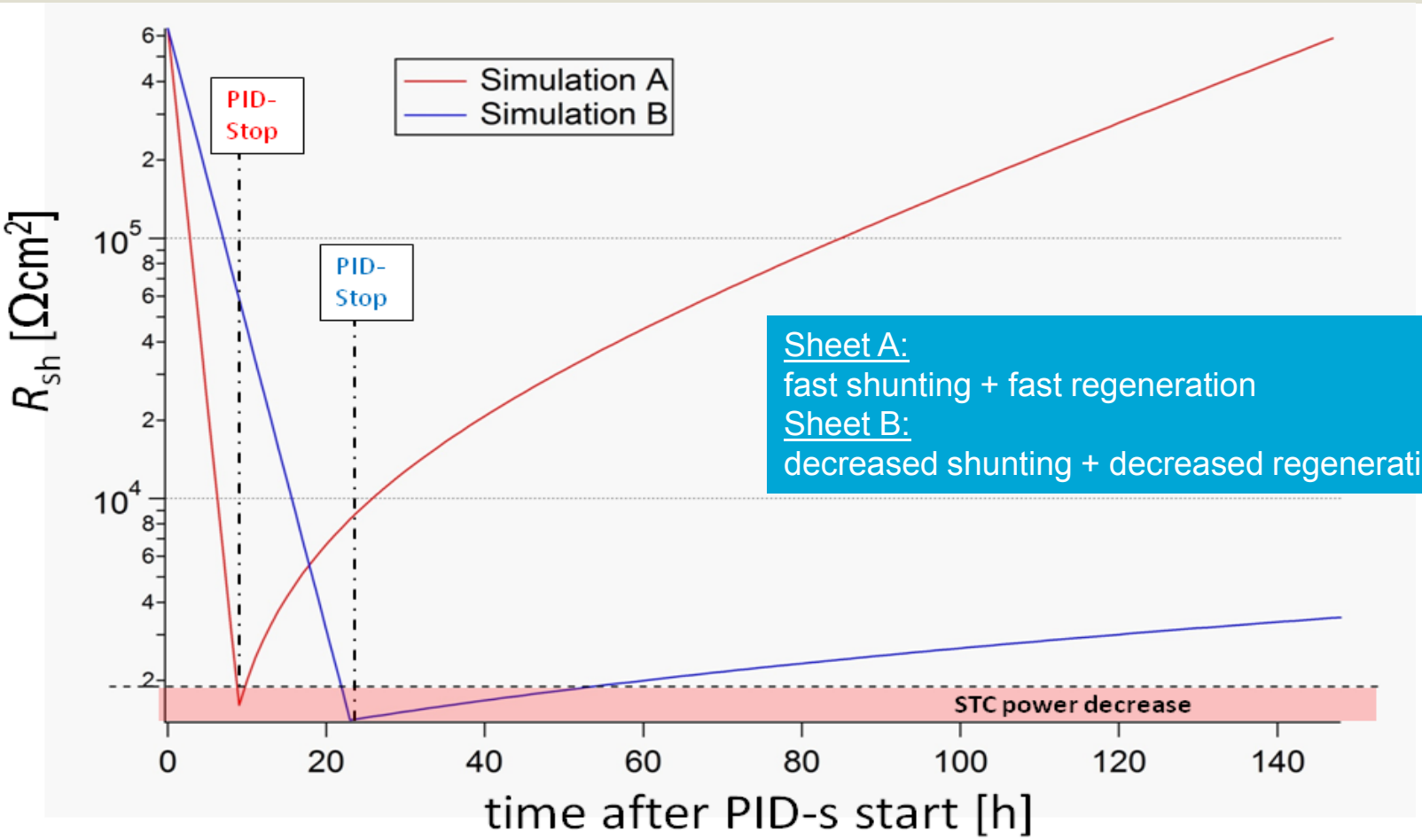
Investigation of degradation and regeneration behavior





→ Decrease in shunting can also lead to a decrease in regeneration

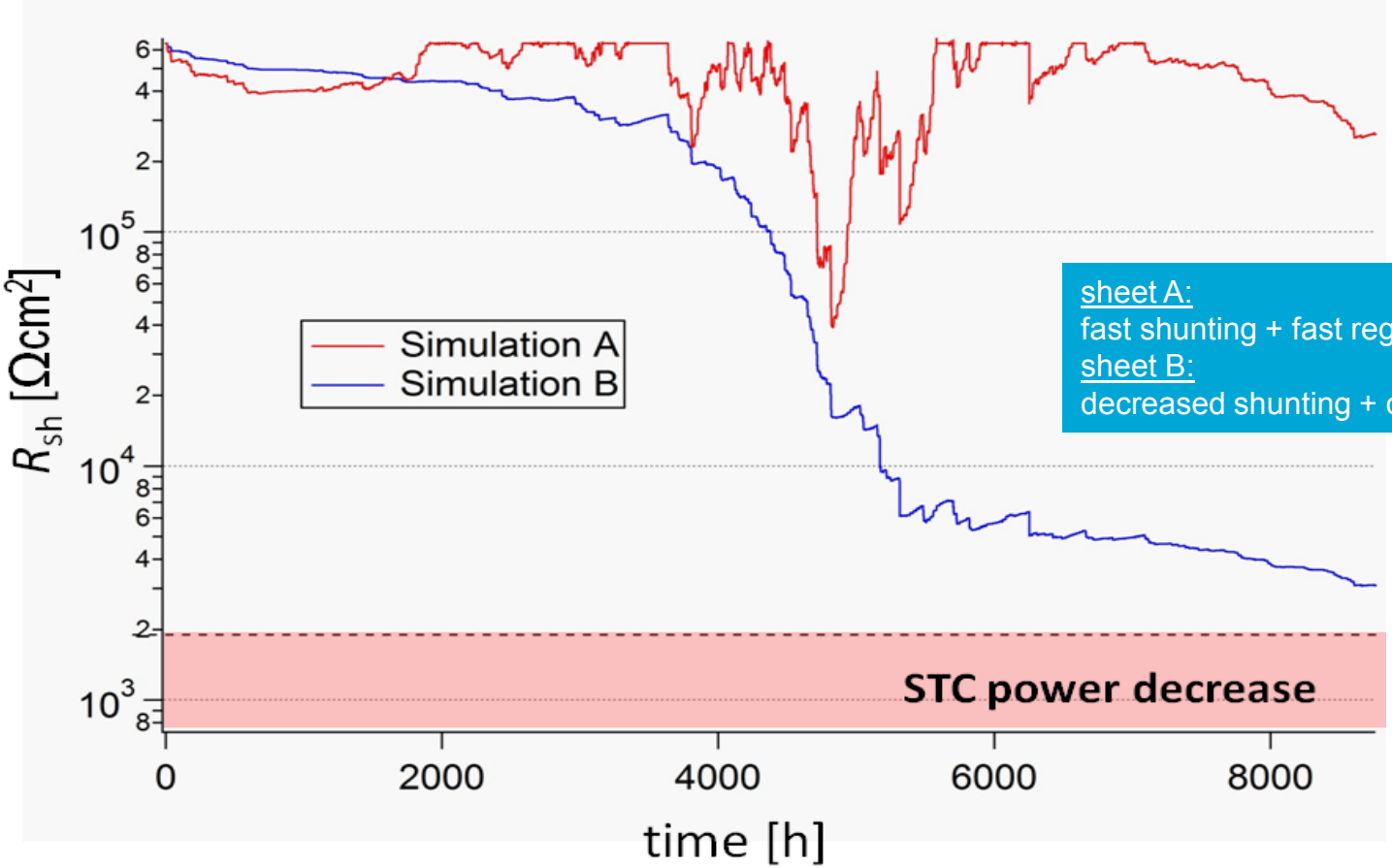
INFLUENCE ON PROGRESSION



Sheet A:
fast shunting + fast regeneration
Sheet B:
decreased shunting + decreased regeneration

Simulation of R_{sh}-kinetics during shunting and regeneration at 49°C

INFLUENCE ON LONG TERM PROGRESSION



sheet A:
fast shunting + fast regeneration
sheet B:
decreased shunting + decreased regeneration

Model-calculations of R_{sh}-kinetics using weather data measured for Thalheim 2012 .

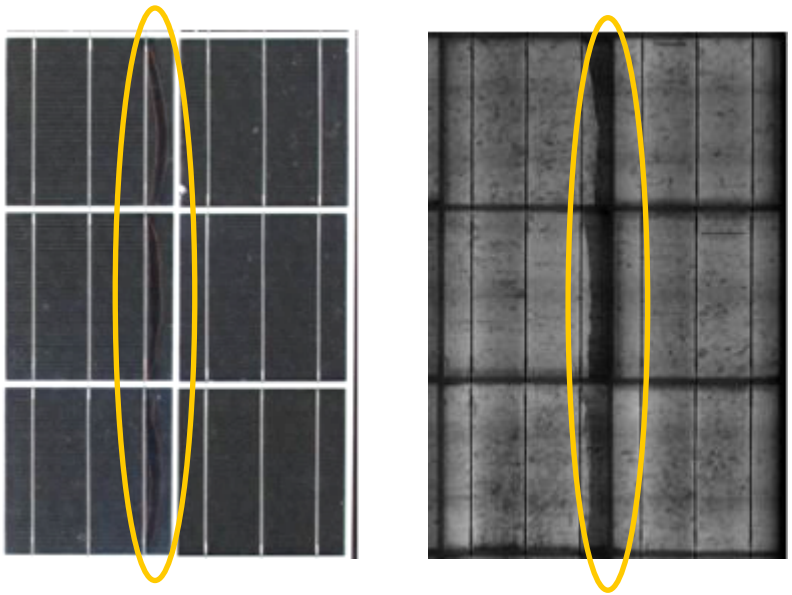
→ A module performing better in PID testing might actually fail earlier in the field

The Influence of the PV backsheet on the Formation of Snail Trails

Fraunhofer Center for Sustainable Energy Systems CSE - Boston

Cordula Schmid, Jacqueline Ashmore

Rafal Mickiewicz, David Meakin



NREL reliability workshop

February, 24th 2015

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Snail Trails: Introduction

- The solar industry is investigating so-called 'snail trails' – small, dark lines that have begun to crop up on modules starting around 2006. [1]
- The phenomenon affects modules from several manufacturers in the U.S., Europe and Asia. [1]
- There is discussion around the exact causes, but researchers suspect a chemical reaction of the silver metallization fingers occurring when moisture penetrates cells due to micro cracks. [2]

[1] Ines Rutschmann, Unlocking the secret of snail trails, Photon International, 01-2012

[2] Köntges et al., Schneckenspuren, Snail Tracks, Worm Marks und Mikrorisse, TÜV Rheinland, 8. Modul-Workshop 2011

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Snail Trails: Introduction

- Snail trails do not emerge in modules stored indoors.
- When applying damp heat to modules stored indoors, snail trail like effects can develop but disappear again.
- Snail trails appear to develop quicker in humid and hot climates and slower in dry and cold climates, for the same module type.
- Irregular snail trails appear to be an indication for inhomogeneous temperature distribution.
- Snail trails develop to a certain width. After that they either stop growing or appear to grow very slowly.
- Degree of EVA cross linking does not correlate with snail trails.

Köntges et al., Snail Tracks (Schneckenspuren), Worm Marks und Micro Cracks, International Energy Agency, IEA PVPS Task 13 Workshop, 27th EU PVSEC, 2012

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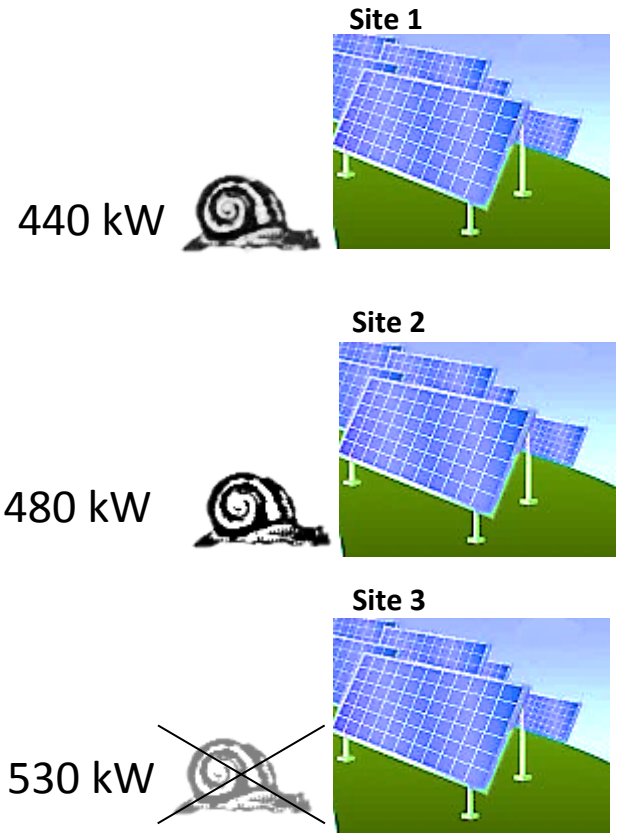
Project background / approach

- 3 sites having the same PV module model installed within 2.5 years in New England were analyzed.
- 2 out of 3 sites showed snail trails.
- From each site 5 fielded modules and 1 module out of storage were analyzed.
  - Crack analysis
  - Visual snail trail detection
  - I-V under STC
  - Core sampling
    SEM, FTIR



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Crack analysis using electroluminescence imaging

- Distribution of crack location.
- Each field in the matrix represents a cell position. The numbers represents the total number of cracks at that specific position.
- In general there is no apparent pattern in the location of the cracks.

Site 1
Σ 5 modules

4	2	1	4	13	2
8	5	0	0	2	2
1	3	0	5	14	1
4	11	3	3	8	4
6	17	8	11	10	4
5	10	10	11	13	4
5	21	6	1	17	2
7	20	6	2	5	2
3	3	1	2	3	3

Site 2
Σ 5 modules

1	1	1	4	1	4
0	7	5	1	4	4
11	7	1	3	2	2
9	12	1	3	3	1
4	5	6	3	4	1
12	11	4	3	7	6
10	32	6	14	1	5
14	15	8	6	7	1
8	11	7	9	1	2

Site 3
Σ 5 modules

0	0	2	2	0	2
2	2	1	4	1	4
1	1	1	2	4	2
6	1	4	0	5	2
6	4	3	2	3	2
5	1	1	2	1	6
4	4	3	3	1	0
1	1	2	1	2	1
7	3	1	1	6	4

Unfielded
1 module

1	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	1	0	0
0	0	0	0	0	0
0	4	0	0	0	0
0	0	0	0	0	0

Unfielded
1 module

0	0	0	0	0	0
0	0	0	0	0	0
1	0	0	0	1	0
1	0	0	0	2	0
0	0	1	0	0	0
0	1	0	0	0	1
0	0	0	0	0	0
0	1	0	0	1	0
0	0	0	0	0	1

Unfielded
1 module

2	1	0	0	0	1
0	2	0	0	2	0
1	0	5	2	2	1
2	0	0	0	2	0
2	6	0	0	0	0
1	1	0	0	0	0
0	0	0	0	1	0
0	0	0	1	0	0
0	0	0	0	0	1

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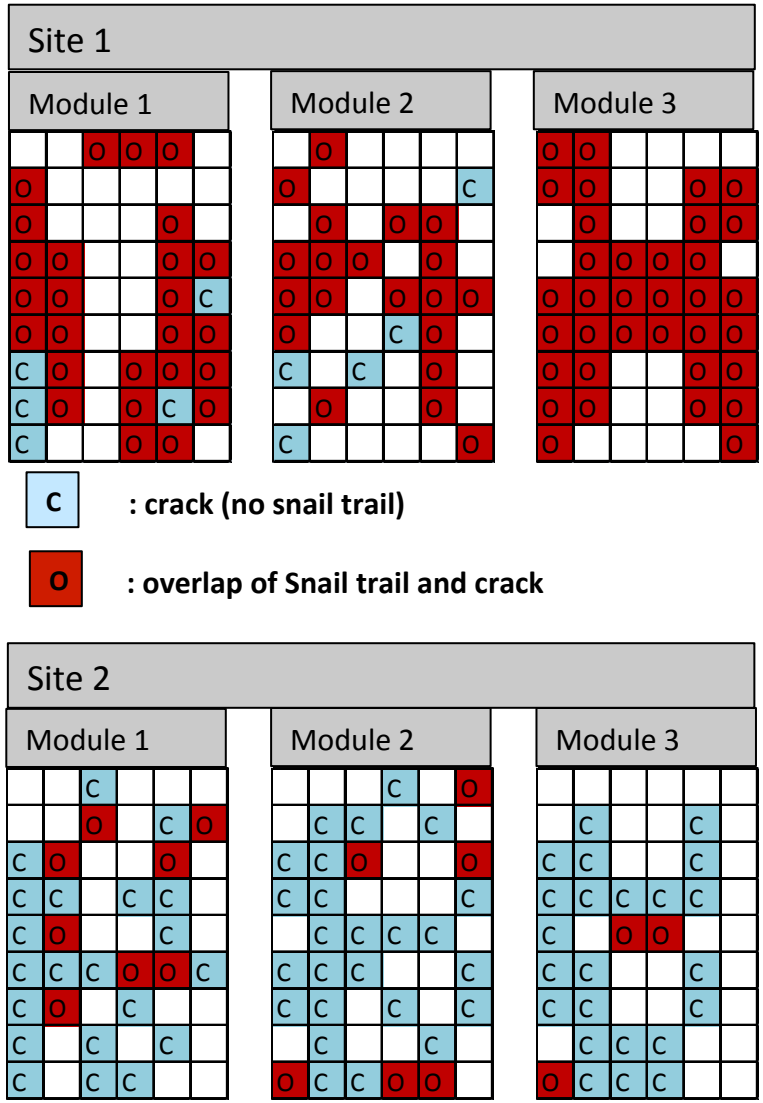
Snail Trail and Crack Correlation

- Nearly 100 % of the snail trails are correlated with cracks in the cells (red fields in matrix).
- Not every crack can be correlated with a snail trail, but this may change over time.



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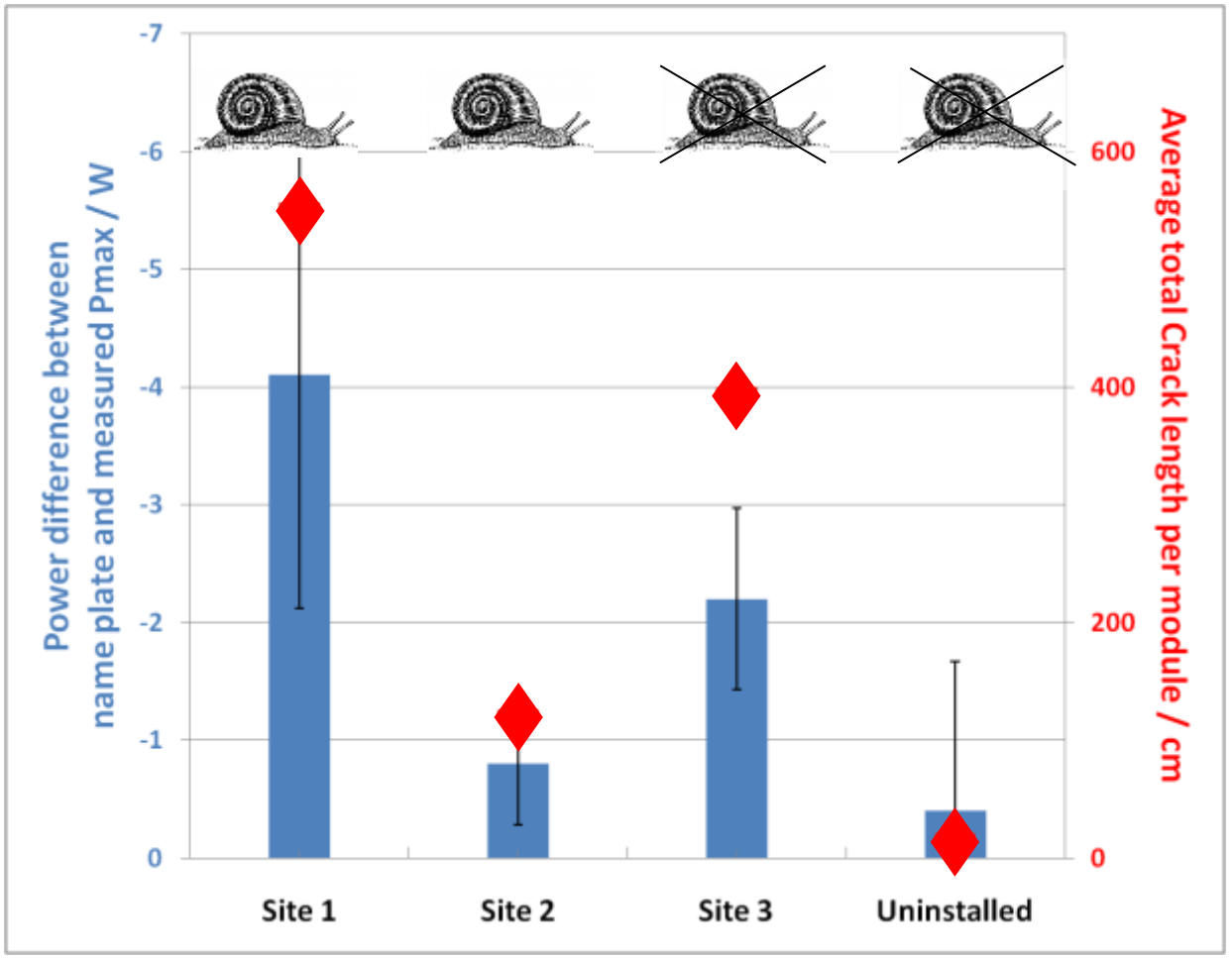
Solar Simulator Performance Testing

Module power loss appears to correlate with the number of cracks, rather than with the number of visible snail trails.



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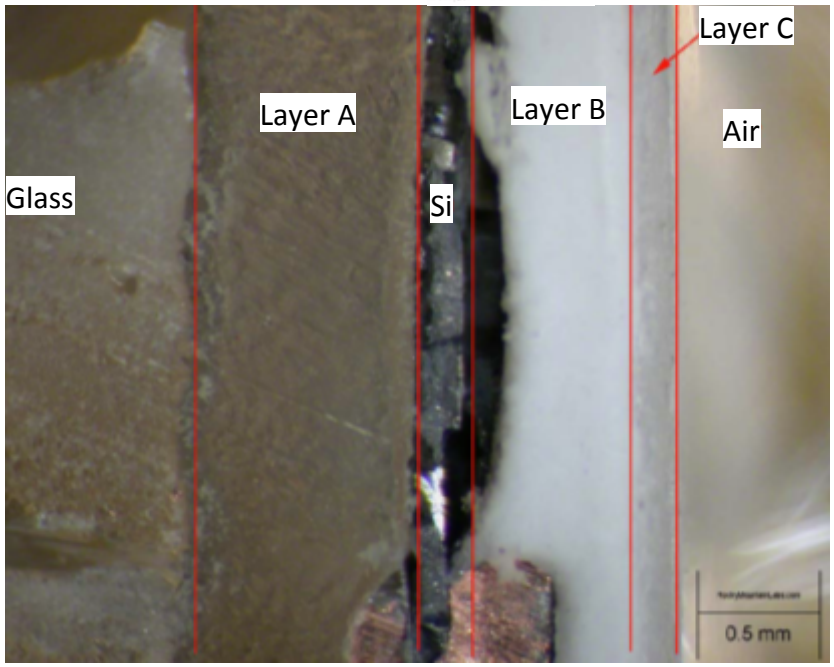
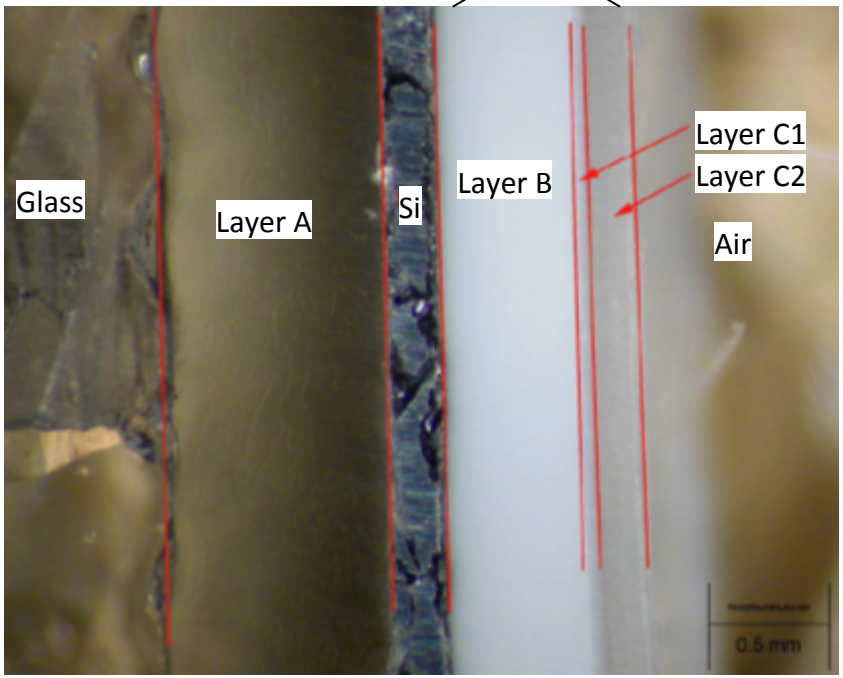
Core sampling

Optical image of a cross section

Site 1



Site 3



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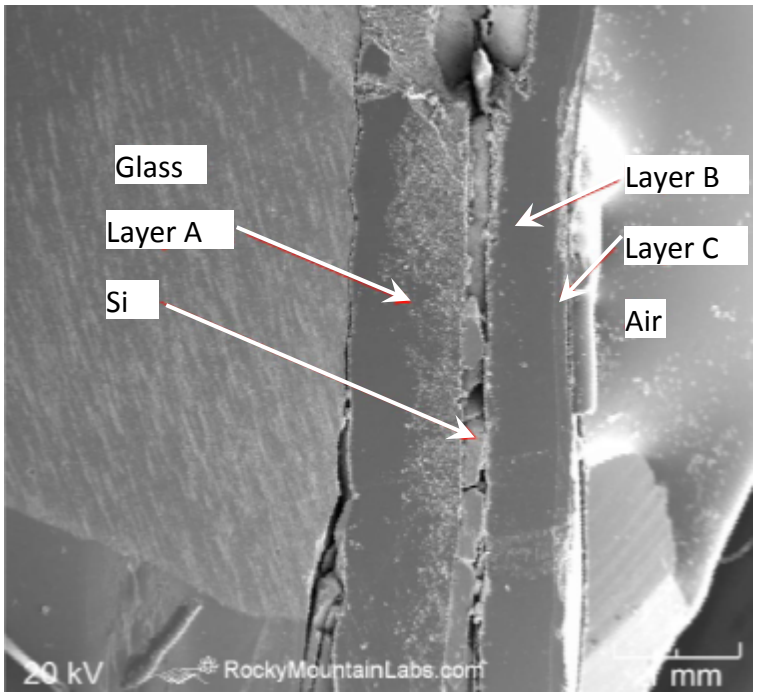
Core sampling

SEM (Scanning electron microscope) image of a cross section

Site 1



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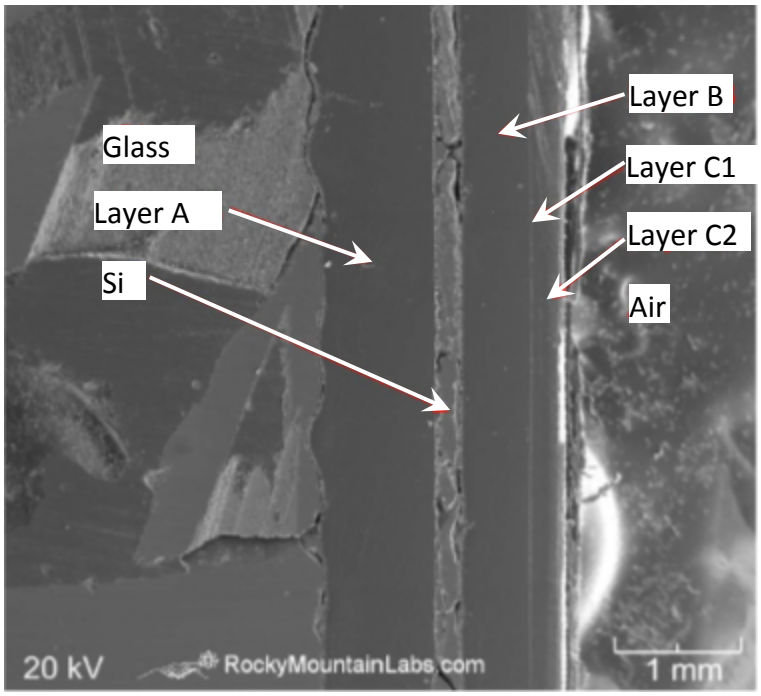

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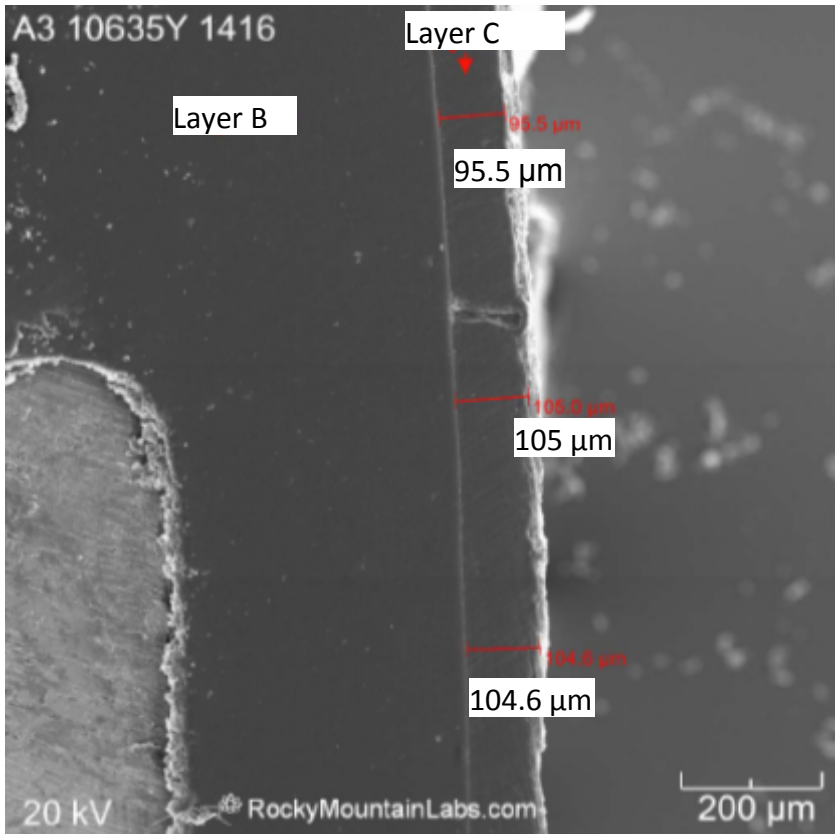
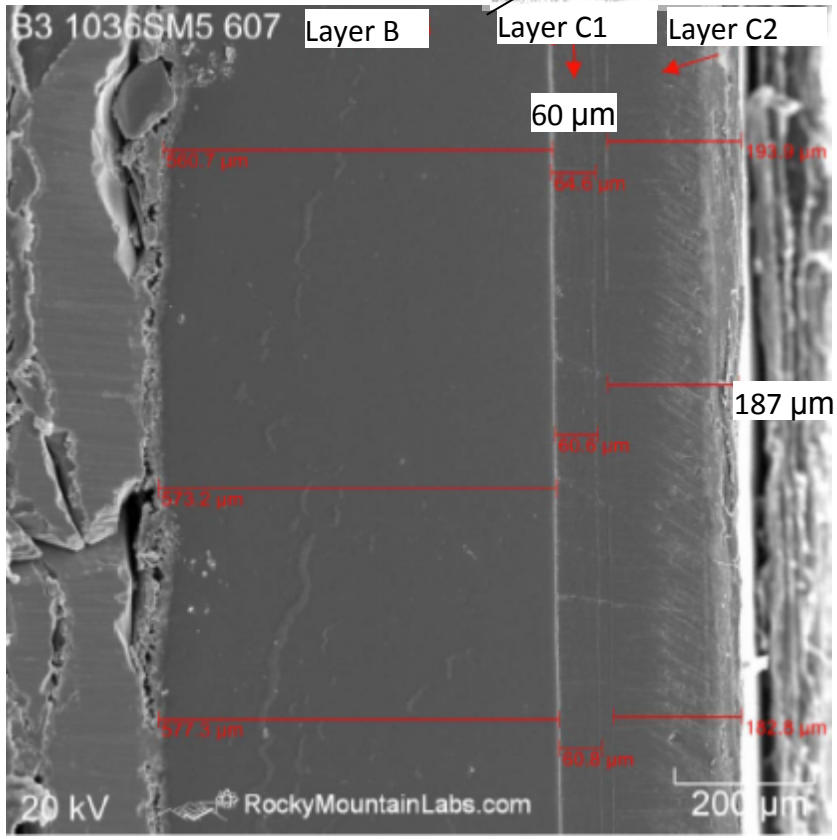
Core sampling

SEM (Scanning electron microscope) image of a cross section

Site 1



Site 3



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Core sampling

Thickness of the layers determined using SEM at cross section

Site 1

Layer	Meas. 1	Meas. 2	Meas. 3	Avg.	
A	909.5	864.0	897.2	890.2	Front encapsulant
B	547.0	533.3	584.3	554.9	Rear encapsulant
C	95.5	105.5	104.6	101.9	Back sheet

Site 3

Layer	Meas. 1	Meas. 2	Meas. 3	Avg.	
A	882.1	926.3	879.2	895.9	Front encapsulant
B	560.7	573.2	577.3	570.4	Rear encapsulant
C1	64.6	60.6	60.8	62.0	Back sheet
C_{Extra}	15.3	16.8	16.3	16.1	Back sheet
C2	193.9	186.9	182.8	187.9	Back sheet

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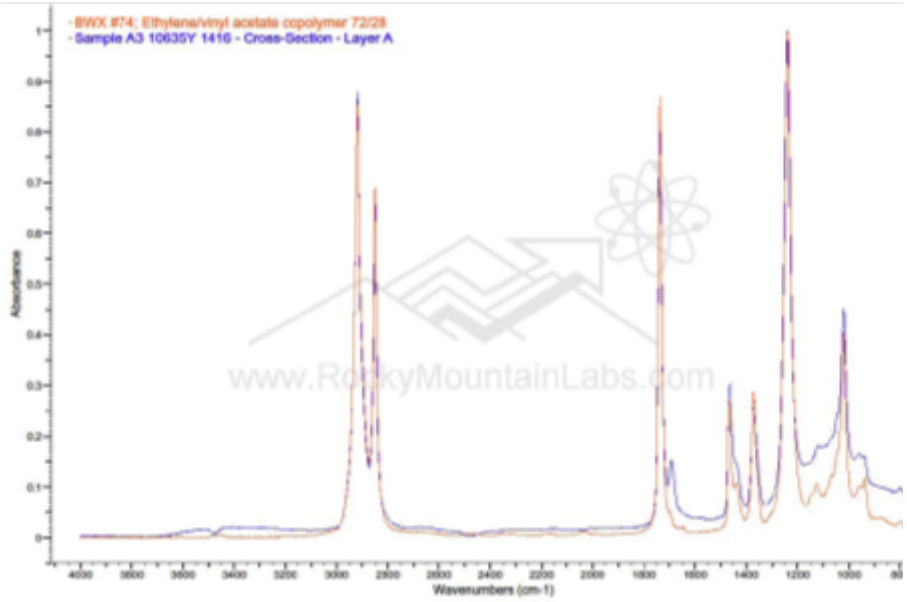
Core sampling

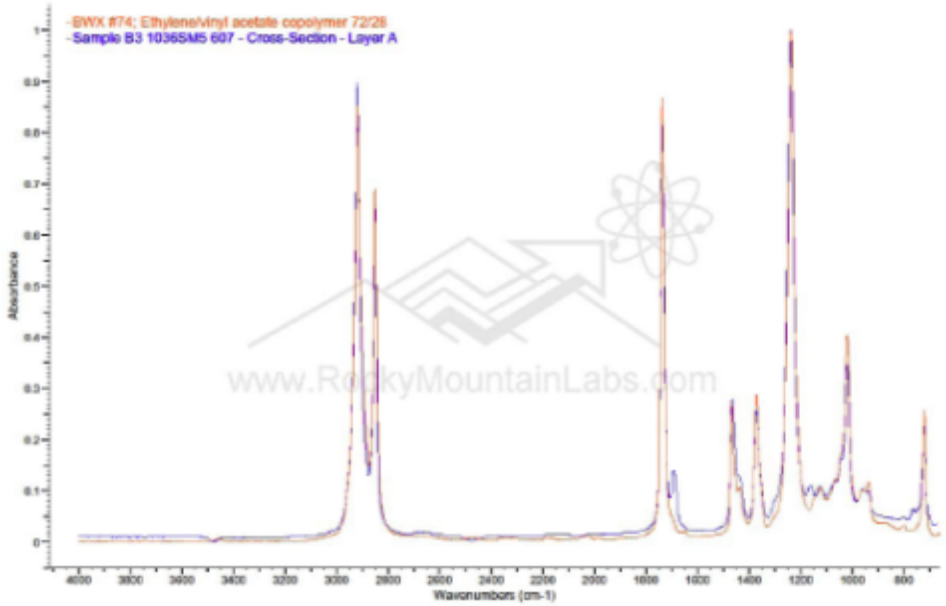
FTIR spectrum of Layer A (front encapsulant)

FTIR spectrum of Layer A (front encapsulant), compared to a library reference spectrum of Ethylene/Vinyl Acetate Copolymer (EVA)

Site 1

Site 3





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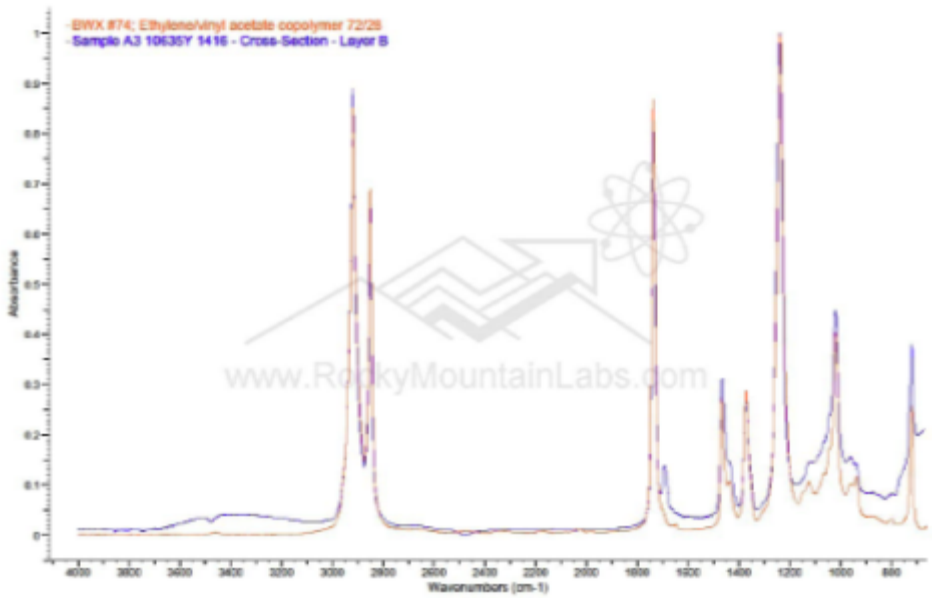
Core sampling

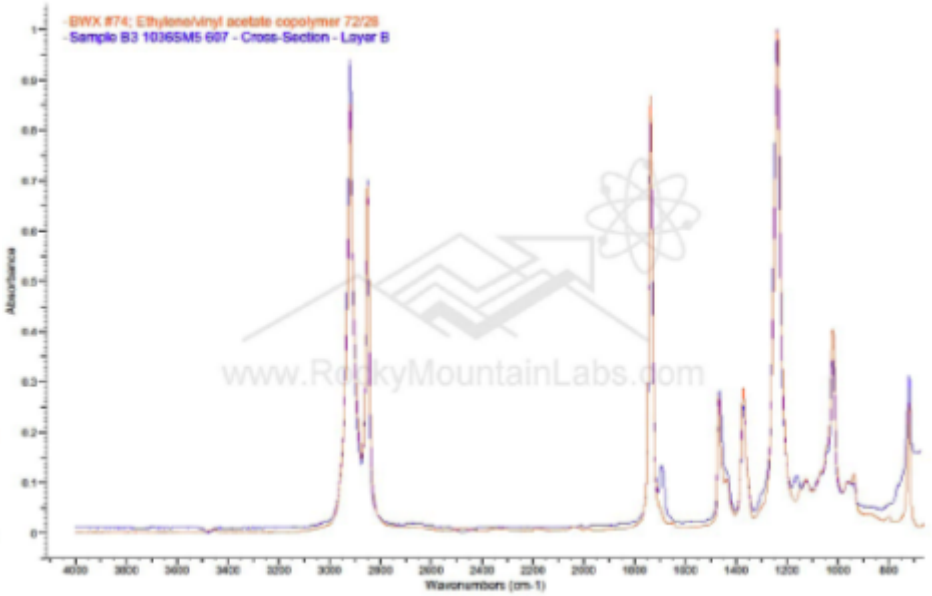
FTIR spectrum of Layer B (rear encapsulant)

FTIR spectrum of Layer B (rear encapsulant), compared to a library reference spectrum of Ethylene/Vinyl Acetate Copolymer (EVA)

Site 1

Site 3





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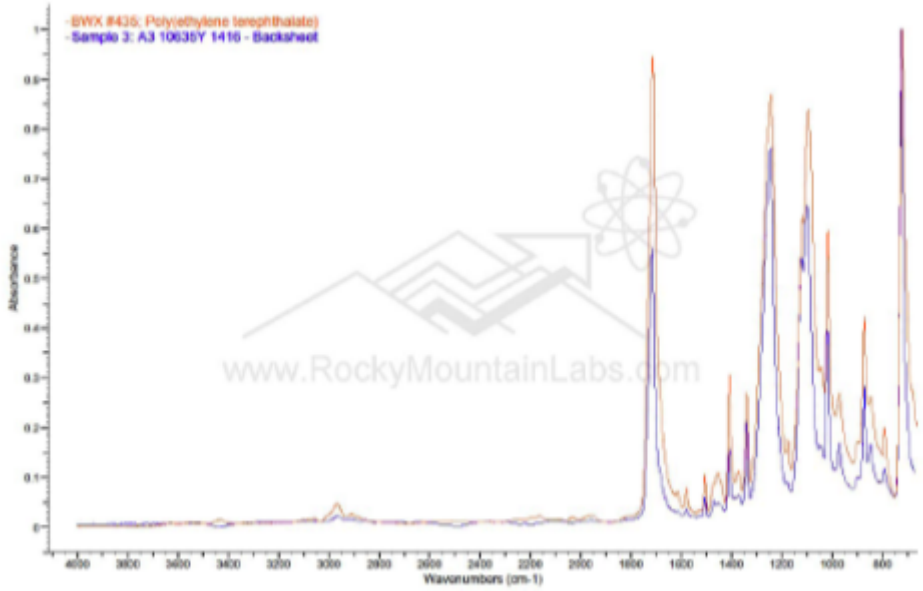
Core sampling

FTIR spectrum of Layer C (back sheet)

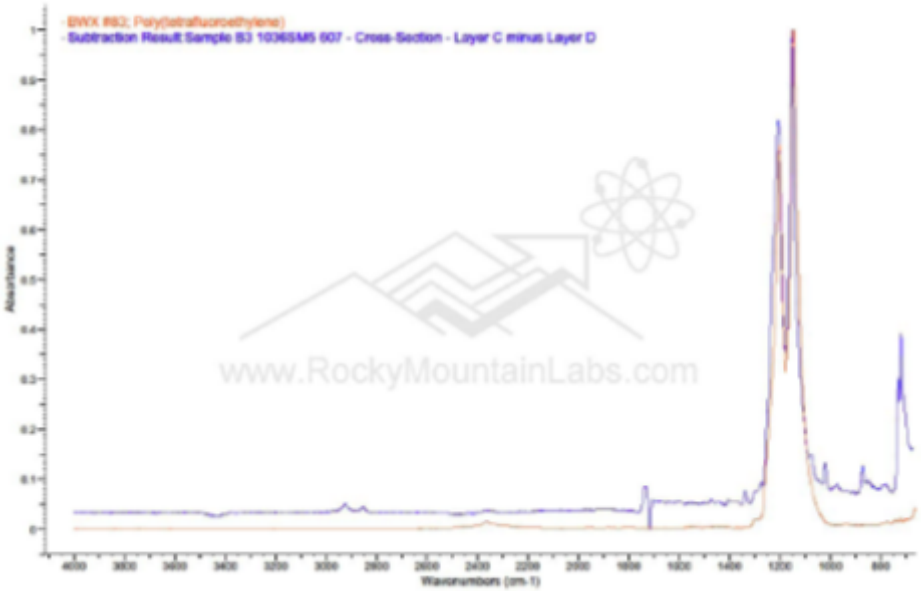
Site 1

FTIR spectrum of Layer C (back sheet), compared to a library reference spectrum of Poly(ethylene terephthalate) (PET)



Site 3

FTIR spectral subtraction result: Layer C (back sheet, part 1), compared to a library reference spectrum of Poly(tetrafluoroethylene) (PTFE)



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Core sampling

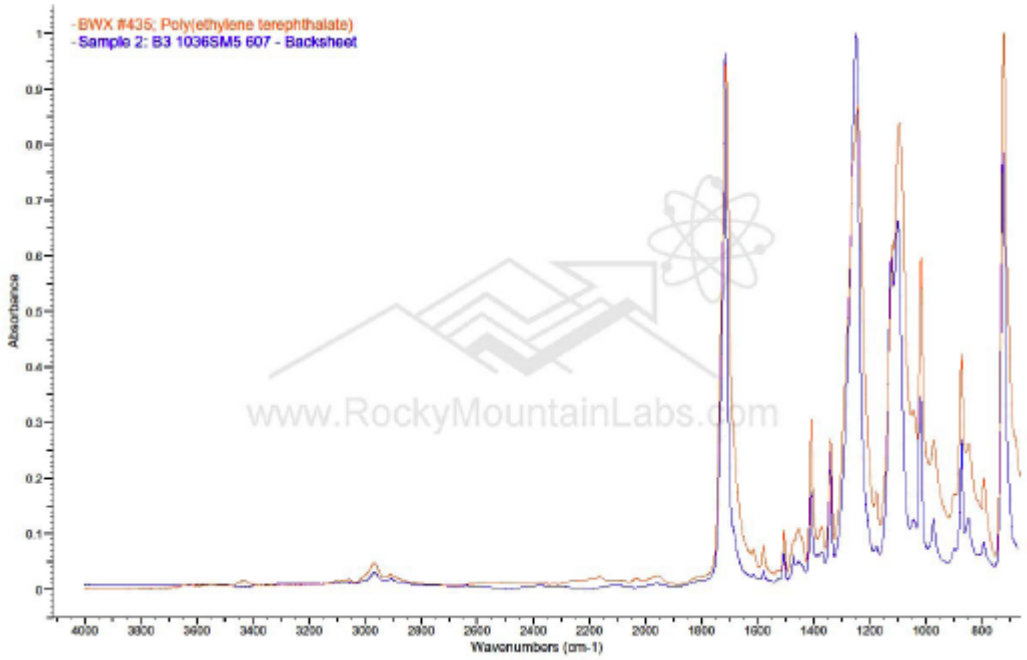
FTIR spectrum of Layer C2 (part 2 of back sheet)

Site 1

No further layer

Site 3

FTIR spectrum of Layer D (backsheet part 2), compared to a library reference spectrum of Poly(ethylene terephthalate) (PET)



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Core sampling

Thickness and material of the layers determined using SEM and FTIR at cross section

Site 1

Layer	Avg. thickness	Polymer type	component
A	890.2	EVA	Front encapsulant
B	554.9	EVA	Rear encapsulation
C	101.9	PET	Back sheet

Site 3

Layer	Avg. thickness	Polymer type	component
A	895.9	EVA	Front encapsulant
B	570.4	EVA	Rear encapsulation
C1	62.0	PTFE	Back sheet
C_{Extra}	16.1	--	Back sheet
C2	187.9	PET	Back sheet

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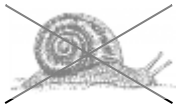
Core sampling

summary:

polymer stacks in the two samples are different in the area of the backsheet

- Site 1: single layer PET backsheet (ca. **100 μm** thick)



- Site 3: three layer backsheet:
  - Layer 1: PTFE (ca. 60 μm thick)
  - Layer 2: (ca. 15 μm thick), too thin for material analysis (likely an adhesive tie layer)
  - Layer 3: PET (ca. 190 μm thick)
  - Total back sheet thickness: ca. **265 μm** thick

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Conclusion

- The discoloration of the silver metallization fingers itself does not have negative consequences for module performance.
- However, the cracks behind the snail trails in the cells could be problematic.
- Modules having thinner backsheets, which are presumable more permeable for moisture and oxygen ingress, contribute to a module's susceptibility to snail trail development.

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Accelerated Degradation by Light Illumination or Current Injection During Heat Tests on Flexible Thin Film Modules

(from the PVQAT TG8 Japan Team's activity)

Keiichiro Sakurai[1,2], Akihiro Takano[2], Hironori Yanase[2], Toshiaki Sakai[2], Hironori Nishihara[2], Tetsuro Nakamura[2], Shinji Fujikake[2], Masayoshi Takani[2]

[a] National Institute of Advanced Industrial Science and Technology (AIST),
[b] Photovoltaic Power Generation Technology Research Association (PVTEC)

PVQAT TG8 – working on thin film modules

International PV Quality Assurance Task Force

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Contacts

International PV Quality Assurance Task Force

The International Photovoltaic Quality Assurance Task Force (PVQAT) is leading efforts to develop standards with three primary goals:

1. Provide comparative information about the relative durability of photovoltaic (PV) modules when exposed to a variety of stresses, giving solar customers a baseline for improving the accuracy of quantitative PV lifetime predictions
2. Create a guideline for factory inspections of the QA system used during manufacturing.
3. Establish capability to issue PV system certifications.

PVQAT includes the following Task Groups. More information is available on each group's progress and current status.

- Task Group 1: PV QA guideline for manufacturing consistency — leaders Ivan Sinicco, Yoshihito Eguchi, Govind Ramu, Gunnar Brueggemann, Wei Zhou
- Task Group 2: PV QA testing for thermal and mechanical fatigue including vibration — leaders Nick Bosco, Tadanori Tanahashi, Simon Xiao
- Task Group 3: PV QA testing for humidity, temperature, and voltage — leaders John Wohlgemuth, Takuya Doi, Neelkanth Dhere, Tony Tang
- Task Group 4: PV QA testing for diodes, shading and reverse bias — leaders Vivek Gade, Yasunori Uchida, Hubert Volz, Chandler Zhang, Paul Robusto
- Task Group 5: PV QA testing for UV, temperature, and humidity — leaders Michael Koehl, Tsuyoshi Shioda, Jasbir Bath, David Miller, Ganxin Jie
- Task Group 6: Communication of PV QA ratings to the community — leaders David Williams, Sarah Kurtz, Pierre Verlinden, Haiyan Qin
- Task Group 8: PV QA testing for thin-film PV — leaders Neelkanth Dhere, Masayoshi Takani, Veronica Bermudez, Yaohua Mai, Jingong Pan
- Task Group 9: PV QA testing for Concentrator PV (CPV) — leaders Nick Bosco, Itai Suez, Rafael Xing, Bruce Wang
- Task Group 10: Connectors — leaders Juris Kalejs, Tony Tang, Shilin Fan
- Task Group 11: QA for PV Systems — leaders Sumanth Lokanath, Shilin Fan, Niuchen Hui.

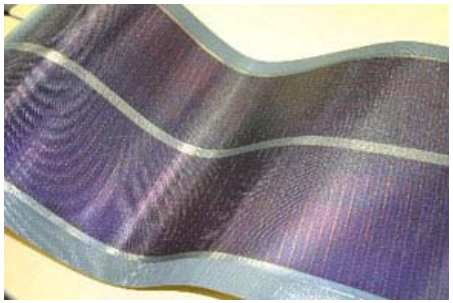
To volunteer for any of these Task Groups, please contact the leader directly or

Hosted by:

AIST
NREL NATIONAL RENEWABLE ENERGY LABORATORY
PVTEC Photovoltaic Power Generation Technology Research Association

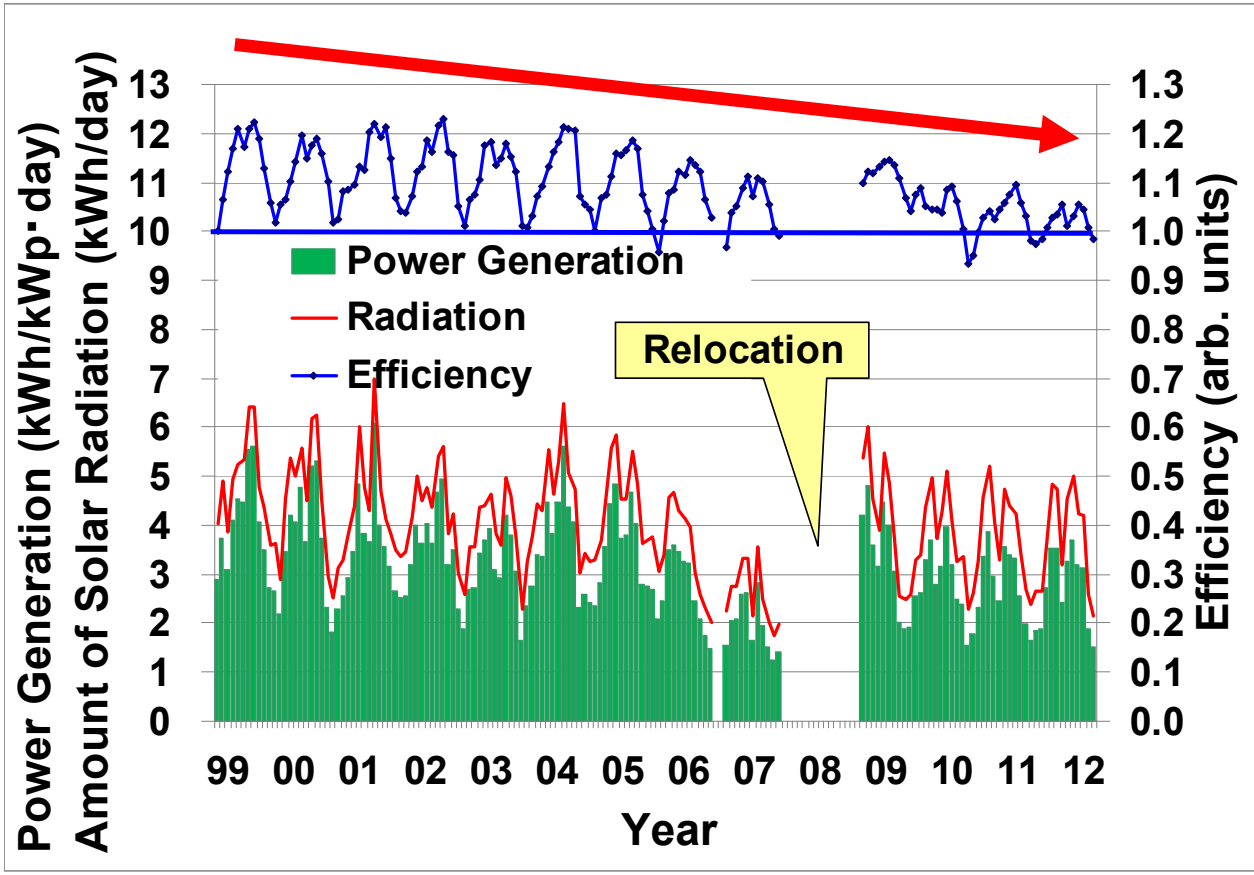
Supporting Organizations
United States Department of Energy (DOE)
European Commission DG JRC
SEMI PV Group

Advisory Board



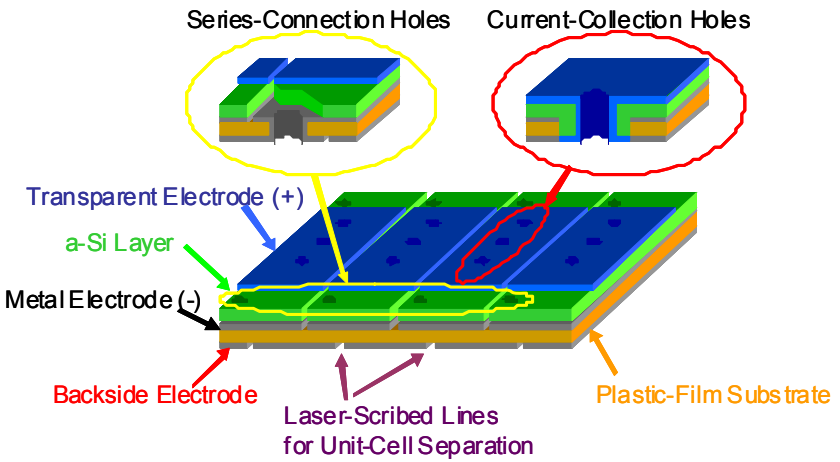
http://www.nrel.gov/ce/ipvmqa_task_force/

Unique degradation mode observed in a prototype Thin film Silicon flexible module(1)

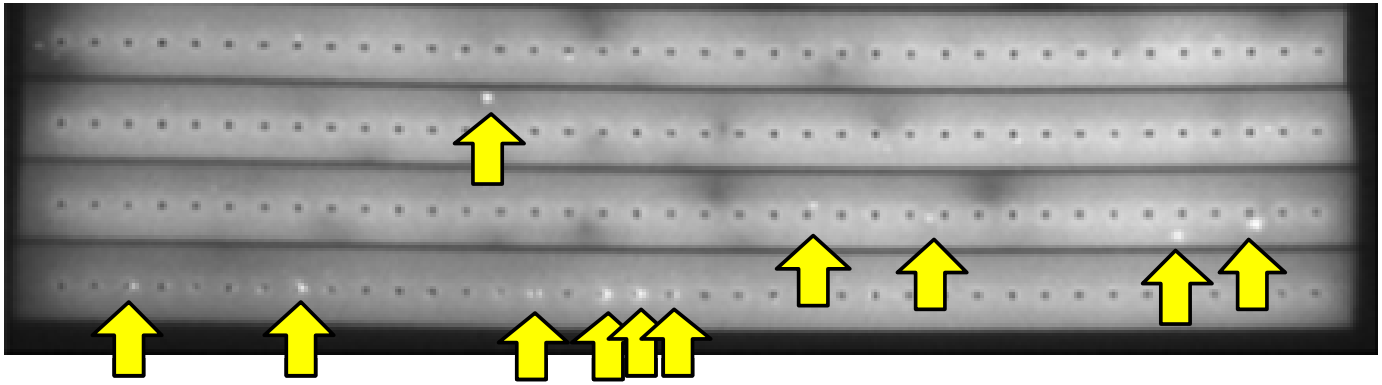


(A.Takano et al, EU PVSEC 2013, 3BO.5.4)

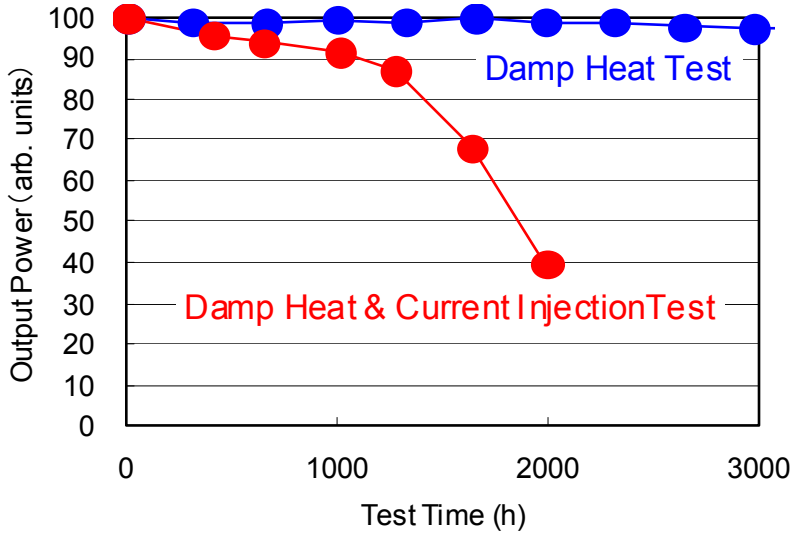
Unique degradation mode observed in a prototype Thin film Silicon flexible module(2)



EL image



(Leak points)



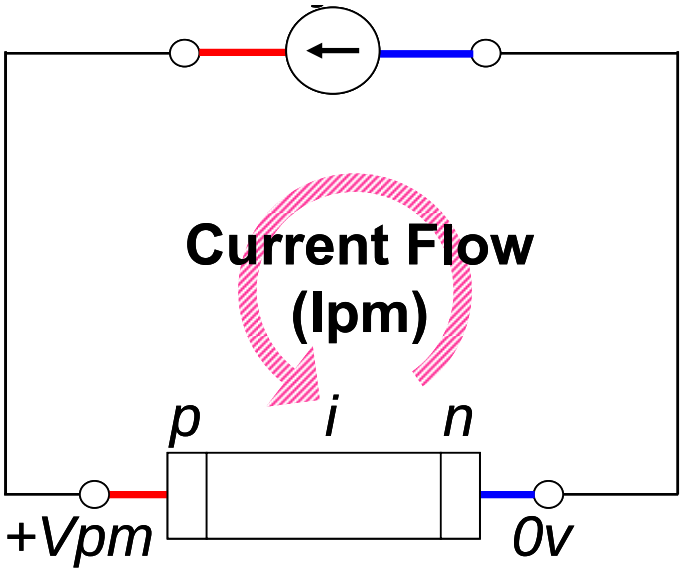
Degradation reproduced by Injecting current during damp heat testing (CDH test)

→ made it possible to fix the problem before mass production!

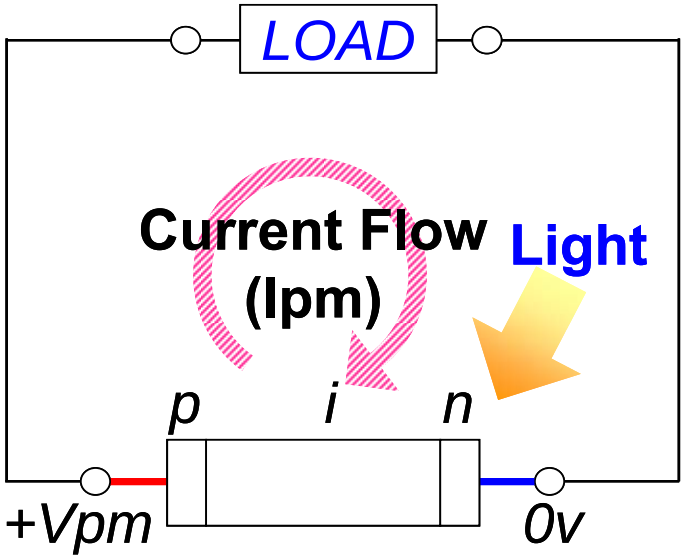
(A.Takano et al, EU PVSEC 2013, 3BO.5.4)

Current injection instead of light irradiation?

Current Injection + DH (CDH)

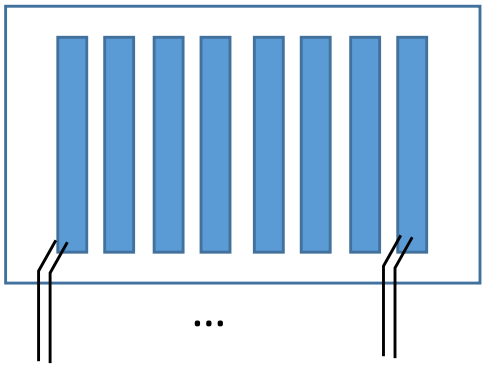


Light Irradiation+ DH (LDH)

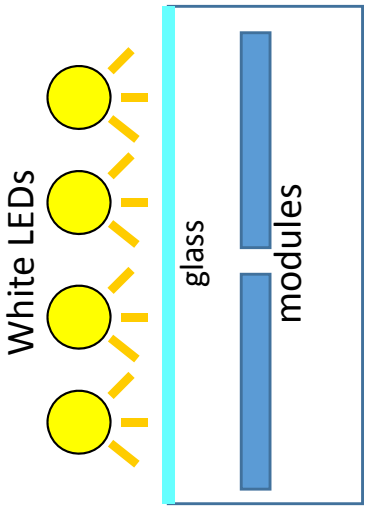


(A.Takano et al, EU PVSEC 2013, 3BO.5.4)

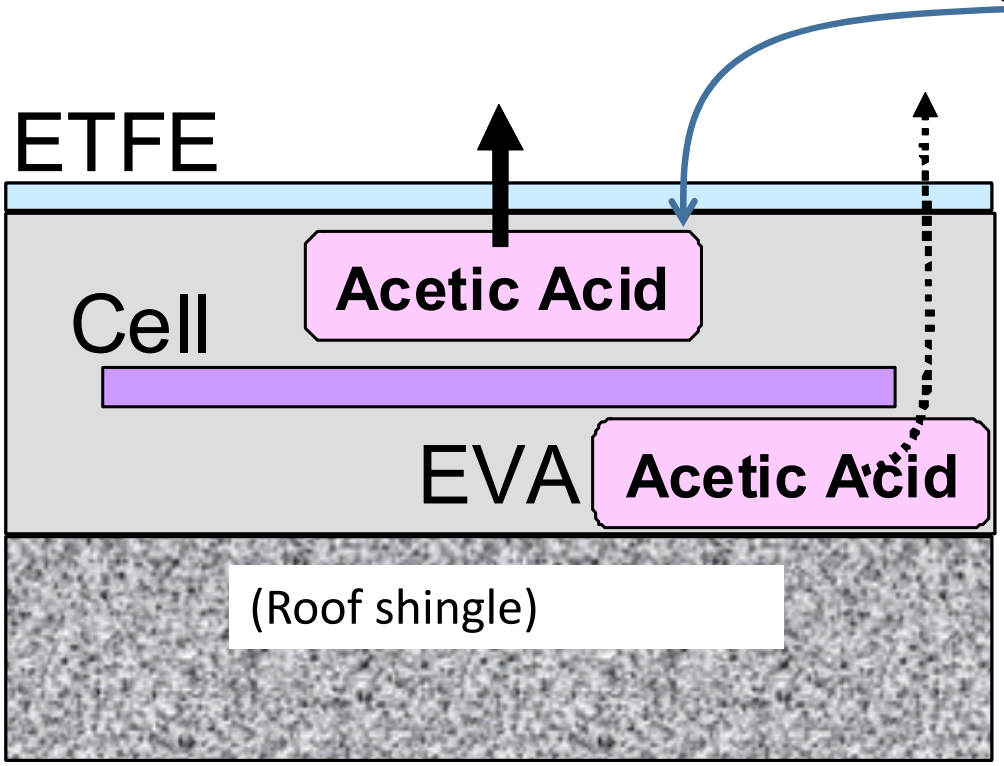
Many panels at one time
Reversed current flow

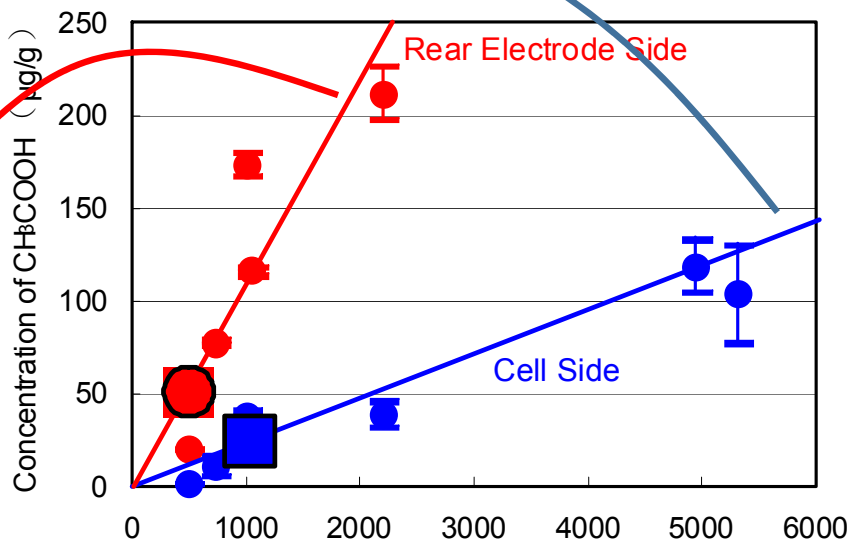


Large chamber (small number of panels)
Normal current flow

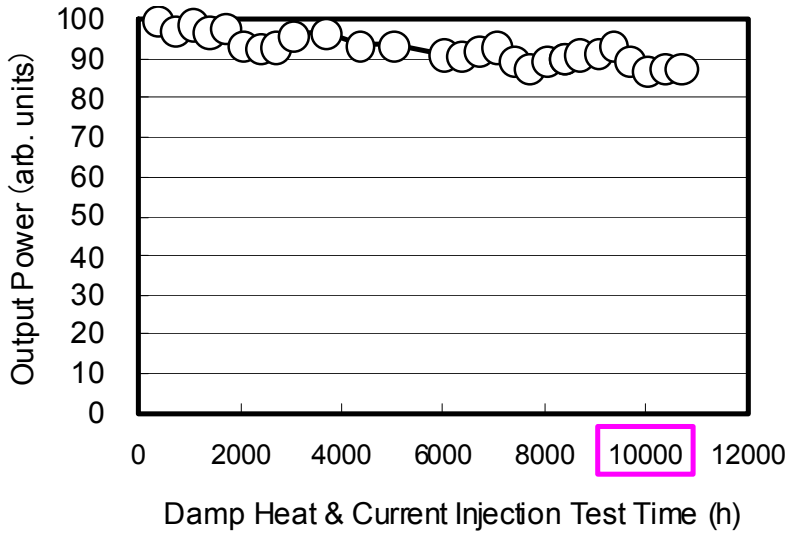


Cause of degradation?



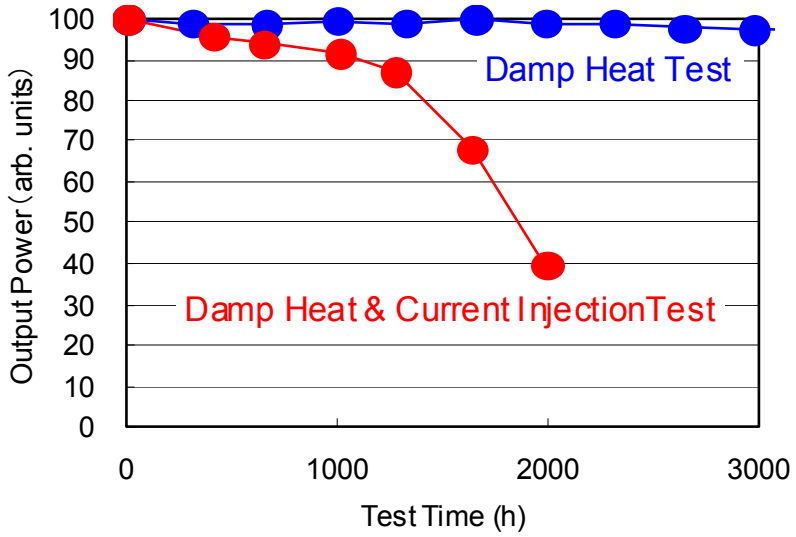


Change EVA to acid-free encapsulant→ longer lifetime



(A.Takano et al, EU PVSEC 2013, 3BO.5.4)

Question…



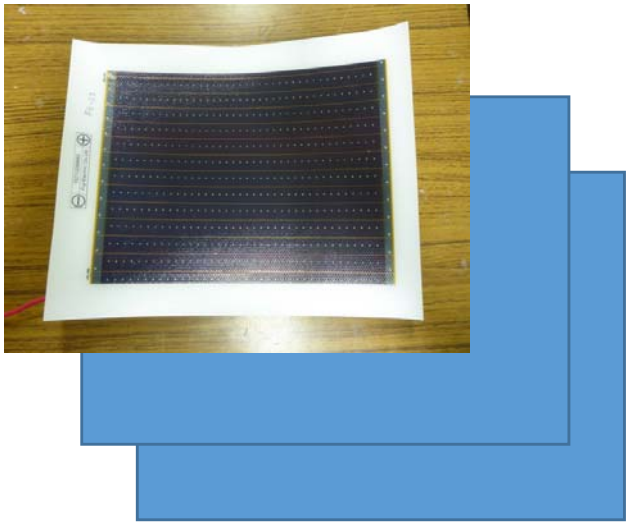
(A.Takano et al, EU PVSEC 2013, 3BO.5.4)

Is there any difference in results between current injection and light irradiation?

Would this CDH test reproduce degradations better on other types of modules as well?

- other flexible thin film Si products?
- flexible CIGS?
- rigid thin films?

Experiments



Flexible TF modules
- Thin film Si
- CIGS purchased in the market
  (not really designed for long-term use)

DryHeat (75～85℃ 20%)
(module temperature)
With visible light
irradiation

Damp/DryHeat with
Current injection

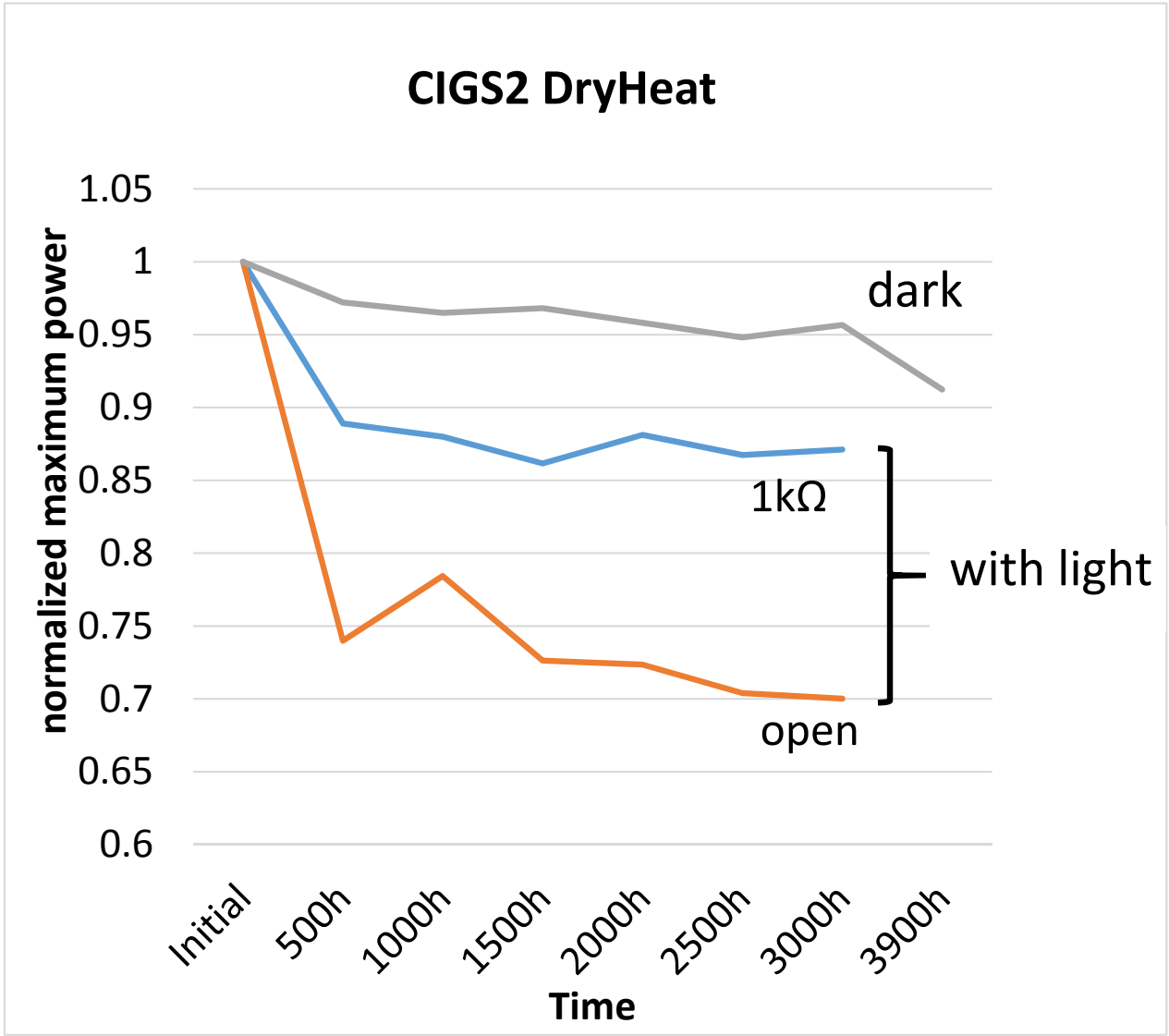
DryHeat (85℃ 20%)
or DampHeat
(dark)

Outdoor

(75～85℃ 20%r.h.
white (=blue+yellow)
LED, power close to
1kW/m^2)

Compare the degradation
(I-V, EL)

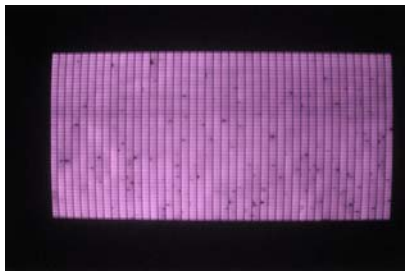
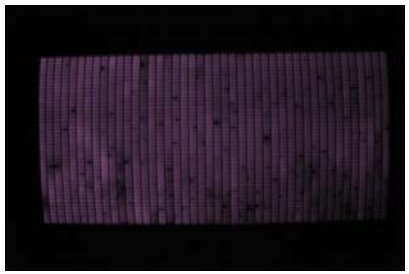
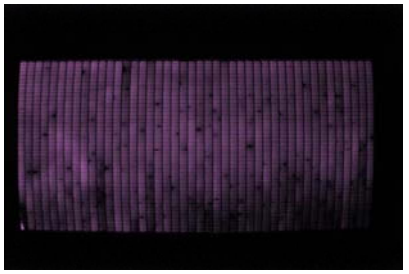
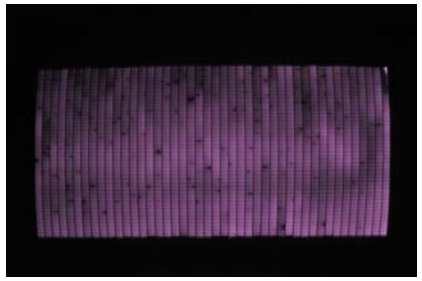
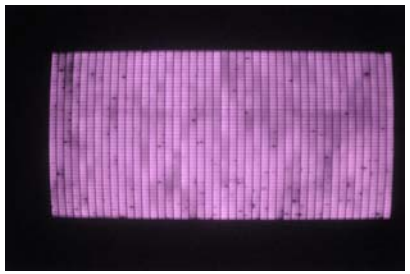
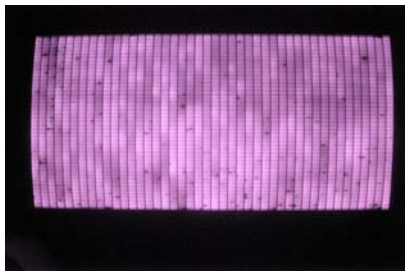
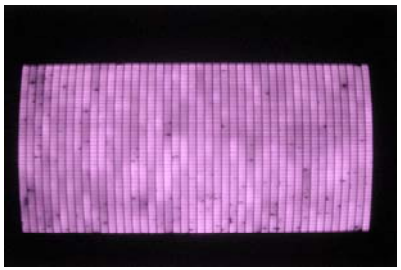
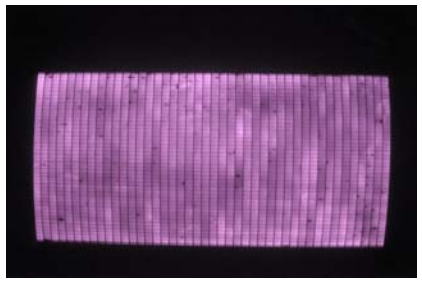
light + DryHeat : I-V: CIGS flexible product 2



- quick initial degradation followed by slow (or no) degradation
- decreased Voc & FF
- retained Isc

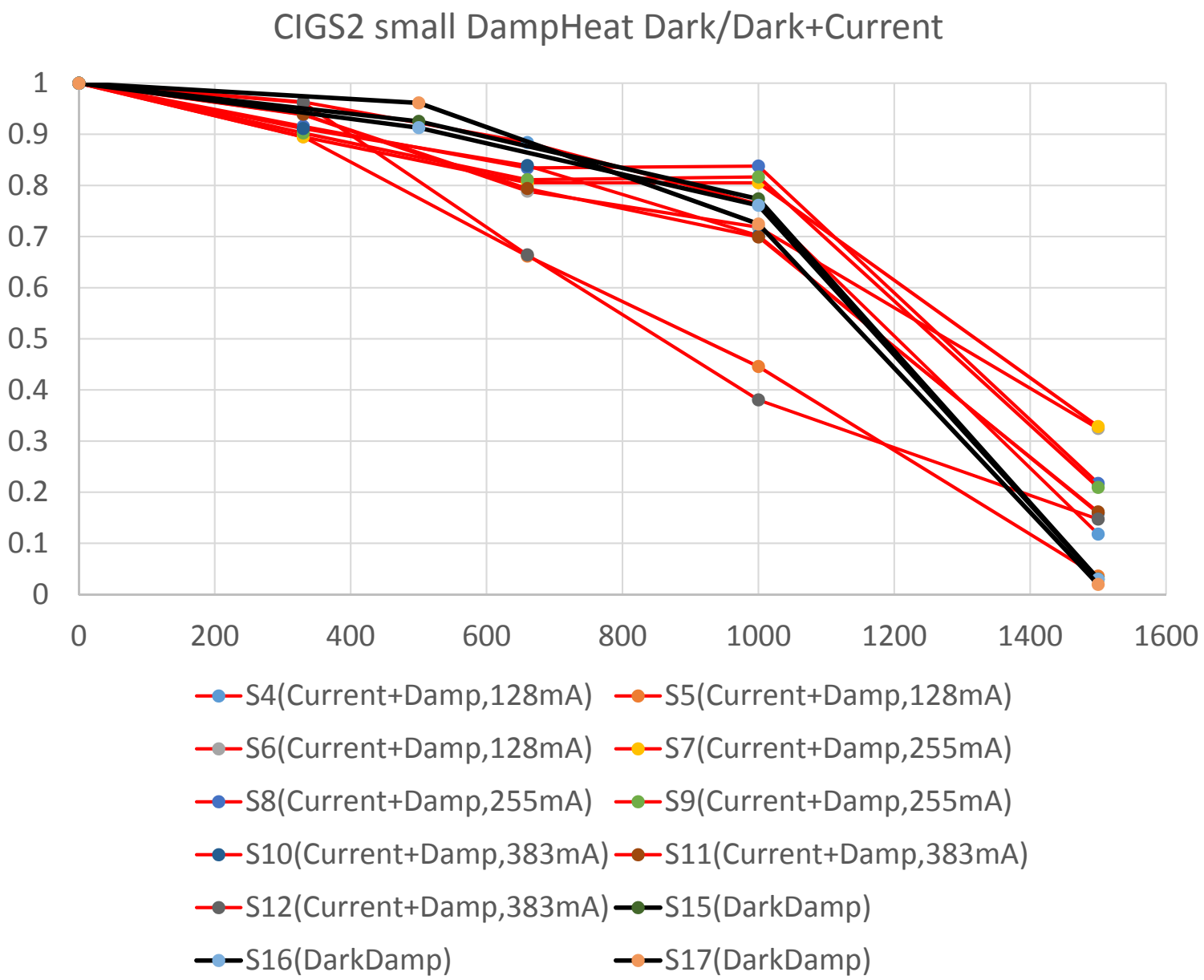
Note: sample number is small, individual difference may be present

light+DryHeat : EL: CIGS2

	initial	500hrs	1000hrs	3000hrs
CIGS2 Light+Heat(1kΩ)				
CIGS2 Light+Heat(open)	(Data lost)			
CIGS2 Heat (dark)				

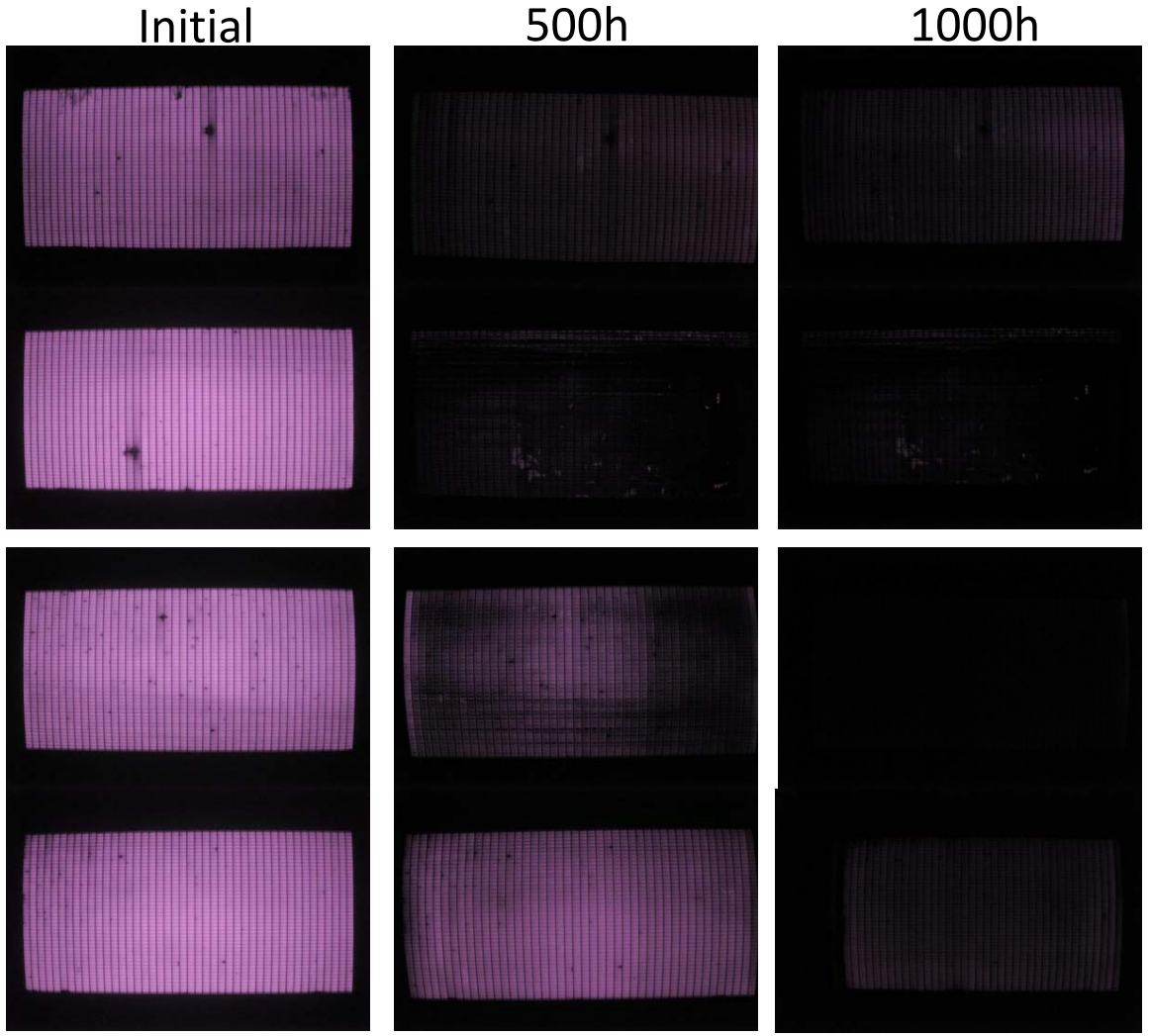
EL images darkened within first 500hrs of Light+DryHeat

current + DampHeat : I-V: CIGS flexible product 2



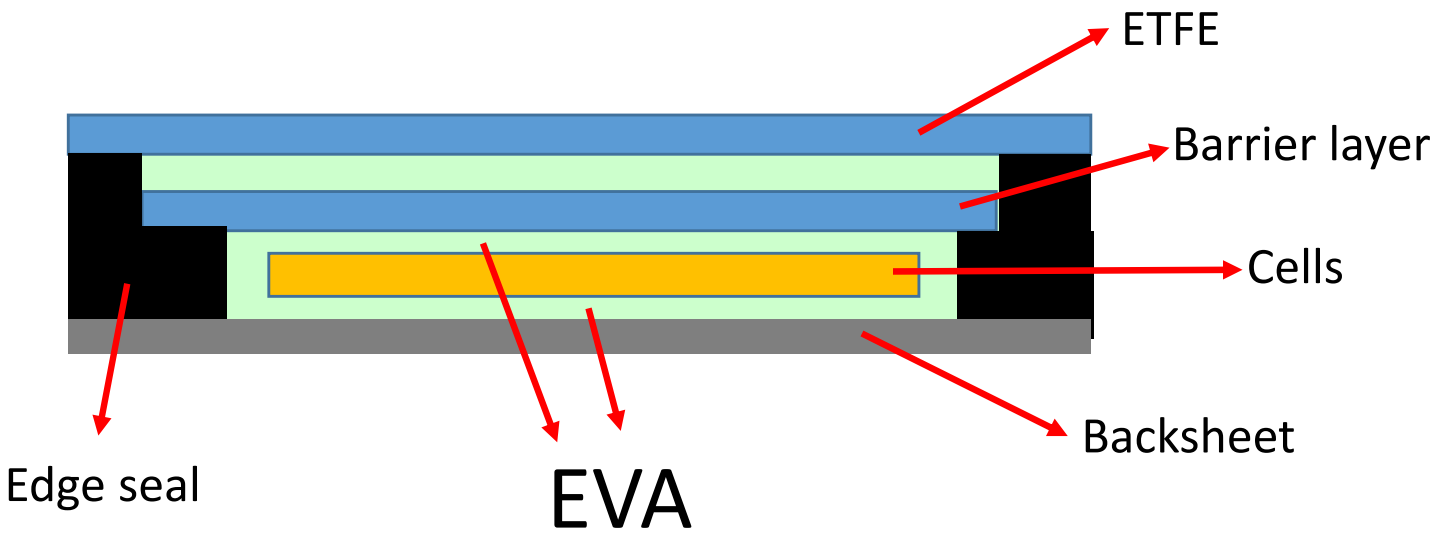
Degrades too fast under DampHeat conditions
-- couldn't observe any dependency with current

light+DampHeat : EL: CIGS2



Darker EL with light + DampHeat too --- darker EL seems clear
(However, difference in I-V not distinguishable up to 1000hrs
-- further tests underway)

CIGS2: Destructive analysis



rip off EVA close to the cell

- Ion Chromatography
- FT-IR (ATR)

Samples:

- Reference (as-purchased)
- Dark+DryHeat 3900hrs
- Light+DryHeat 3100hrs

CIGS2: Ion Chromatography (Reference / Dark+DryHeat / Light+DryHeat)

Acetic acid content in EVA（μg/g）

Reference (as-purchased)	10
Dark+DryHeat	140
Light+DryHeat	34

Increased acetic acid content by DryHeat
Large difference between Light and Dark samples

CIGS2: FT-IR comparison (Dark vs Light, both DryHeat)

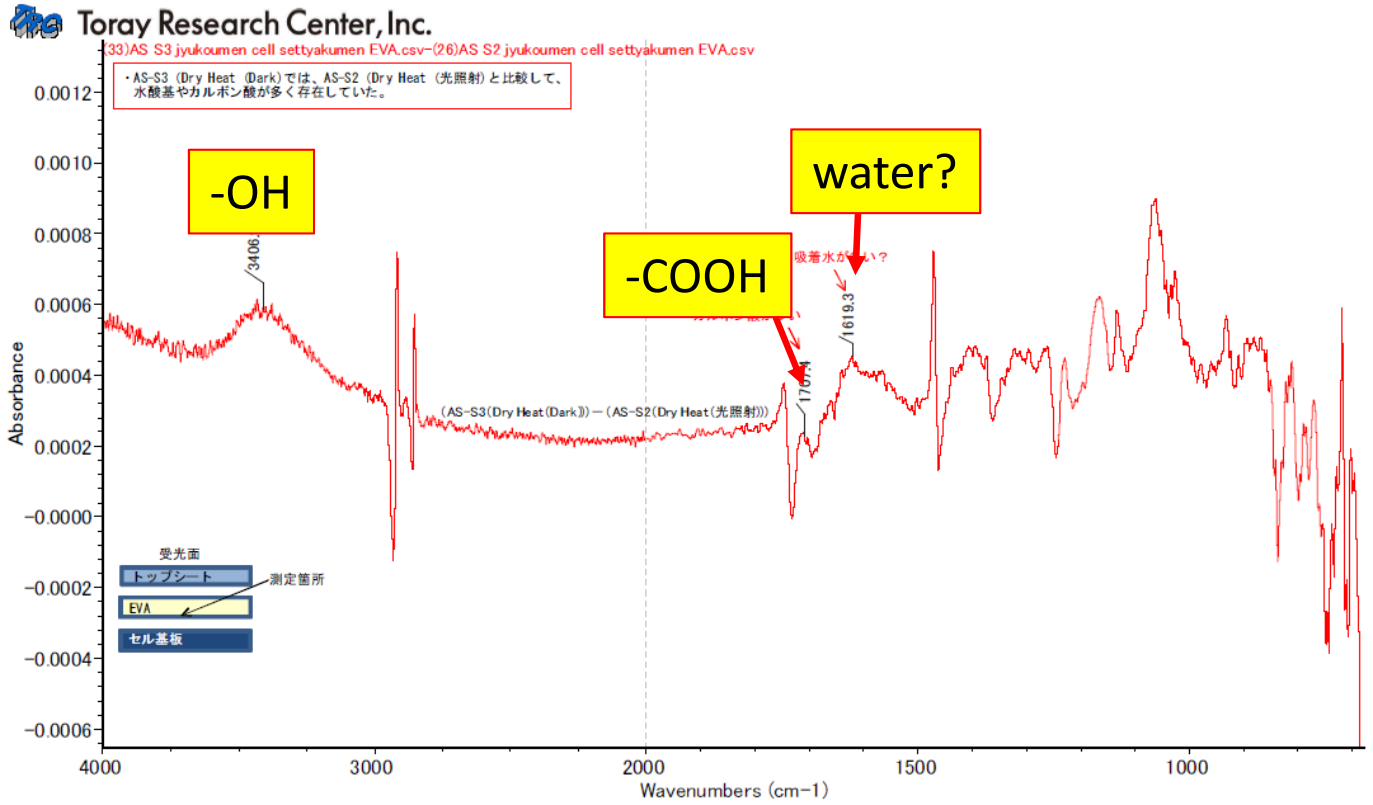


図17：AS-S2（Dry Heat(光照射)）とAS-S3（Dry Heat(Dark)）のFT-IR-ATRスペクトル比較
縦軸スケール：任意
縦軸オフセット：任意
差スペクトル基準ピーク：EVA由来1370cm-1

More -OH and -COOH observed in EVA of Dark+DryHeat sample

Summary

What can be said now:

Adding current injection (or light illumination) to conventional DH test

- was a must for at least one prototype flexible TF-Si
  actually did a crucial job to improve a product's durability
- may work better for at least one flexible CIGS product
  - darker EL by light illumination during DryHeat/DampHeat tests
  - degradation in Voc&FF by light illumination (possible)
  - change in acetic acid content in EVA by light illumination (possible)

If it is proved that the current injection does work better for multiple samples, then it would be worth considering modification of the IEC standard.

More "not-so-robust" samples & tests are needed.

If you can contribute, join us!

Thank you!

Further experiments

Small flexible modules

continue to gather more data (add more samples)

- Compare with outdoor results
- Add rigid modules as well?

Large flexible modules

- Light + Heat:

  underway at AIST
- Outdoor, Current injection+DH:

  To be tested at FSEC

Lab to Field Predictability of First Solar CdTe Production Modules

NREL PV Module Reliability Workshop (PVMRW), February 24, 2015

Dr. Allan Ward

Director, Module and Systems Reliability

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Presentation Outline

Presentation Outline: Lab to Field Predictability of First Solar CdTe Production Modules

- Lab to field correlation of transient and steady state behavior in First Solar CdTe thin film PV technology (4.5 years with high quality periodic measurements on simulator compared to light soak on sister plates)
- Lab to field correlation of transient behavior in “Series 3 Black Plus" current high volume product
- Alternate method to predict metastability
- Accelerated coupon analysis of transient behaviors
- Long term lab to field correlation of FS CdTe PV technology (Analysis of field test site modules, MPP for 4.5 and 7 years)

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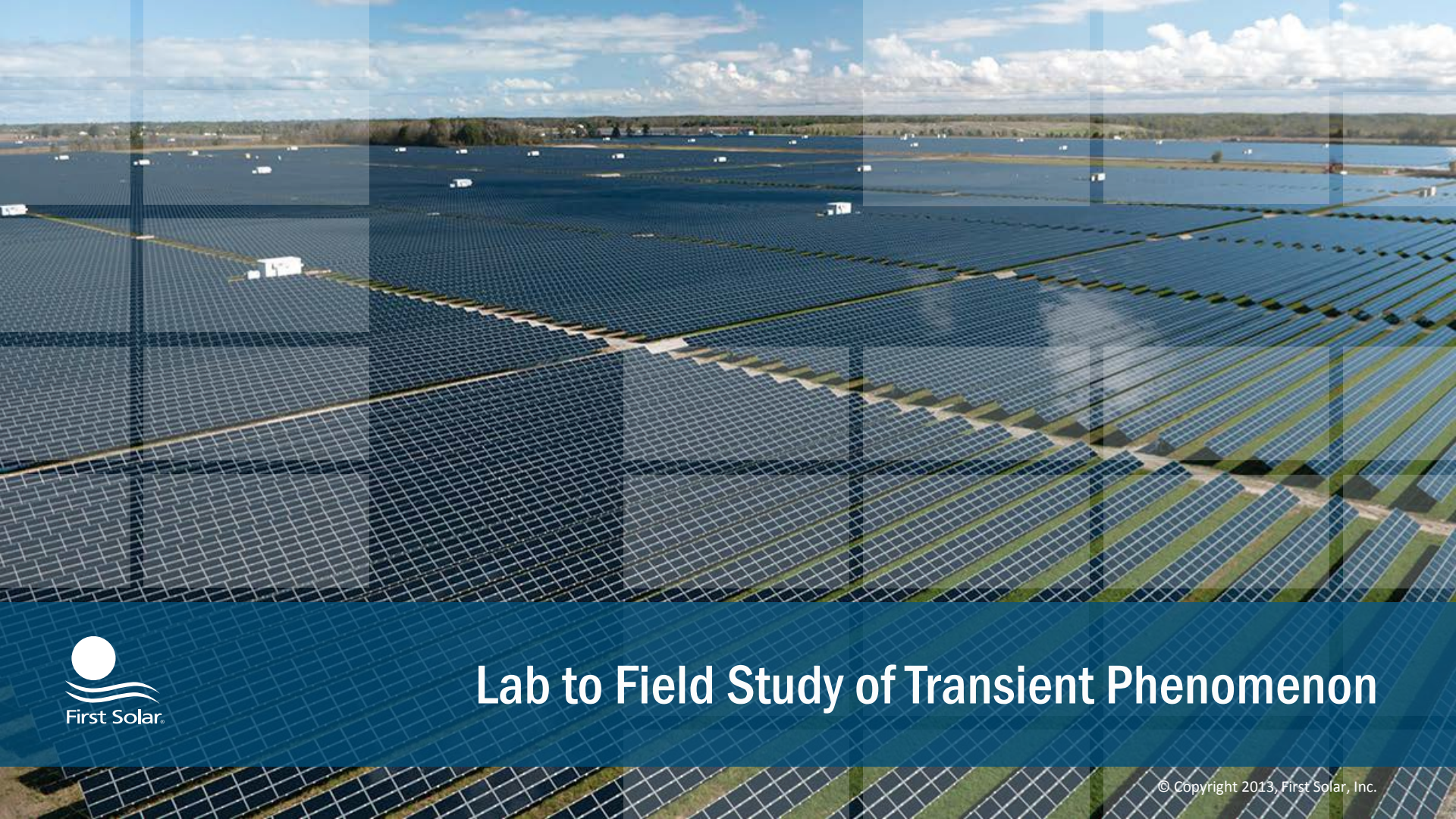

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Lab to Field Study of Transient Phenomenon

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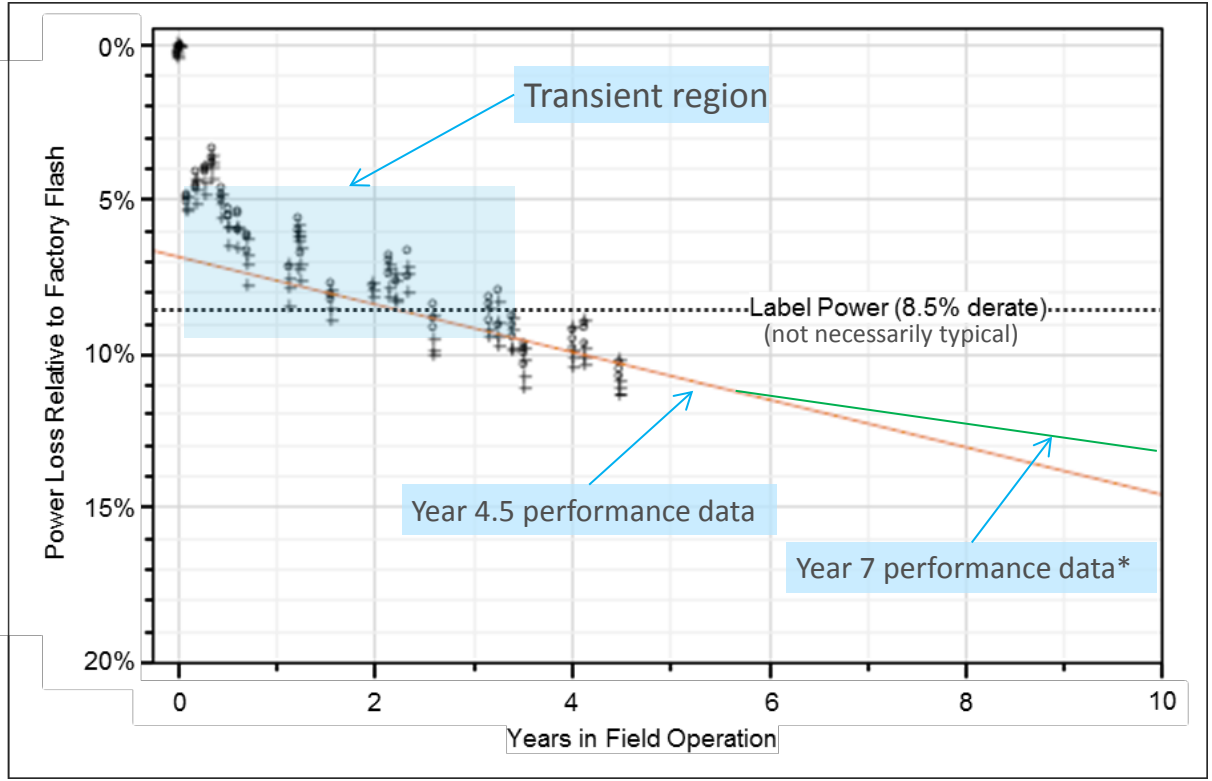
Periodic STC Measurements of Fielded CdTe Modules (Series 3)

- Initial metastability equilibrates trap occupancy to field temperature and bias conditions
- The transient region is greatly influenced by changes in the back contact; the observed damped oscillation is due to the aforementioned metastability behavior and is driven by seasonal temperature changes
- The long term intrinsic cell performance characteristic is believed to change less year over year



*Year data is also Series 3 from a different location (shown later in this presentation)

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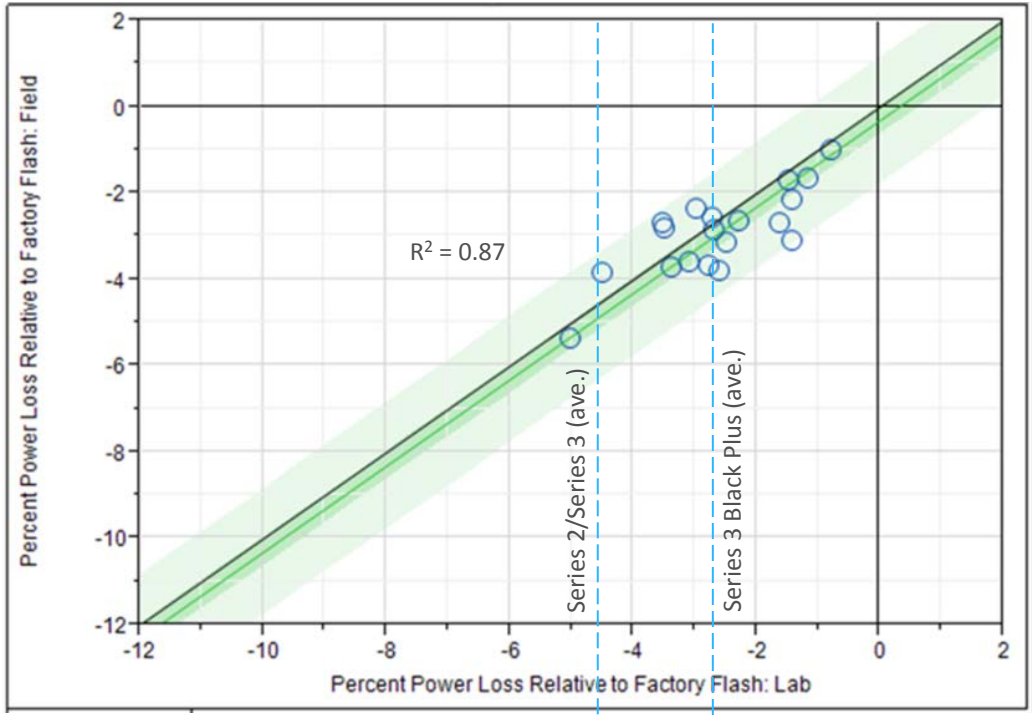
Lab-to-Field Metastability Correlation

- For a given temperature, the initial metastability change in the field is very predictable from lab measurements; the correlation plot shows sister modules exposed to equivalent cell temperatures in the lab and in the field
- Since the metastable point responds to temperature change with a time constant on the order of a few days, an average value for field temperature is sufficient to predict power loss from metastability effects



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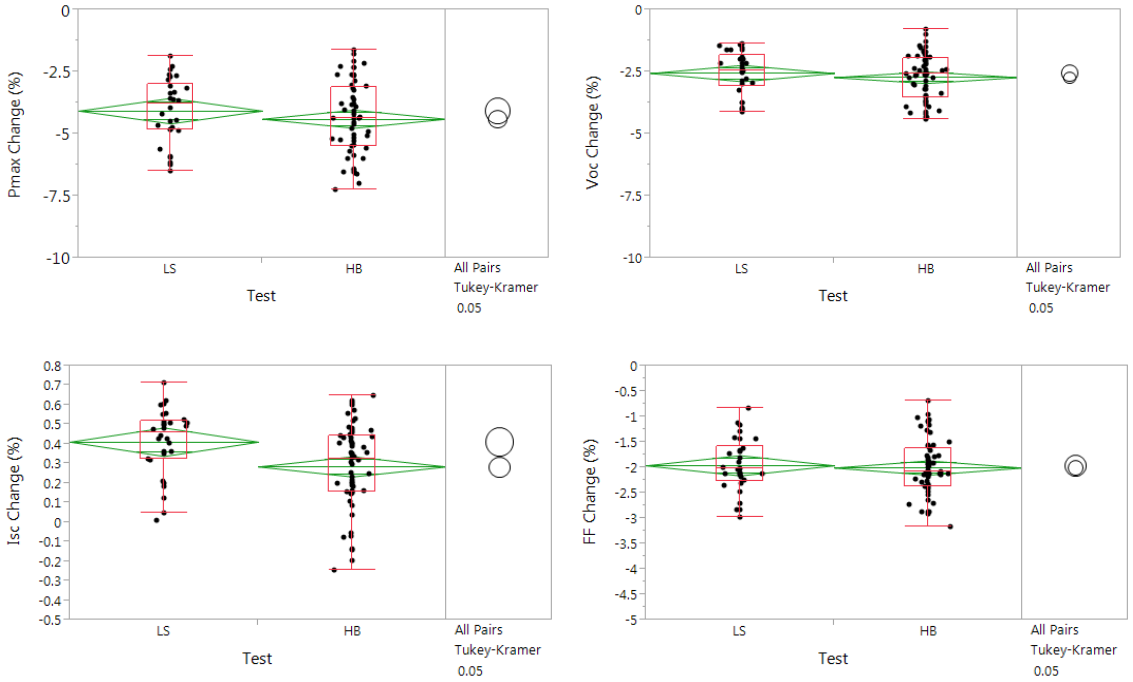
Lab-to-Field Metastability Correlation (Alternate Method)

- It is not necessary to use light soak to predict metastable field behavior for First Solar CdTe modules
- These data show that effectively the same result is obtained using heat and bias (HB) stressing or traditional light soak (LS) testing
- This alternate method is conducive to increased sample throughput (important for reducing design cycle time and supporting high volume manufacturing) and lower capital and operational testing costs



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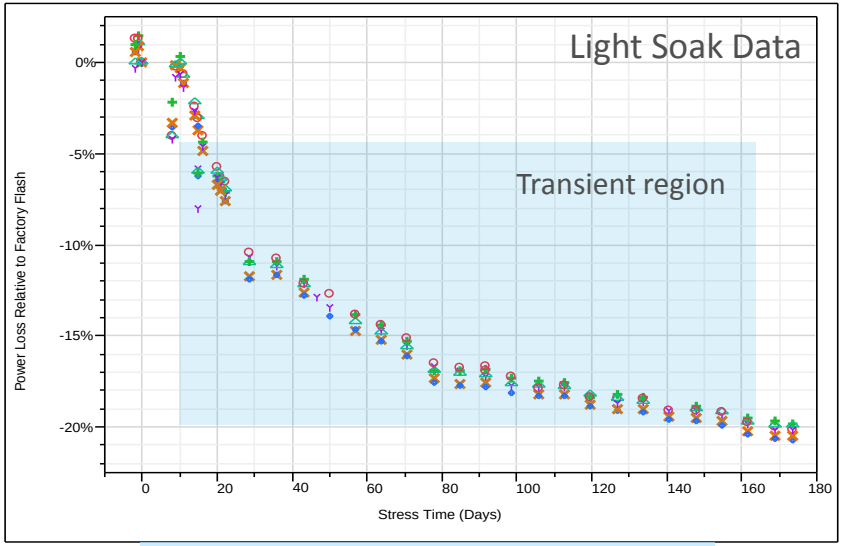
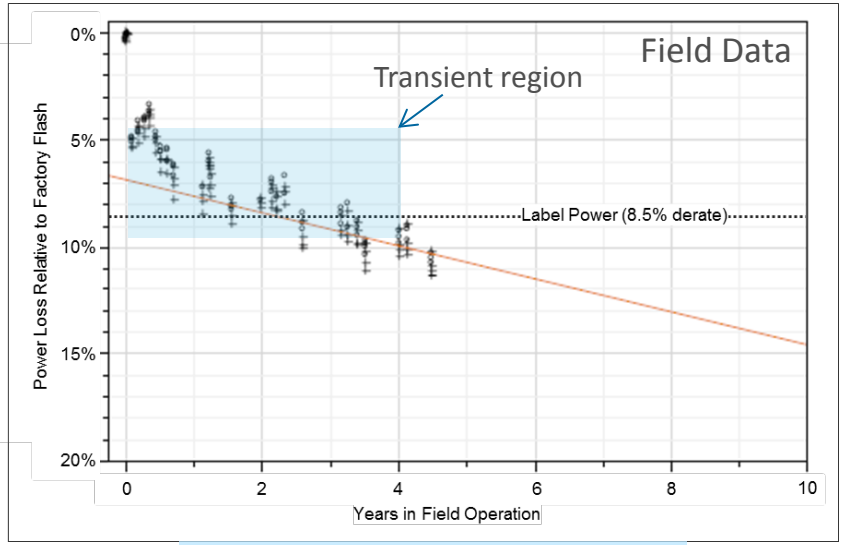
Lab-to-Field Transient Power Loss Correlation (Series 3)



Average light soak cell temperature = 58°C



Average field cell temperature = 21°C

- Transient region activation energy for the magnitude of power loss is approximately 0.3eV, with an additional 5% bias acceleration factor, resulting in a total acceleration factor of approximately 4; this loss is non-recoverable (not a metastability); slide 8 will compare this to coupon results
- Transient region activation energy for the magnitude of the time constant is approximately 0.67eV, resulting in an acceleration factor of approximately 20); slide 9 will compare this to coupon results

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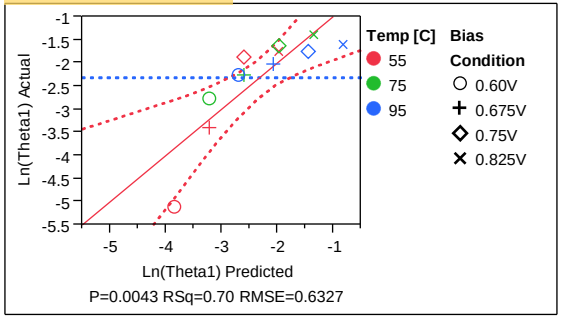
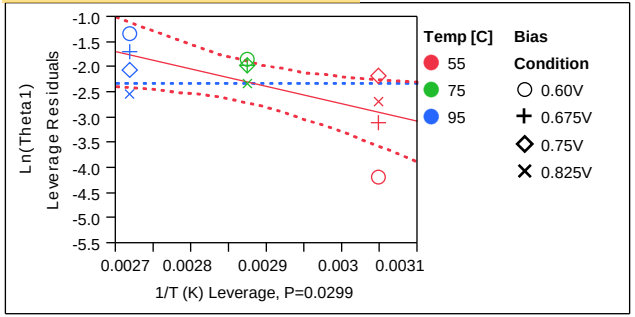
Lab-to-Field Transient Power Loss Acceleration Factors (Series 3)

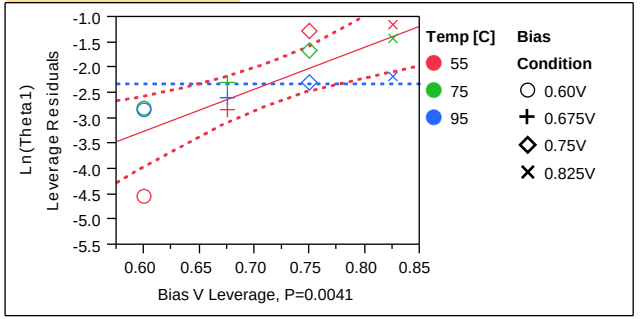
Actual vs Predicted



Leverage Plot (1/Temperature)



Leverage Plot (Bias)



- The activation energy for the magnitude of the transient power loss (denoted as ‘theta 1’ in the plots) as calculated from lab coupon data is 0.3eV, which is consistent with the aforementioned field observations indicating 0.3eV
- The magnitude of the transient power loss has a small dependence on bias (about 5% for a temperate climate)

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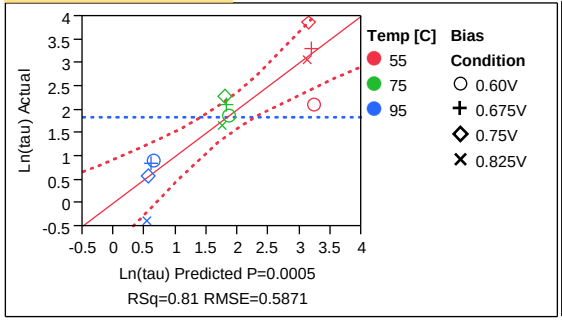
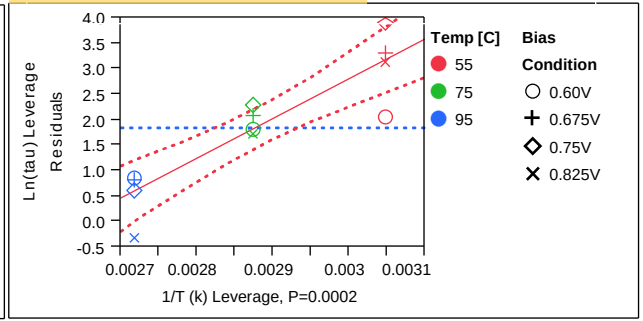
Lab-to-Field Transient Power Loss Acceleration Factors (Series 3)

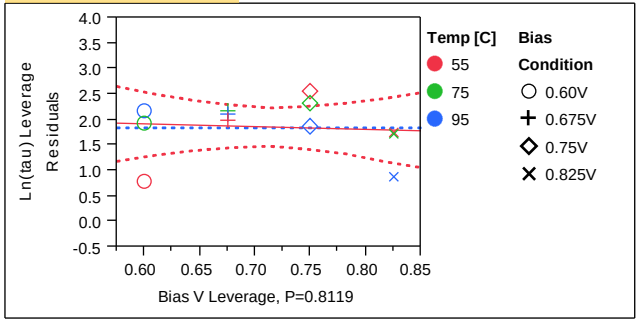
Actual vs Predicted



Leverage Plot (1/Temperature)



Leverage Plot (Bias)



- The activation energy for the time constant (denoted as ‘tau’ in the plots) as calculated from lab coupon data is 0.67eV, which is consistent with the aforementioned field observations indicating 0.67eV
- The time constant has a weak dependence on bias, thus simplifying lab to field predictions

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First Solar

Long term performance characterization

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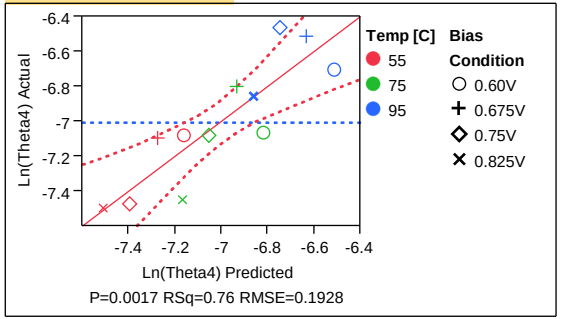
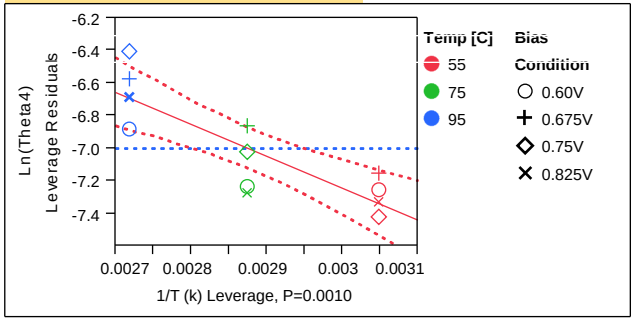
Lab-based Long Term Power Loss Acceleration Factors (Series 3)

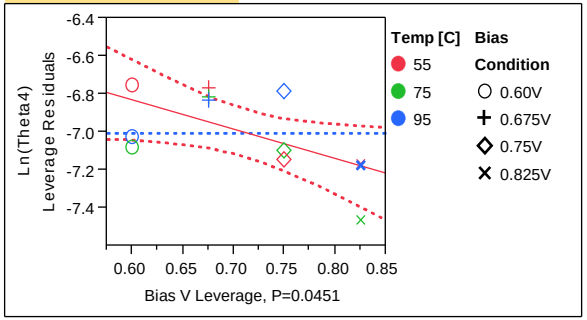
Actual vs Predicted



Leverage Plot (1/Temperature)



Leverage Plot (Bias)



- The activation energy for the slope of the long term reliability characteristic as calculated from lab coupon data is 0.17eV
- The long term slope has a weak dependence on bias, thus simplifying lab to field predictions

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Lab-to-Field Long Term Performance Assessment Challenge

- Long term power changes are too small to measure precisely in the field due to various sources of noise (soiling, BoS component changes, etc.)
- Due to the small acceleration factor for long term modeling, sample conditioning would require very long stress durations
- Therefore, samples were retrieved from the field and studied with 3-temperature tests

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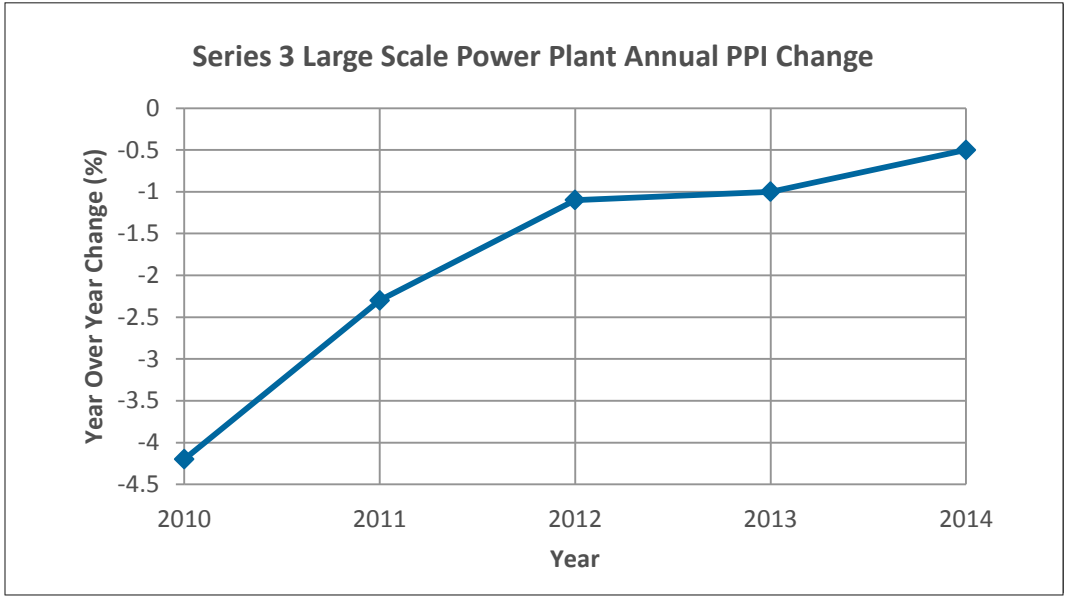
Long Term Cell Performance

- Activation Energy is estimated to be 0.07eV +/- 0.07, with a 95% confidence that it is less than 0.3eV, consistent with the aforementioned lab result of 0.17eV
- Even with a non-zero, low value activation energy (<0.2eV), the implication is that hot spots should not affect intrinsic cell reliability significantly so long as they are less than 105C peak temperature (approximately 50C above nominal cell temperature in the desert summer)
- At the power plant level, the annual output appears to stabilize over time, consistent with a gradual reduction in the rate of change



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Summary

- Lab to field correlation of transient and steady state behavior in First Solar CdTe thin film PV technology was presented using:
  - modules from a temperate climate field test site operated at MPP for 4.5 years
  - modules from a desert climate field test site operated at MPP for 7 years
  - determination of thermal and bias acceleration factors for the magnitude and time constants of all three phases of reliability behavior
- Field metastability can be predicted with high confidence from lab stress tests
- A successful alternate method to predict field metastability was presented
- Accelerated coupon analysis of transient behaviors is consistent with field observations
- The rate of performance change of the intrinsic cell in the field is expected to be less than 0.8%/year after year 6, with an activation energy likely to be less than 0.2eV

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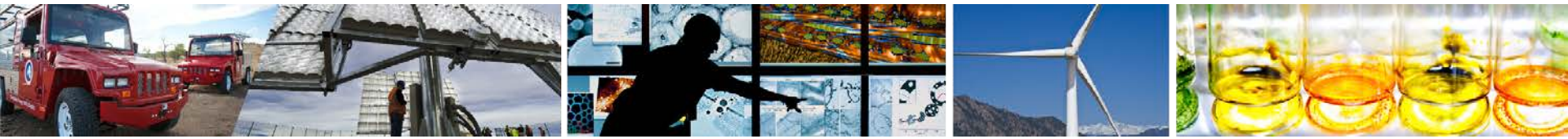
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Transient Behavior in Thin-Film Modules

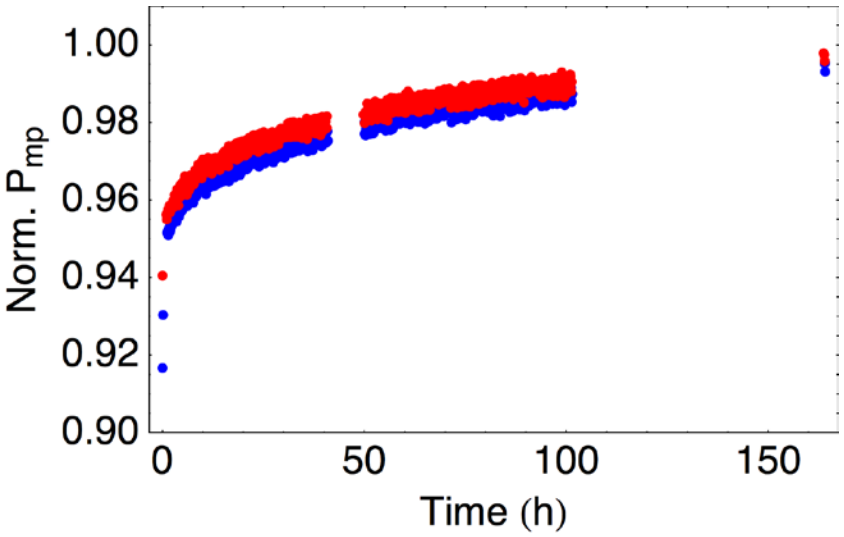
Michael Deceglie
Timothy Silverman
Bill Marion
Sarah Kurtz



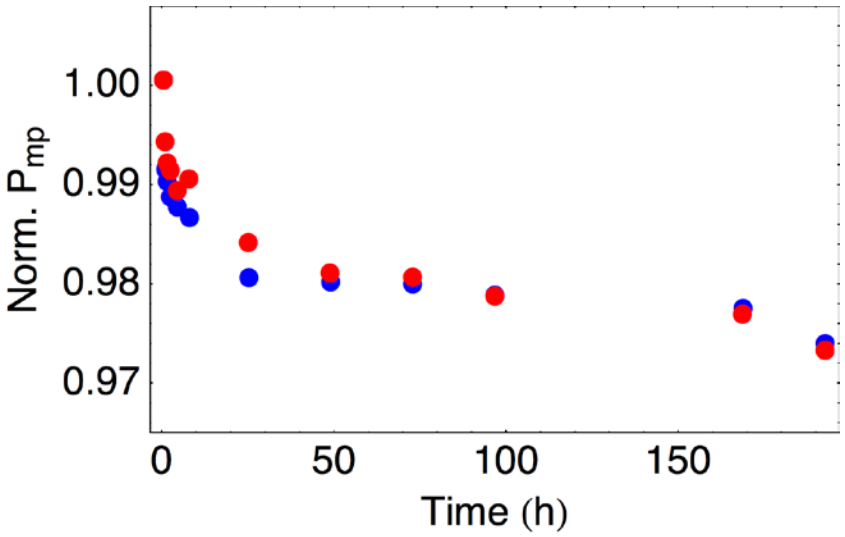
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Metastable performance in thin-films

Light exposure (1000 W m^{-2}, 55°C)



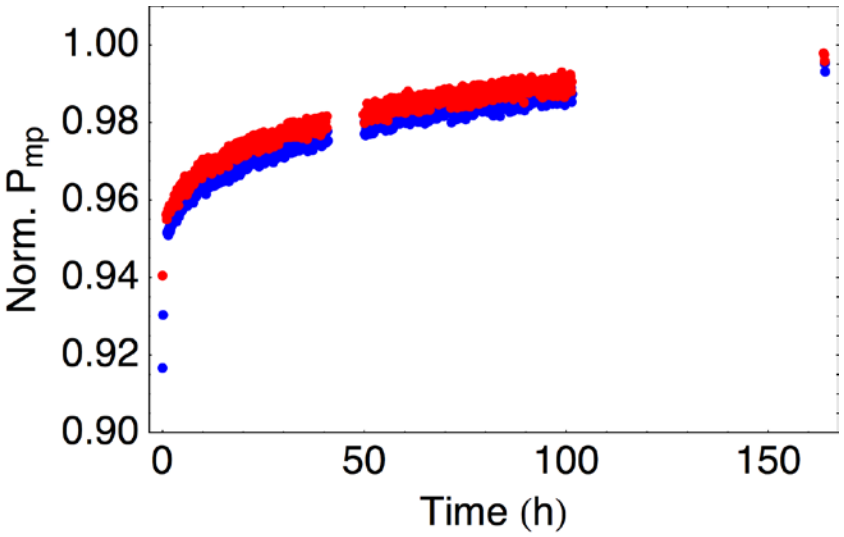
Storage at room temp.



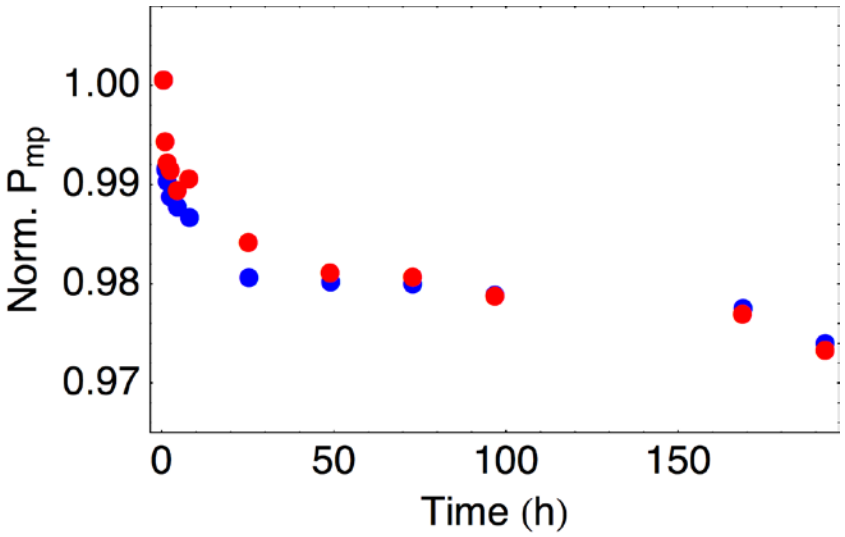
Thin-film modules change performance upon exposure to light and storage in the dark

Metastabilities vs. permanent changes

Light exposure (1000 W m^{-2}, 55°C)



Storage at room temp.

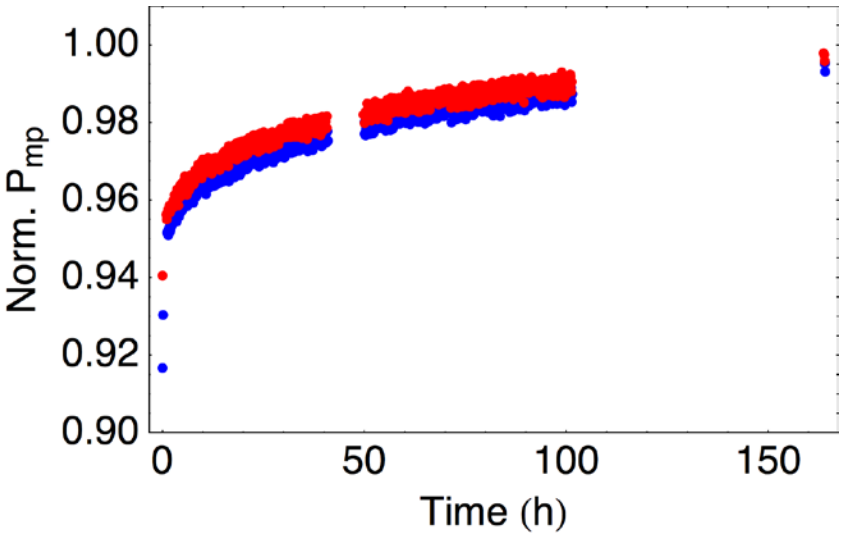


Changes are at often at least partially reversible, especially upon exposure to elevated temperatures

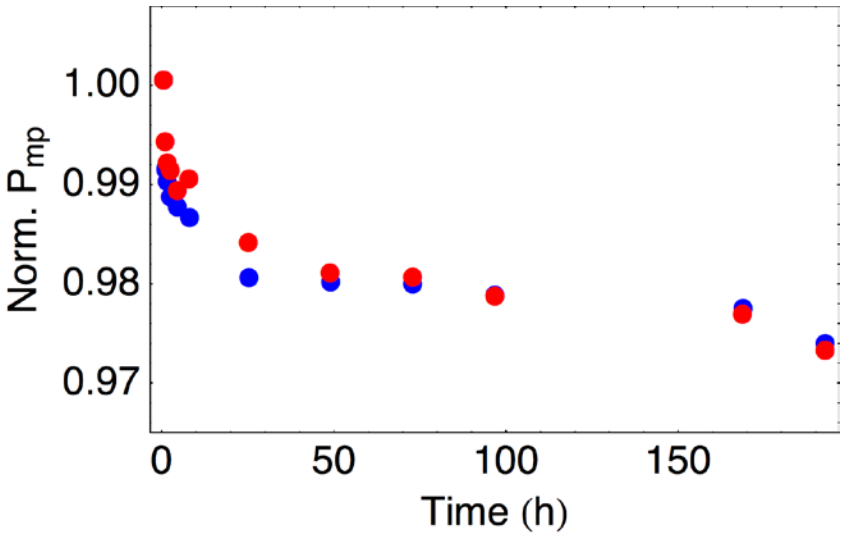
- Initial Norm. P_{mp}: 0.88
- After 165 hours at 55°C: 0.91

Metastabilities vs. permanent changes

Light exposure (1000 W m^{-2}, 55°C)



Storage at room temp.

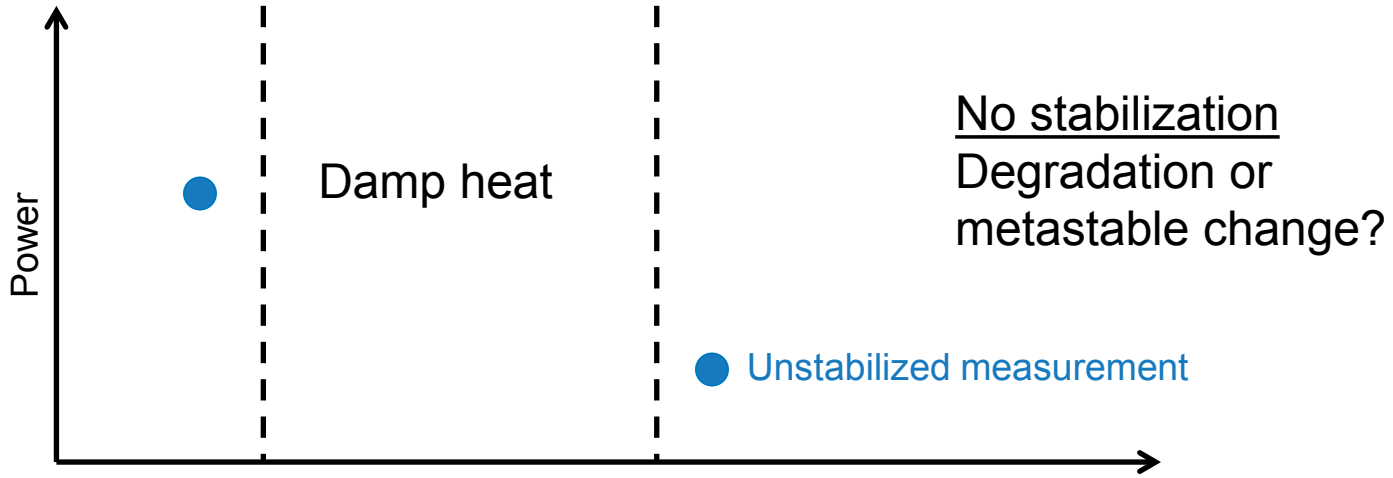


Changes are at often at least partially reversible, especially upon exposure to elevated temperatures

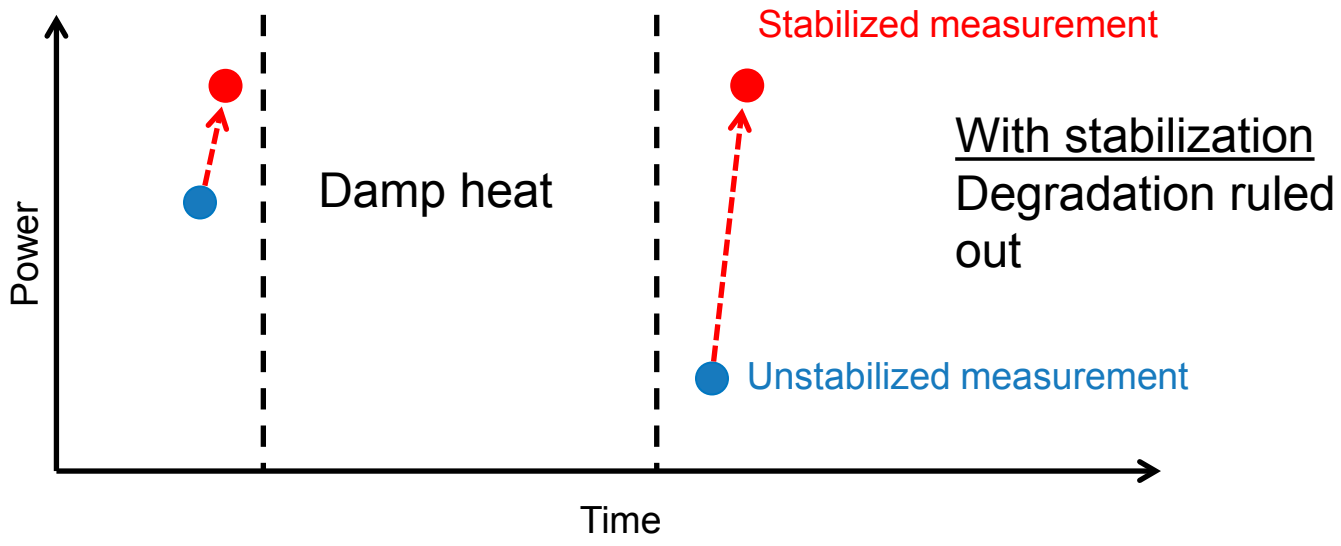
- Initial Norm. P_{mp}: 0.88
- After 165 hours at 55°C: 0.91

Metastabilities: reversible changes
Stabilization: Repeatedly achieving metastable state

Differentiating degradation

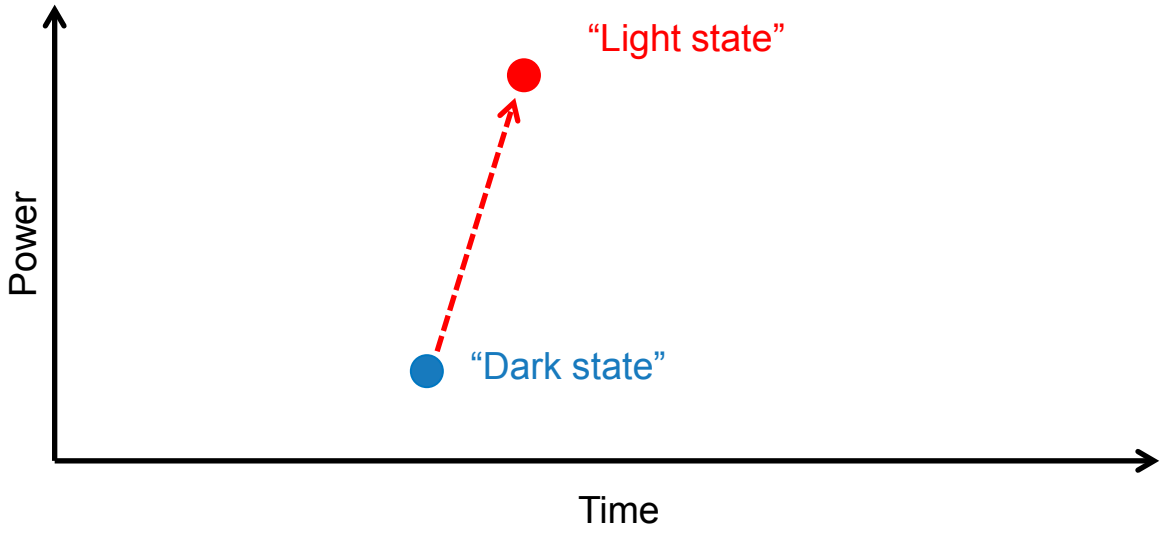


Differentiating degradation

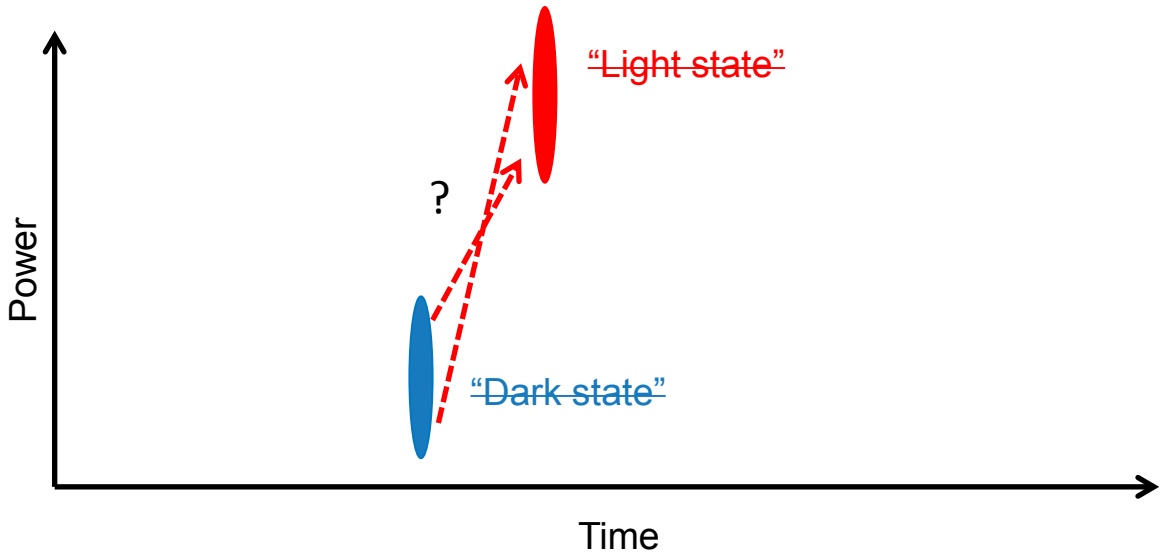


Repeatable stabilization procedure needed before and after reliability test

“The light state”



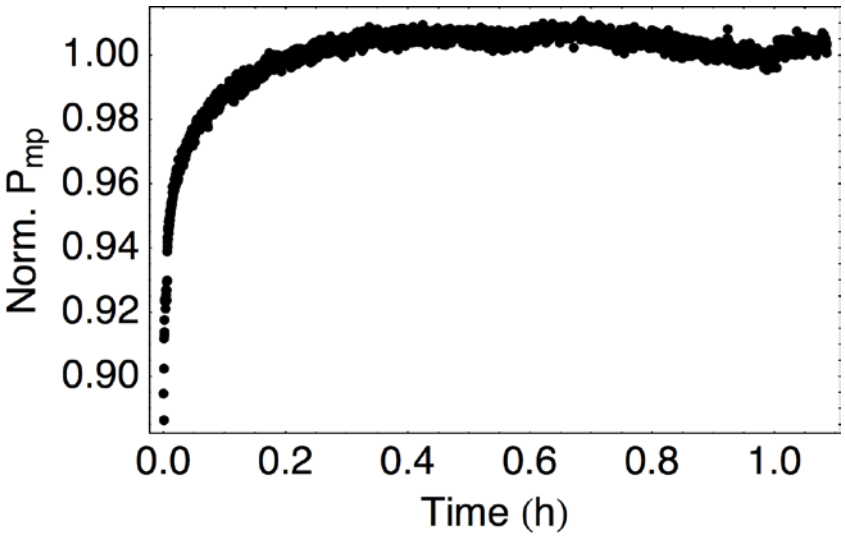
“The light state”

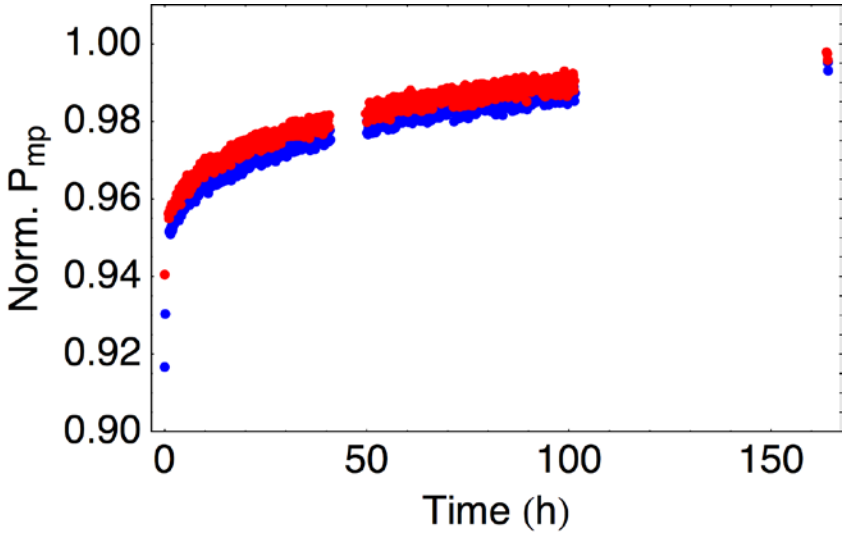


There is not a singular, well-defined light state

Time scales of change

Transient changes in performance of two different types of CIGS modules

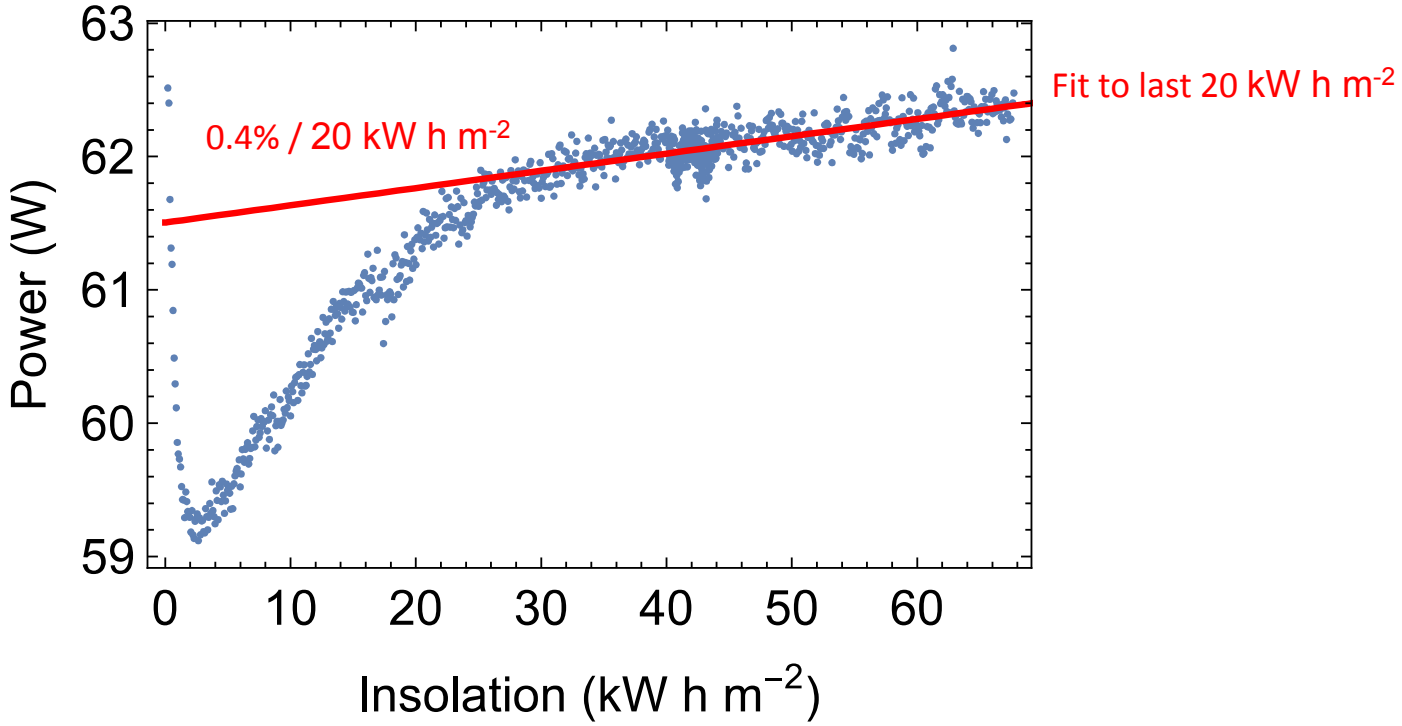




Changes can occur on different timescales for different modules

Must define relevant timescale

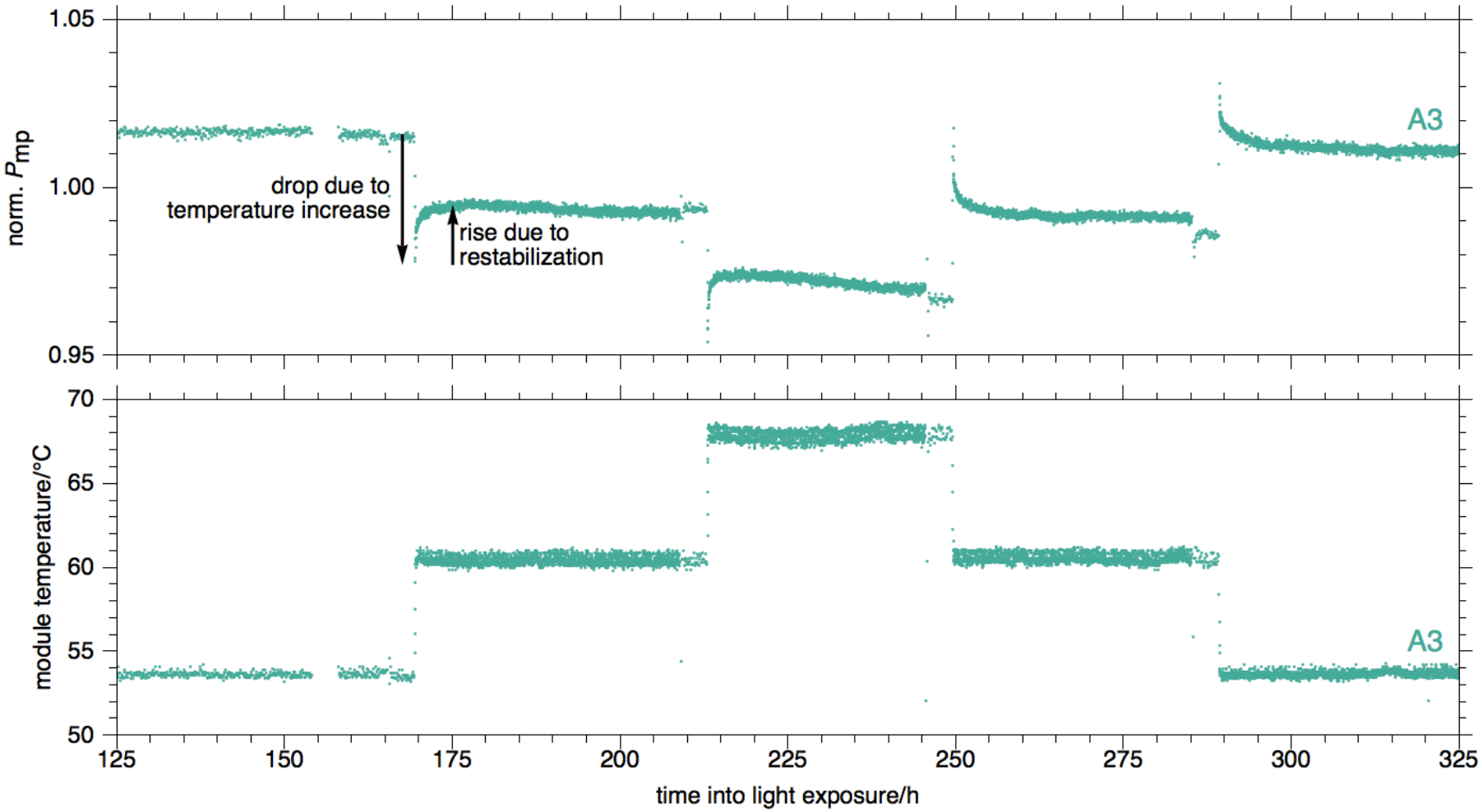
Transient change in CdTe module exposed at 1000 W m^{-2}, constant temperature



We use: <1% per 20 kW h m^{-2}

IEC 61646: <2% in two intervals of 43 kW h m^{-2}

Temperature dependent states



CdTe module exposed to light at different temperatures

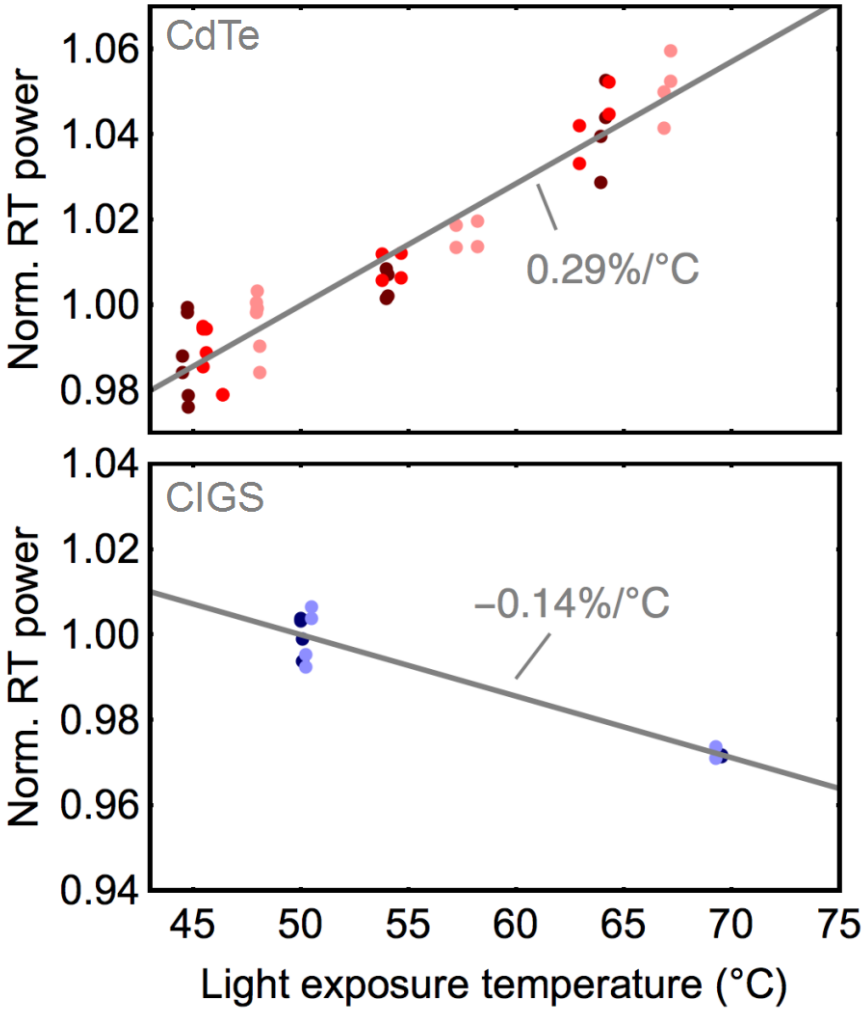
Silverman et al., J. PV 5:1 p. 344, 2015

Quantifying the temperature effect

- Light soak in chamber until stable
  - <1% / 20 kWh m^{-2} change based on in situ IV curves
- Measure IV at room temperature at 30 & 60 minutes after end of light soak
- Repeat light-soak at different back-of-module temperature
- Example:
  - Light soak at 50°C
  - Measure RT IVs
  - Light soak at 70°C
  - Measure RT IVs
  - Light soak at 50°C
  - Measure RT IVs

Discriminates permanent vs. reversible changes

Temperature-dependent “light states”



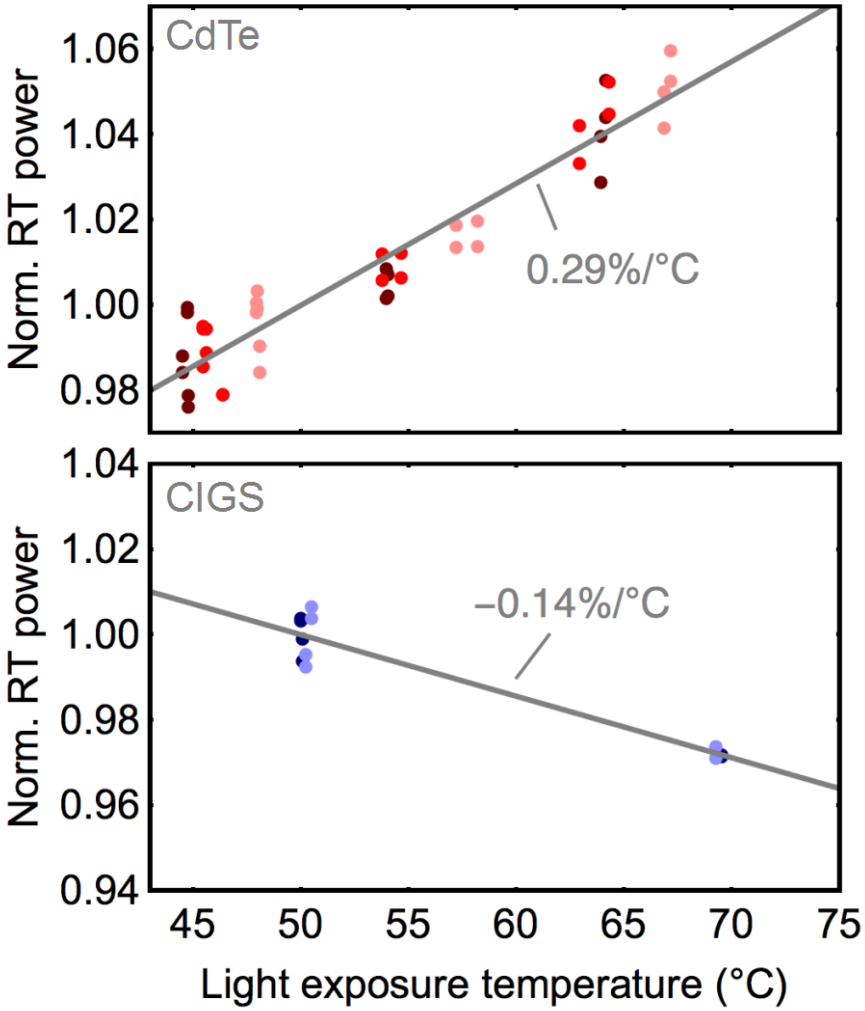
Variations in light-soak temperature affect the final metastable state.

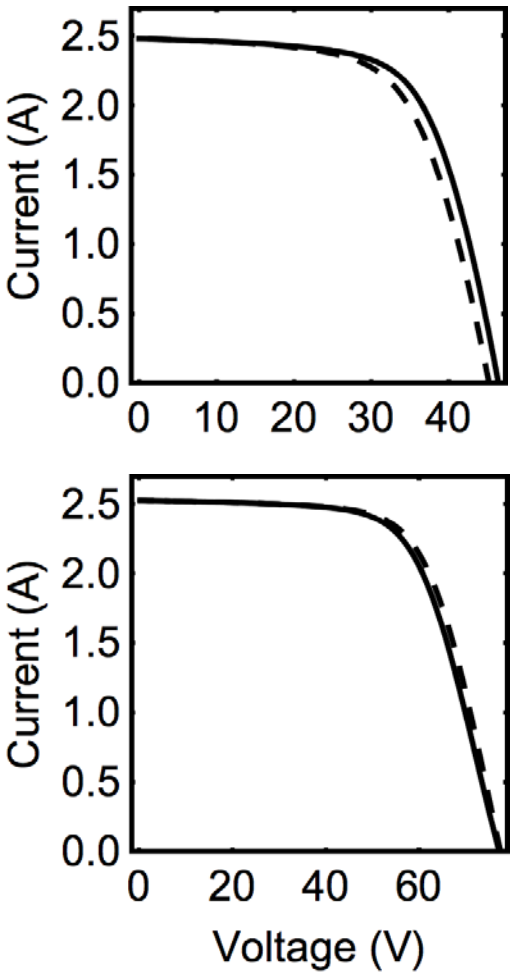
For a 20°C discrepancy:
2.8% change in CIGS
5.8% change in CdTe

(Effects not universal)

Different shades indicate different samples.
Both 30 min and 60 min measurements shown.

Temperature-dependent parameters





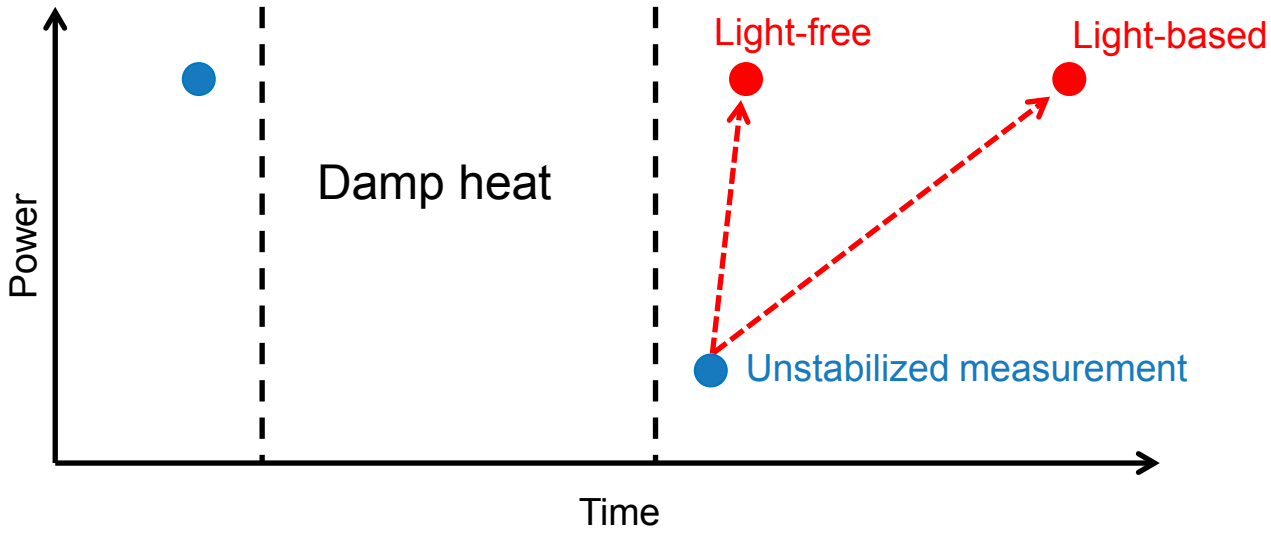
Differences

V_{oc} 3.6 %
FF 3.1%

V_{oc} 0.3%
FF 2.3%

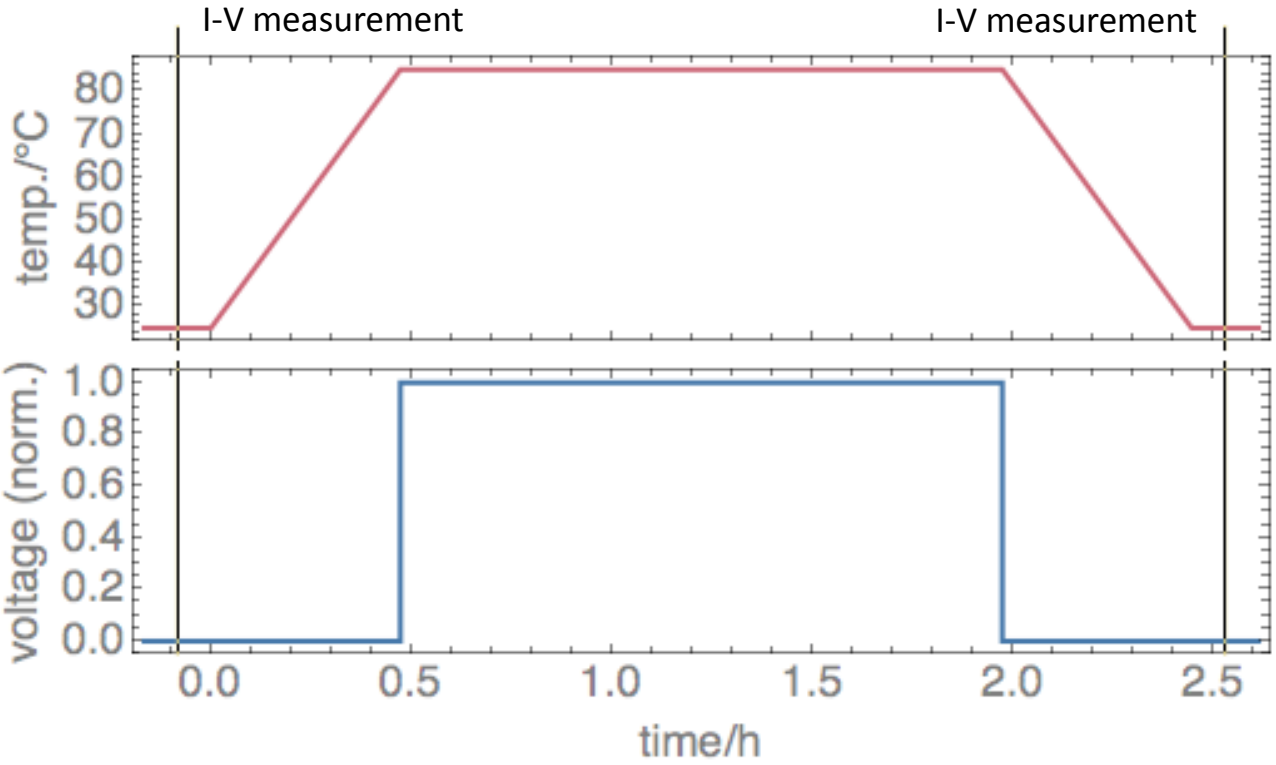
Hot light soak
Cool light soak

Light-free stabilization



- Can be **quicker** and **cheaper**
- Must produce **relevant state**

Bias at elevated temperature (BET)

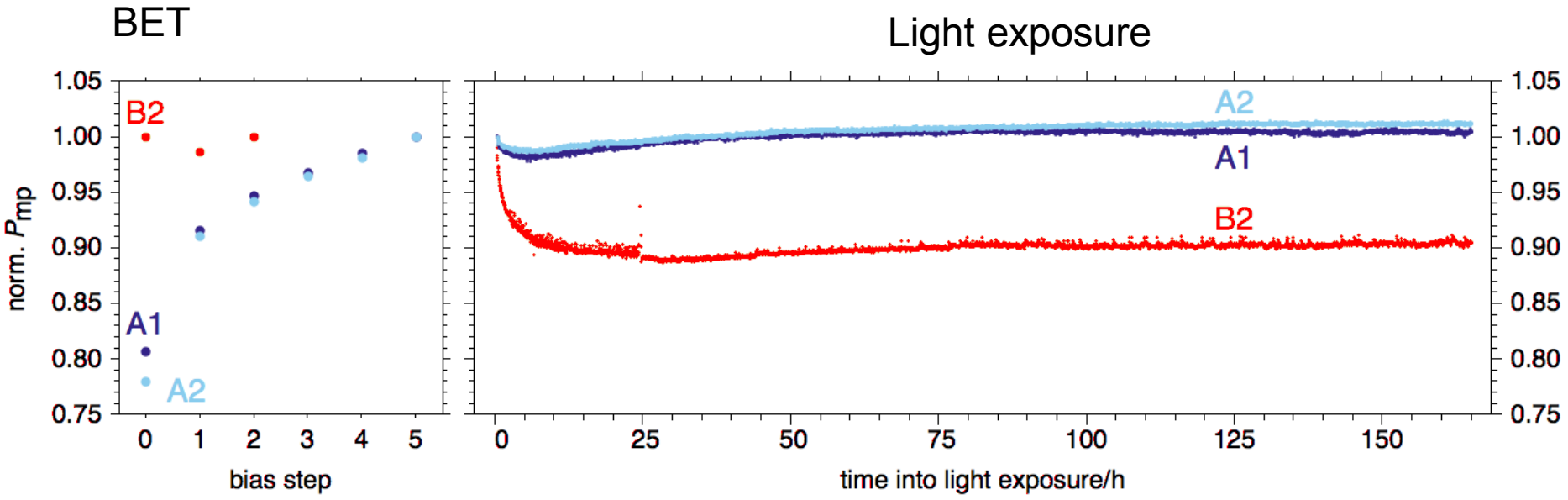


Method based on proposal in draft IEC 61215 update:

- Collect light I-V curve
- Heat to 85°C
- Apply forward bias (0.6 to 0.7) × V_{oc}
- Cool to room temperature
- Collect light I-V curve
- Repeat until power is stable

BET results

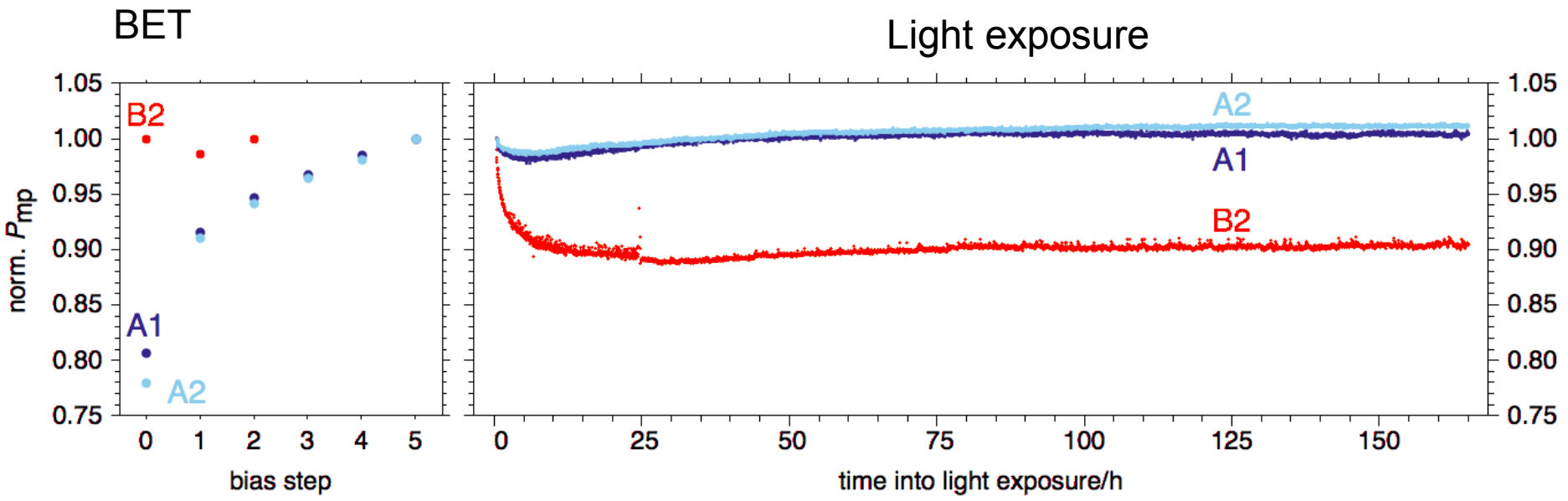
Two types of CdTe module were stabilized with the bias at elevated temperature (BET), then placed in light-soak chamber



For some modules, BET does not produce a light-stable state

Silverman et al., J. PV 5:1 p. 344, 2015

BET results

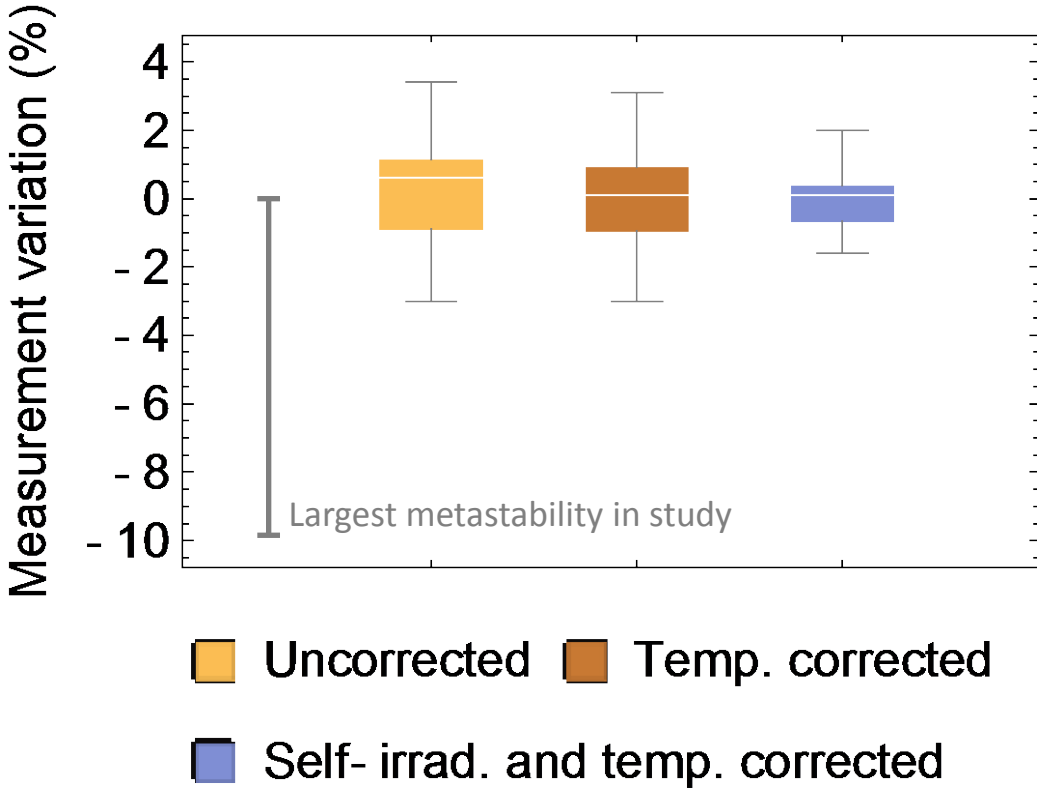


Validation is critical

Silverman et al., J. PV 5:1 p. 344, 2015

Reproducible measurements are possible

- Round robin
  - 5 labs
  - 4 CIGS module types
- Uninterrupted 5 hour light soak
- Module forward biased while cooled
- Prompt IV measurement (within 1 minute)



Deceglie et al., J. PV 5:2 p. 607, 2015

Conclusion

- “Light state” and “Dark state” are ill-defined
  - Timescale
  - Temperature
  - Stimulus (alternate methods)
- Best practices
  - Define the timescale of interest
  - Tightly control the temperature
  - Validate light-free methods
  - Control and minimize the delay between light exposure and measurement

Acknowledgments

Thank you:

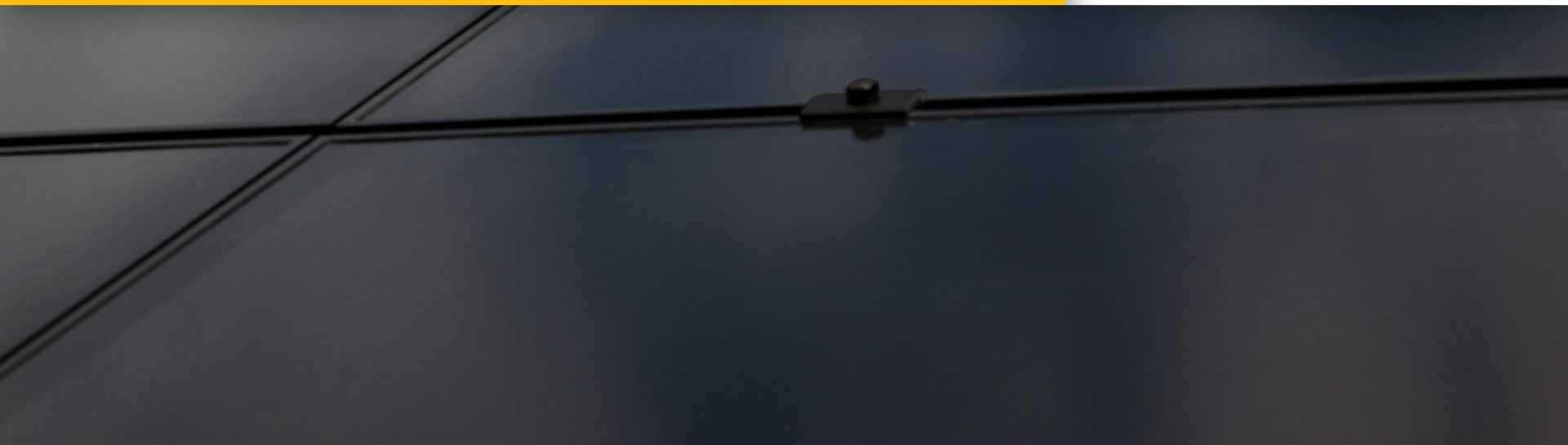
- Steve Rummel, Allan Anderberg, Kent Terwilliger, Greg Perrin, and Keith Emery **(NREL)**
- Daniela Dirnberger and Alexandra Schmid (**Fraunhofer ISE)**
- Stephen Barkaszi **(FSEC)**
- Nicholas Riedel and Larry Pratt **(CFV)**
- Samantha Doshi and Govindasamy Tamizhmani **(TUV Rheinland PTL)**

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory.

Reliability Testing of Monolithic CIGSS in a Glass-Glass Package

Richard Wickham – Director of Quality & Reliability

STION



Outline

- Monolithic Cell Structure
  - Cell Interconnection using MOCVD
  - Stion Process Overview
- Package Design advantages and challenges
  - Glass-Glass Package Assembly
  - Managing Mechanical Stress
- Testing
  - Testing Procedures & Frequency
    - PID Test results
  - Results of Short & Long term Accelerated Aging
  - ALT Stresses

    Damp Heat

    Thermo-mechanical

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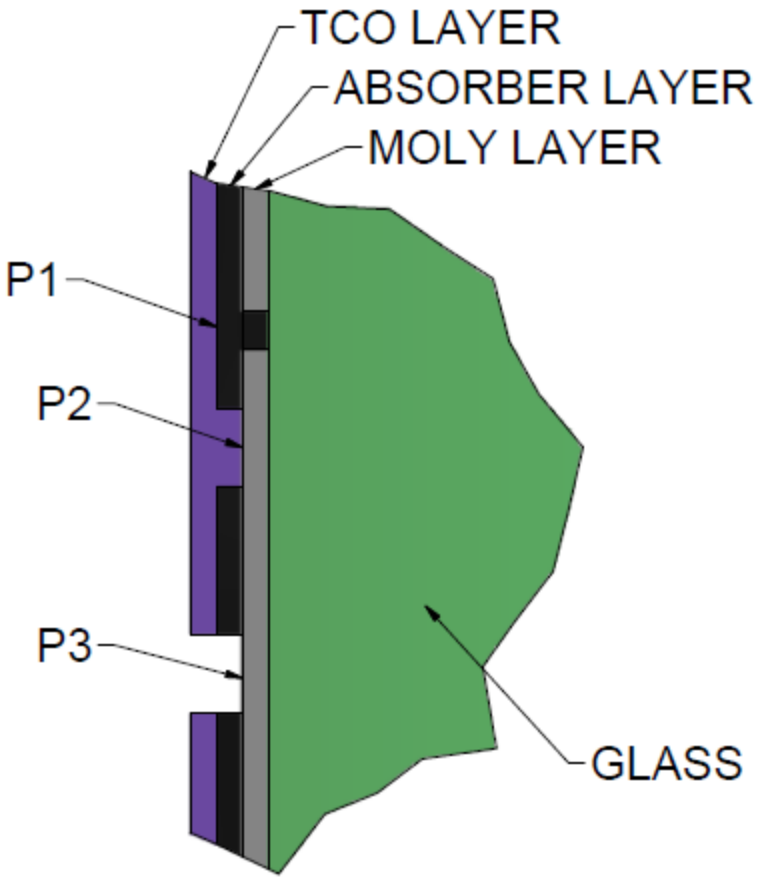
Finished Monolithic Circuit Structure

Key Elements of the Monolithic Structure

Additive film process with laser scribed P1 & mechanically scribed P2 / P3



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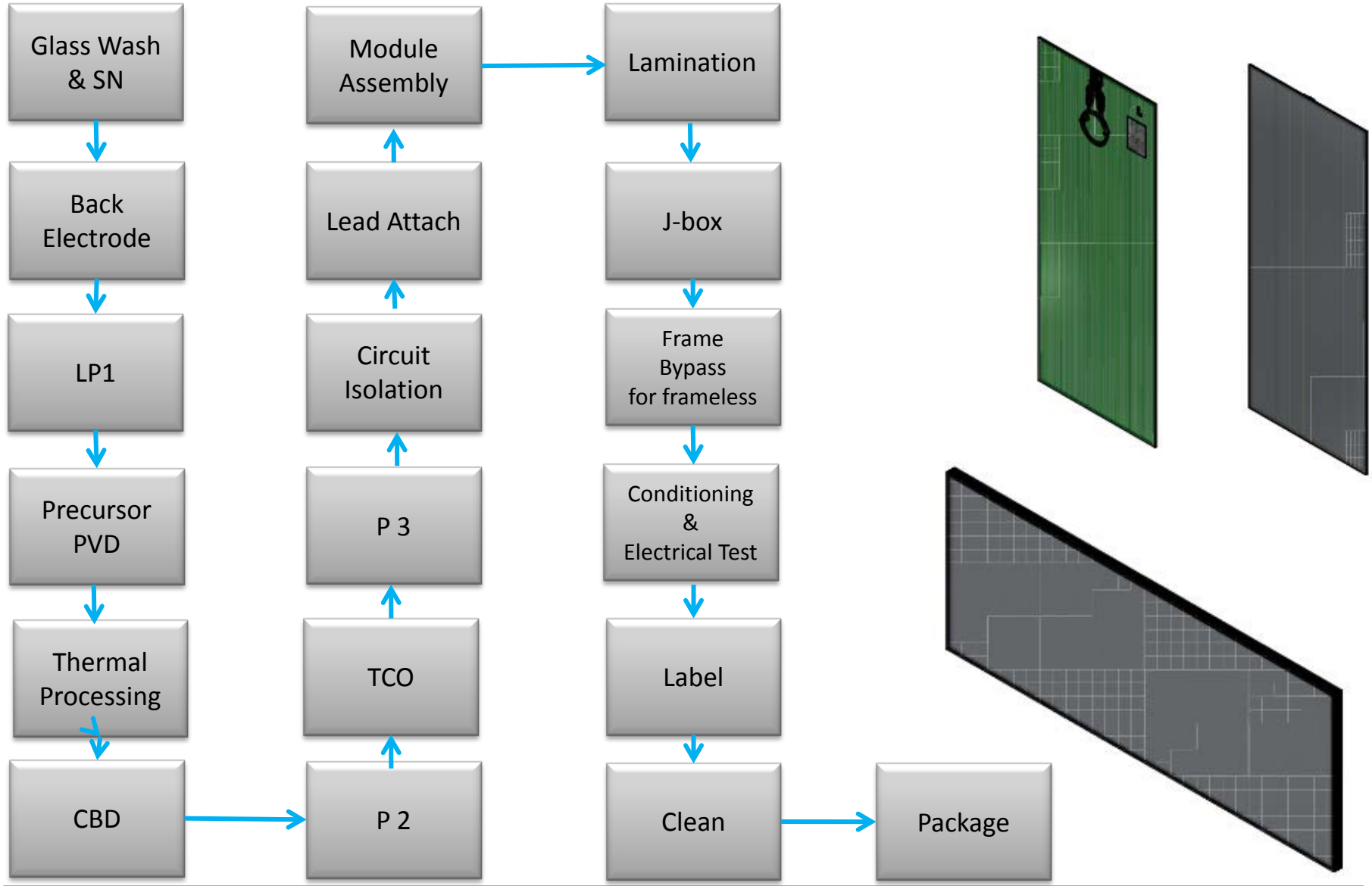
Monolithic CIGSS Manufacturing Process



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Advantages & Challenges

- Advantages
  - Glass permeability to moisture is extremely low – protects moisture sensitive films
  - Excellent insulator to build a circuit on
  - Planar & smooth surfaces aid in production
  - Easy to work with at elevated temperatures
  - Cleaned easily at low cost

- **Challenges**
  - Fragile until laminated
  - Subject to stress fractures / thermal breaks
  - Can be warped if not heat treated properly

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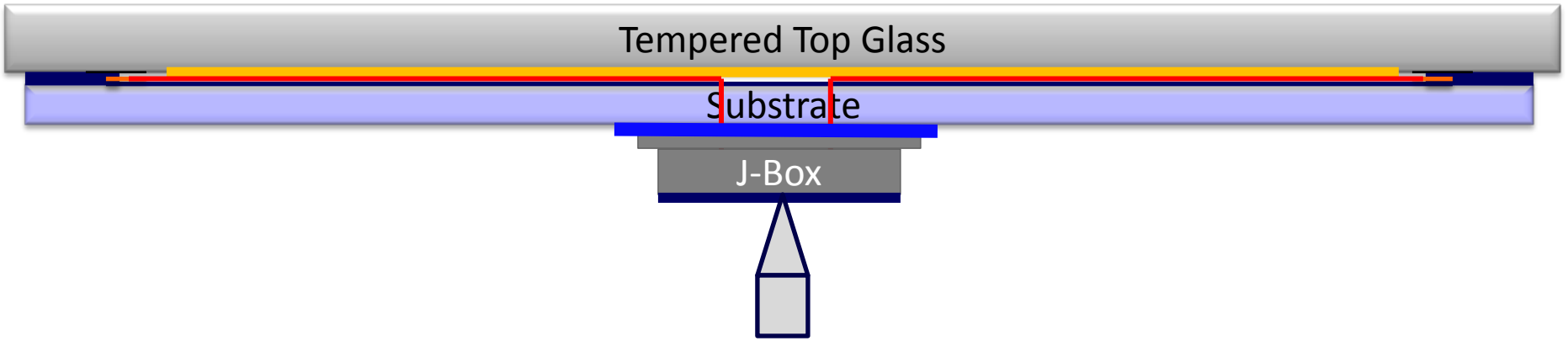
Module Assembly Process (frameless)

Stion Module Assembly
Process Overview



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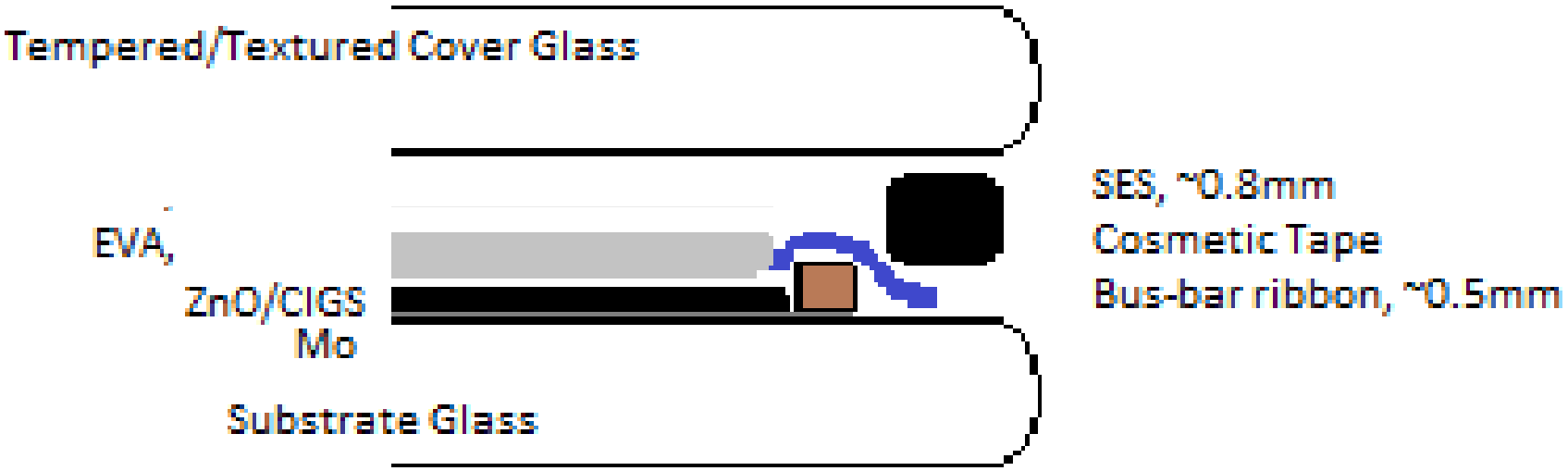
Block Diagram of edge of module

Not to scale



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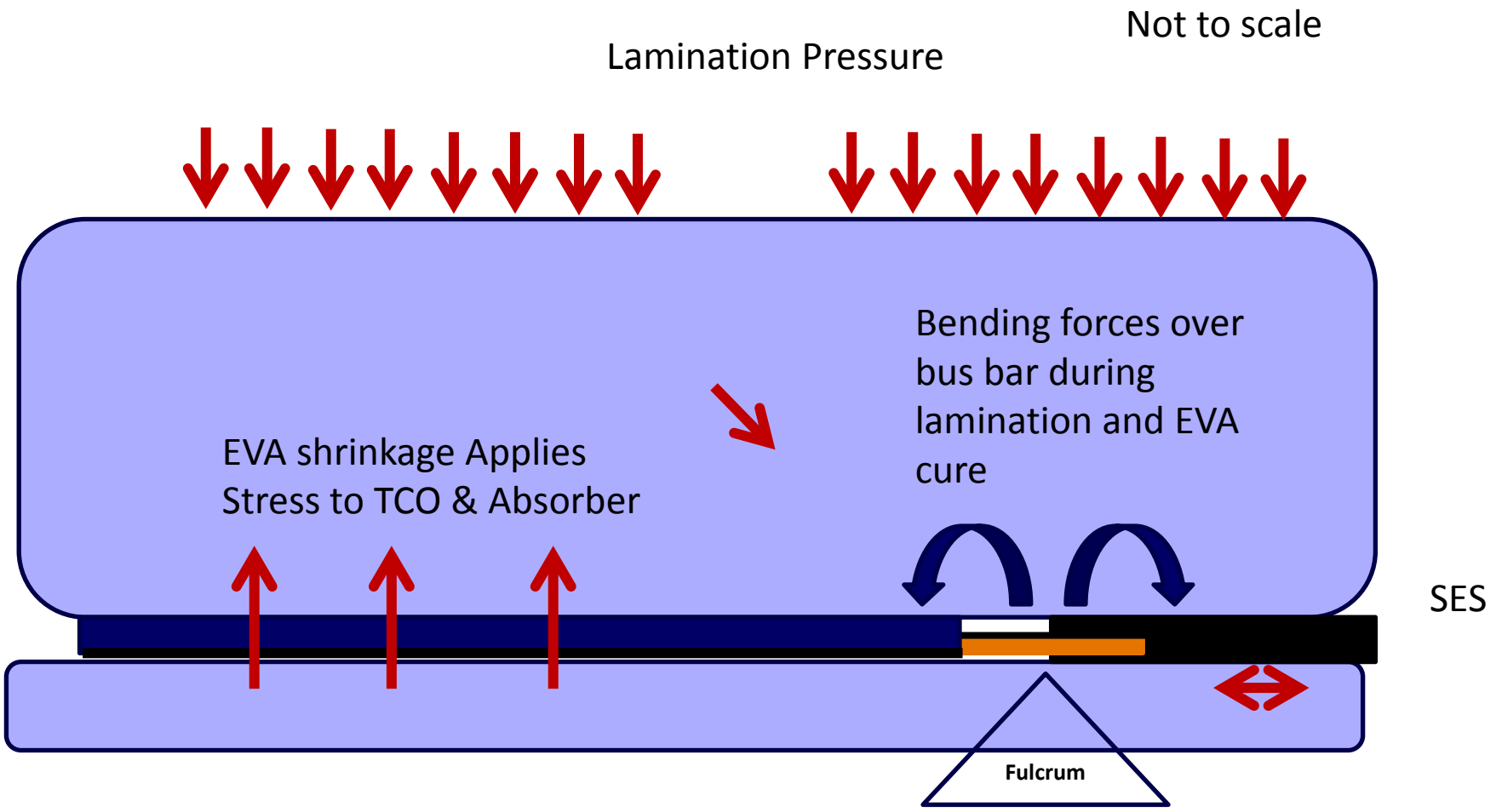
Managing Stresses



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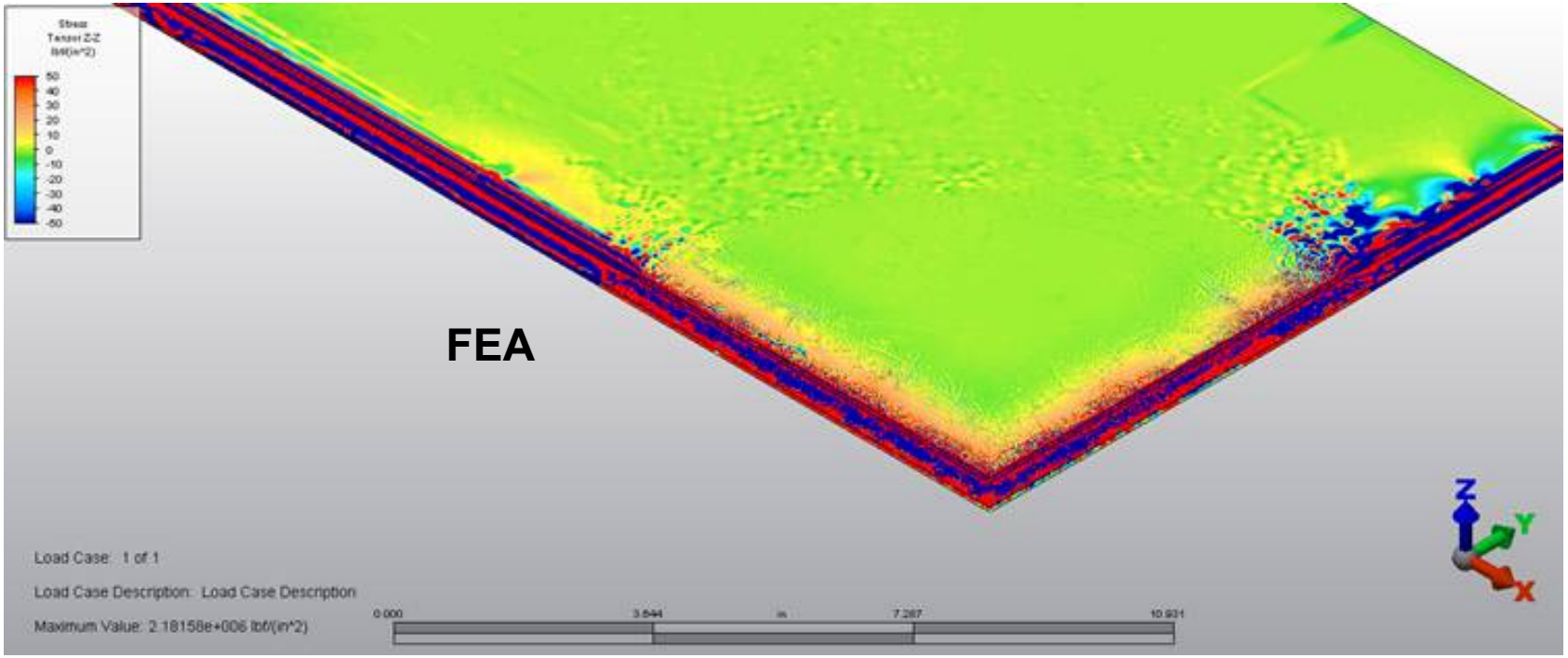
Managing Mechanical Stresses (modeling)



Edge Thickness Measurement Map

Red is thinner / Green is thicker

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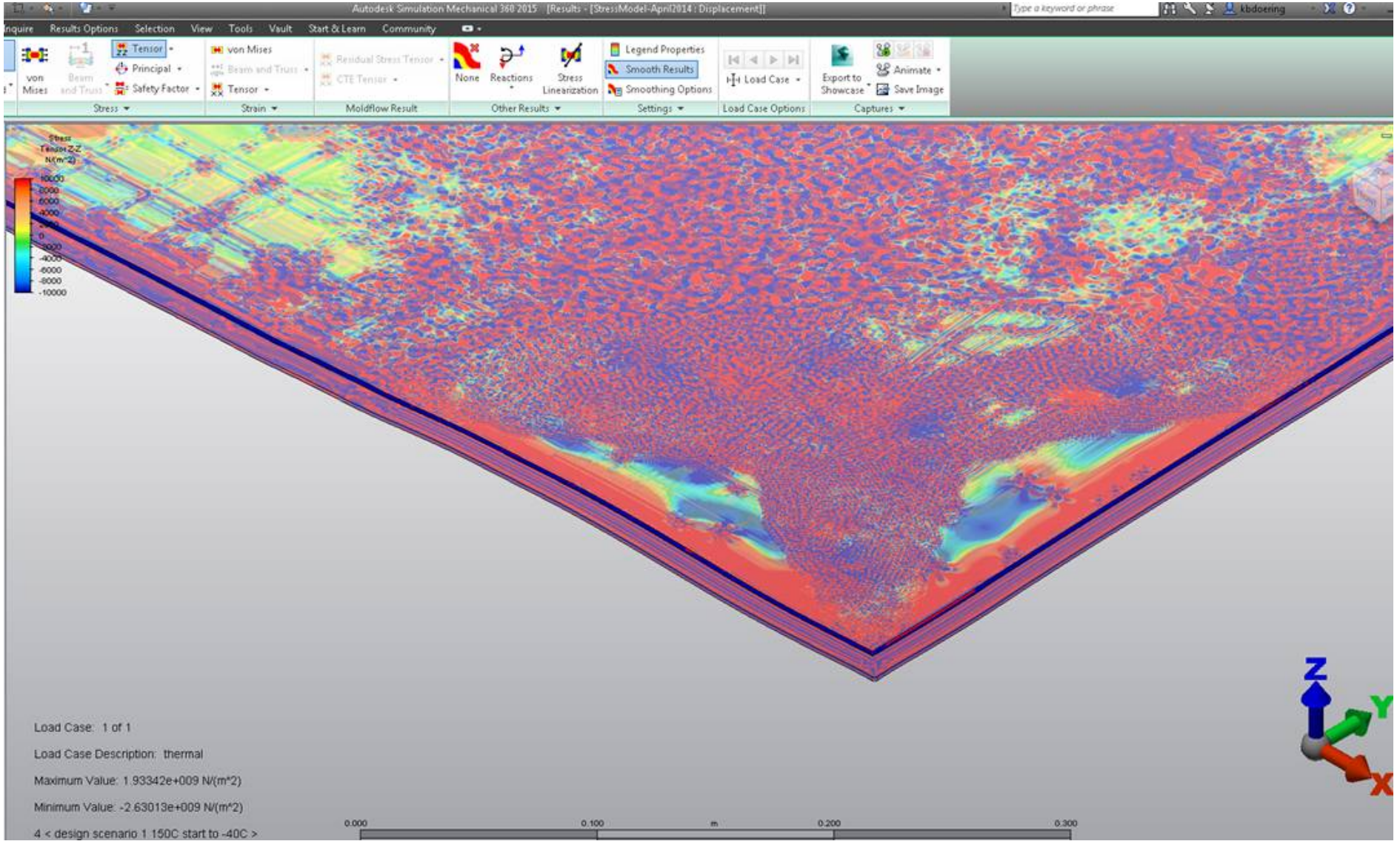
FEA Modeling-complex to achieve high resolution



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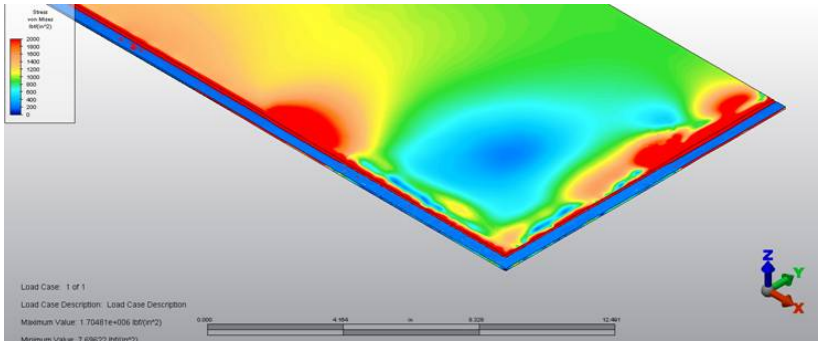
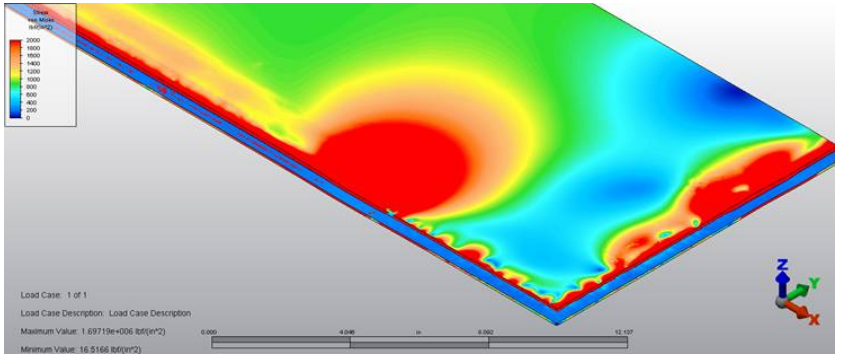
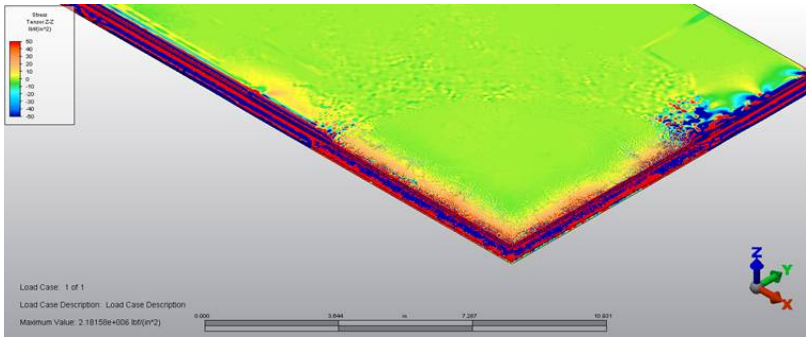
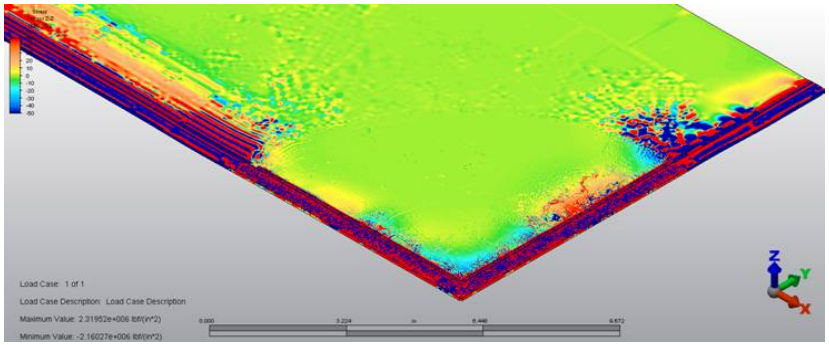
FEA Models to explore internal stress



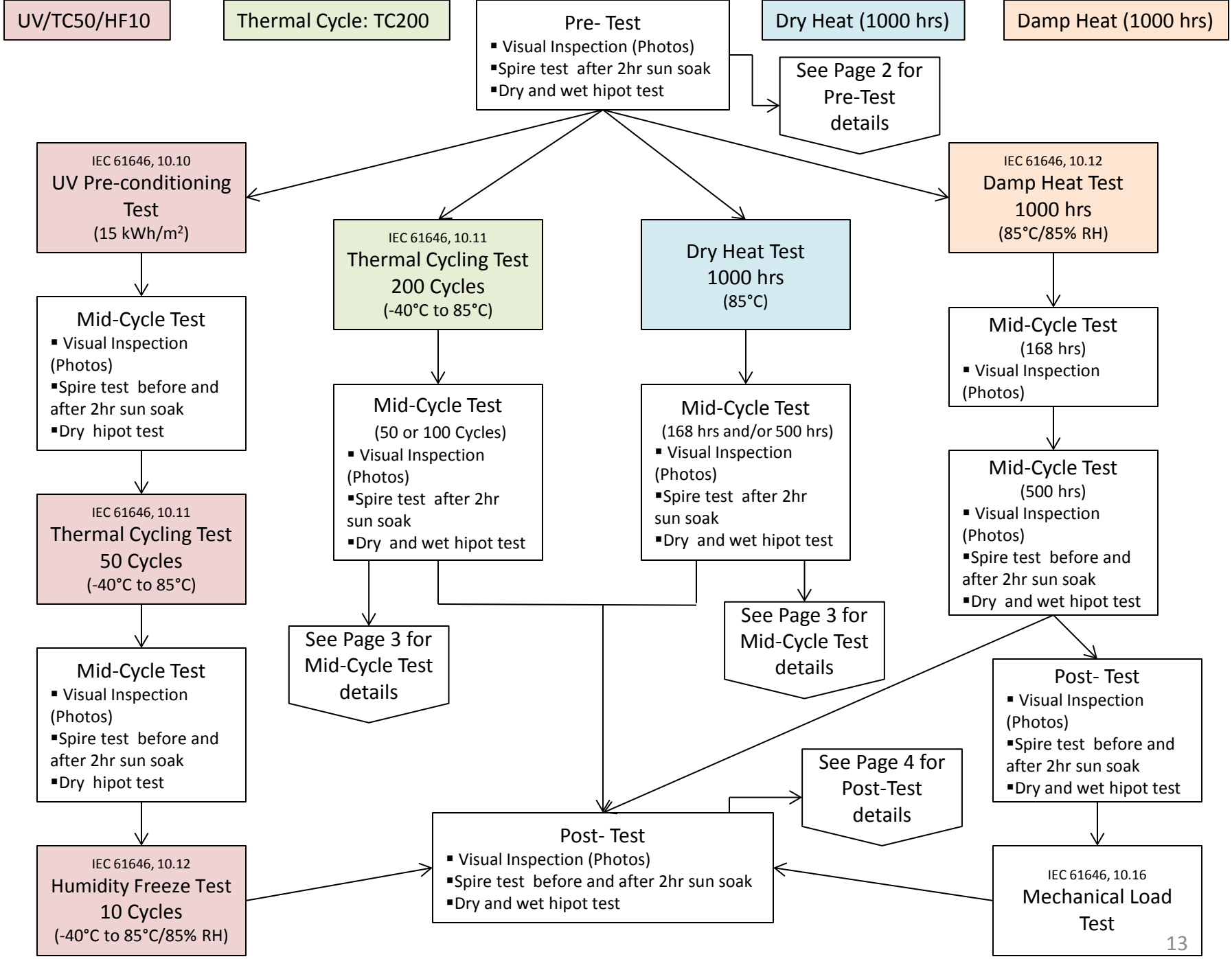






Reliability Process Flow Chart

7/5/13 J. Dees


UV/TC50/HF10
Thermal Cycle: TC200
Dry Heat (1000 hrs)
Damp Heat (1000 hrs)
Pre- Test
▪ Visual Inspection (Photos)
▪Spire test after 2hr sun soak
▪Dry and wet hipot test
See Page 2 for Pre-Test details
IEC 61646, 10.10
UV Pre-conditioning Test
(15 kWh/m²)
IEC 61646, 10.11
Thermal Cycling Test
200 Cycles
(-40°C to 85°C)
Dry Heat Test
1000 hrs
(85°C)
IEC 61646, 10.12
Damp Heat Test
1000 hrs
(85°C/85% RH)
Mid-Cycle Test
▪ Visual Inspection (Photos)
▪Spire test before and after 2hr sun soak
▪Dry hipot test
IEC 61646, 10.11
Thermal Cycling Test
50 Cycles
(-40°C to 85°C)
Mid-Cycle Test
(50 or 100 Cycles)
▪ Visual Inspection (Photos)
▪Spire test after 2hr sun soak
▪Dry and wet hipot test
Mid-Cycle Test
(168 hrs and/or 500 hrs)
▪ Visual Inspection (Photos)
▪Spire test after 2hr sun soak
▪Dry and wet hipot test
Mid-Cycle Test
(168 hrs)
▪ Visual Inspection (Photos)
Mid-Cycle Test
(500 hrs)
▪ Visual Inspection (Photos)
▪Spire test before and after 2hr sun soak
▪Dry and wet hipot test
See Page 3 for Mid-Cycle Test details
See Page 3 for Mid-Cycle Test details
Mid-Cycle Test
▪ Visual Inspection (Photos)
▪Spire test before and after 2hr sun soak
▪Dry hipot test
Post- Test
▪ Visual Inspection (Photos)
▪Spire test before and after 2hr sun soak
▪Dry and wet hipot test
See Page 4 for Post-Test details
IEC 61646, 10.12
Humidity Freeze Test
10 Cycles
(-40°C to 85°C/85% RH)
Post- Test
▪ Visual Inspection (Photos)
▪Spire test before and after 2hr sun soak
▪Dry and wet hipot test
IEC 61646, 10.16
Mechanical Load Test

Reliability: Ongoing Monitoring & Qualification Testing

Weekly Product Monitors			
Test Description	Specifications	Test Conditions	
Damp Heat (DH)	200, 500, 1000 Hours	85 °C / 85% RH	2 samples from End-of-line or FGI per week
Thermal Cycle (TC)	3, 50, 200 Cycles	-40 °C to 85 °C	2 samples from End-of-line or FGI per week

Monthly Product Monitors			
Test Description	Specifications	Test Conditions	
Damp Heat (DH)	200, 500, 1000, 2000, 3000 Hours	85 °C / 85% RH	1 sample from End-of-line or FGI per month
Thermal Cycle (TC)	3, 50, 200, 400, 600 Cycles	-40 °C to 85 °C	1 sample from End-of-line or FGI per month

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Reliability: Ongoing Monitoring & Qualification Testing

Quarterly Product Monitors			
Test Description	Specifications	Test Conditions	
Damp Heat (DH)	4000, 5000, 6000 Hours	85 °C / 85% RH	1 sample from the 3 previous months of Monthly Monitors
Thermal Cycle (TC)	800, 1000, 1200 Cycles	-40 °C to 85 °C	1 sample from the 3 previous months of Monthly Monitors

Monthly Direct to Long-Term Product Monitors			
Test Description	Specifications	Test Conditions	
Damp Heat (DH)	500, 1000, 2000, 3000, 4000, 5000, 6000 Hours	85 °C / 85% RH	1 sample from End-of-line or FGI per month
Thermal Cycle (TC)	200, 400, 600, 800, 1000, 1200 Cycles	-40 °C to 85 °C	1 sample from End-of-line or FGI per month

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Determining Warranty Reserve

FIT (**F**ailures **I**n **T**ime Testing (failures in parts per billion)

- Standard methodology in the Semiconductor Industry
- Based on material characteristics and impurities migration
- Follows recommendations from NREL
- Na^+ Effects on semiconductor performance (CIGSS film or Si)
- Failure of seals and H_2O ingress
- General circuit breakdown from thermal stresses
- Recovery after stress by sun soak
- Uses IEC standard ALT techniques (**A**ccelerated **L**ifetime **T**est)
- DH 85/85-1000hrs. / TC +85/-40C-200Cycles
- Must be samples from standard production (we test 2 per week)
- Samples must pass all warranty requirements or be logged as failures

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Referenced Documents for FIT Testing

1. "Accelerated Testing and Failure of Thin-film PV Modules," T. J. McMahon [NREL], Progress in Photovoltaics: Research and Applications, 2004, vol. 12, p. 235-248.

2. "Long Term Reliability of Photovoltaic Modules," J. Wohlgemuth et al [BP Solar], WCPEC-4 (2006).

3. "Semiconductor Device Reliability Failure Models," R. Blish [AMD] and N. Durrant [Intel], International SEMATECH, Technology Transfer #00053955A-XFR, May 2000.

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FIT Calculation Sheet

Damp heat acceleration

From Reference 1, Ea ranges from 0.5eV to 1.2eV
From Reference 2, 1% change in RH corresponds to 1-deg C rise in temperature

Tacc ('C)	85		
Tacc (K)	358		Temperature in Kelvin
Top ('C)	50		
Top (K)	323		Temperature in Kelvin
Ea (eV)	0.8		activation energy of soda lime glass
Ea (J)	1.28E-19		Ea conversion to J
kB (J/K)	1.38E-23		Boltzmann's constant
AF-thermal	16.57		E-model
RH,acc (%)	85	358	RH,acc (K)
RH,op (%)	50	323	RH,op (K)
AF-RH	16.57		E-model
AF-total, DH	274.49		AF Total AF-thermal*AF-RH (E-model)
DH FIT rate	13943	FITs	Failures-in-time expressed as failure per billion device hours
OP FIT rate	50.79589	FITs	
2 yrs = >	57077.63		
After 2 yrs	0.1%	population failure after 2 yrs operation (50C / 50% RH)	
5 yrs = >	22831.05		
After 5 yrs	0.2%	population failure after 5 yrs operation (50C / 50% RH)	
25 yrs = >	4566.21		
After 25 yrs	1.1%	population failure after 25 yrs operation (50C / 50% RH)	

Temperature cycling acceleration

From Reference 3 (modified Coffin-Manson equation)
# of cycles to failure = Co*(deltaT-deltaT0)^(-q)
Co = material-dependent constant
deltaT = entire temperature cycle-range for device
deltaT0 = portion of the temperature cycle range in the elastic region
q = Coffin-Manson exponent, empirically derived constant

Assume deltaT >> deltaT0
Assume q = 3 (based on solder / ribbon failures)

Then AF (acceleration factor) = (# of cycles to failure @ op)/(# of cycles to failure @ accel)

deltaT-acc	125	(-40 to 85C)	accelerated
deltaT-op	35	(20 to 55C)	real world
q	3		
AF	273.3236	Multiply by 6 because 6 cycles per day in TC	
TC FIT rate	28275	FITs	
OP FIT rate	103.4488		
2 yrs = >	57077.63		
After 2 yrs	0.2%	population failure after 2 yrs operation (24-hr TC)	
5 yrs = >	22831.05		
After 5 yrs	0.5%	population failure after 5 yrs operation (24-hr TC)	
25 yrs =>	4566.21		
After 25 yrs	2.3%	population failure after 25 yrs operation (24-hr TC)	

COMBINED FAILURE RATE 3.4%

References:
1. "Accelerated Testing and Failure of Thin-film PV Modules," T. J. McMahon [NREL], Progress in Photovoltaics: Research and Applications, 2004, vol. 12, p. 235-248.
2. "Long Term Reliability of Photovoltaic Modules," J. Wohlgemuth et al [BP Solar], WCPEC-4 (2006).
3. "Semiconductor Device Reliability Failure Models," R. Blish [AMD] and N. Durrant [Intel], International SEMATECH, Technology Transfer #00053955A-XFR, May 2000.

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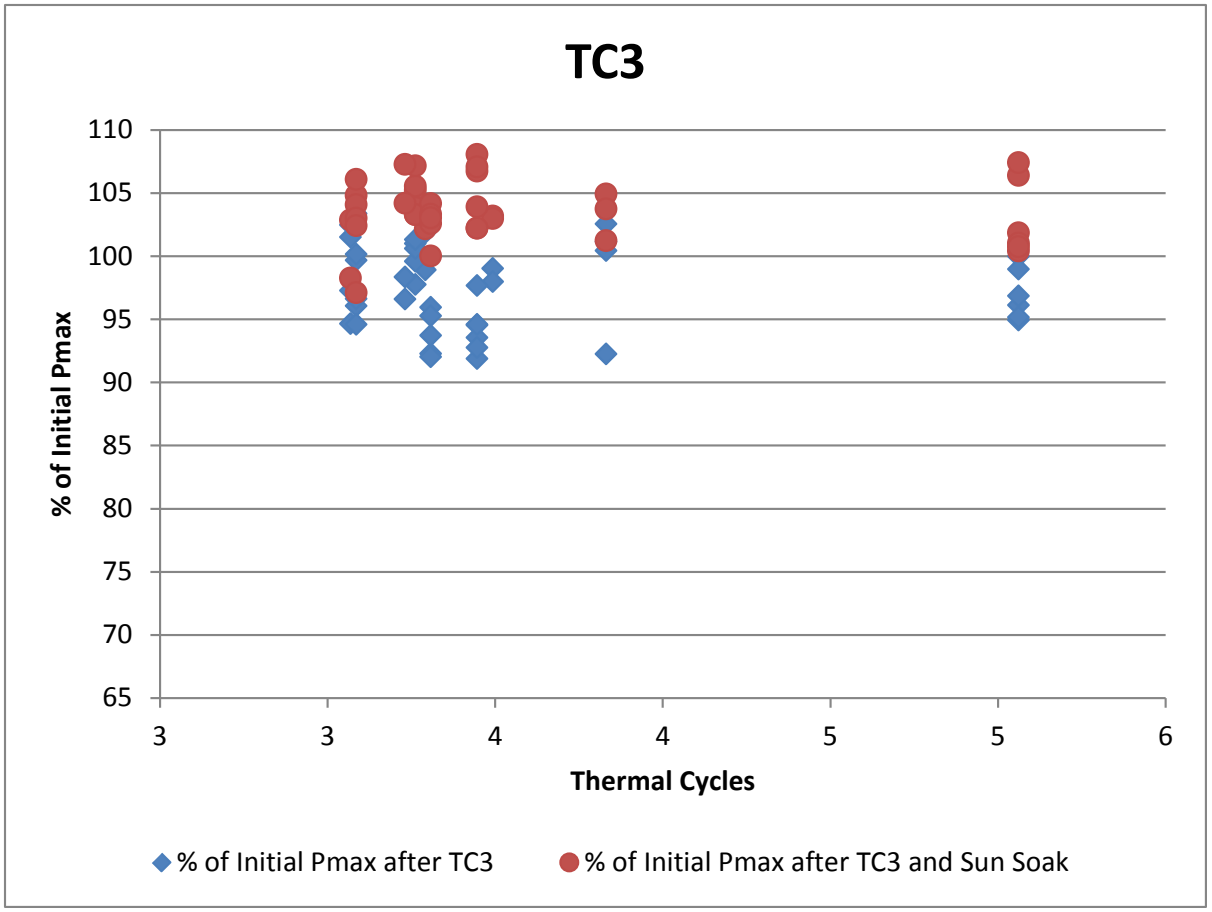
TC3 Recovery



Module Type	SN	Initial Pmax	Actual # of cycles for TC3	Pmax after TC3 Chamber	% of Initial Pmax after TC3	Pmax after TC3 Sun Soak	% of Initial Pmax after TC3 and Sun Soak
STL	100108521	133.73	3	138.23	103.37	140.15	104.80
STL	100109551	132.20	3	126.99	96.06	140.23	106.07
STO	100125805	131.54	3	134.78	102.47	135.31	102.87
STL	100125967	132.40	3	125.32	94.65	130.11	98.27
STL	100126378	133.97	3	135.99	101.50	-	-
STL	100126849	134.19	3	130.53	97.27	-	-
STO	100137292	143.60	3	135.85	94.60	139.44	97.10
STO	100137464	145.47	3	145.00	99.68	151.40	104.08
STO	100142411	141.36	3	141.59	100.16	145.61	103.01
STO	100142414	140.88	3	136.12	96.62	144.26	102.40
STO	100149666	143.66	3	142.11	98.92	149.45	104.03
STO	100149707	143.72	3	146.43	101.89	146.81	102.15
STO	100150941	138.17	3	137.59	99.58	142.69	103.27
STO	100150945	138.56	3	135.46	97.76	145.80	105.23
STO	100152008	135.43	3	136.80	101.01	140.64	103.84
STO	100152022	134.06	3	134.88	100.62	138.48	103.30
STL	100154585	149.84	4	150.49	100.44	151.66	101.21
STO	100154974	126.93	3	128.58	101.30	133.97	105.55
STO	100155009	134.96	3	141.09	104.54	144.62	107.16
STO	100159103	140.56	4	142.18	101.15	147.50	104.93
STO	100159572	124.14	4	114.51	92.25	140.70	113.34
STL	100160644	144.86	4	148.55	102.55	150.29	103.75
STL	100163602	142.60	5	135.36	94.92	145.25	101.86
STO	100164193	143.54	5	137.95	96.11	144.11	100.40
STO	100164202	143.30	3	141.90	99.02	147.83	103.16
STO	100164209	145.20	3	142.28	97.99	149.52	102.97
STO	100167811	138.42	3	136.14	98.36	144.21	104.18
STO	100167831	132.84	3	128.32	96.60	142.49	107.26
STO	100169362	144.64	3	133.47	92.28	144.65	100.01
STO	100169561	144.53	3	138.66	95.94	148.25	102.58
STO	100175563	143.87	3	134.84	93.72	149.85	104.16
STO	100176233	136.28	3	125.41	92.02	140.80	103.32
STO	100176306	138.38	3	131.85	95.27	142.57	103.03
STO	100180897	139.85	5	133.08	95.16	141.29	101.03
STL	100181862	124.51	5	124.50	99.99	132.48	106.40
STL	100182153	131.04	5	129.70	98.97	140.75	107.40
STO	100183735	139.02	5	134.66	96.87	140.05	100.74
STL	100189811	125.67	3	118.82	94.54	135.79	108.05
STL	100189831	124.58	3	116.55	93.55	132.97	106.74
STL	100191373	123.46	3	113.43	91.88	128.30	103.92
STL	100191510	127.28	3	124.30	97.66	136.27	107.06
STL	100195501	134.83	3	127.53	94.58	137.82	102.22
STL	100196142	134.17	3	124.44	92.75	137.15	102.22
	Averages:			133.54	97.59	141.99	103.78

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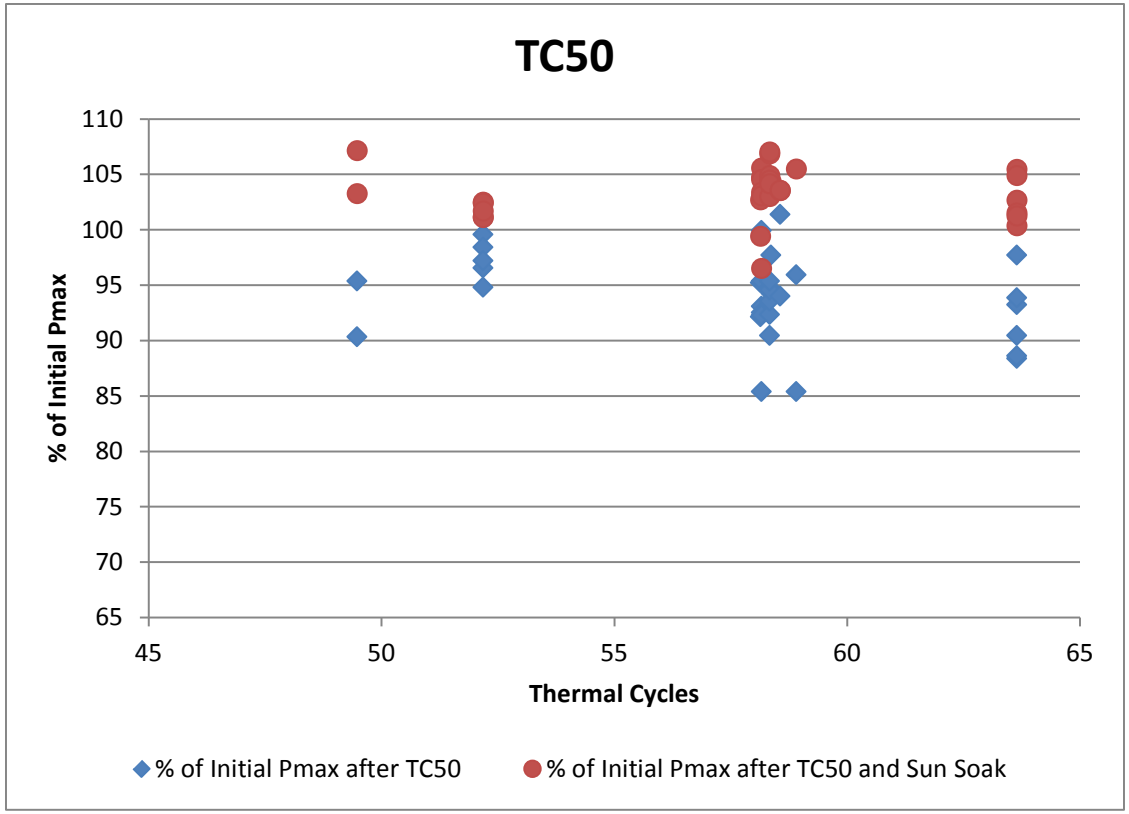
TC50 Recovery



Module Type	SN	Initial Pmax	Actual # of cycles for TC50	Pmax after TC50 Chamber	% of Initial Pmax after TC50	Pmax after TC50 Sun Soak	% of Initial Pmax after TC50 and Sun Soak
STL	100108521	133.73	58	133.65	99.94	140.07	104.74
STL	100109551	132.20	58	123.07	93.09	139.56	105.57
STO	100125805	131.54	58	125.28	95.24	135.06	102.68
STL	100125967	132.40	58	122.02	92.16	131.61	99.41
STO	100137292	143.60	58	122.63	85.40	138.58	96.50
STO	100137464	145.47	58	138.76	95.39	152.06	104.54
STO	100142411	141.36	58	130.80	92.53	146.14	103.38
STO	100142414	140.88	58	130.01	92.28	145.16	103.04
STO	100149666	143.66	58	135.43	94.28	149.92	104.36
STO	100149707	143.72	58	140.44	97.72	149.79	104.22
STO	100150941	138.17	58	125.00	90.47	142.30	102.99
STO	100150945	138.56	58	127.96	92.35	145.33	104.89
STO	100152008	135.43	58	126.73	93.57	141.50	104.48
STO	100152022	134.06	58	127.09	94.81	139.62	104.15
STO	100154974	126.93	58	120.04	94.57	135.59	106.82
STO	100155009	134.96	58	128.72	95.38	144.44	107.03
STO	100159103	140.56	59	134.85	95.94	148.24	105.46
STO	100159572	124.14	59	105.99	85.38	138.42	111.51
STL	100163602	142.60	64	126.04	88.39	146.41	102.67
STO	100164193	143.54	64	133.82	93.23	145.69	101.50
STO	100164202	143.30	59	134.70	94.00	148.33	103.51
STO	100164209	145.20	59	147.21	101.39	150.33	103.53
STO	100167811	138.42	49	125.03	90.33	142.93	103.26
STO	100167831	132.84	49	126.68	95.36	142.31	107.13
STO	100169362	144.64	52	139.66	96.56	146.29	101.14
STO	100169561	144.53	52	143.91	99.57	148.13	102.49
STO	100175563	143.87	52	141.58	98.41	147.30	102.39
STO	100176233	136.28	52	129.20	94.81	137.78	101.10
STO	100176306	138.38	52	134.54	97.22	140.71	101.68
STO	100180897	139.85	64	123.94	88.62	140.35	100.36
STL	100181862	124.51	64	112.61	90.44	131.30	105.45
STL	100182153	131.04	64	128.05	97.71	137.43	104.87
STO	100183735	139.02	64	130.47	93.85	140.72	101.23
	Averages:			129.57	93.95	142.71	103.58

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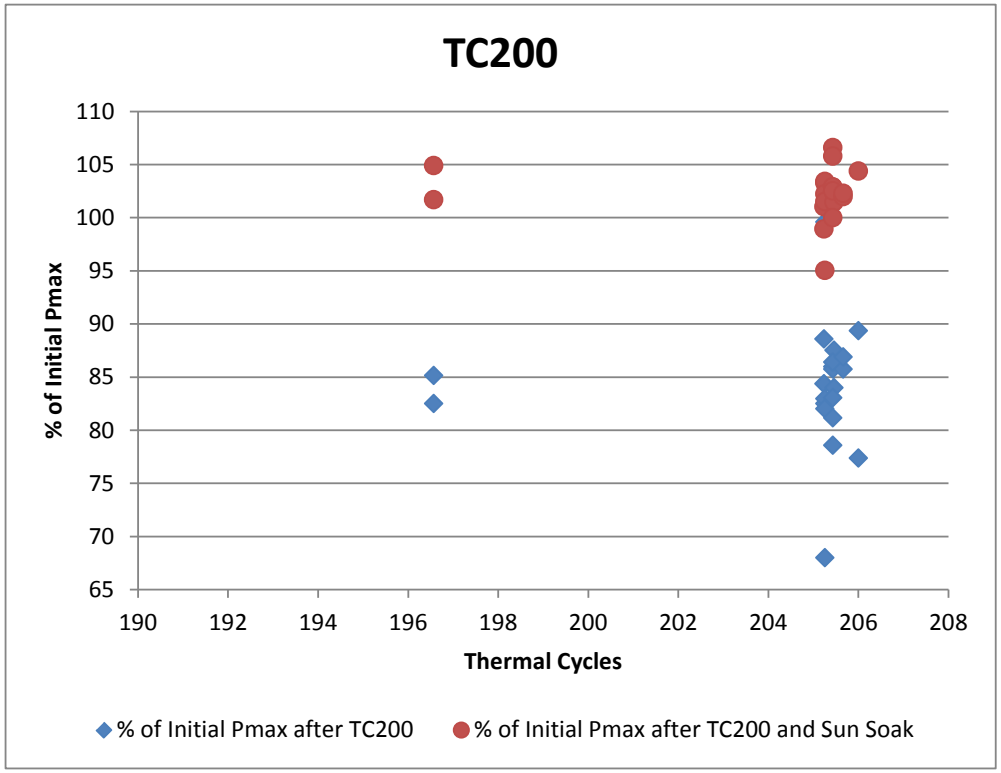
TC200 Recovery



Module Type	SN	Initial Pmax	Actual # of cycles for TC200	Pmax after TC200 Chamber	% of Initial Pmax after TC200	Pmax after TC200 Sun Soak	% of Initial Pmax after TC200 and Sun Soak
STL	100108521	133.73	205	133.17	99.58	138.08	103.26
STL	100109551	132.20	205	109.07	82.51	136.71	103.41
STO	100125805	131.54	205	116.51	88.58	132.90	101.04
STL	100125967	132.40	205	111.70	84.37	130.97	98.93
STO	100137292	143.60	205	97.66	68.01	136.48	95.04
STO	100142411	141.36	205	117.29	82.97	144.50	102.22
STO	100142414	140.88	205	115.54	82.01	143.01	101.51
STO	100149666	143.66	205	120.67	83.99	147.20	102.47
STO	100149707	143.72	205	125.78	87.52	145.81	101.46
STO	100150941	138.17	205	108.59	78.59	138.17	100.00
STO	100150945	138.56	205	112.47	81.17	142.52	102.86
STO	100152008	135.43	205	112.48	83.05	139.34	102.88
STO	100152022	134.06	205	115.25	85.97	137.44	102.53
STO	100154974	126.93	205	108.83	85.74	135.30	106.59
STO	100155009	134.96	205	116.60	86.39	142.78	105.80
STO	100159103	140.56	206	125.59	89.35	146.72	104.38
STO	100159572	124.14	206	96.04	77.36	137.17	110.50
STO	100164202	143.30	206	122.88	85.75	146.13	101.98
STO	100164209	145.20	206	126.17	86.89	148.52	102.29
STO	100167811	138.42	197	117.84	85.13	140.74	101.68
STO	100167831	132.84	197	109.60	82.50	139.34	104.89
	Averages:			115.22	84.16	140.47	102.65

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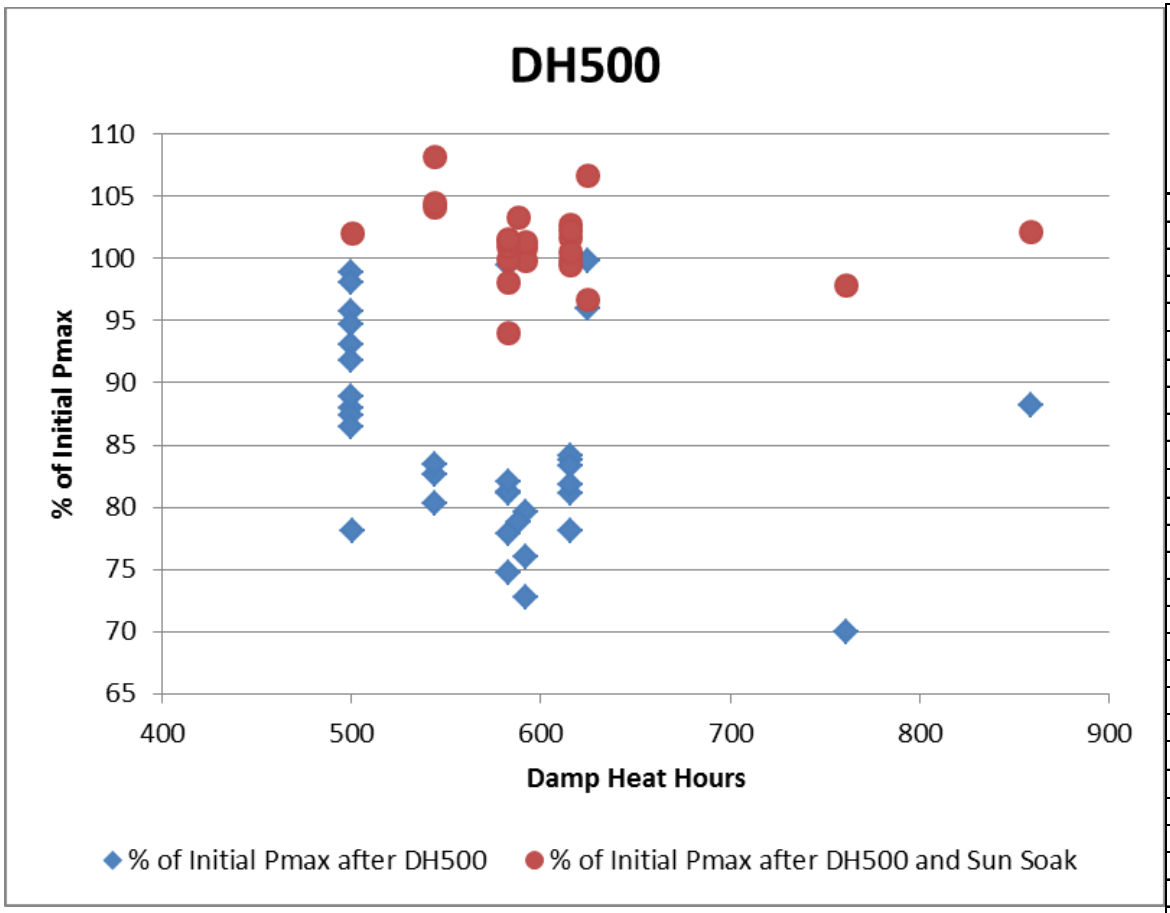
Long Term Stability-Damp Heat 500hrs.



Module Type	SN	Initial Pmax	Actual # of hours for DH500	Pmax after DH500 Chamber	% of Initial Pmax after DH500	Pmax after DH500 Sun Soak	% of Initial Pmax after DH500 and Sun Soak
STO	100091995	134.17	500	132.70	98.91	-	-
STO	100092000	136.70	500	134.00	98.02	-	-
STO	100095396	144.98	500	135.00	93.12	-	-
STO	100095402	139.91	500	123.00	87.91	-	-
STO	100095427	137.23	500	126.00	91.82	-	-
STO	100106140	145.15	500	126.86	87.40	-	-
STO	100106146	143.15	500	127.32	88.94	-	-
STO	100106154	147.85	500	127.85	86.47	-	-
STO	100106192	130.07	500	124.46	95.69	-	-
STO	100106194	127.57	500	120.76	94.66	-	-
STO	100108802	140.18	592	111.53	79.57	141.38	100.86
STO	100125945	122.24	859	107.74	88.14	124.79	102.08
STO	100137343	146.00	592	110.90	75.96	145.71	99.80
STO	100142421	137.69	592	100.12	72.72	139.46	101.29
STO	100149642	143.07	588	112.73	78.79	147.75	103.27
STO	100150953	134.49	544	107.94	80.26	140.02	104.11
STO	100151979	136.74	544	113.00	82.64	142.83	104.45
STL	100154580	151.54	625	145.52	96.03	146.42	96.62
STO	100154969	135.02	544	112.68	83.45	145.97	108.11
STO	100159464	139.44	625	139.15	99.79	148.76	106.69
STO	100163593	141.72	500	110.69	78.10	144.64	102.06
STO	100163933	144.54	616	121.12	83.79	148.50	102.74
STO	100163937	144.99	616	121.97	84.13	147.39	101.65
STO	100167805	140.51	761	98.39	70.02	137.44	97.82
STO	100169482	144.68	583	112.71	77.90	144.61	99.95
STO	100171817	134.30	583	100.32	74.70	131.69	98.06
STO	100175553	140.43	583	113.89	81.10	141.72	100.92
STO	100175555	138.41	583	112.45	81.24	130.07	93.98
STO	100176206	133.02	583	109.16	82.07	134.92	101.43
STO	100176225	136.18	583	135.44	99.46	138.29	101.55
STL	100182205	148.00	616	120.03	81.10	147.75	99.83
STL	100182414	138.86	616	108.50	78.14	138.10	99.46
STO	100183729	139.33	616	116.12	83.35	140.09	100.55
STO	100183736	139.72	616	114.33	81.83	142.90	102.28
	Averages:			118.66	85.21	141.30	101.23

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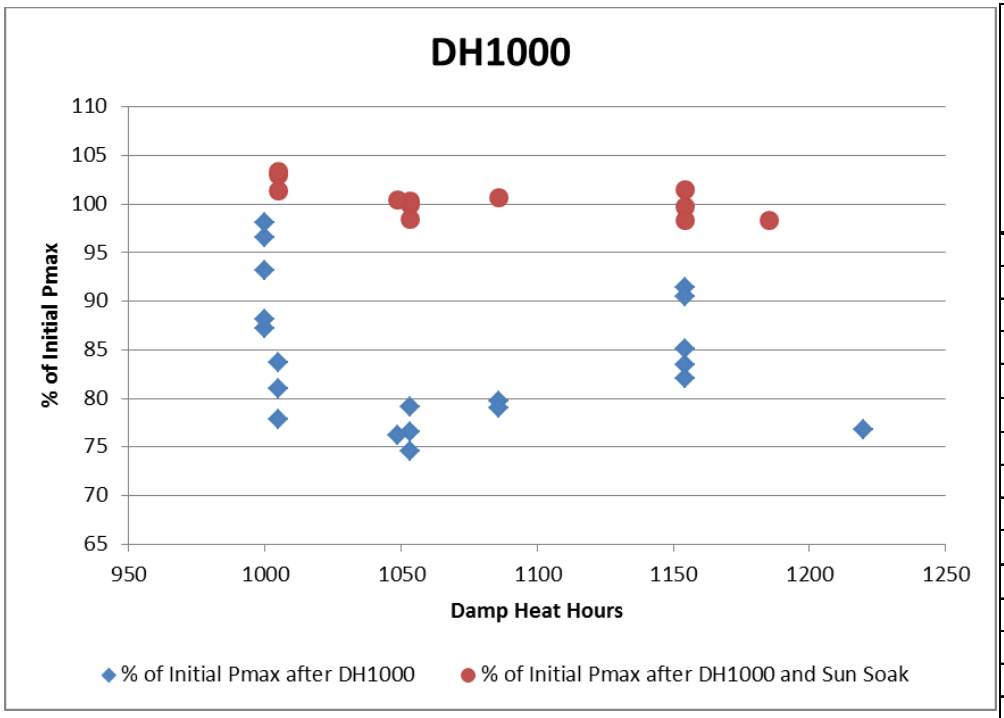
Long Term Stability-Damp Heat 1000hrs.



Module Type	SN	Initial Pmax	Actual # of hours for DH1000	Pmax after DH1000 Chamber	% of Initial Pmax after DH1000	Pmax after DH1000 Sun Soak	% of Initial Pmax after DH1000 and Sun Soak
STO	100091995	134.172	1000	131.64	98.11	-	-
STO	100092000	136.7	1000	132.00	96.56	-	-
STO	100095396	144.98	1000	135.00	93.12	-	-
STO	100095402	139.909	1000	122.00	87.20	-	-
STO	100095427	137.228	1000	121.00	88.17	-	-
STO	100106140	145.145	1154	121.22	83.51	144.79	99.75
STO	100106146	143.15	1154	121.73	85.04	145.19	101.42
STO	100106154	147.852	1154	121.36	82.08	145.34	98.30
STO	100106192	130.066	1154	118.93	91.44	144.37	111.00
STO	100106194	127.57	1154	115.42	90.48	141.21	110.69
STO	100108802	140.177	1053	110.98	79.17	140.06	99.92
STL	100126768	136.807	1220	105.04	76.78	-	-
STO	100137343	145.999	1053	111.82	76.59	143.77	98.47
STO	100142421	137.685	1053	102.58	74.51	138.10	100.30
STO	100149642	143.07	1049	108.99	76.18	143.71	100.45
STO	100150953	134.49	1005	104.65	77.81	136.31	101.36
STO	100151979	136.742	1005	114.47	83.71	140.82	102.98
STL	100154580	151.539	1086	120.78	79.70	-	-
STO	100154969	135.022	1005	109.32	80.97	139.47	103.30
STO	100159464	139.436	1086	110.17	79.01	140.31	100.62
STO	100163593	141.723	1185	91.99	64.90	139.30	98.29
	Averages:			115.77	83.10	141.62	101.92

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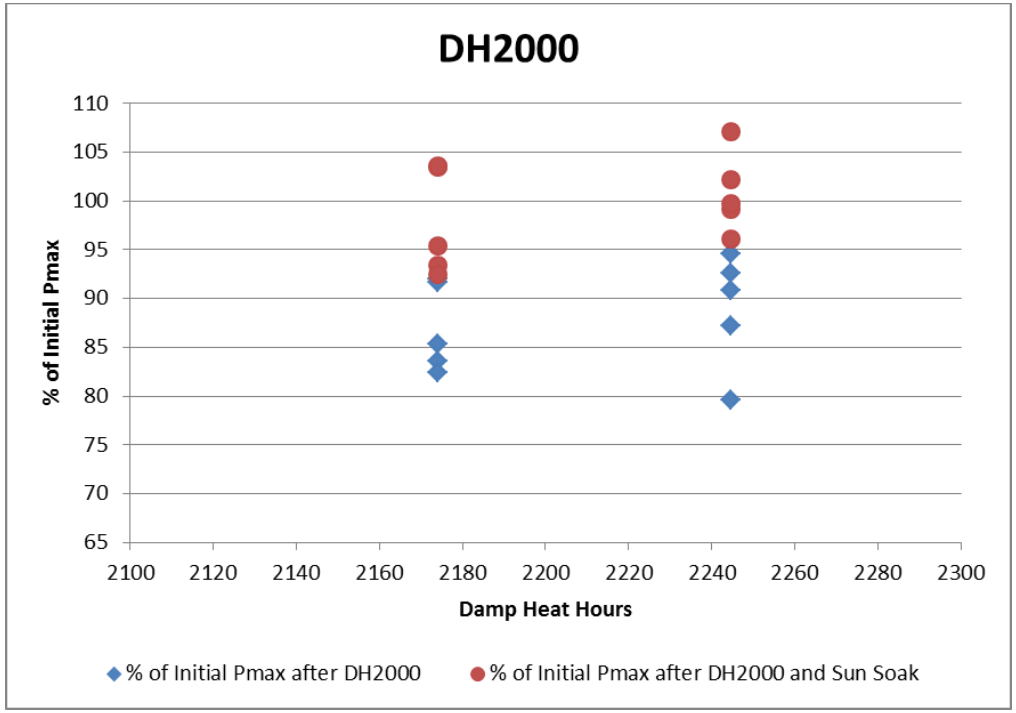
Long Term Stability-Damp Heat 2000hrs.



Module Type	SN	Initial Pmax	Actual # of hours for DH2000	Pmax after DH2000 Chamber	% of Initial Pmax after DH2000	Pmax after DH2000 Sun Soak	% of Initial Pmax after DH2000 and Sun Soak
STO	100091995	134.17	2245	106.82	79.61	143.71	107.11
STO	100092000	136.70	2245	129.34	94.61	139.74	102.22
STO	100095396	144.98	2245	134.29	92.63	143.66	99.09
STO	100095402	139.91	2245	127.04	90.80	139.53	99.73
STO	100095427	137.23	2245	119.70	87.23	131.86	96.09
STO	100106140	145.15	2174	121.35	83.61	135.55	93.39
STO	100106146	143.15	2174	122.23	85.38	136.55	95.39
STO	100106154	147.85	2174	121.91	82.46	136.75	92.49
STO	100106192	130.07	2174	119.65	91.99	134.54	103.44
STO	100106194	127.57	2174	116.85	91.60	132.21	103.64
	Averages:			121.92	87.99	137.41	99.26

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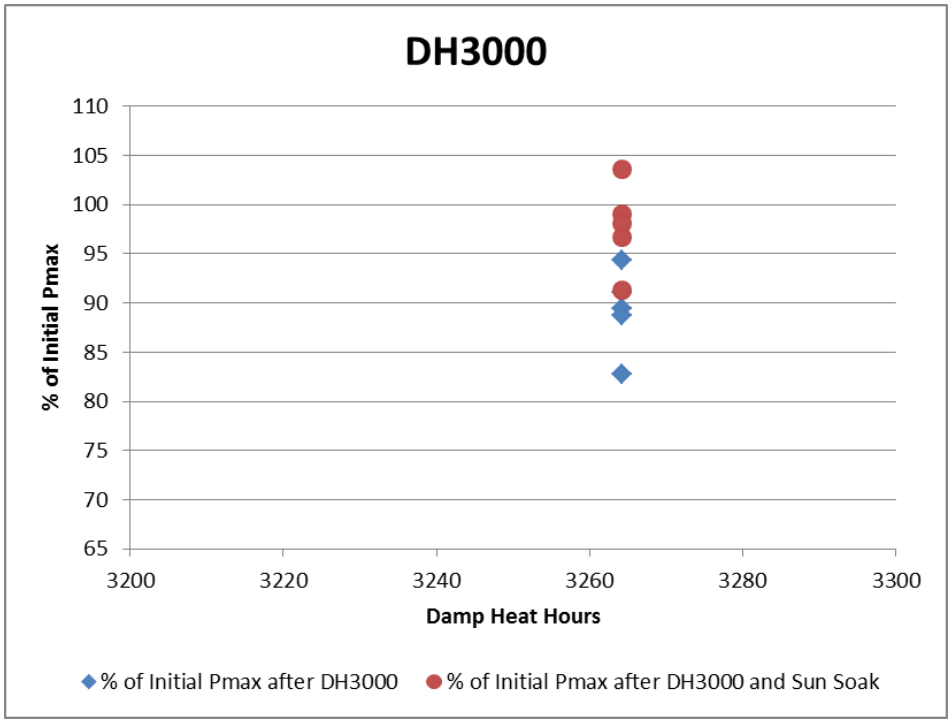
Long Term Stability-Damp Heat 3000hrs.



Module Type	SN	Initial Pmax	Actual # of hours for DH3000	Pmax after DH3000 Chamber	% of Initial Pmax after DH3000	Pmax after DH3000 Sun Soak	% of Initial Pmax after DH3000 and Sun Soak
STO	100091995	134.17	3264	126.57	94.34	138.98	103.58
STO	100092000	136.70	3264	124.50	91.08	135.44	99.07
STO	100095396	144.98	3264	129.69	89.46	140.15	96.67
STO	100095402	139.91	3264	124.19	88.77	137.20	98.06
STO	100095427	137.23	3264	113.58	82.76	125.36	91.35
	Averages:			123.71	89.28	135.42	97.75

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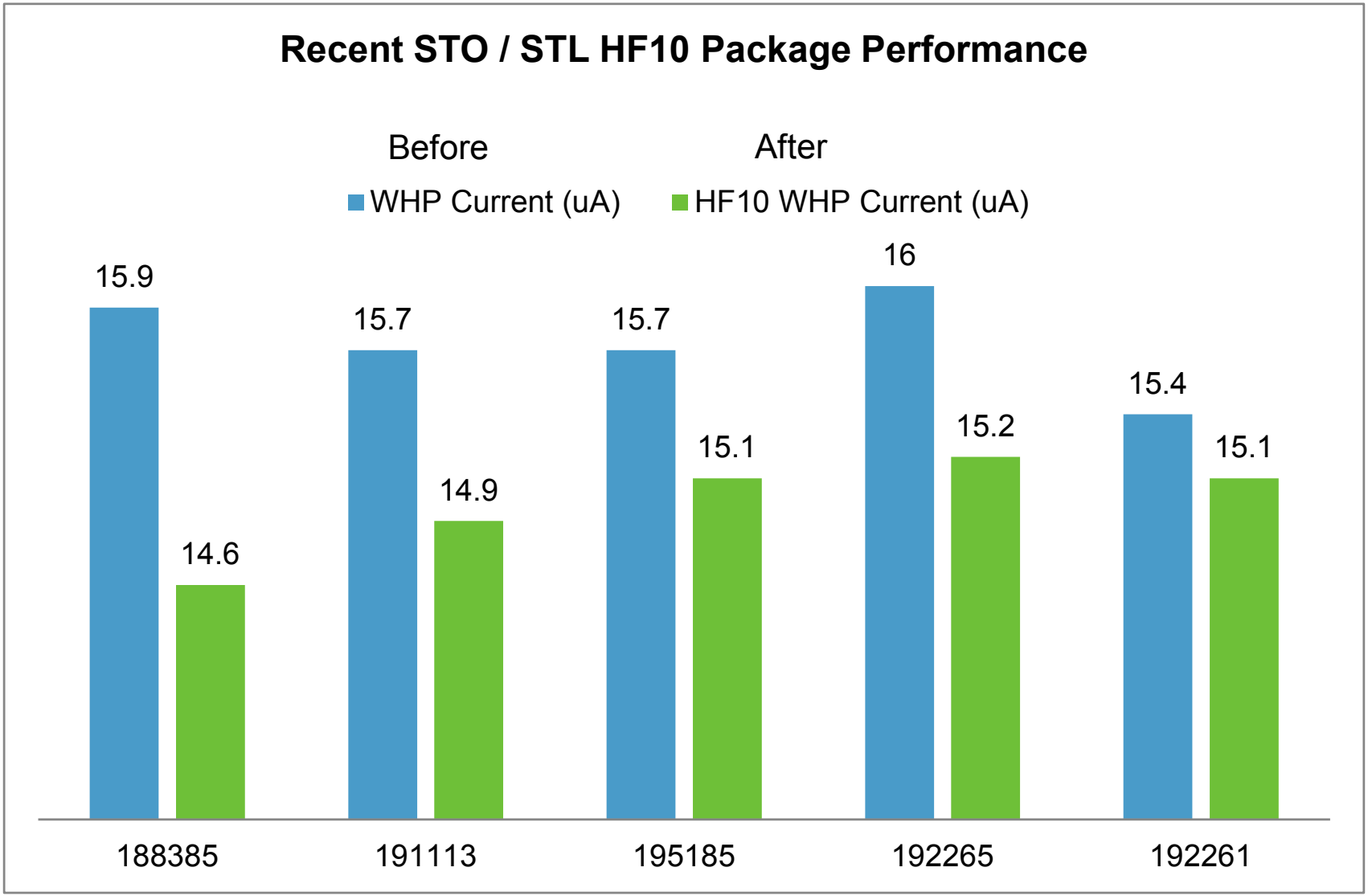
Recent HF 10 Testing



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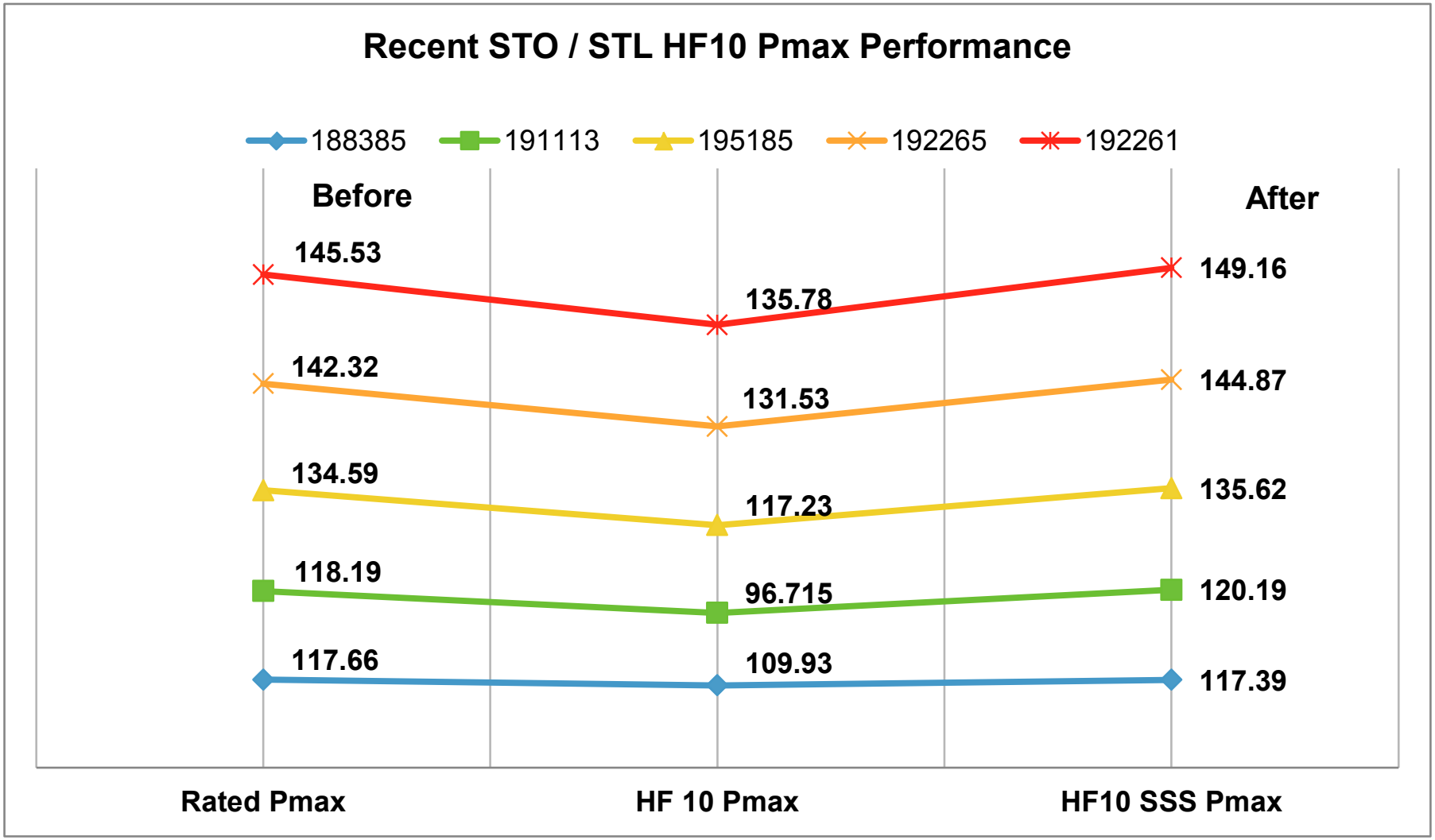
P-max Before & After HF10



All modules recovered to ≥ Production Line Measurements

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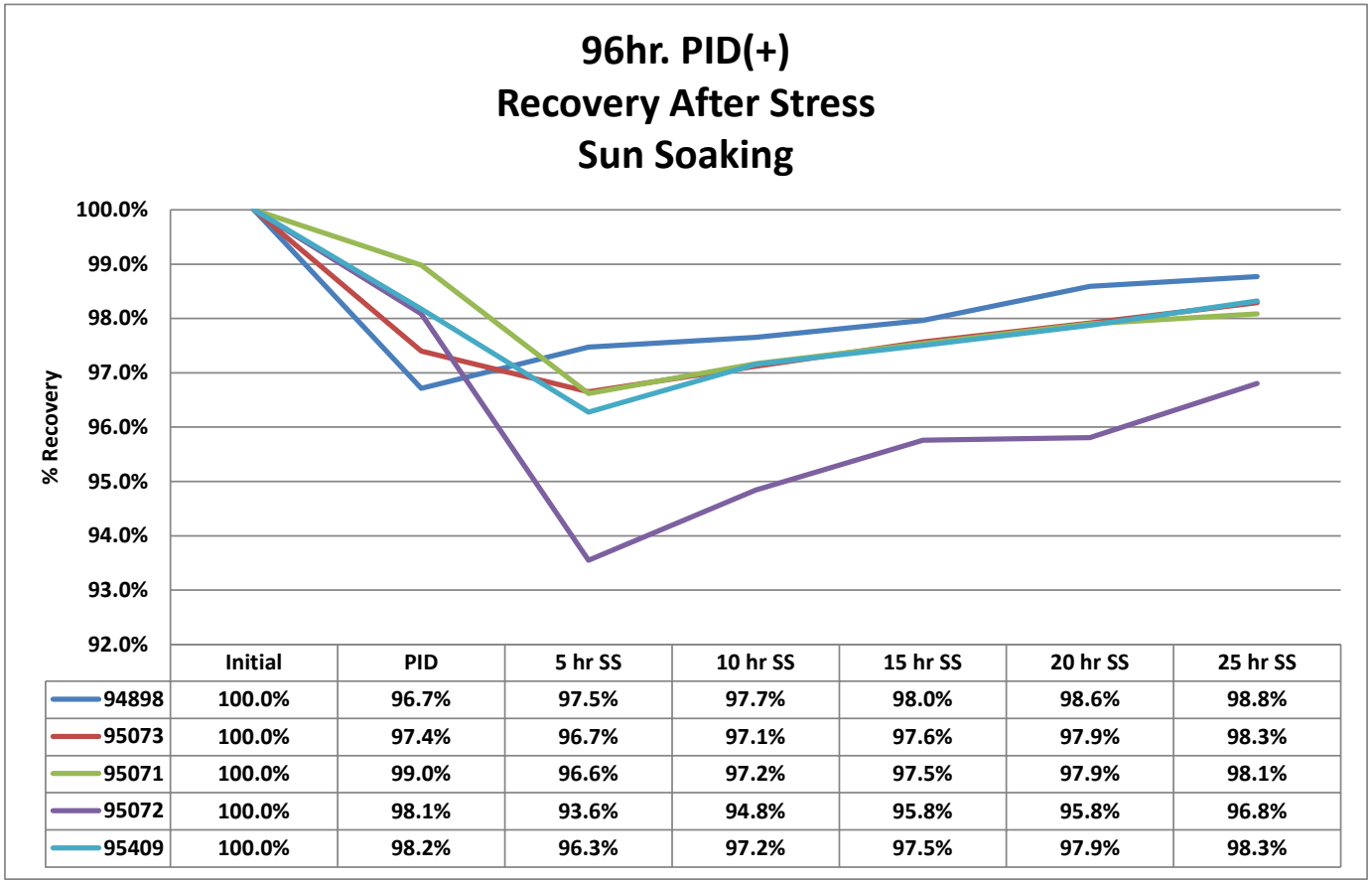
PID (+) (85^{0}C /85% rH) (Class "A" Rating)



	Initial	PID	5 hr SS	10 hr SS	15 hr SS	20 hr SS	25 hr SS
94898	100.0%	96.7%	97.5%	97.7%	98.0%	98.6%	98.8%
95073	100.0%	97.4%	96.7%	97.1%	97.6%	97.9%	98.3%
95071	100.0%	99.0%	96.6%	97.2%	97.5%	97.9%	98.1%
95072	100.0%	98.1%	93.6%	94.8%	95.8%	95.8%	96.8%
95409	100.0%	98.2%	96.3%	97.2%	97.5%	97.9%	98.3%

Recent Testing -Sun Soak to 100% Recovery = 31kWh / m^2

SN	Before PID+ Pmax	Post-PID+ Pmax	Post SS Pmax	kWh/m2 for SS	% of Initial Pmax
100166005	141	110	141	30.97	100.00
100166007	143	114	143	30.97	100.00
100166008	144	112	145	30.97	100.69
1001660010	142	116	143	30.97	100.70

Power drop & recovery are equivalent to dark heat recovery transient

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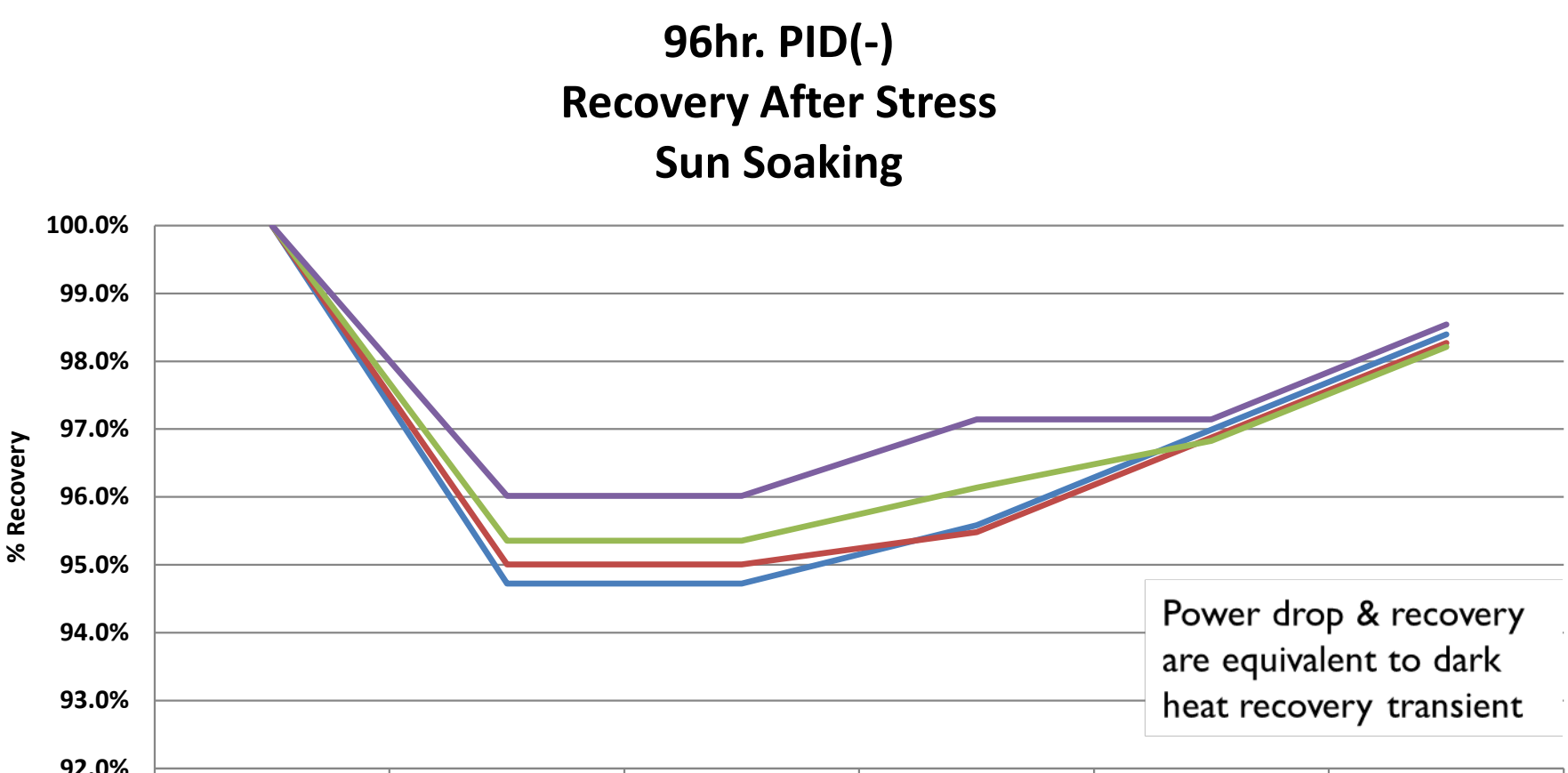
PID (-) (85^{0}C /85% rH) (Class "A" Rating)



	Initial	PID	5 hr SS	10 hr SS	15 hr SS	20 hr SS
95413	100.0%	94.7%	94.7%	95.6%	97.0%	98.4%
94983	100.0%	95.0%	95.0%	95.5%	96.9%	98.3%
95069	100.0%	95.4%	95.4%	96.1%	96.8%	98.2%
94894	100.0%	96.0%	96.0%	97.1%	97.1%	98.5%

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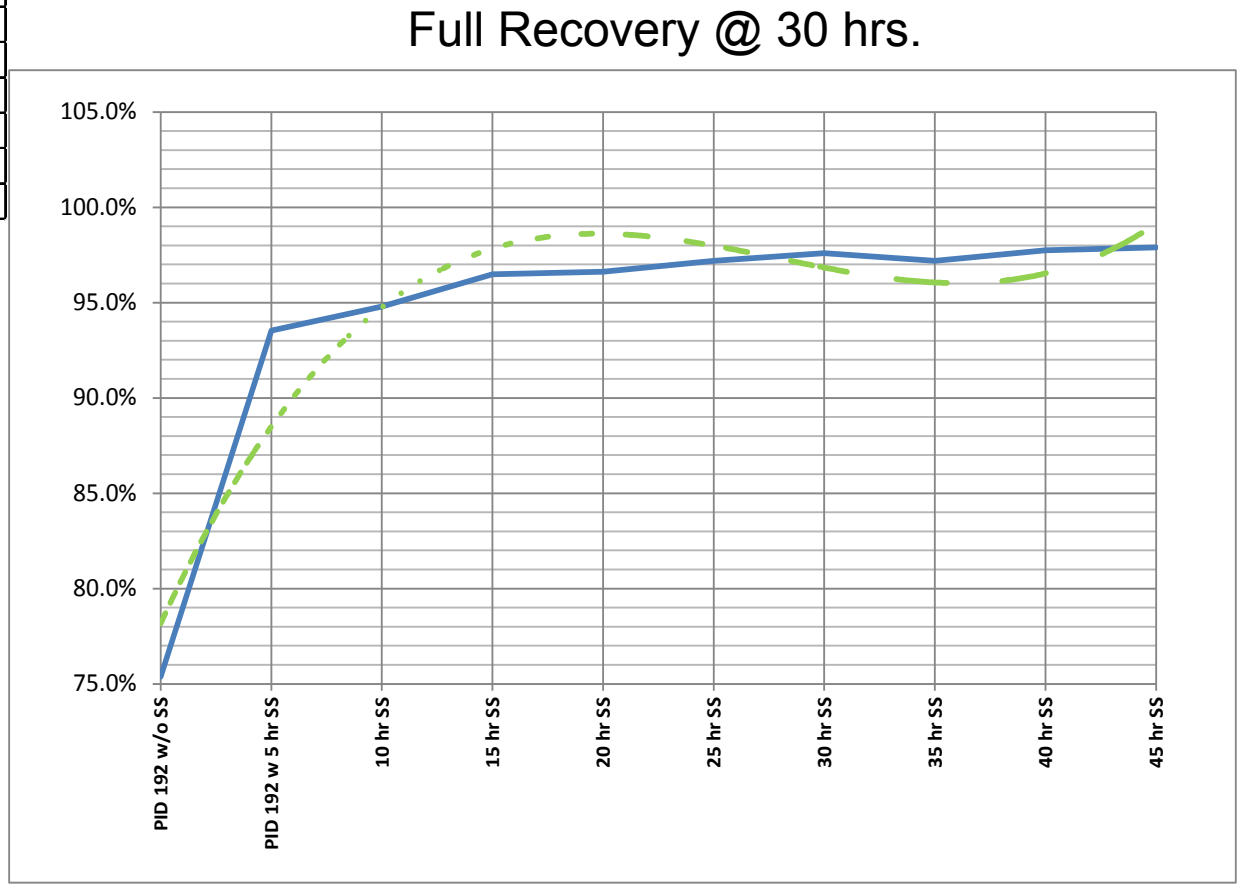
PID Testing (-1000V / 192hrs, 85/85) SS recovery

Condition	Avg	Median	Min	Max
SS	97.2%	97.2%	96.5%	97.9%
5 hr SS	100.8%	100.0%	100.0%	104.2%
PID 192 w/o SS	75.4%	74.6%	72.3%	78.8%
PID 192 w 5 hr SS	93.5%	92.9%	92.3%	97.2%
10 hr SS	94.8%	94.4%	94.3%	95.8%
15 hr SS	96.5%	97.2%	94.3%	97.2%
20 hr SS	96.6%	96.5%	96.5%	97.2%
25 hr SS	97.2%	97.2%	97.2%	97.2%
30 hr SS	97.6%	97.6%	97.2%	98.0%
35 hr SS	97.2%	97.2%	96.5%	97.9%
40 hr SS	97.8%	97.9%	97.2%	97.9%
45 hr SS	97.9%	97.9%	97.9%	97.9%



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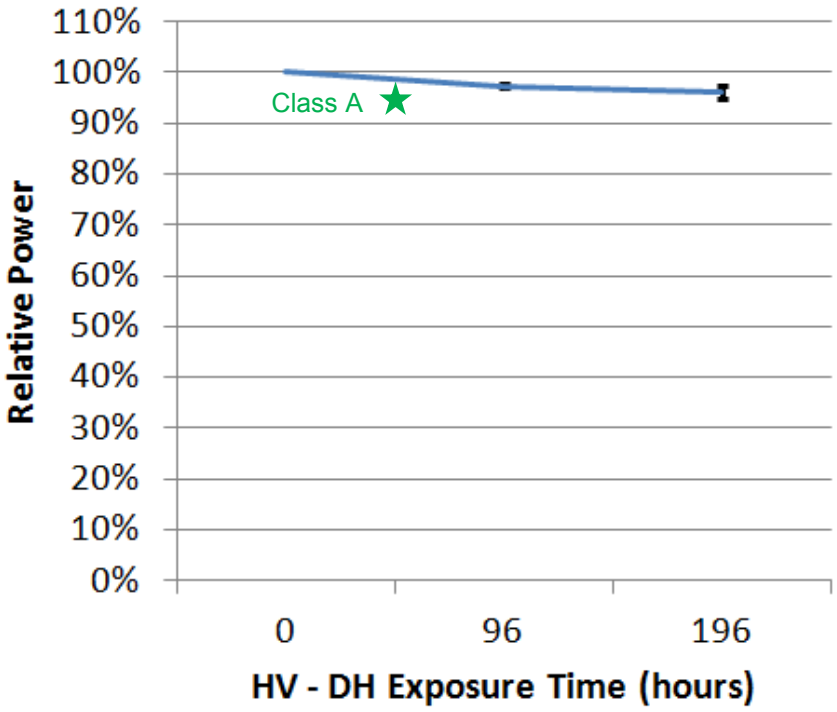
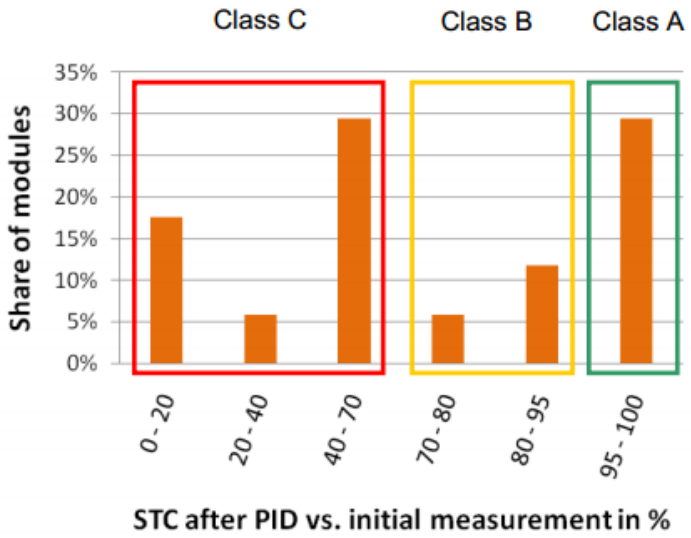
Stion – Class A PID Rating Equivalent

PI- Berlin Ratings

- Class A → ΔP <5%
- Class B → 5% < ΔP < 30%
- Class C → ΔP > 30%



- PI Berlin PID Test Procedure
  - 85%RH, 85°C, -1000 V, 48 hours
  - 2 modules
- Stion Test
  - 85%RH, 85°C, -1000 V, 196 hours
  - 5 modules



From Pi Berlin Test. http://www.pi-berlin.com/images/pdf/investorsday/2011/6-PID-Tests.pdf

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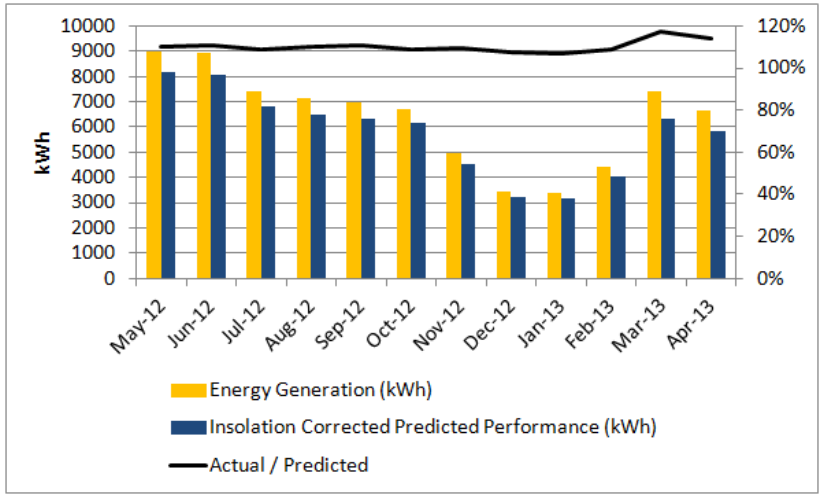
World Class Quality, Reliability & System Performance

- Industry Participation
  - National Renewable Energy Laboratory – Boulder, Colorado (NREL)
  - Photovoltaic Manufacturing Consortium- SUNY, Albany, New York (PVMC)
  - Colorado State University – Photovoltaic Testing Laboratory, Denver, Colorado (CSU)
  - US Department of Energy
- Outdoor Arrays with Performance Monitoring
  - NREL – Boulder, Co – Long Term, installed 2006
  - PVMC- Albany, New York Long Term installed 2010
  - HMS 50KW Carport Array –Hattiesburg, Mississippi
  - US Continental 228KW Array- Corona, California
  - Mississippi Power 4.86KW Array- Gulfport Mississippi
- All arrays have stable performance since installation
  - Data Available



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Thank You

Q & A

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Extrapolating Accelerated UV Weathering Data: Perspective From PVQAT Task Group 5

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NREL PV Module Reliability Workshop
Ballroom Salons A-D, Denver Marriott West, Golden, CO
13:45-14:15 Tues, 2015/2/24

- This presentation contains no proprietary information -

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Overview

- Motivation and goals of TG5.
- E_a interlaboratory experiment for encapsulation (present US-led effort).

  Encapsulation discoloration experiment:
  - Test description
  - Transmittance results (appearance, spectral τ, solar-weighted τ)
  - Effect of specimen temperature (accelerated aging)
  - Effect of light sources (Xe vs. UVA-340 fluorescent)

  Encapsulation attachment strength (CST):
  - Test description
  - Early stress and resilience results

- Application and timeline of TG5 activities.

Not covered today:

- Edge seal attachment strength (part of E_a experiment)
- SoPhia round-robin for backsheet (present Europe effort)
- Other TG5 efforts (China and Japan)

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

- IEC qualification tests (61215, 61646, 61730-2) presently prescribe up to 137 days field equivalent (IEC 60904-3 AM 1.5) UV-B dose. This is << 25 years!
- **Goal**: develop UV- and temperature-facilitated test protocol(s) that may be used to compare PV materials, components, and modules relative to a field deployment.

Core Activities:

1: Consider weathering literature and climate meteorology (*location-dependent information*).
   e.g., known benchmark locations…Miami, FL; Phoenix, AZ
2: Leverage existing standards, including other industries.
   - summary exists from Kurt Scott *et. al.*
3: Improve understanding of existing PV UV tests.
4: Improve understanding of module durability.
   4-1 Collect information about field failure modes.
   e.g., the literature, site inspections
   4-2 Confirm appropriate models for UV aging.
5: Consider suitable UV sources.
   - summary of *module* capable equipment from David Burns *et. al.*
6: **Generate test procedure for accelerated UV aging.**
7: Perform laboratory verification of proposed test standard/failure mode.
   - mini-module study (Japan), SoPhia round-robin (Europe), E_a interlaboratory study (US)

Motivation for the E_a Interlaboratory Experiment (TG5 US)

- Knowing E_a (for rate of change in a characteristic) is critical to prescribing and interpreting a *UV- and temperature*-mediated test.
- Unfortunately, E_a is not known for the UV degradation of common PV materials.

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

The modified Arrhenius equation

Critical unknowns

(Goals for the interlaboratory experiment):

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 specimens aged by different sources, *i.e.*, Xe-arc, UVA-340, metal-halide.
   Is visible light required in addition to UV ?

The Materials Used in the E_a Experiment

- Discoloration of encapsulation has been studied in the literature:
  - We have a sense of the general rate of degradation.
  - We have a sense of the sorts of formulations used (historical and contemporary).
- 6 Materials examined in interlaboratory study:
  - Example: compare peroxide used for cross-linking.
  - Example: compare type or use of UVA.
  - A TPU formulation is chosen as a known bad material.

INGREDIENT	DESCRIPTION	MAKER	MASS {g}					
Elvax PV1400	EVA resin, 33 wt% Vac	E. I. du Pont	100	100	100	100	100	N/A
Z6030	silane primer, gama-methacroyloxy propyl trimethoxysilane	Dow-Corning Corp.	0.25	0.25	0.25	0.25	0.25	?
TBEC	curing agent, OO-Tertbutyl-O-(2-ethyl-hexyl)-peroxycarbonate	Arkema Inc.	N/A	1.5	1.5	1.5	1.5	?
Lupersol 101	curing agent, 2,5-Bis(tert-butylperoxy)-2,5-dimethylhexane	Arkema Inc.	1.5	N/A	N/A	N/A	N/A	?
Tinuvin 329	UV absorber (UVA), benzotriazole type	BASF Corp.	N/A	N/A	N/A	0.3	N/A	?
Cyasorb 531	UVA, benzophenone type	Cytech Industries Inc.	0.3	0.3	0.3	N/A	N/A	?
Tinuvin 770	hindered amine light stabilizer (HALS)	BASF Corp.	0.1	0.1	0.1	N/A	N/A	?
Tinuvin 123	non-basic aminoether-hindered amine light stabilizer (NOR-HALS)	BASF Corp.	N/A	N/A	N/A	0.1	0.1	?
Naugard P	anti-oxidant (AO), phosphite containing	Chemtura Corp.	0.2	0.2	N/A	N/A	N/A	?
		Designation (Note)	EVA A (known bad, "slow cure")	EVA B (improved, "fast cure")	EVA C	EVA D (known good)	EVA E (modern, no UVA)	TPU (known bad)

Encapsulation materials being compared in the transmittance (discoloration) experiment.
The encapsulation adhesion experiment examines Material B only.

Interlaboratory Participation Enables a Wider Range of Study

- Indoor aging is expensive. No one institution has all the resources to apply the complete set of factors we would like to examine.
- Discoloration and adhesion will be studied at (12) -*volunteer*- institutions.
- Example: compare similar instrument makes and models (*e.g.*, Ci5000 & QSUN XE3).
- This overcomes the difficulty of limited availability of aging equipment.

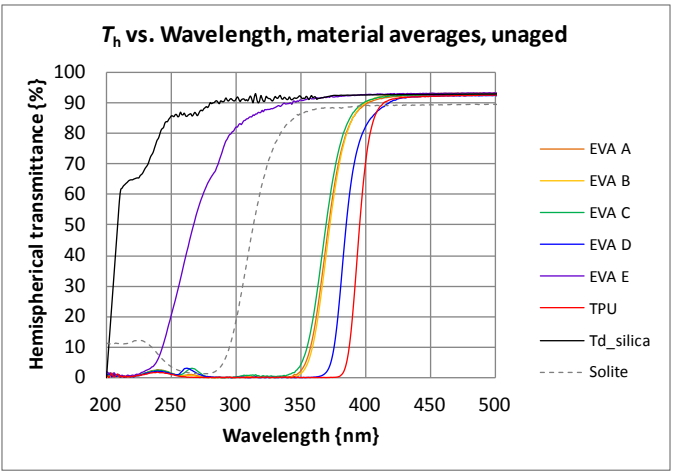
LIGHT SOURCE, FILTER	Xe Arc (right-light/cira filter) or (Suga-Q/#295/Ircut)					Xe Arc (right-light/cira filter)	UVA 340 fluorescent (no filter)		UVA 340 fluorescent (no filter)	Metal-Halide	No light				field deployment (outdoors)
UV LIGHT INTENSITY	NOMINAL (102 W•m^{-2} for 300≤λ≤400)					STANDARD (0.8 W•m-2@ 340 nm)	NOMINAL (1.0 W•m^{-2}@ 340 nm)		NOMINAL (~150 W•m^{-2} for 300≤λ≤400)		0 W•m^{-2}				
CHAMBER RELATIVE HUMIDITY (%)	30 ("low")			50 ("high")		20 ("low")	~7% ("very low")		60 ("high")	30 ("low")	30 ("low")				ambient
CHAMBER TEMEPRATURE (°C)	40	60	80	40	60	80	40	60	60→30→40	60	40	60		80	ambient
PARTICIPANT (INSTRUMENT MODEL)	3M (Ci5000)	3M (Ci5000)	3M (Ci5000)	Mitsui (SX120)	NREL (Ci5000)	Fraunhofer CSE (Ci4000)	QLAB (QUV)	QLAB (QUV)	Fraunhofer ISE (custom)	EPFL	NIST custom)	NIST (custom)		NIST (custom)	ATLAS (EMMA in Phoenix)
		QLAB (QSUN XE3)			QLAB (QSUN XE3)		ATLAS (UVTEST)	NREL (custom UV suitcase)							CWRU (5x in Cleveland)
		ATLAS (SunTest XXL)						Fraunhofer ISE (custom)							ATLAS (rack in Phoenix)
		Suga (SX75)						Suga (FDP)							ATLAS (rack in Miami)
								CWRU (QUV)@1.55 W·m-2 @ 340 nm							NREL (rack in Golden)
															KACST (rack in Riyadh)

Summary of participating laboratories and test conditions

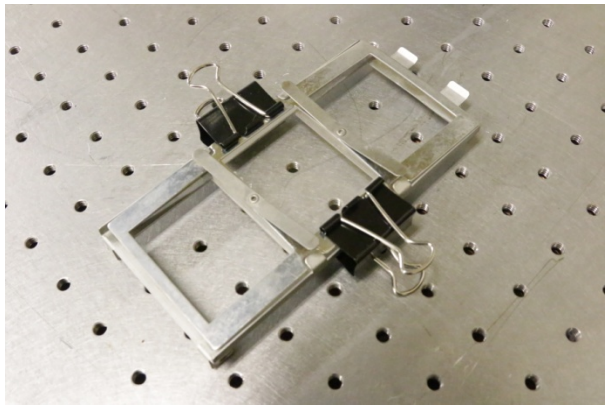
- A standard condition (60°C chamber ambient) allows a broad variety of light sources to be compared.
- Rate of degradation will be compared against field data to allow site-specific acceleration factors to be determined.
- Outdoor data will verify the validity of the indoor test.
- Separate experiment at NIST (EVA-A & EVA-B) will examine action spectrum.

Details of the E_a Methods and Experiment: Encapsulation Transmittance Test

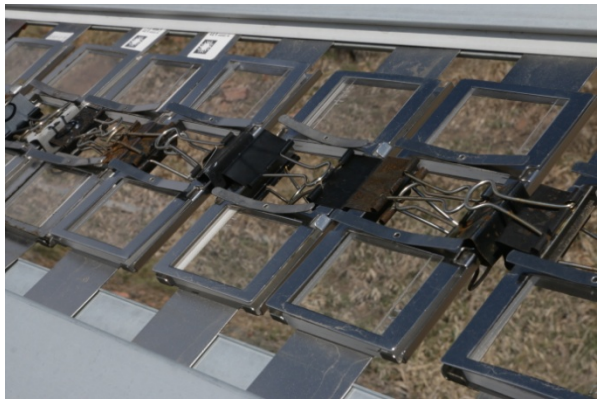
- Glass/polymer/glass coupon specimens measured using a spectrophotometer (with integrating sphere)
- Measure at specimen center (anaerobic, no O_2) and edge (aerobic)
- Analyze: solar-weighted transmittance, yellowness index, and UV cut-off wavelength.



Transmittance will be examined using silica/polymer/silica samples.



Specimen in sample holder for indoor aging at NREL.



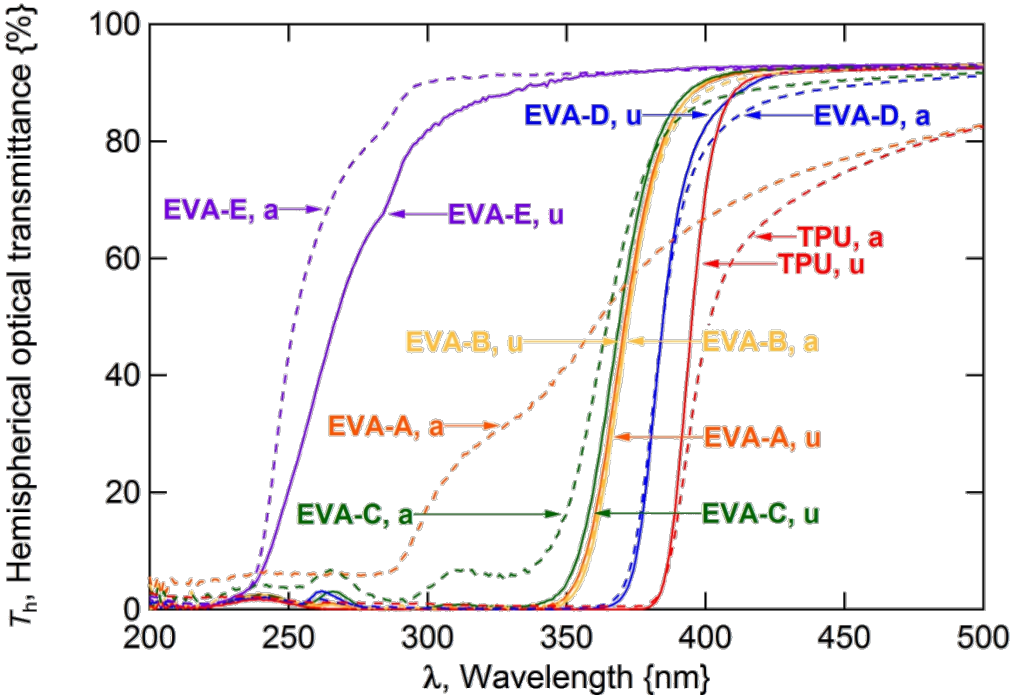
Specimens on outdoor rack, aging in Golden, CO at NREL.

User summary:

- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm)
- Size: 2” x 2”
- Quantity: 3 replicates of 6 materials (pre-conditioned), and 1 reference (not pre-conditioned)
- Aging: 0, 15, 30, 45, 60, 75, 90, 120, 150, 180 cumulative days (indoors) or 0, 1, 2, 3, 4, 5 years (outdoors)
- Measurements (non-destructive): repeatedly age and measure at each laboratory/test site

Formulation Specific Results Emerging From the E_a Experiment

Visual appearance of the UV Suitcase aged specimens at NREL at 180 days. Specimens arranged in columns for EVA-A, EVA-B, EVA-C, EVA-D, EVA-E, and TPU.



Comparison of the spectral transmittance at 180 days (dashed lines) relative to unaged specimens (solid) for the UV Suitcase (UVA-340 fluorescent) aged specimens at NREL.

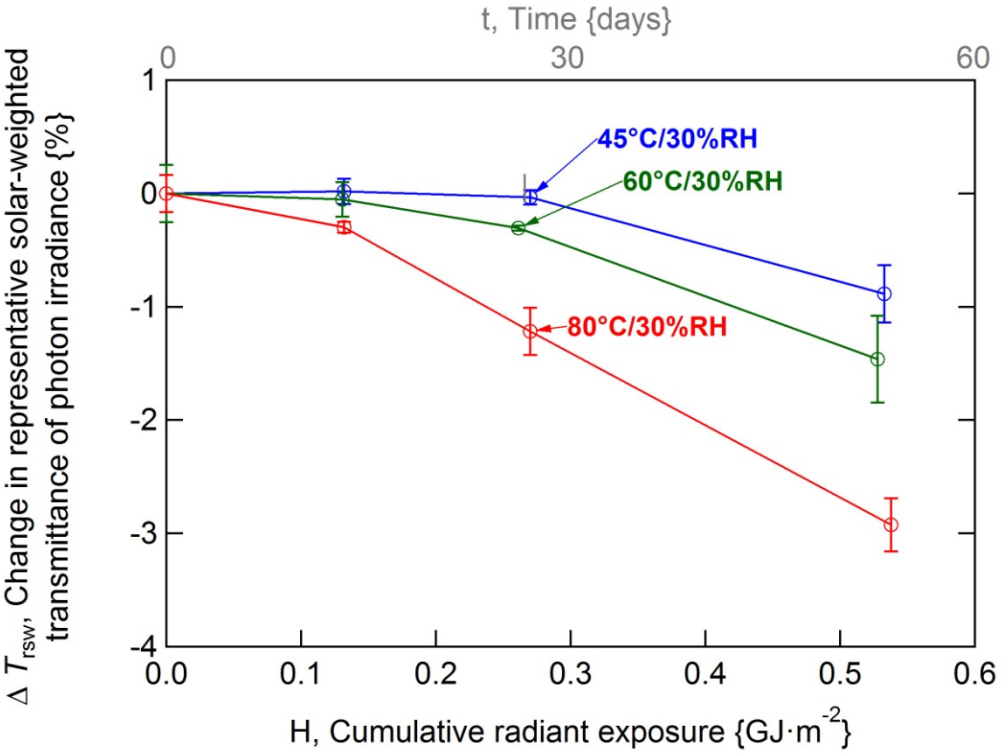
- For EVA-A, EVA-D, and TPU, a significant discoloration is observed that may be correlated to a rounding of the UV cut-off and increased yellowness.
- Result corresponds to the formation of chromophore species.

- For EVA-B, EVA-C, EVA-E, the UV cut-off wavelength is instead decreased and there is an increase in the transmittance. The transmittance is increased broadly for EVA-C.
- Result may be explained by the loss of additive(s) with age.

Effect of Temperature Stands Out in Early Comparison

- Effect of *T* examined directly at 3M: same irradiance, *RH* applied using 3 similar chambers (Ci5000 , Xe lamp with Right Light filter).

- Effect of aging is increased with temperature.
- Same trend observed for EVA-A and TPU (not shown).
- Coupling anticipated from field observation, *e.g.*, increased discoloration at local hot spots in modules.
- E_a can be determined from experiment.

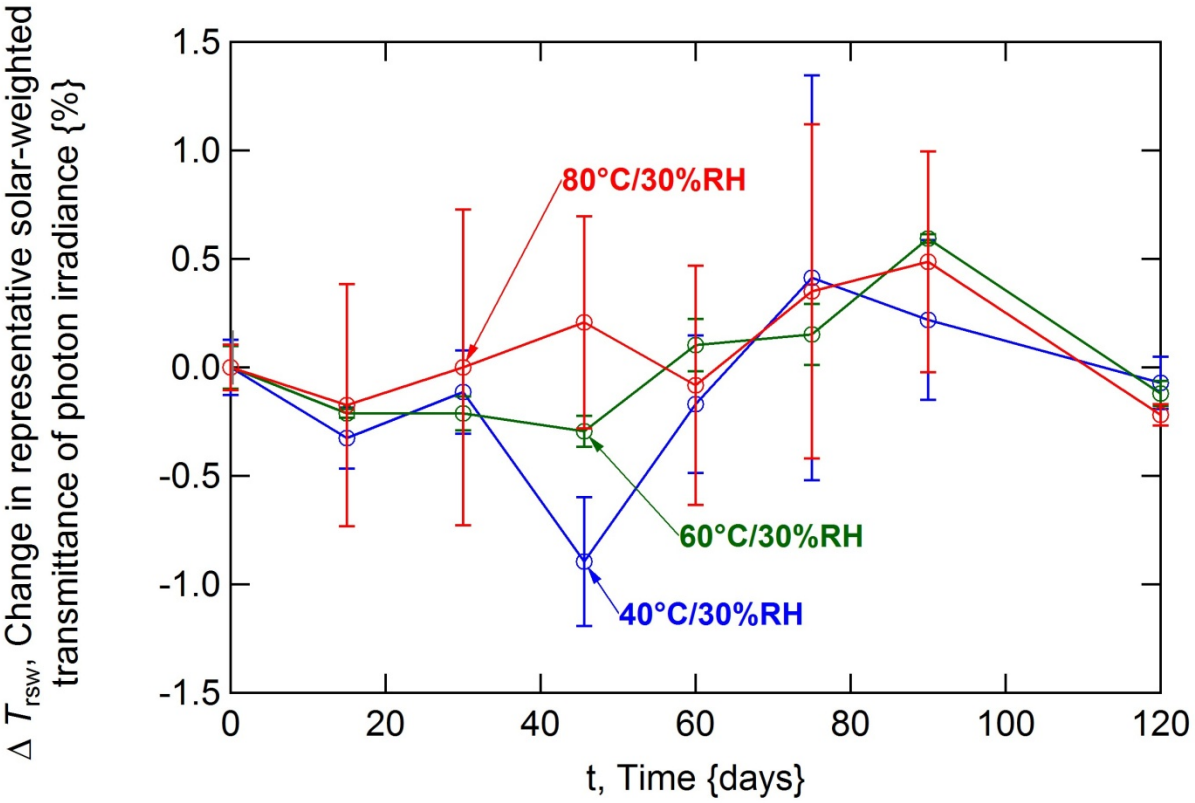


EVA-A: comparison of change in transmittance with aging temperature (aged at 3M, with Xe lamp). The default temperature and humidity conditions were applied in separate chambers.

Dark Chamber Aging: UV Facilitated Degradation

- Control experiment in environmental chambers at NIST.
- Apply default *T* and *RH*, with no UV present.

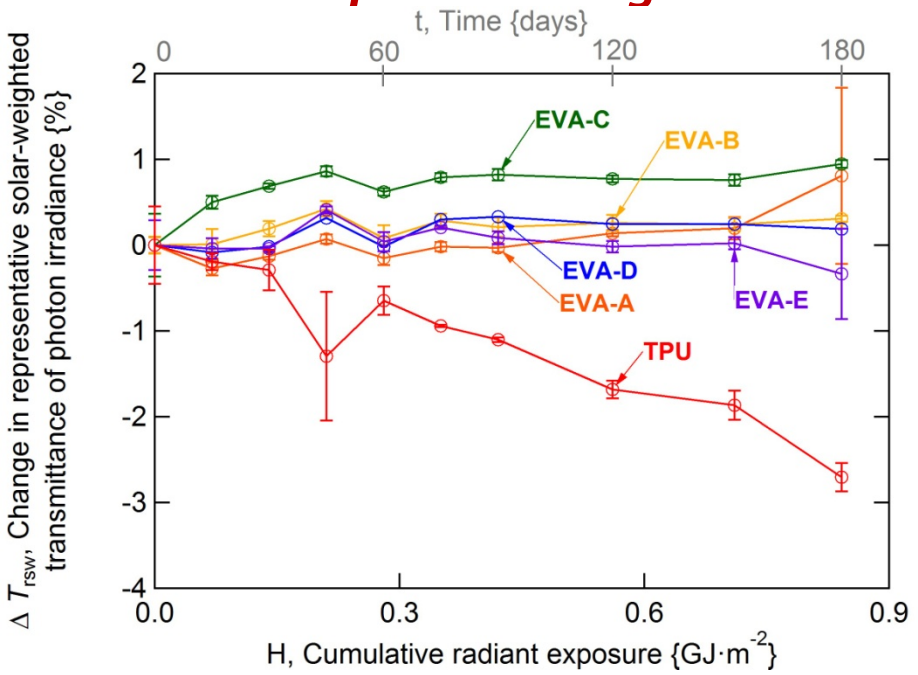
- No discoloration visually observed to date for EVA formulations.
- Some rounding of UV cut-off for EVA-E (no UVA).
- Slight discoloration observed with time for TPU at 80°C, both center and edge. (ΔYI~2).
- Implication: $\Delta\tau$ results from UV degradation.



EVA-A: comparison of change in transmittance in dark chambers (aged at NIST, with no UV) for the default temperature and humidity conditions.

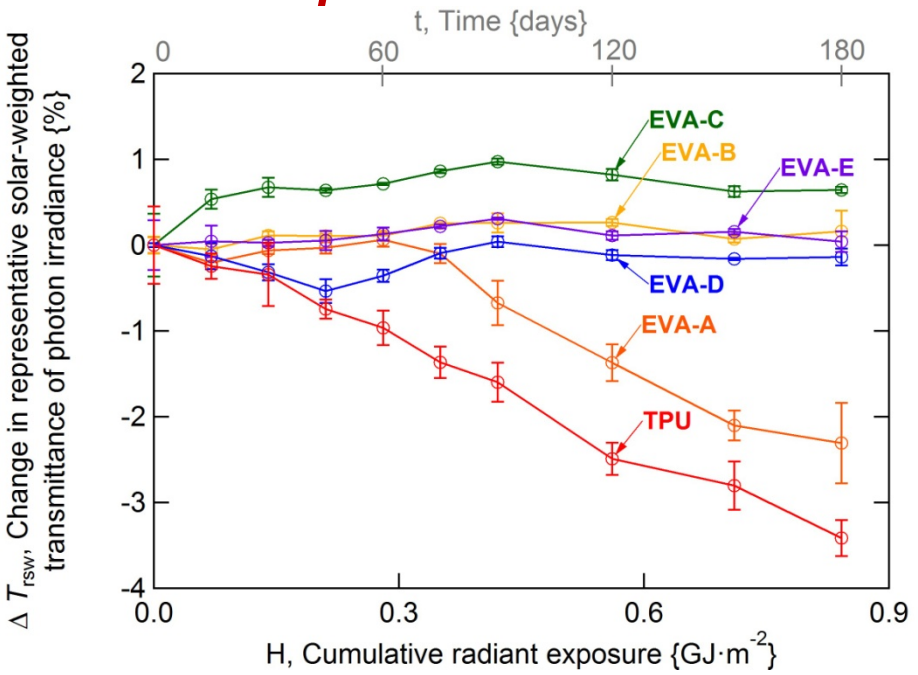
Formulation Specific Results Emerging From the E_a Experiment

Specimen Edge



Change in representative solar weighted transmittance (300≤λ≤1250 nm) for the encapsulation specimens at their center. Results shown for UV Suitcase (fluorescent) at NREL.

Specimen Center



Change in representative solar weighted transmittance (300≤λ≤1250 nm) for the encapsulation specimens at their edge. Results shown for UV Suitcase (fluorescent) at NREL.

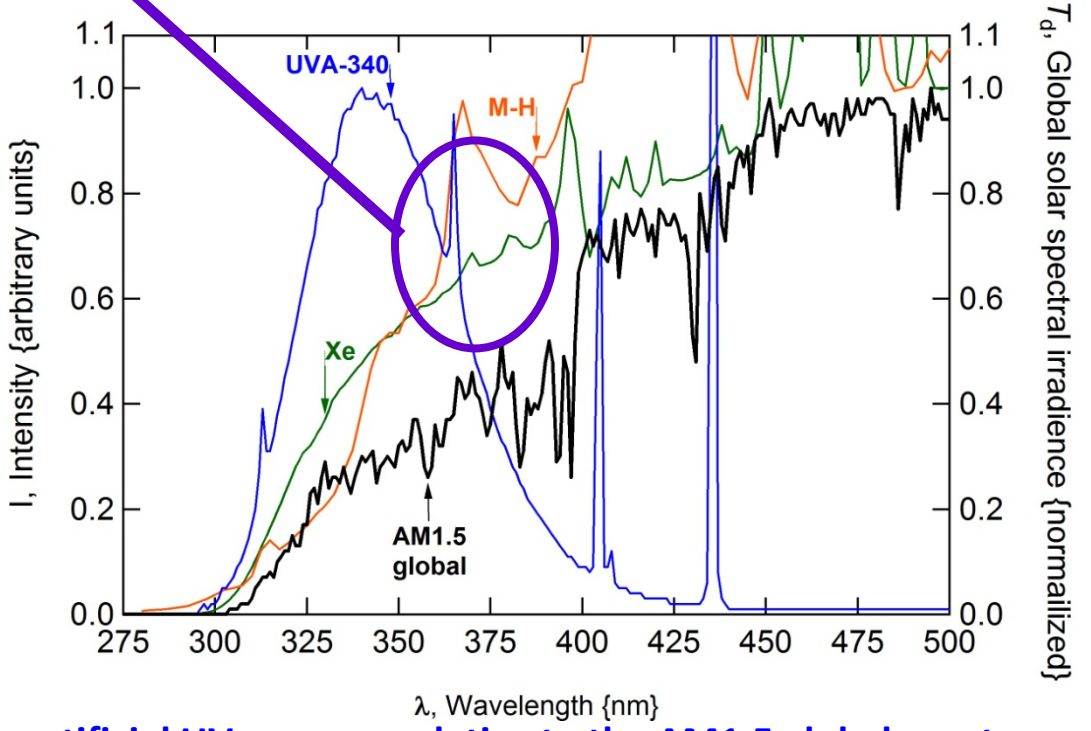
- The effects of aging are less significant at the specimen periphery (except TPU).
- In EVA, a photobleaching effect occurs at edges, but is limited by rate of O_2 diffusion.

Here and previous slides:

EVA's ⇒ effects of aging are dominated by interactions between additives.

E_a Experiment Examines Relevant Source Spectra

- Will compare Xe, UVA-340, M-H, and terrestrial light sources for all formulations examined.
- Depending on specimen's action spectrum (damage susceptibility), UV source *(e.g.,* 360-400) could render different results.
- Aged EVA's have not yet varied significantly between sources.
- Other base materials or components (backsheet) may have stronger spectral dependence.
- NIST SPHERE experiment (passband filters) will provide additional insight.
- Also method: ASTM G178.



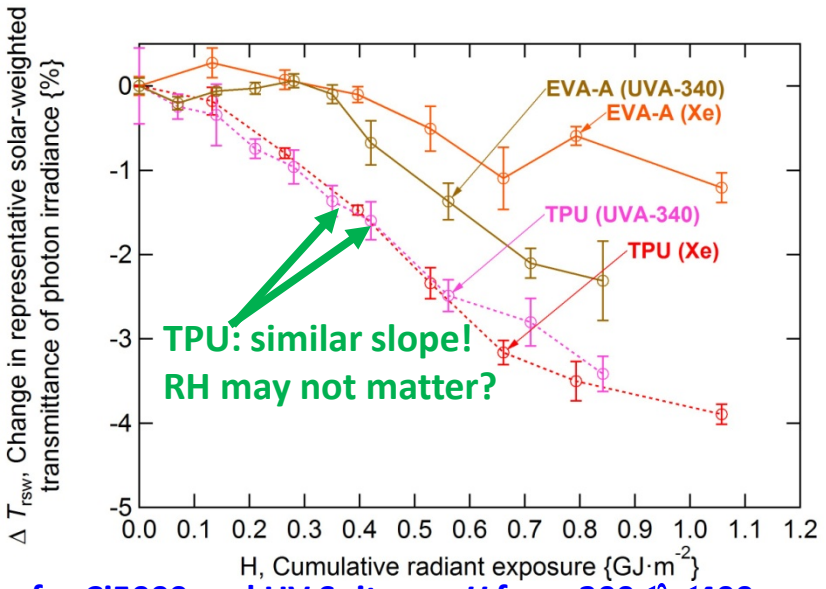
Overlay of representative common artificial UV sources, relative to the AM1.5 global spectrum.

Beginning to Compare Between Artificial Light Sources

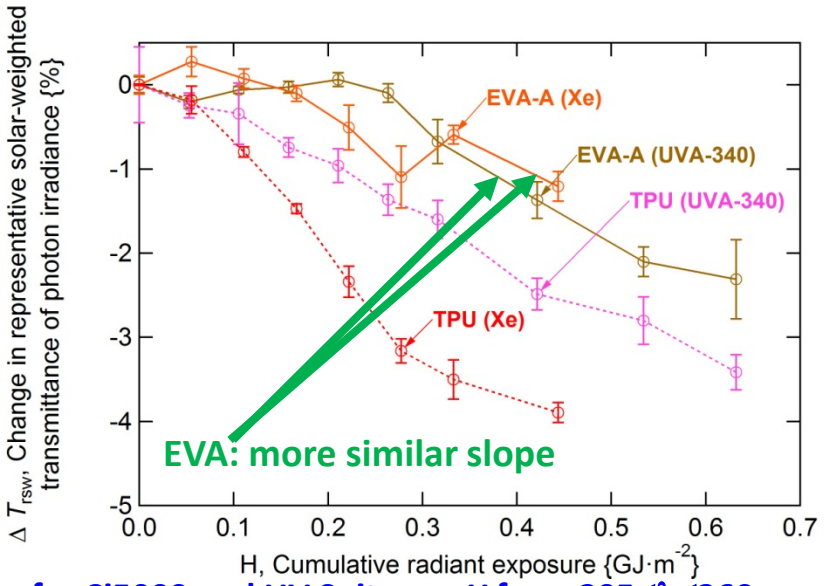
- A common metric for *H* must be agreed upon when comparing Xe-arc and UVA-340 fluorescent sources.
- One might think to overlay data (τ of EVA-A and TPU) at a similar aging condition (chamber 60 °C) for the total UV, $300 \leq \lambda \leq 400$ nm.
- But: UVA-340 lacks emission from $360 \leq \lambda \leq 400$nm.

Fowler, "Developing Steady State Exposure Conditions in an ASTM G154 Fluorescent UV Test Chamber for Backsheet Materials."

- $295 \leq \lambda \leq 360$nm: may be best criteria between Xe and UVA-340 fluorescent.
- Comparing figures implies different action spectrum.
- Quantitative analysis (*e.g.*, E_a) will provide greatest insight.



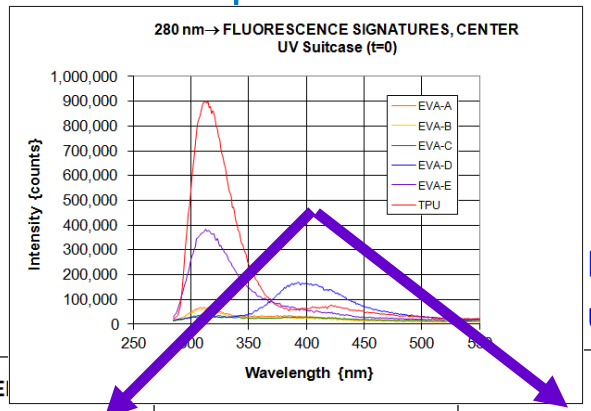
Δτ: Shown for Ci5000 and UV Suitcase, *H* from 300≤λ≤400 nm.



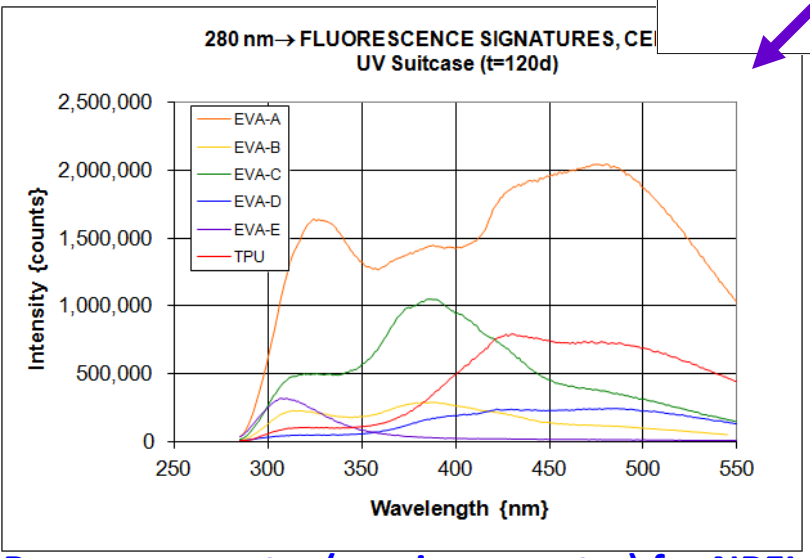
Δτ: Shown for Ci5000 and UV Suitcase, *H* from 295≤λ≤360 nm.

Fluorescence Spectroscopy: Xe and UVA-340 Affect Similarly

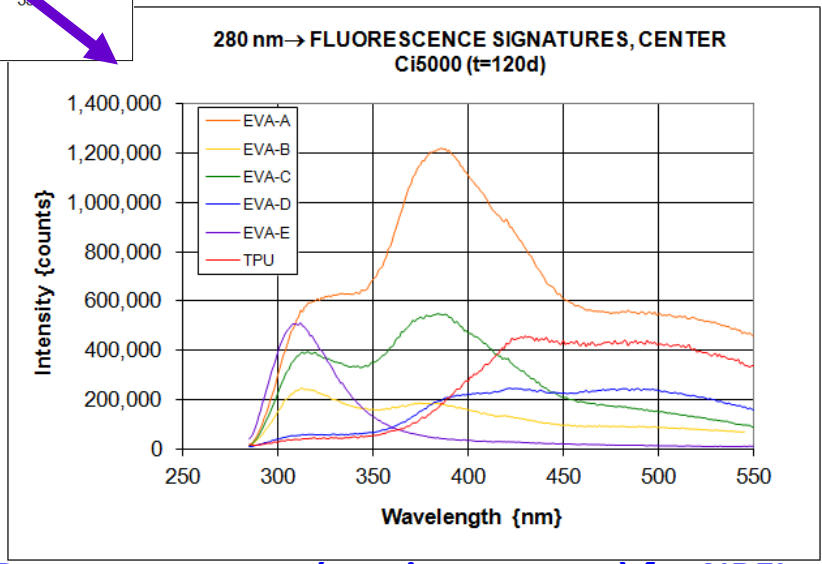
- Photoactive electronic structure evolves significantly with age at the specimen center. (less profound changes seen at periphery).
- Distinct signatures between EVA's suggests interaction between formulation additives.
- Similar profiles suggest specimen chemistry affected similarly for UVA-340 & Ci5000.
- EVA-A: Verify signature at end of the experiment.



Base scan spectra for NREL unaged specimens.



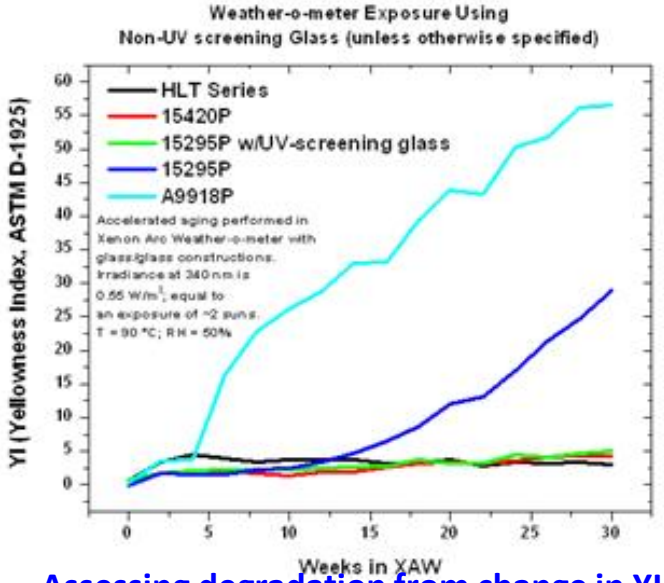
Base scan spectra (specimen center) for NREL UV Suitcase (UVA-340 @2x, 60°C) at 120 days.



Base scan spectra (specimen center) for NREL Ci5000 (Xe @2x, 60°C, 50%RH) at 120 days.

Transmittance: Comparison to Historic & Outdoor Data

- Historically, yellowness index has been used to compare between indoor- and field-aged encapsulation.
- We examine 2 of the classic formulations, using a modern version of the same glass.
- ΔYI, EVA-A: ~8 (Xe, 60°C) vs. ~55 (Xe, 70°C).
- Contiued verification & analysis to follow.



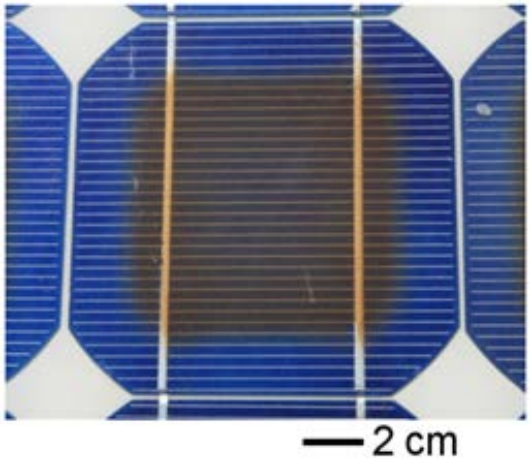
Assessing degradation from change in YI.
Reid et. al., Proc SPIE, 2013, 8825-7.

- Same & similar formulations deployed at APS in 1996.

⇒Conclusion: discoloration resulted from additive interactions (as in E_a experiment).

- Location specific results (center vs. periphery) as in E_a experiment.

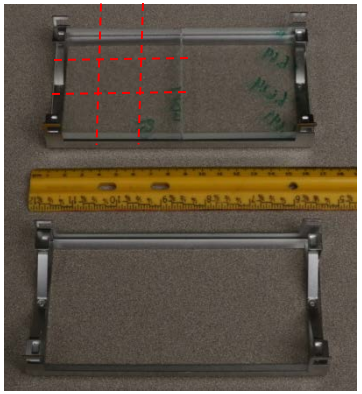
- TG5 will determine location specific acceleration factor for Cleveland, Golden, Miami, Phoenix, & Riyadh.



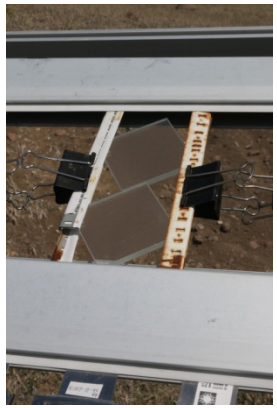
Localized discoloration of EVA (known formulation in module) at the APS site.
Wohlgemuth et. al., Proc IEEE PVSC, 2013, 3260-3265.

Details of the E_a Methods and Experiment: Encapsulation CST Adhesion Test

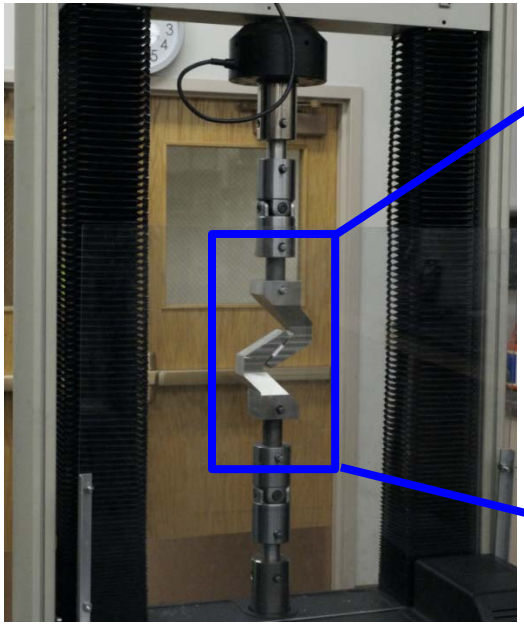
- Better physics-based methods being developed as IEC standard.
- 25 mm square specimens (diced, after aging) examined using loadframe.
- Pristine edge quality is critical. Dice using abrasive water jet cutter.



Sample holder configuration for indoor aging at NREL. Samples are diced after aging.



Specimens on outdoor rack, aging in Golden, CO at NREL.



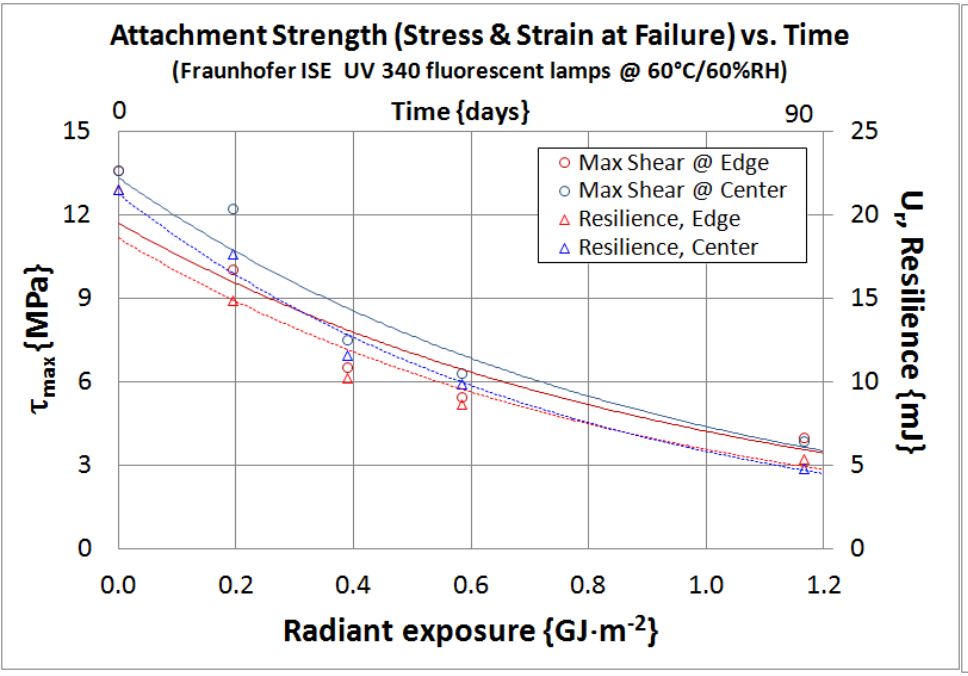
The CST will be used to examine the attachment of EVA. Method from: Chapuis et al., PIP, 22 (4), 2014, pp.405–41. (EPFL)

User summary:

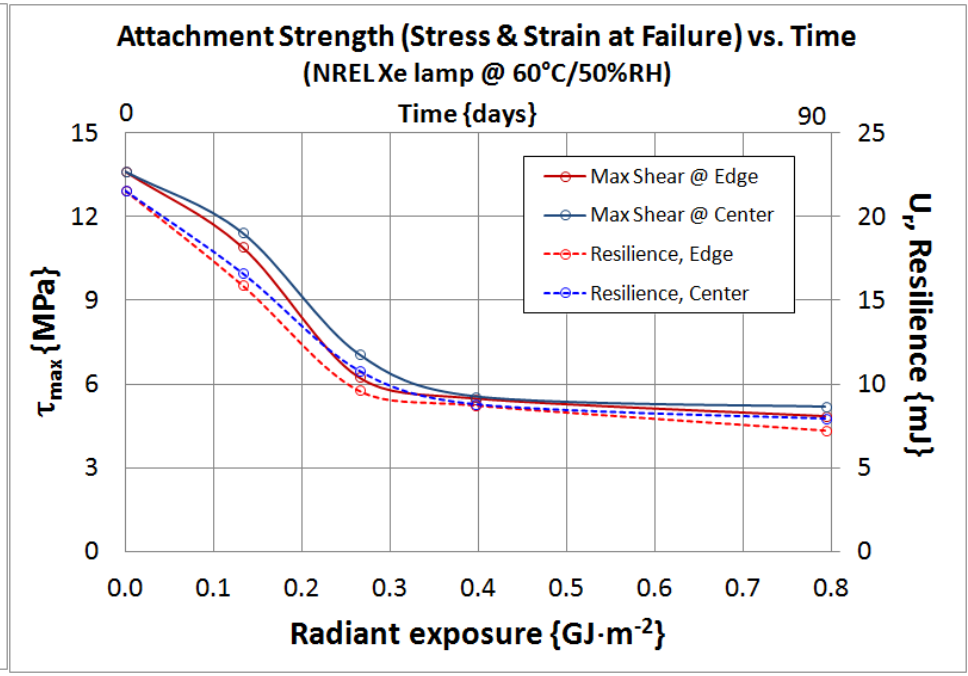
- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm)
- Size: 3” x 3”
- Quantity: 10 replicates of 1 material (pre-conditioned), plus 5 extras (not pre-conditioned)
- Aging: 15, 30, 45, 90, and 180 cumulative days (indoors), or 1, 2, 3, 4, 5 years (outdoors)
- Remove 2 coupons at each increment
- Measurements(destructive): age at each laboratory/test site, then sent to NREL for measurement

Profound Reduction in Attachment Strength Initially Observed

- Examining EVA-B (STR 15295 P/UF), found in many veteran PV installations.
- Strength and resilience were seen to decrease significantly (by 66%) in the first 90 days aging at Fraunhofer ISE.
- Similar magnitude of effect observed for specimens aged at NREL.
- This change exceeds the rule of 50% for pass/fail, typically applied in relative thermal index (RTI) tests.
- Experiment will verify if the strength is maintained after prolonged aging, *e.g.*, as in an absolute minimum requirement.



Change in strength of attachment and resilience for fluorescent UV Custom Chamber at Fraunhofer ISE.



Change in maximum strength of attachment and resilience for Xe Chamber at NREL.

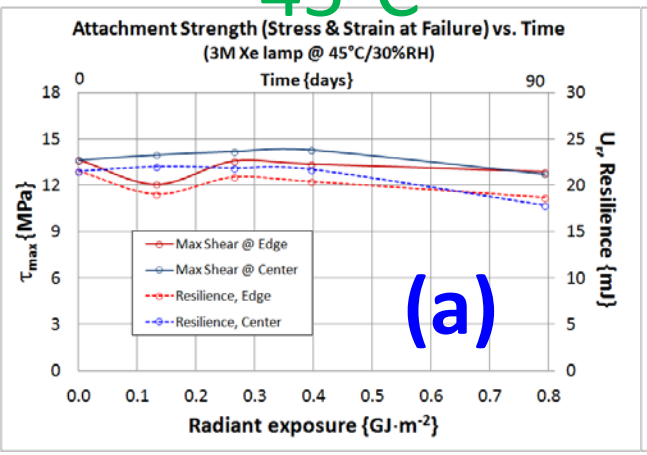
Additional Aging Conditions Suggest More Complicated Story

- 3M samples aged with Xe at 2x UV and 30% RH, T = 45, 60, or 80 °C.
- 3M: little or no effect seen at 45 & 60 °C.
- Fraunhofer ISE & EPFL: minimal effect seen at 40°C (3x) or 60°C (1x).

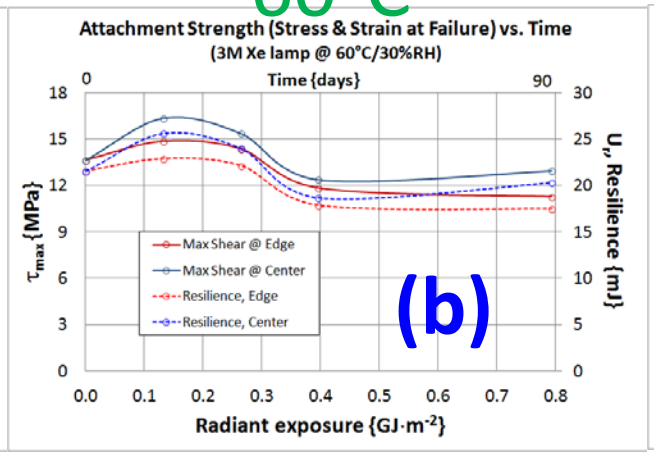
Explanations:

- Threshold of UV, T, or RH required to invoke substantial damage?
- Effect is due only to absorbed moisture (polymer plasticization)?
- Comment: T_m~60°C for EVA.
- Additional results (at 80 °C or in dark) should elucidate.

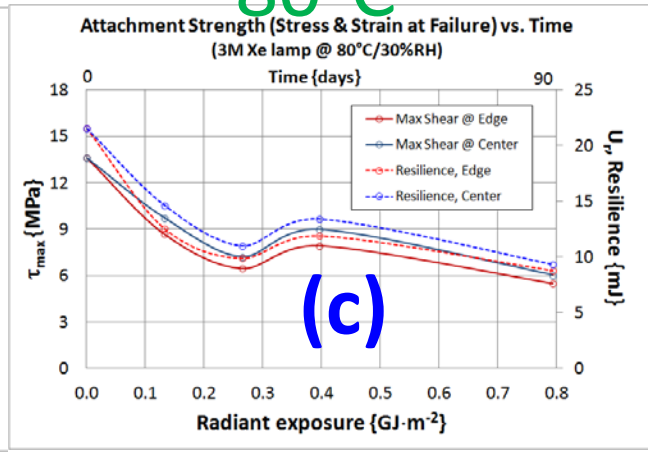
45°C



60°C



80°C



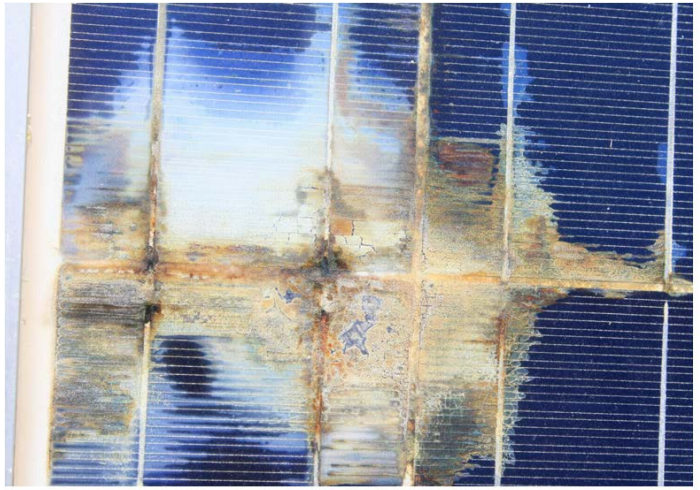
CST results for 3M Ci5000 chambers, Xe @ 2x and 30%RH: (a) 45 °C; (b) 60 °C; and (c) 80 °C.

Adhesion: Comparison to Historic and Outdoor Data

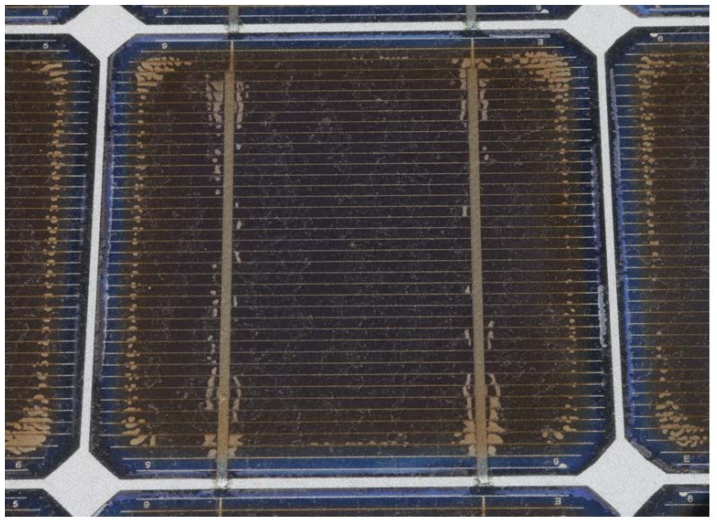
- No good systematic quantitative study of adhesion in the PV literature.
- e.g., accelerated conditions and duration to examine delamination not established.

Anecdotally then:

- Encapsulation/cell interface often weakest.
- Delamination often precedes corrosion.
- May not be tightly correlated with encapsulation discoloration.



Delmaination and subsequent corrosion in EFG-Si cell module at TEP Springerville facility.



Delamination at cell-corners and -interconnect ribbons in mono-Si module at SMUD Hedges facility.

Refer also to:

- Adhesion test method: refer to Bosco *et. al.*, "A Fracture Mechanics Based Approach to Adhesion Testing in the PV Module", Proc. PVMRW 2015.
- Site data: refer to Silverman *et. al.*, "Review of observed degradation modes and mechanisms from fielded modules", Proc. PVMRW 2015.

Application of the UV Test

Direct application:

- IEC 62792 (climate- & configuration-specific aging sequences)
  This is the primary application forTG5 effort.
- IEC 62788 (PV module materials and components)
  -1 = Encapsulation; -2 = Backsheets; -... (tests of characteristics)
  -7 =Weathering
  (may draw directly upon the TG5 results in a UV test)

Indirect or perhaps future influence:

- IEC 61730-1 (module materials & components safety tests)
- IEC 61730-2 (PV module safety tests)
- IEC 61215 (PV module qualification tests)

Timeline of Activities for TG5

- NREL specimens are presently at 150 days (Ci5000) and 180 days (UV suitcase).
- Results will be used to assign t, T, %RH for a climate- & configuration-specific UV test.

	Qualification	QMS	Climate- & Configuration-Specific Test	Service Life Prediction
Current status	Issued as standards	Revised NWIP submitted	Proposed as concepts	Concepts
2014 goal	Submit 61215 (Ed 3) 61730 (Ed 2)	Publish new TS	Initiate E_a test. Create strawman UV standard.	Develop criteria to evaluate QMS related to service life; NWIP
2015 goal	Publish new editions	Start use of the TS in factory inspection	Submit UV standard NWIP. Create strawman test sequence standard. Complete indoor E_a test.	
2016 goal		Revise QMS document to reflect feedback	Publish E_a results. Submit CD of UV standard.	
Chamber test times	Modules: ~ 6 weeks	TBD	~6 months	~18 months

Summary

- "E_a" interlaboratory experiment being conducted to provide a quantitative basis for climate- and configuration-specific UV weathering test.
- Preliminary (qualitative) observations presented.

Encapsulation transmittance:

- Have replicated behaviors of fielded materials (specimen location- and formulation additive-specific discoloration).
- *T* coupling observed for UV aging.
- $\Delta\tau$ degradation in EVA results from **UV** aging.
- Good qualitative comparison between Xe and UVA-340 sources for EVA.

Encapsulation adhesion:

- Attachment strength can decrease drastically (>50%) with age.
- Early results suggest significant factor (UV, *T*, *RH*) dependence.
- Much to be learned about adhesion.

- We look forward to the quantitative values from the experiment.

Acknowledgements

☞There has been fantastic participation in TG5.

Thank you to the many participants for their ongoing support!!!

- If interested in TG5 or the experiments, please contact the corresponding regional TG5 leader. (See title slide)
- Future publication, "Degradation in PV Encapsulation Transmittance: An Interlaboratory Study Towards a Climate-Specific Test", *submitted Proc. IEEE PVSC*.

✋Your questions and feedback are much appreciated. Please help me to cover the important details & perspectives.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

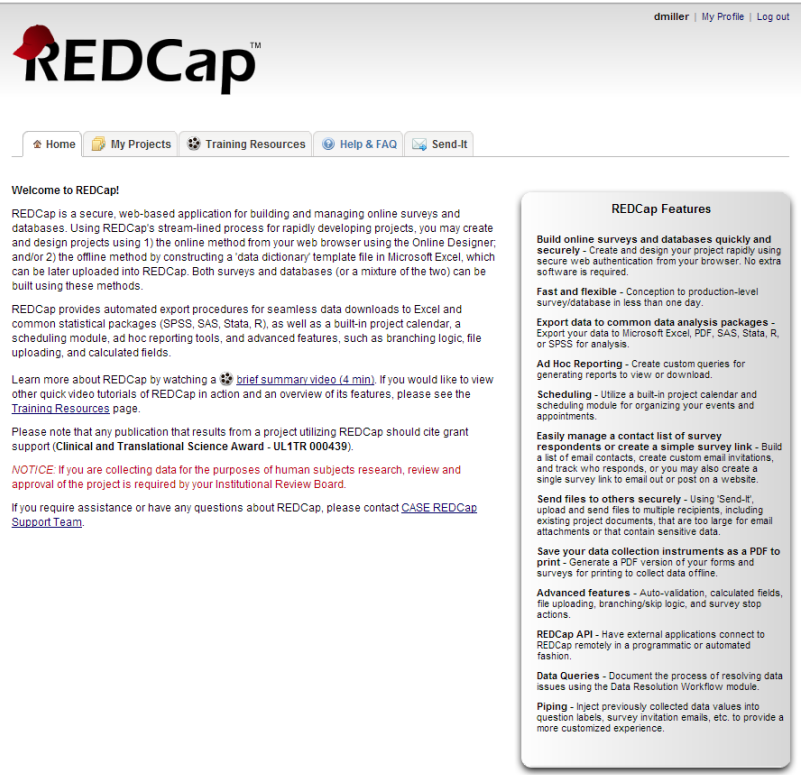
NREL STM campus, Dennis Schroeder

Use of REDCap Database for Transmittance Data

- LOTS of transmittance data will be generated for the experiment.
- Case Western Reserve University volunteered the REDcap database to TG5.
- REDCap comes from the medical (research) industry.

Benefits: Ensures designed experiments, high data capacity, simultaneous user access, automated data quality verification.

- REDCap allows users to view and analyze results in real-time.



Home screen for https://dcru.case.edu/redcap

X		88.79
Y		93.67
Z		100.08
τ, solar weighted ⋈		89.39
τ, representative weighted ⋈		92.07
YI, 1964		0.49
λ_{eUV} {nm}		358.0
readpoint {days}		XXX
sa (serial number)		XXX
λ {nm}	τ ⋈	τ ⋈
200	0.00	0.00
201	0.00	0.00
202	0.02	0.02

Transmittance results will be uploaded to REDCap using an Excel template file.

Moisture Conditioning of Specimens

- Water content is a critical factor in the experiment.
- A set of 3 different conditions were applied to render an internal water content (ppm) similar to that in the aging chamber.
- Specimens were pre-conditioned for 1 month prior to distribution.
- Specimens need to be maintained with a water content during intermission (between aging and measurement).

Temperature		Saturation at RH	Concentration Ratio (vs. 40/30%)	Dew Point	Temperature	Humidity	Recommendation(s)
(°C)	RH (%)	(g/cm^3)		(°C)	(°C)	(%)	
40	30	0.000882	1.0	-9.4	30	45.8	Put in Refrigerator
60	30	0.001297	1.5	4.6	30	72.7	Put in Refrigerator
60	50	0.002162	2.5	25.7	30	90.9	
					23	106.3	Put in sealed jar above water (not in water), at ambient T.
80	30	0.001826	2.1	18.4	23	89.8	Put in sealed jar above water (not in water), at ambient T.
40	50	0.001470	1.7	9.5	25	69.1	Put in 25C/69.1% chamber
80	50	0.003043	3.5	41.7	40	103.5	Put in a jar at 41.7C and 100% RH
					45	93.6	Put in 45C/85% chamber

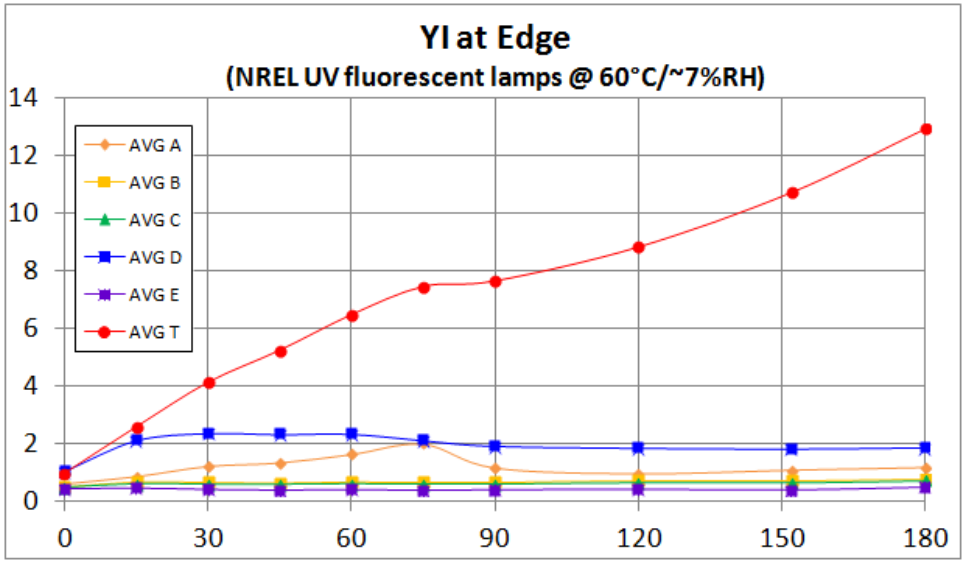
Matrix for the pre-conditioning /storage recommendation for samples for the TG5 experiment.

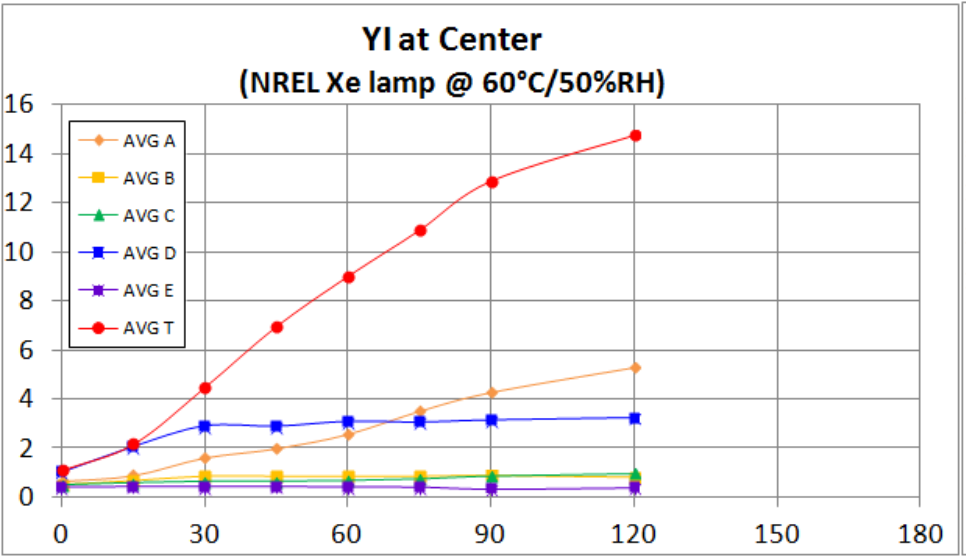
A Comparison of the YI Behavior With Age

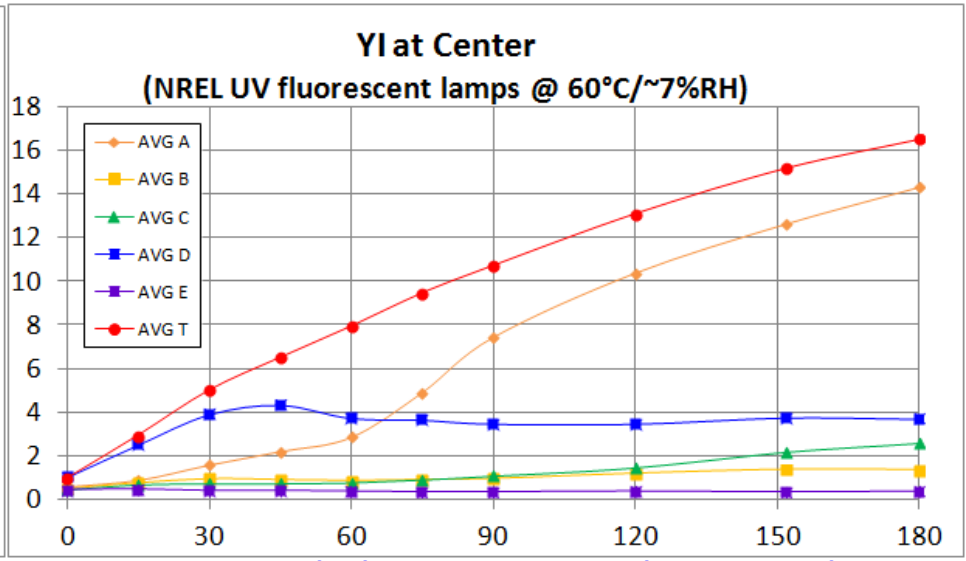
- Center and edge are distinct for EVA's, but similar for TPU.
- Magnitude of YI is not as great here (cooler chamber) as in STR studies.
- TPU more slightly affected by Xe; EVA-A less affected by Xe.

Specific temporal behaviors:

- Initial yellowing of EVA-D.
- Inflection in EVA-A.



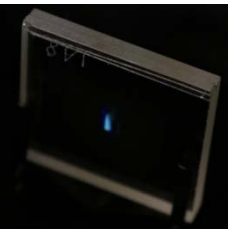


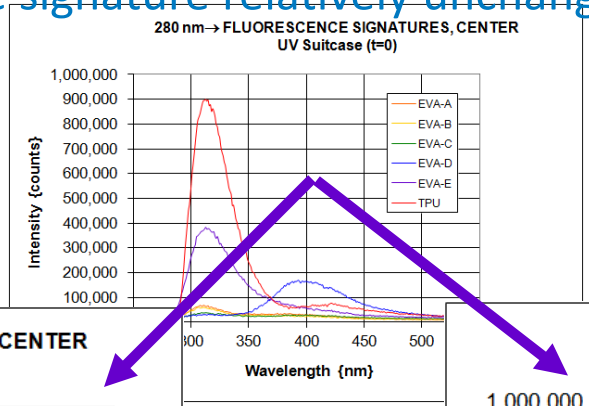


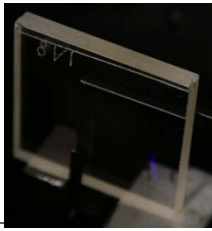
Comparison of the change in YI for specimens aged in the NREL Ci5000 (Xe) and UV Suitcase (fluorescent) chambers.

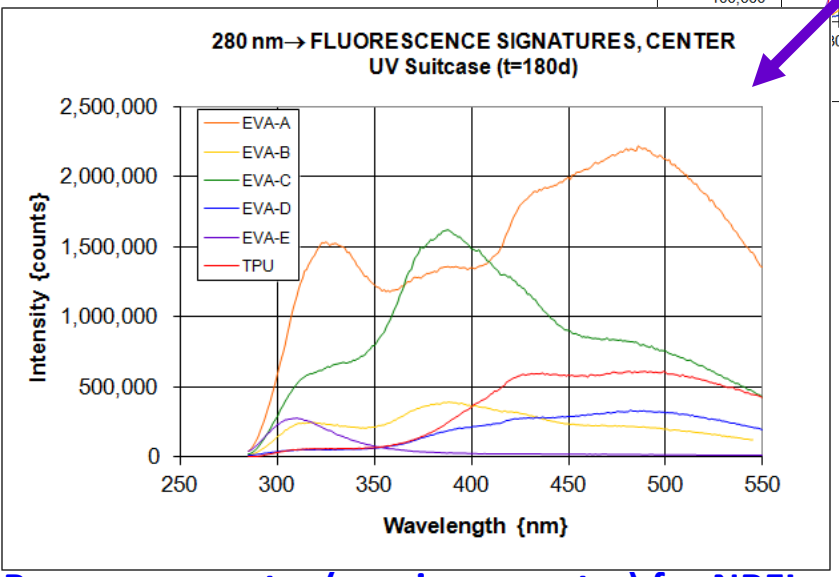
Fluorescence Spectroscopy Confirms Formulation Specific Results

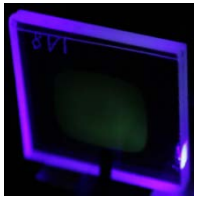
- Photoactive electronic structure evolves significantly with age at the specimen center.
- Fluorescence may correlate to the formation of by-product species and/or the presence of formulation additives.
- Distinct signatures (between EVA's) suggests interaction between formulation additives.
- For EVA, evolution not as pronounced at the specimen periphery.
- EVA-E (no UV-A): Fluorescence signature relatively unchanged!

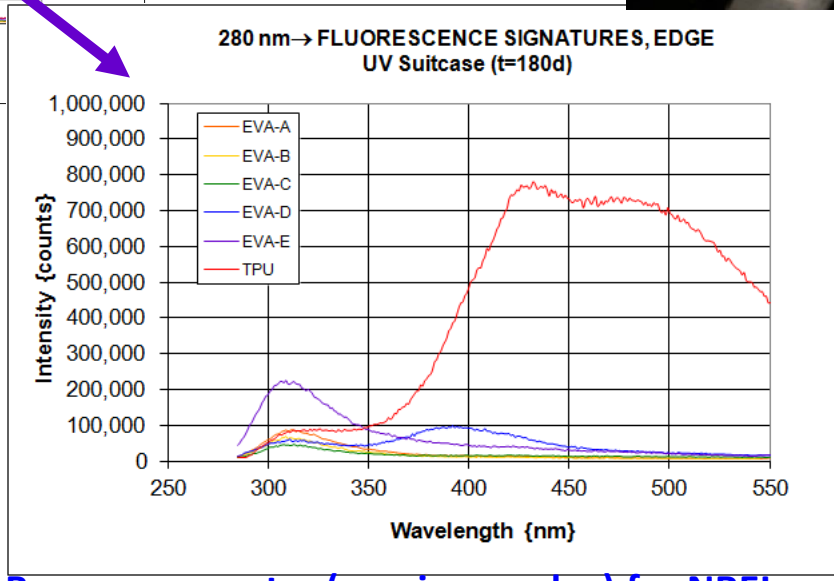








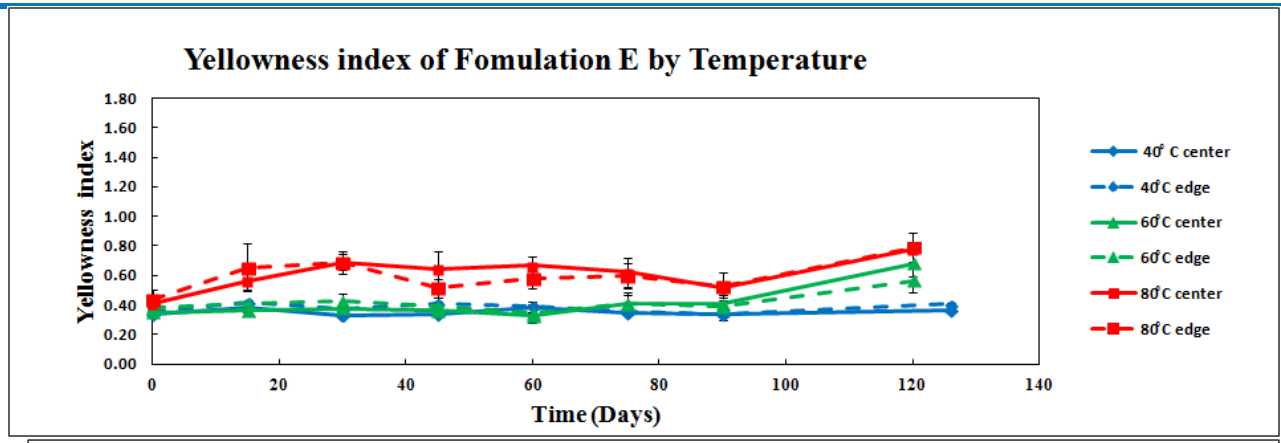


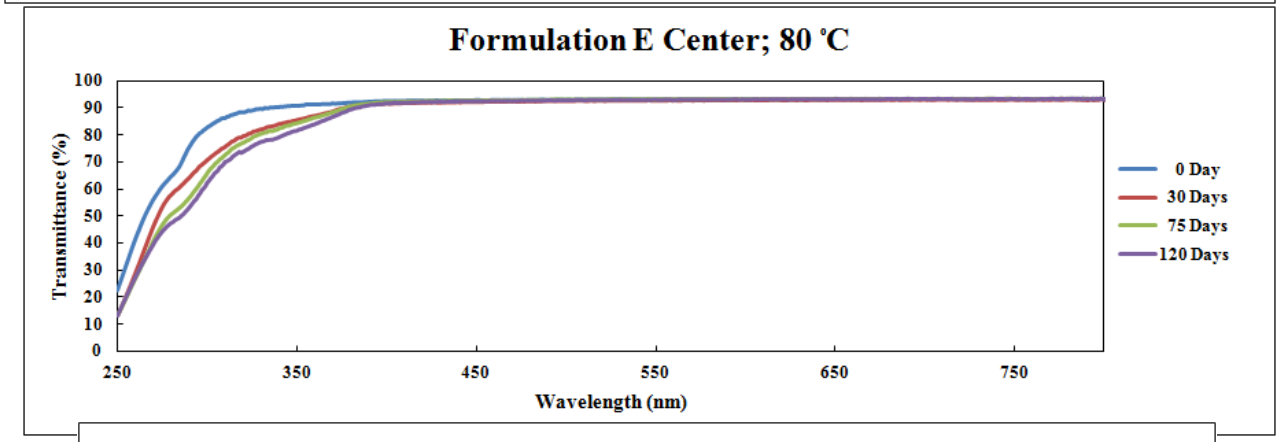


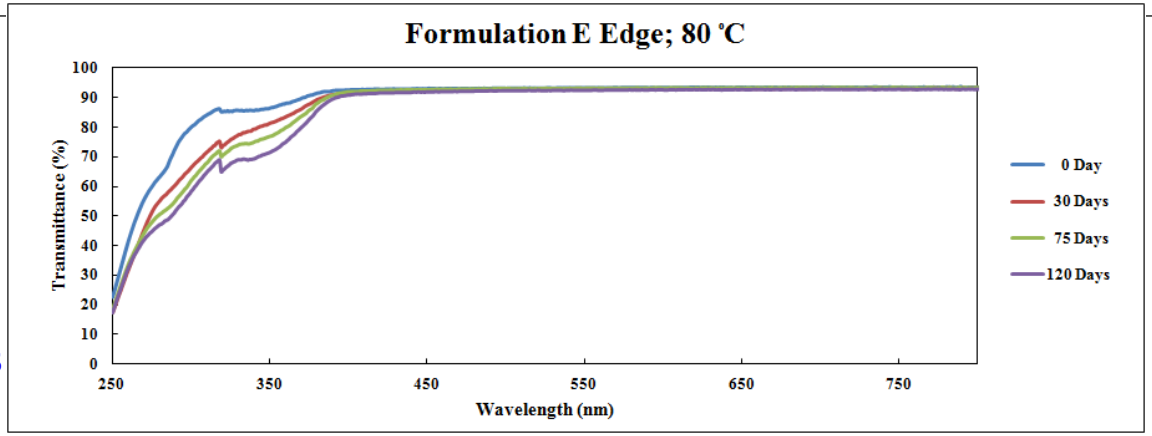
Base scan spectra (specimen center) for NREL UV Suitcase at 180 days.

Base scan spectra (specimen edge) for NREL UV Suitcase at 180 days.

Transmittance Spectra for Dark Aged Encapsulation: EVA-E

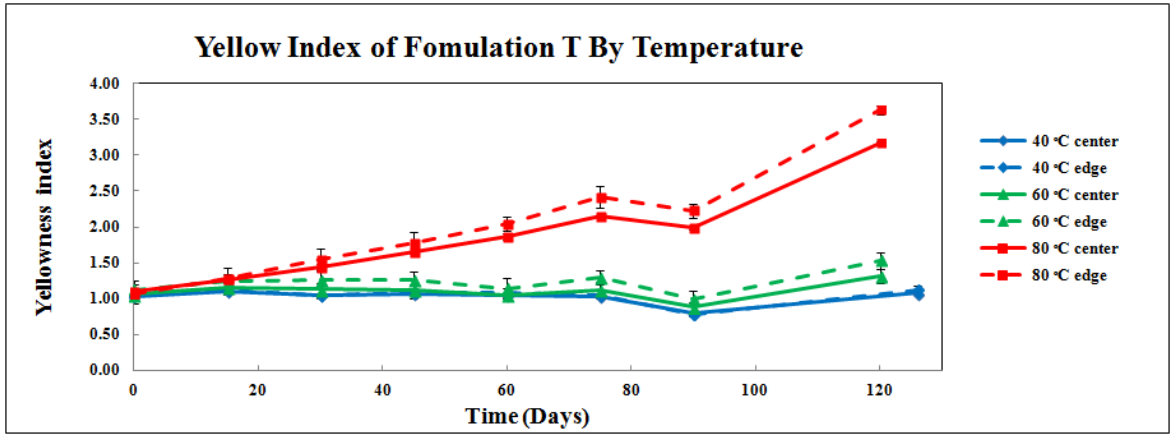


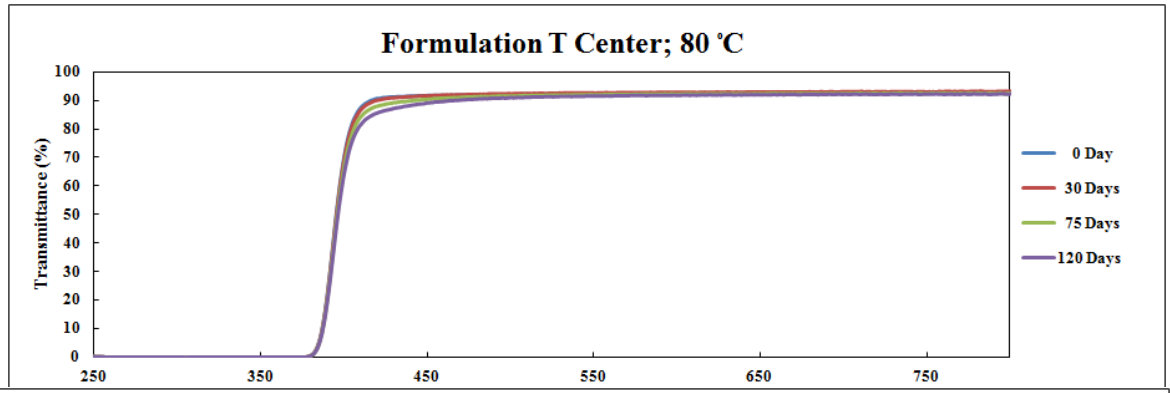


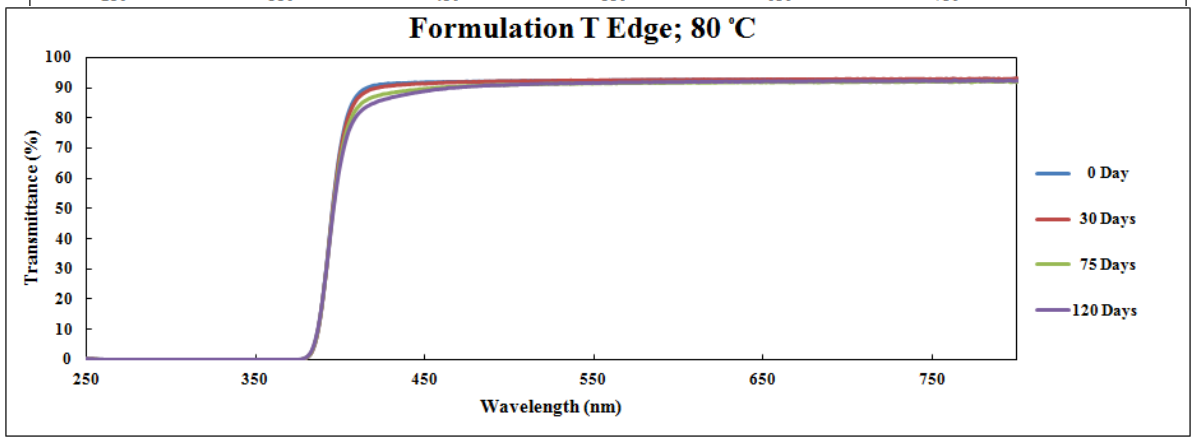


Aging and measurements performed at NIST.

Transmittance Spectra for Dark Aged Encapsulation: TPU







Aging and measurements performed at NIST.

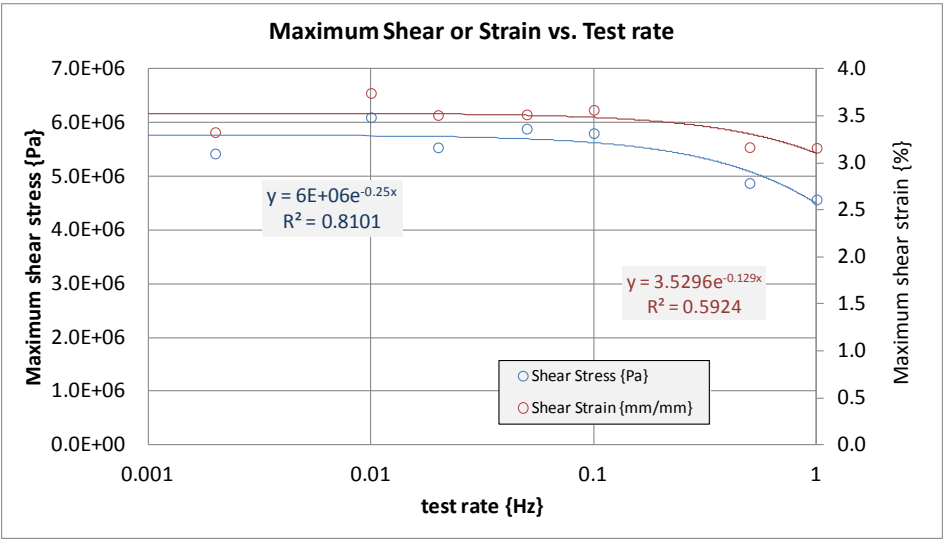
Details of the E_a Methods and Experiment: Encapsulation Adhesion Test

- The test matrix is reduced for the CST (key parameters only).

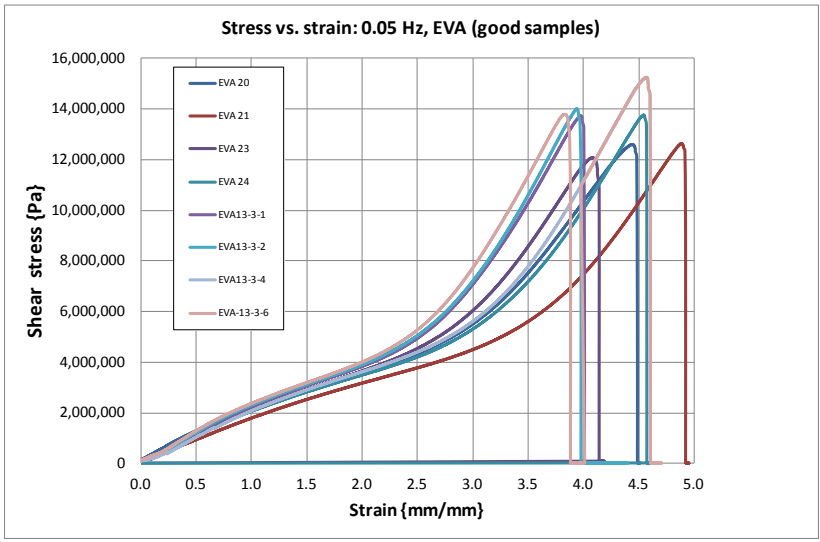
LIGHT SOURCE, FILTER	Xe Arc (right-light/cira filter)					UVA 340 fluorescent (no filter)		UVA 340 fluorescent (no filter)	Metal-Halide	No light			field deployment (outdoors)
UV LIGHT INTENSITY	NOMINAL (102 W•m^{-2} for 300≤λ≤400)					NOMINAL (1.0 W•m^{-2}@ 340 nm)		NOMINAL (~150 W•m^{-2} for 300≤λ≤400)		0 W•m^{-2}			
CHAMBER RELATIVE HUMIDITY {%}	30 ("low")			50 ("high")		~7% ("very low")		60 ("high")	30 ("low")	30	30	30	ambient
CHAMBER TEMEPRATURE {°C}	40	60	80	40	60	40	60	60→ 80 → 40	60	40	60	80	ambient
PARTICIPANT (INSTRUMENT MODEL)	3M (Ci5000)	3M (Ci5000)	3M (Ci5000)	Mitsui(SX120)	NREL (Ci5000)	QLAB (QUV)	CWRU (QUV)	Fraunhofer (custom)	EPFL	NIST	NIST	NIST	ATLAS (EMMA in Phoenix)
		QLAB (QSUN XE3)			QLAB (QSUN XE3)	ATLAS (UVTEST)							CWRU (5x in Cleveland)
													ATLAS (rack in Phoenix)
													ATLAS (rack in Miami
													NREL (rack in Golden)
													KACST (rack in Riyadh)

Test matrix for CST.

- Preliminary work (this study) verified the test settings.
- Unaged specimens are being baselined.



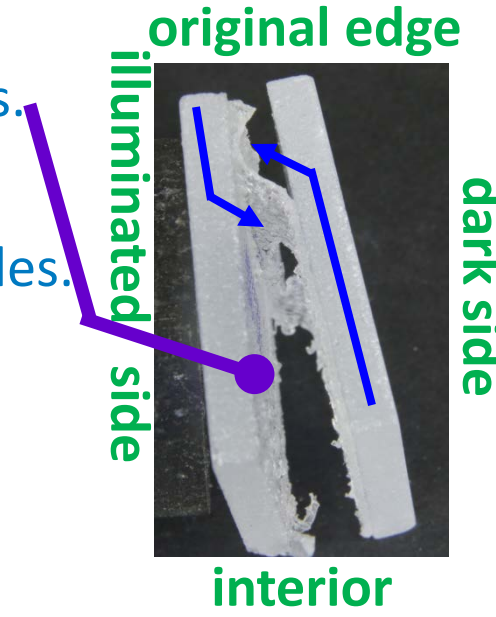
Examination of maximum shear or maximum strain as a function of the test rate.

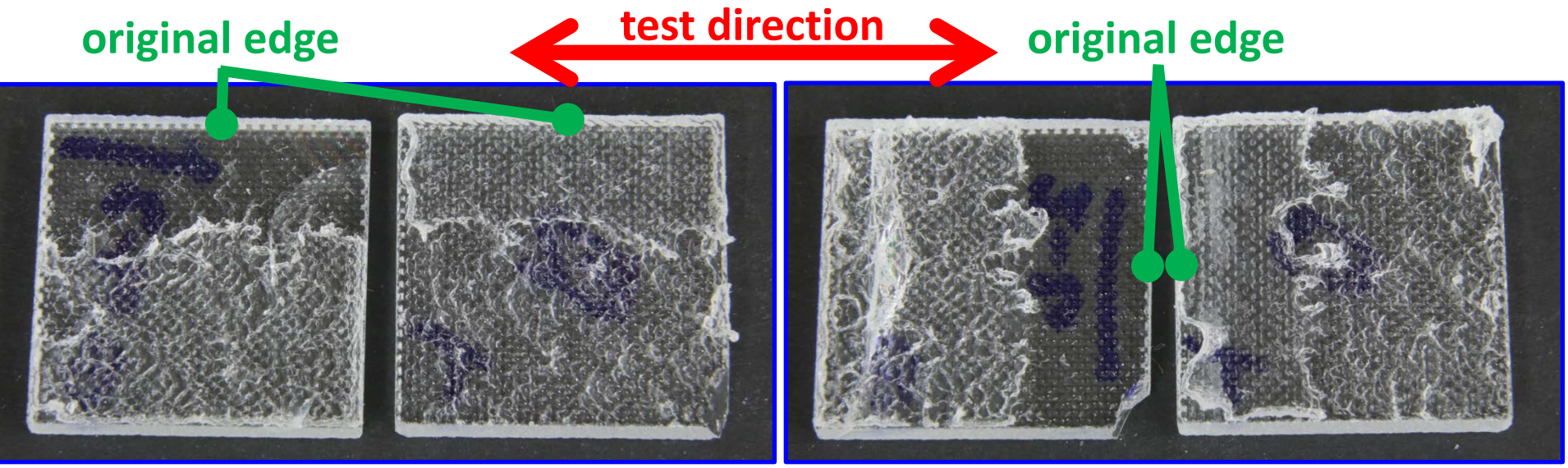


Early results for unaged EVA (uncracked samples only).

FA Identifies UV & T as Key Factors, From Mounting

- Delamination at irradiated (interior) and dark (edge) observed on same samples! vs. irradiated in other chambers.
- Difference in morphology of surface (fibrous interior).
- Strength is comparable for center- and edge-cut EVA samples.
- Samples fixtured using black 2-sided adhesive tape.
- Morphology likely relates to hot edge (~$T_{\text{black panel}}$) vs. cool interior (transparent sample).
- Suggests that both UV and *T* can be significant factors.

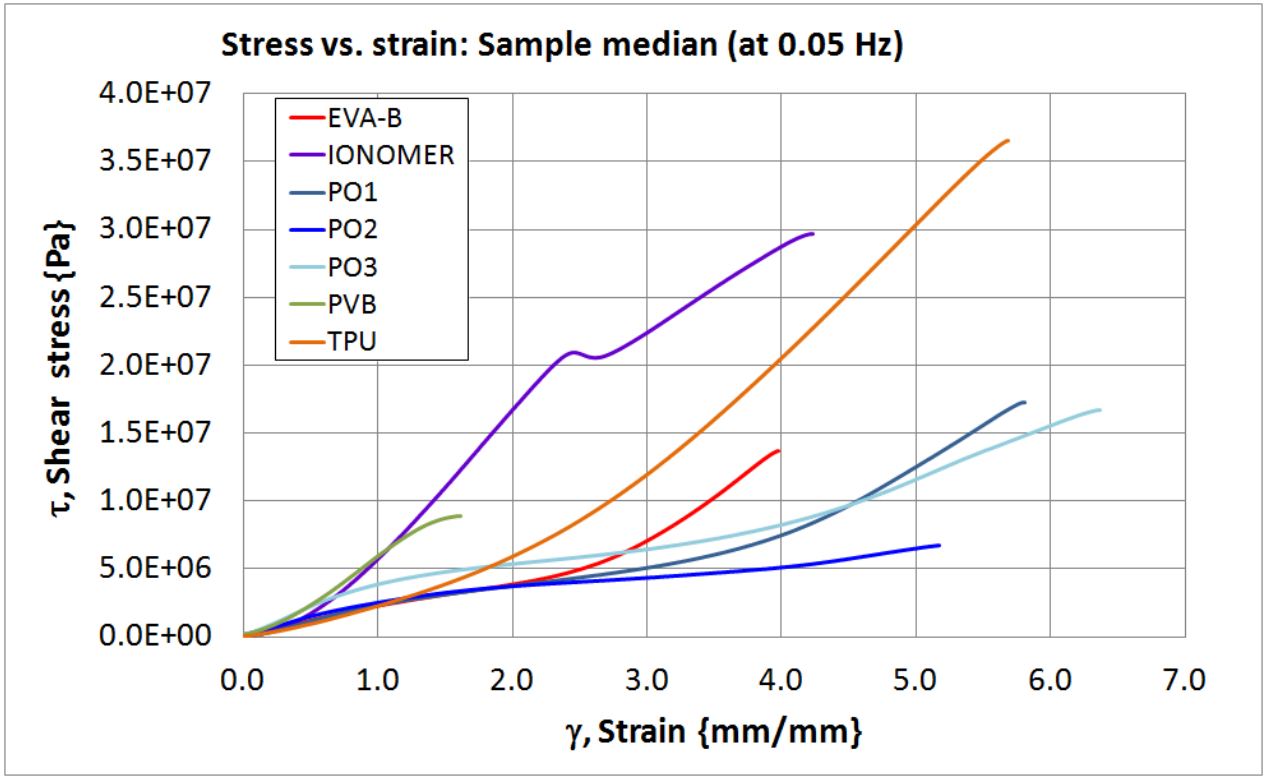




Comparison, 3M aged samples sheared parallel to original sample edge (left); and perpendicular to edge (right).

A Cursory Examination of Other Materials Will Be Performed

- E_a will be evaluated for only the classic "slow cure" EVA.
- Attachment strength of ionomer, polyolefin, PVB, and TPU will be also compared for aging at 2x UV (Xe), 60 °C, 50%RH.
- Attachment strength for some materials exceeds (3x) that of EVA-B.
- Goal: compare the magnitude and relative timescale of aging.



CST stress/strain profiles for the alternate encapsulants.

Details of the E_a Methods and Experiment: Edge Seal Lap Shear Adhesion Test

LIGHT SOURCE, FILTER	Xe Arc (right-light/cira filter)			No light			field deployment (outdoors)
UV LIGHT INTENSITY	NOMINAL (102 W•m^{-2} for 300≤λ≤400)			0 W•m^{-2}			
CHAMBER RELATIVE HUMIDITY {%}	30 ("low")			30	30	30	ambient
CHAMBER TEMEPRATURE {°C}	40	60	80	40	60	80	ambient
PARTICIPANT	3M (Ci5000)	3M (Ci5000)	3M (Ci5000)	NIST	NIST	NIST	ATLAS (EMMA in Phoenix)
							CWRU (5x in Cleveland)
							ATLAS (rack in Phoenix)
							ATLAS (rack in Miami
							NREL (rack in Golden)
							KACST (rack in Riyadh)

Test matrix for Edge Seal materials.

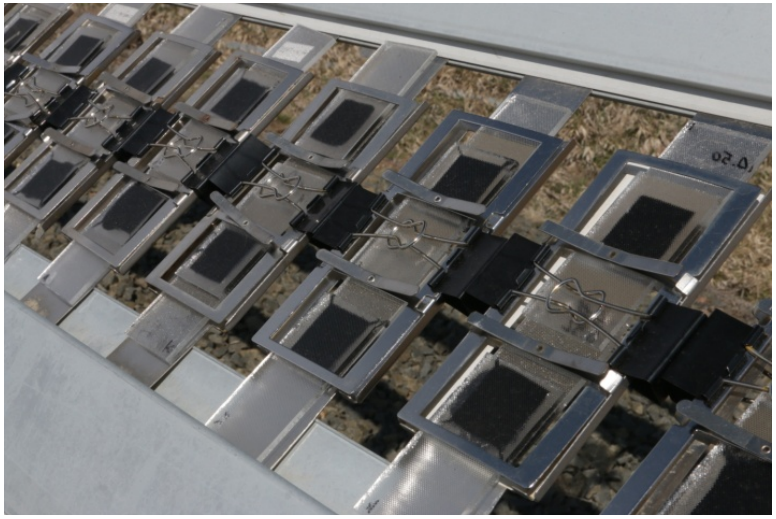
- The test matrix is minimized relative to the encapsulant testing. Assuming the edge seal keeps moisture out, we just need to know the effect of light and heat on degradation.
- Same aging conditions are applied for both the wedge and lap shear test.
- This will provide a direct comparison of the lap shear and wedge methods to help development of adhesion standards.

Details of the E_a Methods and Experiment: Edge Seal Adhesion Characterization

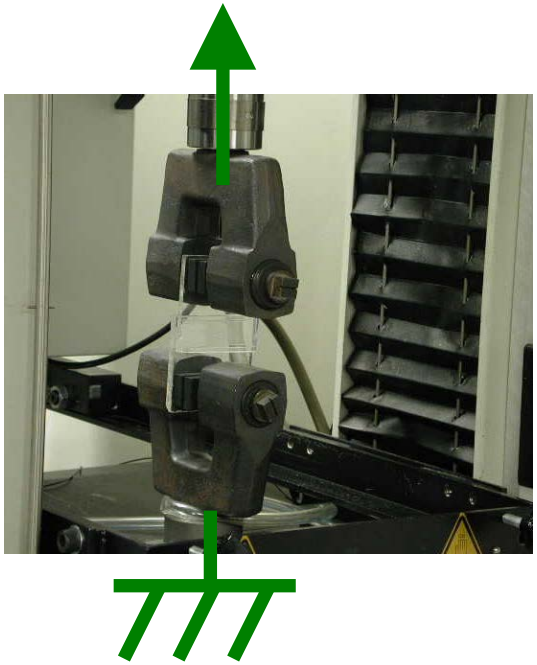
- **Two different Edge Seal Samples.**
- **Test Conditions:**
  - Expose to Dark 40, 60, and 80 ^{o}C at 20% RH.
  - Expose to Light Xenon Arc 40, 60 and 80 ^{o}C at 30% RH, 102 W/m^2 300 to 400 nm.
  - Use Outdoor Exposure (5 sites)
    - Check samples every 6 months.
    - Remove a Lap shear sample at 6 months, 1 y, 2y,…
  - 11 total conditions
- **Samples to be exposed in all conditions:**
  - Wedge check at 250, 500, 1000… Two replicates of two samples (44 samples total, 4 samples per Test Condition)
  - Lap shear samples. 10 replicates. Pull out at 360, 720, 1080, 2160, 4320 h… Use low Fe, non-Ce 3.2 mm Starphire glass. 10 replicates of two samples (20 total) per condition.

Details of the E_a Methods and Experiment: Edge Seal Lap Shear Adhesion Test

- Lap shear is the standard test method for RTI and other certification protocols.
- Edge quality (handling of the glass specimens) is not as critical here.



Specimens on outdoor rack, aging in Golden, CO at NREL.

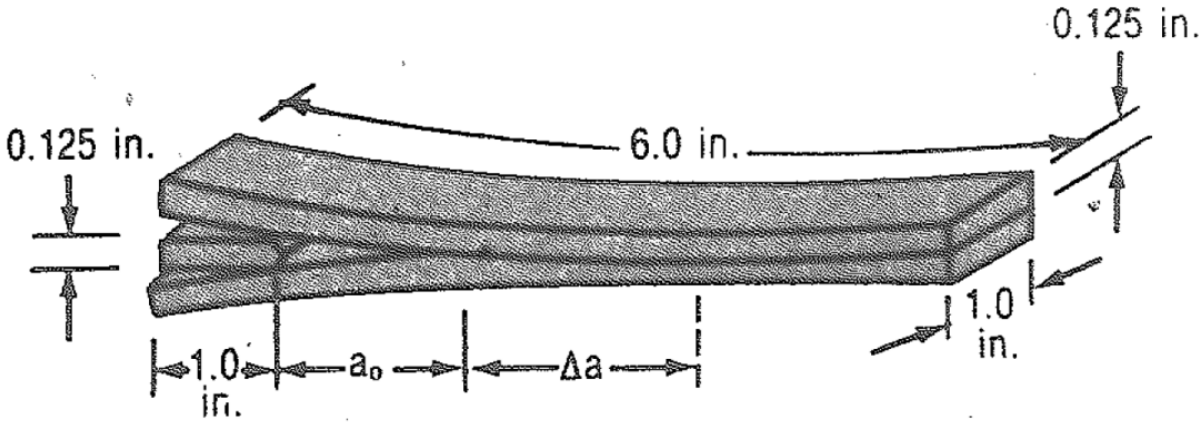


Testing Summary:

- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm). 25 mm X 25mm test area.
- Quantity: 10 replicates of 2 test materials
- Aging: 15, 30, 45, 90, and 180 cumulative days (indoors), or 0.5, 1, 2, 3, 4, 5 years (outdoors)
- Remove 2 coupons of each material at each increment
- Measurements (destructive): aged at each laboratory/test site, then sent to NREL for measurement
- Use a displacement rate of 10 mm·min^{-1}. Record σ_{max}, ε_{max}, and failure mode.

Details of the E_a Methods and Experiment: Edge Seal Wedge Adhesion Test

- Fracture mechanics test for interfacial adhesion ($J \cdot m^{-2}$), not an attachment strength test ($N \cdot m^{-2}$ or $N \cdot m^{-1}$) .
- Specimens will be examined visually and using a micrometer.



G = Fracture Energy

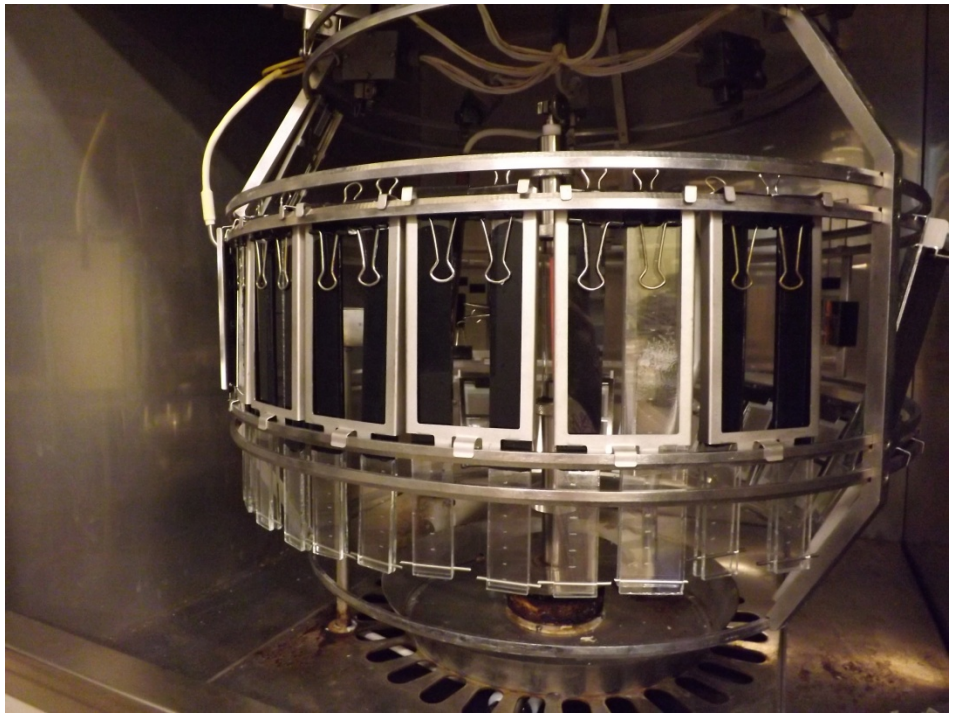
$$G = \frac{3Et^3h^2}{16a^4}$$

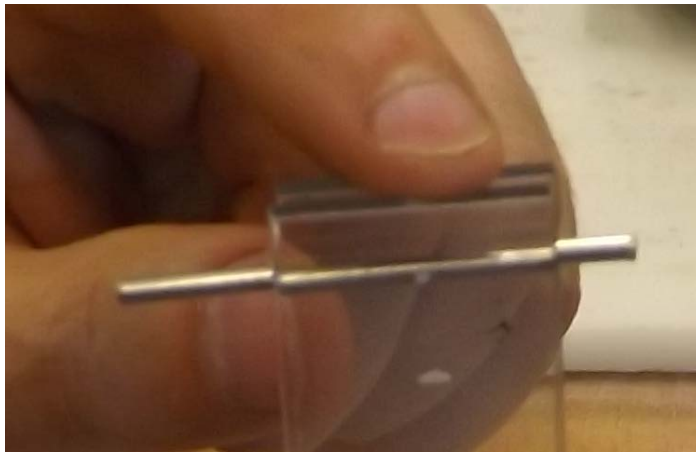
A DCB wedge test will be used to examine the attachment of edge seals.
Marceau *et al.*, Adhesives Age, 1977, 28-34.
Also: ISO 10354, ASTM D3762.

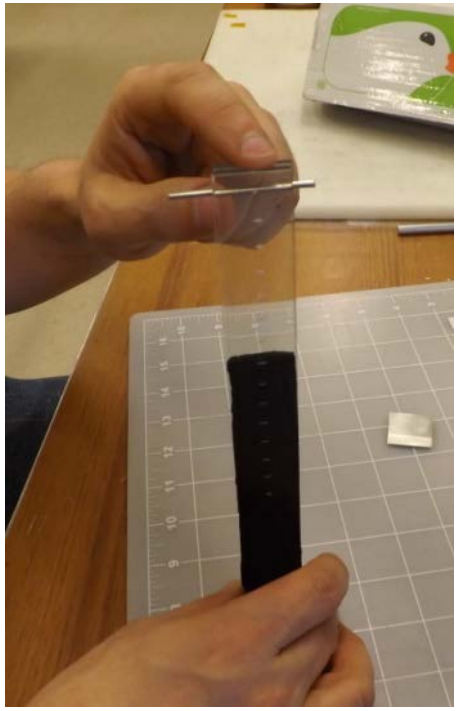
User summary:

- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm)
- Size: 1” x 9”
- Quantity: 2 replicates of 2 test materials
- Aging: 0, 15, 30, 45, 60, 75, 90, 120, 150, 180 cumulative days (indoors) or 0, 0.5, 1, 2, 3, 4, 5 years (outdoors)
- Measurements (semi-destructive): aged and measured at each laboratory/test site

Details of the E_a Methods and Experiment: Edge Seal Wedge Adhesion Test







- Mechanical stress is applied simultaneously with heat, humidity, and UV light.
- Semi-destructive: The bondline continually debonds, releasing mechanical stress till crack growth stops.
- This allows one to get data for very long times without running out of test specimens.

Comparison of Lap-shear to Wedge Test

Lap Shear

- Used more frequently in the industry.
- No mechanical stress during exposure.
- Sample destroyed in testing.
- Easy to measure value.

Wedge

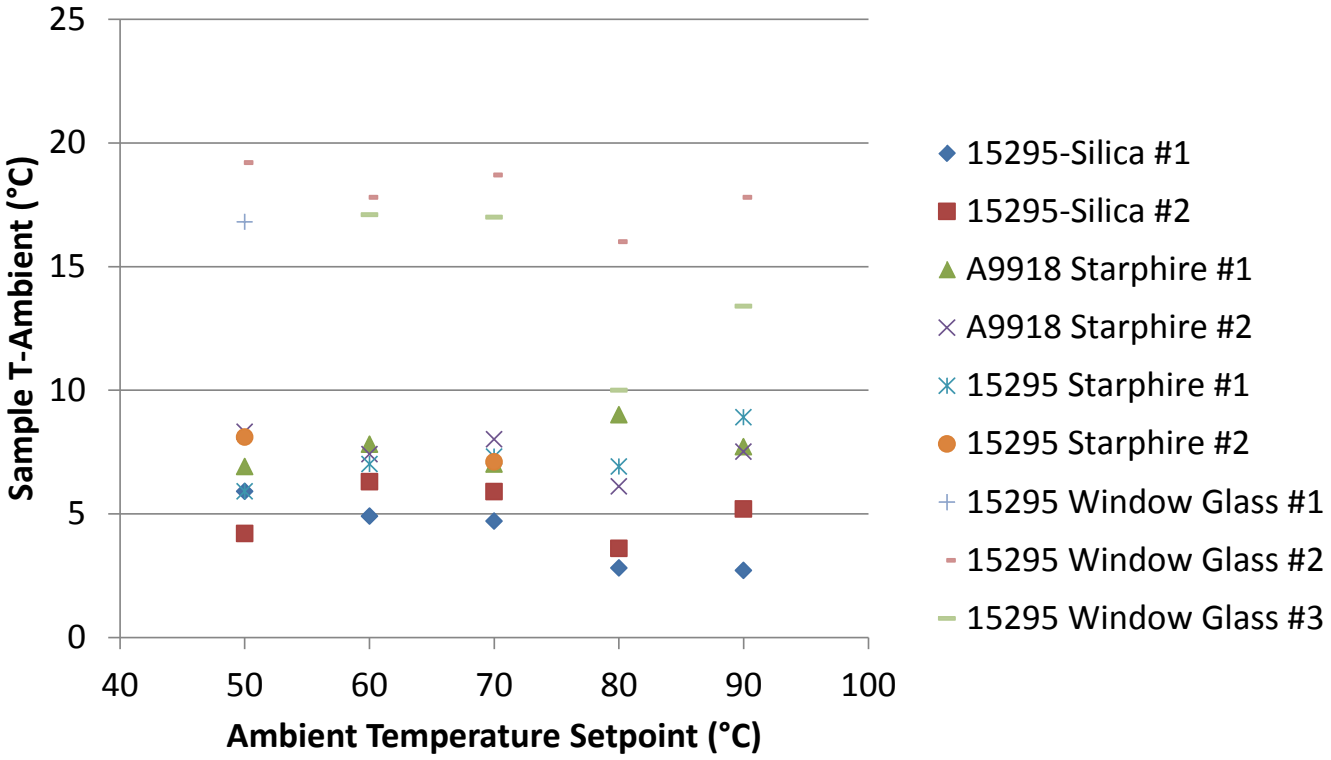
- Less familiar to people.
- Easily able to apply mechanical stress in addition to heat, humidity and light.
- Semi-destructive. Fewer samples are needed.
- Can be difficult to determine crack length in opaque samples with large fracture zones.

We hope to be able to use these results to:

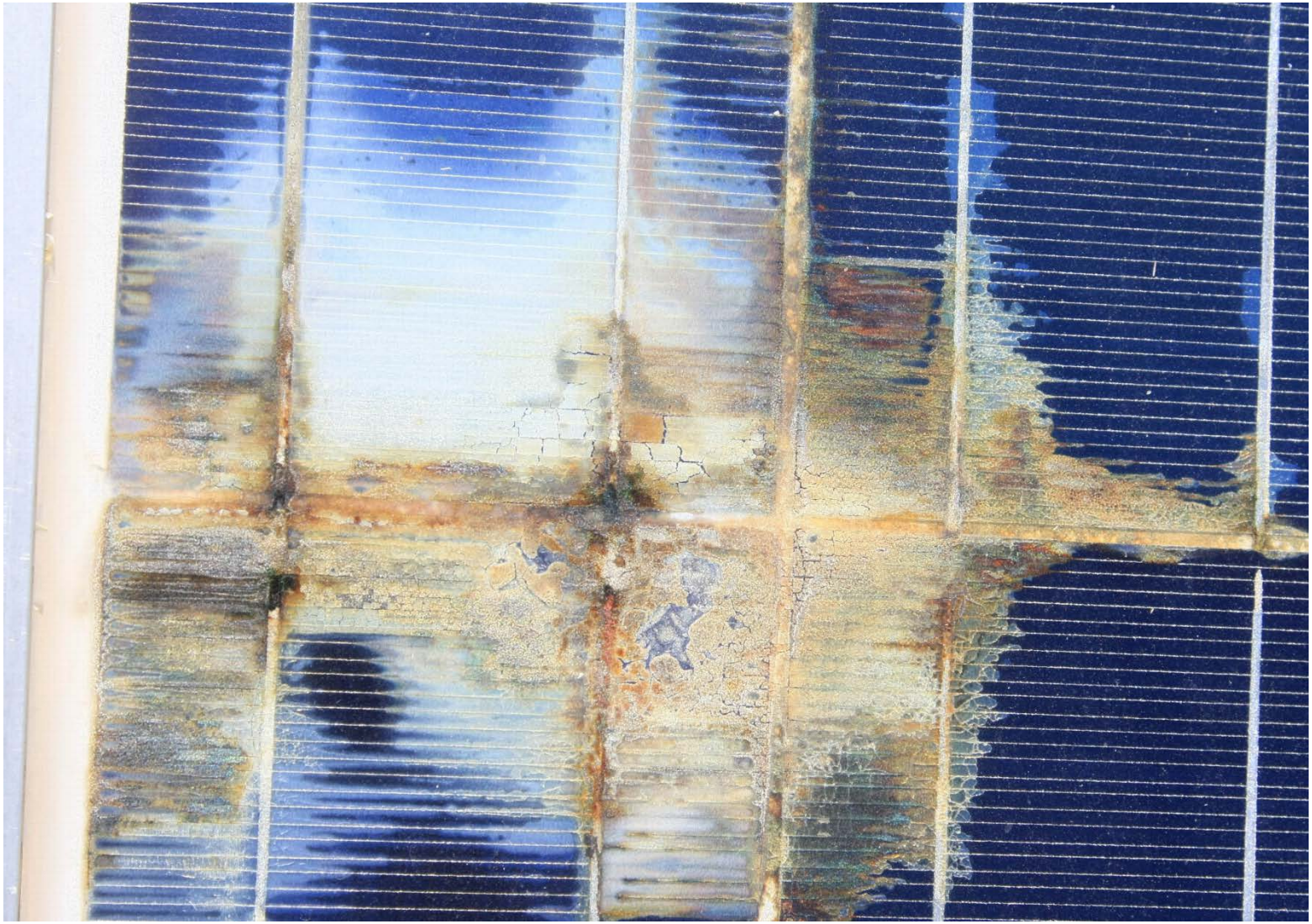
1. Develop a good test method for adhesion.
2. To be able to determine thermal and UV acceleration parameters.
3. Find accelerated stress test conditions predictive of future performance.

We Need Estimates of the Sample Temperature

- In weathering instruments, the sample is heated above the air temperature.
- We are sending thermocouple-equipped samples to the labs to evaluate the heating of their particular instruments.
- Depending on the sample and the chamber, they may be between 2°C and 18°C above the air temperature.



Artwork



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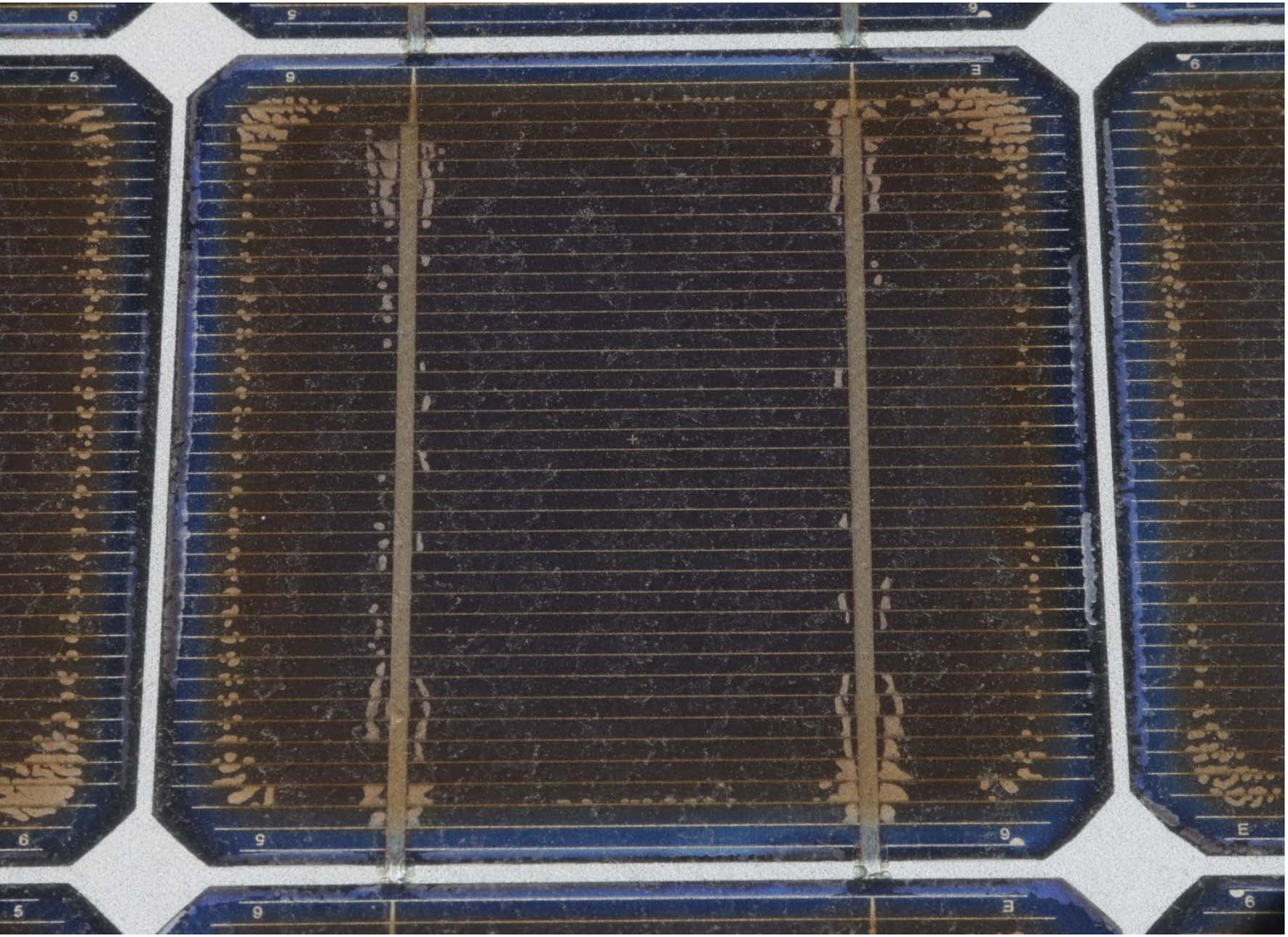


5 cm

ATLAS MATERIAL TESTING SOLUTIONS

AMETEK MEASUREMENT & CALIBRATION TECHNOLOGIES

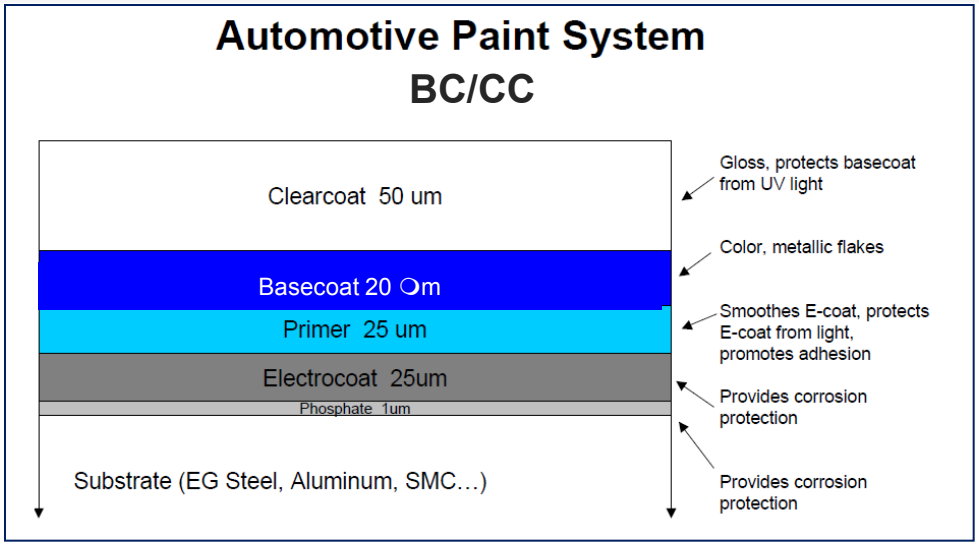
MATERIAL SCREENING | SERVICE LIFE SOLUTIONS | OUTDOOR WEATHERING TESTING

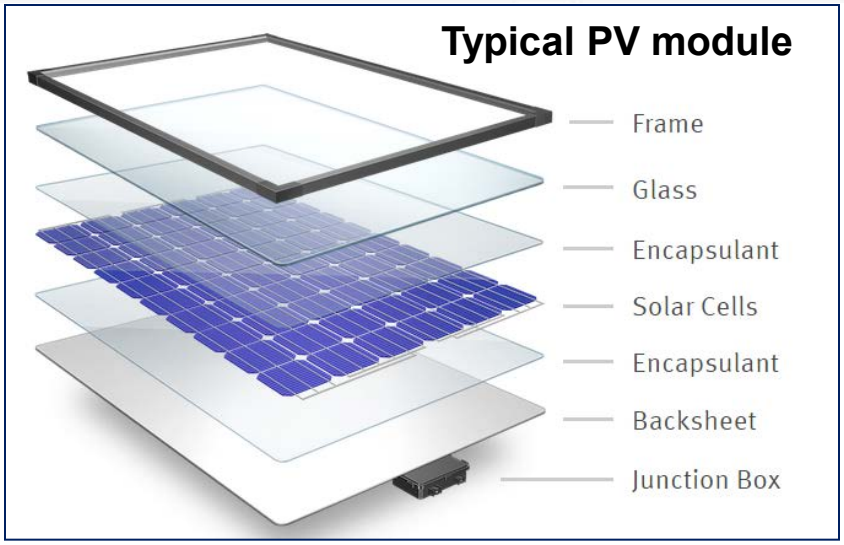
Lessons learned from other industries: A consortium of automotive stake holders' approach in the development of a science based accelerated weathering test standard

NREL PVMRW, February 24, 2015

Allen Zielnik, Senior Consultant – Weathering Science
Kurt Scott – Global Manager, Solar Energy Competence Center
Atlas Material Testing Technology LLC

Why should we care? Automotive paint and PV, more similar than you think!





M.Nichols, Ford Motor Co.

http://www.dupont.com/products-and-services/solar-photovoltaic-materials/what-makes-up-solar-panel.html

- Similar multilayer (built-up v. laminate) structure with UV filtering top layer
- Multiple material-material (diffusion and adhesion) interfaces
- Photo-oxidative and moisture sensitive materials
- Yes, each has different materials and some unique degradation mechanisms ("Denver cracking", EVA acetic acid generation and corrosion)
- PV has two weather exposed surfaces (three including edges) vs. one
- Similar global service environments (not all vehicles are garaged)
- Main difference is scale -- ❍m vs. mm and total service lifetime (10 vs 30 yr)

Automotive industry and weather durability

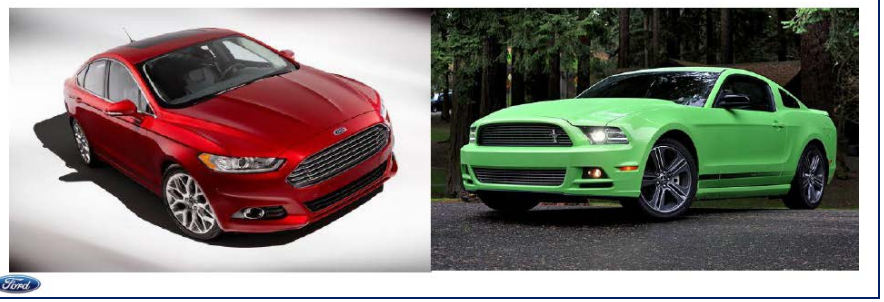
Exterior and Interior Environmental Durability

- Long lived high value product with high customer expectations.
- Need to withstand any and all climates; product is mobile.
- Variable BOM – many suppliers, changing materials, cost pressures.
- A few international weather testing standards, but most OEM's and Tier One suppliers create their own test methods and specs.
- Short product development cycle (short time to test and validate).
- Extensive long term use of accelerated weathering testing for interim acceptance coupled with real-time (5+ yr) outdoor weathering

Paint sells the car . . . or not!

Value of Automotive Coatings

- Coating appearance is a key driver of customer perception of quality.
- Functional Lifetime should be >10 years



Source: M.Nichols, *et al*, "Accelerated Weathering of Automotive Coatings: Exposure Conditions and Analysis Methods", Atlas Technical Conference on Ageing in the Environment, Oxford, UK, September, 2008.

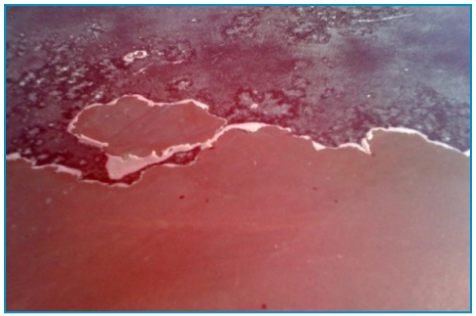
Must Reduce the Risk to an Acceptable Level

Even a poor performing paint system will last 2 years or more; that can mean production of 520,000 – 940,000 vehicles from a single plant before you even realize there is a problem.

Modern automotive paint failure

- The 1977 (Ford) Lincoln Versaille was the first production vehicle to offer clearcoat paint, followed by the VW “Sun Bug” Beetle and, in 1981, the Corvette. By mid-80’s most U.S. made cars and light trucks featured BC/CC.

- In the 80's and 90's new cars on dealer lots needed to be re-painted before they could be sold (initially blue & silver metallics were the worst)
- Today, most passenger cars by all manufacturers use BC/CC systems; failures are still seen by most OEM’s and <u>are often not predicted by current tests</u>.



Natural Weathering Test – Automotive Coatings

45˚ (or 5˚) Direct in a reference climate

5˚ Black Box automotive exposure

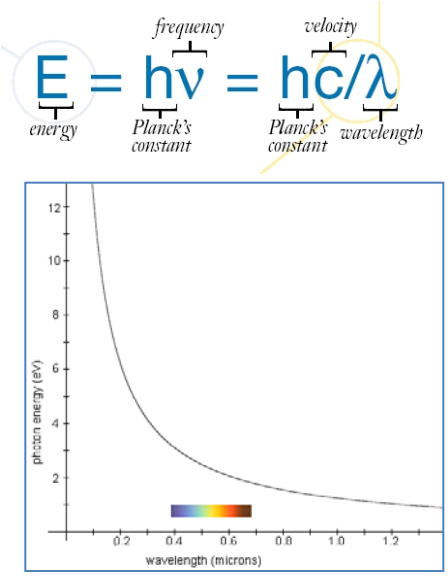
- Natural weathering exposures typically performed in **subtropical climate**
  - Hot, humid (maximum wet time), high annual UV dose – South Florida

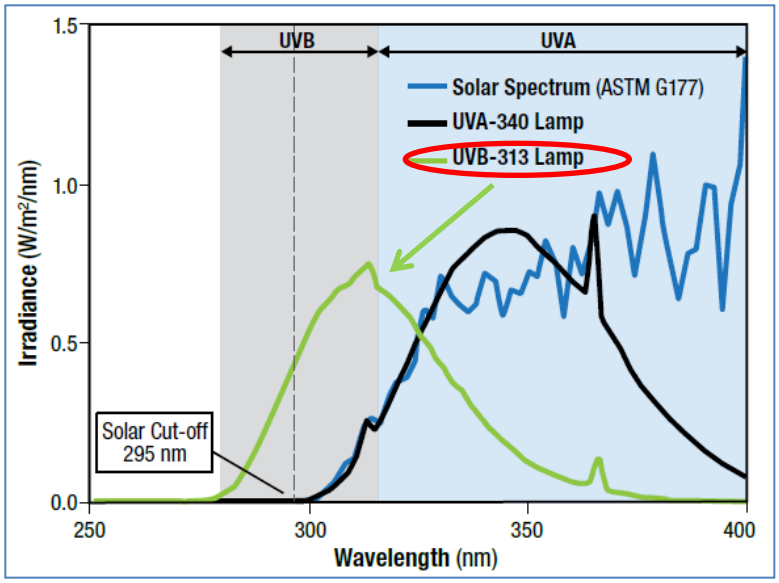
- **Black Box** better simulates *in-situ* automotive temperature / moisture profiles due to dead air space volumes (e.g., underhood, trunk and passenger cabin)

Today, long 5 yr minimum to 10 yr exposure required to approve a new coating formulation or pigment system is burdensome, but the costs of a paint failure are huge.

So what happened?

- The weathering performance of clearcoat/basecoat paint systems was assessed on the basis of gloss loss and color change traditionally used for monocoat paints.
- The testing philosophy used the “bigger hammer” harsher-is-better way to highly accelerate testing using UVB-313 fluorescent lamps with condensation.



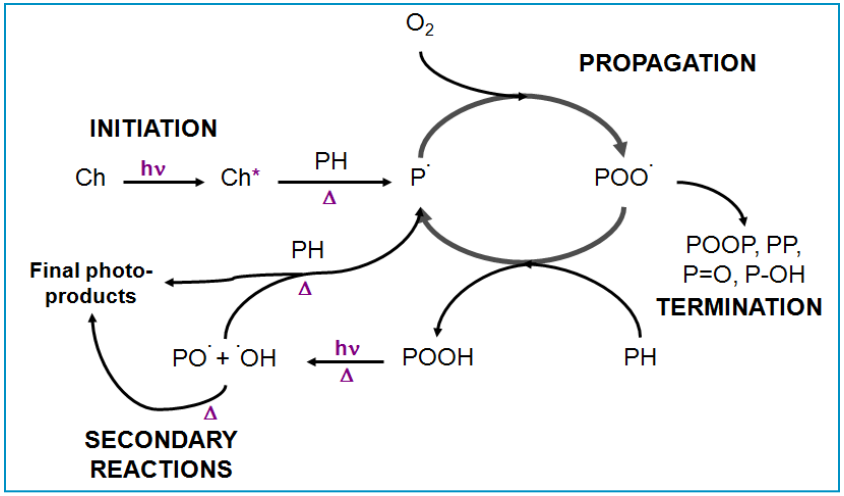


- “Slower” xenon (SAE J1960), EMMAQUA (ASTM G90) testing was still ongoing, but showed some “anomalies”; real-time outdoor testing was begun.
- But based on UVB-313 testing the decision was made to “start painting cars”.
- Note: Fluorescent UV testing is no longer used for paint system qualification although an SAE J2020 test is still “on the books” (original 1989, updated 2003)

What went wrong?

- But, this was inadequate to correctly assess the weathering performance of clearcoat/basecoat paint systems which are entirely capable of failing suddenly and catastrophically by clearcoat cracking and/or peeling with little or no gloss loss indication that failure is imminent.
- Loss of UV absorber (UVA) or HALS, clearcoat oxidation, localized hydrolysis, etc., all contribute to failure.

Polymer Autocatalytic Photooxidation Cycle

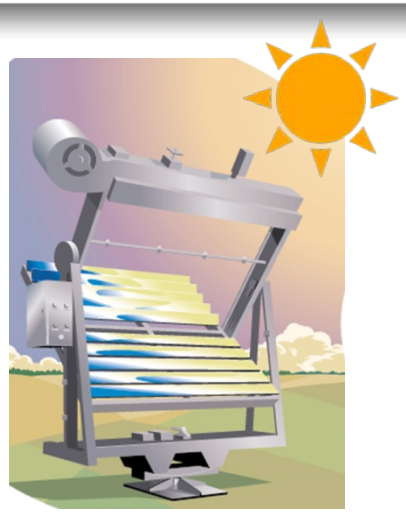


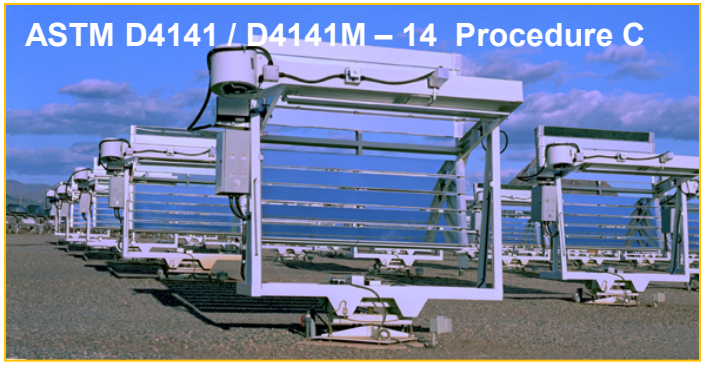
Note: Hydrolysis reactions not shown

- In attempt to be fast and severe, the accelerated test significantly *altered* the natural photo-degradation chemistry –- and in this case did not result in the delamination and other failures soon seen in the field!

Accelerated weathering tests – automotive coatings

Fresnel solar concentrator

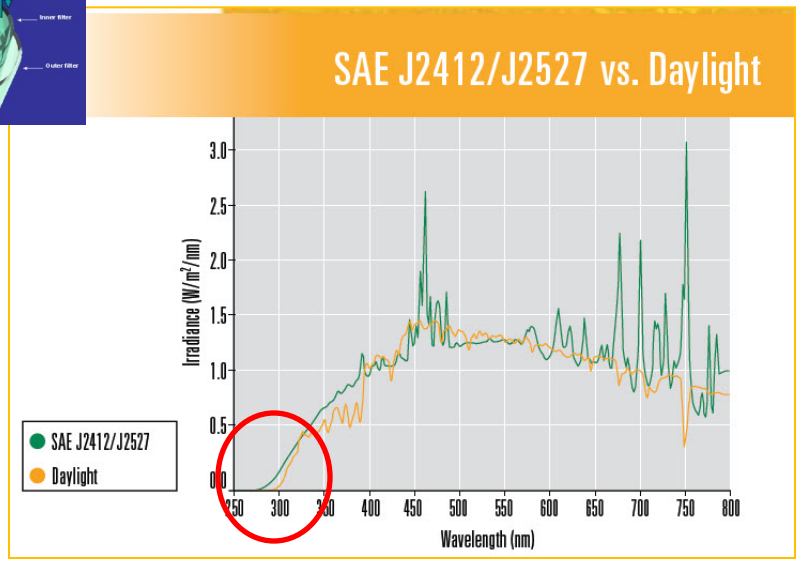




General standard ASTM G-90 EMMA® / EMMAQUA® (with water)

Laboratory – xenon arc light source

Weather-Ometer®



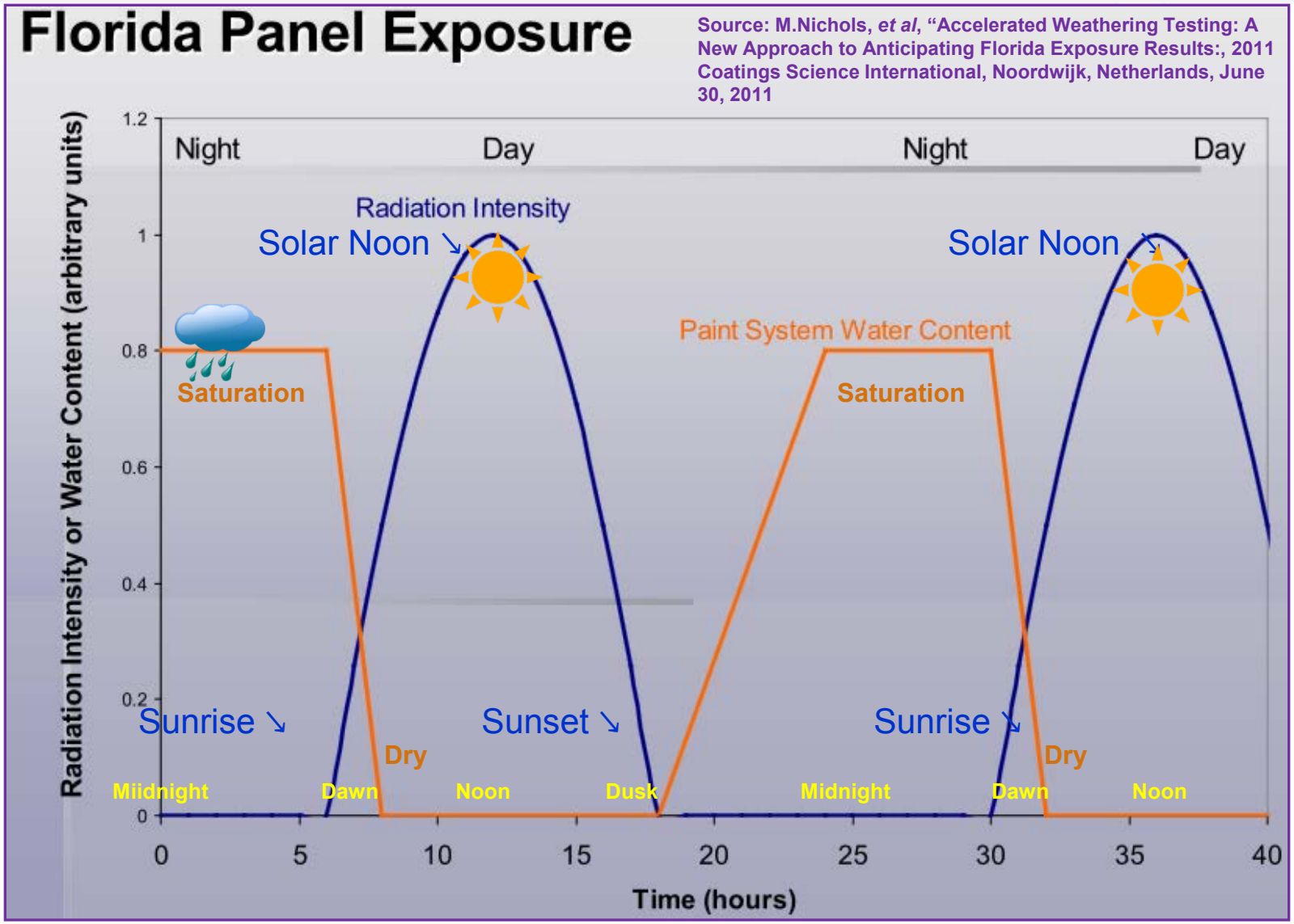
Many other methods also used

OEM	Test Method
Ford	SAE J1960-Daylight Filters
	SAE J2527
	FLTM BO 116-1
	FLTM EU BO 050-1
General Motors	GMW 14650
	SAE J2527
	ISO 4892-2
	GMW 14170
	SAE J1960
Volkswagen	PV3929
	PV3930
Hyundai	MS-300-31
PSA (Peugeot, Renault)	D27 1380
	D27 1389
	D27 1911 / --D (2007)
Fiat	50451
Porsche	ISO 4892-2
Daimler	DBL 7399
	DBL 5555
SAAB	STD 3159
Volvo	STD 1027, 337
International	ISO 11341
	ISO 4892-2
	JASO M351
	JIS D0205
	SAE J1960/J2527

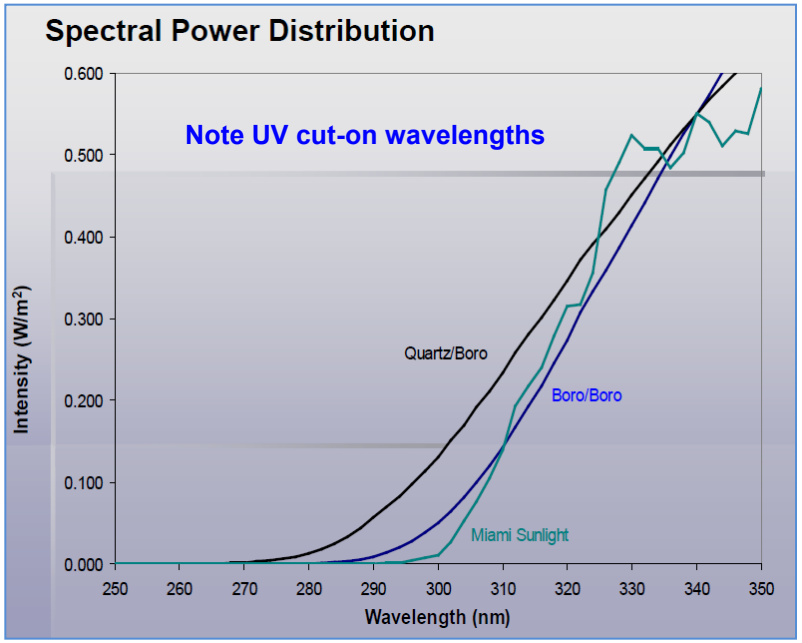
SAE J1960 (now J2527) brief background

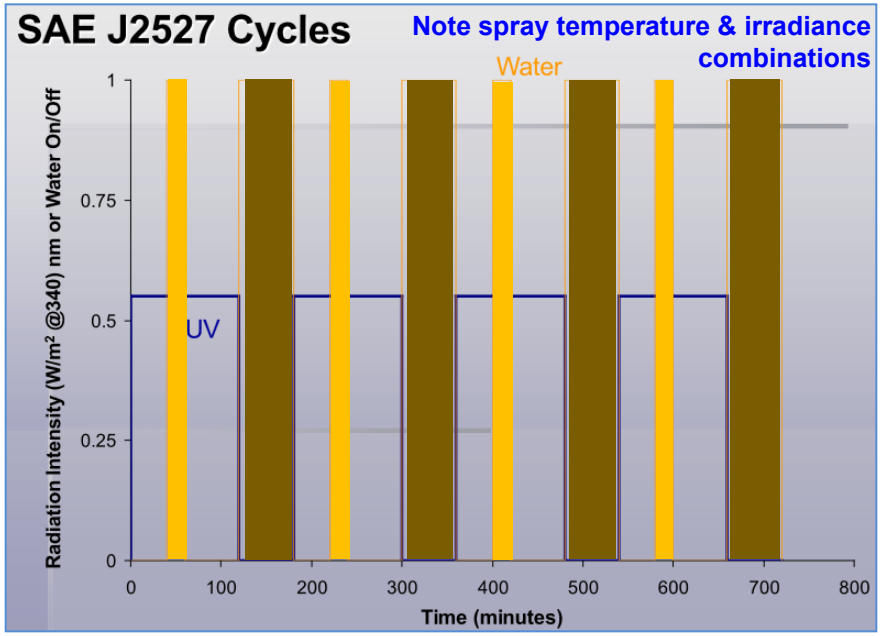
- For over 20 years the *de facto* standard for xenon testing of automotive exterior materials by Detroit "Big 3" & Tier 1 suppliers (but not by European or Asian OEMs)
  - Mid 1980's – original test method development, primarily by GM
  - SAE J1960 (1989) standard using "extended UV" filters; UV more severe than sunlight (lower UV cut-on λ ~270nm)
  - Late 1990's - Ford adopts a "modified" SAE J1960, using "Daylight" filters – less unrealistic UV (cut-on ~285nm)
  - 2004 – SAE J2527 replaces J1960 – "Performance-based version" with choice of "extended UV" or "daylight" filters, *but still excessive UV*
  - **Frequent lack of correlation with South Florida 2 & 5 year results (Note – this is not unique to automotive coatings!)**

So.Florida Diurnal Cycle – Solar Radiation & Moisture



SAE test cycle

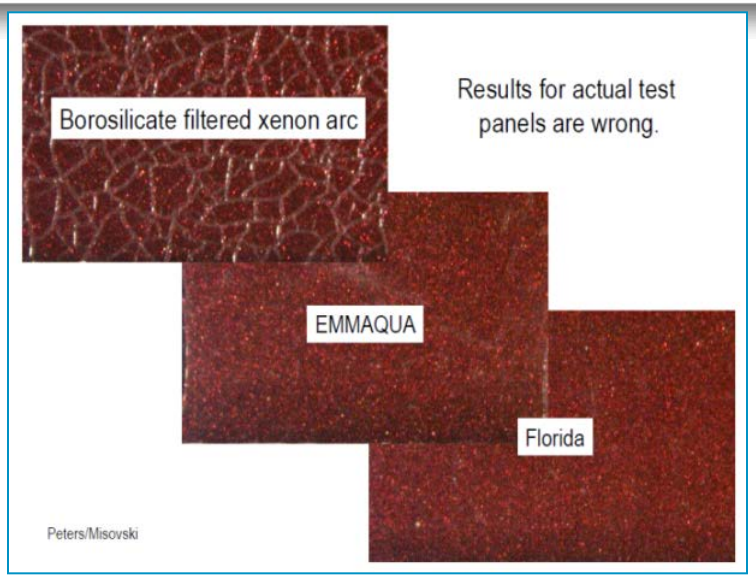




Step#	Water Spray	Irradiance (W/m² @340 nm)	Humidity %	Chamber Temperature (˚C)	Black Panel Temperature (˚C)	Duration (minutes)
1	Off	0.55	50	47	70	40
2	Front Spray	0.55	50	47	70	20
3	Off	0.55	50	47	70	60
4	Back Spray	0	95	38	38	60

Source: M.Nichols, *et al*, "Accelerated Weathering of Automotive Coatings: Exposure Conditions and Analysis Methods", Atlas Technical Conference on Ageing in the Environment, Oxford, UK, September, 2008.

SAE test cycle

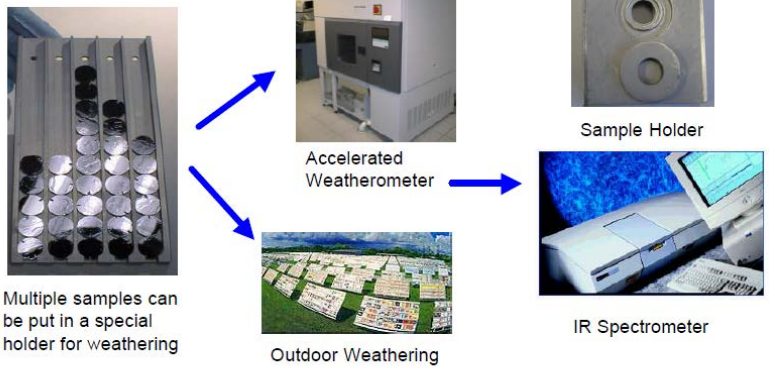


What is Wrong with the Current Tests?

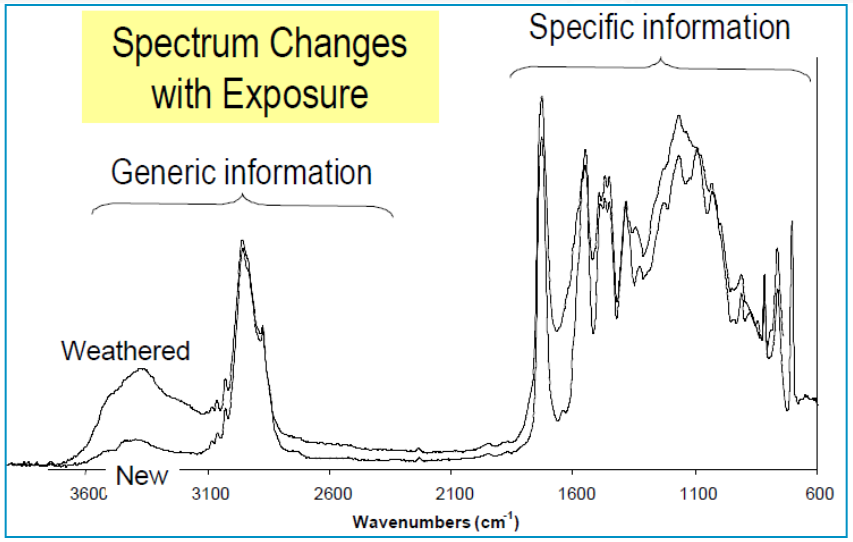
- Light source – output from lamp/filters does not match sunlight
- Temperature – water spray when the light is on
- Time of wetness – panels are wet for a long time outdoors
- Humidity – rarely reach temperature/humidity conditions outside

Source: M.Nichols, *et al*, "Accelerated Weathering of Automotive Coatings: Exposure Conditions and Analysis Methods", Atlas Technical Conference on Ageing in the Environment, Oxford, UK, September, 2008.

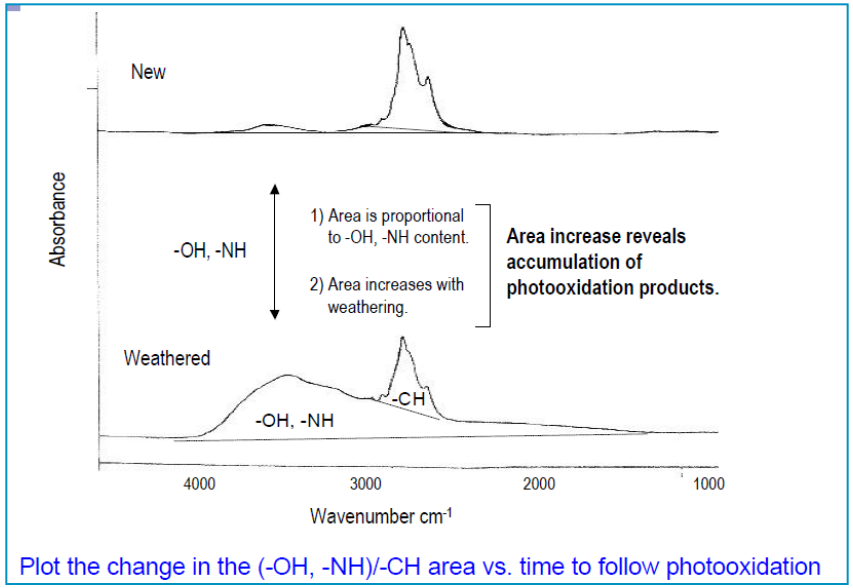
Weather-Ometer & Outdoor Findings



Record IR Spectra as a function of exposure time….



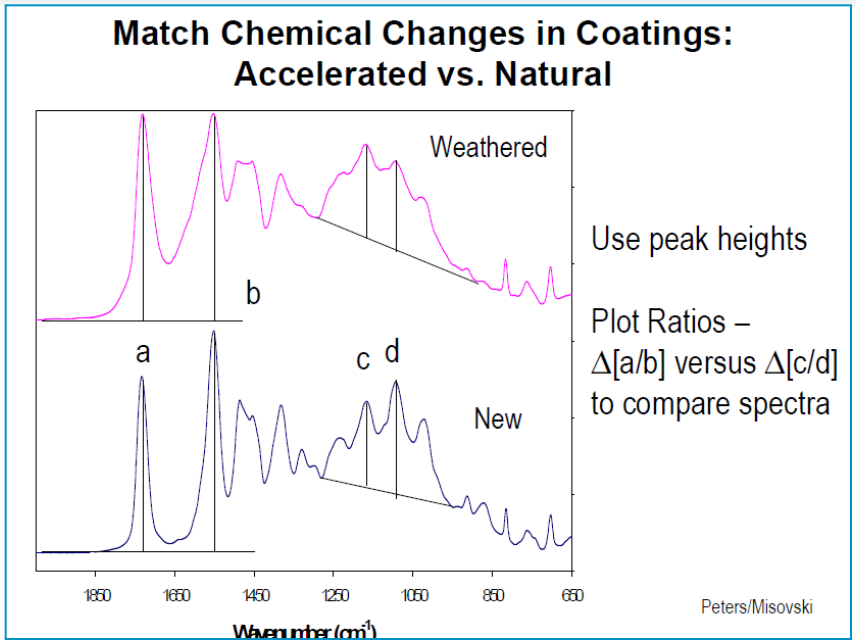
- Accumulation of phootoxidation products by (Δ –OH, -NH / -CH) ratio with PAS-FTIR correlates well with outdoor
- CC's that crack or loss gloss rapidly tend to accumulate higher levels at shorter exposure times.
- PAS-FTIR helps predict systems that will lose gloss or crack

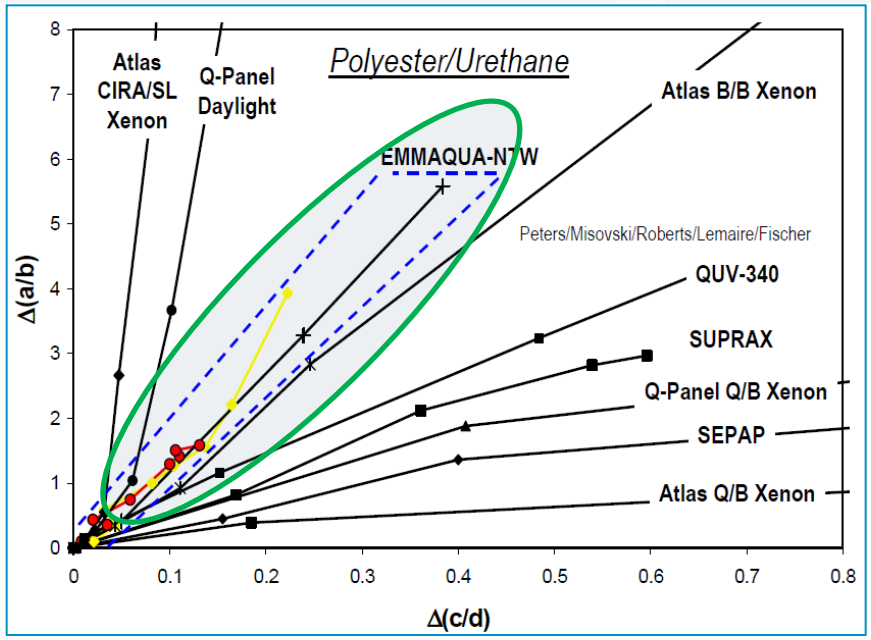


Plot the change in the (-OH, -NH)/-CH area vs. time to follow photooxidation

Source: M.Nichols, *et al*, "Test Methods to Determine the Long Term Weathering Performance of Coatings Systems – Chemical and Mechanical Testing of Paint Systems, October 6, 2005,

Weather-Ometer & Outdoor Findings



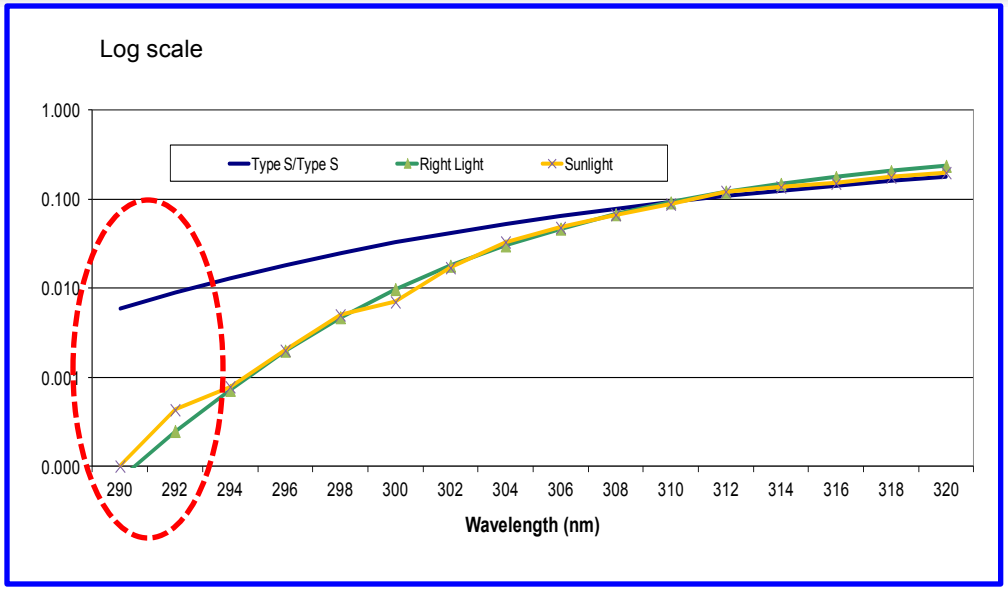


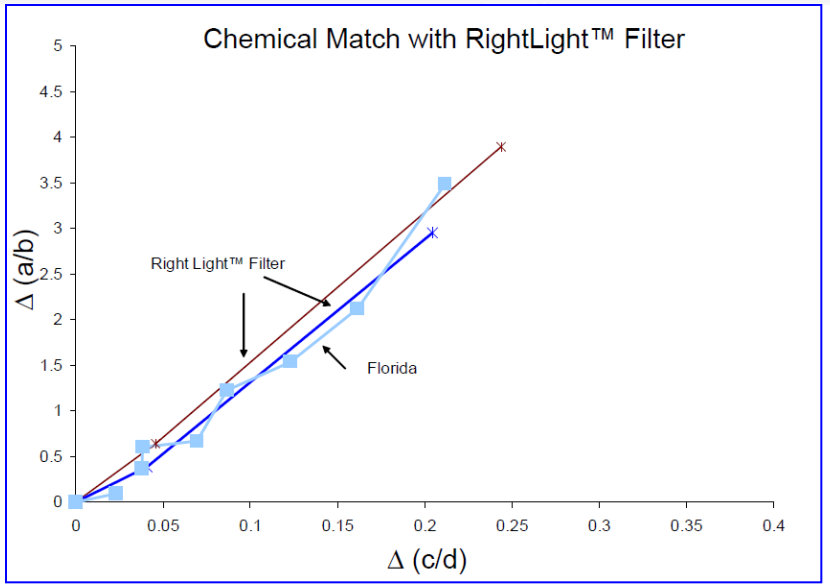
- Ratio plots of more specific FTIR chemical marker peaks showed a good photochemical match of EMMAQUA to outdoors. Various lab accelerated systems with various spectral power distributions (SPD) all skewed the photochemistry.

- Critical need to "Get the light right" in accelerated tests to reproduce the photochemistry. None of the existing lab systems match TSR SPD well enough.

Source: M.Nichols, *et al*, "Accelerated Weathering of Automotive Coatings: Exposure Conditions and Analysis Methods", Atlas Technical Conference on Ageing in the Environment, Oxford, UK, September, 2008.

“Getting the Right Light”





Source: M.Nichols, *et al*, “Accelerated Weathering of Automotive Coatings: Exposure Conditions and Analysis Methods”, Atlas Technical Conference on Ageing in the Environment, Oxford, UK, September, 2008.

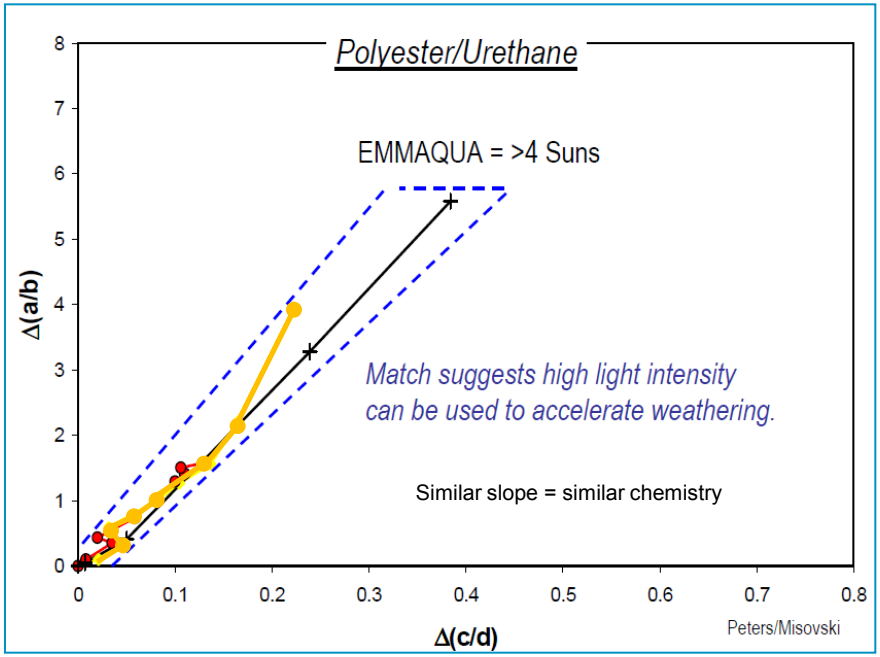
- A new xenon lamp filter set correctly matches the UV cut-on of terrestrial solar radiation *and* correctly reproduces the photochemistry.

“The precise simulation of terrestrial sunlight, particularly in the short UV range, is even more critical for reliable weatherability testing of automotive coatings than originally thought. Xenon light used in conjunction with the Right Light™ filter provides the appropriate ultraviolet spectrum for weathering of today’s complex automotive coatings.”

Dr. Mark Nichols, Ford R&D, Exterior Coatings

Source: Quoted in Atlas Sunspots, Vol. 38, Issue 81; http://atlas-mts.com/technical-information/sunspots

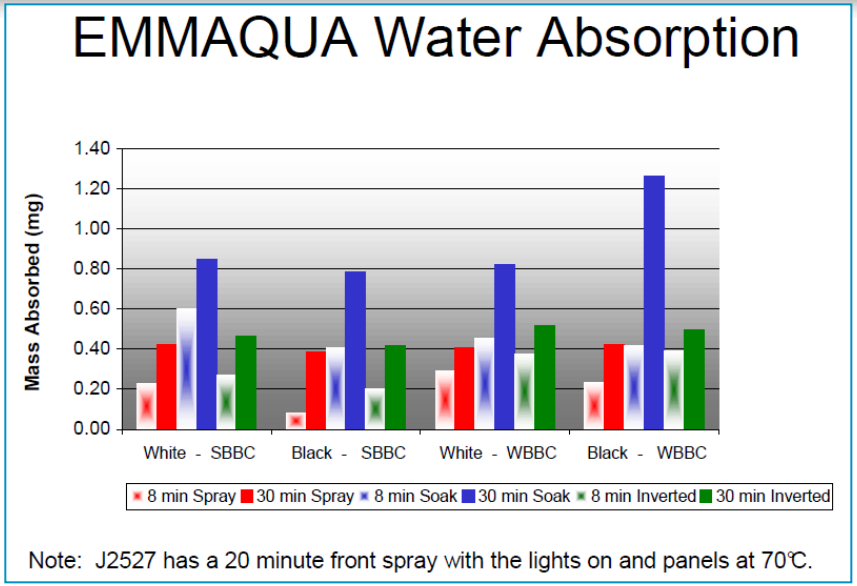
Weather-Ometer & Outdoor Findings



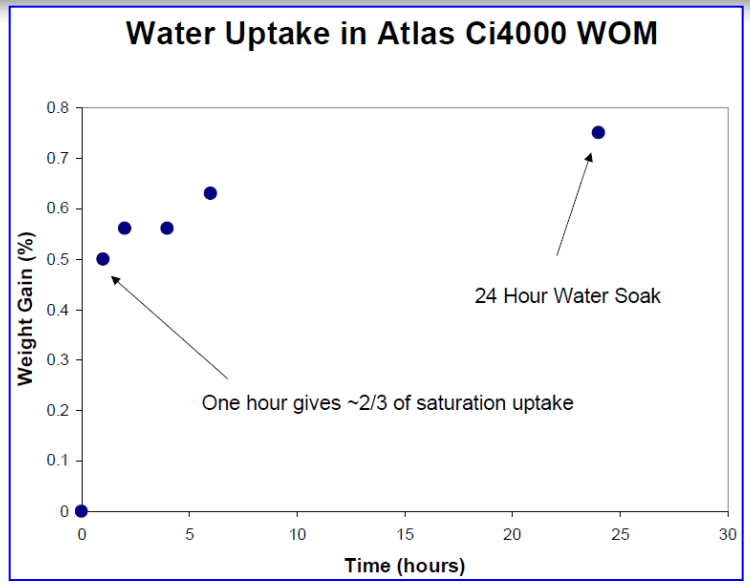
- With the "right light" the photochemistry matches outdoor weathering.
- *BUT*, the paint panels DON'T always or completely reflect that.
- So, there may be chemical effects not detected by FTIR, or a physical effect occurring in addition to the photochemistry known to cause cracking and blistering.

Source: M.Nichols, *et al*, "Accelerated Weathering of Automotive Coatings: Exposure Conditions and Analysis Methods", Atlas Technical Conference on Ageing in the Environment, Oxford, UK, September, 2008.

Findings About Water



Source: M.Nichols, *et al*, "Accelerated Weathering of Automotive Coatings: Exposure Conditions and Analysis Methods", Atlas Technical Conference on Ageing in the Environment, Oxford, UK, September, 2008.



5.5 hours to reach acceptable water uptake (near saturation) based on average Florida wet time

Additional studies have shown that temperature is the most significant factor. Sprays v. immersion – or orientation (vertical/horizontal) has no effect

Effects of water on weathering

- Plastication – reduced modulus
- Swelling – induced stresses due to differential stresses
- Blistering – localized swelling and rupture
- Adhesion – accumulation of water at interface, breakdown of interfacial bonds
- Mass transport – movement of small molecules and reaction products through film
- Mass loss – removal of film (degradation products) from surface of the coating due to erosion

Source: M.Nichols, *et al*, "Accelerated Weathering Testing: A New Approach to Anticipating Florida Exposure Results:, 2011 Coatings Science International, Noordwijk, Netherlands, June 30, 2011

Water Implications and Approaches

Implications for Accelerated Test Cycles

SAE J2527
- 2 Hrs light (w/ 20 minute H_2O spray), 1 Hr dark w/ back spray
- ~4kJ/m^2 @340 nm per 3hr. Cycle (0.55 W/m^2 @340nm)
- One wet-dry interval/cycle

Florida Exposure
- 7.5 kJ/m^2 @340nm per day
- 1 wet-dry cycle per day
- 3600 Hrs. wetness/year (~10 hrs/day)

Possible Approaches

Heat water to accelerate diffusion and shorten saturation time
- Must ensure we do not alter chemistry

Disregard water scaling and accelerate with long light and long but infrequent water soaks
- Must introduce correct mechanical stresses

Source: M.Nichols, *et al*, "Accelerated Weathering Testing: A New Approach to Anticipating Florida Exposure Results:, 2011 Coatings Science International, Noordwijk, Netherlands, June 30, 2011

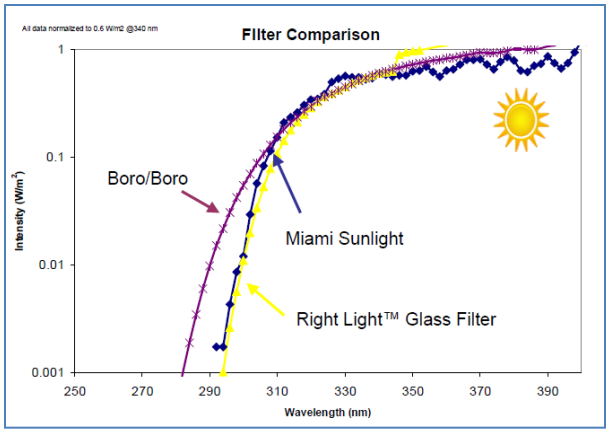
- After considerable experimentation and many iterations, a solution to the problem of long water saturation times, the need for frequent cycling for mechanical stress, and the desire not to modify existing commercial instrument hardware was developed . . . .

Xenon arc devices accelerate weather stresses

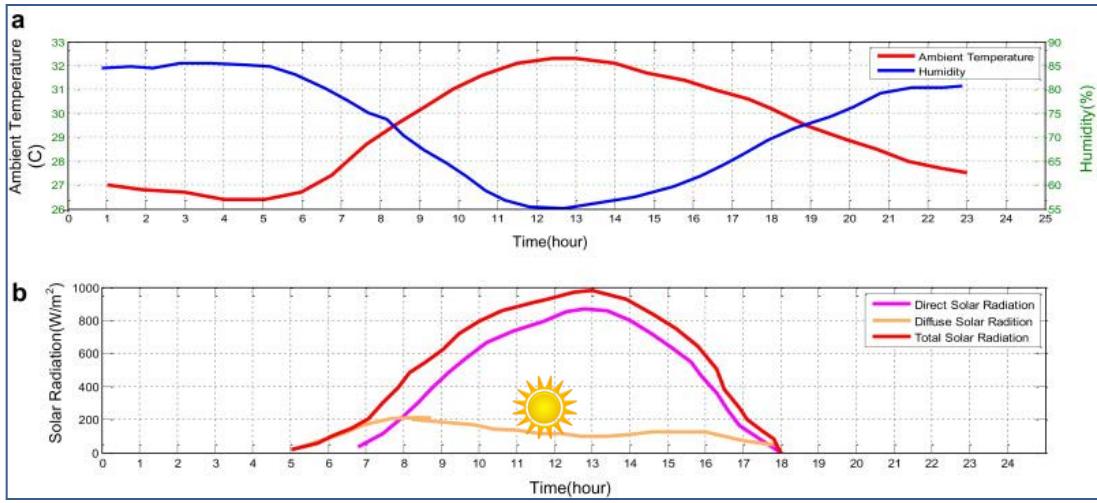
Solar spectrum, daily intensity & cycles

Solar load, heating and cycles

RH%. Dew, rain, cycles



Source: M.Nichols, *et al*, "Accelerated Weathering of Automotive Coatings: Exposure Conditions and Analysis Methods", Atlas Technical Conference on Ageing in the Environment, Oxford, UK, September, 2008.



However, current test methods have very limited, if any, cycling.

The seeds of a better, predictive test

20 years of experimental research findings:

- Much of the failure was traced to a spectral mismatch between the lab light source and outdoors. Fluorescent UV abandoned for qualification tests.
- Ford & GM add automotive glazing UV filtering to interior xenon test methods
- Various tests with ozone-filtered xenon led Ford *et al* to use Boro-S-Boro-S daylight xenon filters rather than SAE J1960 Quartz/Boro "extended UV".
- FTIR spectroscopy showed only EMMAQUA produced the same weathering chemical marker changes as real time outdoor testing.
- Clearcoat UV Absorbers depleted from the top down (microtomy and ATR spectroscopy)
- Search to "Get the light right" led to iterations of improved spectral match filters, especially in UV cut on wavelength and IR heat reduction.
- Extended water soak and EMMAQUA spray cycles revealed inadequate water uptake of coatings with current methods. And it doesn't rain when the sun is brightly shining!

Collaborators

Volvo, Mazda, BASF, DuPont, PPG, Akzo, RedSpot, **Visteon**, **Ciba**, Cytec, **General Electric**, **Sabic**, **Momentive**, **Henkel**, **Atlas, Q-Panel**, Suga, Bruker, 3M, **Exatec**, **Bayer,** AOC, Ashland, Dow, **Fusion UV, NIST**, U. of Michigan, Eastern Michigan U., U. Blaise Pascal, U. Mulhouse France, **NDSU**, Swedish National Testing Institute, **GM, Chrysler**.

The seeds of a better, predictive test

Followed by 10 years of consortium effort leading to ASTM D7869:

- The methodology described is the result of a multi-year collaborative effort between researchers at the following companies:
  - Ford Motor R&D
  - Boeing Commercial Aircraft
  - BASF, Bayer MaterialScience
  - Atlas Material Testing Technology,
  - Q-Lab
  - and later, Honda R&D Americas

Paint Systems Tested

- Automotive
  - ~20 systems, multiple colors
  - All systems were BC/CC
  - Fortified and unfortified
  - Positive controls and known Florida exposure failure mechanisms
- Aerospace
  - Four systems, two colors (blue and white)
  - Two monocoat systems, two BC/CC systems
  - Florida, and in-service performance known

Source: M.Nichols, *et al*, "Accelerated Weathering Testing: A New Approach to Anticipating Florida Exposure Results:, 2011 Coatings Science International, Noordwijk, Netherlands, June 30, 2011

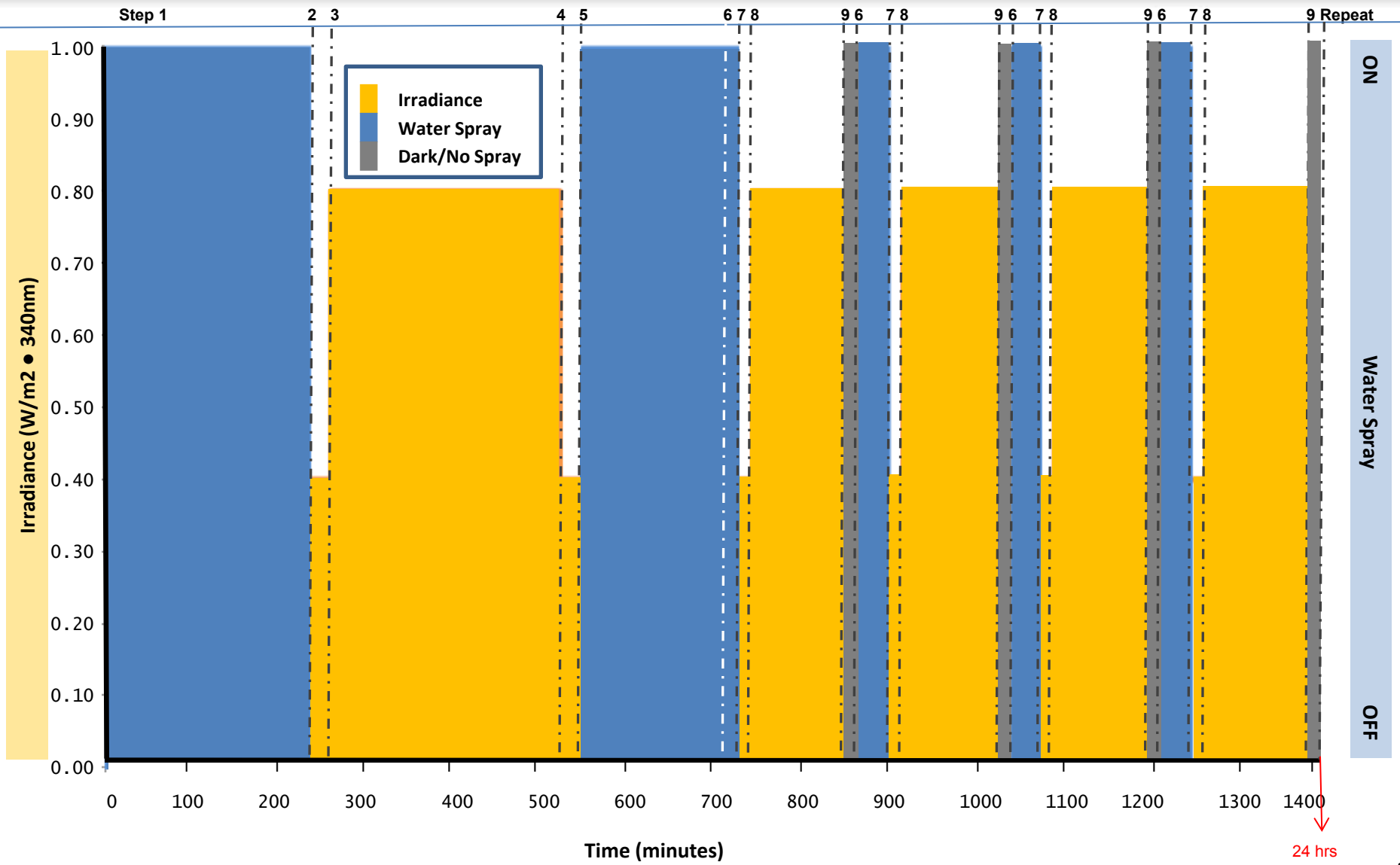
Fast Forward 10 Years -- Putting it all together: A New ASTM Test Method D7869

For reference only, this will be explained in the following slides . . .

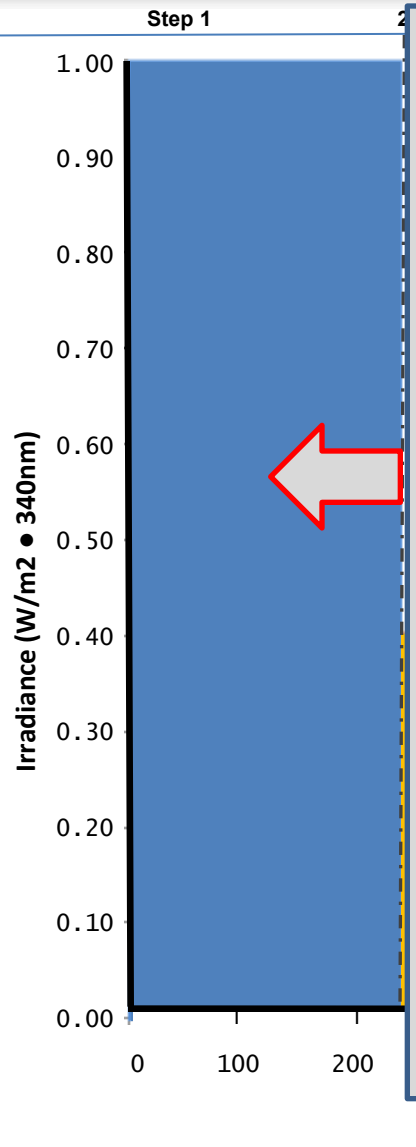
ASTM D7869 Test Cycle Sequence

Step Number	Step Minutes	Function	Irradiance Set Point[1] @340nm ($W/m^2/nm$)	Black Panel Temperature Set Point[1]	Chamber Air Temperature Set Point[1]	Relative Humidity Set Point[1]
1	240	dark + spray	-	40°C	40°C	95%
2	30	light	0.40	50°C	42°C	50%
3	270	light	0.80	70°C	50°C	50%
4	30	light	0.40	50°C	42°C	50%
5	150	dark + spray	-	40°C	40°C	95%
6	30	dark + spray	-	40°C	40°C	95%
7	20	light	0.40	50°C	42°C	50%
8	120	light	0.80	70°C	50°C	50%
9	10	dark	-	40°C	40°C	50%
10	Repeat steps 6-9 an additional 3 times (for a total of 24 hours = 1 cycle)					

Final Iteration ASTM D7869 Test Cycle



Step 1 – Deep Moisture Saturation



240 min, Dark + Spray, BPT 40°C, CHT 40°C, 95% RH

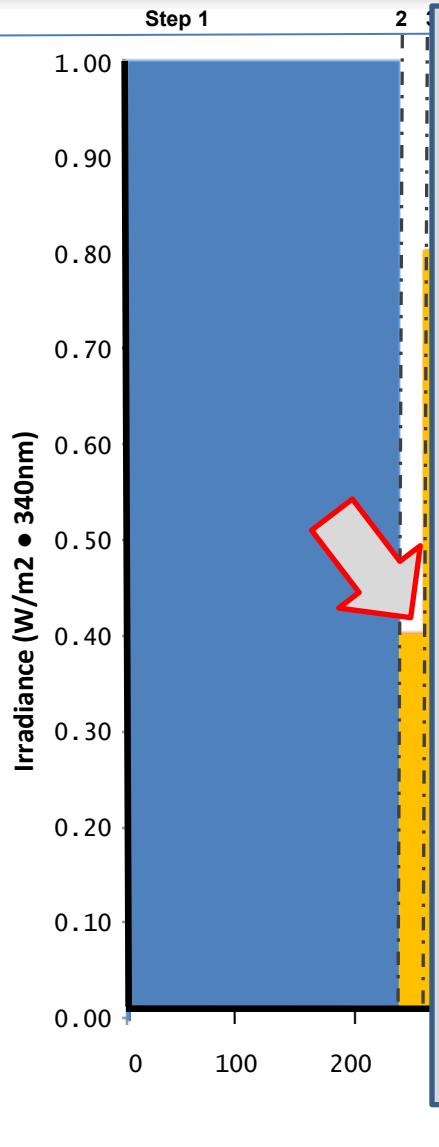
- **Purpose** - to produce water uptake within the coating that is similar to the maximum uptake in a normal day outdoors in south Florida

- Water uptake *more than* what is achieved in Step 1 did not produce significant changes in test results. However, water uptake *less* than what Step One achieves did fail to produce degradation of the types found in Florida

- Dark cycle, because almost all wetness in Florida occurs when there is no sunshine. The vast majority of wet time is caused by nighttime dew.

- Outdoor data show that natural specimen wet temperature is lower in Florida, typically 20°C to 25°C. But outdoor wet periods were also much longer, ranging from 8h to 16h. ***So 4h at 40°C produces similar water uptake to the much longer, but cooler, Florida wet periods***

Step 2 – Removing the water



30 min, Light, 0.40 W/m^2 @ 340nm *with new filter*, BPT 50°C, CHT 42°C, RH 50%

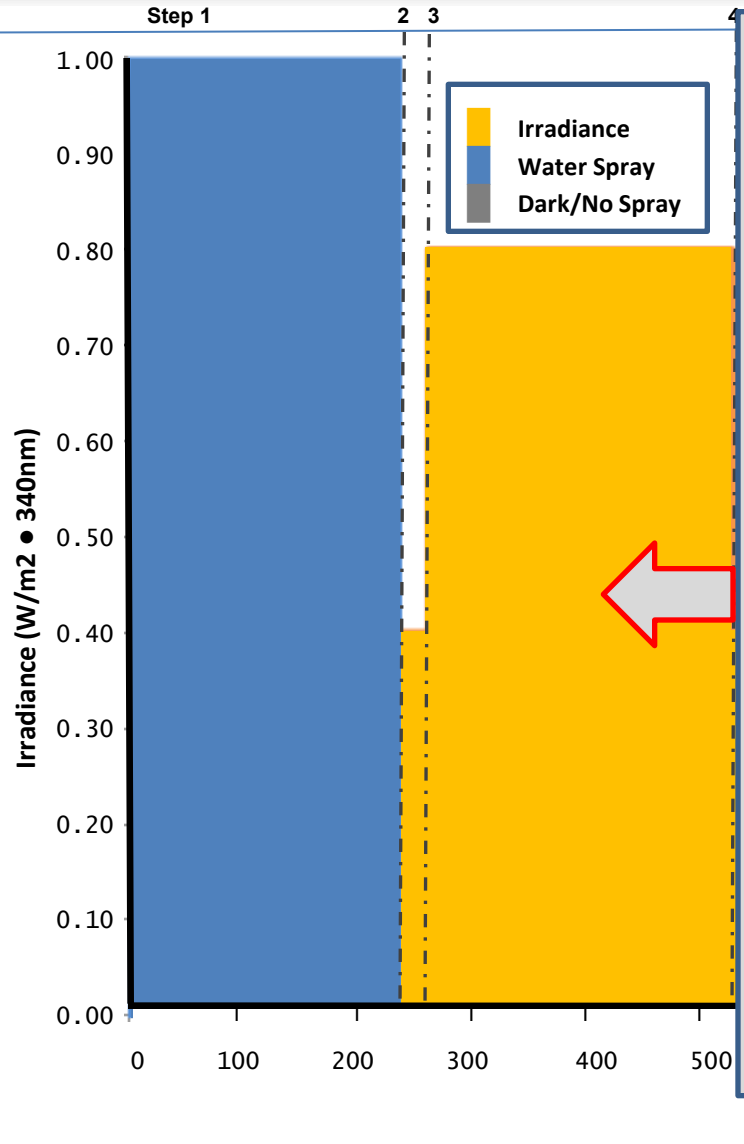
- **Purpose** - to remove all of the water from within the coating layers

- The irradiance is set at a relatively low level, 0.40 W/m2/nm, **because Florida data has shown that all the water was driven out from the coating before the sun ever got high** enough in the sky to produce higher irradiances

- The Black Panel Temperature is set at 50°C, because Florida data has shown that by the time the sun heats the specimen to 50°C, almost all of the water has been removed from the coating

- A time of 30 minutes was chosen because data has shown that ***30 minutes at 50°C is the time required to take the water content to near zero.***

Step 3 – Exposure to the Right Light



270 min, Light, 0.80 W/m^2 @340nm, BPT 70°C, CHT 50°C, RH 50%

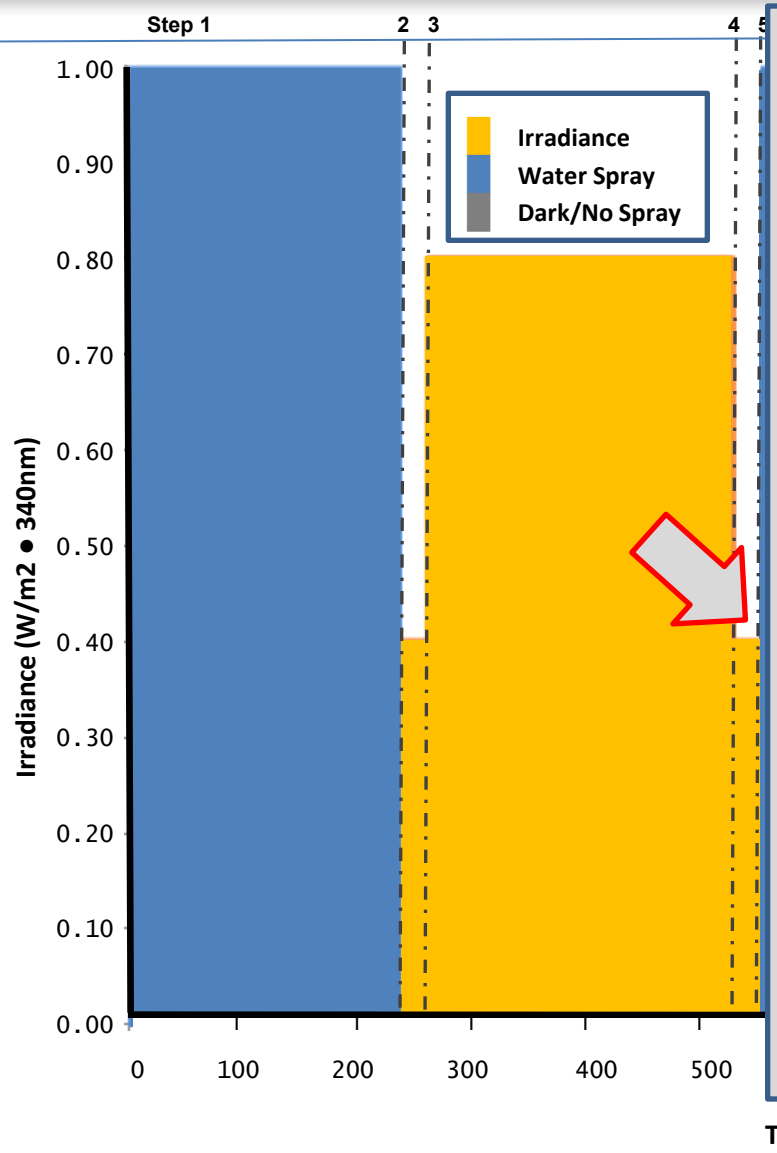
- **Purpose** – to simulate the effects of bright sunlight on the coatings.

- Most Florida sunlight exposure occurs at much lower irradiances than noon midsummer sunlight. So this irradiance can be expected to produce significant acceleration.

- **The irradiance is set at somewhat higher than the maximum irradiance seen in Florida with noon midsummer sunlight.**

- **The Black Panel Temperature is set at 70°C, because this approximates the maximum specimen temperature averaged across the color palette.**

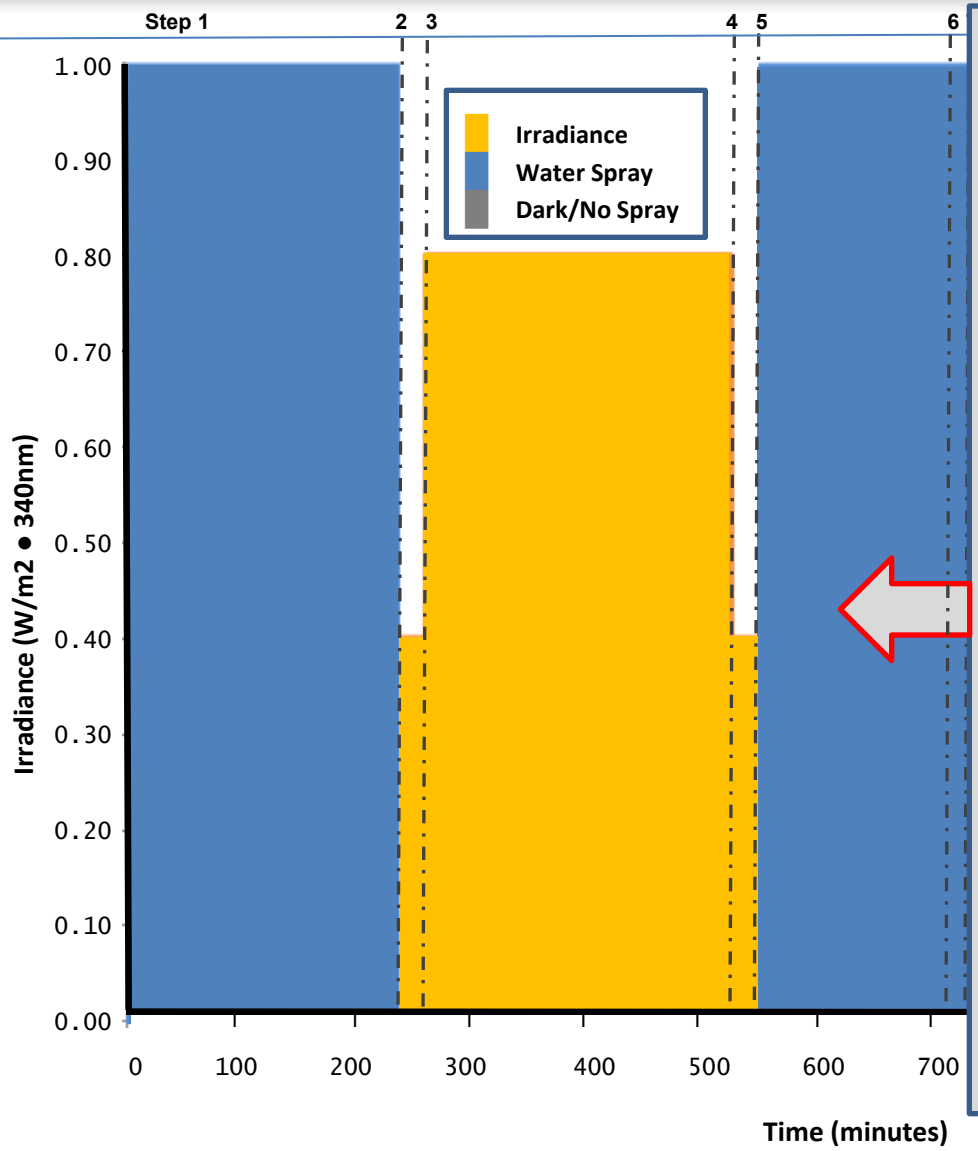
Step 4 – “Relaxation”



30 min, Light, 0.40 W/m² @ 340nm, BPT 50°C, CHT 42°C, RH 50%

- **Purpose** - to **transition** between the hot, high-irradiance “daytime” step and the dark, cool, wet “night time” step.
- This step gradually **reduces thermal stresses** within the coating, similar to what occurs as the sun gets lower in the sky during the evening.
- Unnatural effects can be produced if the test does not cool down the specimens before water is introduced. For instance, excessive cracking and micro cracking can be produced if cold water is sprayed onto a hot specimen.
- **The relatively low set points for irradiance and temperature are typical of what has been measured in FL late afternoon and early evening.**

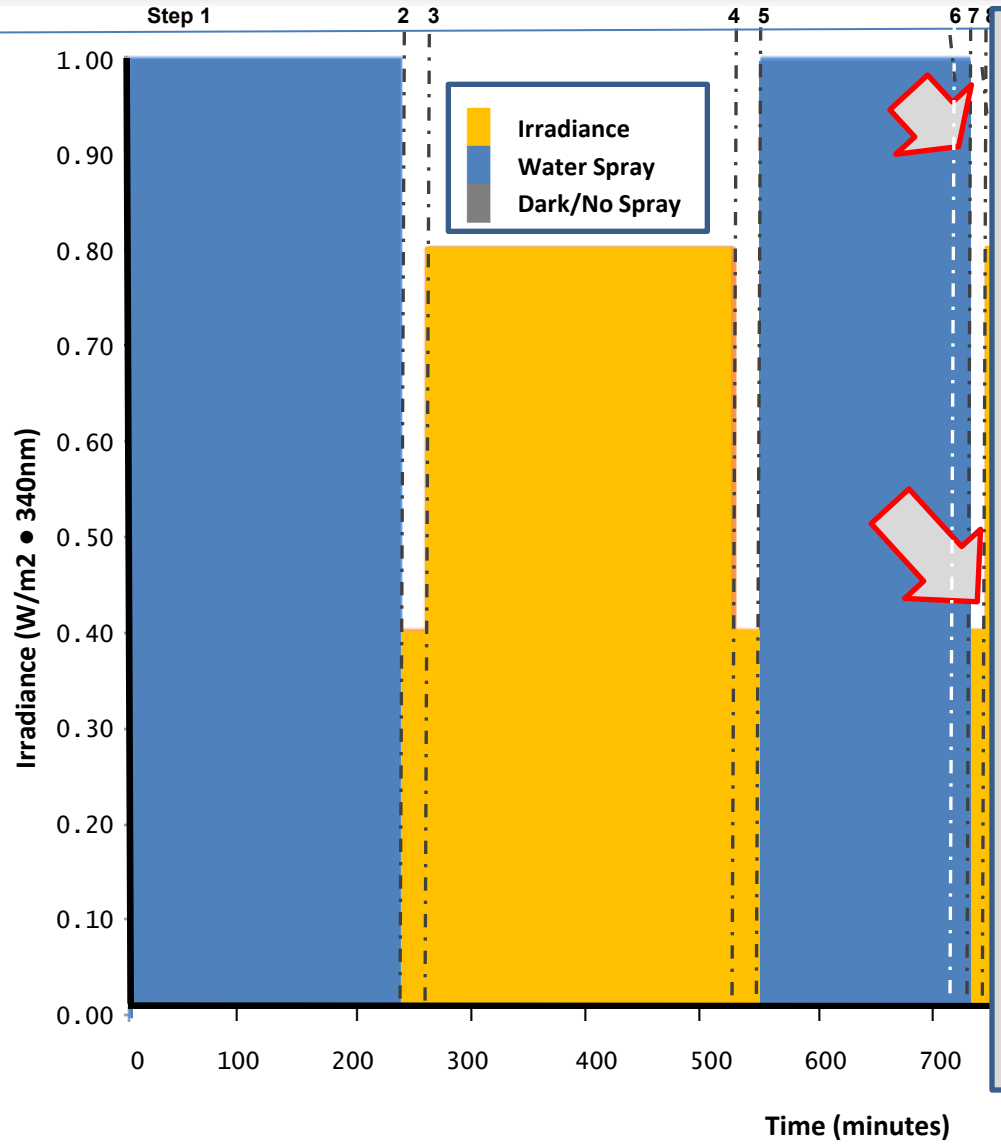
Step 5 – Water (Again)



150 min, Dark + Spray, BPT 40°C, CHT 40°C, 95% RH

- **Purpose** - to produce significant water uptake within the coating, but at somewhat less than the maximum uptake observed
- The temperatures and humidities in Step 5 are the same as in Step 1, for the same reasons.
- **The data has shown that the maximum water uptake does not occur every day in Florida. This step is intended to simulate those days of less than maximum uptake.**

Steps 6 & 7 Rain Event and Controlled Dry Out



30 min, Dark + Spray, BPT 40°C, CHT 40°C, 95% RH

- **Purpose** – to simulate a very short time water event, such as a night where little condensation occurs, **or a very short rain event**

20 min, Light, 0.40 W/m² @340nm, BPT 50°C, CHT 42°C, RH 50%

- **Purpose** – to **remove the water** from the coating at a controlled rate

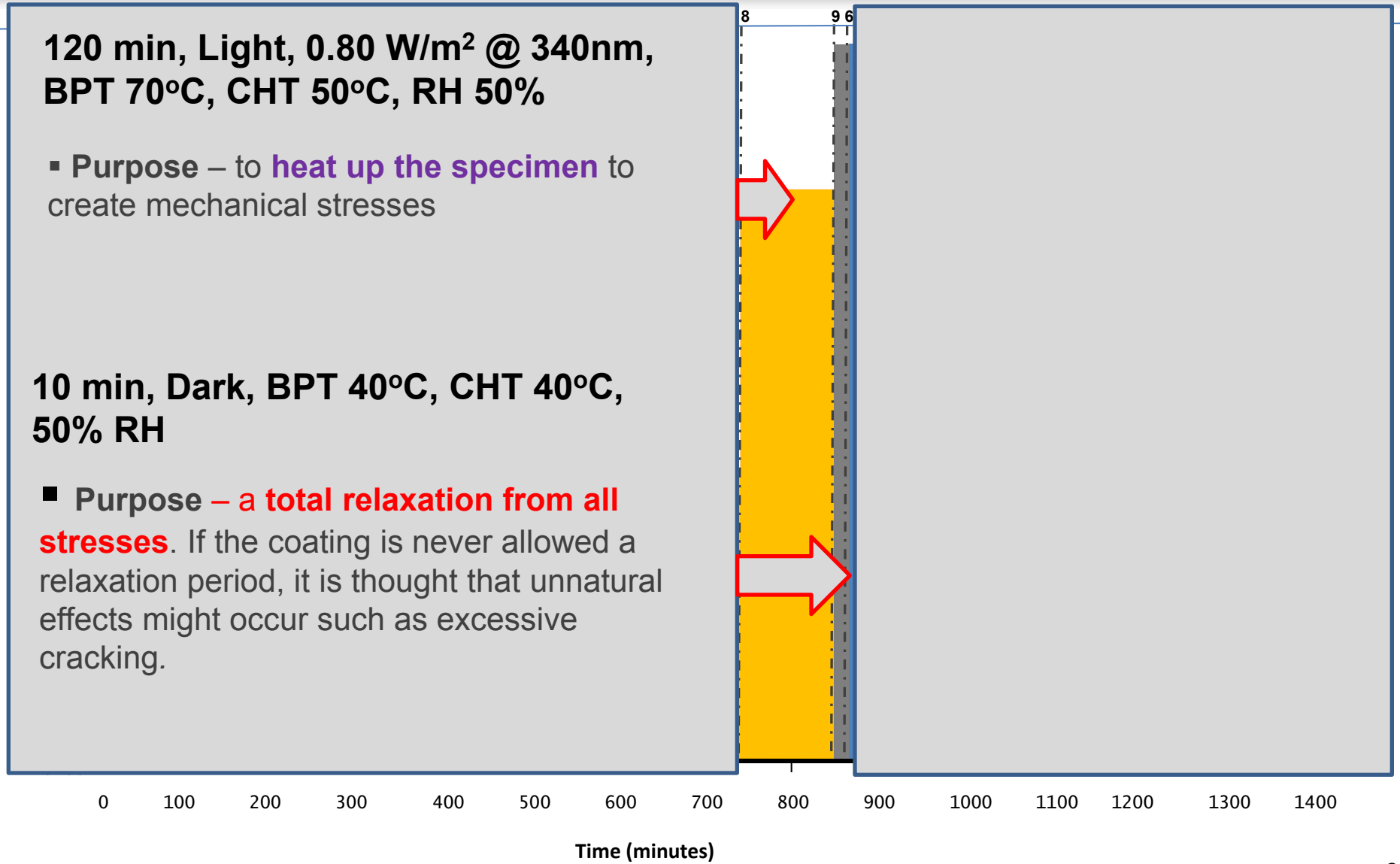
Steps 8 & 9 – Heat/Mechanical Stress & Relaxation

120 min, Light, 0.80 W/m^2 @ 340nm, BPT 70°C, CHT 50°C, RH 50%

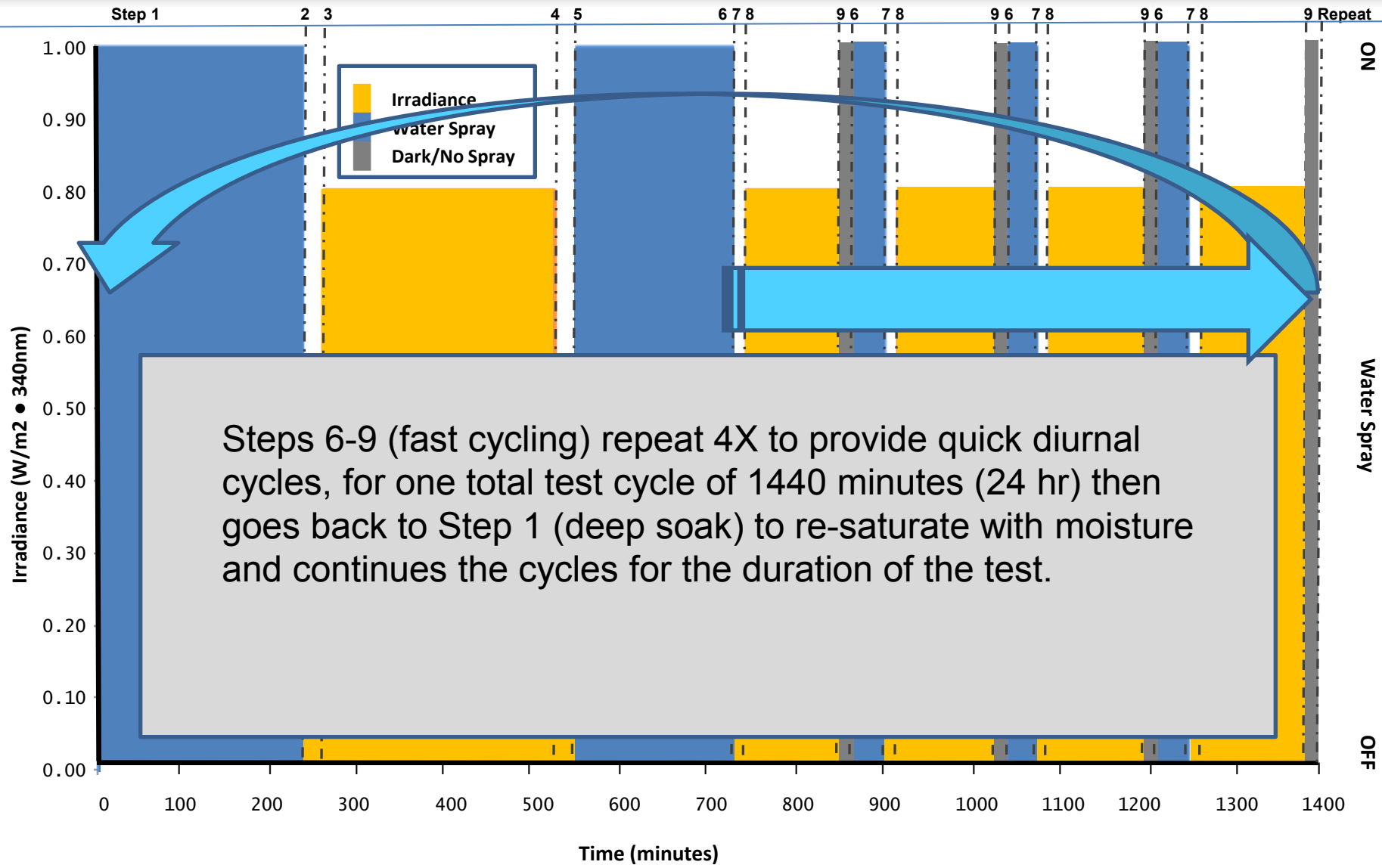
- **Purpose** – to **heat up the specimen** to create mechanical stresses

10 min, Dark, BPT 40°C, CHT 40°C, 50% RH

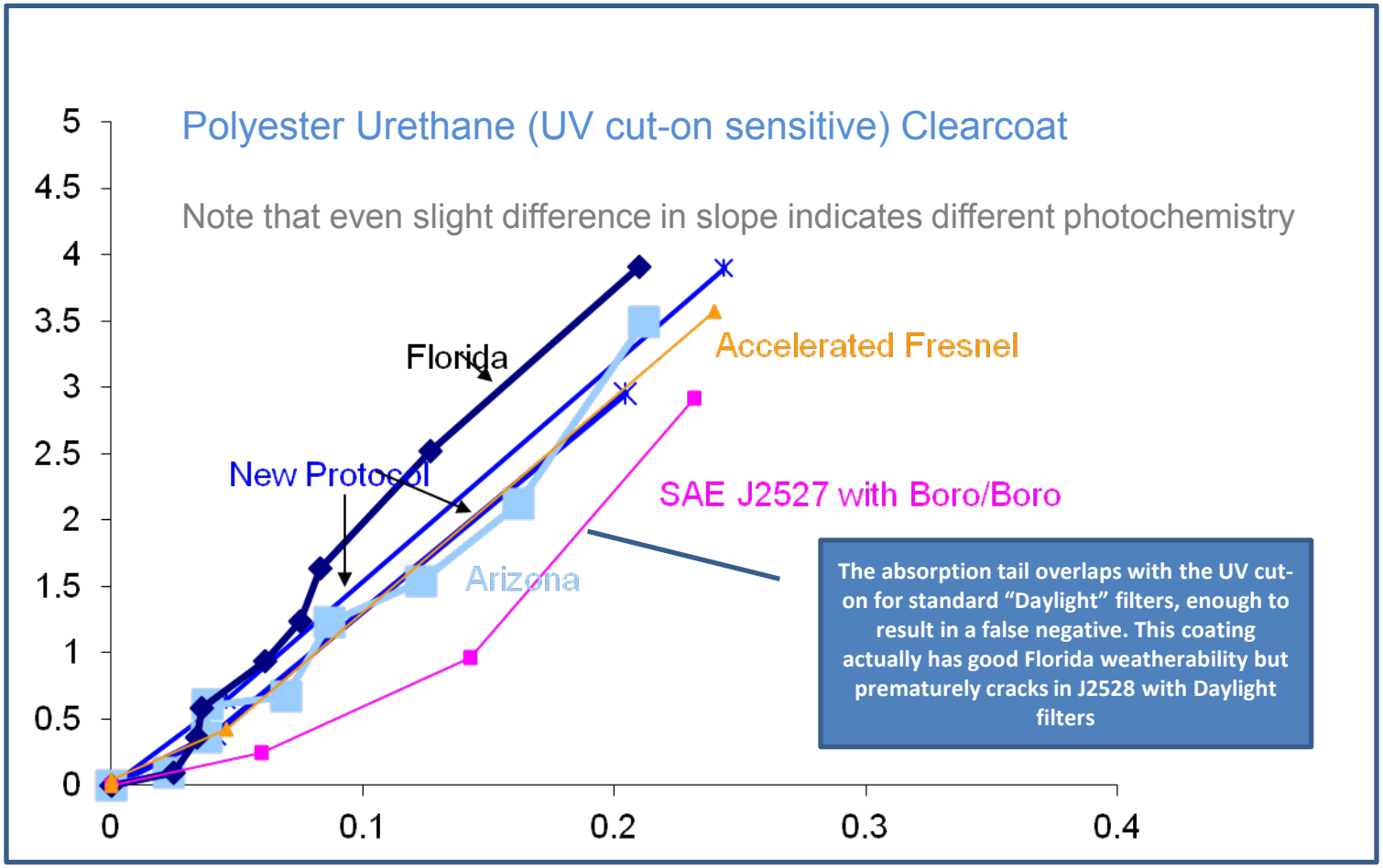
- **Purpose** – a **total relaxation from all stresses**. If the coating is never allowed a relaxation period, it is thought that unnatural effects might occur such as excessive cracking.



Final Iteration ASTM D7869 Test Cycle



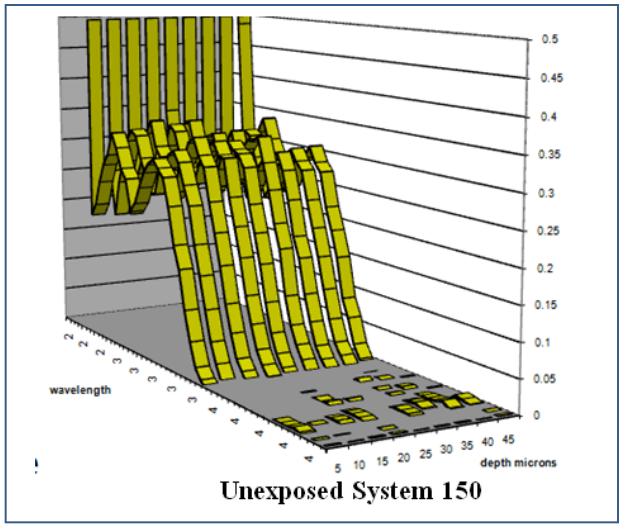
But Does It Work?

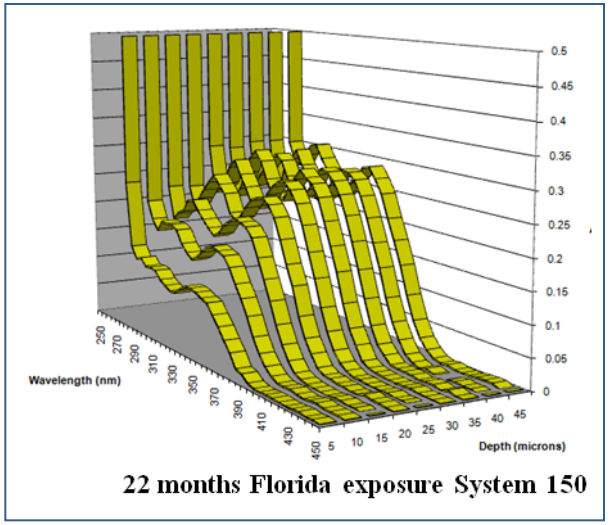


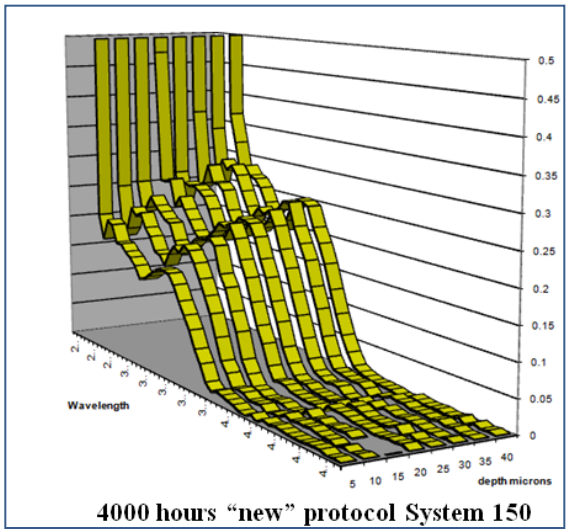
Source: M.Nichols, *et al*, "Accelerated Weathering of Automotive Coatings: Exposure Conditions and Analysis Methods", Atlas Technical Conference on Ageing in the Environment, Oxford, UK, September, 2008.

But does it work?

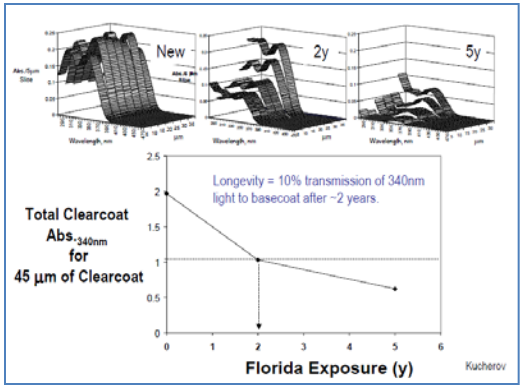
Gradient loss of UV absorber (from free radical attack) Carbamate SBBC







Source: M.Nichols, *et al*, "Accelerated Weathering Testing: A New Approach to Anticipating Florida Exposure Results:, 2011 Coatings Science International, Noordwijk, Netherlands, June 30, 2011



Loss of UV absorber in CC consistent with Florida results

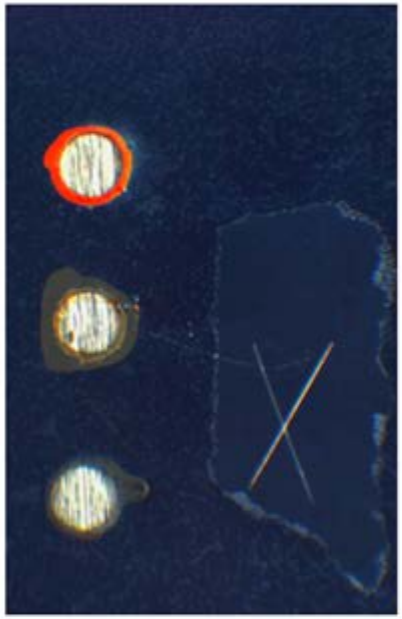
Note failed system allowed 10% UV transmission in 2 yrs FL

Source: M.Nichols, *et al*, "Accelerated Weathering of Automotive Coatings: Exposure Conditions and Analysis Methods", Atlas Technical Conference on Ageing in the Environment, Oxford, UK, September, 2008.

But did it work?

System 97 2K Polyurethane WBBC on blue basecoat

Florida Exposure	J2527	New Protocol

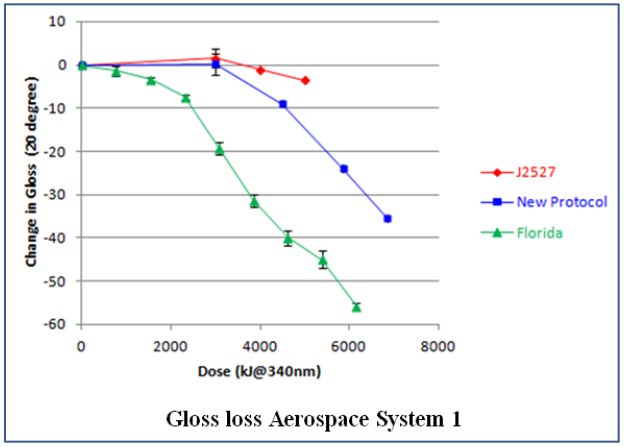


System 97 failed two years Florida exposure by delamination of the clearcoat from the basecoat, and also had severe blistering of the clearcoat. The same system in the new protocol also exhibited clearcoat delamination and blistering while SAE J2527 showed neither delamination failure nor blistering.

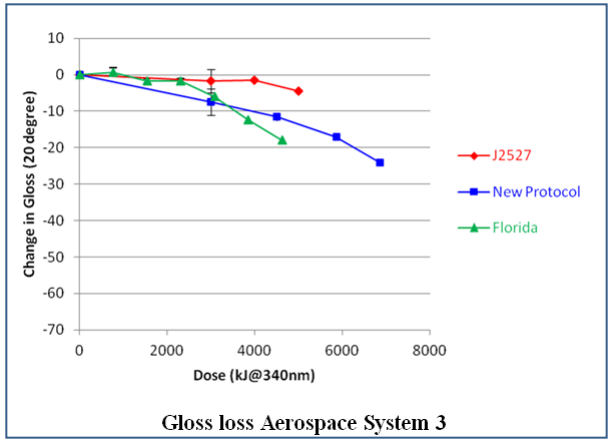
Source: M.Nichols, *et al*, "Accelerated Weathering Testing: A New Approach to Anticipating Florida Exposure Results:, 2011 Coatings Science International, Noordwijk, Netherlands, June 30, 2011

But did it work?

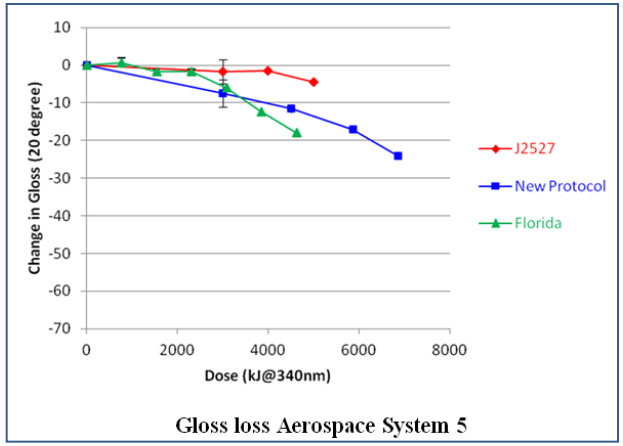
Comparison of monocoat aircraft coatings for gloss loss – 3 different paint systems



Gloss loss Aerospace System 1



Gloss loss Aerospace System 3



Gloss loss Aerospace System 5

Florida J2527 New Protocol

The inconsistent correlation of accelerated weathering results with South Florida performance has been a hindrance to aerospace coatings development. Coatings that perform well in accelerated testing have failed prematurely in service, while others, whose performance was differentiated in accelerated testing, performed equivalently in service.

These graphs illustrate this point where it is shown that SAE J2527 cannot discriminate between the performance of monocoat and basecoat/clearcoat systems while Florida shows significant differences.

Source: M.Nichols, *et al*, "Accelerated Weathering Testing: A New Approach to Anticipating Florida Exposure Results:, 2011 Coatings Science International, Noordwijk, Netherlands, June 30, 2011

Still work to do for aerospace – higher UV levels (*but not lower cut-on*), altitude freeze, O_2, other ????

It works – further improvements still to be made

New Protocol Results Compared to SAE J2527 and Florida – Automotive

- Physical failures correctly reproduced
- Degradation chemistry is correct
- Additive loss rate – better than J2527, slower than Florida???
- New protocol is as fast as J2527 on a *dose basis*
- New protocol is ~40% faster on a *time basis* due to increased irradiance level during light cycle and improved water distribution in paint system
- Acceleration Factor 7 ⟶ 10

Source: M.Nichols, *et al*, "Accelerated Weathering Testing: A New Approach to Anticipating Florida Exposure Results:, 2011 Coatings Science International, Noordwijk, Netherlands, June 30, 2011

✓ The new protocol is now required by Ford worldwide to qualify all new paint systems and external components (roof racks, side mirrors, bumper fascia, badges, etc.

✓ Honda Motor is rolling out the method as a requirement for their suppliers.

✓ Other OEMs and groups have expressed interest in the new method

Implications for PV materials and module testing

Key takeaways for PV:

Serves as a model for science-based test method development

- Weathering can be complex: both both chemical and physical
- Chemical - Full spectrum light source required - proper activation energies
- Can't ignore material-specific degradation mechanisms
- Physical – Full spectrum source for appropriate thermal heating effects
  - Stress material to material interfaces (no fluorescent UV testing) similar to nature
- Chemical - Get the Right Light for proper actinic reactions in critical, high energy UV cut-on region – don't alter the photochemistry for "speed"
- Physical / Chemical – Cycling is important - steady state isn't natural
  - Material to material interface (adhesion)
  - Promotes cracking, delamination, corrosion as seen in nature
  - Transitions are where much of the stress occurs
- Need to match service environment climate conditions and cycles for the test to be predictive – *implications for climate-based module durability ratings and suitability for use of specific materials*

Thank you!

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Lifetime prediction—why is this so hard?

James E. Pickett
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This presentation contains no confidential information.

Why do we do this?

1. To meet a customer's specification
2. To reduce risk

Why is this so hard?

- We probably are not asking the right questions in the right way
- Applying engineering models to a science problem
  - emphasis on setting and meeting specifications
  - desire for standard tests with correlation factors
  - desire for fast turn-around; pass/fail criteria
- Both physical and chemical changes
- Chemical changes due to “bad” chemistry
  - very slow chemical reactions that are not well understood
  - chemists study reactions that go to high yield in < 24 hours
  - 1% conversion in 10 years is enough to destroy a polymer
  - usually have multiple, competing degradation pathways
- Cannot usually use qualification tests for lifetime prediction

A question of correlation

What is the correlation between Test X and how long this will last in my application?

What is the correlation between tensile strength of steel and how long of a bridge span I can build?

If steel with tensile strength of 250 MPa can make a 20 meter span, I can use steel with 2500 MPa to make a 200 meter span, right?

Test results give one piece of data to be used in a predictive model

What is lifetime?

The properties of the system have changed so that the article no longer meets performance needs.

Some characteristics of change

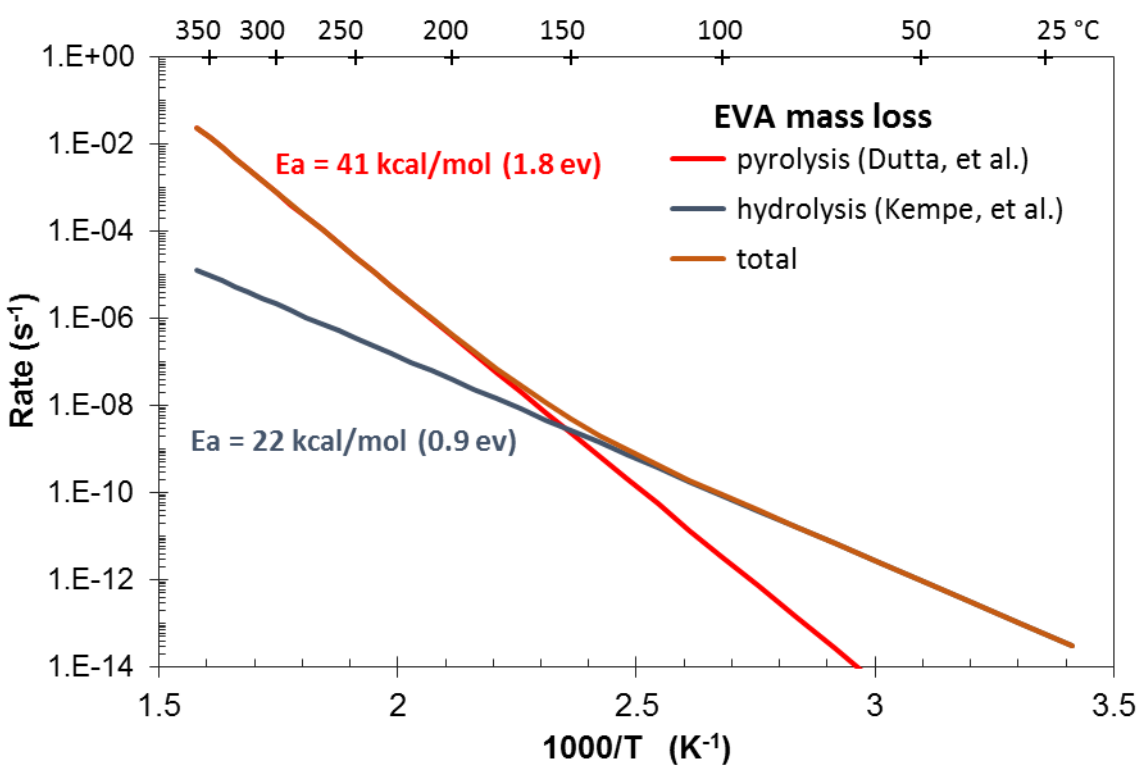
- Physical and chemical
- Gradual or catastrophic
- Determined by ***rates*** of underlying processes
- Caused by environmental stresses
- Multiple routes

There is no such thing as accelerated ***life*** tests, only accelerated ***degradation*** tests

How mechanisms change

- Complex phenomena often have multiple pathways with different activation energies
- High E_a processes can dominate at higher (test) temperatures
- Low E_a processes can dominate at lower (use) temperatures *"bad chemistry"*

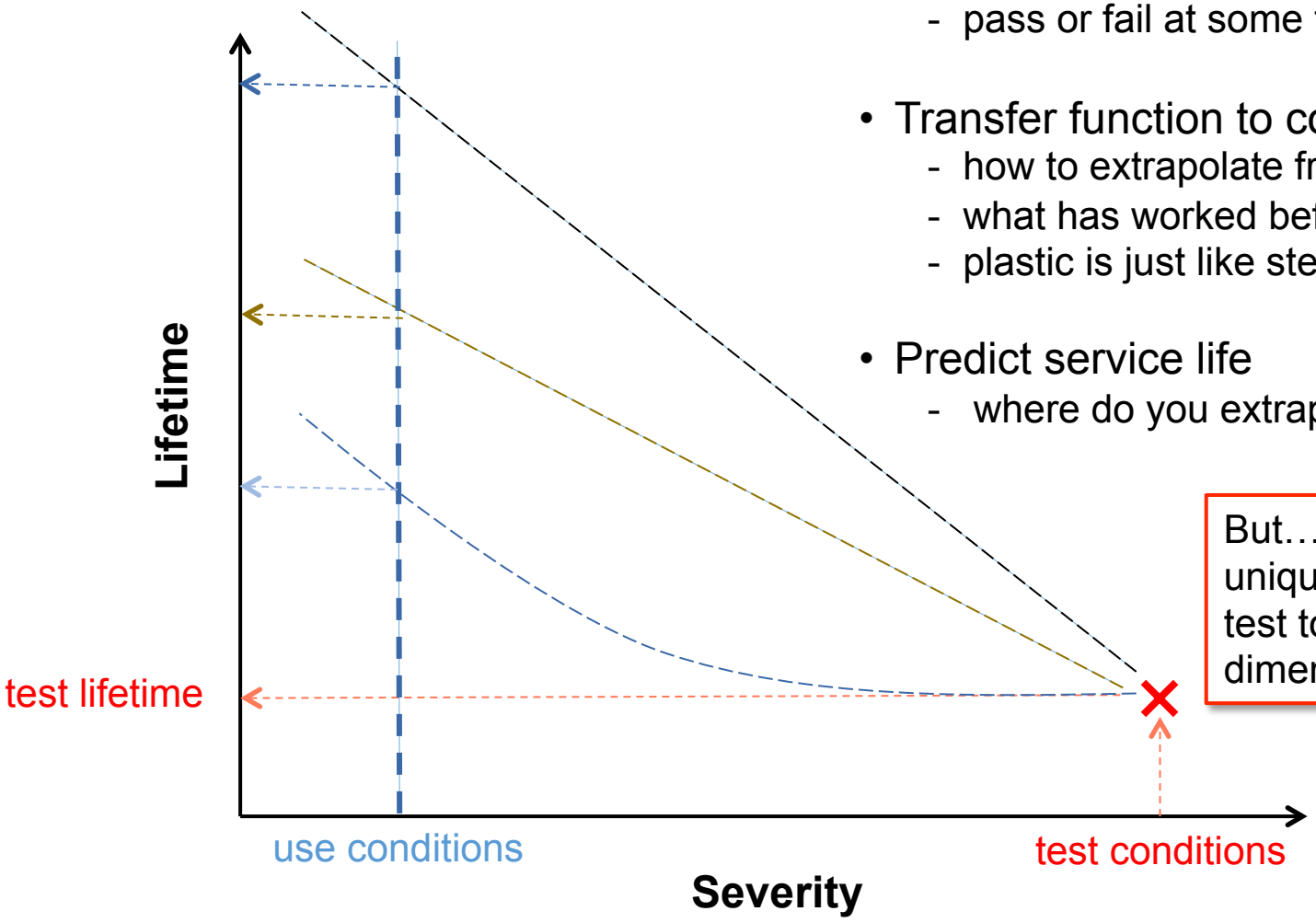
$$k = A_1 \exp(-E_{a1}/RT) + A_2 \exp(-E_{a2}/RT) + \ldots$$



See papers by Gillen, Celina, Clough e.g. Polymer **46** *(*2005) 11648–11654

The *status quo*

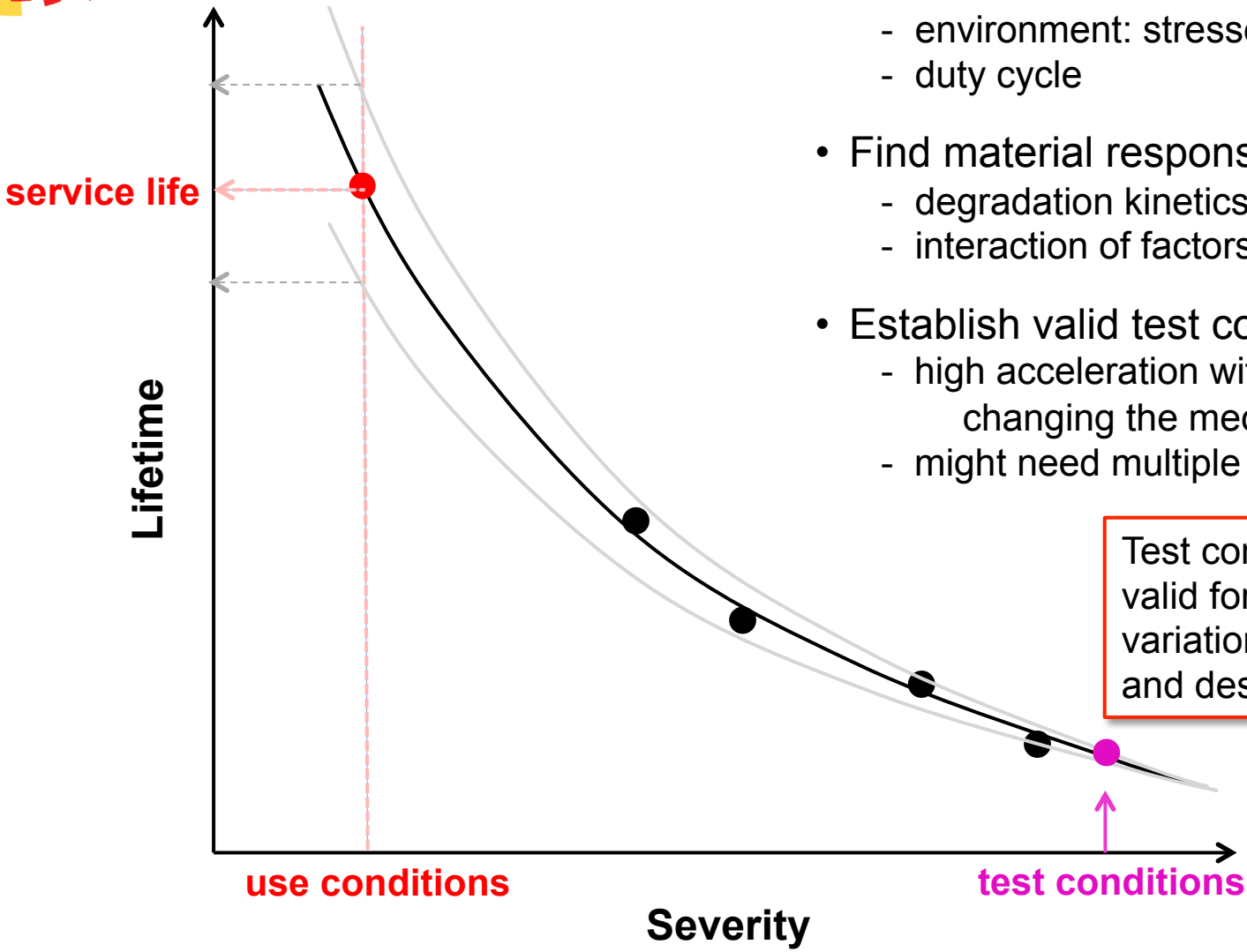
- Carry out a standard ALT or HALT
  - "severe" conditions
  - pass or fail at some time
- Transfer function to correlate "real world"
  - how to extrapolate from one point?
  - what has worked before?
  - plastic is just like steel, right?
- Predict service life
  - where do you extrapolate to?



But… there may be no unique path connecting test to use in this multi-dimensional space

The three “easy” steps

- Define the use conditions
  - environment: stresses and magnitude
  - duty cycle
- Find material response to conditions
  - degradation kinetics
  - interaction of factors
- Establish valid test conditions
  - high acceleration without changing the mechanism
  - might need multiple tests



Test conditions should be valid for some range of variations of composition and design.

Step #0: Before you start

- How badly do you need to know?
  - what is the risk if the system fails?
  - what type of resources can be committed?
  - are you trying to meet some arbitrary specification?

- What is failure?
  - consequences of failure – design for 95% or 150% of worst case?
  - soft or hard?
  - can you measure changes that occur before failure?

- What has been the experience so far?
  - have there been field failures?
  - what is known about similar systems?
  - are there samples or retains?

Step #1: Define use conditions

- Benchmark to a defined environment, e.g. Miami or Phoenix?

- Determine relevant environmental stresses and their magnitude
  - temperature, moisture, chemical, mechanical, electrical, sunlight, biological, …
  - literature, measure, model

- Must know duty cycle, not just the most extreme conditions
  - *must survive the extremes but endure the means*
  - measure or model the actual conditions on the part
  - need time-parsed (e.g. hourly) or binned data
  - essential for applying a cumulative damage model using kinetics

- Retrieve and analyze aged and failed parts from the field
  - helps to know what degradation looks like
  - provides validation for test conditions

Step #2: Find material response to stresses

- Apply stresses at several levels alone and in combination, if possible

- This is a science project
  - simple DoE's may not give enough information
  - really need to understand what is happening physically and chemically
  - **must understand where acceleration is coming from**

- Look for underlying processes that can be monitored
  - rates of change, not just time to failure
  - rates can predict failure time

- Develop rational model that fits the data
  - beware of "free" acceleration
  - understand the assumptions

Step #3: Establish valid test conditions

- Step 2 actually will lead to a prediction, but a test is useful for material variations and modifications *assuming validity of underlying assumptions*
  - never lose sight of the assumptions
  - once the original designer is gone, tests become sacred

- Acceleration requires taking at least one factor outside of its natural range
  - e.g. reducing down time decreases effects of diffusion
  - use lessons from Step 2 to understand risk
  - avoid going through a phase transition
  - verify that the failure mechanism is the same as field samples

- Acceleration must be rational
  - it should follow from lessons from Step 2
  - avoid or understand sources of “free” acceleration
  - don’t be too greedy: ADT is very hard, HADT can be just silly

- May not be able to get the full story from one set of conditions

Hydrolytic stability

- Plastic PV front sheet application
- 7-10 mil films of polycarbonate, Melinex PET, and resorcinol polyarylate
- Test by bend around ¼" diameter rod
- Constant humidity jars at 95, 83, 75, 50, (23) %RH
- In ovens at 95, 85, and 75 °C

temp (°C)	RH (%)	PC (days)	PET-A (days)	PET-B (days)	PET-C (days)	PET-D (days)	RPA-A (days)	RPA-B (days)	RPA-C (days)
95	95	182	21	25	21	19	11	21	32
	83	206	25	28	25	25	14	28	35
	75	245	32	28	32	28	19	35	42
	65	357	56	49	49	49	25	63	70
	50	560	70	63	63	63	28	77	88
	23	-	119	112	112	102	102	140	168
85	95	399	84	84	84	77	28	63	-
	85	483	98	98	98	70	42	77	-
	83	469	98	105	98	98	42	98	-
	75	591	126	133	126	105	49	112	-
	65	907	207	207	207	175	84	178	-
	50	1301	266	266	266	231	105	259	-
75	95	907	231	221	231	207	84	154	-
	83	-	294	287	294	252	112	210	-
	75	-	357	343	357	280	112	-	-
65	95	-	-	-	-	-	189	-	-

Polymer Degradation and Stability, **98**, 1311-1320 (2013);
Service Life Prediction of Exterior Plastics. Vision for the Future, C.C. White et al., Eds., Springer (2015)
Kempe and Wohlgemuth, NREL PV Module Reliability Workshop, Golden Colorado, February 26-27, 2013.

Hydrolytic stability

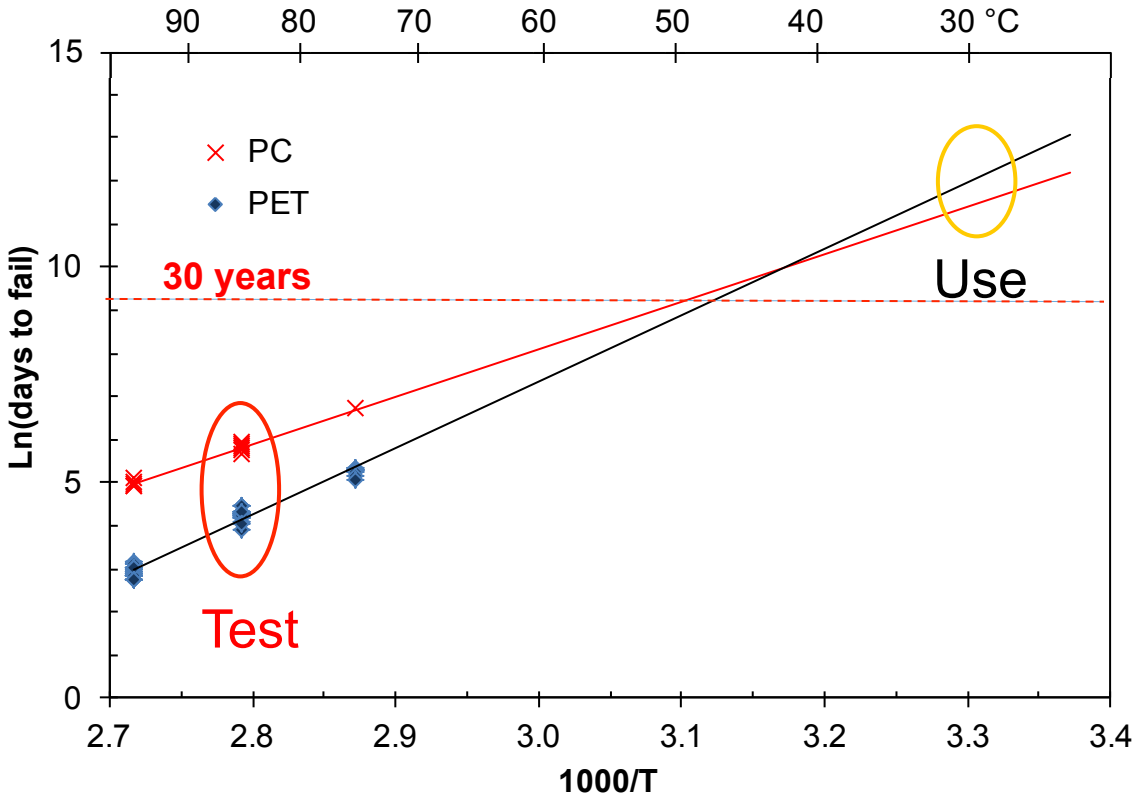
$$1/t_{fail} = A \exp\left(\frac{-E_a}{RT}\right)[RH]^n$$

- Found 1-hour parsed climatic data (Typical Meteorological Year)
- Used models for to calculate PV module temperature & RH for each hour
- Calculate progress toward failure for each hour of year
- Add it up to find progress toward failure for each year
- Calculate # of years to get to failure

	PC	**PET**
E_a (kcal/mol)	22.1	30.5
Ln(A)	25.2	38.7
n	2	2
predicted life (years)	**837**	**1023**

Folly of the qualification test

- 85 °C and 85% RH (1000 hours) carved into stone
- But… need two more pieces of information to be useful
  - slope (E_a, assuming Arrhenius extrapolation is valid)
  - effective use temperature and other conditions
- PC hydrolysis slower than PET at 85 °C, but faster < 43 °C



Other examples

- Coatings on polycarbonate
  - lifetime limited by UV absorber stability
  - find loss rate in 1-2 months testing, predict max. lifetime

$$t_{fail} = \frac{1}{k}\log_{10}\left[\frac{10^{kD_{fail}} + T_0 - 1}{T_0}\right]$$

k is UVA loss rate
T_o is initial transmission
D_{fail} is transmitted UV dose to cause failure

- *Journal of Testing and Evaluation,* **32**, 240-245 (2004).

- Predictive accelerated weathering of engineering thermoplastics
  - examined effects of UV source, temperature, moisture
  - critical to get lamp spectrum right
  - critical to get "rain" right
  - found conditions that will predict Miami weathering ± 20% at 95% confidence for certain classes of engineering thermoplastics
  - no guarantee it works outside of these classes of materials
  - in **Service Life Prediction: Challenging the Status Quo**, Federation of Societies for Coatings Technology (2005) pp. 93-10
    .

Technical needs and challenges

- **Characterization of use environments**
  - measurements, sensors, and modeling of harsh environments
  - characterization of actual duty cycles
  - data sets useful for cumulative damage models (like meteorological data sets)
- **Methods for multi-variable testing**
  - "combinatorial" testing
  - apply multiple stresses simultaneously at several levels with high throughput
- **Define useful mechanical data that can be obtained non-destructively or on very small samples**
- **Define measurable changes that underlie failure mechanisms**
  - enables kinetic models for predicting failure
  - e.g. what are the measurable chemical and physical changes that lead to adhesion failure?
  - can sensors be developed to measure these changes early and easily?
- **Characterization of changes observed in field-aged or failed samples**

Conclusions

- **We should abandon quest for the holy grail of tests**
  - has not worked for > 50 years
  - *cannot* work across multiple materials
  - must separate *qualification* testing from *lifetime* testing

- **Recognize lifetime prediction as a science problem**
  - multiple variables under multiple levels
  - develop models that make chemical and physical sense
  - know where acceleration is coming from
  - never lose sight of the assumptions

Natural Resources Canada | Ressources naturelles Canada

Initial analysis of a 22-year old PV system in Quebec, Canada

Poster Presentation By: Alex Bradley, Dupont
Tanya Dhir, McMaster University
Yves Poissant, CanmetENERGY

McMaster University

DUPONT The miracles of science™

Introduction

Installed in 1992, the 23.5 kW PV array near Montreal, Quebec is possibly the oldest continually monitored PV system in Canada. The climate is temperate, with low temperatures, significant snow falls and freeze-thaw events in winter, and high temperatures in summer. With a growing PV industry, it is important to have data to support 20 year+ estimated lifetimes for both PV modules and the entire system. A basic visual inspection of all modules was completed, and seven modules representing various observations were removed for further analysis. This poster presents these observations. Further inspections of the 22 year old modules are underway, including analysis of monitored performance data.

CanmetENERGY PV System, Varennes, QC, Canada

Initial year of operation:	1992	**Encapsulant:**	EVA
Location:	Montreal, Canada	**Backsheet:**	PVF/PET/Tie Layer
# of modules:	552 inspected	**P_{max}:**	42.6 W
System size:	23.5 kW	**Cell Efficiency:**	10%
Mounting configuration:	Roof Open Rack	**Date of inspection:**	December, 2011
Cell type:	Monocrystalline Silicon (some poly)	**Max. System Voltage:**	600 V
Module Manufacturer:	Astropower Canada	**Fixed tilt or tracking:**	45 degrees, fixed tilt

System degradation over years

- Visual inspection after 20 years revealed 21% of modules had backsheet delamination and 10% had visible cell corrosion and encapsulant delamination (without encapsulant discoloration). Snow (load or freeze-thaw) may have contributed to minor frame loosening or bowing allowing moisture to penetrate the module laminate.
- Upon inspection of the system, seven modules were selected for further study. Two modules were in good conditions, two had junction boxes hanging, one was heavily corroded, and two had delaminated backsheets.
- Relative change from original IV measurement, for six modules:

  P_{max} Range: -10% (-0.5%/yr) to -26% (-1.3%/yr)

  Average P_{max} : -18% (-0.9%/yr)

  Average I_{SC} : -11%

  Average V_{OC} : -3%

  Average FF : -5%

  Power loss is mainly a function of I_{sc}

Results Summary

a. Modules with low to moderate power loss exhibit uniform degradation and diode hot spots.

b. Modules with high power loss exhibit visible encapsulant delamination, cell corrosion, and diode hot spots.

c. Module manufacturing inconsistencies are borne out over time as observed through inhomogeneous degradation in side-by-side outdoor exposure.

d. Inter-related module subcomponents undergo concurrent phenomena, which can make the lifetime of any one component limited by a different component's failure mechanism or stress, such as edge seal, frame, and adhesive.

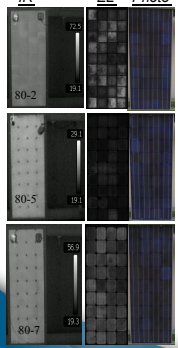
e. Framing (screws) and edge seal gaskets may have loosened, initiating cell corrosion and backsheet delamination

c

Inhomogeneous cell corrosion

Inhomogeneous backsheet delamination

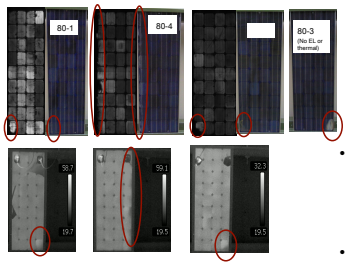
a



	P_{max}	I_{sc}	V_{oc}	FF
80-2	11%	9%	2%	1%
80-5	17%	12%	4%	2%
80-7	10%	6%	3%	1%

- Diodes exhibiting hot spots
- No encapsulant discoloration or cracked cells

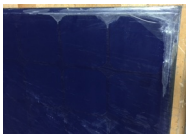
b



	P_{max}	I_{sc}	V_{oc}	FF
80-1	18%	15%	1%	3%
80-3	Not functional			
80-4	24%	15%	4%	8%
80-6	26%	12%	2%	14%

- Four modules visible encapsulant delamination and cell corrosion correlate with highest power loss (a function of Isc and FF).
- Diodes exhibiting hot spots.
- No encapsulant discoloration or cracked cells observed.

d



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Solar panel design factors to reduce the impact of cracked cells and the tendency for crack propagation

Andrew M. Gabor[1], Rob Janoch[1], Andrew Anselmo[1], and Halden Field[2]
[1] BrightSpot Automation LLC, Westford, MA USA
[2] PV Measurements Inc., Boulder, CO USA

***ABSTRACT* — Cracked cells represent a danger for high degradation rates of solar panels in the field. They also increase the sensitivity of system performance to shading events. This paper provides background on the origins of microcrack and crack generation, and outlines several approaches that can be taken at the wafer, cell, module and system levels to both reduce the occurrence of cracked cells in the first place, and to reduce their impact when they do occur. Outdoor IV testing under a variety of module shading conditions was performed to explore some of these approaches and to verify modeled results.**

1. Introduction

Most cracked cells within modules have their origin at the soldering (stringing) operation. The copper wires contract much more during post-soldering cooldown than the silicon, and the thermo-mechanical stress causes microcracks in the silicon beneath and adjacent to the silver busbars. It also causes cracks and discontinuities in the metallization. Softer copper wires with lower yield strength can yield more during cooling to reduce the stress, and such wires have been widely adopted. Solder with a lower melting temperature can reduce the stress, but the properties of such solder may be unattractive for other reasons such as brittleness, cost, and toxicity. Thinner wires will reduce the stress for multiple reasons, but this can increase resistive power losses. Stresses introduced during the lamination process can compound the problem.[1] [2]

Crack propagation within modules frequently has its origin in the asymmetric construction of most modules where a thick and stiff glass coversheet is present on the top side, and a thin and more pliant polymer backsheet is located behind the cells. When a module is bent concave down (e.g. – wind or snow pressing on the glass side), the cells are placed into tensile stress, and microcracks can propagate into full cracks.[1] The continuity of the metallization across these cracks is usually sufficient at first, but aging and mechanical load studies have shown accelerated degradation rates for modules with cracked cells as the continuity deteriorates and portions of the cells drop out of the circuit, as is shown in the Figure below from ISFH.[3]

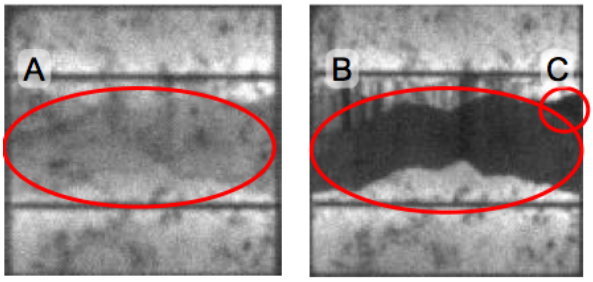

Fig. 1: Electroluminescence (EL) image of a cell with a crack a) before, and b) after humidity-freeze cycling. from ISFH[3].

Cells with such "open" cracks have reduced I_{sc} and I_{mp} values which puts them into a state similar to that of a partially shaded cell, where cell-to-cell mismatch losses occur and the cell can even be forced into reverse bias and dissipate power or force a bypass diode to engage with the loss of the entire string's power. Cells dissipating power in reverse bias represent dangers of hot spot heating and accelerated module degradation rates. Shading of these already hotspot-prone cells can significantly compound the problem. Bypass diodes have also been known to fail in the field, and thus, relying on them increases the risks for safety and module damage.

Much of the PV industry at the present appears to be accepting of the status quo. The literature is full of module EL images showing cracked cells, and justification of such defects by examples of relatively low efficiency degradation as these cracks propagate and open up, as is shown in the Figure below. Products across all industries tolerate some level of "defects" of various natures, and "over-engineering" the solar panels can result in a product that actually offers a higher levelized cost of electricity. The danger is in the statistics where

some percentage of modules have significantly worse degradation and have increased sensitivity to module shading. A small number of well-publicized performance and safety problems could have a negative impact on the growth of the industry. Fortunately, a wide variety of cost-effective solutions exist for the cracking problem.

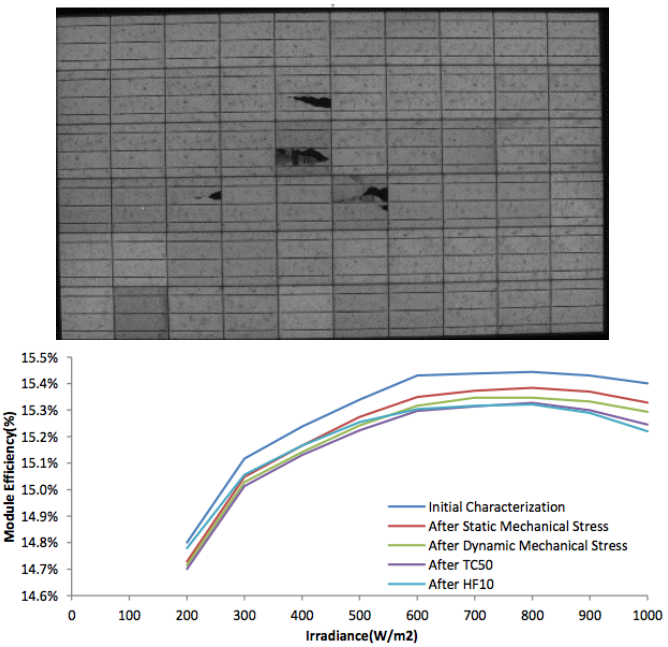

Fig. 2: . Electroluminescence image and efficiency vs. irradiance of a module after environmental testing - from Yingli.[4]

2. *Solutions*

Solutions to reduce the tendency for crack propagation and/or the impact of open cracks on module performance are found at the wafer, cell, module, and system levels. While some solutions are found with advanced cell architectures (e.g. – back contacted cells), we mainly restrict ourselves here to the commonly used architectures with busbars on both the front and back sides.

2.1. *Wafer-level solutions*

2.1.1. *Thicker wafers*

Microcracks are less likely to propagate in thicker wafers.[5] However, the path toward lower costs involves a further reduction in wafer thickness, so this is a poor solution. In fact, it is precisely the cell cracking problem that has stalled the industry in its efforts to reduce wafer thicknesses below 180 microns for the last several years. Thus, even though some of the solutions listed below may entail increased cost, these may be balanced by potential savings achieved by enabling future wafer thickness reductions.

2.2. *Cell-level solutions*

2.2.1. *More busbars/interconnect-wires*

The most common scenario in which an open crack causes a loss in effective cell area is one where the crack occurs beyond one of the outer busbars and the edge of the cell. In contrast, if a single open crack forms between two busbars, the redundancy in the wiring allows the current to still be collected, although at the expense of increased resistive power losses in the fingers. It is less likely to have 2 open cracks between busbars to allow the loss of effective area in these regions. The larger the number of wires/busbars, the smaller the area that can be completely lost at the edges of the cells, and the lower the resistive power losses when open cracks form between busbars. This solution has the potential downside of creating a larger number of open cracks per module due to the increase in the number of wires.

This solution is well underway within the industry with the past trend from 2 to 3 busbars and the present trend toward 4 or 5 busbars. The various wire array solutions using a larger number of round wires (SmartWire™ - Meyer Burger, MultiBusbar™ - Schmid, and Merlin™ - GT Advanced Technologies) offer a particularly elegant solution from a technical perspective, although their cost-performance benefits are less clear.

2.2.2. *Wires placed closer to the cell edges*

The most common approach in determining the positions of the busbars/wires is one where the resistive power losses in the fingers is minimized. This occurs where the finger length f between one of the outer busbars and the edge of the cell is roughly

$$f = (w - N \bullet b)/(2N), \qquad (1)$$

where w is the cell width, N is the number of busbars, and b is the busbar width. The distance between any two busbars is roughly $2f$. Often, as the number of busbars increases, the width of each busbar (and wire) is reduced, so that we can assume the product $N \cdot b$ is roughly constant at ~ 4.5mm. With this assumption, we can calculate the maximum percentage of lost active area if an open crack occurs along the edge of one of the outer busbars as is shown below.

For a design with just 2 wires on a 156mm-wide cell, f is ~ ¼ of the cell width, and an open crack along this wire could result in a loss of ~25% of the cell current. For 5 wires, the loss is only ~ 10%, but the value of adding additional wires quickly diminishes regarding this concern.

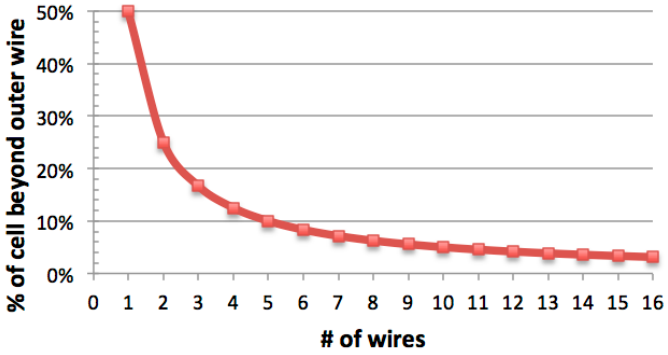

Fig. 3: Calculation of the worst-case scenario for cell area or current loss if an open crack occurs just outside one of the outermost wires as a function of the number of wires.

With the number of busbars now increasing within the industry beyond 3, we recommend placing the outer two busbars much closer to the cell edges (see Figure 4), since this will have a relatively small impact on resistive power losses in the fingers and could have a significant impact on module sensitivity to cracked cells. Should a crack occur outside the outer busbars, much less area will be lost.

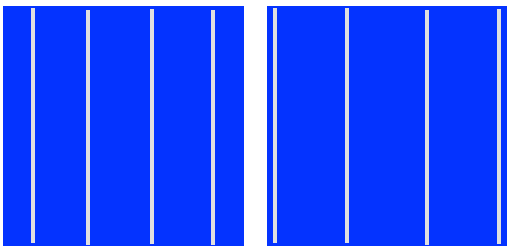

Fig. 4: 4-busbar cell with the conventional (left) and recommended (right) designs.

2.2.3. Rectangular cells

The wire thickness is generally chosen to minimize resistive power losses which are proportional to the third power of the busbar length. A recent trend in module design is to use half-size cells so that the length of the wires is cut roughly in half. With the peak current along the wires cut in two, one can significantly reduce the wire thickness without incurring significant resistive power losses. These thinner wires cause less stress in the silicon, and thus reduce the density of microcracks and the chances for crack propagation. Rectangular cells have the additional benefits of enabling more light harvesting from light reflected off regions around the perimeter of the cells, and a slight reduction in NOCT values. They have the downside of an additional processing step to cut the cell, a potentially weak edge where the cut occurs, lower throughput of the soldering equipment, and a slightly larger module size due to the increased number of gaps between cells and an associated increase in the related materials costs such as encapsulant, glass, and backsheet.

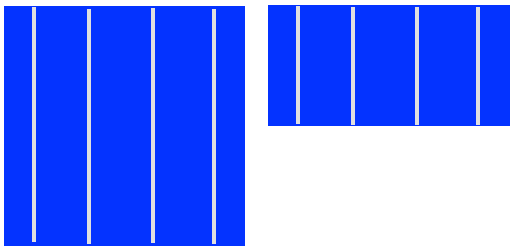

Fig. 5: Square cell and half-size cell designs.

2.2.4. Optimized metallization pastes and metallization patterns

As is often the case in the solar cell industry, the paste vendors are responsible for much of the

progress in performance and costs. Improvements to the Ag and Al paste compositions, and to the geometries of the busbars[6], fingers, and rear Al/Ag overlap regions [7] have potential to reduce the severity of the cracking problem.

2.2.5. Cells with reverse "breakdown" at low voltages and uniform power dissipation

As was mentioned above, a shaded and/or cracked cell that is forced to operate at the current level of the rest of the string may be forced into reverse bias to "find" this current level. Rather than dissipating this power uniformly, most cells usually have localized shunts which means that the reverse current flows through small localized areas which heat up and can cause module damage (hot spots). Thus manufacturers often limit the cell current at a given reverse voltage (e.g. - <3A at -12V), and rely on bypass diodes to protect the cell, module, and array should the cell be forced far into reverse bias.

Reverse bias I-V characteristics vary widely among various wafer types, cell architectures, and even from cell to cell for a given technology. A variety of physical mechanisms are responsible for recombination that leads to increased currents in reverse bias.[8] A cell which enters "breakdown" mode at a relatively low reverse bias voltage would "fail" the common test at -12V, but actually may be superior in terms of module safety and performance. If the breakdown occurs at a low enough voltage, the product of current and voltage at the operating point may be low enough that only a fraction of the string's power is dissipated across the cell, and if this power is dissipated in a uniform fashion across the area of the cell, no damage may be done to the module. Examples of cell architectures that can exhibit such reverse bias characteristics include variations of the IBC design where there is a long length of abutted p-n regions such as the classic Sunpower design,[9] and the Zebra[10] and Mercury[11] designs. Figure 6 shows an example of the reverse bias characteristics of the Zebra cell.

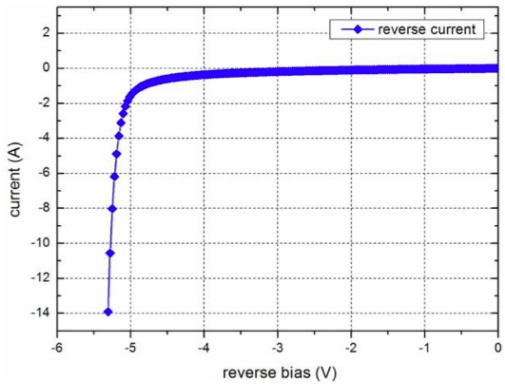

Fig. 6: Dark, reverse bias I-V curve of a Zebra IBC cell - from ISC-Konstanz[10].

In testing some old Evergreen Solar String Ribbon cells, we found a wide range of reverse breakdown characteristics, some of which occurred at quite low voltage (see Figure 7). In this case, thermal camera images showed the heating under reverse bias to be non-uniform but over generally larger areas than was seen for monocrystalline cells. This raises the question of whether non-standard wafer types could be engineered to possess favorable reverse bias characteristics in a more consistent and uniform manner.

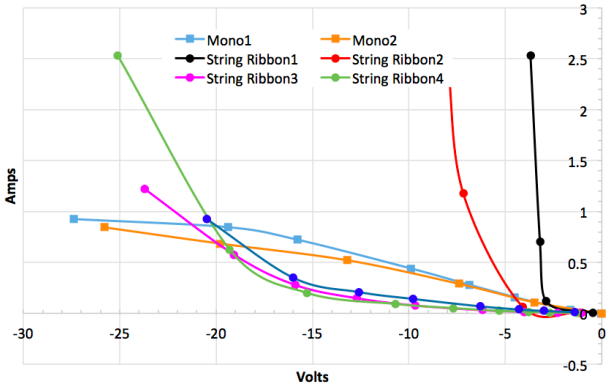

Fig. 7: Dark reverse bias characteristics of different cell types.

2.3. Module-level solutions

2.3.1. Optimized soldering materials, equipment and quality control

Most manufacturers have already migrated to very soft interconnect wires to reduce damage to the silicon, yet the industry uses a wide array of stringing equipment to solder these wires to the cells. Some equipment is more gentle than others,

and proper setup and maintenance of the equipment is critical. Some companies still use operators to hand-solder wires, and acceptable quality control for this critical operation is near impossible when using hundreds of operators. Additionally, hand soldering involves a sequential operation of first soldering the front wires and then the back wires. Such an operation is inherently more damaging than the simultaneous soldering operation performed by stringing equipment.

While the emergence of electroluminescence (EL) testing has provided an incredibly valuable tool to aid in detecting open cracks following the stringing operation and during subsequent module processing, the reality is that cells can be heavily damaged by the soldering process, yet not develop visible cracks until after the module EL and IV testing. It is after the modules leave the factory and experience vibrations during shipment, and flexing during installation and snow/wind loads in the field that the majority of cracks will form. For this reason, the development of new measurement tools is needed to aid in process optimization and quality control. For example, in earlier work in soldering process and materials development at Evergreen Solar,[1] a breakage strength tester was used to quantify the soldering induced damage. Such a tester may provide complementary information beyond that given by more common wire pull strength tests.

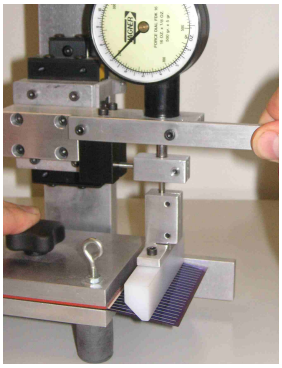

Fig. 8: Breakage strength tester utilized at Evergreen Solar for production quality control.[1]

Furthermore, one might consider it misleading for module manufacturers to proudly display module EL data to its customers showing crackfree modules, when modest bending of the modules of the type certainly seen in the field will cause cells to crack. A more forthcoming approach may be to subject the modules to some of these stresses in the factory prior to final EL and IV testing. The challenge here is that the initially closed cracks will usually have little impact on IV test results until they undergo long-term field exposure. In the future, it may be possible to develop factory tests to predict how the module will perform once these cracks open up.

2.3.2. Glass/glass module construction

Another recent industry trend is the adoption of glass backsheets. Such modules reduce crack propagation for two reasons. First, with a similar thickness and stiffness of material in front of and behind the cells, they are now located near the neutral plane such that bending the module in either direction is unlikely to place the cells under significant tensile stress, and thus the microcracks are unlikely to propagate. Secondly, depending on whether or not a frame is implemented, such modules may be stiffer overall and show less deflection for a given load. This design is not new, and old glass/glass modules built by Mobil-Solar/ASE/Schott and installed in challenging environments have shown extremely low degradation rates. Such modules also incorporated advanced ionomer encapsulant. Modern glass/glass modules using EVA encapsulant, while largely solving the crack propagation problem, must carefully address concerns related to acetic acid formation in this non-breathable design. If no water gets into the module, then acetic acid should not form, but 30 years is a long time, and some water may be present during module construction or find its way in through edges and wiring access points.

Similarly, other materials that add stiffness behind the cells (e.g. – Al foil/sheets), can also contribute toward increasing the symmetry of the panel construction. Such materials may also impart other benefits to the module as discussed next.

2.3.3. Backsheet materials that build compressive stress into the cells

If a backsheet material with a suitable CTE, stiffness, and thickness is chosen, the differential contraction during cooling from the lamination process may cause the cells to be "pre-loaded" into compressive stress. In this way, any subsequent bending of the modules that may otherwise have put the cells into tensile stress and caused crack propagation, will instead either just reduce the level of compressive stress or bring the cells to tensile stress levels that are lower than what would have occurred with conventional module designs. The Al backsheet utilized in TenKsolar modules is an example of such an approach.

While glass is close to an ideal coversheet material, one could also imagine a combination of coversheet and backsheet materials such that the usual asymmetry of stiffness is reversed and that snow or wind loads placed on the front side of the module actually place the cells into compressive stress. Since front side loads are more common than backside loads in the field, this approach may have some advantages.

2.3.4. Cells wired in parallel

If each cell in a module has a certain probability of developing a "problematic" crack, let us imagine that we divide each cell into two or more smaller cells that we wire in parallel. This can be accomplished by soldering wires from the top busbars of one cell to the top busbars of the adjacent cells in parallel before the wires extend to the backside of the next group of cells. In order to have the same lost area due to open cracks in the parallel-connected group, multiple problematic cracks would need to occur in the group. Since this is much less likely to occur than a single problematic crack in a full-size cell, the parallel-wired cell approach is much less likely to push cells into reverse bias power dissipation mode.

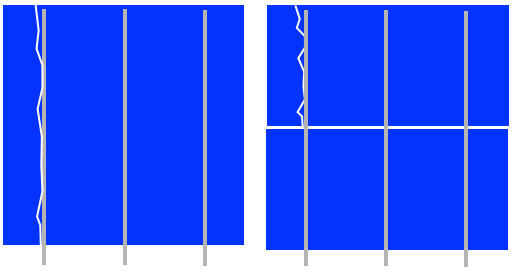

Fig. 9: A full cell with a crack, and two rectangular cells wired in parallel with one cracked cell.

An extreme example of such a design is the low-concentration architecture developed by Solaria where specially engineered glass focuses light on narrow slices of cells wired in parallel.[12] Parallel wiring of full-size cells has been adopted by TenKsolar to enable non-uniform illumination from its light harvesting system architecture as is shown below.[13]

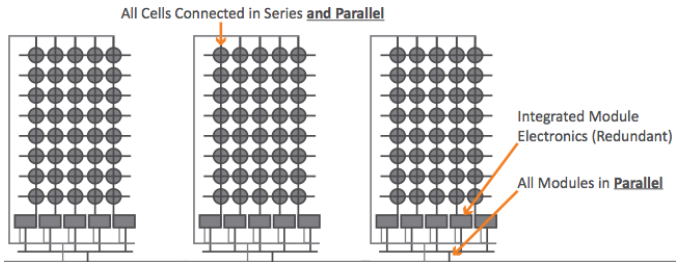

Fig. 10: Parallel cell wiring approach used by TenKsolar.[13]

2.3.5. Strings wired in parallel

The same logic that justifies cells wired in parallel applies to strings wired in parallel, although today's standard 60-cell or 72-cell modules generally place all cells in series.

To compare parallel vs series wiring we performed outdoor testing of an old Evergreen Solar panel (circa 1998) with 2 strings of 20 cells each. The panel allowed an easy change from series to parallel configuration of the strings with the change of jumper elements in the junction box. No bypass diodes were present in the junction box.

We performed IV measurements using a new, low-cost but high-accuracy, portable IV testing unit from PV Measurements. The module was measured outdoors under roughly 800 W/m^2 while one cell was shaded at varying levels in both

parallel and series configurations. Shading of the cell roughly simulates the condition of having open cracks that cause the same percentage of lost area. All current values were normalized to the change in current of a separate reference cell, although the reference cell varied little under the blue-sky conditions. As can be seen in Figure 11, the parallel configuration performs better under shading. These old-generation String Ribbon cells have FF's that are far worse than those of modern day cells, and we would expect the difference between series and parallel configurations to be even greater for modules using cells with high FF's.

The same robustness of the parallel-wired design to cell shading applies similarly to robustness for cracked cells with lost area. The potential disadvantages of the parallel wiring approach are 1) more complicated wiring within the modules, and 2) higher resistive power losses and/or thicker and more expensive wires at both the module and system levels.

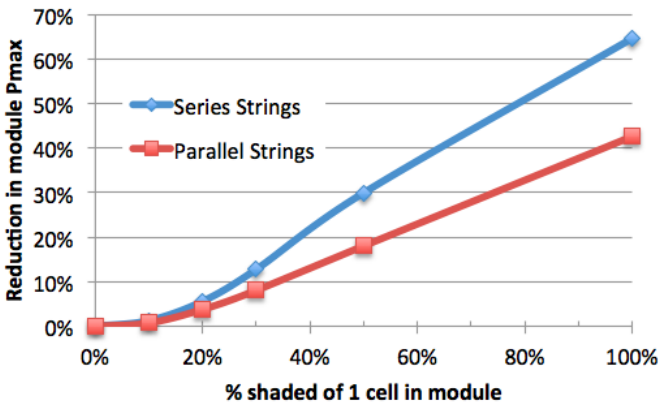

Fig. 11: Outdoor measured IV curves for a String Ribbon module at variable shading with strings in series and parallel wired modes.

We also examined the series/parallel vs cell shading/breakage issue by simulating module IV curves using the summation of individual cell IV curves with Microsoft Excel. We chose all cells to have identical IV curves except for the one shaded/broken cell. We used interpolation algorithms to enable the summing of IV curves at the same voltage values. A single diode model was used with an additional term to represent the reverse bias term, similar to the approach followed by PI-Berlin.[14] We examined two cases for the reverse bias characteristics since the power dissipation in the shaded/broken cell depends strongly on these characteristics. Figure 12 shows the IV curves for illuminated cells with both a high "breakdown" voltage and a low breakdown voltage that matches the IBC cell characteristics.

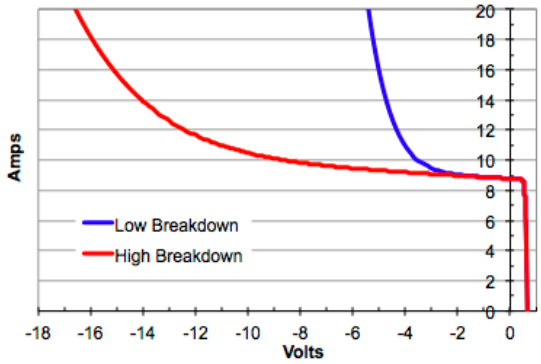

Fig. 12: Simulated IV curves for cells with high and low breakdown voltages that were used in the module simulations below.

Figure 13 shows the IV curves for a 60-cell module with no bypass diodes using 156mm cells where either all cells are connected in series or where two 30-cell strings are connected in parallel. The shading/lost-area of one cell in each module is varied from 0 to 100%. As can be seen, the low-breakdown condition helps tremendously when a large % of the cell is shaded or broken away. For more standard cells with high breakdown voltages, the parallel wired configuration is beneficial.

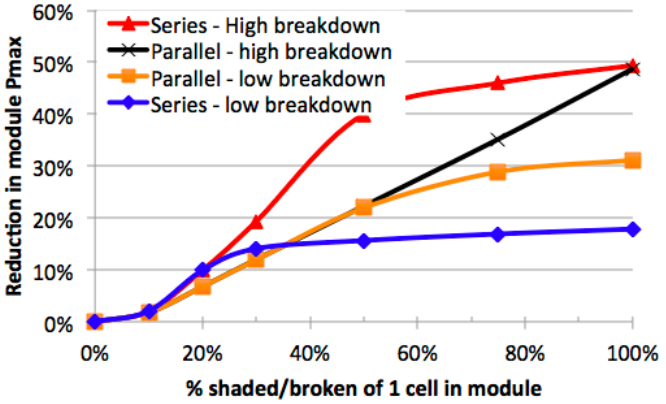

Fig. 13: Effect of broken-cell lost-area or shading of one cell in a 60-cell module with either all cells wired in series, or for 2 parallel strings.

2.3.6. Stiffer modules

Increasing the stiffness of modules will reduce the amount of deflection for a given front-side load, thus reducing the tensile stress levels and cracking within the modules. A wide variety of approaches can be pursued to make stiffer modules:

- Thicker front glass.
- Glass backsheets instead of polymer. See section 2.3.2.
- Alternative encapsulants with higher modulus values (e.g. – Ionomer). Such encapsulants may be more expensive, and the impact of alternative encapsulants with different modulus values and glass transition points on interconnect wire fatigue must be considered. Also, there is some concern that stiffer encapsulants or encapsulants with higher glass transition temperatures may contribute to increased cracking in the field.[15]
- Sturdier frames and/or frames with additional stiffening elements such as crossbars. This increases materials and shipping costs. However, the costs should be examined at a system level since clever engineering can increase module costs but reduce racking/installation costs and vice versa.

2.3.7. Electrically conductive adhesives, composites, and films

Since the primary formation mechanism for microcrack formation is related to the soldering operation, replacing solder with more flexible materials that "harden" at lower temperatures and that impart less stress on the silicon should largely solve the problem. However the PV industry is justifiable conservative when it comes to changing a design that has served it well for many decades. The primary materials being considered as replacements include silver-filled conductive adhesives, composite materials containing a mixture of a polymer based and particles of solder, and tape materials with conductive particles embedded in an adhesive coating.

2.3.7.1. Silver-filled conductive adhesives

While these materials cost more than the solder coating on standard interconnect wires, one can potentially eliminate the busbar silver in the cell, and contact the fingers directly with this approach to offset these costs. The main risk with this approach is degradation (increase) of the contact resistance over time between the conductive adhesive and the wire. Multiple industries have shown excellent stability when contacting silver surfaces with these conductive adhesives, and thus good prospects exist for contacting interconnect wire with a thin coating of silver. Unfortunately, a silver coating adds cost to the wire, and the more desirable approach would be to contact a low-cost tin-coated wire surface. However, galvanic corrosion over time at a Sn-Ag interface, even with advanced stabilization packages, makes this a highly risky approach. A better approach may be to skip metal coatings entirely, and to contact the Cu wire surface directly although some organic protection layers may be desired to reduce discoloration, depending on the encapsulant used. Recent work at ISC-Konstanz looks quite promising on Ag-coated or bare Cu wires.[16]

Finally, while many industries deal successfully with such dispensed materials, the maintenance and downtime at the stringer associated with these "messy" materials could be a barrier for some companies. Screen printing is also a possibility for application of these materials.

2.3.7.2. Composite polymer/solder materials

These interesting materials contain a mixture of low-temperature solder particles in a thermoset resin. For example, Hitachi Chemical sells the products CP-300 and CP-450. The polymer component will presumably deform during cooling from the solder melting point to take up the differential contraction between the copper wires and the silicon, and thus eliminate microcracking within the silicon. The differential contraction between the wire and the silicon is less when solders are used with lower melting points, and while such solders are often brittle, the polymer

component may reduce concerns related to fracturing of such solders. The resin base can also help ensure good adhesion strengths. Unfortunately, there is very little in the literature concerning the performance of these materials.

2.3.7.3. Films with conductive particles

These materials are sold by companies such as Dexerials and Hitachi Chemicals. Their primary application is within the flat panel display industry, although it appears likely that Panasonic has used this approach for connecting its HIT cells. These tapes have a release liner that requires disposal, and the materials costs are likely higher than those for conductive adhesives. However, these materials are inherently "non-messy" and so stringer uptime should be high. Most importantly, their possible track record at Panasonic/Sanyo adds to the confidence concerning module durability. Recent work again at ISC Konstanz[17] looks promising in terms of module stability, at least for designs with front busbars, and potentially for lower-cost designs where the conductive films contact the fingers directly.

2.3.8. Increased number of bypass diodes

Some groups are looking at increasing the number of bypass diodes in the modules to protect against shading and damaged cells.[18] In this way, one doesn't lose a third or more of the panel output when a problem occurs.

2.4. System-level solutions

2.4.1. Module level electronics

Implementing maximum power point trackers, microinverters, and charge controllers at the module level is another industry trend that may help when it comes to low performing modules with cracked cells. In this way, the low performing modules may have less of an impact on the performance of the whole string of modules.

2.4.2. Racking that reduces module bending

This is related to the stiffening of modules topic, and as mentioned above, the module laminate, module frame, and racking need to be considered together as a unified system. Most designs merely support the modules at 4 points near the edges. Cost effective designs to reduce module bending may be best implemented during module installation in the field.

3. Conclusions

We have outlined a wide variety of solutions to the cracked cell problem. The table below summarizes these solutions into categories of whether they act as a cure to fundamentally reduce the formation/propagation of cracks or whether they act more as a bandaid to reduce the impact of the cracks. We have also subjectively ranked them according to their desirability taking into account various risk, cost, and factory disruption factors.

Table 1. Ranking of solutions discussed in this paper.

Method	Cure/ Bandaid	Desir-ability
Optimize soldering and QC	Cure	High
Improved metallization	Cure	High
Racking to reduce bending	Cure	High
Glass/glass construction	Cure	High
Stiffer modules	Cure	High
Compressive stress from backsheets	Cure	High
Conductive adhesives	Cure	High
More wires	Bandaid	High
Wires closer to edges	Bandaid	High
Low reverse breakdown	Bandaid	High
Strings wired in parallel	Bandaid	Med
Cells wired in parallel	Bandaid	Med
Rectangular cells + thin wires	Cure	Med
Module level electronics	Bandaid	Med
Increased bypass diodes	Bandaid	Med
Thicker wafers	Cure	Low

It is our assumption that a growing number of manufacturers will fundamentally solve the cracking problem, giving them a marketing advantage over their competitors who ignore the problem. A few years from now, we may look back in disbelief at the fractured EL images that are presently considered acceptable.

We have also demonstrated the usefulness of an outdoor module IV measurement system with high

accuracy that is an order of magnitude less expensive than an indoor system with a light source. Enabling more researchers to perform experiments on module performance will benefit the industry. Also, since crack propagation and crack opening generally happens after the modules leave the factory, field testing of individual modules with such equipment can provide valuable information on module degradation rates.

4. Acknowledgements

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Development of Qualification Tests for Glass-Less c-Si Modules

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INTRODUCTION

An increasing number of PV module start-up companies have developed glass-less silicon modules during recent years.

By replacing the glass front sheet with a thin transparent polymer sheet and using a back panel instead of an aluminum frame, the module weight can be reduced by as much as 85 % compared to a conventional PV module.

Glass-less lightweight modules have a number of **advantages** including:

- Enable PV on weight constrained buildings.
- Reduced transportation costs.
- Reduced installation time due to easier handling and new mounting methods.
- Attractive to military and transportation related applications.
- Lower glare allows the application around high traffic areas and airports.
- Innovative mounting approaches such as adhesives instead of a rack.

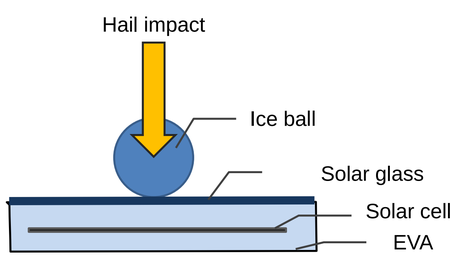
Glass-less modules attached using an adhesive approach

MOTIVATION

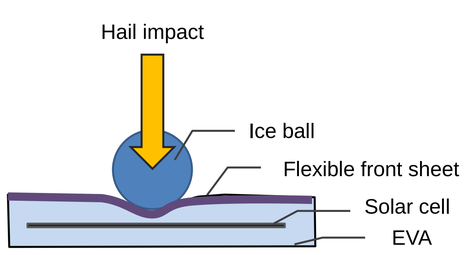
Before glass-less modules can be broadly adopted commercially, the market needs certainty about the long-term reliability.

One of the more challenging reliability requirements for modules without a glass superstrate is the ability to withstand hail storms.

In accordance with the IEC 61215 standards, the hail resistance test is mandatory for the qualification of PV modules.



Impact deformation of conventional PV module during hail impact

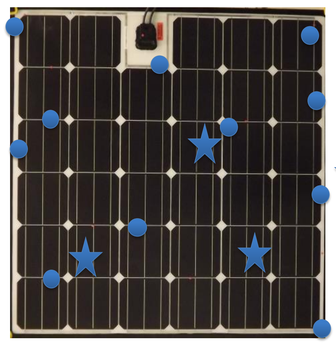


Impact deformation of glass-less PV module during hail impact

APPROACH

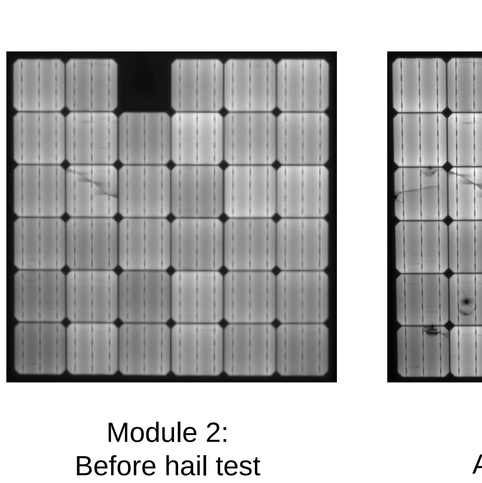
- Hail tests were performed on three glass-less modules of the same design. During the hail test modules were mounted according to the manufacturer's guidelines using an adhesives tape to attach the modules on a asphalt shingled test roof.
- In order to evaluate if the hail damage leads to further power decrease a subsequent thermal cycling sequence TC200 was carried out.
- Crack analysis using electroluminescence imaging after each test.
- I-V measurements under STC after each test.

RESULTS

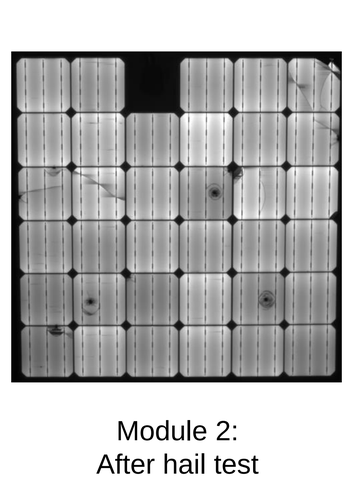


● : Hail impact locations in accordance with IEC 61215.

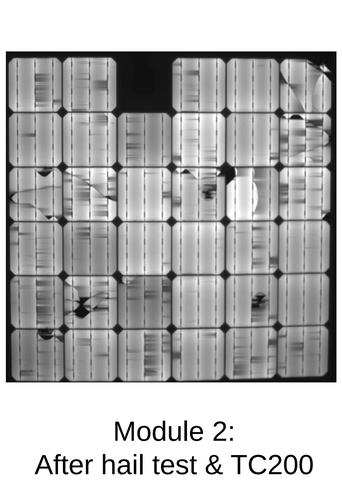
★ : Hail impact locations which go beyond IEC 61215.



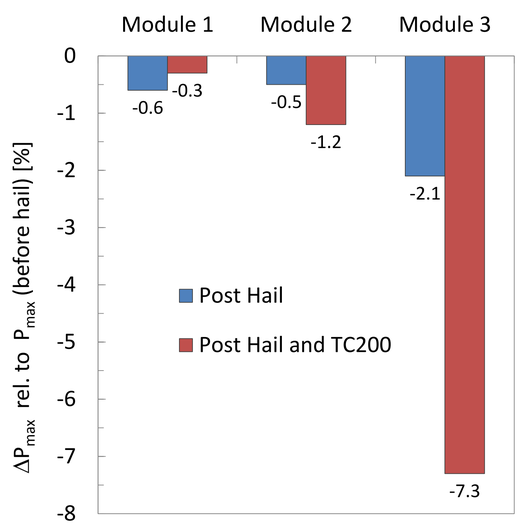
Module 2: Before hail test



Module 2: After hail test



Module 2: After hail test & TC200



Change in P_{max} after hail test and after hail &TC200 relative to P_{max} (initial value).

- After hail test: ΔP_{max}= 1.1 ± 0.7 % (5 % pass/fail criterion in IEC 61215).
- Cracks visible in the hail impact areas.
- After hail & TC200 ΔP_{max}= 2.9 ± 3.1 %.
- Due to the small sample size and the brittle nature of silicon there is a high statistical scatter in the results.

CONCLUSION

- The additional power loss after thermal cycling shows that thermal cycling after hail testing should be incorporated into a glass-less module durability test protocol.
- This work is part of a larger effort to establish an appropriate durability standard for glass-less modules which considers stresses during both degradation and damage caused by potential stresses during installation as well as operation.

This work was supported by the US Department of Energy SunShot Initiative.
The experiments were carried out at the CFV Solar Test Laboratory.
This presentation contains no confidential information.

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Requirements on accelerated testing to ensure 25 years without moisture ingression problems

Introduction

The aim of this study was to find out the correlation between moisture stress in the field and accelerated tests. To do this a model for the equivalent moisture load in different climates was generated. The model is based on the moisture barrier behavior of standard PV edge sealants (e.g. butyl). In the model a number of different climate sites around the world were implemented, with different installation alternatives. The model calculations were used to determine the necessary test times and conditions corresponding to 25 years of moisture load in the field. Three different installation options were simulated for every climate; “standard modeling” based on NOCT tests according to standards, “free field installation” and “bad backside ventilation”.

Method

1. &Setup of moisture acceleration model based on previous work on moisture transmission in polymers with and without desiccants
2. &Accelerated testing in different environments, with different edge seal widths and with different edge seal materials to validate model
3. &Setup of module environment model based on ambient temperature, ambient humidity, in-plane irradiance and type of installation
4. &Implementation of hourly climates from different sites around the world
5. Calculation of test times corresponding to 25 years in the field

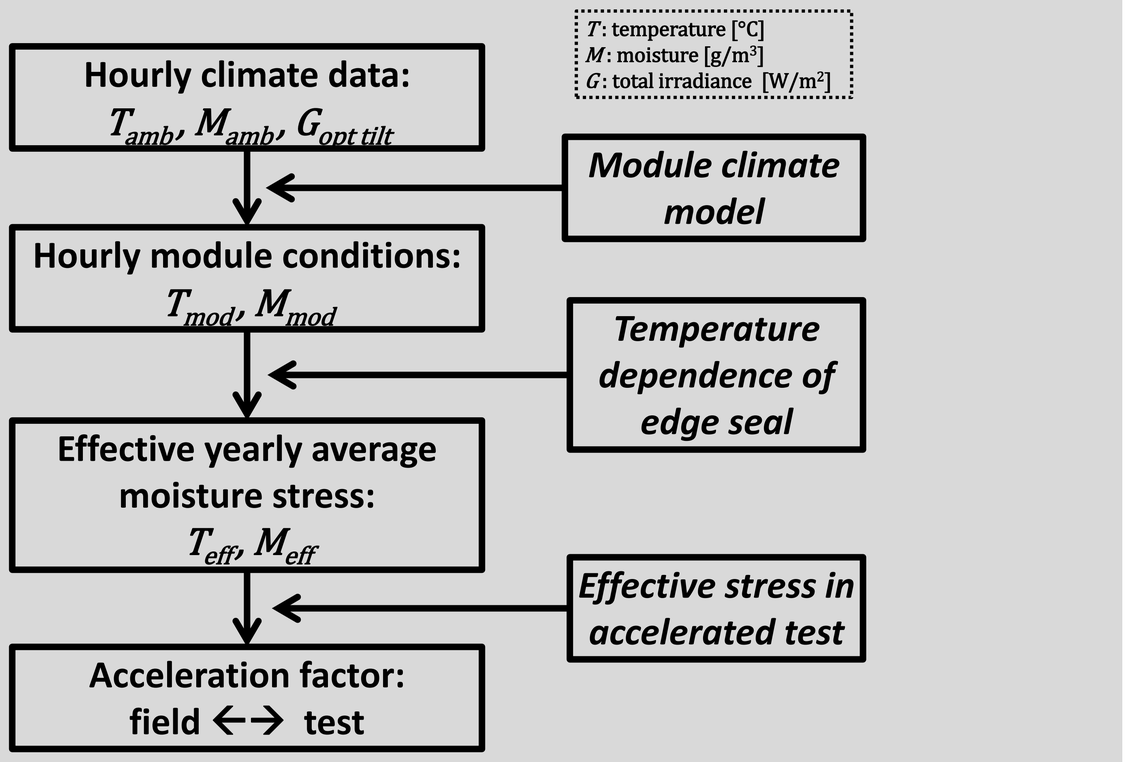
Results

Effective moisture load in different climates

Hours in DH 85 °C & 85 % RH that is equivalent to 25 years in the field				
[hours per 25 years]		Free field installation	Standard modeling	Bad backside ventilation
Temperate climate	Bremen	256	340	518
	Munich	247	340	539
	Bern	293	393	604
	Moscow	192	256	387
	Camborne	268	352	529
	Stockholm	190	254	387
Polar climate	Tromsö	89	113	161
	Östersund	119	159	246
Desert	Alice Springs	793	1175	1983
	Tamanrasset	511	749	1250
	Riyadh	960	1352	2137
	Johannesburg	523	784	1361
Tropical	Jodhpur	1454	1954	2932
	Kuala Lumpur	2124	2744	3968
	Miami	1573	2117	3219
	Accra	2266	3009	4495
	Brasilia	1010	1383	2155
	Bangkok	2385	3133	4606
	Singapore	2234	2887	4183
	Hainan	1605	2089	3051
Mediterranean climate	Zaragoza	504	706	1121
	San Francisco	431	611	997
	Perth	730	1061	1769
	Athens	736	1044	1691

Fig. 1: Table with required test times in DH 85 °C & 85 % RH corresponding to 25 years in the field with different installation types in different climates.

Schematic view of moisture load model



Module overtemperature modeling

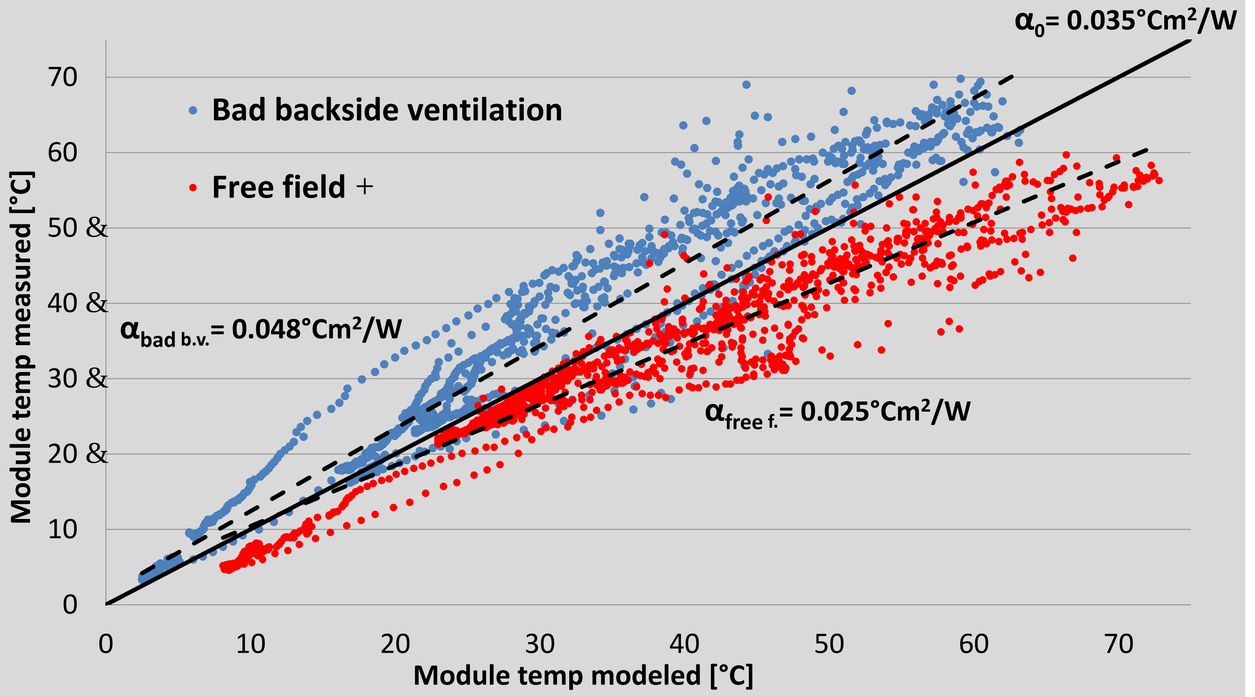


Fig. 4: Measured module temperature vs. modeled module temperature for different installation types. Best fit model parameters are indicated by the dashed lines

Summary & conclusions

- In non-tropical climates the DH1000 in the IEC standards is a good test to quantify the moisture resilience over a module lifetime in the field
- In tropical climates the equivalent moisture load over 25 years is much worse than in the DH1000 test. Considerably longer test times are needed to prove the moisture resilience in such climates.
- The type of installation is very important for the environmental stress that a module will experience over 25 years in the field. The difference in moisture stress between free field installations and installations with bad backside ventilation (e.g. residential roof top) is roughly a factor of 2.

This presentation contains no confidential information

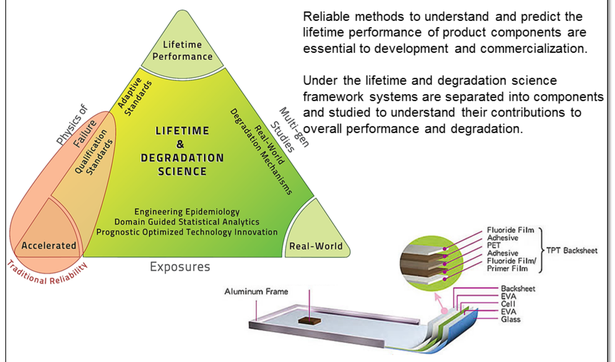
Degradation Analysis of Poly(ethylene terephthalate) via Fluorescence Spectroscopy

Devin A. Gordon[1], Abdulkerim Gok[1], Cara L. Fagerholm[1], David M. Burns[2], Timothy J. Peshek[1], Laura S. Bruckman[1], Roger H. French[1]

[1]Case Western Reserve University, Cleveland, Ohio United States
[2]3M Company, St. Paul, Minnesota, United States

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No.

Introduction



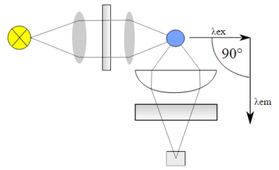
Reliable methods to understand and predict the lifetime performance of product components are essential to development and commercialization.

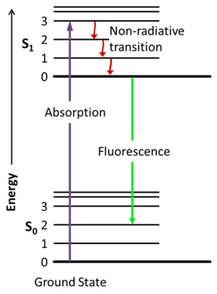
Under the lifetime and degradation science framework systems are separated into components and studied to understand their contributions to overall performance and degradation.

Fluorescence Spectroscopy

- Sample excitation by light source followed by detection of emission radiation
- Probes molecular structure
- Can be used to monitor chemical changes in materials

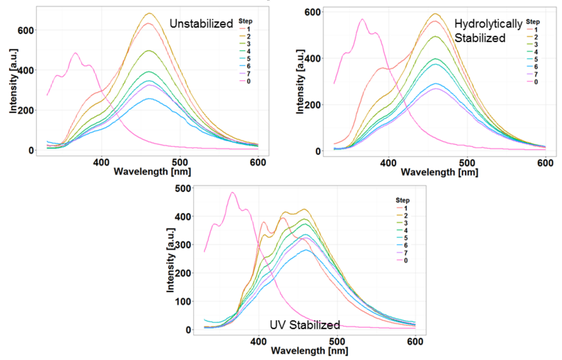
Excitation: $S_0 + h\nu_{ex} \rightarrow S_1$
Emission$_{(Fluorescence)}$: $S_1 \rightarrow S_0 + h\nu_{em} + \Delta$



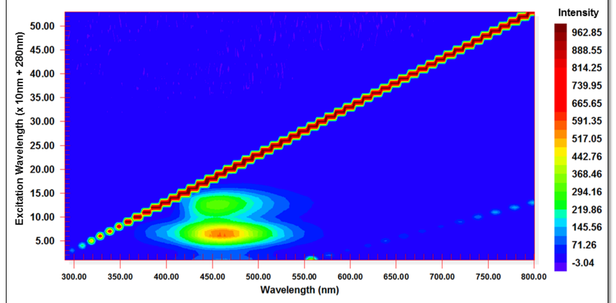


Modified ASTM-G154 Exposure Results

- Decrease in PET fluorescence intensity – Loss of distinctive PET peaks
- Redshift in fluorescence emission in all grades



Future Work: Three-Dimensional Matrix Fluorescence Spectra

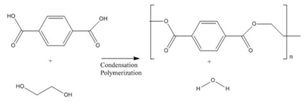


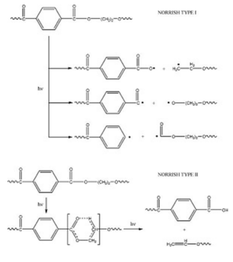
Objectives:

- Measure and plot three-dimensional excitation and emission matrix spectra to maximize data collection and information.
- Identify PET Degradation mechanism pathways for various exposure types.

Poly(ethylene terephthalate)

- Condensation polymer of terephthalic acid and ethylene glycol
- Useful as core layer in PV backsheets because of its high dielectric breakdown strength and low cost
- Degrades under exposure to environmental stressors
- Stabilizers added to mitigate or prolong degradation processes

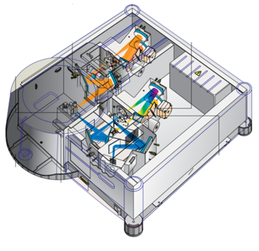


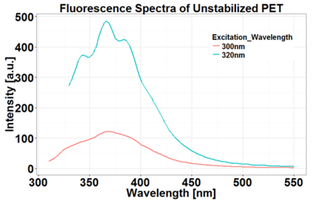


Material	Thickness
Unstabilized PET	75 µ
UV-Stabilized PET	50 µ
Hydrolytically Stabilized PET	125 µ

Fluorescence Spectroscopy of PET

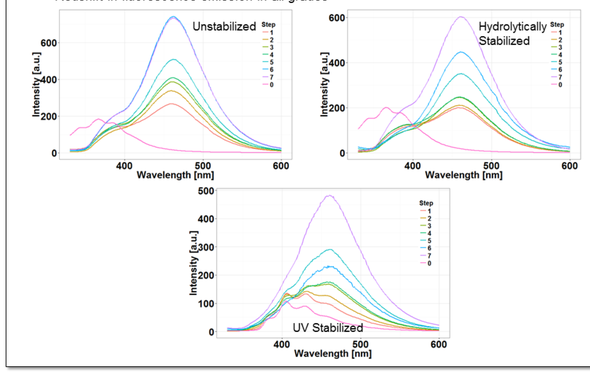
- Instrumentation Agilent Cary Eclipse Fluorescence Spectrophotometer
- Allows characterization of PET and degradation products
- Performed with 300 nm and 320 nm excitation wavelength
  - Note the differences in spectra
  - However, both demonstrate same trends with exposure steps





ASTM-G154 Exposure Results

- Increase in PET fluorescence intensity - Loss of distinctive PET peaks
- Redshift in fluorescence emission in all grades

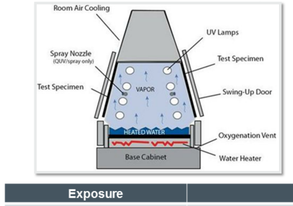


Acknowledgments

- Case Western Reserve University
- Solar Durability and Lifetime Extension Center
  - Nick Wheeler
- 3M Company
- National Science Foundation
- Humboldt University of Berlin
  - Ronald Steffen

Accelerated Weathering

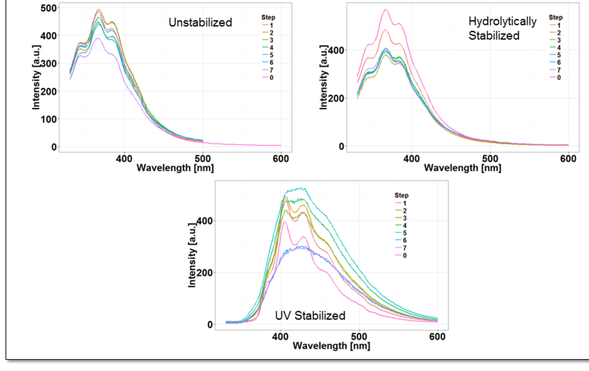
- Exposure protocols in Q-Lab QUV Accelerated Weathering Testers and Cincinnati Sub-Zero Environmental Test Chamber
- Administered combinations of heat, humidity and UV irradiance



Exposure	Description
ASTM G-154	8 hours of UVA exposure of 1.55 W/m^2 at 340 nm and 70 °C followed by 4 hours of condensing humidity at 50 °C in the dark
Modified ASTM G-154	Continuous UVA exposure of 1.55 W/m^2 at 340 nm at 70 °C
Damp Heat	Continuous exposure at 85 °C and 85% relative humidity

Damp Heat Exposure Results

- Decrease in PET fluorescence intensity - Loss of distinct PET peaks in UV Stabilized grade



Conclusions and Work in Progress

Conclusions:

- Fluorescence properties of unstabilized and stabilized grades of PET were characterized
- Changes in fluorescence spectra were observed after accelerated weathering
  - Provide insight into the molecular structure changes of PET as a result of degradation
- Observed different fluorescence responses as a function of weathering exposure type
  - Provide insight into degradation mechanism and synergistic effects of exposures
- Observed function and effect of UV and hydrolytic stabilizer additives
- Of the exposure types, the cyclic combination of heat, humidity, and UV irradiance exposure proved most damaging

Work in Progress

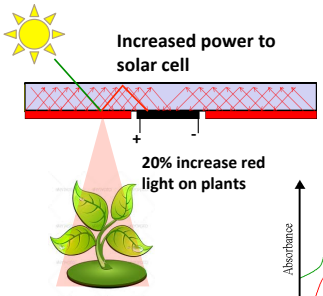
- Full fluorescence spectrum measurements for luminescence intensity mapping
- FTIR measurements to correlate results with specific structural changes
- Larger study of transparent and opaque samples
- Nanoindentation to correlate degradation with loss of mechanical properties

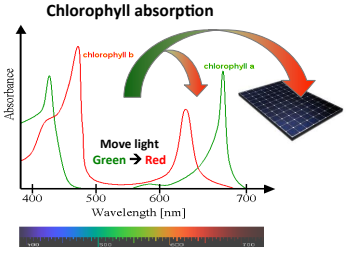
Reliability of Luminescent Solar Concentrators for Greenhouse Application

Soliculture
Grow Generate

Ingrid Anderson*, Melissa Osborn, Glenn Alers
*Director of Research, Soliculture
ingrid.anderson@soliculture.com

How it works:





Green light: High solar intensity but low photosynthetic efficiency

Shift green light → red light improve plant growth, generate power

Generate power AND help plant growth

The market:

Greenhouses are big

Example: 300 acre glass greenhouse

>500 million ft² in North America

Greenhouses use a lot of electricity

Cooling, pumping, lighting, refrigeration

$150,000/year bill typical

Greenhouses are just the beginning

Open-field agricultural crops have same results as greenhouse crops

Potential is large for co-location

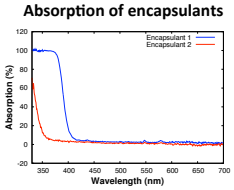
Electricity revenue DOUBLES net profit for farmer

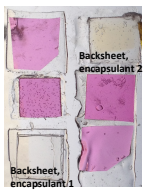
Clear backsheet reliability:

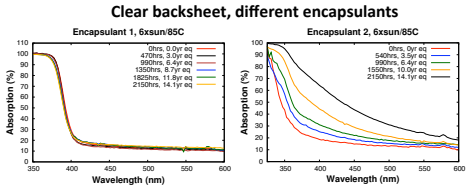
Current clear backsheets are not made for full sun exposure

Backsheet must be protected by UV-absorbing encapsulants

Soliculture is exploring appropriate UV cutoff of EVA







UV-absorbing encapsulants improve reliability

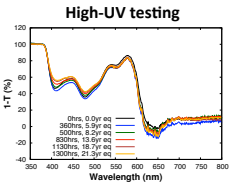
LSC backsheet reliability:

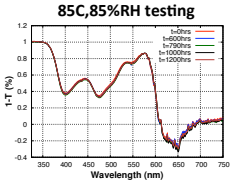
Dye-impregnated plastic is protected by UV absorbers in film and encapsulant

Dye lasts for over 20 years with 36x sun at 60C

Slight yellowing after 15 years

Spectrum does not change after over 1000 hrs in 85C/85%RH testing





Dye is stable in plastic for 20 years equivalent

PV Module Hotspot Detection

J. Gallon, G.S. Horner, J.E. Hudson, L.A. Vasilyev, K. Lu,
Tau Science Corporation, Hillsboro, OR, USA

Abstract

Hotspot defects are known to cause reliability problems in both thin-film and conventional c-Si modules. Detection of hotspots in completed modules can identify potential failures before the module is installed in the field. We describe several root causes for hotspot failures in PV modules, and demonstrate an infrared measurement technique, IRIS™, to quickly identify and characterize the severity of module hotspots.

Background

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

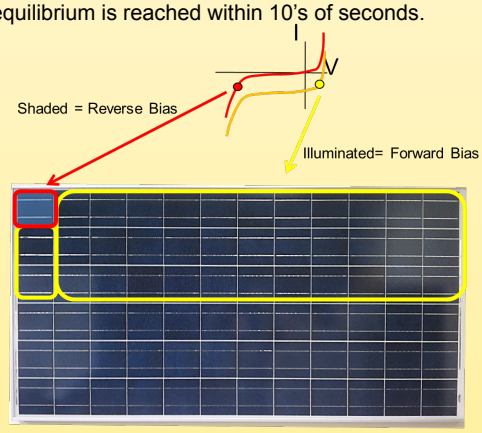
Assume that one cell (outlined in red) is shaded while all other cells are fully illuminated.

Causes of shading might include:

- Bird or Leaf
- Dirt or Snow
- Building Shadow… etc.

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

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



Hotspots: Common Causes

Cell Manufacture

- Incomplete edge isolation
- Crystalline defects intersecting junction
- Metal-decorated cracks
- Overfiring: pn junction "punchthrough"
- Scribeline shunts- incomplete removal or redeposition
- Metal particles & bridges on backside
- Print alignment errors

Module Manufacture

- High resistance or "cold" solder points
- Current mismatch between cells

Typical Damage (x-Si)

Mild (<80°C rise)

- Low damage probability

Moderate (~80-200°C rise)

- Backsheet bubbles
- Coverglass cracking
- ***loss of quasi-hermetic seal***

Extreme (>200°C rise)

- Cell damage

Long term effect

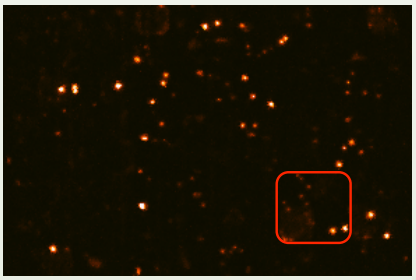
Moisture Intrusion
→ Corrosion & Power Loss
→ Warranty failure.

Manufacturing Requirement

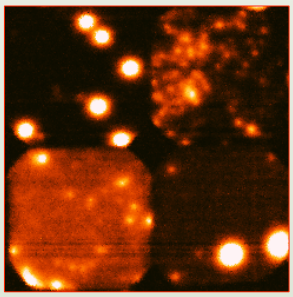
- Reduce Warranty Exposure by identifying hotspot modules with high reliability (>99.9% accurate) inspection.

Module Measurement Method

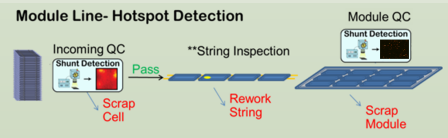
Method: Lock-in & Time-resolved Thermography[Patents Pending]
Camera: LWIR (8-12 micron)
Speed: a) Inline: ~20 seconds / module
b) R&D: 30ms- 5 min.



Complete Module Inspection



Analysis of Module Regions



Summary

Using this technique, hotspots may be conclusively identified before or during field installation with IRIS inspection machines capable of >25 modules per hour. The technique works in ambient light and directly measures the local heating due to defects.

Tau Science
Process Control for PV

Emerging Issues for Photovoltaic (PV) Modules: Surface Soiling and Fundamental Photon Coupling

Lawrence L. Kazmerski,* Antonia Sônia A.C. Diniz,† Cristiana M. Brasil,† Marcelo Machado Viana,†
Lauro V. Machado Neto,† Leila de Oliveira Cruz,+ and Govindaswami TalizhMani**

*Renewable and Sustainable Energy Institute (RASEI), *University of Colorado Boulder and National Renewable Energy Laboratory,* Golden, Colorado
†*Pontificia Universidade Católica de Minas Gerais (PUC Minas),* Belo Horizonte, Brasil
+*Instituto Militar de Engenharia (IME)*, Rio de Janeiro, Brasil ** *Arizona State University*, Arizona

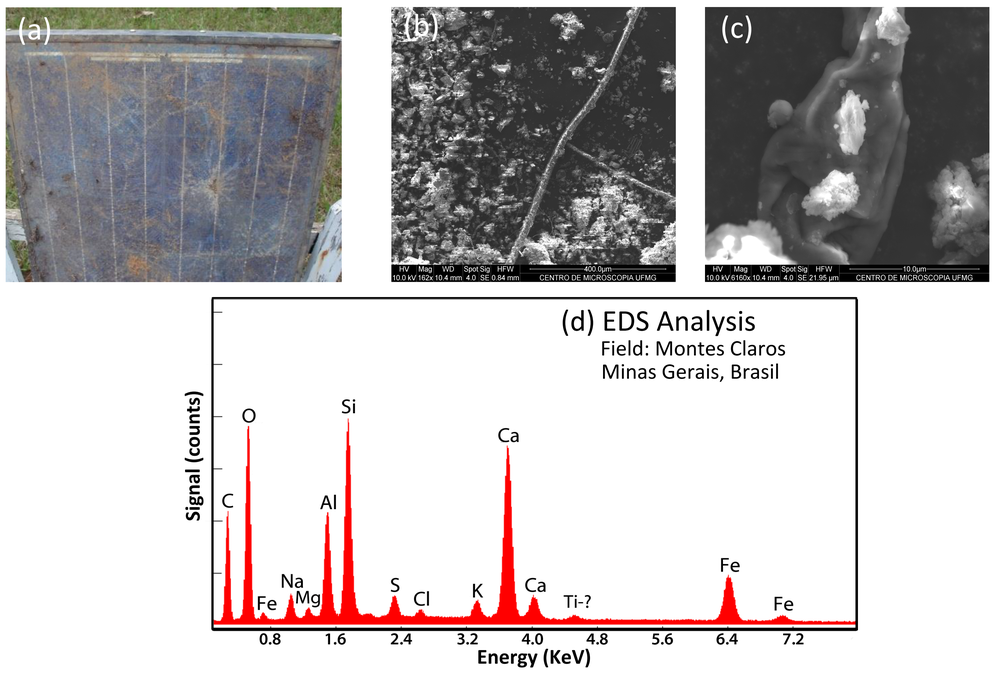
PVReliability.org
Confiabilidade de Sistemas Fotovoltaicos

Activities and Objectives

This new, collaborative research program has been commissioned by the government of Brasil (through the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—CAPES, under "Pesquisador Visitante Especial" and "Ciência sem Frontieras" programs). The **mission** is to enhance ongoing research in solar-technology reliability, linking worldwide efforts with those important for the now-growing solar investments in the Brasil markets. The **objectives** encompass three interrelated areas important to module *surface* reliability and performance—at the very *first* point of interaction for the incoming solar photons:

- **Soiling Science and Technology** *(Creating and validating protocols and procedures, establishing joint test fields in representative climate zones, developing and deploying dust-monitoring stations in key locations, collecting samples and monitoring dust-performance relationships, comprehensive dust/soling chemical and physical analysis, fundamental adhesive-property characterization [from the nanoscale], and developing a framework for dust testing standards based on Brasil's specific climatic conditions)*
- **Coatings and Films for Performance Enhancement** *(Nanotechnology-based antireflection and dust mitigation coatings, including novel dual-purpose designs)*
- **Next-Generation Materials Science:** *Materials by Design (Design and realization of next-generation (nanoscale) coatings by revolutionary materials science and discovery)*

Initial Soiling Investigations: Chemical & Physical Analyses



Figur 2 Preliminary characterization of dust sample from PV module (a) in test field a Montes Claros (Mina Gerais). (b an (c are secondary electron images of dus particles, with the light particles (seen i (c)) likely being glass from the broken module surface. (d ED compositional analysis o dus soiling sample, with the Si-O from the glass. These analyses wer performed to validate the procedures for dus characterization i Brasil. Other characterization includes: AFM, STM, HREM, SAM, SIMS, XPS, PES, XAFS, EDS, ICP-MS, FTIR, and XRD.

Monitoring Station Design

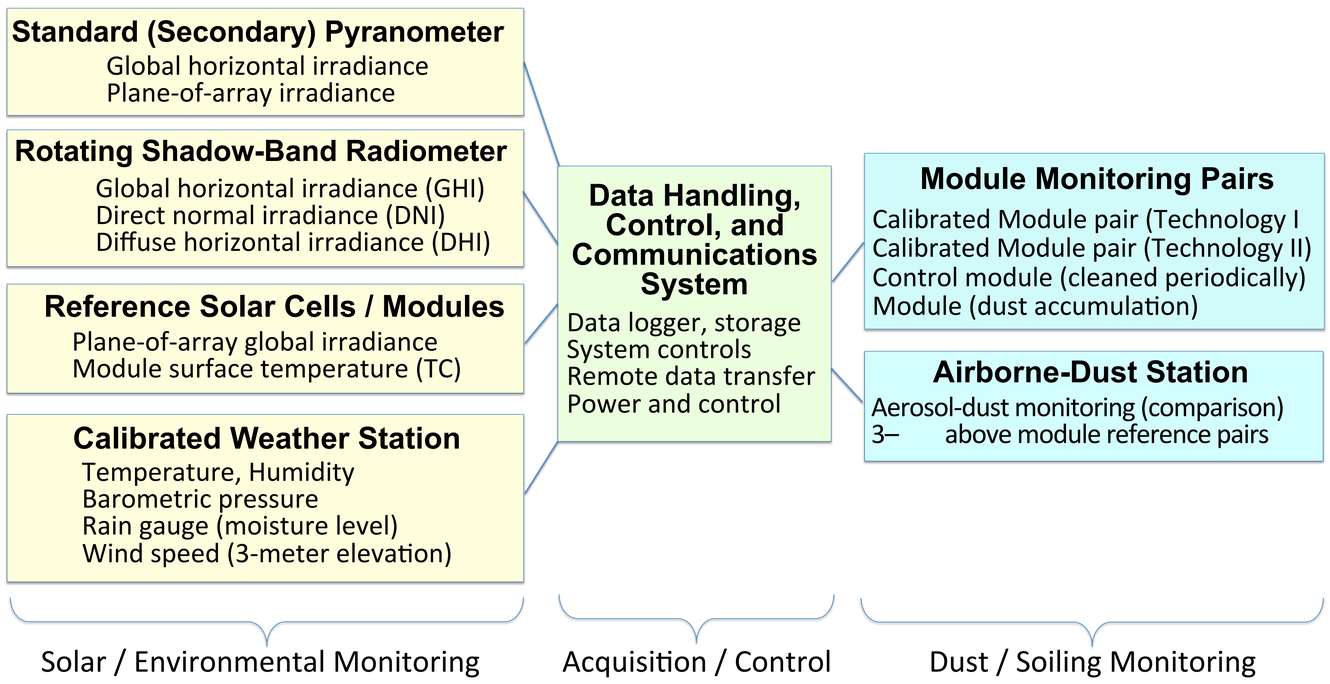


Figure 1. Functional description of components of "Dust / Soiling Monitoring Station," indicating interactions and equipment / system capabilities.

Brasil Partner and Test Locations

- R&D Lead partner (test site)
- Collaborating partner (Test / monitoring site)
- Pending test / monitoring site

Partner Responsibilities

PUC-Minas and RASEI:
- Research management
- Monitoring stations (design, siting, siting, deployment, data acquisition and interpretation)
- Dust / coatings characterization
- Materials design / evaluation
- Reliability testing / monitoring
- Industry points-of-contact

IME:
- Lead for coatings development an deposition
- Soiling monitoring / testing

ASU:
- Lead for standards
- Soiling monitoring / reliability

UFMG; CNPEM
- Dust, thin-film characterization

PUC-RS; USP; UF-Bahia
- Field testing; dust monitoring

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This poster contains no proprietary information.

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IME
ASU
CAPES

Water Cooking for Backsheet and PV Module Endurance

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Introduction & Objectives

☐ Water cooking is applied as an efficient screening tool to evaluate various structures of PV module backsheet from three suppliers against thermal and humidity stressing. Visual check, adhesion, yellowing, water vapor transmission rate (WVTR) and FT-IR spectral are inspected. De-lamination among layers and PET hydrolysis occur after 600 ~800 hours.

☐ Comparing with extended damp heat reliability in P-mono modules, it has well correlation between water cooking to damp heat result. The acceleration factor is around 6 to 8 times faster than damp heat test.

Experiment

For water cooking test, de-ionized water (the resistivity > 18 MΩ-cm, at 25℃) in 6-liter beaker is heated on a temperature programmable hot plate. Water temperature is controlled within 100℃±2℃.

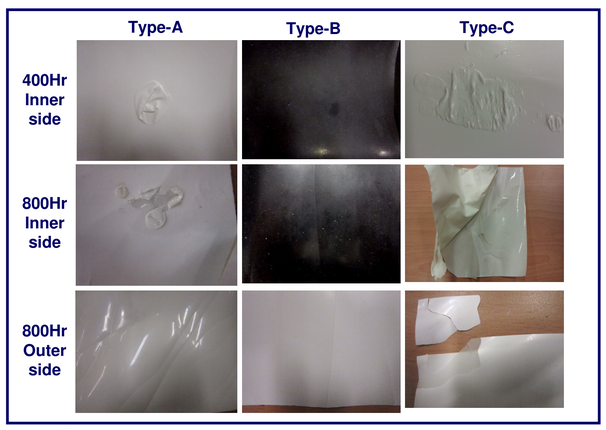
Backsheet Type	A	B	C
Outer Layer (Air side)	PET(50um)	PVDF(20um)	PET(50um)
Adhesive			
Middle Layer (Insulation Layer)	PET(125um)	PET(125um)	PET(125um)
Adhesive			
Inner Layer (Cell side)	Primer(100um)	EL(150)	EVA(100um)

Layer structure of backsheets

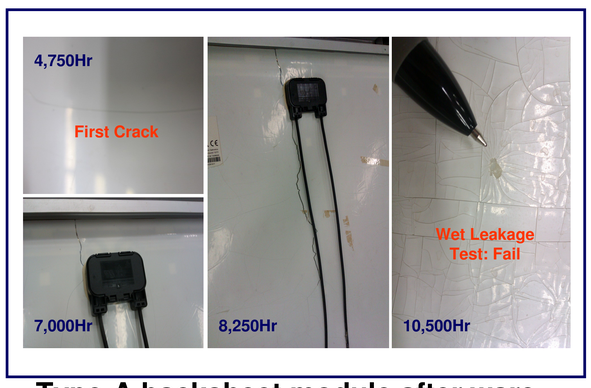
Setup for water cooking test

Results

Visual Appearance after Water Cooking and Damp Heat

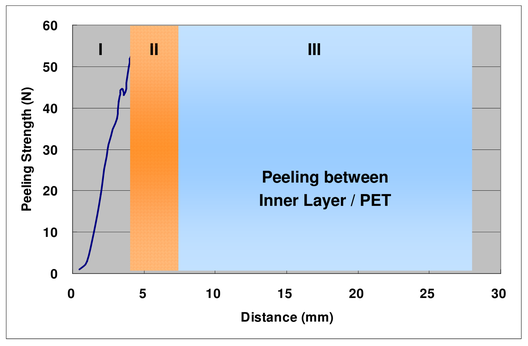


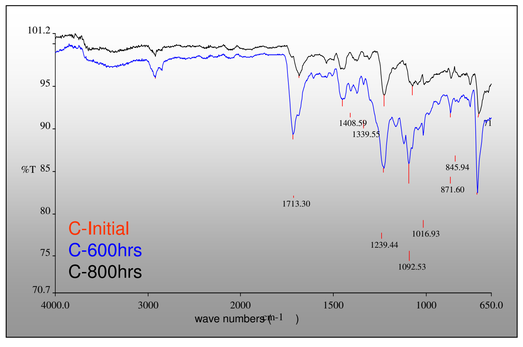
The endurance for water cooking : type-A > type-B > type-C.



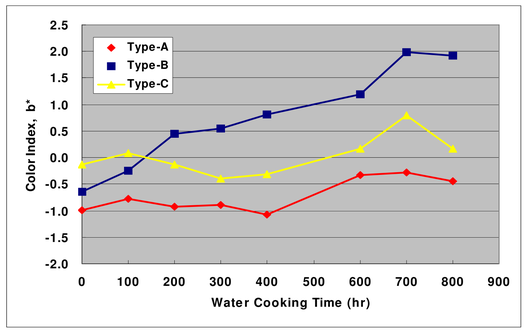
Type-A backsheet module after ware-out damp heat test

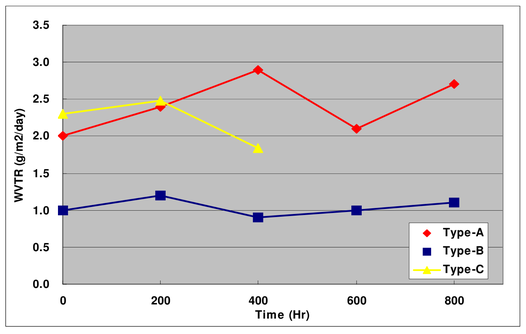
Peeling Test & FT-IR Analysis



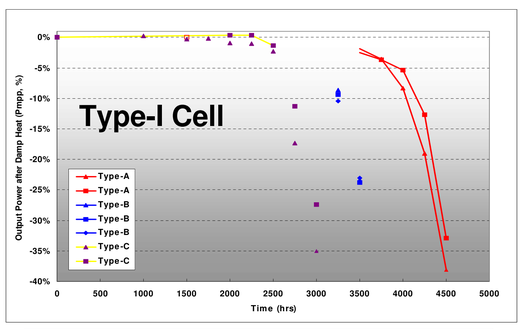


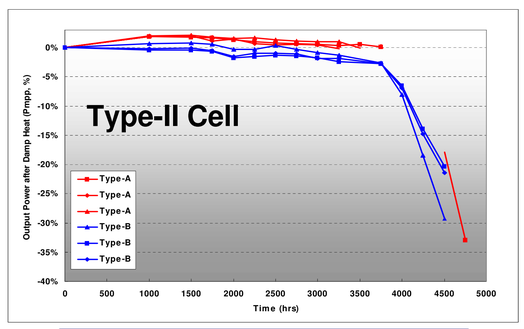
Yellowing Effect & Water Vapor Transmission Rate

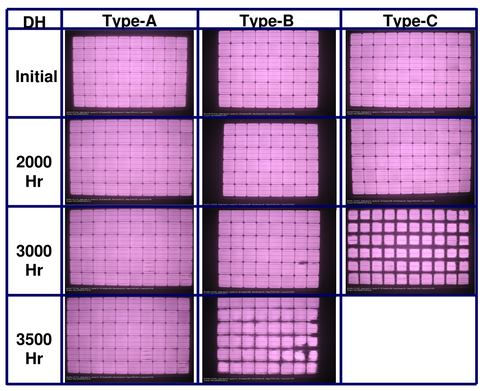


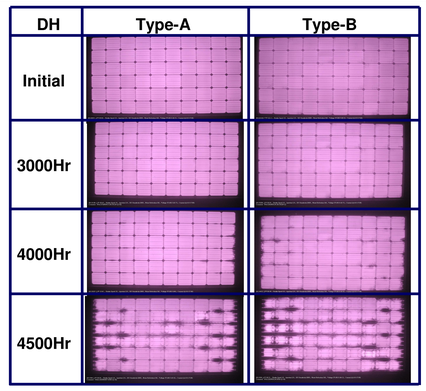


Reliability Evaluation by Extended Damp Heat Test









The endurance performance for those backsheets is type-A > type-B > type-C.
The result from damp heat follows the tendency as water cooking.

Conclusion

☐ Water cooking test is applied as a fast screening tool to investigate various types of backsheets. Physical and chemical properties such as visual appearance, layer to layer adhesion, PET hydrolysis, yellowing effect and WVTR are distinguished among those backsheets. Comparing the timing for first cracking formation, the accelerated factor for water cooking is around 6 to 8 times higher than damp heat.

☐ The tendency from water cooking corresponds to the result of long-tern damp heat with 2 different types of P-mono cells. We confirm water cooking is efficient and reliable method to evaluate backsheet endurance and predict the influence of backsheet on PV module reliability.

This presentation contains no confidential information.

BenQ Solar

Accurately Measuring PV Soiling Losses Using Module Power Measurements

M. Gostein and B. Stueve, Atonometrics, Inc.

Non-uniform PV soiling can't be measured by short-circuit current alone. '

Non-Uniform PV Soiling

- In some conditions, soiling may accumulate non-uniformly on PV modules
- Wind, rain, condensation, temperature, and gravity all affect soiling distribution
- Often, soiling is concentrated at module edges

Example of edge soiling on utility-scale tracking system:

From: F. Brill, "EnviroPolitics Blog: PSEG building solar farms--and not just in New Jersey," 16-Nov-2012. [Online].

Examples on ground and roof-mount systems:

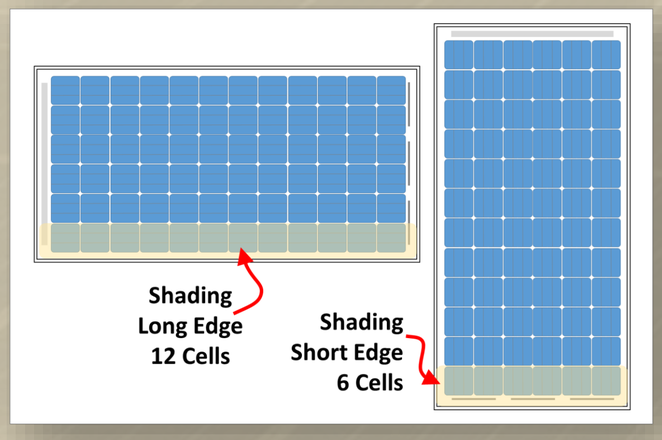
From: E. Lorenzo, R. Moretón, and I. Luque, "Dust effects on PV array performance: in-field observations with non-uniform patterns," *Progress in Photovoltaics: Research and Applications*, 2013.

Pmax vs. Isc as Soiling Metric

- "Soiling Ratio" (SR) metric can be based on losses in measured current (Isc) or power (Pmax)
- Isc measurement simpler, but only approximates true power loss in case of uniform soiling
- Experiment shows Isc measurements can severely over- or under-estimate true power loss for non-uniform soiling on c-Si PV modules

Experiment with Simulated Soiling

72-cell c-Si module, two orientations



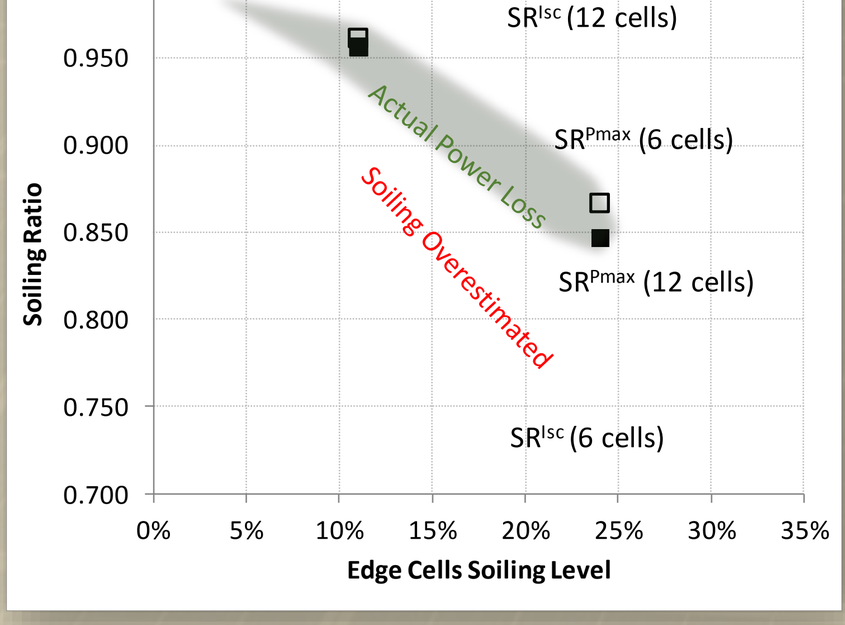
Soiling Ratio Metrics

$$SR^{Isc} = \frac{\text{Measured Isc Soiled }^{**}}{\text{Predicted Isc Clean}}$$ **Current**

$$SR^{Pmax} = \frac{\text{Measured Pmax Soiled }^{**}}{\text{Predicted Pmax Clean}}$$ **Power**

***Irradiance- and temperature-corrected*

Results

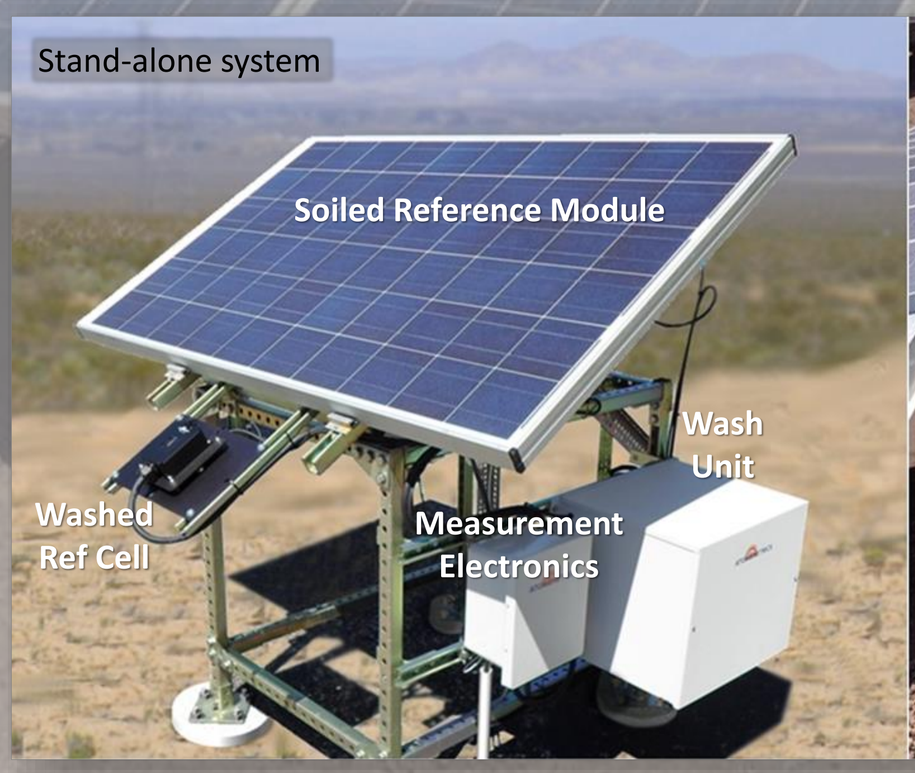


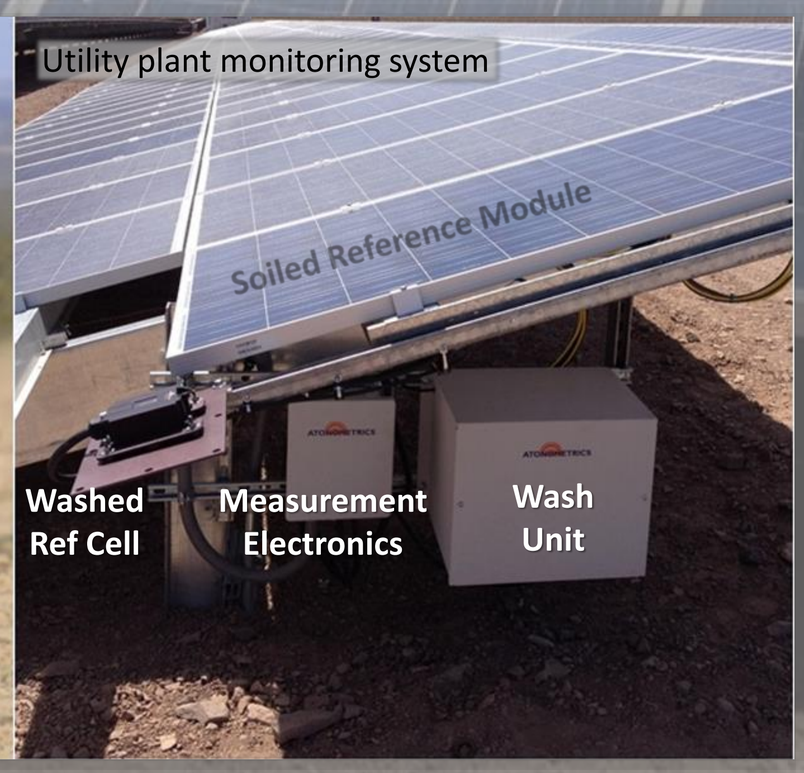
Explanation: Module has 3 internal bypass diodes. Shaded 12-cell string on long edge is bypassed by internal diode, so Isc is not limited by shading; but shading 6 cells across all strings results in the shaded cells controlling and limiting Isc.

From: Gostein, Littmann, Caron, Dunn, Proceedings of the 39th IEEE Photovoltaic Specialists Conference (PVSC), Tampa, FL, June 2013.

Soiling Measurement System

- Soiling measurement: use "soiled" module and "clean" control
- "Clean" control: may use automatically cleaned reference cell
- For "soiled module" use actual PV module representative of site, to capture module-specific effects and non-uniformities
- <u>Should measure both module current and power</u>





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ATONOMETRICS

CFV solar test laboratory

600 Hour Potential Induced Degradation (PID) Testing on Silicon, CIGS and HIT Modules

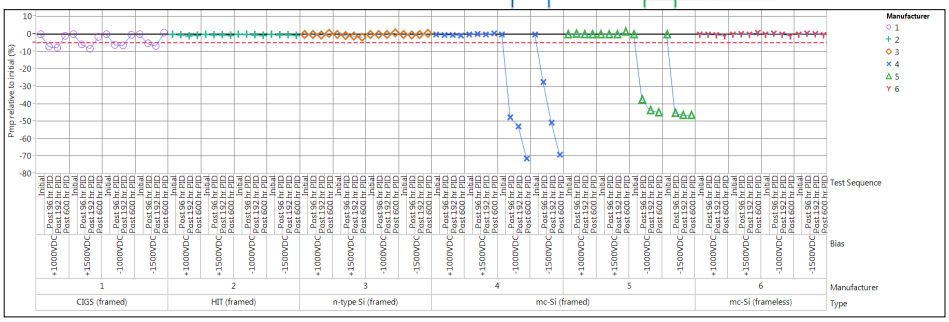
Nicholas Riedel*, Larry Pratt*, Erica Moss and Michael Yamasaki
CFV Solar Test Laboratory, Inc., Albuquerque, NM

Introduction

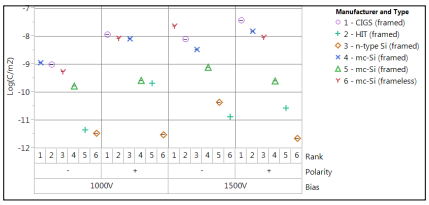
Potential induced degradation (PID) tests are performed on Silicon, CIGS and HIT modules in accordance with the IEC 62804 DTS, with slight modifications. Four PV modules from six manufactures are tested (24 test samples) under biases of -1000 VDC, +1000 VDC, -1500 VDC or +1500 VDC for a total stress duration of 600 hours. The electrical bias represents a potential to ground. Module performance is characterized at STC in a h.a.l.m. class $A^+A^+A^+$ flash solar simulator before PID testing, after 96 hours of PID tests, after 192 hours tests and after 600 hours of PID tests.

Results

The Silicon modules from manufacturers 4 and 5, when placed in negative bias, are the only samples that show greater than 5% Pmp degradation. Both of these modules are framed multi-crystalline (mc-Si) with glass/polymeric backsheet construction. The final degradations of manufacturer 4 and 5 are nearly the same regardless of whether the bias is set to -1000V or -1500V. The degradations in Pmp are mostly due to degradation of Vmp rather than Imp, as is illustrated by the I-V curves.



- The mc-Si modules with significant PID show dissimilar patterns in EL images.
- CIGS module 'Manufacturer 1' shows final Pmp losses of 0.8 and 1.6% at +1000V and +1500V bias, respectively. Note: These modules were only preconditioned before the initial and final characterizations.
- HIT module 'Manufacturer 2' shows 0.6% final Pmp loss, on average, regardless of bias or polarity.
- Manufacturer 3 shows 1.6% Pmp loss after 600 hours at +1500V. No losses observed at other test biases.
- Frameless mc-Si 'Manufacturer 6' shows 1% final Pmp loss at -1000V and +1000V.

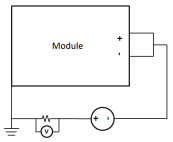


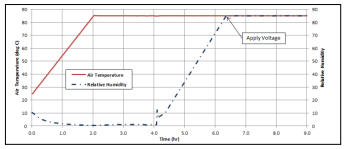
Leakage current density (Coulombs/m²) measured during the initial 96 hour PID tests.

- All modules passed dry insulation (per IEC 61215 § 10.3) and wet leakage (per IEC 61215 § 10.15) before and after the 600 hour PID tests.
- The average leakage current of the test samples is 65% higher at 1500V than at 1000V bias.
- The leakage current density of Manufacturers 1, 4 and 6 is higher by two to three orders of magnitude than that of Manufacturers 2 and 3.

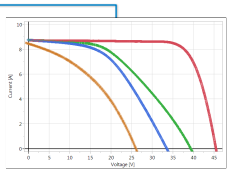
Procedures

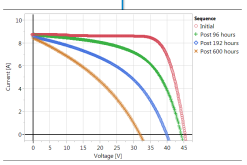
The PID tests were performed in an Espec environmental chamber. The PID test conditions were set as outlined in IEC 62804 DTS : 60° C air temperature, 85% relative humidity, voltage biases of +1000 V, -1000 V, +1500 V or -1500 V for a total test duration of 600 hours. The temperature and humidity were applied according to First Solar's guidelines for PID testing. The intention of this profile is to prevent condensation from forming on the module. The electrical bias was turned off at the end of the stress dwell (i.e. before temperature and humidity were ramped down). Leakage current was monitored throughout the test.



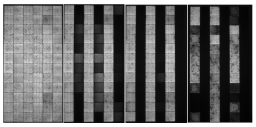


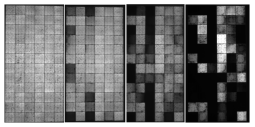
Wiring diagram of a test module in negative bias (left) and the temperature/humidity profile prescribed by First Solar's Testing Guidelines (Rev 4) used in this study (right)



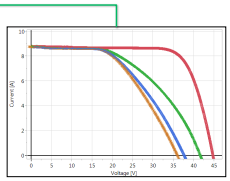


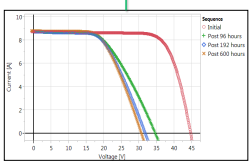
I-V curves of manufacturer 4 at -1000V bias (left) and -1500V bias (right)



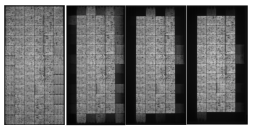


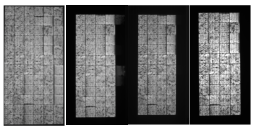
EL images of manufacturer 4 at -1000V bias (left) and -1500V bias (right). The initial, post 96 hour, post 192 hour, and final images are shown.





I-V curves of manufacturer 5 at -1000V bias (left) and -1500V bias (right)





EL images of manufacturer 5 at -1000V bias (left) and -1500V bias (right). The initial, post 96 hour, post 192 hour, and final images are shown.

Conclusions

- Two of the six manufacturers show critical power loss from PID, but only when in negative bias. Both of these modules are framed mc-Si with glass/polymeric backsheet construction.
- The range of final Pmp measured on the four samples of each manufacturer is less than 2% regardless of which electrical potential (1000 V vs 1500 V) was applied.
- Two manufacturers (no. 1 and 6) show considerable leakage current, but Pmp loss was less than 2%.

References

- First Solar, "Testing Specifications and Guidelines for CdTe Modules (Rev 4)", 2014.
- P. Hacke, et al., "System Voltage Potential-Induced Degradation Mechanisms in PV Modules and Methods for Test" in 37th *IEEE PVSC*, 2011
- IEC 61215, Edition 2.0, 2005
- IEC 60904, Photovoltaic Devices, Parts 1-10
- IEC 62804, CDV Draft, Aug 2014

Sorting test of bending load on the interconnector in crystalline silicon photovoltaic modules

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[1]Photovoltaic Power Generation Technology Research Association (PVTEC), Japan
[2]ESPEC, Japan, [3]National Institute of Advanced Industrial Science and Technology (AIST), Japan

INTRODUCTION

Background : Han et al. reported that the ribbon cracks occupy about 8 % of all failure modes of photovoltaic (PV) modules in the field by the literature survey in 2012. The ribbon cracks mean that the current path is cut off and the power generation of PV modules is lost. However, thermal cycling (TC) test specified in IEC 61215 evaluates the failure of the soldering or the cell cracks, and cannot reproduce ribbon cracks.

Purpose : In this study, we tried to evaluate the sorting test for the breakage of ribbon for extracting the weak point or the defect inherent in the modules.

MATERIALS AND METHOD

Figure 1. Photographs of load cycle bending machine.

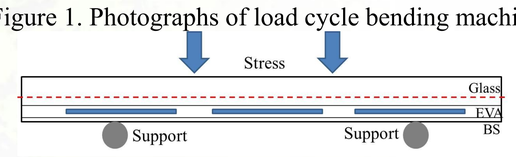


Figure 2. Images of 4 point stress.

Table 1. Specifications of materials used in PV module.

Material	Specification	Supplier
Cell	Multicrystalline-Si cell (156 mm × 156 mm)	Q Cells
Glass	Semi-tempered glass	AGC
Encapsulant	EVA	Nondisclosure
Interconnector	A-SPS (Leaded, Ag)	Hitachi Cable
Back sheet	PVF / PET / PVF	Nondisclosure
Size	540 mm × 200 mm × 4 mm	-

Figure 3. Photograph of PV module sample.

Table 2. Test conditions.

Stress	500 N
Bending / unbending	4 s / 4 s
Bending cycle	10,000 times each test
Temperature	-20℃ / 25℃ / 80℃

SIMULATION

Table 3. Materials properties used in simulation at 23°C.

	Unit	Glass	Silicon	EVA	PET	Copper	Solder	Ag
Young's modulus	Pa	7.31E+10	1.31E+11	1.68E+07	1.60E+06	1.30E+11	2.20E+10	8.27E+10
Poisson's ratio	-	0.22	0.27	0.45	0.33	0.34	0.37	0.37
Thermal expansion coefficient	1/°C	9.03E-06	4.15E-06	2.70E-04	2.50E-05	1.70E-05	2.40E-05	1.93E-05
density	g/cm³	2.5	2.33	0.95	1.4	8.96		10.49

Table 4. Young's modulus of EVA.

Temperature (°C)	-20	23	80
Young's modulus (Pa)	1.40E+08	1.68E+07	1.03E+06

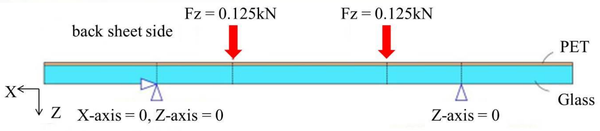


Figure 4. Boundary condition of simulation.

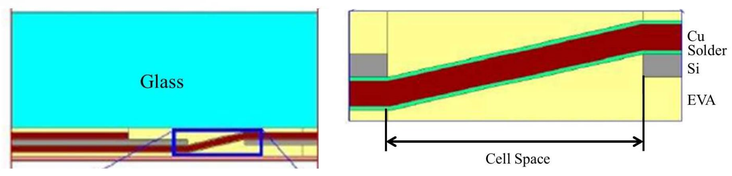


Figure 5. Cross section of model.
Cell space was modified from 1 mm to 5 mm at each simulation.

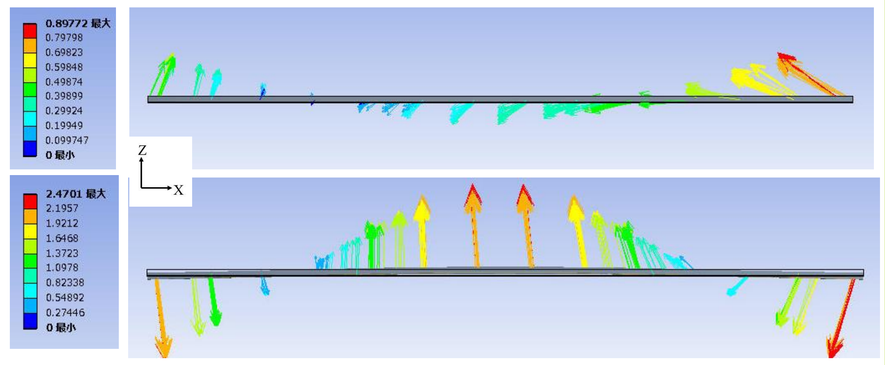


Figure 6. Results of FEM simulation of thermal stress and bending load from back sheet side at -20°C. Displacement was dominated by bending load.

RESULTS & DISCUSSION

	EL initial	EL after test	I-V	Ribbon Break
1 mm		10,000 cycles		○
2 mm		20,000 cycles		○
5 mm		20,000 cycles		○
10 mm		30,000 cycles		○

Figure 7. Results of 4 point load cycle bending test.

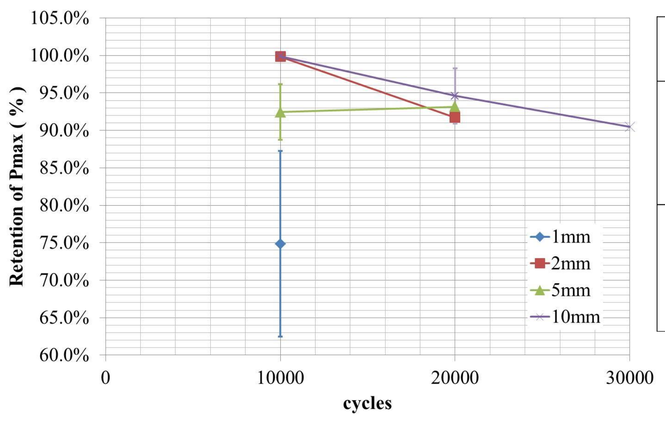


Figure 8. Retention of P_{max}.

Modules with the space	Microscope	Cross-section
1 mm		
2 mm		

Figure 9. Microscopic view and cross section image.

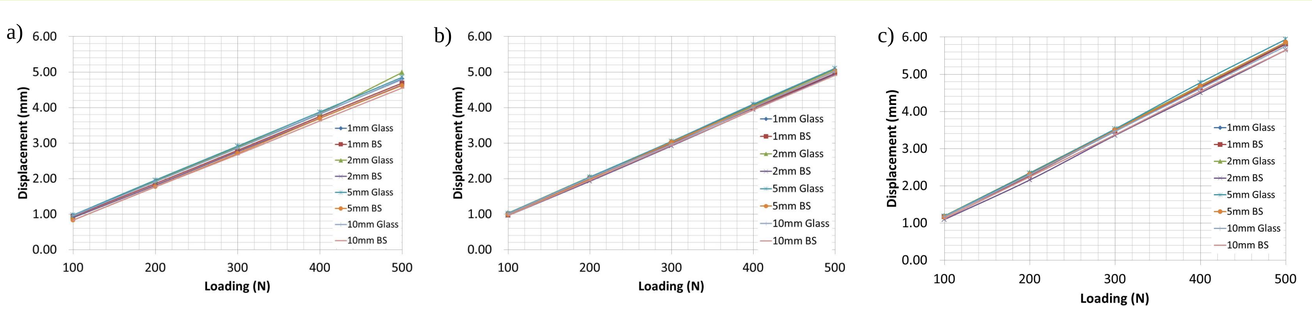


Figure 10. Results of displacement of module with each cell space.
a) -20°C, b) 23°C and c) 80°C .

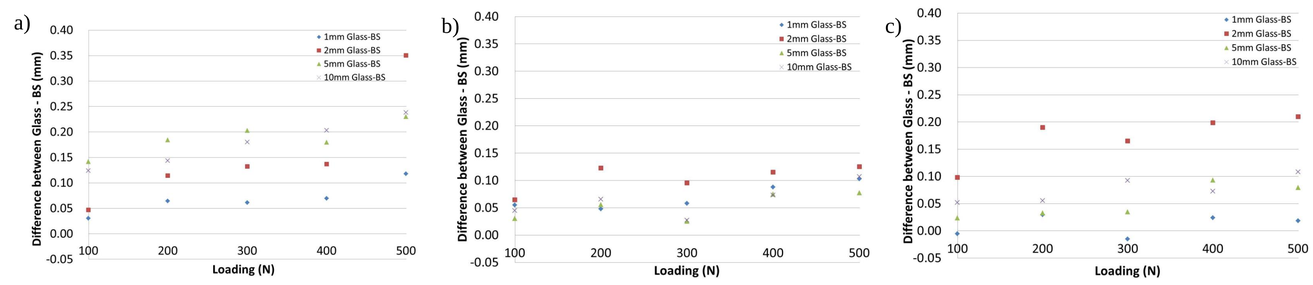


Figure 11. Results of difference between displacements by glass-side load and back-sheet-side load for each cell space.
a) -20°C, b) 23°C and c) 80°C.

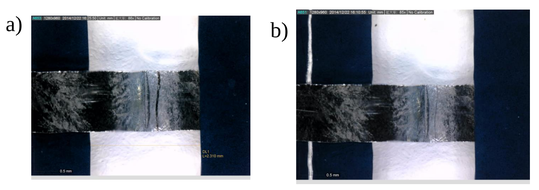


Figure 12. View of ribbon after test.
a) no bending and b) 500N.

Table 5. Results of measurement at cell space.

1 mm (mm)		2 mm (mm)		5 mm (mm)	
No bending	Bending	No bending	Bending	No bending	Bending
1.07	1.04	1.83	1.79	5.03	4.98
difference	0.03		0.04		0.05

Table 6. Comparison of displacement of modules between simulation and measurement.

	Simulation (mm)						Measurement (mm)		
Cell space	1 mm		2 mm		5 mm		1 mm	2 mm	5 mm
Tem perature	Only thermal stress	Bending load	Only thermal stress	Bending load	Only thermal stress	Bending load	Bending load		
-20	0.40	2.50	0.4	2.47	0.32	2.25	4.69	4.64	4.63
23	0.48	2.40	0.47	2.40	0.29	2.40	4.97	4.95	5.03
80	0.15	2.70	0.15	2.67	0.15	2.28	5.81	5.65	5.86

Table 7. Results of the maximum stress level of ribbon.

	Only thermal stress (MPa)			Bending load (MPa)		
	Cell space					
Temperature(°C)	1 mm	2 mm	5mm	1 mm	2 mm	5 mm
-20	1231.9	1231.1	920.4	1236.2	1199.8	1445.8
23	891.7	809.2	668.9	891.4	805.3	1188.5
80	493.8	476.0	365.5	1041.0	924.4	881.6

1. As a result of the bending load test using the test modules with various spaces between the cells, the maximum power (P_{max}) was decreased by about 25% for the module with the space of 1 mm. P_{max} was decreased by about 10% for the modules with the space of 2 mm, 5 mm and 10 mm and complete breakage of ribbon was observed (Figures 6, 7 and 8).
2. As a result of the displacement of module with each cell space, the displacement was proportionally increased with an increase in bending load and temperature. The highest displacement was about 6 mm by 500 N at 80°C. As a result of the difference between displacements by glass-side load and back-sheet-side load, displacement by glass-side load was larger than that from back-sheet-side load (Figures 10 and 11).
3. Cell space was contracted by bending load of 500 N (Figure 12 and Table 5).
4. FEM simulation underestimated the displacement of modules. Especially difference between displacements from simulation and measurement was larger over by 2 times. It was also found that displacement strongly depends on temperature only in the case of measurement (Table 6).
5. The maximum stress level of ribbon of bending load for cell space of 1 mm was the largest of all (Table 7).

SUMMARY

In this study, it was found that the space over 1 mm between the cells is needed for high reliability and the bending load test is useful for the evaluating test for the breakage of ribbon.

Contact Person : Soh Suzuki (so-suzuki@espec.co.jp)

This work was supported by New Energy and Industrial Technology Development Organization under Ministry of Economy, Trade and Industry, Japan.
This presentation dose not contain any proprietary or confidential information.

in situ AC Impedance Measurement in c-Si PV Modules during Rapid Thermal Cycling Test

Tadanori Tanahashi[1], Soh Suzuki[1], Norihiko Sakamoto[2], Akihiro Mito[2],
Katsuhiko Shirasawa[3] and Hidetaka Takato[3] ([1]ESPEC CORP., [2]AIST-NMIJ, [3]AIST-FREA)

FREA FUKUSHIMA RENEWABLE ENERGY INSTITUTE, AIST

Technology development for the high-rate introduction of renewable energy

NMIJ ESPEC

Introduction & Procedures

Motivation & Background

FREA: Fukushima Renewable Energy, AIST

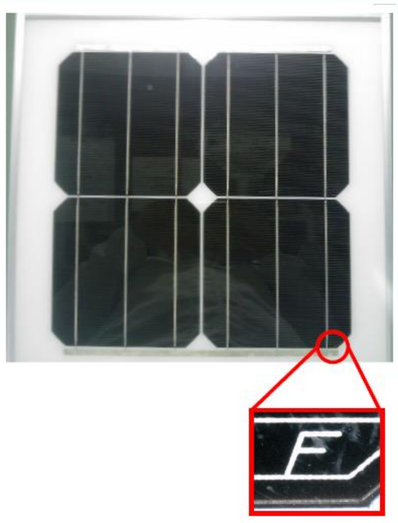
Aim: High Efficiency / Low Cost c-Si PV Cells & Modules
Thin Wafer PV Cells, Light Weight PV Modules…

Our Task: Thin Wafer PV Cells + Ribbon with Opt. Properties
-> Reliable / Durable Interconnected PV Modules

To Confirm the Reliability of Soldering Interconnection on these New Designed PV Modules,

- Higher Stress than Conventional Thermal Cycling
  - -40 °C/85 °C → -60 °C/100 °C
  - Thermal Cycling → Rapid Thermal Cycling
  - 200 cycles → 3,000 cycles +
- *in situ* Detection of Failures during Testing
  in situ AC Impedance Spectroscopy

Thin Wafer PV Cells / Light Weight Glass → "FREA PV Module"



Tested PV Mini-Module

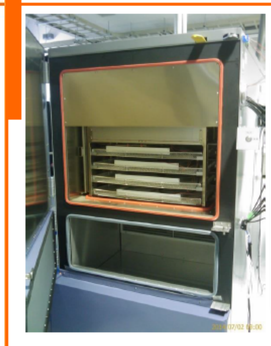
Thin Wafer PV Cells
Mfg. in FREA Lab.
100 μm Thickness
n-type c-Si / p-doped

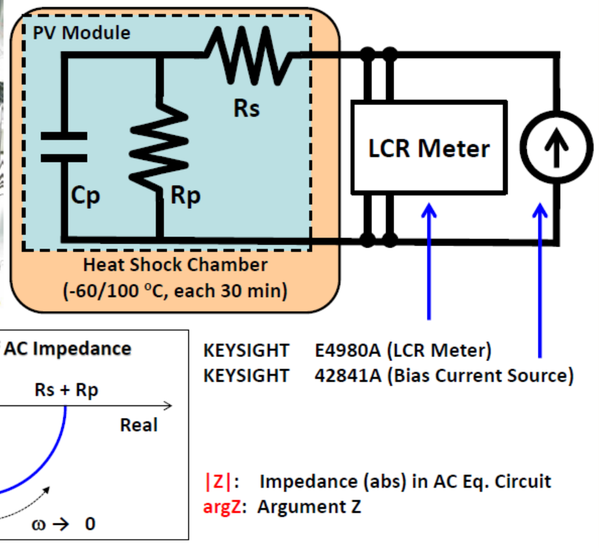
Chemical Strengthen Glass
0.8 mm Thickness

Interconnection
Cu-Ribbon (1.3 mm)
by Soldering

with J-Box & Cables

Experimental Setup & AC Equivalent Circuit of PV Module





KEYSIGHT E4980A (LCR Meter)
KEYSIGHT 42841A (Bias Current Source)

|Z|: Impedance (abs) in AC Eq. Circuit
argZ: Argument Z

Summary

We previously reported that the "spike-like" elevation of whole impedance was observed, which was calculated by the measurement of I_{AC} and V_{AC}, prior to the occurrence of interconnection failure during Rapid Thermal Cycling (RTC) test. In this study, the AC impedance parameters (|Z| and θ) were continuously measured during this testing.

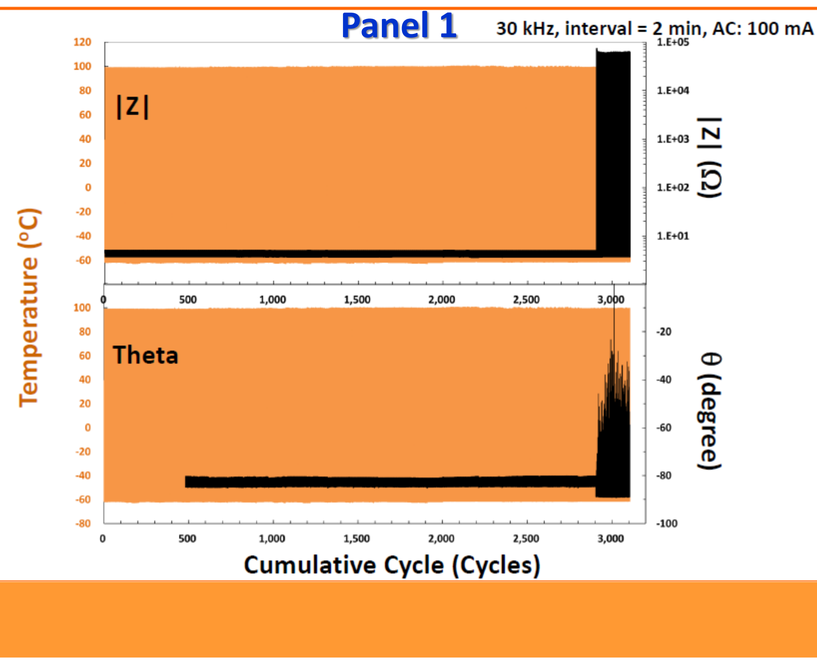
Then, we obtained the results as follows;

- The logarithmical impedance-elevation identified by |Z| elevation was observed at ca. 3,000 cycles of RTC (**Panel 1**). Interestingly, the increasing of |Z| consistently accompanied with θ decreasing.
- These level-changes of |Z| and θ were observed in the temperature elevation phase, and also in the low temperature phase after the PV modules were sufficiently adapted at low temperature (**Panel 5-8**).
- When the PV module was completely adapted to any temperature just after these phenomena were happened, the level-changes of AC parameters were not detected at all (**Panel 9-10**). Simultaneously, any alterations of EL and IR images were not confirmed at room temperature (**Panel 11**).
- From the AC impedance spectroscopy (20 Hz ~ 50 kHz) during the |Z| elevating period (at -60 ºC), it is revealed that the levels of |Z| and θ were >10^4 Ω and almost -90º, respectively (**Panel 12-13**).

These results suggest that the soldering failure in PV modules (including the disconnection in junction box) can be observed when the RTC testing was conducted for prolonged cycles (ca. 3,000 cycles), and that this failure can be detected only during the RTC testing, as a complete detachment between electrical junctions, by the continuous *in situ* AC impedance measurement.

AC Impedance: Time Course during Rapid Thermal Cycling

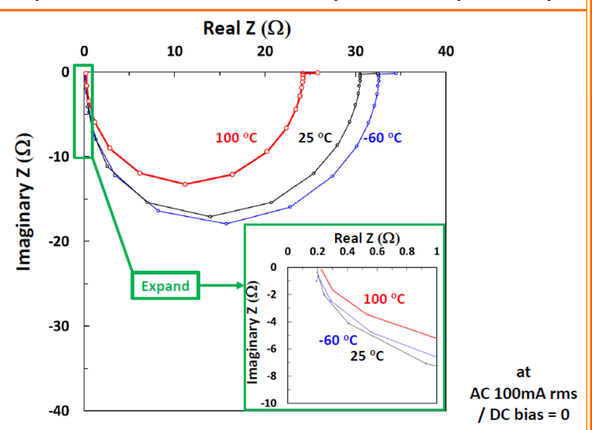
Panel 1 30 kHz, interval = 2 min, AC: 100 mA



Experimental Results

Panel 2

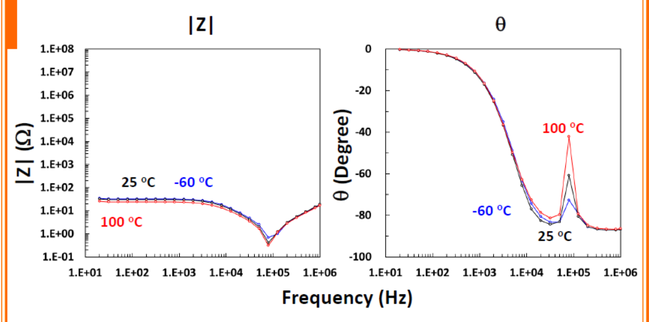
AC Impedance Characteristics: Temperature Dependency



at AC 100mA rms / DC bias = 0

Panel 3

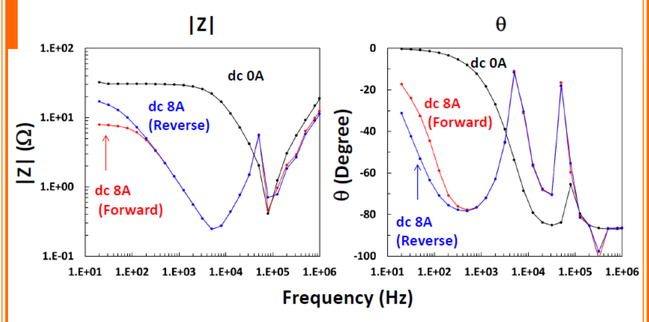
AC Impedance Characteristics: Temperature Dependency



at AC 100mA rms / DC bias = 0

Panel 4

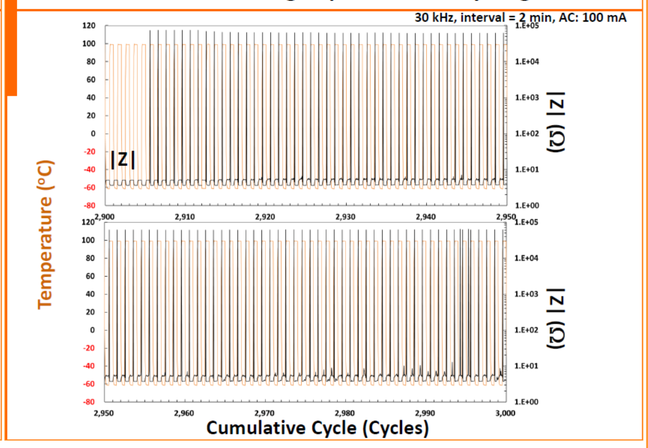
AC Impedance Characteristics: DC Bias Effects



at AC 100mA rms / 25 °C

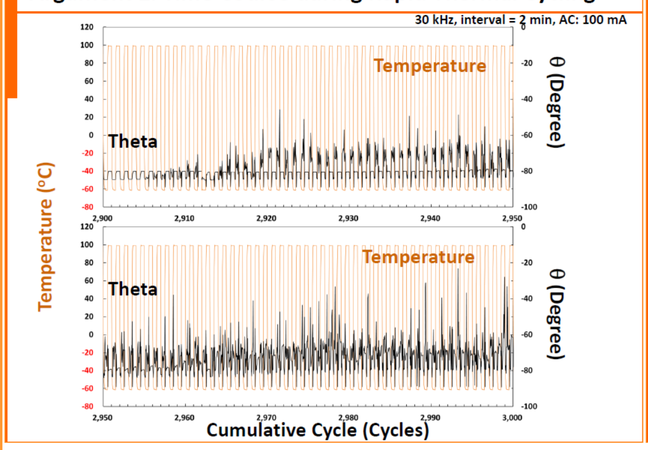
Panel 5

Abs Z: Time Course during Rapid Thermal Cycling



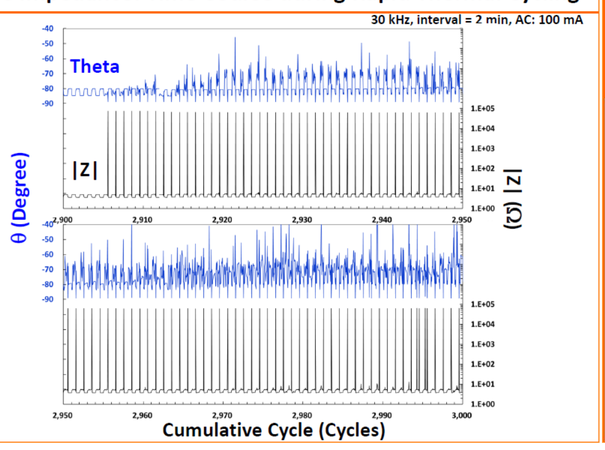
Panel 6

Argument Z: Time Course during Rapid Thermal Cycling



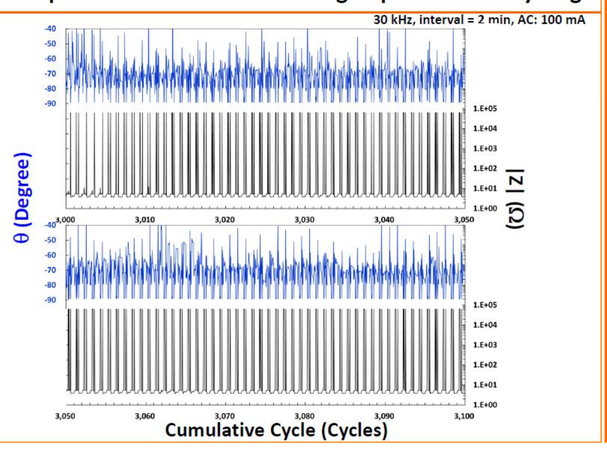
Panel 7

AC Impedance: Time Course during Rapid Thermal Cycling



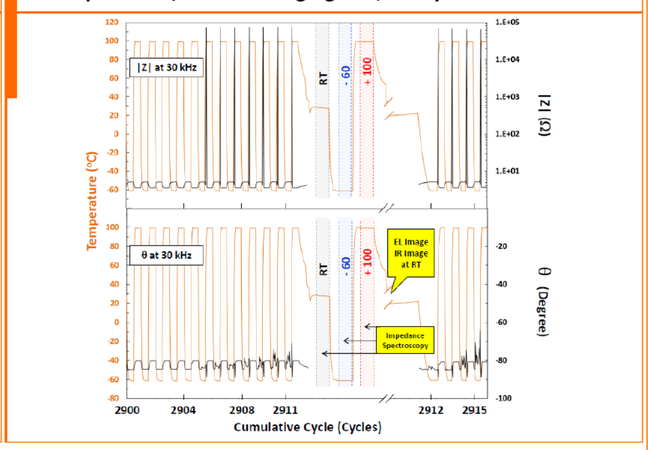
Panel 8

AC Impedance: Time Course during Rapid Thermal Cycling



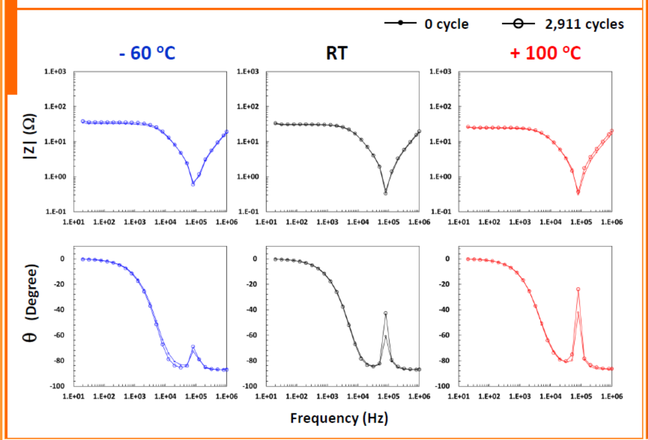
Panel 9

AC Impedance / EL & IR Imaging at 2,911 cycles



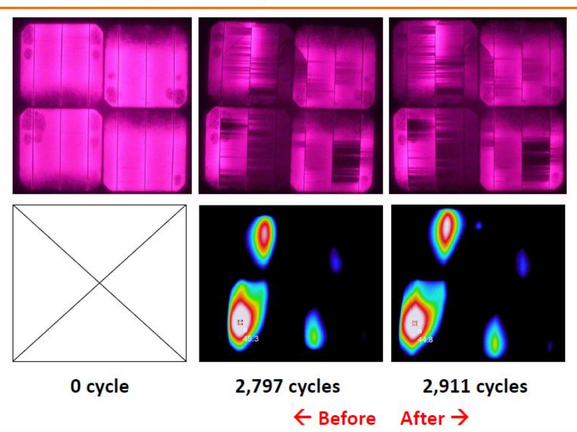
Panel 10

AC Impedance Spectroscopy at 2,911 cycles



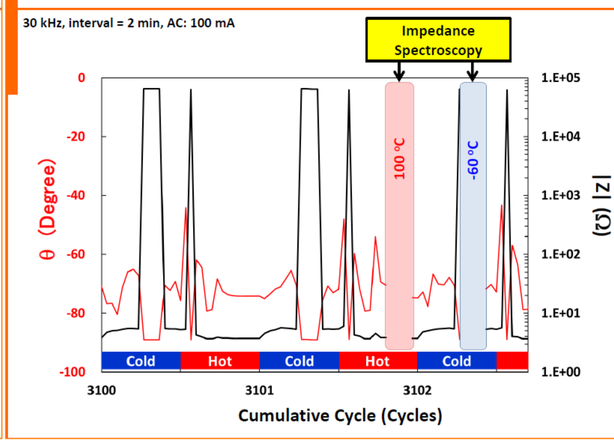
Panel 11

EL & IR Imaging at 2,911 cycles



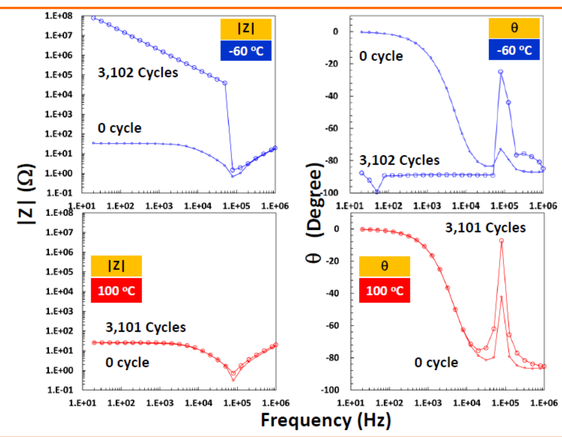
Panel 12

AC Impedance at Late Phase



Panel 13

AC Impedance Spectroscopy at Late Phase



Contact Person: Tadanori Tanahashi (t-tanahashi@espec.co.jp)

This work was supported by the "Next-generation Crystalline Si PV Consortium" (National Institute of Advanced Industrial Science and Technology, Japan).

This poster does not contain any proprietary or confidential information.

This presentation contains no confidential information.

Tj measurement of bypass diode for PV modules

(J-TG 4 activities of QA Forum / QA Task Force 4 ; Diode, Shading & Reverse Bias)

This work was performed in cooperation with Onamba, Sanken Electric, Nihon Inter Electronics, Kyocera and SHARP.

Feb. 24-25, 2015 *@ Denver Colorado, USA*

Yasunori Uchida

JET (Japan Electrical Safety & Environment Technology Laboratories)

1. Introduction (1)

In the bypass diode (BD) thermal test required by IEC61215 Cl.10.18 and IEC61646 Cl.10.18, it is necessary to measure the junction temperature (Tj) of the BD. But it is not possible to measure it directly.

Two methods are conceivable, which are "Vf-Tj method" and "Tlead method (or Tcase method)".

"Vf-Tj method" is based on the physical characteristics of the diode where the Vf (at certain forward current If) and the Tj are related.

Thus "Vf-Tj method" is considered as a primary method.

1. Introduction (2)

"Tlead method", in comparison, is considered as a secondary method. Because it uses the parameter Rth (thermal resistance) to relate the lead temperature to the junction temperature.

"Tlead method" is commonly used because of its simplicity. But it may involve larger error.

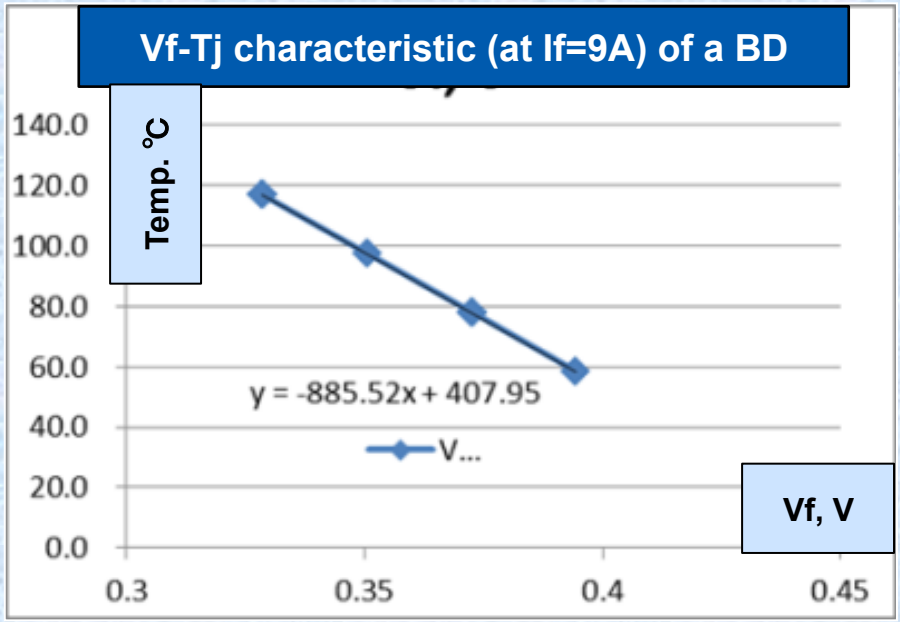
This paper deals with the analysis and the experiments about how much error "Tlead method" may have.

2-1. Vf-Tj method

In “Vf-Tj method” it is necessary to obtain first the "Vf-Tj characteristics” which is practically linear as shown below. The formula to show the characteristics will change by an individual diode and the forward current applied.

An example of Vf-Tj characteristics:

$$Tj = -885.52 \times Vf + 407.95$$



2-2. Tlead method

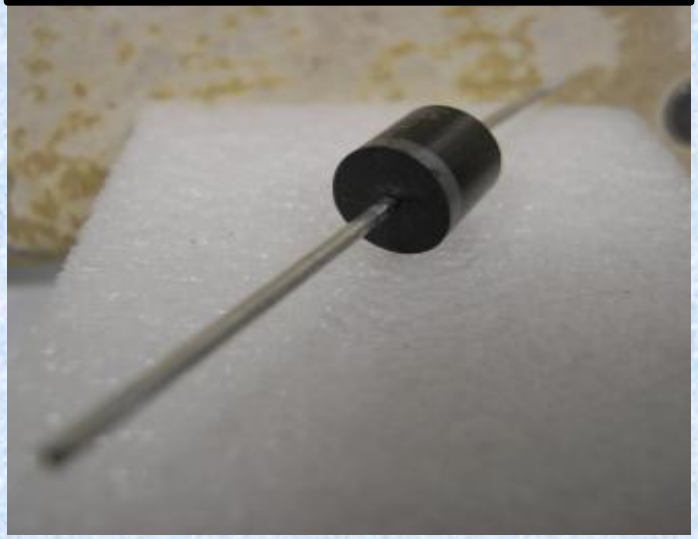
The relation between Tj and Tlead is expressed as below using the parameter of thermal resistance (Rth).

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

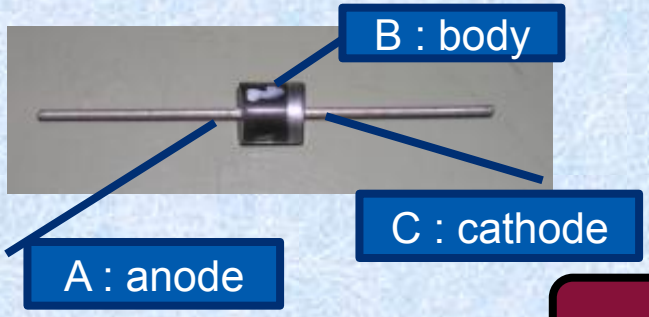
The value of Rth is usulally supplied by the diode manufacturer.

The problem is that the value supplied is not a real Rth, but an apparent value of Rth which will vary according to the heat dissipating condition where the diode is installed. (see next slide)

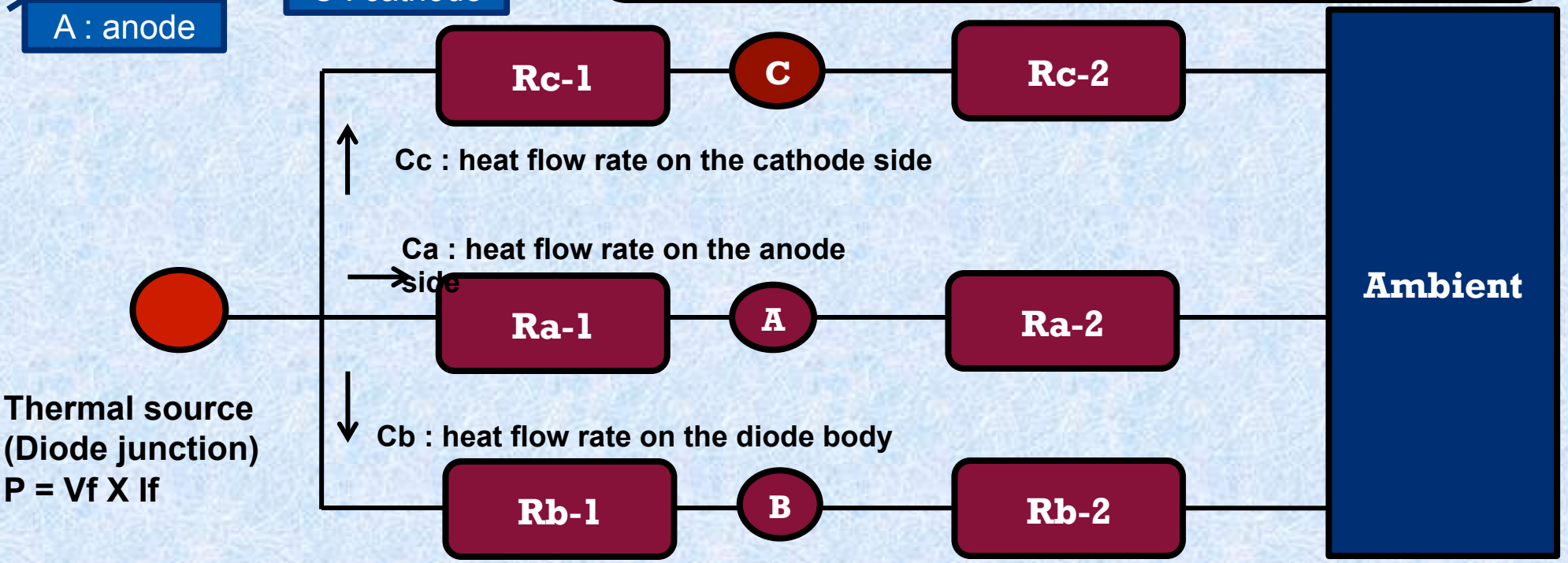
Axial type diode



2-3. Heat flow and Rth



✪ presented at NREL PVMR Work-shop 2013 ✪
Thermal resistance varies by the difference of heat dissipating condition such as a J-box.



Apparent Rth will vary according to the heat flow ratio which varies with the radiation condition of each route *!!!!!*

$$Tj = Tlead + Vf \times If \times Cc \times Rth(real) \rightarrow Rth(apparent)$$

3-1. Comparison tests

The purpose is to compare "the Tj (Tj_2) obtained by the Vf-Tj method" and "the Tj which is determined by the Tlead method from the Rth values supplied by the diode manufacturer“(Tj_1).
The procedure is as follows;

❶ After applying forward current(If=9A) to the diode for one hour, the forward voltage(Vf) and Tlead are measured.

❷ By using Rth supplied by diode manufacturer, the junction temperature (Tj_1) is calculated by Tlead method.

$$Tj_1 = Tlead + Rth\text{-}d \times Vf \times If$$

❸ By using “the functional formula between Vf and Tj” obtained from the Vf-Tj characteristic, Tj_2 is calculated.

$$Tj_2 = a \times Vf + b$$: a and b are the characteristic constants

❹ " Tj_1 " and " Tj_2“ are compared.

3-2. Test samples

Four different types of BD were incorporated in the J-boxes.

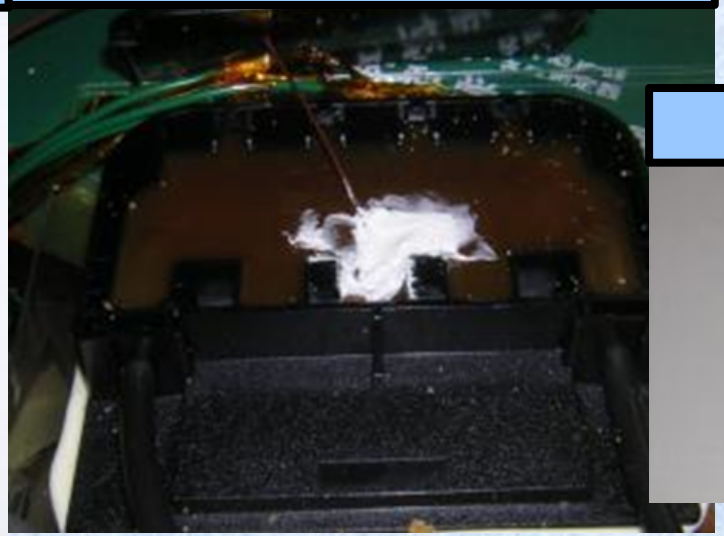
■BD-1, BD-3 and BD-4 are axial type diodes.

■BD-5 is a surface mount type diode (TO-220)

All J-boxes are potted by Si resin. Thermocouples were attached as indicated by the manufacturer, for example 3mm from the diode body.

BD-1,3,4

BD-5



TO-220 diode

3-3-1. Comparison (Tj ; Junction temperature, ℃)

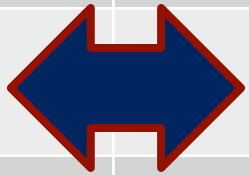
Tj values indicated below show the measured results and the difference between "Tj_1" and "Tj_2".

Kind of BD	Tj_1	Tj_2	$Tj_2 - Tj_1$
BD-1 / axial	151.7℃	159.8℃	8.1℃
BD-3 / axial	150.2℃	162.1℃	11.9℃
BD-4 / axial	151.8℃	157.7℃	5.9℃
BD-5 / TO-220	100.8℃	108.5℃	7.7℃

The test results showed the difference about 10℃.

3-3-2. Comparison (Rth ; Thermal resistance, W/℃)

BD ID#	❶ Presented by diode manufacturer	❷ Single BD	❸ In J-box
BD-1	2.5	4.5	5.8
BD-3	3.5	6.3	9.2
BD-4	2.5	3.9	4.6



Actually Rths from the values obtained by the above measurement (②&③) are different to the values supplied by the manufactures. This indicates the risk of using “Rth values ①” supplied by diode manufacturer.

4. Comparison results with other facilities

The measurements cooperatively made by other organizations (a diode manufacturer and a module manufacture) confirmed that the similar results were be obtained.

◆ **Rth (W/℃) : JET vs Diode manufacturer A / sample : Axial diode V-1**

❶ Rth supplied by diode manufacturer V	at forward current (If)	❷ Rth by JET	❸ Rth by diode manufacturer A
2.5	5A	2.3	3.2
	9A	3.0	3.5
	11A	3.2	3.4

◆ **Rth (W/℃) : JET vs PV module manufacturer A / sample : Axial diode V-2**

❶ Rth supplied by diode manufacturer V	at forward current (If)	❷ Rth by JET	❸ Rth by PVm Manufacturer A
2.5	5A	4.7	3.0
	9A	4.9	3.8
	11A	4.9	3.7

Conclusion and proposal

♦ **The test results showed that about 10℃ difference** may exist between the calculated Tj by "Tlead method" and the real Tj (Tj measured by Vf-Tj method).

♦ This difference could not be overlooked. It is considered appropriate to revise **the pass criteria of the test to have 10℃ margin to the diode manufacturer's maximum junction temperature rating in the case of the "Tlead method" is used.**

♦ It is recommended and considered desirable to apply the "Vf-Tj method" as far as possible, as a better method of measurement.

♦ It would be desirable if other organizations could perform the similar tests.

Temperature Cycling Due to Water Spray in Laboratory Weathering Devices

Sean Fowler

Q-Lab Corporation

Purpose of the Study

IEC TC82/WG2 “experts” are nearing consensus on steady state weathering conditions for exposures of backsheet materials. Some experts want to adopt water spray to add moisture and temperature cycling to the test. A set of conditions has been proposed. This study looks at the effect on temperature of the proposed spray cycles and estimated specimen temperature in the proposed cycles.

Steady State Conditions

There is preliminary agreement among the working group experts on the following conditions, although temperature evaluations continue. There is ongoing discussion on the duration and construction of test specimens.

Xenon Arc: Optical filter defined in ASTM D7869 (Atlas Right Light™ and Q-Lab Daylight-F)

Irradiance:	0.80 W/(m^2·nm) @ 340 nm
Black Panel Temperature:	95°C
Chamber Air Temperature:	70°C
Relative Humidity:	20%

Fluorescent UV: UVA-340 Lamps

Irradiance:	0.80 W/(m^2·nm) @ 340 nm
Black Panel Temperature:	75°C

Proposed Cyclic Exposures

Xenon Arc (ASTM D7869 optical filter)

Irradiance: 0.80 W/(m^2·nm) @ 340 nm

Chamber Air Temperature: 70°C

Uninsulated Black Panel: 95°C

Relative Humidity: 20%

Cycle:

102 Minutes Light only

18 Minutes Light + Front Water Spray

Proposed Cyclic Exposures

Fluorescent UV (UVA-340 Lamps)

Irradiance:	0.83 W/(m^2·nm) @ 340 nm
Uninsulated Black Panel:	75°C
Relative Humidity:	Not controlled (Typically <10%)

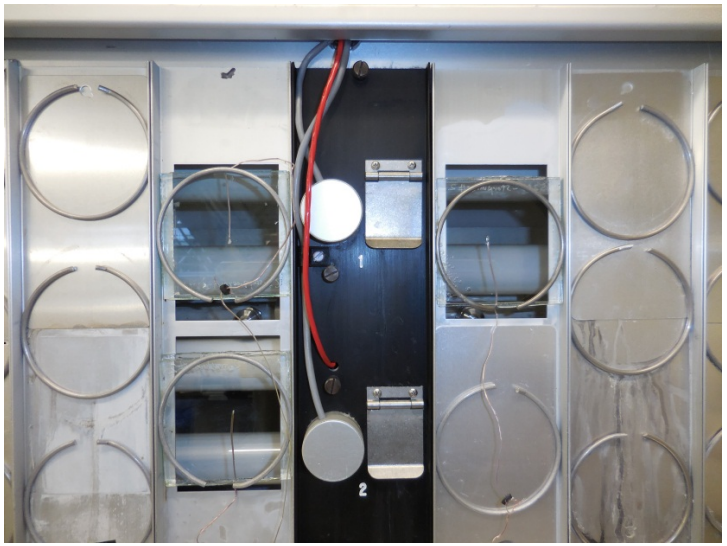
Cycle:
3:50 Lamps On
0:10 Water Spray, Lamps Off (no temp spec)

* 4% Irradiance increase to compensate for 4% of cycle in dark condition

Experiment

- Determine effect of proposed spray cycles on black panel temperature.
- During steady state conditions, measure temperature of NREL coupons and compare to black panel and/or chamber air temperature

Photos of specimens



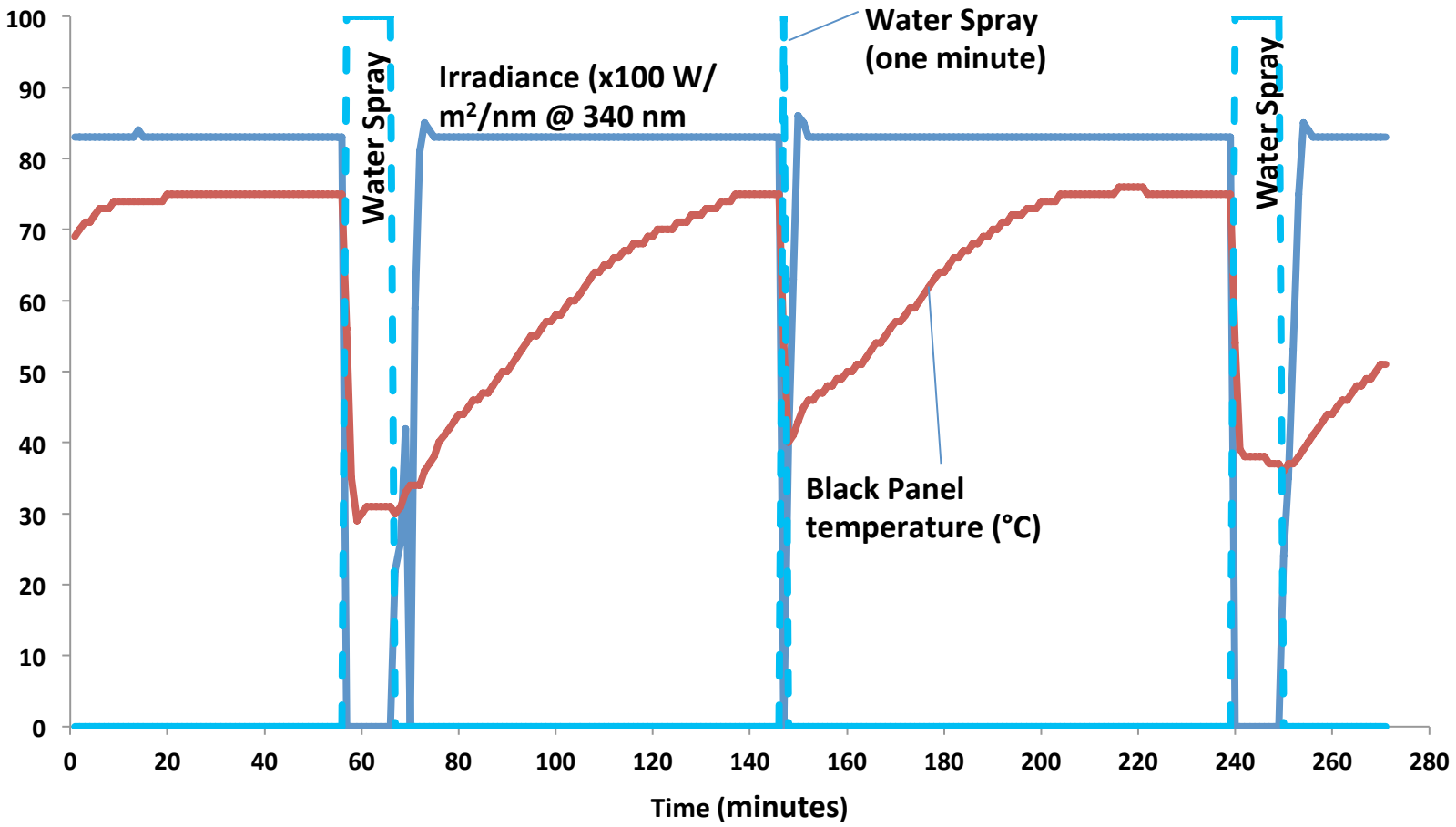
Fluorescent UV (QUV)

Xenon Arc (Q-SUN)

Results – Fluorescent UV

- Black panel temperature in fluorescent UV test decreased from 75°C to 30°C): this equated to ΔT = 45°C (warmer water resulted in 36°C during second spray phase
- A happy mistake in fluorescent UV program cycle provided useful information.
- Fluorescent UV black panel temperature during 10 minutes of water spray achieved equilibrium with incoming water temperature
- One minute of water spray decreased temperature to 40°C
- NREL specimens averaged 82.3°C

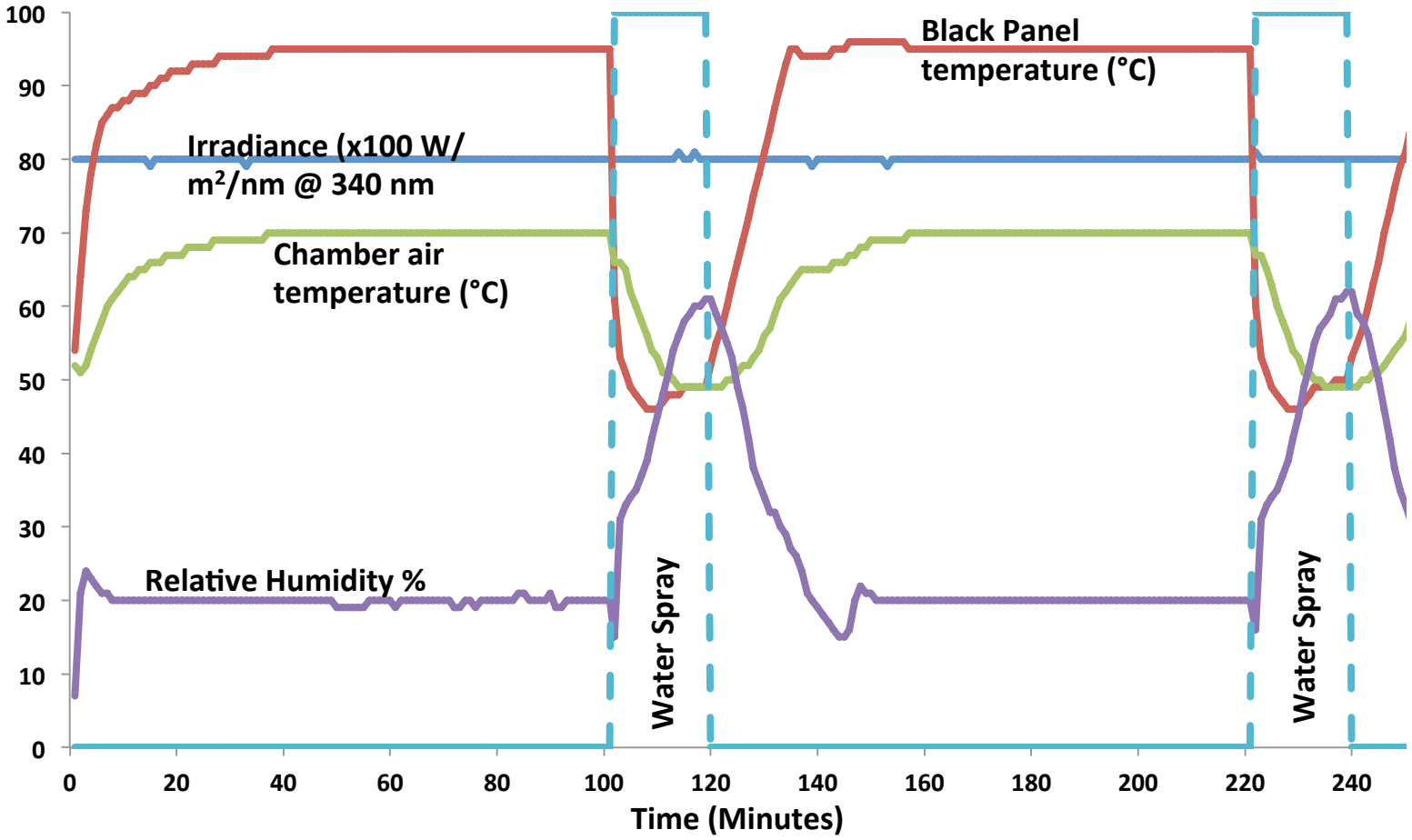
Fluorescent UV



Results – Xenon Arc

- BP temperature decreased from 95°C to 46°C during 18 minute light plus spray cycle($\Delta T = 49°C$)
- NREL specimens averaged 71.6°C during 85°C BP and 60°C chamber air settings; estimated 81.6°C at 95°C/70°C settings
- Fluorescent UV specimen temperature: 82.3°C
- Xenon arc specimen temperature: 81.6°C

Xenon Arc


Black Panel temperature (°C)
Irradiance (x100 W/ m²/nm @ 340 nm
Chamber air temperature (°C)
Relative Humidity %
Water Spray
Water Spray
Time (Minutes)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160
180
200
220
240

Spray Contact Time

- Question: Xenon arc spray time is 36 minutes per 4 hours while fluorescent UV is only 10 minutes. Doesn't this mean the xenon is spraying a lot more water?
  - Answer: No. Xenon spray cycles work differently; they are intermittent. In a flat array machine, spray is programmed to pulse in order to mimic rotating rack with fixed nozzles. Specimens are sprayed 5 seconds on, 55 seconds off, every minute (this is adjustable)
  - This equates to 180 seconds of spray during that 36 minutes, compared to continuous 600 seconds during fluorescent UV water spray

Conclusions

- Proposed test conditions achieve very similar specimen temperature in both xenon and fluorescent UV devices:
  - Fluorescent UV specimen temperature: 82.3°C
  - Xenon arc specimen temperature: 81.6°C
- Spray cycle in fluorescent UV could be reduced from 10 minutes (maybe to 5 minutes) and still achieve the same thermal cycling

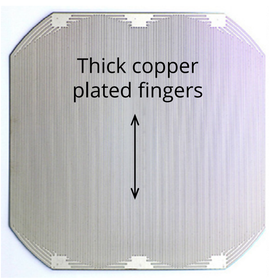
Robustness of SunPower Cells to Wind Stress via High-Cycle Vibration Testing

John Lippiatt & Akira Terao
SunPower Corporation, 51 Rio Robles, San Jose, CA 95134

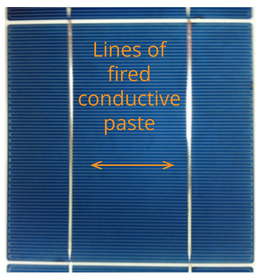
Introduction

It has been previously demonstrated (Degraaff et al 2010) that SunPower's back contact solar cells have low power losses upon cracking due to interdigitated electroplated metallization (a.k.a. "fingers") that retain the cell integrity. In this study it is further demonstrated that the thick SunPower fingers retain cell integrity with long-term fatigue loading. A newly developed vibration test which mechanically fatigues cracked cells in laminated coupons is used to build fatigue (S-N) curves. These are combined with laminate displacement data from fielded modules to generate lifetime estimates for cyclic wind load fatigue. The fatigue test could not be performed on multi-crystalline front contact cells due to their tendency to fall apart when cracked prior to lamination.

Backside of SunPower Cell



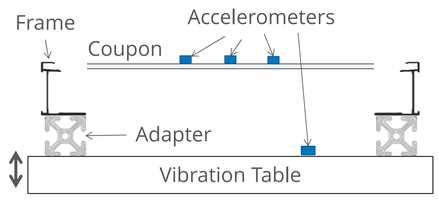
Frontside of Traditional Cell



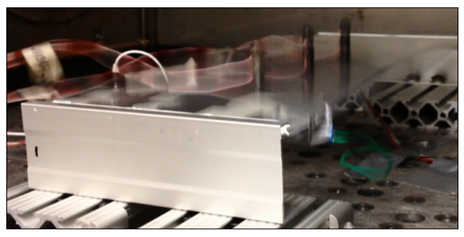
Materials and Methods

Fatigue Testing
Small laminated coupons containing a pre-cracked cell were mounted to a vertical axis vibration system in such a way to allow for flexural bending of the coupon. The vibration test system was configured to dwell at a fixed amplitude at the primary bending resonance of the coupon. The curvature at the cell crack was used as a proxy for the stress level. It was calculated from data collected using accelerometers attached to the coupon.

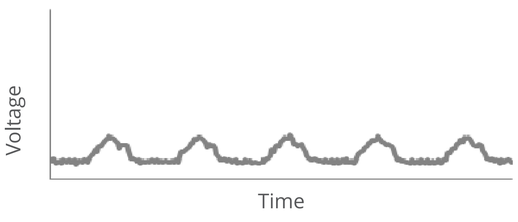
Diagram of test setup



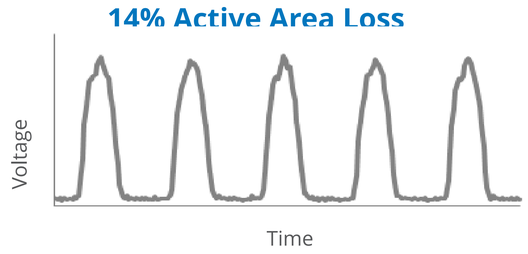
Vibration Test in Progress



3% Active Area Loss



14% Active Area Loss



In-Situ Monitoring
During fatigue testing a fixed current was applied to the cell and the resulting voltage waveform was captured. The amplitude of the signal correlates with the amount of lost active area in the cell due to finger breakage. The failure threshold was chosen to be 10% loss in active area.

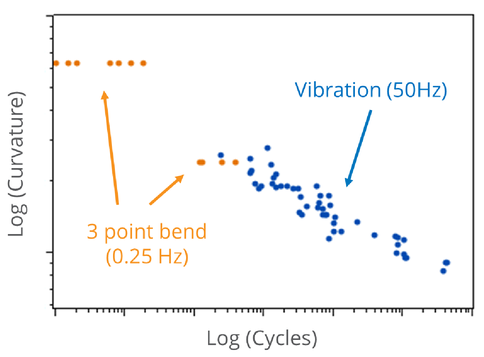
Mission Profiling
Two SunPower modules on the windward corner of a single axis tracker in a windy location were instrumented with displacement sensors. Two weeks of data were collected at a sampling rate of 10 Hz. Included in the dataset are two separate wind events with gusts over 65mph. This dataset was assumed to be very aggressive when extrapolated and the resulting lifetime estimates were expected to be conservative.

Displacement Sensor Under Module

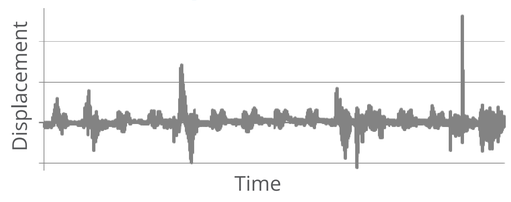
Data Treatment and Results

Test Data
Vibration testing was conducted over a range of stress levels to generate S-N curves. These curves have reasonable agreement with low frequency mechanical testing in a three point bend configuration. The shape, slope, and variance observed in the data is consistent with fatigue testing of metals as reported in the literature.

S-N Curve



Laminate Displacement Time History



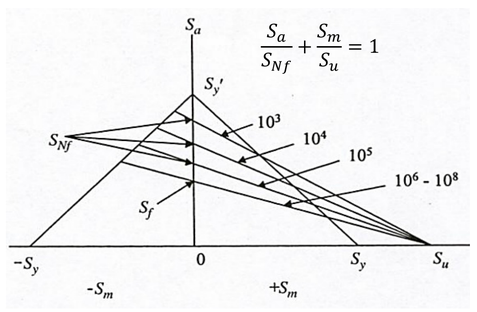
Simplified Rainflow Counting Output

Range	Mean						
	-4	-2	0	2	4	6	8
1	-	4376	3.7e5	12935	276	40	9
3	-	470	1849	780	44	14	3
5	-	11	8	40	10	3	-
7	-	-	1	7	2	2	-
9	-	-	-	2	-	-	-
11	-	-	-	-	-	-	-
13	-	-	-	1	-	-	-

Field Data
The entire mission profile dataset was converted to a list of cycles through the use of a rainflow counting algorithm (ASTM E1049-85). Cycles with less than 0.25mm range were considered insignificant and discarded. Displacement was converted to curvature using a correlation from a previous experiment mapping the surface of a module under mechanical load.

Lifetime Calculation
Since almost all of the cycles in the mission profile had a non-zero mean the Goodman correction was applied to convert the data into equivalent fully reversed curvature cycles which were directly compared to the test data. Finally, Miner's rule was used to generate lifetime estimates with the S-N curve. Even when using the lower 95% confidence band of the fitted S-N data, the predicted lifetime was over 500 years.

The Goodman correction



https://www.efatigue.com/training/Chapter_4.pdf

Conclusions

Based on the findings in this study, SunPower's cell metallization can survive mechanical fatigue damage due to wind loading over the standard 25 year warranty period with a comfortable margin, even when the underlying cell is cracked. Future development could include: application of the same technique to the cell interconnect fatigue, addition of shipping loads to the mission profile, and creation of a standard vibration fatigue test spectrum with 25 year equivalence.

Literature Cited

D. DeGraaff, et al., "Qualification, Manufacturing, and Reliability Testing Methodologies for Deploying High-Reliability Solar Modules", PVSEC 2010 (Valencia, Spain)

ASTM E1049-85 (1997), "Standard Practices for Cycle Counting in Fatigue Analysis", ASTM International, West Conshohocken, PA, 2011, www.astm.org

Acknowledgements

Thanks to Ze Cellier for performing 3pt bend testing and to Nick McKibben for providing the mission profile dataset and curvature-displacement correlation

This research was funded in part by Total S.A.

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PV Module Reliability Workshop, February 24 - 27, 2015, Golden, CO

Utilization of Ultra-Intense UV Weathering Chambers for Rapid Acceleration of PV Component Testing

Tatsuo Nakamura, Douglas Vermillion

Abstract

Crystalline PV component manufacturers continuously strive to improve product durability and reliability through recommended tests, and proprietary in house testing. A 25 – 30 year life cycle is expected.

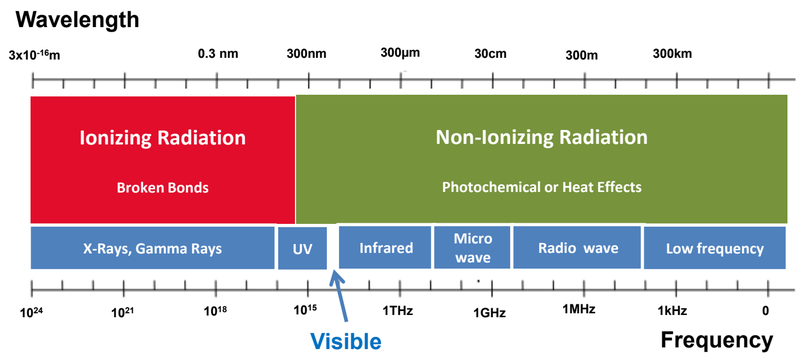
Outdoor exposure testing is necessary for validating long-term product performance, but the use of accelerated testing is necessary for expediting the evaluation process. Fluorescent and Xenon lamp based UV weathering chambers are commonly used for accelerated testing, and are supported by some correlation data to outdoor exposure testing.

PV component manufacturers have recently been utilizing metal halide lamp based UV weathering chambers for proprietary in-house testing to further accelerate the simulation of outdoor exposure. Metal halide tools are relatively new, and the amount of correlation data is somewhat limited, but users have found that the benefit of rapidly accelerated testing is of strategic importance with regard to product development and testing.

Different material compositions will react with different acceleration rates when evaluated in any UV weathering chamber option with fluorescent and Xenon lamp options providing acceleration factors of 1 – 10 times natural sunlight. Metal halide lamp based weathering chambers provide acceleration factors of up to 30-times natural sunlight.

UV Light and Ionizing Radiation

- **Earth surface UV radiation beginning in the UV-B band is categorized as "Ionizing Radiation" and has enough energy to break chemical bonds.**
- **The most significant effect on materials from light energy is caused by UV radiation breaking chemical bonds.**
- **Visible and IR radiation are categorized as "Non-Ionizing Radiation" and which have somewhat minimal photochemical and heating effects on materials.**



Source: EYE Applied Optix

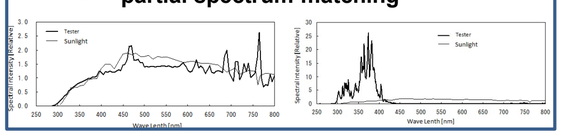
Accelerated Weather Testing Methodology

Procedure

- **Chamber with Combination Cycling Of:**
  1. **Temperature**
  2. **Humidity & Soaking**
  3. **UV Light**
- **Correlation to Outdoor Testing to Validate Acceleration Factors**

UV Light Generating Options

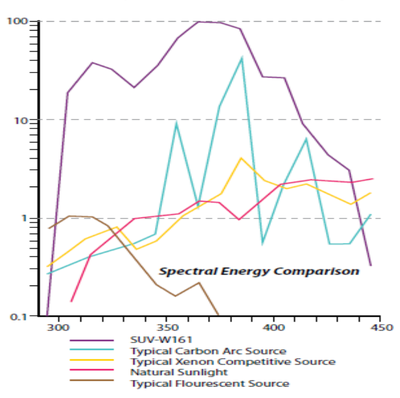
- **Mercury Fluorescent**
  - **1 – 3 "Sun" acceleration**
  - **partial spectrum matching**
- **Xenon**
  - **1 – 10 "Sun" acceleration**
  - **full spectrum matching**
- **Metal Halide**
  - **20 – 30 "Sun" acceleration**
  - **partial spectrum matching**



Metal Halide UV Light Source Acceleration

- **Metal halide offers significant acceleration factors compared to traditional mercury fluorescent and xenon light sources due to the intensity of the UV radiation produced (see plot below).**
- **The use of intense UV radiation expedites the testing process with acceleration factors up to 10 times those of xenon tools.**
- **Metal halide tools produce repeatable results.**

Logarithmic Plot of UV Energy Intensity
Produced by Various Chamber Light Sources



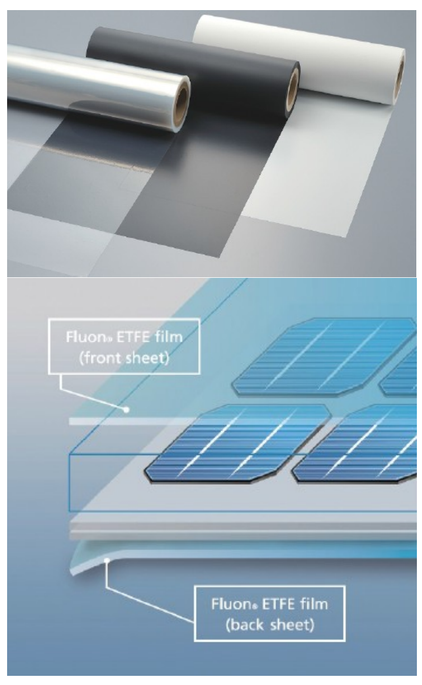
Benefit of Expedited Testing-
Time to Color Shift of Material Sample

Light Source	Hours	Days
Natural Sun	10,000	420
Xenon	1000	42
Metal Halide	100	4.2

Source: Iwasaki Electric

AGC Solar Fluon ETFE Film

Metal Halide Used for PV Front/Back Sheet R&D



AGC Solar Accelerated Test Procedure

•1000W/m² (300 – 400nm)

•Black Panel Temperature = 63° C

•Cycle:

✓10 Hours	**Light Irradiation (50% R.H.)**
✓10 Seconds	**Shower**
✓2 Hours	**Blackness/Condensation (30° C, 100% R.H.)**
✓10 Seconds	**Shower**

Source: Information provided courtesy of AGC Solar

AGC Solar Fluon ETFE Film

Accelerated Test Analysis

Retention of Mechanical Properties

Tensile Test	Zero Hour	After 500 Hours	After 1000 Hours
Elongation	300-400%	95-100% *	95-100% *
Strength	55-65 MPa	90-95% *	85-95% *

* Percent of original measurement

Change in Optical Properties

Test		Zero Hour	500 Hours	1000 Hours
Transparency at 360 nm	%	<=0.1	<=0.1	<=0.1
Visible Light Transmission	%	24 – 26	23 – 26	22 – 25
Solar Transmittance	%	36 – 37	36 – 37	35 – 36
Solar Reflectance	%	60 – 62	61 – 63	61 – 63
Color Difference ΔE*		-	-	<0.7

Source: Information provided courtesy of AGC Solar

Metal Halide Correlation Table

Correlation With Outdoor Data

Test Material	Test Cycle Irradiation/ Humidity (hrs)	Irradiation Level (W/m²)	BP Temp°C	Humidity (%RH)	Test Duration (hours)	Equivalent Exposure (years)	Acceleration Factor
Polypropylene (PP)	12 / 6	1500	83	50	100	1yr outdoor	88
Polyvinyl chloride (PVC)	4 / 2	1050	50	50	150-300	1yr outdoor	58--29 *
Acrylonitrile butadiene styrene (ABS)	12 / 6	1500	63	50	80	1yr outdoor	110
Polycarbonate (PC)	6 / 6	1500	63	50	100	1yr outdoor	88
Polymethyl Methacrylate (PMMA)	12/6	1500	83	50	200	800hr (comp)	4X (comp)
Polyethylene (PE)	6 / 6	1500	63	50	120	1yr outdoor	73
Polyoxymethylene (POM) (polyacetal)	12 / 6	1500	83	50	100	1yr outdoor	88
Polyester	continuous UV	1050	83	N/A	25	1yr outdoor	350
Urethane	6 / 4	1500	63	50	200	2yr outdoor	88
Typical fabric	continuous UV	1050	83	N/A	20	250hr (comp)	12.5X (comp)
Melamine painting	24 / 24	1500	63	50	50	1yr outdoor	175
Fluorine painting	12 / 12	1500	63	50	1000	10yr outdoor	88
Acrylic painting	24 / 24	1500	63	50	50	1yr outdoor	175
Painted Slate	8 / 2	1500	63	50	100	1yr outdoor	88

Source: Japan Weathering Test Center & Iwasaki Electric
Location: Central Honshu Prefecture, approximate equivalent is St. Louis area

Summary

- **Metal halide weather testing offers significantly accelerated testing compared with traditional fluorescent and xenon tools by a factor as high as ten.**
- **Correlation data for metal halide tools does exist.**
- **Many internationally based companies are using metal halide tools for strategic R & D.**
- **North American based companies are using metal halide tools for strategic R & D, and maintain proprietary testing and correlation data.**
- **EYE Applied Optix will work with customers and partners to publish additional data over time, and is actively seeking a North American partner for research to present at the next annual session.**

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This poster contains no proprietary information, 2015

LONG-TERM SOILING IN A MODERATE SUBTROPICAL CLIMATE

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European Commission, Joint Research Centre, Institute for Energy and Transport, Renewables and Energy Efficiency Unit, Via E. Fermi 2749, TP-450, I-21027 Ispra (VA), Italy.

Introduction

This poster outlines the results of 28 silicon-based PV modules which were installed from 1981 to 1985 in a open rack configuration in the outdoor test facility of the ESTI laboratory. The system was composed of modules produced by a single manufacturer, but they were manufactured at different times and as such incorporate different materials [e.g. modules using plain glass (6) or surface textured glass (22)]. Each module was composed of two series-connected laminates mounted in a single frame. The modules were dismantled in 2014 and different characterizations were performed prior to cleaning the surface of the modules to assess the extent of long-term soiling. Different cleaning methods were investigated from manual cleaning to the use of high pressure water washing.

Module characteristics

Original ESTI code	Module Type	N° modules exposed	Superstrate	Encapsulant	Substrate	N° cells	Cell type	Cell layout
BBxx	A	6	Flat glass	Silicone	White silicone	68	Ø 10cm mono-Si	
SOxx	B	7	Textured glass	Silicone	White silicone	68	Ø 10cm mono-Si	
COxx	C	7	Textured glass	Silicone	White silicone	72	Ø 10cm mono-Si	
BOxx	D	8	Textured glass	Silicone	White silicone	72	Ø 10cm mono-Si	

Table I Main characteristics of the modules.

The array is composed of a set of 28 crystalline silicon wafer based photovoltaic modules which were subjected to long-term continuous outdoor exposure for more than 30 years without cleaning.

The climatic conditions of Ispra (located in northern Italy) at 220 m above sea level, where the weathering was executed, are considered to be a moderate subtropical climate (-10 ºC to +35 ºC, with less than 90% RH).

The modules main design details are listed in Table I; four types are represented. Fig. 1 shows the typical soiling distribution on the modules and the view of the complete array before removal from the rack.

Fig. 1 (above) Single Si module, detail of the soiling between laminates and view of the complete array (bottom).

Cleaning setup

IV curves of the modules were measured before cleaning (at the end of 2014), after a manual cleaning with standard detergent for glass using a cloth or a soft sponge, and after an additional cleaning using a high pressure water machine for 3 minutes at a distance of 30cm.

Electrical performance

IV characteristics were obtained using a PASAN IIIB solar simulator at 1000 W/m^2 and 25.0±0.1 ºC.

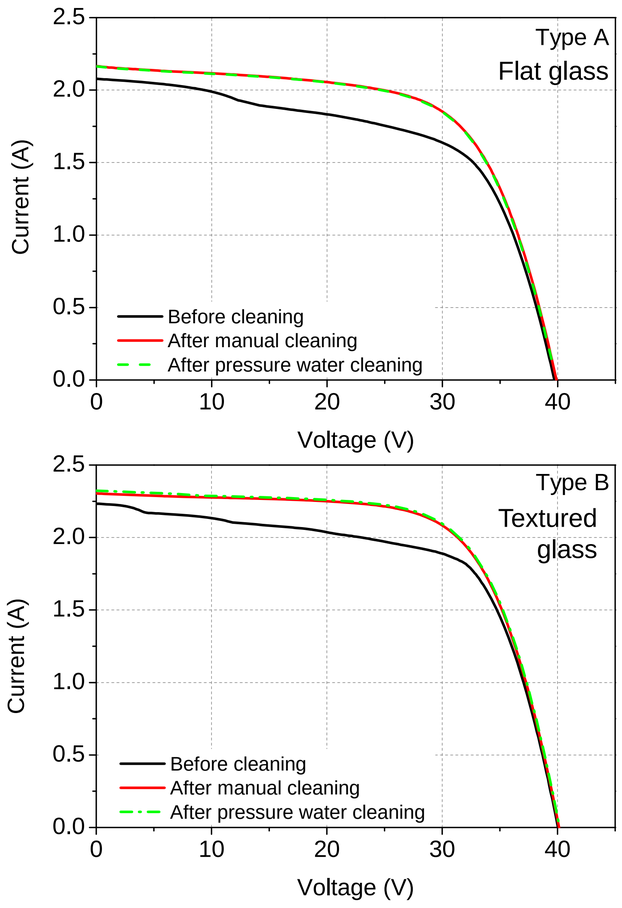

Fig. 2 IV curves of soiled modules of type A and B, cleaned manually, and with an additional pressure water procedure.

The effect of cleaning procedure on glass type

- Manual cleaning is effective on all the modules.
- Additional high pressure water spraying gives no additional improvement to plain glass modules.
- Textured glass modules show a further small improvement using a high pressure water spray, following manual cleaning.

Results by module type

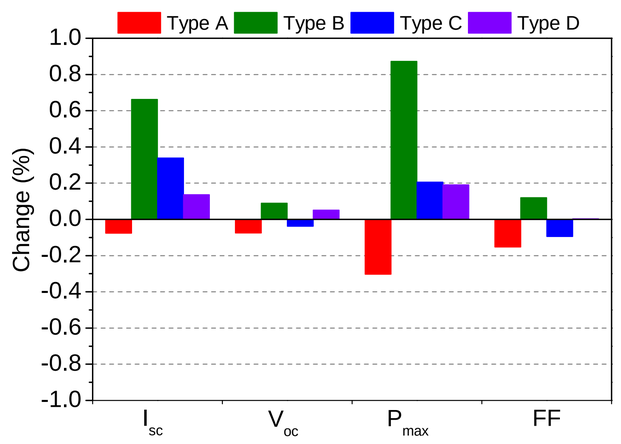

Fig. 3 Average change in % of representative modules of each type measured after additional cleaning with high pressure water, in comparison to manual cleaning.

A batch of 14 representative modules were cleaned manually and with a pressure washer. As shown in fig. 3 there are very small differences between manual cleaning and the additional cleaning with high pressure water. As such, the whole set of modules were measured after both cleaning processes.

- The slight increase in the P_{max} (~0.9%) of type B modules after the additional cleaning with high pressure water is mostly due to an increase of the I_{sc} (fig. 3).

The average increase in P_{max} after both cleaning procedures, compared to the soiled modules, is greatest for type A (11,5%). However, the variation in the extent of soiling for the textured glass modules is much higher (Fig. 4).

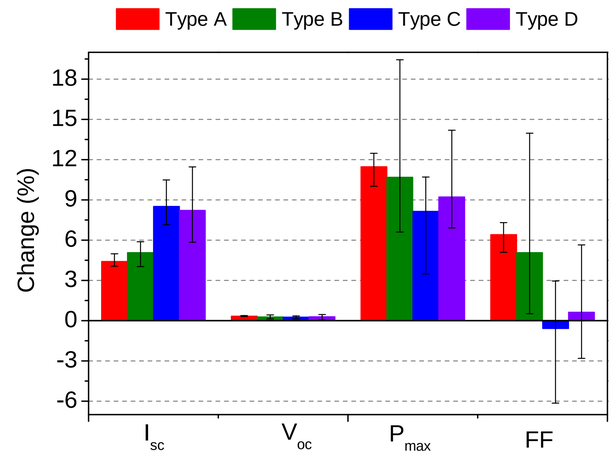

Fig. 4 Average change (%) of modules parameters following both manual cleaning and high pressure water, compared to the initial soiled modules (black bars indicate the max. and min. values)

Overall Results

	I_{sc}	V_{oc}	P_{max}	FF
Average Δ (%)	6,68	0,30	9,80	2,67
St dev (%)	2,17	0,09	3,03	4,05

Table II Average change in % of modules parameters of the whole array.

The average change values of the whole set are listed in table II. P_{max} increases 9,8 % and the I_{sc} 6,7 %. However, only a small average change between the different cleaning procedures is observed (within the measurement uncertainty band).

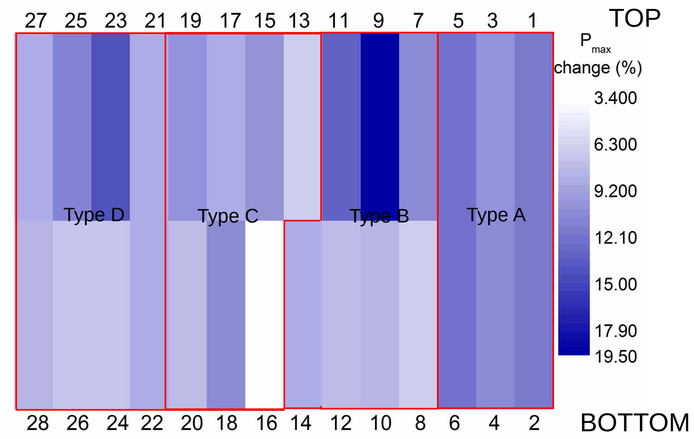

Fig. 5 Average change (%) distribution of the whole array in the same position than in the field (viewed from the front).

Conclusions

- ✓ More uniform soiling behaviour was observed for the flat glass modules, those with textured glass exhibited a greater variation in soiling.
- ✓ Manual cleaning was effective at improving the output of all the module types.
- ✓ Additional high pressure water spraying on plain glass modules showed no further improvement, but showed small improvements on the textured glass modules.
- ✓ Overall improvements in P_{max} after cleaning ranged from 3.5% to 19.4%, with an average value of 9.8%

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Characterization of Fire Hazards of Aged Photovoltaic Balance-of-System Connectors

Eric Schindelholz[1], Benjamin Yang[2], Kenneth Armijo[1], N. Robert Sorensen[1], Olga Lavrova[1]

[1] Sandia National Laboratories, [2] Georgia Tech Research Institute

Overview of Research

This work investigates balance of systems (BOS) connector reliability from the perspective of arc fault risk. Accelerated tests were performed on connectors for future development of a reliability model. Thousands of hours of damp heat and atmospheric corrosion tests found BOS connectors to be resilient to corrosion-related degradation. A procedure was also developed to evaluate new and aged connectors for arc fault risk. The measurements show that arc fault risk is dependent on a combination of materials composition and design geometry. Thermal measurements as well as optical emission spectroscopy (OES) were performed to further characterize the arc plasma. Together, the degradation model, arc fault risk assessment technique, and characterization methods can provide operators of photovoltaic installations information necessary to develop a data-driven plan for BOS connector maintenance as well as identify opportunities for arc fault prognostics.

Significance of Work

Arc faults are a low-probability but high-consequence hazard in photovoltaic systems. The rate of arc faults is expected to increase as the worldwide installed capacity of photovoltaic systems continues to grow. In the US alone, there have been a number of high profile fires caused by arcing in PV systems. Some of these incidents have been traced to balance of systems (BOS) connectors, with risk and prevention being identified as a critical area to address. The reliability of BOS connectors has been relatively uncharacterized beyond qualification tests.

Current & Future Work

Work is currently underway to further characterize the arc fault risk of aged connectors. Alternate corrosion test environments are being explored, such as simulated marine atmospheres. We are actively developing methods to extract additional information from optical emission spectroscopy (OES) measurements, such as electron plasma temperature. Further work is being conducted to explore the physics of failure of connector arc fault.

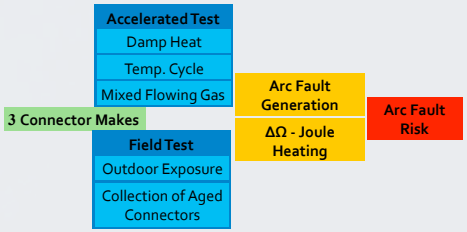
Motivation and Approach

Motivation

What is the impact of corrosion degradation on arc fault risk?

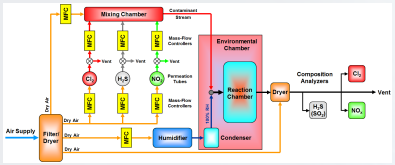
- contact corrosion
- pin & socket materials incompatible
- cyclic mechanical stress on wire/contact
- manufacture/install defect
- foreign debris interferes with connection
- constant mechanical stress results in wire creep

Experimental Approach



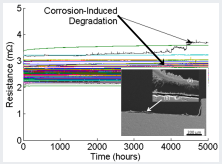
Results: Contact Resistance

Mixed Flowing Gas Exposure



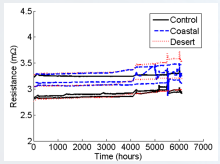
Field Test at SNL, NM

Battelle Class II



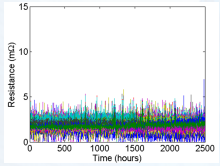
Corrosion of plating, but connectors overall robust to accelerated tests

85°C/85%RH Damp Heat



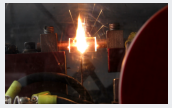
No discernable difference between non-contaminated (control) and coastal or desert-simulating contaminants

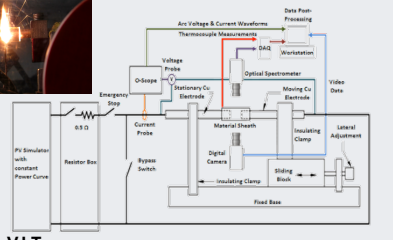
Field Test



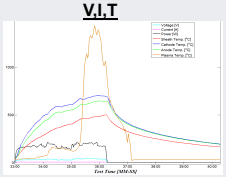
No failures observed in 2500 hours of 51 connectors; test is on-going

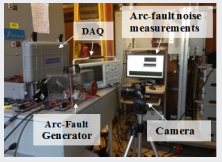
Arc Fault Experimental Platform



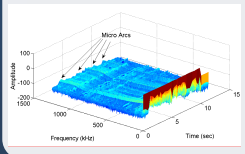


V,I,T

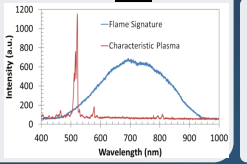




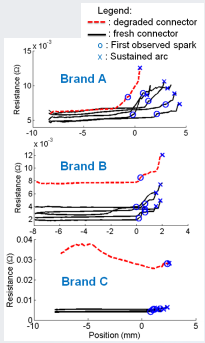
FFT



OES

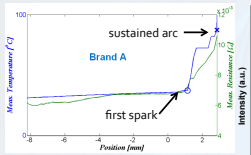


Results: Arc Fault Generation



Connector separation distance prior to arc serves as a proxy for arc fault risk.

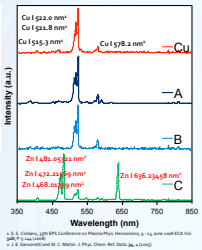
Temperature



Temperature increases measurably between first spark and sustained arc

Materials and electrode geometry likely have significant influence on arc fault risk

OES Analysis



Spectra can identify connectors with similar composition (A and B) vs. one containing other elements (C). Can potentially measure electron plasma temperature

Conclusions

- BOS connectors robust to corrosion-related accelerated tests examined thus far
- Procedure to evaluate arc fault risk of connectors established
- Arc fault risk likely dependent on several factors, such as geometry and composition
- Temperature and emission spectrum analysis can reveal additional information about underlying degradation and arc fault processes

U.S. DEPARTMENT OF ENERGY

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National Nuclear Security Administration

Thermal Modeling of PV Modules Using Computational Simulation

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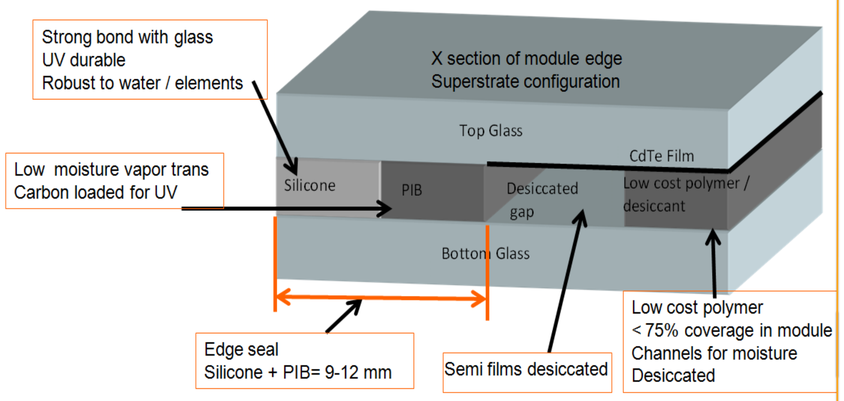
[1]Direct Solar, Fort Collins, CO, 80523, USA
[2]Colorado State University, Fort Collins, CO, 80523, USA

Introduction:

A novel module architecture has been created for thin film PV modules that greatly increases reliability, while minimizing process time, process equipment footprints, capital expenditure costs, and material costs. Prototype modules have already passed IEC and UL damp-heat tests without showing any degradation. This architecture has been optimized for mass-produced CdTe applications, but can be tailored to many PV technologies



The developed edge-sealed module delivers:

- Extreme robustness to moisture
- Excellent adhesion under prolonged UV exposure
- Process cycle times under one minute
  - Similar to other processing steps
- Small manufacturing tool footprint
- Reduced materials costs
- Reduced capital costs

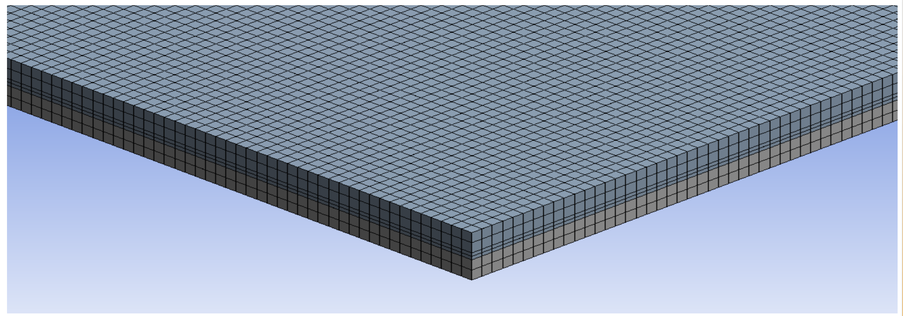
Item	Prototype module	Design A (low case)	Design B (mid case)	Laminate (Dupont) w/ edge seal
Encapsulation cost	$3.87	$1.71	$2.08	$3.84
Savings from laminate	-$0.03	$2.13	$1.76	$0
Cost **SAVINGS** for 85 watt 120x60 cm module ($/Wp)	~0	$0.025	$0.021	--

NOT INCLUDED in cost:

- Capital equipment costs
- Improved manufacturing efficiencies
- Reduced plant footprint
- Increased reliability

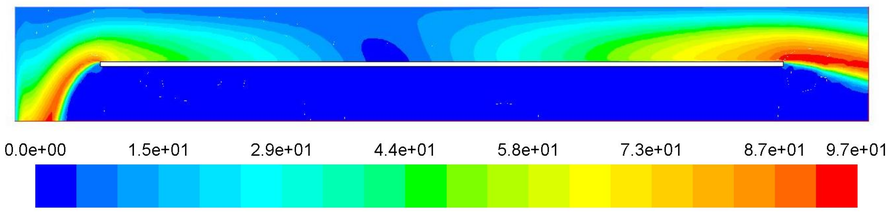
Thermal Performance Modeling Parameters:

- Geometry modeled within 0.1mm
- Real material properties included:
  - Thermal, Optical, and Electrical
- NREL AM1.5 spectra used for solar input
- Convection simulated using a 2D model
  - Wind speed varied from 5 → 10 → 20mph
  - Wind direction varied from 0-90° normal to the module edge at 15° intervals



Two Dimensional Wind Model:

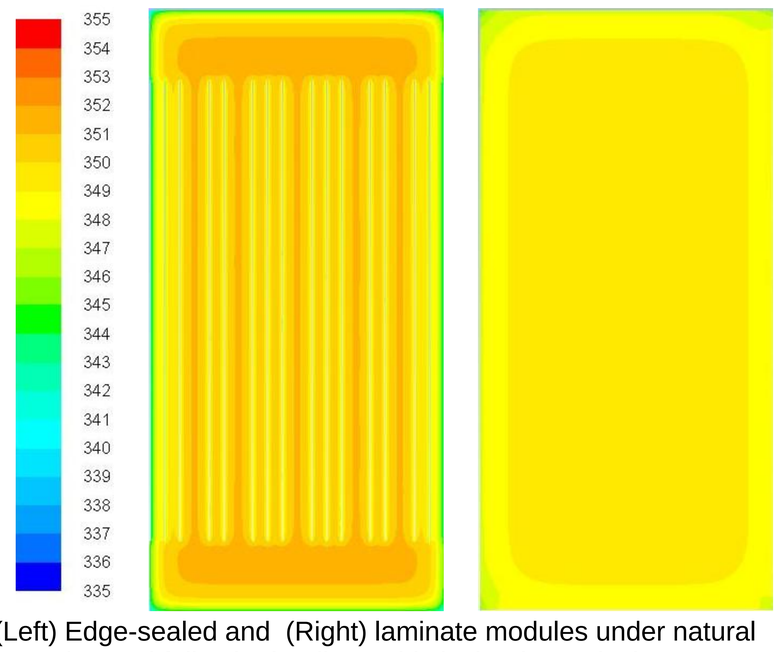
- Steady state wind conditions simulated
- Heat transfer coefficients obtained for each face



Two dimensional wind speed profile of a panel with forced convection at 20mph 60° normal to the module edge (in m/s)

Three Dimensional Thermal Models:

- Only panel included in domain (no outside air)
  - Conv. coef. and solar spectra boundary conditions



(Left) Edge-sealed and (Right) laminate modules under natural convection and full solar loading. This is the theoretical worst-case operating temperatures of both modules. (Temperature in Kelvin)

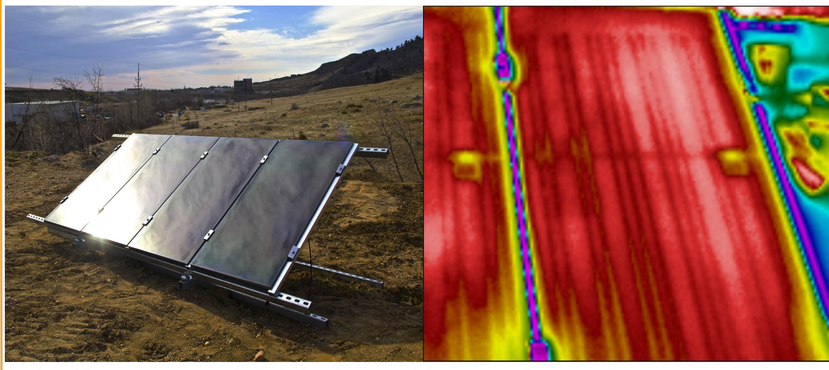
Modeling Results:

Wind Speed (mph)	Wind Direction (deg)	Edge-Sealed Module (K)	Laminate Module (K)	**Difference (K)**
5	0	330.28	327.70	**2.58**
	45	317.38	317.62	**0.24**
	90	313.85	313.85	**0.00**
10	0	320.08	317.28	**2.80**
	45	310.22	310.52	**0.30**
	90	308.20	308.33	**0.13**
20	0	313.21	310.67	**2.54**
	45	306.56	306.62	**0.06**
	90	305.52	305.55	**0.03**

The modeling results show little difference between the temperature of edge-sealed and laminated modules in varying wind conditions. The direction of the wind also was shown to play a large role in determining the operating temperature of the module.

Experimental Validation:

- Edge-sealed and laminated module array created
- IR camera used to monitor temperatures
- Solar / wind data obtained from nearby array
  - Environmental conditions reinserted as boundary conditions in model for validation



(Left) Test array (Right) Thermal image of array from IR camera

Conclusions:

- Wind velocity and direction affect operating temp
- Computational analysis is an effective method for predicting the thermal performance of CdTe modules in real-world conditions
  - Highly sophisticated simulation technique reduces the number of modeling assumptions
  - New module designs can now be evaluated before manufacturing
- Architecture and analysis method can be used across many PV technologies

This work was performed under DOE SBIR/STTR Grant Number DE-SC0010237

PV Soiling Rate Variation over Long Periods

Figgis, Ben (1); Martinez Plaza, Diego (1); Mirza,Talha (2)

(1) Qatar Environment and Energy Research Institute, (2) GreenGulf Inc. QSTP-B

ABSTRACT

Soiling of PV modules can significantly decrease their power output, especially in desert environments where there is much dust and little rain[1]. It is desirable to clean PV modules as infrequently as possible, because doing so uses manpower and scarce water. Therefore it is useful to study the soiling loss over long periods, to determine whether the soiling rate eventually slows down or even stabilizes (ie. a maximum dust layer thickness is reached).

BACKGROUND

A 35,000 m^2 Solar Test Facility was established at Qatar Foundation, Doha, in 2012 in order to identify solar energy technologies suitable for the local climate, and study the effects of dust and heat. The research supports the deployment of PV in the country; current plans include 200 MW of PV and a carbon-neutral 2022 World Cup football tournament[2]. Of particular concern is soiling of PV panels, causing them to lose performance. This study aims to understand long-term soiling behavior in the absence of cleaning or rain.

METHODOLOGY

Four PV arrays were set up at the Solar Test Facility. Each comprised eight polycrystalline PV modules, connected to identical grid-tied inverters, and operated at maximum power point conditions. The only difference between the arrays was the cleaning interval: (i) one week (“high”), (ii) two months (“medium”), (iii) six months (“low”), and (iv) not cleaned (“never”). Of course, all arrays were subject to rain. The test period was two years commenced February 2013.

Each array’s daily DC electricity production, module back-surface temperatures, and plane-of-array irradiance were recorded every minute. Daily Performance Ratios (PR) were calculated based on DC energy production, normalized by the installed array capacity (kWp) and irradiance, and adjusted to Standard Test Condition of 25 ℃[3].

Additionally, meteorological data and aerosols concentration were recorded.

FINDINGS

Energy losses of each array due to soiling are shown in Figure 1. The results are expressed as the arrays’ PR relative to the long-term average PR of the weekly-washed array, ie. the weekly-washed array is treated as the “100%” benchmark. It is seen that:

- The soiling rates generally appear to be higher in winter than in summer, ie. The lines are steepest in the months around January-February, and relatively flat around June-July.
- The greatest power loss occurred on the never-washed array, which after 234 days produced only 32.4% of the DC power of the weekly-washed array
- The soiling rate tends to decrease the longer the time since last cleaning, as seen by comparing the slopes of the medium, low and never-washed arrays approaching November 2014
- However dust continued to accumulate on the never-washed array even after 234 days, ie. The line was still going down when it rained in November 2014.

The latter two observations are illustrated more clearly in Figure 2, which presents the average daily soiling rate versus time since last cleaning or rain. It is seen that for PV modules cleaned within the past month, the average energy loss was roughly 0.5 %/day, while after six months the rate fell to around 0.2 %/day.

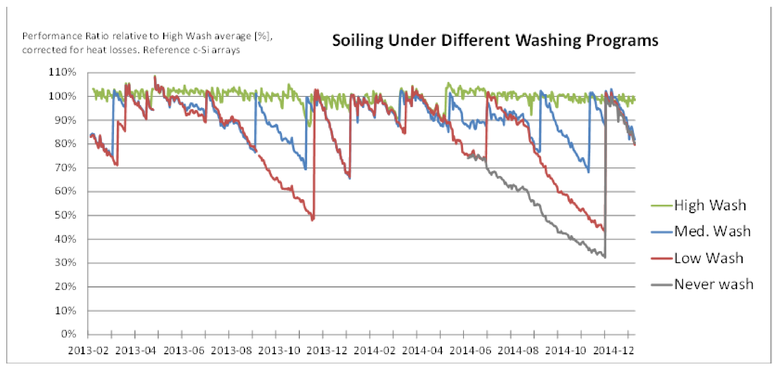


Figure 1. PV energy production decrease due to soiling.

Dust continued to accumulate at a substantial rate even after 234 days without cleaning.

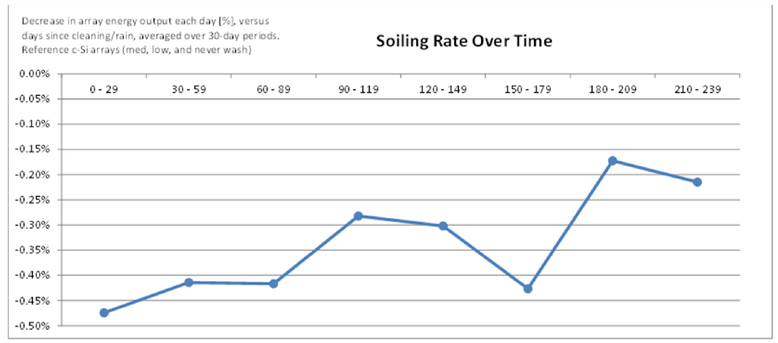


Figure 2. PV soiling rate versus days since last cleaned.

The daily soiling rate after 6 months was around half that of when recently cleaned.

Figure 3. Test stands at Solar Test Facility in Qatar.

Four cleaning schedules were tested: weekly, every 2 months, every 6 months, and never.

CONCLUSIONS/ SUMMARY

The results indicate that even after very long periods, dust continues to accumulate at a significant rate on PV modules in the desert. This suggests that the dust forms a mechanically-stable structure even at appreciable thicknesses, rather than becoming weak and blown off by wind, as might have been expected (and desired).

The daily soiling rate was generally greater in winter than in summer. It is speculated that this was because condensation formed on the modules in the early morning, causing dust to stick, rather than there being a greater concentration of airborne dust. Further work is required to understand this effect.

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(1) Sarver T, Al-Qaraghuli A, Kazmerski L. (2013) ‘A comprehensive review of the impact of dust on the use of solar energy’. Renewable and Sustainable Energy Reviews 22 (2013) 698–733

(2) S. Pathak, 200MW Solar Power Plant to Be Ready in 8 Years: Kahramaa’, in Qatar Tribune, ed. Doha: Qatar Tribune, 2013.

(3) Bing G, Javed W, Figgis B, Mirza T (2015) ‘Effect of Dust and Weather Conditions on Photovoltaic Performance in Doha, Qatar’

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Texas A&M University at Qatar

FURTHER INFORMATION

Qatar Environment & Energy Research Institute, ww.qeeri.org.qa

This presentation contains no confidential information.

Hot-spot measurements on crystalline silicon solar cells with different reverse-current characteristics

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Introduction

- Hot spots in general are a major failure mode of modules (reliability and safety)
- 8% of all IEC 61215 failures are related to the hot spot test according to TÜV (2012)
- This work links hot spot test results of cells in bare and in laminated state with focus on:
  - Correlation of maximum hot spot temperatures bare vs. laminated cell
  - Temperature increase over time for module hot spots with test times up to 10 minutes
  - Use worst case shading conditions to measure the maximum hotspot temperature

Test procedure

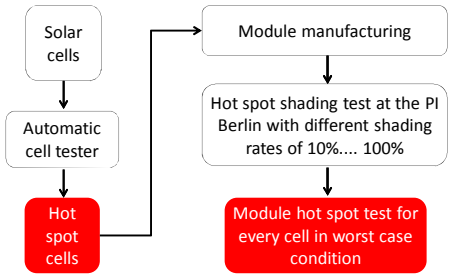

Fig. 1: Test procedure: *Automatic tester* performs IV curves incl. hot spot test for bare cells (@-12V). After lamination the PI Berlin hot spot test is performed. In addition to 100% also lower shading rates (ShR) can be used to find worst case condition (max. T) for every cell.

Module hot spot test at the PI Berlin

Fig. 2: The module hot spot test uses HQI lamps which generate 700 W/m² and a temperature of approx. 65 °C on module backside surface. For first test each cell is completely shaded for 15s (module is short-circuited). Backsheet temperature is monitored with an IR camera.

Hot spot IR images: bare vs. laminated

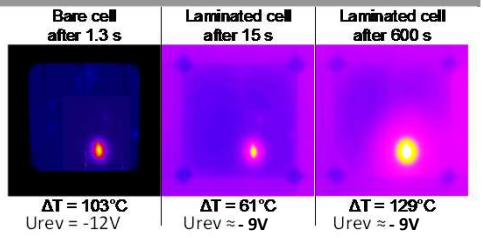

Fig. 3: The IR image on the left shows the hot spot of a bare cell after applying a reverse voltage of -12V for 1.3s. The middle and right IR images show the same cell during the module hot spot test after 15s and 600s. All temperatures are corrected by the environmental temperature T_{env} which was 25°C for bare cell and approx. 65°C for module test ($\Delta T = T_{hotspot} - T_{env}$). Cell reverse voltage when shaded is **-9V** instead of -12V.

T max: Bare cell (1.3s) vs. laminated (15s)

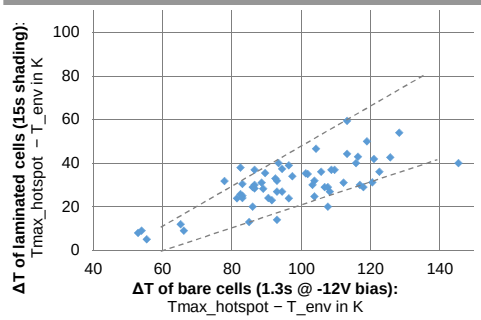

Fig. 4: Comparison of hot spot temperatures of bare cells (after 1.3s @-12V bias) vs. laminated cells (after 15s shading). The weak correlation is caused by hot spot size: small hot spots are overrated when testing bare cells with very little thermal mass (m_cell = 10g)

Module hot spots: Tmax after 15s vs. 10min

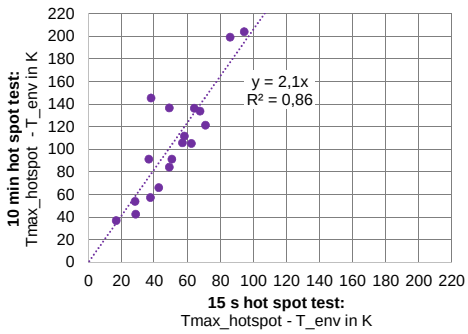

Fig. 5: Correlation of hot-spot temperatures on module surface after 15 s and 10 min (time factor 40). The linear regression within this time shows a factor 2 for the difference in hot-spot temperatures for both times.

Next step: From reverse current to partial shading and worst case temperatures

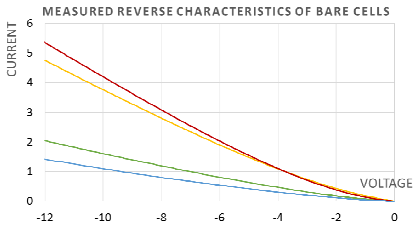

Fig. 6: Exemplarily measured reverse characteristics of 4 cells indicate the current *and* shading rate needed to operate the cell in worst case condition.

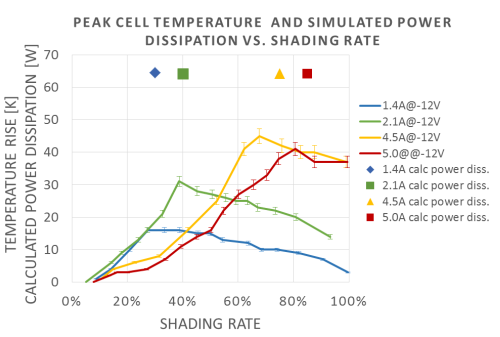

Fig. 7: Temperature rise and simulated maximum power dissipation matches the shading rate. But despite of same values of approx. 60W power dissipation the ***maximum temperature rise is very different for each cell.*** Maximum hotspot temperature should not be determined with reverse measurements only but with IR camera to detect "current density" of hotspot.

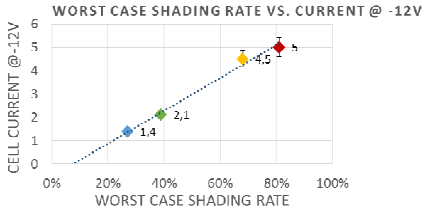

Fig. 8: Partial shading of those cells show a good correlation of *shading rate* and *current@-12V*.

Conclusion

In this study hot spot behavior of bare and laminated cells have been compared. After sorting bare cells by high hotspot temperature those cells were laminated into modules. After performing a module shading test the following can be stated:

For bare cells a reverse bias of 12V applied for 1.3s is sufficient to reach close to max temperatures (Fig 3)

Correlation bare vs. laminated hotspot: After lamination those cells show a wide spread of hot spot temperatures when performing a 15s shading test → not very strong correlation (Fig 4). It is assumed that small hot spots are overrated when testing bare cells with little thermal mass

Temperature progression of module hot spots shows a correlation of factor 2 in temperature when extending shading time from 15 s to 10 min (Fig 5)

Partial shading and worst case: Adding several shading grids to the hotspot tester will enable PI Berlin to find the real worst case shading conditions. It is not sufficient to just select the cell with highest reverse current (IEC test) but to really test every cell in its worst case shading conditions and monitor the max. temperature with an IR camera

Performance Analysis of c-Si Modules Post 10 Year Deployment Hot and Humid Climate – Cocoa, FL

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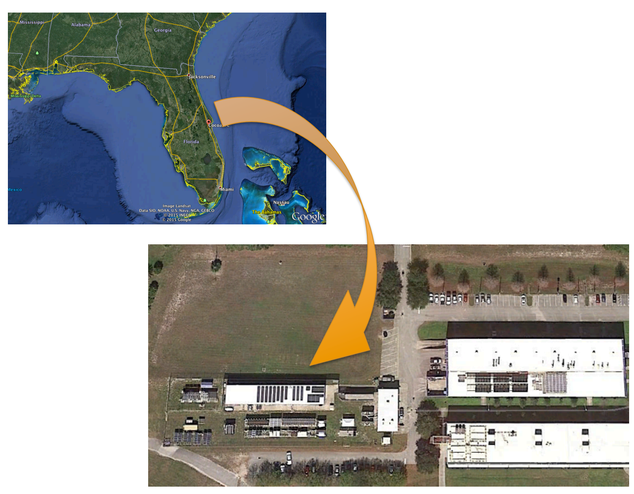
[1]Florida Solar Energy Center, University of Central Florida, Cocoa, FL, U.S..
[2]c-Si Division, U.S. Photovoltaic Manufacturing Consortium, Orlando, FL, U.S.

Summary

An 8.25 kW rooftop system installed in a hot and humid climate was base lined and monitored for a decade. The system consisting of over 150 solar modules was installed at the Florida Solar Energy Center (FSEC) in 2004. At the time of installation the modules were typical of the high quality modules commercially available. Prior to installation, the performance for each module was measured using an indoor solar simulator to obtain I-V measurements at standard test conditions. At the conclusion of the decade a subset of these 55W mono-crystalline solar modules were inspected and characterized. Electrical performance data of the modules was collected both before and after cleaning to understand influences of dirt accumulation. Additionally, module leads/ connectors were tested for resistive losses. Defect detection was carried out using electroluminescence imaging to provide insight into the degradation mechanisms leading to performance loss. The objective of this work is to provide valuable statistical information regarding the long-term reliability and degradation rate of c-Si modules in the hot and humid climate of Florida .

Site Installation

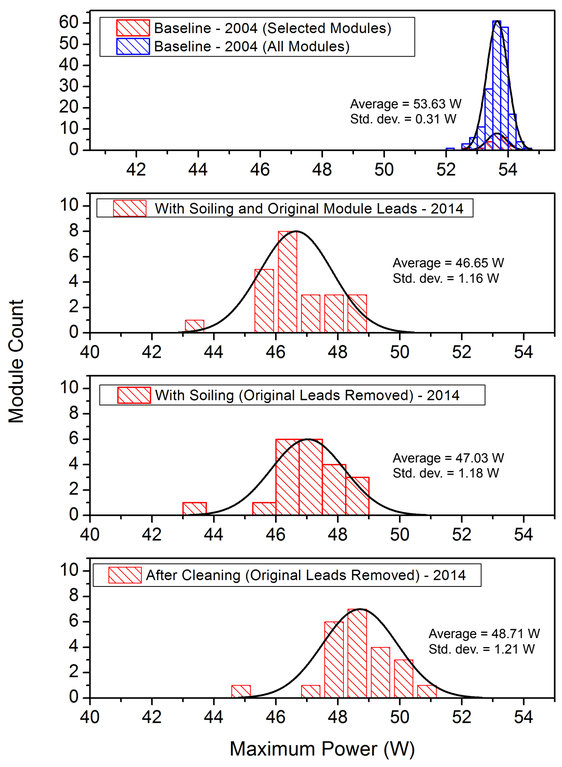
- Geographic Location:
  - 28° 23’
  - 80° 45’
  - Elevation 35’ (ground)
- Physical Address
  - 1679 Clearlake Road
  - Cocoa, FL 32922
- Environmental Stresses
  - Average hot 83.5 F in August
  - Average cold 63.8 F in January
  - 48.7” annual precipitation
  - 75% average daily humidity



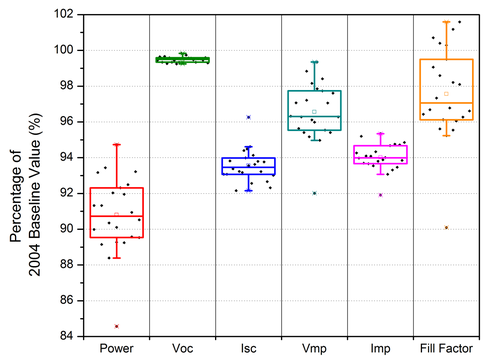
Experimental

- Pre Exposure:
  - All module were characterized at STC prior to installation at the FSEC site
  - A small subset of module (~5) were left unexposed during this period
- Post Exposure:
  - A subset of 25 modules were selected for removal.
  - Modules were characterized with a SPIRE solar simulator at STC in three stages
    - Before cleaning with original MC3 leads
    - Before cleaning (Bypassing original MC3 leads)
    - After cleaning (Bypassing original MC3 leads)
  - Electroluminescence imaging was carried out on selected modules

Power Degradation



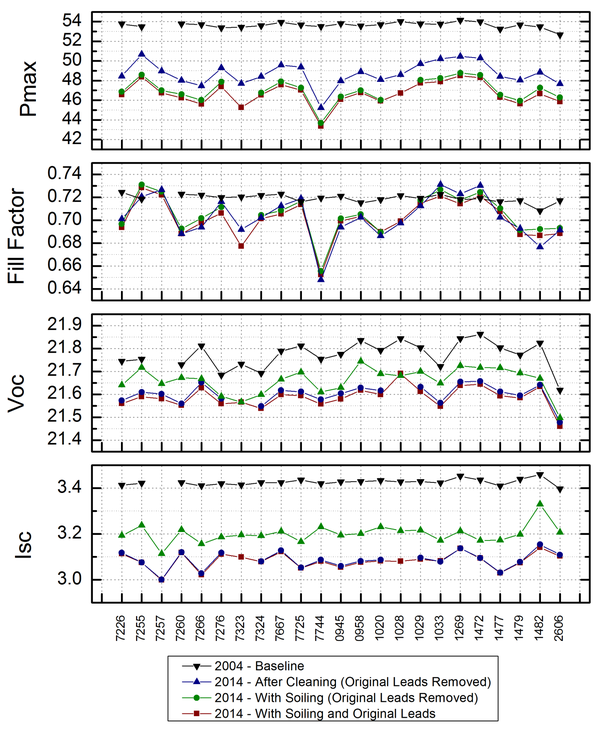
The initial performance variation was relatively small with a standard deviation of 0.31 W. After the 10 year exposure, the variation among the modules increased as seen in the histogram plots to the left. The average module power decreased by 4.92 W, or 90.82 % of the original value. This is equivalent to an average degradation rate of 0.908% per year over the 10 year period. As shown in the figure below, the degradation is a combination of a reduction in I_{sc} and Fill Factor.



Effect of Soiling and Contact Leads

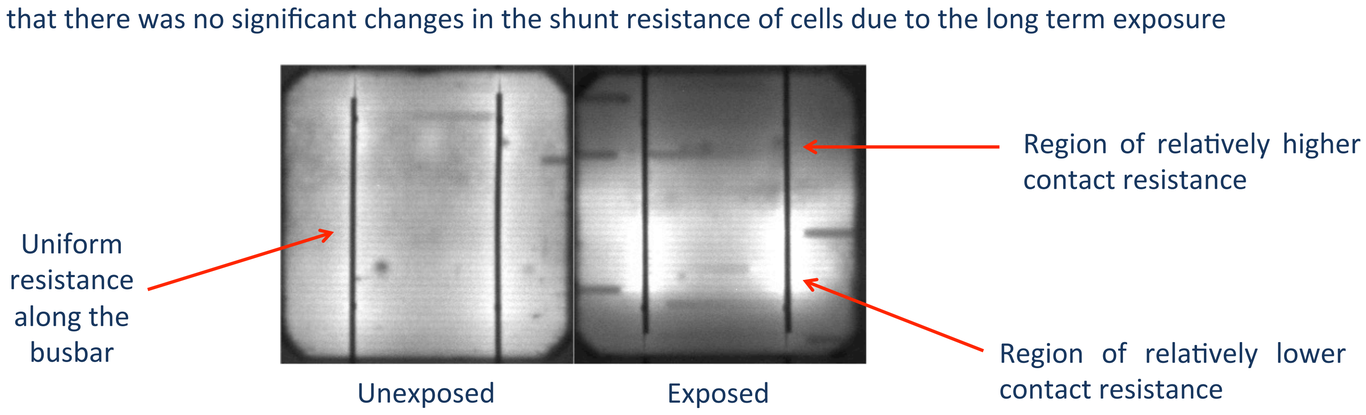
The resistance of the leads and the effect of soiling were captured using a series of I-V measurements. The original MC3 connector were removed bypassed, and measurements were taken directly from the terminal contacts. The figure to the right shows the performance parameters for each module, plotted for each measurement stage.

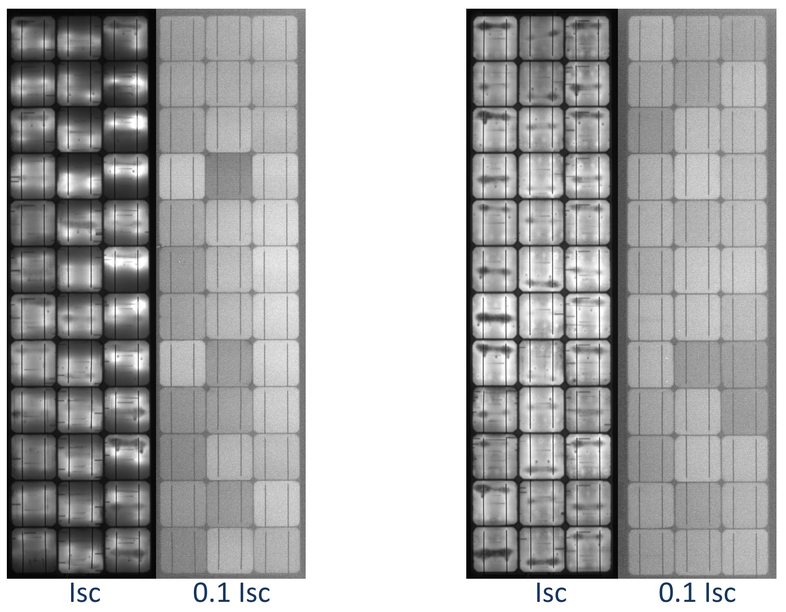
- Average power loss due to the leads
  - 0.31 W at Max Power
- Average loss due to Soiling
  - 1.75 W at Max Power
  - 0.115 A at I_{sc}



Electroluminescence Analysis

Electroluminescence imaging was carried out on selected modules including several unexposed modules. Two images were taken for each module at a forward current of I_{sc} and 0.1 I_{sc}. A variation in the contact resistance between the interconnecting busbar and the cell was consistently observed within cell of the exposed modules. An example from two modules is shown in the following figures. The low current images confirmed that there was no significant changes in the shunt resistance of cells due to the long term exposure





Conclusion

This long-term study identifies the degradation rate of standard c-Si modules deployed in the hot and humid climate of Florida. The degradation rate was determined to be just under 1 % per year, with the modules retaining an average of 90.8% of there original measured value. The effect of soiling and resistance of the contact leads was investigated and attributed to an additional loss of 3.84%. The modules in their operational state (including soiling and original leads) were performing at 87% of there original measured value. Electroluminescence imaging was used to identify any defects that developed during operation. These results represent only the preliminary performance evaluation of this system, with future investigations planned. This system remains in service at the Florida Solar Energy Center.

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Tracking PV Changes: Bridging Between Thin-Film Cells and Modules

Russell Geisthardt, Andy Moore, John Raguse, and Jim Sites

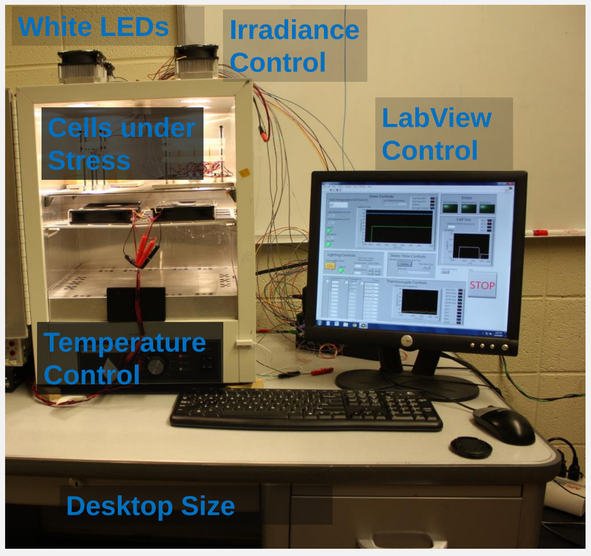
Department of Physics, Colorado State University, Fort Collins, CO 80523

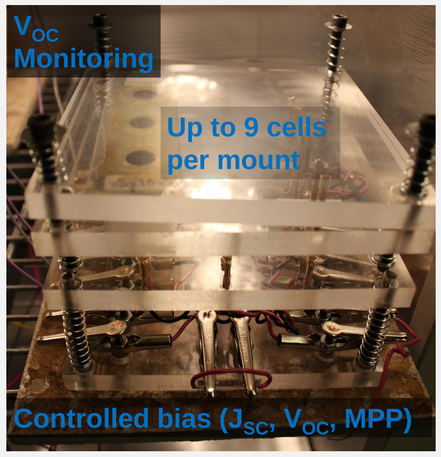
Abstract

Although field testing of modules is the best indicator of their reliability, detailed tracking of changes in cells exposed to elevated temperatures under simulated solar conditions can make several practical contributions to the understanding and correction of reliability issues. In general, cell studies are cheaper, faster, more flexible, and more comprehensive. An important goal is for a cell to replicate a module as closely as possible, which would include the same cell edges, contacts, and encapsulation as in a module. Types of measurements where cell-level tracking can be more comprehensive include current-voltage and capacitance-voltage as a function of temperature, and spatial-uniformity tracking through electroluminescence and light-beam-induced current.

Cell Stressing System

- Compact desktop size
- Independent temperature and irradiance control
- White LED illumination with good spectral and irradiance match to sunlight
- Good temperature uniformity and stability (1 °C)
- Controlled voltage bias conditions (J_{SC}, V_{OC}, MPP, etc.)
- Automated system, stress, and characterization logging
- Suite of external characterization tools
  - Possibility for in-situ tracking



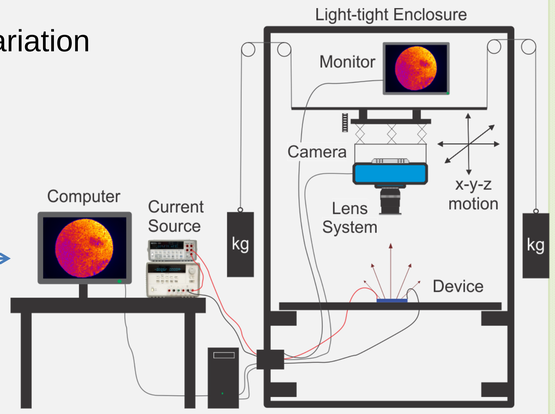


Reasons for cell measurements

- Understand device physics of degradation mechanisms
- Isolate device degradation from encapsulant and scribe degradation
- Full characterization available for cells
- Easier to work with than modules

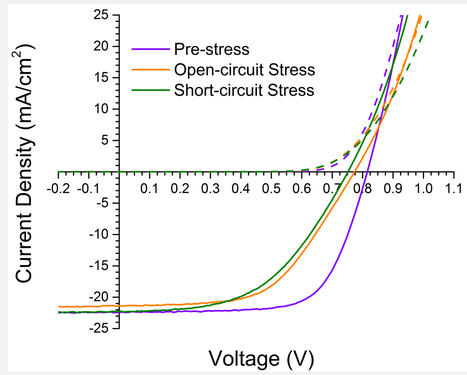
Characterization Suite

- Current-Voltage (J-V)
  - Temperature, intensity, and spectral variation
  - Cell parameter analysis (J_0, A, R_s, r_{sh})
- Quantum Efficiency (QE)
- Capacitance
  - Frequency and voltage dependence
  - Admittance Spectroscopy
- Electroluminescence (EL)
  - Tracks well with V_{OC}
  - Easily extended from cells to modules
- Light-Beam-Induced Current (LBIC)
  - QE spatial mapping
  - 4 wavelengths, 1-100 um resolution, variable voltage bias

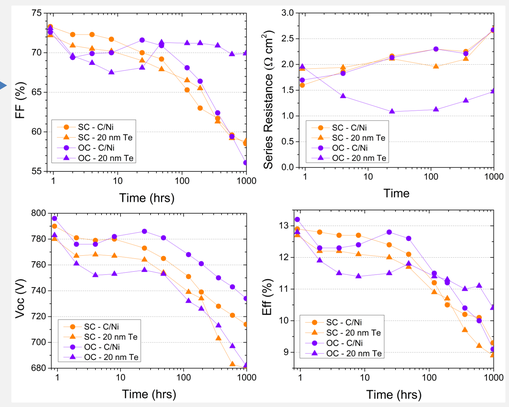


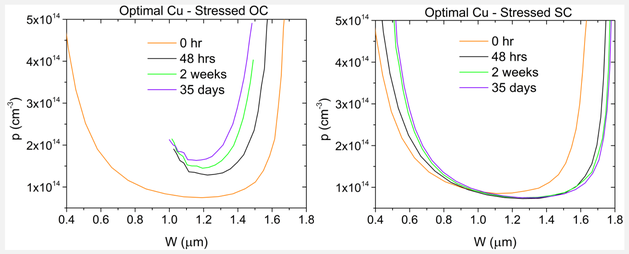
Preliminary Results

- Cells exhibit degradation under stress
  - Mechanisms depend on stress condition
    - Open-circuit-stressed cells lose more current
    - Short-circuit-stressed cells lose more voltage
    - Both lose significant fill factor (series resistance)
  - Mechanisms depend on processing conditions (eg., back contact)

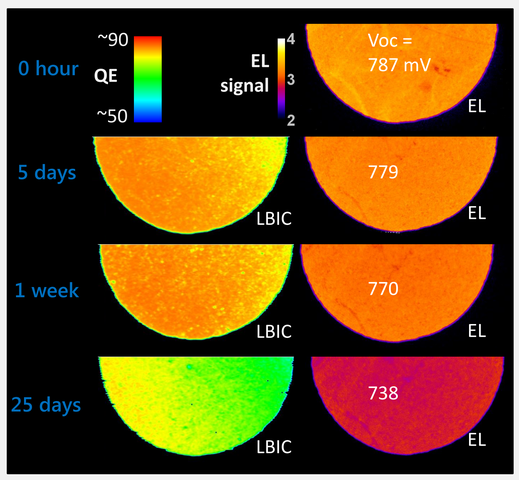


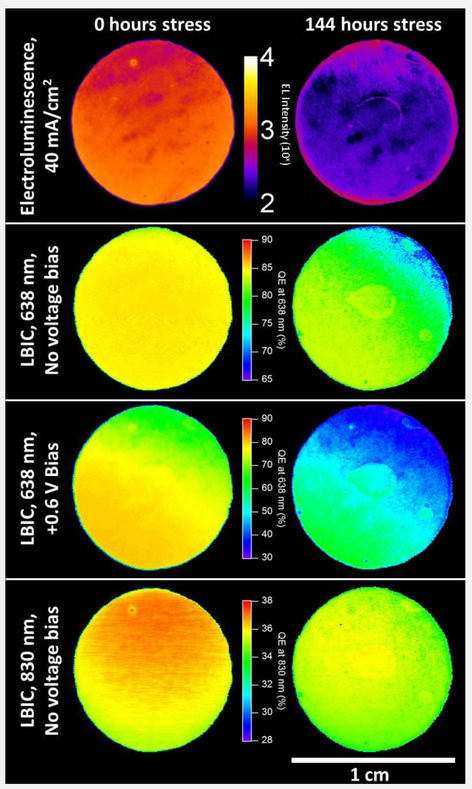
- C-V analysis shows changes in doping profile connected to stress conditions





- Uniformity typically degrades with stress
  - EL can be tracked regularly with stress
  - May show uniform or localized degradation
  - Some features may be predictive of degradation





Summary

- Compact cell stress system recently constructed
- Allows for comprehensive studies of device physics degradation mechanisms
- Preliminary work shows degradation in cell performance and uniformity

Acknowledgements

This work is supported by the DOE SunShot Program, FPACE Award DE-EE0005399 and PREDICTS Award DE-EE006344. Thank you to the PV Manufacturing Lab for cell fabrication, and to Kevan Cameron and Jason Kephart for additional contributions. This presentation contains no confidential information.

Pitfalls of Energy Yield Prediction Models Based on Time 0 and STC Module Characterization

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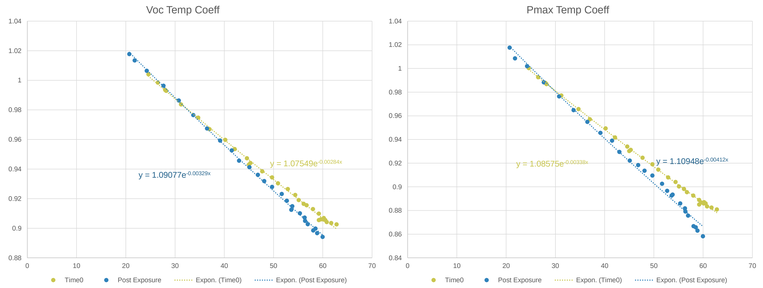
Abstract

- Many parameters are required for generating prediction models. While these models are quite sophisticated, the output is only as good as the input. Module manufacturers are responsible for developing a module PAN file. This file is used by PVSYST to predict energy yield for the lifetime of a system. Some of these input parameters include temperature coefficients, operating temperature, module mismatch, performance verses irradiance, Rseries and Rsh, angle of incidence modifier, and initial degradation rate. These parameters can be tested and real characterization results can be used to generate the most practical and accurate PAN files possible. However, many of these parameters can change upon exposure. In some cases, these shifts can occur within the first year or less causing the energy yield predictions for the remaining 24yrs to be less than accurate. Furthermore, especially in thinfilm modules, specific care must be taken to prevent metastability in the module performance to give erroneous results. In this paper we will discuss real world energy yield compared to modeled energy yield for several PV systems and show where the models have fallen short as a result of actual parametric shifts in module characteristics upon exposure.

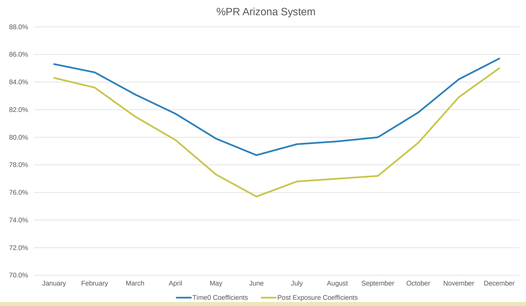
Temperature Coefficients

- Temperature coefficients (alpha, beta, and gamma) are used to model system level energy yield for various climates and seasons.
- Temperature Coefficients can change upon outdoor exposure.



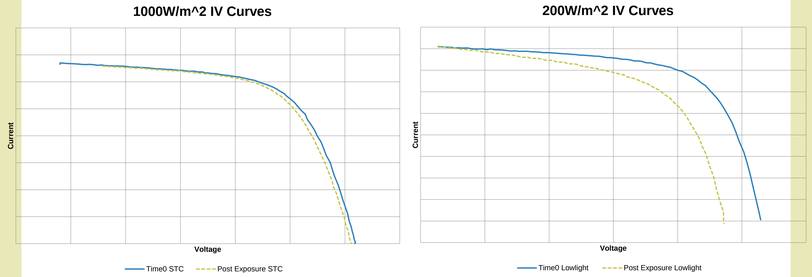
Impact to Modeling

- After exposure, less than 6 months in this case, the temperature coefficents degraded for both Voc and Pmax.
- The impact of this shift in temperature coefficients will result in significant loss in energy yield (predicted and actual) for this Arizona system.



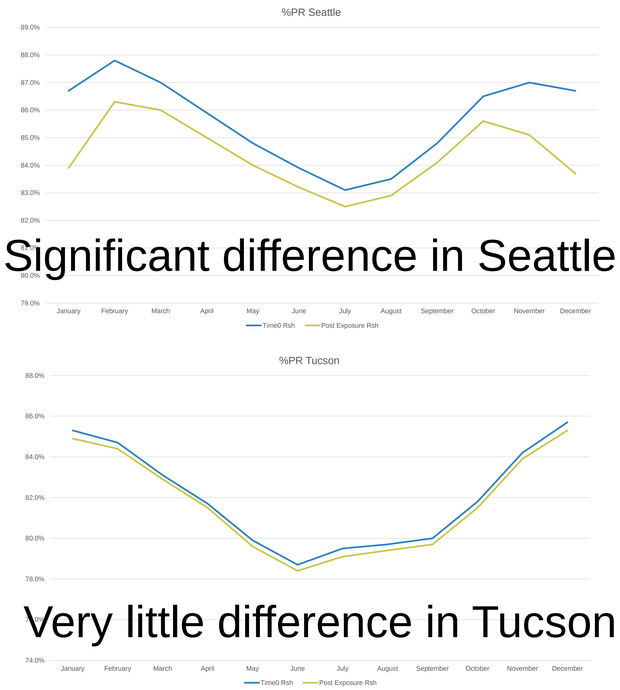
Performance vs Irradiance

- PVSYST PAN files include the modules performance vs irradiance characteristics.
- This is primarily dependent on the module Rsh at various light levels and fit with an exponential.
- Some degradation mechanisms drastically change the module Rsh after outdoor exposure.
- This degradation in Rsh may only be evident in lowlight conditions.



Impact to Modeling

- Adjusting the Rsh vs Irradiance exponential in the PAN file to more accurately represent post light soaked characterization is important in energy yield predictions for cloudier climates.

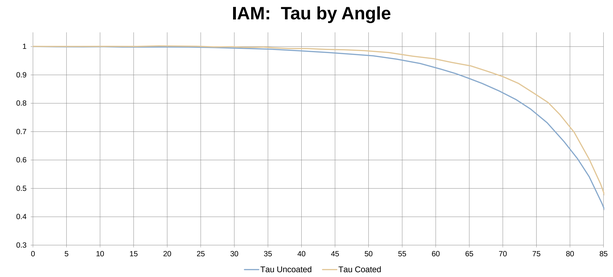


Significant difference in Seattle

Very little difference in Tucson

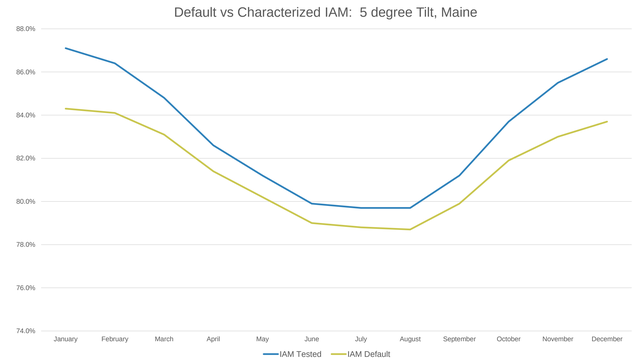
Incident Angle Modifier

- The Incident Angle Modifier (IAM) is used in PVSYST to model performance at various angle of incidence (AOI).
- Manufacturers that use AR coatings or have surface structure should test IAM to get a more accurate performance vs AOI.
- These coatings and surface structures may change with exposure or significantly impact soiling and should therefore be tested post exposure.



Impact to Modeling

- Characterizing IAM can make a significant difference to energy yield predictions, especially for installations that are not at optimum tilt



Conclusions

- Generating accurate PAN files for PVSYST energy yield modeling is important for ensuring energy yield predictions and installation financials are as sound as possible.
- Many inputs into module PAN files have been shown to change with time and exposure.
- Characterizing PAN file parameters after real world exposure can make a significant difference in modeling results.
- PAN file characterization should be done periodically, as certain shifts in materials and/or processes may change these performance behaviors as well.

2015 Photovoltaic Module Reliability Workshop
NREL, Golden, CO
February 24, 2015

Stability of encapsulants using various string-ribbons

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Motivation

Replacing a Cu string-ribbon with Al can effectively cut the cost of a photovoltaic module.
Furthermore reducing the usage of Cu is expected to realize long-life encapsulants because Cu acts as a catalyst of thermal-oxidative degradation of polymer.

$$ROOH + Me^{n+} \rightarrow RO\cdot + Me^{(n+1)+} + OH^-$$
$$ROOH + Me^{(n+1)+} \rightarrow ROO\cdot + Me^{n+} + H^+$$

Me : Metal (Cu, Co, …)

Therefore, we have compared the degradation of encapsulants using various string-ribbons by discoloration and mechanical strength.

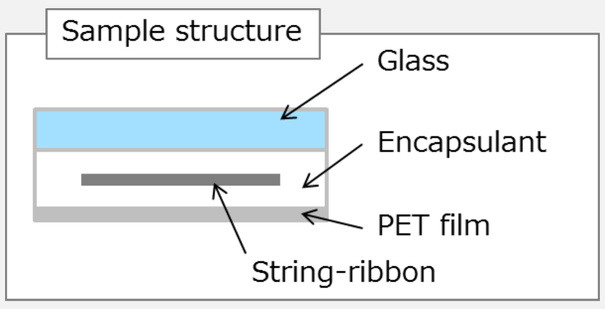
Conciusions

- **Cu acts as a catalyst for the thermal-oxidative degradation of encapsulants.**
- **The degradation rate differs among encapsulants.**
- **Encapsulants which show large degradation with Cu-ribbon show no degradation with Al-ribbon.**

Discoloration

(1) High temperature storage test

Condition
- **130 ºC**
- **1000 hours**
- **Ambient air**

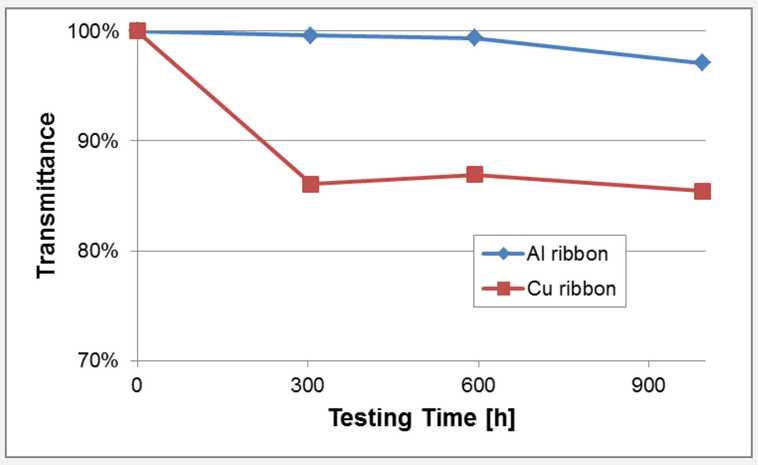


(2) Evaluation method

- **Reflectivity measurement**
- **Appearance inspection**

(3) Results

The encapsulant in contact with Cu-ribbon is discolored, whereas no discoloration is observed with the Al-ribbon.

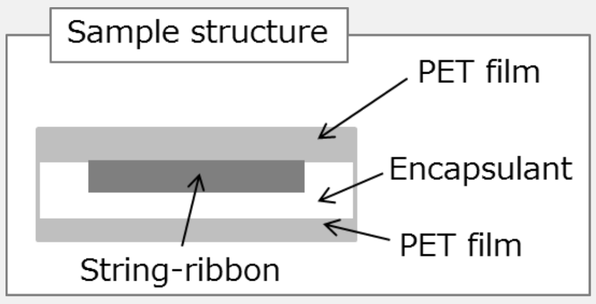


Cu acts as a catalyst for the thermal-oxidative degradation of encapsulants.

Tensile strength

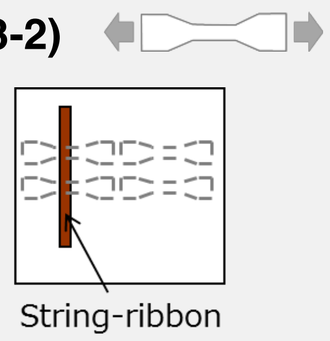
(1) High temperature storage test

Condition
- **130 ºC**
- **600 hours**
- **Ambient air**



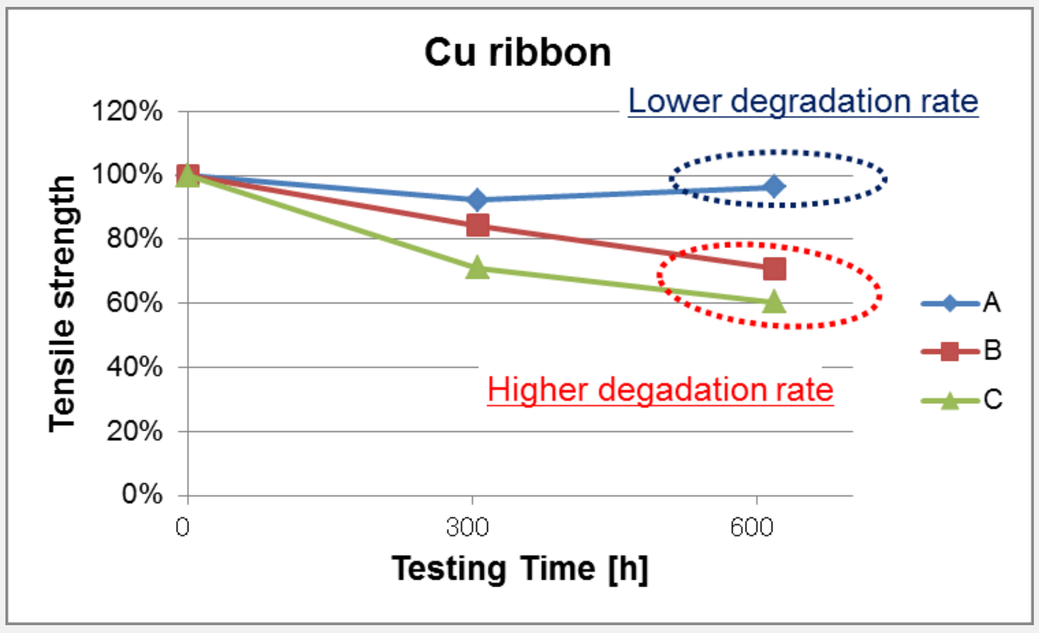
(2) Evaluation method

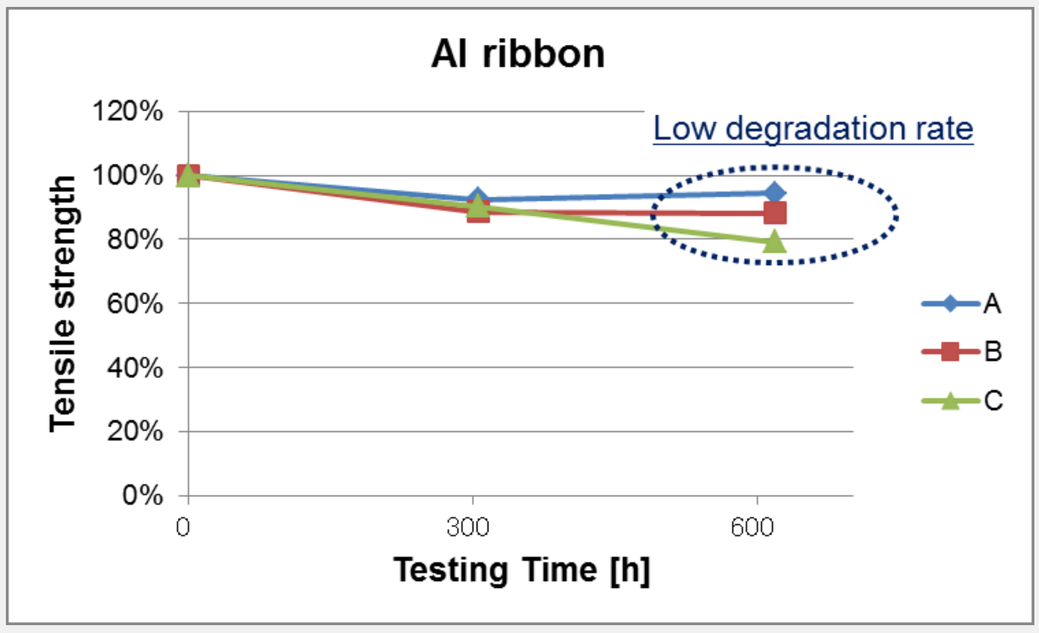
Condition
- **Dumbbell shape(JIS K7113-2)**
- **Room temperature (25 ºC)**
- **4.0 mm/sec**



(3) Results

- **The tensile strength of encapsulants using the Cu-ribbon decreases over testing time, and the degradation rate differs among encapsulants.**
- **Encapsulants that show large degradation with the Cu-ribbon show no degradation with the Al-ribbon.**





Sample	A (PO)	B(EVA)	C (PO)
Cu ribbon	○	△	△
Al ribbon	○	○	○

Replacing the Cu-ribbon with the Al-ribbon increases options of the encapsulants; in other words, it has the potential to reduce cost of the encapsulants.

This presentation contains no confidential information.

Thermal Resistance Measurements of Bypass Diode / Junction Boxes for Predicting Field Stressors

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[1]University of Central Florida
[2]Jabil Circuit Inc.

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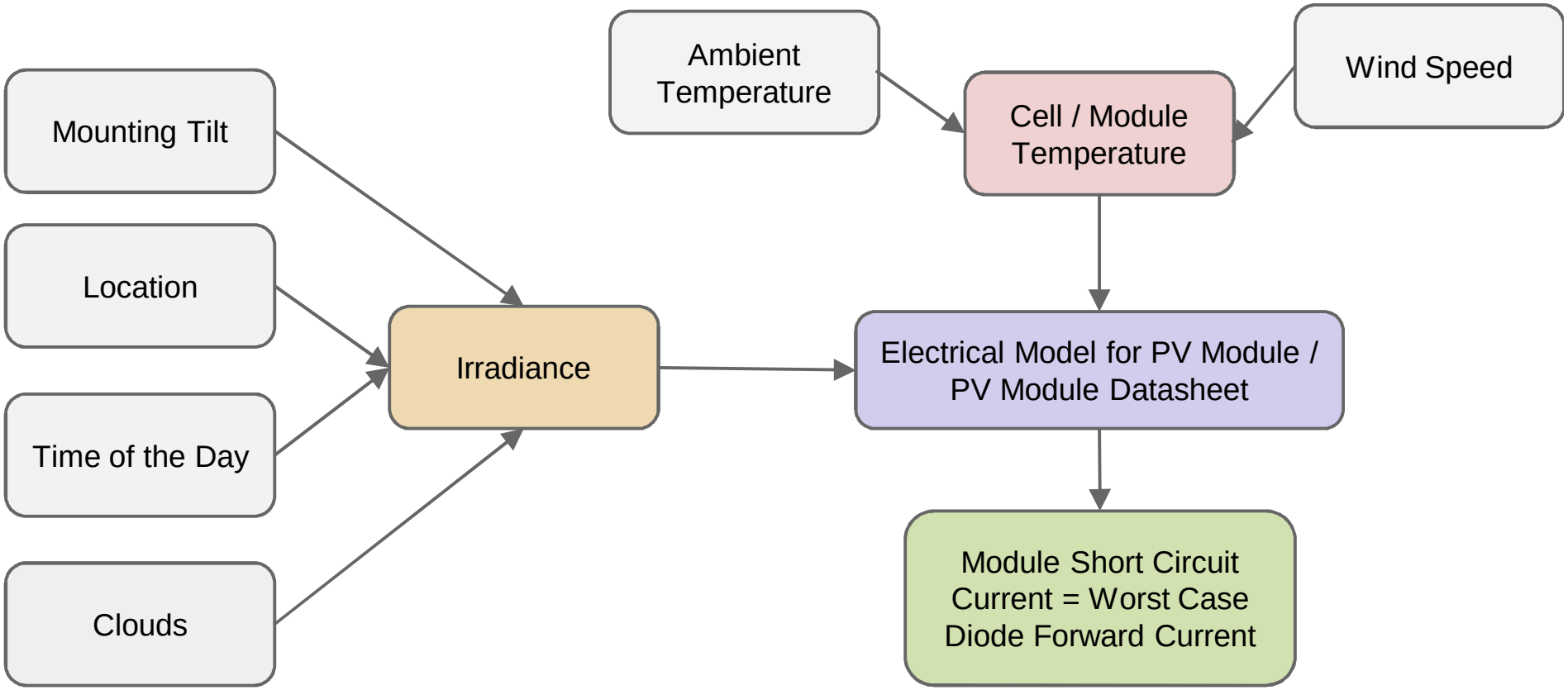
Bypass Diode Reliability

- Bypass diodes are primary components in PV modules that provide protection against shading by limiting the reverse voltage across a shaded cell.
- A bypass diode failed in short circuit results in immediate PV module failure, while a bypass diode failed in open circuit can cause significant safety hazards.
- The operating junction temperature (TJ) and difference between maximum and minimum temperature during thermal cycling (ΔTJ) of bypass diodes in field deployed modules determines their long term reliability.
- The stressors TJ and ΔTJ need to be estimated for diodes in modules deployed in various climatic zones during service life.

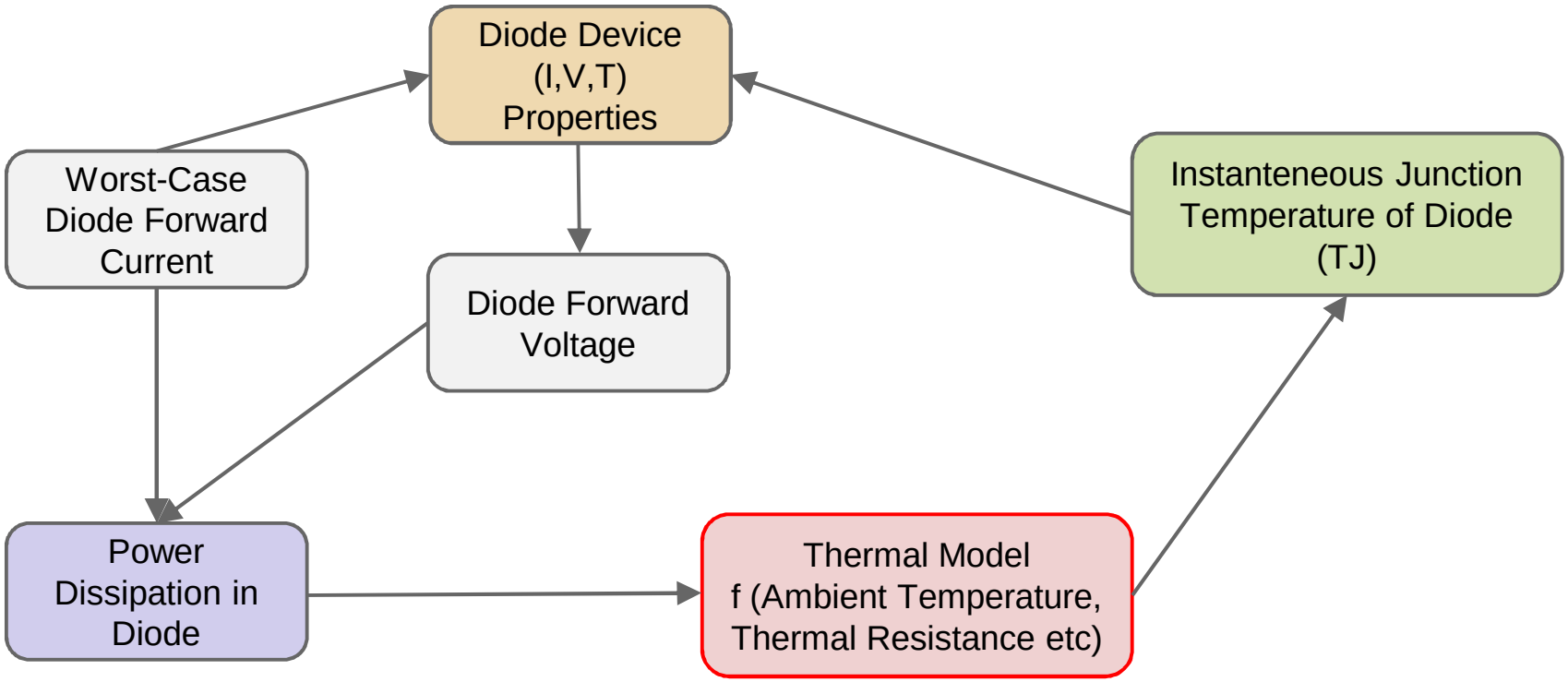
Estimating Stressors in Field

- In order to quantify the thermal stresses experienced by a bypass diode in the field, it is necessary to estimate the junction temperature (TJ) as a function of environmental and shading conditions.
- Worst-case shading for bypass diode is when the module is short circuited and a cell is 100% shaded.
- Worst-case stressors experienced by bypass diodes in various climatic zones can be quantified if TJ of the diode can be predicted from the Typical Meteorological Year (TMY) data.
- The goal is to perform thermal characterization of bypass diodes / junction boxes in the lab and then use models to predict TJ in field based on the TMY data.

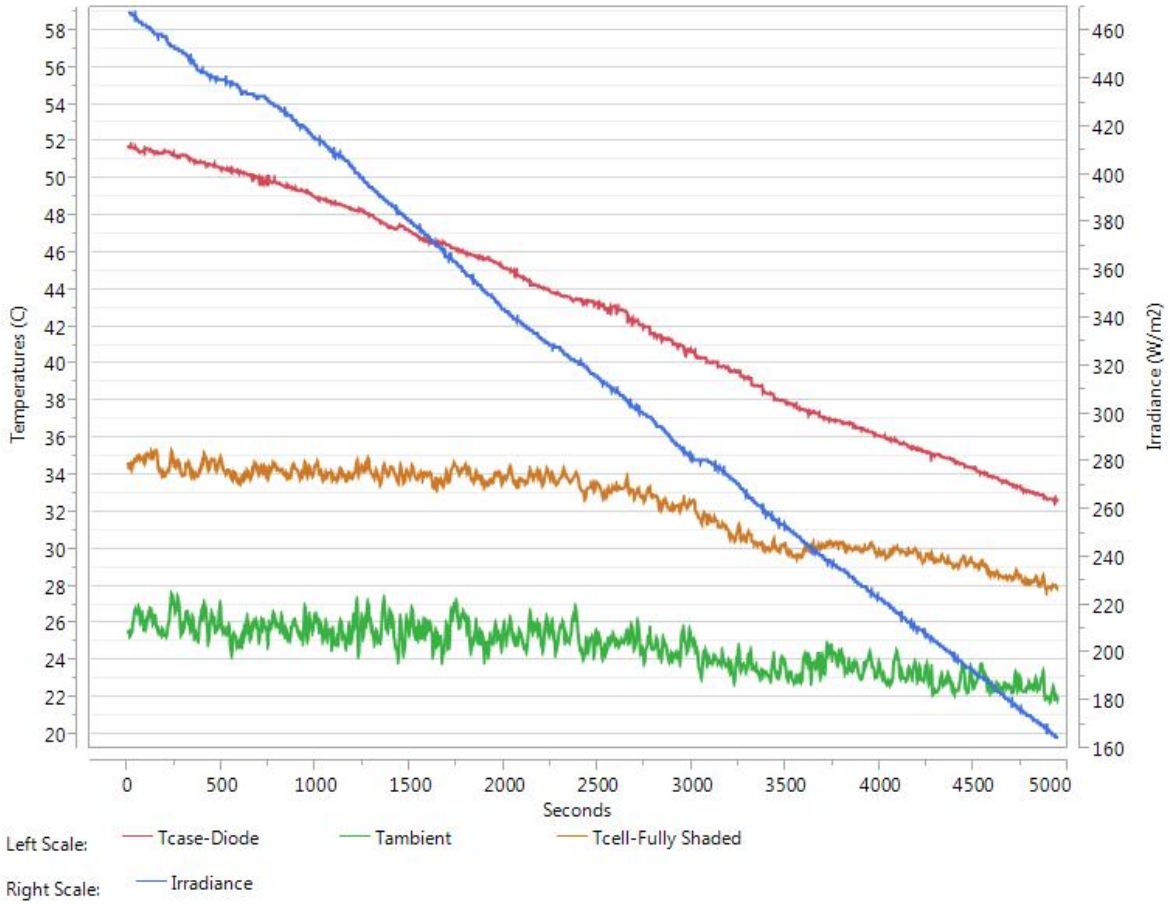
Predicting Worst-Case Diode Forward Current from TMY Data



Predicting Diode Junction Temperature from Power Dissipation

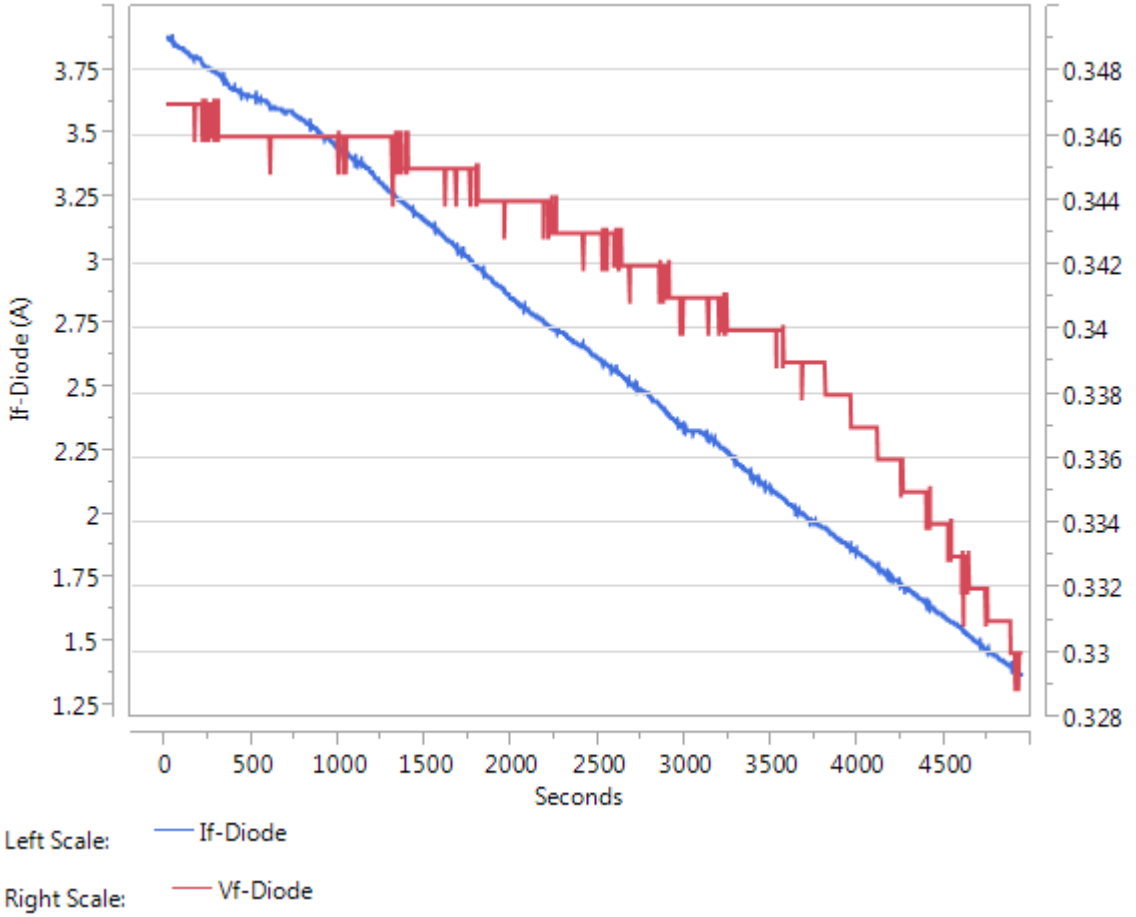


Outdoor Measurements: Irradiance and Temperatures



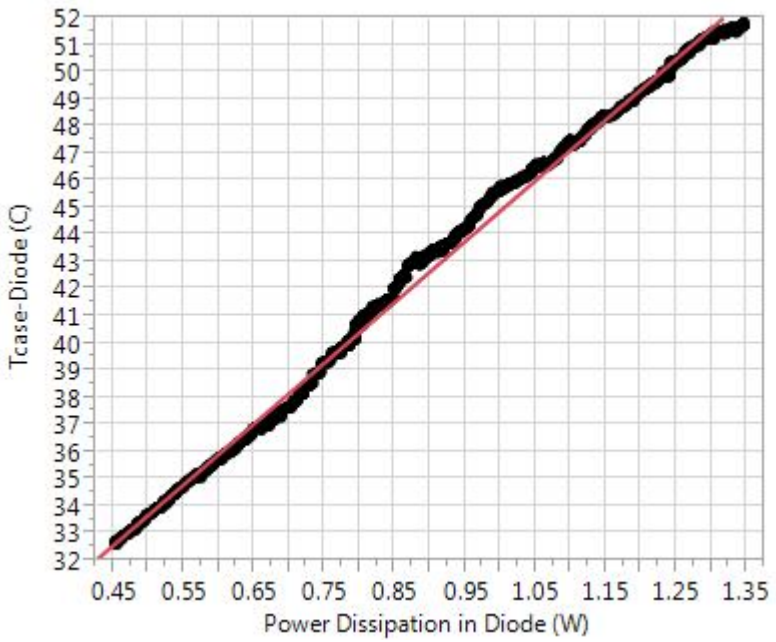
- Diode case temperature follows the irradiance on a sunny day
- Even for low irradiance and ambient temperature values, diode temperature could be significantly higher.
- Wind has introduced noise in the ambient and cell temperature measurements

Outdoor Measurements: Diode Current and Voltage



- Diode Current reduces as irradiance reduces over time.
- Reduction in current causes reduction in Tcase.
- However, Vf shows setp-wise behavior due to two balancing forces:
- Lower current → Lower Vf, and
- Lower current → (Lower temperature)→ Higher Vf

Diode Temperature vs Power Dissipation



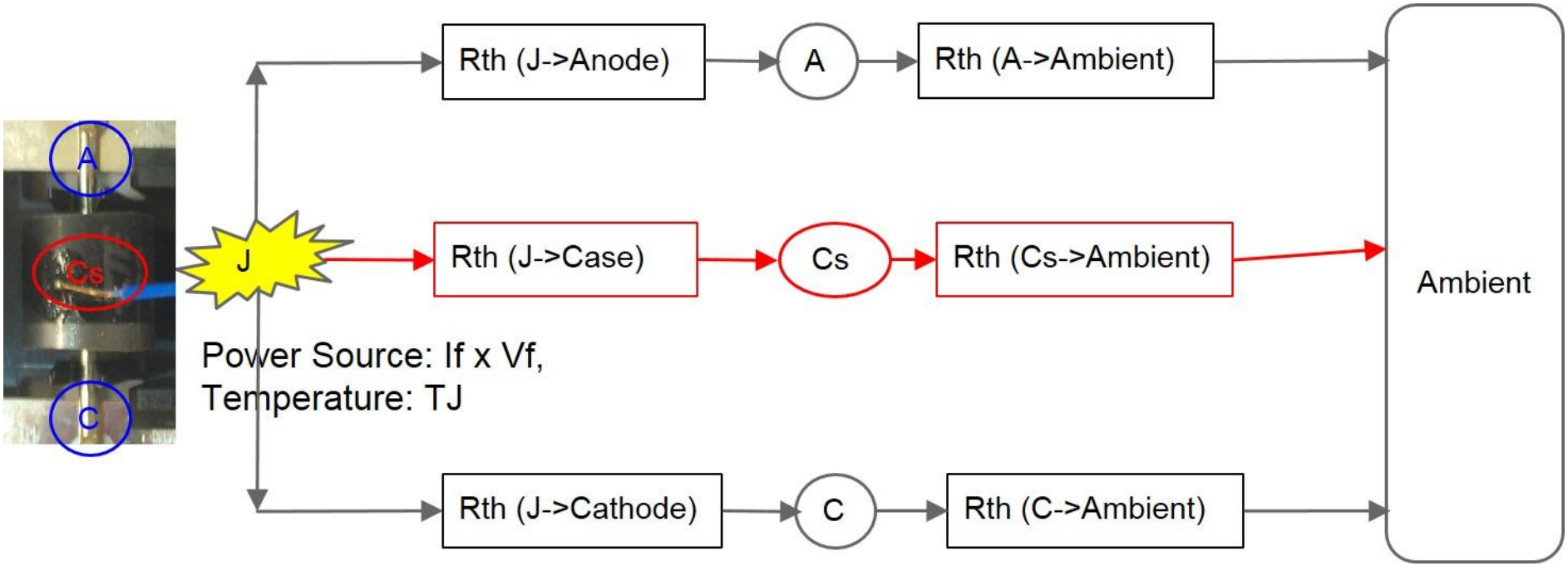
- On a sunny day, steady reduction in diode current results in gradual reduction in Tcase over time.
- A state of quasi-thermal equilibrium is maintained throughout the process.
- Correlation between electrical and thermal properties can be best described by an “apparent” ambient temperature and thermal resistance.

Tcase-Diode (C) = 22.50 + 22.42 x Power Dissipation in Diode (W)

“Apparent” Ambient Temperature (Tambient)

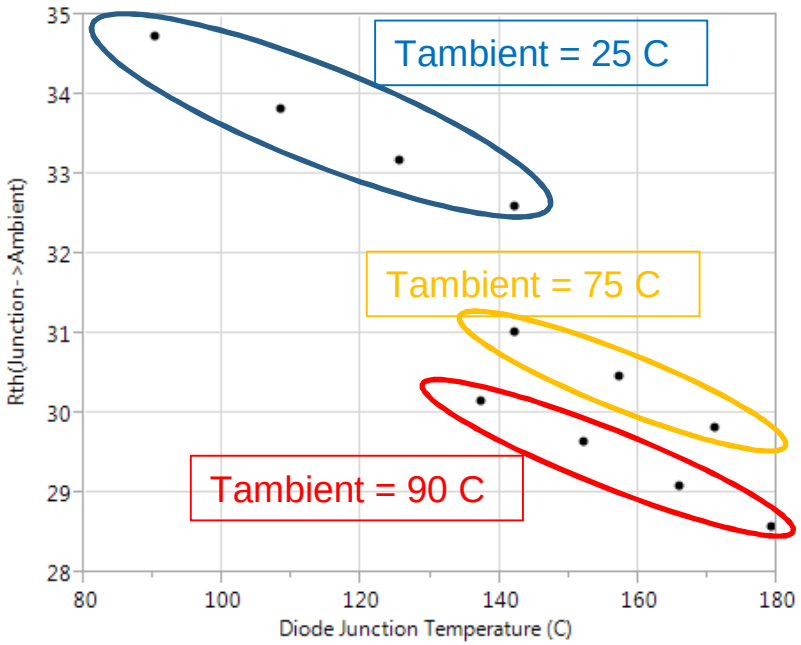
“Apparent” Thermal Resistance (Rth)

Simplified One-Dimensional Thermal Model



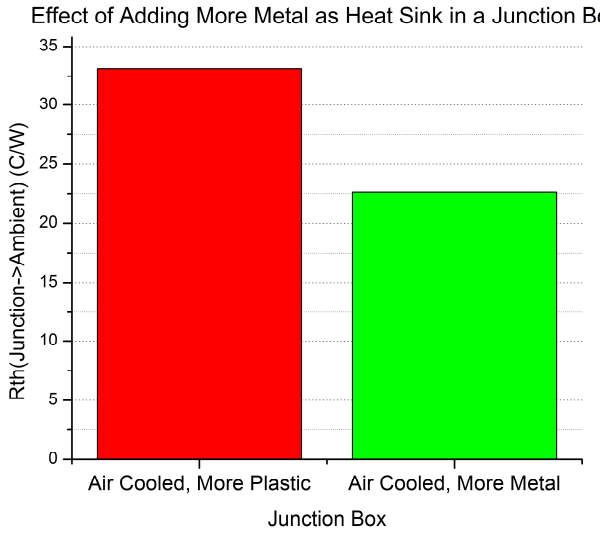
$$At\ Thermal\ Equilibrium: Rth(Junction \rightarrow Ambient) \sim \frac{(TJ - TAmbient)}{(If\ \times Vf)}$$

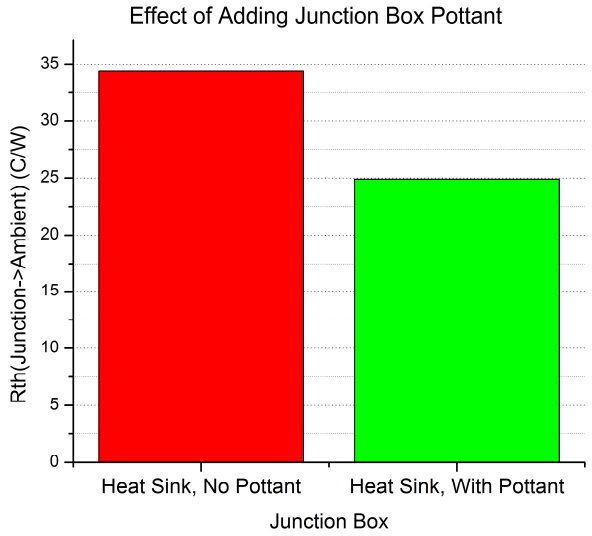
Rth(Junction→Ambient) vs TJ



- The value of Rth(Junction→Case) = 3.5 was used from diode datasheet to calculate TJ from Tcase.
- In an environmental chamber, Rth(Junction→Ambient) was calculated for Tambient = 25 C, 75 C and 90 C. and If = 6,8,10,12 A.
- However, Rth(Junction→Ambient) was found to vary significantly with Tambient and TJ itself.
- This may be because of increasing heat transfer by radiation at elevated temperatures which is not accounted for by simplified 1-D thermal model.

Rth(Junction→Ambient) @ Standard Conditions for Comparing Performance of Junction Boxes





- Rth(Junction→Ambient) was compared for different types of junction boxes at Tambient = 25 C, If = 10 A.
- For large, air cooled junction boxes, adding more metal (and surface area) as a heat sink can significantly reduce the thermal resistance.
- For small junction boxes with metallic heat sink, addition of junction box pottant can significantly reduce the thermal resistance

Conclusions and Future Work

- On a sunny day, under worst-case shading scenario for a diode, the diode is in a state of quasi-thermal equilibrium as current changes gradually with the irradiance.
- The diode case temperature is directly proportional to the power dissipated in the diode with “apparent” ambient temperature and thermal resistance as the coefficients.
- However, Rth(Junction→Ambient) calculated from the simplified 1-D model is found to vary with Tambient and TJ itself. Therefore, this approach is of limited value for predicting field stressors.
- Rth(Junction→Ambient) when measured at standard conditions can be useful to compare thermal properties of bypass diodes / junction boxes.
- We are exploring other approaches for predicting field stressors from thermal characterization of bypass diodes / junction boxes.

Assessment of Two Tests in IEC 62788-5-2 Edge Seal Durability Tests by IEC TC82 WG2 TG5 PVAQT5

Quanex building products

Michael Kempe
National Renewable Energy Laboratory

Lori Postak Quanex IG Systems, Inc.

Nancy Phillips 3M

David Burns 3M

David Miller
National Renewable Energy Laboratory

Purpose:

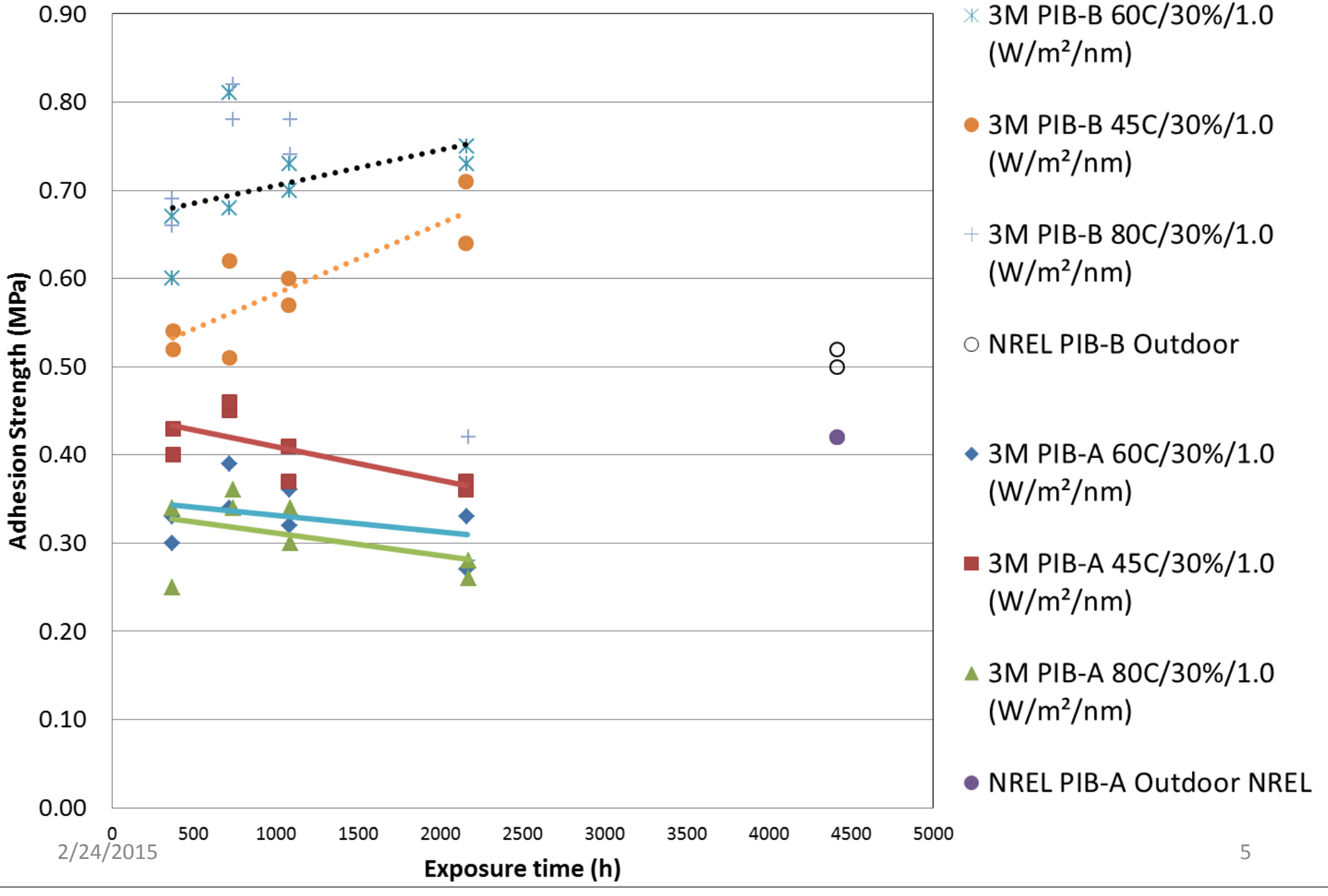
Use two commercially available edge sealants to evaluate tests in the Edge Seal Durability standard IEC 62788-5-2.

- Overlap Shear
- Wedge Test

Overlap Shear Tests

- Low iron Glass/Glass 25.4mm wide x 75 mm long
- Adhesive thickness ~0.6 mm
- Adhesive area 25.4 mm x 25.4 mm
- Strain rate 10 mm/min
- Two replicates per time period
- Chamber Exposure - Xenon @ 45°C 60°C 80°C
- Outdoor Exposures - NREL Golden, CO

Lap Shear PIB A and B
Various UV exposures & temperatures

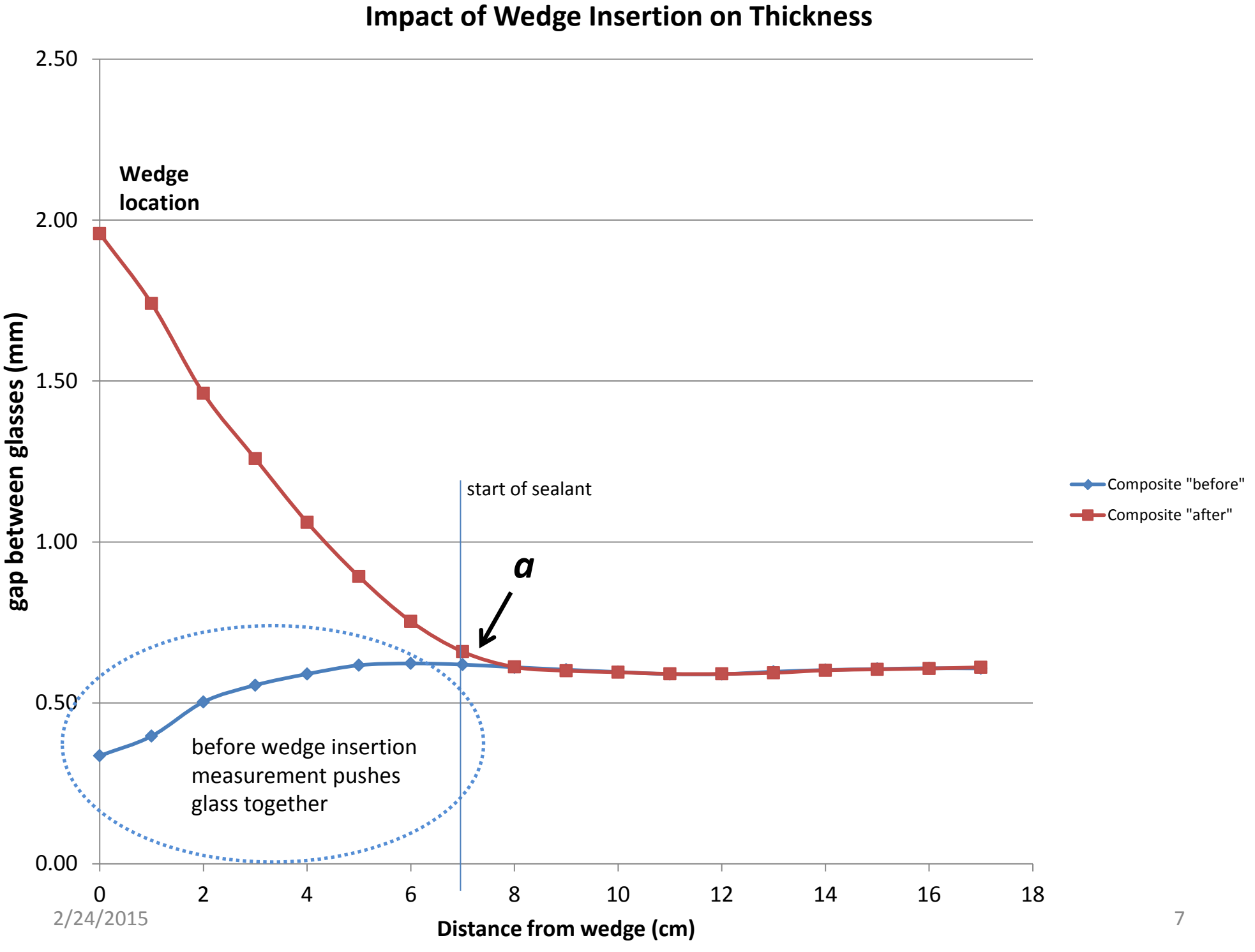


Wedge Test Calculating Griffith's Criterion G_{th} "Fracture Toughness Threshold"

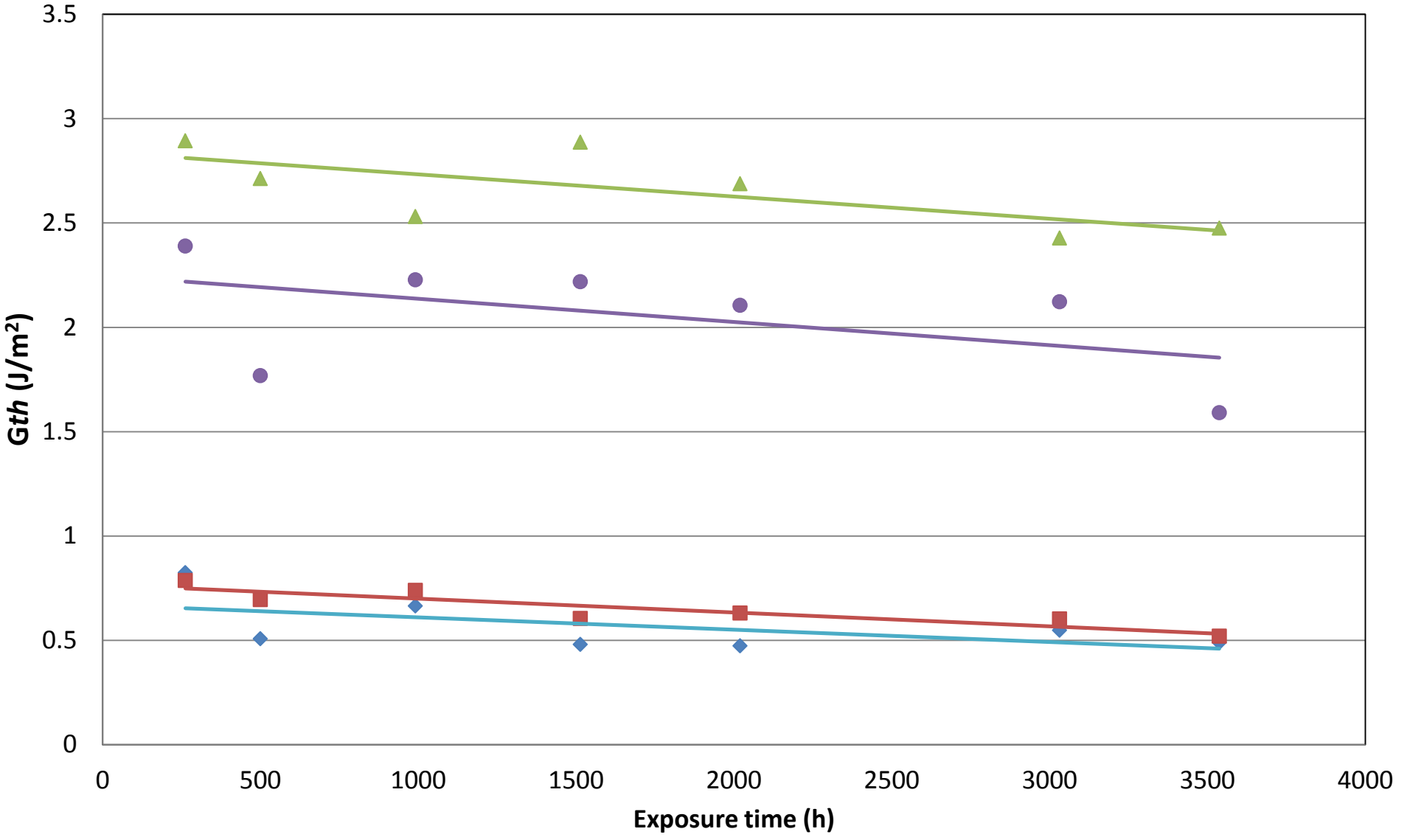
$$G_{th} = \frac{3Et^3h^2}{16a^4}$$

- E= 72 GPa low-iron glass
- t= 3.18 mm beam thickness
- h= wedge size - initial adhesive thickness

  wedge 2 and 2.38 mm, adhesive thickness ~0.60 mm
- a= distance from wedge to the 5% change in thickness
  - –Used change in thickness since no delamination occurred

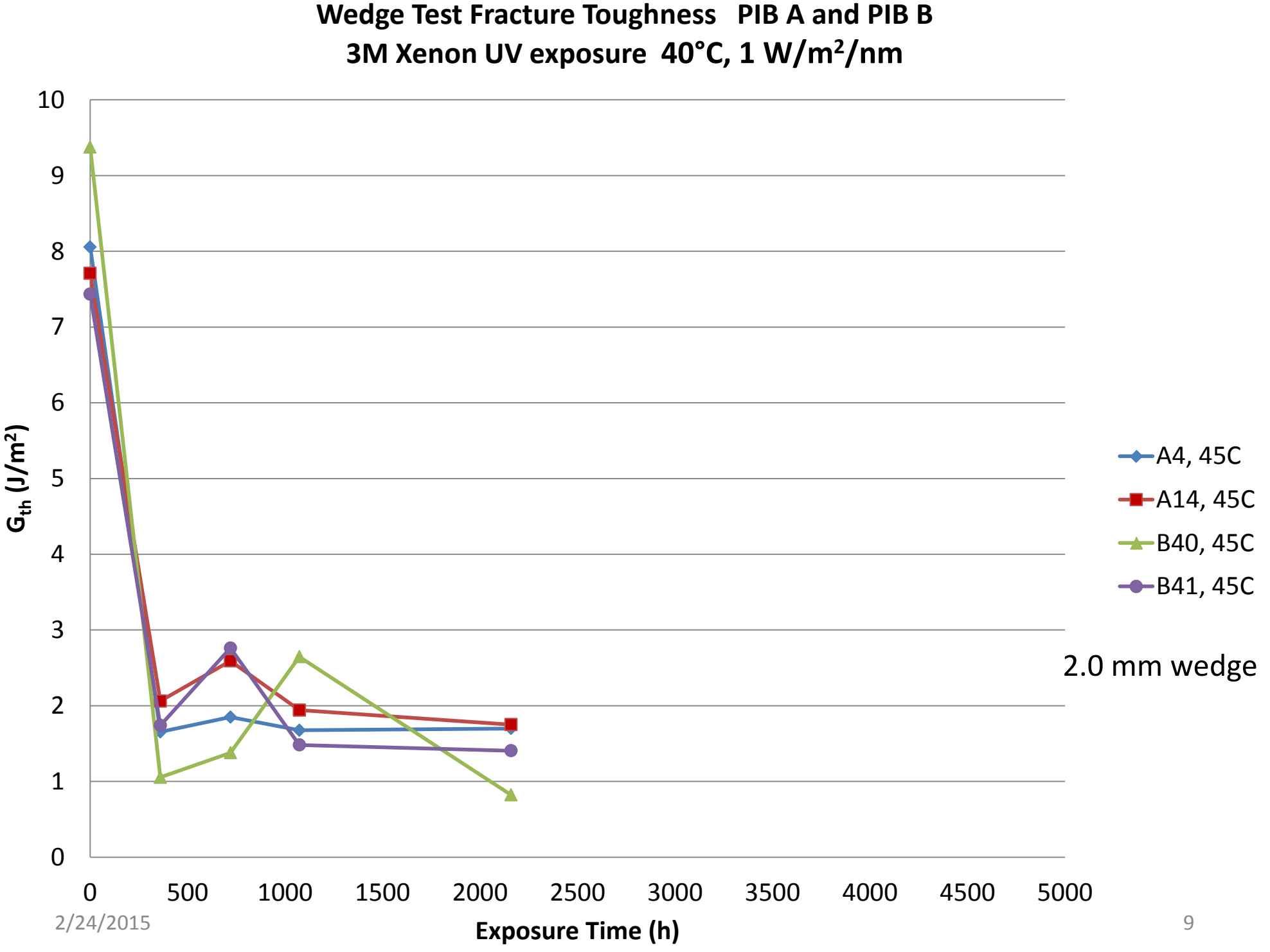

Impact of Wedge Insertion on Thickness
2.50
2.00
1.50
1.00
0.50
0.00
gap between glasses (mm)
Wedge location
start of sealant
a
before wedge insertion measurement pushes glass together
0
2
4
6
8
10
12
14
16
18
Distance from wedge (cm)
Composite "before"
Composite "after"

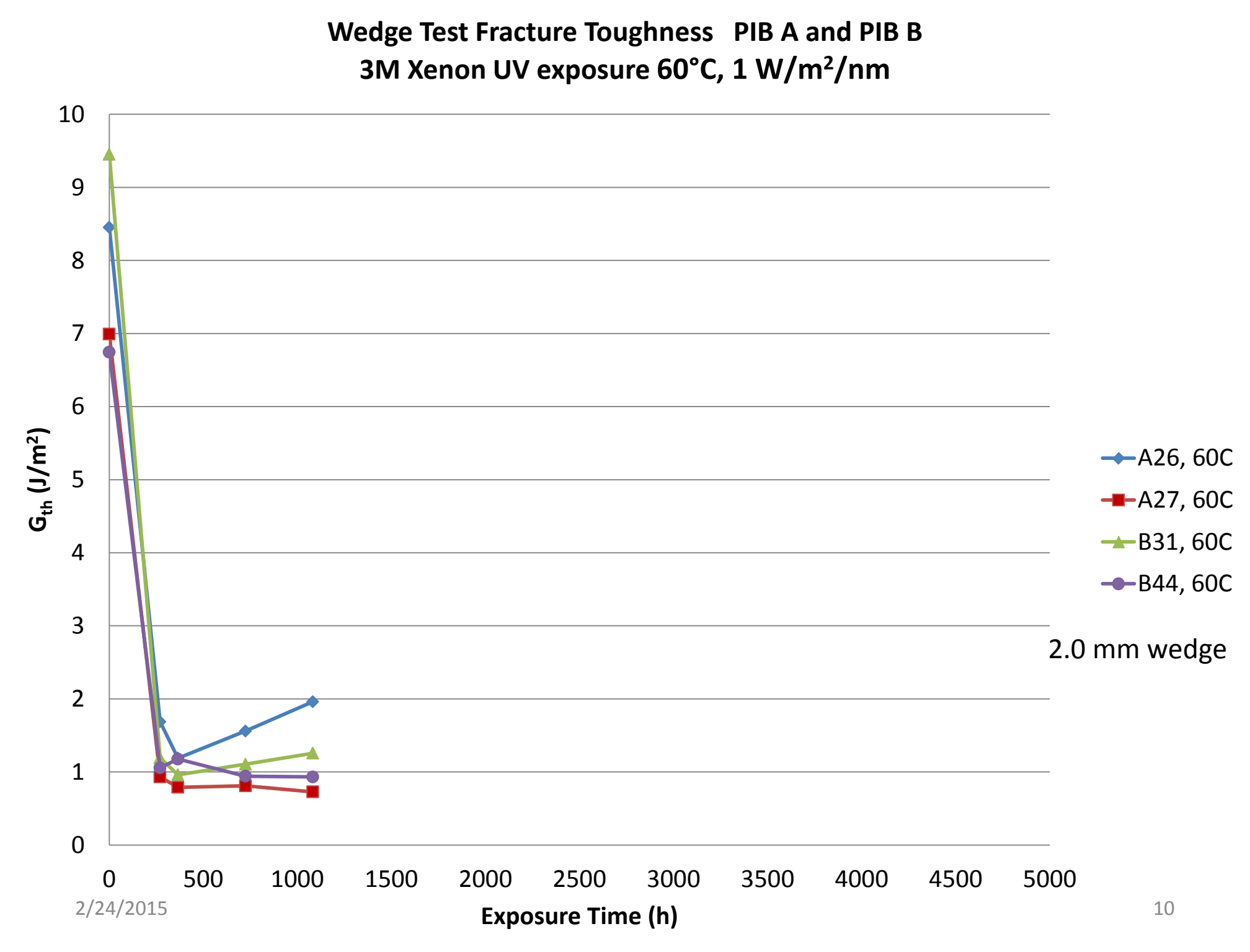
Wedge Test Fracture Toughness PIB A and PIB B
NREL Xenon UV exposure 60°C Chamber

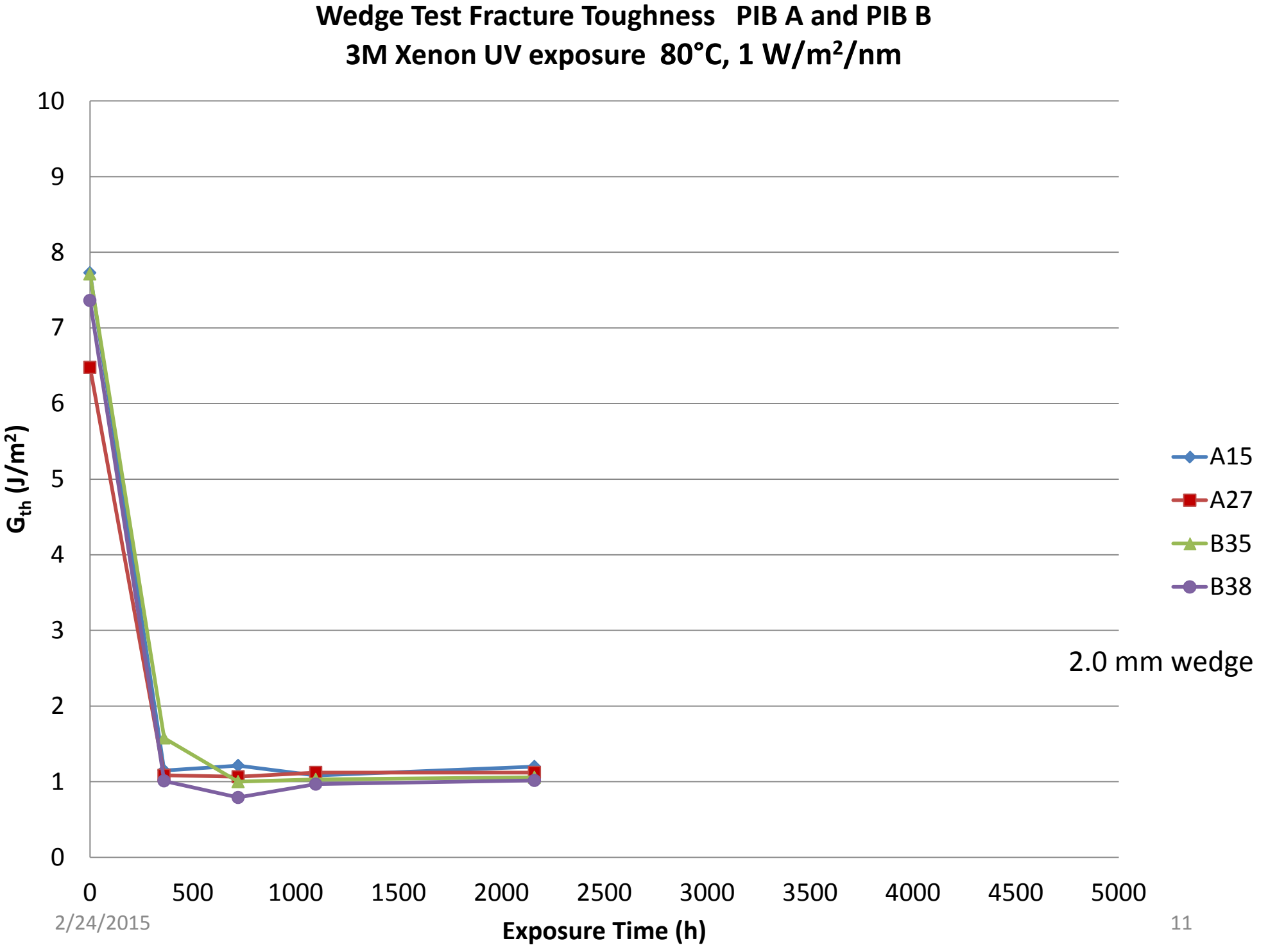


2.38 mm wedge

- B45 NREL, SERF Ci4000, 114 W/m2 (300-400 nm), CHT=60C, BPT=85
- B46 NREL, SERF Ci4000, 114 W/m2 (300-400 nm), CHT=60C, BPT=85
- A39 NREL, SERF Ci4000, 114 W/m2 (300-400 nm), CHT=60C, BPT=85
- A40 NREL, SERF Ci4000, 114 W/m2 (300-400 nm), CHT=60C, BPT=85

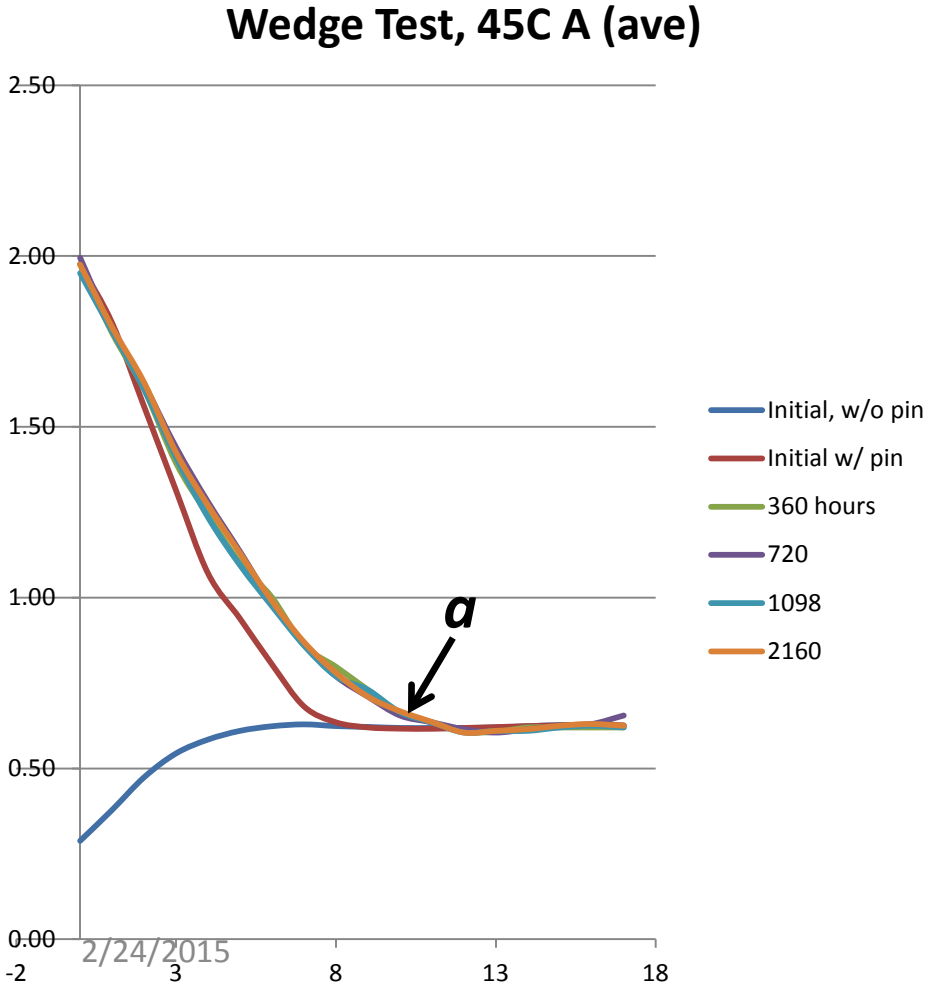

Wedge Test Fracture Toughness PIB A and PIB B
3M Xenon UV exposure 40°C, 1 W/m²/nm
10
9
8
7
6
5
4
3
2
1
0
G_{th} (J/m²)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Exposure Time (h)
A4, 45C
A14, 45C
B40, 45C
B41, 45C
2.0 mm wedge


Wedge Test Fracture Toughness PIB A and PIB B
3M Xenon UV exposure 60°C, 1 W/m²/nm
10
9
8
7
6
5
4
3
2
1
0
G_{th} (J/m²)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Exposure Time (h)
A26, 60C
A27, 60C
B31, 60C
B44, 60C
2.0 mm wedge

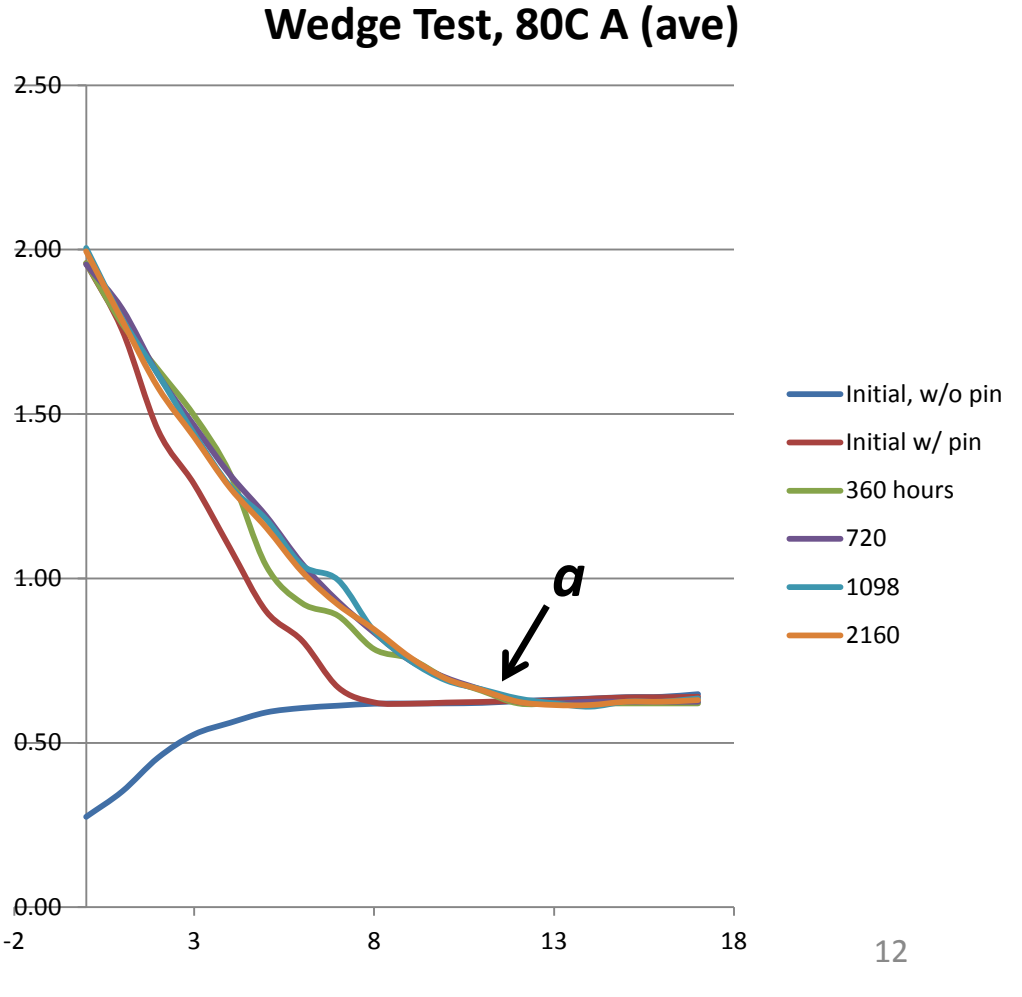

Wedge Test Fracture Toughness PIB A and PIB B
3M Xenon UV exposure 80°C, 1 W/m²/nm
10
9
8
7
6
5
4
3
2
1
0
G_{th} (J/m²)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Exposure Time (h)
A15
A27
B35
B38
2.0 mm wedge

Data driving the G_{th} Calculation

Thickness change @ 45C



Thickness change @ 80C



Special thanks to all of the Edge Seal Task Group members for their participation in meetings and especially to labs providing testing support. NREL, NIST, 3M, ATLAS, CWRU and Energy Research Institute (Saudi Arabia)

Long Term Performance of CIGS Modules in Multiple Environments

Kristopher Toivola, Paul Robusto, Bill Kessler

Introduction

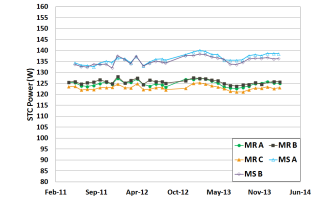
Outdoor module testing is critical for long term performance monitoring and validating accelerated laboratory testing results.

MiaSole has tested modules for multiple years in four Climate Zones:

1.) **Desert** - Arizona
2.) **Mediterranean** - California
3.) **Continental** - Ohio
4.) **Tropical** - Florida

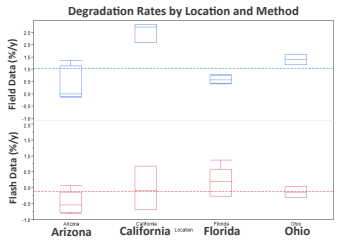
Test install at Florida Site

Arizona Location Example



Location	Module	Months in field	Change in Pmax (%)	Degradation Rate per year from flash tests(%)	Degradation Rate per year from regression of field data (%):
Arizona	MR A	34	-2.00	-0.71	-0.09
	MR B	34	-1.51	-0.53	-0.01
	MR C	34	-2.30	-0.81	-0.13
	MS A	33	0.16	0.06	1.37
	MS B	33	-0.94	-0.34	0.89
	Average			**-0.47**	**0.41**

Degradation rates for all sites:



Average degradation rate for all modules determined by field regressions was +1.03%/year, and average degradation rate from spire flash data was -0.12%/year.

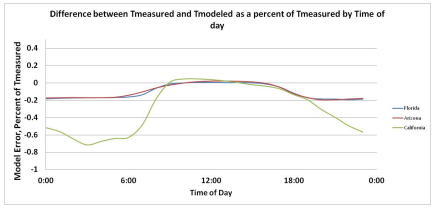
Temperature Model

Sandia Temperature model used as basis for our temperature regressions

$$T_{Module} = Irradiance * \left(e^{a+b*Windspeed}\right) + T_{Ambient}$$

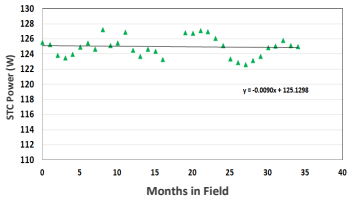
Temperatures model accurate during peak power producing hours:

California: -0.17C
Arizona: -0.16C
Florida: -0.46C



The percent difference between model temperature and measured temperature is very small during peak power producing hours (8am and 6pm). Model over predicts temperature at night as it does not account for irradiative losses.

Extracting Degradation Rates

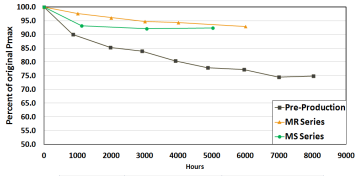


Module field performance was translated to Standard Test Conditions:

$$STC\ P_{Max} = P_{Max} * \left(\frac{1000\ W/m^2}{Irradiance}\right) * \left(1 + T_{Coef} * (25 - T_{measured})\right)$$

Degradation rates determined by linear regression of results, and compared to before and after Spire flash measurements

Accelerated Testing Performance and Outdoor Results



Average Degradation Rates	Degradation Rate per year from flash tests(%)	Degradation Rate per year from regression of field data (%):
Pre-Prodution	**-1.20**	**-0.86**
MR	**0.00**	**0.50**
MS	**-0.23**	**1.49**

Degradation rates improve from preproduction to MR and MS production modules

Similar improvements shown in Damp Heat 85C/85% relative humidity testing

Conclusion

- MiaSole CIGS modules were tested in multiple climates for several years
- Degradation rates determined by both flash testing and outdoor regression were low and in good agreement
- Improvements in degradation rates from pre-production modules also evident in long term Damp Heat results
- Temperature module confirmed accurate with long term outdoor data

Kristopher Toivola
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2015 NREL PV Reliability Workshop, 24-27 February 2015

Mitsui Chemicals Group

Encapsulant effect on PID durability of various crystalline PV cells

R. Tanaka & H. Zenkoh

Mitsui Chemicals Tohcello, Inc.

Motivation

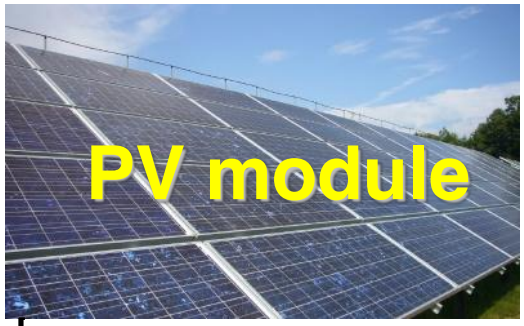
Mitsui Chemicals Group

- In PV modules, cross-linked EVA encapsulants are commonly used because of their transparency, thermal creep resistance and durability
- Mitsui Chemicals Tohcello (MCTI) is PV encapsulant manufacturer and has over 30 years history in this business
- For demand of the high reliability module in PV market, we have developed polyolefin encapsulant(POE)
- We performed DH, XWOM, PID tests compared them between MCTI-POE and other type encapsulants

Design concept of polyolefin encapsulant

Typical properties of encapsulant

Mitsui Chemicals Group



MCTI's POE is designed and developed to meet requirements for PV module encapsulant

Superior to EVA | Equivalent to EVA

Encapsulant properties

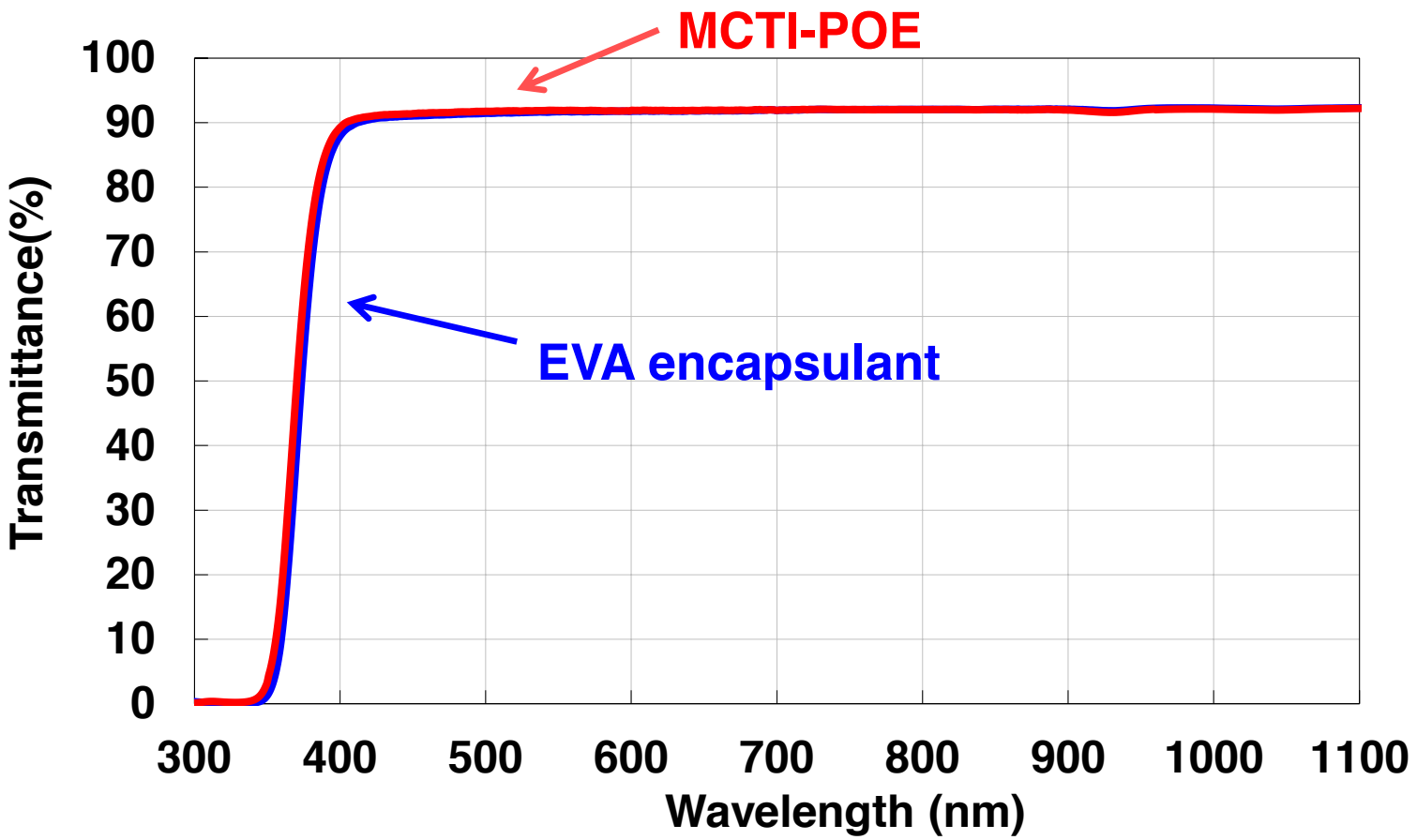
- Module efficiency
  - Transparency
- Long term durability
  - Cell crack → Low stiffness
  - Thermal stability → Cross linking
  - Discoloration → UV durability
  - Moisture corrosion → Adhesiveness, Low WVTR, Acid free
  - PID → High volume resistivity

Property table

Items		Unit	MCTI-POE	EVA encapsulant
Base polymer		-	Polyolefin	EVA
Thermo plastic or Cross-linked		-	Cross-linked	Cross-linked
Optical transmittance (400-1100nm)		%	92	92
Water absorption (23°Cx24hr)		%	≤ 0.01	0.1
Water vapor permeability (23°C/90%RH)		g·mm/m2/day	0.6	5
Volumetric Resistivity (23°C)		Ω·cm	≥ 1 x 10^{17}	≥ 1 x 10^{14}
Young's modulus		MPa	10	15
Adhesive strength to Glass	w/o Backsheet	N/cm	18	20
	with Backsheet	N/cm	≥ 100	≥ 100

Design concept of polyolefin encapsulant

Optical transmittance



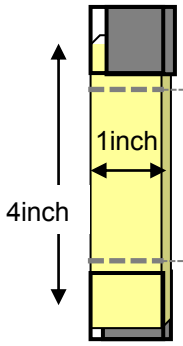
MCTI-POE and EVA encapsulant have the same optical property.

Thermal Stability

Mitsui Chemicals Group

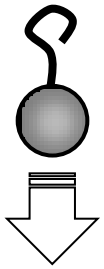
Elongation of encapsulant at 120°C

grade	type	elongation
MCTI-POE	Cross-linking	**0%** No creeping
EVA encapsulant	Cross-linking	**0%** No creeping
Conventional POE	Thermo plastic	**>200%** creeping



Elongation

$$= \frac{\text{Distance C after 120°C x 1hr}}{\text{Original distance C}}$$

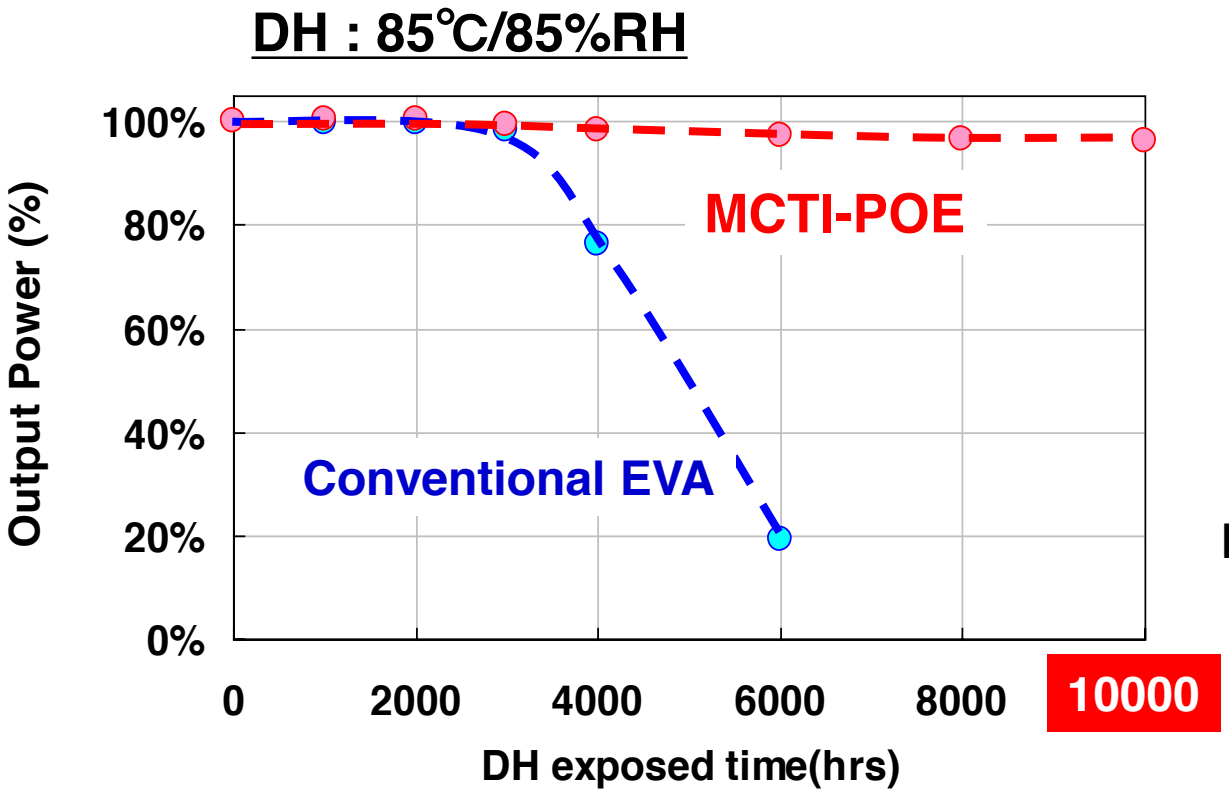


3000 Pa x 120°C x 1hr

* 3000Pa is about 30 times stress compared to actual module stress.

- **Cross-linked MCTI-POE and EVA is thermally stable even at 120℃.**
- **In case of thermo plastic type, significant creeping is observed.**

DH durability with polyolefin encapsulant

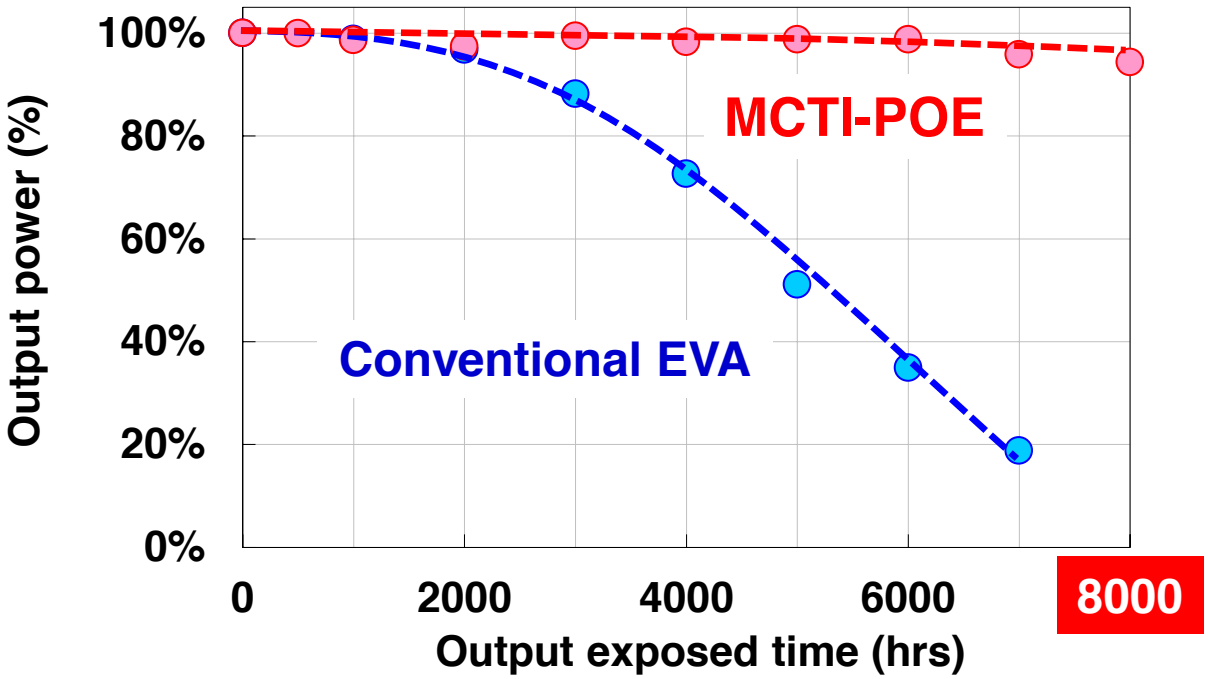


Multi-crystalline module
(18cells,250mm x 300mm)

- **MCTI-POE, which is acid-free, does not cause the corrosion.**
- **Power loss of module is less than 5% even after DH10000hrs.**

XWOM durability of module

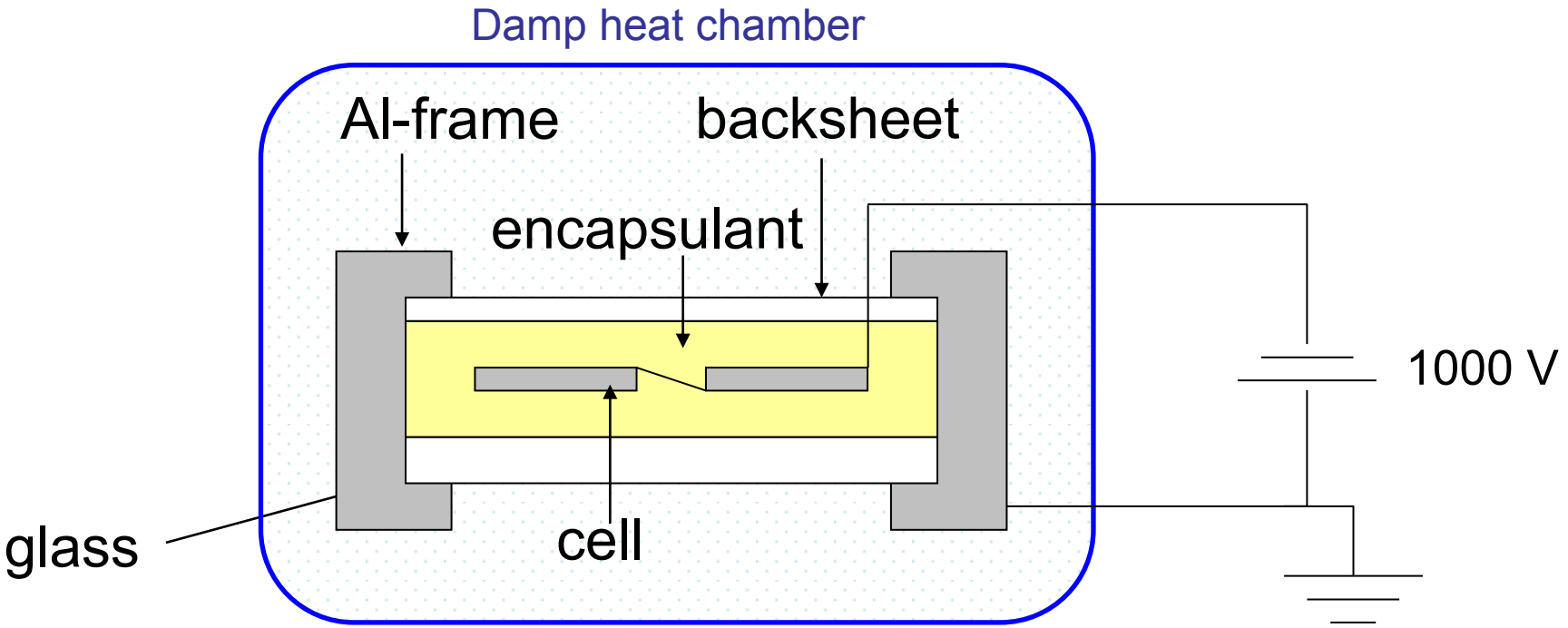
XWOM, 3SUN(180W/m2@300-400nm) B.P.T 110°C



Multi-crystalline module
(18cells,250mm x 300mm)

- **MCTI-POE, which is acid-free, does not cause the corrosion.**
- **Power loss of module is less than 5% even after XWOM8000hrs.**

PID acceleration tests method



Test conditions

Cell :single cell or full module

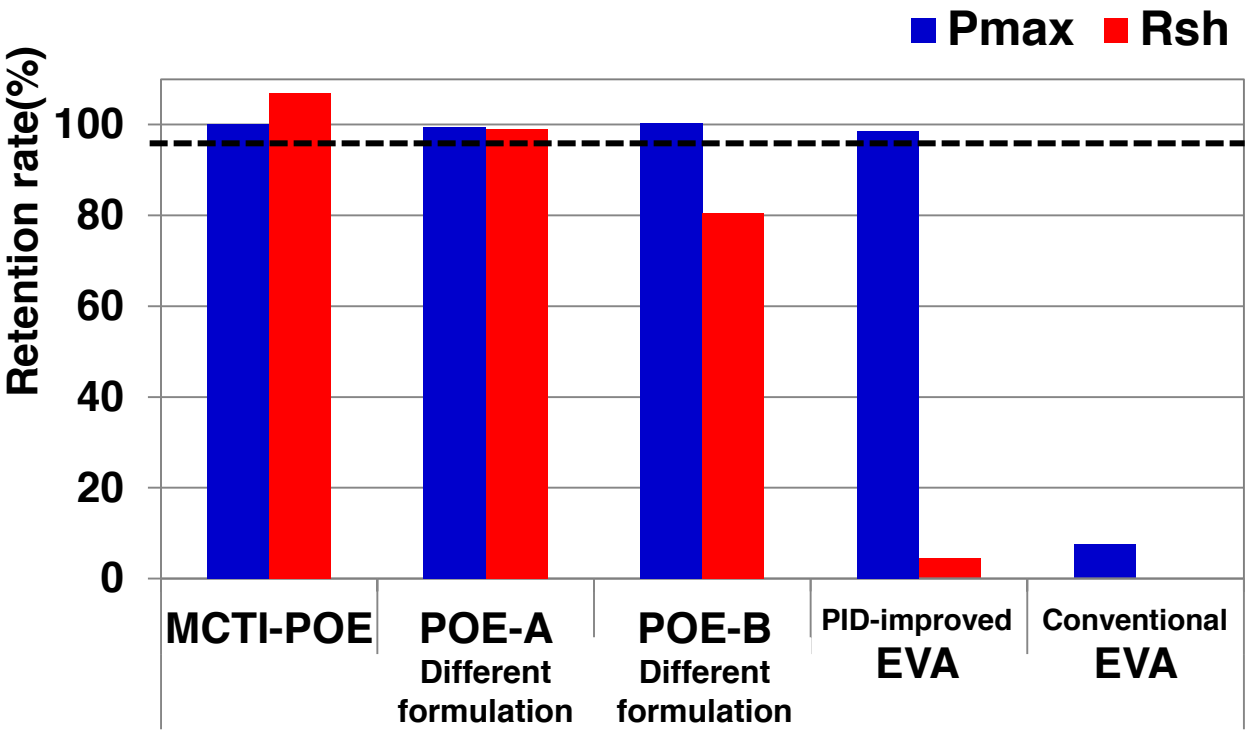
Exposure time : 96h - 240hr

Voltage : -600V or -1000V

Temp. : 60^0C85% or 85^0C85%

Module durability

PID durability with "P type PID-durable" cell



95%

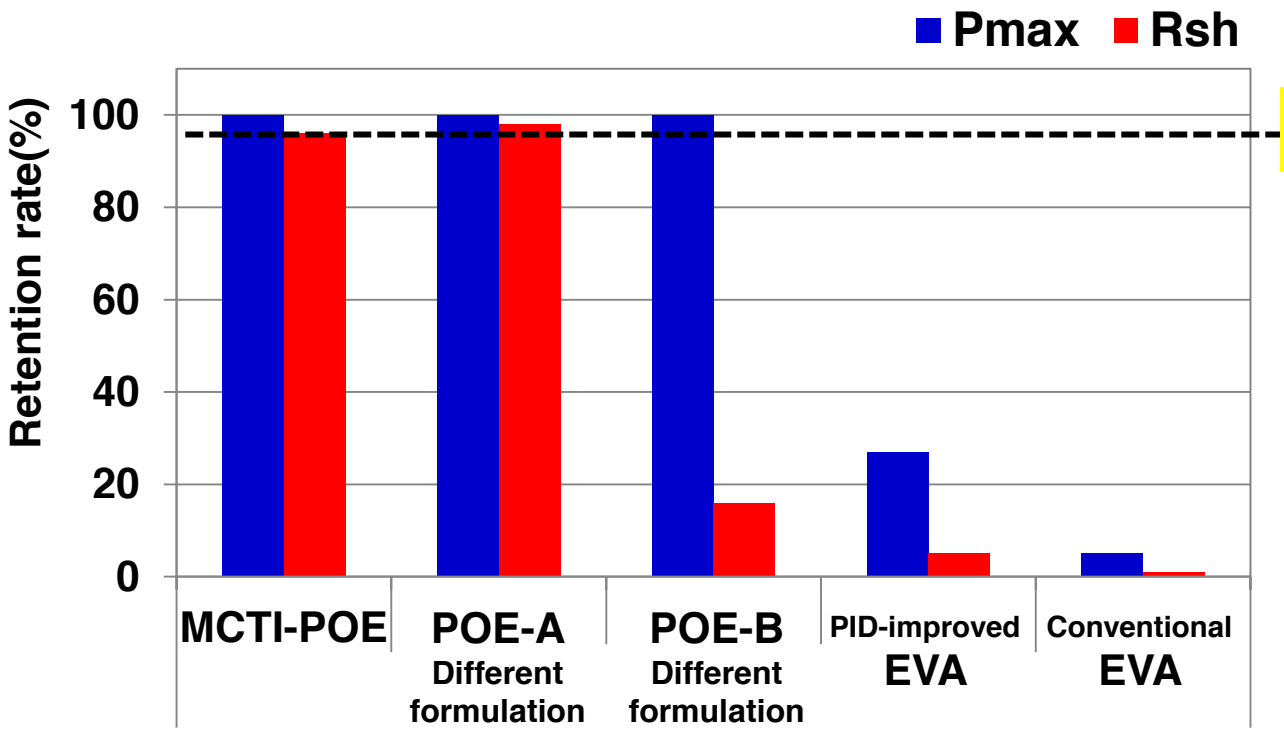
Test condition

- evaluated by third-party
- 60°C85%RH, Water covered, -1000V, 96hr
- 4cells (2x2cells)
- **PID-durable cell**

- **PID-improved EVA can be improved PID durability and keep the initial level of Pmax.**
  But Rsh is decreased, which represent the beginning of PID phenomena.
- **MCTI-POE shows no degradation on both Pmax and Rsh.**

Module durability

PID durability with "P type PID-sensitive" cell



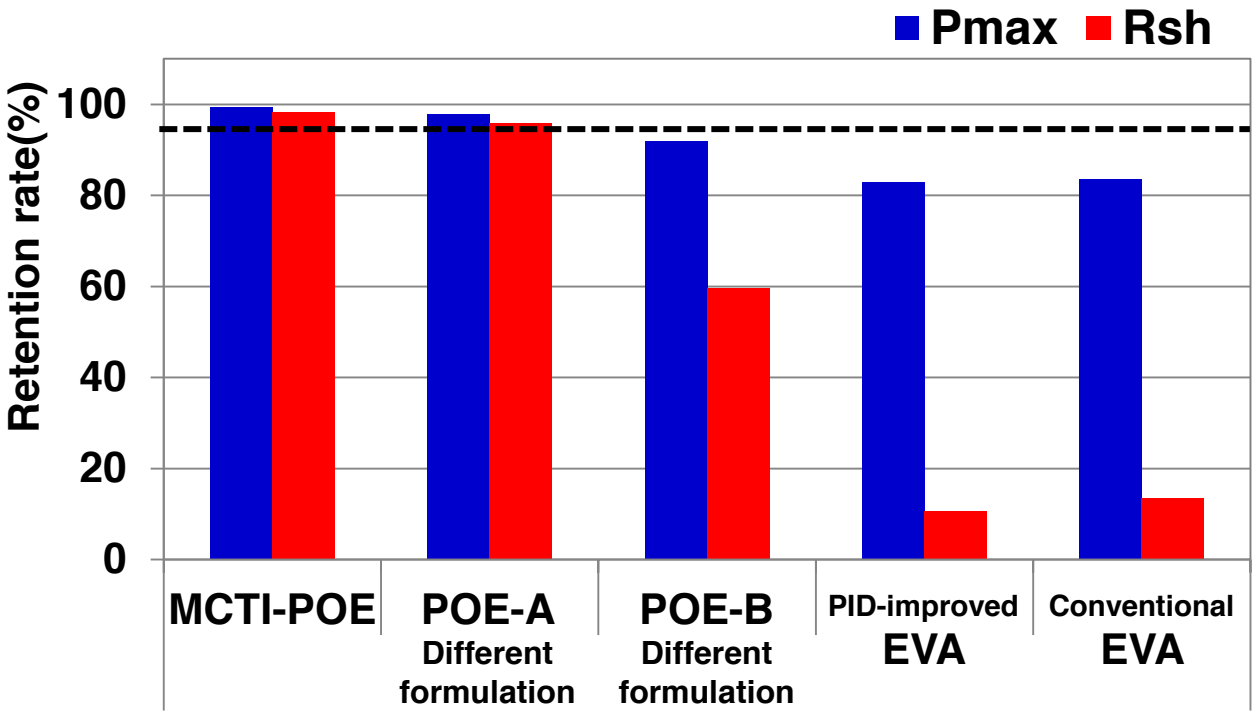
Test condition

- 85°C85%RH, -1000V, 24hr
- 1cells
- PID-sensitive cell

- PID-improved EVA occur power loss in severe PID test condition.
- POE keeps initial output power even if using PID-sensitive cell.

Module durability

PID durability with "N type" cell



95%

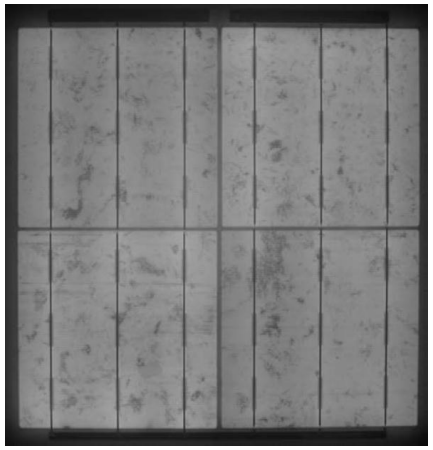
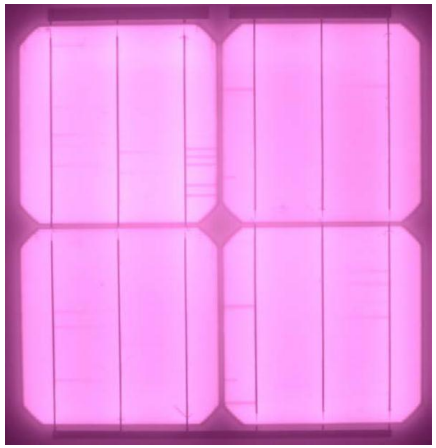
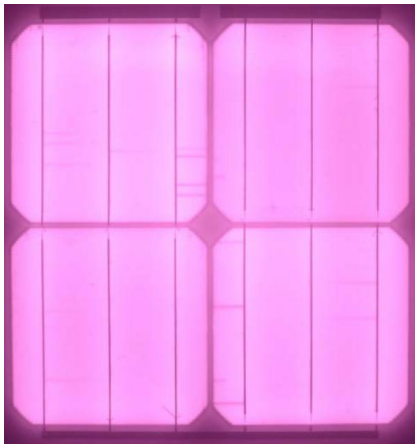
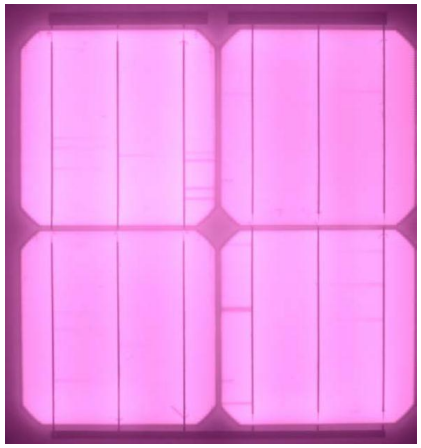
Test condition

- evaluated by third-party
- 60°C85%RH, Water covered, -1000V, 96hr
- 4cells (2x2cells)

- **PID-improved EVA can NOT keep initial level of Pmax.**
- **MCTI-POE shows no degradation on both Pmax and Rsh. But POE-B occur power loss.**
- **PID powerloss is observed on POE-B module.**

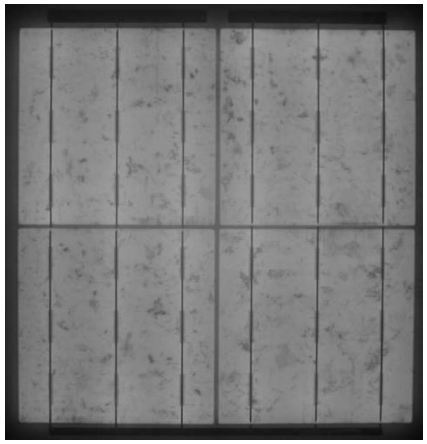
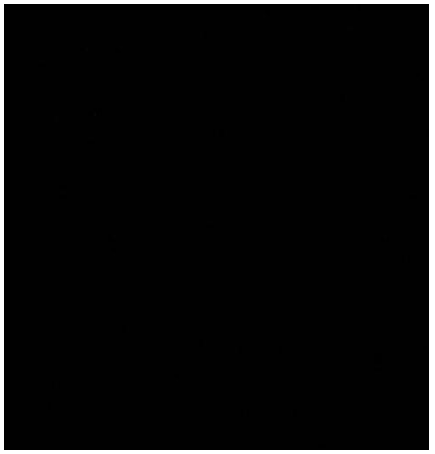
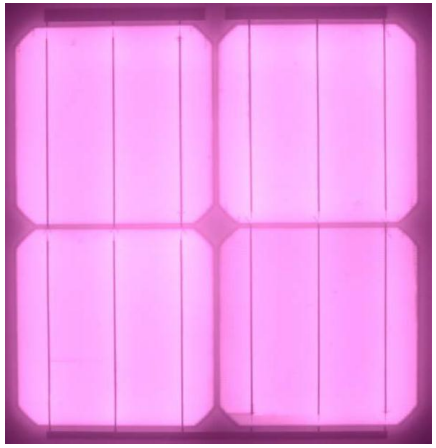
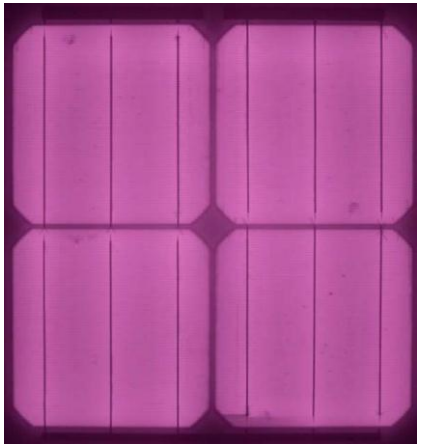
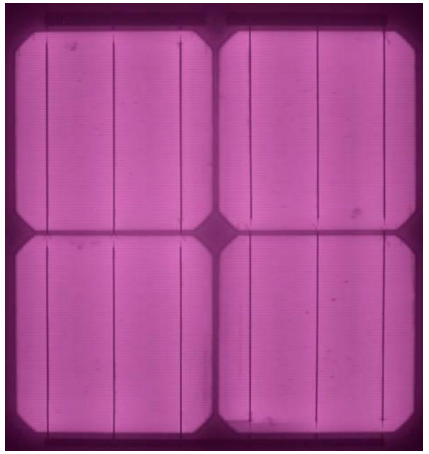
PID EL-image of “MCTI-POE”

Mitsui Chemicals Group

	0hr	24hr	96hr
P type PID-sensitive			
N type			

PID EL-image of “Conventional EVA”

Mitsui Chemicals Group

	0hr	24hr	96hr
P type PID-sensitive			
N type			

Summary

- **Durability of PV modules laminated with POE and EVA encapsulants were compared**

- **MCTI-POE , which is cross-linking polyolefin, shows excellent reliability on the all tests**

- **MCTI-POE can pass PID tests in both P type" and "N type" cell.**

  ***We continue to investigate the root cause of N-type cell's PID phenomena**

- **We have already started mass production of the cross-linking polyolefin encapsulant named "SOLAR ASCE™".**

Influences of lamination conditions on device durability for EVA-encapsulated PV modules

Jiang Zhu*, Dan Wu, Daniel Montiel-Chicharro, Michael Owen-Bellini, Tom Betts, Ralph Gottschalg

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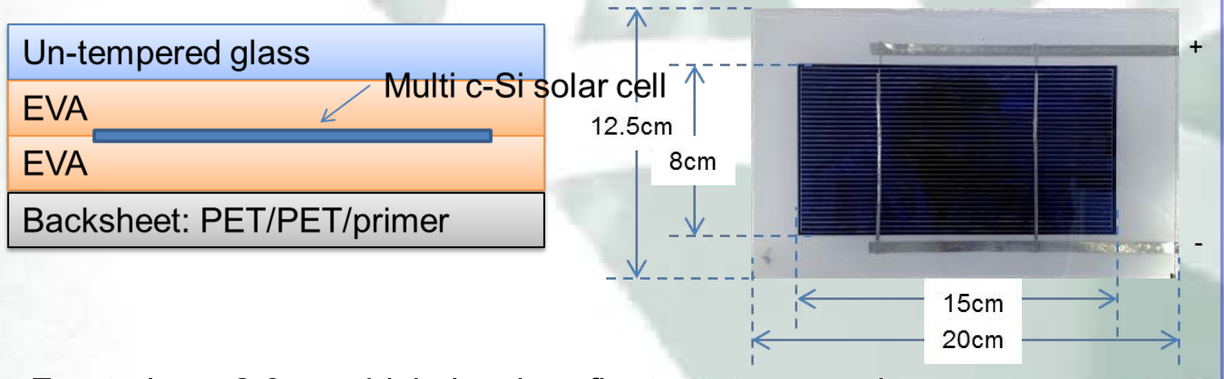
1 Abstract

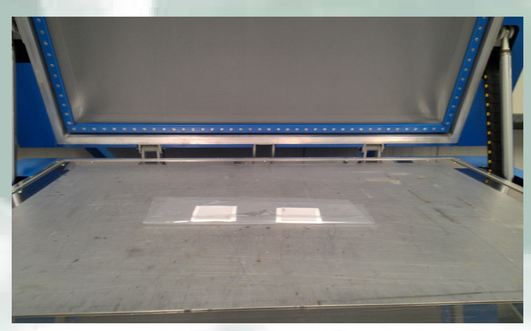
PV modules rely on their encapsulation to provide durability. The pottant, in the majority of cases this is EVA, is protected by foils and glass to minimise encapsulant related degradations. This paper investigates the effect of lamination temperature on encapsulation quality and its impact on module durability in accelerated ageing tests. A safety temperature margin is observed for each type of EVA used. Lamination temperature outside this margin may cause changes in chemical reaction rates and alterations of phase transition of polymers. This will then influence the chemical, mechanical, and optical properties of the encapsulation materials and affect the performance and durability of PV modules.

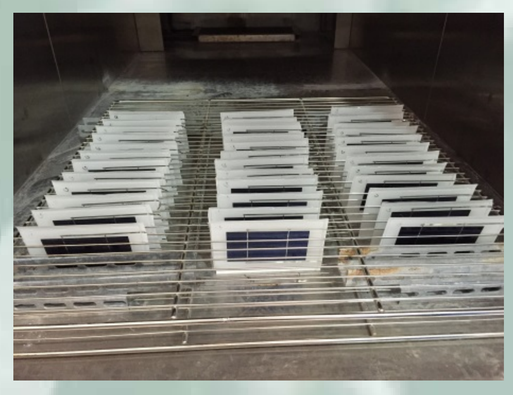
2 Mini-module Structure and Materials



- Front glass: 2.9mm thick, low iron float, un-tempered
- Encapsulant: 600μm thick, fast cure and ultra-fast cure EVA
- Backsheet: tri-layer insulating polymer consisting PET/PET/primer layer
- Cell: 1.8W multi c-Si cells

3 Lamination and Ageing

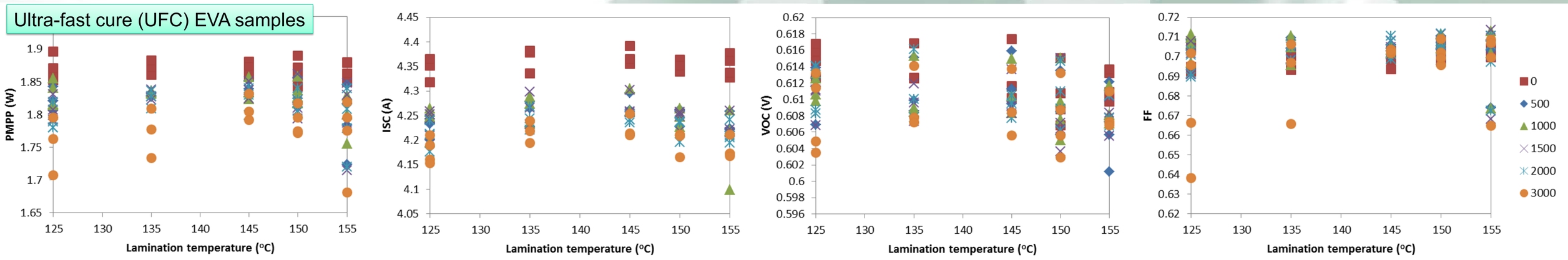




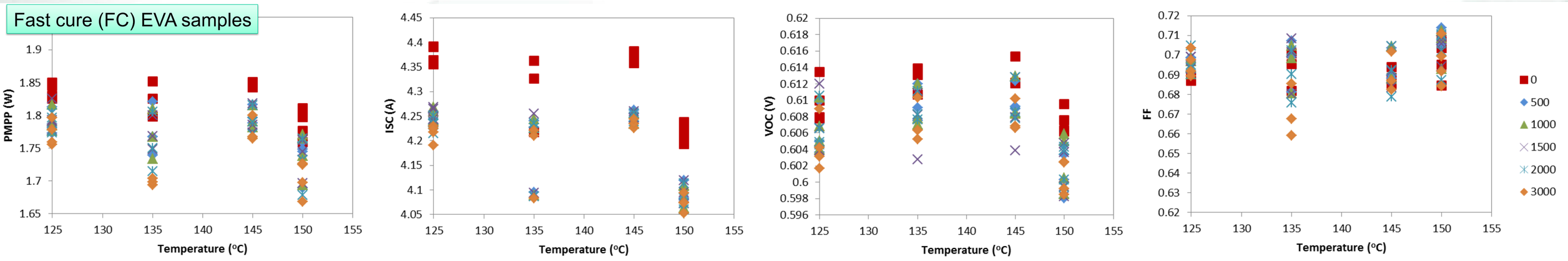
- Curing temperature
  - 125ºC, 135ºC, 145ºC, 150ºC and 155ºC
- Curing time
  - 10min (fast cure EVA), 7min (ultra-fast cure EVA)
- Damp-heat test at 85ºC and 85% R.H.

4 Ageing of P_{MPP}, I_{SC}, V_{OC} and FF over 3000 Hours

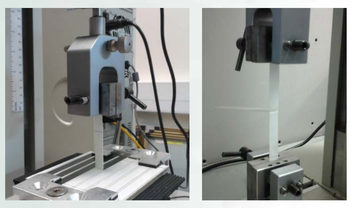
Ultra-fast cure (UFC) EVA samples

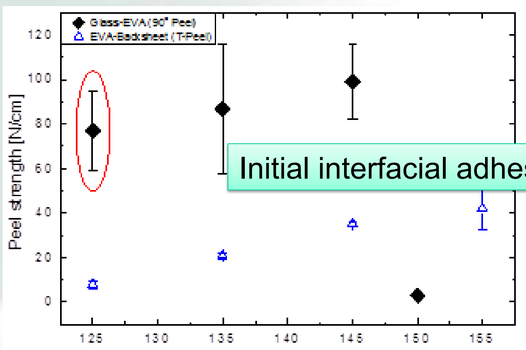


Fast cure (FC) EVA samples

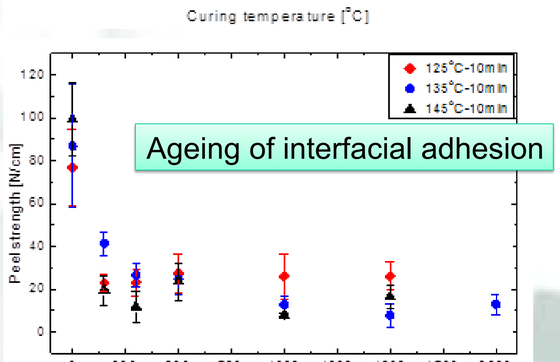


5 Ageing of Interfacial Adhesion and Bulk EVA

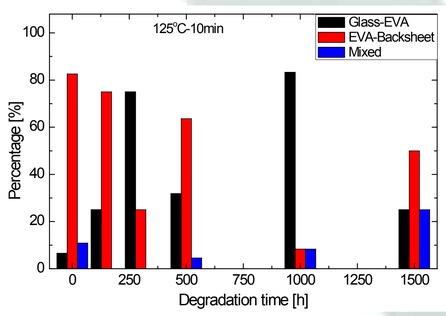




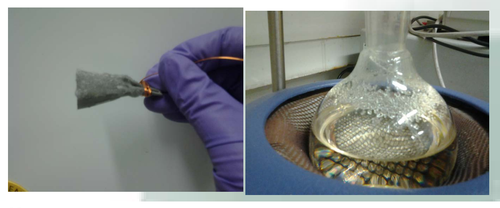
Initial interfacial adhesion

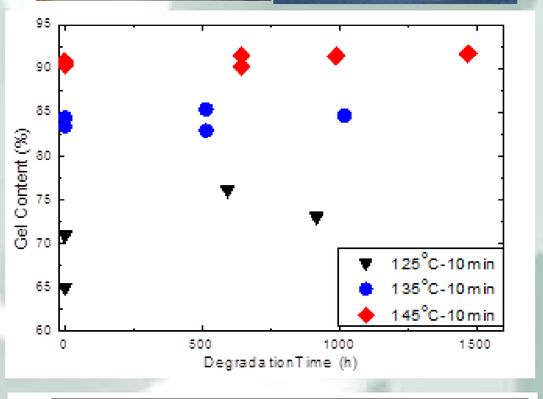


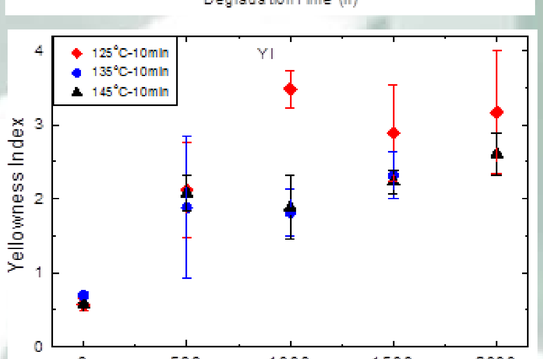
Ageing of interfacial adhesion



Change of failed interface







6 Conclusions

- Mini-modules with UFC EVA showed clear safety margin of lamination temperature (145ºC-150ºC), where lower and higher lamination temperatures led to bigger P_{MPP} degradations
- Mainly contributed by I_{SC} losses, which favours 145ºC
- V_{OC} degradation favours 135ºC
- FF stable except some samples outside safety margin
- Mini-modules with FC EVA showed bigger P_{MPP} degradation at 135ºC and 150ºC
- Mainly contributed by I_{SC} losses, but 135ºC saw bigger losses in FF
- V_{OC} degradation favours 135ºC
- Higher interfacial adhesion at 145ºC before ageing, but higher at 125ºC after DH ageing
- Glass/EVA interfacial failure dominated at 135ºC, while 125ºC and 145ºC saw mixed failures at glass/EVA and EVA/backsheet
- Gel content stable over DH ageing
- Optical losses happened largely in first 1000h

CREST

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Loughborough University

Processing and Device Oriented Approach to CIGS Module Reliability

Kannan Ramanathan
and Rebekah Garris
NREL

Proposal:

- Process and Performance driven R&D should be integrated with Reliability
- Device level changes are a big part of module reliability. Greater attention to device issues at the process stage is needed and can only help the big picture.

Status/ Gaps:

- Device fabrication and understanding is now more mature than a decade ago.
- Many reported effects such as metastability can be understood and described by models.
- Lab and industry devices are reaching same level performance in spite of vastly different processing approaches.
- Lab – industry cooperation is now stronger (F-PACE).
- Cell level stability has been neglected. This is a good time to pick up the pace.

Impact:

- It is possible the drivers of cell and module performance also drive stability.
- Examples provided here illustrate the ability of scientists in Lab and academia to solve industry issues.
- Continued cooperation can provide clarity to seemingly complex issues.
- Assurance of reliability is necessary to gain consumer acceptance.

Past collaboration with Shell Solar, Thin Film Partnership, 1998-2003:

SSI approaches National Team with "transient effect" problem.

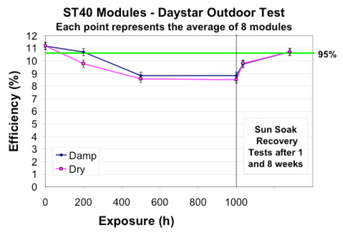
Change under light soaking was a problem for testing and certification, not a performance issue.

Wanted to understand root cause.

Accelerated Test Results

Problem statement

- "Degradation" is due to dark heat, not humidity ingress.
- Thermal effects are reversible transients.
- Losses due to dark heat exposure may not reflect real world effects.



Shell Solar

NREL – Shell Solar Interleaving Study, 1998-2001

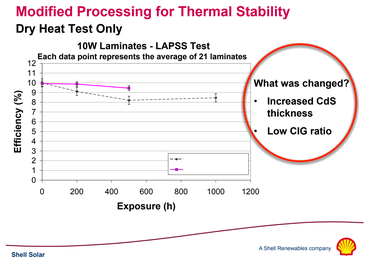
	# of samples													
SSI absorbers	Patterned	Unpatterned	SSI CdS	SSI ZnO, P3 & Meas.	SSI ships to NREL	NREL CdS	NREL Std. ZnO	NREL Thin ZnO	NREL ships to SSI	SSI CdS	SSI ZnO	SSI P3 & Meas.	SSI ships to NREL	NREL grids & Meas.
SSI Baseline	9		X	X										
		2	X	X	X									X
SSI Baseline, Held at SSI	9									X	X	X		
Traveling SSI Baseline	9				X	***	***		X	X	X	X		
NREL Baseline CdS & ZnO	5				X	X	X		X			X		
		2			X	X	X							X
Exp. 1, NREL CdS / SSI ZnO	5				X	X			X		X	X		
		2			X	X			X		X		X	X
Exp. 2 NREL CdS & thin ZnO / SSI ZnO	5				X	X		X	X		X	X		
		2			X	X		X	X		X		X	X

Problem mitigation

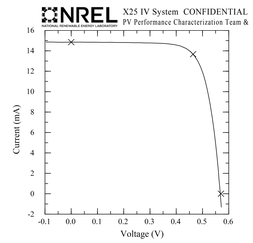
NREL process interleaving work was done on 10x10 cm mini-circuits and small area devices. Special substrates were provided by SSI.

NREL process: thicker CdS, different recipe. Led to higher V_{oc}

Led to process change and improved stability (2003)

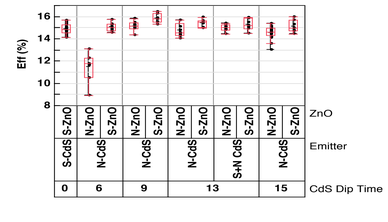


Similar work for Stion (F-PACE) shows performance gain



Industry baseline CdS cell: 15%

NREL begins study of CdS interface.

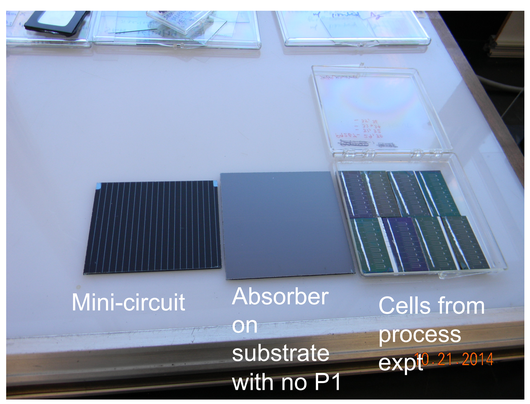


Experiments showed 1% (abs) efficiency improvement. Led to pilot and full scale experiments. Factory process modified. Current product has higher voltage, more power.

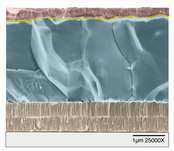
Device level studies: necessary complement to module reliability:

Small area devices enable a host of device characterizations not possible in modules.

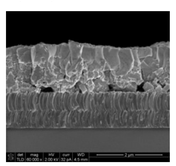
Small area device capability enables testing and validation of process modifications.



Process to Measurements to Root Cause Identification: Methodology to sort out observed effects



Best known CIGS device (lab)



CIGS device by different process, different cell design

- Initial device characterization
- Decide test/ stress to answer specific question
- Decide relevant packaging
- Conduct tests

- What effects are inherent to CIGS?
- What effects are due to specific process/ device design?
- What process change is needed and why?

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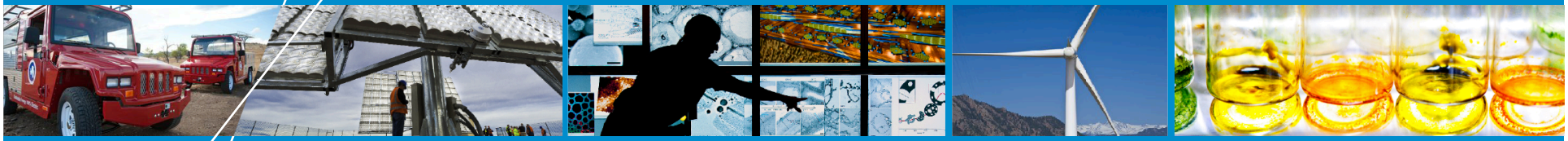
Overview of PVQAT: Update and Perspectives



Sarah Kurtz, John Wohlgemuth,
Masaaki Yamamichi, Tony Sample,
George Kelly, Govind Ramu

PV Solar Resource Workshop

February 25, 2015

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.

Outline

- **PVQAT: International PV Quality Assurance Task Force – historical perspective**
- **Projects**
  - Climate-specific (use-environment-specific) durability testing
  - Consistency of manufacturing
  - System verification
- **IECRE vs PVQAT; How to become involved**
- **Current status and multiyear targets**
- **Goals for today**

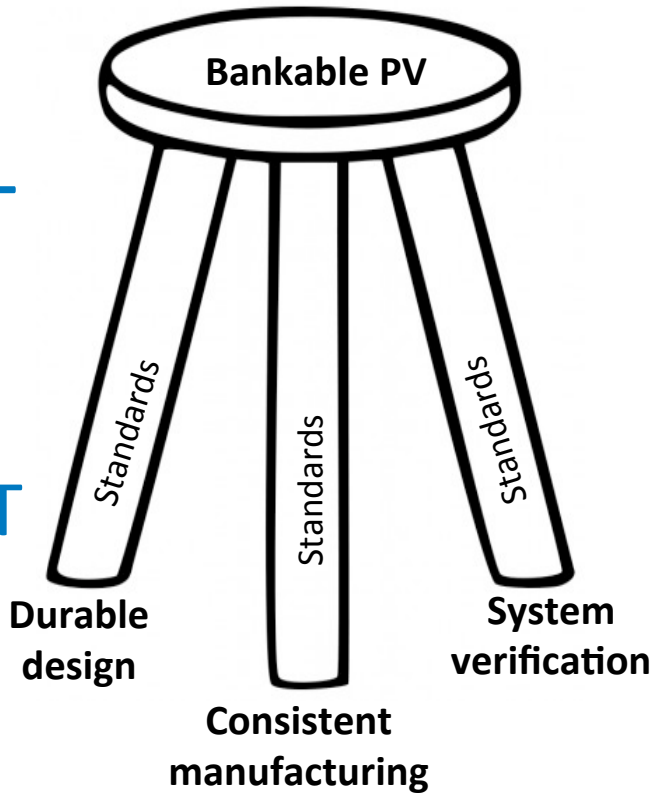
PVQAT History

- In 2010, when METI was preparing to launch a new incentive program, METI asked DOE to work together to improve PV reliability
- AIST and NREL were asked to organize international effort
- First international meeting was held in 2011

- PVQAT = International PV Quality Assurance Task Force

Outline

- PVQAT: International PV Quality Assurance Task Force
- **Projects**
  1. **Climate-specific (use environment-specific) durability testing**
  2. **Consistency of manufacturing**
  3. **System verification**
- How to become involved in PVQAT
- Current status and multiyear targets
- Goals for today



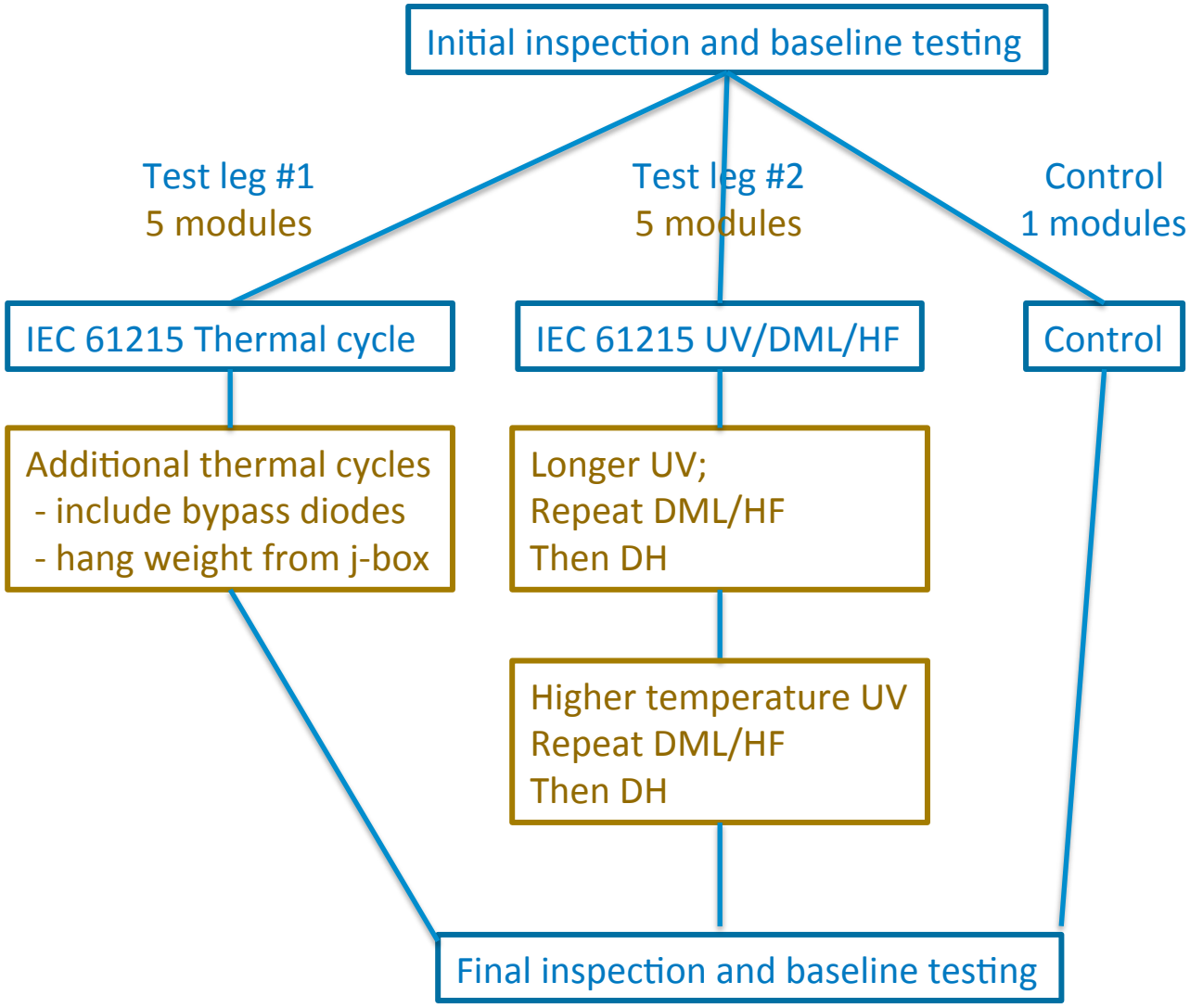
1. Climate-specific durability testing

- **Does IEC 61215 test adequately for all use environments? What are the gaps?**
- **Failure mechanisms missed by IEC 61215**
  - Potential-induced degradation
  - Cracked cells
- **Wear-out mechanisms**
- **Use-environment-specific issues**
  - Desert climate (high temperature)
  - Tropical climate (heat and humidity)
  - Close-roof mounting (high temperature)

1. Status of climate-specific test

- **IEC 62892-1 "Testing of PV Modules to Differentiate Performance in Multiple Climates and Applications – Part 1 Requirements for Testing" submitted to IEC as a Committee Draft**
- **Feedback:**
  - Should be "climate-specific" *not* "comparative"
  - Should be designed to be implemented as a follow up to IEC 61215 for easy implementation
- **Still many details to be defined – will be subject of Break out session #2 today**

1. Proposed climate-specific test – revised to feedback



Materials

Longer UV for discoloration (not mechanical properties that require full module)

Discussion:
Break out #2 today

2. Consistency of manufacturing - status

- **PV-specific version of ISO 9001 has been proposed to IEC**
- **Feedback: Consistent implementation will be a challenge**
  - Training of auditors
  - Some recommend providing a check list
- **Draft technical specification (DTS) may be submitted to IEC in April; published late '15**
- **Today discuss in Break out #1:**
  - Remaining questions for DTS
  - Next steps

Discussion:
Break out #1 today

3. System Verification

- **Confidence in system requires oversight:**
  - Design
  - Installation
  - Operation
- **Status**
  - IECRE formed as means for implementation
  - National committees are being formed
  - Rules are being written
- **Tomorrow's workshop is dedicated to this**

IEC and PVQAT

- **IEC International Electrotechnical Commission**
  - Primary PV international standards organization
  - Formal organization relies on volunteers nominated through formal national committees (providing necessary structure for standards development)
- **PVQAT**
  - Supports IEC
  - Informal organization – anyone can volunteer
  - Brings more energy to research and writing efforts so standards writing can progress more quickly
- **Joint efforts are effective when well coordinated**

How to become involved in PVQAT

- Most PVQAT meetings are teleconferences, so it's easy to participate, especially if you don't mind the strange hours!
- Identify which task group interests you: www.pvqat.org (or www.pvqat.com for Chinese)
- Contact appropriate task group leader
- Request access to wiki at http://pvqataskforceqarating.pbworks.com/w/page/42004200/FrontPage or email sarah.kurtz@nrel.gov

International PV Module Quality Assurance Task Force

PVQAT Multiyear Goals

	IEC Qualification	1. Climate (use)-specific Durability Test	2. Consistent manufacturing	3. IECRE System Verification	Service Life Prediction
2013 status	Issued as standards	Concepts proposed	Initial draft	IECRE proposed	Concepts
2014 status	Submitted Ed 3 61215 Ed 2 61730	Research to understand technical issues	Revised draft submitted	Created System, REMC, and basic rules	Suggest implementation through QMS
2015 goal	Publish new editions; submit amendments	Submit initial drafts for all test legs	**Publish specification; Start use**	Complete formation of National committees, definition of scope and rules of procedure.	Initial proposal
2016 goal		Revised drafts of all test legs	Revision to reflect feedback	Published procedures; **issue first certificates**	Revised proposal

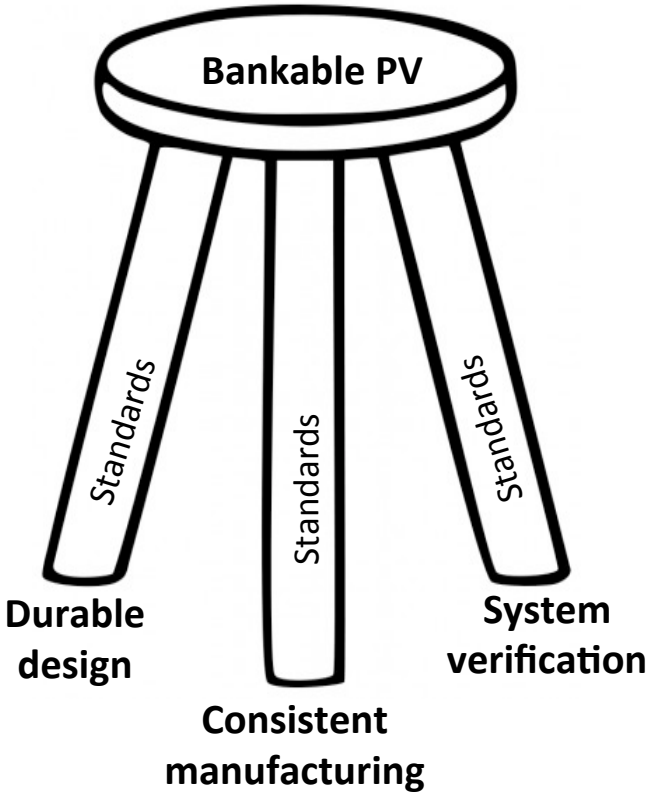
Goals for today

- **Morning sessions will give background**
- **Break out #1: PV-specific version of ISO 9001**
  - Discuss what is needed for consistent implementation (Training? Checklist?)
  - See background information distributed by email on Saturday, Feb. 21
- **Break out #2: Climate (use) specific test**
  - Discuss sequential approach to implementation
  - Discuss multiple questions

Conclusions

- **PVQAT is working to empower IEC to improve PV standards**
- **Three primary projects:**
  1. Climate-specific (use environment-specific) durability testing
  2. Consistency of manufacturing
  3. System verification
- **We welcome your participation toda an i the future!**

www.pvqat.org



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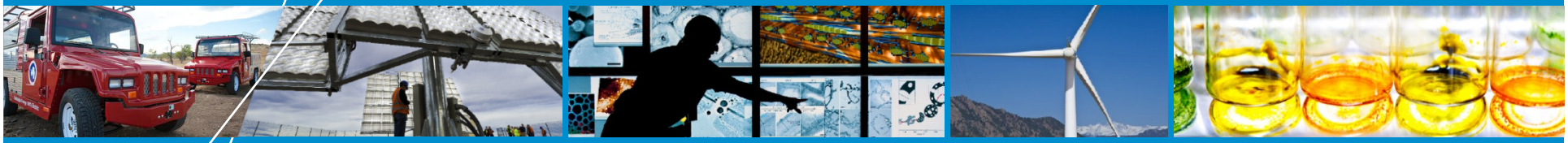
Sarah.Kurtz@nrel.gov



Thank you to the dozens who have been regularly contributing to this work!

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Overview of IEC TS 62941 Guideline for Manufacturing Quality Assurance

Govind Ramu, SunPower Corp.| February 25, 2015

2015 International PV Quality Assurance Task Force (PVQAT) Workshop

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- PV QMS Standard timeline
- PV QMS Requirements –
  - Brief review of key requirements Vs ISO 9001
- PV QMS- Future possibilities
- Appendix

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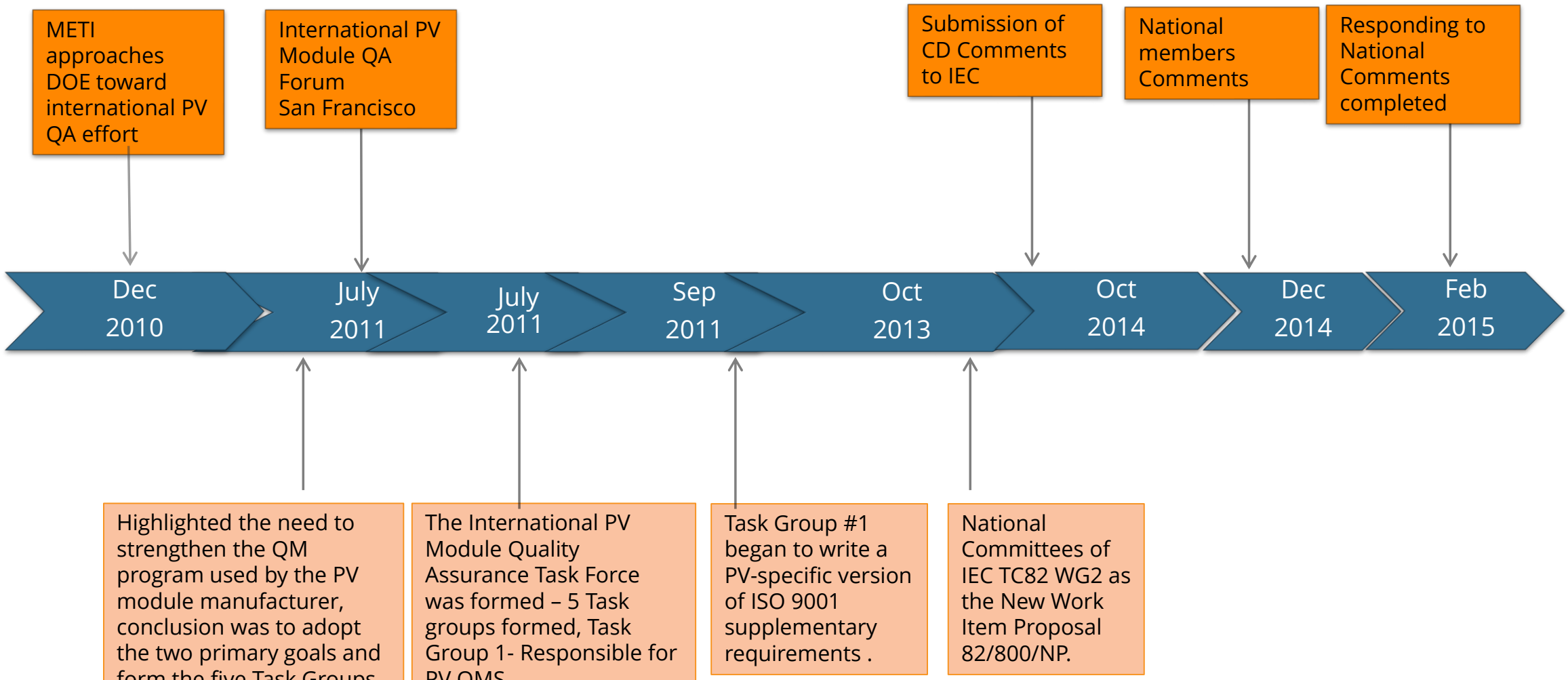
PV QMS Standard Development Timeline '



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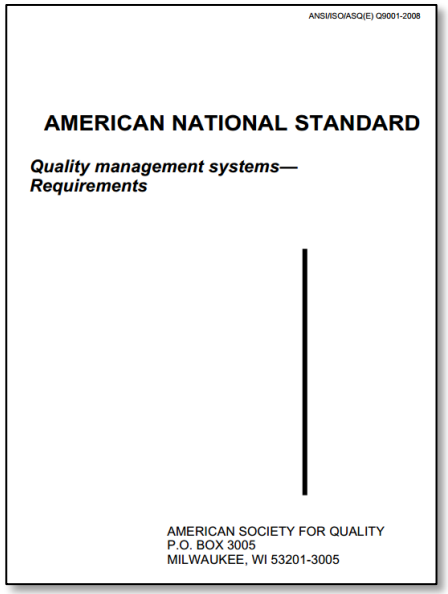
ISO 9001



ANSI/ISO/ASQ(E) Q9001-2008

AMERICAN NATIONAL STANDARD

Quality management systems—Requirements

AMERICAN SOCIETY FOR QUALITY
P.O. BOX 3005
MILWAUKEE, WI 53201-3005

IEC TS 62941

82/875/CD

COMMITTEE DRAFT (CD)

IEC/TC or SC: TC82	Project number IEC 62941 TS Ed.1	
Title of TC/SC: Solar photovoltaic energy systems	Date of circulation **2014-07-25**	Closing date for comments **2014-10-31**
Also of interest to the following committees	Supersedes document 82/800/NP, 82/857/RVN	

Proposed horizontal standard
☐ Other TC/SCs are requested to indicate their interest, if any, in this CD to the TC/SC secretary

Functions concerned:
☐ Safety ☐ EMC ☐ Environment ☒ Quality assurance

Secretary:
G. Kelly - USA

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Title:
IEC 62941 TS:
Guideline for increased confidence in PV module design qualification and type approval

(Titre) :

Introductory note

This document is based on extensive preparatory work by Task Group 1 of the International PV Quality Assurance Task Force (PVQAT). Comments submitted in response to 82/800/NP (see 82/857/RVN) have all been considered and incorporated into this draft. This draft was also presented and reviewed at the WG 2 meeting in Busan, Korea, on 16-18 June 2014.

Establishment of consensus for this document is very important, as it is expected to become the basis for future conformity assessment activities under the IECRE system. National committees are requested to review the draft carefully and provide comments to be addressed during the preparation of the subsequent DTS (final voting stage).

Supplementary requirements to ISO 9001:2008

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PV QMS Key Requirements '

- PV module's design to align the expected lifetime
- Product realization that includes appropriate certification, qualification, including both type approval and safety testing
- Product traceability through the entire supply and delivery chain
- Ongoing, periodic monitoring program to ensure consistency of aspects of manufacturing
- Special Process controls
- Power rating tolerance
- Resource Management
- Closed loop learning from field information
- Supplier Management
- Manufacturing and testing
- Process auditing
- Use Statistical methods, sampling

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PV QMS Requirement – Design Controls '

- Focus on the organization's control of the PV module's design to align the expected lifetime with its relationship to the organization's warranty
- Controls:
  - Design related records retention policy to support warranty serving
  - Design Failure Mode Effects Analysis (FMEA)
  - Reliability testing, periodic testing, Long term outdoor testing, etc.
  - Lessons learned from previous designs (Closed loop learning)
  - Customer communication- Application notes detailing specific attention and/or care needed

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PV QMS Requirements – Process Controls '

- Use of appropriate statistical tools and statistically significant sample sizes to make decisions that affect quality of process and products at all stages of the lifecycle
- Use of appropriate quality engineering tools to build PV modules with consistent quality and reliability
- Controls:
  - Measurement System Analysis (MSA) e.g. Gauge Repeatability & Reproducibility (GR &R) and more
  - Process FMEA
  - Poke Yoke (error proofing)
  - Control Plan
  - Statistical Process Control (SPC)
  - 8D methodology for problem solving

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PV QMS – Special Processes '

- Control of Special Processes* (e.g. soldering, lamination)
- Control of processes for ESD protection
- ESD- Electrostatic Discharge (ESD) safe environment at the raw material storage, processing, assembly areas, as appropriate
- Controls:
  - Process qualification, critical controls identification, operator qualifications
  - Software validation
  - ESD Program audit
  - Certification and periodic recertification process for qualified personnel

- *”Where the resulting output cannot be verified by subsequent monitoring or measurement and, as a consequence, deficiencies become apparent only after the product is in use or the service has been delivered” – ISO 9001:2008.

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PV QMS Requirements – Supplier Controls '

- Receiving inspection and/or testing such as statistical sampling based on performance.
- Supplier notify and seek approval when there is any change of products, process, manufacturing location or significant process excursion that may affect form, fit, function, reliability or performance
- Controls:
  - Periodic supplier audits
  - Performance monitoring
  - Traceability requirements
  - Process Change management

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PV QMS Requirements - Reliability '

- An ongoing, periodic monitoring program to ensure consistency of aspects of manufacturing that may affect safety, performance, and reliability
- Controls:
  - Reliability test plan
  - Design and development change control
  - Supplier material change control
  - Control Plan (Manufacturing impact on reliability)
  - Statistically adequate sampling plan
  - Reliability Monitoring Program (RMP)

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PV QMS Requirements - Traceability '

- Requirement to improve product traceability through the entire supply and delivery chain to enact positive control of the product for recalls and warranty claims
- Controls:
  - Traceability to requirements arising from all previous failure information, customer complaints, competitive analysis, supplier feedback
  - Traceability to design and development changes
  - Traceability at supplier's end for changes made
  - constituent key materials and components
  - lot/batch level
  - Traceable to supplier, date, Mfg. location
  - Traceable to Internal processes, process conditions, equipment
  - Traceable to operators (manual processes)
  - Reworked/repaired products
  - Product traceability information outside of packaging

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PV QMS – Resource Management '

- Resources needed to maintain the product warranty system, product reliability measurements, provision of after-sales service
- Succession planning for key functions that affect customer, quality reliability, safety and performance
- Controls:
  - Product warranty database management system
  - Technical support resources
  - Succession planning, periodic review

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PV QMS Requirements - Certification '

- A product realization that includes appropriate certification (e.g. IEC qualification, including both type approval and safety testing), a design lifetime that enables alignment with warranty
- Controls:
  - Design FMEA/ Risk assessment
  - Internal/external qualifications
  - External Certification (e.g. IEC/TS 62915)
  - Design Changes that may require certification/recertification
  - Any applicable supplier certifications
  - Reference modules certified/traceable to recognized certification body
  - Warranty modeling
  - Customer return Failure Analysis

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PV QMS Requirements – Manufacturing and Testing '

- Manufacturing feasibility at the necessary scale, including risk analysis during contract review
- Out of control process- containment of product and 100% inspection (as appropriate)
- Tests performed on 100% of the products for validation of performance and safety
- Control plan for solar simulators and how they are used in the performance rating of modules
- Controls:
  - Process FMEA
  - Control Plan
  - Measurement System Analysis – uncertainty calculations

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PV QMS Requirements - Inputs

- Information incorporated into the requirements of the QMS
- Inputs:
  - Previous failure information database management
  - Customer complaints
  - Competitive analysis
  - Supplier feedback
  - Closed loop learning

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PV QMS – Power Rating '

- Assignment of PV module power rating with allowed tolerance including measurement uncertainty
- Controls:
  - Nameplate power of a module with an allowed tolerance at standard test condition
  - Statement of the tolerance of power measurement in the label of the produced module-IEC61215, IEC61646 , or IEC 62108
  - Communication with customer – Power Warranty
  - Control program IEC 60891 and IEC 60904 – Power measurement
  - Determine parameter sets for the acceptance tolerance
  - Determine measurement uncertainty

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PV QMS future Possibilities (Brainstorm ideas) '

- Expansion of IEC 62941 audit checklist by asking more rigorous questions (e.g. Special processes)
- PV design, manufacturing and service metrics periodic submission to a vetted third party for analysis and publication of Best in class, top decile, median values (with anonymity- double blind process) for industry benchmarking
- PV QMS extended to suppliers of “key materials” (Similar to PPAP from Automotive industry)
- PV QMS transition to PV IMS “Integrated Management system” to include Environmental, occupation health and safety requirements for PV manufacturing
- Graded approach to PV QMS audit outcome based on maturity levels. Audits go beyond compliance
- Exchange of epidemic failure information by PV technology
- Benchmark QMS practices with other well established industry sectors (e.g. Automotive, Telecom, Aerospace)

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References, Bibliography & Acknowledgements '

- **References:**
  - ISO 9001:2008 Quality Management System requirements
  - IEC TS 62941- Guideline for increased confidence in PV module design qualification and type approval (Draft)
  - JIS Q 8901:2012- Terrestrial photovoltaic (PV) modules -- Requirement for reliability assurance system (design, production and product warranty)
- **Bibliography:**
  - ISO 19011:2011 Guidelines for auditing management systems
  - ISO 9001:2015 Quality Management System requirement (Draft standard)
- **Acknowledgement:**
  - Ms. Sarah Kurtz, Reliability Group Manager, Principal Scientist, PhD, National Renewable Energy Laboratory, Golden, CO 80401
  - Task Group 1 International team members
  - SunPower Corporation, San Jose, CA USA Quality, Reliability & Management

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SOLARBUYER

An independent auditor's view on manufacturing QMS

Ian Gregory | Managing Director | igregory@solarbuyer.com
225 Cedar Hill Street, Suite 200, Marlborough, MA 01752, USA

Our focus

The independent PV module and inverter experts

Technical Diligence

Procurement Assistance

Quality Assurance

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Key stats

- 35 individual clients in 2014
- More than 70 manufacturers evaluated
- More than 150 in-depth quality audits conducted
- More than 100 years in-house PV experience
- Over $2.5B in solar module transactions managed
- Quality assurance conducted on THOUSANDS of modules

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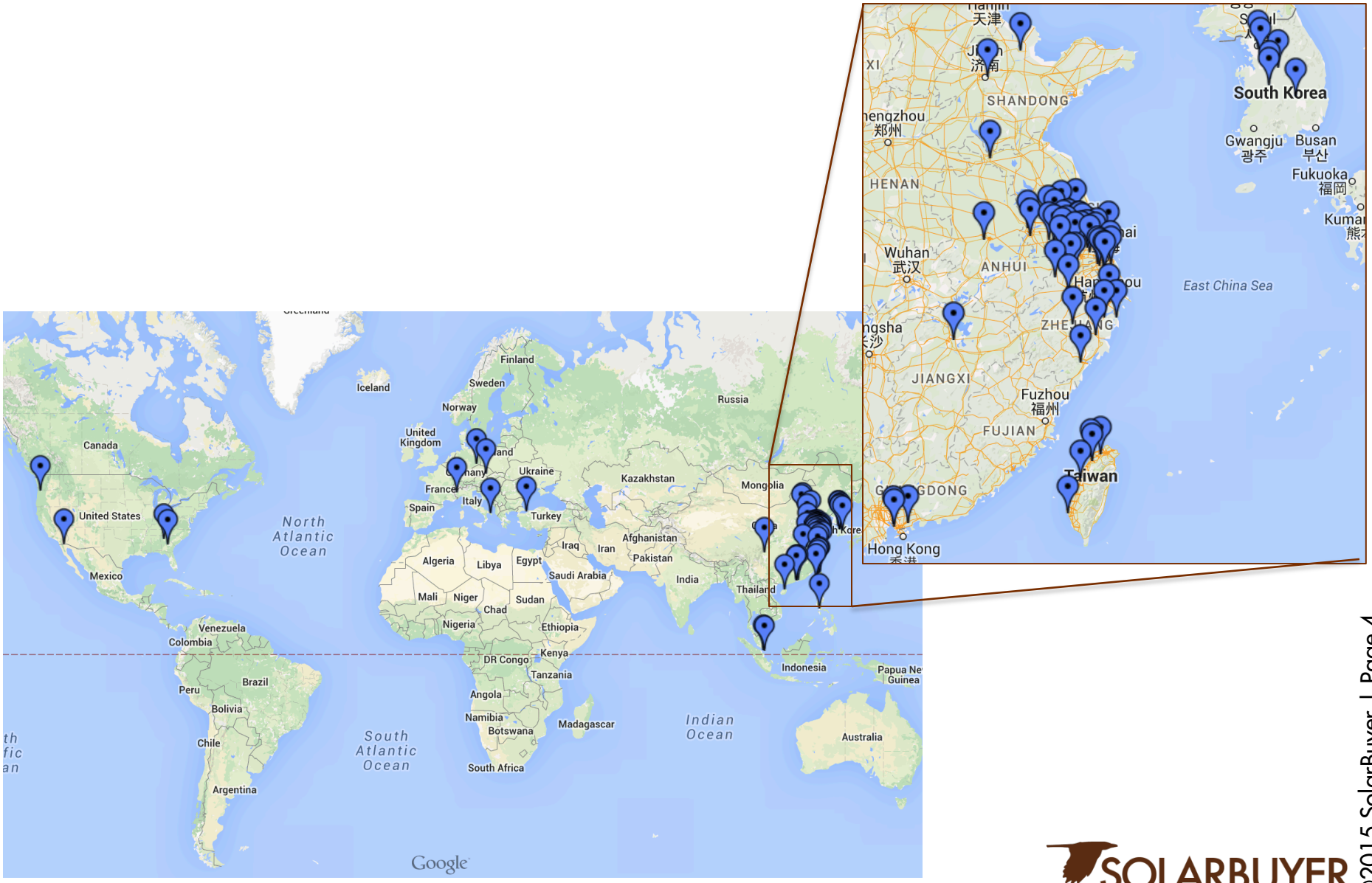
150 audits across the globe



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Four key messages

1. Module quality is variable
2. There are common quality challenges
3. Latency is the major challenge
4. Quality will define bankability

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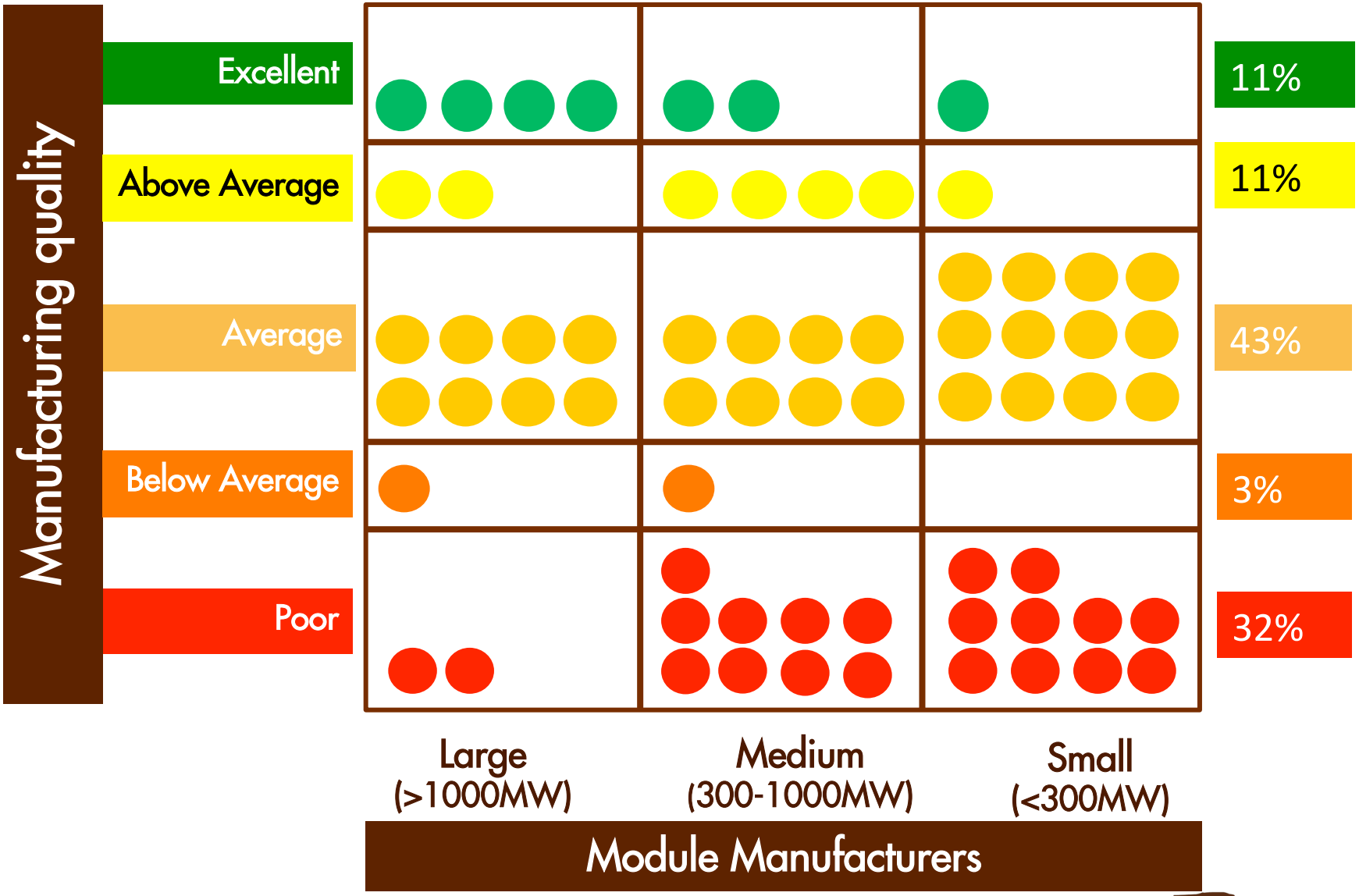
1. Module quality is variable



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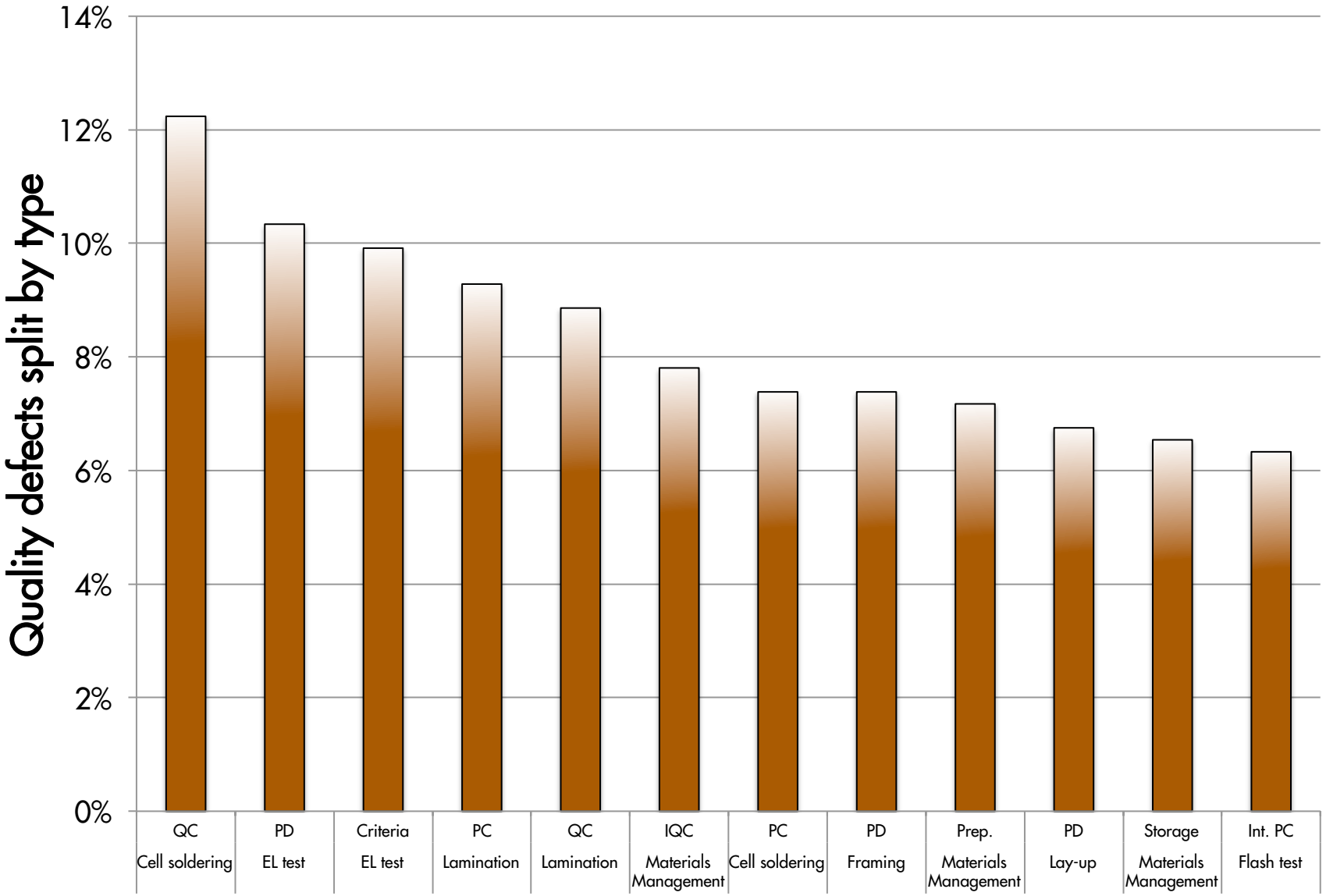
2. There are common quality challenges



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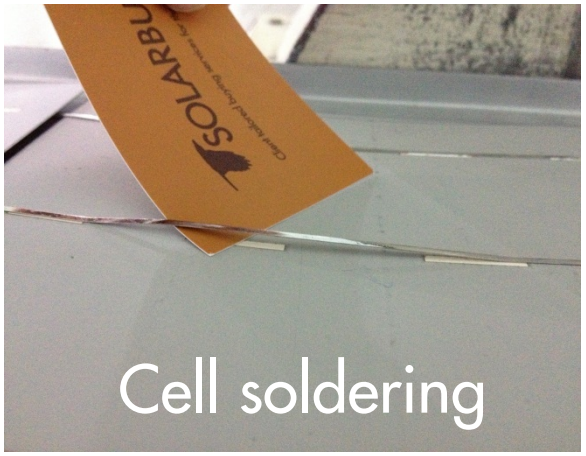
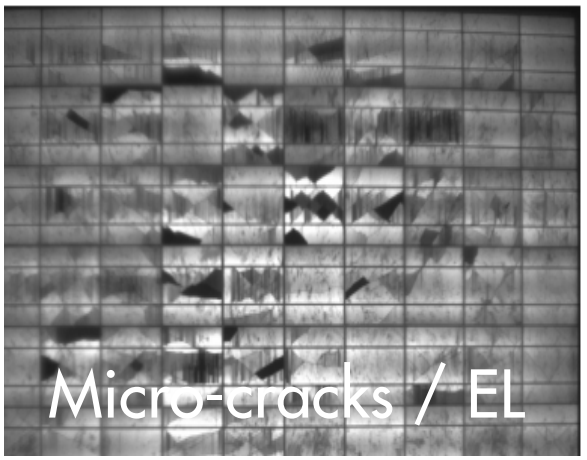
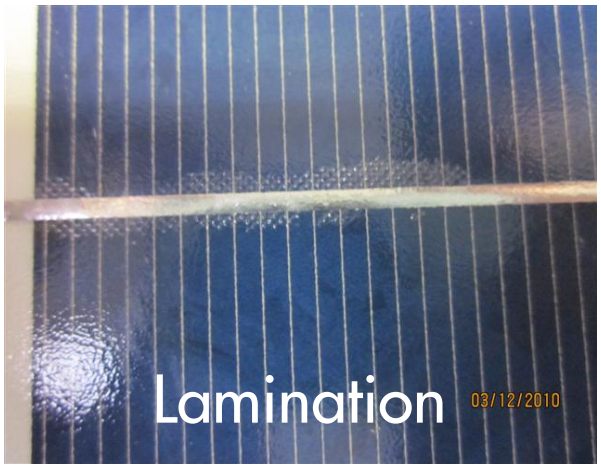
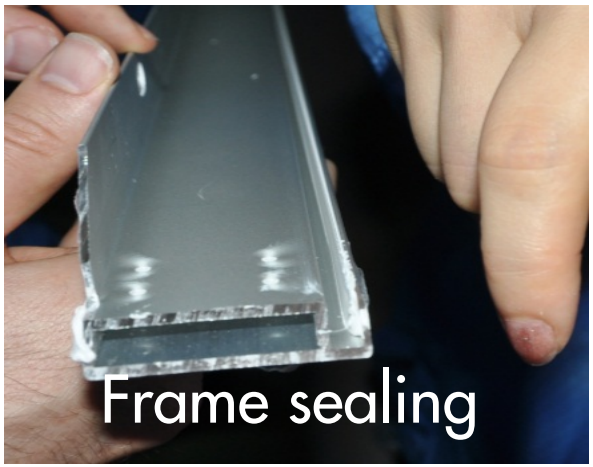
2. There are common quality challenges









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3. Latency is the major challenge

- Overt defects are well screened at time of manufacture
- Embedded latent defects may only appear after shipping or field exposure
- Latent defects caused by the following are challenging to manage:
  - Sub-standard material quality
  - Under- or over-soldering of cells
  - Inadequate lamination
  - Contamination
  - Mechanically weakened cells
- Predicting future performance loss or failure by latent defects is challenging

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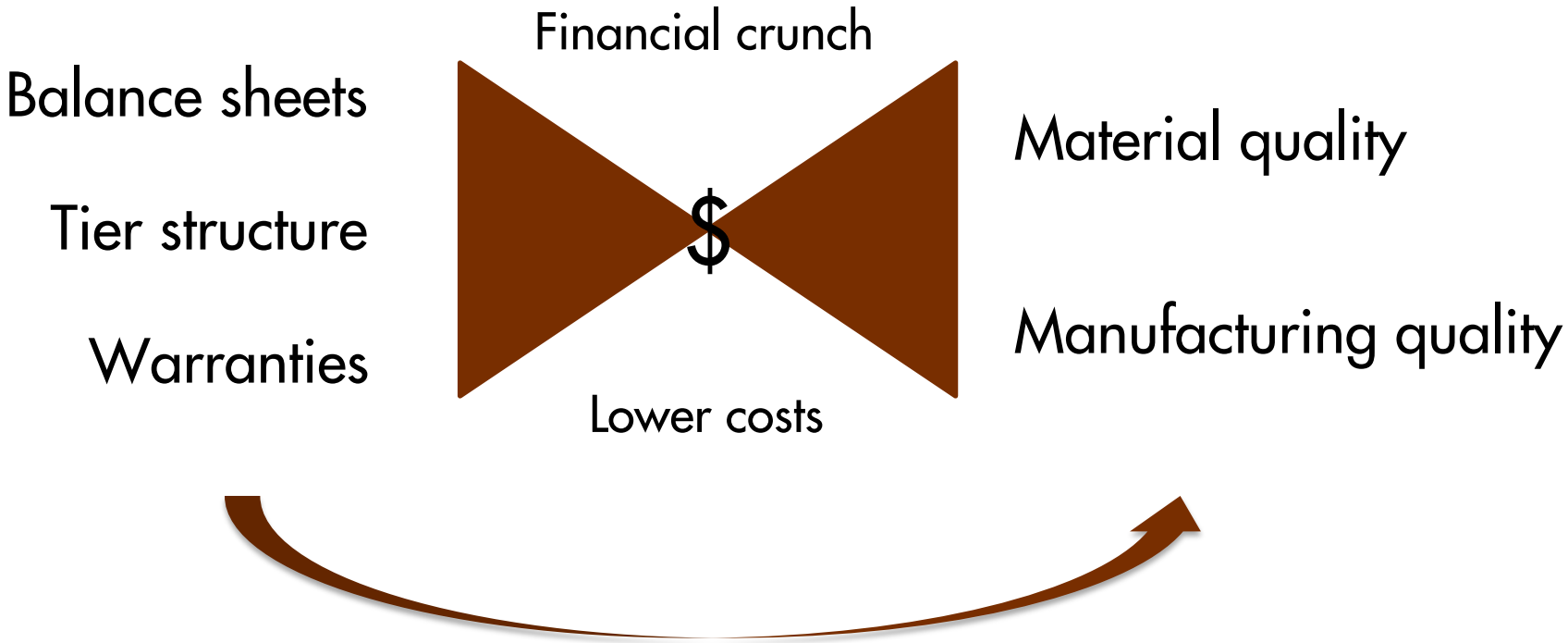
4. Quality will define bankability



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As long as we have modules, we need quality modules

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THANK YOU

Ian Gregory | Managing Director | igregory@solarbuyer.com
225 Cedar Hill Street, Suite 200, Marlborough, MA 01752, USA

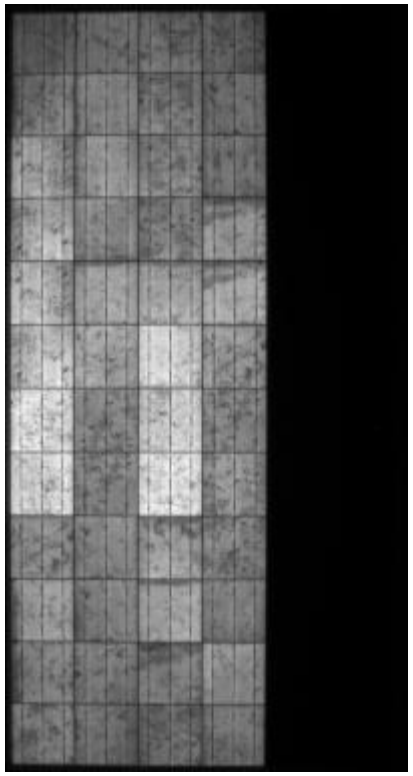
Connecting the Dots

Collaborating from factory to field to reduce long-term module quality risk for specific project locations

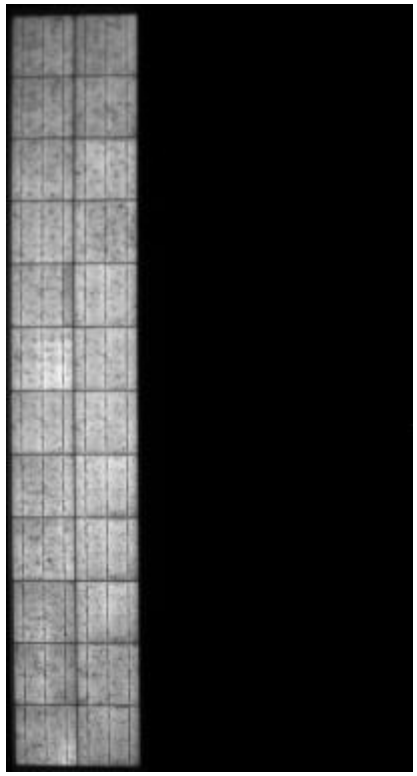
Jon Previtali
Wells Fargo Environmental Finance
NREL PV Reliability Workshop
February 2015

Example 1: Diode Failures

Observed warping / deformation of junction box lid due to excessive heat from Diodes – Post TC400



Observed diode failure at TC400



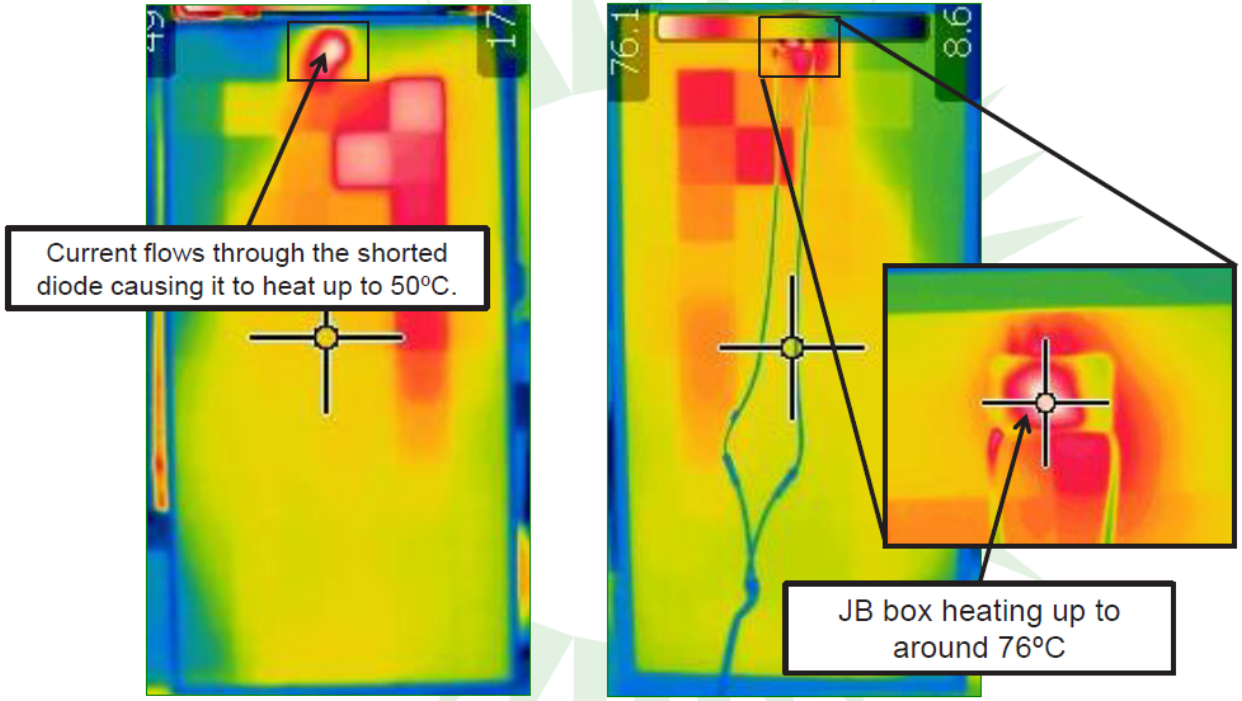
Observed 2-diodes failure at TC600

Example 1: Diode Failures

Situation

- Utility scale, location confidential, ~$50 million, 20 year investment.
- ~50k modules installed.
- Diodes failed in a small subset of population during extended lab tests.
- Root cause analysis by module manufacturer: poor diode quality and lack of electric testing in factory (visual only). Supported by factory inspector (SolarBuyer) and test lab (RETC).

Image taken while exposed to the sun and under load.



Example 1: Diode Failures

Project Acquisition Solution

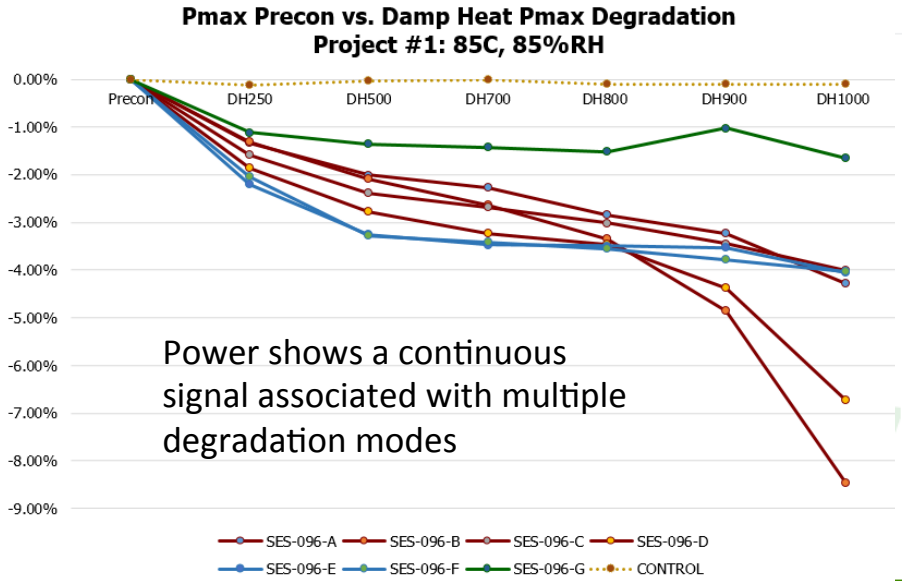
- None: *this level of testing was not a condition precedent to funding.*

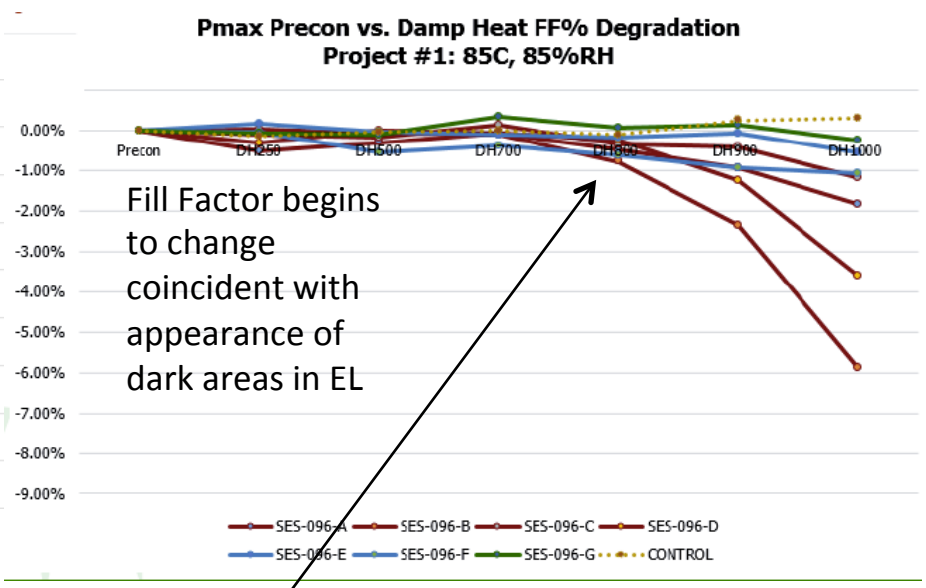
Project Operations Solution

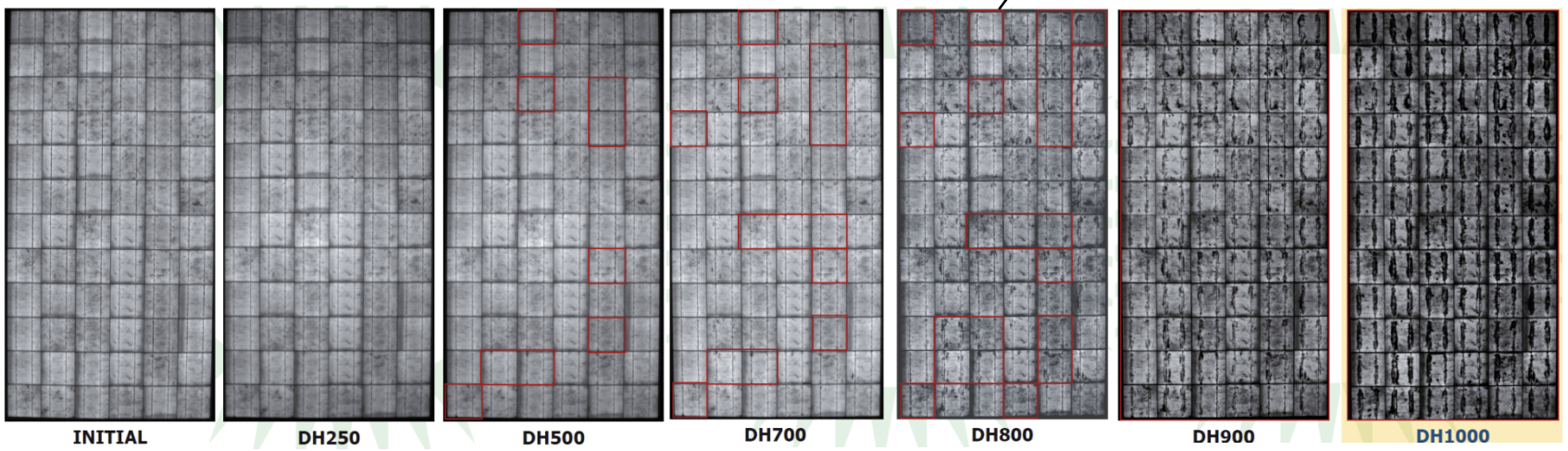
- Assembled a team: test lab (RETC), factory inspector (SolarBuyer), module manufacturer, project operator.
- Safety risk determined to be low by test lab (RETC).
- Field monitoring protocol recommended and demonstrated at test lab (RETC).
  - IR scanning or portion of arrays and conditional string-level Voc testing if minimum heat delta observed.
- Module warranty amended to call out issue.
- O&M agreement modified to include field monitoring protocol.
- *Module-level* testing not specified, however, so after one year operator has done areal IR imaging – effectiveness TBD.

Example 2: Abnormal PV Cell Corrosion

Module IEC Test Observation: EL Darkening Correlating with Fill Factor Loss



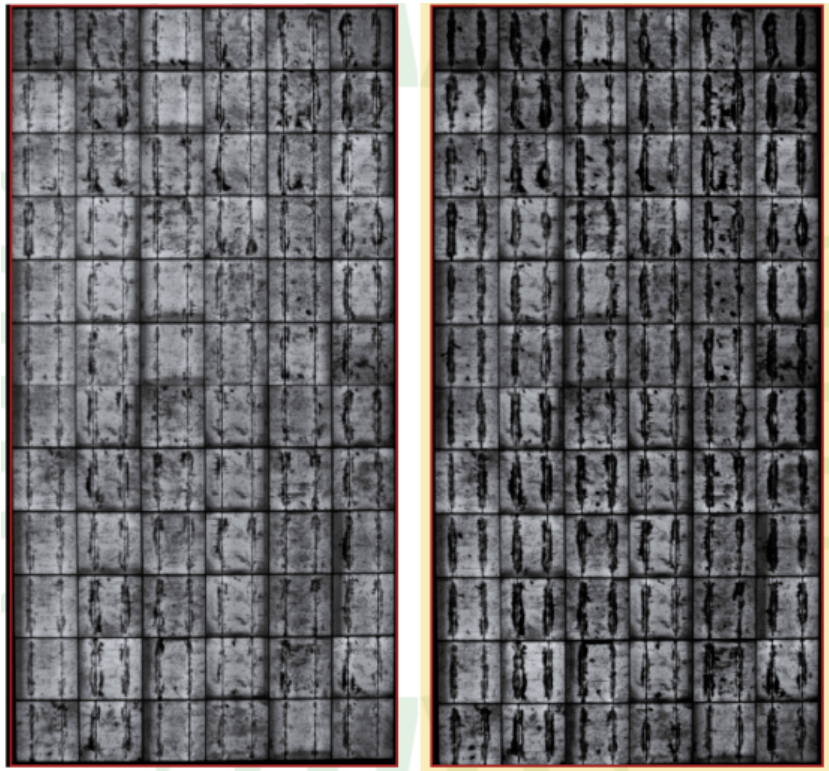




Example 2: Abnormal PV Cell Corrosion

Situation

- 20+ MWdc, Central Valley CA, ~$100 million, 20 year investment.
- ~90k modules installed.
- Samples failed IEC tests slightly (corrosion).
- Root cause analysis by module manufacturer: inconclusive after significant effort.
- ~6 months before PPA liquidated damages and ITC claim expiration (3 months after COD).



Example 2: Abnormal PV Cell Corrosion

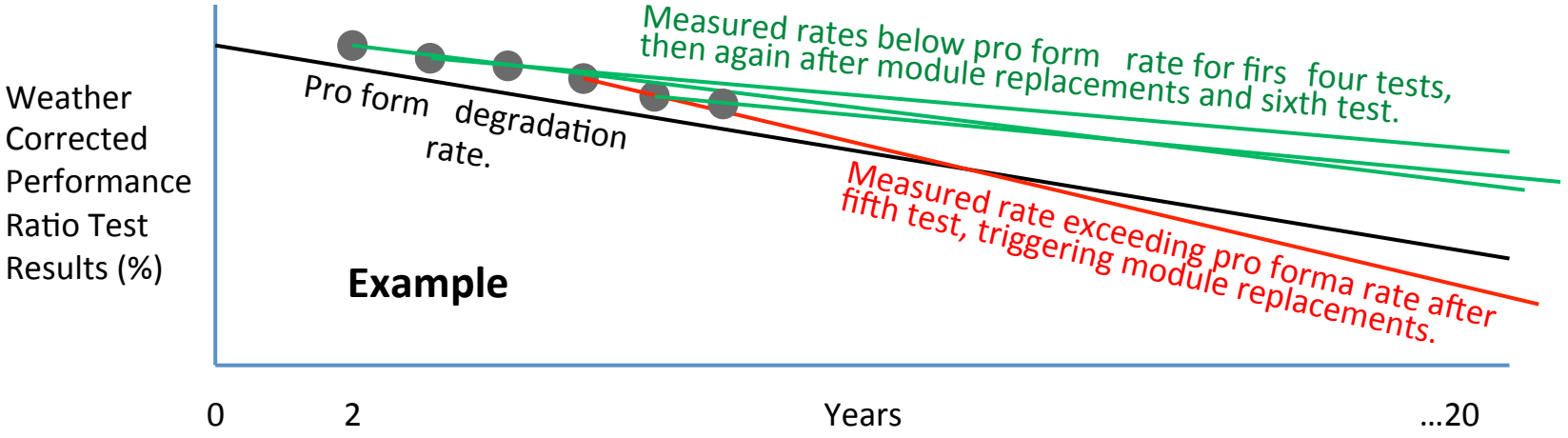
Project Acquisition Solution

- Assembled team: lab (RETC), science advisor (NREL), factory inspector (SolarBuyer), independent engineer (Leidos), project developer, module manufacturer.
- Test plan created.
- Suspect module population identified.
- Matrix of multi-factor chamber tests performed.
- Corrosion mechanism modeled.
- Effected area estimated using image analysis.
- Location-specific, corrosion degradation rate estimated using TMY (Whitfield paper).
- Corrosion degradation rate added to baseline degradation (Jordan study).
- New degradation rate used for production estimate.
- New financial pro forma and new purchase price found (slightly less).
- Project acquired.

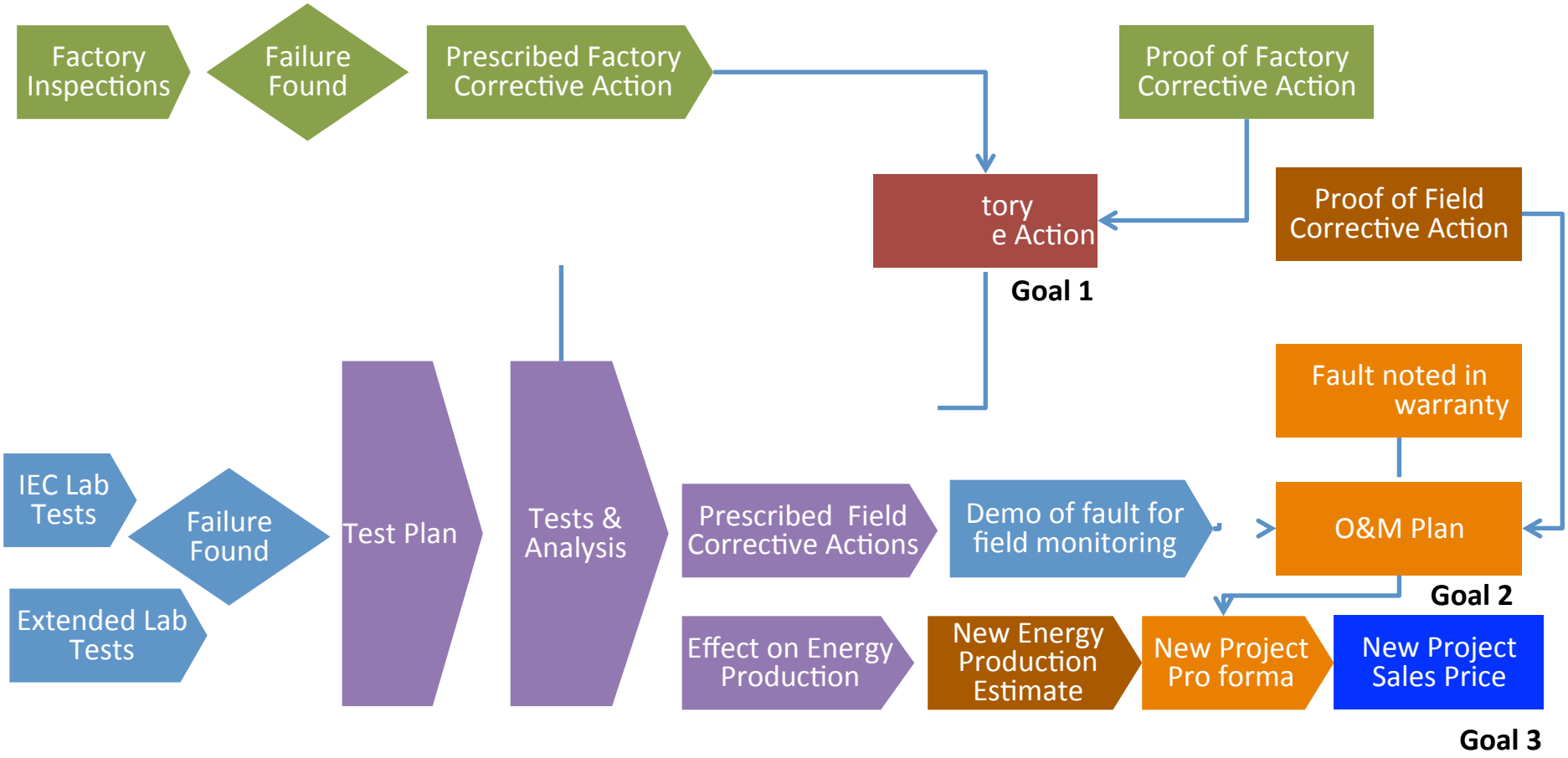
Example 2: Abnormal PV Cell Corrosion

Project Operations Solution

- Module warranty amended to call out issue (not good enough).
- O&M agreement amended to perform advanced monitoring and system-level testing.
- Small test array built at project location with suspect modules.
- String-level IV curve monitoring done through combiner boxes. Assessed yearly.
- System-wide performance ratio test done yearly after two years.
- If degradation rate is thought to be higher than the pro forma rate **by an independent engineer** using both string and system test results, surplus revenue will be “trapped”.
- Modules will be replaced using trapped revenue until degradation rate is brought down to pro forma rate again.



(Ad Hoc) Coordinated Module Quality Assurance Process

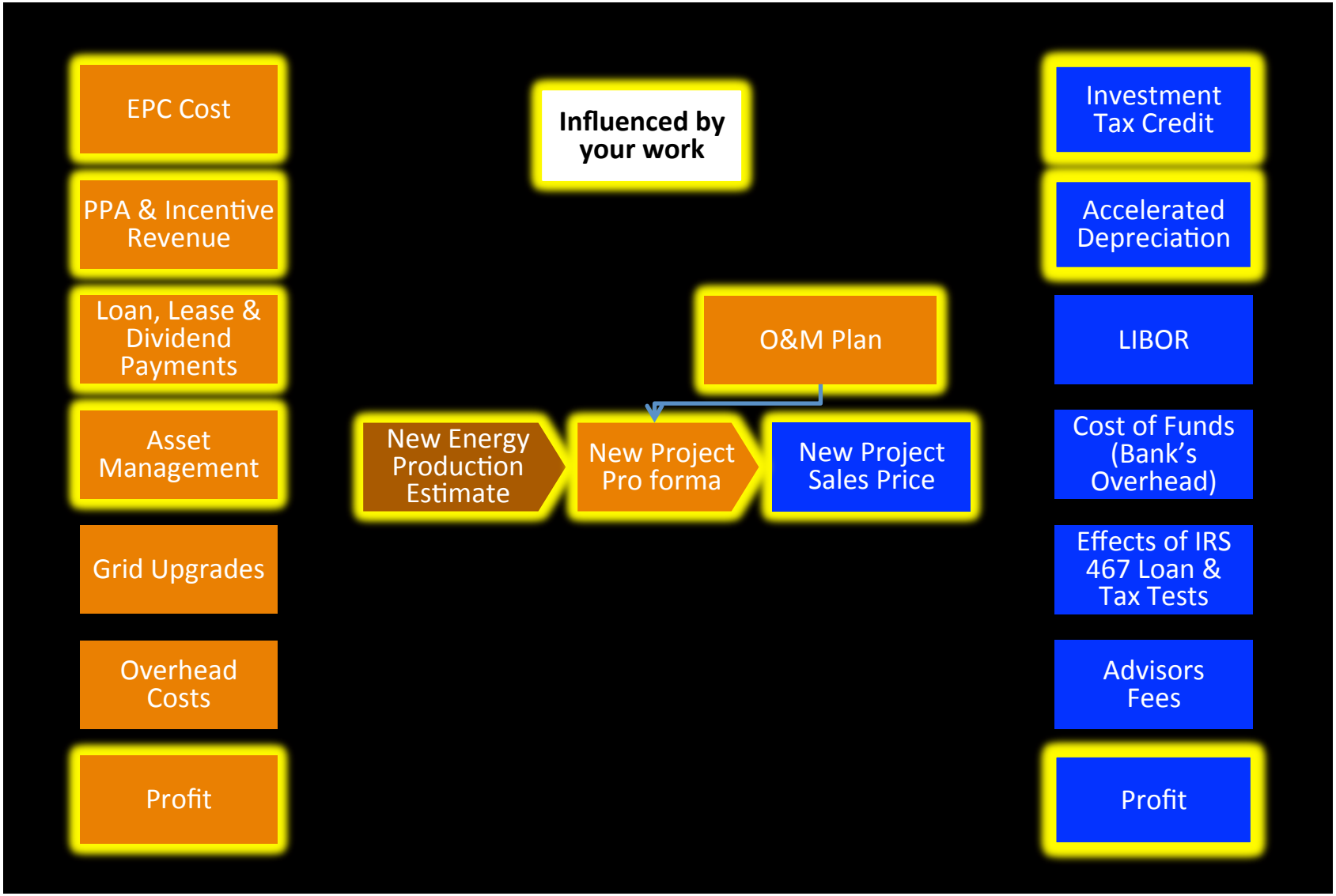


Keys to Success: Expertise, Collaboration & Data Sharing

Factory Inspector | Test Lab | Project Developer / Operator | Module Vendor | Independent Engineer | Bank | Team*

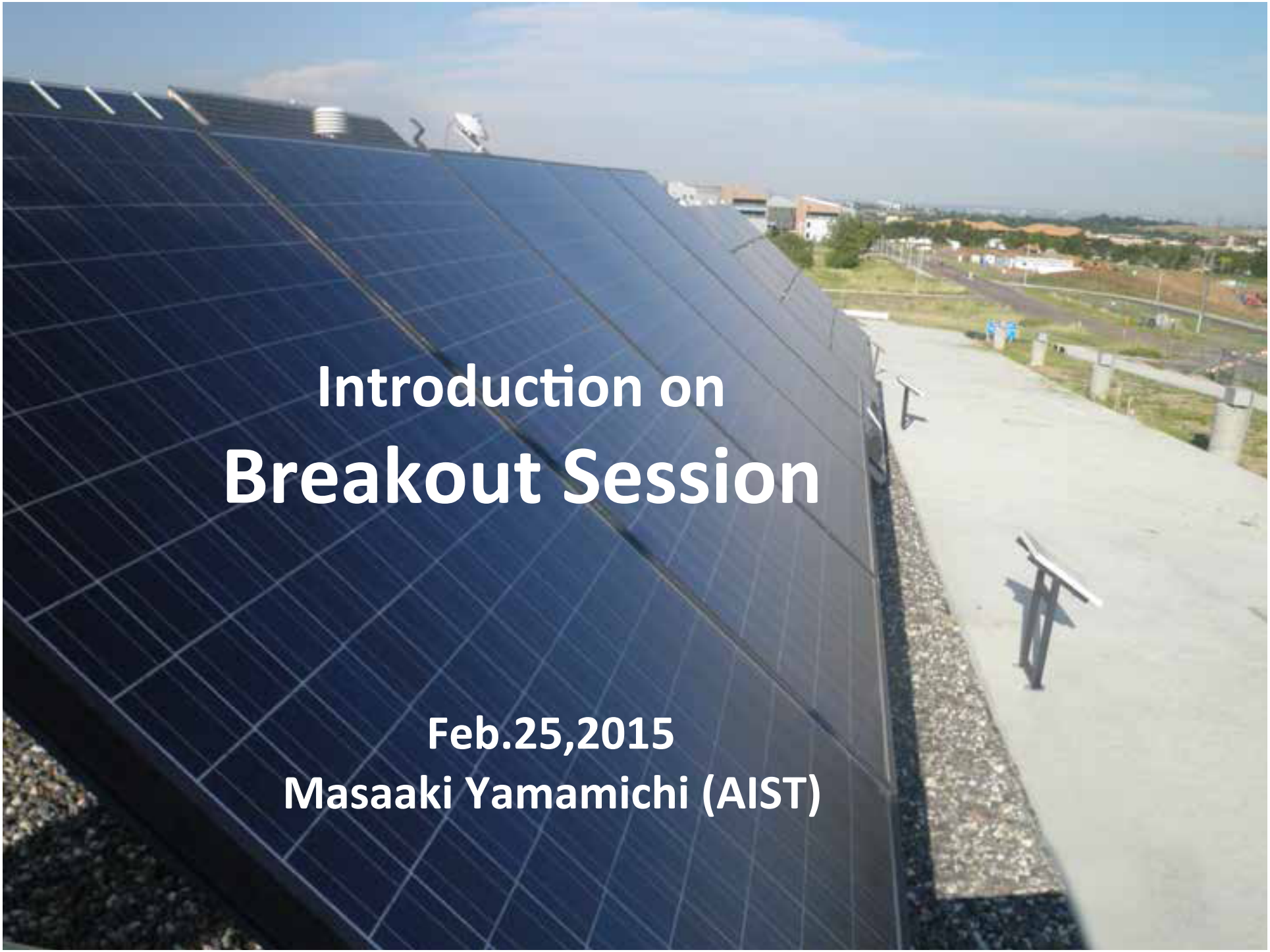
* Sometimes includes science advisor

Tax Equity Project Finance: Inside the Black Box



Thank you from Wells Fargo!

Jon Previtali
Wells Fargo Environmental Finance
415-947-1980
jonathan.m.previtali@wellsfargo.com



Introduction on
Breakout Session

Feb.25,2015

Masaaki Yamamichi (AIST)

Outline:

1:40–3:30 - Breakout Discussion

GROUP 1 Breakout Discussion: QMS Audit (Factory Inspection) and QMS Rating

GROUP 2 Breakout Discussion: Climate-Specific Rating

Participants will be divided into two topic groups, Group1 and Group 2, by your interest.

4–4:20 p.m. Breakout Session Wrap-Up *Each breakout session team*

4:20–5 p.m. Report of Breakout Session

—Breakout session chairs

GROUP 1 Breakout Discussion: QMS Audit (Factory Inspection) and QMS Rating

—Moderators: Govind Ramu, (SunPower) and Jenya Meydbray (DNV GL)

This Group will discuss issues for effective implementation of the IEC TS62941 Guideline for Manufacturing QA, currently under development, including clarification of requirements and audit practices by a test lab/accreditation body. This group will also cover philosophical questions on the need for QMS ratings and desirable QMS rating systems.

- **Feedback from test lab (accreditation body) and module manufacturers**
  - Audit of JIS8901 Certification—Yasunori Uchida, JET
  - DNV GL Product Qualification Program
    —Jenya Meydbray, DNV GL
  - TUV-Rheinland QMS Audit Program
    —Matthias Heinze, TUV Rheinland PTL
- **Open Discussion**
  - Are there questions about the proposal for IEC TS62941 and the need for an international QMS standard?
  - -How should IEC TS62941 be implemented—audit in factory inspection, checklist, training and certification of auditors, certification process, or other method?
  - Should a comparative QMS rating system differentiate companies and products according to the product quality?

GROUP 2 Breakout Discussion: Climate-Specific Rating —Moderators: John Wohlgemuth and Chris Flueckiger

IEC82/766/NP 62892-1 provides a framework for climate-specific rating; however, details of tests, including numbers to specify test conditions, are open for further discussion.

Members of this Group are expected to provide suggestions / recommendations for the successful development of effective IEC standards on climate-specific rating tests.

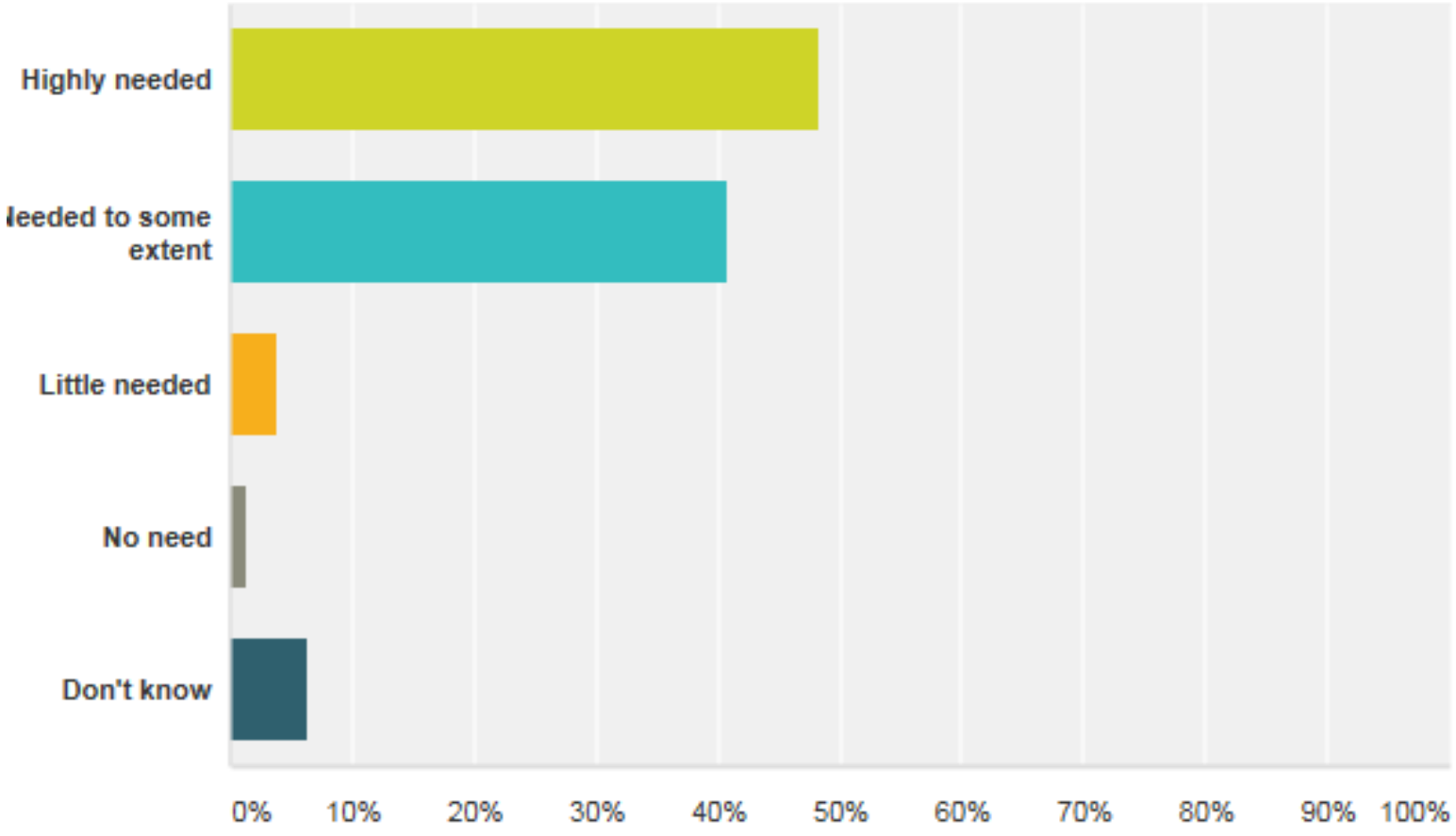
- Test Protocol and Numbers
- How will test results be linked with rating?
- Qualification Plus
- Discussion of Each Task Group Approach

Summary of the survey

- # of responses 82
- 90% of the people feel need for an international standard for PV-specific QMS.
- 60% answered proposed IEC 62941 is effective
- Preferred topics to be discussed in Breakout session #1 are widely diversified
- 75% supported an idea of climate specific rating
- .The most preferred topics to be discussed in Breakout session #2 is “Leg 2”, followed by “Sampling out of production”

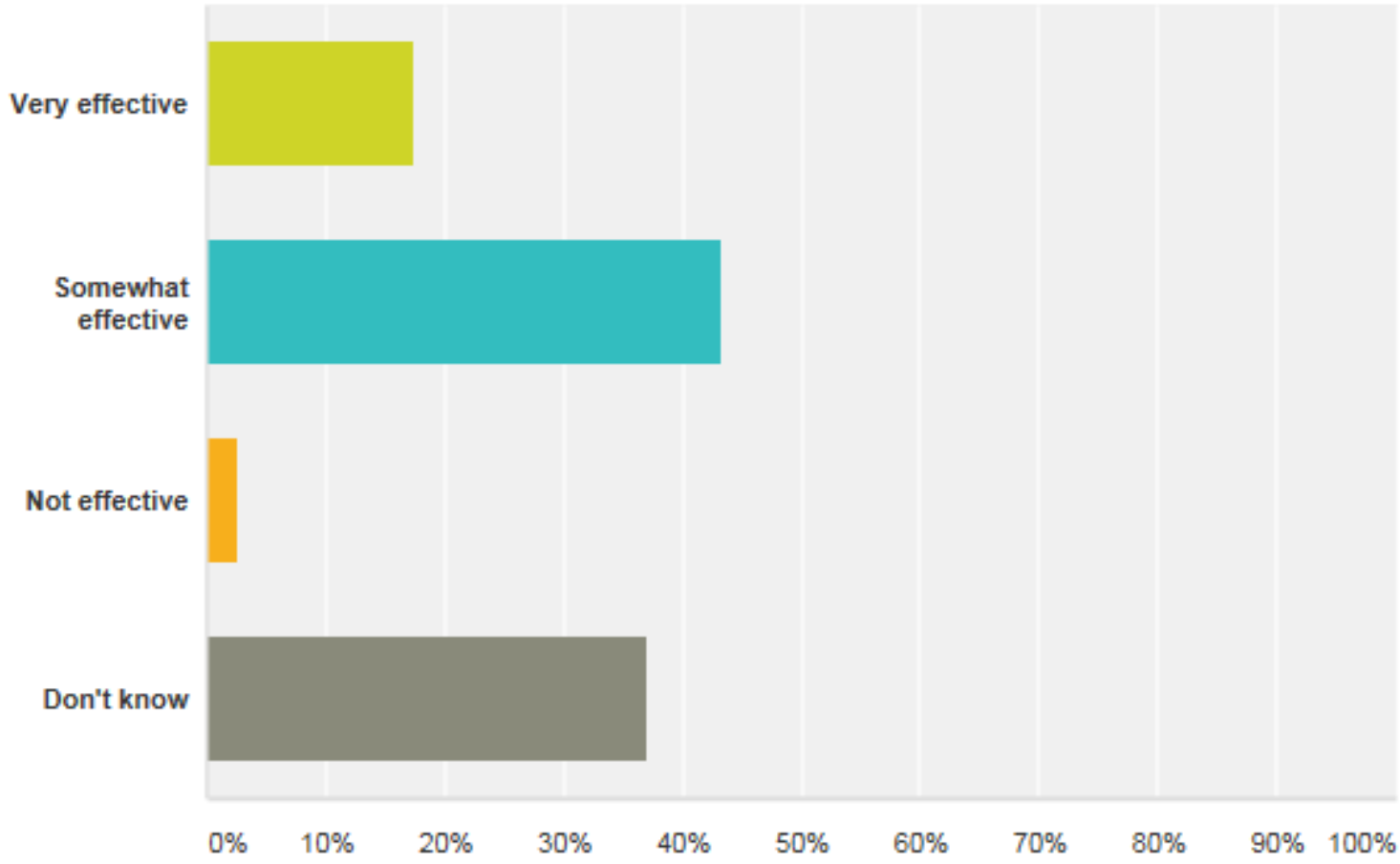
Survey Results

What do you think about the Need for an international standard for PV-specific QMS?



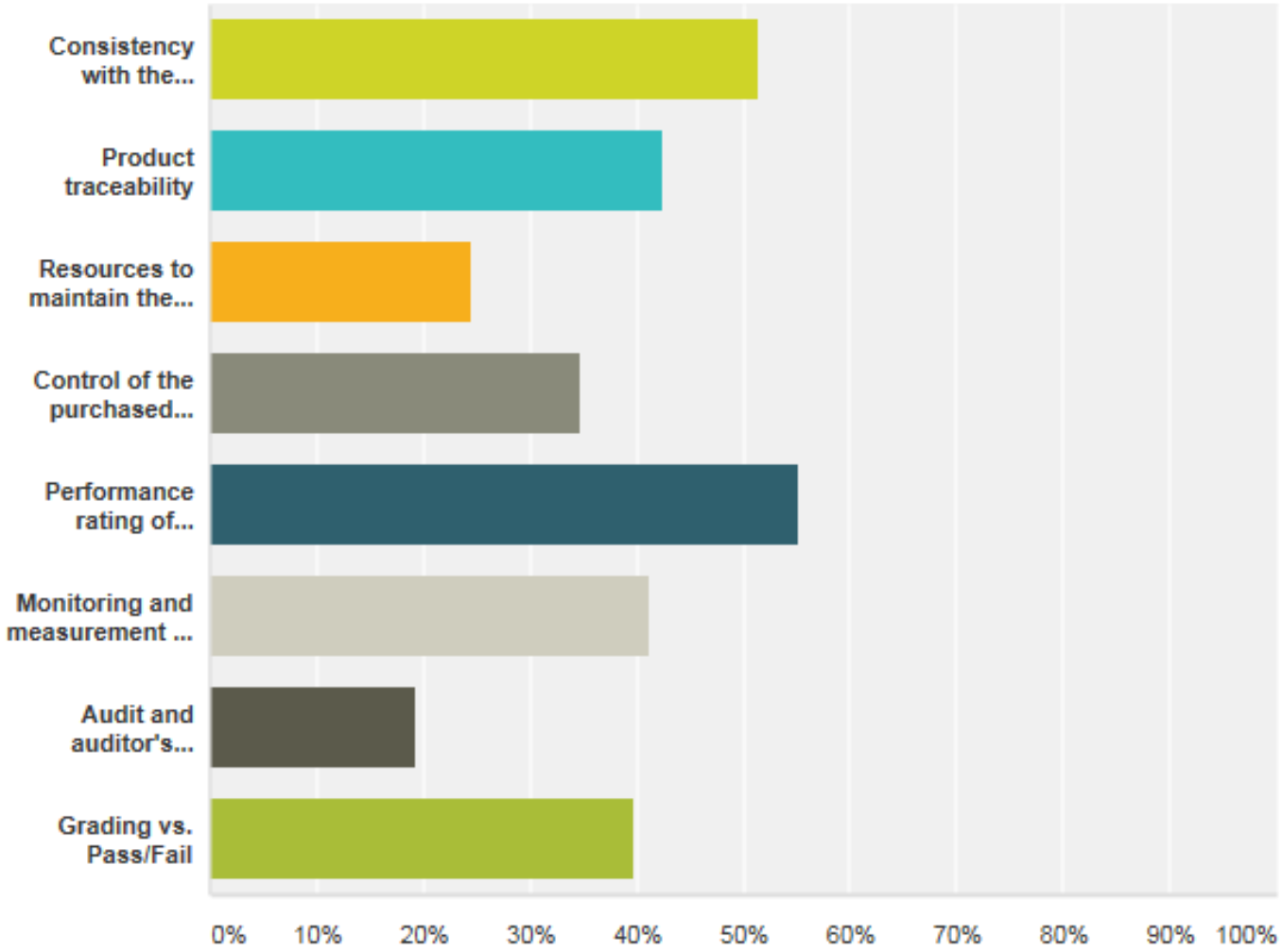
Survey Results

What do you think about the Effectiveness of the current draft of IEC 62941?



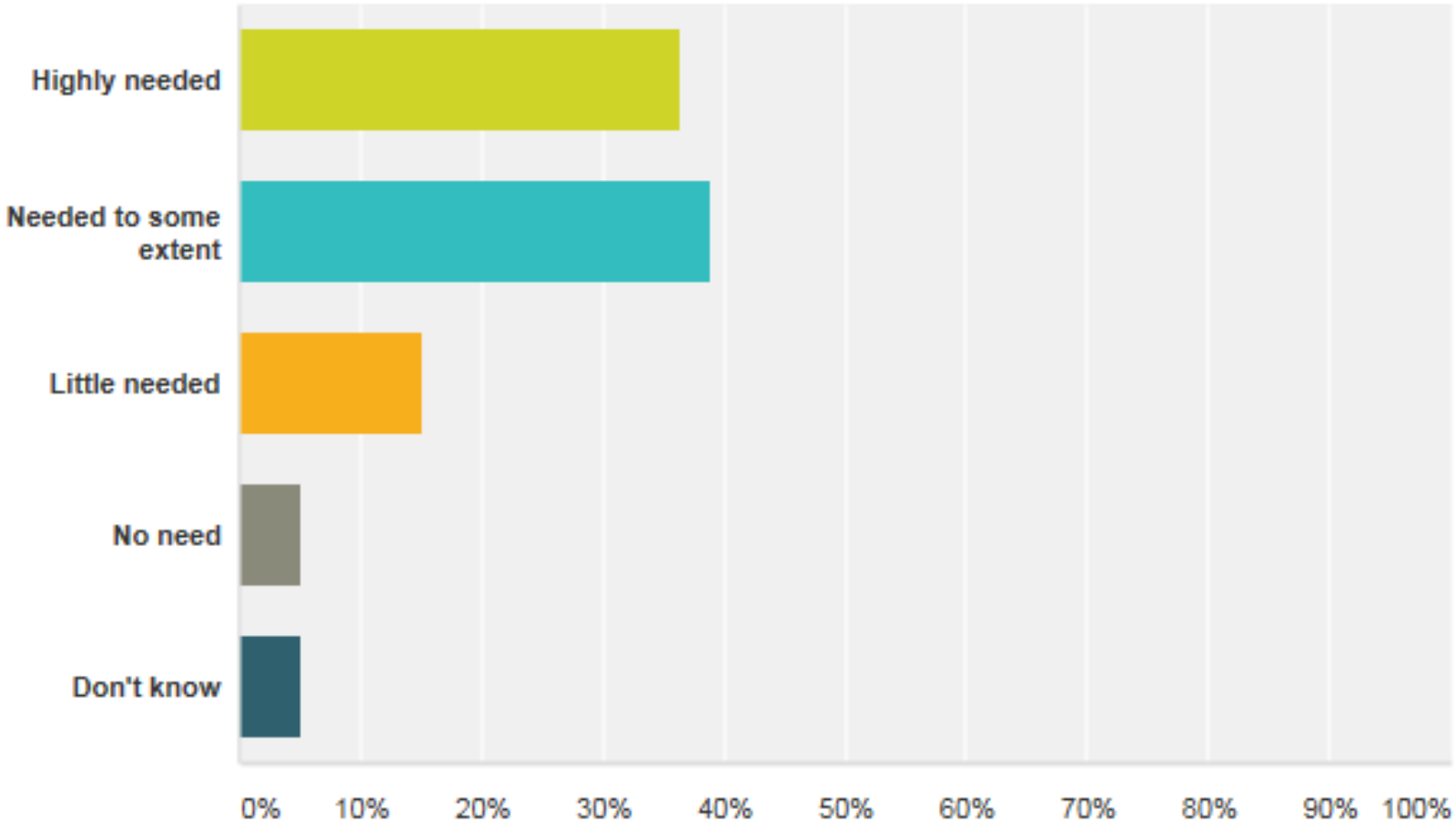
Survey Results

Which topics in QMS would you like to talk about during the break out session?



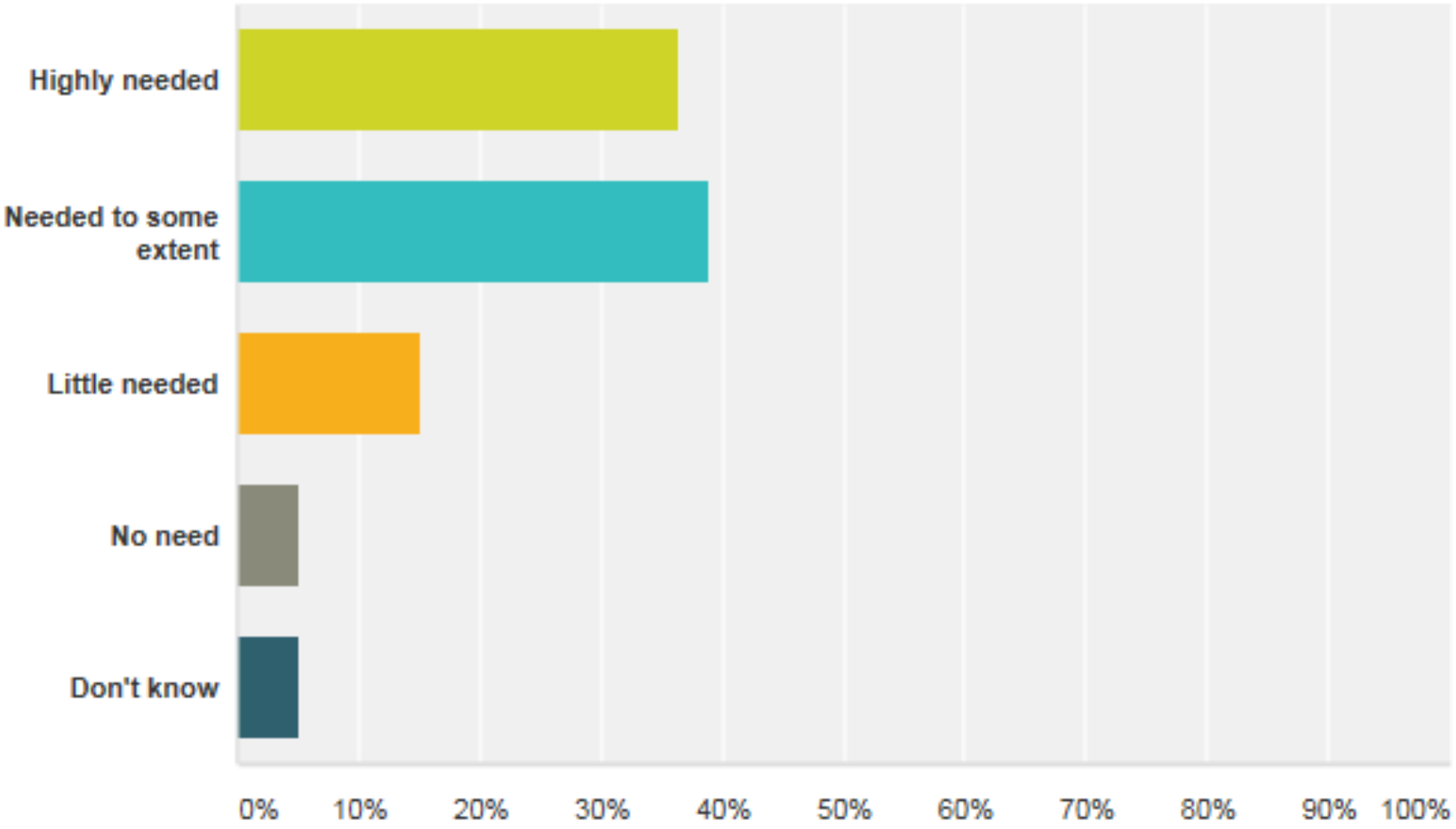
Survey Results

What do you think about the Need for a Climate-specific rating system?



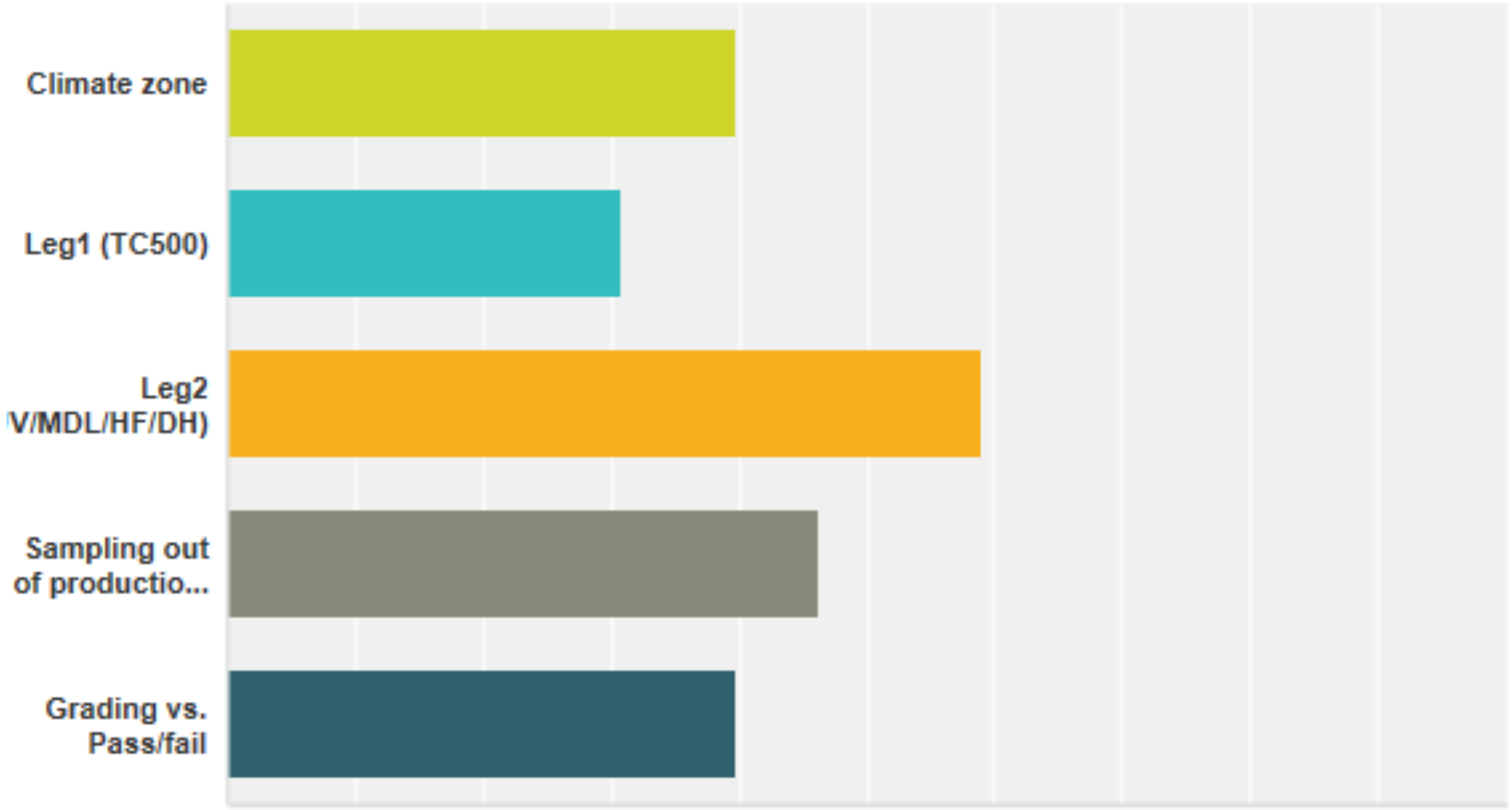
Survey Results

What do you think about the Effectiveness of the proposed Climate-specific rating system?



Survey Results

Which topics would you like to discuss during the break out session?



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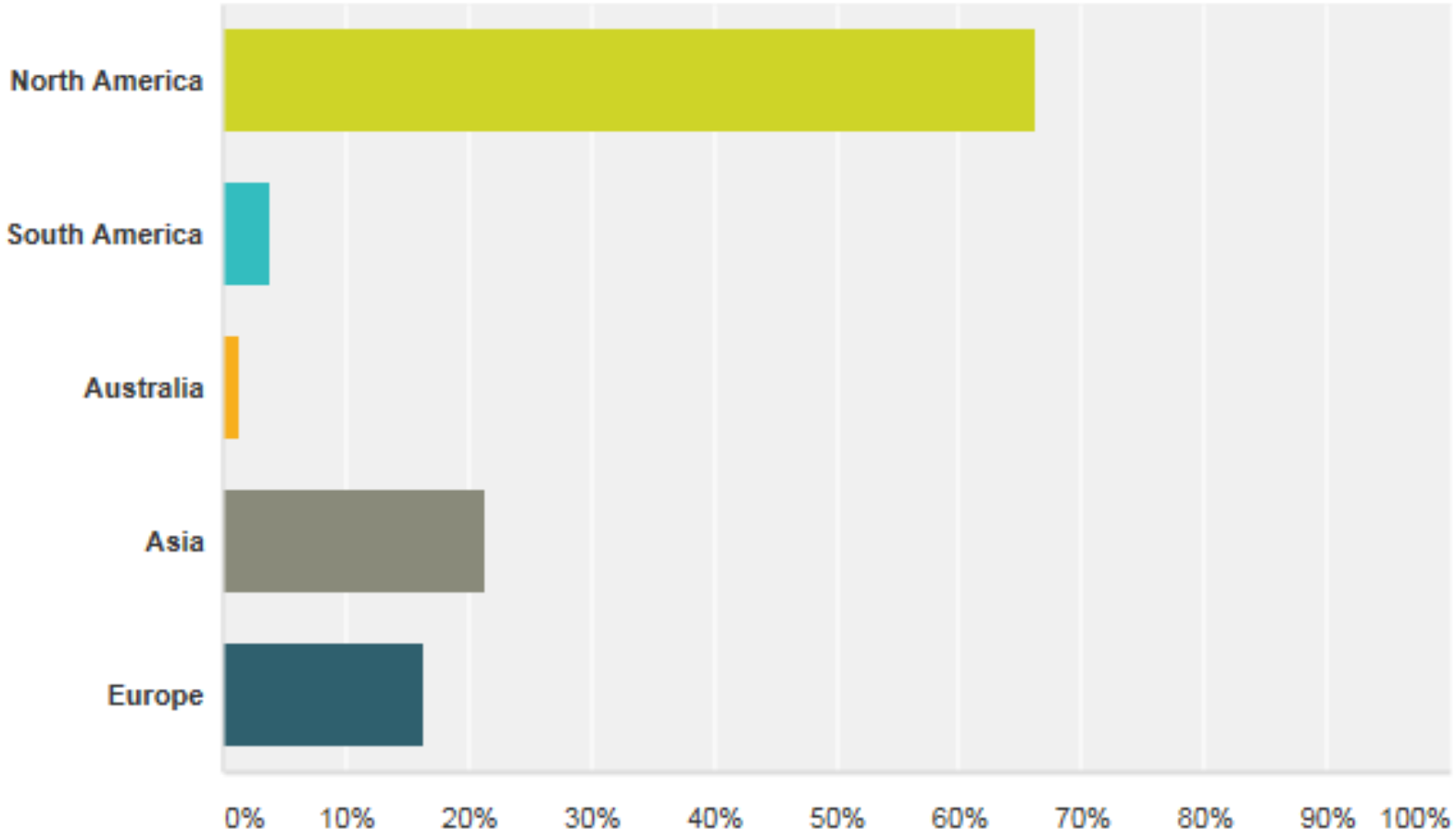
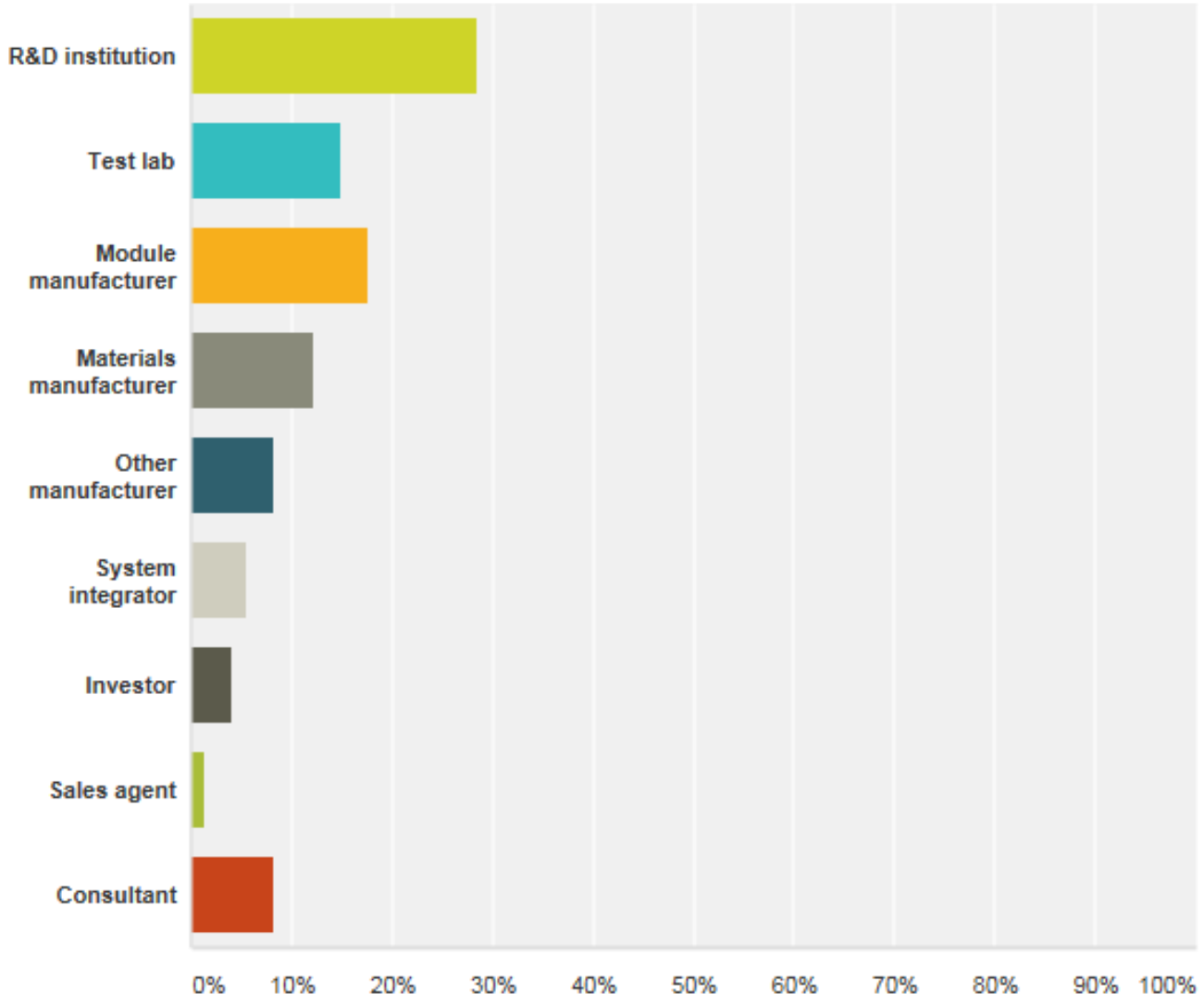


Please identify your affiliation



Current situation of QMS certification by JET based on JIS Q 8901

NREL PV Module Reliability Workshop Session
February 24, 2015

Yasunori Uchida

RESEARCH & BUSINESS DEVELOPMENT CENTER

JAPAN ELECTRICAL SAFETY & ENVIRONMENT TECHNOLOGY LABORATORIES

一般財団法人　電気安全環境研究所

JET

Contents

1. Introduction
2. Outline of JIS Q8901
3. Major requirements defined in JIS Q8901
4. Major check points
5. Outcomes of the JET Certification audit
6. Summary

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Introduction – International Quality Assurance Task Force (PVQAT)

◆ July, 2011:
- First International PV Quality Assurance Forum in SF, USA, organized by NREL, JRC and AIST.
- Formed the 5 task Group
  - ✓Task 1 : Quality Management System
  - ✓Task 2-5 : Accelerated tests (NOTE: *11 Task Groups form now)

◆ Fall, 2011:
Task #1 began to write a PV-specific version of ISO 9001

□ Status of TG1 and QA forum activity was reported in IEC/TC82/W2 meeting and International QA forum.

◆ **TG1 Members**:

Grobal coordinator **: *Ivan Sinicco*** ***(TEL solar)***

U.S.A Leader: ***Govind Ramu*** ***(SunPower Corp.)***

Europe Leader: ***Gunnar Brueggemann*** ***(TEL solar)***

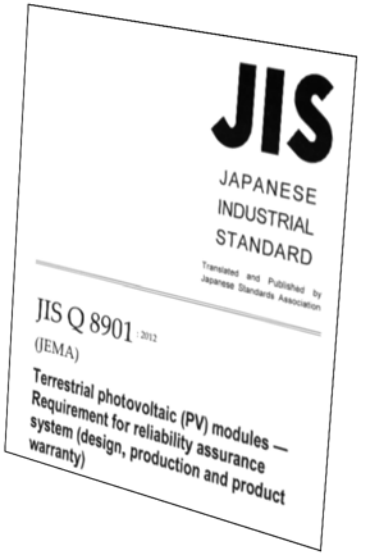
China Leader: ***Wei Zhou*** ***(Trina solar)***

Japan Leader: ***Yoshihito Eguchi*** ***(JET)***

◆ **Report at**

http://www.nrel.gov/docs/fy13osti/58940.pdf

◆ **Establishment of the JIS standard (Feb.2012)**



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What is JIS Q8901?

- JIS* Q8901:Terrestrial photovoltaic module – Requirement for reliability assurance system (design, production and product warranty)
  (JIS*: Japan Industrial Standard)

- Developed by JEMA** based on suggestions from PVQAT TG#1 Japan Team
  (JEMA**: The Japan Electrical Manufacturers' Association)

- Defines requirements for QMS in design, production, and product warranty to secure power output warranty of the PV modules.

- JIS Q8901 certification by members*** of Japan PV Module Certification Bodies Council (PVCBC) started in Jul, 2012 .
  (***JET, TUV-Rheinland, UL, VDE)

- Full text in English can be purchased at
  http://www.webstore.jsa.or.jp/webstore/Com/FlowControl.jsp?lang=en&bunsyoId=JIS+Q+8901%3A2012&dantaiCd=JIS&status=1&pageNo=0

Areas covered by JIS Q8901

4. Quality management for design, production and performance warranty

4.1 Consistency of functional lifetime with design and production

4.2 Consistency of functional lifetime with performance warranty

4.3 Reliability ensured in design

4.4 Quality management for production (ISO-9001 7.5)

4.5 Performance warranty for product after delivery

5. Retention of records

Major requirements defined in JIS Q8901

- The party for product liability to ensure that functional lifetime is consistently insured in design and production of PV modules. The party may subcontract some of its responsibilities for design, production and power output performance warranty to third parties.
- The performance specified in the warranty ensured by the combination of reliability of product itself and warranty services over the period specified in the warranty.
- Functional lifetime set in accordance with features and installation conditions of the PV modules.
- The rules and systems for managing and controlling the design process and verification method of the design output to ensure reliability of the PV modules
- appropriate verification items and methods to verify if the specified performance of the PV module can be expected over the functional lifetime.
- proper verification items and methods for the reliability of specified performance in the function lifetime for cell, key materials, ,connection method and internal circuit.

Major requirements defined in JIS Q8901

- To notify an installer of PV modules of precautions for use and/or installation if necessary
- Manufacturing of PV modules managed under Clause 3.5 (manufacturing and offer of service) of JIS Q 9001.
- Consistency between the contents of performance guarantee of PV modules and the operational rules and systems.
- Disclosure of contents of performance guarantee, guarantee conditions pertaining to it and matters necessary for after-sales-service as warranty to the purchasers of PV modules.
- To organize the system for service etc. to secure the guarantee.
- The rules and/ or structure for the receipt of consultation requests from purchasers when some problems occur, diagnosis to identify the problem, compensation after it was identified, measures for preventing the recurrence, etc.
- The corresponding rules in case of the occurrence of severe troubles.
- Retention of the records necessary for the operation of services during the period of performance guarantee.

Major check points in audit

- Consistency of functional lifetime with design and production
- Consistency of functional lifetime with performance warranty
- Scheme for ensuring "Performance lifetime“ in the case of "Functional lifetime“ < "Performance lifetime", has to be documented
- Documents that provide the installation conditions
- Documents that specifies conditions exempting the performance warranty.
- Rules and procedures to ensure the functional lifetime of the modules embodied in the design including verification methods of the design.
- Reliability verification methods for key materials and/or connection method.

  Ex. Cell, Back-sheet, EVA, Glass, Al-frame etc.
- Quality management/control system for manufacturing

  Ex. Certificate of ISO9001, Audit report, Non-conforming result, corrective actions, range of certification, etc.
- Change control system for design, manufacturing process, and key materials.

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Major check points in audit

- Relationship between contents of performance warranty and operational rules for warranty services
- Presentation materials for customers on "contents for performance warranty" and "necessary information concerning the warranty conditions and after service.

  Ex. Model for warranty, product warranty, warranty period, contents of warranty
- Service system to ensure the warranty

  customer communication (language)

  problem/trouble handing including diagnosis of suspicious modules and definition of severe trouble

  education and training of service staff

  recurrence prevention

  record retention and management system for service operation (as long as "product warranty period + one year“)
- Rules and procedures to protect customer‘s information.

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Outcomes from "JIS Q 8901" review

- JET started the QMS certification service from July 2012.
- Inquiries from many companies (PV module manufactures and sales agent), including from overseas
- JET communicated potential customers on requirements defined in JIS Q8901
- Some customers applied for JET audit and successfully acquired QMS certification.

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Outcomes from "JIS Q 8901" review

Comments from the auditees

- Through preparation for JIS Q8901 we were able to have good opportunity to reconsider with a long-term reliability assurance.

- Verification of a functional life-time printed on the label.
ラベル上の印刷の機能耐用年数の証明

- Acceptable business scheme to ensure product warranty in case of withdrawal from PV business or bankruptcy.
業務撤退や倒産等の場合の対応の仕組み等

- Requirement for after-sales service stations in Japan.
日本でのアフターサービスの拠点

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Outcomes from "JIS Q 8901" review

Comments from JET auditors

- This is not a goal, it is a beginning rather.

- In the future, to more ensure “a long-term reliability assurance”, it is important to perform the continuous improvement concerning the verification method and system.

- Functional lifetime in design should be validated by outdoor exposure data of similar product of as many years as possible.

長期信頼性に関し、できるだけ長期の曝露ﾃﾞｰﾀに基づき設計を進めていくべき。

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Outcomes from "JIS Q 8901" review

Comments from companies declined from application for JET audit

- They gave up the acquisition of QMS certification due to one or more of the following reasons,
  - ✓ No/insufficient outdoor exposure testing data.
  - ✓ No rules/systems to assure the long term reliability.
  - ✓ No/insufficient testing data for various materials.
  - ✓ No/insufficient records to assure quality of key materials.
  - ✓ No “after sales service center” in Japan.
  - ✓ No “after sales service system” in Japan.
  - ✓ No rules for the replacement of failure PV module.
  - ✓ No education and training system.
  - ✓ No processing rules if the PV module business is closed.
  - ✓ The storage period is not "the guarantee + more than 1 year".
  - ✓ No rules and evidence for identify the products.

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Summary

- JET has audited 8 companies for certification of JIS Q8901.

All of them successfully passed and acquired certificate.

- Some companies gave up application on the half way of their preparation for the audit, who realized that they were not able to satisfy the requirements at that time.

- JISQ8901 is not perfect standard to secure PV module reliability.

With "continuous improvement" concept featured in the policy of ISO9001, further review and action is needed from now on.

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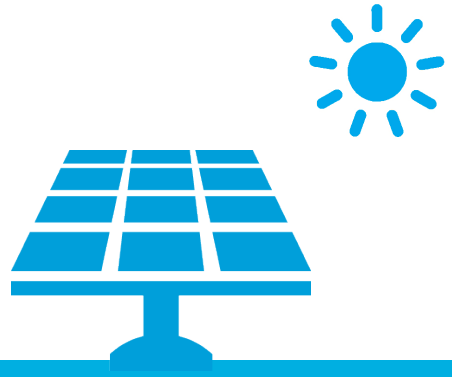

PV Qualification

Jenya Meydbray, Section Head
PVMRW - 2015

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About Us

- DNV GL is the world's largest renewables advisory firm
  - Solar advisory since 2003
  - 13 major global offices focused on Solar
  - Advised on over 25 GWs of PV power plants
- Independent Engineering / Owners Engineering / Module & Inverter Testing
- Supports Banks, Developers, IPPs, EPCs, and manufacturers
- Module & Inverter Testing: PV Evolution Labs acquired by DNV GL March, 2014

Module & Inverter Testing

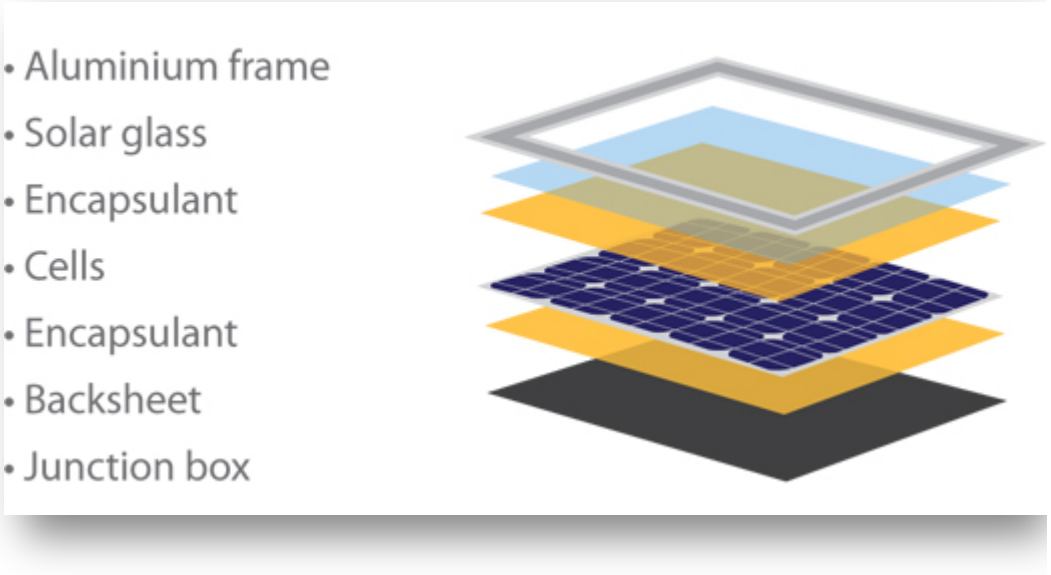
- Focused in two areas
  - Qualification Testing
  - Batch Testing

- **Qualification**
  - Comprehensive 3rd party testing evaluation
  - Apples to apples across many manufacturers
  - Large downstream partner network
    - ~90 companies: banks, IPPs, developers, EPCs

DNV·GL

PV Module Construction

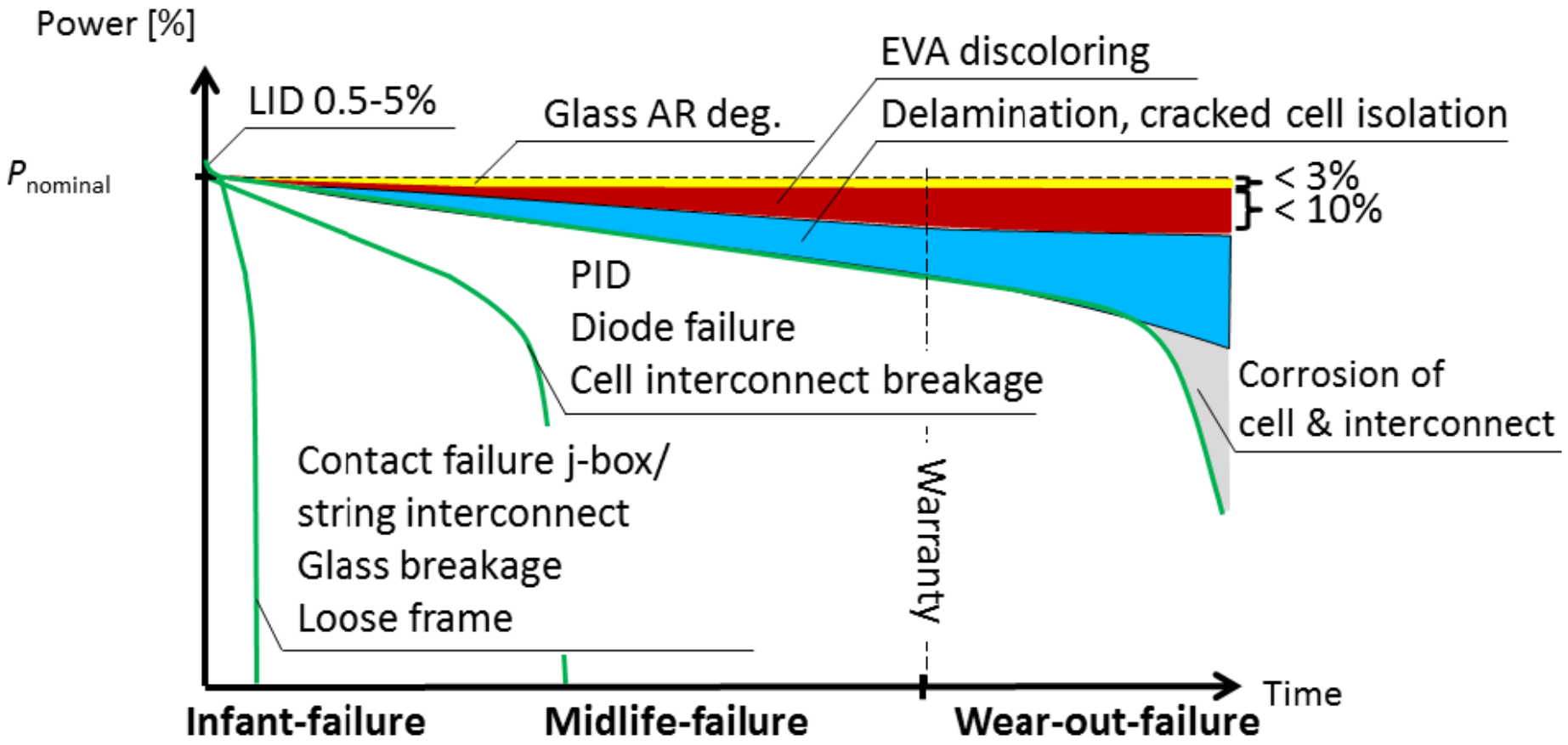
- PV modules are made of metal, silicon, glass and polymers and are expected to last a LONG time.
- Your unborn kids will be graduated from college before your PV module warranty expires.



- Each of these materials expands and contracts at different rates when heated or cooled causing interfacial fatigue
- The package must stay adhered
- The electrical conductors must stay isolated from the environment
- The cells must continue to operate and the circuit must continue to carry current

PV Module Degradation Scenarios

- *Review of Failures of Photovoltaic Modules*, IEA PVPS 2014



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Compared to IEC

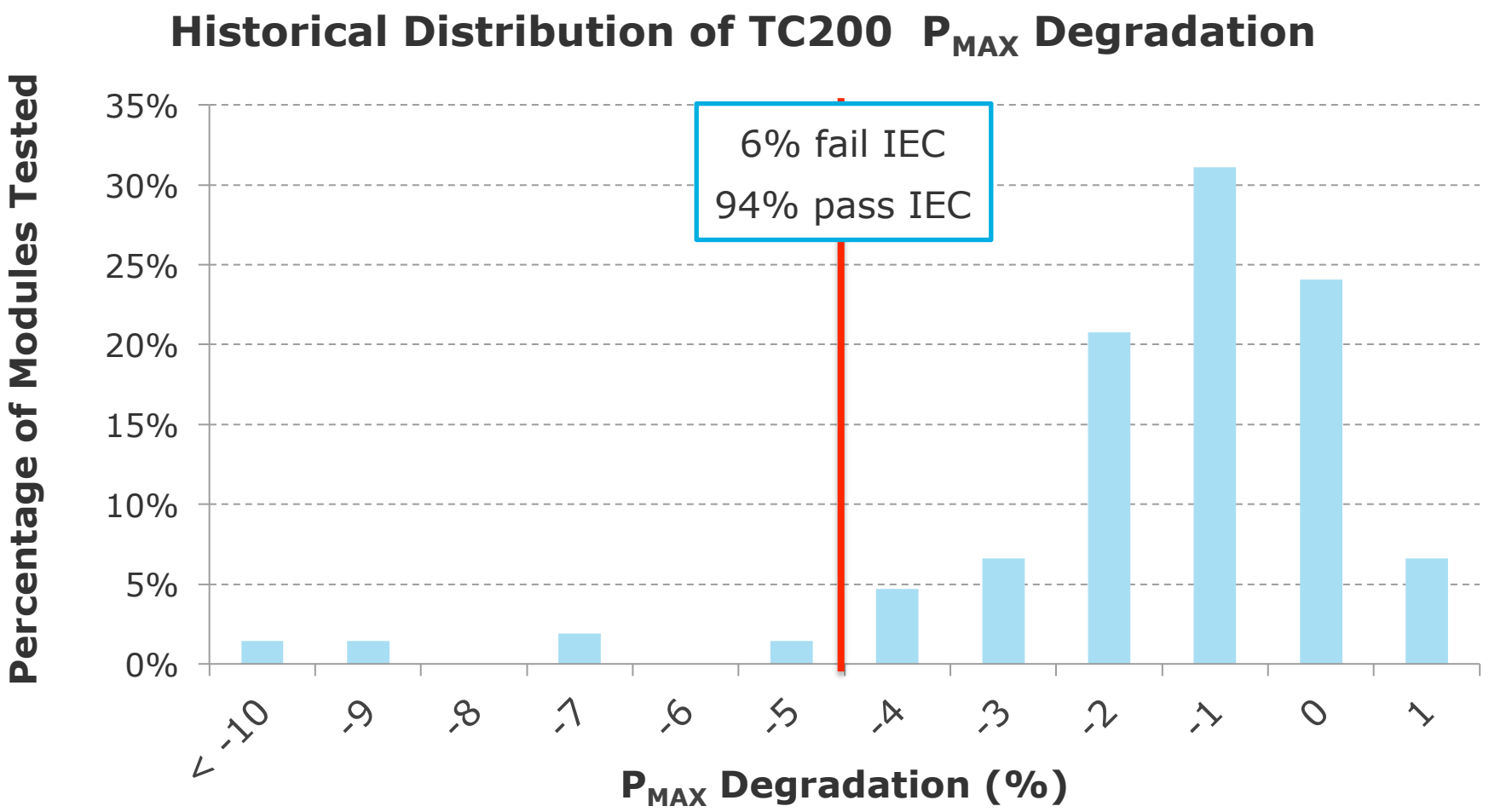
- **Reliability Tests**

	Thermal Cycling	Damp Heat	Humidity Freeze	UV Exposure	Mechanical Load	PID
DNV GL Qualification Test	800 TC cycles	3,000 DH hours	30 HF cycles	90 kWhs of UV	Dynamic Load	600 hours
IEC 61215 Standard	200 TC cycles	1,000 DH hours	10 HF Cycles	15 kWhs of UV	Static mechanical load	None

- **Performance Tests**
  - PAN Files: for energy estimates in PVSyst or Helioscope
  - IAM: Incidence Angle Modifier
  - LID: Light Induced Degradation

DNV·GL

Lab Experience



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DNV GL Qualification Expertise

- Our Product Qualification Program covers
  - Modules
  - Inverters
  - Racking

- Contact me to sign up if you are an
  - Equipment Manufacturer
  - Buyer
  - Investor

- Jenya.Meydbray@DNVGL.com

Update of PVQAT Task Groups— TG leaders 10.35 am to 12 Noon

Govind Ramu (SunPower Corp.) TASK GROUP 1

National Comments (Issued 12/4/2014 by Project Leader)

1	USA	27
2	CH	7
3	CN	19
4	CA	10
5	JP	6
6	DE	3
7	FR	1
8	IT	1
9	NC	1
10	PT	1
11	ZA	1
	Total	77

	P-members	O-members	Non-members	Total
Y : comments received	11	0	0	11
N : no comments	21	5	1	27
- : no response	3	8	0	11

Editorial	15
General	22
Technical	39
Other	1
Total	77

Courtesy: Yoshihito Eguchi-san

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Draft Standard Comments – an Important Update

- Request to add Audit Checklist to conduct certification audits:
  - There is a general consensus among the core team. However following are the 3 major deployment questions:
    - Should the checklist in Annex D be included as an Annex in IEC 62941?
    - If so, should it be informative (for information) or normative (required as a minimum requirement?)
    - Would the checklist be more useful if it included some optional questions that help define a stronger QMS?
  - See Pros and Cons in the following slides

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Question 1

YES '

Should the checklist in Annex D be included as an Annex in IEC 62941? '

PRO	CON
Consistent auditing across auditors and certification bodies. Improves audit effectiveness.	Audit focus shifting from actual audit to filling up lengthy checklists
Auditors don't skip any requirements inadvertently	Auditors spending vast majority of time in the meeting rooms and not walking through the manufacturing
Tool to collect evidence of compliance and audit notes – a traceable record for subsequent auditors to review and audit changes.	Auditor may not probe deeper using "process approach" . Tendency to just ask top level questions only from the checklist.
Auditor training aid on PV QMS standard requirements	Increase in Audit days (to accommodate audit and checklist documentation completion)

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Question 2

Normative '

Should the checklist be provided as a suggested guide (referred to by IEC as “informative”) or as a minimum requirement (referred to by IEC as “normative”)?

Normative	Informative
Set minimum requirement for certification. Expected to complete as part of the audit process	Act as a guideline for requirements. Optional. Certification bodies may or may not use the checklist.
Consistency	Plausible Inconsistency
The certifying bodies are accustomed to developing their own checklist and a requirement of using a specific checklist may be objectionable to them.	Flexibility in application of certification body’s own developed checklist.
Foundational ISO 9001 requirements are not mandated to have a checklist. This may result in auditors conducting audit partially with checklist and partially without checklist. Possible tactical issues.	Align with same expectation as foundation ISO 9001. Certification bodies that required checklist for 9001 from their auditors will embrace PV QMS Checklist irrespective of whether it is normative or informative.

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Question 3

Additional rigor questions informative '

Writers identified multiple ways to strengthen IEC 62941 by asking more rigorous questions. Would the checklist be more useful if it included some optional questions that help define a stronger QMS?

PRO	CON
If informative, the additional rigor questions will be helpful to organizations as a collective knowledge of experience from broad range of Solar PV experts.	If normative, the additional rigor questions will become new requirements. This will require adding these requirements back to standard
Help address known failure modes in the industry. Helps with learning curve for new manufacturers	Organization may have to pay additional cost to conduct full coverage of checklist including “additional rigor” questions
Helps organization to reach higher levels of maturity. Raises the bar among manufacturers	Require additional guidance and training to ensure the “rigor questions” are well understood, consistently across the auditor community.
Potentially help organization achieve higher grading of QMS (once QMS Comparative ratings are rolled out)	May increase operational cost if not well understood and deployed

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Auditor Training '

- Key components of auditor training
  - Basic qualifications
  - Experience (QMS and PV industry)
  - Auditing experience (First party, second party, third party)
  - Keeping auditing experience current (Audit log)
  - Knowledge and experience in interpreting outputs of Quality Engineering applications (e.g. FMEA, SPC, MSA, etc.)
- Auditor training Material
  - Interpretation guidelines
  - Consistent training, periodic qualification as requirements change
  - Develop criteria for qualifying training organizations.

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Back up slides '

Certification Roll out Brainstorm (1/2) '

- Identify PV Module Manufacturing QMS certification body.
  - Proposed minimum criteria: Renewable energy division, international presence, accreditation of ISO 9001 certification
  - Process for periodic renewal and conditions for termination
  - Develop certification logo as proof of qualification to train, audit or certify to this standard.
  - Develop presentation for certification body to consider this standard as product offering. (Finance community backing of this standard as criteria/preference for contract bid).
  - Develop Market potential business case - PV Module manufacturing new registrations+ PV Module Manufacturing with existing ISO 9001 registrations.
  - Invite certification bodies to a seminar to launch this new standard.
  - Invite applications from registration bodies for review.
  - Approved registration bodies
  - Legal process and paperwork
  - Periodic renewal, termination, compliant management
  - Decide how to pay for the administration body- (Portion of certification fee or member organization annual fee or Govt. funding)

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Certification Roll-Out Brainstorm (2/2) '

- Define Auditing process including:
  - Process: Audit person days -offsite, onsite, multisite, certification, surveillance, recertification, decertification
  - Auditors qualification: QMS audit expertise, PV Module experience + complete PV QMS training, pass exam OR PV Module experience + complete PV QMS training, pass exam accompanied by an experienced QMS expert auditor + typical certification body requirements
- Auditor training:
  - PV QMS interpretation document
  - Develop criteria to qualify training organizations
  - Manage certification of training organization and periodic renewal
- Quarterly, Annual Performance reporting on the overall process
- Certification and Training Volunteer committee – Annual or biannual term. (To oversee overall process)

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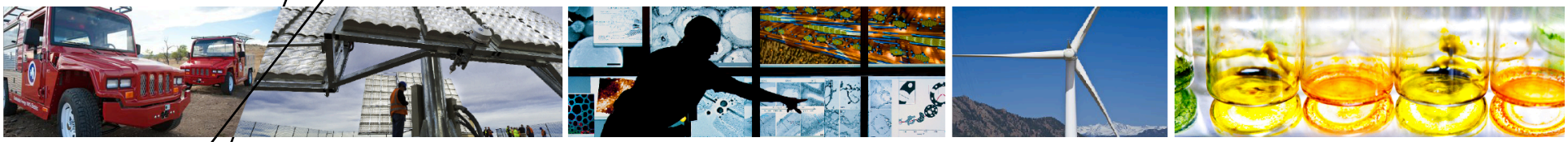
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

PVQAT
TG2 Update



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.

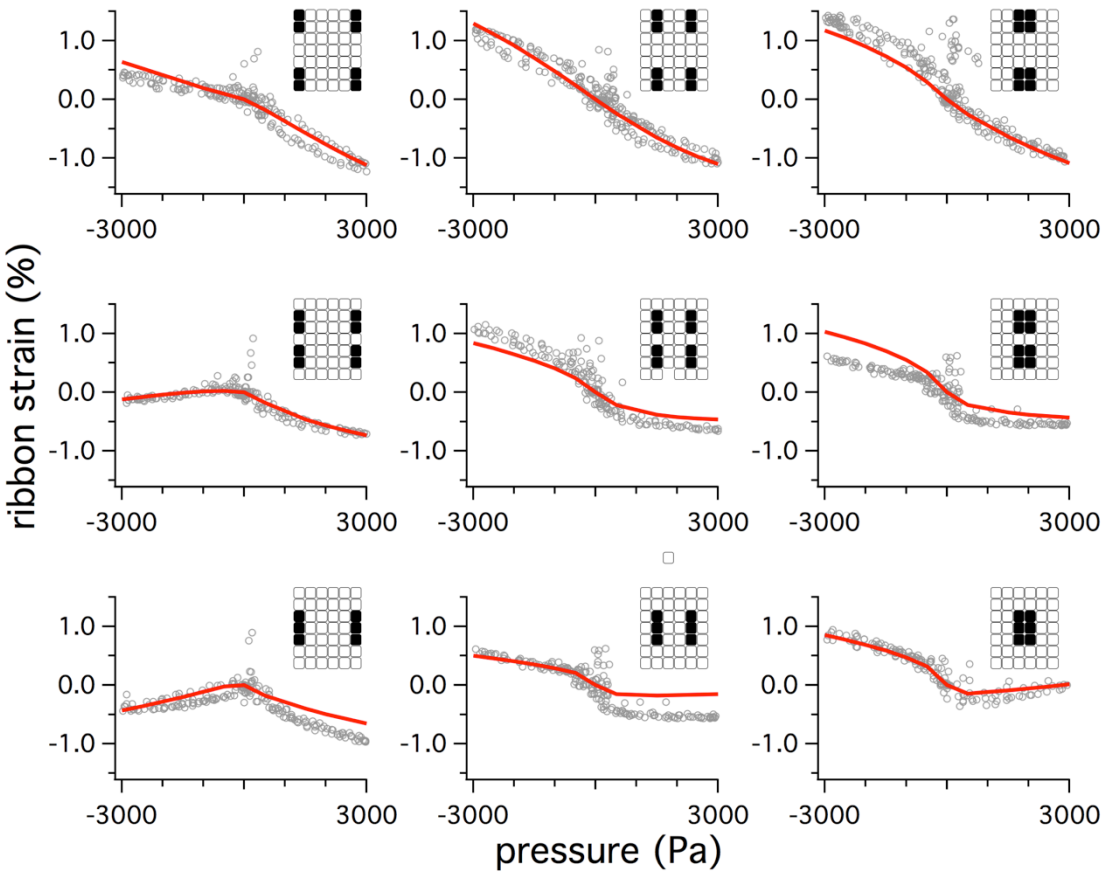
directive

Thermal and Mechanical Fatigue

- What are the appropriate number of thermal cycles for a long-term reliability test
- Should this number be climate specific
- What is the effect and appropriate level of DML testing

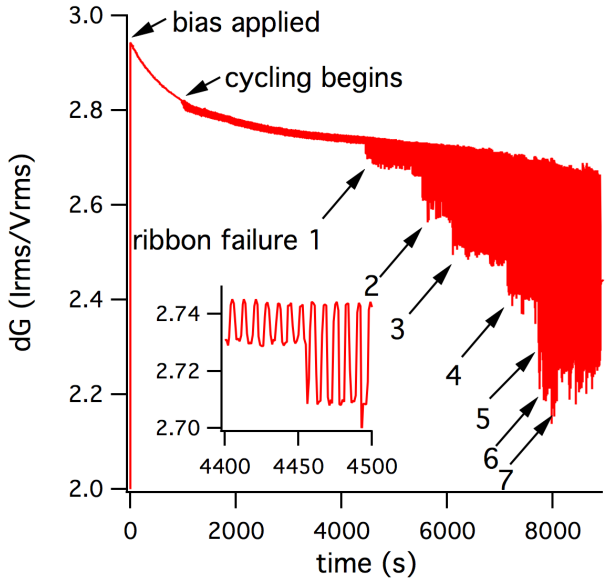
DML: FEM and mechanical loading

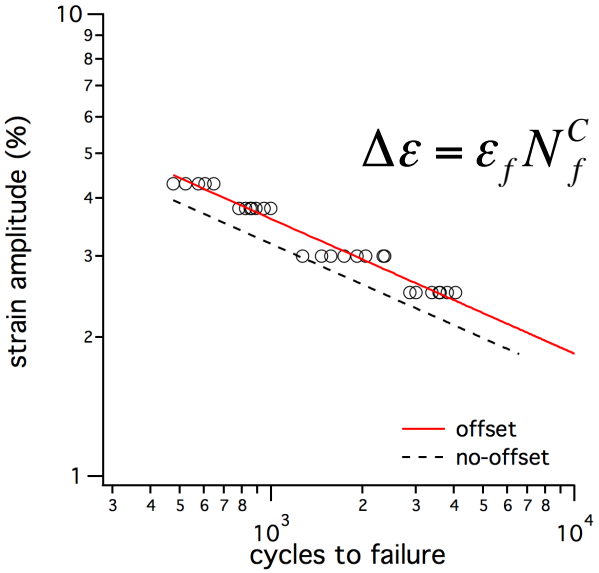
DML fatigues ribbon interconnects



cell-to-cell strain
–3 kPa to +3 kPa
measured and simulated

dynamic mechanical loading





Thermal Cycling

$\Delta\varepsilon_{105C} = 2.5\%$:

$N_f^{offset} = 3726$

$N_f^{no-offset} = 2420$

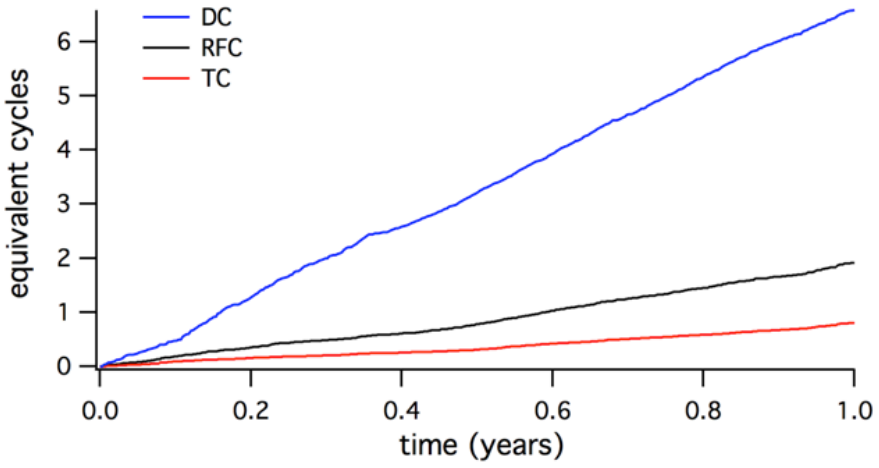
Poster 43:

In-situ impedance measurement in c-Si PV modules during rapid thermal cycling

ESPEC $N_f \approx 3000$

Failures only evaluated during in-situ measurement

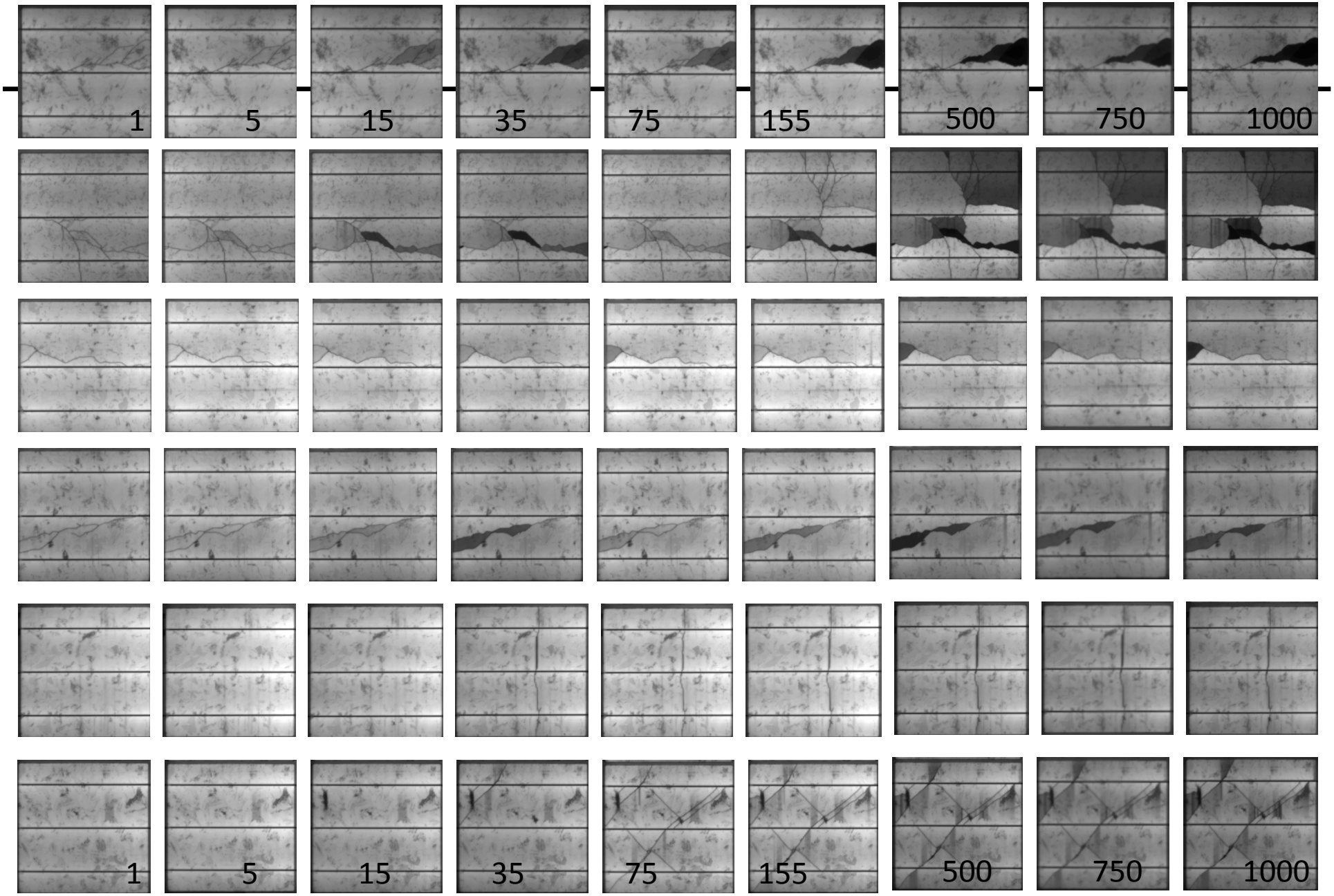
thermal cycling and service



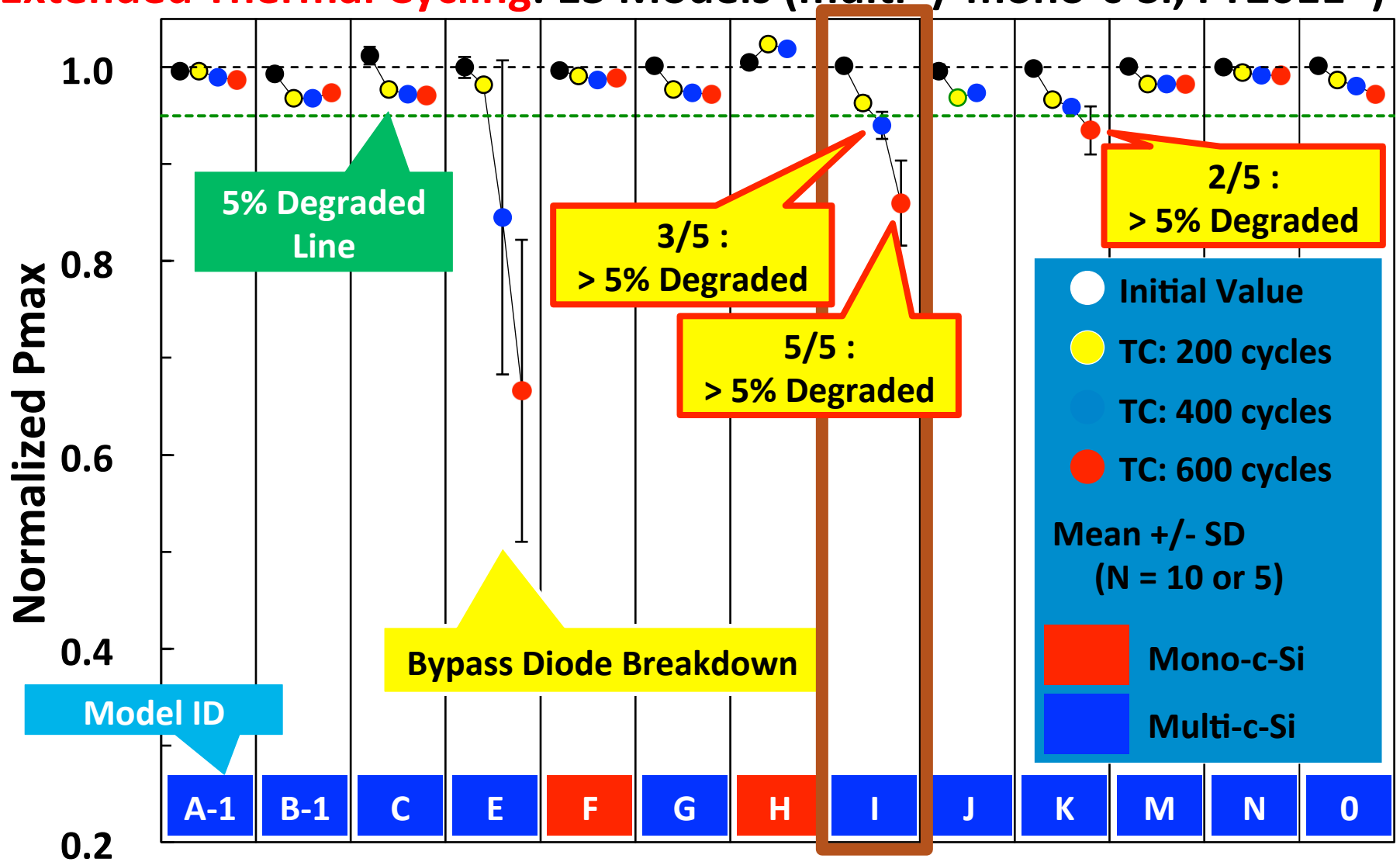
Normalize by the number of cycles to failure for the ± 1kPa DML cycle or the IEC TC cycle

25 years is equivalent to less than 175 cycles

*This evaluation must be qualified for the specific module evaluated.


1
5
15
35
75
155
500
750
1000
1
5
15
35
75
155
500
750
1000

Extended Thermal Cycling: 13 Models (multi- / mono-c-Si, FY2011~)



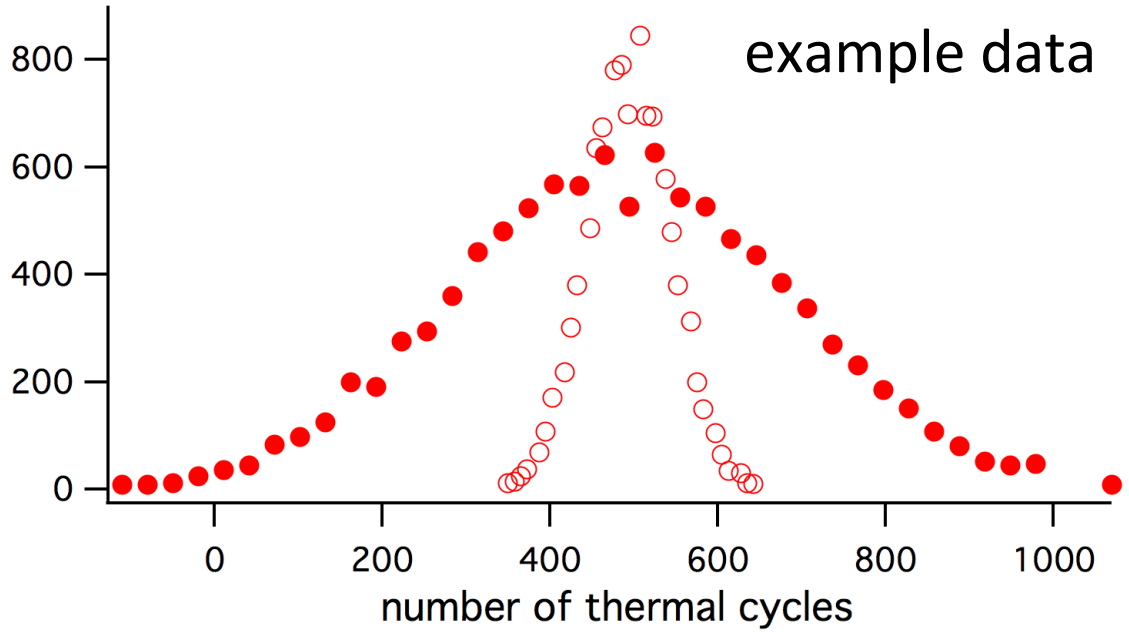
Asia Standards and Conformity Assessment Promoting Project (JP), 2011-2014

thermal cycling: current work

Uncertainty analysis:

Monte Carlo simulation

Laminate material properties and geometry



PVQAT TG2

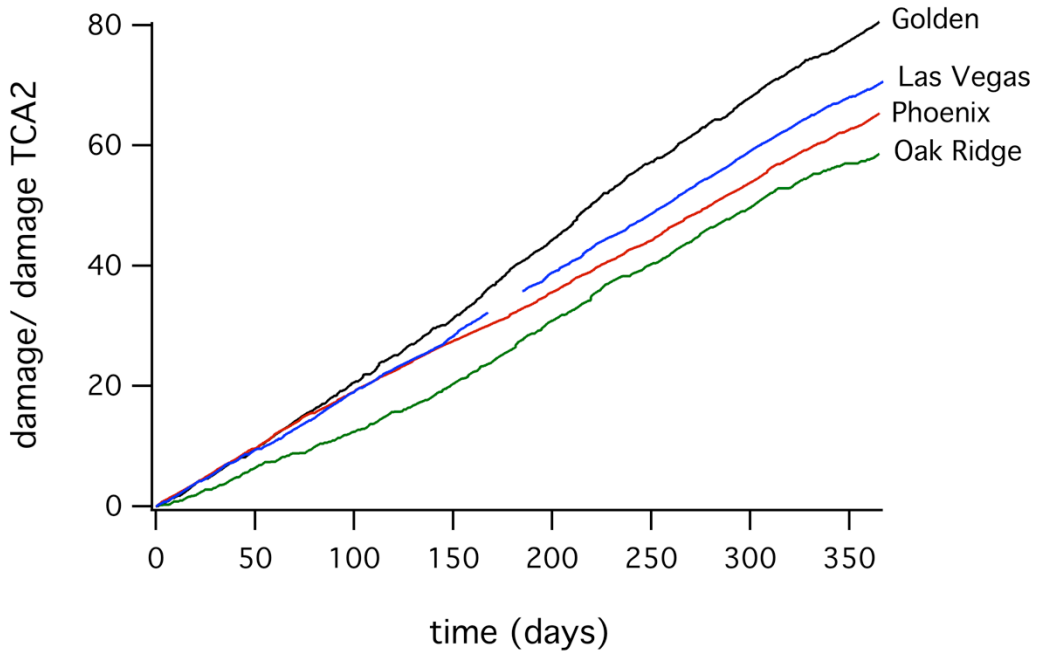
TC: 500 independent of climate zone

DML: ±1kPa, 1000 cycles in UV/TC/HF/DH sequence

Challenge: Failures are typically due to a quality excursion

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

simulating an entire year



A year in Oak Ridge, Tenn. does 70% as much damage as a year in Golden, Colo.

Update on the activities of PVQAT Group 4: Diodes, Shading and Reverse Bias

Vivek Gade — Jabil, representing the Americas
Paul Robusto — Miasole, representing the Americas
Yasunori Uchida — JET, representing Japan
Hubert Volz – Multi-Contact Essen, representing Europe
Jos Van Loo – Diotec Europe
Xian Dong — Zhongshan University, representing China
Chandler Zhang — Hohai University, representing China

US Task Group 4 Update

IEC Technical Specification on ESD

- A technical specification/Guideline: IEC 62916 was approved in early 2014
- IEC 62916 was sent out Jan 21, 2015 for final review and will become a draft technical specification

Model for Predicting Vulnerability of Diodes to Thermal Runaway

- Vivek Gade and Narendra Shiradkar have developed a theoretical framework for assessing the vulnerability of bypass diodes for thermal runaway based on the diode datasheet parameters.
- Currently options of incorporating this into NWIP on thermal runaway proposed by Japanese group are being explored.

Thermal Runaway Testing at SunEdison

- Kent Whitfield and Shuying Yang at SunEdison tested various diodes for thermal runaway at ambient temperatures of 50 C and 90 C and forward current equal to 1.25 x Isc
- It was concluded from the experiments that the condition of ambient temperature= 90 C and short circuit current equal to 1.25 x Isc in the thermal runaway test draft maybe too harsh and a somewhat lower ambient temperature maybe better.

US Task Group 4 Update Continued..

Estimating Field Stressors Affecting Bypass Diodes

- Models are being developed at Jabil to estimate the field stressors (TJ and ΔTJ) during service life of bypass diodes as a function of shading configuration and TMY data of various locations.
- Outdoor experiments are being performed on a rooftop array in Florida to monitor the diode junction temperature for model verification.

Thermal Resistance Measurement of Bypass Diodes / Junction Boxes

- Thermal resistance (Junction→Ambient) has been measured using 1-Dimensional heat conduction model for 9 different types of bypass diode / junction box samples at various ambient temperatures and forward currents.
- It is shown that the thermal resistance (Junction→Ambient) at standard conditions (say Tambient = 25 C, If = 10 A), can be used to quantify heat dissipation properties of various junction box designs (Poster #32 at PVMRW 2015)

Extended Bypass Diode Test According to Qualification Plus

- Extended bypass diode test as described in the Qualification Plus Standard (Ambient temperature = 75 C, I = Isc, Duration = 96 hours) is being carried out at Jabil on 9 different types of bypass diodes / junction boxes.
- This test is expected to generate useful representative data for describing the effect of Extended Bypass Diode Test on various sample types.

Thermal Cycling With Current Through the Diodes

- It was proposed that during thermal cycling test, current should be cycled through the diodes for last 50 thermal cycles
- Experiments have been initiated at Jabil to understand the effect of such thermal /current cycling on diodes.

Japanese Task Group 4 Update

- **NWIP on Thermal Runaway**
- Diodes can undergo thermal runaway during forward bias to reverse bias transition when the shading is suddenly removed.
- NWIP draft for "Thermal runaway test for bypass diodes" was submitted by team from Japan to TC82/WG2 and it has been accepted.
- Preparation of special measuring equipment for establishing Vf-Tj relation to calculate Tj has been undertaken by the team from Japan
- It has been shown that the VF-TJ method is more elaborate and accurate method of junction temperature measurement.
- The difference between the junction temperatures measured using VF-TJ method and Tlead method could be close to 10 C. (Poster # 46 at PVMRW 2015)

European Task Group 4 Update

- Hubert Volz has proposed a method for characterizing the forward I-V properties of the bypass diodes in a junction box in design phase.
- This method can be used for determining the current rating of the new junction box designs.
- The method involves holding the junction box at various temperatures in oven and passing known about of current through the diode for a short duration to measure the forward voltage.
- Data is then extrapolated to get the I-V characteristics of diodes at other temperatures.
- They have also proposed a thermal model for junction box based on various thermal resistances.

Chinese Task Group 4 Update

- The Chinese regional Task Group 4 was started in July 2014, with 22 participant organizations, including diode manufacturers, junction-box manufacturers, module manufacturers, system installers, universities, and testing and auditing organizations.
- The Chinese Group has initiated efforts to:
  - Define a diode test to be used to confirm that a diode is good, since sometimes the diodes increase in resistance without failing completely in the open or shorted configuration.
  - Define a high temperature durability test for diodes.
  - Support international efforts already underway on ESD and thermal runaway associated with the transition between the forward and reverse bias conditions.
- It has been decided to arrange quarterly conference calls between the Chinese group and the US group in order to coordinate the efforts.

Goals of Task Group 4

PVQAT Task Group	2014 Status	2015 Goals	2016 Goals
Task Group 4	1. ESD Technical Specification IEC 62916 is under review 2. NWIP on Thermal Runaway was approved	1. Complete IEC 62916 2. Revise thermal runaway test specification 3. Experiments to support TG2 initiative of diode thermal cycling testing in leg #1 4. Submit NWIP on high temperature, reverse bias endurance testing of cells	1. Complete the test standard for Thermal Runaway 2. Complete the test standard for high temperature, reverse bias endurance testing of cells

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Status Update PVQAT Task Group 5

Presenter & US TG5: David.Miller@nrel.gov;
China TG5 : fjt79@163.com (Leo Feng, CEI);
Europe TG5 : michael.koehl@ise.fraunhofer.de;
Japan TG5: Tsuyoshi.Shioda@mitsui-chem.co.jp

NREL PV Module Reliability Workshop
Golden Ballroom Salons A-D, Denver Marriott West, Golden, CO
Weds, 2015/2/24

- This presentation contains no proprietary information -

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

- IEC qualification tests (61215, 61646, 61730-2) presently prescribe up to 137 days field equivalent (IEC 60904-3 AM 1.5) UV-B dose. This is << 25 years!
- **Goal**: develop UV- and temperature-facilitated test protocol(s) that may be used to compare PV materials, components, and modules relative to a field deployment.

Core Activities:

1: Consider weathering literature and climate meteorology (*location-dependent information*).
   e.g., known benchmark locations…Miami, FL; Phoenix, AZ
2: Leverage existing standards, including other industries.
   - summary exists from Kurt Scott *et. al.*
3: Improve understanding of existing PV UV tests.
4: Improve understanding of module durability.
   4-1 Collect information about field failure modes.
   e.g., the literature, site inspections
   4-2 Confirm appropriate models for UV aging.
5: Consider suitable UV sources.
   - summary of *module* capable equipment from David Burns *et. al.*
6: **Generate test procedure for accelerated UV aging.**
   Presently performing experiments to provide technical basis & confident decisions.
7: Perform laboratory verification of proposed test standard/failure mode.
   - mini-module study (Japan), SoPhia round-robin (Europe), E_a interlaboratory study (US)

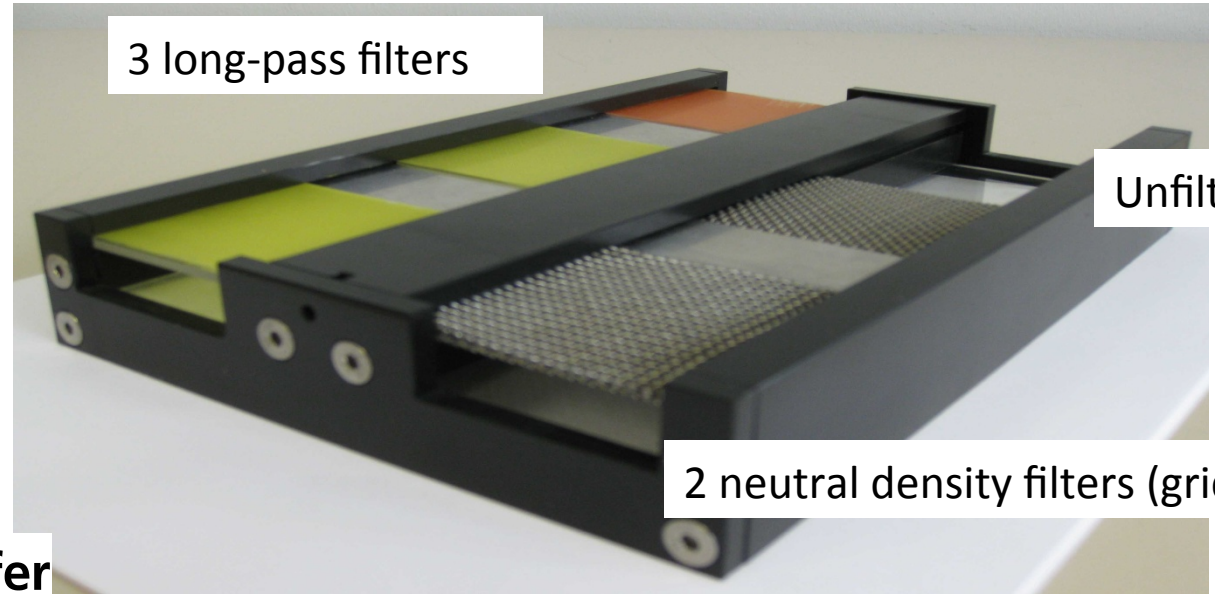
China TG5: Plan for Activities

- Formed in 2014.
- Presently formulating plan based on input from 2014.
- Will compare indoor & field aging.
- Analyze meteorological conditions in China vs. other world locations.
- Outdoor sites:
  - QiongHai (HaiNan province, hot & humid)
  - Turpan (XinJiang province, hot & dry)
- Expect to conduct experiments examining materials and components (likely encapsulation and backsheet). May use coupons and mini-modules.

UV – Round Robin Samples (experiment on going)

SOPHIA European Research Infrastructure

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



Fraunhofer ISE

- Backsheet R-R continues. Expect dissemination of results soon.

Japan TG5: Mini-Module Experiment, Applied Stress Sequence

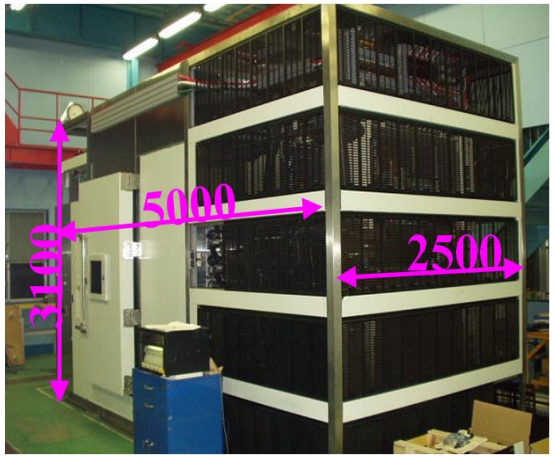
UV weathering test of 4-cells small size module

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

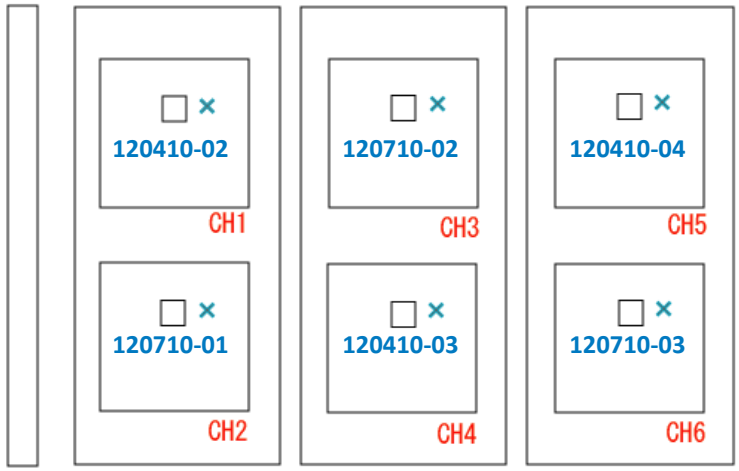
Encapusulant ･･･ EVA (fast cure)
EVA A ･･･ Within the shelf life
EVA B ･･･ Over the shelf life



Sample ID and Test sequence

ID	EVA	UV330h 1st RUN	UV660h 2nd RUN	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	→	→

Module layout in the UV chamber



X: Thermocouple gage
☐ : Junction BOX

Japan TG5: Activities

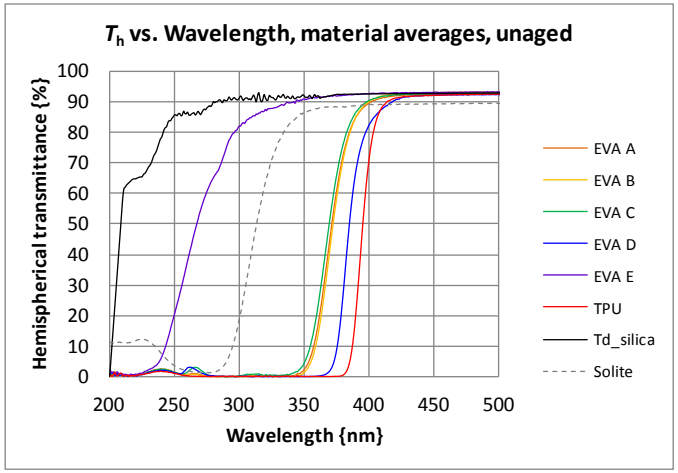
- Early effort examined the sequence of applied stress (*e.g.*, UV → aging sequence → DML; or UV → aging → DH).
- Different results (I/V, discoloration) were obtained, depending on the sequence of stress applied.

- Recently: examination of fielded modules.
- Interest in delamination.

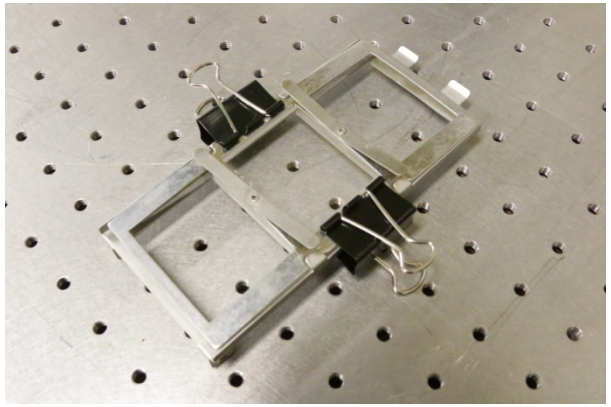
- Have started second mini-module experiment.
- This also examines the sequence of applied stress tests.
- Wet leakage test has become of interest as pass/fail.

US TG5: Details of the E_a Methods and Experiment: Encapsulation Transmittance Test

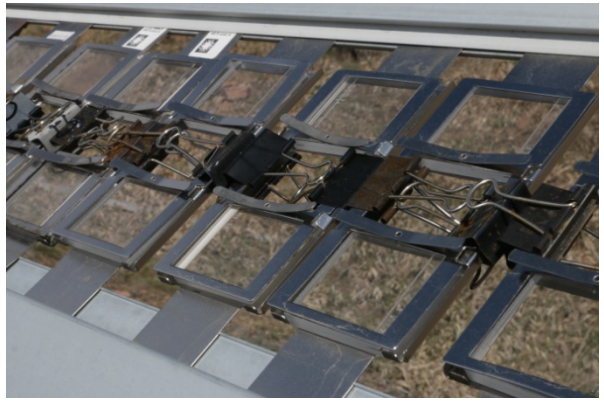
- Glass/polymer/glass coupon specimens measured using a spectrophotometer (with integrating sphere)
- Measure at specimen center (anaerobic, no O_2) and edge (aerobic)
- Analyze: solar-weighted transmittance, yellowness index, and UV cut-off wavelength.



Transmittance will be examined using silica/polymer/silica samples.



Specimen in sample holder for indoor aging at NREL.



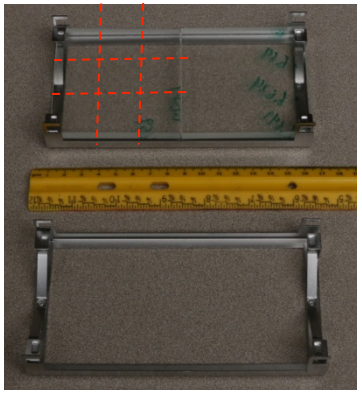
Specimens on outdoor rack, aging in Golden, CO at NREL.

User summary:

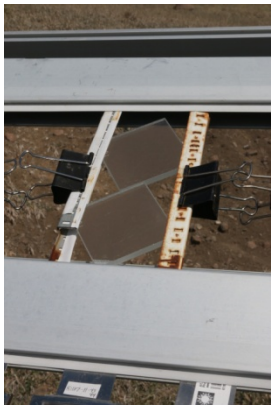
- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm)
- Size: 2” x 2”
- Quantity: 3 replicates of 6 materials (pre-conditioned), and 1 reference (not pre-conditioned)
- Aging: 0, 15, 30, 45, 60, 75, 90, 120, 150, 180 cumulative days (indoors) or 0, 1, 2, 3, 4, 5 years (outdoors)
- Measurements (non-destructive): repeatedly age and measure at each laboratory/test site

US TG5: Details of the E_a Methods and Experiment: Encapsulation CST Adhesion Test

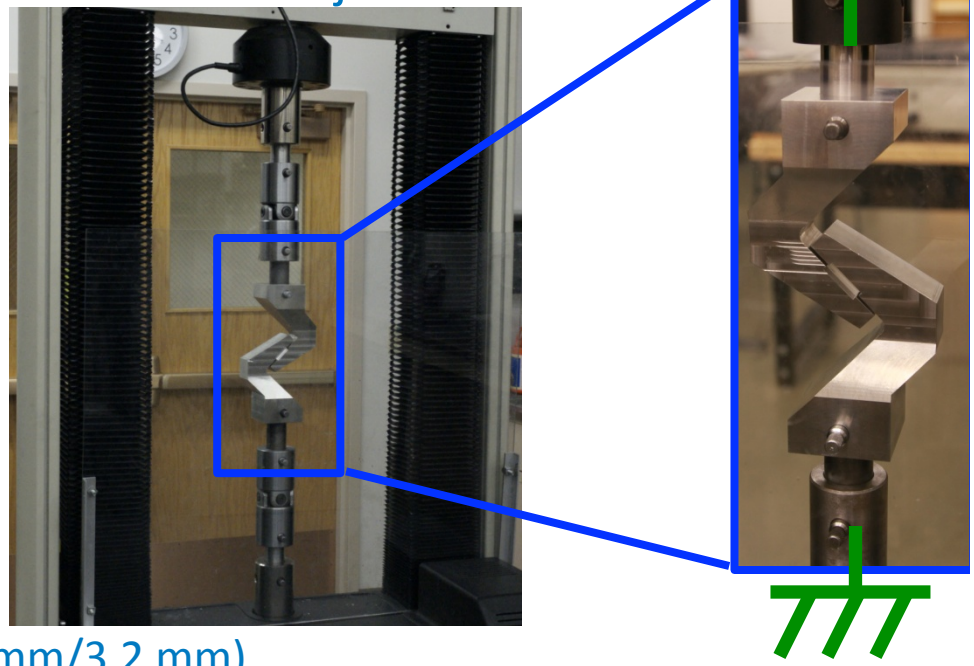
- Better physics-based methods being developed as IEC standard.
- 25 mm square specimens (diced, after aging) examined using loadframe.
- Pristine edge quality is critical. Dice using abrasive water jet cutter.



Sample holder configuration for indoor aging at NREL. Samples are diced after aging.



Specimens on outdoor rack, aging in Golden, CO at NREL.



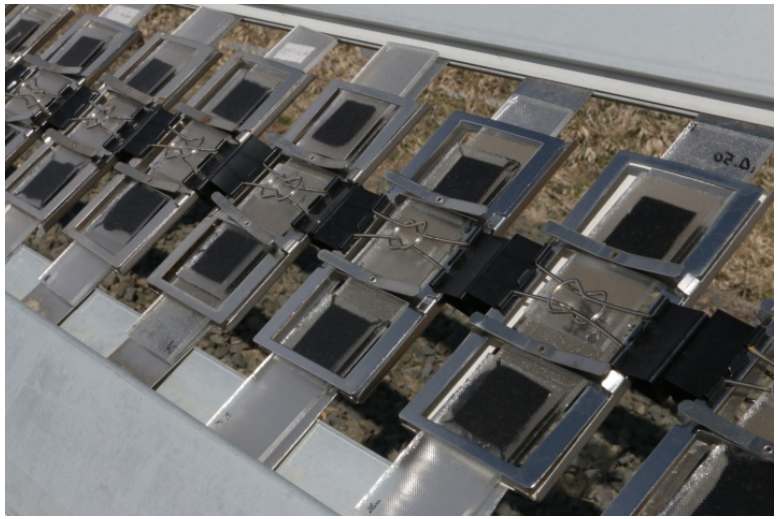
The CST will be used to examine the attachment of EVA. Method from: Chapuis et al., PIP, 22 (4), 2014, pp.405–41. (EPFL)

User summary:

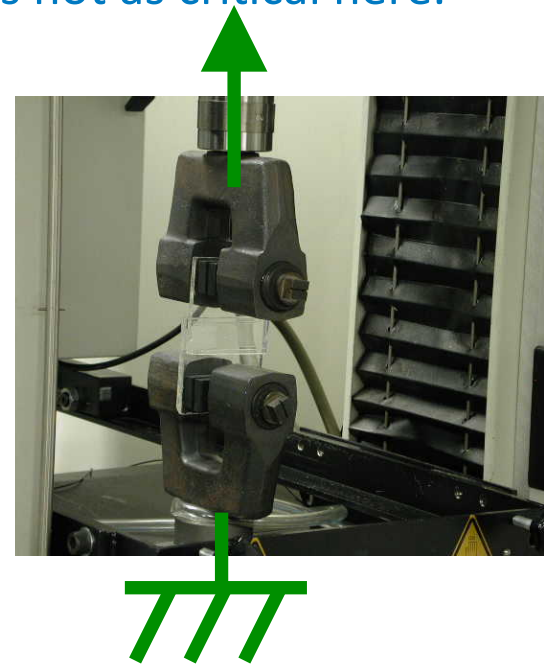
- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm)
- Size: 3” x 3”
- Quantity: 10 replicates of 1 material (pre-conditioned), plus 5 extras (not pre-conditioned)
- Aging: 15, 30, 45, 90, and 180 cumulative days (indoors), or 1, 2, 3, 4, 5 years (outdoors)
- Remove 2 coupons at each increment
- Measurements(destructive): age at each laboratory/test site, then sent to NREL for measurement

US TG5: Details of the E_a Methods and Experiment: Edge Seal Lap Shear Adhesion Test

- Lap shear is the standard test method for RTI and other certification protocols.
- Edge quality (handling of the glass specimens) is not as critical here.



Specimens on outdoor rack, aging in Golden, CO at NREL.

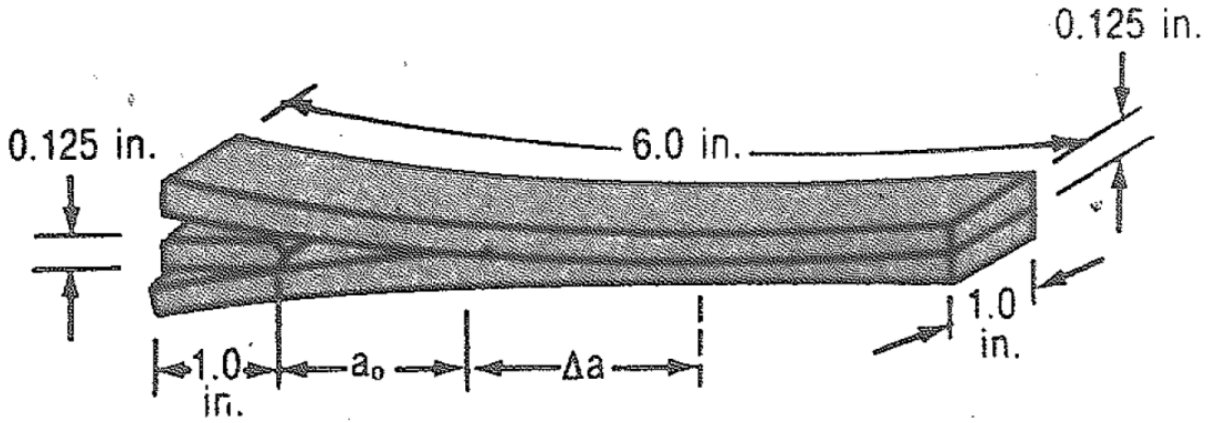


Testing Summary:

- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm). 25 mm X 25mm test area.
- Quantity: 10 replicates of 2 test materials
- Aging: 15, 30, 45, 90, and 180 cumulative days (indoors),
  or 0.5, 1, 2, 3, 4, 5 years (outdoors)
- Remove 2 coupons of each material at each increment
- Measurements (destructive): aged at each laboratory/test site,
  then sent to NREL for measurement
- Use a displacement rate of 10 mm·min^{-1}. Record σ_{max}, ε_{max}, and failure mode.

US TG5: Details of the E_a Methods and Experiment: Edge Seal Wedge Adhesion Test

- Fracture mechanics test for interfacial adhesion ($J \cdot m^{-2}$), not an attachment strength test ($N \cdot m^{-2}$ or $N \cdot m^{-1}$) .
- Specimens will be examined visually and using a micrometer.



G = Fracture Energy

$$G = 3Et^3 h^2 / 16a^4$$

A DCB wedge test will be used to examine the attachment of edge seals.
Marceau *et al.*, Adhesives Age, 1977, 28-34.
Also: ISO 10354, ASTM D3762.

User summary:

- Geometry: glass/polymer/glass (3.2 mm/0.5 mm/3.2 mm)
- Size: 1” x 9”
- Quantity: 2 replicates of 2 test materials
- Aging: 0, 15, 30, 45, 60, 75, 90, 120, 150, 180 cumulative days (indoors) or 0, 0.5, 1, 2, 3, 4, 5 years (outdoors)
- Measurements (semi-destructive): aged and measured at each laboratory/test site

Timeline of Activities for TG5

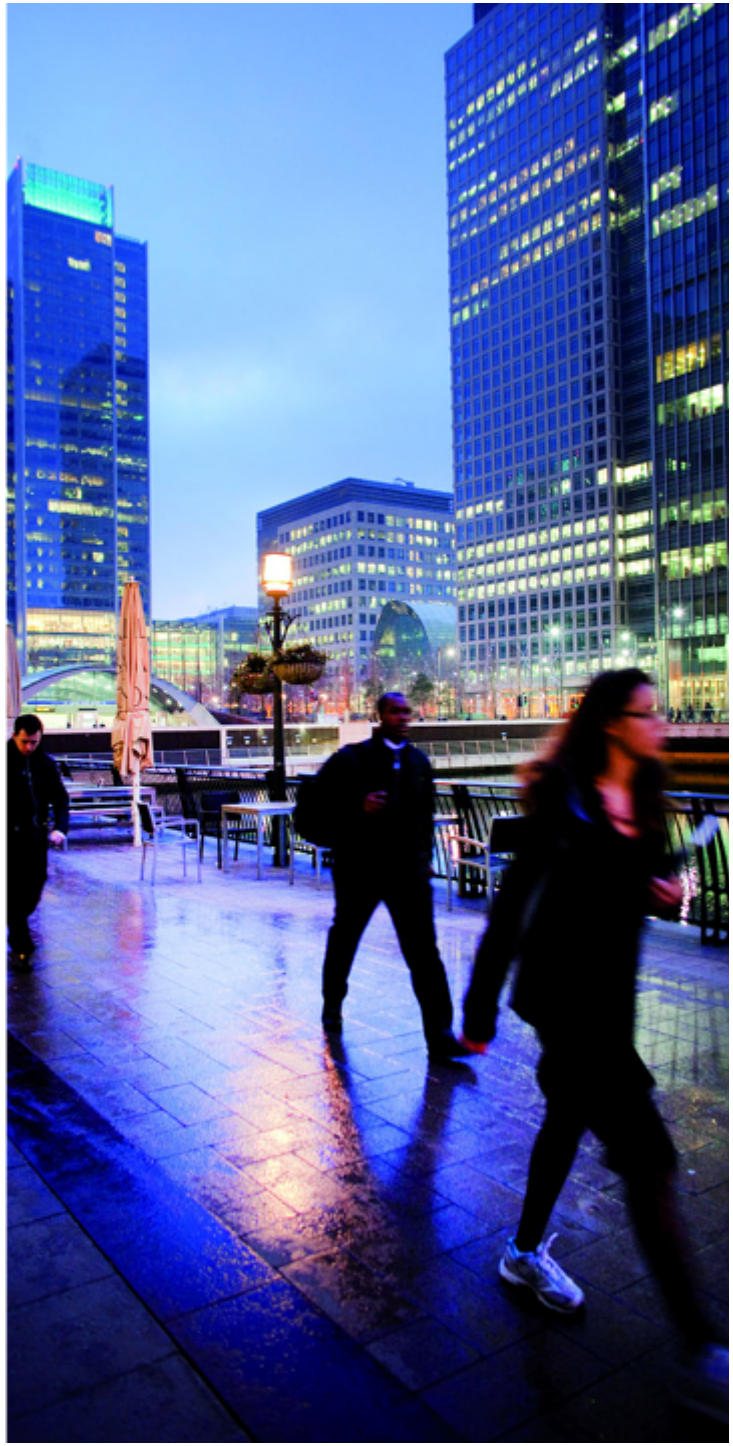
- NREL specimens are presently at 150 days (Ci5000) and 180 days (UV suitcase).
- Results will be used to assign t, T, %RH for a climate- & configuration-specific UV test.

	Qualification	QMS	Climate- & Configuration-Specific Test	Service Life Prediction
Current status	Issued as standards	Revised NWIP submitted	Proposed as concepts	Concepts
2014 goal	Submit 61215 (Ed 3) 61730 (Ed 2)	Publish new TS	Initiate E_a test. Create strawman UV standard.	Develop criteria to evaluate QMS related to service life; NWIP
2015 goal	Publish new editions	Start use of the TS in factory inspection	Submit UV standard NWIP. Create strawman test sequence standard. Complete indoor E_a test.	
2016 goal		Revise QMS document to reflect feedback	Publish E_a results. Submit CD of UV standard.	
Chamber test times	Modules: ~ 6 weeks	TBD	~6 months	~18 months

PVQAT WG12
Soiling and Dust

25th february 2015

Mike Van Iseghem & Sarah Kurtz



WHAT'S NEW FROM THE SOILING WG SINCE NOV '14

Activity

- 1 or 2 audio web confs per week
- Wiki on pbworks very usefull

New structure

- participant list (~90 people) in 4 areas

LATEST STRUCTURE SOILING WG

Indoor tests simul deposition, durability ARC

Model for dust and soiling – Predict

Soiling sensors – Quantify loss, chemistry

Cleaning Solutions – Operational issues

POTENTIAL GOALS SOILING WG

2015 - Extra participation needed from areas like

- cleaning solutions - operations
- aerosoles and deposition - CSP people
- climat, géology - academics

2015 - Prepare cleaning standards, criteria agreed between

- operational cleaning solutions
- module manufacturer – ARC durability

2016 – Models to become less site specific

PVQAT #12 SOILING AND DUST

Wiki

- on pbworks.com (account request if not registered yet)

http://pvqataskforceqarating.pbworks.com/w/page/87300091/Soiling%20and%20Dust

Contains « list of participants » in PVQAT#12

- open xlsx file ; some pb for updating lines and « X » in our current list of categories; any suggestion for improvement welcome (MS onedrive, …?)

Organisation

- Sub-WG3, 5 and 6 were joined (antiSoiling coatings, indoor tests and ARC durability
- We are a self supported group, entirely based on volonteers, always in need of extra volonteers, on specific issues, « from doodle to sub-WG leader »
- Bridges towards dust and soiling CSP, potentially a new WG

Your contacts

- Mike Van Iseghem, EDF R&D, based just south of Paris
- Sarah Kurtz, NREL, near Denver, Colorado

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 by establishing an international standard.

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 propose new items to be considered for standardization and play a role in the evolution of the standards. Furthermore it allows you to contribute to the technical accuracy and applicability of the standard.

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 participation 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 either one or both of the following people, and expressing your interest with a short description of your expertise and providing your official contact and billing information. George, 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

Both of us will be happy to assist you.

Effect of QUV A with Thermal Cycling Exposure on PV Backsheets

Amy Lefebvre, Greg O'Brien, Ron Partridge, James D. Knapp, Bryan Douglas, Gunter Moeller, Dana Garcia
Arkema Inc. King of Prussia, PA

Introduction

- PV backsheets are the only insulation that can be "relied upon" on the backside of a module per the new IEC standard working group.
- Backsheets must be shown to be weatherable over the expected module lifetime.
- Current test standards, including IEC 61215, require only a minimal amount of UV exposure.
  - Less than three months of direct exposure in Miami, Florida.
- Constant temperature QUV A accelerated testing on backsheets has resulted in degradation of the polymer matrix, pitting, microcracking, and accumulation of pigment on the outer surface.
- Larger scale cracking and delamination has not been observed in the accelerated testing - but has been observed in fielded modules.
  - This could be due to the thermal cycling seen in the field that is not present in constant temperature accelerated QUV A conditions.
- **The objective of this poster is to report on preliminary results from QUV A exposure testing conducted with thermal cycling on PV backsheets.**

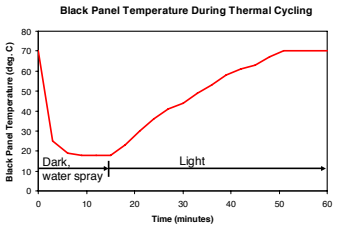
Accelerated Weathering Conditions

Accelerated Testing Conditions:

QUV A with Thermal Cycling	Irradiance at 340 nm	Temperature (black panel)	Duration	Water
Light Period	1.55	70 deg. C	3.25 hrs.	none
Dark Period	none	see figure	0.25 hrs.	water spray
		50 deg. C	3 hrs.	condensation
Total Cycle Time			24 hrs.	

Repeat 6 times before condensation period.

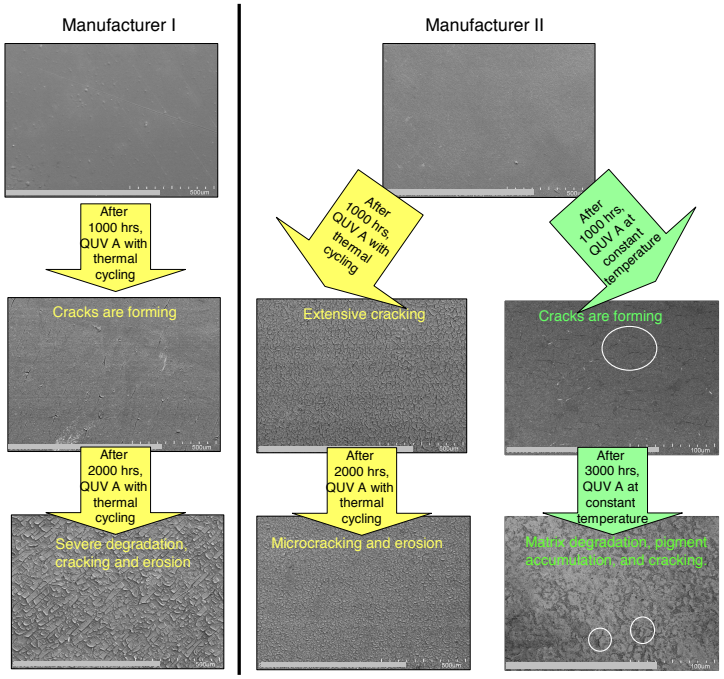
QUV A at Constant Temperature	Irradiance at 340 nm	Temperature (black panel)	Duration	Water
Light Period	1.55	60 deg. C	8 hrs.	none
Dark Period	none	50 deg. C	4 hrs.	condensation
Total Cycle Time			12 hrs.	



Backsheet Materials Tested:

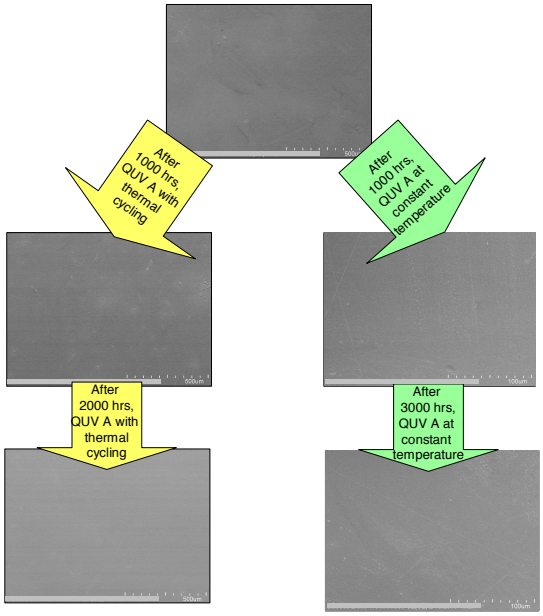
- KPE® Backsheet – Kynar® film/PET/EVA backsheet
- PPE Backsheet – PET/PET/EVA backsheet from two different manufacturers
- Outer weatherable surface of backsheets are facing the lamp.

PPE Backsheets- SEM images before and after QUV A exposures



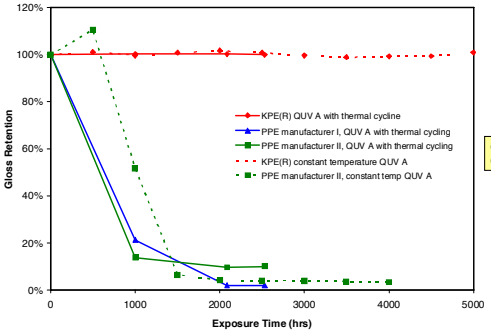
- Regardless of manufacturer, PPE backsheets are cracking and degrading after accelerated weathering exposure.
- QUV A with thermal cycling accelerates crack formation in PPE backsheets vs. constant temperature QUV A conditions.
- After only 2000 hrs of exposure, degradation of the polymer matrix and cracking of the PPE backsheet is occurring.

KPE® Backsheets- SEM images before and after QUV A exposures



- No changes in KPE® backsheets are observed in either constant temperature QUV A or QUV A with thermal cycling exposures.

Gloss Retention



- Gloss retention monitors surface changes (erosion, cracking) of the backsheet outer surface.
- The PPE gloss retention drops quickly under all conditions, but with thermal cycling the loss is more rapid than with constant temperature.
- The KPE® shows extreme stability and no surface degradation – under any testing condition (constant temperature or thermal cycling).

Conclusions

- Running QUV A with thermal cycling reliably and consistently is possible in commercial QUV cabinets.
- Crack formation is accelerated in QUV A with thermal cycling conditions vs. QUV A at constant temperature conditions in PPE backsheets is observed.
  - Mechanical stresses induced by thermal cycling accelerated microcracking of the backsheet.
- KPE® backsheets were not observed to crack or degrade when exposed to either QUV A with thermal cycling or QUV A at constant temperature conditions.
- Gloss retention of PPE backsheet decreased more rapidly for samples exposed to QUV A with thermal cycling versus constant temperature conditions due to accelerated crack formation.
- In the absence of SEM imaging, gloss retention can also be used to monitor changes in the outer weatherable layer of backsheets.

This presentation contains no confidential information.

Kynar® is registered trademark of Arkema, Inc..
KPE® is a registered trademark of Arkema France.

Field Evaluation of Photovoltaic Modules and Systems at GREEN-IPUC/PUCMinas, Brasil

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[1]Study Group of Energy (GREEN), Pontifical Catholic University of Minas Gerais (PUC Minas), *Belo Horizonte, Minas Gerais, Brasil*; [2]Companhia Energética de Minas Gerais (CEMIG-D), *Belo Horizonte, Brasil*; [3]Renewable and Sustainable Energy Institute (RASEI), University of Colorado Boulder and National Renewable Energy Laboratory, *Golden, Colorado, USA*

Introduction

The GREEN-IPUC *(Grupo de Estudos em Energia-Instituto Politécnico da PUC Minas)* is a technical laboratory that belongs to the Polytechnical Institute of the Pontifical Catholic University of Minas Gerais, located in Belo Horizonte, Minas Gerais, Brasil. Its activities are centered in research, deployment, and qualification assurance of ***solar photovoltaic*** and ***solar thermal*** technologies and distributed generation deployment with renewables.

The Systems and Scope

This study presents the investigation of performance losses of photovoltaic systems in Brasil, and the identification of component failure and durability issues. It covers some 1000 stand-alone PV systems, composed of solar-home systems (sized 150 Wp) and school systems (about 2000 Wp), that are operated by CEMIG D. These PV systems are installed in the state of Minas Gerais, with the oldest being10 years in operation. The *stand-alone systems* are located at the northern and eastern regions of Minas Gerais. These regions are considered subtropical climate zones, with dry winters (low humidity) and rainy summers. Also, there are a set of PV systems implemented under several photovoltaic rural-electrification demonstration programs, such as the US-Brasil program initiated in 1995, PRODEEM in 1997, and Luz Solar in 1999, with the oldest being15 years in operation. These systems had not had a rigorous evaluation for their reliability and operation performance—reporting any module aging or identifying major degradation mechanisms.

Performance Losses

The investigation of the performance of these PV systems started with an evaluation of the history of PV systems failure from the CEMIG database. This was followed by a selection of typical solar-home PV systems based in years of field exposure (CEMIG database) and selection of modules that had been replaced because of performance issues and put into storage. All modules had crystalline Si cells. From the database and storage, a sample set of 20 modules from the oldest systems was chosen, typically the most damaged and exhibiting degradation. Also identified were the systems with maintenance issues and with at least 10 years of field exposure. A sample of these PV systems was inspected in the field during technical visits, and the PV modules with the worst degradation modes were taken from the field and analyzed at the laboratories of GREEN Solar-IPUC in Belo Horizonte. The major PV module degradation modes were identified as gradual encapsulation discoloration and encapsulant delamination—proposed to be caused by the existing high incidence of ultraviolet radiation and high temperature. The inspection of all the system components revealed a high-rate of inverter failure (despite a routine maintenance schedule followed by CEMIG's technicians) due to high temperatures encountered inside the storage cabinets where they are installed and the lack of appropriate ventilation inside the inverter.

Performance Investigation Results

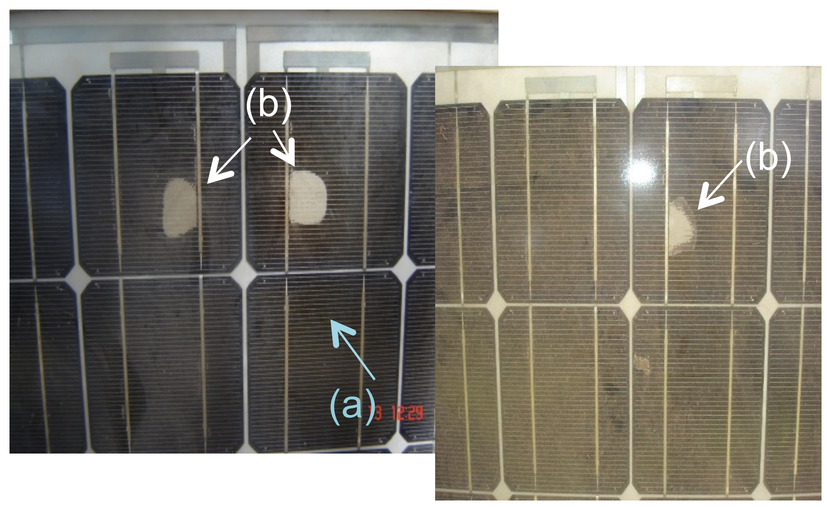

Figure 1. Examples of (a) browning and (b) encapsulant delamination for modules from stand-alone systems. Several areas of browning and delamination are highlighted by the arrows—although many such areas can be seen.

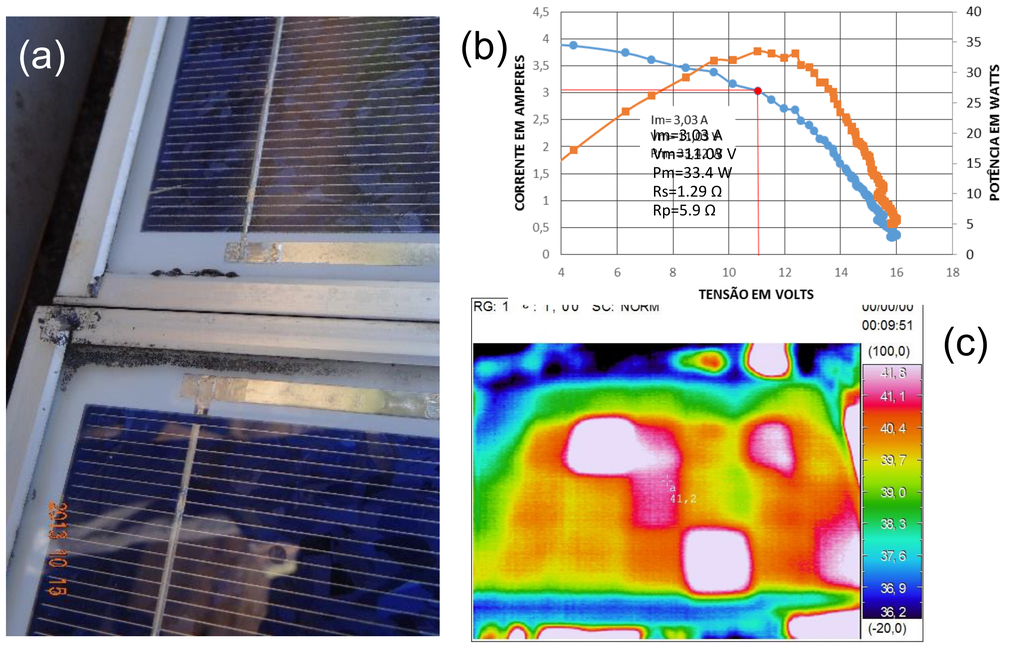

Figure 2. Reliability studies (a) Degraded modules; (b) Current-Voltage characteristic of lower module; and (c) Infrared image of lower module in (a).

Extensive corrosion at the interconnections, junction boxes, and system wiring was also discovered. In addition to major interconnect corrosion, extensive encapsulant discoloration, and prolonged inverter failures, some modules had fairly severe module soiling issues with up to 20% transmission obscuration.

Contact: asacd2012@gmail.com; asacd@pucminas.br

Acknowledgement: Funding has been provided by FAPEMIG and and PUC Minas; and, CEMIG for the systems and modules. This poster contains no proprietary information.

Highly Durable Anti-Reflective Anti-Soiling Coating for PV Module Glass

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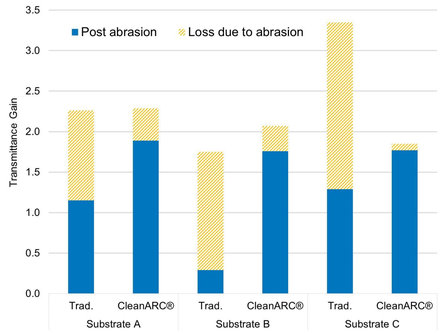
Abstract

- Greater than 4% of light is lost due to reflection at the interface of air and glass
- Soiling losses in arid regions have been reported as high at 30% per month
- Desert environments provide the most challenging conditions for coating durability
- Enki CleanARC® coating, a new highly durable anti-reflection and anti-soiling coating was compared to traditional coatings for durability and field tested at several US locations demonstrating significant anti-soiling performance
- The results were used to model project level value creation, and showed up to a 3x increase in value compared to traditional coatings

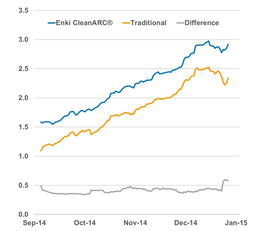
Reflection Before and After Abrasion

Initial coating performance is expressed as the percentage increase of transmittance (%ΔT/T) of solar weighted photons. Below are the initial optical gains of the Enki CleanARC® coating vs. a traditional coating on different glass substrates, and the loss due to standard abrasion testing.



While the traditional film show a higher initial performance, the degradation is far worse and they **failed** the test criteria, with greater than 0.5% loss. The Enki CleanARC® coating passed the specification and had higher energy gains than the traditional coating after abrasion.

Field Performance Test Array



10kW Yingli Test Array at Sandia National Laboratories, Albuquerque, New Mexico, USA.

Comparative energy generation between Enki CleanARC® coating and a competing traditional coating.

30 day moving average shows about 0.5% positive difference between Enki CleanARC® and the competing coating.

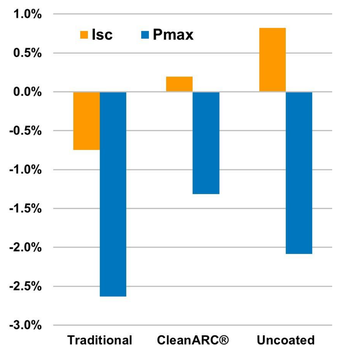
Damp Heat Performance Test

Traditional Coating

Enki CleanARC® Coating

Control (uncoated)

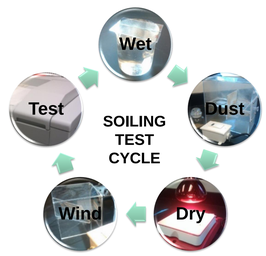
Test modules after 1000 hours damp heat (DH) testing at Underwriters Laboratories (UL). The modules with the CleanARC® coating were **visibly defect free** after cleaning with water, as opposed to the traditionally coated and control module

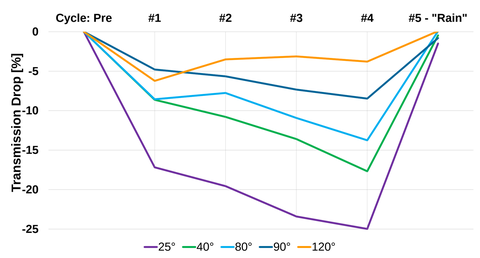


The change of I_{sc} and P_{max} of the modules after the DH test was measured at UL using a flash tester.

- CleanARC® coated and uncoated modules have no reduction in I_{sc}.
- Power loss is highest for the traditional coatings, and lowest for the CleanARC® coating
- Module with the CleanARC® coating displayed on average a lower loss than the control glass, exhibiting the added protective capability of this film against glass degradation by severe moisture exposure.

Laboratory Soiling Test





- A selection of glass coatings with different surface energies were subjected to a series of soiling test cycles
- Each test cycle included wetting the surface, applying dust with blowing air, drying, removal of loose dust with blowing air, and then testing for optical transmission loss.
- There is a very clear correlation between soil accumulation and surface energy as measured by water contact angle. Hydrophobic coatings with low surface energy and high contact angle performed best.
- Enki CleanARC® is represented by the coating with a 90° water contact angle.

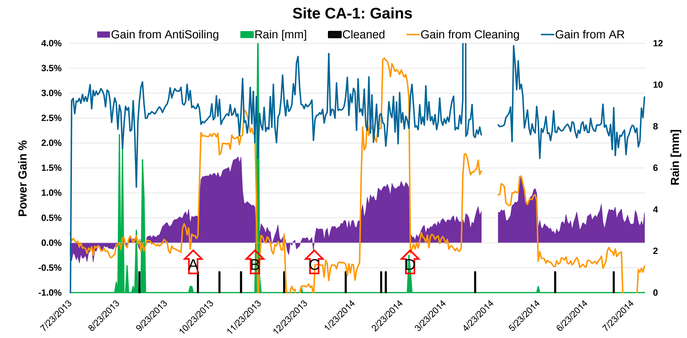
Anti-Soiling Field Test

Testing of CleanARC® coating's anti-soiling performance was performed at 10 sites across the USA in collaboration with a major system operator. Data has been collected for over 1 year.

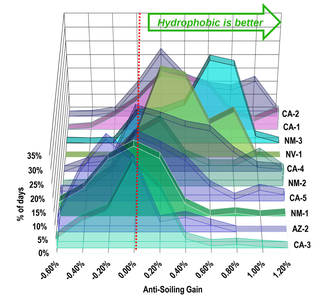
	Dirty	Cleaned	
Coated	E_{HD}	E_{HC}	
Uncoated	E_D	E_C	

Isolating both the Anti-Reflection and Anti-Soiling components of the power required four calibrated cells from Atersa, with half of the cells periodically cleaned.

$E_C - E_D$ = Cleaning Gain
$E_{HC} - E_C$ = Anti-Reflection Gain
$(E_{HD} - E_D) - (E_{HC} - E_C)$ = Anti-Soiling Gain



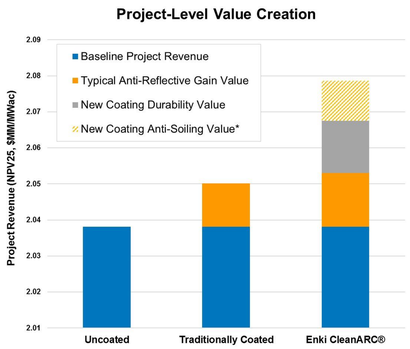
Anti-Reflection power gains were typically between 2-4%. Cleaning (soiling) gains ranged between 1-2% for certain periods. Anti-Soiling could be seen between rain cleaning and rain events (e.g. A-B and C-D in graph).



For 7 of 10 sites, the Anti-Soiling gains were clearly positive with an overall average daily gain of 0.35%.

Three of the sites demonstrated negative gains, indicating that for these climates and soiling types, perhaps a hydrophobic coating is not preferred.

Conclusions and Result



The CleanARC® coating can increase a project's energy yield and ROI through its anti-soiling properties and long-term durability. Our analysis shows it can deliver up to 3x more value than traditional coatings, resulting in over 1% additional energy production over the modules' lifetime.

* Project-level anti-soiling and cleaning value varies based on site specific conditions. The example assumes the solar project is located in central California with a baseline production of 1,738 MWh/MWdc; PPA rate of $70/MWh; 6% discount rate;0.5% baseline annual power degradation; 4% baseline soiling loss fraction, and one module wash per year.

ROUND-ROBIN VERIFICATION AND FINAL DEVELOPMENT OF THE IEC 62788-1-5 ENCAPSULATION SIZE CHANGE TEST

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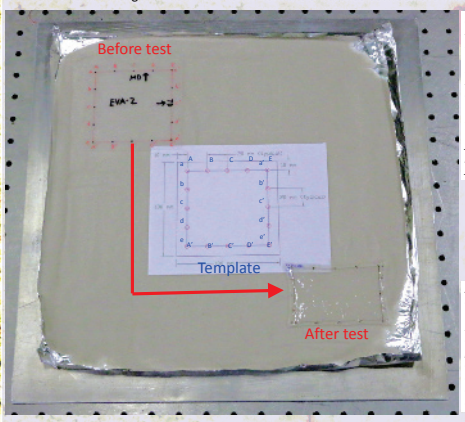
Introduction

Polymeric encapsulation materials may a change size when processed at typical module lamination temperatures. The relief of residual strain, trapped during the manufacture of encapsulation sheet, can affect module performance and reliability. For example, displaced cells and interconnects threaten: cell fracture; broken interconnects (open circuits and ground faults); delamination at interfaces; and void formation. The IEC 62788-1-5 standard quantifies the maximum change in linear dimensions that may occur to allow for process control of size change. Developments incorporated into the Committee Draft (CD) of the standard as well as the assessment of the repeatability and reproducibility of the test method are described here. No pass/fail criteria are given in the standard, rather a repeatable protocol to quantify the change in dimension is provided to aid those working with encapsulation.

Test Protocol: Method, Equipment, and Specimen Sampling

The test procedure generally follows as:

1. Size, mark, and measure the specimen(s) size (to ±0.5 mm) in their unprocessed state.
2. Place specimen(s) in a oven on a preheated substrate consisting of handle/aluminum foil/"graded" sand layers.
3. Maintain the specimen(s) in the oven for 5 minutes.
4. Remove the specimen(s) from the oven, allow them to cool to ambient, and measure their final size.
5. Calculate the change in linear dimension from the difference between the initial and final measurements.



LEFT: *Photograph of representative EVA specimens (top left) before and (bottom right) after performing the test. A template (made to scale) was used to mark the test specimens. In the test, specimens (100 mm squares) are placed on a layer of ASTM C788 "graded" sand (2-4 mm thick, to minimize friction) which is located on an aluminum foil (20-25 □m thick, to render uniform temperature). The foil, at least 300 x 300 mm in size, is placed here on an aluminum sheet, used for support an ease of handling.*

$$\Delta L = 100 \times \frac{L_f - L_i}{L_i}$$

ABOVE: *The change in linear dimension is calculated as a percentage. A negative value indicates the encapsulant has shrunk; a positive value indicates the encapsulant has increased in size. In practice all magnitudes and signs of size change have been observed. The results are distinguished between the machine extrusion direction (**MD**) and transverse direction (**TD**) for rolls of encapsulation.*

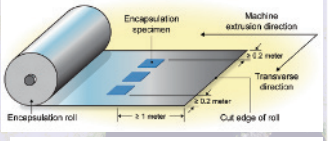
Standardized measurement locations were defined between the New Work Item Proposal (NWIP) and CD versions of the standard. The effects of the location within the specimen or at the edge of the specimen were quantified in discovery experiments at the time the NWIP was submitted. From that, a set of (5) measurements for the MD and (5) for the TD should be obtained 1 cm from the specimen periphery. The measurement grid is meant to minimize bias between measurements at the corners relative to the middle of the specimen. In practice, some materials were more prone to size-change at the corners (*e.g.*, the line aa'), while other materials were more affected at their middle (*e.g.*, the line cc'). For 6 specimens, the maximum and difference (maximum minus minimum) should be reported to identify ***greatest*** change in size that may occur for unconstrained material. The average and standard deviation should also be reported to give a more ***representative*** sense of the size change that may occur during the lamination of PV modules.

ABOVE: *A leveling tool may be used to grade the sand substrate. In the example here, a "C" shaped object is used to flatten the sand. The tool shown is recessed (out of plane to the photo) in its center (between the handles at the edges). The tool shown will level the sand between the handles when dragged over the sand in the direction towards the top or bottom of the photo. In practice, any straight-edge (such as a blade, rigid applicator, ruler, roller, or similar object) may be used to grade the sand.*

ABOVE: *A circulating closed-loop controlled oven is required for the test. The differences in the duration and magnitude of radiation present are readily distinguished in the figure. If an aluminum foil substrate at least 300 mm x 300 mm in size is used, multiple specimens may be tested simultaneously in the oven. If space permits, sand used in subsequent tests may be equilibrated in the oven, e.g., in a jar or other container, while it is being used for the size change test.*

Test equipment was better defined after the NWIP and interlaboratory study. A straight-edge or leveling tool may be used to flatten the "graded" sand substrate to the thickness of 2 mm to 4 mm. (The use of talc, kraft paper, glass, stainless steel, and liquid water as substrate materials was explored previously, see references). A convection oven (accurate to ±2.5 °C) was specifically identified for the standard upon review of the initial work. Circulating air will aid the specimen(s) to more quickly achieve and stabilize at the test temperature. Convection is expected to improve the temperature uniformity within the oven and the repeatability of the applied temperature between tests. Circulating ovens were used in the round-robin test described below. From the round-robin, it may be necessary to baffle the fan, *e.g.*, through strategic placement of shelves, in order to prevent blowing sand or inadvertent specimen movement during the test.

Material samples are to be obtained at the beginning, middle and end of at least two separate rolls of encapsulation. Each sample set consists of a specimen obtained from the interior in addition to two specimens obtained closer to the edges of the roll (as shown in the schematic). A minimum of 18 specimens would therefore be examined for datasheet reporting. Additional sampling may be performed for the purpose of quality control and manufacturing process control. The quantities and protocol for sampling are not strictly specified in this case, rather these should be consistent with the manufacturer's own procedures.



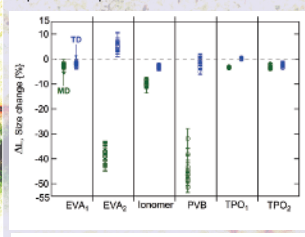
ABOVE: *Schematic identifying the designated sampling locations at the ends of a roll of encapsulation. The requirements for specimen location relative to the periphery of the roll are shown, such that the cutting and handling of the roll should not greatly affect the specimens prior to examination.*

Experimental Results

Round-robin verification of the test was performed using (6) representative materials, including: poly(ethylene-co-vinyl acetate) (EVA); poly(ethylene-co-methacrylic acid metal salt) ("ionomer"); polyvinyl butyral (PVB); thermoplastic polyethylene/polyoctene copolymer (TPO, aka polyolefin); and thermoplastic polyurethane (TPU). Two types of EVA were examined: one that was processed to reduce size change ("EVA$_1$"), and one that was not necessarily manufactured to reduce size change ("EVA$_2$"). Two TPO materials, obtained from different manufacturers, were examined.

The goal of the round-robin was to quantify the repeatability (variability within each laboratory) and reproducibility (the variability between the laboratories in addition to the repeatability). The round-robin was conducted for the CD version of the standard as in ISO 5725-2 and ASTM E691. ***From the round-robin, the repeatability and reproducibility are no better than the order of 1%.*** A correlation was observed between the variation and magnitude of the measurements.

During its development, including: discovery experiments; an interlaboratory experiment; CD version; and subsequent publication, the standard was improved significantly from its original implementation as a manufacturer's test protocol. For example, two materials examined in the round-robin were significantly improved from previous versions examined in the interlaboratory study.



ABOVE: *Box-plot of the round-robin data. The results are given first for the machine extrusion direction (**MD**) in green and then the transverse direction (**TD**) in blue. The average and standard deviation of the 6 specimens examined is shown for each of the 12 participating laboratories. Outliers have been removed from the box-plot and summary tables. Outliers were identified using Mandel's h and k statistics to evaluate variation between and within laboratories, respectively. Outliers were then confirmed using Cochran's test (for h) or Grubb's test (for k).*

□L Results: Machine Extrusion Direction (%)

Material	MAX	DIFF	x	s_x	s_r	s_R	r	R
EVA_1	1.30	-7.35	-2.59	0.97	0.54	1.04	2.73	2.91
EVA_2	-31.83	14.62	-38.72	6.62	1.01	6.13	18.55	17.17
Ionomer	-7.00	9.00	-9.18	1.30	2.26	2.56	3.64	7.15
PVB	-27.23	26.94	-44.78	3.44	5.53	6.36	9.64	17.81
TPO_1	-2.74	1.21	-3.25	0.20	0.18	0.26	0.56	0.72
TPO_2	-1.63	3.14	-3.17	0.49	0.64	0.78	1.36	2.19

□L Results: Transverse Direction (%)

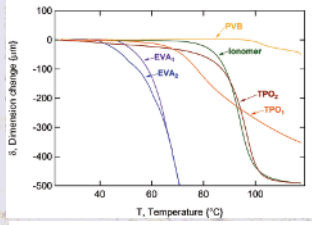
Material	MAX	DIFF	x	s_x	s_r	s_R	r	R
EVA1	0.84	-5.72	-2.01	0.76	0.59	0.91	2.12	2.55
EVA2	13.38	-12.87	5.63	2.56	0.95	2.52	7.16	7.06
Ionomer	-1.55	3.85	-3.51	0.73	2.09	2.19	2.05	6.14
PVB	3.21	-9.57	-1.26	1.43	1.73	2.17	4.01	6.08
TPO1	0.75	-1.00	0.21	0.19	0.15	0.23	0.54	0.66
TPO2	-0.51	3.48	-2.41	0.57	0.60	0.79	1.60	2.22

ABOVE: *Summary of the round-robin experiment. Quantities include: the maximum size change observed at each laboratory (MAX, as reported in the standard); the difference (DIFF, maximum minus minimum, as reported in the standard); the average (x, as reported in the standard); the standard deviation (s_x, as reported in the standard); the repeatability of the standard deviation (s_r); the reproducibility of the standard deviation (s_R); the repeatability (r); and the reproducibility (R). All values apply to a percent change in the linear dimension of the test specimens.*

Materials characterizations, including thermomechanical analysis (TMA) and differential scanning calorimetry (DSC), were performed on the round-robin materials to examine their mechanical response relative to their phase transition temperatures. These characterizations clarify the physical state and response for each material relative to the processing temperature used during the test. The temperatures in the round-robin were recommended by the material manufacturer. DSC identifies that all of the samples were examined in their melt state (note other PVB formulations may not exhibit a melt transition). TMA identifies that the materials may be affected by a mechanical load at the test temperatures used in the round-robin, confirming their propensity to strain relieve during the test. EVA may exhibit melt transitions up to 80 °C. EVA typically begins to cross-link above 120 °C, limiting strain relief. It is therefore recommended to examine EVA at 100 °C. Strain relief is not limited in materials that do not cross-link with temperature; therefore, they should be examined in their melt or glassy states, as recommended by their manufacturer.

MATERIAL	TEST TEMPERATURE IN R-R (□)	DSC				TMA
		$T_g = T_□$ (□)	T_c (□)	T_{m1} (□)	T_{m2} (□)	T_s (□)
EVA 1 (balanced)	150	<-25	37	48	65	58
EVA 2 (unbalanced)	150	<-25	37	44	65	58
Ionomer	140	<-25	58	55	86	87
PVB	165	42	86	97	146	99
TPO 1	150	<-25	50	49	65	69
TPO 2	150	<-25	78	46	95	88

ABOVE: *Summary of: test temperatures used in the round-robin; the glass transition (alpha-relaxation) temperature, T_g; the crystallization (freezing) temperature, T_c; the melt temperature, T_m; and the softening point temperature, T_s. DSC was performed using a Q2000 (TA Instruments, Waters LLC) to execute a single heating and cooling cycle up to 220 °C at 10°C·min^{-1}. For all materials, two melt events were observed upon initial heating, as indicated with the subscripts -1 and -2. "< -25" is used to indicate when T_g could not be identified within the lower limit of the DSC scan.*



ABOVE: *Data profiles for the TMA characterization. The softening point is determined from the profile, when a measurable change in dimension may be invoked as the temperature is increased. Penetration probe measurements were performed using a Q400 (TA Instruments, Waters LLC) to perform a single heating up to 120 °C at 10°C·min^{-1}. while applying a load of 0.1 N.*

Summary

A standardized test for the characterization of change in linear dimensions of encapsulation sheet has been developed and verified.

The round-robin experiment described here identified that the repeatability and reproducibility of measurements is on the order of 1%.

Recent refinements to the test procedure to improve repeatability and reproducibility include:

- The use of a convection oven to improve the thermal equilibration time constant and its uniformity
- Well-defined measurement locations reduce the effects of sampling size -and location- relative to the specimen edges
- A standardized sand substrate may be readily obtained to reduce friction that would otherwise complicate the results
- Specimen sampling is defined, so that material is examined at known sites across the width and length of rolls
- Encapsulation should be examined at the manufacturer's recommended processing temperature, except when a cross-linking reaction may limit the size change. EVA, for example, should be examined 100 °C, between its melt transition (occurring up to 80 °C) and the onset of cross-linking (often at 100 °C).

Acknowledgements

The authors are grateful to: Dr. Michael Kempe, Dr. Sarah Kurtz, Dr. John Pern, and Stephen Glick of the National Renewable Energy Laboratory for their help/discussion with specimen fixturing, specimen handling, experimental methods, and other subsequent analysis. Thanks also to the standard committee for the size change test within IEC Technical Committee 82, Working Group 2, including: Hidenori Asai, James Bratcher, Yohei Deguchi, Konrad Fredrich, Jim Galica, Steven Haldeman, Qiang Huang, George Kelly, Claudio Liciotti, Yanping Shen, Luke Strzegowski, Yuhai Sun, Ethan Wang, Taoyun Xiao, Jianmei Xu, Eiichiro Yokochi, Hirofumi Zenkoh, Zhen Zhang, Danial Zhou, Betty Zhu, and Oihana Zubillaga. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

For More Information, refer to the publications:

D.C. Miller, L. Ji, G. Kelly, X.H. Gu, N. Nickel, P. Norum, T. Shioda, G. Tamizhmani, J.H. Wohlgemuth, "Examination of Size-Change Test for PV Encapsulation Materials", Proc. SPIE, 2012, 8472-29. http://www.nrel.gov/docs/fy12osti/54186.pdf http://www.nrel.gov/docs/fy12osti/56320.pdf

IEC 62788-5 – Measurement Procedures for Materials Used in Photovoltaic Modules: Part 1: Encapsulants. Part 5 – Measurement of Change in Linear Dimensions of Sheet Encapsulation Material Resulting From Applied Thermal Conditions," International Electrotechnical Commission: Geneva, (submitted).

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PV Photovoltaic Module Reliability Workshop
Golden, Colorado
February 24-27, 2015
NREL/PO-5J00-63849

AMERESCO SOLAR

System reliability aspects of currently available PV modules with atypical string length

Donald B. Warfield, Ameresco Solar, Tomball, TX

Observations

It has been brought to our attention by one of our customers that many of their standalone systems were failing after 12 to 18 months. They had tried to systematically replace batteries, believing them to be at fault, but the trouble continued to recur. We were made aware of the problem, because we supplied the charge controllers which were found to be performing correctly.

One of the first issues that came under our scrutiny was the number of cells in the module they had chosen. This module had only 32 cells in series.

Performance measurements

One of these 32-cell modules was used in our tests. An Ameresco 90-J was also tested as a 36-cell comparison. I-V curves were taken at midday with a Day-Star curve tracer.

Both performed within their stated specifications on a bright spring day in Tomball TX. The 32-cell module tested exhibited a Vpmax at temperature of 14.3v. The Ameresco 90-J module used as a control exhibited a Vpmax of 16.5v under similar conditions.

Discussion

But do those design specifications permit this 32 cell module to fully charge a 12v battery under midday conditions in typical field applications?

Back in the early days of PV we determined that modules that have fewer than 35 cells in series have a difficult time maintaining battery health over the intended life of the system. This involves several issues: 1) the actual

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Vpmax of the module at expected performing temperatures; 2) the voltage required to adequately charge the battery and the need to fully charge and "equalize" that charge on a regular basis; 3) tare losses associated with system wiring and blocking diodes; and 4) the tare losses associated with the functioning of charge controllers either from the device's series resistance or the controller's required algorithms.

Discussions with the staff at Morningstar determined that their product line with the exception of one product require a 'headroom' of 1v over battery voltage for proper functioning. Since most system sizing calculations are based upon performance near Pmax that reduces the effective battery charging voltage of this module to 13.3v. The addition of any additional derating factors like wiring resistance, isolating diodes, and connection degradation can only further exacerbate the situation.

Depending on the choice of battery technology, the typical max charging voltage required for 12v service is from 14.1 to 14.5 volts. So the 32-cell test module performed at about 1 volt lower than required. Note that the module could perform at a higher Vpmax under cooler conditions or lower irradiance conditions, but this would severely curtail the available sun-hours for systems designed with such a module. This curtailment would need to be taken onto account within the system-sizing algorithm.

This should not be news to anyone who has been in the off-grid PV business for a long time. In the early days, it was determined by trial and error that at least 35 cells in series were required to produce survivable 12v battery-charging systems. But in recent times there are entire manufacturing companies with no experience in standalone system and their module design is merely a response to cell size and the market's footprint requirements. That, coupled with our industry's focus on cost reduction, has produced modules which are not suited for their intended use.

This document contains no confidential information

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PV Module Reliability Workshop, February 24 - 27, 2015, Golden, CO)

Utilization of Ultra-Intense UV Weathering Chambers for Rapid Acceleration of PV Component Testing)

Tatsuo Nakamura, Douglas Vermillion)

Abstract

Crystalline PV component manufacturers continuously strive to improve product durability and reliability through recommended tests, and proprietary in house testing. A 25 – 30 year life cycle is expected.

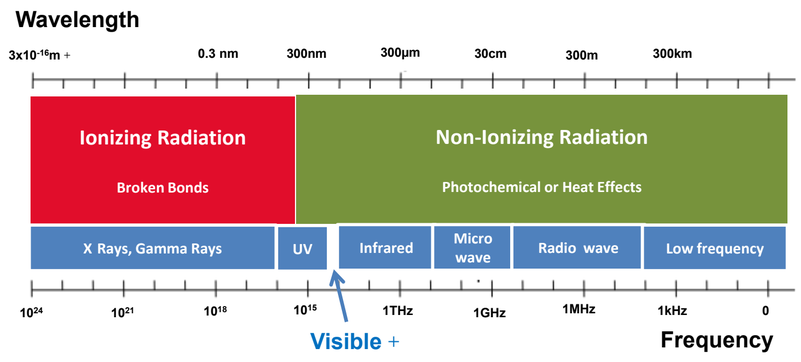
Outdoor exposure testing is necessary for validating long-term product performance, but the use of accelerated testing is necessary for expediting the evaluation process. Fluorescent and Xenon lamp based UV weathering chambers are commonly used for accelerated testing, and are supported by some correlation data to outdoor exposure testing.

PV component manufacturers have recently been utilizing metal halide lamp based UV weathering chambers for proprietary in-house testing to further accelerate the simulation of outdoor exposure. Metal halide tools are relatively new, and the amount of correlation data is somewhat limited, but users have found that the benefit of rapidly accelerated testing is of strategic importance with regard to product development and testing.

Different material compositions will react with different acceleration rates when evaluated in any UV weathering chamber option with fluorescent and Xenon lamp options providing acceleration factors of 1 – 10 times natural sunlight. Metal halide lamp based weathering + chambers provide acceleration factors of up to 30-times natural sunlight. +

UV Light and Ionizing Radiation

- **Earth surface UV radiation beginning in the UV-B band is categorized as "Ionizing Radiation" and has enough energy to break chemical bonds.**
- **The most significant effect on materials from light energy is caused by UV radiation breaking chemical bonds.**
- **Visible and IR radiation are categorized as "Non-Ionizing Radiation" and which have somewhat minimal photochemical and heating effects on materials.**



Source: EYE Applied Optix

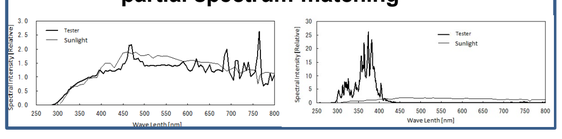
Accelerated Weather Testing Methodology

Procedure +

- **Chamber with Combination Cycling Of:**
  1. **Temperature**
  2. **Humidity & Soaking**
  3. **UV Light**
- **Correlation to Outdoor Testing to Validate Acceleration Factors**

UV Light Generating Options

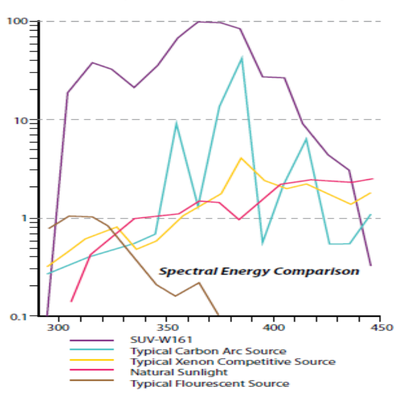
- **Mercury Fluorescent**
  - **1 – 3 "Sun" acceleration**
  - **partial spectrum matching**
- **Xenon**
  - **1 – 10 "Sun" acceleration**
  - **full spectrum matching**
- **Metal Halide**
  - **20 – 30 "Sun" acceleration**
  - **partial spectrum matching**



Metal Halide UV Light Source Acceleration

- **Metal halide offers significant acceleration factors compared to traditional mercury fluorescent and xenon light sources due to the intensity of the UV radiation produced (see plot below).**
- **The use of intense UV radiation expedites the testing process with acceleration factors up to 10 times those of xenon tools.**
- **Metal halide tools produce repeatable results.**

Logarithmic Plot of UV Energy Intensity)
Produced by Various Chamber Light Sources)



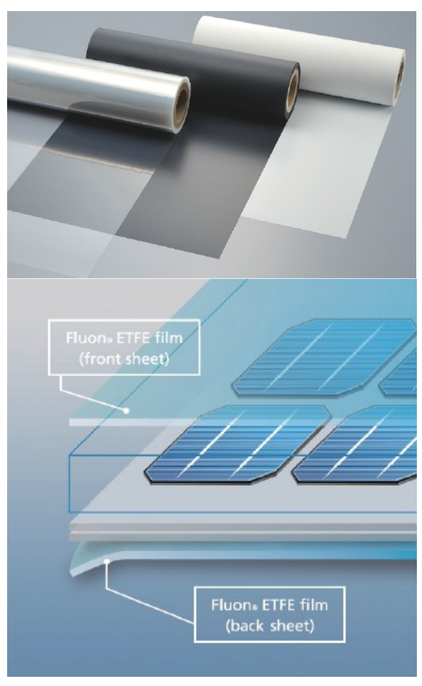
Benefit of Expedited Testing-
Time to Color Shift of Material Sample

Light Source	Hours	Days
Natural Sun	10,000	420
Xenon	1000	42
Metal Halide	100	4.2

Source: Iwasaki Electric

AGC Solar Fluon ETFE Film

Metal Halide Used for PV Front/Back Sheet R&D)



AGC Solar Accelerated Test Procedure

•1000W/m² (300 – 400nm)

•Black Panel Temperature = 63° C

•Cycle:

✓10 Hours	**Light Irradiation (50% R.H.)**
✓10 Seconds	**Shower**
✓2 Hours	**Blackness/Condensation (30° C, 100% R.H.)**
✓10 Seconds	**Shower**

Source: Information provided courtesy of AGC Solar

AGC Solar Fluon ETFE Film)

Accelerated Test Analysis

Retention of Mechanical Properties +

Tensile Test	Zero Hour	After 500 Hours	After 1000 Hours
Elongation	300-400%	95-100% *	95-100% *
Strength	55-65 MPa	90-95% *	85-95% *

* Percent of original measurement

Change in Optical Properties

Test		Zero Hour	500 Hours	1000 Hours
Transparency at 360 nm	%	<=0.1	<=0.1	<=0.1
Visible Light Transmission	%	24 – 26	23 – 26	22 – 25
Solar Transmittance	%	36 – 37	36 – 37	35 – 36
Solar Reflectance	%	60 – 62	61 – 63	61 – 63
Color Difference ΔE*		-	-	<0.7

Source: Information provided courtesy of AGC Solar

Metal Halide Correlation Table

Correlation With Outdoor Data

Test Material	Test Cycle Irradiation/ Humidity (hrs)	Irradiation Level (W/m²)	BP Temp°C	Humidity (%RH)	Test Duration (hours)	Equivalent Exposure (years)	Acceleration Factor
Polypropylene (PP)	12 / 6	1500	83	50	100	1yr outdoor	88
Polyvinyl chloride (PVC)	4 / 2	1050	50	50	150-300	1yr outdoor	58--29 *
Acrylonitrile butadiene styrene (ABS)	12 / 6	1500	63	50	80	1yr outdoor	110
Polycarbonate (PC)	6 / 6	1500	63	50	100	1yr outdoor	88
Polymethyl Methacrylate (PMMA)	12/6	1500	83	50	200	800hr (comp)	4X (comp)
Polyethylene (PE)	6 / 6	1500	63	50	120	1yr outdoor	73
Polyoxymethylene (POM) (polyacetal)	12 / 6	1500	83	50	100	1yr outdoor	88
Polyester	continuous UV	1050	83	N/A	25	1yr outdoor	350
Urethane	6 / 4	1500	63	50	200	2yr outdoor	88
Typical fabric	continuous UV	1050	83	N/A	20	250hr (comp)	12.5X (comp)
Melamine painting	24 / 24	1500	63	50	50	1yr outdoor	175
Fluorine painting	12 / 12	1500	63	50	1000	10yr outdoor	88
Acrylic painting	24 / 24	1500	63	50	50	1yr outdoor	175
Painted Slate	8 / 2	1500	63	50	100	1yr outdoor	88

Source: Japan Weathering Test Center & Iwasaki Electric
Location: Central Honshu Prefecture, approximate equivalent is St. Louis area

Summary

- **Metal halide weather testing offers significantly accelerated testing compared with traditional fluorescent and xenon tools by a factor as high as ten.**
- **Correlation data for metal halide tools does exist.**
- **Many internationally based companies are using metal halide tools for strategic R & D.**
- **North American based companies are using metal halide tools for strategic R & D, and + maintain proprietary testing and correlation data. +**
- **EYE Applied Optix will work with customers and partners to publish additional data over time, and is actively seeking a North American partner for research to present at the next annual session.**

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This poster contains no proprietary information, 2015)

Moisture ingress into PV modules: long-term simulations and a new monitoring technique

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Goals and Motivations

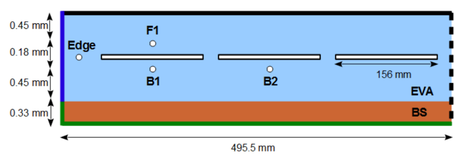
- **Predict moisture ingress into PV modules during long-term outdoor exposure, identifying impact of climate conditions and encapsulation scheme**
- **Improve modules life-time by better understanding water-related degradation mechanisms (e.g. delamination [1,2], potential induced degradation (PID) [3])**

Approaches

- **Water ingress is modeled with 2D Finite Elements Method (FEM) as a diffusion problem and simulated for:**
  - **three different climatic conditions**
  - **two different encapsulation schemes.**
- **A new monitoring technique is then employed to measure the relative humidity inside the PV modules and validate the simulation model.**

Water ingress modeling

Simulations model



- Water ingress in PV module materials described by Fick's Second Law of Diffusion:

$$\frac{\partial c(x,t)}{\partial t} = D(t)\frac{\partial^2 c(x,t)}{\partial x^2}$$

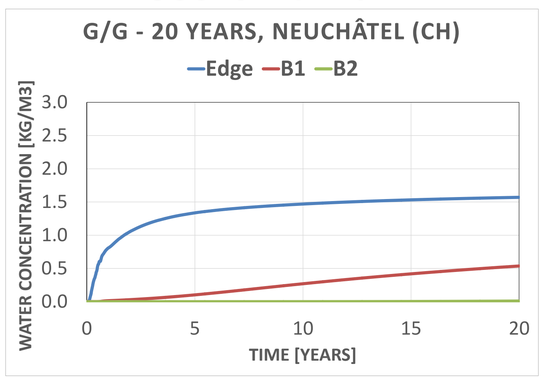
- Solved by FEM with experimentally determined water diffusion coefficient D and solubility S of EVA and backsheet
- Water concentration at the outer surface calculated with Henry's law:

$$c_{surf}(t) = S(t) \cdot p_{H_2O}(t)$$

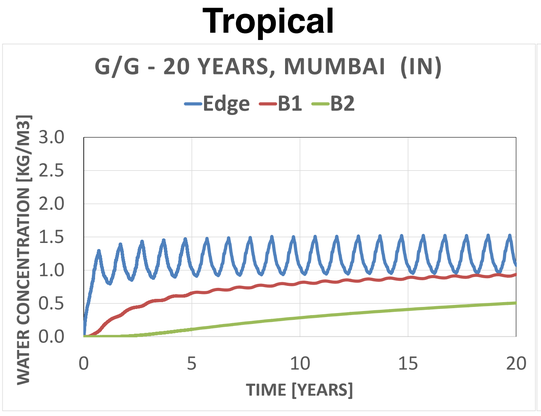
- 2-D geometry assuming infinite length in the 3rd dimension
- Symmetries (dotted lines) exploited to reduce computational times, with Glass/Glass (G/G) scheme also vertically symmetric
- Modules assumed initially dry
- Output: time-evolution of water concentration in different positions in the module (edge, front, back)

Glass/Glass: 3 climates, 20 yrs

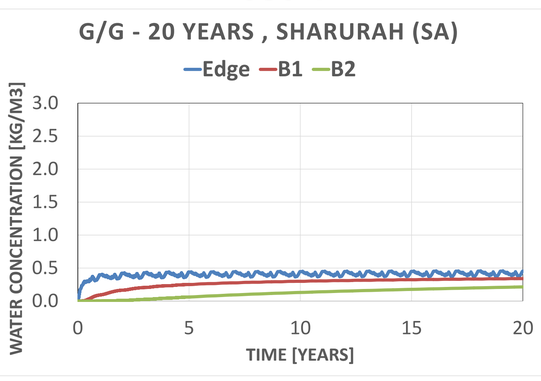
Cool & Humid



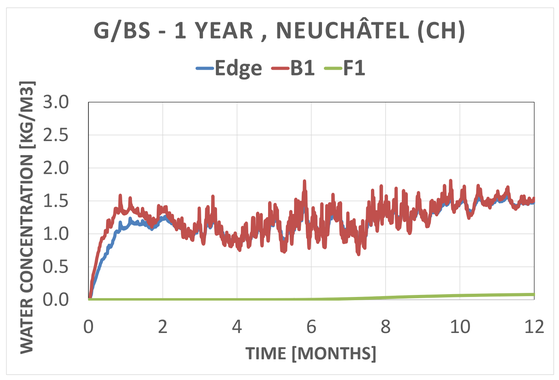
Tropical



Desert



Glass/Backsheet: 1 climate, 1 yr

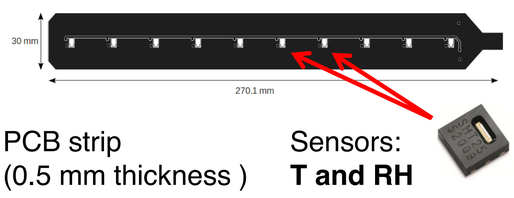


Observations

- As expected: fastest moisture ingress in tropical climate (high temperature and high relative humidity), with clear seasonal variations, particularly at the edge
- G/G reduces moisture accumulation with respect to G/BS (moisture content at cell back already larger in G/BS after 1st year than in G/G after 20 years).
- In G/BS, seasonal variations clearly visible at the cell back (increase in water concentration during cold and humid winter).
- G/BS simulations must now be extended to longer time-scales, such as in [4].

New monitoring technique: Encapsulated relative humidity sensors

Working principle



PCB strip (0.5 mm thickness)

Sensors: **T and RH**

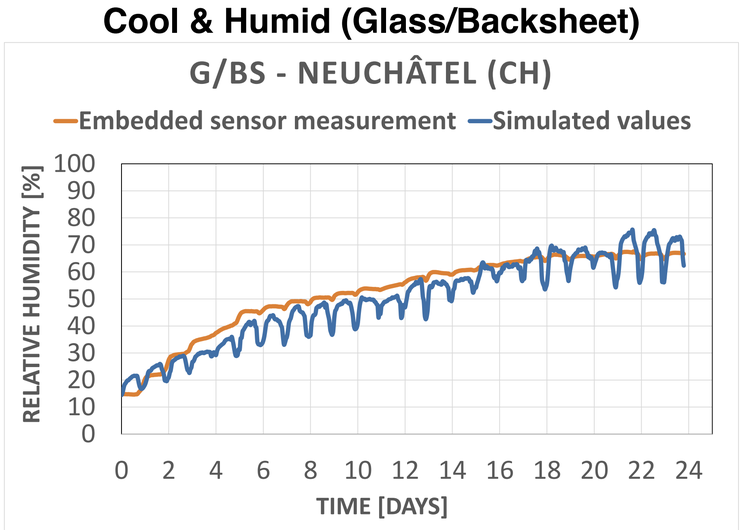
- Miniature digital relative humidity (RH) and temperature (T) sensors were soldered on a Printed Circuit Board (PCB) strip.
- The PCB strip was then laminated in G/G and G/BS samples.

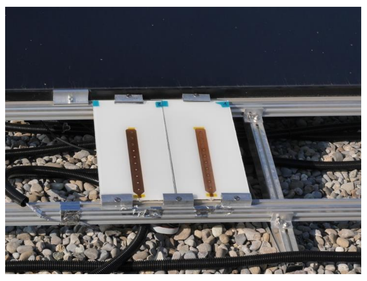
Measuring water concentration inside PV modules

- The technique has been preliminarily tested in climatic chamber
  → care must be taken when sensor operates outside its normal specified range
- Samples were then installed outdoor to track evolution of internal RH.

Simulations vs Measurements

Cool & Humid (Glass/Backsheet)





Time-evolution of RH inside a G/BS sample in outdoor conditions (cool & humid climate) as measured by a sensor and simulated by FEM

First results: Good agreement between measurement and simulation

Conclusions/Outlook

- ***Water concentration inside PV modules was simulated for different climates and encapsulation schemes:***
  - ***As expected, tropical climate induces fastest water ingress, however cool & humid climate also features high water content after 20 years***
  - ***G/BS after 1 year already shows higher water content than G/G after 20 years***
- ***For G/BS, good agreement between simulated results and outdoor monitoring. But further (ongoing) experiments required, also in climatic chambers.***
- ***Optimized choice for encapsulant materials, and in-depth investigation of moisture-related failure modes (e.g. delamination, PID) can be performed based on this analysis.***

[1] M. D. Kempe, "Modeling of rates of moisture ingress into photovoltaic modules", Solar Energy Materials and Solar Cells, vol. 90, no. 16, pp. 2720–2738, 2006
[2] N. Kim et al., "Experimental characterization and simulation of water vapor diffusion through various encapsulants used in PV modules", Solar Energy Materials and Solar Cells, vol. 116, pp. 68-75, 2013
[3] J. Berghold et al., "Potential Induced Degradation of solar cells and panels", EU PVSEC, 2010
[4] P. Hülsmann et al., "Simulation of Water Vapor Ingress into PV-Modules under Different Climatic Conditions", Journal of Materials, Volume 2013

Acknowledgments

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Quality and Reliability - sometimes the customer wants more …

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ABSTRACT

Quality and reliability of PV products, in particular PV modules, are recently attaining one of the top positions as brand-selection criteria for customers. Still, PV modules make an important contribution to the entire system cost. A key dilemma for customers (ultimately it is them / their banks / their insurance companies , who pay the bill) is “how to build a good concept for choosing the most reliable PV product”. Modules as-built offer very little possibilities to draw conclusions about reliability without further information (e.g. through production audits) or inspection more sophisticated compared to visual (e.g. by EL). Moreover, customers operating aged (e.g.: 10 years+) systems often can do their assessments on visual appearance of the modules, only. Power-wear-out and dysfunction of modules is taken for granted if only optical changes are visible. Malfunction of the inverter or insufficient O&M are sometimes not considered. In this contribution, an example is given for a series failure in solar modules built by third party. This frequent failure relates to not to energy output but to cosmetic appearance of the modules. Special safety issues are not reported.

IMPORTANT NOTE

All failures reported refer to modules that have neither been manufactured nor sold by SolarWorld.
Data have been acquired by a 3rd party service provider specialized in solar module claims handling.

Observation: failure (modules made & sold by 3rd party)

Customers claim „white spots“ and use the word „delamination“. Modules have been typically built and sold between 1999 and 2003 by a third party module & cell manufacturer

Claims are typically raised after 7+ years-in-field. It was reported that all warranty issued to customers does explicitly link to power loss, only (not cosmetic issues, workmanship …).

Three categories of delamination / white spots are observed:

- **Type A:** „white spot“: highly visible, white discoloration stops at each cell perimeter (compare Fig. 1 and 2)
- **Type B:** delamination in the edge region that violates creepage path towards aluminum frame and may be hazardous (Fig. 3) - reject
- **General delamination:** as widely known. A very bad example (resulting in voids and cell crack) is given in Fig. 4.

Fig. 1: Type A „white spot“ delamination. Center cells and edge cells affected

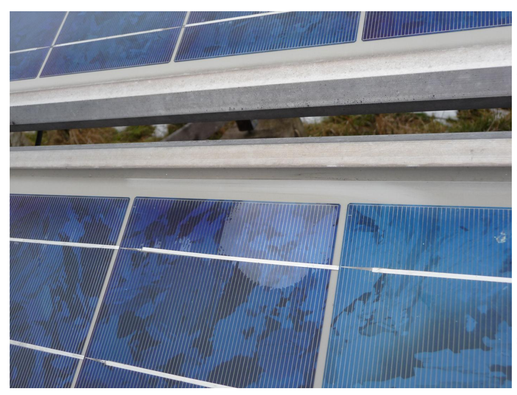


Fig. 2: Type A „white spot“ delamination. Delamination does not exceed perimeter of the cell

Fig. 3: delamination (bubble) extending to the aluminum frame. Creepage no longer given - reject

Fig. 4: very bad example of „general delamination that results in voids and even cell breakage – clear reject

First Analysis

The dataset is based on 22,328 returned modules. All modules have been classified by multiple failure possibilities.
More than 90% of the returned modules show “delamination”, whereas the overwhelming contribution is the “Type A” failure mode.
A statistical lot of 2,838 of modules out of the 22,328 modules has been flash tested and **only 13% of the tested modules had a power less than promised in the warranty document**.

Preliminary Root Cause Analysis for Type A white spots:

Production data for the modules under consideration are not available. However, a strong hypothesis could be established with two assumed factors:

1. ARC on solar cell is with TiO_2 which is known to be prone to hydrolytic distortion against the EVA. Typically, mechanical barriers like ribbons / bus bars or the cell‘s perimeter tend to stop the visible effect (comp. Figs. 1 / 2).
2. poor control of lamination process. The laminate construction consists of front glass EVA (unknown brand), crane glass (most likely to support the lamination process) and a backsheet containing an Al barrier layer.

Further Analysis

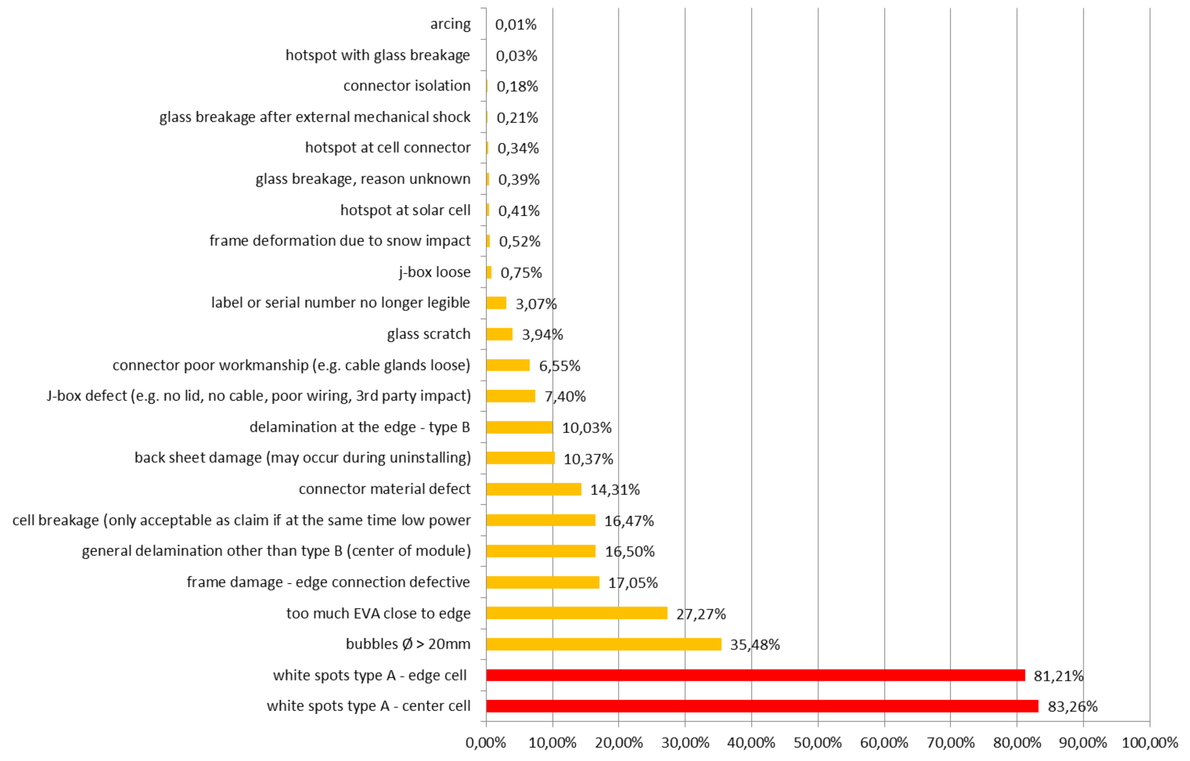
Further analysis about the behavior of Type A „white spots“ showed:

- No clear correlation between observed power loss (w.r.t. name plate) and the number of cells with the Type A signature could be established. A test aiming to correlate the delaminated (Type A) surface of n=9 modules to the power loss revealed a correlation as weak as $R^2 = 0.054$

- Stress tests according to the well known IEC cycles showed either no change in output power or the losses in output power could be made traceable to influences other than the Type A „white spots“. Though, especially DH1000 increases the size of Type A „white spots“ considerably.

- Thermal IR analysis showed that under short-circuit conditions and irradiance levels close to 1 sun, the observed average temperature tends to be slightly higher for Type A „white spot“ cells in comparison to unaffected cells within the same module. The observed temperature difference was in the low 1 digit Kelvin range. In particular not hot-spot problems have been seen.

Fig. 5: failure pareto of 22,328 returned modules. Multiple failures are possible: total of all failure modes is > 100%



Summary and Conclusion

Despite the fact, that in average 87% of the claimed modules fulfil the power warranty customers claim for cosmetic reasons (mainly „Type A“ failures).
Obviously, it was impossible for the manufacturer to communicate to customers that „Type A“ defects do not affect the power, are not observed to considerably shorten lifetime, and do not exhibit a safety problem.
The perception of the customer is simply „poor quality“.

Sometimes the customer wants more than …
… what is included in the warranty terms.

This presentation contains no confidential information

Prevention of Potential-Induced Degradation with Ionomer film by Reducing Sodium-ion Accumulation in PV Modules

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[3]Yingli Group Co., Ltd., Baoding, China
[4]DuPont Silicon Valley Technology Center, Sunnyvale, CA, USA

1. Abstract

- Transformerless (TL) inverters have increased efficiency compared to traditional ones. However, the voltage in systems using TL inverters can reach 1500 Vdc. → This increases demand for modules with PID-resistive properties.
- We evaluate an Ionomer-based encapsulant and compare it against two traditional types of encapsulant materials, standard EVA and PID-resistant EVA
- The severe PID degradation seen in EVA can be fully suppressed by inserting a 100 µm ionomer layer between the front glass and EVA. Additional accelerated aging tests according to extended IEC61215 protocol were passed.
- Analysis of PID exposed mini-modules show significantly higher sodium accumulation near the solar cell surface for the std EVA than for the ionomer.
- Preliminary data for a "one-encapsulant" solution shows PID suppression.

2. Methodology

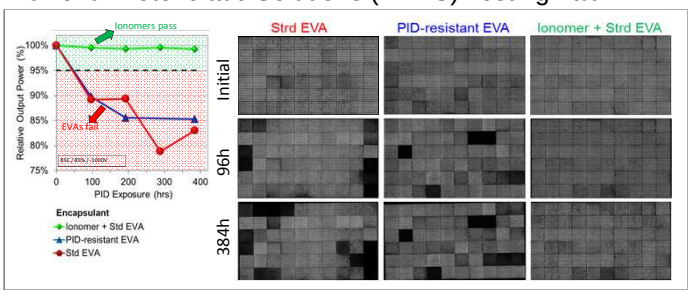
- Three encapsulants:
  - (a) Std EVA
  - (b) "PID-resistant" EVA
  - (c) Thin Ionomer + Std EVA

Thin DuPont™ PVX5004 Ionomer PID-resistant Film

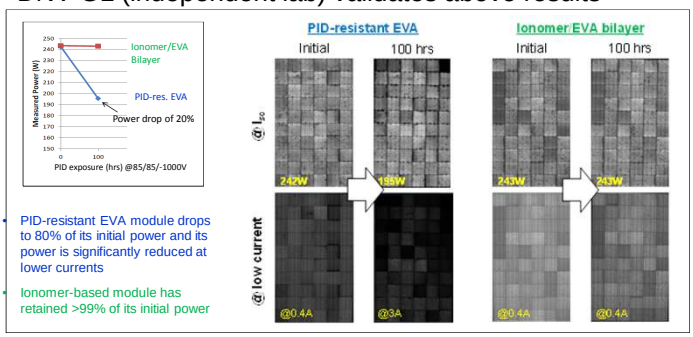
- PID sensitive 1st quality commercial 17.6% efficiency solar cells
- DH, TC, and TCHF Exposure on 6x10 cell modules
- PID Exposure: – 6x10 cell modules: 60 or 85C / 85%RH / -1000V / 0-96-384h

3. Ionomer Film prevents PID

DuPont Photovoltaic Solutions (DPVS) Testing Lab

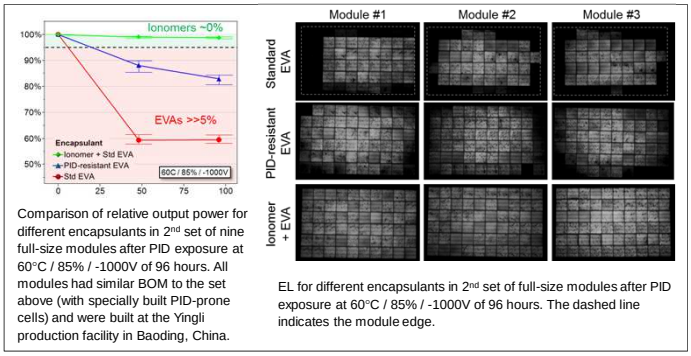


DNV-GL (independent lab) validates above results



- PID-resistant EVA module drops to 80% of its initial power and its power is significantly reduced at lower currents
- Ionomer-based module has retained >99% of its initial power

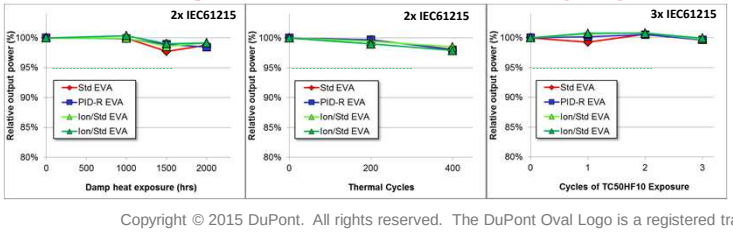
Yingli Research Lab (China) confirms the results



Comparison of relative output power for different encapsulants in 2nd set of nine full-size modules after PID exposure at 60°C / 85% / -1000V of 96 hours. All modules had similar BOM to the set above (with specially built PID-prone cells) and were built at the Yingli production facility in Baoding, China.

EL for different encapsulants in 2nd set of full-size modules after PID exposure at 60°C / 85% / -1000V of 96 hours. The dashed line indicates the module edge.

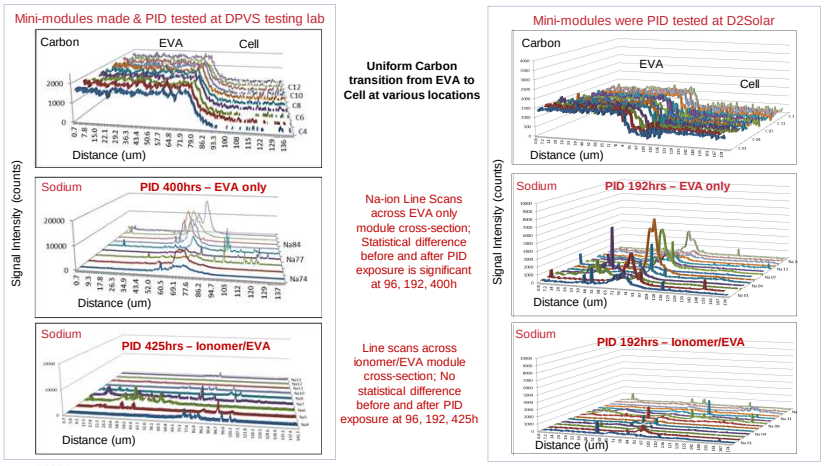
4. Ionomer passes Accelerated Aging Tests

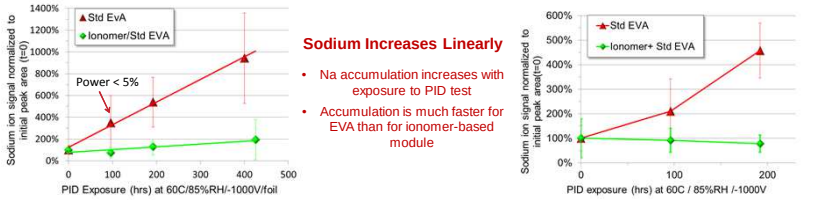


5. Minimizing Na^+ accumulation prevents PID

Na Ion Migration Profile Measured Using LA-ICP-MS in a PV Module

Laser Ablation – Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS): A laser beam is focused and scanned across the sample surface of the module's cross-section, generating particles from the top 5-20 µm of the sample surface. The particles are introduced into a high temperature Argon plasma, which serves as a ionization source. The resulting elemental ions are analyzed by a mass spectrometer. Modules were exposed to extended PID conditions of 60C/85%RH/-1000V/foil.



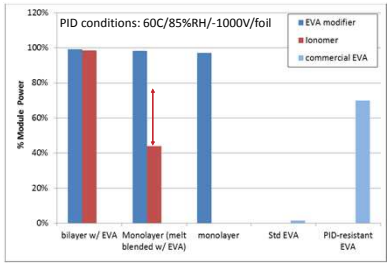


Sodium Increases Linearly

- Na accumulation increases with exposure to PID test
- Accumulation is much faster for EVA than for ionomer-based module

6. Next Gen "One Encapsulant"

An EVA modifier was tested in mini-modules as a bilayer (EVA modifier/EVA construction) and as a melt blend with EVA; both types of encapsulant have excellent transmission and suppress PID. The modified EVA encapsulant has passed 192h of PID exposure, while the ionomer/EVA melt blends do not suppress PID as well. Further research and module testing is needed.



7. Conclusions

- Thin ionomer between a Standard EVA and front glass suppresses any PID degradation
- 'PID-resistant' EVA cannot prevent PID degradation
- Sodium ion accumulation at cell surface was demonstrated for EVA-based encapsulant
- Ionomer-based encapsulant effectively prevents accumulation of the sodium ions
- Preliminary research shows a promising candidate for a "one-encapsulant" solution to PID

Acknowledgements: Special thanks to John Jensen, Mark Hoffman, Jen Norwood Ray Celikay and Gail Raty for their contribution to this work. Special thanks to DNV-GL for power & EL measurements.

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TETRA – Thermal Environment by Transient Response Analysis: Auto-calorimetry toward material and structure evolution studies in concentrator photovoltaic cells

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1. Introduction

Eutectic Sn-Pb solder joints have been widely studied in the microelectronics industry. On cooling after reflow and with cyclic thermo-mechanical fatigue, solder joints are known to undergo **spinodal decomposition**, **intermetallic grain growth**, **Kirkendall void growth**, **micro-crack** and **macro-crack** formation, and other processes [1].

Our **objective** is to demonstrate whether these processes affect the **thermal and reliability properties of a 3JPV solder joint**, and whether this can be detected in a **simple, non-destructive, thermal test during stress cycling**.

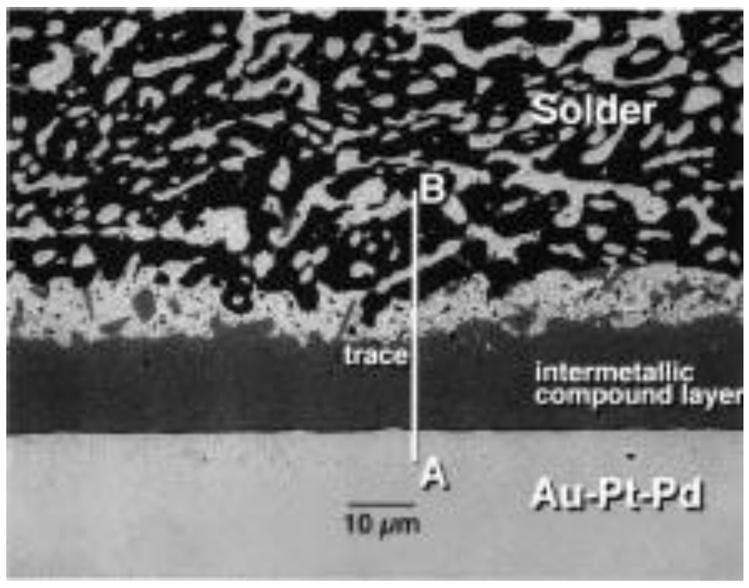


Fig. 1: Microstructure of aged Sn-Pb solder on AuPtPd metal. [1]

Previous work in this program [2] used a high-concentration solar simulator to develop cyclic thermal transients of approximately 65K for 8 seconds in 3JPV cells, but device failure was not seen after 7,000 cycles.

Solder joint failure has been induced using conventional oven cycled stress [3], where 1,000–2,000 cycles at ramp rates of 7.5 to 140K/min were used.

2. Method

Multi-junction photovoltaic cells (MJPV) convert concentrated sunlight to electrical power with efficiencies approaching 50%. MJPV cells can also be operated as a **self-thermometer** and a **self-heater**, without added structure or componentry, which enables **auto-calorimetry** using only a programmable source-monitor unit (SMU).

Thermal transients can be introduced into the cell using the self-heater, and the device response can be followed using **junction temperature T_j**. **Thermal transient response** is informative regarding the state and evolution of materials and structures in the cell [4,5]. Transient response is found to change in different ways, after **hot and cold thermal shocks**.

Auto-calorimetry:

Segment 1: low-current monitor (10mA) for ambient temperature

Segment 2: known energy dose (400mA, 1s) injected into junctions

Segment 3: low-current monitor transient response

Proxy for cyclic thermo-mechanical fatigue:

Hot shock: 115°C hot plate, 10 seconds

Cold shock: –196°C liquid nitrogen dip, 10 seconds

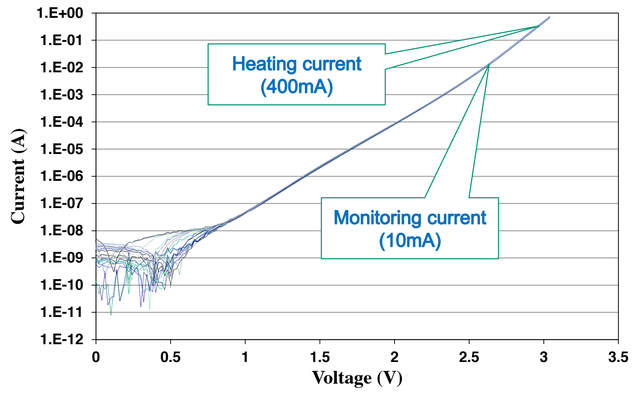


Fig. 3: Dark forward I-V curves of some 3JPV cells at room temperature.

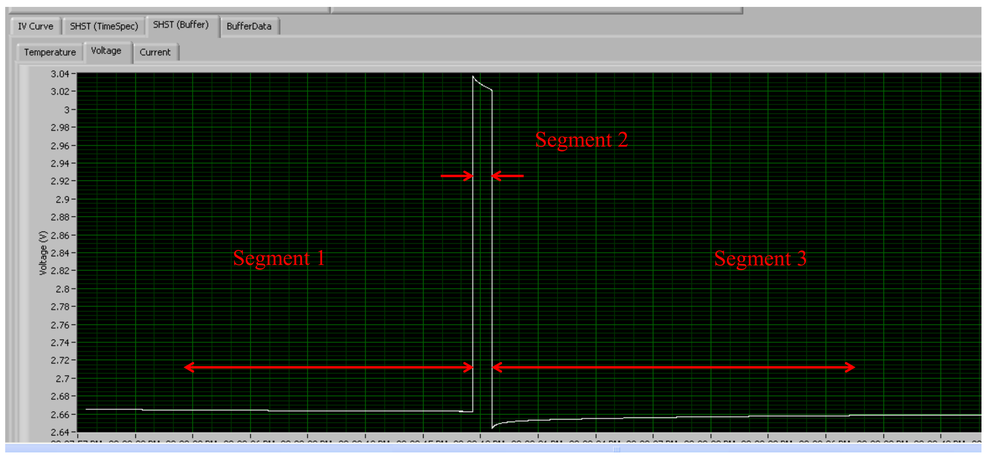
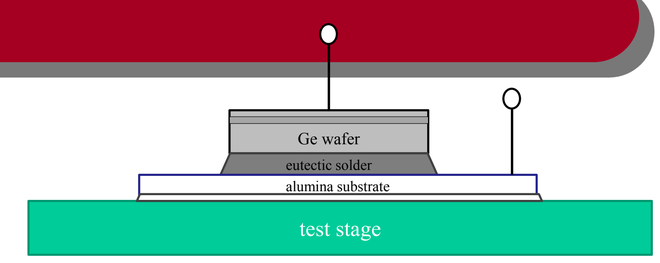


Fig. 2: TETRA three-segment scan.



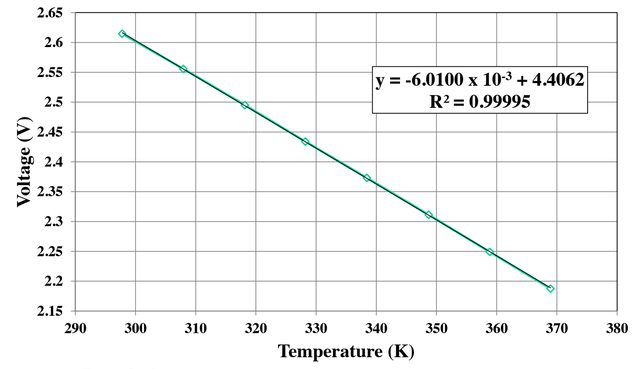


Fig. 4: Junction temperature calibration curve.

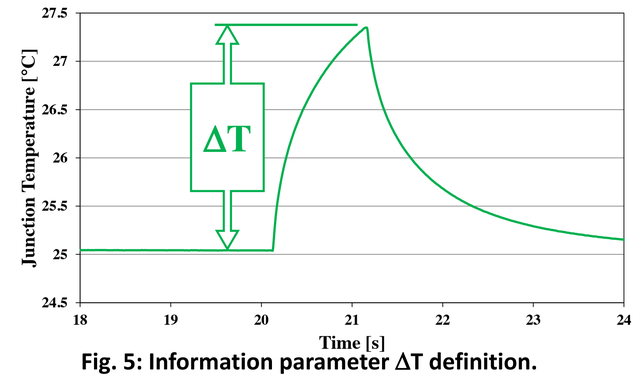


Fig. 5: Information parameter ΔT definition.

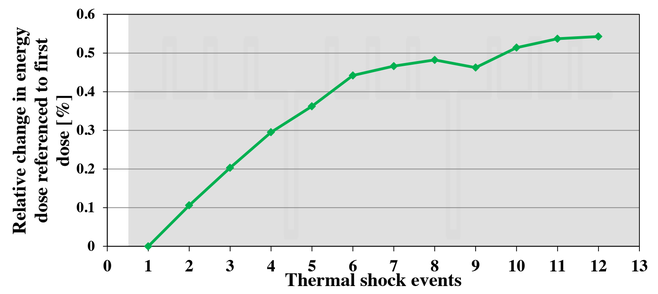


Fig. 6: Energy dose uniformity.

3. Preliminary Results

Preliminary results show **useful sensitivity**, expected test stage material dependence, sample thermal mass effect, transient **time constant structure**, and **substrate curvature change on shocks**.

Future work will explore **piezoelectric** artifacts, **cyclic fatigue monitoring,** differential structure functions, and other transient parameters.

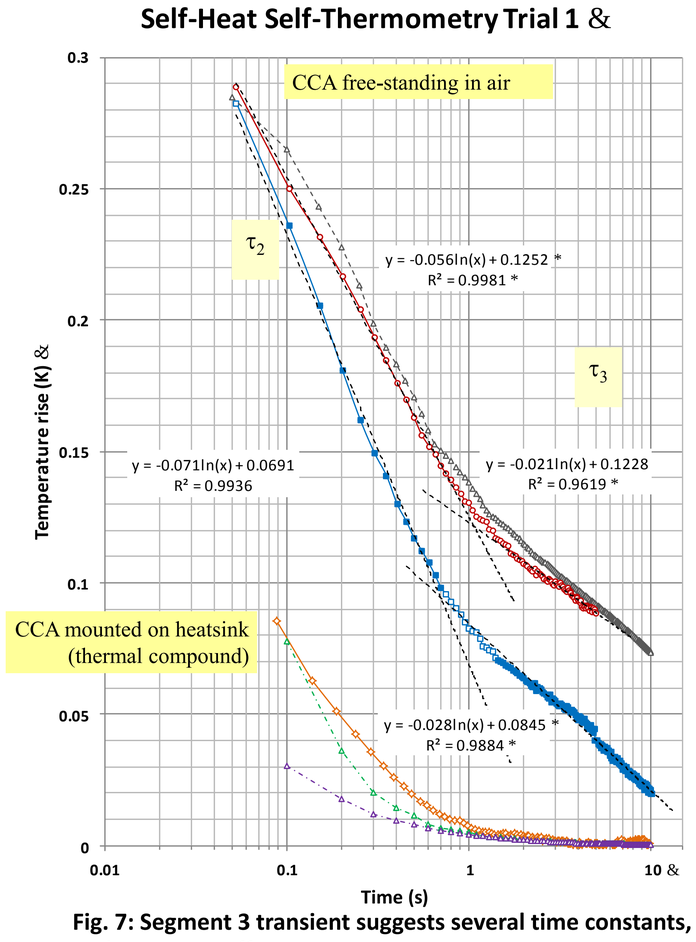


Fig. 7: Segment 3 transient suggests several time constants, and test stage effect.

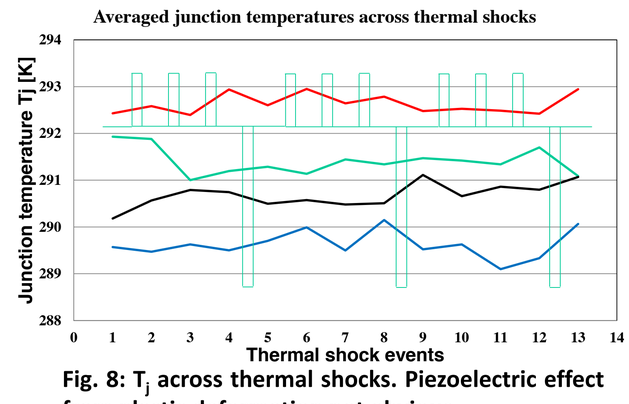


Fig. 8: T_j across thermal shocks. Piezoelectric effect from plastic deformation not obvious.

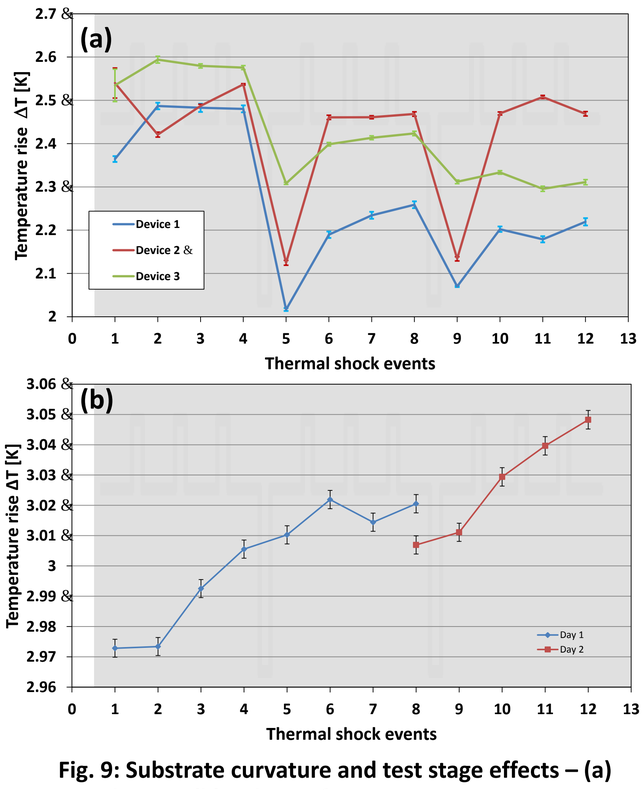


Fig. 9: Substrate curvature and test stage effects – (a) metal stage; (b) polymer foam stage.

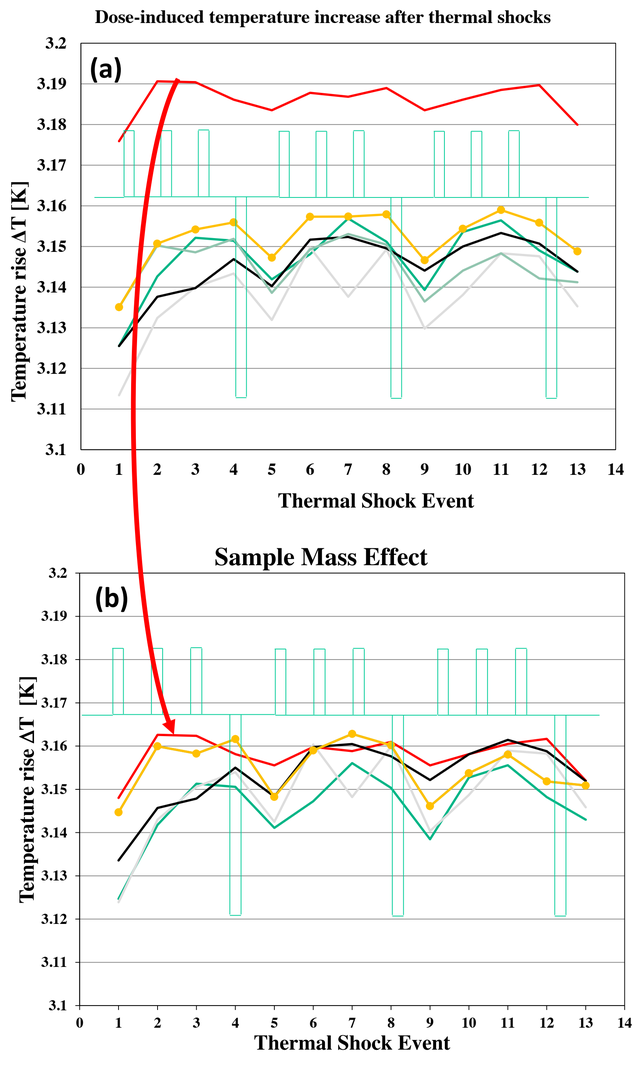


Fig. 10: Mass sensitivity (5 samples) – (a) raw data; (b) normalized to sample mass.

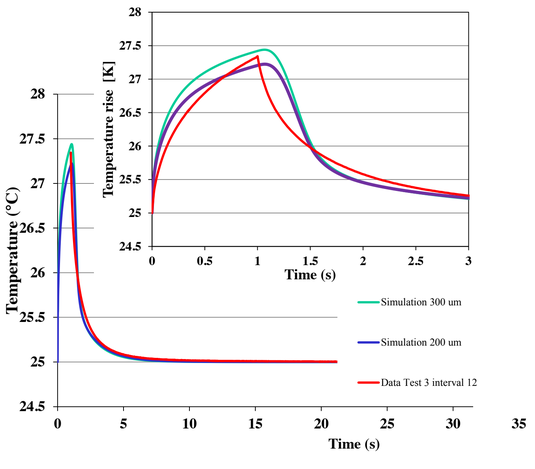


Fig. 11: Finite–element modeling Segments 2 & 3, on metal stage (COMSOL).

References

1. P.T. Vianco et al., "Intermetallic Compound Layer Development During the Solid State Thermal Aging of 63Sn-37Pb Solder/Au-Pt-Pd Thick Film Couples" IEEE Trans. Comp. Packag. Man. Tech. A, 20(4)(1997)478
2. R.M. Beal, K. Hinzer, et al., "High-intensity light-cycling of HCPV assemblies using the XT-30 solar simulator" Proc. NREL PVMRW 2012
3. N.S. Bosco et al., "On the effect of ramp rate in damage accumulation of the CPV die-attach" 37th IEEE PVSC, 2012
4. V. Szekely "A new evaluation method of thermal transient measurement results" Microelectronics Journal 28 (1997) 277-292
5. A. Vass-Varnai, M. Rencz et al., "Application of Thermal Transient Testing for Solar Cell Characterization" Proc. 28th IEEE SEMI-THERM Symposium

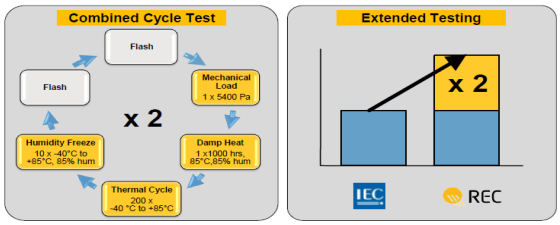
Rolling Reliability Test in REC Solar and Correlation Between Reliability Test and Field Degradation

Jia Ying Ye, Teck Cheng Tan, REC Solar, Singapore

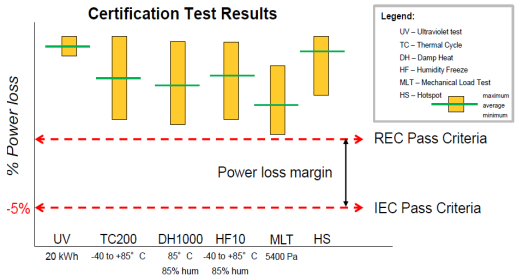
Introduction: REC internal "Rolling Reliability Test" (RRT) has been established to periodically and systematically monitor the production with extended accelerated aging tests, to ensure the constant quality and reliability. Results from the reliability tests are then compared with the real-life field-aged modules for correlation study. While the studies on the acceleration factor of reliability tests are calculated mainly based on the maximum power, the acceleration impact for various parameters vary significantly. In order to study the correlation between reliability test and field degradation, it might be necessary to determine the acceleration factors for individual parameters.

Stringent qualification and ongoing reliability tests in REC

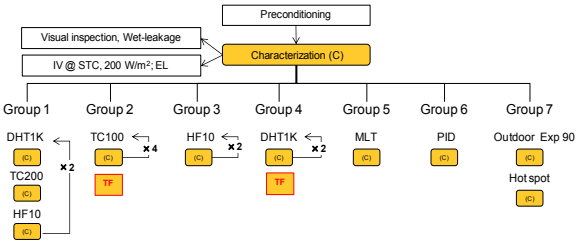
Extreme testing ensures performance in the most severe environments and increased reliability.



More stringent pass criteria than industry standards to ensure reliability



Rolling Reliability Test: Ongoing reliability monitoring



Failure Reporting, Analysis, and Corrective Action System (FRACAS) is established for continuous control of quality

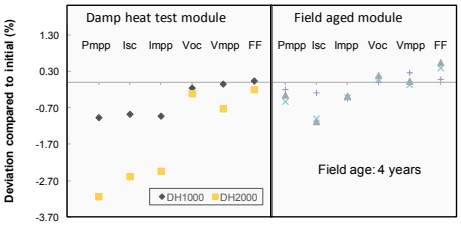
Lifetime and degradation simulation to correlate with real-life reliability

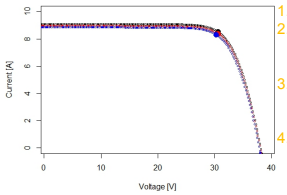
Arrhenius Relationship [1,2]

$$Rate \propto \exp\left[\frac{-E_a}{kT}\right] \qquad (*)$$

Correlation between field aged and test aged modules

Case 1: Damp heat aged module VS. modules from sub-tropical area (Germany, operating since December 2010)

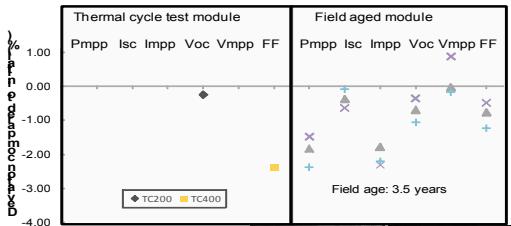


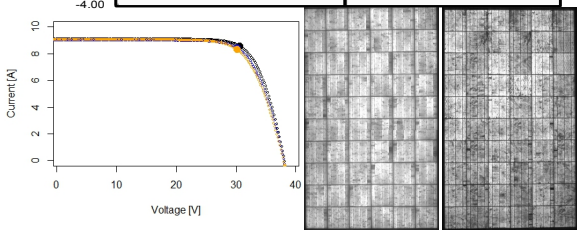


1. Acceleration factor of 30X based on (*)
2. Decrease in Isc is the main contributor to the power drop for both field aged and DH tested modules.
3. For field aged modules, the FF increase because the Isc decreases while the series resistance does not change significantly.
4. For modules after damp heat test, Isc decrease and series resistance increased due to corrosion of the interconnection. Thus FF remains or decreases.

➢ <u>The acceleration factor of damp heat to the Isc is approximately half of that to the series resistance.</u>

Case 2: Thermal cycling aged module VS. modules from arid area (Colorado, operating since July 2011)





1. Acceleration factor of 8X for Pmpp
2. For modules operating in arid climates, loss in FF is more evident. Increase in series resistance leads to significant decrease in Impp.
3. TC aged modules show additional decrease in Vmpp due to increased series resistance.
4. EL images show finger breaks in both thermal cycle aged modules and the field aged modules

➢ <u>Increase of series resistance is reflected from the decrease in both Impp and Vmpp.</u>

Summary:

1. The acceleration factor to different parameters (Pmpp, Isc, Voc, series resistance etc.) is different for a specific accelerated aging test.
2. In order to study the correlation between reliability test and field failure, it might be necessary to look into the acceleration factors for individual parameters, which will be further investigated with the RRT program in future.

[1] Kurtz et al, 34th IEEE Photovoltaic Specialists Conference, Philadelphia, Pennsylvania, June 7–12, 2009.
[2] Koehl et al, Solar Energy Materials & Solar Cells 99 (2012) 282-291.

This presentation contains no confidential information.

Financial Implications of Module Degradation Uncertainty for Utility-Scale Solar Facilities

Mark Reusser, Matt Dorogi, Ph.D., Larry McClung, P.Eng.

Introduction

Uncertainty in module degradation rates can greatly impact the value of utility-scale crystalline solar projects. Through Monte Carlo analysis and PVsyst(1) system models, we explore the impacts of module degradation rate uncertainty on the overall uncertainty in the value of plant production.

Methods

Modeling Data

> PVsyst models developed during the financing or sale phase of the respective projects were used as generation models, with only the DC:AC ratio modified.

> Meteorological data from the NSRDB(2).

Production Value:

> Production value was determined by applying the Power Purchase Agreement energy value for a 25 year period to the project .

Uncertainty Calculation:

> Uncertainty was developed using Monte Carlo simulation with ~45 years of NSRDB GHI data representing inter-annual resource variation, a normal distribution representing model uncertainty and Initial degradation rate d istribution from 1,920 published degradation rates(3).

Degradation Model:

> Degradation was assumed to be linear, and was applied annually.

Projects

Annual Global Horizontal Irradiance		
Location	**(kW/m2)**	**Racking Type**
Boise, ID	1,709	Single-Axis Tracking
Imperial Valley, CA	2,142	Single-Axis Tracking
Toledo, OH	1,404	20-degree Fixed Tilt

1. A. Mermoud, “PVsyst: Photovoltaic Software,” Retrieved October 23, 2014 from www.pvsyst.com/en
2. “National Solar Radiation Database,” Retrieved December 6, 2011 from http://rredc.nrel.gov/solar/old_data/nsrdb/
3. D. Jordan, S. Kurtz “Photovoltaic Degradation Rates—an Analytical Review,” Progress in Photovoltaics: Research and Applications, vol. 21 pp. 12–29, 2013.

BOISE, ID

Figure 1. Boise, ID. AC:DC ratio of 1.1

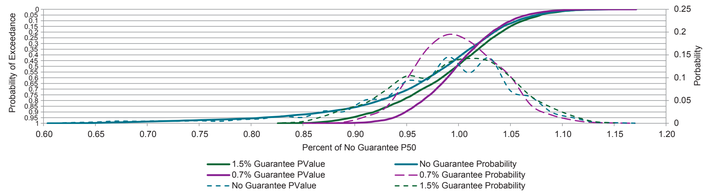
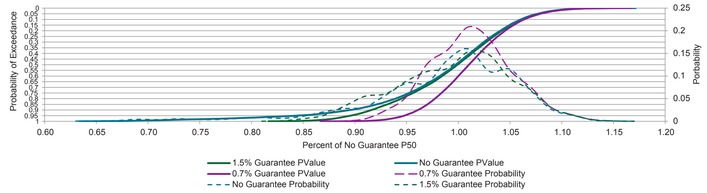


Figure 2. Boise, ID. AC:DC ratio of 1.5



IMPERIAL VALLEY, CA

Figure 3. Imperial Valley, CA AC:DC ratio of 1.1

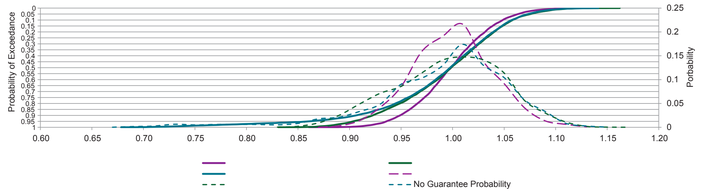
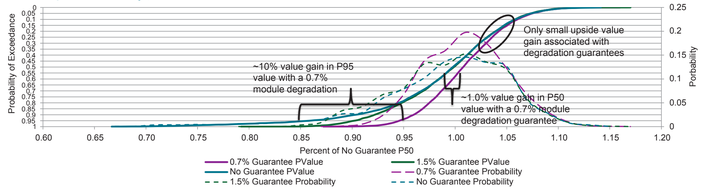


Figure 4. Imperial Valley, CA AC:DC ratio of 1.5



TOLEDO, OH

Figure 5. Toledo, OH. AC:DC ratio of 1.1

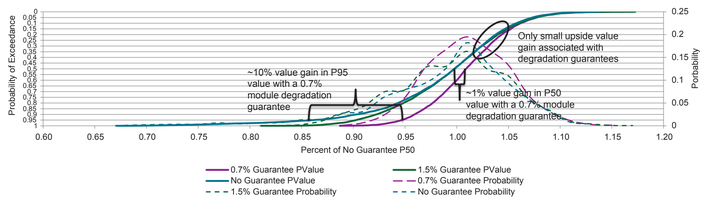
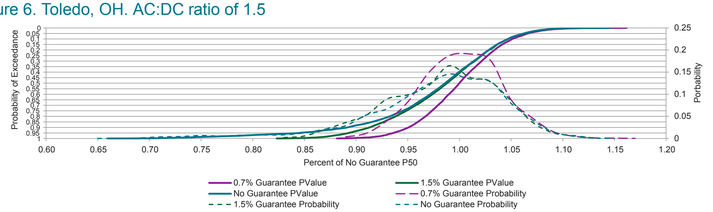


Figure 6. Toledo, OH. AC:DC ratio of 1.5



Selected Value Comparisons

Location	DC:AC Ratio	Guaranteed Deg. Rate (%/yr.)	PValue	Value Gain Respective to no warranty (%)
Boise, ID	1.1	0.7	P5	0.3
		0.7	P50	1.1
		0.7	P95	9.8
		1.5	P5	0.3
		1.5	P50	0.1
		1.5	P95	4.6
Boise, ID	1.5	0.7	P5	0.0
		0.7	P50	1.1
		0.7	P95	5.0
		1.5	P5	-0.1
		1.5	P50	1.1
		1.5	P95	5.3
Imperial Valley, CA	1.1	0.7	P5	0.0
		0.7	P50	1.0
		0.7	P95	9.7
		1.5	P5	0.0
		1.5	P50	0.0
		1.5	P95	4.6
Imperial Valley, CA	1.5	0.7	P5	0.0
		0.7	P50	1.0
		0.7	P95	9.7
		1.5	P5	0.0
		1.5	P50	1.0
		1.5	P95	4.9

Discussion

Limitations:

In this study, the we do not consider the cost of monitoring module degradation or enforcing the associated module warranties. Furthermore, it should be noted that the value of any guarantee is dependent on the stability and longevity of the entities backing the guarantee. We note that the pool of module degradation rates used to develop the distribution are not manufacturer or model specific. This is by design as module manufacturers are often not specified until late phase design. Similarly, the pool of degradation rates was developed over multiple decades, and may therefore, not represent the most contemporary modules.

Observations

We note that the greatest value of the module warranties occurs at the highest Probability of Exceedance Values (“PValues”) across all of the projects studied. This is significant as most projects are financed at PValues significantly larger P50. Conversely, there is much less upside gain as a result of the module warranties. Regarding the 95 percent PValues, we note the largest gains in value due to module warranty are generally at the lowest DC:AC ratio, except at the Imperial Valley site, where it is relatively consistent. The value gained at the 50 percent PValue is significantly less. These observations are indicated graphically on fig. 4-5. We therefore conclude that the study indicates that the value of module warranties will be best captured during the financing phase of the project because warranties significantly reduce the project risk, but have less effect on the 50 Percent PValue and project upside potential.

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LPVO Laboratory of Photovoltaics and Optoelectronics

Outdoor Stabilization of Thin-Film Photovoltaic Module Performance

University of Ljubljana, Faculty of Electric ngineering, 25, SI-1000 Ljubljana, Slo of Electrical Engineerin

Introduction

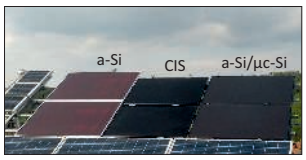
Thin-film (TF) photovoltaic (PV) modules go through the process of preconditioning before they reach the metastable and rated operating point. We expose six TF PV modules of three different technologies:

- amorphous silicon (a-Si a,b),
- micromorph tandem silicon (a-Si/µc-Si a,b) and
- chalcopyrite (CIS a,b)

to outdoor conditions to receive 500 kWh/m^2 of total solar irradiation (H_{poa}) and monitor the STC performance and electroluminescence (EL).

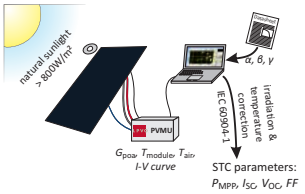
Experimental

Outdoor exposure

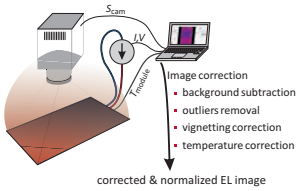


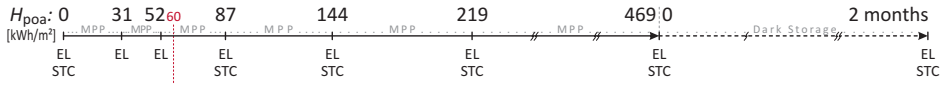
Location: Ljubljana (N46°02.69', E14°29.38')
Orientation: south, inclination: 30°

STC performance



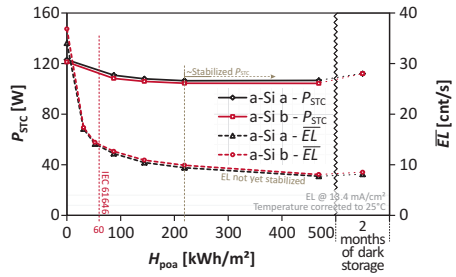
Electroluminescence



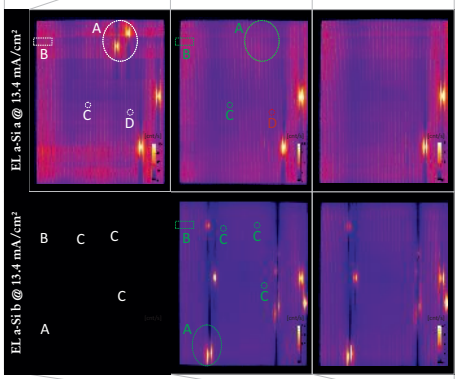


Results

Amorphous silicon

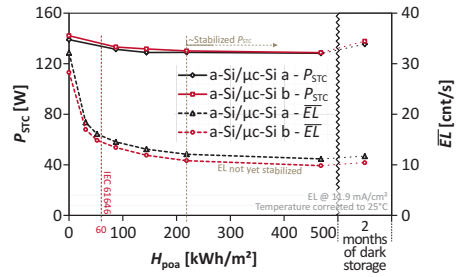


Module	Initial	After irradiation		After dark storage	
	P_{STC} [W]	P_{STC} [W]	dP_{STC}	P_{STC} [W]	dP_{STC}
a-Si a	123.0	106.7	-13.3%	112.0	+5.0%
a-Si b	121.2	104.4	-13.9%	112.0	+7.4%
	$\overline{EL}$ [cnt/s]	$\overline{EL}$ [cnt/s]	$d\overline{EL}$	$\overline{EL}$ [cnt/s]	$d\overline{EL}$
a-Si a	34.0	7.7	-77.3%	8.1	+5.1%
a-Si b	36.8	8.1	-78.1%	8.5	+5.5%

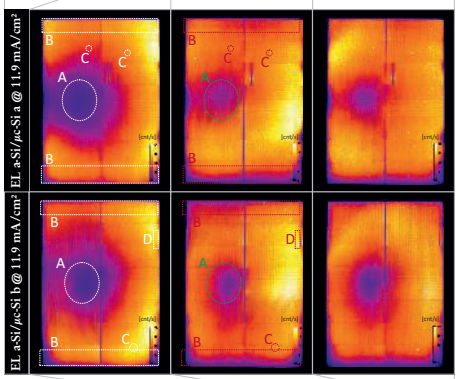


Inhomogeneity dynamics:

A: insufficient P3 cuts . . . mitigation	A	A	/
B: systematic shunts . . . . improvement	B	B	/
C: shunt . . . . . improvement	C	C	/
D: shunt . . . . . formation	D	D	/

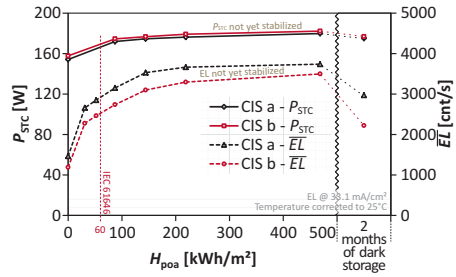


Module	Initial	After irradiation		After dark storage	
	P_{STC} [W]	P_{STC} [W]	dP_{STC}	P_{STC} [W]	dP_{STC}
a-Si/µc-Si a	139.0	128.3	-7.7%	135.4	+5.6%
a-Si/µc-Si b	142.2	128.7	-9.5%	137.7	+7.0%
	$\overline{EL}$ [cnt/s]	$\overline{EL}$ [cnt/s]	$d\overline{EL}$	$\overline{EL}$ [cnt/s]	$d\overline{EL}$
a-Si/µc-Si a	32.2	11.2	-65.3%	11.7	+4.9%
a-Si/µc-Si b	28.3	9.8	-65.2%	10.4	+5.8%

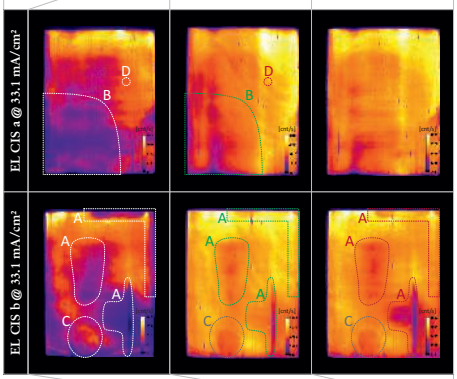


Inhomogeneity dynamics:

A: large dark area . . . . . improvement	A	A	/
B: edge inhomogeneity . deterioration	B	B	/
C: bright spot. . . . . formation	C	C	/
D: shunt . . . . . formation	D	D	/



Module	Initial	After irradiation		After dark storage	
	P_{STC} [W]	P_{STC} [W]	dP_{STC}	P_{STC} [W]	dP_{STC}
CIS a	154.2	179.8	+16.6%	175.0	-2.7%
CIS b	157.8	182.2	+15.5%	176.8	-3.0%
	$\overline{EL}$ [cnt/s]	$\overline{EL}$ [cnt/s]	$d\overline{EL}$	$\overline{EL}$ [cnt/s]	$d\overline{EL}$
CIS a	1464.6	3738.2	+155.2%	2970.9	-20.5%
CIS b	1189.9	3497.3	+193.9%	2219.5	-36.5%



Inhomogeneity dynamics:

A: inhomogeneous area . changes	A	A	A
B: inhomogeneous area . improvement	B	B	/
C: „constant" circle . . . . . constant	C	C	C
D: shunt . . . . . formation	D	D	/

Conclusion

Outdoor performance stabilization

- a-Si based TF PV modules initialy **degrade**.
- CIS based TF PV modules initialy **improve**.

Dark storage shows the opposite behaviour

- a-Si PV modules **improve**, while CIS **degrade**.

- EL exhibits higher sensitivity to changes than performance parameters.
- Some detected inhomogeneities show temporal changes, among them also mitigation and improvement.

Acknowledgment

- Slovenian Research Agency
  - Research Programme P2-0197
- Ministry of Education Science and Sport
  - Post-Doc funding for M.Bokalič through EU Social and Cohesion Fund (UL FE-664)

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Limiting Effects of Temperature on the Performance of a Si-PV Array in Trinidad and Tobago

Nia Thompson | The University of the West Indies

Problem / Question

To what degree is the efficiency of a PV cell affected by the cell temperature in Trinidad and Tobago?

Hypothesis

- The cell temperatures of PV Modules will be higher than NOCT
- At some Temperature value there will be a decrease in Power output hence efficiency, this value will be above NOCT

Project Overview

Renewable Energy Projects

Solar Power Projects

University of Trinidad and Tobago
O'Meara Campus (2.2 kW)

Trinidad and Tobago Electricity Commission
Mt. Hope Compound (2.2 kW)

Project done by Trinidad & Tobago's Electricity Commission to investigate Grid tie capabilities. Site consists of 10 220 W units installed at 11 º South An anemometer was also installed connected to the web box so that wind data can also be recorded.

Randomly selected days from a four month data set courtesy T&TEC solar panel grid integrated system at their Mount Hope building. Time showed a 24hour segment where readings were taken at 5minute intervals but actual panel data was only recorded (at what was assumed to be 6am because of the strange make up of the data it is subjected to some interpretation) between 6am and 6:30pm. The values for current and voltage recorded from the T&TEC panel were based on the values entering the Inverter, not necessarily taken at the MPP, and definitely not at open circuit voltage or short circuit current. The actual size of the array and the reference values of; efficiency, Isc, and Voc was not known. The type of panel and actual size of the panel was not known. The purpose of proceeding with the calculations was to develop a proper method for use when pertinent data is obtained.

Variables / Research

Controlled variables

- The Array used was located at the Trinidad and Tobago Electricity Commission Building Mt. Hope Trinidad

Independent variable

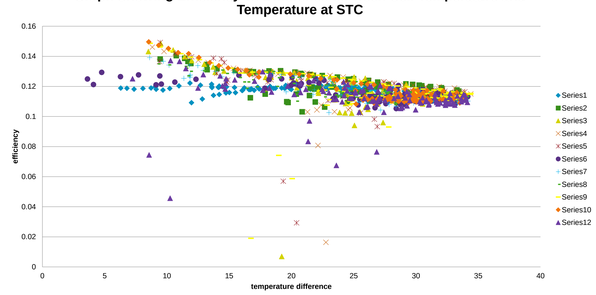
- The Irradiance values observed were grouped in 100 W/m^2 ranges when measured. It was assumed that the ±99 W/m^2 irradiance difference between the values would not significantly affect findings.
- Cloudy day was indicated by fluctuating irradiances
- Clear day by a rise and fall pattern of little fluctuation.

Dependent variable

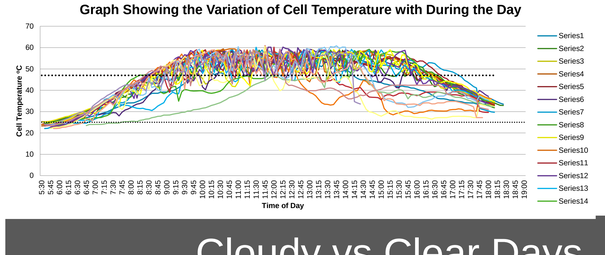
- The Power increased with the Irradiance values
- The variation of Temperature was recorded

General Observations

Graph Showing Efficiency vs Difference between Cell Temperature and Temperature at STC



Graph Showing the Variation of Cell Temperature with During the Day



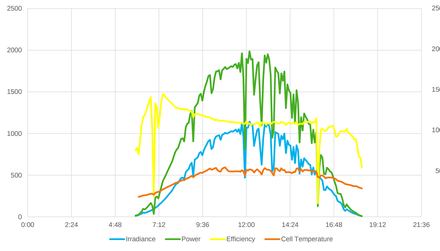
These graphs show the efficiencies and temperatures of several randomly chosen days over a 4 month period in 2012.

The top shows the variation of efficiency for each day (given in a different color)

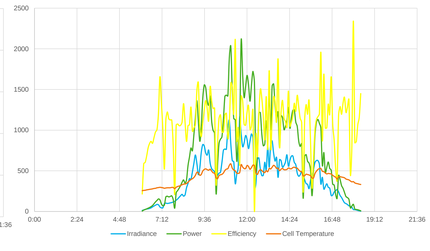
The bottom shows the variation of Cell Temperature taken from the back surface of a module. There are two indicator lines the lower showing STC temperature 25 ºC, the higher line at 47 ºC the typical NOCT temperature.

Cloudy vs Clear Days

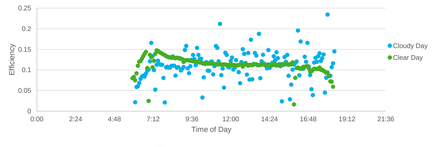
The Variation of Irradiance, Efficiency and Power for a Clear day



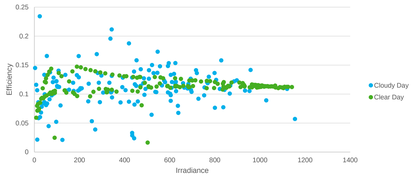
The Variation of Irradiance, Efficiency and Power on a Cloudy day



The Variation of Efficiency During the Day



Efficiency versus Irradiance

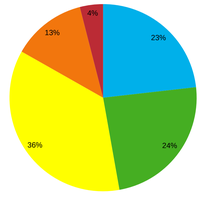


Trinidad and Tobago's Climate has two seasonal variations, due to the movement of the ITCZ. As a result there are two typical days observed clear and cloudy days. These graphs show randomly chosen clear and cloudy day and compare the variation of Irradiance, Cell Temperature and Efficiency on both days.

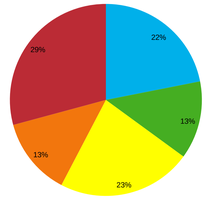
The last graph shows the variation of efficiency with Irradiance.

The pie charts below show the distribution of 5 Irradiance ranges within those two days.
Blue- less than 100 W/m^2
Green- 100-300 W/m^2
Yellow- 300-600 W/m^2
Orange- 600-900 W/m^2
Red- Over 1000 W/m^2

Irradiance Distribution on a Cloudy Day

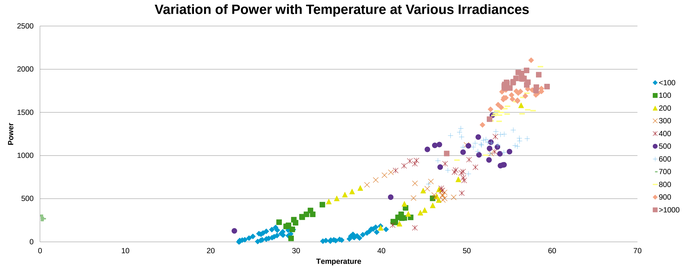


Irradiance Distribution on a Clear Day



Results

Variation of Power with Temperature at Various Irradiances



The graph above shows the variation of power with temperature for various irradiance levels. It shows linear increase of power with Irradiance and consequently cell temperature. However for Irradiances above 500 W/m^2 as the temperature increases the power decreases slightly.

Analysis & Conclusion

The greatest design advantage of the photovoltaic (PV) solar cell, is that the greater the intensity of the solar radiation incident on its surface, the greater the amount of current that can be generated. However, the solar radiation can only be absorbed within a particular range of wavelengths dependent on the material from which the PV cell is made. The remaining spectral wavelengths is absorbed as heat, which means the greater the intensity of the solar radiation, the greater the temperature of the cell which lowers the conversion efficiency of the cell which limits the current flowing through the cell. PV cells are manufactured to specific performance parameters set at Standard Test Conditions (STC irradiance of 1000 W/m^2 25 ˚C cell temperature and air mass of 1.5), which do not naturally occur in the real world environment (especially not at near equator latitudes). Electrical characteristics of photovoltaic cells have temperature coefficients which are evaluated indoors for manufacturers, but outdoor field tests are a useful technique of testing coefficients. These can further be used in outdoor performance modeling to show the long term performance of the PV cell. For a poly-crystalline solar cell the temperature coefficient is approximately 0.45%/K. Makrides et al. 2010 showed maximum module temperatures of 54 ºC. In this study the temperature coefficients reached as high as 0.5%/K for poly-crystalline PV modules. For crystalline silicon cells (the main type of PV cells currently manufactured and the type of PV used in this study) approximately 50% of the incoming solar radiation is absorbed as heat (Chow 2010), setting a maximum possible efficiency of 40%. These factors can cause the cell temperature to be higher than ambient, through absorptance of the solar radiation especially since day-night variation in ambient temperature is fairly significant in Trinidad approximately 10ºC.

The array parameters of cell temperature, module current and voltage, as well as the inverters' output current and voltage were recorded and showed cell temperatures up to 59 ºC on clear sky days. The standard convention was that, (Sklopaki,2009)NOCT- nominal operating cell temperatures were estimated using a standard 45ºC ±2ºC, which would estimate the actual cell temperatures under real world conditions, but they were found to overestimate temperatures for open rack mounted PV's (in temperate countries).

There was a clear 'heat up' and 'cool down' period that showed an inverse relationship with conversion efficiency.

During clear days, the voltage achieved a maximum value with irradiance between 300-600 W/m^2 and cell temperatures below 45 ºC, which was only for approximately 20% of the day (6am to 6pm). Between 200-400 W/m^2 the decrease in voltage with increased cell temperature is not as pronounced as with higher or lower irradiance values. For approximately 25% of the day the irradiance was over 900 W/m^2 with cell temperatures above 53ºC. This could be the reason the performance of a PV module is lower in Trinidad as average Irradiance is 500 W/m^2.

However it was found that during cloudy days the irradiance was under 300 W/m^2 for 20-44% of the day, but maximum voltage was achieved during moments of clear skies where the irradiance was over 600 W/m^2 and cell temperatures were below 50 ºC, which occurred for less than 11% of the day.

Efficiency values started the day slightly higher on a clear day but the cloudy day saw efficiency spikes where the clear day had a steady decrease. Other studies have shown that at low irradiance there is generally a decrease in efficiency in the PV panel (Biicher, 1997; Paretta et al., 1998; Schumann, 2009; Suzuki et al. 2002; Zinsser et al., 2009). The time of the day that showed the highest efficiency on clear days was less than 200 W/m2. On the cloudy day efficiency values showed some unexplained abnormalities, spiking way above theoretical values. The temperature effect can be seen in these graphs as the same irradiance values give a lower efficiency with higher cell temperatures.

The Irradiance distribution charts just show the percentage exposure the array received and can show the operating efficiency expected on similar days.

This shows that two patterns are generally expected with Trinidad's Climate and whereas the average Irradiance falls within expected range of 500 W/m2 the slight increase in temperature within a particular Irradiance value does affect the power and the efficiency of the PV array.

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This presentation contains no confidential information.

Prolonged Lifetime Performance of Meyer Burger`s Hetero Junction Solar Modules

Meyer Burger Team
Contact: Rainer Grischke rainer.grischke@meyerburger.com

MEYER BURGER

Introduction

- PV module guarantee of 30+ years is required
- Encapsulants function as adhesion of module components and provide protection from environmental impact
- EVA currently covers over 90 % of the market
- First long term outdoor experience uncovers excessive failure of EVAs
- Other encapsulants clearly show improved performance over EVA
- Especially TPOs provide extended module reliability demonstrated in DH and TC tests
- TPO allows for short lamination time < 8 min (GG, one chamber)

Material Performance

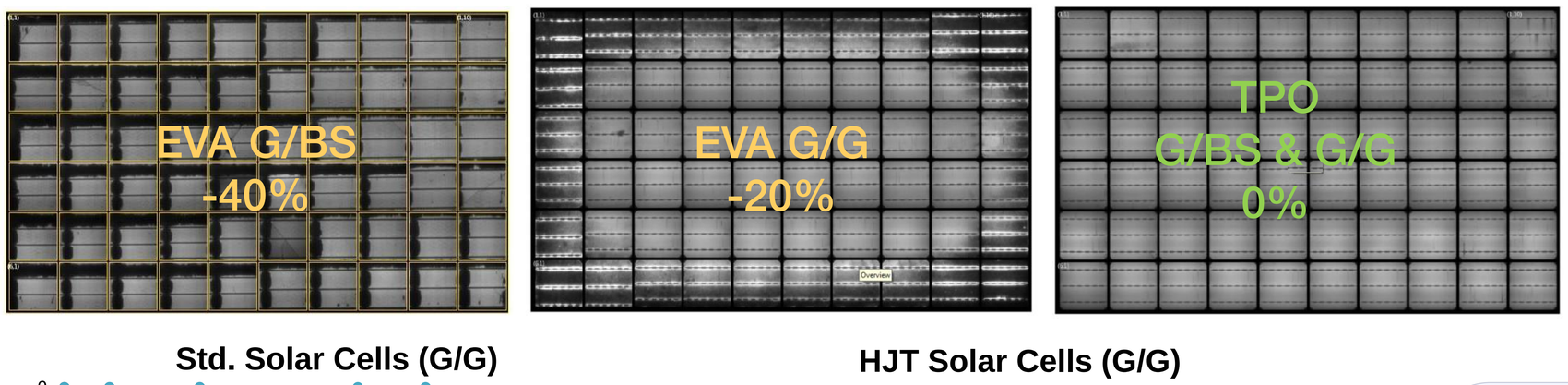
- Water Absorption Properties

Encapsulant	Water absorption (%)	WVTR (g/m²/day)	Probability of moisture ingress related degradation
EVA	0.2-0.3	10-30	+
PVB	0.4-0.5	25	+
TPO	<0.1	<5	-
Silicone	<0.1	>35	-
Ionomer	<0.1		-

- PID (potential induced degradation) stability of TPO
- No yellowing of TPO

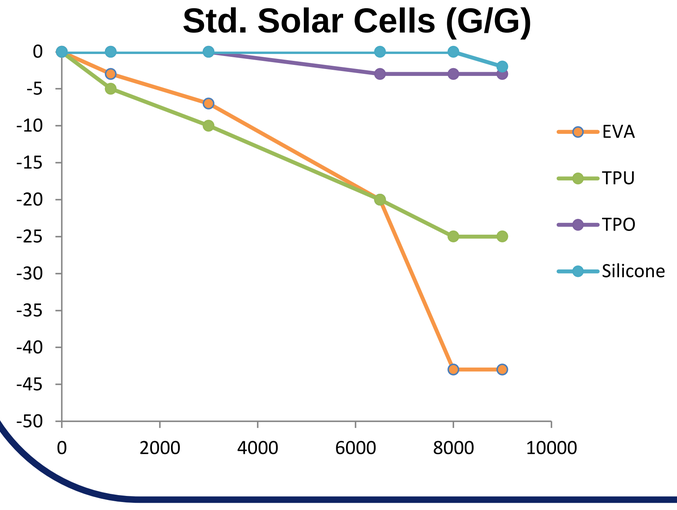
Reliability

EL after 7000 hours Damp Heat Test (85% RH, 85°C)

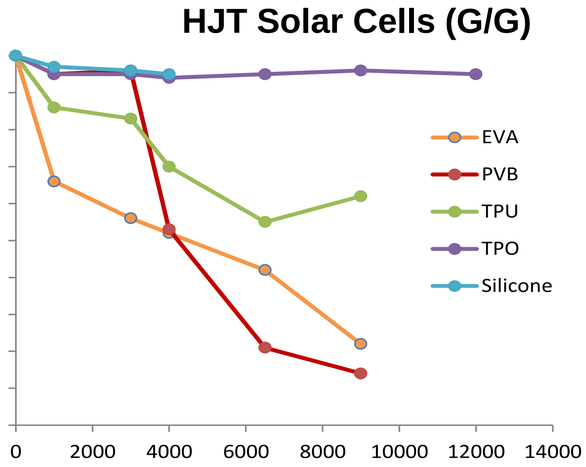


- Moisture ingress leads to cell degradation
- HJT solar cells are even more sensitive to moisture compared to std. cells
- TPO is intrinsically better regarding cell degradation

Std. Solar Cells (G/G)



HJT Solar Cells (G/G)



1200 Thermal Cycles (-40°C to +85°C)

	Initial	TC 600	TC 1200
Eff. [%]	19.5	19.3	19.3
J_{sc} [mA/cm²]	35.4	36.2	35.8
V_{oc} [mV/cell]	722	712	721
FF [%]	76.3	75.0	75.0
Degr. [%]	0	-0.9%	-0.8%

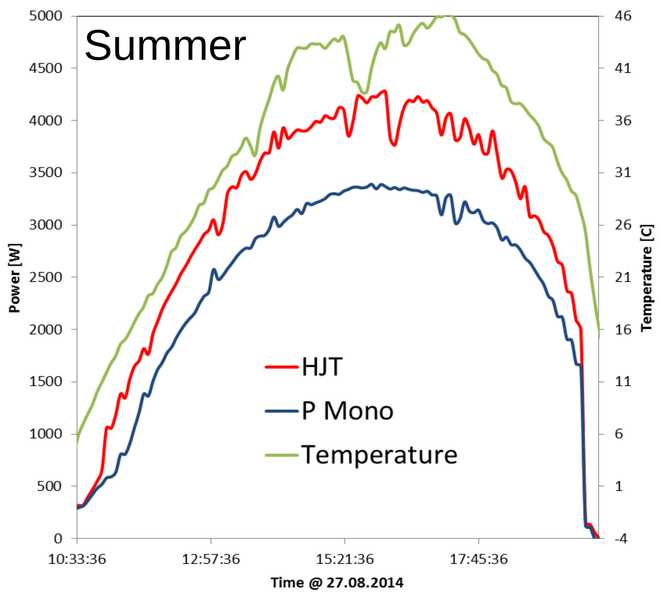
Outdoor: Monterosa @ 9460 ft

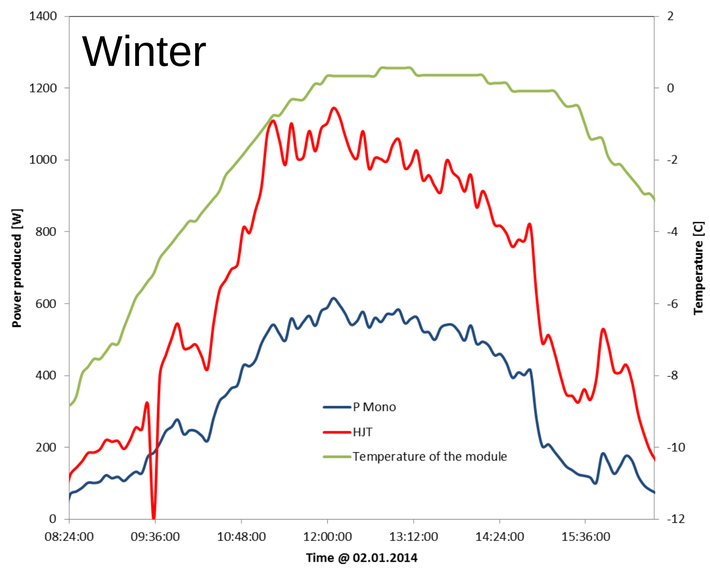
Test field: HJT-SWCT-GG @ 311 W => 4.665 kW
p c-Si mono-3BB-GG @ 252 W => 3.78 kW

TPO encapsulant; 5 mm glass at the front and at the back; mounted with pads at the back glass.

	2013*	2014**
HJT	4046W	4165W
p-mono	3254W	3253W

	Date	Time	Irradiation	Temp.
*	1 Sep`13,	3pm	915 W south, 1002W west	37°C
**	27Aug`14	3pm	891 W south, 1000W west	43°C





Yield HJT vs. P Mono: Summer + 25% Winter + 55%

Conclusion

TPO encapsulants show improved module reliability over EVA:

- High water vapor resistivity
- No degradation; No delamination
- No PID
- No yellowing

Meyer Burger Technology Ltd.

www.meyerburger.com

An Open Platform
To Speed-Up & Cost-Down
the PV Reliability R&D

2015. 2. 25.

Soo-Young Oh, Won-Shup So, Min-Soo Kim, Jae Hak Jung, Jin-Ho Park

Yeungnam University

This presentation contains no confidential information.

Contents

1. Introduction

2. SORES (Solar cell REliability Simulator)

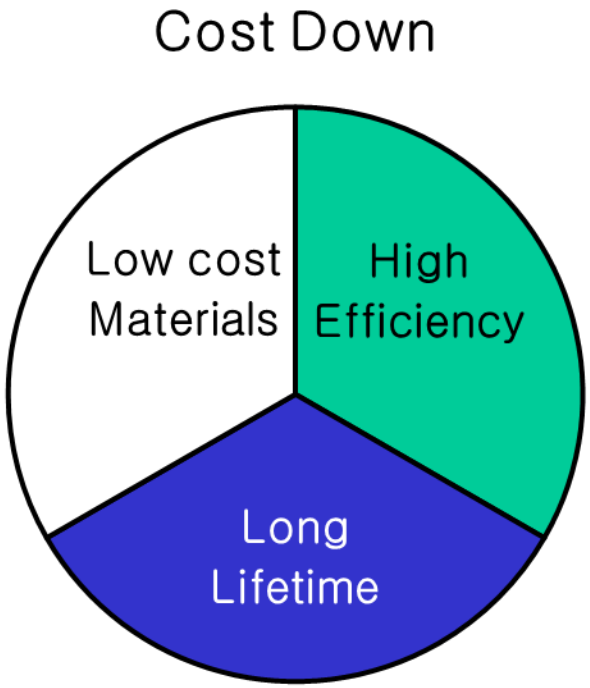
3. SORES Application:
   - Platform for PV Reliability R&D

4. Summary & Future Plan

1. Introduction (1) : Cost Down

○ **The Name of the Game in PV Industry is "Cost Down".**

○ **The Means of Cost Down need Reliability testing**



1. Introduction (2) : Reliability Testing

○ Problems of PV Reliability Testing

► **Qualification (Lab AST)** : Pass/Fail (No data available)
No Guarantee of Lifetime
Time-consuming(3~6Month) & Expensive

► **Outdoor Field Testing** : Too Long to get Results. (>20 Years)

- Existing PV Power Generation Plant:

  * Not well Characterized & Monitored.

  * Difficult for quantitative analysis

1. Introduction (3) : Missing Link

Quantitative Relation : ?

Qualitative Relation : Yes

Lab Accelerated Stress Test

Outdoor Field Performance

1. Introduction (4) : Missing Link ←SORES

Quantitative Relation : SORES

Qualitative Relation : Yes

Lab Accelerated Stress Test

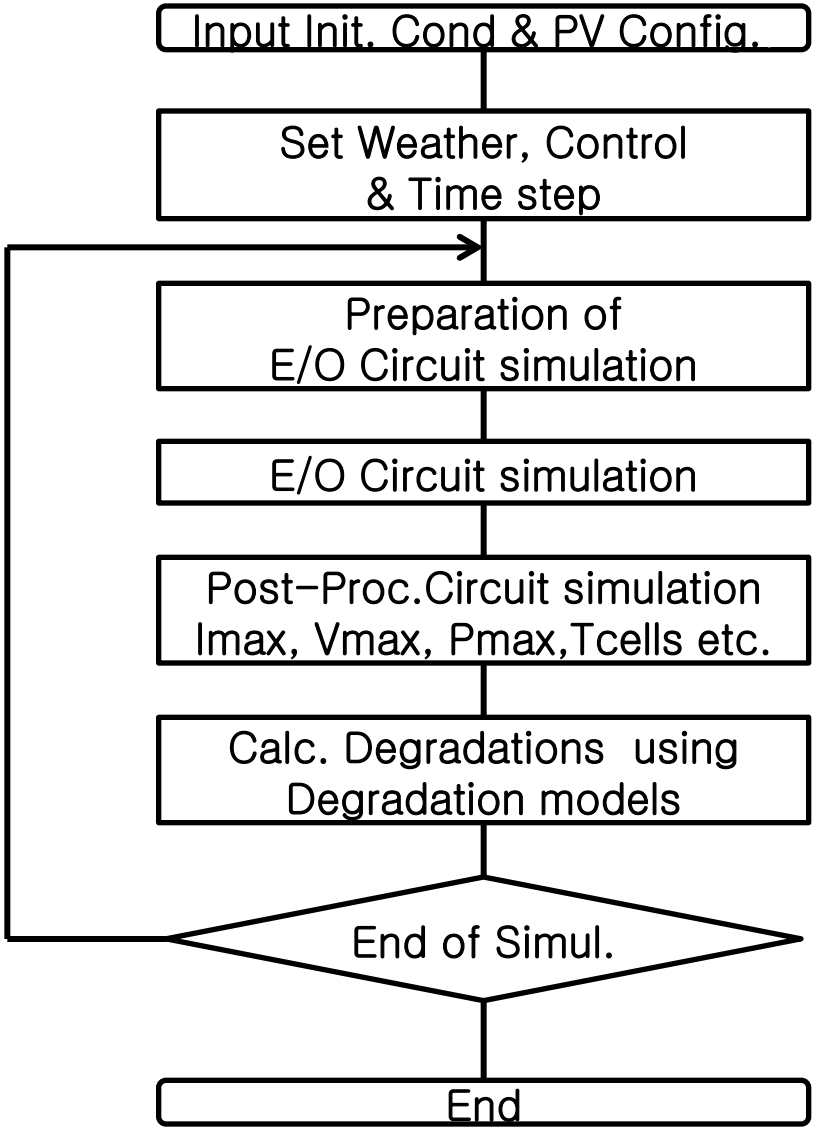
Outdoor Field Performance

2. SORES (1) : Physics-based PV Reliability Simulator

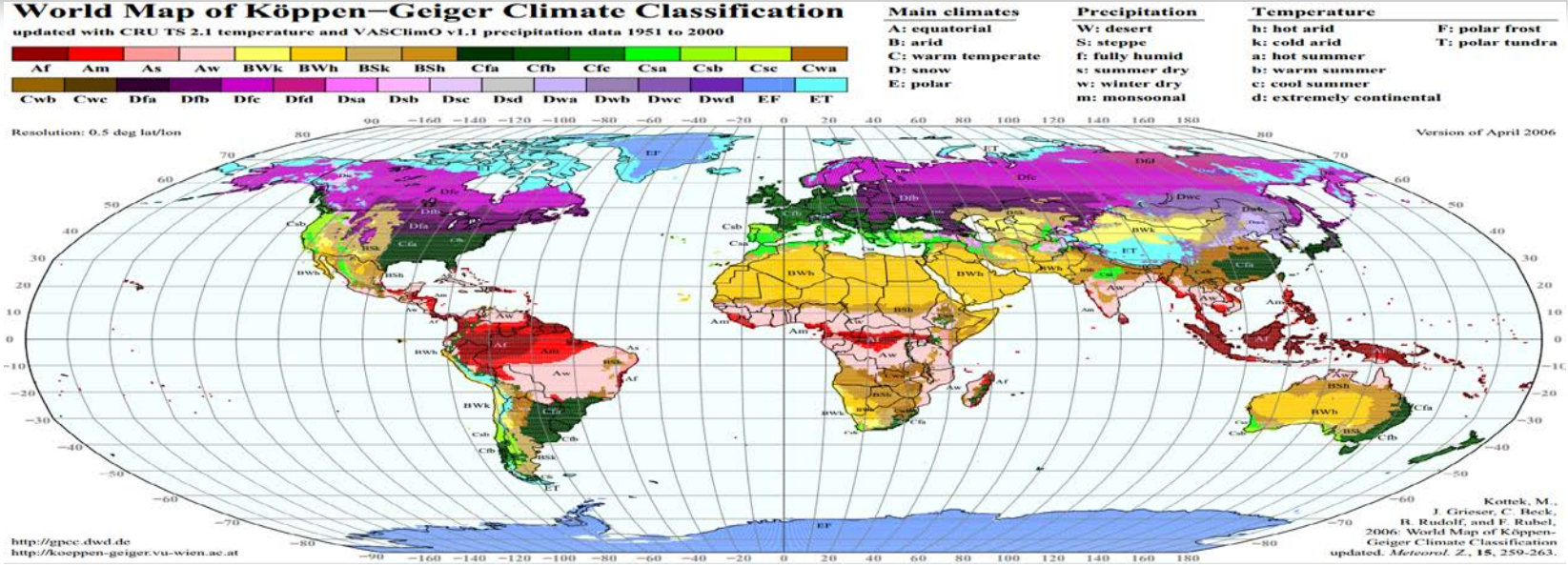
❖ Idea

- PV cell : Electro-Optical Diode
- PV Module : Electro-Optical circuit
- Solar Power Generation : Running Electro-Optical circuit
- Degradation of Solar Power Generation can be physically simulated by Time-Evolution Electro-Optical Circuit Simulation with PV Degradation Models.

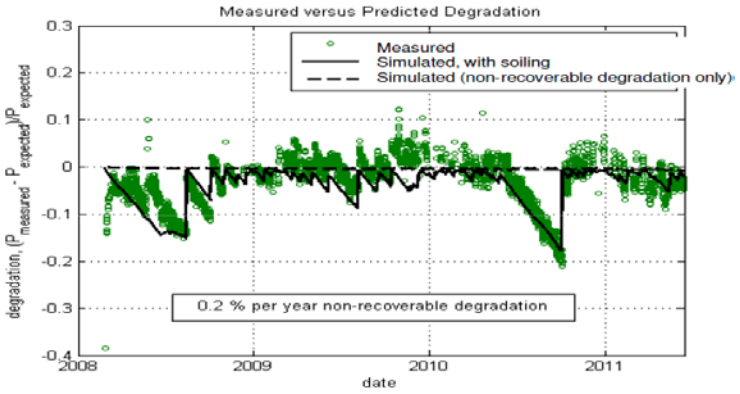
2. SORES (2) : Flow Chart



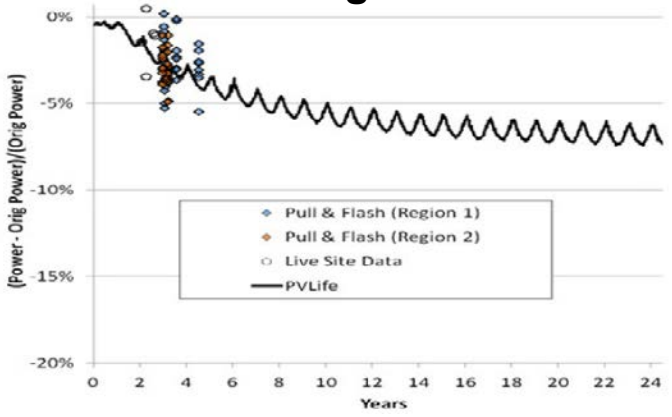
2. SORES (3) : Input-Output



Short-term



Long-term



2. SORES (4) : PV Failure Modes

Failure Modes
Broken Interconnects
Broken Cells
Corrosion
Delamination of Encapsulant
Encapsulant loss of Elasticity or Adhesion
Encapsulant Discoloration
Solder Bond Failure
Broken Glass
Hot Spots
Ground Faults
Junction Box Failures
Connection Failures
Structural Failures
Bypass Diode Failures
Open circuits leading to arcing

John H. Wohlgemuth and al, *IEEE International Reliability Physics Symposium , Monterey, California ' April 10-14, 2011*

2. SORES (5) : Degradation Model Development

Modeling of Encapsulant Decoloration

1) Physical Model :

- M. Mikofski, M. Anderson, S. Caldwell, D. DeGraaff, E. Hasselbrink, D. Kavulak, R. Lacerda, D. Okawa, Y.C. Shen, A. Tedjasaputra, A. Terao and Z. Xie, "A dynamic cell-by-cell pv system model to predict lifetime performance and reliability," *26th European Photovoltaic Solar Energy Conference and Exhibition, pp. 105-112, 2011.*

2. SORES (6) : Degradation Model Development

Modeling of Encapsulant Decoloration

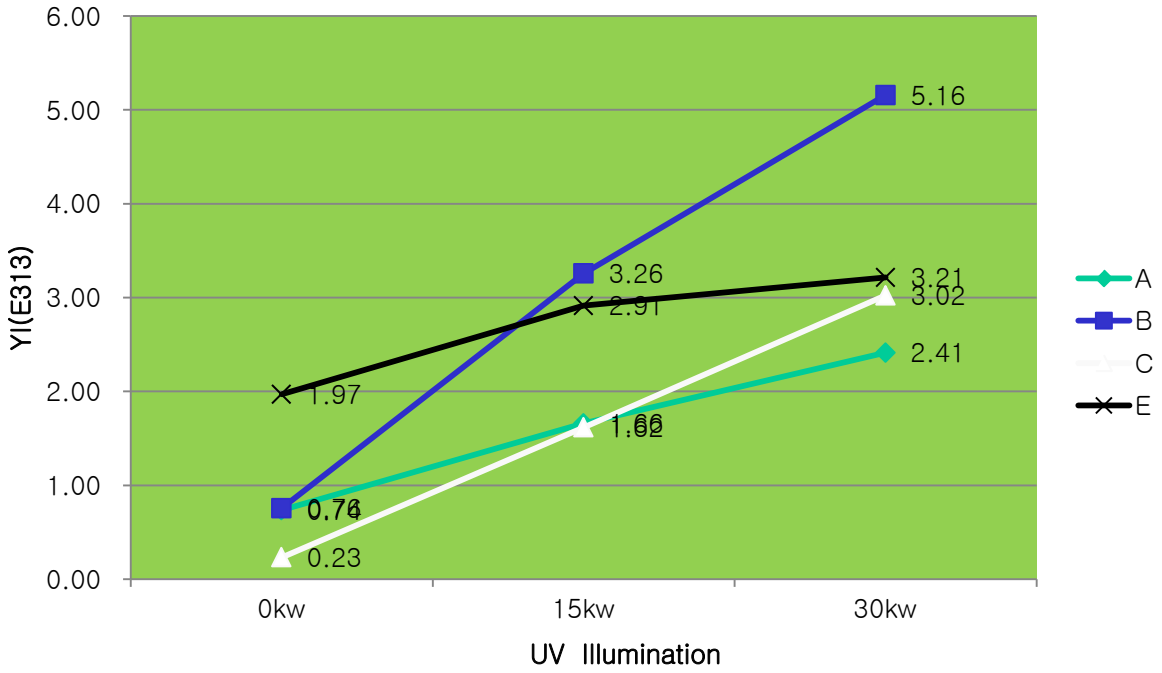
2) Empirical Model : UV Yellowing Measurement : Yellow Index (E313)

<UV Test Sample Preparation & Measurement>

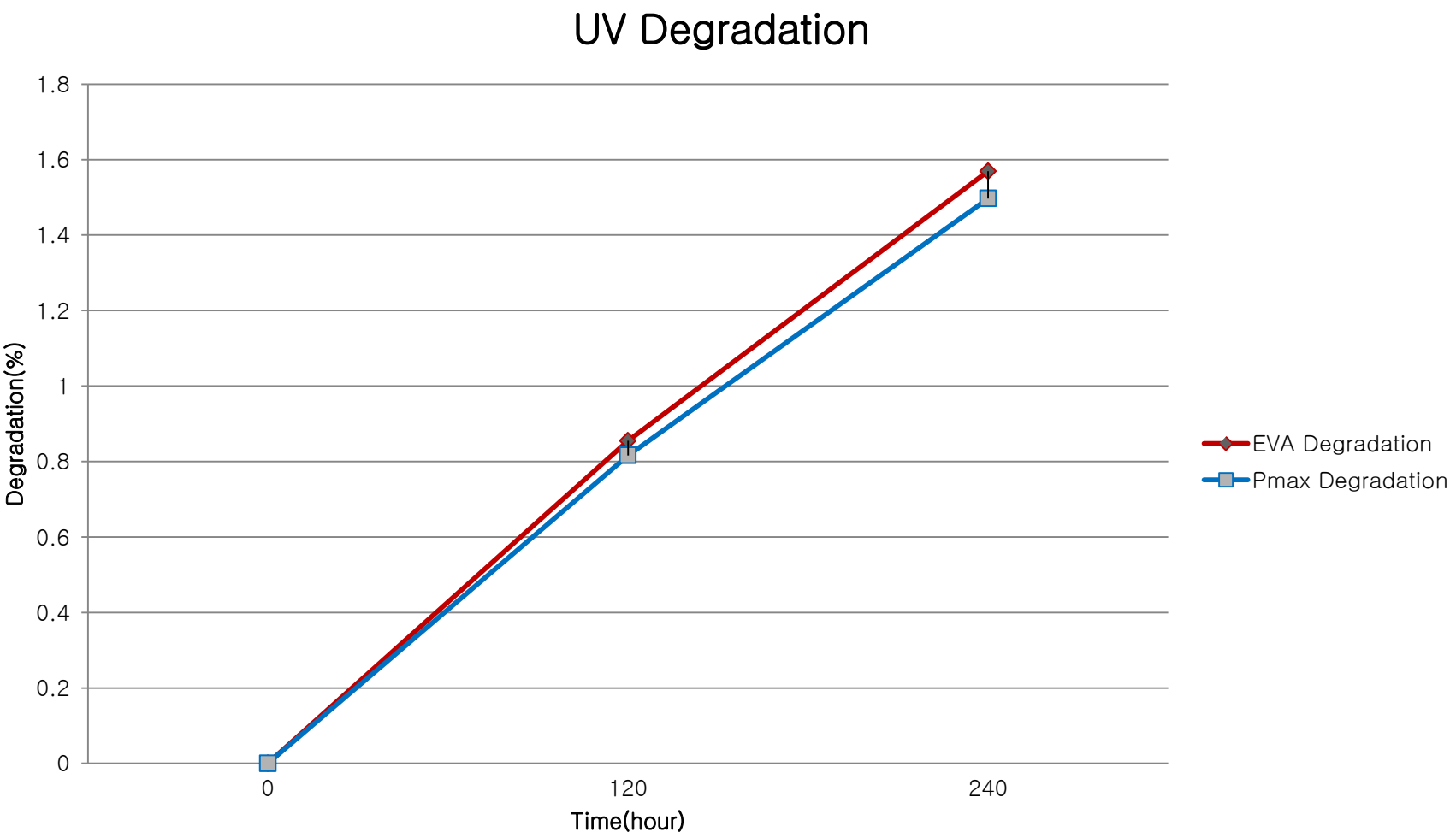
2. SORES (7) : Degradation Model Development

Modeling of Encapsulant Decoloration

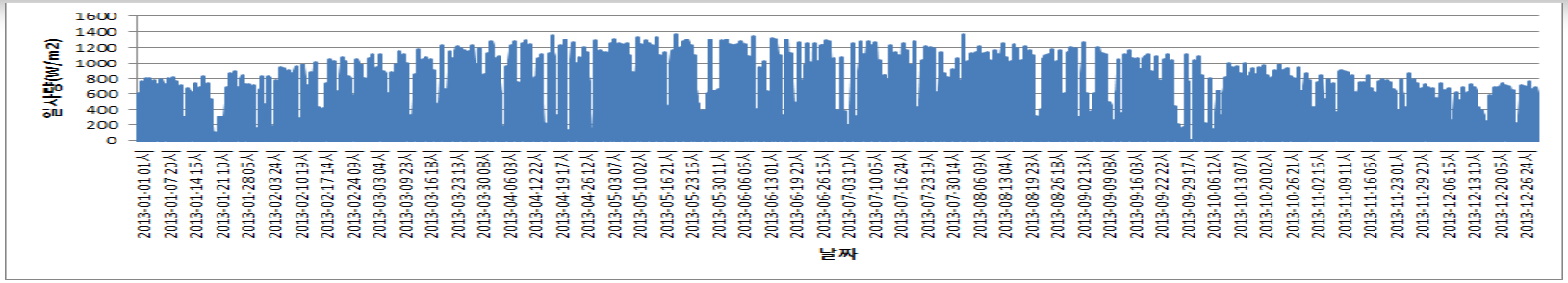
2) Empirical Model : UV Yellowing Measurement : Yellow Index (E313)



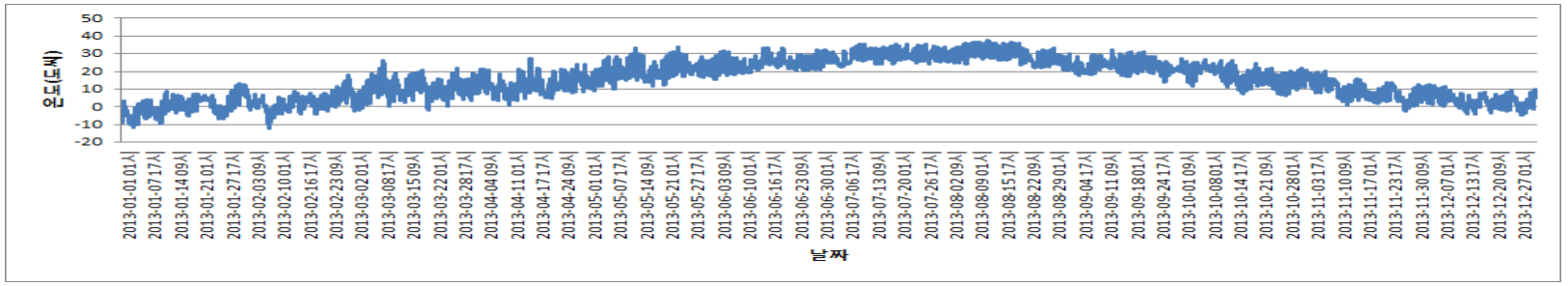
2. SORES (8) : SORES-Lab. AST Benchmark



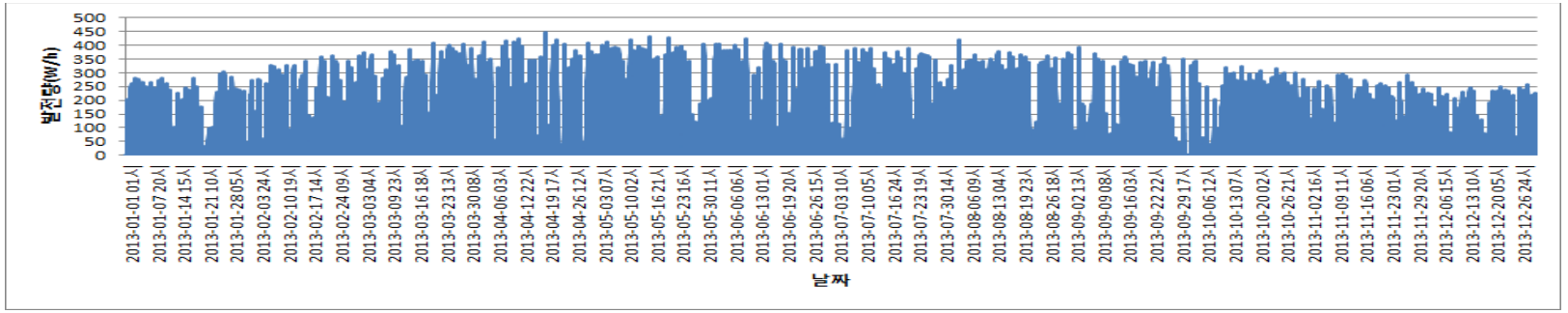
2. SORES (9) : UV Degradation Simulation



<Input : Solar Radiation in Daegu, Korea>

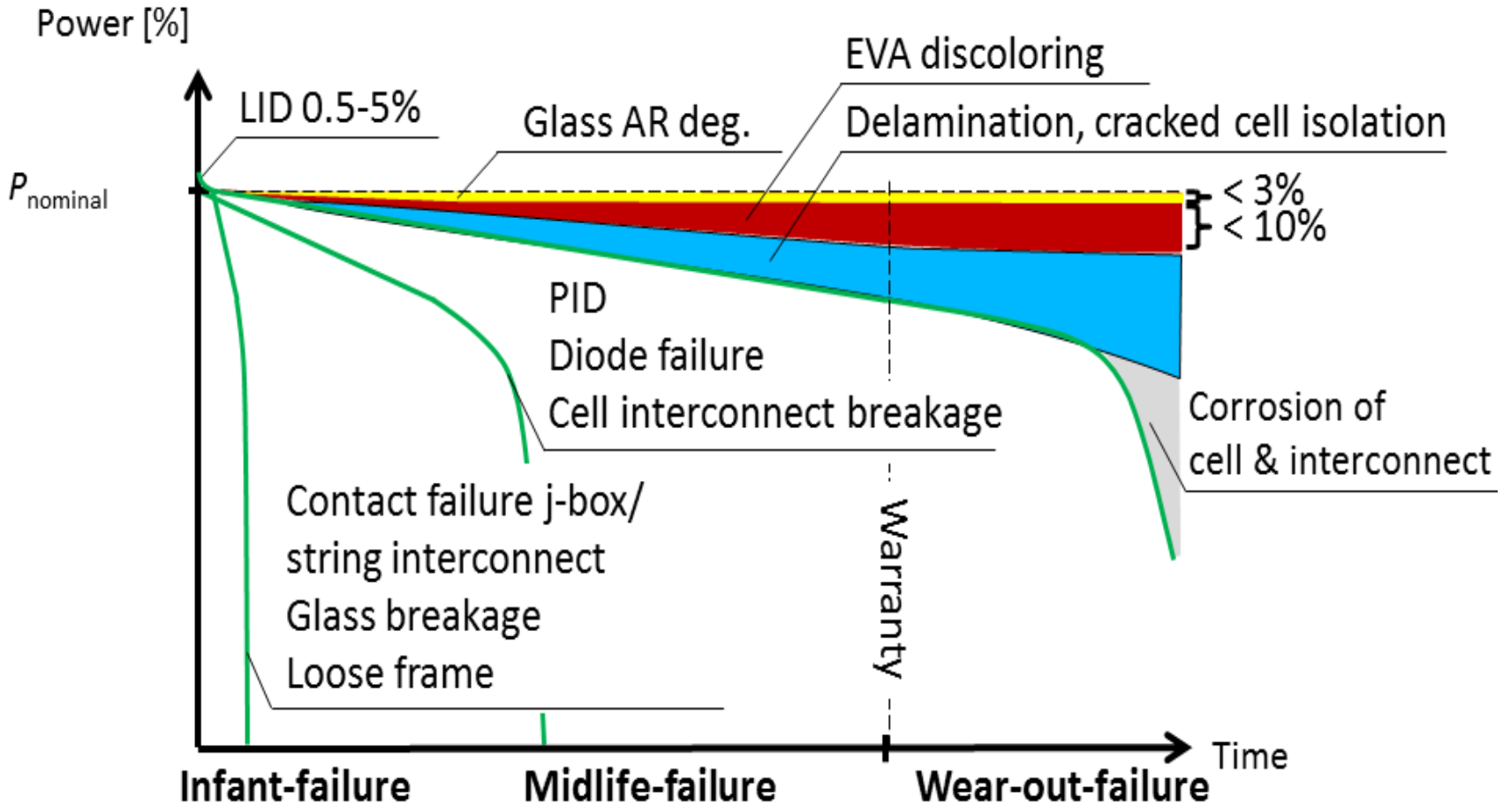


<Input : Temperature in Daegu, Korea>



<Output : Solar Power Generarion in Daegu, Korea>

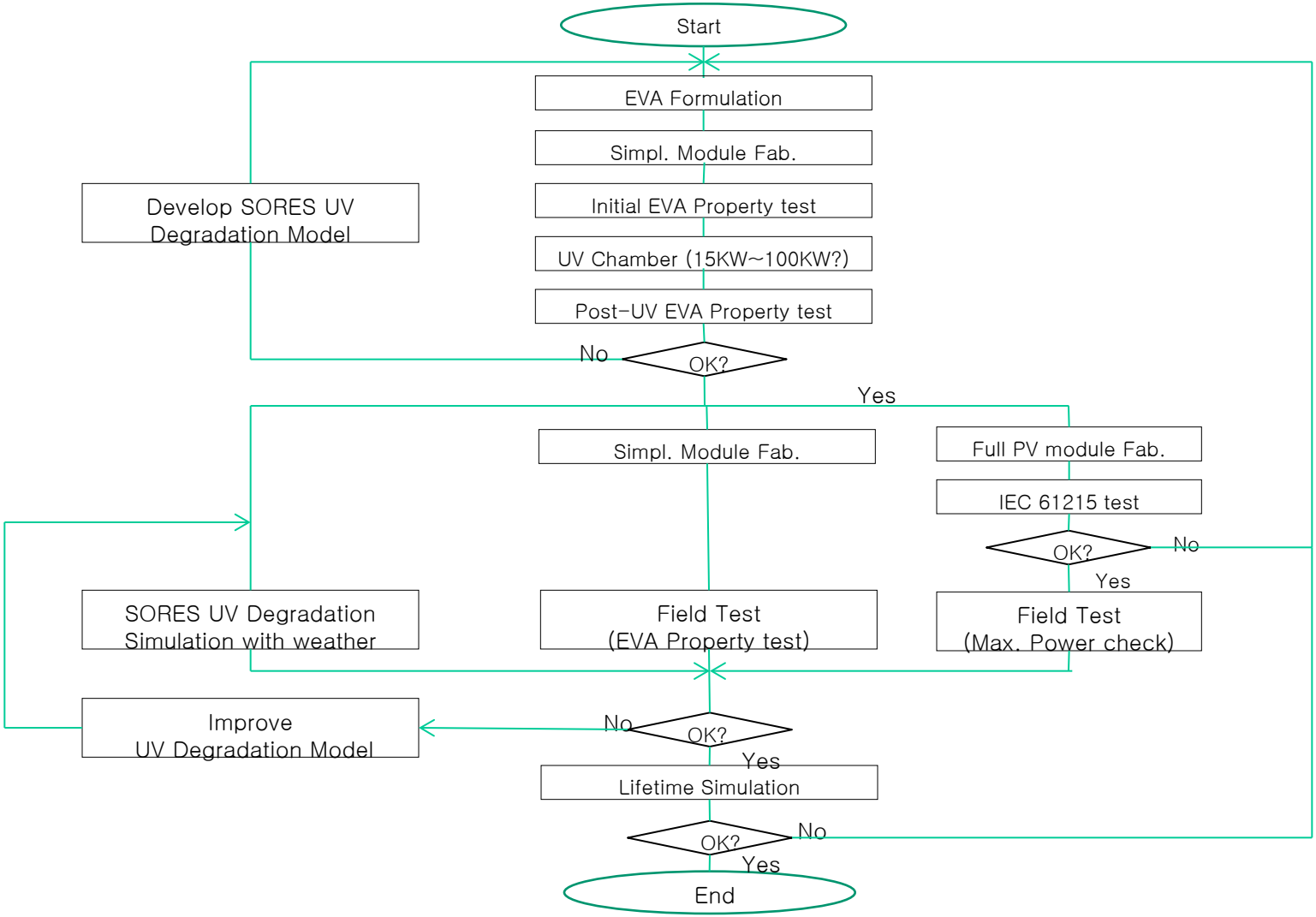
3. SORES Application (1) : EVA Development



Report IEA-PVPS T13-01:2014

3. SORES Application (2) : EVA Development

EVA Development Flowchart



4. Summary & Future Plan (1)

- The Name of the Game in PV Industry is "Cost Down". But the Means of Cost Down need Reliability testing.
- PV Reliability testing is Time-consuming & Expensive.
- PV Qualification doesn't give the Test Data & guarantee of Lifetime. It only gives the Pass/Fail.
- Missing Link : Lab. AST ←→ Outdoor Field Testing
  No Quantitative Link

4. Summary & Future Plan (2)

- SORES provides the Quantitative Link between Lab. AST & Outdoor Field Testing.
- SORES is the Platform for the PV Reliability R&D.
- Yeungnam University will provides SORES as a Open Platform for PV Reliabilty R&D with the Degradation Model API.

Thank You

Depth Profiling of Chemical and Mechanical Degradation of PV Backsheets after Exposure to Simultaneous UV, Temperature and Moisture

Chiao-Chi Lin, Peter J. Krommenhoek, Stephanie Watson and Xiaohong Gu*

NIST engineering laboratory
Polymeric Materials Group

Introduction

The backsheet provides electrical insulation and physical support, and acts as a barrier against the moisture and weathering to the photovoltaic (PV) module. The degradation of the backsheets can be detrimental to the safety and performance of the modules. This is a costly problem for industry due to the lack of comprehensive knowledge of multilayer system during weathering.

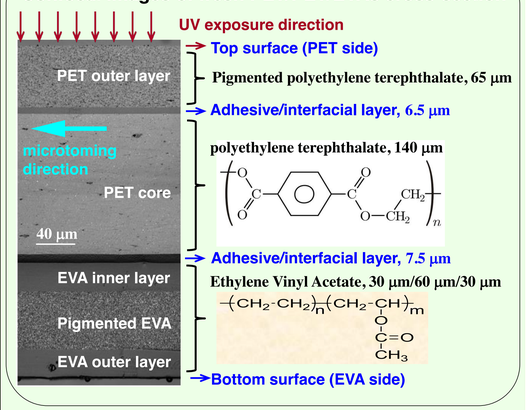
In this study, a new depth-profiling technique, combining cross-sectional nanoindentation, atomic force microscopic quantitative nanomechanical mapping (AFM-QNM) and Raman imaging, was used to measure mechanical and chemical properties of a multilayered PET/PET/EVA backsheet before and after exposure to accelerated laboratory conditions under simultaneous UV, temperature and moisture. New insights into the degradation mechanisms of individual layers and interlayer structures of the backsheets during accelerated testing will be presented.

Experiments

PET/PET/EVA Backsheet

- Cross-sectional samples were prepared by cryo-microtomy
- Epoxy was used to mount the samples

Confocal images of fresh PET/PET/EVAs cross-section



Accelerated Laboratory Exposure

- Samples: Free-standing films of PET/PET/EVA backsheet before and after SPHERE exposure for 67 days
- Exposure conditions: UV irradiance (300 nm-400 nm): 170 W/m^2 T = 85 °C; RH = 5% (dry) and 60% (wet)

NIST 2-meter SPHERE*

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

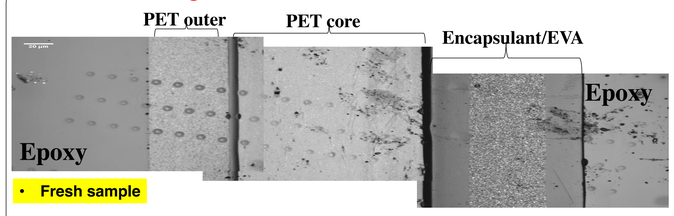
Characterization

- Nanoindentation (cross-sectional),
- Atomic force microscopy with QNM (cross-sectional),
- Raman microscopy with laser l = 785 nm (cross-sectional)
- UV-Visible reflection mode (top/bottom-surface)
- ATR-FTIR (top/bottom-surface)
- Laser scanning confocal microscopy (both)

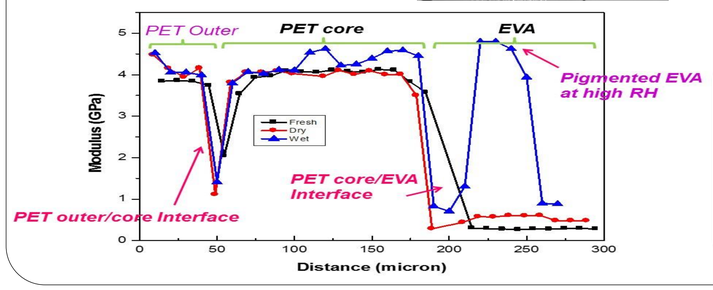
Cross-Sectional Chemical and Mechanical Characterization

Mechanical Depth profiling by Nanoindentation

Confocal image of residual indents after nanoindentation



- Fresh sample



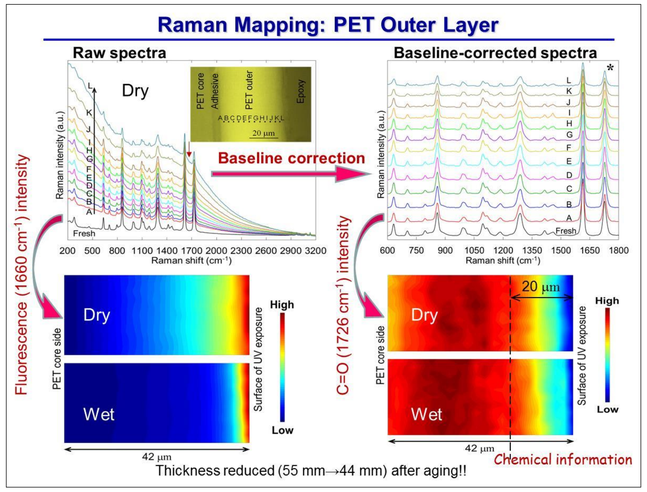
Modulus (GPa) by Nanoindentation			
Layer	Fresh	Exposed to UV/85°C/5% RH for 67 d	Exposed to UV/85°C/60% RH for 67 d
PET Outer Layer	3.81±0.23	4.13±0.16	4.29±0.41
PET Core Layer	4.01±0.44	4.00±0.12	4.33±0.43
EVA (All)	0.28±0.02	0.48±0.13	2.72±1.92

- The PET outer/core and PET core/EVA interfaces have the lowest moduli.
- The moduli of PET outer-most layer, part of PET core layer and EVA pigmented layer were increased after exposure to UV, particularly at high RH.
- The effect of relative humidity on the change of modulus was observed.

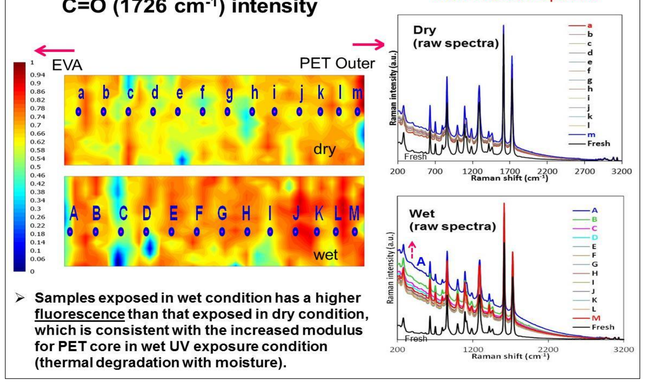
Chemical Depth Profiling by Raman Imaging

Raman spectra in each layer reflected the effect of UV and T/RH on degradation of backsheet across the thickness. The intensity change in the background fluorescence or around the band of interest (e.g. C=O or C-H) was used to represent chemical changes of backsheet after exposure.

Raman Mapping: PET Outer Layer

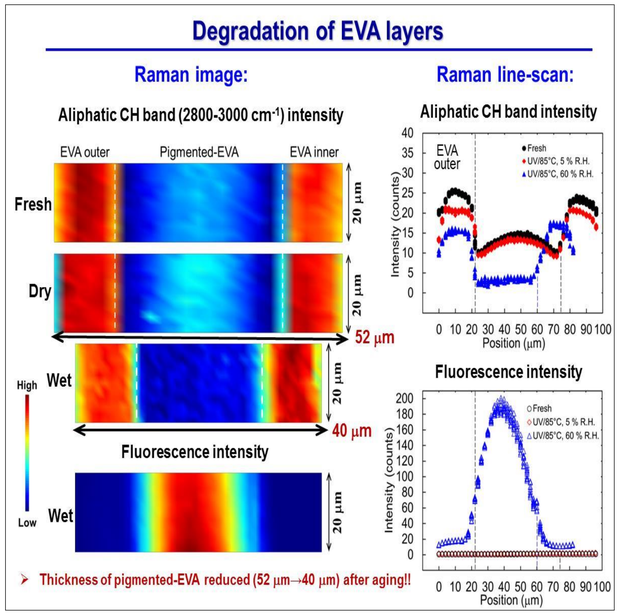


Raman Mapping: PET Core Layers



- Samples exposed in wet condition has a higher fluorescence than that exposed in dry condition, which is consistent with the increased modulus for PET core in wet UV exposure condition (thermal degradation with moisture).

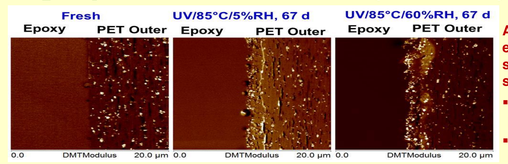
Degradation of EVA layers



- The outer-most region of PET outer layer (~20 μm from surface) showed the highest fluorescence. The result is consistent with the increased modulus detected by nanoindentation.
- Thickness reduction was observed for both PET outer layer and pigmented EVA central layer after UV exposure in wet condition.
- The pigmented EVA layer displayed strong emission (yellowing) after exposure to UV wet condition, which was consistent with the mechanical depth profiling data.
- RH accelerated thermal degradation in all EVA layers.
- Non-uniform degradation was observed across backsheet multilayers after exposure to UV/T/RH. The PET outer layer and pigmented EVA layer changed most based on Raman imaging.

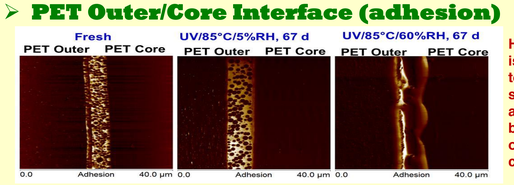
Interfacial Mapping by AFM QNM

Epoxy/PET Outer Interface (modulus)



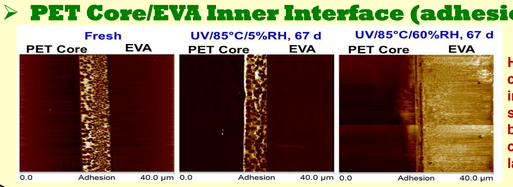
After UV exposure, PET surface showed
- aggregated pigments
- enhanced modulus

PET Outer/Core Interface (adhesion)



High humidity is detrimental to the structure of adhesive layer between PET outer and PET core layers.

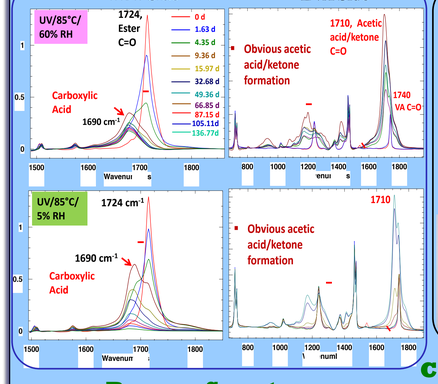
PET Core/EVA Inner Interface (adhesion)



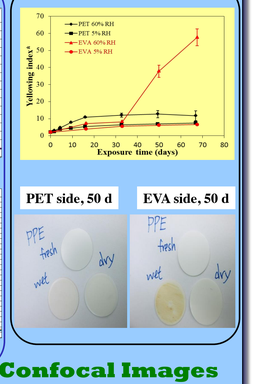
High humidity changed the interfacial structure between PET core and EVA layers.

Surface Characterization

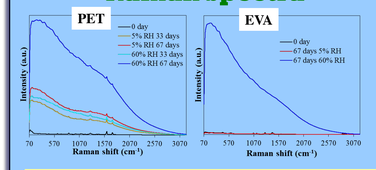
ATR-FTIR Spectra



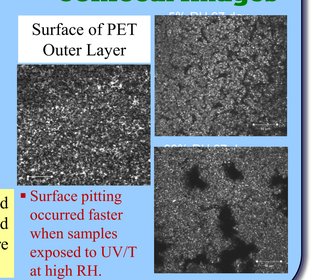
Yellowing Index



Raman Spectra



Confocal Images



- Surface characterizations of PET top layer and EVA bottom layer showed that UV/RH played a key role in PET degradation, and moisture accelerated yellowing of EVA.
- Surface pitting occurred faster when samples exposed to UV/T at high RH.

Summary &

- Cross-sectional chemical and mechanical profiling is an effective tool to understand property changes of individual layers in multilayered PV backsheet during aging.
- Both nanoindentation and Raman spectroscopy suggest that high humidity accelerates the photo-degradation of backsheet materials in the presence of UV radiation.
- This study indicates that the long-term interlayer adhesion in backsheet system could be challenging, especially in humid service environments.

PHOTOVOLTAIK-INSTITUT BERLIN

TEST SEQUENCE DEVELOPMENT FOR EVALUATION OF PID ON THIN-FILM MODULES

Thomas Weber, Juliane Berghold, Florian Heilmann, Margarete Roericht, Stefan Krauter* and Paul Grunow
PI Photovoltaick-Institut Berlin AG (PI Berlin), Wrangelstraße 100, 10997 Berlin, Germany, e-mail: weber@pi-berlin.com
*University of Paderborn, Department of Electrical Engineering, Institute for Sustainable Energy Concepts, Pohlweg 55, D-33098 Paderborn, Germany

→ The Approach

This work presents results obtained with thin-film modules under Bias-Damp-Heat (BDH) conditions in in- and outdoor tests. The development of a standard test for potential induced degradation (PID) for c-Si is in progress, however for thin-film technologies, there is no IEC standard draft submitted yet. The intention is to support the development of a standard for PID testing also for thin-film technology. Leakage currents (LCs) are measured outdoor for 30 days in Berlin in June. Those LCs are amended with indoor measured LCs in climate chambers to get values for every prevailing parameter range. So module life-times can be simulated for different places in the world. Module degradations are carried out in accelerated aging tests under BDH resulting in a specific degradation level of P80 (-20% to initial power) and the charge of the investigated module. Finally, the life-times are calculated by considering the indoor and outdoor measured LCs.

Design of Experiment

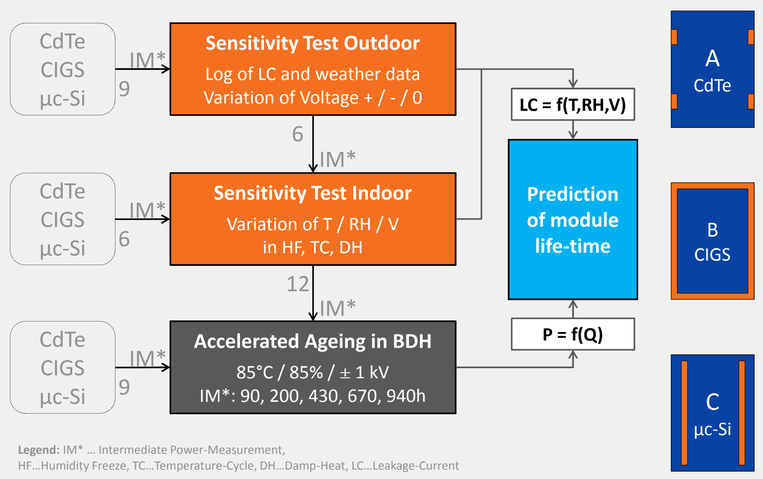


Fig. 1: Schematic of the test procedure: sensitivity test (orange), accelerated ageing (grey), and simulation for the prediction of module lifetimes (light blue). Three module technologies (shown far right) were investigated.

Outdoor Measured Leakage Currents

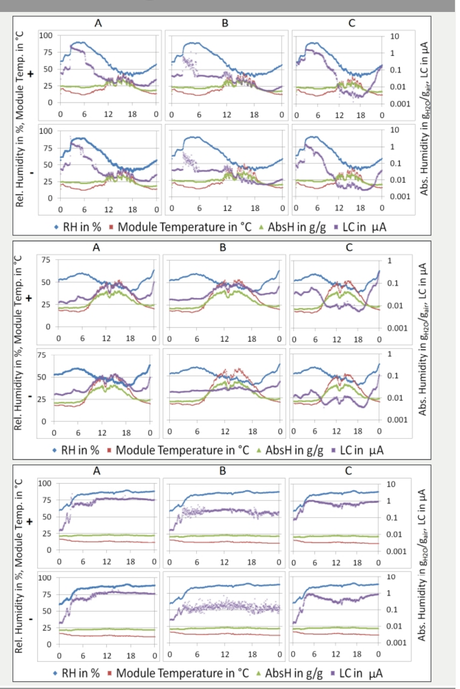


Figure 2: Outdoor LC for modules A, B and C under +/- bias measured on three different weather conditions. Depicted are relative humidity (RH), module temperature and absolute humidity (AbsH).

Top: rain in the morning, moderate temp.

Middle: sun and warm weather

Bottom: rain whole day long and cold

Sensitivity Analysis, relev. Parameters

a)	< -10	-10-0	0-10	10-20	20-30	30-40	40-50	50-60	60-70	> 70
> 75	4	174	704	694	203	4	-	Hours of each parameter space		
65-75	-	7	155	274	237	29	-			
50-65	-	-	65	257	406	159	7	-	-	-
40-50	-	-	1	64	217	193	31	-	-	-
30-40	-	-	-	8	81	127	48	2	-	-
< 30	-	-	-	-	3	8	9	-	-	-

Time [t] = hours ×

Relative Humidity RH in %

b)										
> 75	0.018	0.036	0.057	0.117	0.084	1.600	-	Leakage Current in µA, CIGS -1kV		
65-75	-	0.036	0.032	0.048	0.069	0.064	-			
50-65	-	-	0.014	0.021	0.034	0.032	0.047	-	-	-
40-50	-	-	0.007	0.009	0.016	0.017	0.021	-	-	-
30-40	-	-	-	0.004	0.008	0.011	0.012	0.017	-	-
< 30	-	-	-	-	0.004	0.005	0.006	-	-	-

Current [I,C] = µA =

c)								
> 75	0.000	0.023	0.143	0.292	0.062	0.023	-	Transferred Charge in As
65-75	-	0.001	0.018	0.047	0.059	0.007	-	
50-65	-	-	0.003	0.019	0.050	0.019	0.001	-	-	-
40-50	-	-	0.000	0.002	0.013	0.011	0.002	-	-	-
30-40	-	-	-	0.000	0.002	0.005	0.002	0.000	-	-
< 30	-	-	-	-	0.000	0.000	0.000	-	-	-

Charge [Q] = As

Figure 3: Illustration of charge calculation: (a) number of hours for which each parameter space of temperature and relative humidity prevails for a statistical year in Berlin; (b) measured leakage currents (from sensitivity tests) representative of a CIGS module, indicated as mean values for each parameter range; (c) charge for each parameter range, calculated by multiplying time in (a) and current in (b).

Parameter Dependent LC-Change

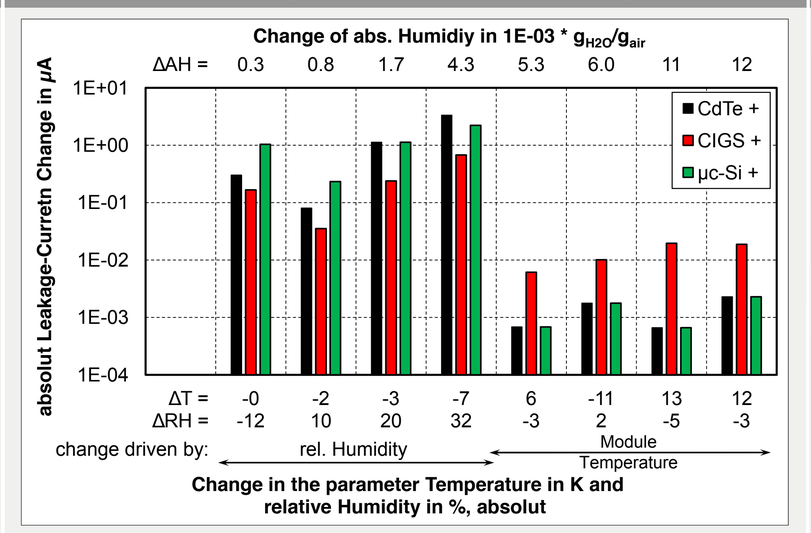


Figure 4: Analysis on the (abs.) change of outdoor LC for different changes in the parameters T and RH or AbsH (upper axis). The first data range is driven by humidity and the second by temperature. Results are measured on all types.
→ Leackage Currents are driven mainly by humidity.

Accelerated Ageing in BDH: ΔP = f(Q)

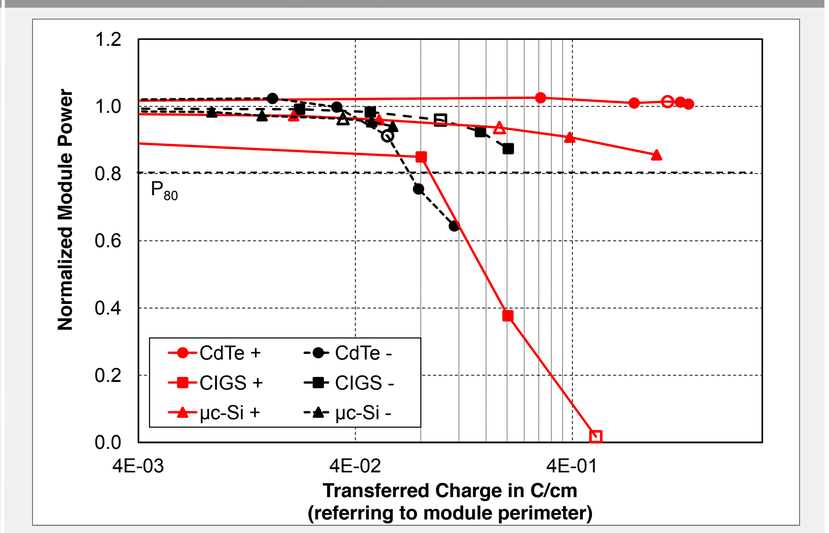


Figure 5: Degradation behavior of modules A, B and C tested in BDH as function of the transferred charge per perimeter. **P_{80} life-time** means: years till 80% of initial power remain. Empty form marks measurement after 430h

Simulation of Module Life-Times

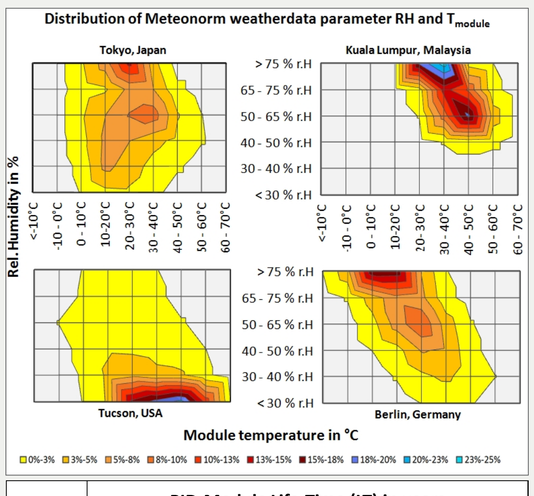


Figure 6: Analyzed meteonorm weather data for Tokyo (Japan), Kuala Lumpur (Malaysia), Tucson (USA) and Berlin (Germany). The simulation of life-times was done with analyzed data sets of these locations.

Module	PID-Module Life-Time (LT) in years (Module LT maybe limited by other mechanisms)			
	Kuala Lumpur	Berlin	Tokyo	Tucson
CdTe +	83	166	183	362
CIGS +	9	41	37	127
µc-Si +	51	135	157	1659
CdTe -	3	8	10	31
CIGS -	13	141	77	637
µc-Si -	20	21	39	294

Classification of the Results (in years):
< 25 ... PID critical
> 25 > 40 ... likely PID uncritical
> 40 ...means likely no PID

Table 1: Simulated module life-times with regard to PID for all investigated locations and module types (left), and suggested classification scheme for evaluation purposes (right).

Power Degradation Evaluation

Technology dependent **Preconditioning (PC) methods** in comparison to a flasher only measurement of PID stressed modules:
PC method from the CdTe producer of type A and a CIGS PC method for the modules of type B was used.

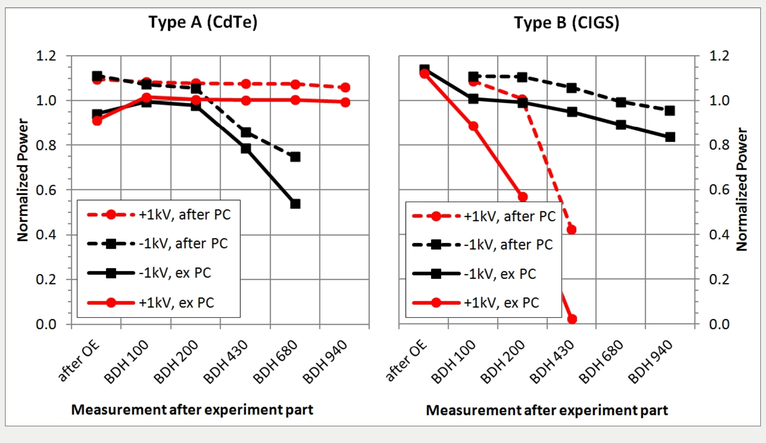


Fig. 7: Evolution of module power for type A and type B. For CdTe the PC result in an 10% improvement of power increasing up to 20% for higher module degradations. PC for CIGS improves the power measurement up to 12% (B-) and 40% (B+). The improvement effect is not constant.

→ Conclusions

- **The evaluation of PID degradation from accelerated aging tests is possible by correlating with outdoor LCs**
- **Simulating different weather conditions enables to distinguish life-times**
- **The results reveal a high humidity driven PID-effect for all thin-film modules**
- **Warm and dry climates seem to be very suitable to avoid PID of thin-films**
- **Module type A (CdTe) is very stable, if not installed under negative system voltages**
- **Module type C (µc-Si) shows negligible degradation under negative BDH test. Simulating its life-time 20% power drop in 20 years might be too critical**
- **In contrast, module B (CIGS) and module C (µc-Si) shows heavy degradation under positive BDH test but the simulated life-times are acceptable for moderate climates (exc. For hot, humid conditions like Kuala Lumpur)**

→ Outlook

- **The evaluation of preconditioning methods for power meas. methods is necessary and comparison to outdoor STC-power measurement has to be shown**
- **To avoid high temperature induced degradation mechanisms from 85°C tests through performing accelerated BDH tests at max. temperatures of 60°C**

Sequential and Weathering Module Testing and Comparison to Fielded Modules

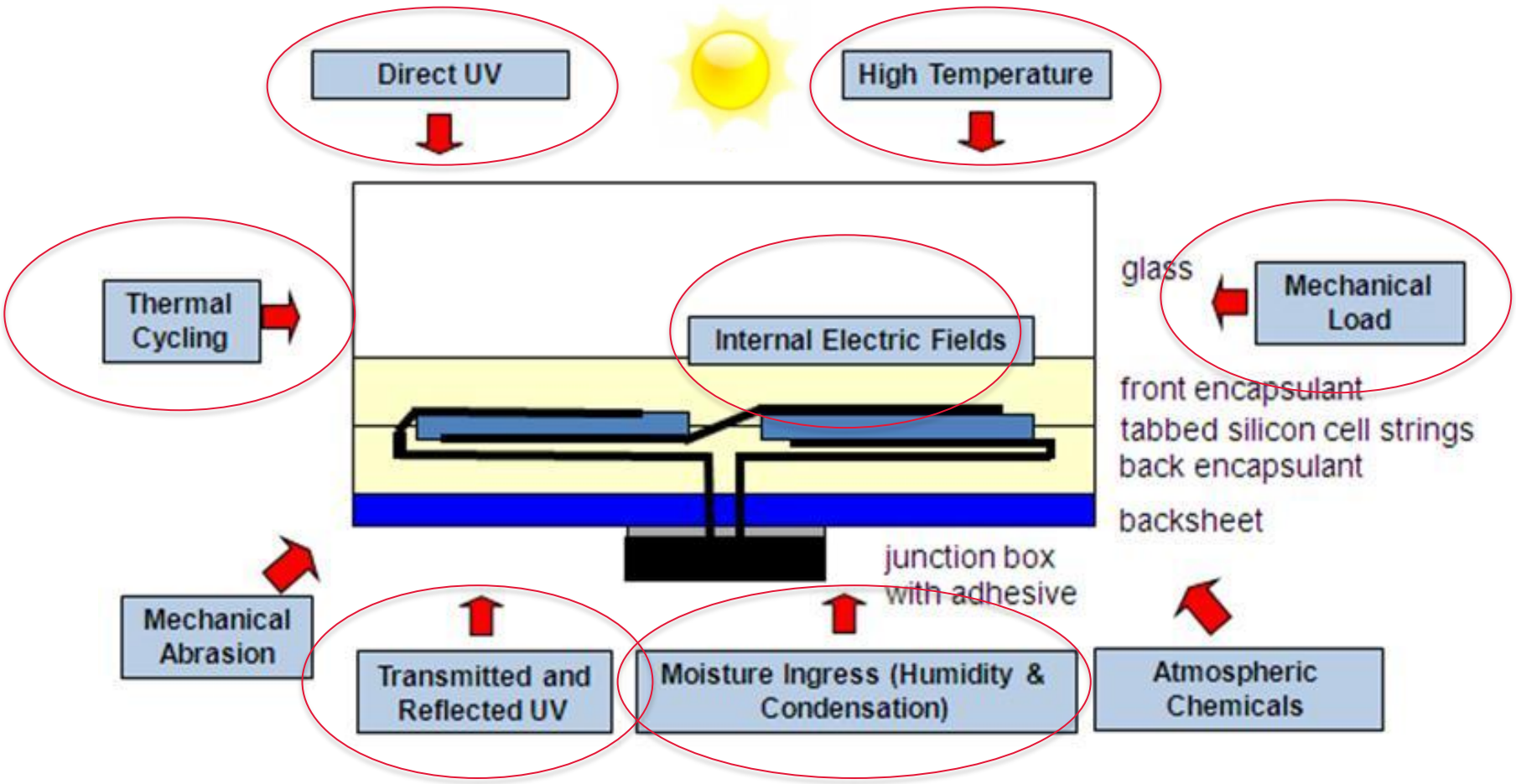
NREL PV Module Reliability Workshop 2015

W. Gambogi[1], J. Kopchick[1], T. Felder[1], S. MacMaster[1], A. Bradley[1], B. Hamzavytehrany[1], C.-F. Wang[2], H. Hu[2], Y. Heta[3], Lucie Garreau-Iles[4] and T. J. Trout[1]

(1) DuPont, Wilmington, DE, USA; (2) DuPont (China) Research& Development and Management Co., Ltd., Shanghai, P.R.C., (3) DuPont K.K., Utsunomiya, Japan; (4) Du Pont de Nemours International S.A., Geneva, Switzerland

This poster contains no confidential information

Environmental Stresses in the Field



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

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Fielded Module Studies

- Inspected modules in the field ranging from newly commissioned to 30 years installed
- Developed inspection protocols and analysis tools to assess composition and failure modes
- Developed module sampling and materials analysis methods
- Goal is to better understand the relationship of materials properties and field performance with accelerated testing

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Summary of Observations from the Field

- Adhesion loss and delamination
- Outer layer backsheet cracking and yellowing
- Inner layer backsheet yellowing
- Hot spot cracking, yellowing and softening
- Outer layer yellowing on rooftop system

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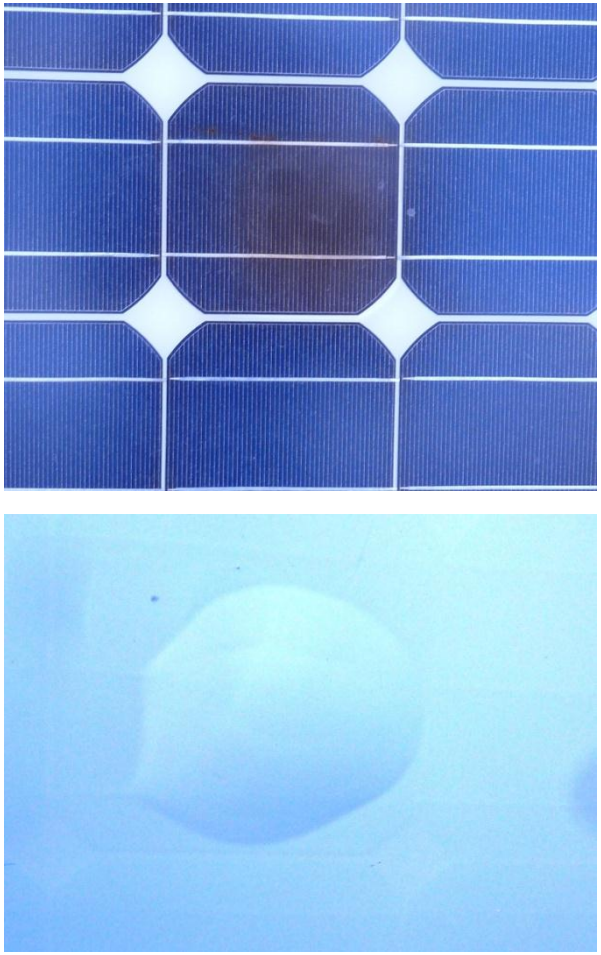
Field Studies: PVDF-Based Backsheets with Hot Spots & Delamination



Hot spot/cell causing delamination of PVDF-based backsheet on module in Spain

Additional examples of delamination on PVDF-based backsheet from hot spots in modules in Israel

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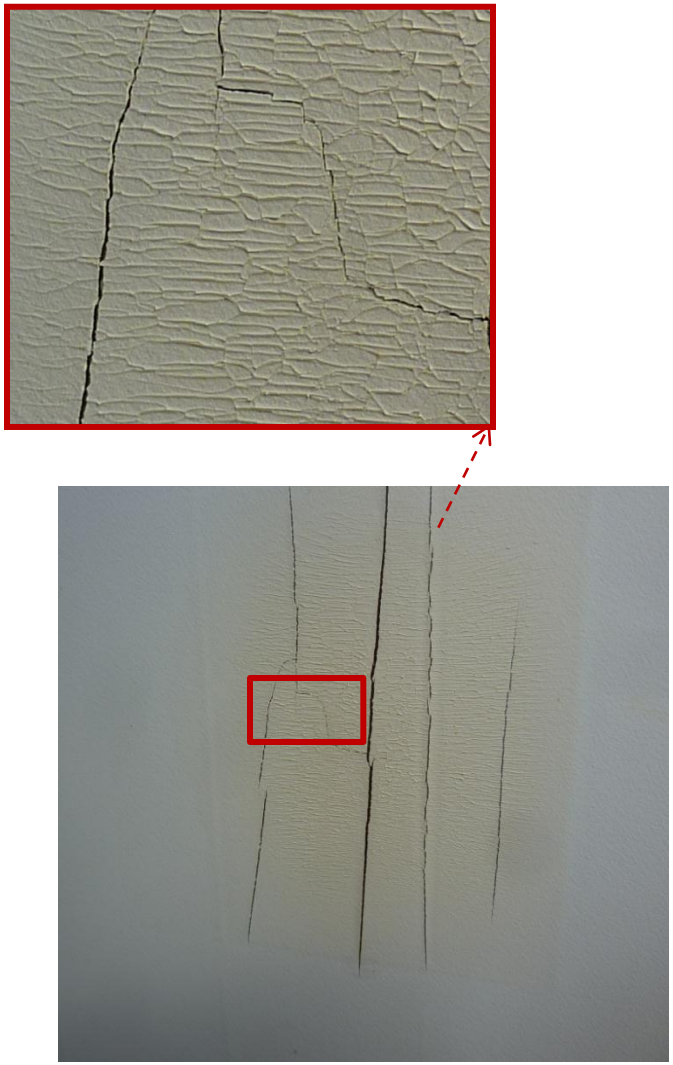
Field Studies: PVDF-Based Backsheet with Yellowing and Cracking



PVDF-based backsheet from module in Spain

- Module removed from service
- Cracking & yellowing

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Polyester-Based Backsheet Cracking After 4 years

Crack in backsheet exposing tabbing ribbon and potential electrical leakage path

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Field Studies: Yellowing and Cracking of PET-Based Backsheets in Rooftop Application

- PV array (12 modules) mounted on a metal corrugated rooftop of the commercial building for 15 years with ~150mm from corrugation to back of the solar panel
  - Outer PET layer cracking and brittle
  - High level of yellowing
  - Highest levels of yellowing near the edges of the array
- Other examples of PET-based backsheet yellowing, delamination and embrittlement have been previously described and examples from the field given

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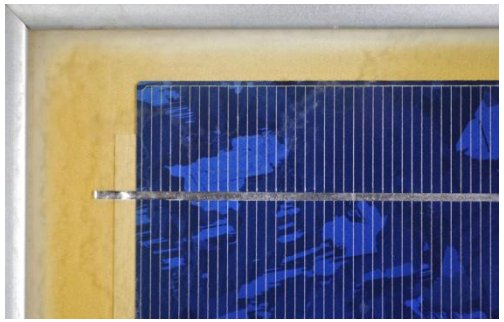
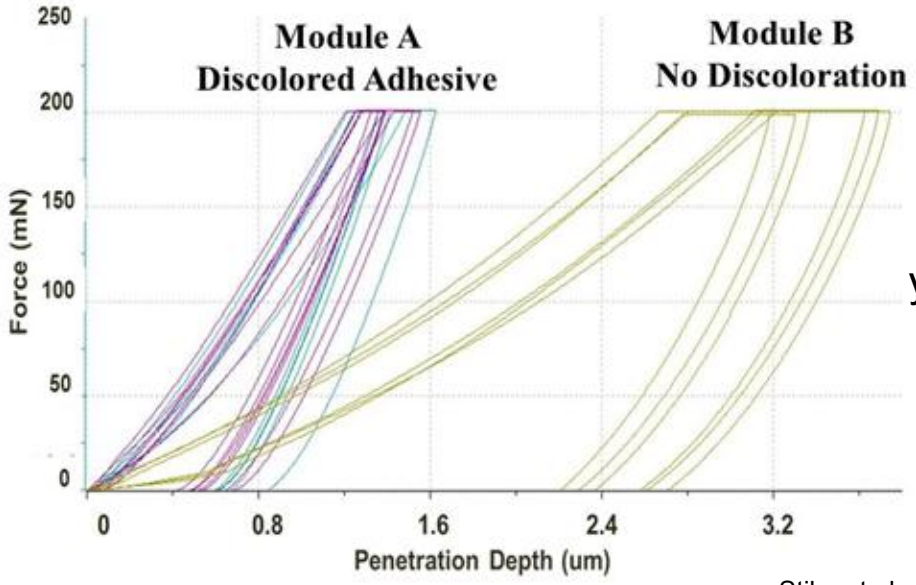
Field Studies: PVDF-Based Backsheet Frontside Yellowing



- Frontside yellowing observed in:
  - 5 different countries (Belgium, Spain, USA , Israel, and Germany)
  - Modules less than 5 years in the field
  - 5 different manufacturers

Gambogi et al., EUPVSEC 2013, Paris

Nano-indentation of inner layer of backsheet



Embrittlement associated with yellowing of inner layer

Stika et al., IEEE PVSC 2014

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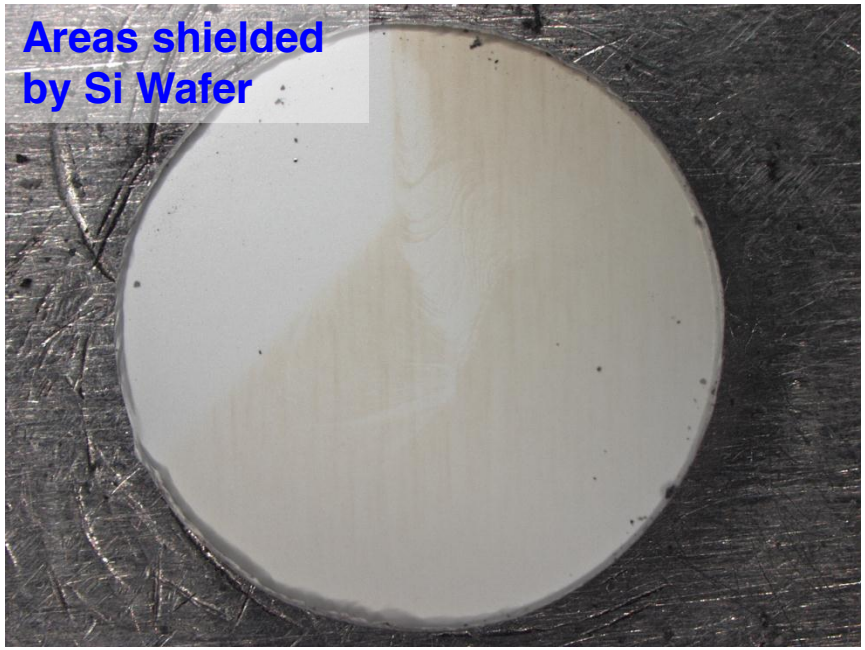
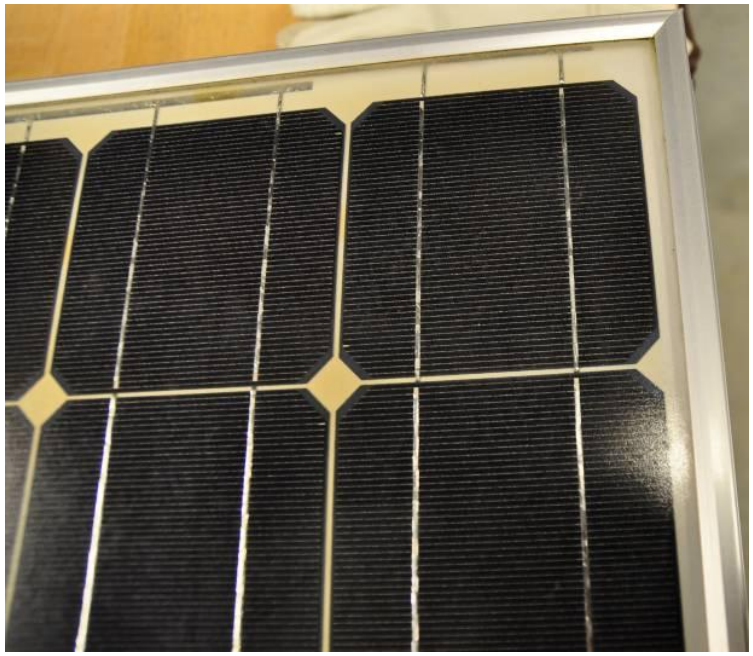
PET Inner Layer Discoloration

Area below cell has not discolored, indicating UV contributed to inner layer PET yellowing

4 years in field, 100% discoloration found in typical commercial/industrial systems (250-750 kW) both rooftop and ground mount, USA





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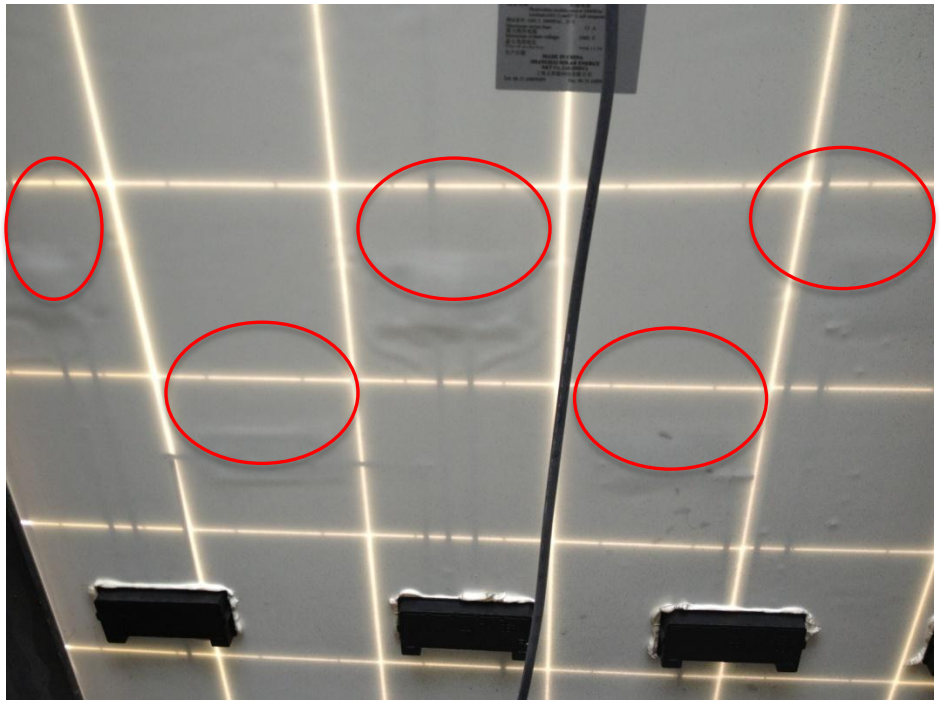
Rooftop Array, FEVE (5 years, Shanghai), >30% modules

Large amount of delamination



Bubbling and yellowing

	Control FEVE-based coated backsheet, no field exposure	FEVE backsheet samples with 5 years field exposure in Shanghai	Change
b* value (color)	0.04	2.57	**2.53**
60° Gloss change	70.2	44.9	**25.3**

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Shortcomings of Current Qualification Tests

- Current IEC qualification standards were designed to identify early failures due to module design; does not predict long-term durability
- IEC qualification standards do not adequately address durability of materials to UV exposure and weathering
- UV and weathering tests are not applied to modules due to the equipment challenges associated with large area UV and weathering exposure
- IEC qualification conditions do not address synergistic effects of multiple stresses in the field
- We propose sequential testing using damp heat (DH), thermal cycling (TC) and UV exposure (UVA) to better predict long term outdoor performance

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DuPont Accelerated Testing Protocols

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

* IEC 61215 UV pre-conditioning, 15 kWh/m² (280-385nm), **front exposure only, ~70 days outdoors**

- UV testing needs to be extended to adequately address backsheet performance in the outdoor environment
- Dosage for UV testing should match 25 year outdoor exposure to insure durability; assumes a 12% albedo exposure on junction box side
- Damp heat testing to 1000 hours is more than sufficient for PET hydrolysis damage of backsheets over 25 years of outdoor exposure

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Basis for Sequential Exposure

- Outdoor environment has multiple stresses operating throughout PV module service life
- DH1000 (85C, 85%RH, 1000h) is considered to be >25 years equivalent in the harshest climate, based on NREL model
- UVA1000 (UVA, 65W/m2, 300-400nm, 1000h) is estimated to be ~ 6 years equivalent exposure on the backsheet side of a module
- TC200 (-40C, 85C, 200 cycles) is a standard thermal stress condition in qualification and recent recommended changes propose extension to multiple exposures
- Sequential DH and UVA exposure results in materials degradation similar to the field; thermal cycling creates mechanical stresses similar to those experienced by modules in the field

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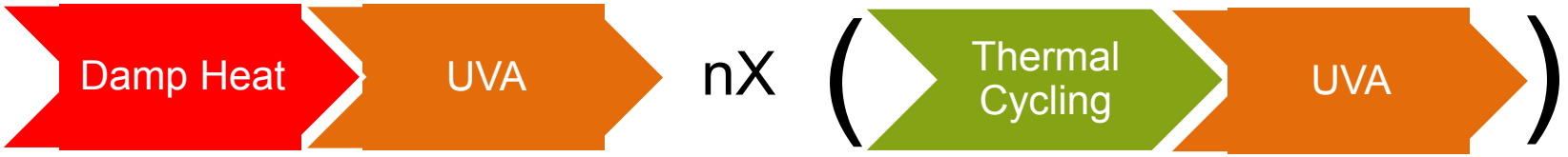
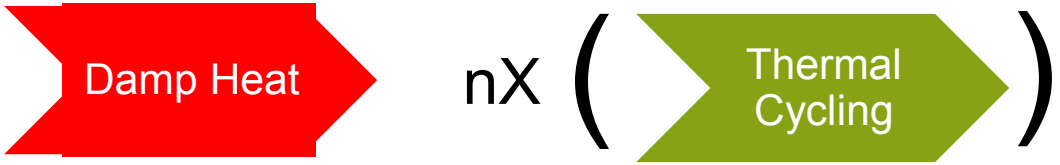
Recommended Sequential Tests



Backsheet or Modules

Backsheet Yellowing, Cracking



Full-size Laminates or Module

Backsheet Cracking

Backsheets: weathering (Xe), 102m light, 18m light + water spray
Module: resistive loading, weathering exposure (above)

Backsheet Yellowing, Mechanical Loss
Module: Power Loss

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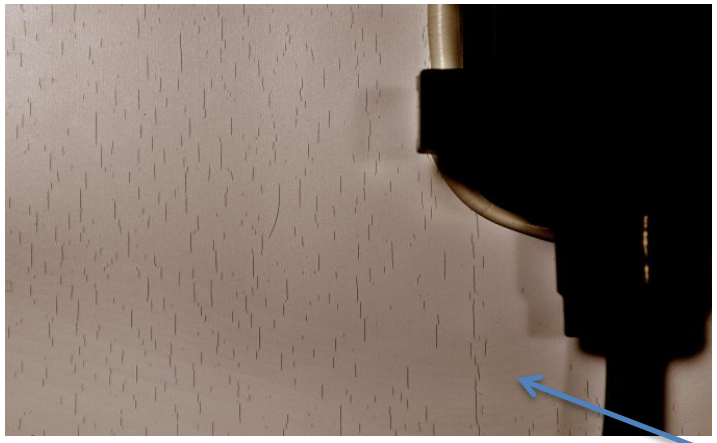
Sequential Stress Testing of PVDF/PET/FEVE

Damp Heat → UV → Thermal Cycling

DH1000/UVA1000/TC200

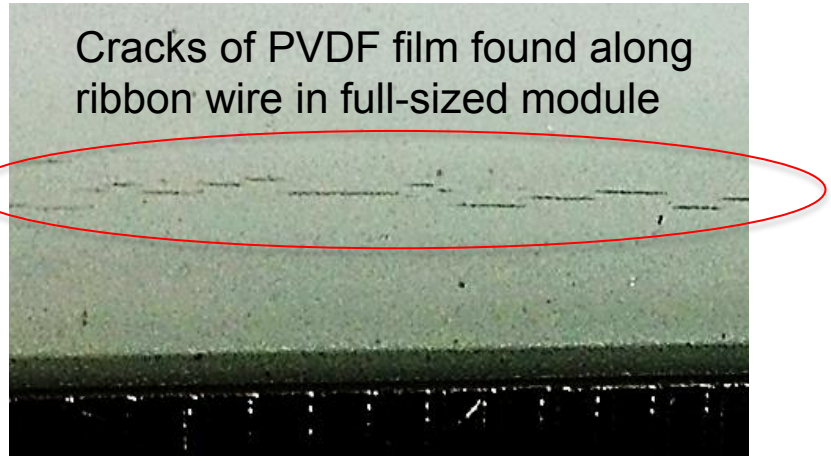


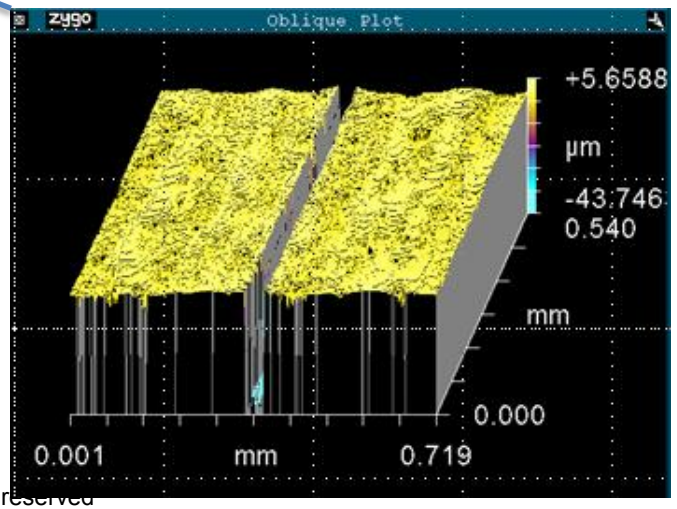
Fine cracking of PVDF layer of 1s PVDF-based backsheet

Damp Heat → Thermal Cycling → Damp Heat → Thermal Cycling

2x(DH1000/TC200)

Large cracks in 1s PVDF-based backsheet





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Sequential Testing of Full-Size Module Format

Full-Size Framed Laminate (glass/EVA/EVA/backsheet)

Backsheet	***DH1000***	***TC200***	***TC400***
1s PVDF1	OK	cracks	more cracks
1s PVDF2	OK	OK	minor cracks
1sPVDF3	OK	OK	many cracks
TPT	OK	OK	OK
TPE	OK	OK	OK

Backsheet	***DH1000***	***TC50HF10***	***2x(TC50HF10)***
1s PVDF1	OK	OK	cracks
1s PVDF2	OK	minor cracks	minor cracks
1sPVDF3	OK	OK	few cracks
TPT	OK	OK	OK
TPE	OK	OK	OK

Full-Size Module (DH1000/UVA1000/TC200)

Backsheet	***DH1000***	***UVA1000***	***TC200***
1s PVDF	OK	OK	cracks*
1s PVF	OK	OK	OK

TPT: Tedlar® PVF/PET/Tedlar® PVF
TPE: Tedlar® PVF/PET/primer

* Cracks were along all back busbar ribbons on the module using 1s PVDF-based backsheet

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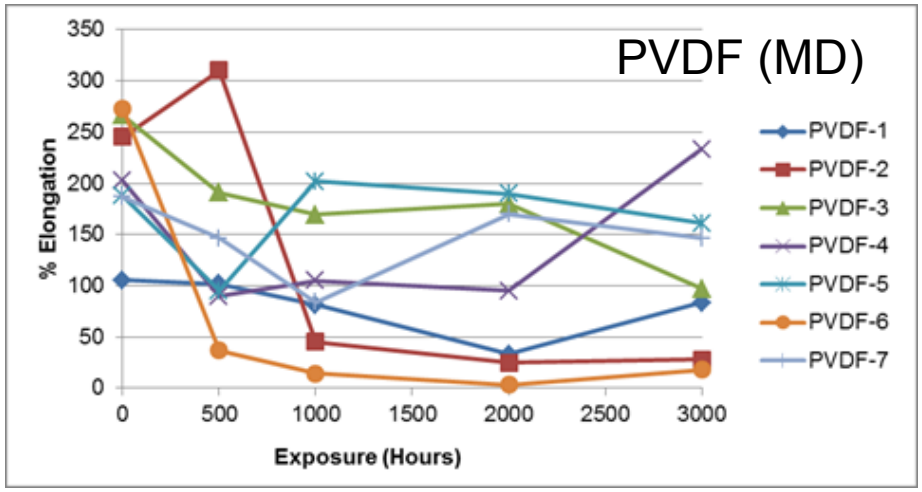
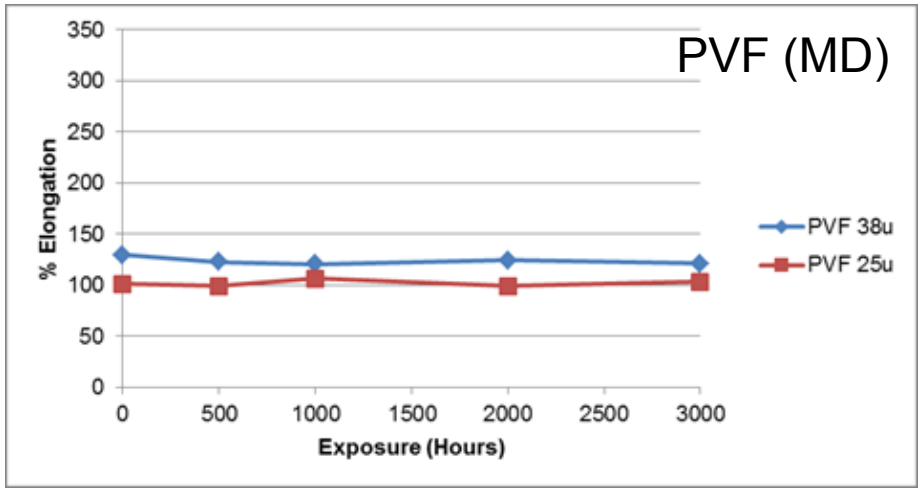
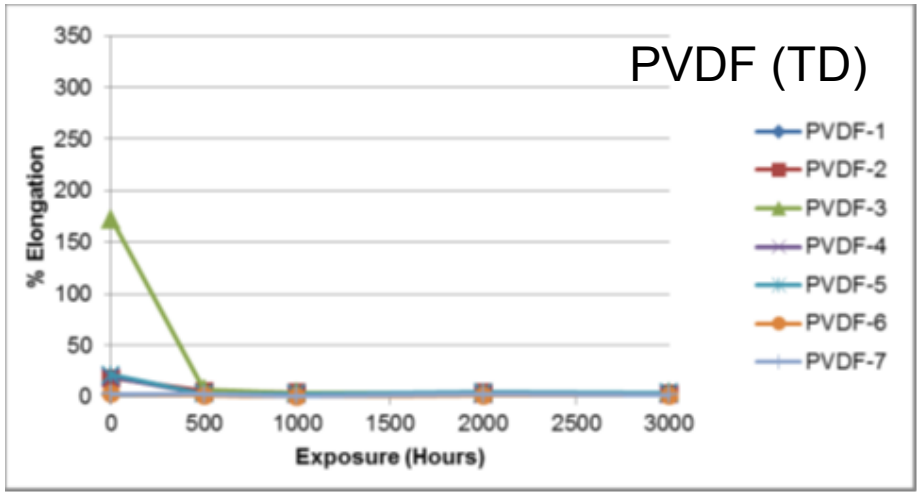
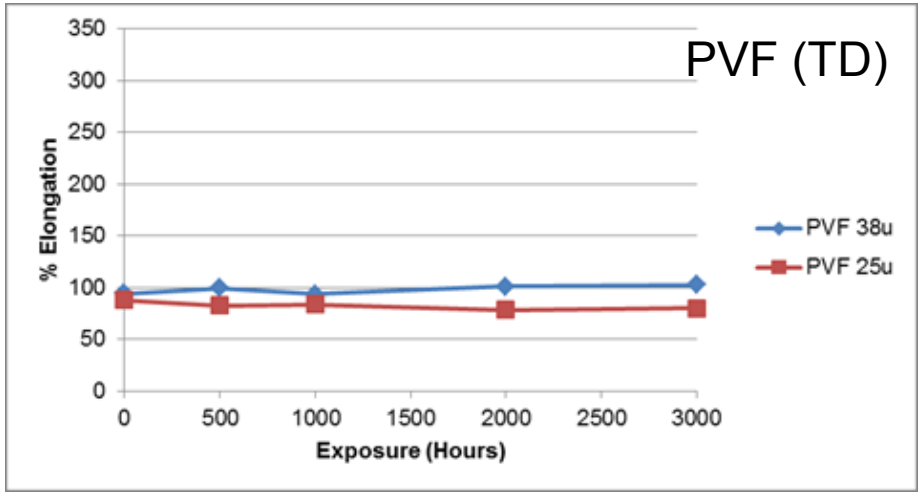
Mechanical Stress: PVDF Films Have Low TD Elongation and Get Brittle after Damp Heat Aging









Lower elongation may make PVDF film more vulnerable to cracking

Test Conditions: DH (85°C, 85%RH)

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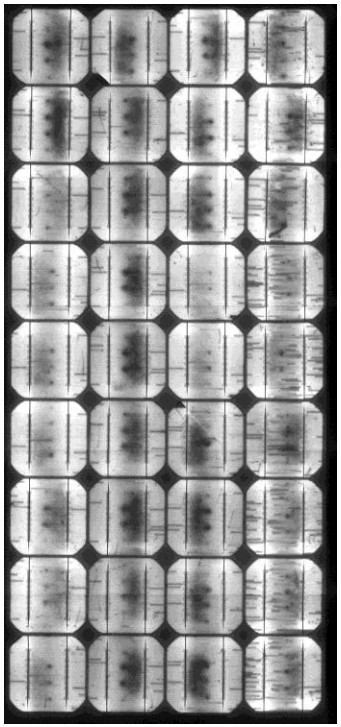
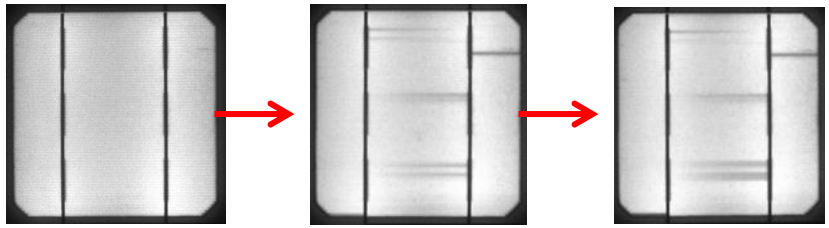
Loaded Module Weathering Compared to Field and Other Tests

Field



- Age: 15 years ,ΔP: -1.2%/yr

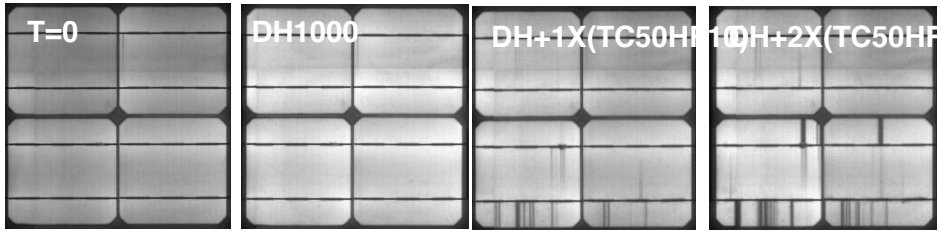
Load Module Weathering (DH500, WOM)



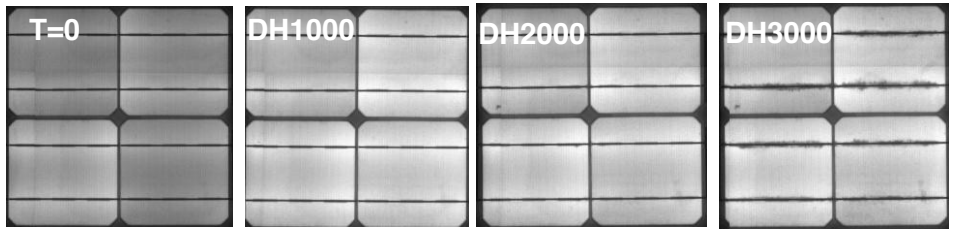
DH500 | 150 kWh/m2 UV | 180 kWh/m2 UV

- 25y desert exposure ~2290 kWh/m2 UV

Sequential (DH1000, TC/HF)



Extended Damp Heat



- Fine line degradation seen in fielded modules
- Similar to what is observed in loaded module weathering and sequential tests
- Not observed in extended damp heat

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Conclusions

- Field inspections and fielded module analysis are key to fundamentally understand of PV component performance and durability
- Multiple stress testing is critical to understanding the interaction and synergistic effects of outdoor exposure
- Testing of full-size modules and laminates provides new insights into the performance and durability of component materials in the PV module
- Future directions include assessment of unaddressed stresses in the field, shortening accelerated test protocols and improved correlation

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The miracles of science™

Solar energy

REDUCE INVESTOR'S RISK BY TESTING AND MODELING CRITICAL FAILURE MODES

Mike Van Iseghem, Benoît Braisaz - EDF R&D, site des Renardières, 77818 Moret-sur-Loing, France
Khalid Radouane - EDF EN, Cœur Défense, France

ENVIRONMENTAL STRESSES

Climatic stresses:
Desert
Coastal
Snow & Wind
...

Transport & Installation

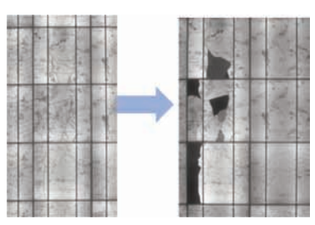
Mounting configurations

MECHANISMS LEADING TO DEGRADATION

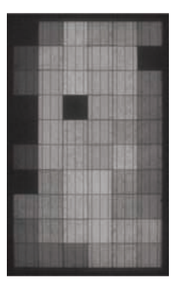
Cell cracks, hot spots, humidity in- and outflow, ion migration (reversible and irrversible) chemical reactions : EVA/acetic acid, corrosion, ...

TEST AND MODEL CRITICAL FAILURE MODES

- **Cell cracks**
  mechanical stress followed by thermal cycling.



- **PID**



INDOOR STRESS TESTS - categories

How to reduce Design and Quality issues?

	IEC Qualification	Comparative	Service Life	Protection against specific module risks
Purpose	Minimum design qualification	Comparison of products	Reduction of cost while meeting warranty	**2nd qualification test, complementary to IEC Fast, combined stresses**
Quantification	Pass/Fail	Relative	Absolute	**Resistance to specific failures**
Climate or application (mounting)	Not differentiated	Differentiated	Differentiated	**Differentiated**
Specificity	Silicon, thin film, cpv	Package specific	Product specific	**Products and risk specific**
Chamber test times	< 2 months	6 months	3 years (?)	**2 months (?)**

Source: Sarah Kurtz, NREL, Juin 2014
Sophia workshop et PVQAT status on module testing

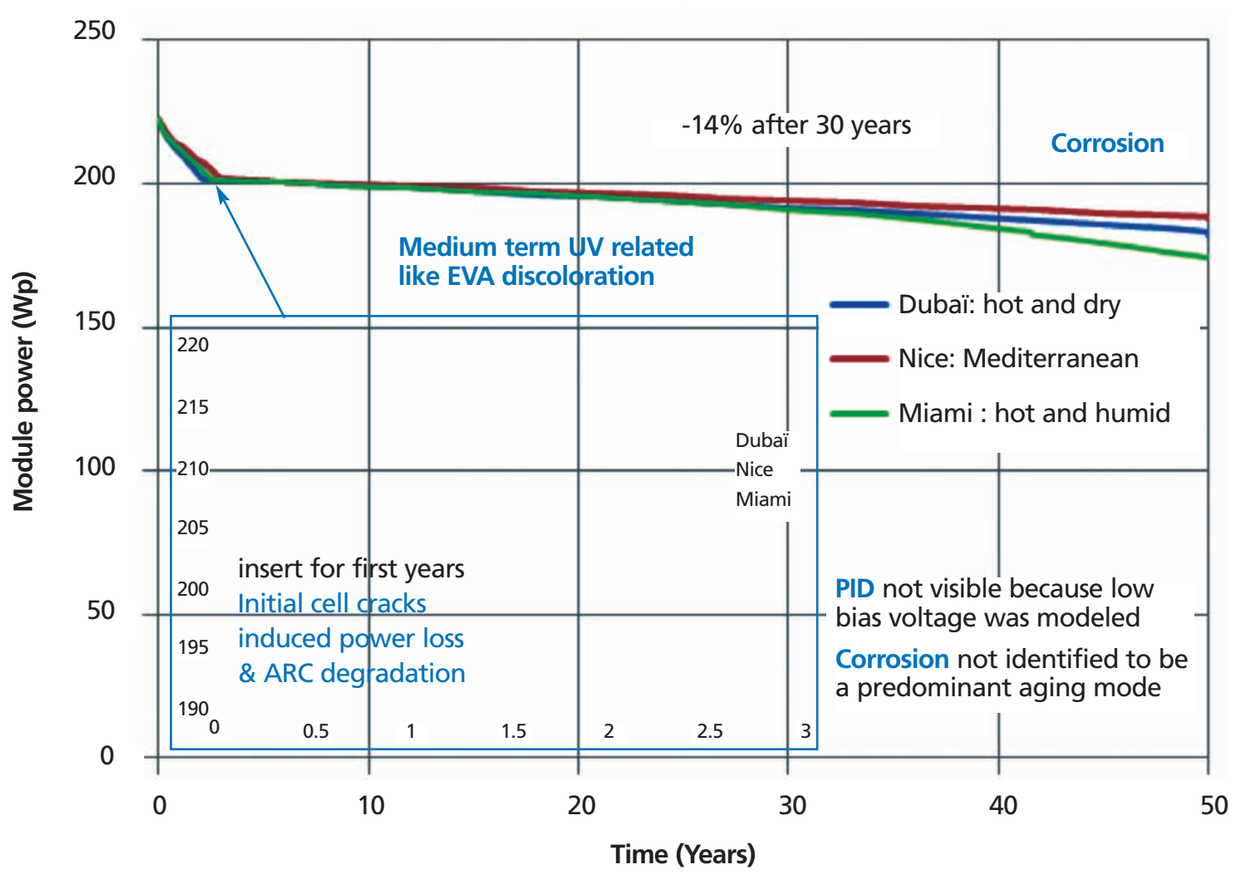
4th type of test protocole for risk mitigation on specific failure modes

At the module's frontsheet:
- Declining Anti-Reflective Coating (ARC).
- Delamination and optical loss.
- Discoloration, partial and diffuse shading …

ESTIMATIONS OF INDUCED PERFORMANCE LOSS

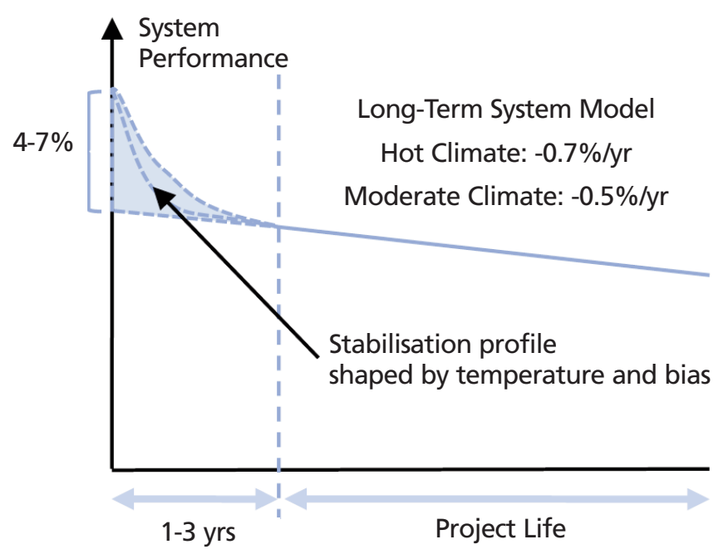
Emperical and/or modelled degradation rates are obtained. In our model (below), each major failure mode evolution is modeled, it's impact can be described in a cell by cell model of a PV plant, for hypotheses see mentioned articles.

Standard C-Si with evolution of major failure modes



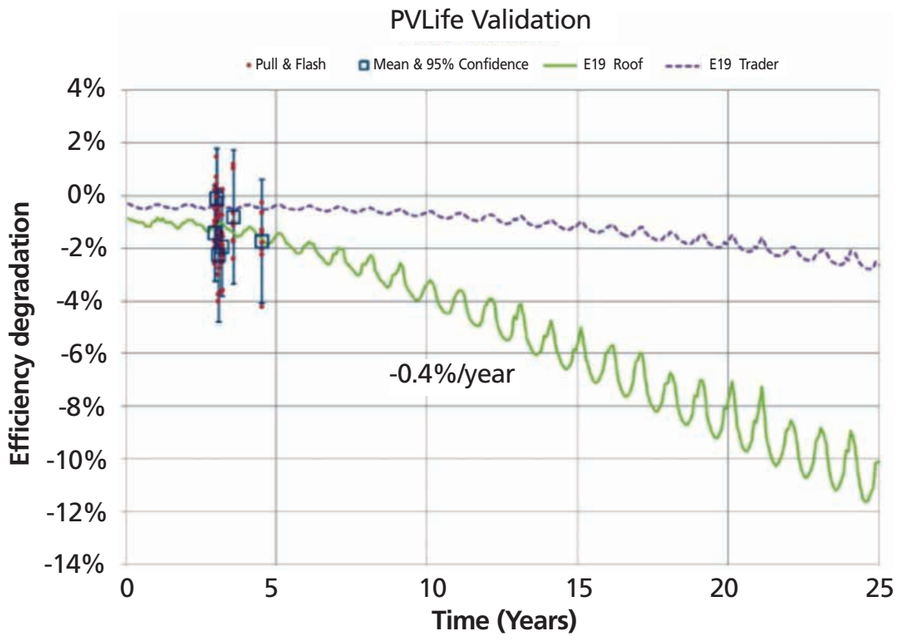
Source B. Braisaz, C. Duchayne, M. Van Iseghem, K. Radouane (EDF), PV aging model applied to several meteorological conditions - EU PVSEC 2014 - 5CO.5.4.

CdTe model



Source N. Strevel, L.Trippel, M. Gloeckler, Performance characterization and superior energy yield of First Solar PV power plants in high-temperature conditions, Photovoltaics International, August 2012, pp148-154.

other model for specific C-Si



PV life predictions and validation for rooftop mounted (green lines) and open rack (purple) Sunpower E19 modules - Source : M. Mikofski, D. Kavulak, D. Okawa, Y-C. Shen, A. Terao, M. Anderson, E. Hasselbrink et al. (SunPower Corp), PVLife: An Integrated Model for Predicting PV Performance, Degradation over 25+ Years - IEEEE 2012.

SOME PERSPECTIVES

- Need for better physical assumptions in failure-mode models.
- Improved soiling models for O&M strategies.

NREL Workshop 24-28 february 2015

This presentation contains no confidential information.

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2014 Inverter Reliability Workshop Survey Results

Tuesday, February 24, 2015

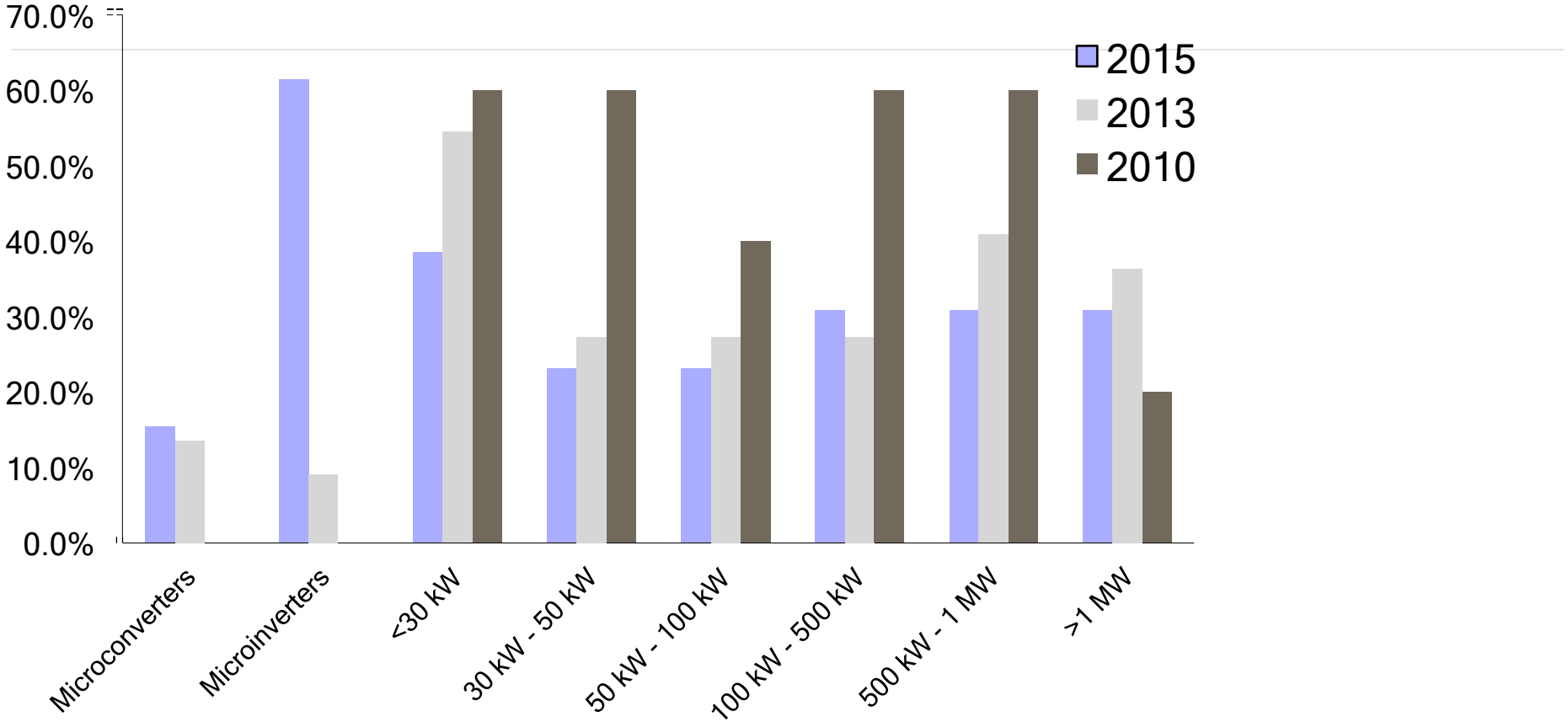
18

Total Responses

Survey

Powered by SurveyMonkey

Q1: What size inverters does your company produce?



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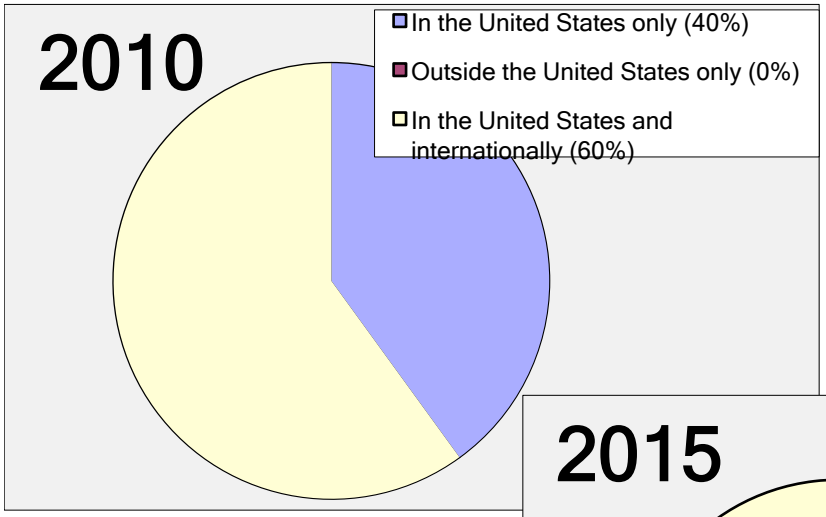
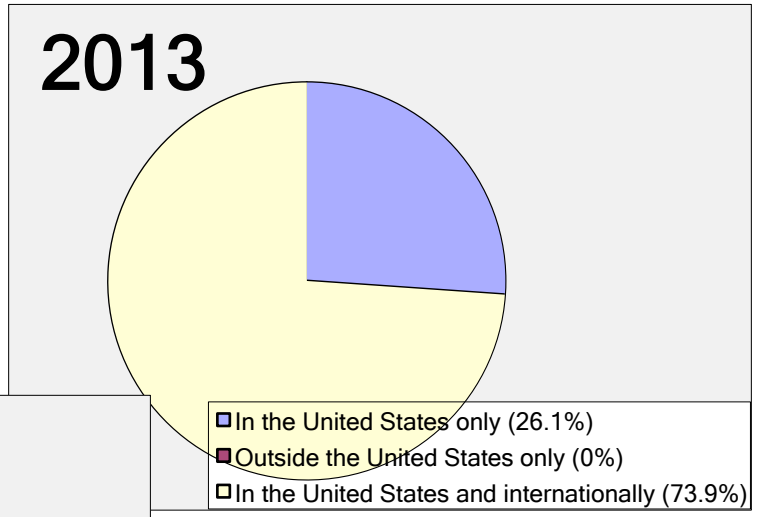
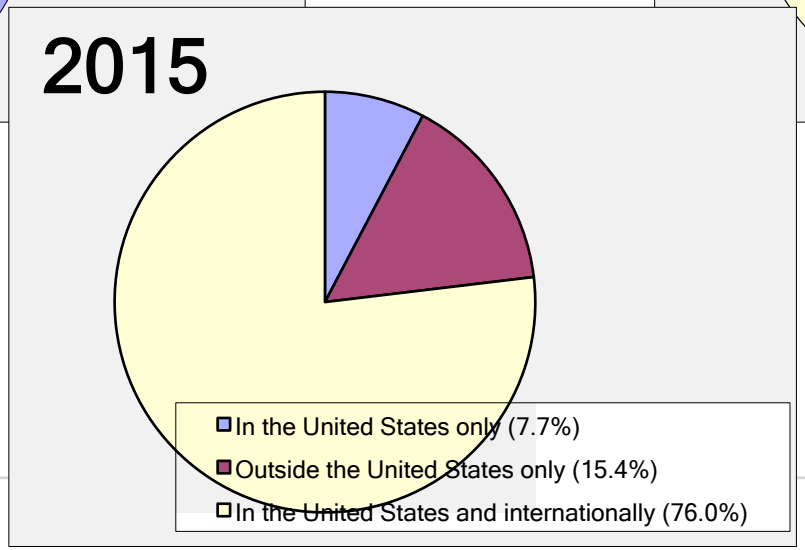
Q2: Where has your company sold inverters for PV systems?







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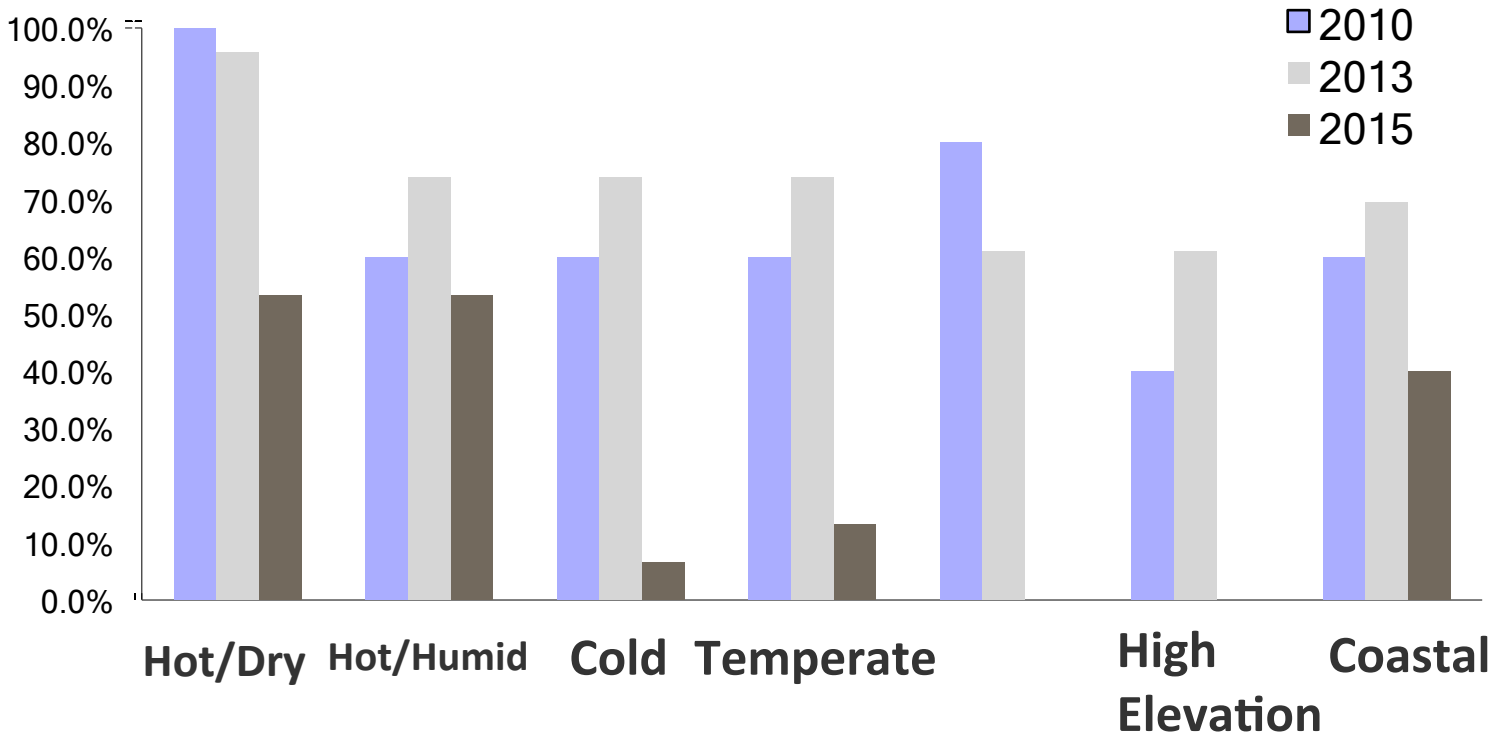
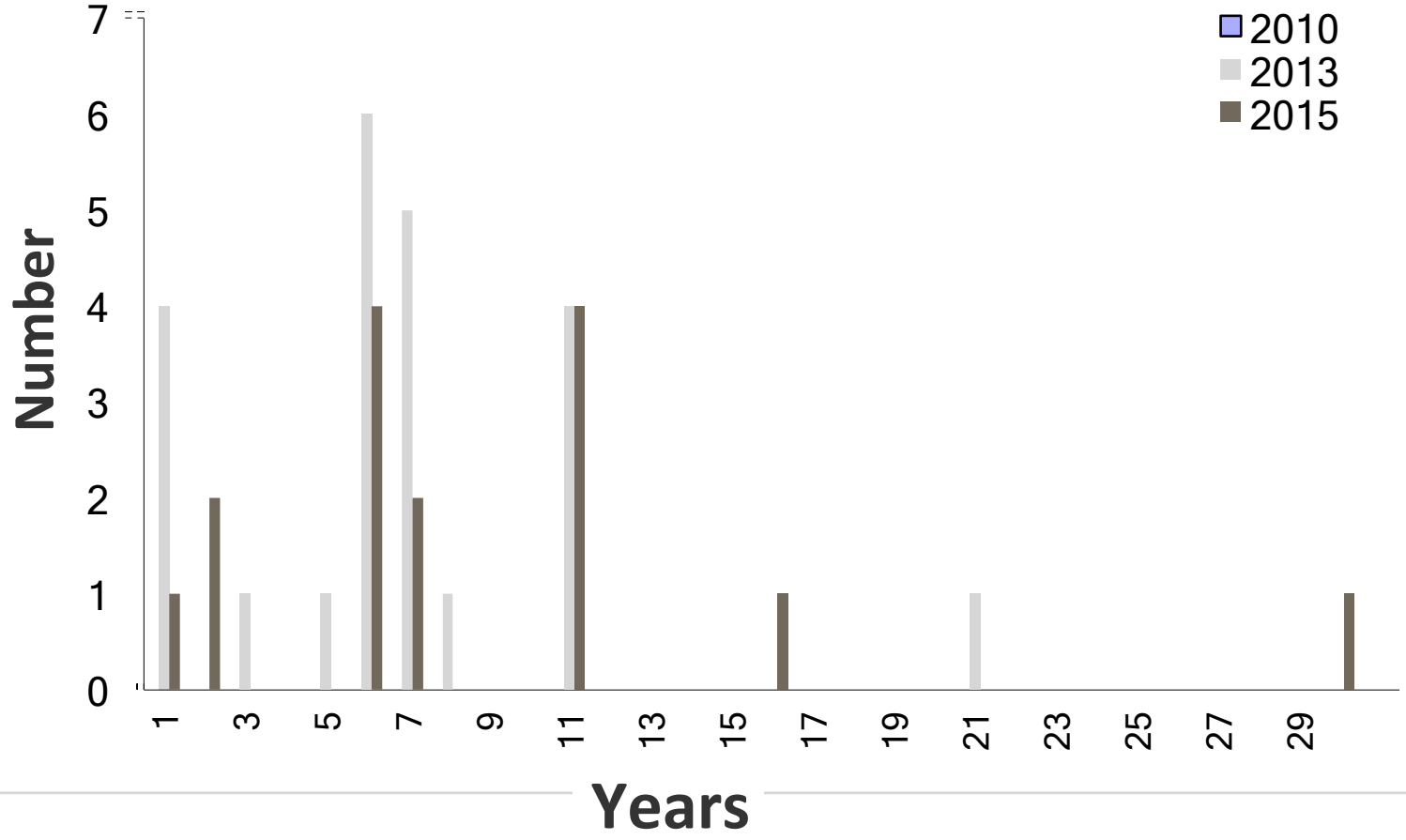
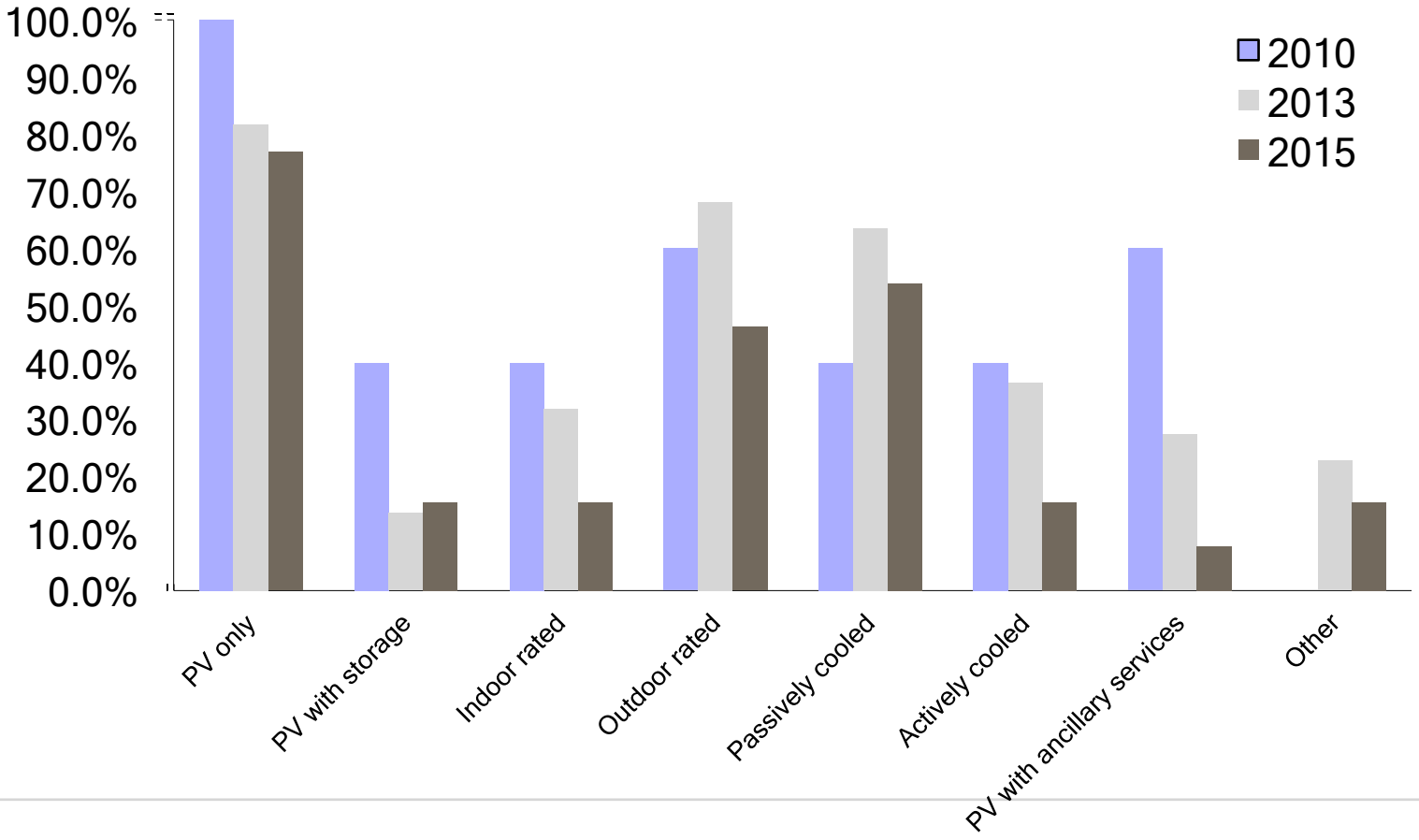
Q3: Which climate zone is most severe in terms of field failure or system stress?



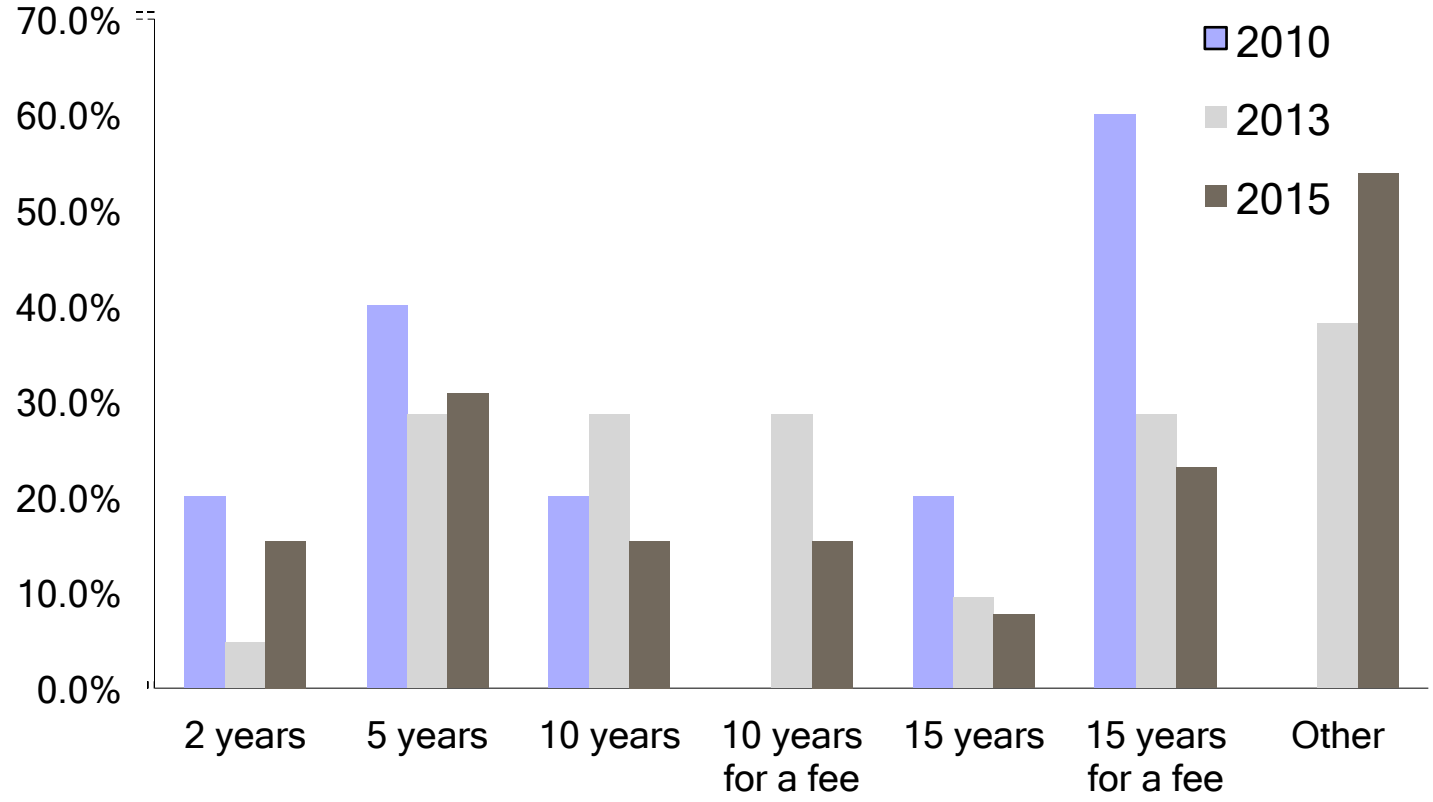
Q4: How many years has your company been in the PV inverter business (rounded up to whole number)?



Q5: What different types of inverters has/does your company design and market?



Q6: What is the warranty offered by your company?



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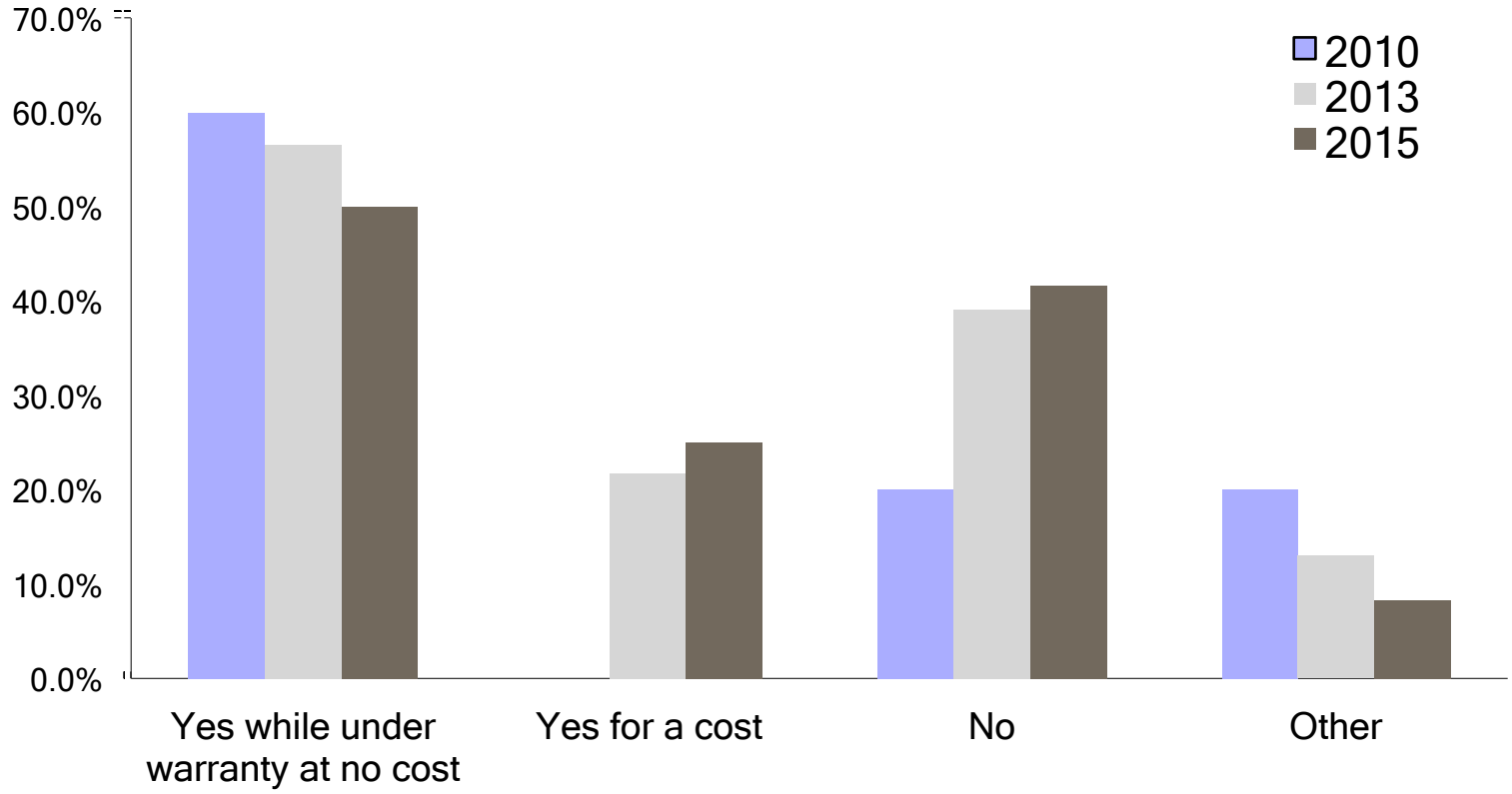
Q7: Does your company service your inverters?



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Q8: How long do you believe your inverters will last in the field (expected lifetime vs. warranty)?

2013

- unknown
- 10 years (4)
- 12 -15 years (2)
- 15 years (5)
- 16 years
- 20 years (8)
- 25 years (2)
- >25 years
- 30 years
- >30 years

2015

- 5 years (2 year warranty)
- 7 years
- 10 years
- >10yrs **(2)**
- 10-20 years
- 12 years
- 12-25 years
- 15years
- 20 years
- > 25
- >40 years
- 50 years

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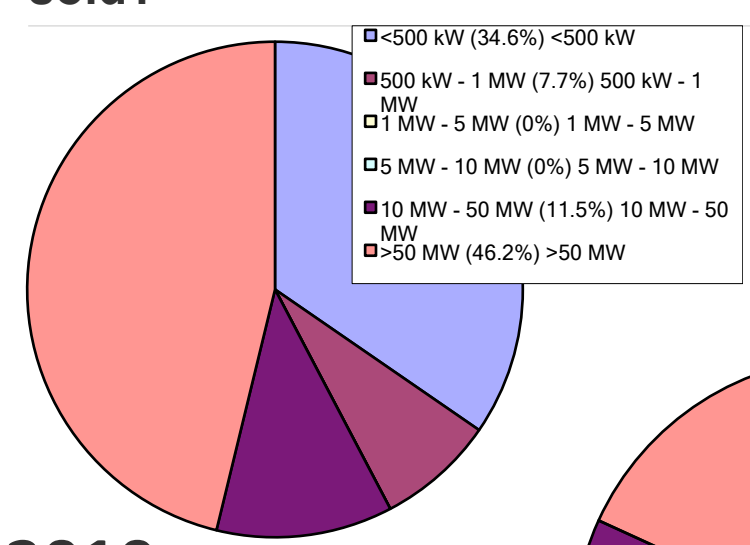
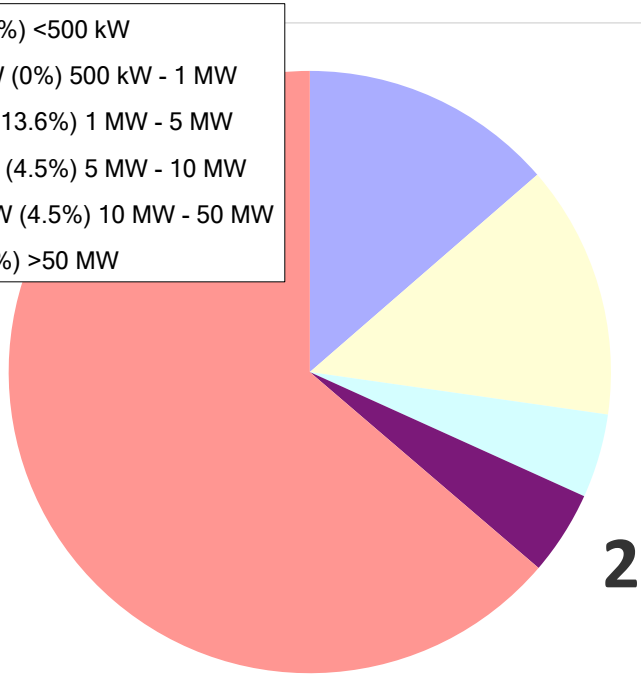
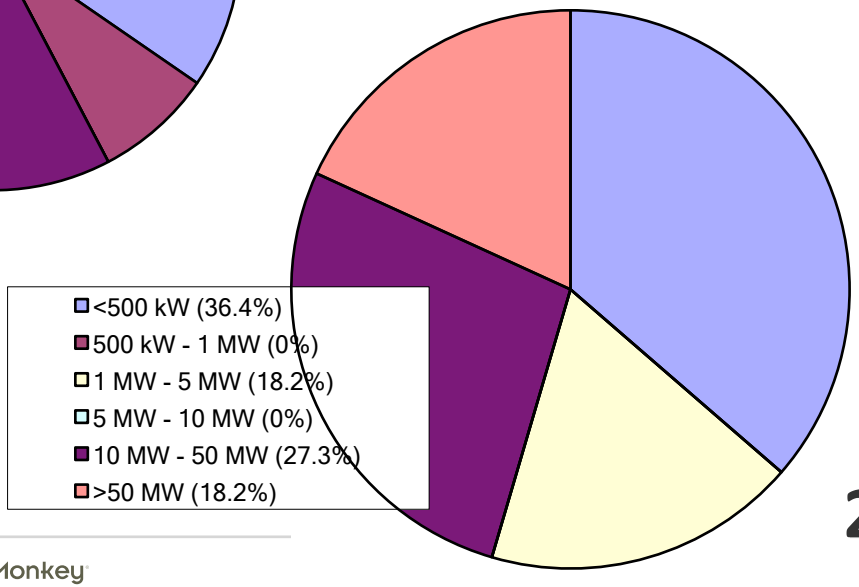
Q9: To date, what is your company's cumulative capacity of PV inverters sold?



2010



2013



2015

Powered by SurveyMonkey

Q10: How does your company define inverter failure? (e.g. x% efficiency loss, loss of communication, no power output)

- Any customer dissatisfaction (5)
    - Any issue that requires service visit or return of inverter
- Power down/no power output (7)
    - downtime in excess of warranty provision
- Degraded power output (3)
    - <70% power output
    - >5% loss in energy harvest d
- Loss of communication (4)
- Loss of major functionalities (3)
- Physical damage

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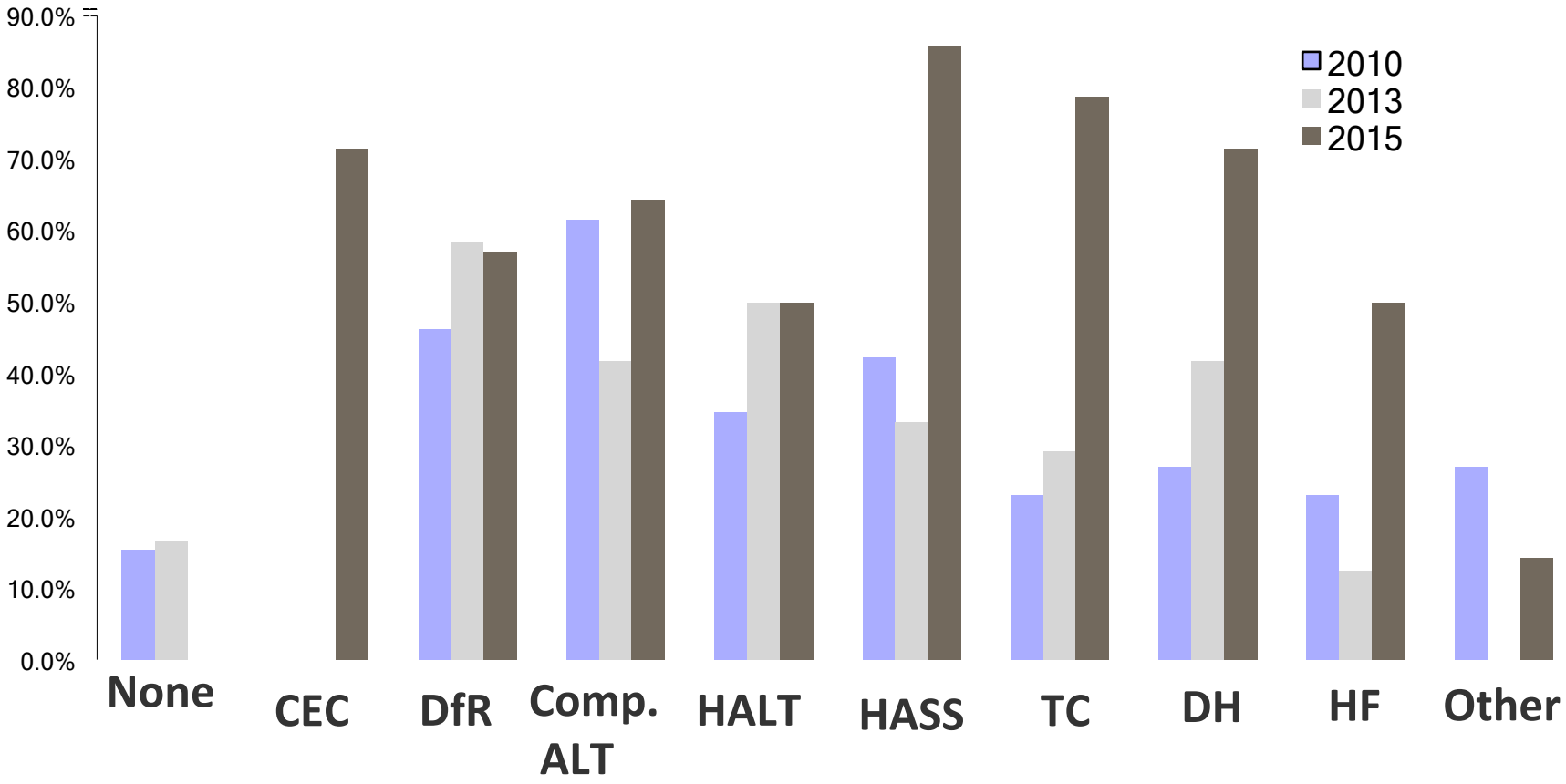
Q12:How does your company define inverter reliability?

- Probability of failure within a certain time period in given condition
  - Meeting stated efficiency, communication, and specifications (7)
  - No unscheduled service calls within warranty period (2)
  - Annual loss in efficiency lower than minimum threshold

- Statistical Analysis
  - Annualized Failure Rate / Useful life
  - Failures in Time (FIT)
  - Mean Time Before Failure (MTBF)
  - R(t)=exp(-t/MTBF)

Q13: What reliability testing does your company currently perform?



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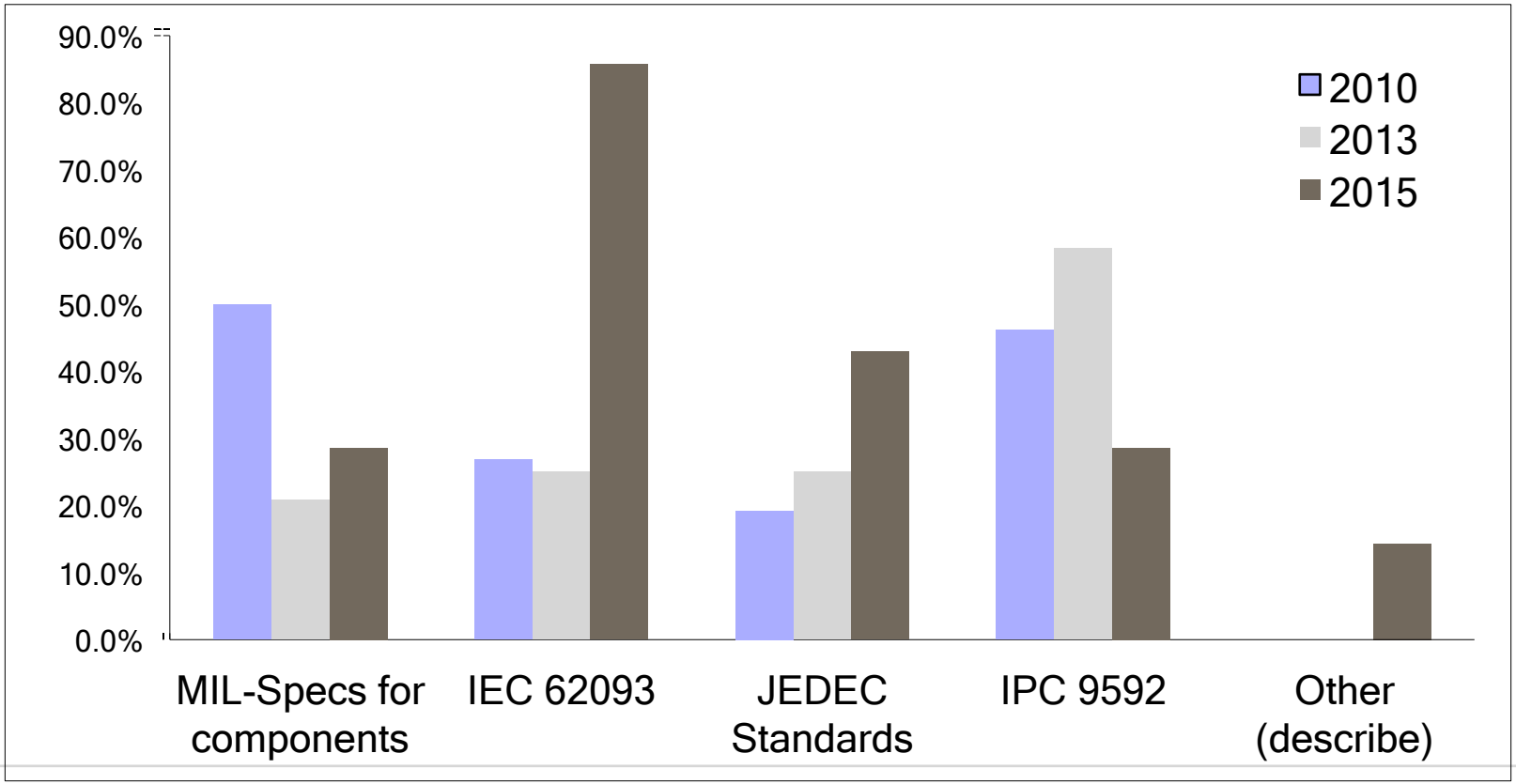
Q14: What reliability-related standards or guidelines does your company currently use?



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Q15: What are your top three (3) vulnerabilities or reliability issues for your inverters?

2010 **2013** **2013**

- Electrical Transients/Grid events **(21)** **(12)** **(8)**
- Environmental **(5)** **(10)** **(3)**
  - Dust, Corrosion, Moisture
- Temperature **(17)** **(4)** **(2)**
  - Excursions, Cycling, Cooling
- Component failure/degradation **(4)** **(1)**
  - IGBT **(4)** **(1)** **(2)**
  - DC Capacitors **(3)** **(4)** **(1)**
  - Boards/Control **(5)** **(4)** **(1)**
  - Solder Joints **(1)** **(1)** **(1)**
  - Software **(2)** **(2)** **(0)**
  - Interconnects/Contactors **(3)** **(1)** **(0)**
  - Fans **(1)** **(1)** **(0)**
  - Protection **(2)** **(0)** **(2)**
  - Inductors **(0)** **(1)** **(0)**
  - Sensors **(0)** **(1)** **(0)**
- Communications **(5)** **(10)** **(3)**
- Installer / third party errors **(2)** **(5)** **(0)**
- Site Issues
  - High DC/AC Ratio **(0)** **(1)** **(0)**
  - Grounding/Leakage **(0)** **(1)** **(1)**

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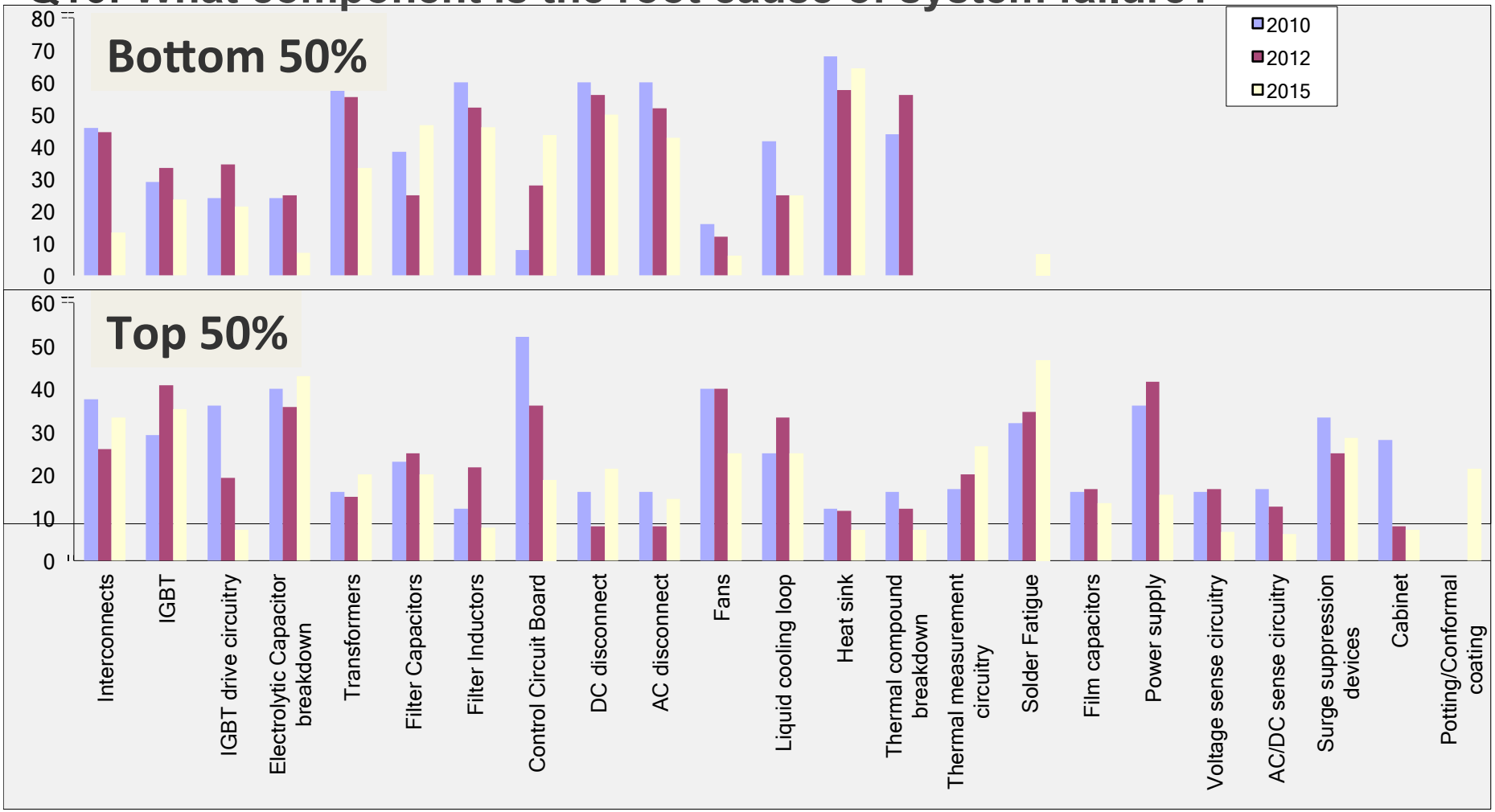
Q16: What component is the root cause of system failure?



Q19: From OEM perspective what you would like DOE, national laboratories, standard development organizations, and utilities to do to help increase inverter reliability?

- Long term, outdoor testing (4)
- Real world simulation and Reliability Testing
  - ALT testing with correlation (5)
  - Research into higher reliability components (2)
  - Program on collecting field failures and analyze & model the results for future design (6)
  - BOM cost analysis, market analysis/reports
- Spell out clear performance criteria and acceptable degradation levels for spec
- Standards development (15)
  - PV Sites, reliability testing, qualification testing, component reliability
- Prognostics and Health Management (2)

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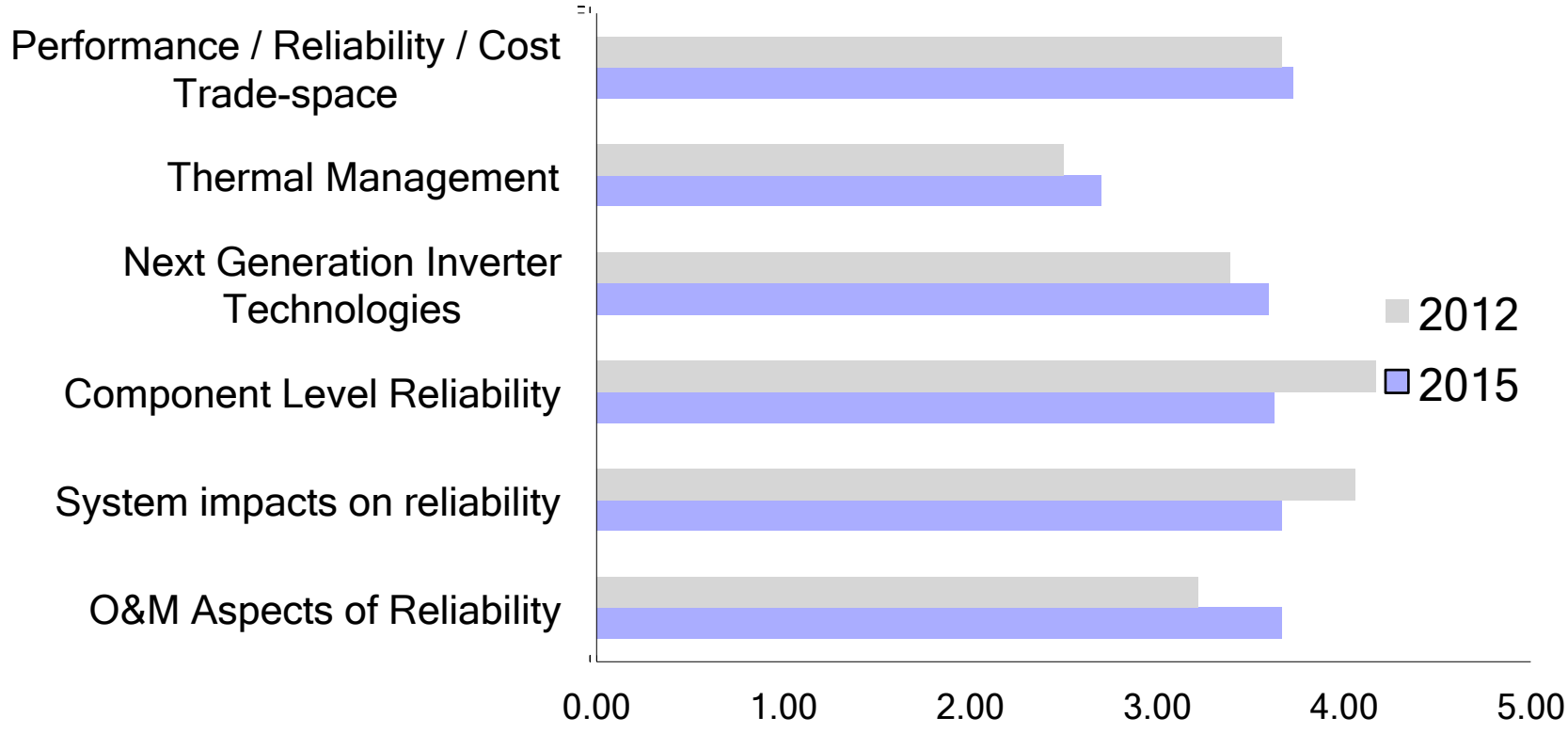
Q18: Order of interest Of the following session topics (1- of most interest to me, 6 - of least interest to me):



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Designed-in Reliability

Matt Ursino
Sr. Reliability Engineer
matt.ursino@solectria.com

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Yaskawa Quality

is more than a measurement. Its an Experience

By any Measurement, the Quality of Yaskawa Products is Second to None

We're the only industrial drives and motion control manufacturer to win the Deming prize – the most prestigious quality award in manufacturing.

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Designed-in Reliability

How do we “design-in” reliability?

1) **Careful selection of components**
2) **Derating components to increase design margins**
3) **Stress Testing (HALT, ALT, HASS, etc.)**

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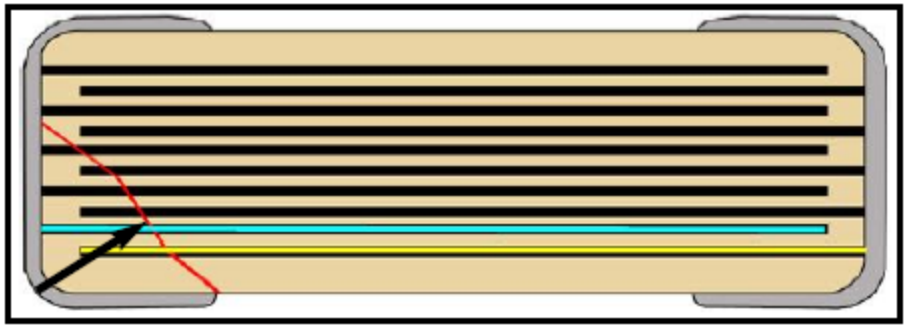
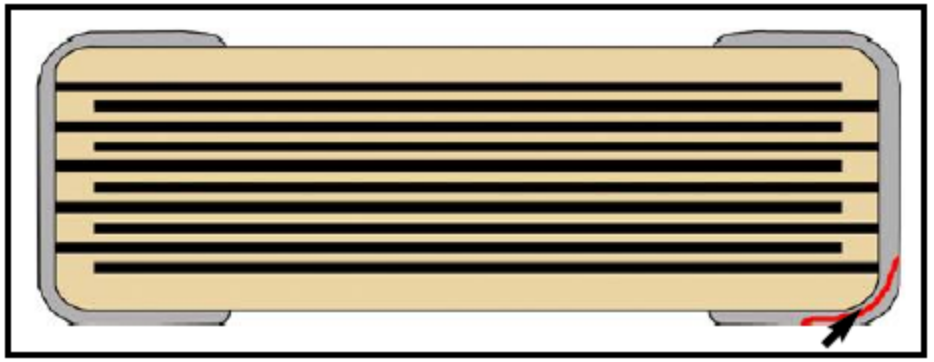
Careful component selection:



Ceramic Capacitors - Flex cracks

Yellow electrode represents (+); blue electrode represents (-); flex crack leads to short circuit.

Flexible termination



Flexible termination moves flex cracks to the end termination, away from the ceramic body.

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Film Capacitors vs. Electrolytic

Identical cap bank composed of 600V capacitors

Electrolytic Capacitors	MTBF = 2.7 million hrs	Useful Life 10-15 yrs
Film Capacitor	MTBF 2.6 million hrs	Useful Life 20-30 yrs

MTBF calculation via Telcordia Standard

Electrolytic Caps have dry-out failures in 10-15 years

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Derating of components

Basically running a component well below their max ratings:

For example Operating an 800V Film capacitor at 600V

or

For example Operating a resistor at 50% of it's max rated power

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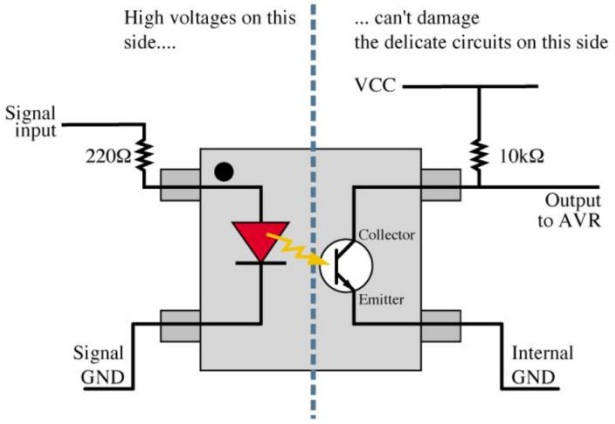
Opto-couplers

Ambient Temps



Used in many critical GFDI circuits as well as other voltage isolation circuits.

25C MTBF = 129 million hrs (FIT 7.75)

60C MTBF = 5.38 million hrs (FIT 186)

That's 24 times reduction in MTBF 60C vs. 25C!!!

MTBF calculation via Telcordia Standard

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Types of Stress testing:

What is HALT (Highly Accelerated Life Testing)?

HALT is a stress testing method used to determine the operating and destruct limits of a design - why those limitations exist and what is required to increase those margins. HALT, therefore, stresses products beyond their design specifications and looks for weak links in the design.

What is ALT (Accelerated Life Testing)?

ALT is the process of *testing* a product by subjecting it to conditions (temperatures, voltage, vibration rate, pressure etc.) in excess of its normal service parameters in an effort to uncover potential modes of early wear-out/failure in a relatively short amount of time.

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And what about HASS (Highly Accelerated Stress Screen)?

HASS testing is an accelerated reliability screen that can be done in production and can reveal latent flaws not detected by ESS, burn-in and other test methods. HASS testing uses stresses beyond specification, but within the capability of the design as determined by the HALT.

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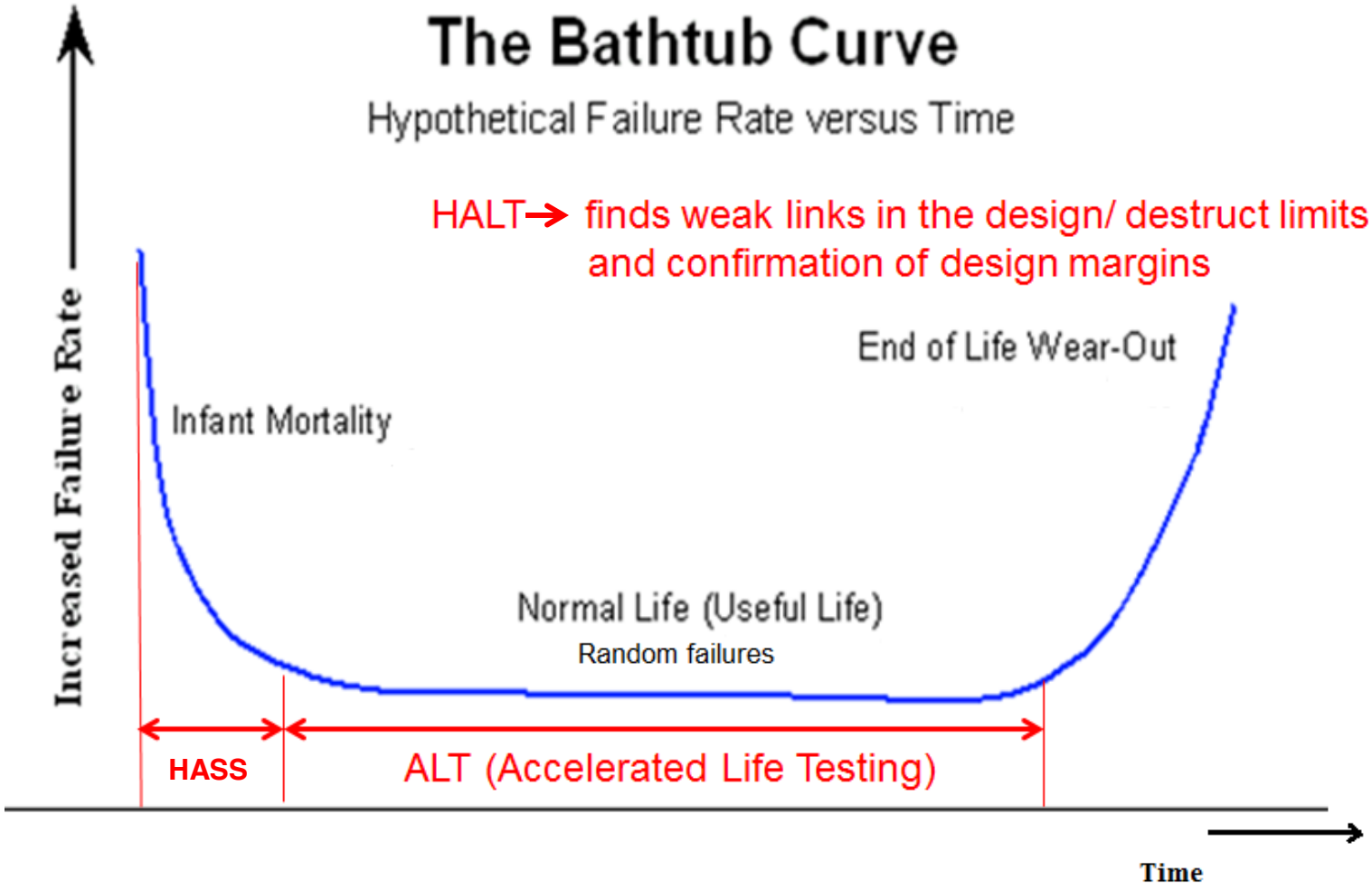

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HALT Testing at Solectria

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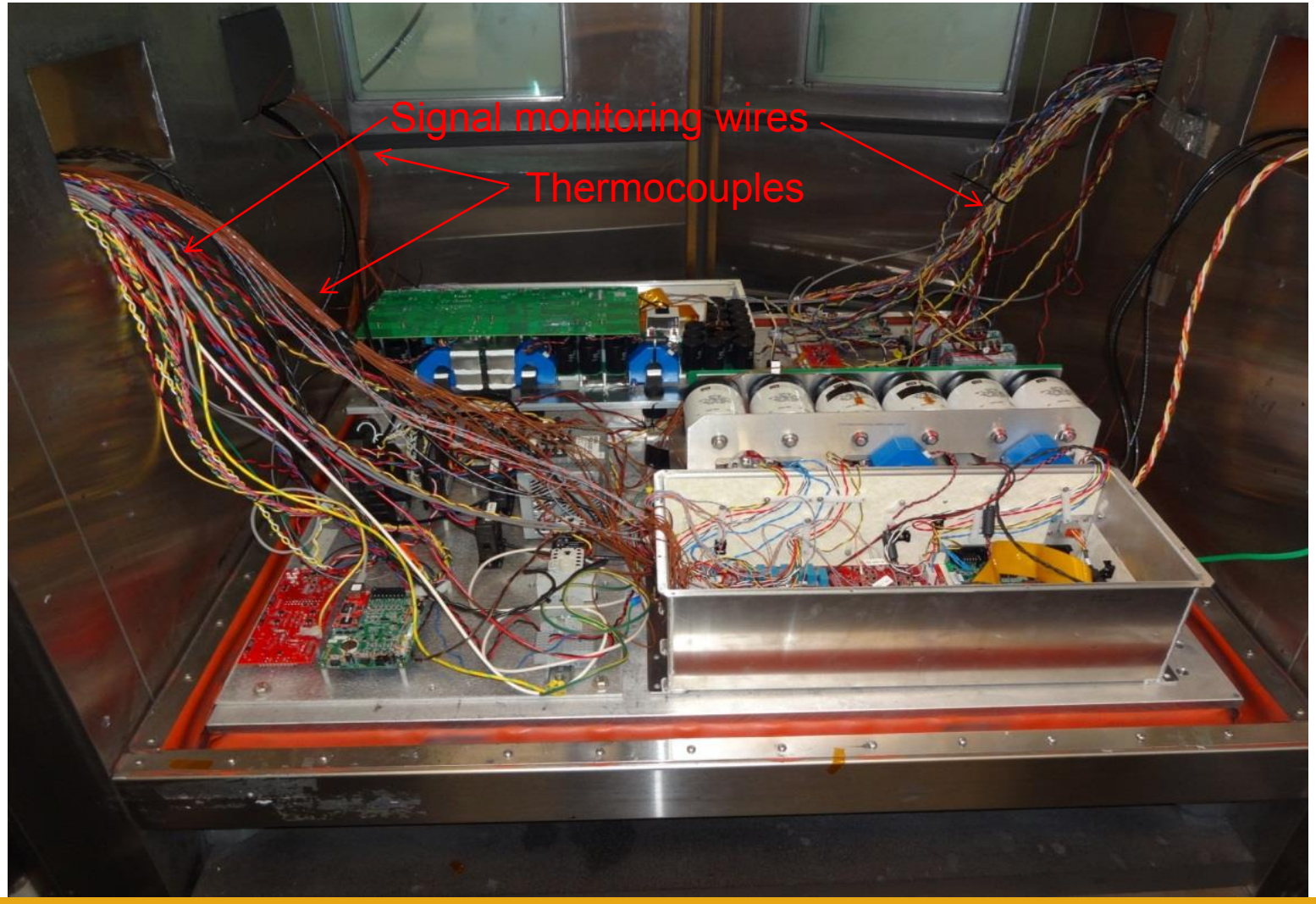
Typical HALT set up



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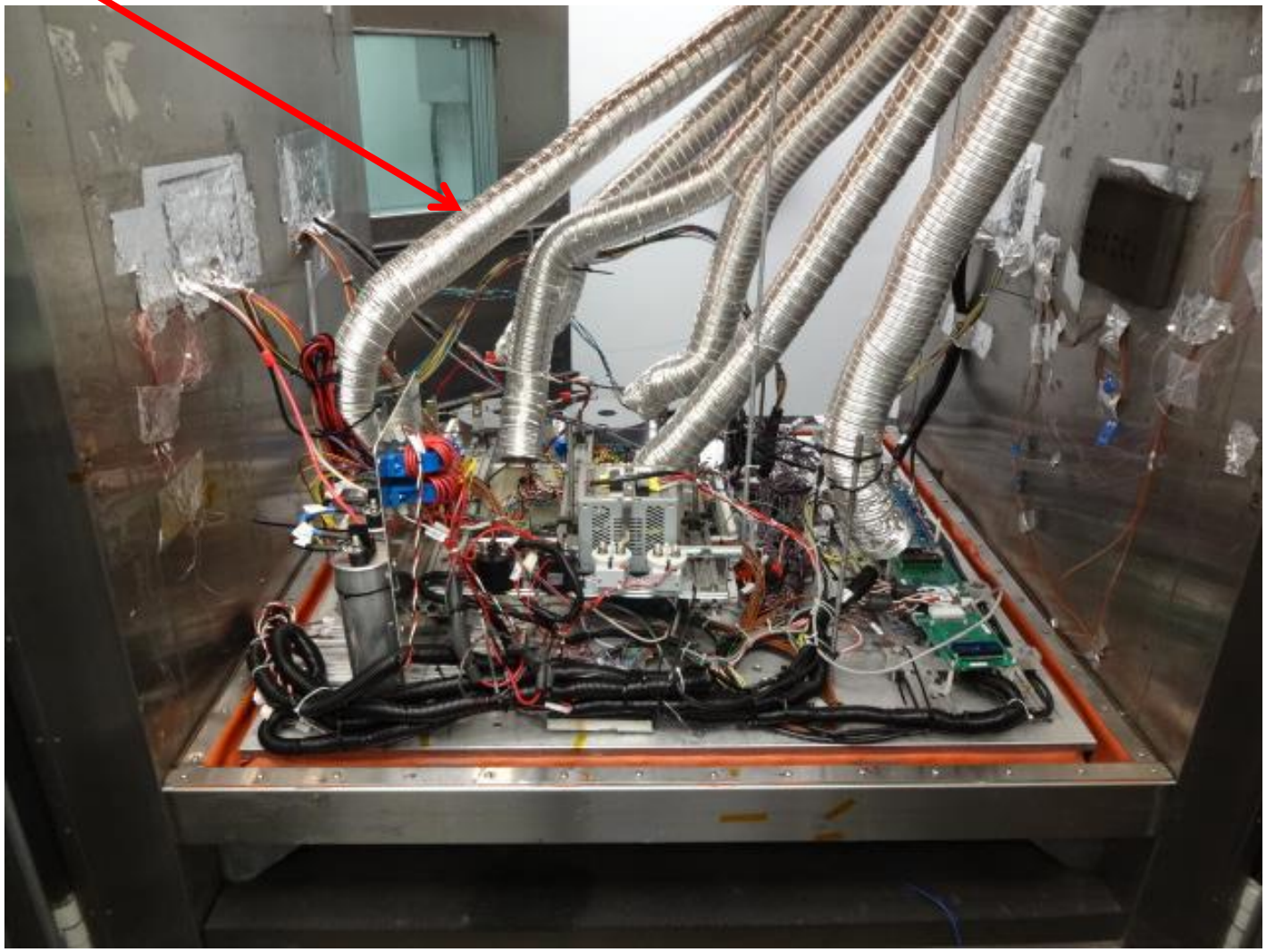
Cold and Heat being guided to critical circuits via air ducts



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Phase 1 Thermal Step Stress

- 10C steps, 15 minute dwells
- 2minutes before end of dwell we induced a GFDI fault

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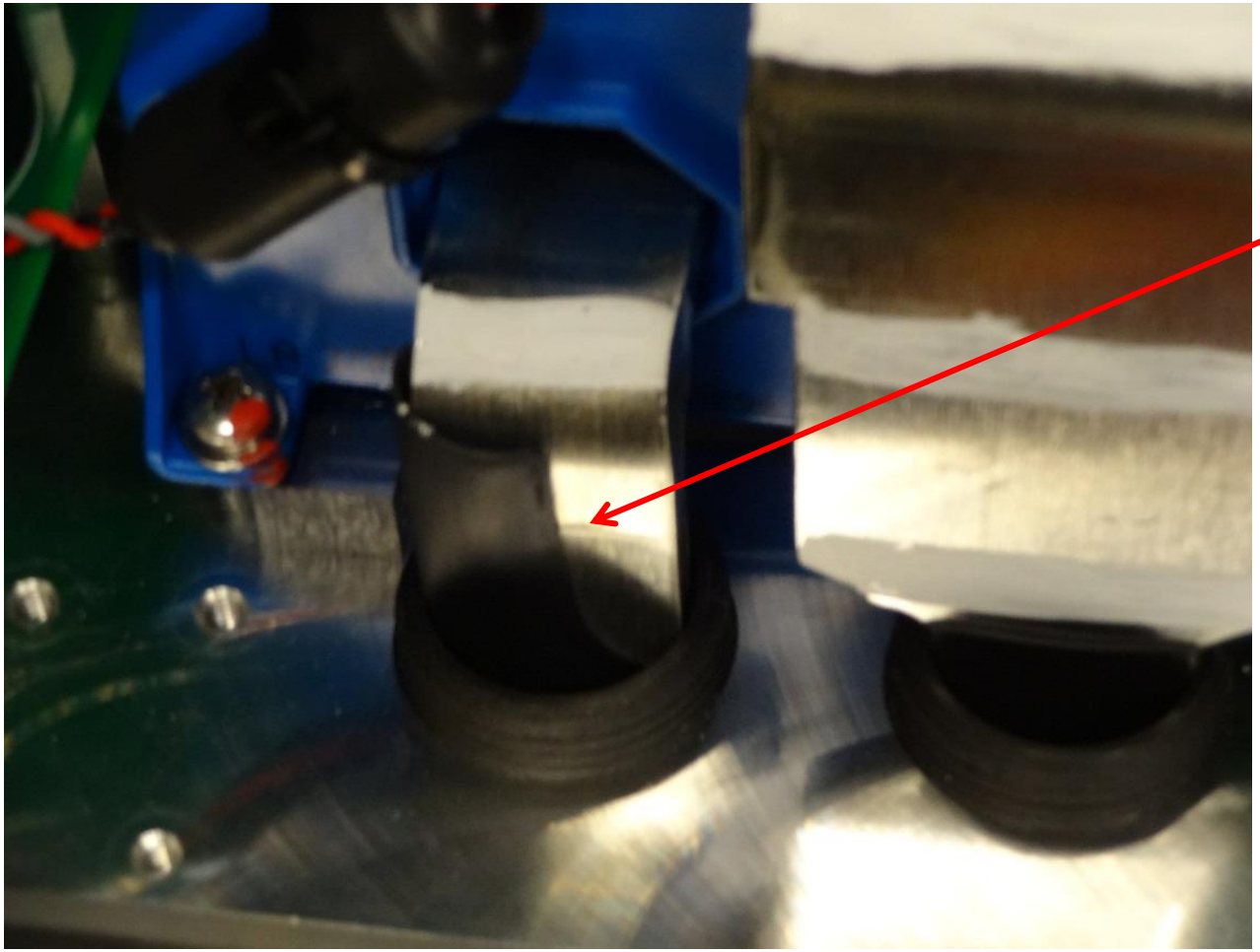
Example of finding during thermal step stress



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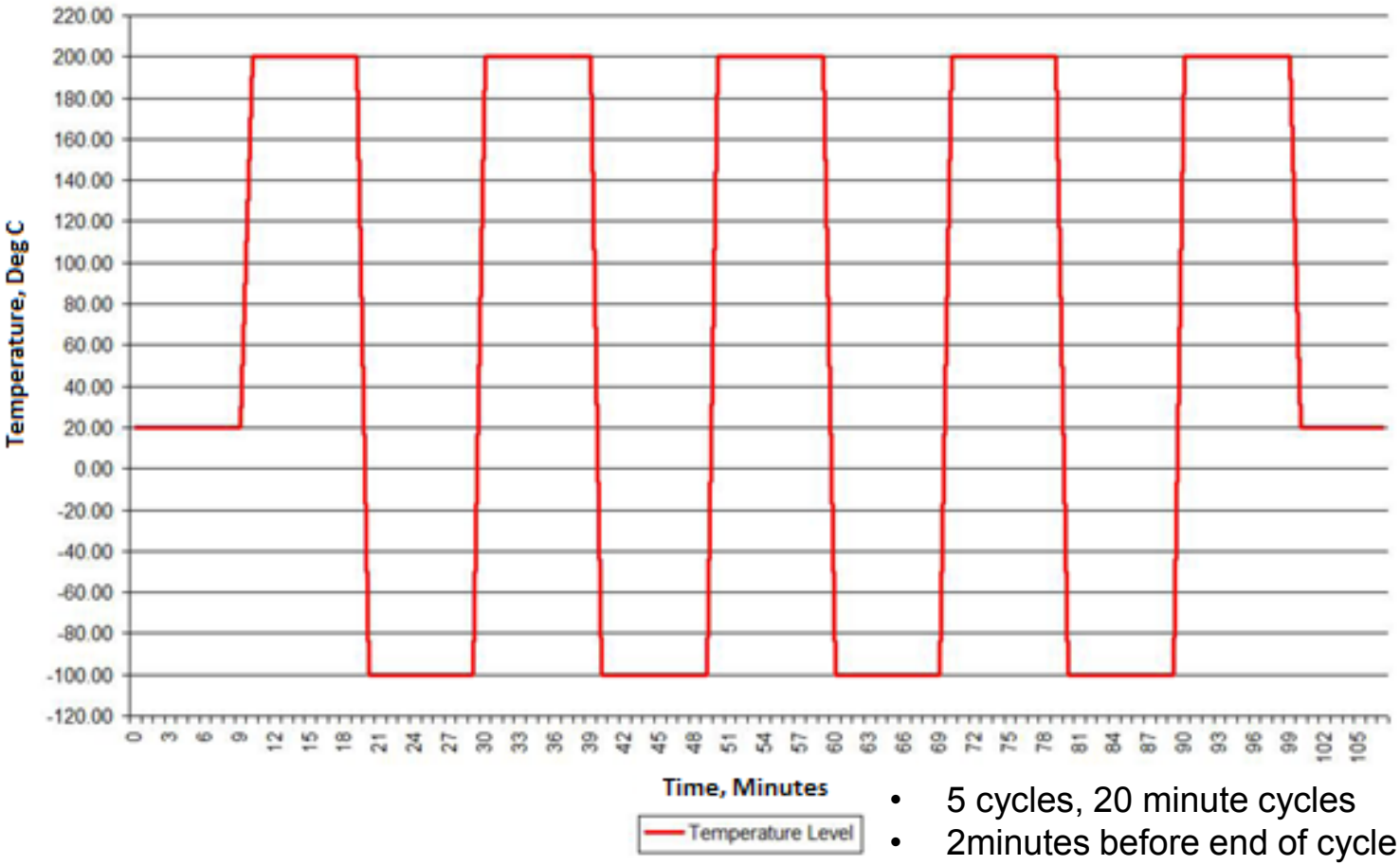
Phase 2 Rapid Thermal Stress



- 5 cycles, 20 minute cycles
- 2minutes before end of cycle we induced a GFDI fault

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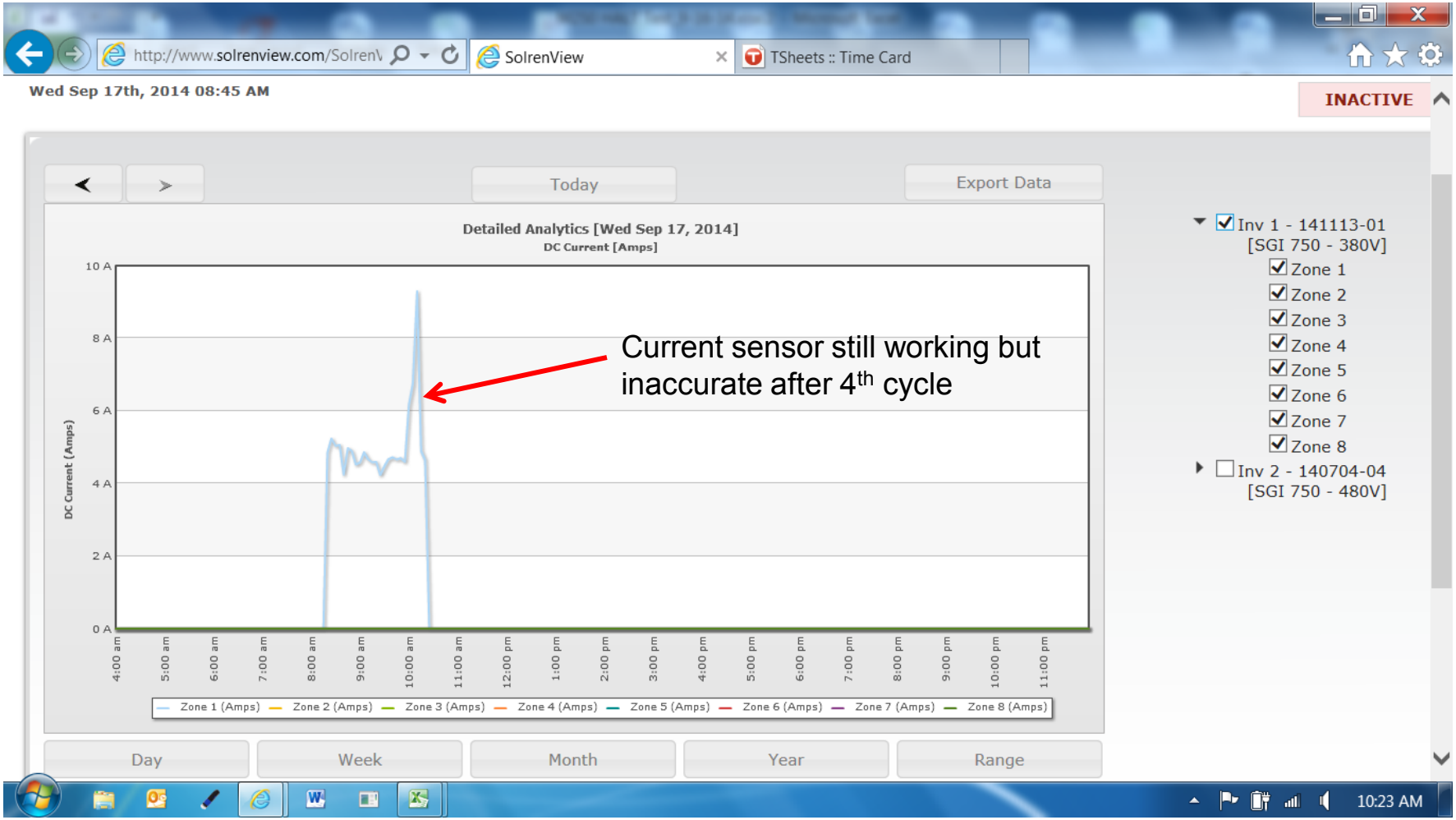
Example of findings during thermal cycle stress



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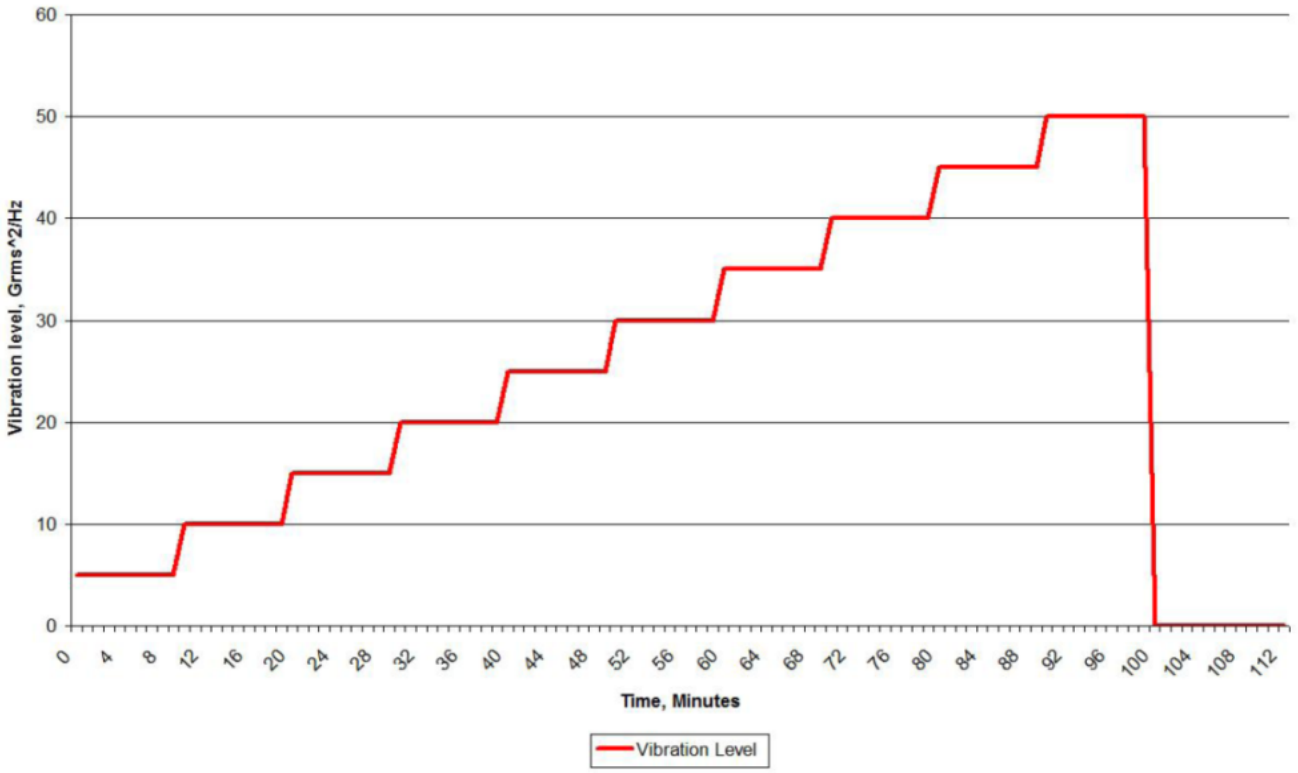
Phase 3 Vibration Step Stress



- 0gRMS to 60gRMS in 5gRMS increments
- 10 minutes dwells
- Starting at 30gRMS, 9 minute dwells + 1 minute at 5gRMS
- 2 minutes before end of dwell we induced a GFDI fault

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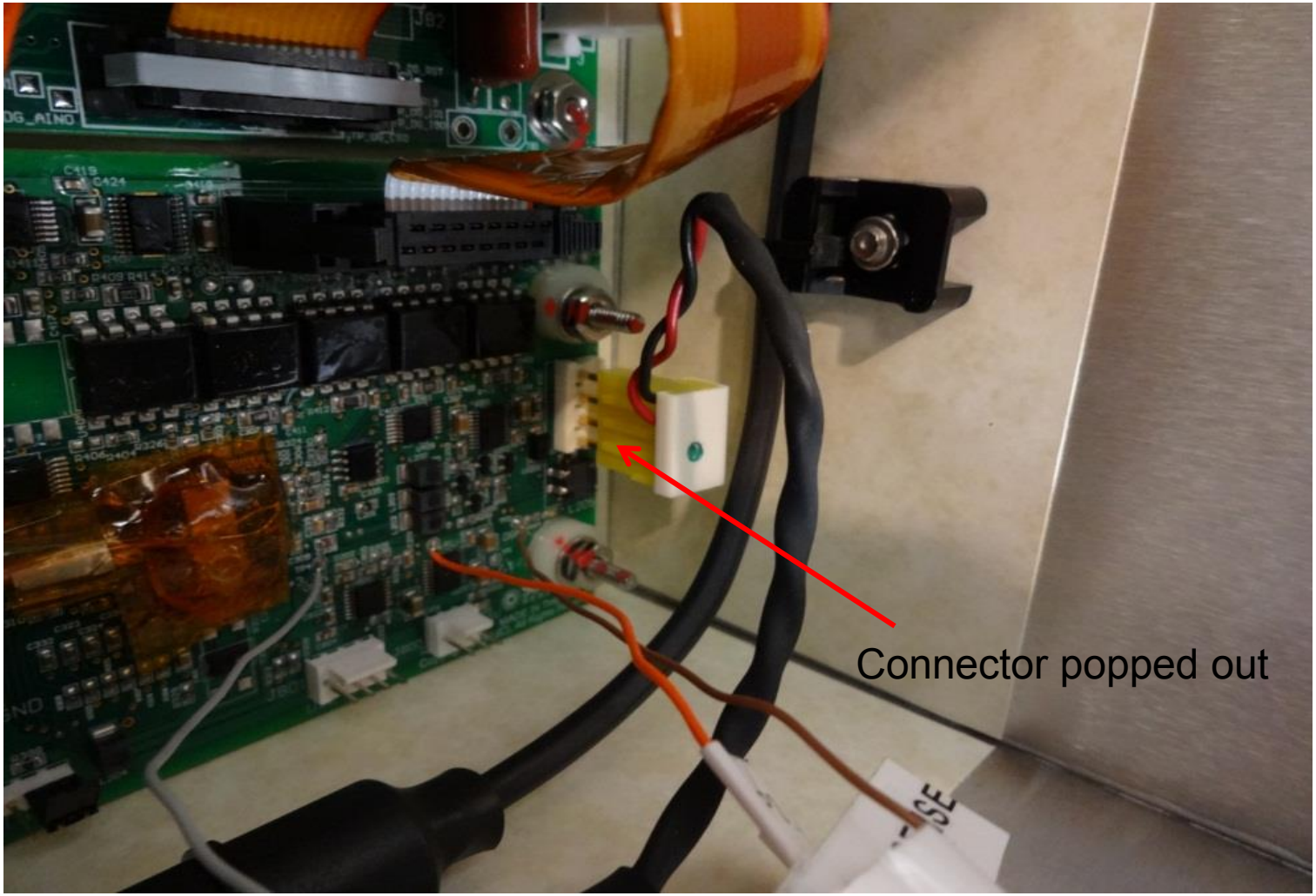
Examples of findings during vibration stress



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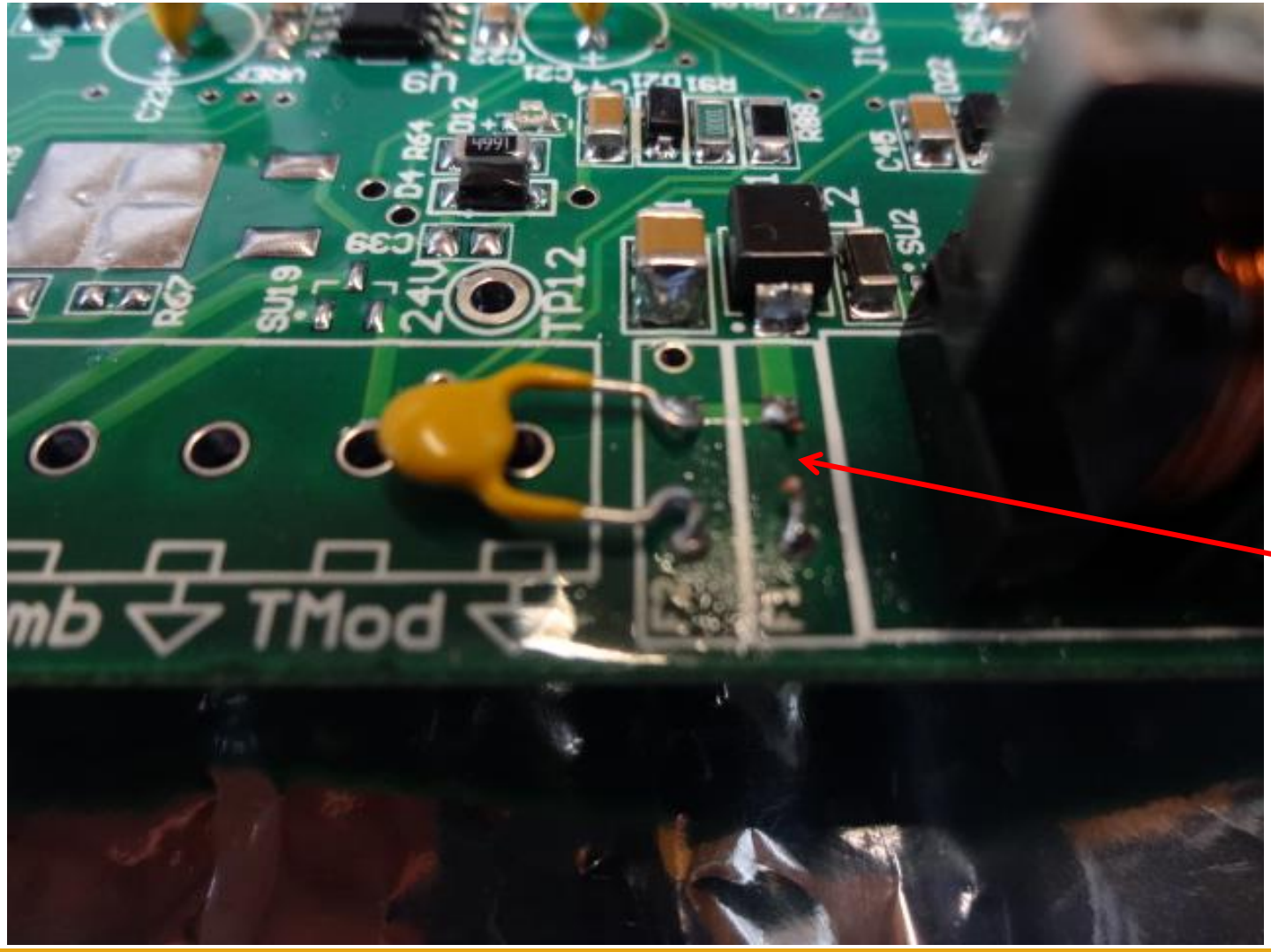

Component sheared off
(need to add RTV)

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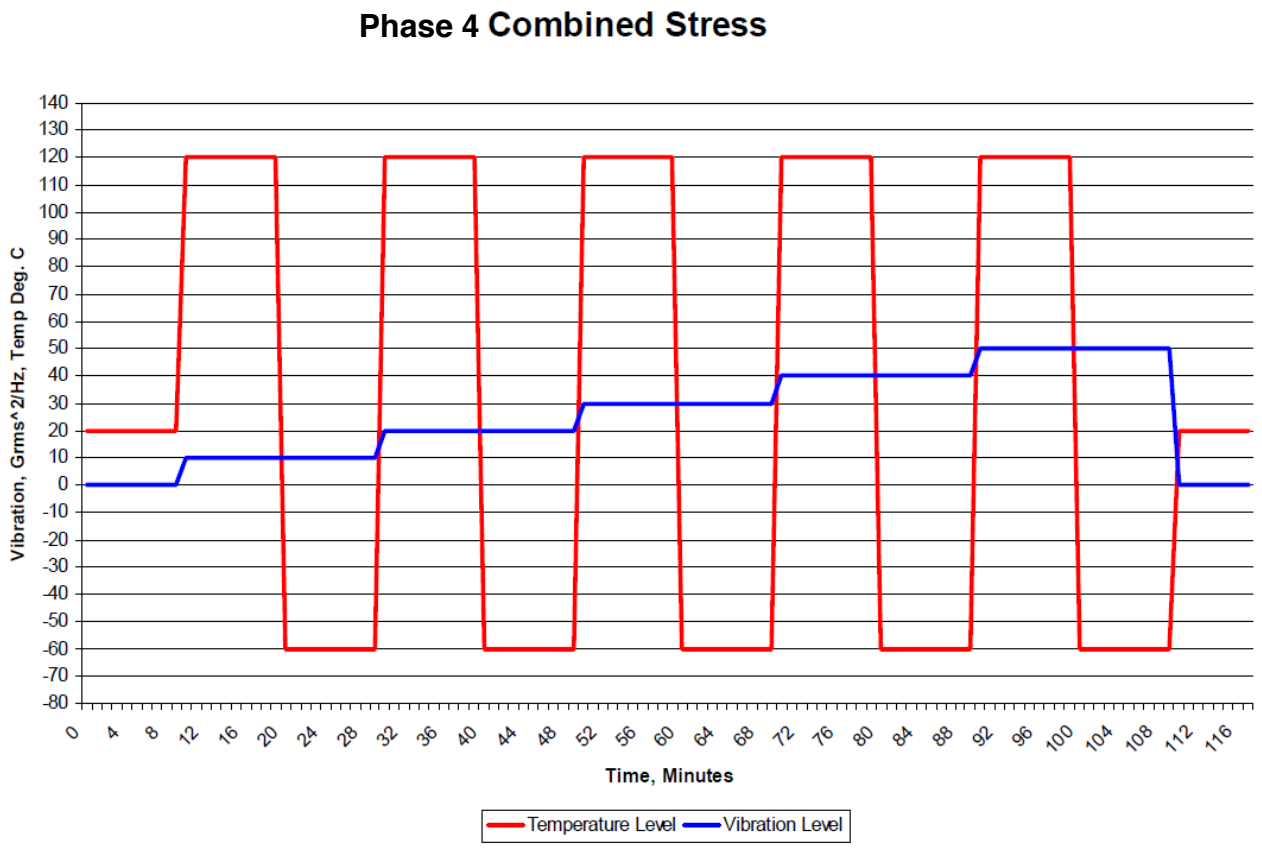

Figure 7: Sample Combined Stress Test Graph

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Examples of findings during Combined stress test

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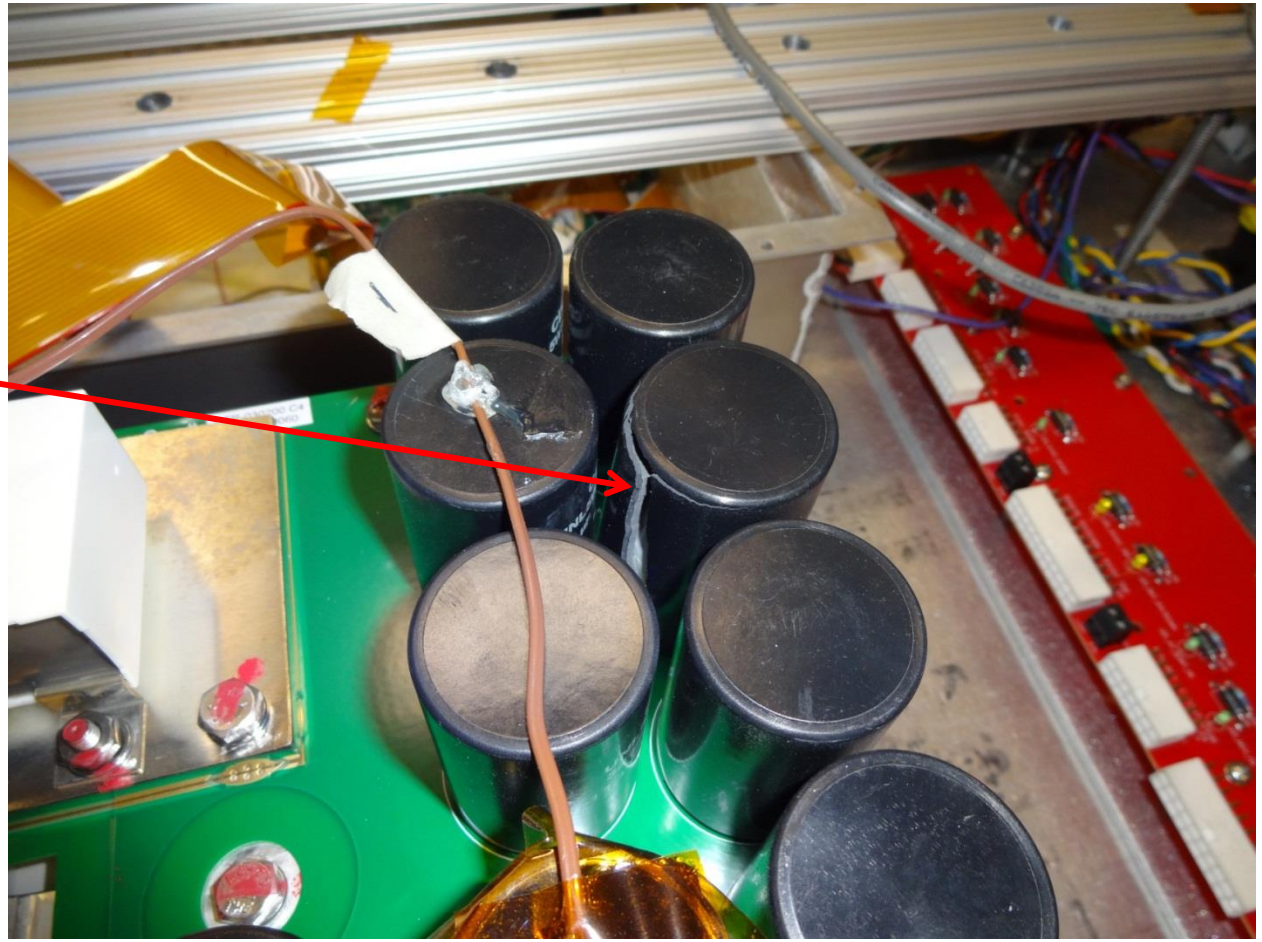
Cracked high voltage capacitor



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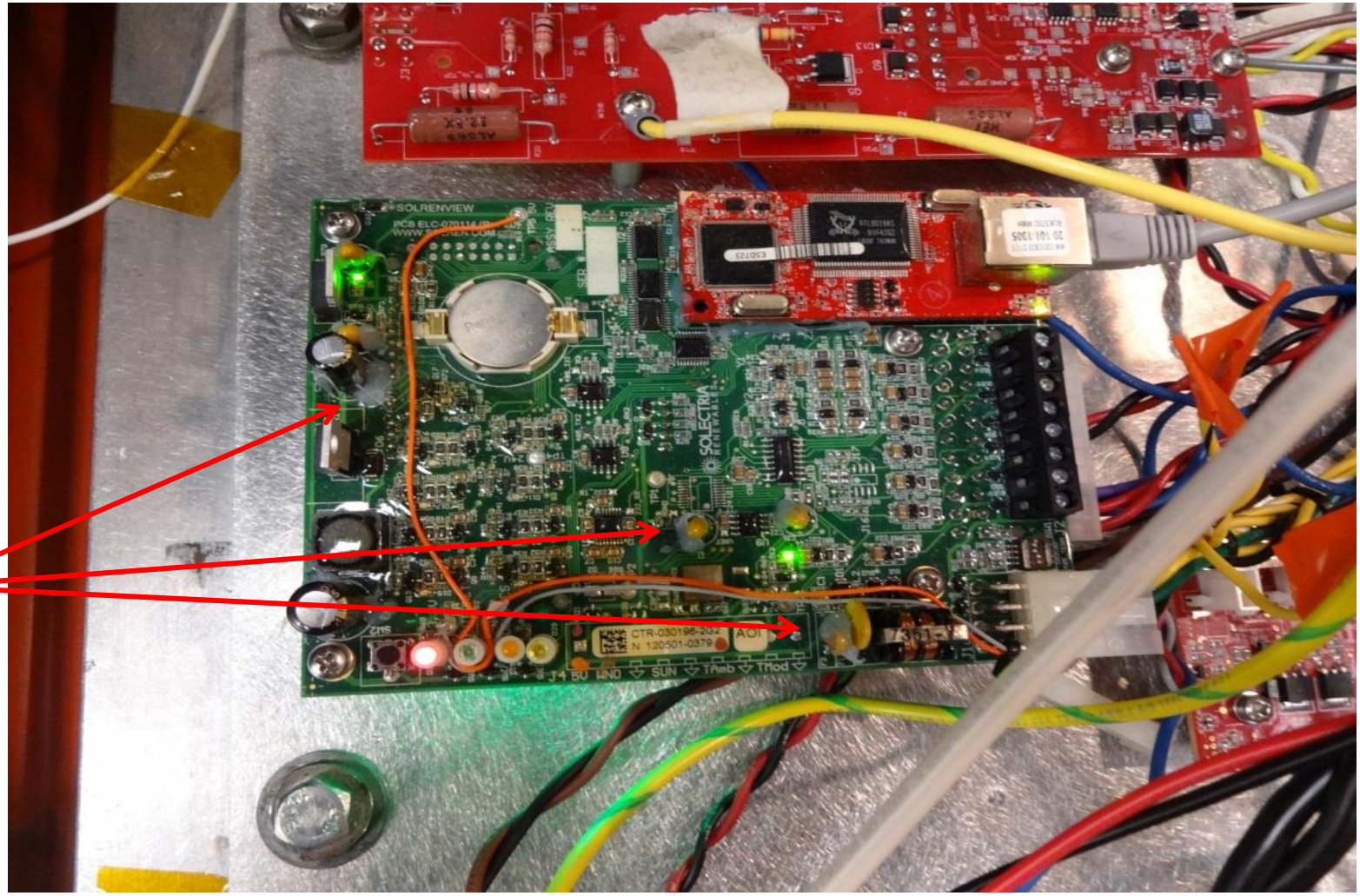
Test of ruggedized components with RTV



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ALT at Solectria

Increase ambient temperature

Block air intake to reduce air-flow

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Solectria ALT (Accelerated Life Testing) set up:

1) Limit air-cooling by blocking intake, power stages should be on the edge of going into derating mode.

2) Adjust intake air temp and blocking to achieve 70C cabinet temp and 80C inside power stage enclosure (DMGI enclosure)

3) Operate at maximum voltage and power level.

4) Run <u>continuous</u> cycles with the following power levels. 100% power for 11 hrs and 5% power for 1 hr, this will thermal cycle the power stages and all components inside the cabinet

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Calculating Acceleration Factor

Comparative form of Arrhenius Equation

$$\text{Acceleration Factor} = e^{**}\left[(E_a / k) (1/T_1 - 1/T_2)\right]$$

where T1 is the reference temperature (e.g. 25°C / 298.15°K)
and T2 is the actual use temperature.

e	= 2.718281
E_a	is the "Activation Energy" for the physical process(es) that lead to wearout, in eV
k	is Boltzmann's Constant, 8.617×10^{-5} eV / K
T	is Temperature in degrees Kelvin (Celsius degrees plus 273.15)
eV	means "Electron Volt"

Most component manufacturers recommend using an Activation Energy (E_a) between 0.7 and 1 eV

	MIL-HDBK-217F notice 1	MIL-HDBK-217F notice 2	MIL 217 plus
Update year	1995	1996	2007
Bipolar logic	0,4 eV	0,4 eV	0,8 eV
CMOS logic	0,35 eV	0,35 eV	0,8 eV
BiCmos logic	0,5 eV	0,5 eV	0,8 eV
Linear	0,65 eV	0,65 eV	0,8 eV
Memories	0,6 eV	0,6 eV	0,8 eV
VHSIC	0,4 eV	0,4 eV	0,8 eV

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Acceleration Factor for Cabinet Components

The “Typical/Average” cabinet temp in the field is 40C

Block air-flow to achieve a cabinet temp of 70C

Activation Energy (E_a) = 0.8eV

Acceleration Factor = e **[(E_a / k) (1/T_1 - 1/T_2)]

	T1 (°C)	T1 (°C)	Ea (eV)	T1 (°K)	T2 (°K)
Enter values	40	70	0.8	313.15	343.15
				Ae/k	9283.97
Acceleration Factor =		13		1/T1 - 1/T	2.79E-04
					2.592

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How long do we need to run ALT to equal 20 years?

A typical inverter operates 14 hrs a day for 20 years

Total hrs = 14hrs/day x 365 days x 20yrs = 102,200 hrs

102,200 hrs / Acceleration Factor AF = 13

102,200 hrs/13 = 7862 hrs

Since we are running ALT for 11 hrs @100% power and 1 hr @5% power that's 22 hrs/day running at Full Power.

7862 hrs ÷ 22 hrs/day = 357 days or about 12 months

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Questions?

Accelerated Reliability Testing for Commercial and Utility PV Inverters

Ron Vidano

February 25, 2015

Abstract

Accelerated testing is an efficient strategy to improve reliability for commercial and utility photovoltaic inverter equipment. The two most often used tests are highly accelerated life testing (HALT) and accelerated life testing (ALT).

HALT is a technique that yields results within a few days due to the nature of the acceleration factors used in the test whereby the unit is subjected to progressively higher stress levels and the inclusion of combined temperature and vibration. HALT is an invaluable method to uncover design weaknesses and is used at both the system as well as assembly level.

Accelerated Life Testing (ALT) is useful to determine wear-out mechanisms or lifetime within confidence limits. ALT is capable of determination for product reliability in a short time period of weeks or months by environmental acceleration factors. ALT can find dominant failure mechanisms and is a valuable tool for the discovery of wear-out failure. In addition, ALT methods can serve as qualification criteria to prescribed lifetime confidence limits.

ALT at the system level involves integration of multiple units such as an inverter and power supply within a large environmentally controlled facility. Subsystem life testing can be completed within smaller environmental enclosures or may be accomplished as a component integrated within the inverter at the unit or system level testing facility.

For ALT, the acceleration factor, length of the test, number of samples, confidence required, and test environment are known. The most common temperature acceleration factor is based upon the Arrhenius model. For PV inverters another acceleration factor is the duty cycle whereby testing may be accomplished continually as opposed to the sun-cycle restrictions for on-site exposure. In addition, inclusion of solar simulation methods provides for inverter cycling experienced during environmental and solar resource extremes. One element of efficient ALT qualification is envelope performance testing at environmental extremes.

It is advantageous to synergize the HALT methods to determine design weaknesses and ALT procedures which provide insight into wear-out lifetimes. Once, it has been determined that the inverter design can attain expected lifetimes, burn-in procedures are developed and used to ensure that the product does not contain process or assembly defects.

Methodology - Reliability Assurance Milestones During Inverter Product Lifecycle

AE uses a closed loop reliability process

Design for Reliability

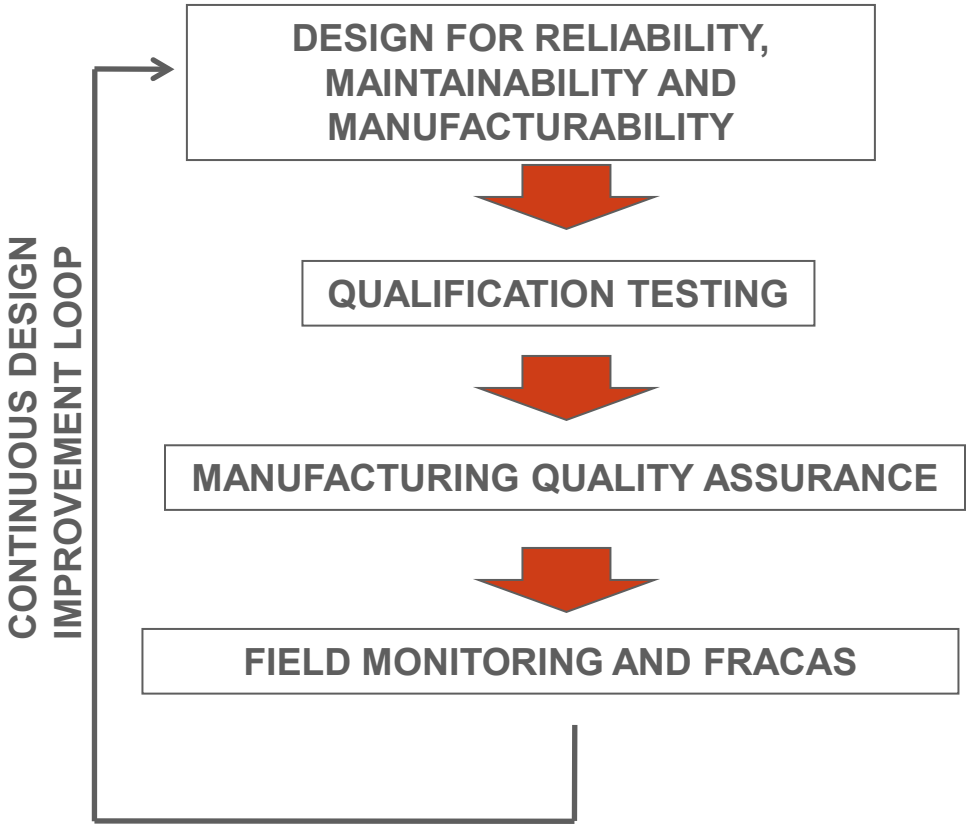
- MTBF, DFMEA, Fault Tree

Reliability Test

- Quantitative: ALT, Thermal
- Qualitative: HALT

Qualification Test

- Power profile, efficiency, harmonics, waveform, modulation, control loop, compliance, WCSA, limits, control & communication, burn-in development



Range of PV Inverters for Accelerated Testing

- String Inverters such as the 3TL Gen3 24kW

- Central Inverters such as the 500TX and 500NX

- Utility Inverters such as the 1000NX

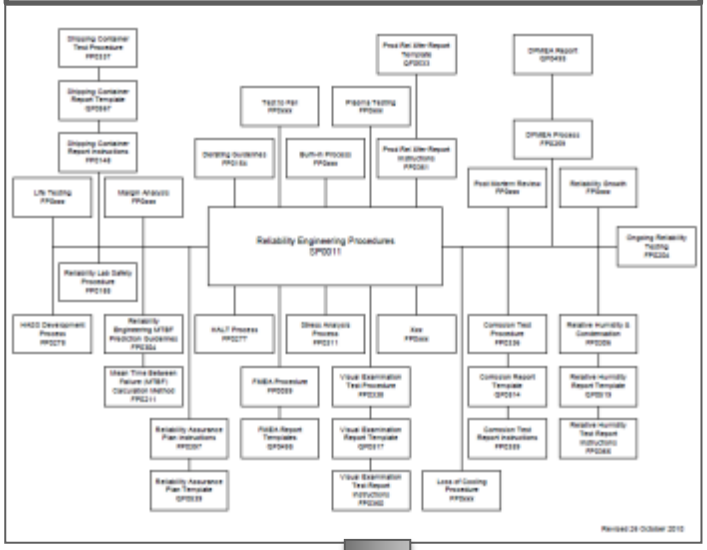
AE Reliability Assurance Background

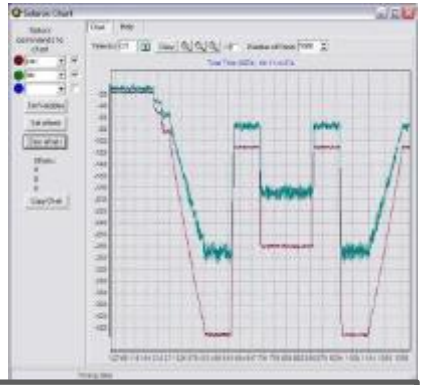
- AE's Solar and Precision Power Supply customer base requires a reliability focus.
- All products are required to meet a very low AFR

+

- PV Inverter products have unique challenges
  - Grid and Solar Simulators
  - High Firmware Contact – HIL Methods
  - Harsh Environment
  - Stringent Warranties
  - Monitoring
  - Inverter Reliability Must Compensate for BOE Issues
  - 20-Year Durability
  - >99% Availability
  - High Efficiency

AE Reliability Assurance Program





Advanced Power Supply Infrastructure and Simulation

Inverter Reliability Assurance Program

- Design for Reliability (DfR) Focus Areas
  - Modularity; Improves reliability, repair, test, and manufacturing
  - Derating; Component and subassembly derating to reduce operating stress
  - Temperature Management; Achievement of reduced operating temperatures
  - Predictive Methods – MTBF, DFMEA, Fault Tree Assessments
- Reliability Test
  - **Verification of potential causes based upon DFMEA**
    - **Subassembly ALT, Thermal, Thermal Cycle**
    - **Environmental Testing – Temp/Humidity, Salt Fog**
    - **HALT**
    - **System Level ALT**
- Experience; Reliability Growth
  - Product lifecycle learning experiences into design
    - Improvements based upon assurance testing and field experience

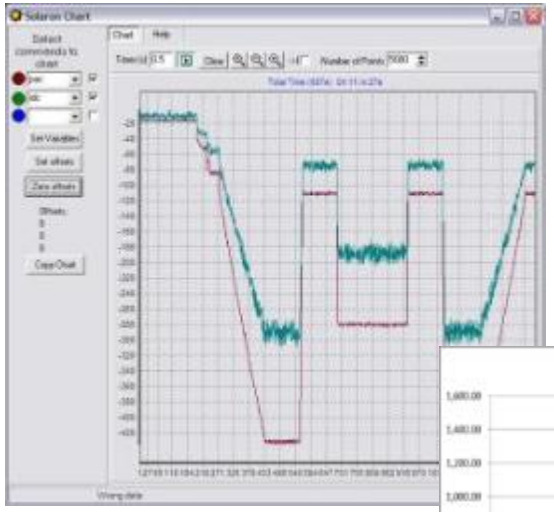
Focus For This Presentation

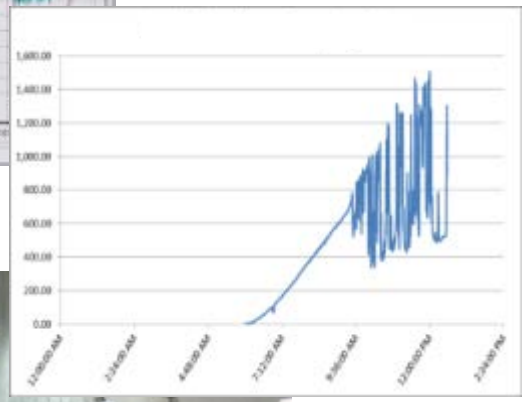
Accelerated Testing Applied to PV Inverters

- **Accelerated Life Testing**
  - **Temperature**
  - Humidity, Temperature-Humidity
  - Voltage
- Temperature Cycling
- Power Cycling
- **Highly Accelerated Life Testing**
  - **Cold step stressing**
  - **Hot step stressing**
  - **Rapid thermal transitions**
  - **Vibration step stressing**
  - **Combined environments**

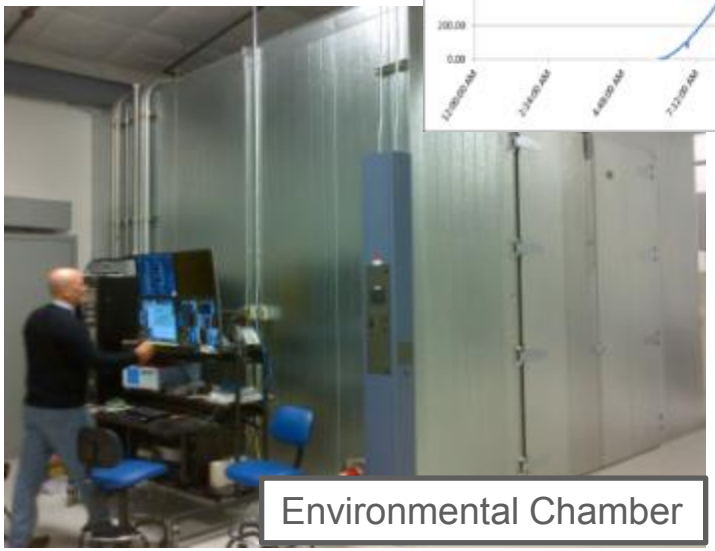
Performance Testing – Solar Simulation

- AE has installed programmable supplies to perform solar simulation testing
- Example of NREL test profile demonstrated with 1000NX inverter
- Example of actual site irradiance data programmed for test





Advanced Power Supply AC2000P



Environmental Chamber

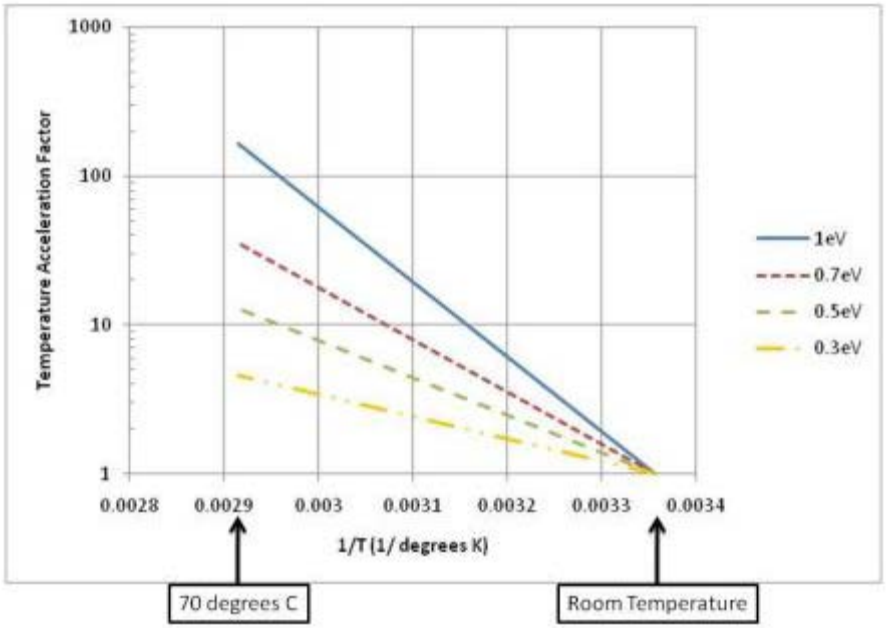
Accelerated Life Test (ALT) – Temperature Acceleration

Durability tests such as subsystem and system level accelerated life testing (ALT) are key tools to qualify the reliability of new designs.

The most common temperature acceleration factor AF(T) is based upon the Arrhenius model

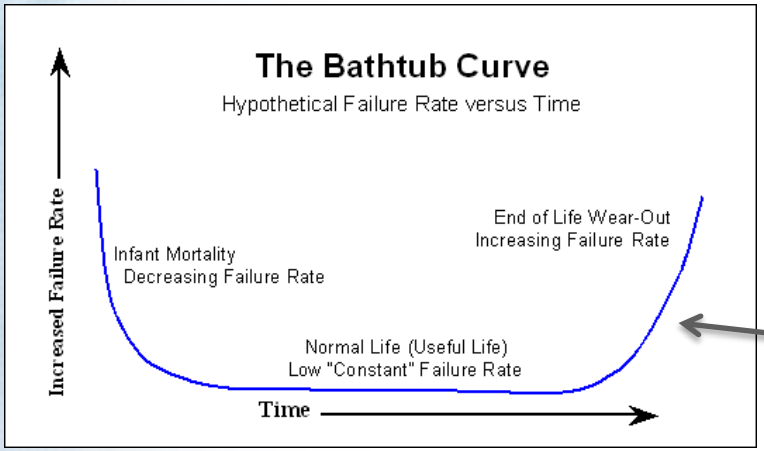
- K_b is the Boltzmann's constant, T_o is the initial ambient temperature in °K, T is the life test temperature in °K, and E_a is the activation energy in eV.

The acceleration factor scales for different activation energies and life test temperatures.



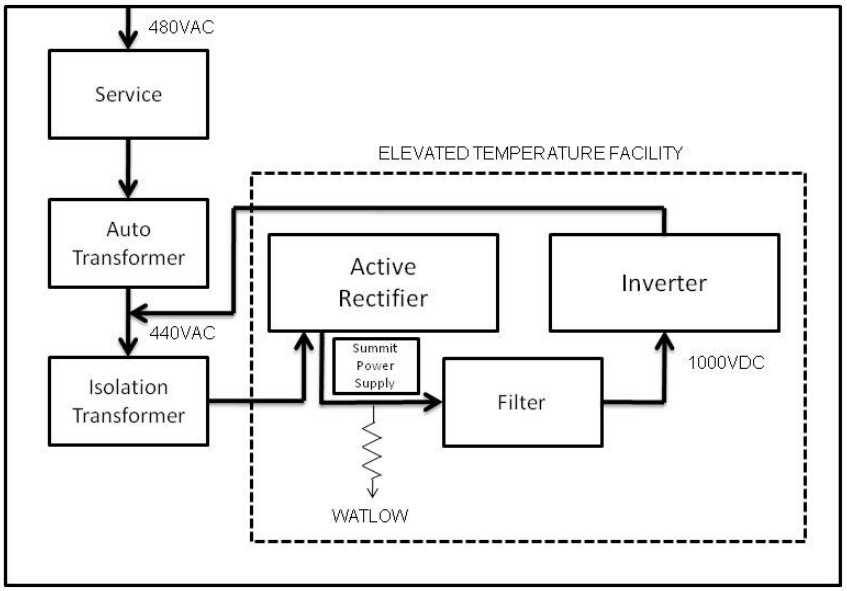
$$\lambda \propto \text{Failures}/(\text{Total Device Hours} \times AF(T))$$

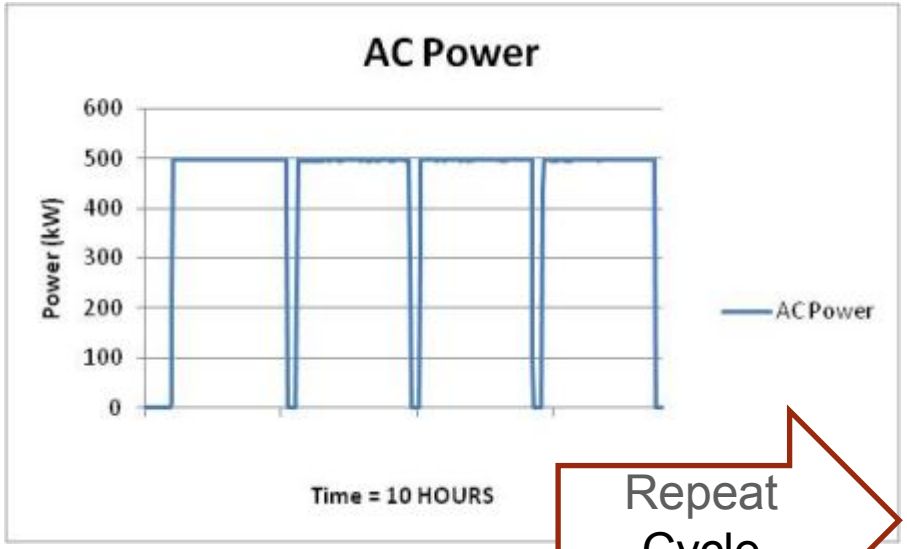
$$AF(T) = \exp[(E_a/K_b)(1/T_o - 1/T)]$$



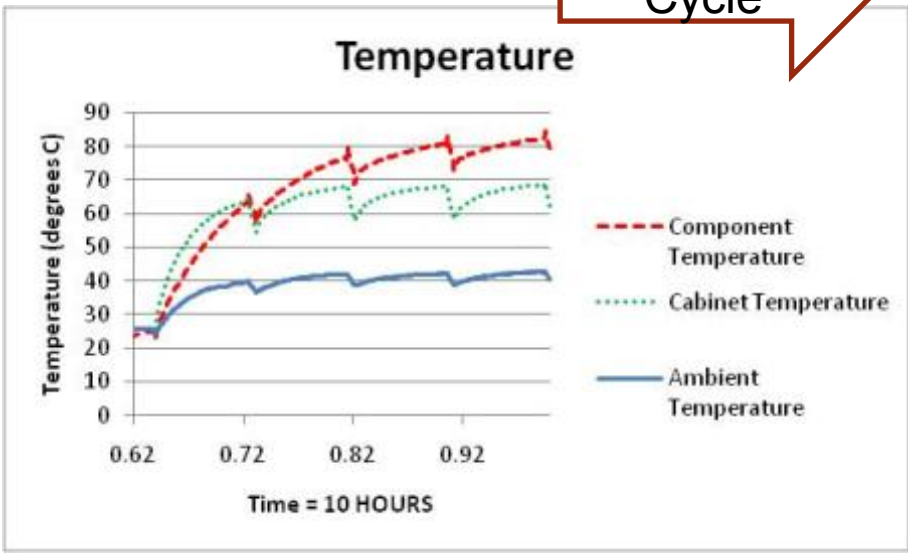
ALT is a gage of the inverter durability to reach end-of-life failure rate region

Long Term Life Test Profile Example; System Level ALT





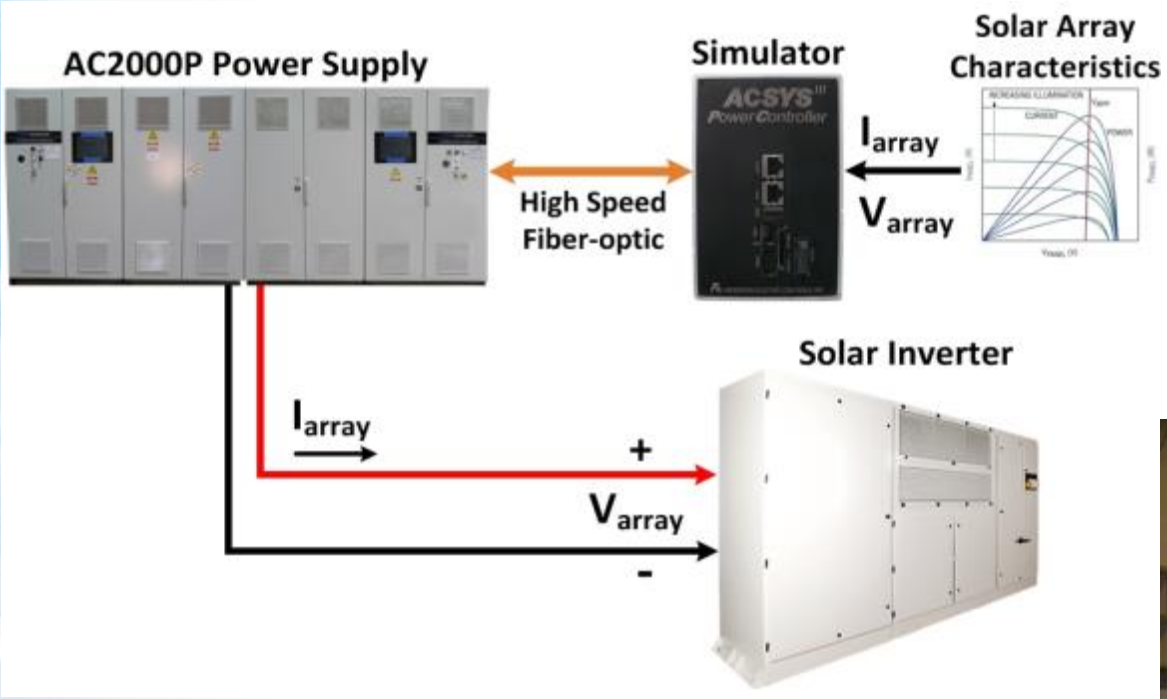
Repeat Cycle



AE has performed ALT for up to two calendar years upon inverters at 50degC, 24X7

Short Term Life Test Profile Example; System Level ALT

AE has developed accelerated life test facilities in Fort Collins, CO and Bend, OR which are capable of grid test simulation at high temperatures using advanced programmable power supplies with solar simulators



Anderson Electric Controls Supply and Solar Simulator Inverter housed within AE environmental chamber

Using solar simulators, AE has performed ALT for up to two calendar months upon inverters at 50degC, 24X7

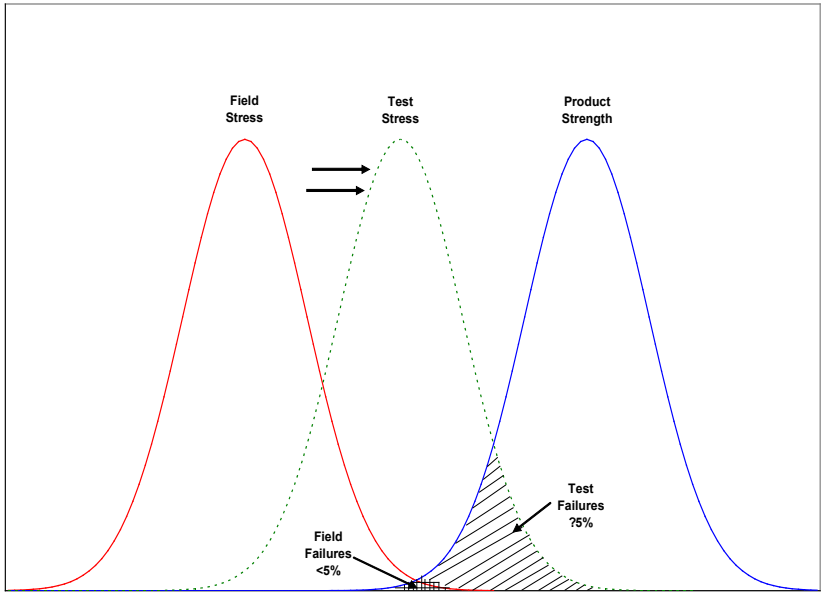
AE Background with HALT, HASS

- Highly accelerated life test (HALT) is a qualitative technique pioneered by leading firms such as HP to develop very reliable printers
- AE adopted the technique to develop reliable precision power supplies used in semiconductor processing
- Several HALT chambers were installed for testing and qualification as well as highly accelerated stress screening (HASS) chambers
- HALT has been used for the past seven years to test and quality PV inverter systems and subsystems

Highly Accelerated Life Test - HALT

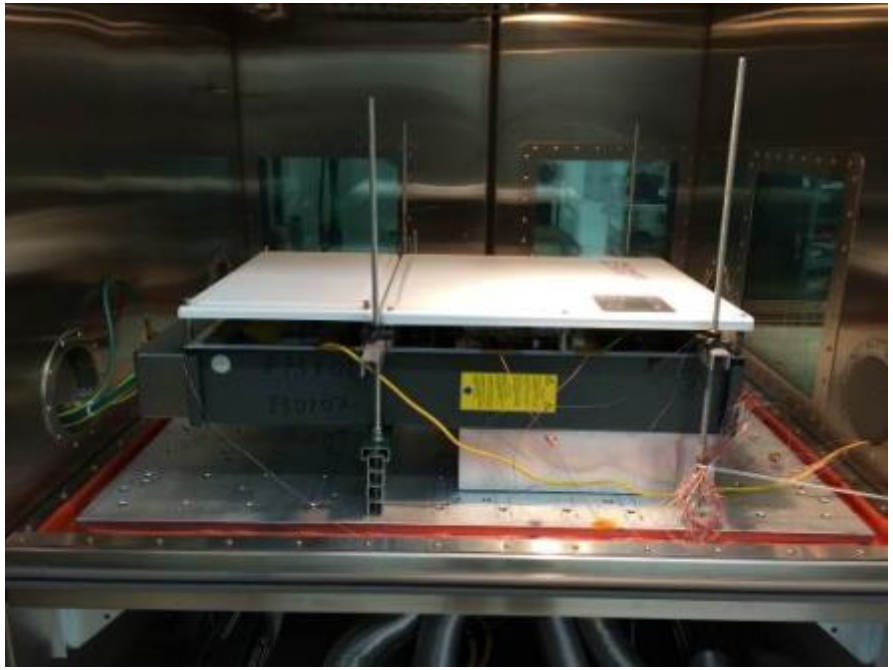
- HALT is intended to uncover design and design margin issues
  - Five stresses
    - Cold step stressing
    - Hot step stressing
    - Rapid thermal transitions
    - Vibration step stressing
    - Combined environments

    in addition to maximum loading the inverters are exercised under power
- Corrective Actions
  - Achievement of acceptable design margins; Temperature margins, Vibration margins, Combined stresses



HALT; PV Inverter Subsystems and Systems

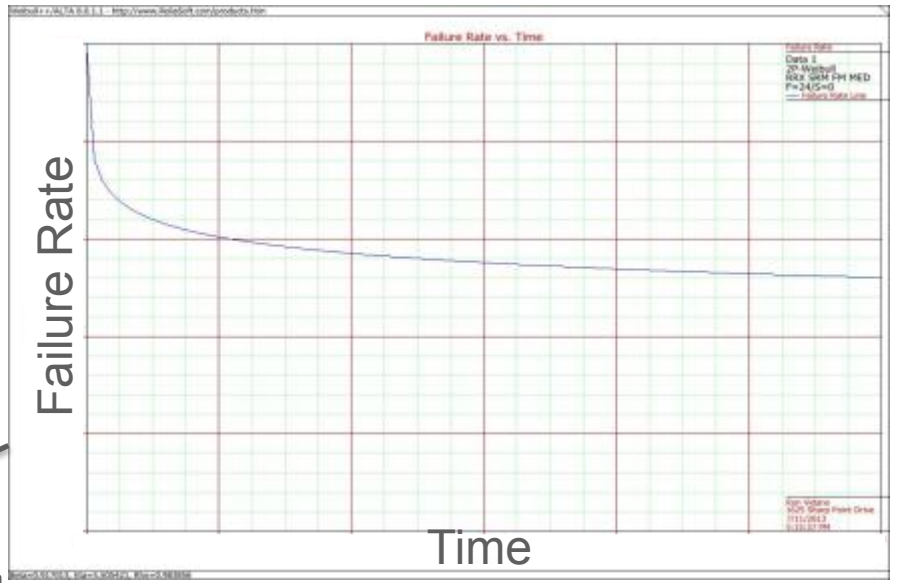
- Utility Inverters
  - Entire Switching Assembly (Engine)
  - DC Contactor Assemblies
  - Aux Power Supplies
  - Cable Assemblies
  - Line Reactors
  - Communication Subsystem
  - PCBAs
    - Digital Control
    - Analog
    - Sensor Control
- String Inverters
  - Entire 3TL 24kW
  - Entire 3TL 48kW



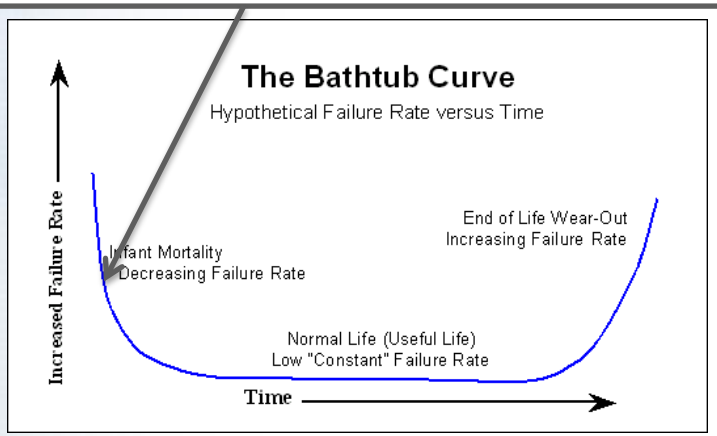
System Level Burn-In for Utility Inverters

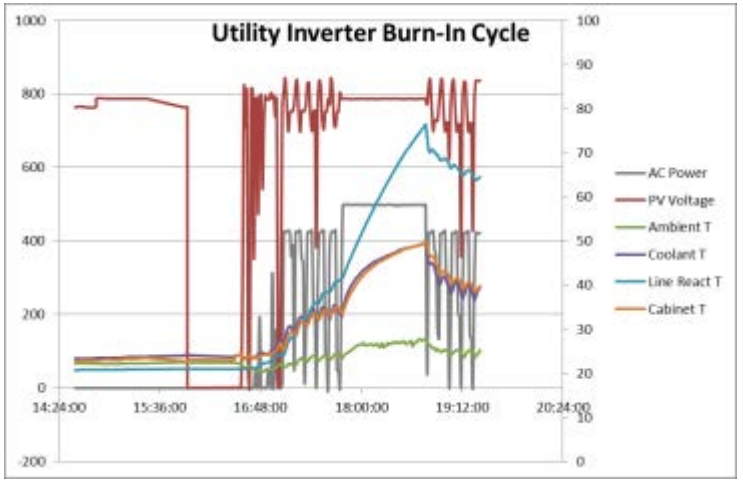
- Burn-in testing takes place at the unit level to stress the components for a designated period time to precipitate component early lifetime mortality - Temperature and Voltage Acceleration Factors
- The burn-in cycle contains voltage and power cycling which is done to ensure that power connections such as the bolted-joint assemblies are robust as well as to test low power electrical connector interfaces

Weibull statistics are accumulated to assess the burn-in cycle



Production Burn-In reduces the number of failures in the early (decreasing failure rate) lifetime region





Conclusions

- Accelerated life testing can be effectively employed for both subsystem and system level qualification of central, utility and string inverters
- HALT qualification is most effective at the subsystem level for central and utility inverters
- For string inverters, HALT qualification offers a unique approach for reliability improvement of the entire product

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Standardization and Reliability Testing of Module-Level Power Electronics (MLPE)

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Outline

- Development of qualification standard for MLPE
- FMEA survey on MLPE failures
- Reliability evaluation of 17-year old AC modules
- Summary

Development of qualification standard for MLPE

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ANSI/TUV-R 71830

Microinverters and Microconverters – Design Qualification and Type Approval

Potential References:

- IEC 61215: Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval
- IEC 61646: Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval
- IEC 62093: Balance-of-system components for photovoltaic systems - Design qualification natural environments
- ECN-C-04-032: Design qualification of inverters for grid-connected operation of photovoltaic power generators
- TUV-2PfG 2305: Test program for junction boxes with active electronics
- California Energy Commission (CEC) List of Eligible Inverters per SB1 Guidelines
  http://www.gosolarcalifornia.ca.gov/equipment/documents/Sandia_Guideline_2005.pdf
- IEC 61683: Photovoltaic systems - Power conditioners - Procedure for measuring efficiency
- UL 1741: Standard for Inverters, Converters, Controllers and Interconnection Systems for use with Distributed Energy Resources

[The profiles of stress tests for MLPE qualification test standard need to be adjusted - without compromising the intent of the standard - to match the qualification and safety standards of modules and inverters (IEC 61215/61746, UL 1741, IEC 61730 & UL 1703) so they can be combined to reduce the testing cost and time]

Qualification Testing: What it is and isn't

What it is

- Qualification test standard complements the safety standard but not a safety standard
- Qualification tests are a set of well defined accelerated stress tests
- 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 products will pass (If not there will be no commercial market.)
- Qualifies the design and helps to eliminate infant mortality (later we will look at the bathtub curve)

The Qualification testing is performed to qualify the design and packaging of a product. It provides a baseline for subsequent acceptance testing, comparative testing and lifetime prediction testing. In other words, qualification testing is the minimum requirement before initiating acceptance testing, comparative testing and lifetime testing. The qualification testing is typically completed before the production decision is made, and all other tests are typically completed after the initiation of production.

All the above should be considered as ground rules to develop qualification standard!

Adopted from: IEC 61215: What it is and isn't, J. Wohlgemuth, PVMRW 2012; Accelerated Lifetime Testing, G. Tamizhmani et. al., SolarABCs.org

Qualification Testing: What it is and isn't

What it is not

Qualification testing is not intended to:

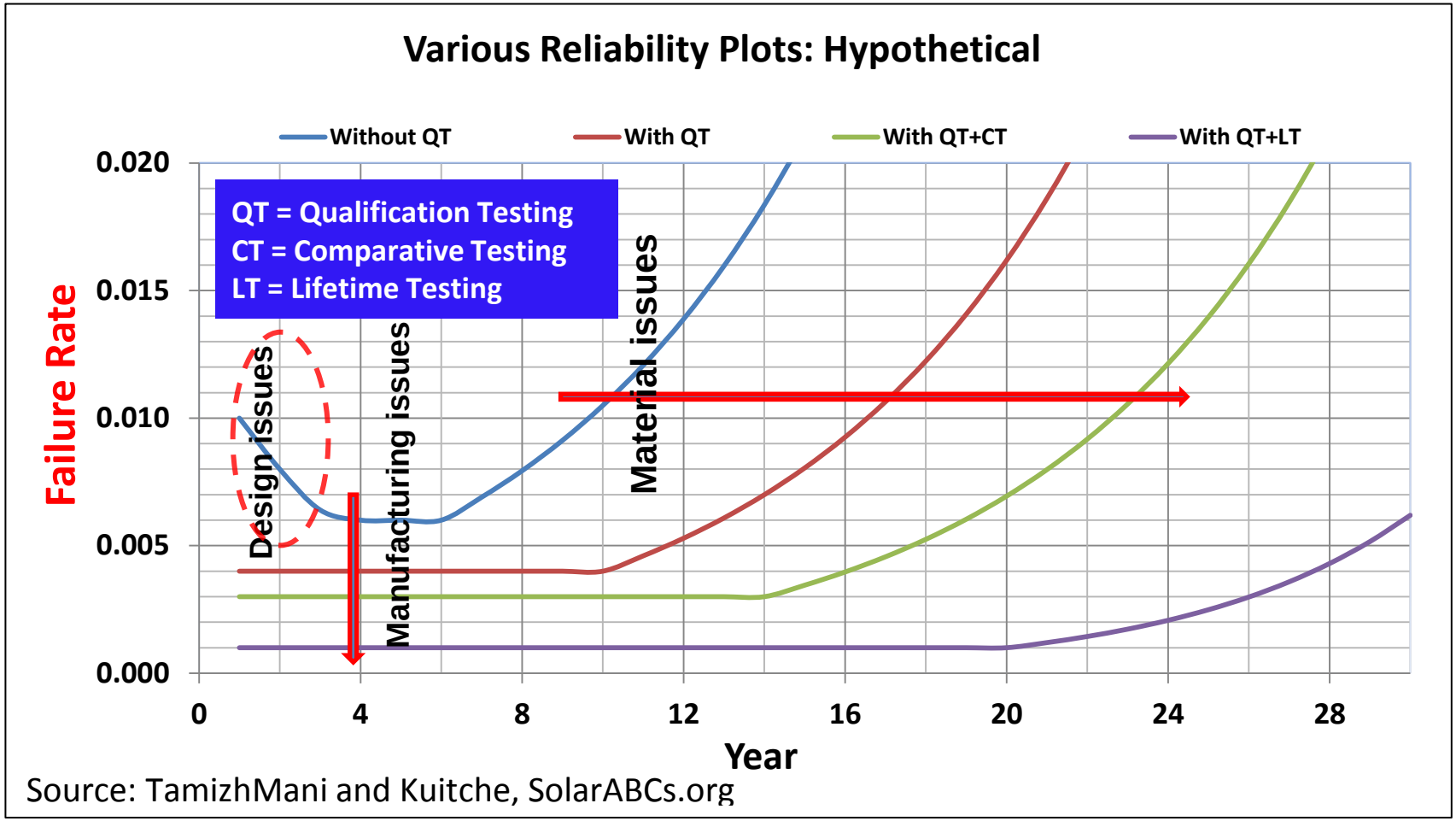
- Differentiate between products that may have long and short lifetimes (later we will look at the bathtub curve)
- Identify and quantify wear-out mechanisms (later we will look at the bathtub curve)
- Address all failure mechanisms in all module designs
- Address failure mechanisms for all climates and system configurations
- Quantify lifetime for different applications or climates.

All the above should be considered as ground rules to avoid distraction from the goal!

Adopted from: IEC 61215: What it is and isn't, J. Wohlgemuth, PVMRW 2012; Accelerated Lifetime Testing, G. Tamizhmani et. al., SolarABCs.org

Qualification Testing: What it is and isn't

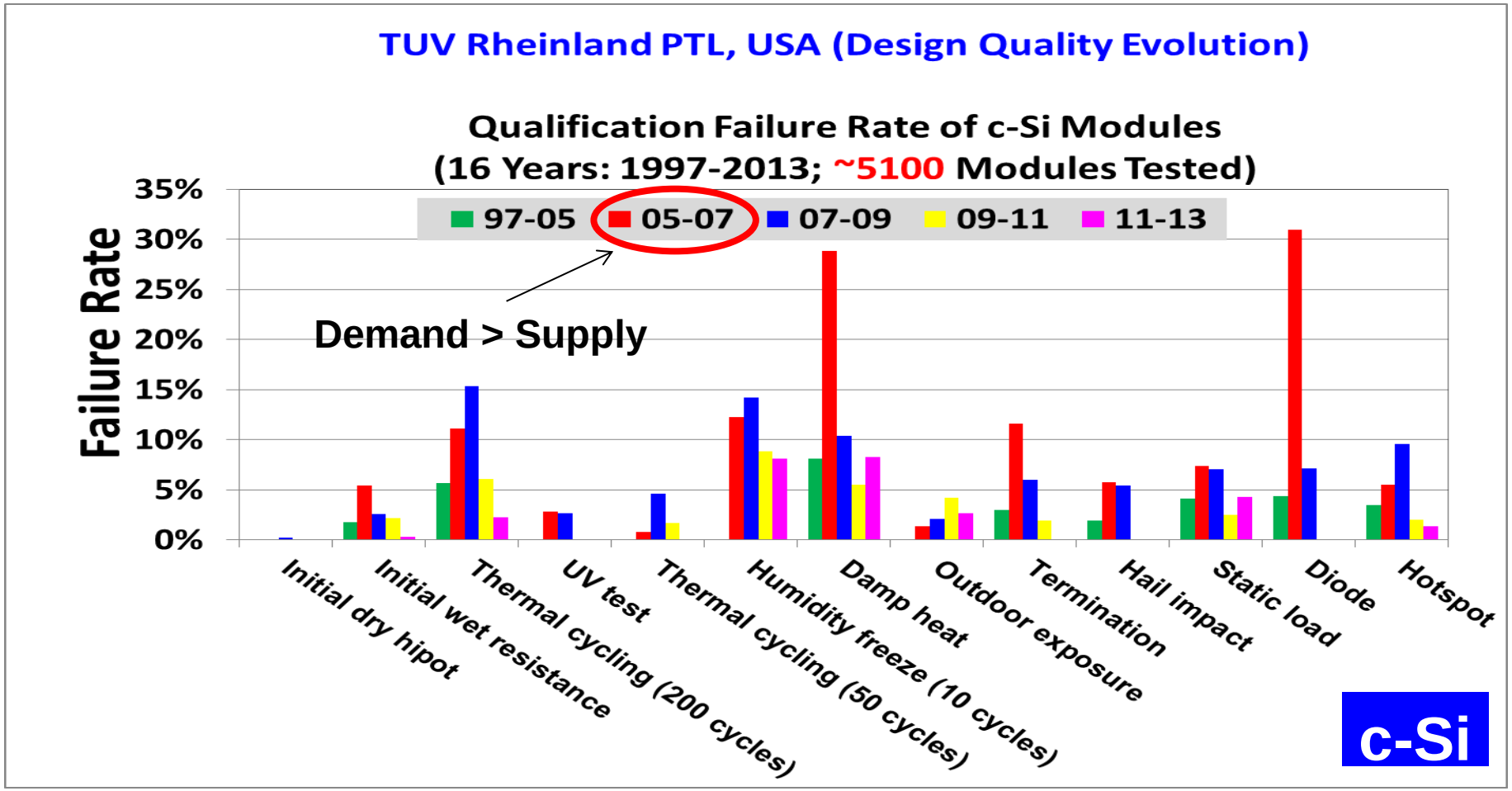
	Qualification	Comparative	Lifetime
Purpose	Minimum design requirement	Comparison of products	Substantiation of warranty
Quantification?	Pass/fail	Relative	Absolute
Mechanisms studied	Infant mortality	Wear out	Wear out
Climate or application	No differentiation	Differentiated	Differentiated



Adopted from: Kurtz and Wohlgemuth, NREL; Accelerated Lifetime Testing, G. Tamizhmani et. al., SolarABCs.org

PV Module Design Quality Evolution: 1997-2013

Demand and supply may influence the design quality!

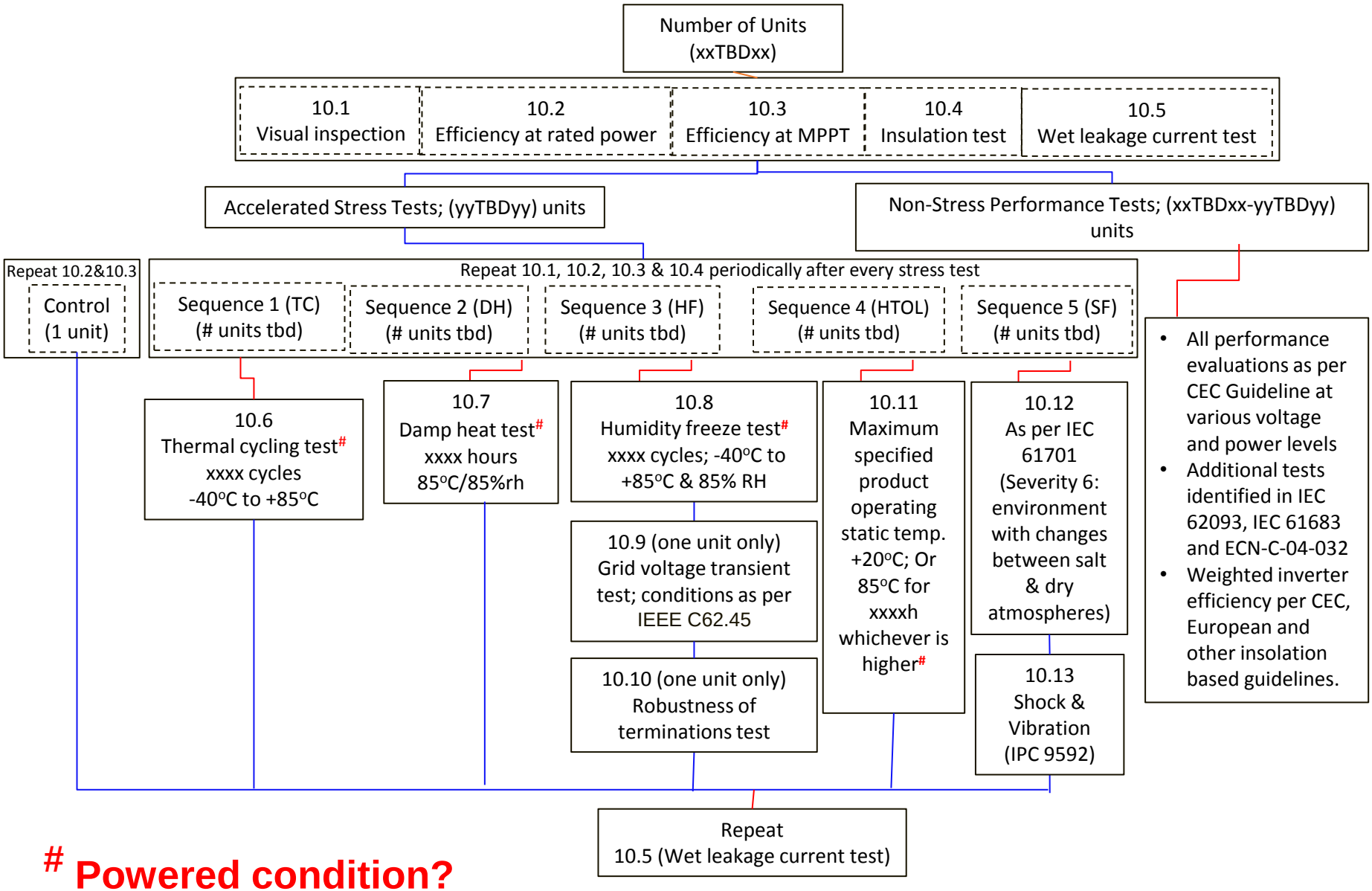


- Overall design quality evolution in the 1997-2013 period: WORST period is 2005-2007
- Design quality in the latest period of 2011-2013: Generally speaking, BEST period!
- Initial wet resistance failure in the 2011-2013 period: Lowest!

We need to monitor the design quality of MLPE over time!

ANSI/TUV-R 71830 Standard (Nov2014-v1)

MLPE Qualification Standard Test Sequence

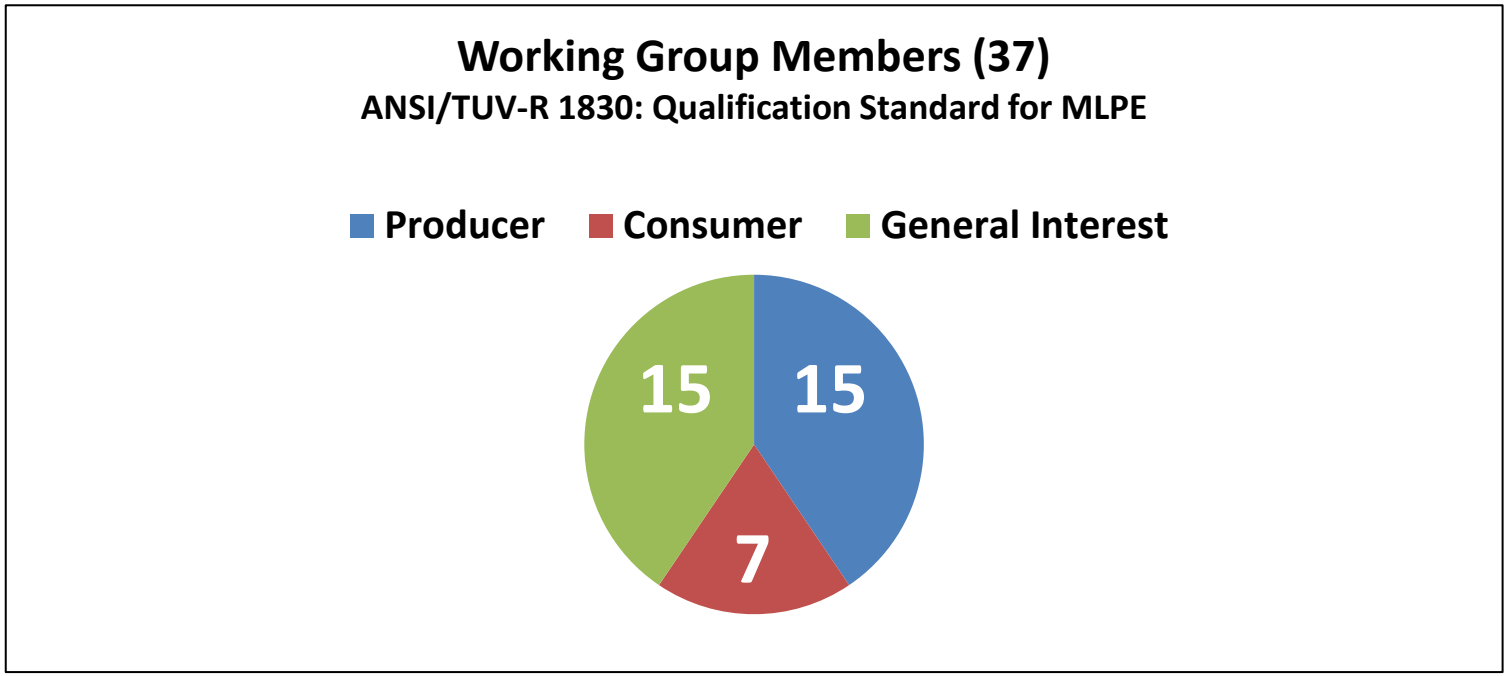


Powered condition?

* Pass/Fail TBD for the sequence and individual stress test: No changes from initial?; Retest when one or more units fail

** Number of units = 1 (IEC62093-ed1); 2 (IEC61215); 3 (UL1741); 5 (Qual PLUS); 8 (IEC62093-draft ed2)

ANSI/TUV-R Standards: Applying for Membership



Applying for Membership

http://education.tuv.com/join-ansi-working-groups/

Or

Contact: Jerome Novacek, JNovacek@tuvptl.com

FMEA Survey

RPN = S * O

S = Severity; **O** = Occurrence

S = how strongly the effects of the failure will affect system

O = probability of a failure mode for a predetermined time period

RPN is a numeric/statistical ranking approach for each failure mode

Survey on the probability of occurrence of a specific failure mode

In a list of major sources for critical failures for MLPE products, please rank each component based on their probability of occurrence: MOSFETs, diodes, electrolytic capacitors, multilayer ceramic capacitors, film capacitors, interconnects, AC and DC disconnects and fuses, GFID device, MOSFET gate circuitry, control and other micro electronic circuitry, solder fatigue, PCB, surge suppression device, auxiliary power supply, inductor and transformers and potting compound.

The top 5 at-risk components as identified by the survey are (as per S*O metric):

Item	Failure	Cause
DC Input-DC Input Connection	Intermittent contact	loose connection
AC Output-AC Connectors	Intermittent contact	loose connection
Power Conversion-Low Voltage DC to High Voltage DC	Open & Short circuit failures of DC Link Capacitor	Wear out of electrolytic capacitor in DC Link
AC Output-Protection against OV due to grid disturbances	short circuit	Varistor failure-short from surge
Power Conversion-Low Voltage DC to High Voltage DC	Open & Short circuit failures of MOSFET/Diode	Device degradation (threshold voltage, leakage current)

The survey also asked respondents to list their top three reliability concerns or environments for the system as a whole.

Top 3 reliability concerns	Number of responses
Temperature cycling	9
Solder joint fatigue	7
Humidity corrosion	2
Component quality	4
Moisture Ingress	2
External Grid events	2
Lightning	1
Poor rack/ module grounding	1
High Wind causing the mounts to fail	1
Communications	1
Effects of Potting compound on magnetics and other components	1

These survey results will need to be taken into account during the standard development

Reliability evaluation of 17-year old AC modules

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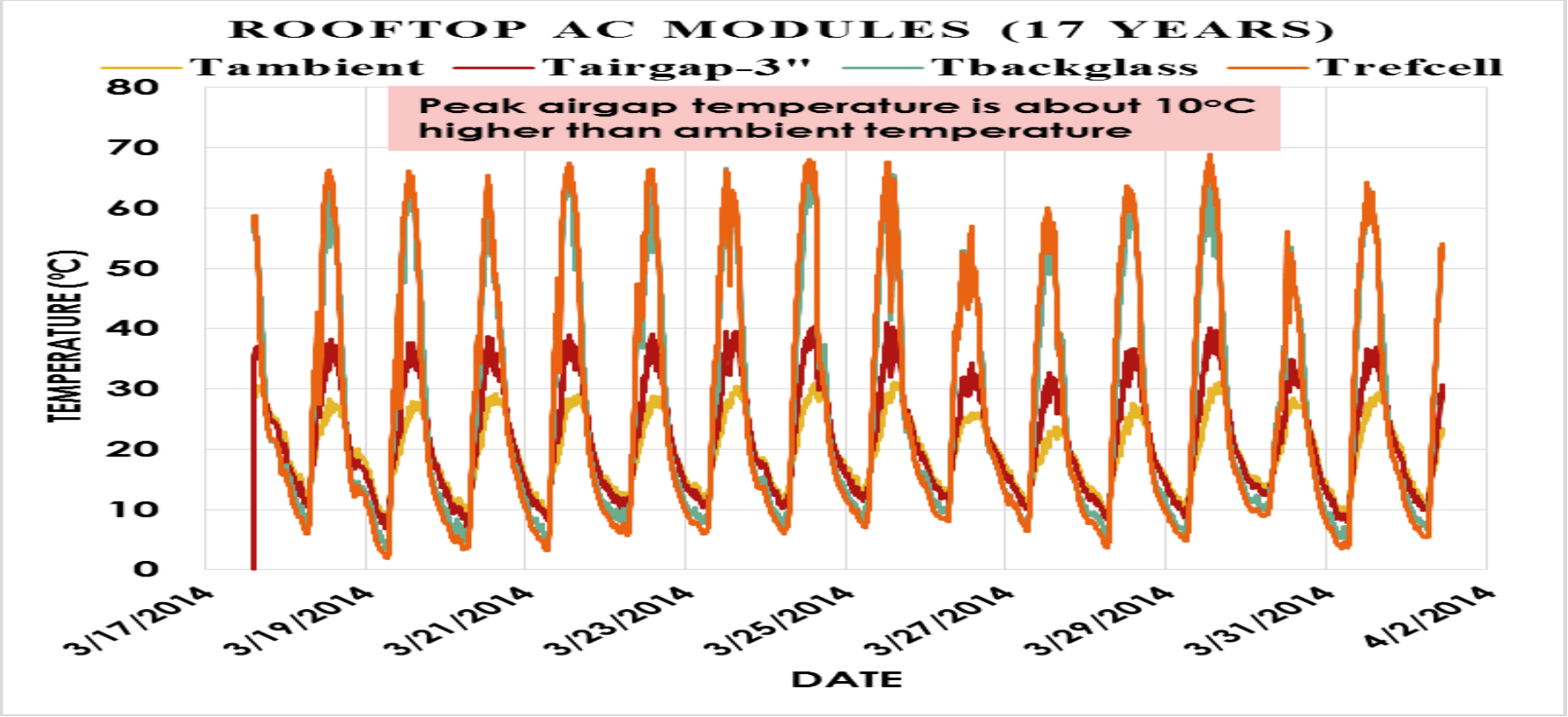
Characteristics of 17-year old AC modules operated in a hot-dry climate

PV Module STC Rating	
Pmax	285 W
Voc	62.8 V
Isc	6.3 A
Vmp	50.3 V
Imp	5.7 A

Ascension Microinverter	Parameter
Rated Voltage	120 V ac
Output Current	0-2.5 A ac
Output Power	0-300 W ac
Maximum ambient temperature	60°C

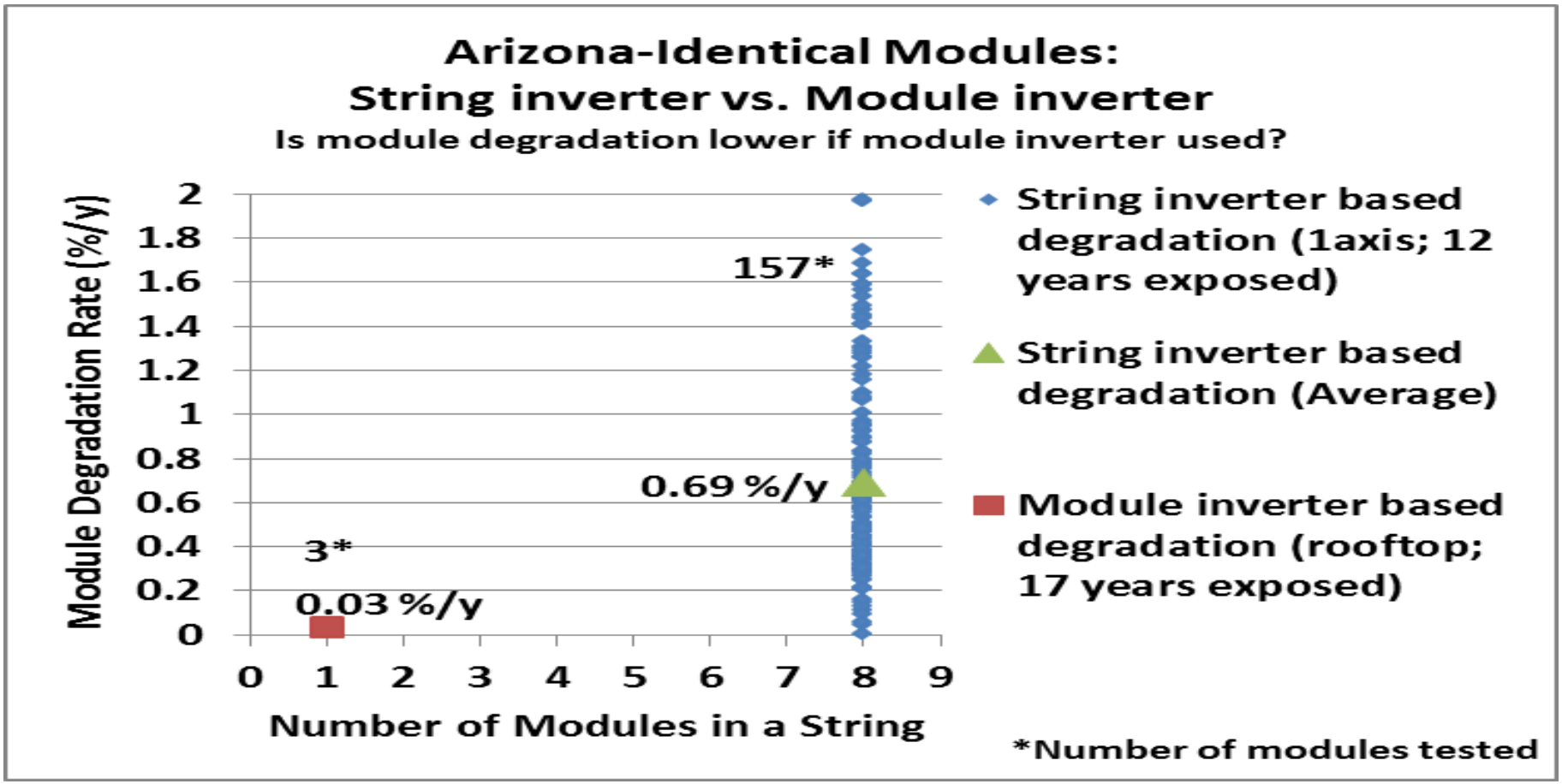
- All four DC modules were determined to be functional
- 2 out of 4 microinverters were determined to be fully functional
- All four DC/AC conversion units were determined to be functional but only 2 out of 4 controller units were determined to be functional

Operating conditions of 17-year old AC modules



- Various temperatures were monitored before removing AC modules from rooftop
- Peak air gap temperature is about 10°C higher than ambient temperature for 3” air gap modules
- Peak air gap temperature will be much higher than 10°C if the air gap is reduced or air flow is restricted (module backsheet temperature as high as 95°C is possible!)
- Record high ambient temperature for this site is 52°C

DC power output of 17-year old AC modules



- Degradation of individual-AC modules is compared with degradation of stringed-DC modules (8 modules per string inverter)
- Identical modules from same manufacturer and identical climatic condition for both systems (Tempe and Chandler, AZ)
- 1 axis system - 12 years of field operation – String inverter – 8 modules in a string – 157 modules in total tested
- Rooftop system - 17 years of field operation – Individual AC Modules – 3 modules in total tested
- Only 3 AC modules have been tested – Statistically insignificant to make any conclusion!

Summary

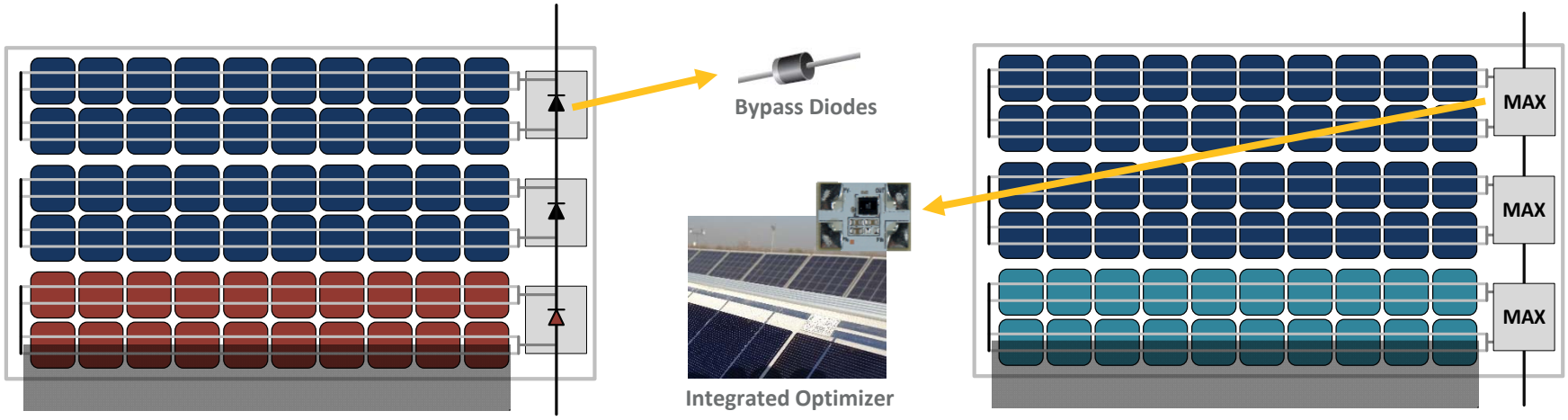
- Development of qualification standard for MLPE
  - Potential tests and test sequences have been identified
  - All major environmental stress may need to be performed under powered conditions
- FMEA survey on MLPE failures
  - Based on the survey results, the identified tests may need to be revised
- Reliability evaluation of 17-year old AC modules
  - Ambient operating conditions for MLPE units identified
  - Current topology is changed but the lessons learned (conversion unit vs. control unit) from the 17-year old AC modules may be useful to develop robust designs

Thanks for your attention!

Reliability Overview for Electronic Systems in Solar Applications

Eric Boskin, Ph.D., Principal MTS, Advanced R&D, Maxim Integrated
Seth Kahn, MSEE, Executive Director, Solar Products, Maxim Integrated
NREL PV Module Reliability Workshop, Golden, CO
February 25, 2015

Maxim Cell-String Optimizer



Conventional Solar Panels

Maxim Enabled Solar Panels

- Single-chip power converter performing MPPT on individual cell-strings
- High level of integration leads to high reliability and low cost
- Cell-string granularity offers concrete benefits scaling from unshaded utility scale arrays to shaded residential systems

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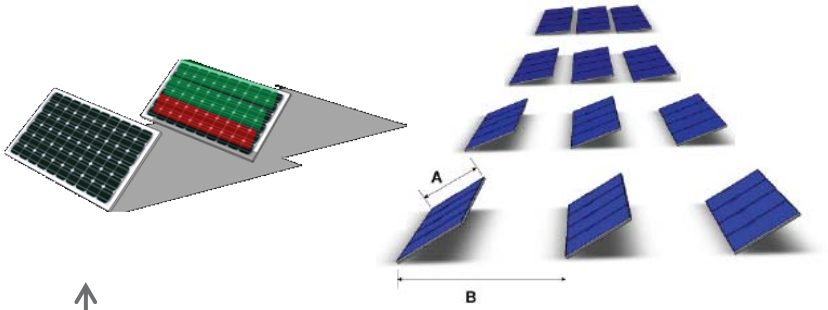
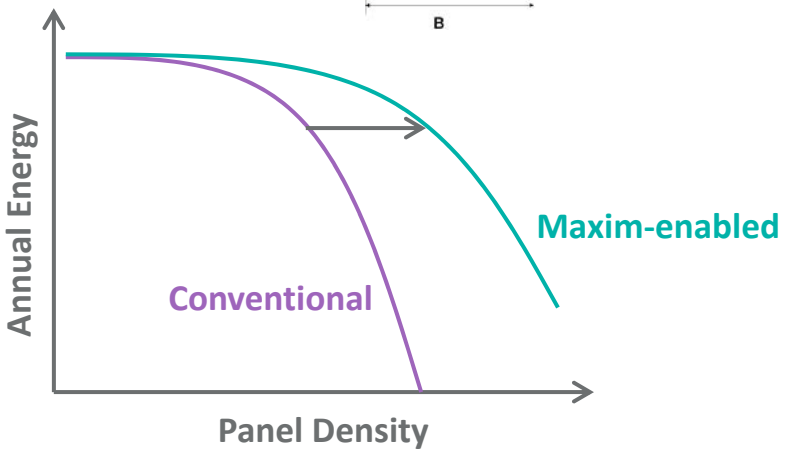
The Benefit is Lower Cost of Energy





- Self-shading is the primary factor to determine # of panels in a system
- Maxim technology provides higher shade tolerance and therefore higher density
- Denser and larger systems can reduce the CAPEX and LCOE up to 20%

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Agenda

- Sleazy marketing pitch (done)
- What do we mean by reliability?
- How do we estimate reliability?
- Example related to electronics in Solar applications

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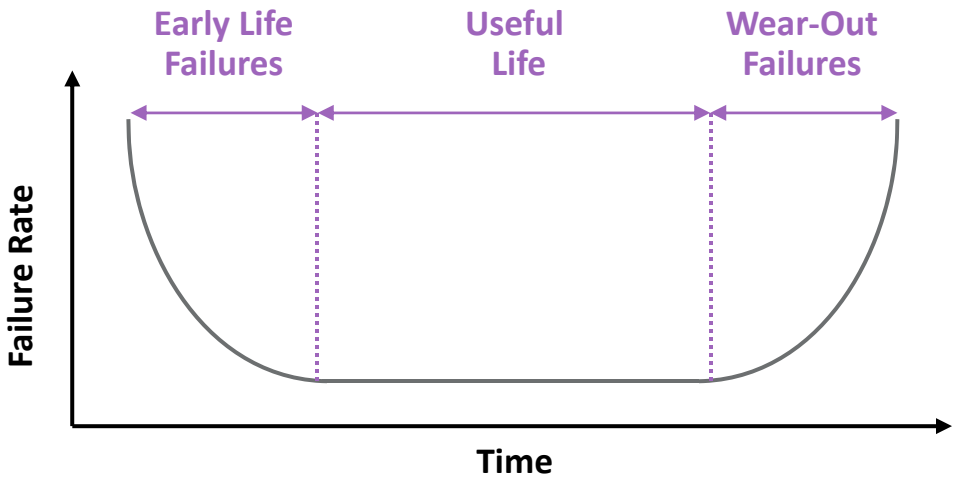
The Bathtub Curve



- Reliability: the probability of a product meeting its performance specifications under normal usage conditions versus time
- The "bathtub curve" plots failure rate versus time; shows three distinct regions
  - > Early life failure region
  - > Useful life region
  - > Wear-out region

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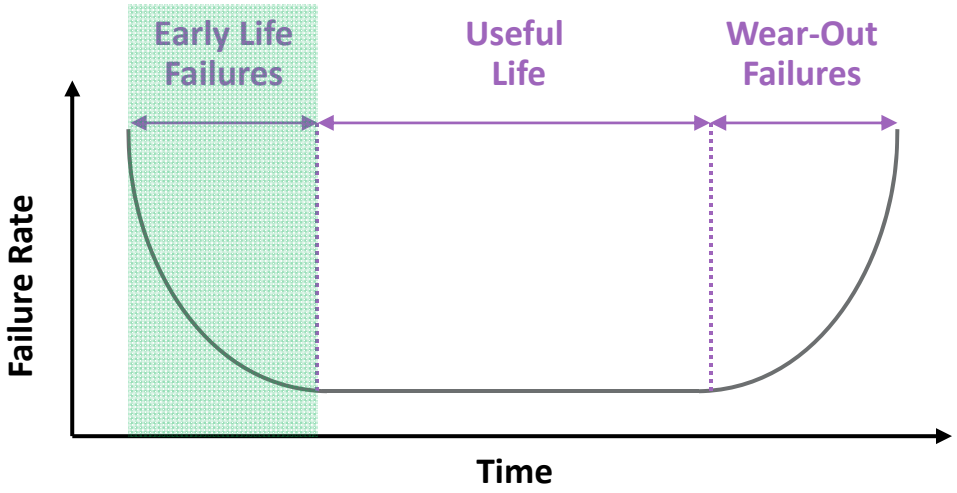
Early Life Region



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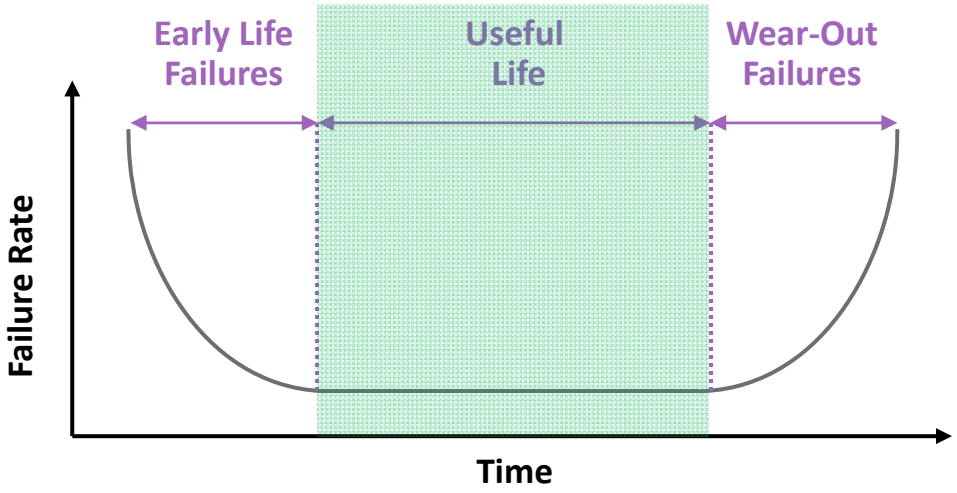
Useful Operating Region



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  - > Wear-out region

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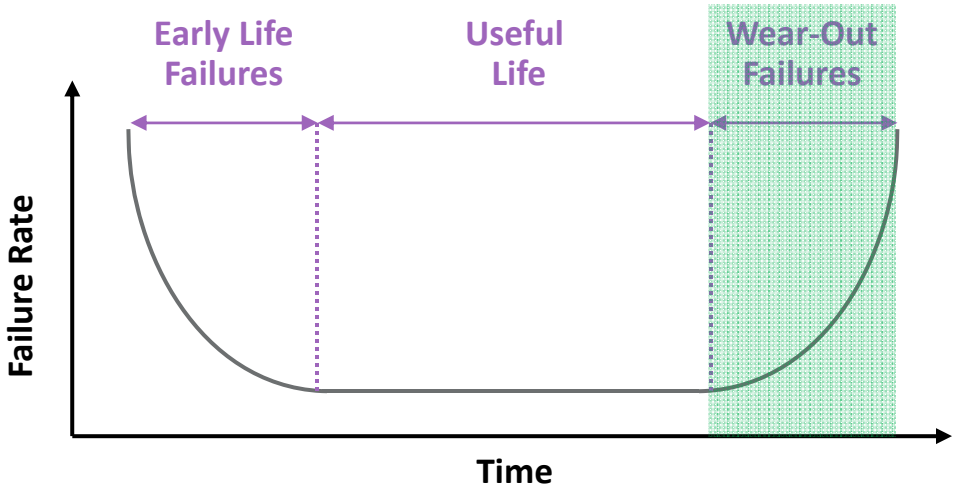
Wear-Out Region



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  - > Wear-out region

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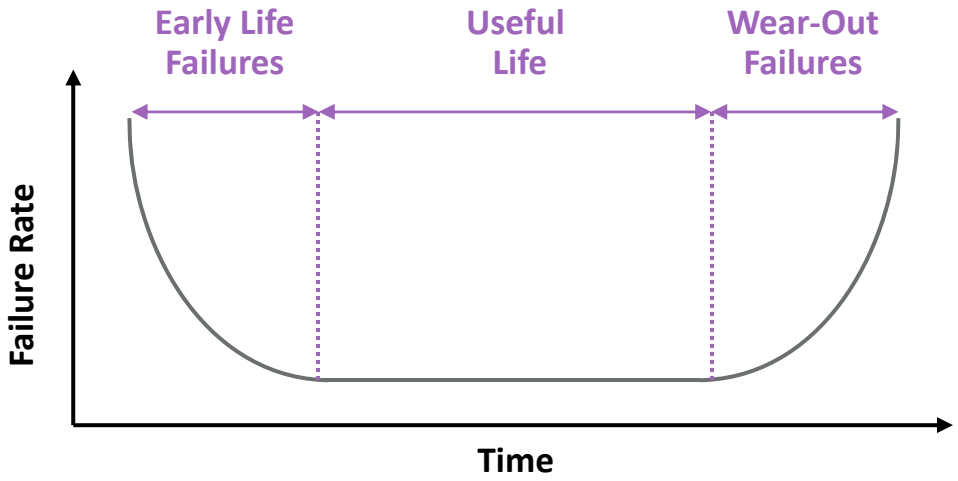
Common Semiconductor Reliability Tests



Early Life

- Electrical Test Coverage
  - Wafer
  - IC
  - PCA
  - PV Panel
- Handling / Assembly
  - X-ray inspection
  - Optical inspection

Useful Life

- Stress Tests
  - Voltage Acceleration
  - Temperature Acceleration

Wear Out

- Stress Tests
  - Temperature Cycling
  - Electromigration
  - TDDB
  - HCI
  - Humidity Bias

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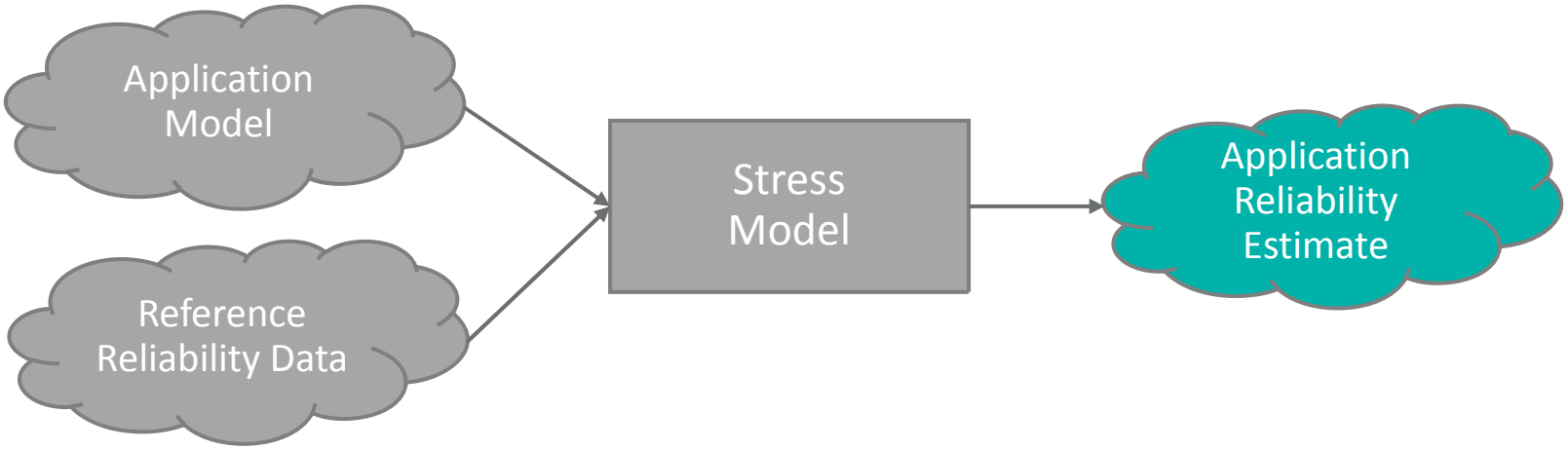
Estimating Useful Life Failure Rate



- We need three basic components to estimate the device FIT rate
  1. A stress model
  2. An application model
  3. Reference reliability data

> Discussion focused on Useful Life FIT but also applies to other regions

> FIT = Failure In Time; # of failures per Billion operating hours

> MTTF = 1 / FIT

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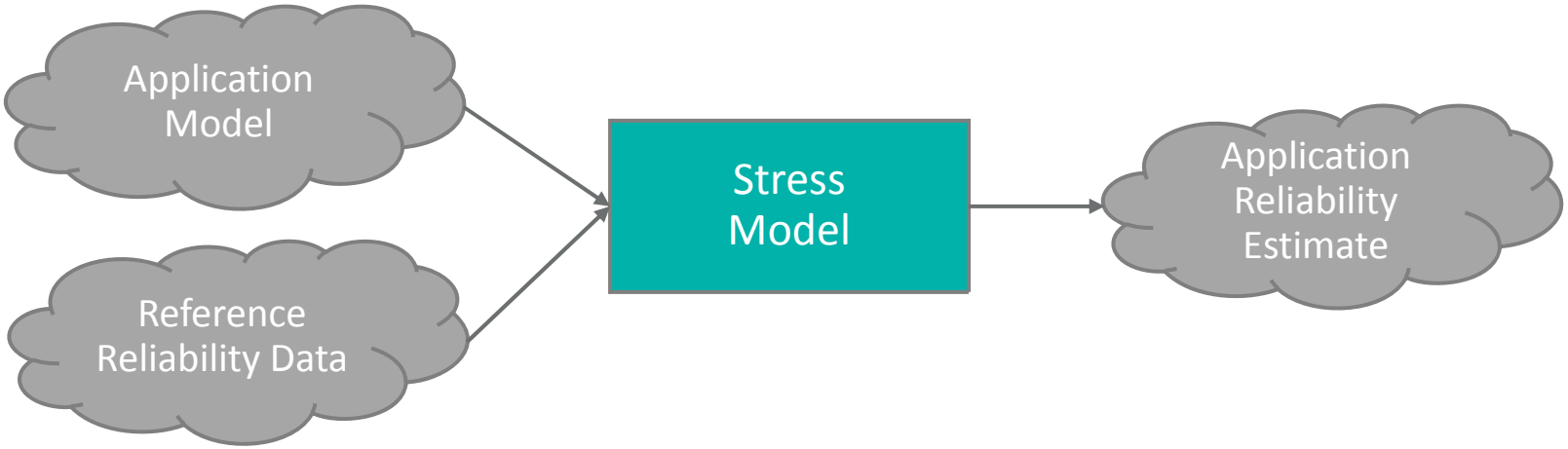
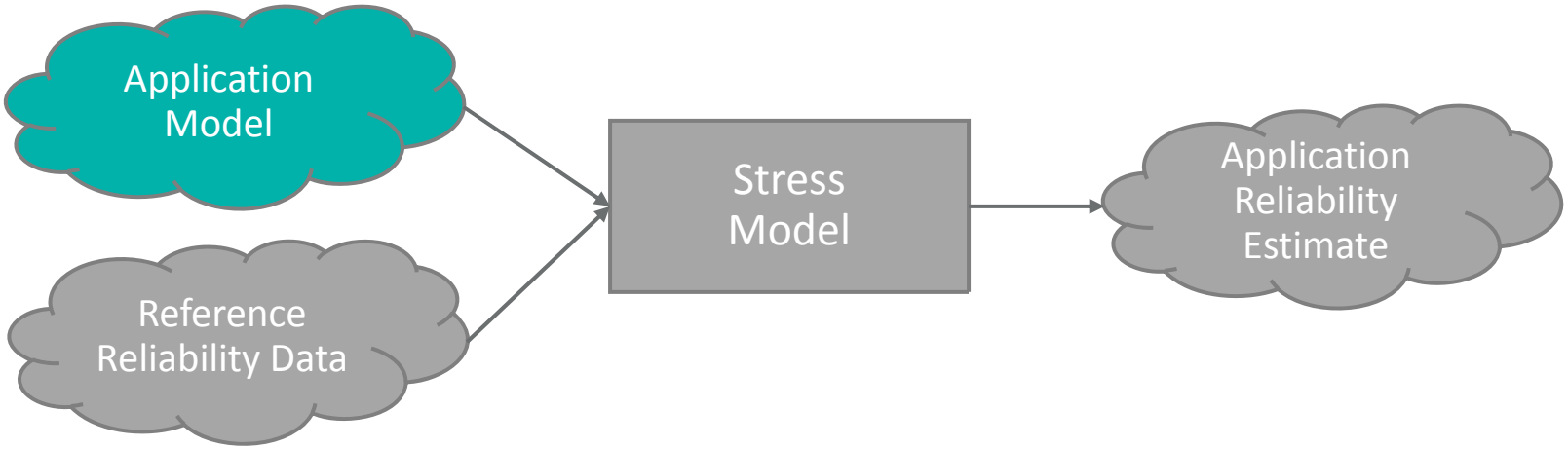
Estimating Useful Life Failure Rate



- We need three basic components to estimate the device FIT rate
  1. A stress model
  2. An application model
  3. Reference reliability data

  > What is the relationship between usage conditions and reliability?
  > Can describe electrical, mechanical, or other physical relationships

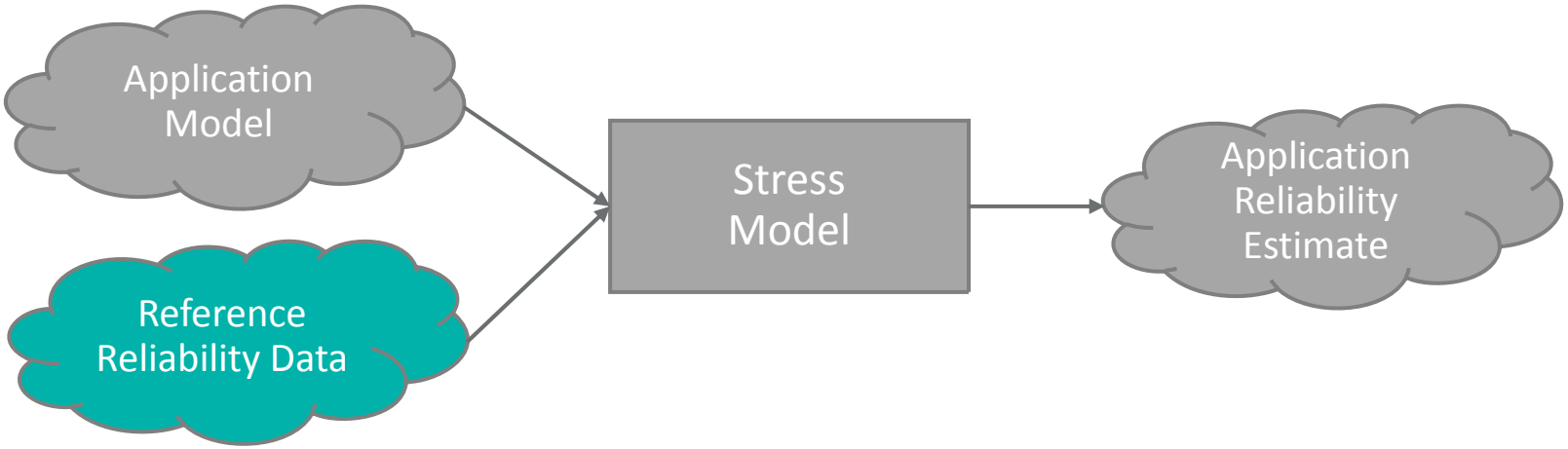
Estimating Useful Life Failure Rate



- We need three basic components to estimate the device FIT rate
  1. A stress model
  2. An application model
  3. Reference reliability data

  > What are the usage conditions in the application?
  > This could be a typical usage model or historical data

Estimating Useful Life Failure Rate



- We need three basic components to estimate the device FIT rate
  1. A stress model
  2. An application model
  3. Reference reliability data

  > Data sourced from product qualification or technology characterization
  > Data sourced from the field (operational data)
  > Data of either type sourced from similar technology / products

Stress Model

- Must identify the stress impact of each parameter and failure mechanism
- Acceleration Factors relate reliability in one condition to another

$$AF = \frac{\lambda_{USE}}{\lambda_{REF}} = e^{\left[\frac{-E_A}{k}\left(\frac{1}{T_{USE}} - \frac{1}{T_{REF}}\right)\right]} \cdot e^{[\alpha(V_{USE} - V_{REF})]}$$

Example for Silicon Devices[1]

$$AF = \frac{\lambda_{USE}}{\lambda_{REF}} = \left[\frac{V_{USE}}{V_{REF}}\right]^{\alpha} \cdot 2^{\left[\frac{T_{USE} - T_{REF}}{10}\right]}$$

Example for MLCC Capacitors[2]

Where λ is the failure rate

- With time varying conditions, a Net Acceleration Factor can be calculated as a time weighted average of individual usage conditions

$$AF = \sum_{t=1}^{T} \frac{AF(t)}{T}$$

1. JEDEC Standard JEP122, Failure Mechanisms and Models for Silicon Devices
2. Multilayer Ceramic Chip Capacitors FIT Data and MTTF/MTBF, http://product.tdk.com/capacitor/mlcc/en/faq/faq00024.html

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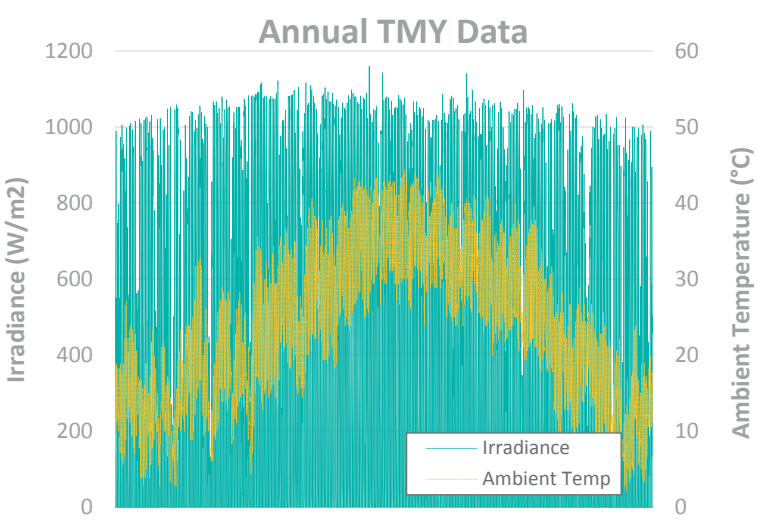
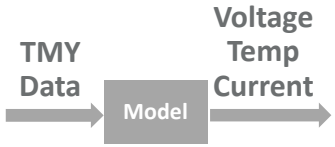
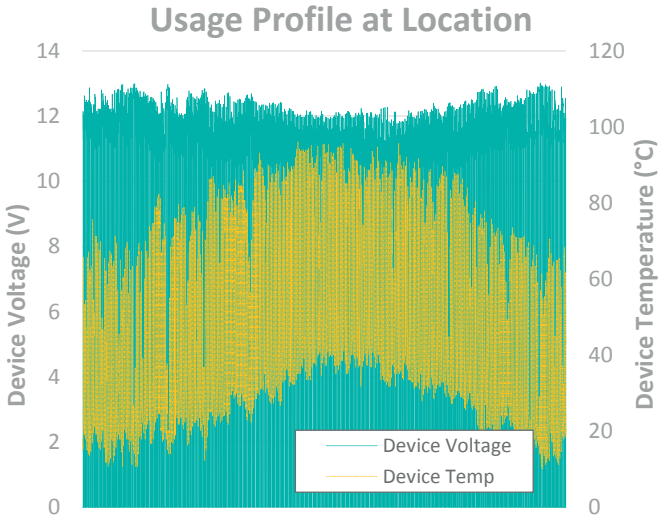
Application Model







- TMY dataset is used to predict long term reliability in Solar applications
- TMY data converted to component voltage, current, and temperature conditions

$$T, V, I = f_{TMY}(T, G)$$

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Reference Reliability Data

- Failure rates can be determined experimentally or operationally[1]

$$\lambda_{CL} = \frac{\chi^{2}{}_{\%CL,2f+2}}{2 * device - hours * AF}$$

$X^2_{\%CL,2f+2}$ is the chi-squared statistic with confidence internal *%CL* and *f* failures

- Typical reliability statistics can then be calculated

$$FIT = \lambda \cdot 10^9 \qquad MTTF = \frac{10^9}{FIT \cdot 24 \cdot 365}$$

- Failure rates for complex electronic systems are calculated by summing the failure rate of each individual components[2]

$$\lambda_{SYSTEM} = \sum_{1}^{N} \lambda_{COMPONENT}$$ for each component N

1. JEDEC Standard JESD74A, Early Life Failure Rate Calculation Procedure for Semiconductor Components
2. JEDEC Standard JESD85, Methods for Calculating Failure Rate in Units of FITs

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Practical Example

- As an example, assume we have the following reference data points
  1. Burn-In: 500 devices at 15V / 125°C for 1k hours with 0 failures
  2. Other Application: 5M devices at 12V / 75°C for 10 years and 8 hr/day with 2 failures

- We can calculate the relative stress between each and the Phoenix solar application

$$AF = \frac{1}{8760} \cdot \sum_{t=1}^{8760} e^{\left[\frac{-E_A}{k}\left(\frac{1}{T_{TMY}} - \frac{1}{T_{REF}}\right)\right]} \cdot e^{[\alpha(V_{TMY} - V_{REF})]} \cdot \left[\frac{V_{TMY}}{V_{REF}}\right]^{\alpha} \cdot 2^{\left[\frac{T_{TMY} - T_{REF}}{10}\right]}$$

  1. Burn-In: 92x more stressful than Phoenix solar application
  2. Other Application: 4.0x more stressful than Phoenix solar application

- Relative to the Phoenix solar application, the references provide the following data:
  1. Burn-In: 46 million device-hours with zero failures
  2. Other Application: 584 billion device-hours with two failures

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Practical Example

- With the data translated to the Phoenix solar application, we can then calculate FIT

$$\text{Chi-Squared Statistic}: \quad \chi^2(90\%\ \text{Confidence}, 2\ \text{failures}) = 10.65$$

$$FIT = \frac{10^9 \cdot \chi^2}{2 \cdot device - hours \cdot AF} = \frac{10^9 \cdot 10.65}{2 \cdot 584.046 x 10^9\ hours \cdot 1} = 0.0091$$

The example data suggests 0.0091 failures per billion device operating hours in Phoenix

- If this sounds unreasonably low, consider the results with respect to a 10MW field:

$$10MW \cdot \frac{1\,panel}{300W} \cdot \frac{3\ devices}{panel} = 100{,}000\ devices$$

$$25\,years \cdot \frac{365\ days}{year} \cdot \frac{24\ hours}{day} = 219{,}000\ hours$$

$$10MW \cdot 25\,years = 219\ \text{billion device-hours}$$

$$219\ \text{billion device-hours} \cdot \frac{0.0091\ \text{failures}}{\text{billion device-hours}}$$

$$1.996\ failures$$

The example data suggests 2 failures in a 10MW field operating 25 years in Phoenix

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Summary

- We have shown how to extend semiconductor industry reliability methods to the Solar application
- An example calculation was used to estimate useful life field failure rates
- Similar techniques can be used to calculate onset of wear-out
- Takeaways:
  - > Semiconductor industry standard accelerated stress models can be directly used in Solar reliability analyses
  - > Solar TMY datasets can be used to estimate long term electromechanical stress to devices deployed in the Solar application
  - > The three components needed for this methodology are reference reliability data, a stress model, and application conditions

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Thank You

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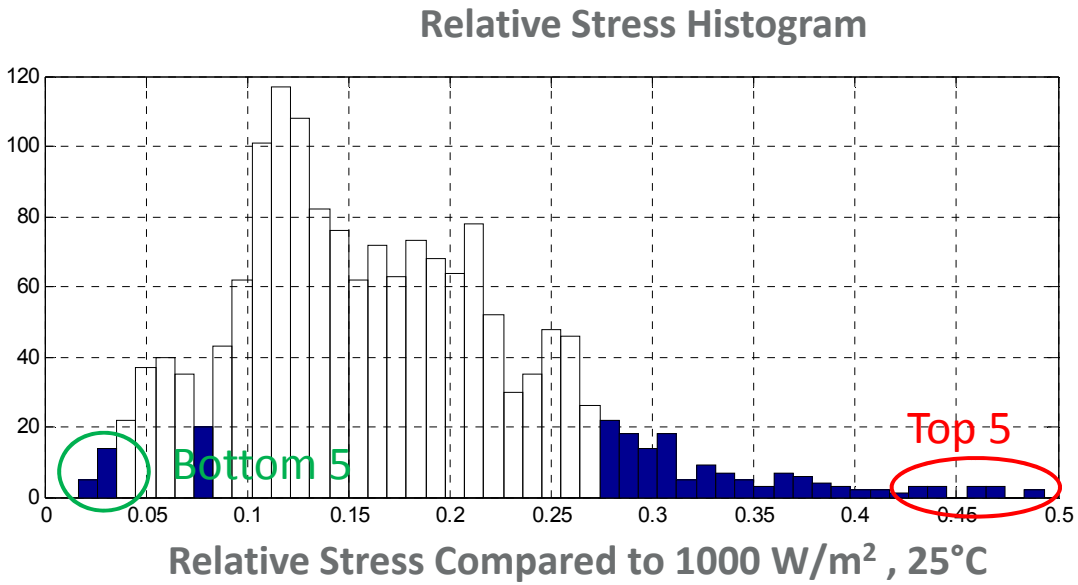
Appendix



Rank	Location	Stress
1	USA TX Abilene Regional Ap [ut] (TMY3).csv	0.493
2	Australia AUS Port_Hedland (INTL).csv	0.492
3	United Arab Emirates ARE Abu_Dhabi (INTL).csv	0.471
4	Egypt EGY Aswan (INTL).csv	0.47
5	USA CA Needles Airport (TMY3).csv	0.467
...		
1615	USA AK Deadhorse (TMY3).csv	0.025
1616	USA AK Shemya Afb (TMY3).csv	0.024
1617	Canada NT Resolute (INTL).csv	0.019
1618	USA AK Barrow (TMY2).csv	0.017
1619	USA AK Barrow W Post-w Rogers Arpt [nsa - A	0.017

- Calculation of relative stress operating at TMY locations compared to reference panel operating on-sun at a constant 1000 W/m² + 25°C
- Interesting Facts
  - > Highest: Abilene TX Regional Airport, 0.493x stressful as reference
  - > Lowest: Barrow Alaska , 0.017x stressful as reference
  - > Range: 29x difference in stress between highest and lowest stress TMY locations
  - > Phoenix is a decent proxy for “worst-case” studies: #9 , 0.443x stress

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Managing Large Microinverter Fleets

Mark Baldassari
Dir, Codes and Standards

enphase ENERGY

Introduction

- **Enphase Energy System**
  - Microinverters
  - Scalability
  - Envoy Communication Gateway
  - Enlighten System Monitoring
- **Script Driven Updates**
- **Updating Systems on Oahu**
- **What can you do with data?**

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Reliability, AGF, and Managing Large Fleets

- **re●li●a●ble**
  - Capable of being relied on; dependable
- **As penetration levels increase, utilities will have to rely upon Advanced Grid Functions to help stabilize the grid**
- **Inverter performance needs to change as functions are added**
- **Reliably managing large inverter fleets is necessary**
  - What does that look like?

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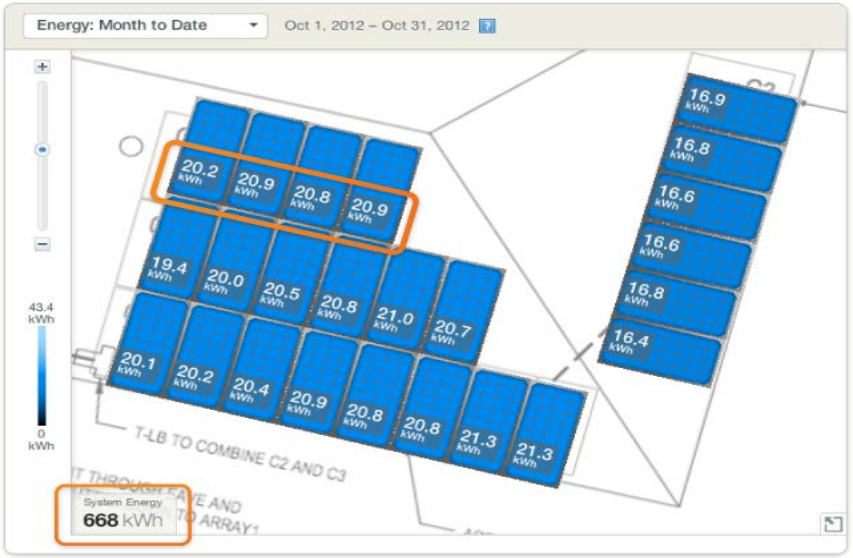
Enphase Energy System

Microinverter Basics

- One microinverter for each PV module
- Software driven architecture
- Powerful communication capability

- Easy to install with Engage Cable

Microinverter Basics



- Enlighten Remote Monitoring System
- Per module visibility
- Full telemetry: AC and DC volts, frequency, power, and temperature

- Scalable from a single unit to multi-megawatt power plants

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Microinverter Basics

- Engage Cable System

- Envoy Communication Gateway

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Cloud Management of Multiple Systems

All Envoys report data to Enlighten via the internet.

Access performance info anywhere, anytime with one easy-to-use interface.

API access to integrate with third party systems.

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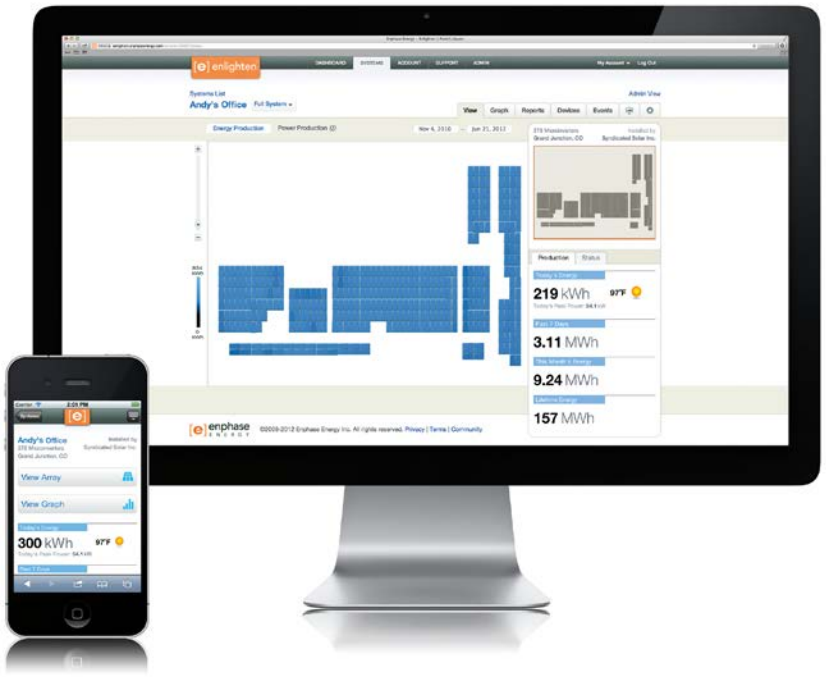
The Right Version for the Right User

Enlighten Manager

Panel uptime & troubleshooting for the **solar professional**



MyEnlighten

Energy performance and education for the **system owner**

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Leadership in Monitoring

- 125,000 systems actively monitored in 54 countries provide continuous feedback
- 800 *Gigabytes* per day!

Let's Look Under the Hood

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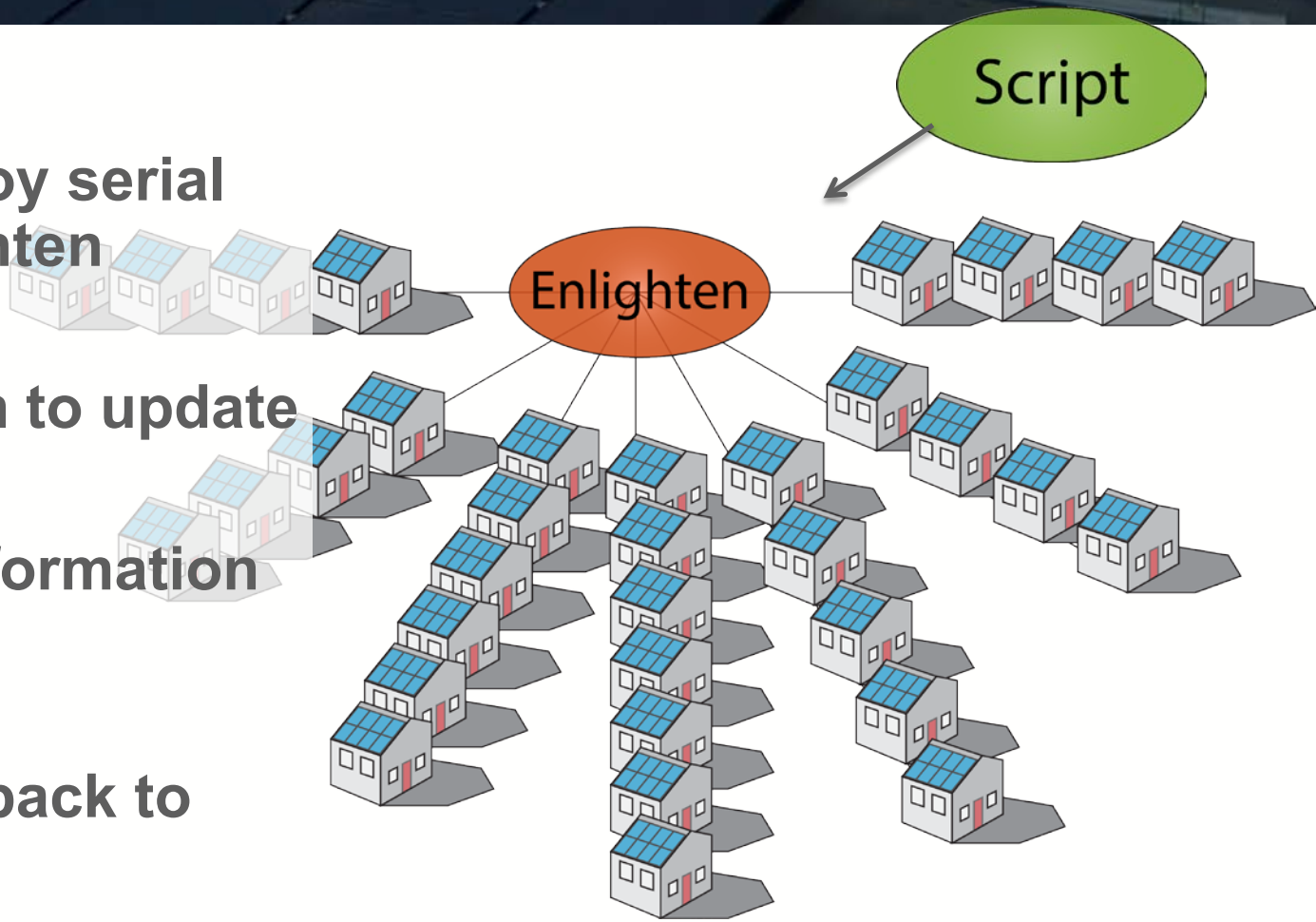
Script Driven Updates

- Identify Sites
- Determine Envoy serial numbers Enlighten updates Envoy
- Script is written to update sites
- Envoy takes information and updates microinverters
- Envoy reports back to Enlighten
- Upgrades are automatic



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Hawaii Islands – Oahu, Maui, Hawaii, Lanai, Molokai

800,000 Microinverters Remotely Retrofitted on Oahu—in One Day

By Peter Fairley
Posted 5 Feb 2015 | 16:00 GMT

Share | Email | Print

IEEE SPECTRUM
Follow on:

Photo: iStockphoto

- 872,000 Microinverters
- > 200 MW
- 34,000 Sites
- Within the first few hours 75% updated
- Sites are continuously updated as they check in

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Accessing the Enlighten Systems API

Systems Endpoints	What is it good for?
Index	A list of systems
Summary	Energy summary for a system (day, week, month, lifetime, status)
Energy_lifetime	Daily energy totals for the lifetime of the system
Monthly_production	Total energy produced on a system in a given month
Stats	5-minute production of microinverters
Rgm_stats	15-minutes production of meters
Inventory	Listing of serial numbers on a system (NO production data)
Envoys	A list of envoys on a given system

- **Energy(J)**
- **AC Volt (V)**
- **AC Freq (Hz)**
- **DC Volt (V)**
- **DC Current (A)**
- **Temp (C)**
- **Power (W)**
- **Energy (Wh)**
- **Events – ACVOOR, ACFOOR, AI, etc**

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What is Next?

- Enphase has strong infrastructure to support big data. This needs to grow as conditions change
- Enphase is developing tools for use by utilities to visualize the massive amounts of data collected
- We are working with utilities to define visualization types and user interface
- Enphase is in its infancy. We plan to learn and grow

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Thank You

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Smart Inverter Grid Support Functions *and* *Potential Impact on Reliability*

Aminul Huque, PhD
Technical Leader

Inverter Reliability Workshop
2015 NREL Photovoltaic Reliability Workshop – Golden, CO
February 25, 2015

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Smart Inverters

WEIL Western Electric Industry Leaders

"There is an immediate need for new solar to be fitted with "smart inverters" to provide necessary voltage support to integrate effectively and prevent costly renovations and reliability impacts"

– *Western Electric Industry Leaders, Aug 2013*

What is a Smart Inverter?

- *Inverter that can modify it's output to better integrate into the grid*

- *Autonomous response to V/F or responding to communicated signal*

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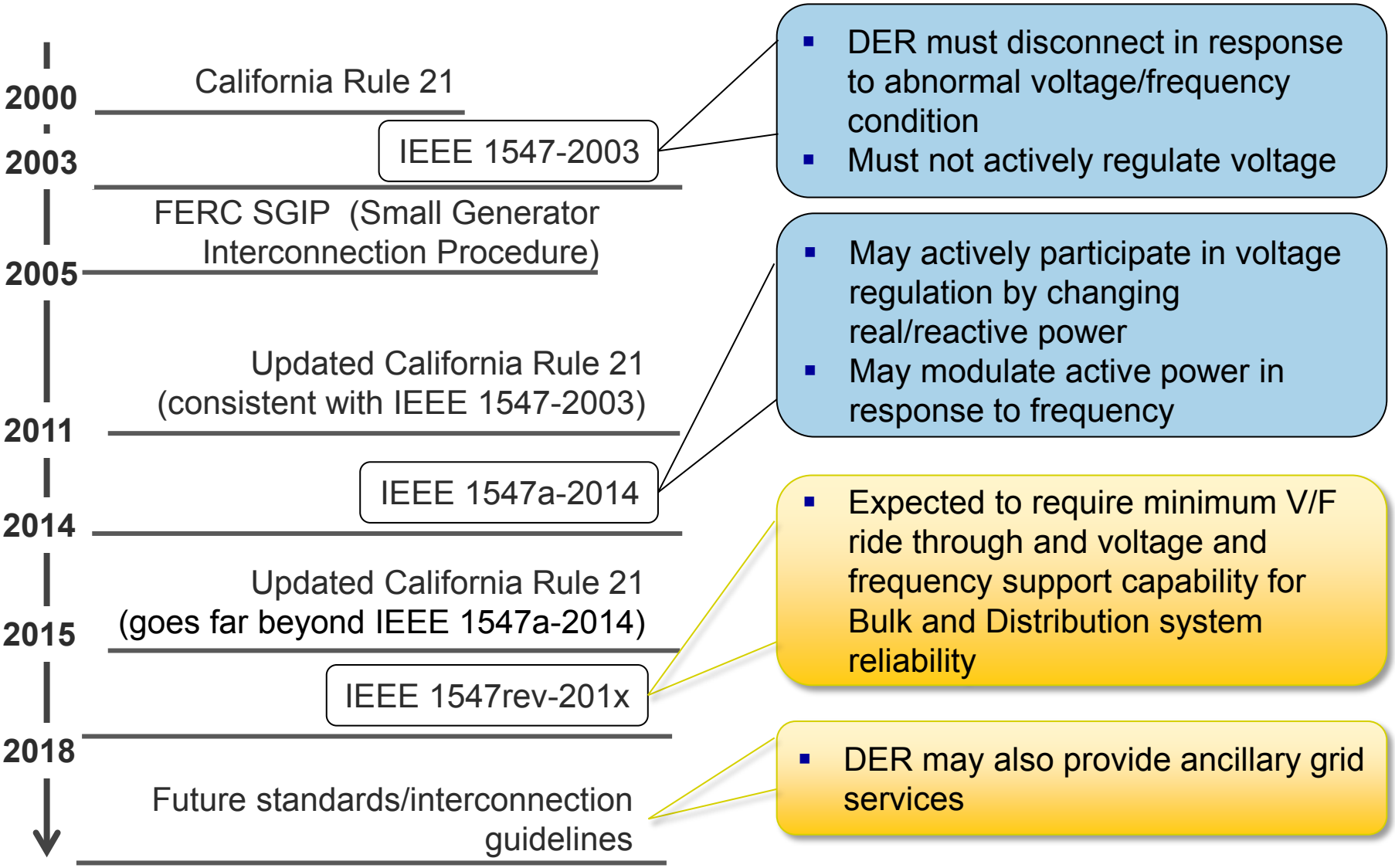
DER Interconnection Standards and Guidelines

IEEE 1547 and others are recognizing the importance of DER providing grid support …



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Smart Inverter Grid Support functions

- Remote ON/OFF
- Power Factor Control
- Volt / var
- Volt / Watt
- Frequency /Watt
- Reactive Power Control
- Low/ High Voltage and Frequency Ride Through
- Power Curtailment

Go to www.epri.com and search **3002002233**

IEC

IEC 61850-90-7

IEC 61850 Object Models for Photovoltaic, Storage, and Other DER inverters

Draft Version 10a

dnp Distributed Network Protocol

DNP Application Note AN2013-001
Version 2013-01-14

DNP3 Profile for Advanced Photovoltaic Generation and Storage

1 Introduction

This document describes a standard data point configuration, set of protocol services and settings – also known as a *profile* – for communicating with photovoltaic (PV) generation and storage systems using

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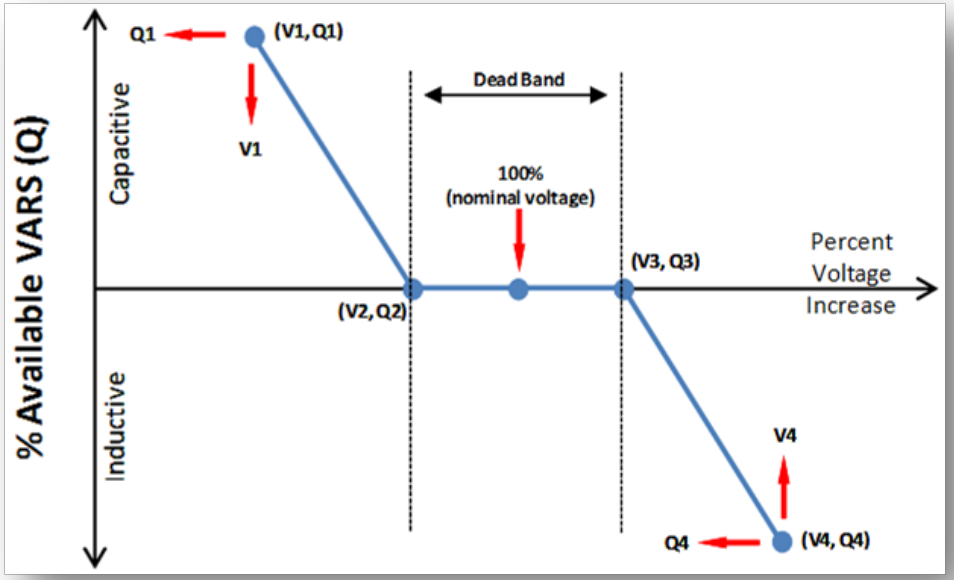
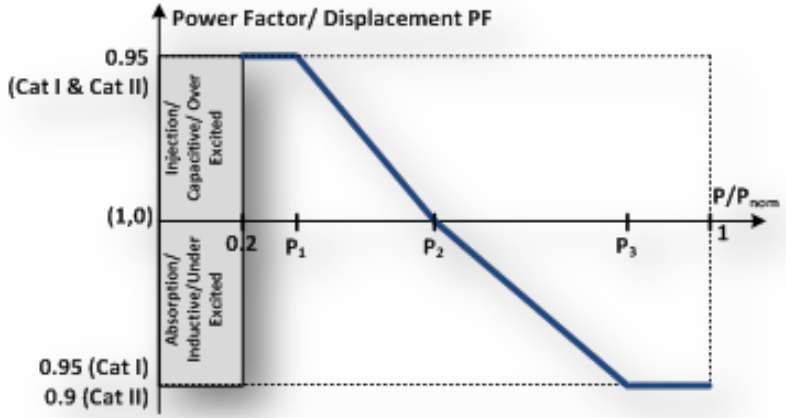
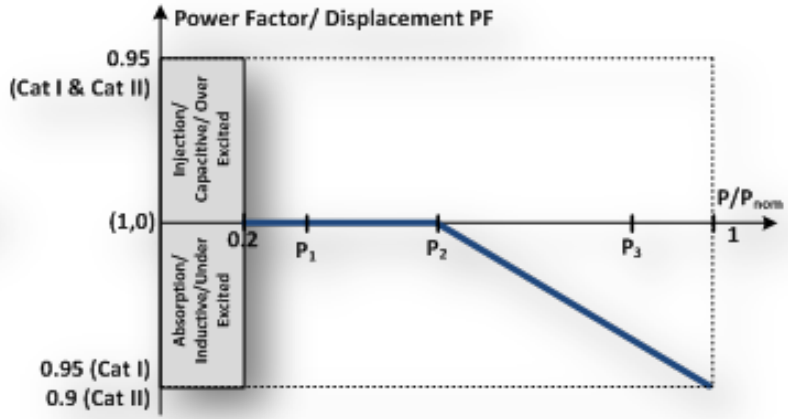
Voltage Regulation by Reactive Power Support

- Power factor mode
- Volt-var mode
- Active power-power factor mode (Volt/Watt)
- Reactive power mode







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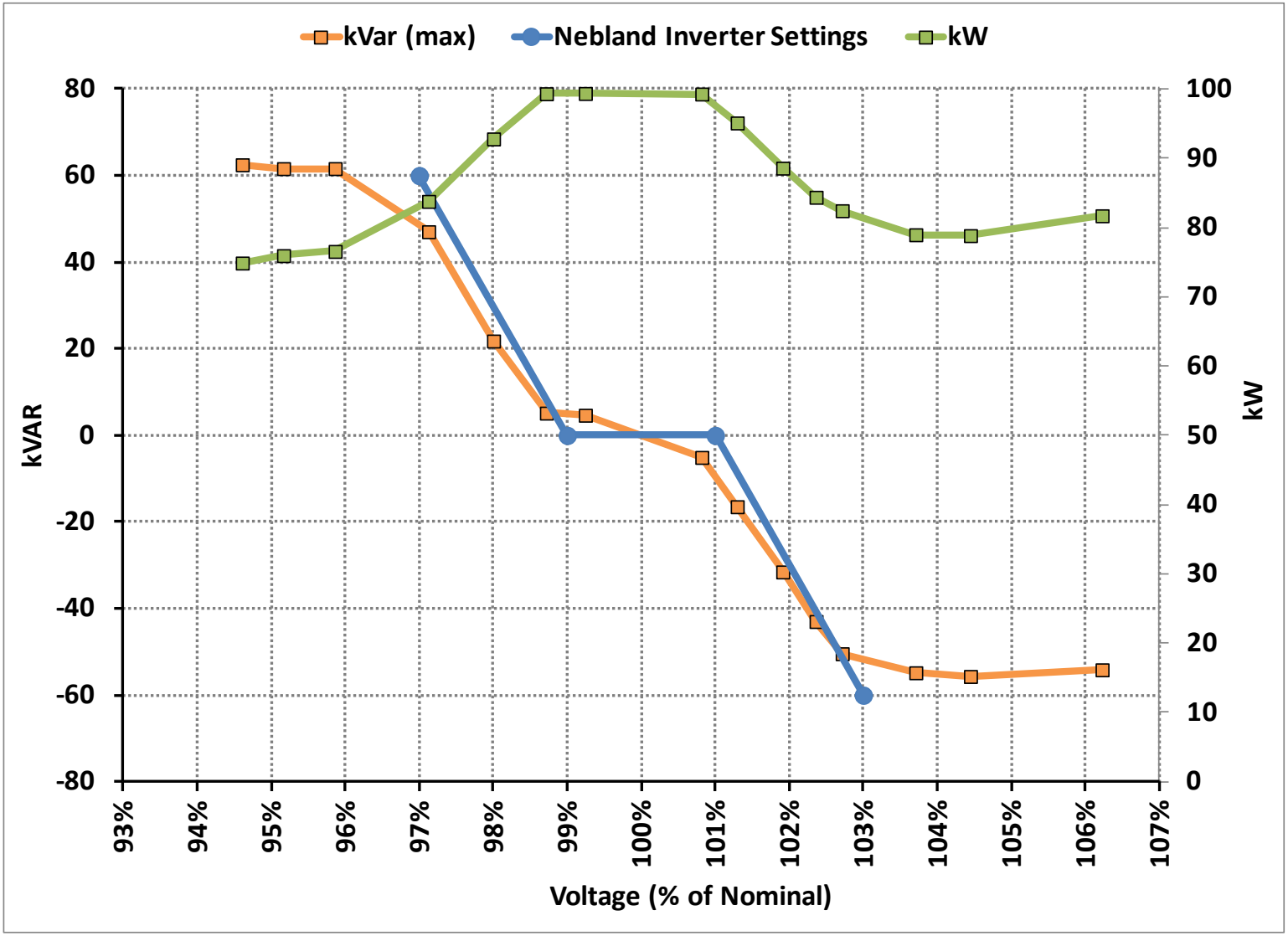
Volt-Var Function

Max Var (vars before watts) Mode; Inverter was operating at rated power



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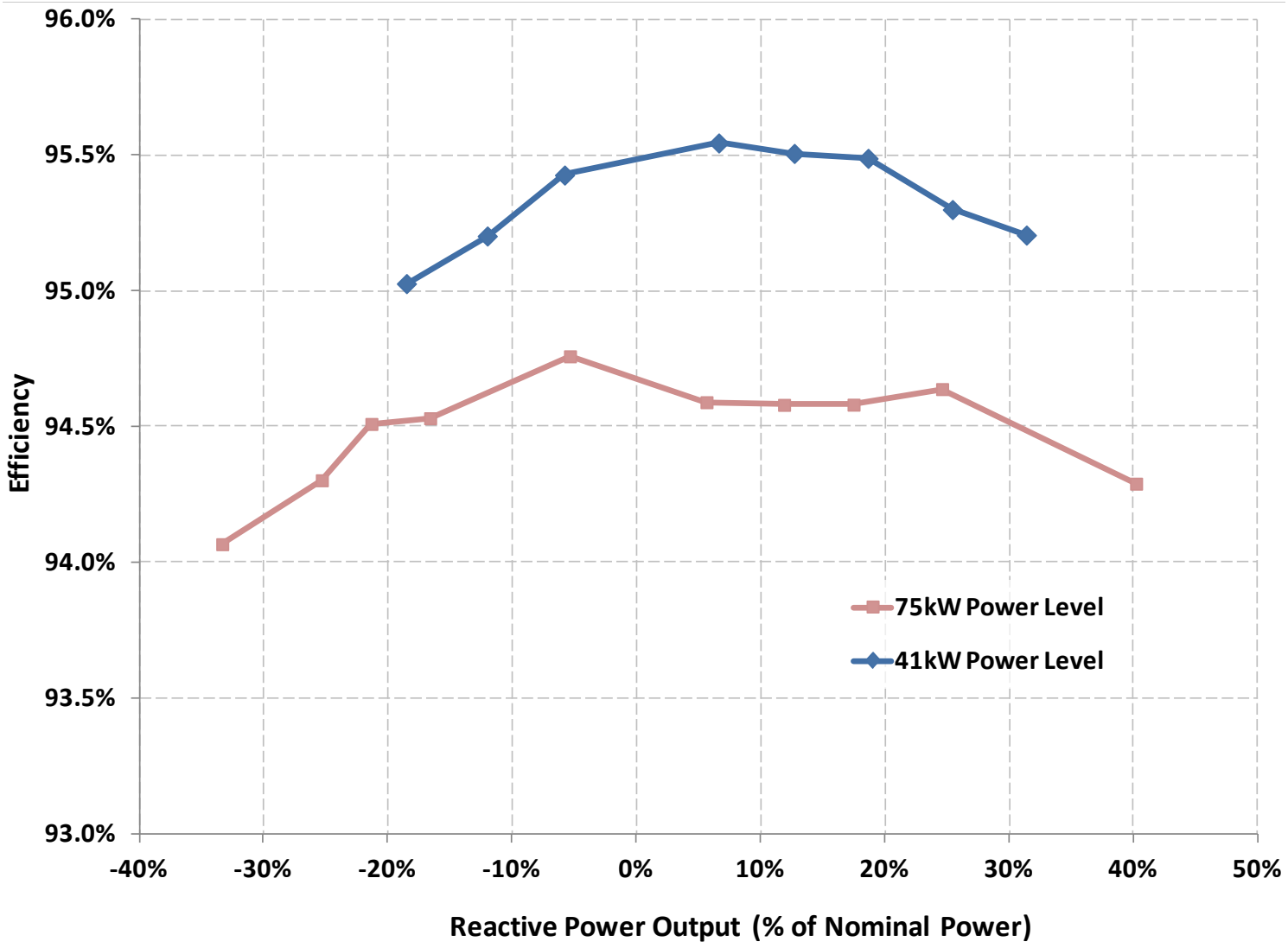
Reactive Power Support – Impact on Efficiency



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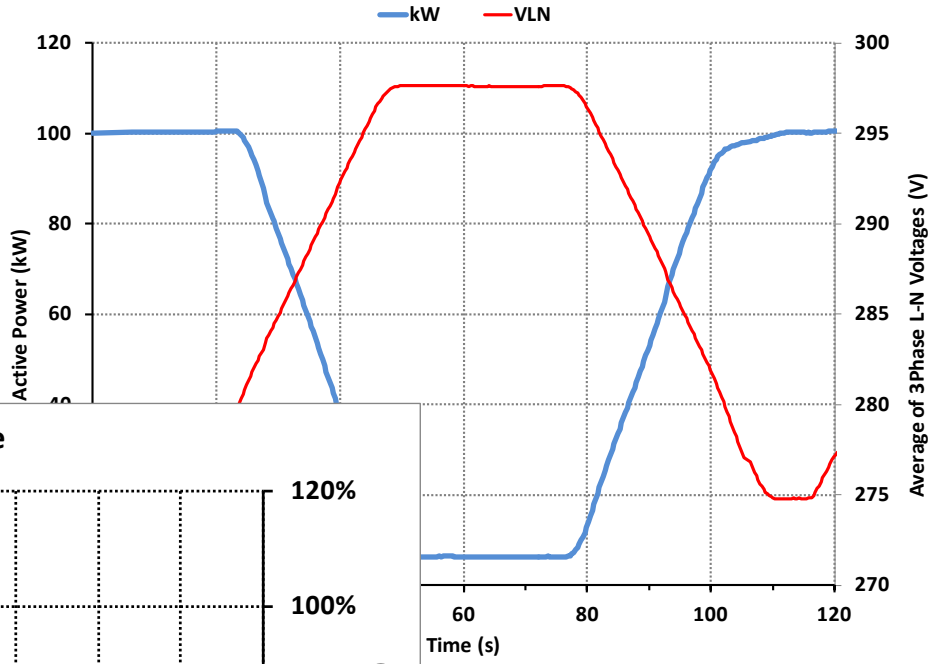
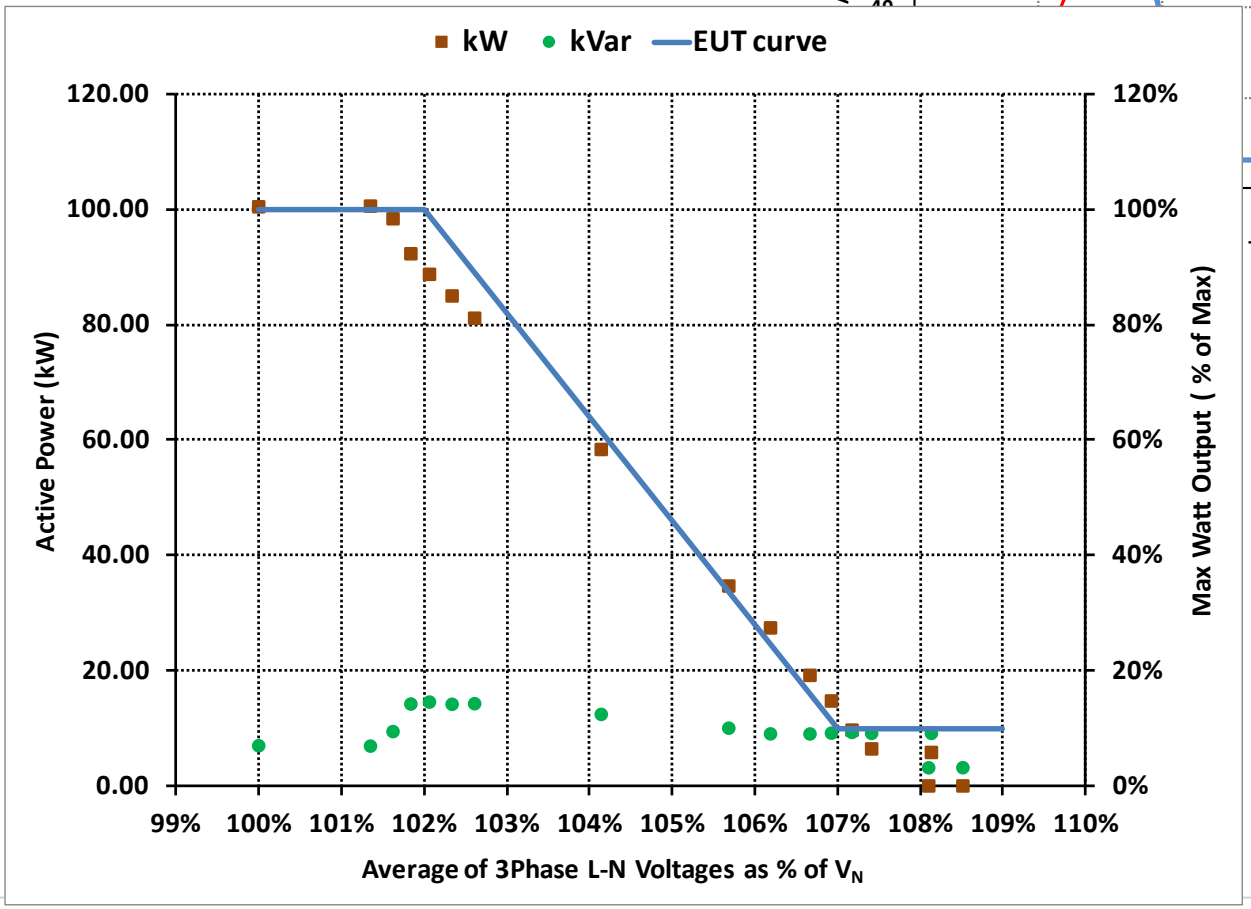
Volt-Watt Function





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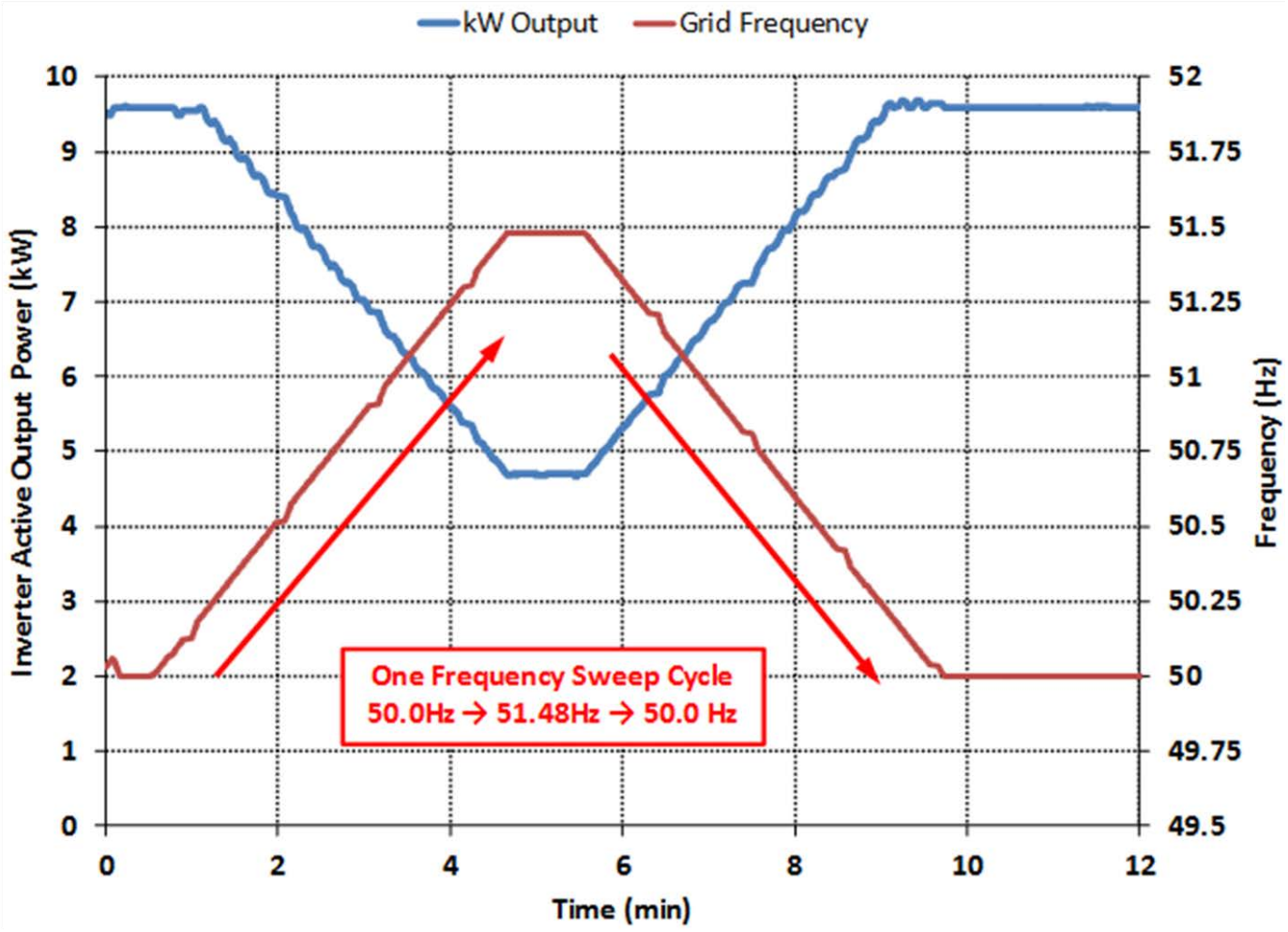
Frequency-Watt Function

Voltage Step: V_N to Target Voltage (up to 108.6% of V_N)



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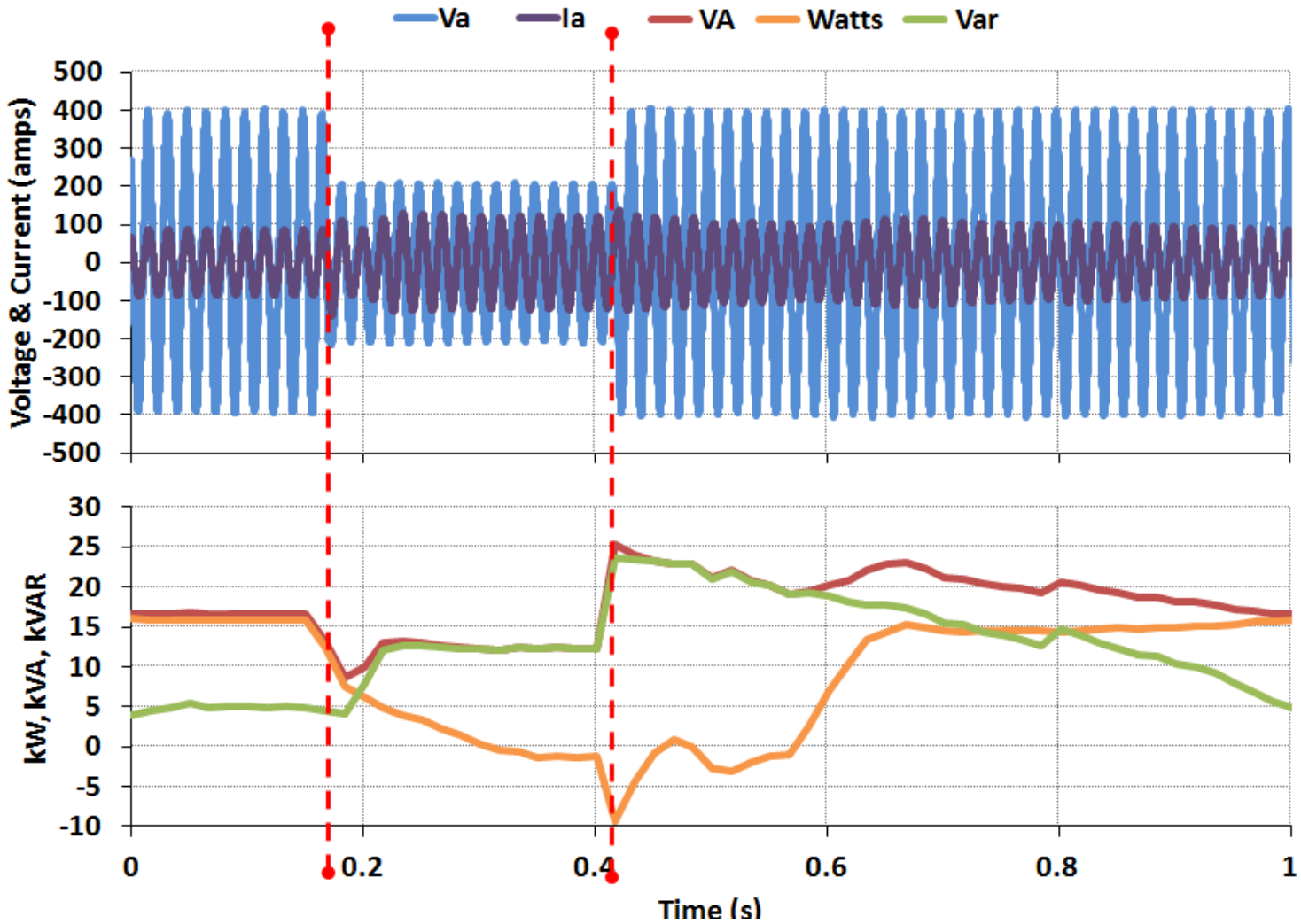
Low Voltage Ride Through



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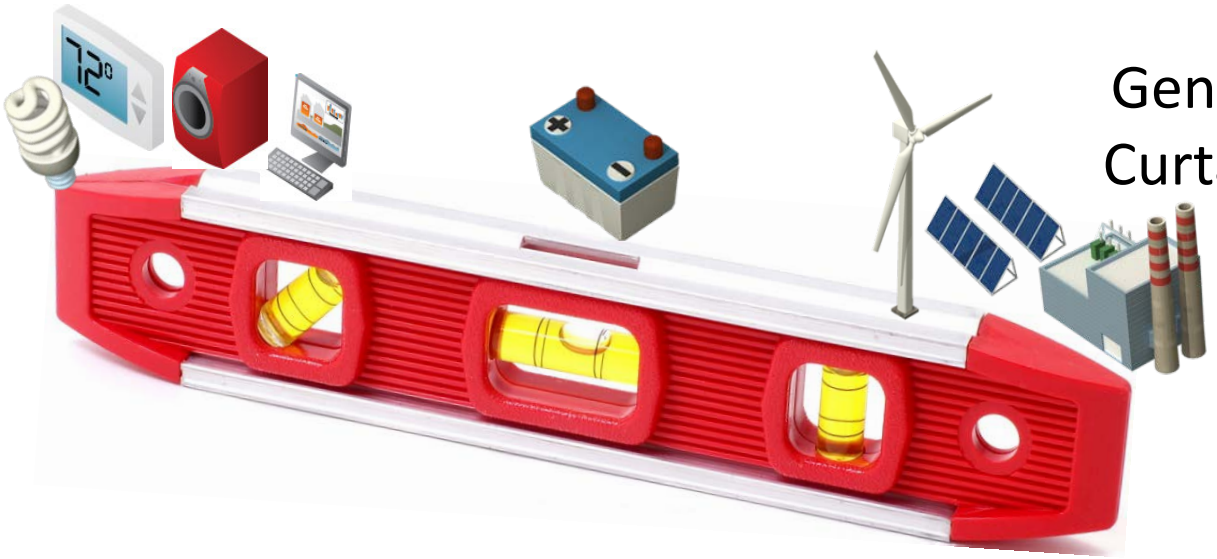
Active Power Limiting/ Curtailment

100% → In 6 seconds → 25% → In 4 seconds → 75%

Demand Response



Generation Curtailment

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Potential Impact on Inverter Reliability

- Reactive power support for voltage regulation – increased loss/ increased operating temperature
- Active participation in voltage regulation through volt-var mode may increase period of inverter operation at higher current magnitude – potential impact on device life span
- Providing reactive power support during night time will significantly increase the operating hours
- Industry practice of higher PV array DC to inverter AC ratio will also require the inverter to operate at higher current level for longer duration

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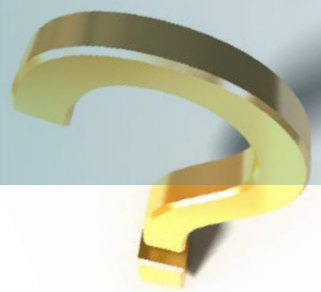
Questions



Contact:
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The Impact of Smart Inverters:

How Rule and Regulation Will Transform DG into Smart Systems

John Berdner

enphase® ENERGY

Presentation Overview

Acknowledgements

Attached to Integrated

Smart Inverter Functions

- Improved grid stability
- Voltage regulation

Monitoring and Distributed Control

- Provides insight into grid below the substation
- Makes DER adaptable

Valuation Methodologies

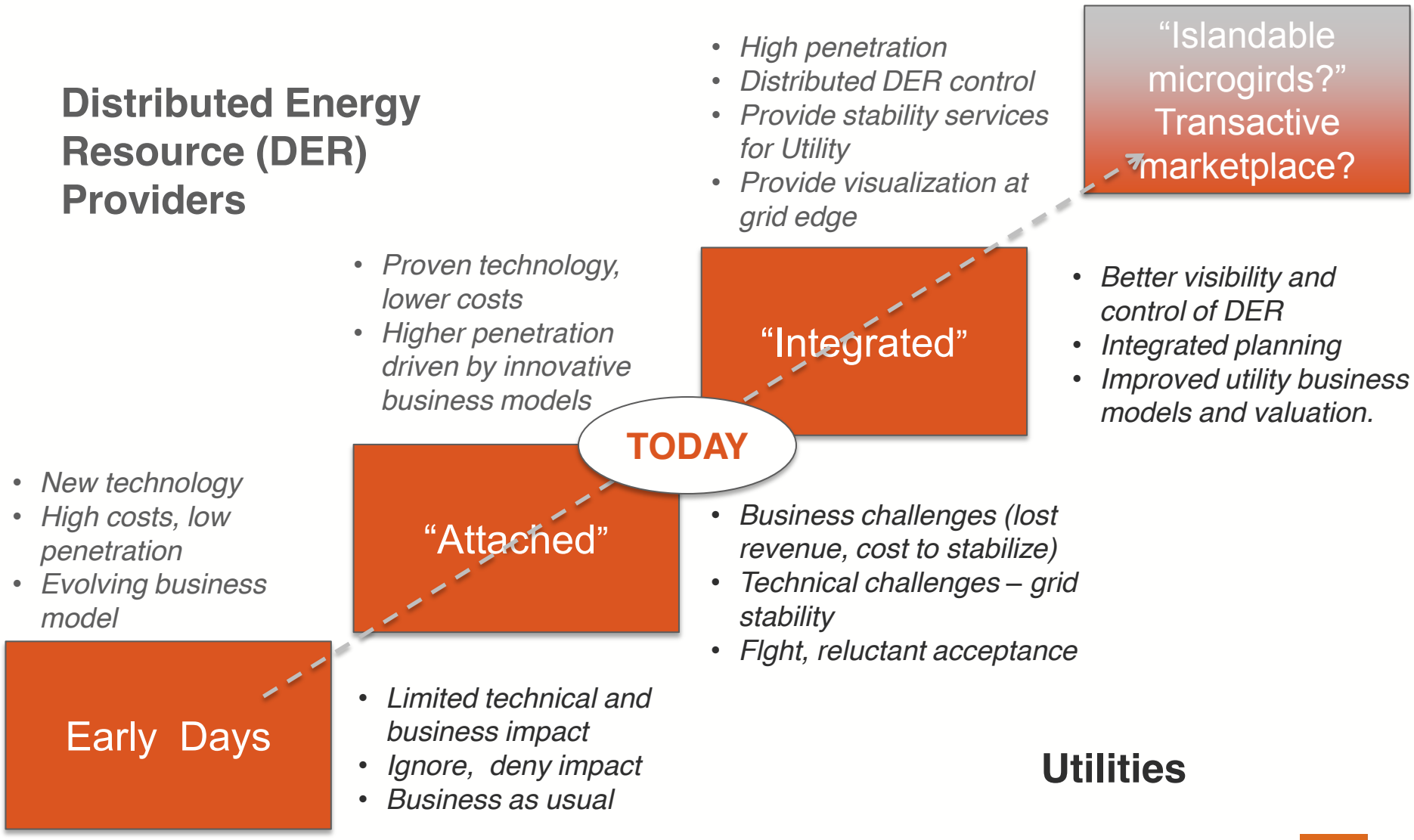
- Below the Substation

Next Steps

Acknowledgments

- This presentation gives an overview of the Status of Advanced inverter functionality and the CA Rule 21 requirements and related UL 1741 / IEEE 1547 requirements under development.
- The summaries provided herein are based on the work done to date by the California Smart Inverter Working Group (SIWG), Sandia, Hawaiian Electric Inc. and the UL 1741 / IEEE 1547 Working Groups for ride through, anti-islanding, and real and reactive power control.
- This work is part of an evolving consensus based activity involving utilities and inverter industry members of the Smart Inverter Working Group and those participating in the UL 1741 / IEEE 1547 revision process. – PLEASE PARTICIPATE!

From Attached to Integrated



The Old Days (2000 - 2003)

- **Grid tied PV systems were rare**
- **General philosophy was:**
  - Produce unity power factor
  - Get out of the way quickly if anything bad happened
  - Tight trip limits
  - No requirements for ride through
- **Relevant Standards**
  - UL 1741, IEEE 1547, 1547.1

Today (2014 - 2016)

- **CA rule 21 approves smart inverter functionality. Phase 1 autonomous behaviors (Dec 2015)**
  - Voltage and frequency ride through
  - Real and reactive power control
  - Return to service behaviors / ramp rate control
- **Hawaiian Electric Inc. implements mandatory ride through requirements (Jan 2015)**
- **CA rule 21 Phase 2 in development. Bi-directional communication standards for inverters (TBD)**
- **Relevant Standards**
  - UL 1741 IEEE 1547, 1547.a,1547.1
  - IEC 61850, IEEE 2030.5
  - UL 1998 (firmware certification)

New Regulatory Concepts (in the US)

- **Voltage and frequency ride through**
  - ***Must not trip*** requirements during abnormal excursions
- **Real and reactive power control**
  - Provides frequency stability and voltage regulation
- **Operating regions with differing behaviors**
  - Multiple areas are bounded by pair points of Voltage/time or frequency/time
- **Cease to energize (momentary cessation)**
  - A mode where the DER must cease to energize the area EPS but ***must not trip***.
- **Return to service**
  - The criteria and behaviors required as the DER re-energizes the area EPS following an excursion

CA Rule 21 - Status

- **The CPUC issued a final ruling on Phase 1 requirements on 18 December, 2014.**
  - The three IOU's filed tariffs with the PUC in January 2015
- **Revised Rule 21 Phase 1 is now in effect**
  - Permissive upon publication of Supplement A in UL 1741.
  - Becoming mandatory upon the latter of: 31 Dec 2015 or; 12 months after the publication of Supplement A in UL 1741
- **Phase 2 discussions on communications are underway**
  - Ability to update and verify settings of DER remotely
  - Initially envisioned as periodic set it and forget it (autonomous operation)
  - Near real time control envisioned for larger systems

CA Rule 21 – Status (cont)

- **Phase 2 is moving toward consensus on data Models and Protocols**
  - IEC 61850 data model
  - SEP 2, IEEE 2030.5 protocol
- **Still debating which entities/devices communicate with each other**
  - Direct utility communications of DER units seems unlikely except for very large DER units
  - Direct utility communications to facilities level for large plants
  - Indirect communication to distributed DER through an abstraction layer seems like best model
    - Utilities, ISO's, Muni's, Co-ops
    - Manufacturers, System integrators, third party aggregators

Communications Example – Hawaii Settings

- **On Oahu PV Generation is approximately 250 MW on a 1200 MW grid.**
  - In aggregate, PV is single largest generation unit.
- **Hawaiian Electric (HECO) experienced two frequency events in last 18 months on Oahu**
- **Modeling suggested changes were needed to voltage and frequency ride through**
  - HECO worked with inverter industry to develop a two stage implementation plan
  - Interim settings based on existing UL certifications
  - Phase 2 settings required new certifications
- **At and of 2014 Enphase completed remote updates to ~ 800k inverters over two day period**

HEI's Phase 2 Settings

Full Ride Through Settings for O`ahu, Maui, and Hawai`i

January, 2015

Frequency Ride Through

Operating Region	Range (Hz)	Operating Mode	Duration (s)		Return To Service - Trip	
			Ride Through	Trip	Criteria (f, Hz)	Time Delay (s)
OFR2	f > 64.0	Cease to Energize	None	0.1667	60.1 ≥ f ≥ 59.9	300 - 600*
OFR1	64.0 ≥ f > 63.0	Ride Through	20	21	60.1 ≥ f ≥ 59.9	300 - 600*
NORH	63.0 ≥ f > 60.0	Normal Operation	Indefinite	Indefinite	-	-
NORL	60.0 ≥ f ≥ 57.0	Normal Operation	Indefinite	Indefinite	-	-
UFR1	57.0 > f ≥ 56.0	Ride Through	20	21	60.1 ≥ f ≥ 59.9	300 - 600*
UFR2	56.0 > f	Cease to Energize	None	0.1667	60.1 ≥ f ≥ 59.9	300 - 600*

Voltage Ride Through

Operating Region	Range (% of Nominal)	Operating Mode	Duration (s)		Return To Service - Trip	
			Ride Through	Trip	Criteria (% of Nominal)	Time Delay (s)
OVR2	V > 120	Cease to Energize	None	0.1667**	110 ≥ V ≥ 88	300 - 600*
OVR1	120 ≥ V > 110	Ride Through	0.92	1	110 ≥ V ≥ 88	300 - 600*
NORH	110 ≥ V > 100	Normal Operation	Indefinite	Indefinite	-	-
NORL	100 > V ≥ 88	Normal Operation	Indefinite	Indefinite	-	-
UVR1	88 > V ≥ 70	Ride Through	20	21	110 ≥ V ≥ 88	300 - 600*
UVR2	70 > V ≥ 50	Ride Through	10-20*	11-21*	110 ≥ V ≥ 88	300 - 600*
UVR3	50 > V	Permissive Operation	None	0.5	110 ≥ V ≥ 88	300 - 600*

From HEI's 23 Feb 2015 Update to HPUC

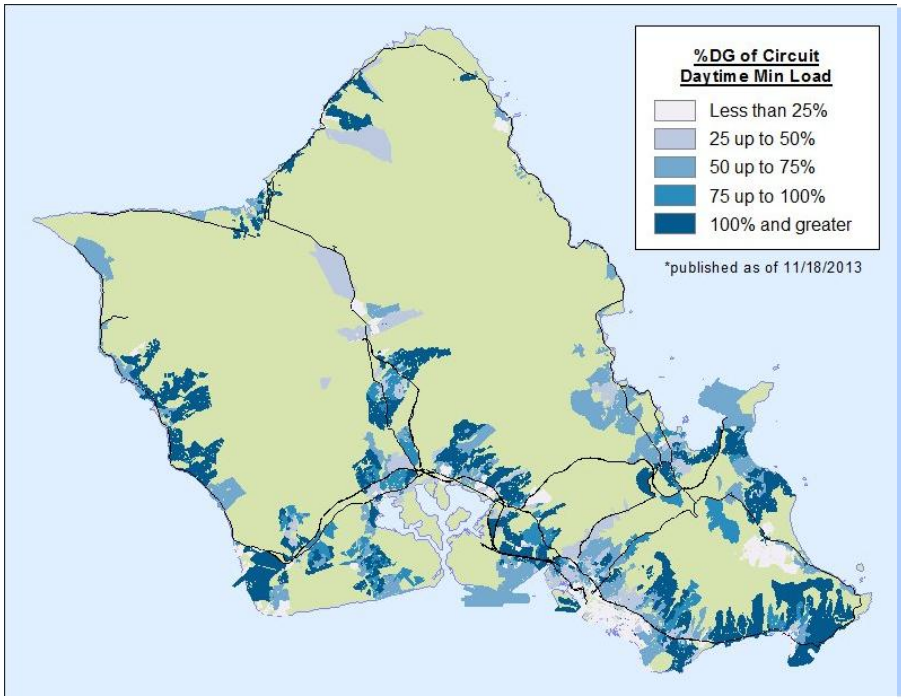
Docket No. 2014-0192 - Instituting a Proceeding to Investigate Distributed Energy Resource Policies, Monthly Update on Plan to "Clear the Queue." Filed October 31. 2014

" With respect to interim settings, the Companies are pleased to report that Enphase Energy successfully upgraded the operating behavior of approximately 154 MW of its smart microinverter capacity installed in Hawai'i to achieve interim ride-through settings. This preliminary estimate represents about 107 MW on O'ahu, 22 MW on Hawai'i Island, 25 MW on Maui, 0.1 MW on Moloka'i, and 0.2 MW on Lana'i. This unprecedented technological accomplishment is a result of ongoing collaboration between Enphase, Hawaiian Electric and other industry partners to find technical solutions for integrating high levels of PV in Hawai'i at a low cost to end-customers. Because Enphase's microinverters are software-defined, Enphase was able to make these updates remotely and quickly, saving tens of millions of dollars by avoiding the need to send personnel out in the field to update the settings manually."

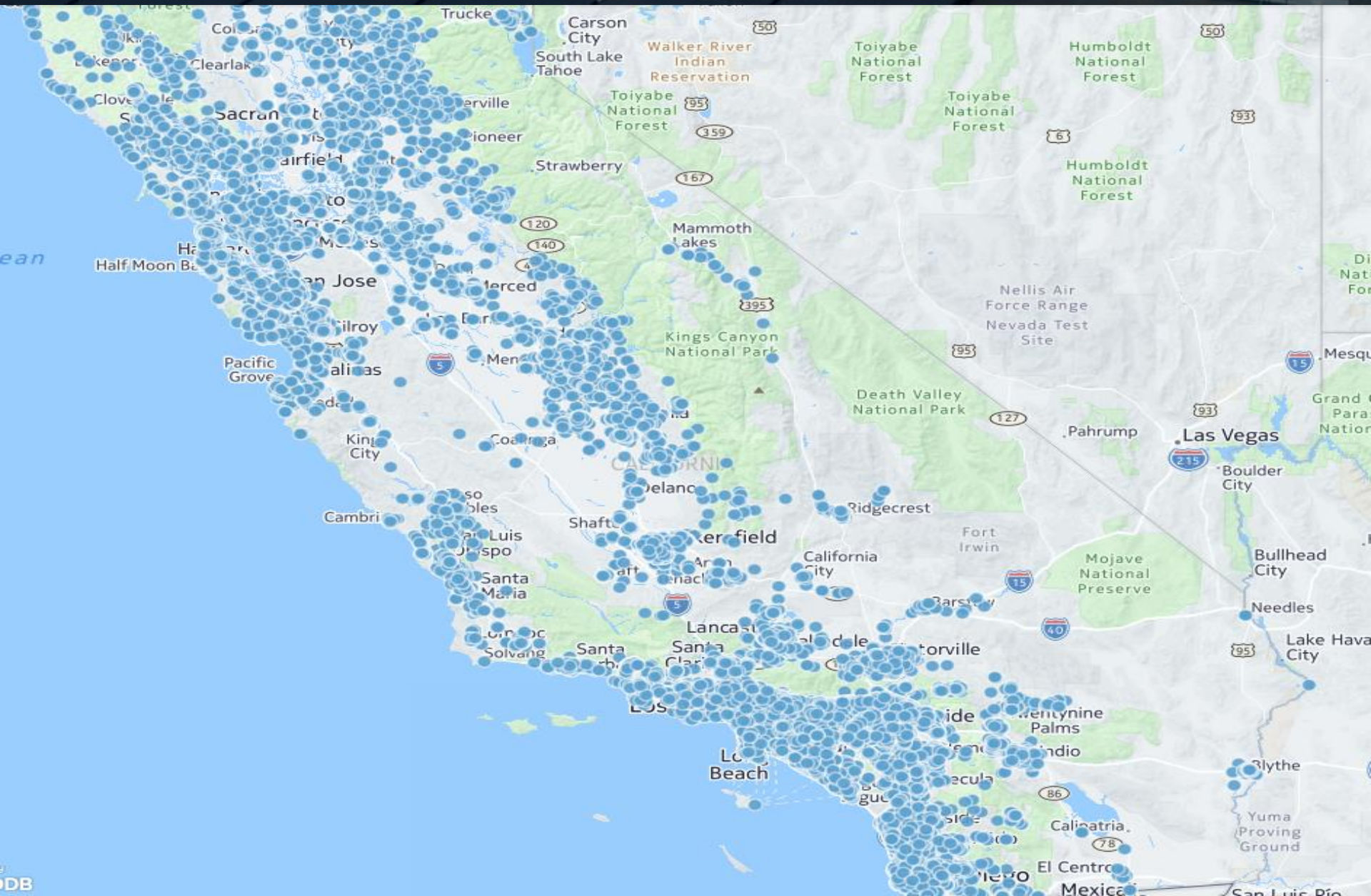
Enphase Footprint in Hawaii

By HECO's estimate, Enphase inverters are used in 60% of all PV and 90% of residential PV installed in the State

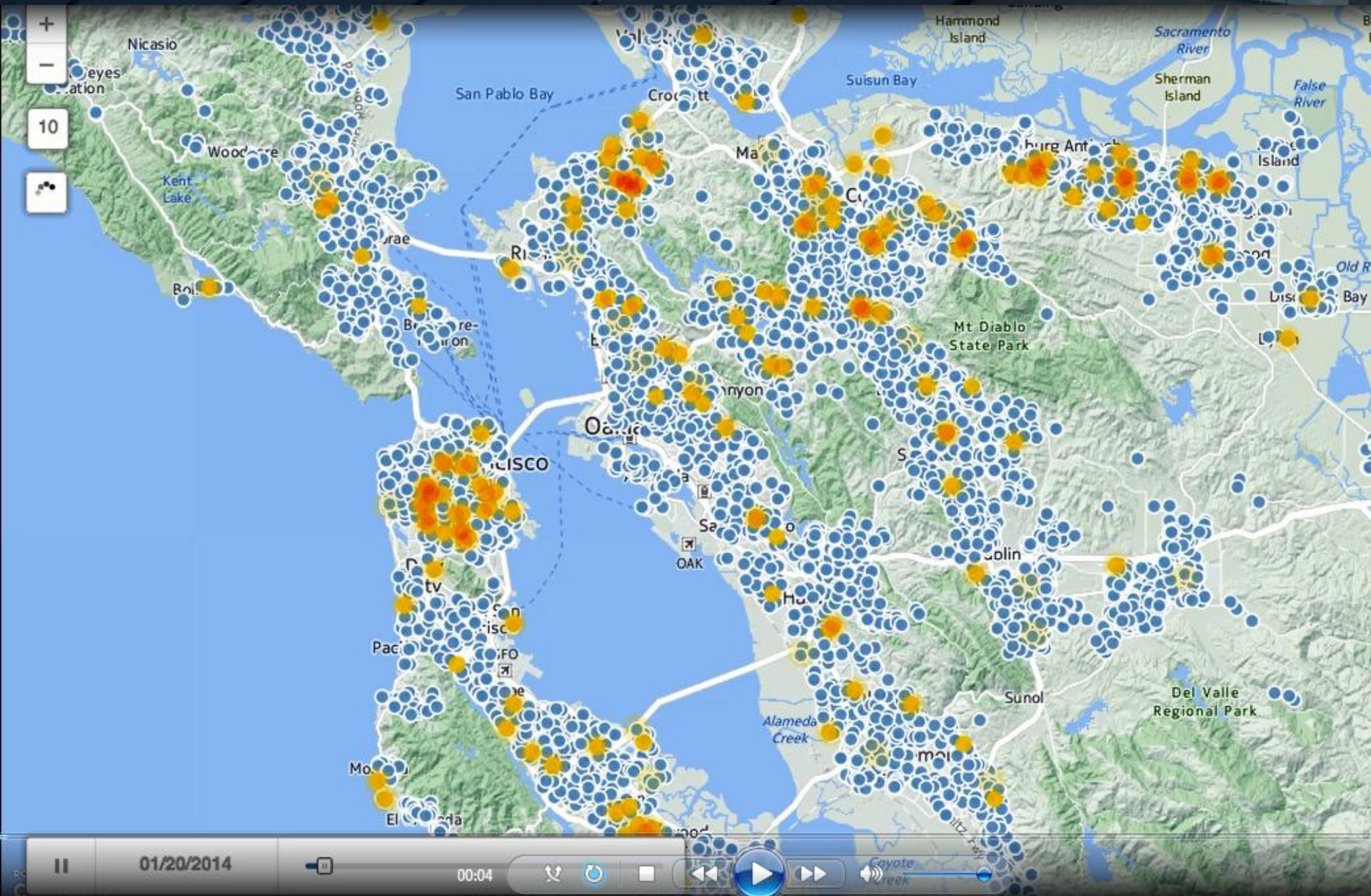
- There is very high correlation between impacted feeders and Enphase system locations



Enphase Footprint in California



Voltage Out of Range Visualization Movie



But, Is This Worth Doing ?

- **No standardized methodology exists to determine value of DER with advanced functionality.**
  - Traditional value analysis occurs only down to substation level
  - The majority of DER is located below the substation
  - Historic methodologies do not consider smart inverters located at the grid edge
- **CPUC is engaging in DRP process to determine methodology for establishing the value of DER**
  - Significant value may exist below the substation especially when voltage regulation is considered
- **Integral Analytics / Enphase value study (preliminary)**
  - Value appears to increase as level of control granularity increases

IA-Enphase Study: Benefits of dynamic KVAR control

PRELIMINARY

- **Analysis at the grid edge, with small scale storage competing with kVar "injections", we find that the two are fairly comparable in terms of net savings and benefits (for avoided costs, grid purchases, and power factor changes)**
  - *Base Case: Optimally Located PV*
  - *Optimally Placed PV with Storage Added:* *14% more savings*
  - *Optimal PV with kVar/ Power Factor Control:* *24% more savings*
  - *Optimal PV, kVar and Storage:* *26% more savings*

What is needed ?

- **Overcome customer privacy limitations**
  - Add limited privacy release to interconnection agreements
  - Allow confirmation of system location information for operation purposed only.
- **Develop cyber security standards for command and control of DER**
- **Conduct value analysis of smart inverter functionality located at the grid edge**
  - Requires highly granular data below the substation
  - Include dynamic Var optimization along the feeder
- **Create standardized model formats for smart inverters**
  - Steady state and quasi time series
  - Validate models with pilot studies

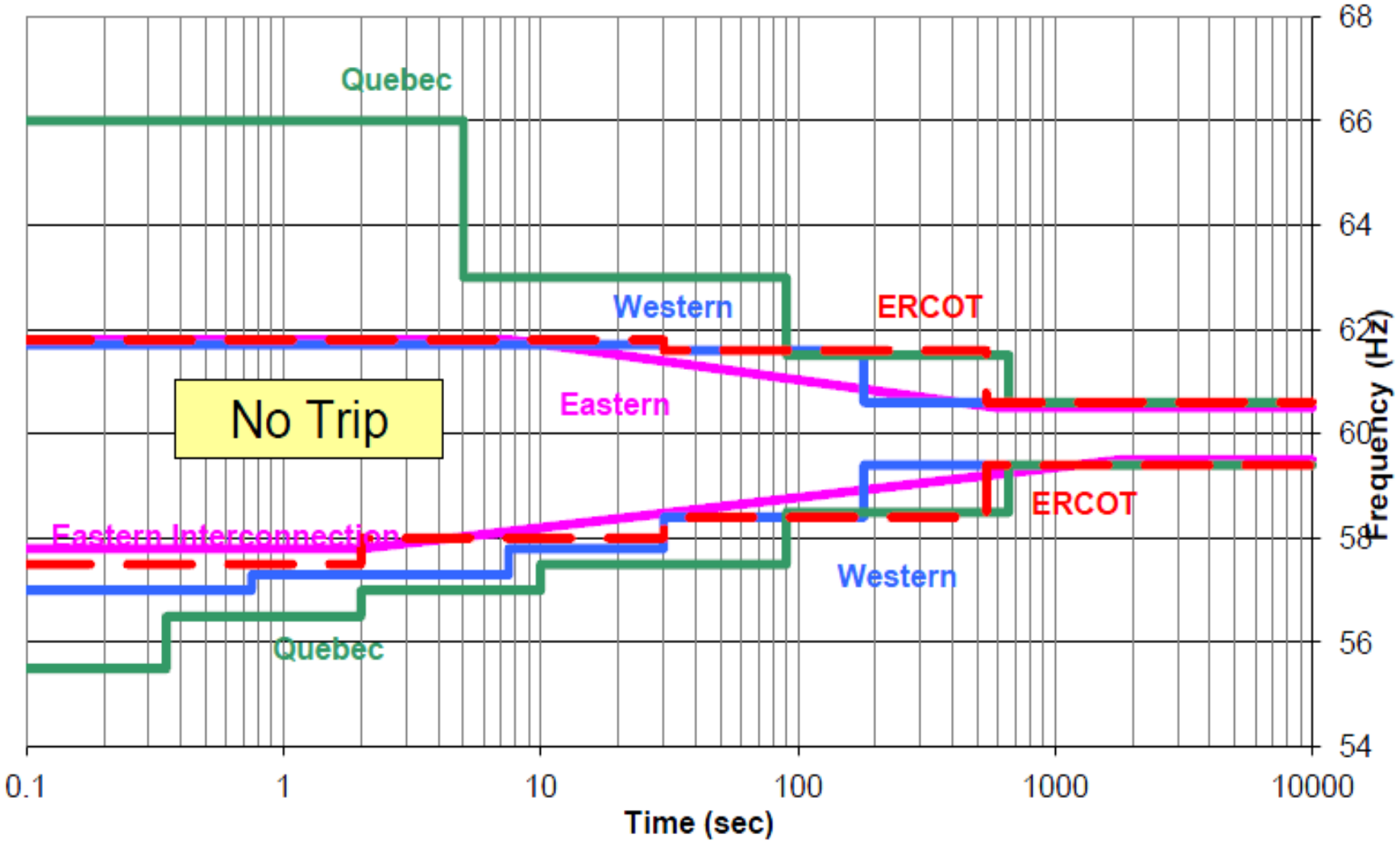
Thank you for your attention

jberdner@enphaseenergy.com

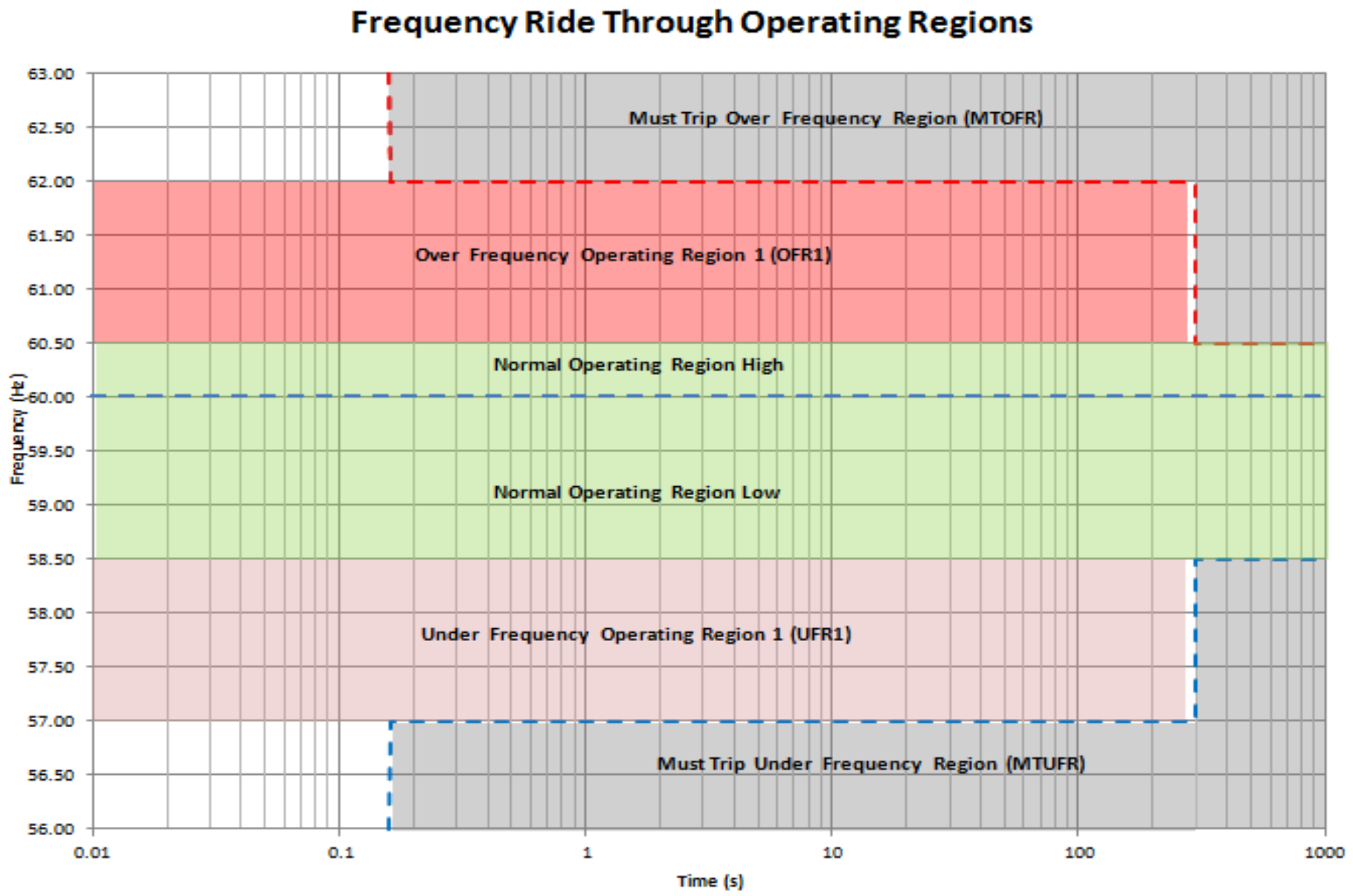
V, f Ride Through

- **Fundamentally, ride through is needed to avoid cascade failure of the utility grid during severe under frequency events, and to a lesser degree, severe under voltage events.**
- **Limit loss of generation to "an acceptable level"**
  - During severe under frequency events DER should remain online until local load shedding schemes have activated.
  - Local Load shedding schemes will shed load AND generation simultaneously thereby minimizing the net loss of generation during an event.
  - If DER is lost ahead of load, grid instability may quickly worsen and possible lead to cascade failure.

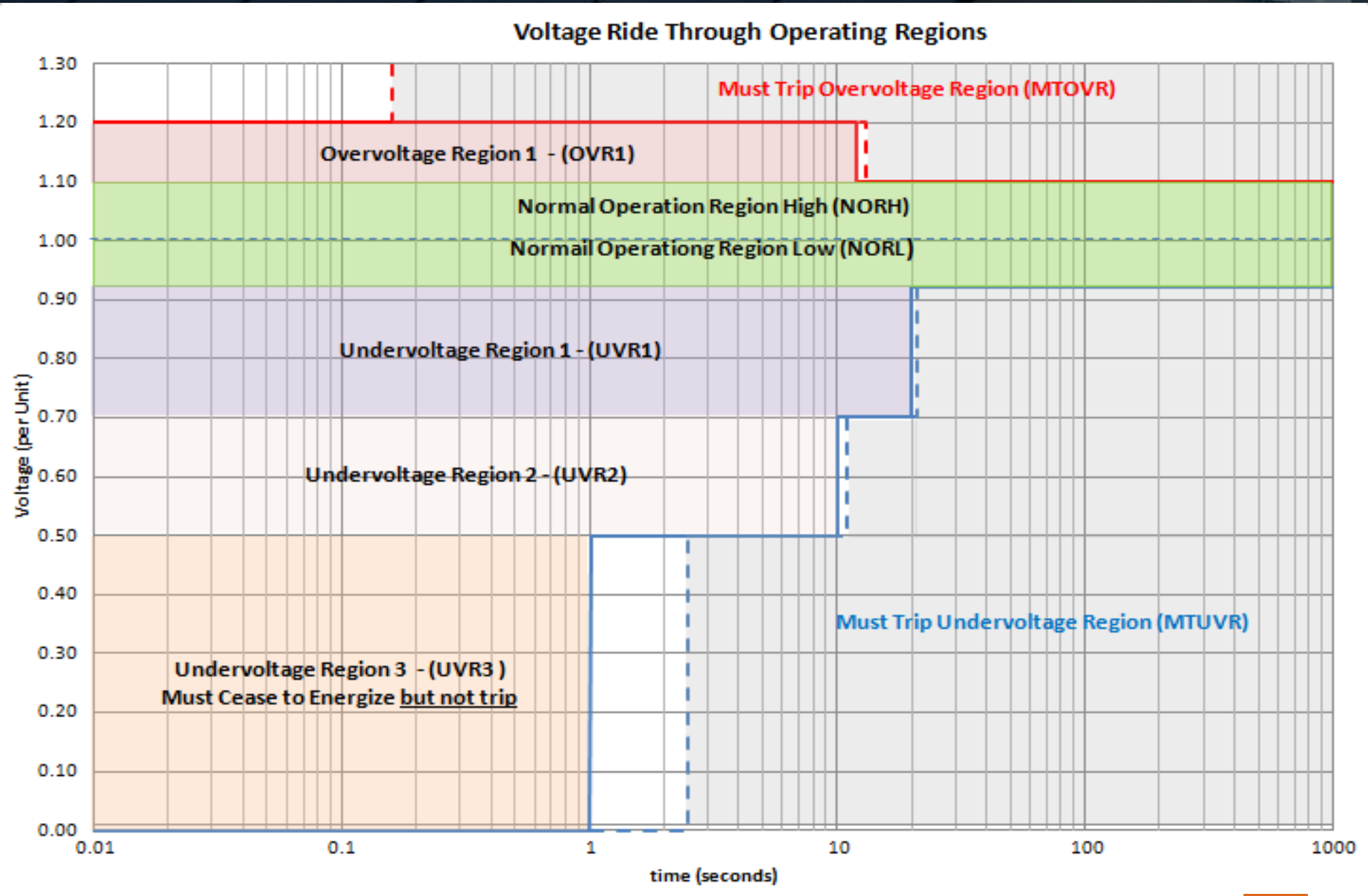
NERC Off-Nominal Frequency Curves



Operating Regions – Frequency



Operating Regions - Voltage



Real Power Control Functions

- **Maximum Power Level**
  - Fixed, based on time of day, in response to external command
- **Volt/Watt**
  - Reductions in power in response to rising voltage
  - Relatively ineffective compared to reactive power control
  - Optional in CA, R21 Phase 1
- **Frequency/Watt**
  - Reduces power based in response to rising frequency.
  - Adds frequency stability during over frequency events
  - Secondary control method in system wide restarts (frequency events)
  - Optional in CA, R21, Phase 1, Mandatory in HI, R14H

Return to Service / Ramp Rate Control

- **Return to Service**
  - Criteria and behavior at startup, following a ride through event, or following a trip.
- **Startup / Restart Ramp Rate**
  - Criteria – within normal V, f parameters
  - Intentional delay – 15 seconds (0-300 sec)
  - Ramp Rate – 2%/sec (0-100%/sec)
- **Normal Ramp Rate**
  - Criteria – V,f within any operating region
  - Intentional delay – 0 seconds (0-300 sec)
  - Ramp Rate – 100%/sec (0-100% /sec)
    - Ramp Rate applies during normal operation

Reactive Power Control Functions

- **Primarily for Voltage Regulation on Feeders**
  - Watt priority – produces Var only if doing so does not reduce real power output
  - Var priority – requires over sizing DER or reductions in real power output
- **Fixed Power Factor**
  - Programmable PF (+/- 0.85)
  - Slightly inductive PF offsets voltage rise due to real power ($V = I^2 * R$)
- **Volt/Var**
  - Varies Var production in response to voltage
  - Includes dead bands and gradients\
  - May lead to circulating Va r/voltage stability issues.
- **Commanded Var**

Failure Mechanisms of Insulated Gate Bipolar Transistors (IGBTs)

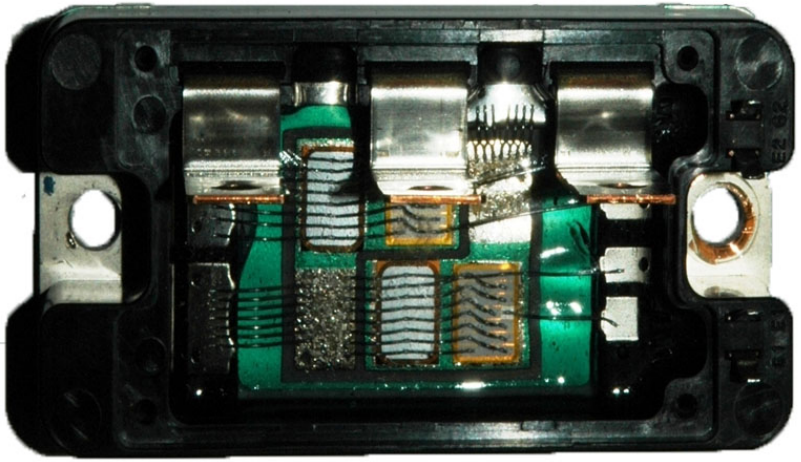
Nathan Valentine, Dr. Diganta Das, and Prof. Michael Pecht

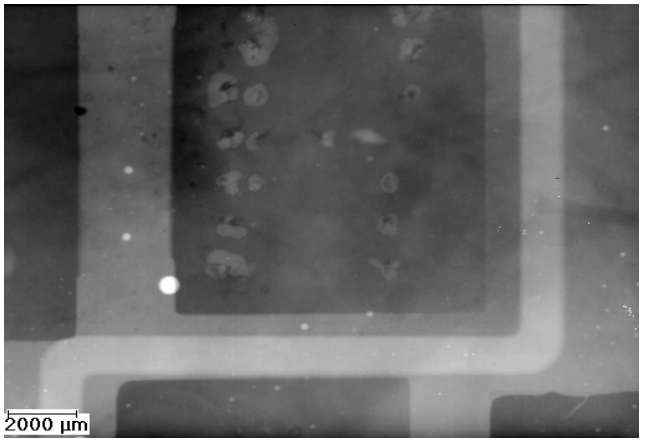
www.calce.umd.edu

Center for Advanced Life Cycle Engineering (CALCE)

2015 NREL Photovoltaic Reliability Workshop

diganta@umd.edu





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CALCE Introduction

- The Center for Advanced Life Cycle Engineering (CALCE) formally started in 1984, as a NSF Center of Excellence in systems reliability.
- One of the world's most advanced and comprehensive testing and failure analysis laboratories
- Funded at $6M by over 150 of the world's leading companies
- Supported by over 100 faculty, visiting scientists and research assistants
- Received NSF Innovation Award and NDIA Systems Engineering Excellence Award in 2009 and IEEE Standards Education Award in 2013.

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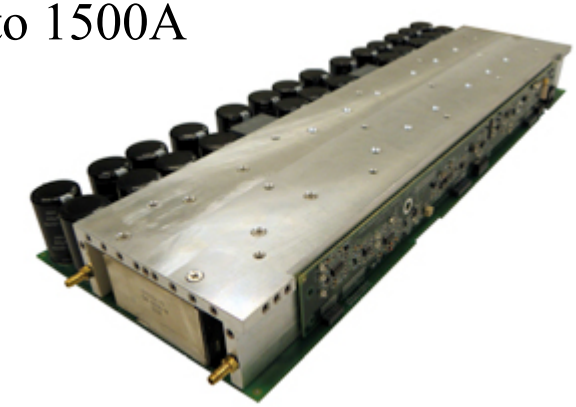
IGBT Applications

- Need for more compact power converters achieved through faster device switching
- IGBTs are the ideal choice with switching frequencies of 1kHz-150kHz and current handling of up to 1500A

Induction Heating Units



Power Converters

Electric Cars

Electric Trains

Uninterruptible Power Supplies

Wind Turbines

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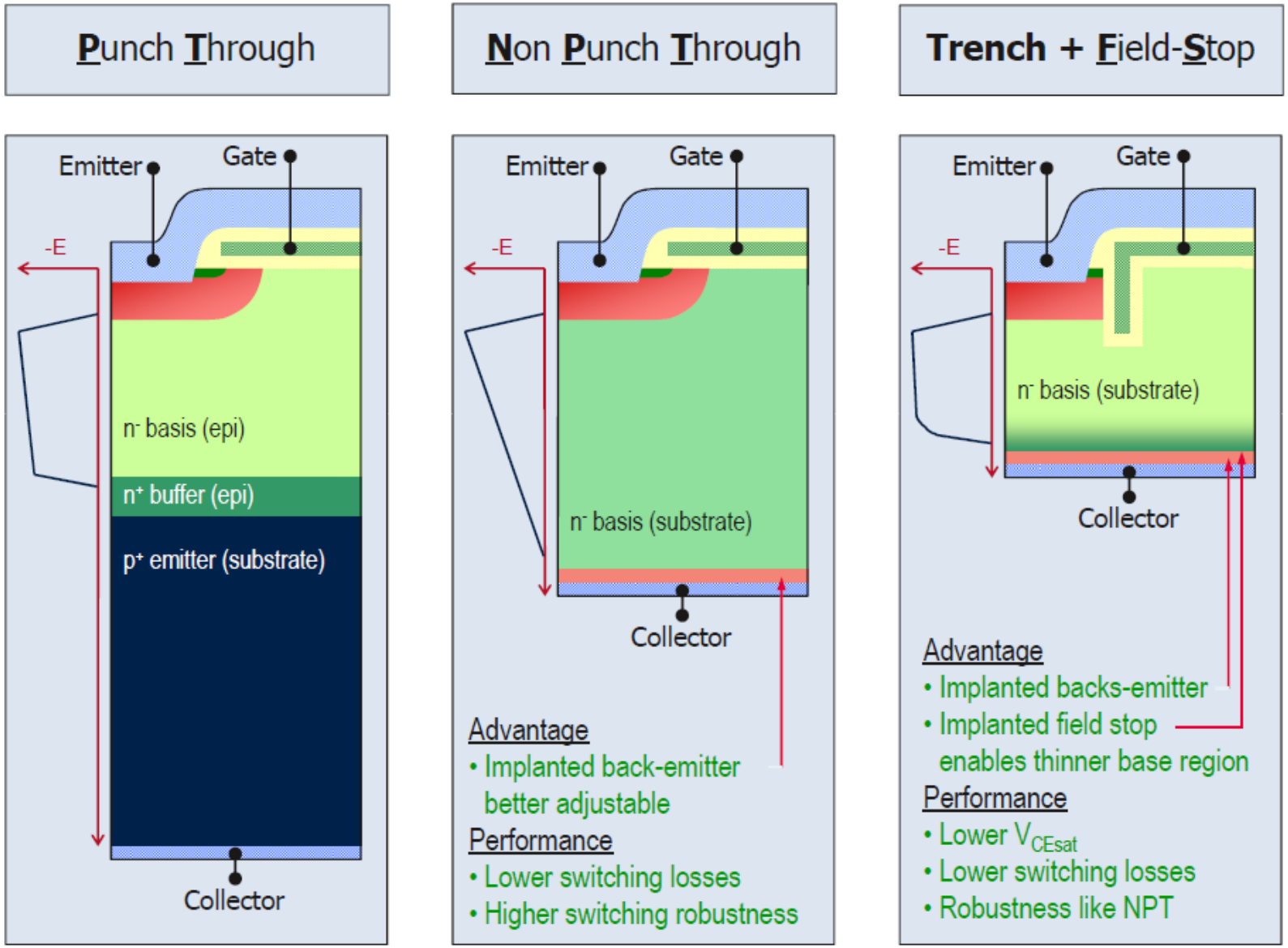
IGBT Technologies



Source: Infineon

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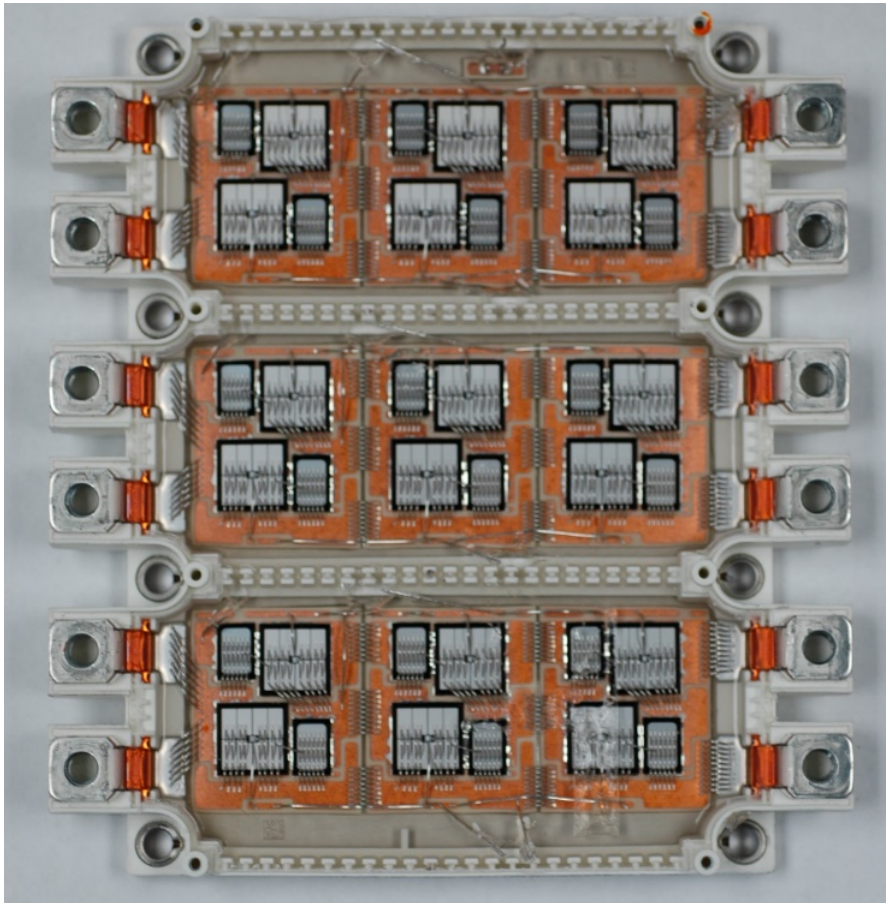
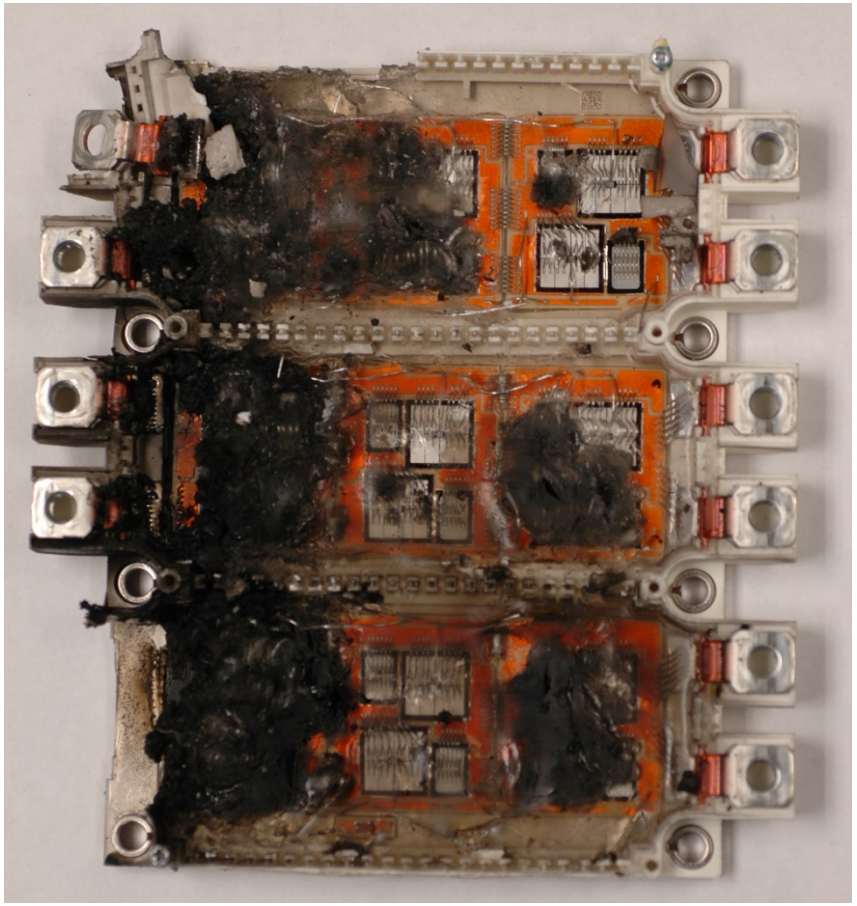
Failed Wind Turbine IGBT Module



Unused IGBT



Failed IGBT which experienced a thermal runaway, burning the module

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Steps in Reliability Evaluation

- Quantify the life cycle conditions
- Failure Modes, Mechanisms, and Effects Analysis (FMMEA) > reliability analysis, assess design tradeoffs and revise/update design
- Part, material and supplier selection
- Virtual qualification (VQ), including stress and thermal analysis

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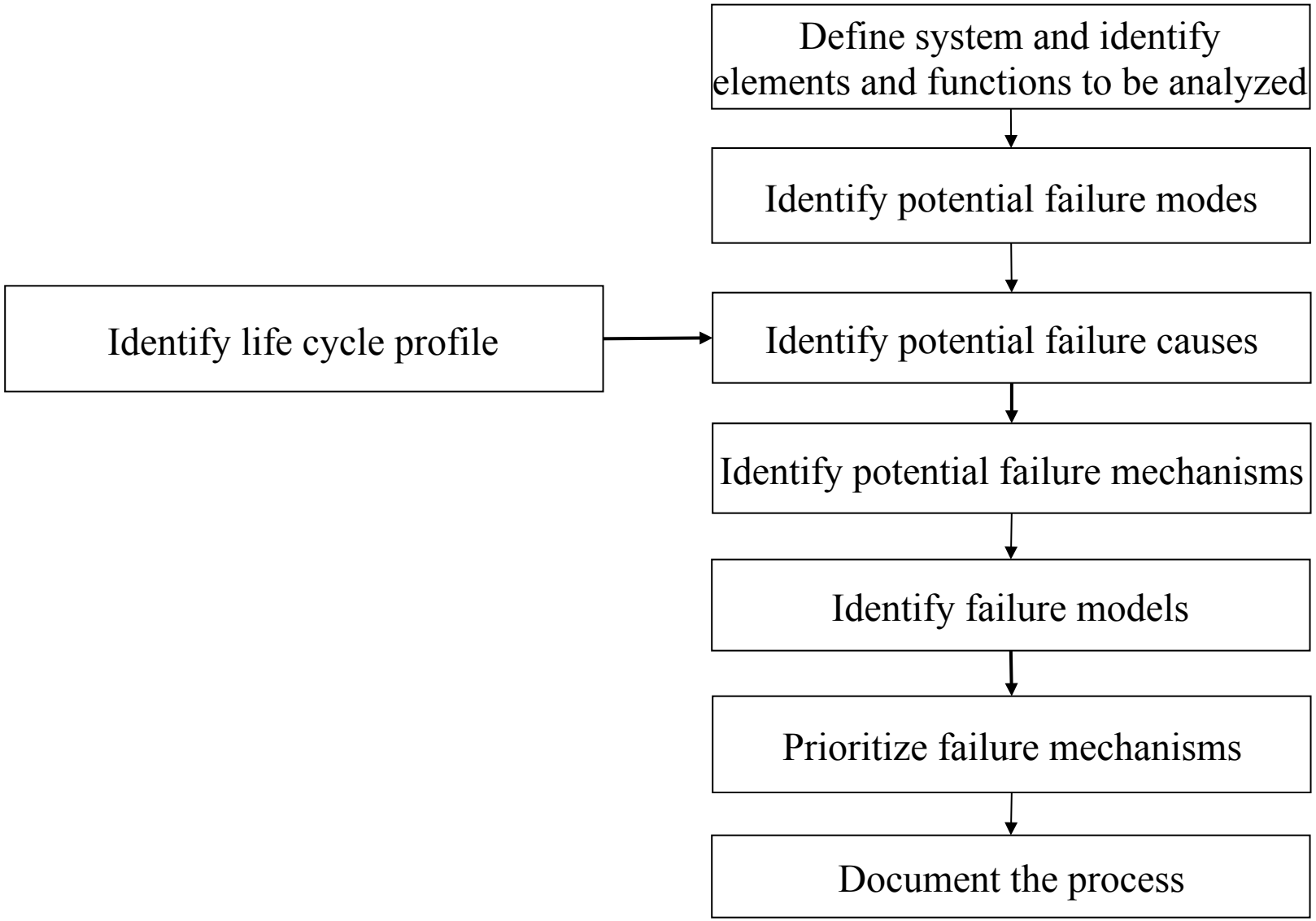
FMMEA Methodology



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IGBT Failure Modes and Mechanisms

- Failure modes in an IGBT are simple at top level:
  - Short circuit
  - Open circuit
  - Parameter drift
- Parameter drift occurs as a part degrades and the electrical characteristics such as $V_{CE(ON)}$ or I_{CE} drift from the acceptable operating range due to the accumulation of damage within a device or module

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Failure Modes and Mechanisms

Potential Failure Modes (Sites)	Potential Failure Causes	Potential Failure Mechanisms (Parameters affected)
Short circuit, loss of gate control, increased leakage current (Oxide)	High temperature, high electric field, overvoltage	Time dependent dielectric breakdown ($V_{th,}$ g_m)
Loss of gate control, device burn-out (Silicon die)	High electric field, overvoltage, ionizing radiation	Latch-up ($V_{CE(ON)}$)
High leakage currents (Oxide, Oxide/Substrate Interface)	Overvoltage, high current densities	Hot electrons (V_{th}, g_m)
Open Circuit (Bond Wire)	High temperature, high current densities	Bond Wire Cracking, Lift Off ($V_{CE(ON)}$)
Open Circuit (Die Attach)	High temperature, high current densities	Voiding, Delamination of Die Attach ($V_{CE(ON)}$)

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Examples of Failure Models

Failure Mechanism	Failure Sites	Failure Causes	Failure Models
Fatigue	Die attach, Wirebond/TAB, Solder leads, Bond pads, Traces, Vias/PTHs, Interfaces	Cyclic Deformations (Δ T, Δ H, Δ V)	Nonlinear Power Law (Coffin-Manson)
Corrosion	Metallizations	M, ΔV, T, chemical	Eyring (Howard)
Electromigration	Metallizations	T, J	Eyring (Black)
Conductive Filament Formation	Between Metallizations	M, ΛV	Power Law (Rudra)
Stress Driven Diffusion Voiding	Metal Traces	σ, T	Eyring (Okabayashi)
Time Dependent Dielectric Breakdown	Dielectric layers	V, T	Arrhenius (Fowler-Nordheim)

Δ: Cyclic range
Λ: gradient
T: Temperature
H: Humidity
V: Voltage
M: Moisture
J: Current density
σ: Stress

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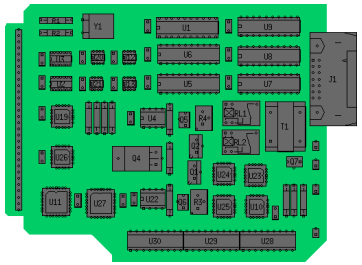
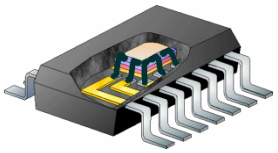
CALCE Simulation Assisted Reliability Assessment (SARA®) Software

http://www.calce.umd.edu/software

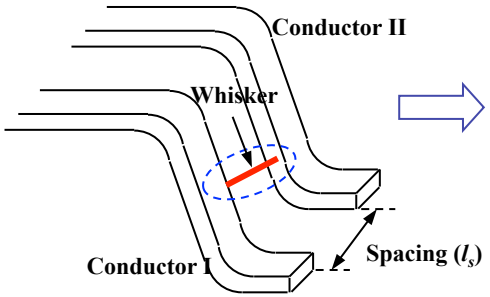


calcePWA
Circuit Card Assemblies

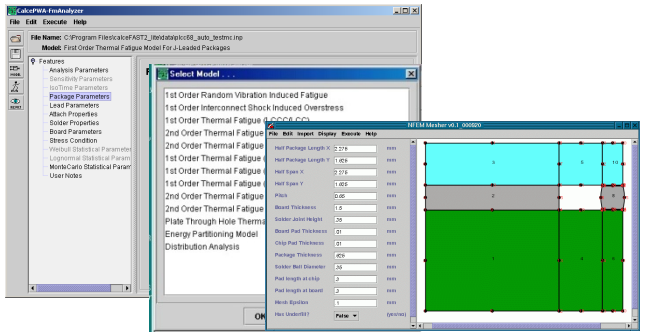
Thermal Analysis
Vibrational Analysis
Shock Analysis
Failure Analysis



calceEP
Device andPackage
Failure Analysis



calceTinWhisker FailureRiskCalculator



calceFAST
Failure Assessment
Software Toolkit

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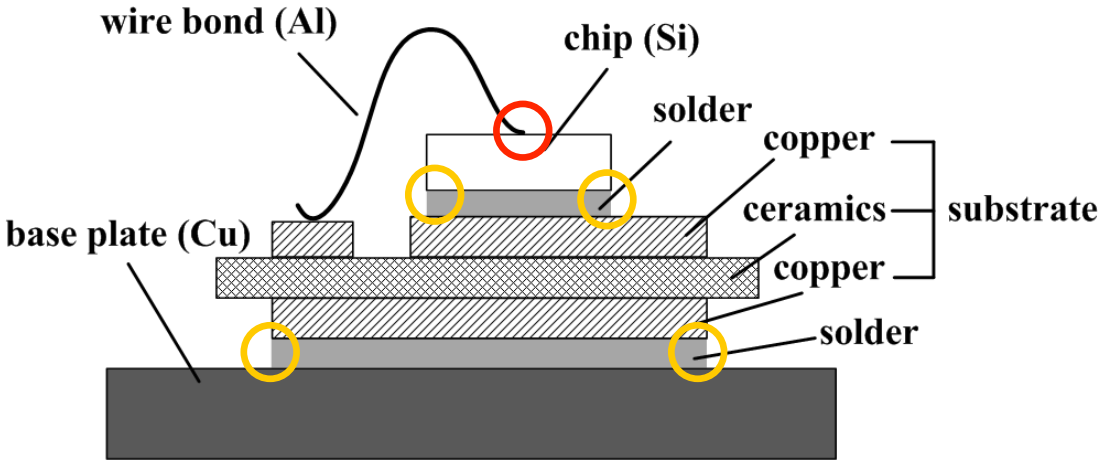
Thermally-Induced Stresses in IGBT

Material	CTE (10^{-6} K^{-1})	Conductivity (W m^{-1} K^{-1})
Al_2O_3	6.8	24
AlN	4.7	170
Si_3N_4	2.7	60
BeO	9	250
Al	23.5	237
Cu	17.5	394
Mo	5.1	138
Si	2.6	148
AlSiC	7.5	200



- Bond Wire Fatigue
- Solder Joint Fatigue

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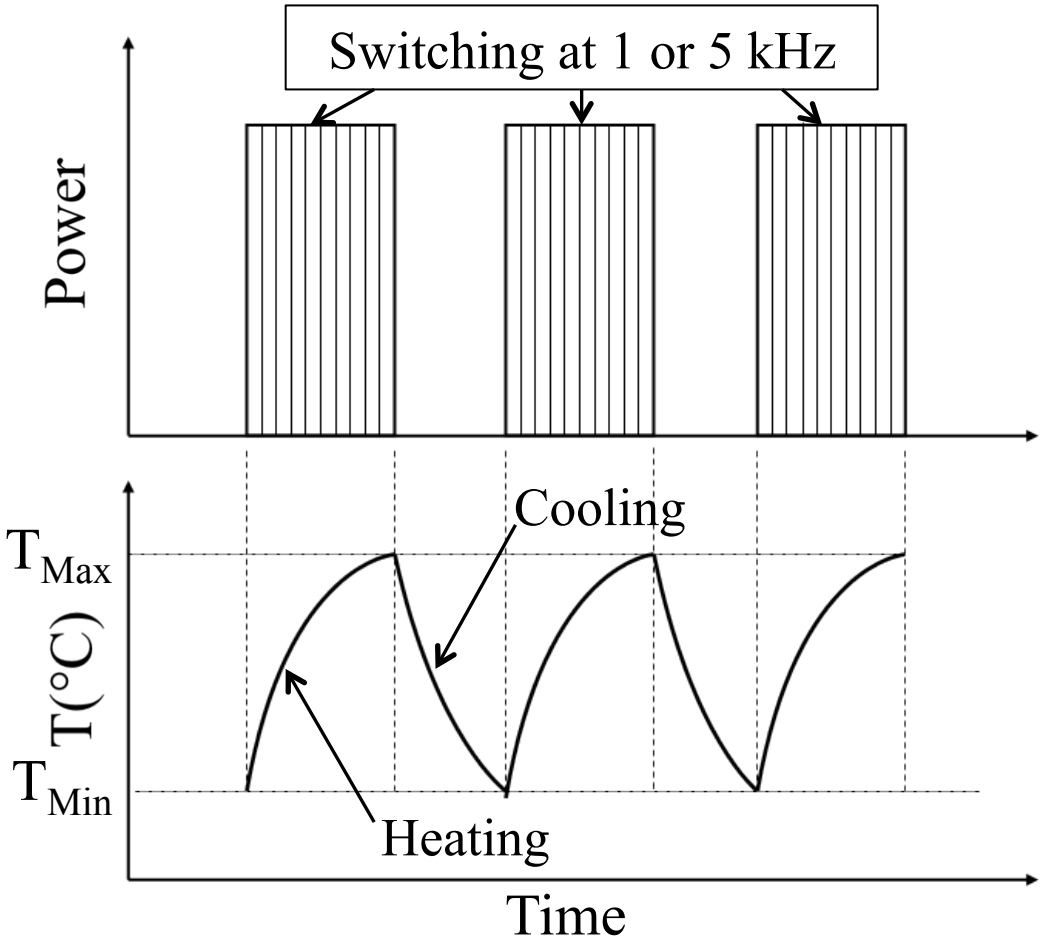
IGBT Power Cycling Experiment

- IGBT samples were power cycled between specified temperatures T_{Min} and T_{Max}. The devices were switched at 1 or 5 kHz. Cooling was carried out passively by exposure to ambient temperature.
- This 'power' (thermal) cycling was repeated until failure occurred by latchup or by failure to "turn on".



Power cycling illustration

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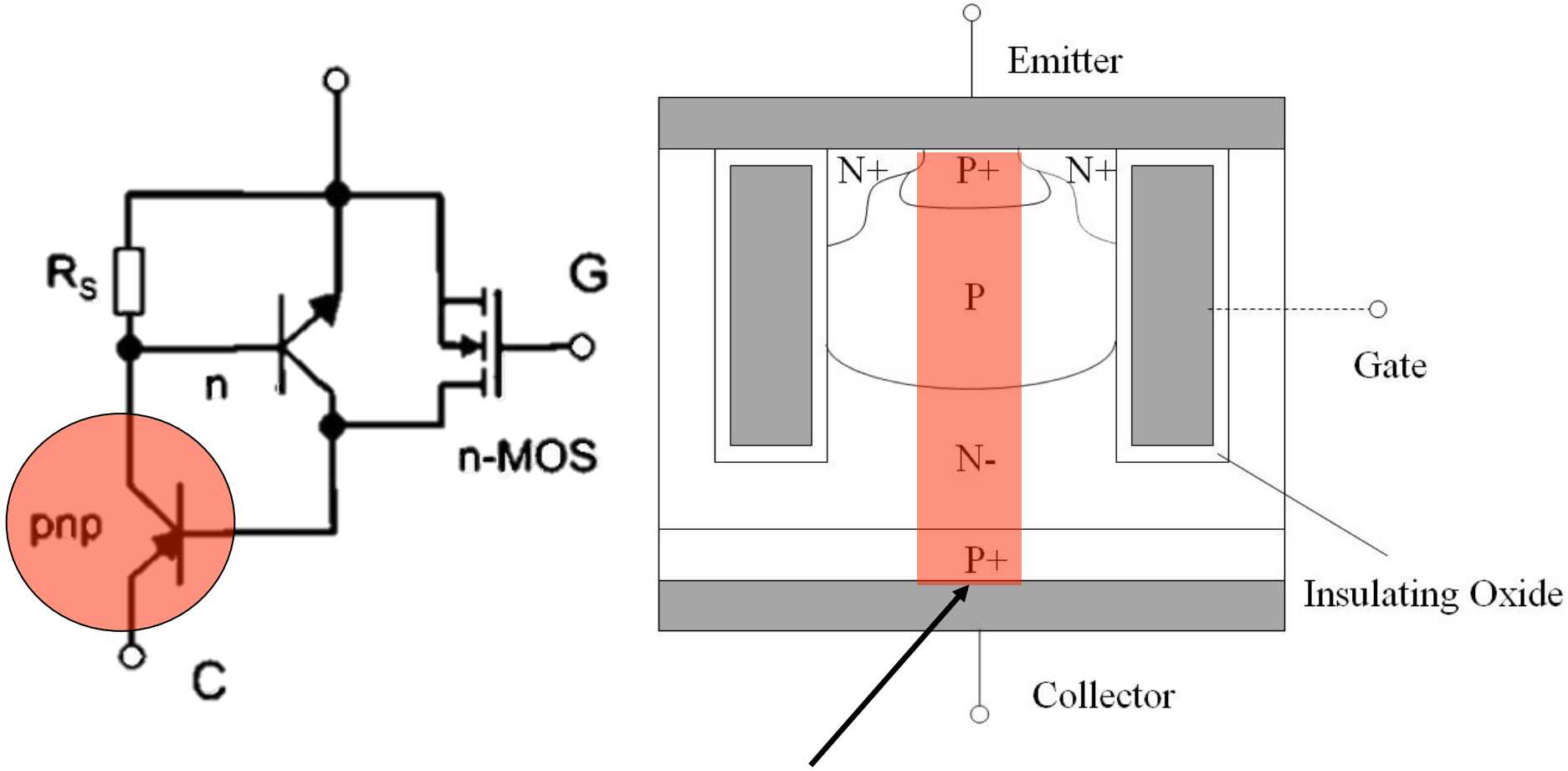
Parasitic Thyristor in IGBT Structure



Internal PNP Bipolar Transistor

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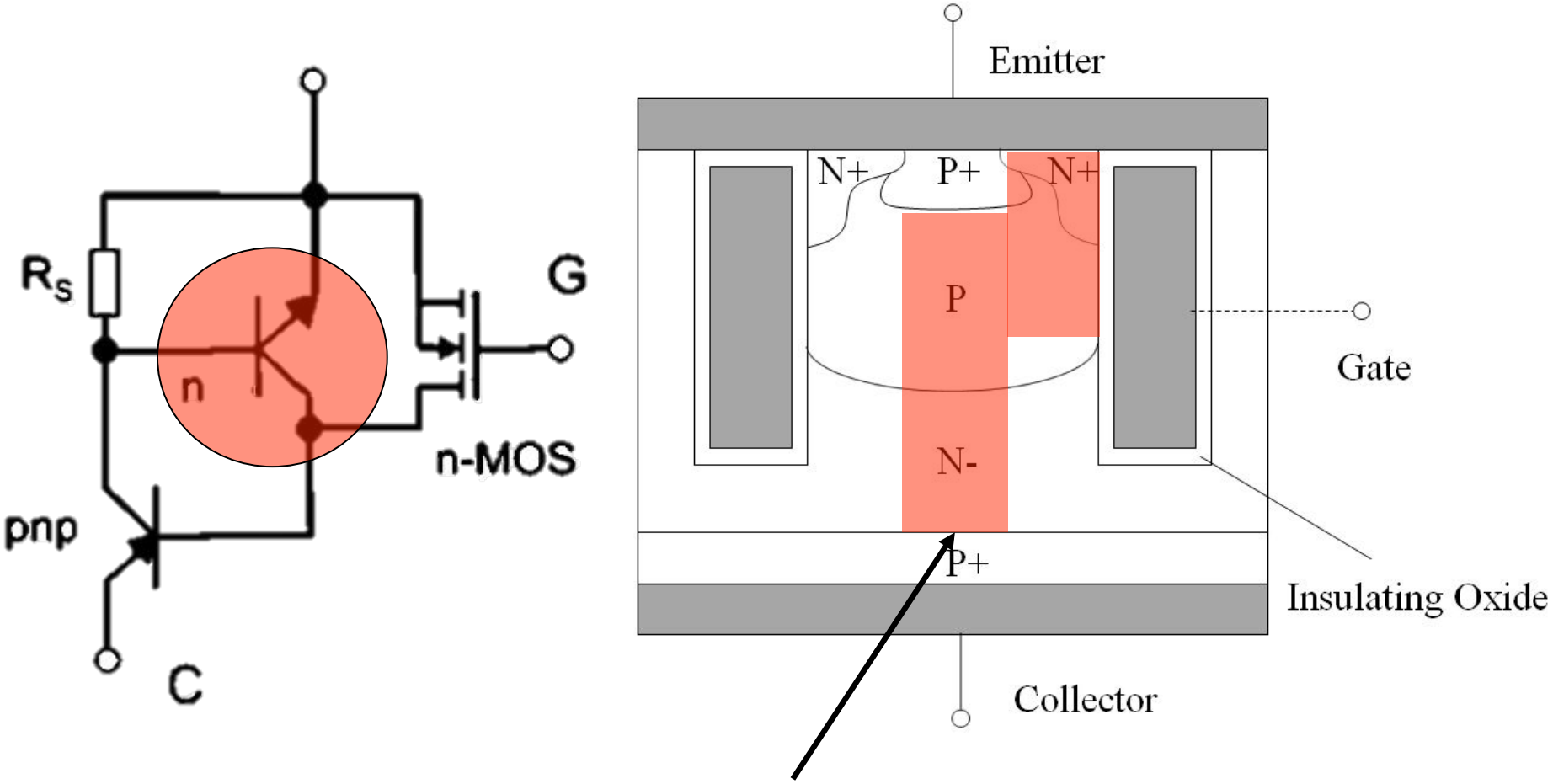
Parasitic Thyristor in IGBT Structure



Parasitic NPN Bipolar Transistor

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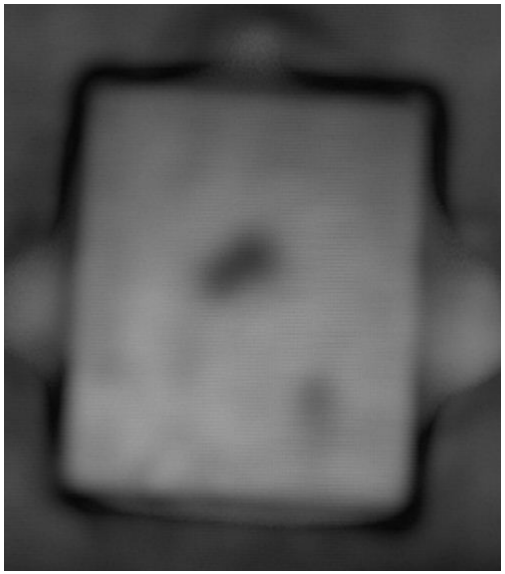
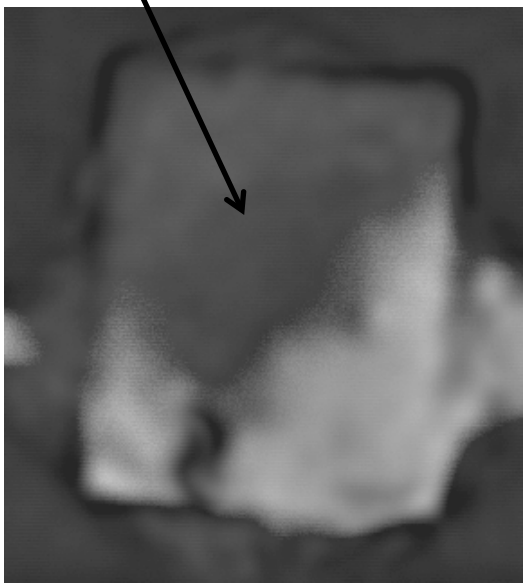
Die Attach Acoustic Scan Images



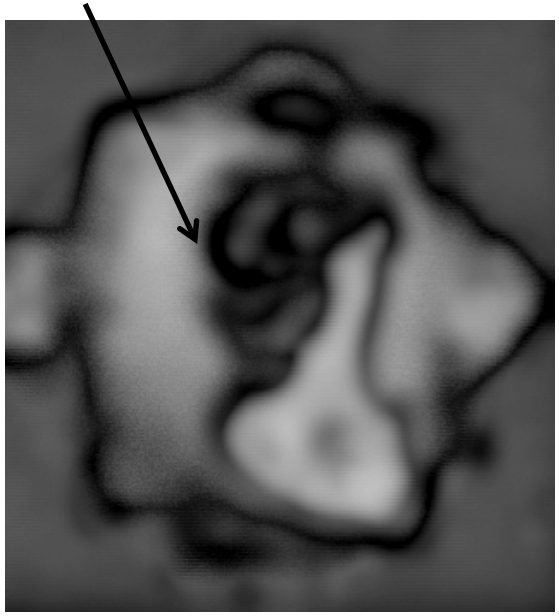
New IGBT sample.

Delaminated surface



Failure to turn on after 3126 power cycles, ΔT = 75°C. Die attach shows delamination.

Melted die attach



Failure by latchup after 1010 power cycles, ΔT = 100°C. Melting T of die attach = 233°C*.

*Specification sheet for Sn65Ag25Sb10 solder from Indium Corp. Indalloy 209.

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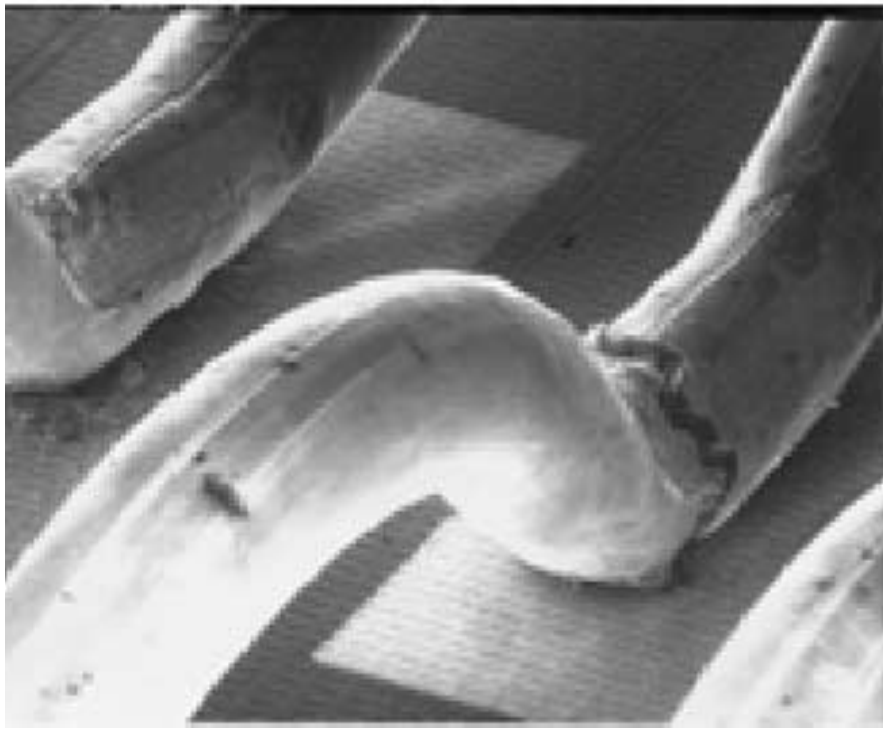
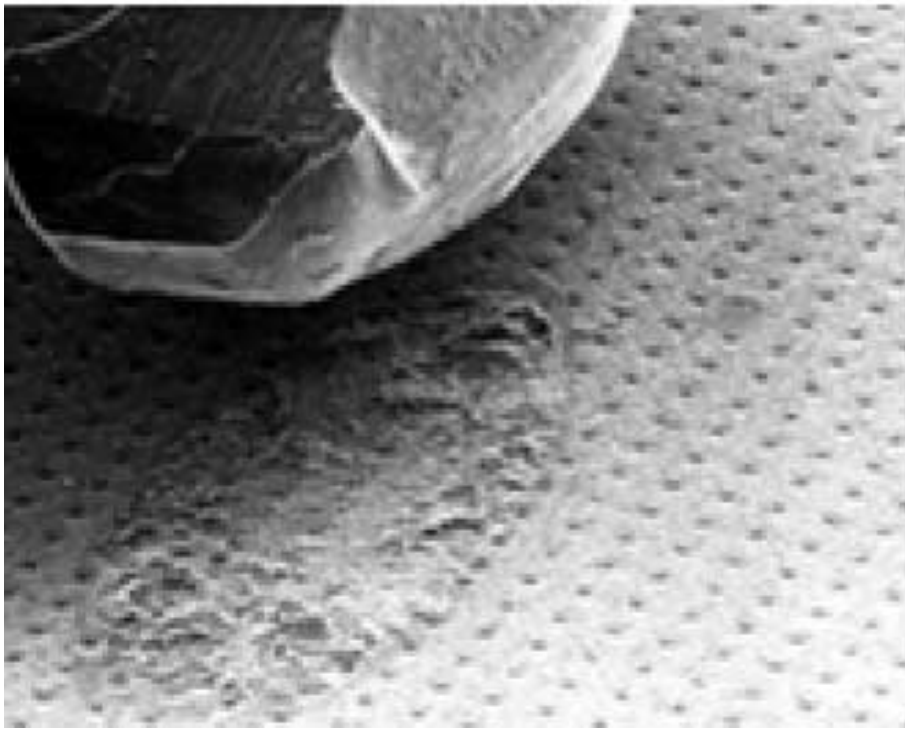
Bond Wire Failures



Bond Wire Cracking



Bond Wire Liftoff

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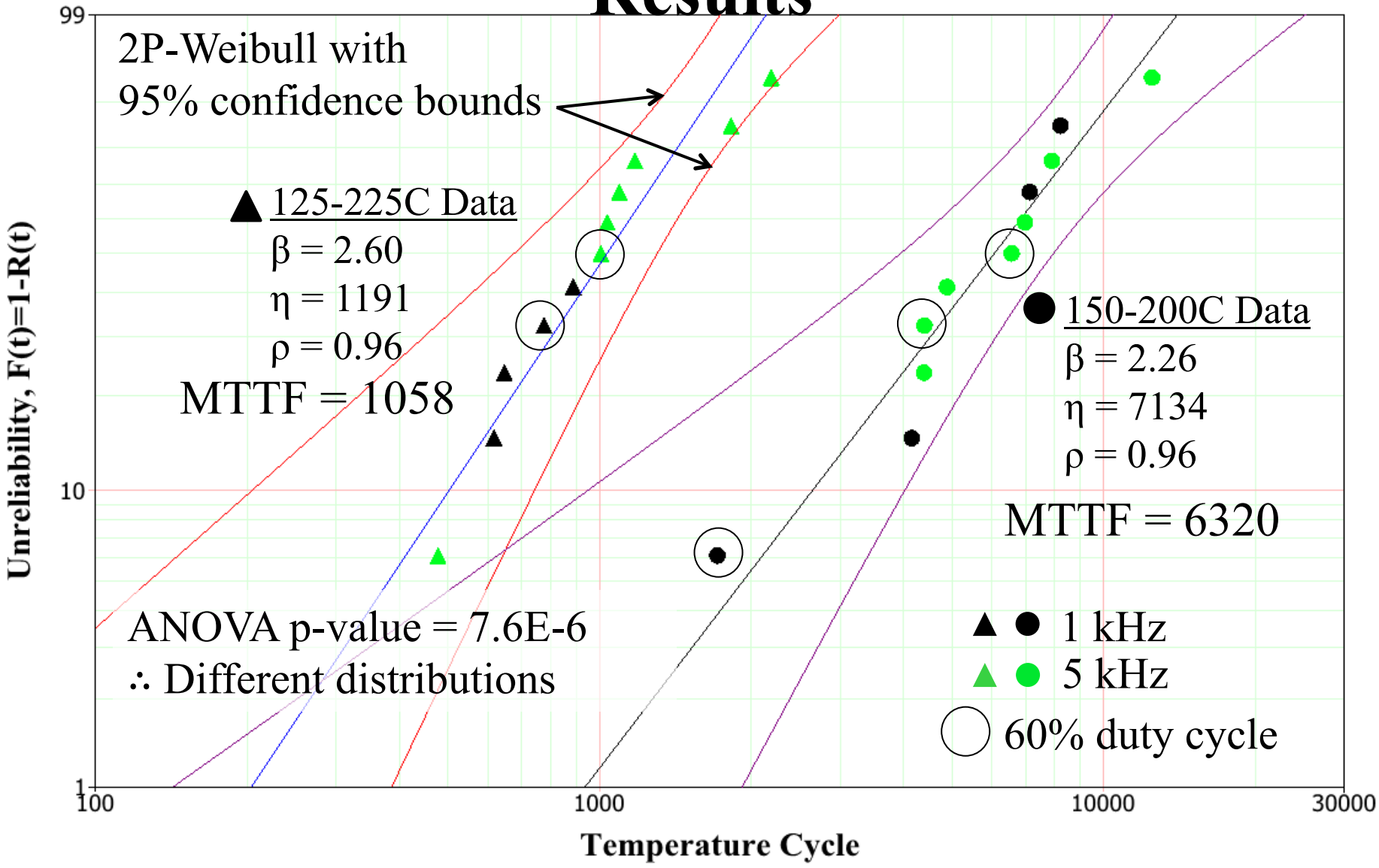
Lifetime Statistics of Experimental Results



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Prediction of Other Reliability Metrics

Temperature Range	MTTF (Cycles)	[B5%Life; B95%Life] (Cycles)
150-200°C	6320 cycles	[1922; 11,582]
125-225°C	1058 cycles	[381; 1815]

MTTF varies with loading conditions and from part to part. Predicting service life of an IGBT based on a population MTTF results in a high uncertainty.

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Physics of Failure Based Lifetime Prediction

Temperature	PoF Lifetime Prediction	Experiment MTTF
150-200°C	15,300 cycles	6320 cycles
125-225°C	10,800 cycles	1058 cycles

- Thermo-mechanical fatigue due to variations of power dissipation has been identified as a failure mechanism of IGBT.
- Die attach fatigue failure model was used in the CalceFAST software. The model was based on the Suhir's interface stress equation coupled with the Coffin Manson equation.
  - Model inputs were: ΔT, cycling period, materials, and dimensions.
  - Failure criteria were based on separation of die attach material.
- This model does not represent latchup failures and the actual degradation involves intermetallic growth which changes the crack propagation due to brittle fracture.

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Limitations of the Die Attach Method

- Die attach area reduction may not be linear as assumed since thermal stress is highest in the perimeter and reduces as cracks move toward the center of the die. Crack growth in the brittle intermetallic is not the same as the original material.
- Power dissipation changes with time as efficiency degrades.
- The latchup Tj is not always 255C due to difference in current density between operating conditions, metallization degradation, and chip manufacturing variations.
- The developed thermal stack model does not represent the actual thermal resistance network due to unknown spreading resistance, dissipation through the encapsulant and bond wires, and changing conductivity through the growing intermetallic.

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MIL-217 Handbook: Reliability Prediction of Electronic Equipment

- MIL217 Handbook provides formulas to estimate failure rate of military electronic equipment. **Constant failure rate is assumed.**
- No formula was provided for IGBT, therefore a MOSFET and Bipolar Junction Transistor (BJT) was modeled in series to represent an IGBT.
- Failure rate is calculated by multiplying a base failure rate with several conditional factors. For example:

$$\lambda_p = \lambda_b \pi_T \pi_A \pi_Q \pi_E \text{ failures}/10^6 \text{ hours}$$

where λ_P = part failure rate

λ_b = base failure rate

π_T = temperature factor

λ_A = application factor

λ_Q = quality factor

π_E = environment factor

Temperature factor does not account for temperature cycling input.

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Comparison of MTTFs

Temperature Profile	MIL-HDBK-217	Die Attach Fatigue Model	Experimental Data 2P-Weibull
150-200°C	115,843 hours	15,300 cycles	18.7 hours (6320 cycles)
125-225°C	96,327 hours	10,800 cycles	12.2 hours (1058 cycles)

- MIL-HDBK-217 method does not account for temperature cycling loading and other relevant loading conditions.
- Die attach fatigue model provides a better estimate than the handbook. Improvement to the model includes obtaining material fatigue properties, incorporating intermetallic growth into the crack propagation, and estimation of junction temperature.
- Predicting lifetime using a population MTTF cannot account for variability from part to part.

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Motivation for Health Monitoring Approach (for IGBT and System)

- Using MTTF to predict IGBT lifetime is not sufficient to avoid unexpected failures in the field due to the variability in prediction.
- Handbook approach ignores relevant loading conditions, device characteristics, and failure mechanisms leading to erroneous lifetime predictions.
- Physics-based lifetime prediction cannot avoid unexpected failures in the field due to variations from part to part and field loading conditions.
- An alternative approach to avoid failures is to monitor IGBT health individually under operation by using a data-driven method to analyze the operating data and detect for faulty conditions before failure occurs.

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What We Need to Do?

- Relevant material properties for the critical failure mechanisms
- Ability to update the failure models quickly
- Modeling platforms for the units and components

- Life cycle condition information from monitoring
- Use of data for determination of anomaly at the level of interest
- Remaining useful life assessment ability

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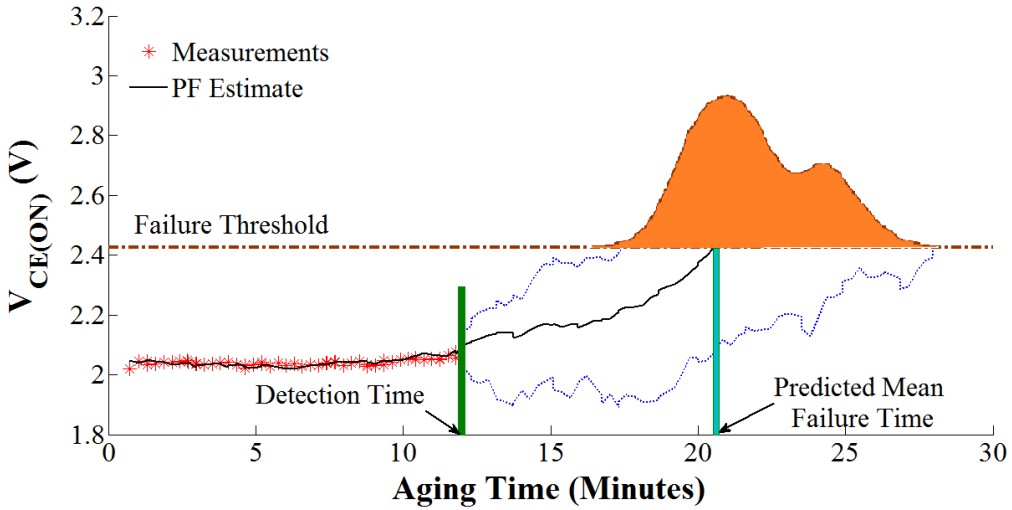
IGBT Prognostics

- Patil et. al. [9] IGBTs were monitored for V_{CE} and I_{CE} during continuous power cycling. Proposed a method to predict remaining useful life (RUL) of IGBT under power cycling by extrapolating V_{CE} curve to a failure threshold using particle filter
- Sutrisno et. al. [10] generated a K-Nearest Neighbor algorithm for fault detection of IGBTs under continuous power cycling conditions using monitored electrical characteristics such as V_{CE} and I_{CE} .



[9] N. Patil, "Prognostics of Insulated Gate Bipolar Transistors," Ph. D. dissertation, Dept. Mech. Eng., University of Maryland, College Park, MD, 2011.

[10] E. Sutrisno, "Fault Detection and Prognostics of Insulated Gate Bipolar Transistor (IGBT) Using K-Nearest Neighbor Classification Algoritihm," M.S. dissertation, Dept. Mech. Eng., University of Maryland, College Park, MD, 2013.

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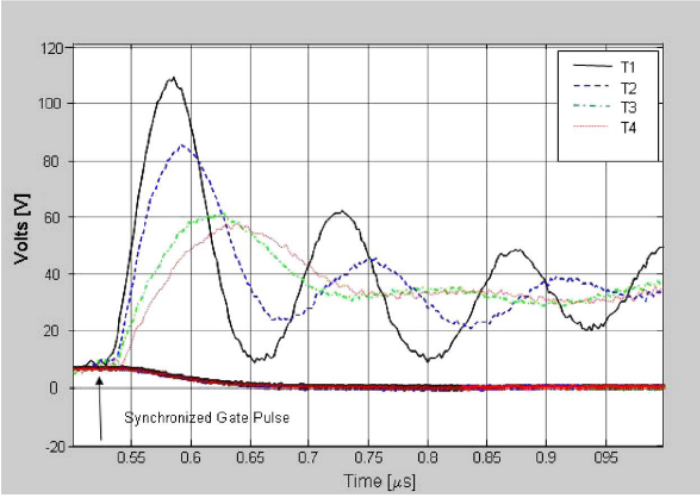
IGBT Prognostics

- Xiong et al. [11] proposed an online diagnostic and prognostic system to predict the potential failure of an automotive IGBT power module. A prognostic check-up routine was implemented that would be activated at a preset frequency and current during vehicle turn-on and turn-off.
- Ginart et al. [12] developed an online ringing characterization technique to diagnose IGBT faults in power drives. Analysis of the damping characteristic allowed the authors to identify failure mechanisms



[11] Y. Xiong, Xu. Cheng, Z. Shen, C. Mi, H. Wu, and V. Garg, ―Prognostic and Warning System for Power-Electronic Modules in Electric, Hybrid Electric, and Fuel-Cell Vehicles,‖ IEEE Transactions on Industrial Electronics, Vol. 55, No. 6, pp. 2268-2276, 2008.

[12] A. Ginart, D. Brown, P. Kalgren and M. Roemer, ―Online Ringing Characterization as a Diagnostic Technique for IGBTs in Power Drives,‖ IEEE Transactions on Instrumentation and Measurement, Vol.58, No.7, pp.2290-2299, 2009.

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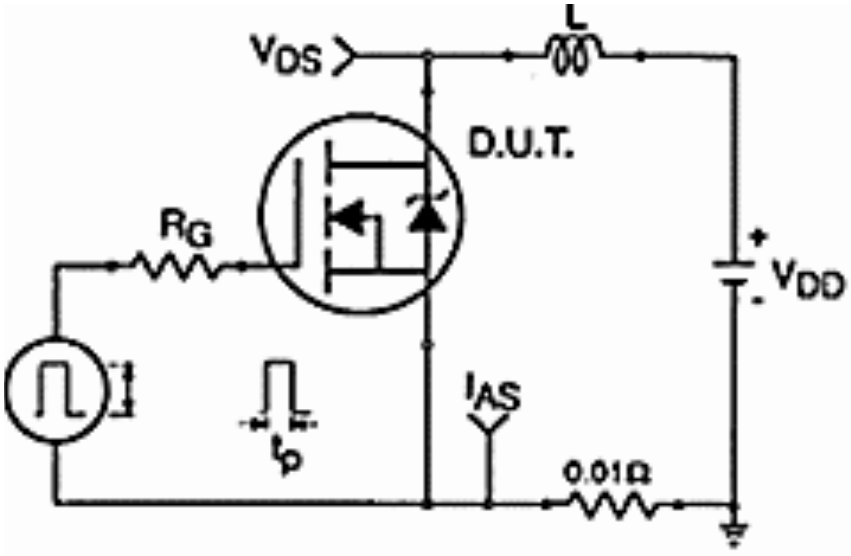
Unclamped Inductive Switching (UIS) Current Imbalance

- IGBTs operated with inductive loads can experience voltages well above their breakdown rating if no voltage clamp is implemented
- Voiding and delamination caused by either aging or voiding leads to current imbalance within the IGBT cells, causing local heating



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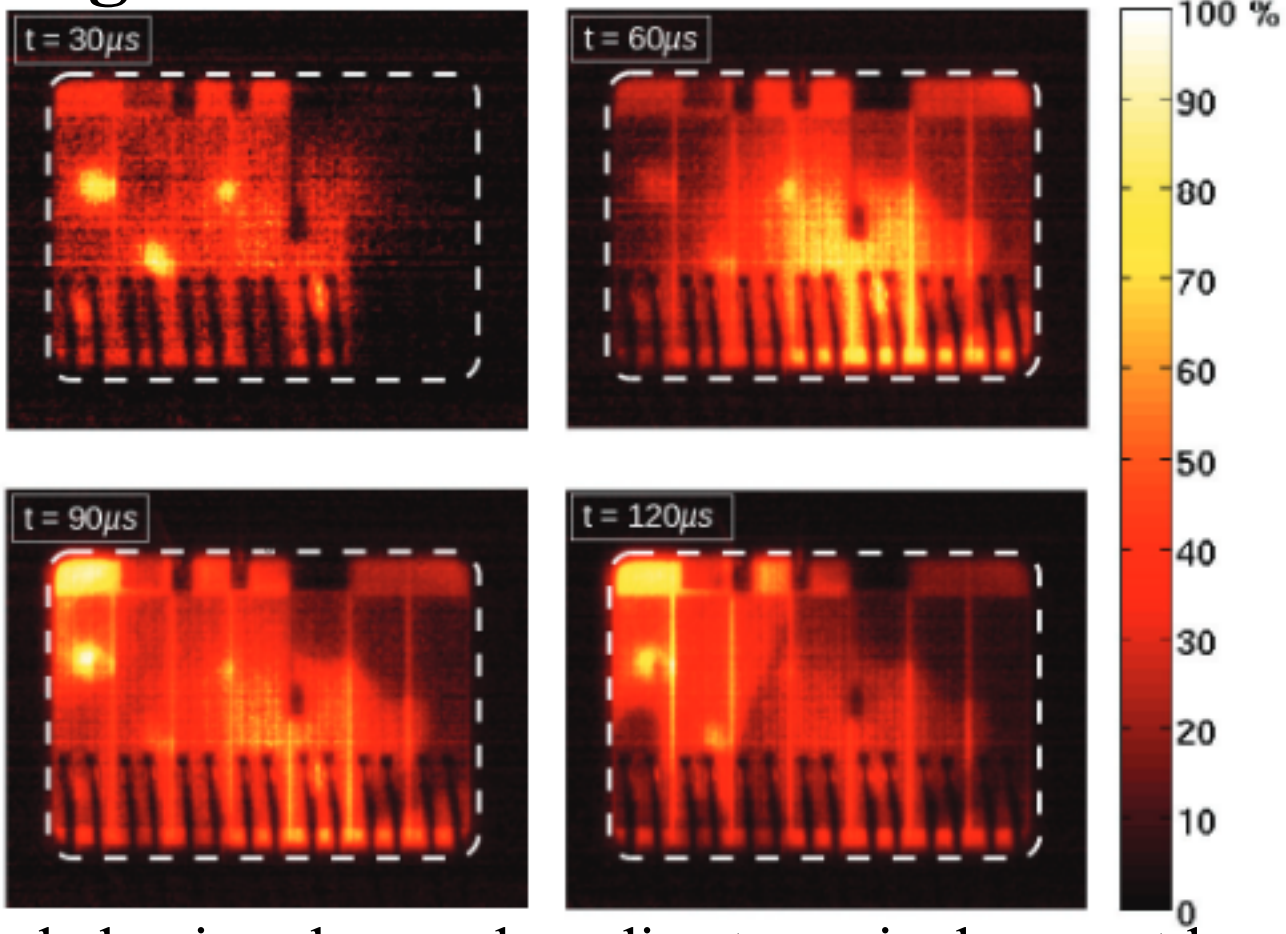
Heating within IGBT under UIS Conditions



Unstable behavior observed on die at nominal current localized heating [13]

[13] M. Riccio, A. Irace, G. Breglio, P. Spirito, E. Napoli, and Y. Mizuno, "Electro-thermal instability in multi-cellular Trench-IGBTs in avalanche condition: Experiments and simulations," in Proc. IEEE 23rd Int. Symp. Power Semiconductor Devices and ICs (ISPSD), May 23–26, 2011, pp. 124–127.

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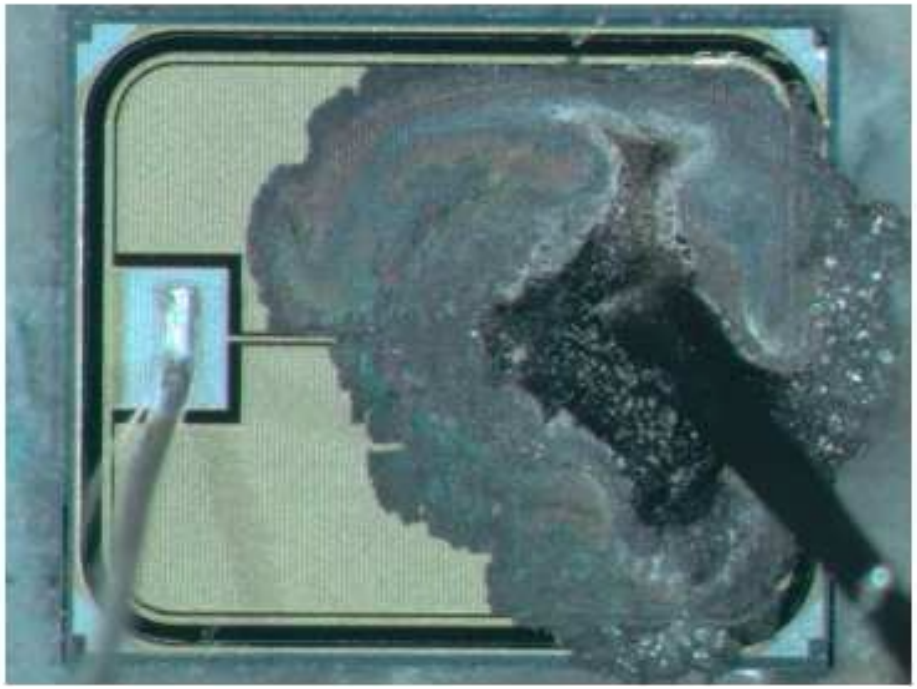
Dynamic Avalanche at Turn-off

- Similar to UIS conditions, dynamic avalanche can cause current imbalance between the cells of the IGBT
- Dynamic Avalanche can be self-induced if the gate resistance is too low causing high gate currents

Burned emitter contact pad for discrete IGBT



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Corrosion and Accelerated Testing

Rob Sorensen

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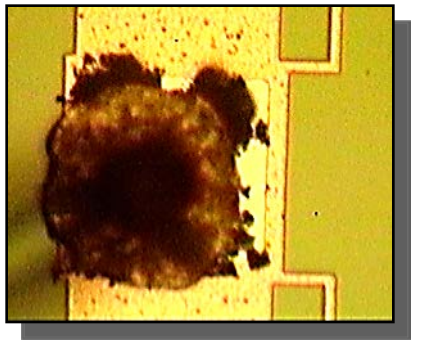
Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

What is corrosion?

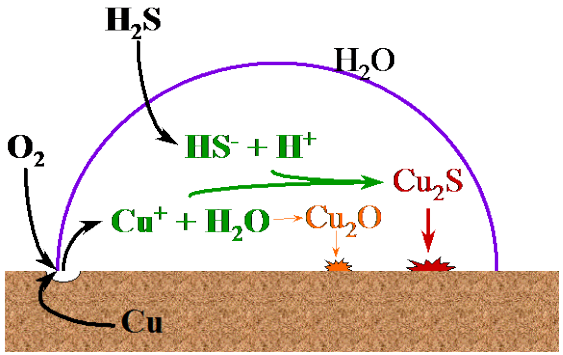
Environmental degradation of materials



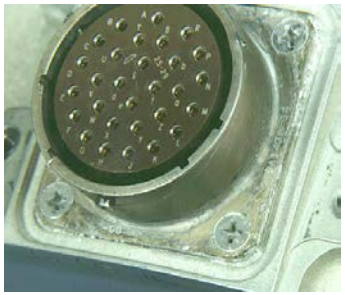
- Aqueous (general & localized attack)
  - electrochemical
  - oxidation / reduction
- Atmospheric
  - gas-metal reaction (slow)
  - condensed phase electrochemical
  - pollutant gasses (ppt levels of H_2S, NO_2, Cl_2 …)

Processing

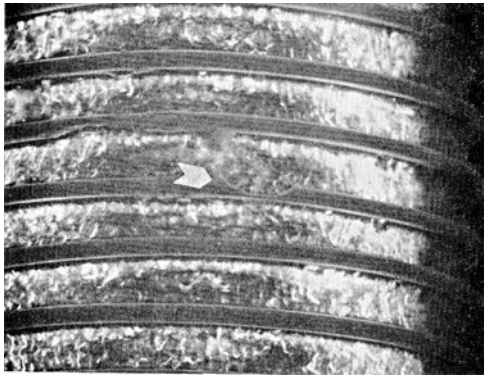
Use

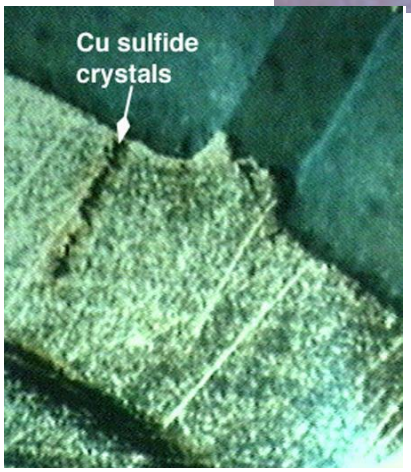


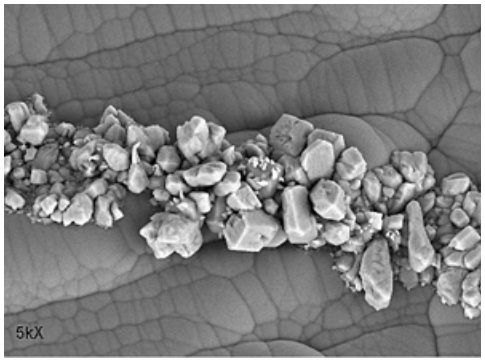
Corrosion normally occurs due to defects or unexpected environments

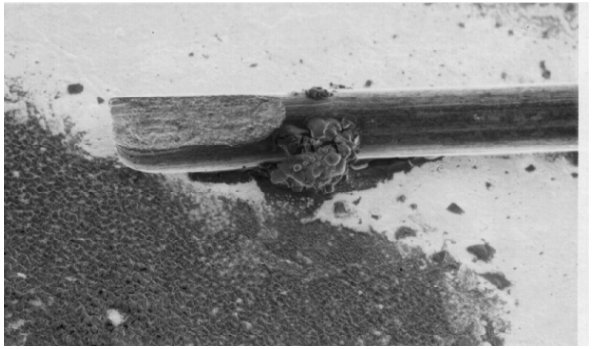


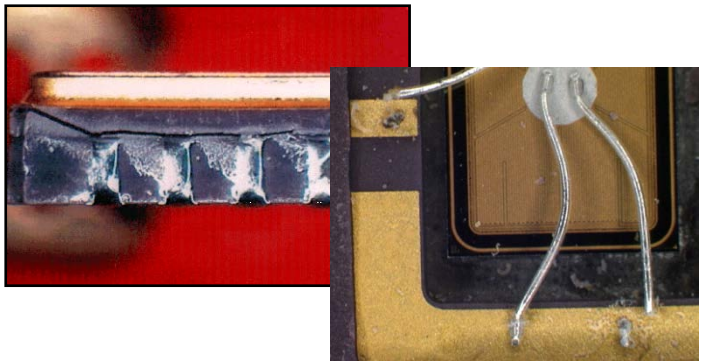
Cruise missile fuel line

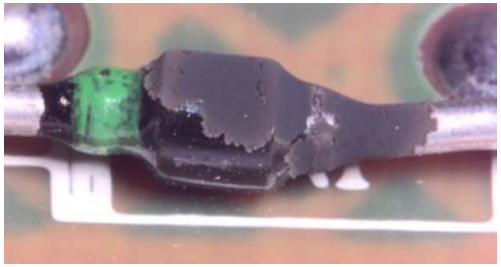


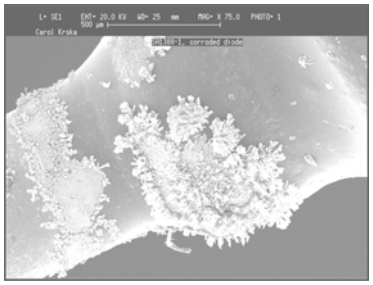




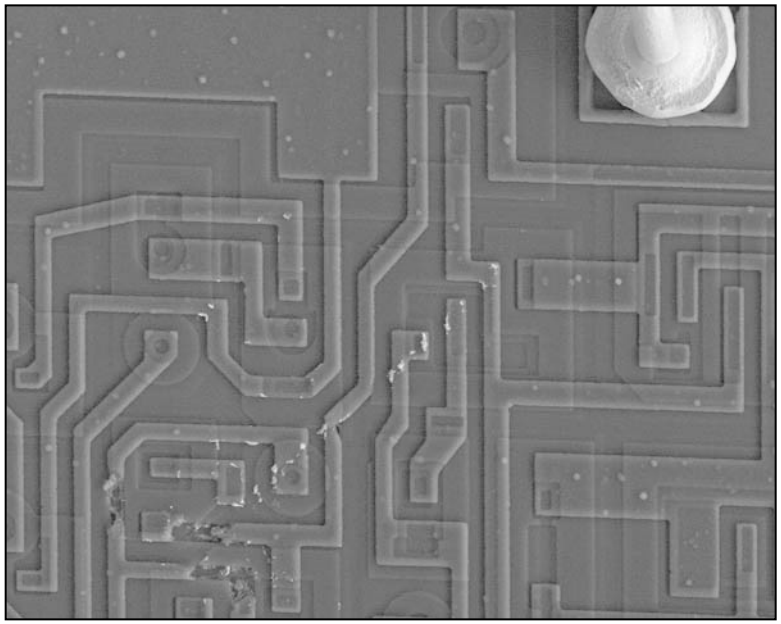


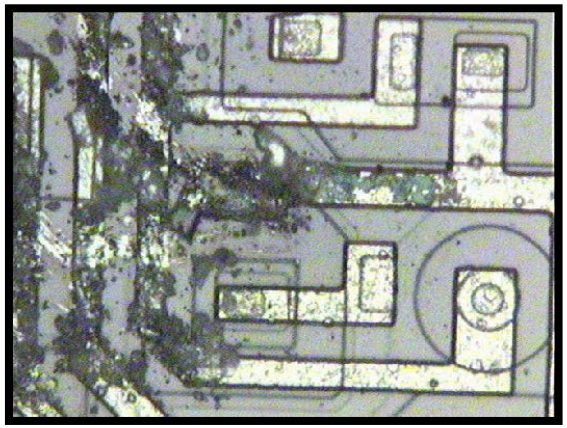






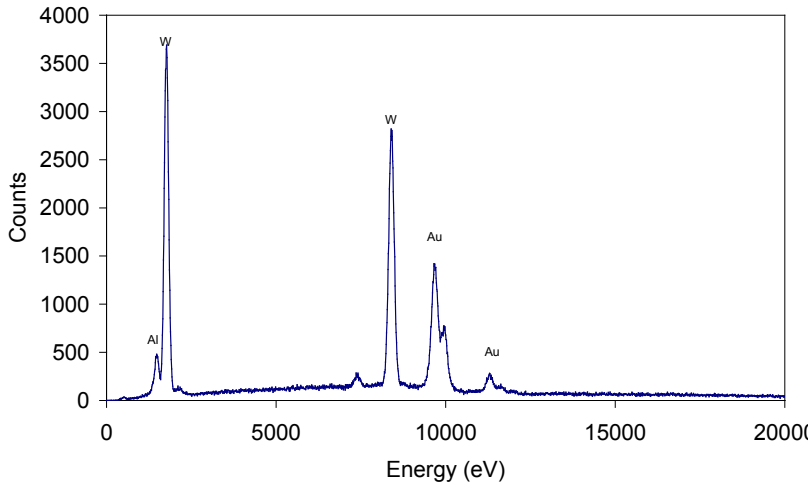
A plastic encapsulated IC failed after 5 years in dormant storage.





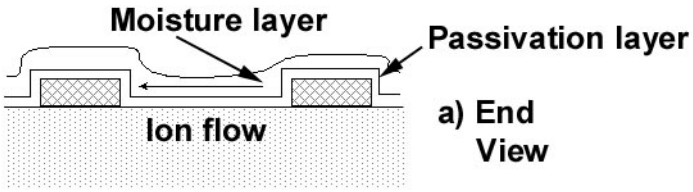
Defects:

- Damaged passivation
- Au (galvanic couple)

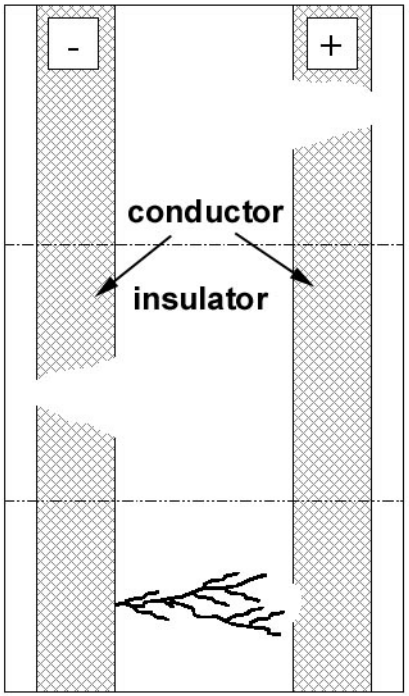


Several non-traditional corrosion mechanisms exist in microelectronics that involve electrical bias

- **Electrolytic dissolution**
- **Cathodic corrosion (alkalization)**
- **Electrolytic migration**



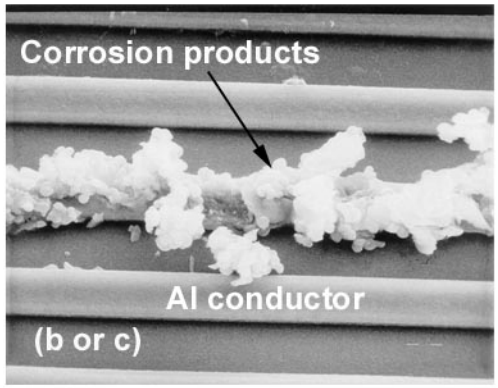
a) End View

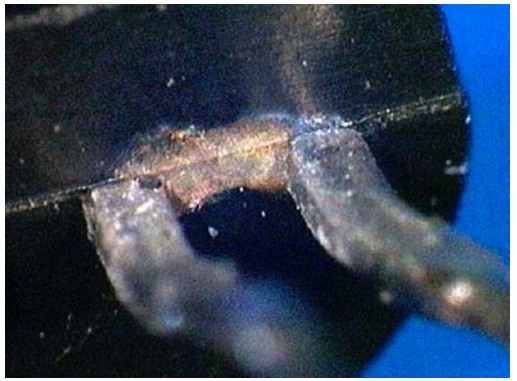


b) Electrolytic Dissolution

c) Cathodic Corrosion

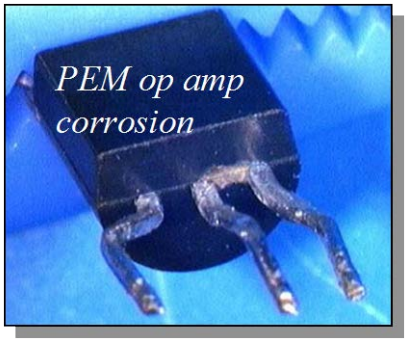
d) Electrolytic Migration



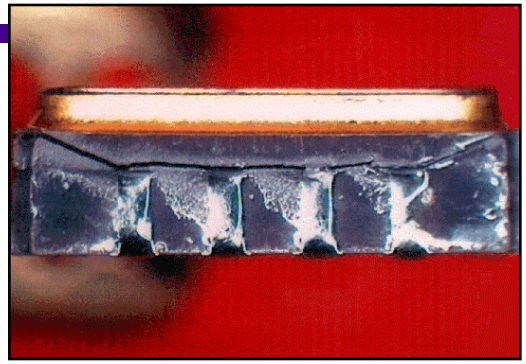


Conditions required for electrolytic migration

- Applied voltage
  - powered system
- Susceptible alloy
  - Ag used in ground plane
  - Solder
  - Copper
- Conductive surface
  - flux residue (activator)
- Electrolyte
  - High humidity
    - Temperature cycling
  - Seacoast environment (NaCl)



Corrosive environments can contact metallization features

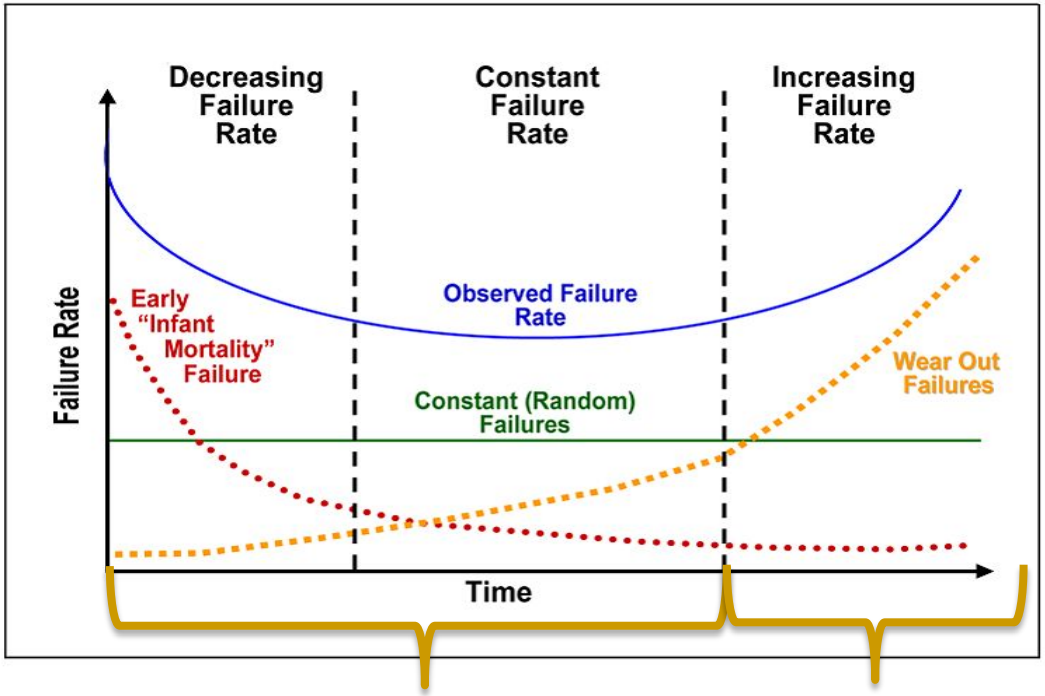


- **Breach in hermetic packaging in CHP**
- **Use of encapsulants in PEMs with high water permeability**
- **Specific unintended exposures (e.g., military)**
  - **high T, RH, [Cl-] possible**

Materials Degradation Affects Reliability

Probability of failure-free performance, item's useful life, or a specified timeframe specified environmental duty-cycle conditions.

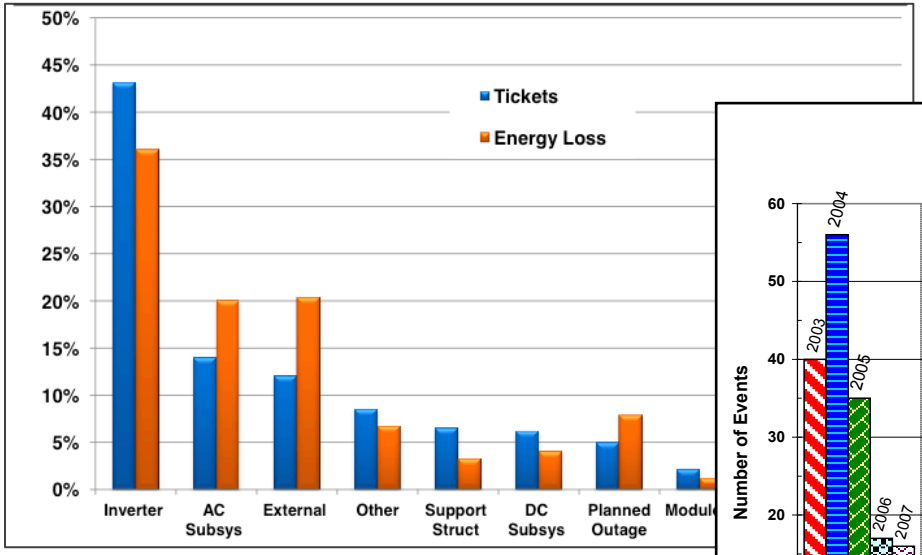
Reliability ⟷ Cost



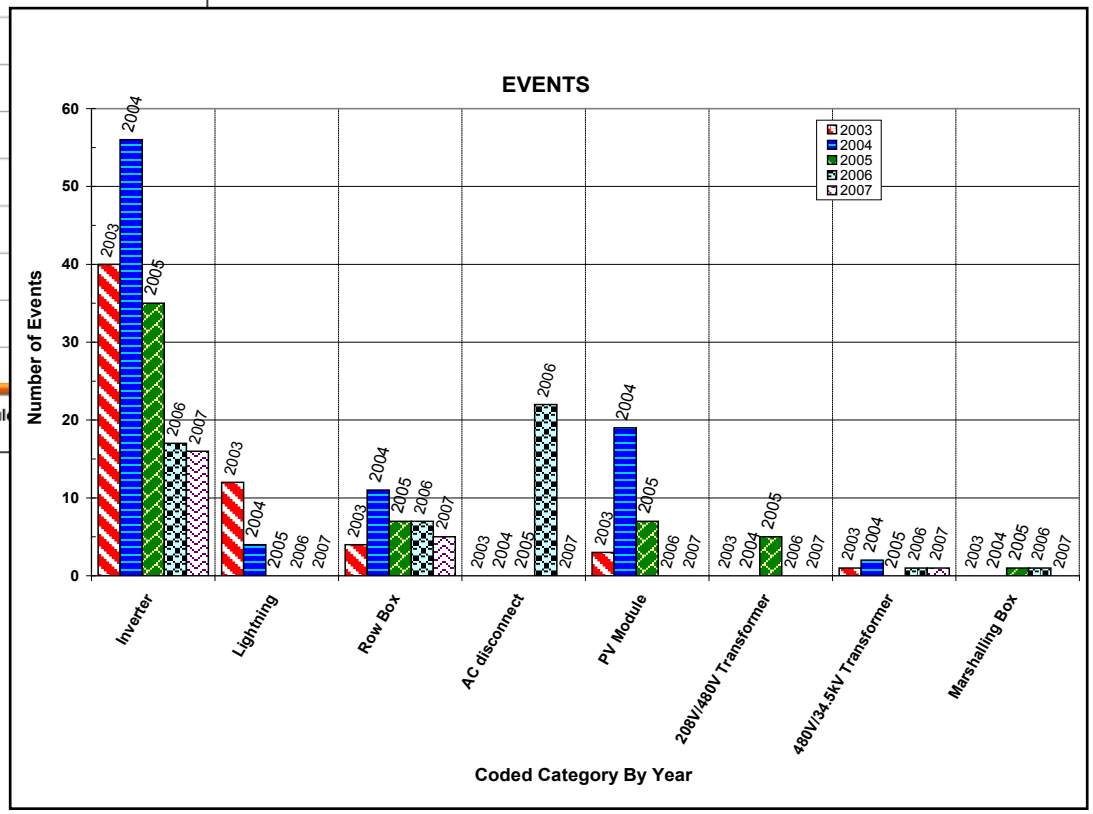
Accelerated testing plays a key role in determining reliability

- **Must be applicable to failure modes**
  - **Reproduce field failures**
- **Acceleration factor**
  - **Range of stresses**
  - **Long term tests**

The inverter is a significant contributor to reliability issues



Sun Edison – Owner/Operator (A. Golnas, "PV System Reliability: An Operator's Perspective," in 38th Photovoltaic Specialists Conference, Austin, TX, Jun. 2012, pp. 1–32.)



Tucson Electric Springerville Plant.

Sandia Study

What is ALT & why?

What?

- Component life tests
- High stresses
  - Single or combined
  - Activate “appropriate” failure modes
  - Measureable
- Time compression (cyclic stresses)
- Failure analysis

Why?

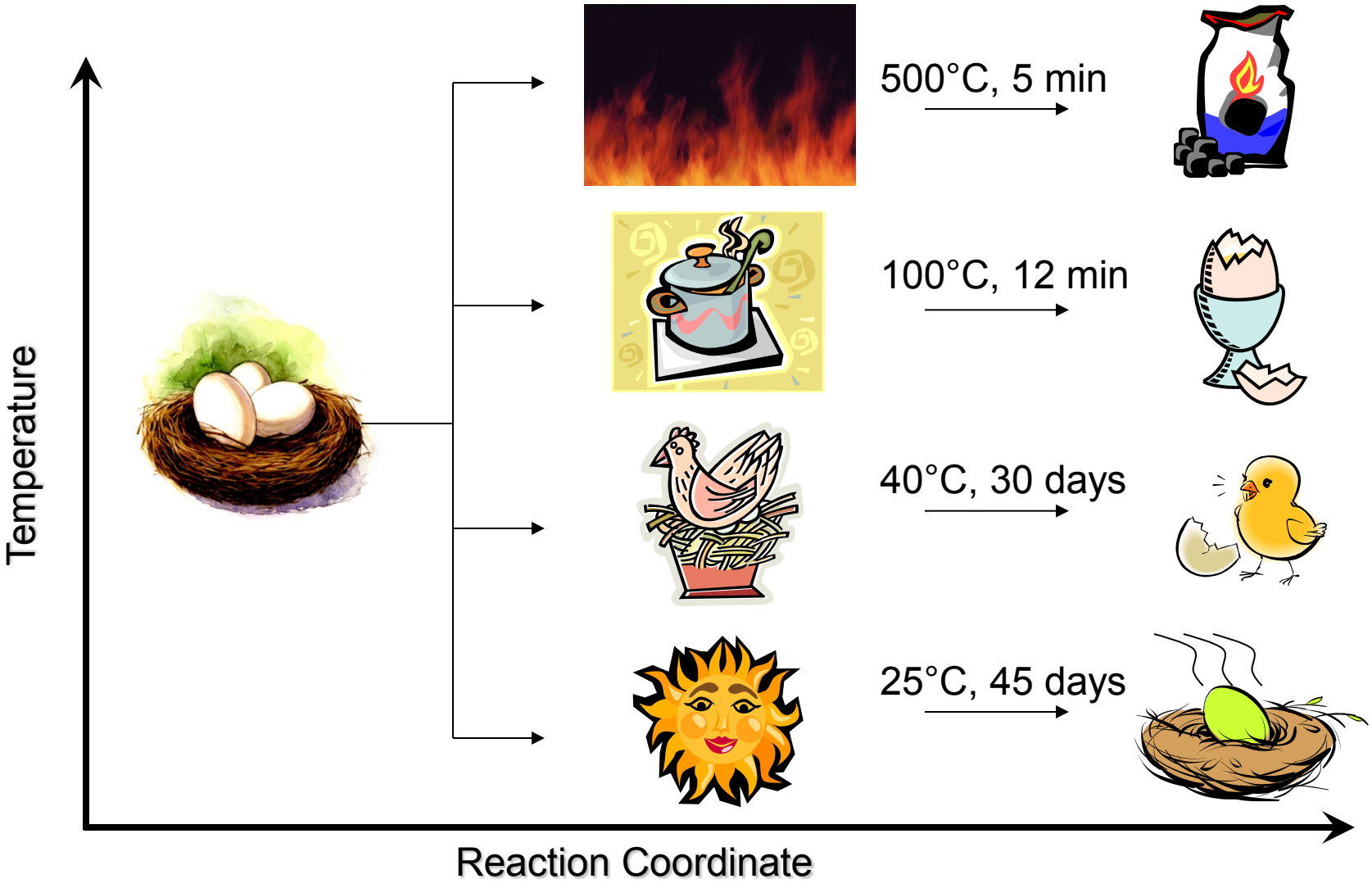
- Time
- Full system is expensive and complicated

Failure Modes for Crystalline Silicon
(John Wolgemuth – BP Solar)

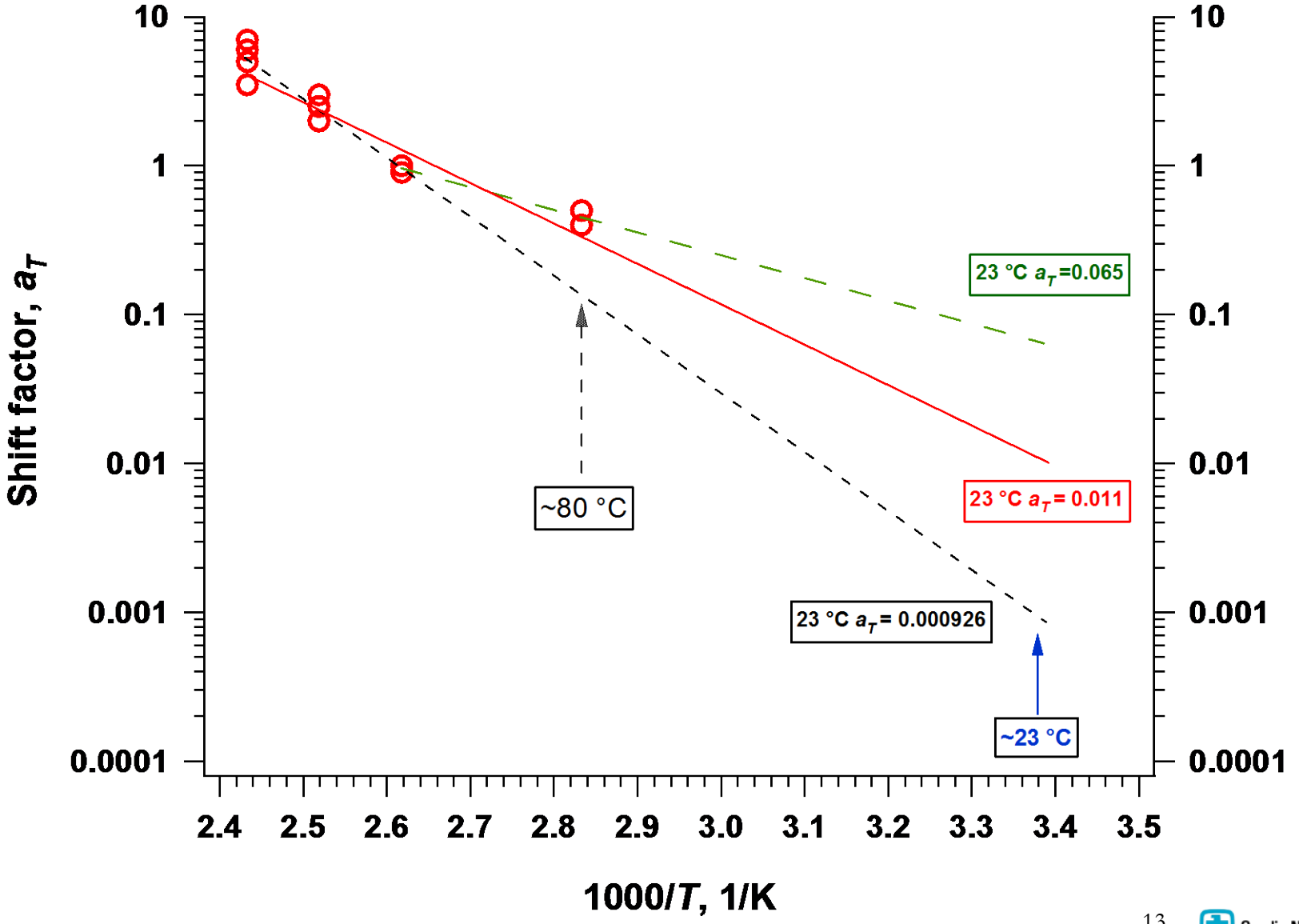
- Broken interconnects
- Broken Cells
- Corrosion
- Delamination and/or loss of elastic properties
- Encapsulant discoloration
- Solder bond failures
- Broken glass
- Hot Spots
- Ground faults
- Junction box and module connection failures
- Structural failures

Would you expect a single test to capture all of the expected failure modes?

It is important to understand the degradation mechanism and select appropriate stress level

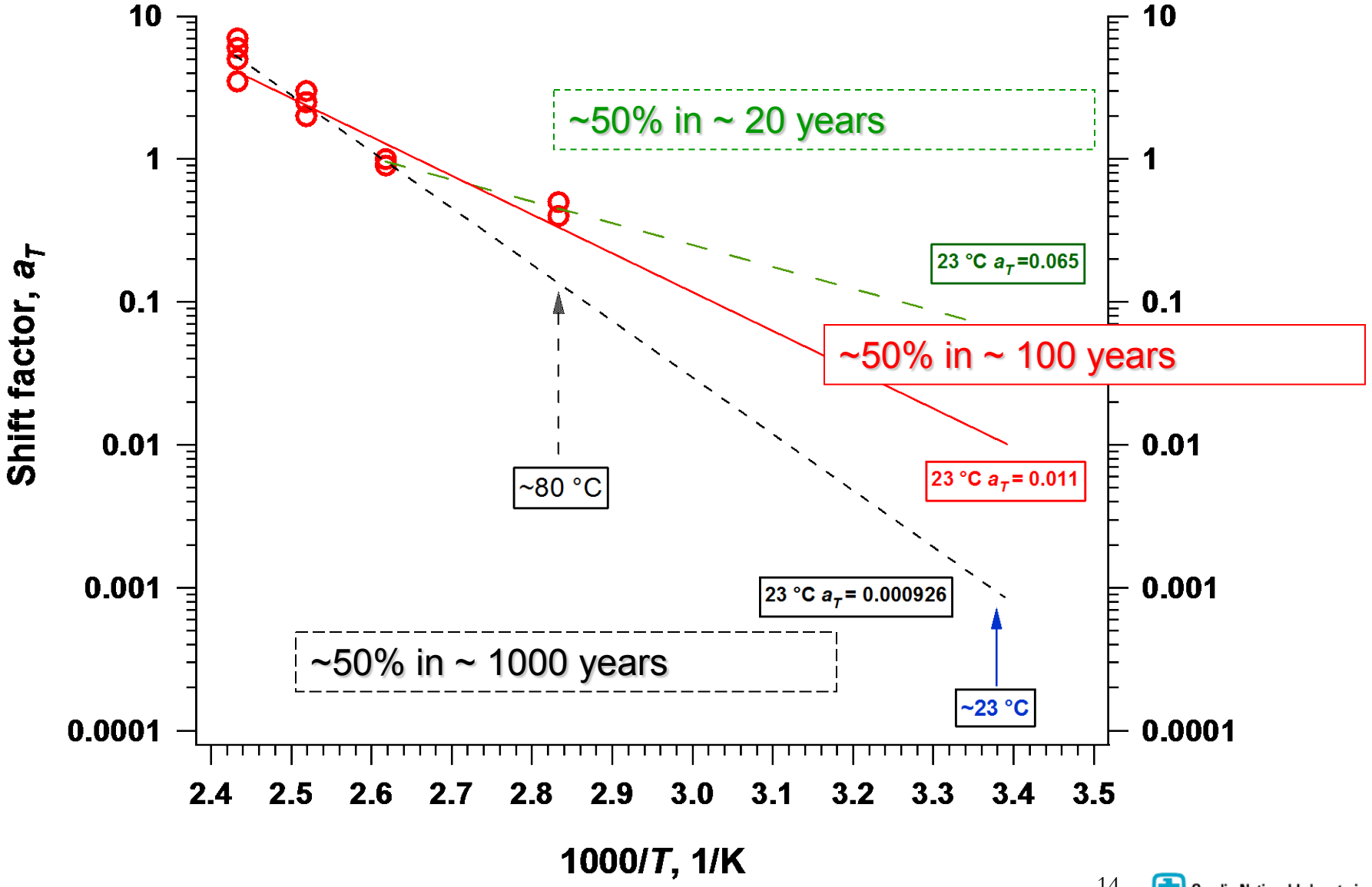


High T data are extrapolated to “use” conditions (room temperature)



Sandia National Laboratories

How you extrapolate can influence lifetime predictions.



Two approaches to accelerated testing are used throughout industry

➢ Qualitative Accelerated Tests

- HALT tests
- HAST tests
- HASS tests

} Small sample size
Severe level of stress

Increase reliability (product improvement)
Qualify new designs
Design quantitative ALT

Reliability under normal use conditions

➢ Quantitative Accelerated Life Tests

- Controlled application of accelerated stress
- Produces acceleration factors (AF)
  - Usage rate acceleration (Time compression)
  - Overstress acceleration

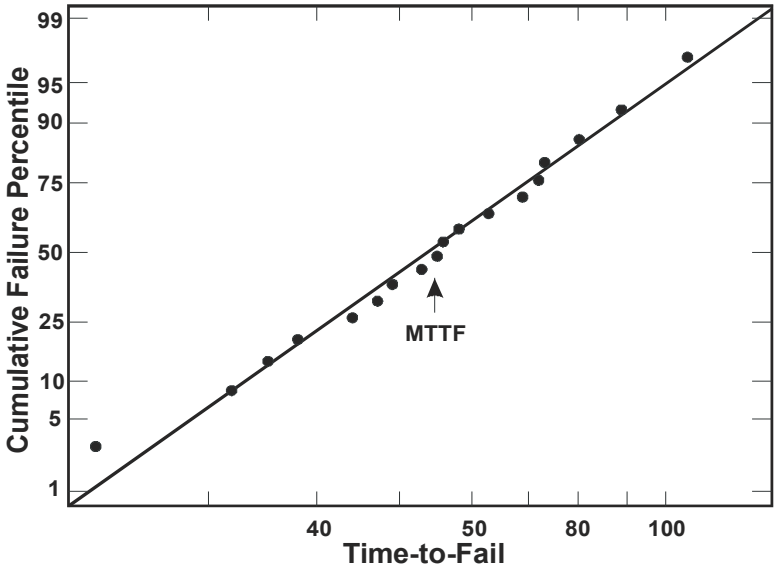
Used to determine TTF
Determine reliability

Long Time
Need degradation / failure mechanisms

The Goal of an ALT program is to produce acceleration factors

- **Often empirical correlations**
- **Limited root-cause analyses**

$$AF = \left(\frac{MTTF_{field}}{MTTF_{test}} \right)$$

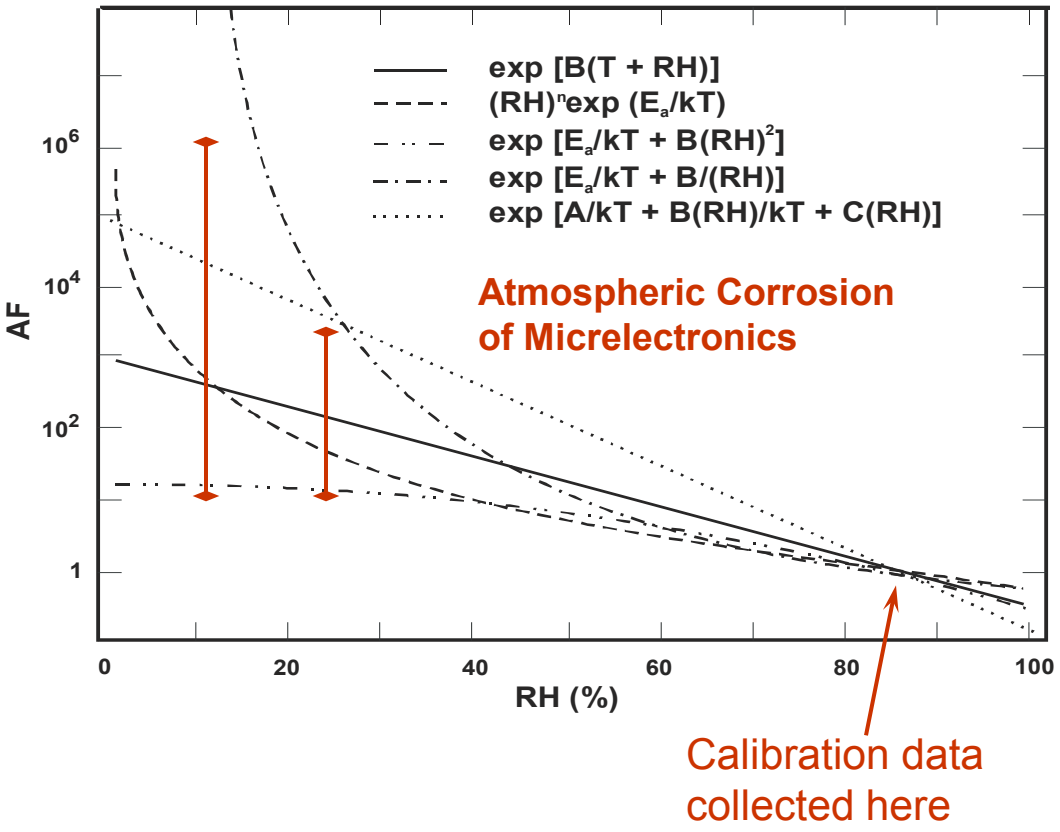


$$AF = \exp\left[\frac{E_a}{k} \left(\frac{1}{T_o} - \frac{1}{T} \right) \right] \left(\frac{RH}{RH_o} \right)^n \left(\frac{a + bV}{a + bV_o} \right)$$

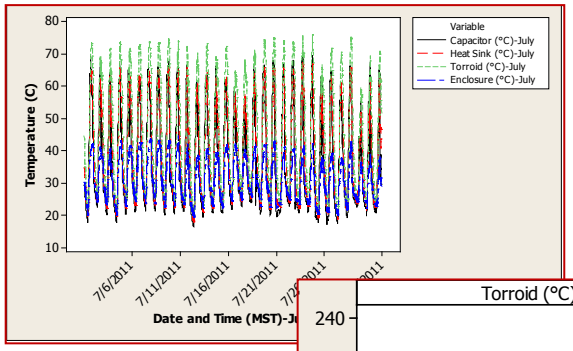
ALT must capture valid degradation / failure mechanisms

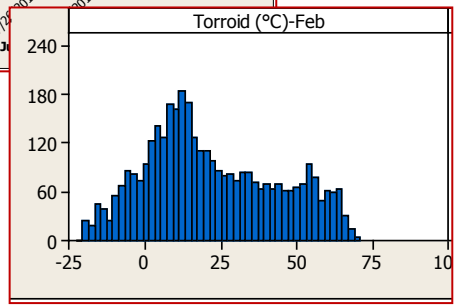
Example:

- Five recognized models for corrosion in micro-electronics
- All agree at 85%RH
- Disagreement at 10%-30% prevent uniform application of either model

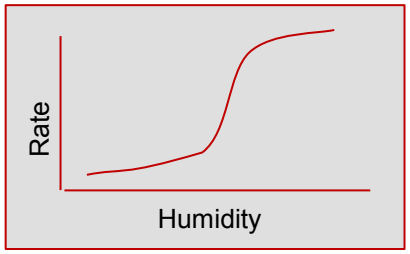


Acceleration factors depend on the stress characteristics





- Thermal (Arrhenius)
  - Activation energy
  - Verify no mechanism change
  - Bin damage by time at temperature
- ΔT
  - Linear (time compressions),
  - Increased temperature range
  - Frequency analysis (rainflow counting)
- Voltage
  - Linear (must understand relationship)
- Humidity
  - Tends to be complex (adsorbed water)

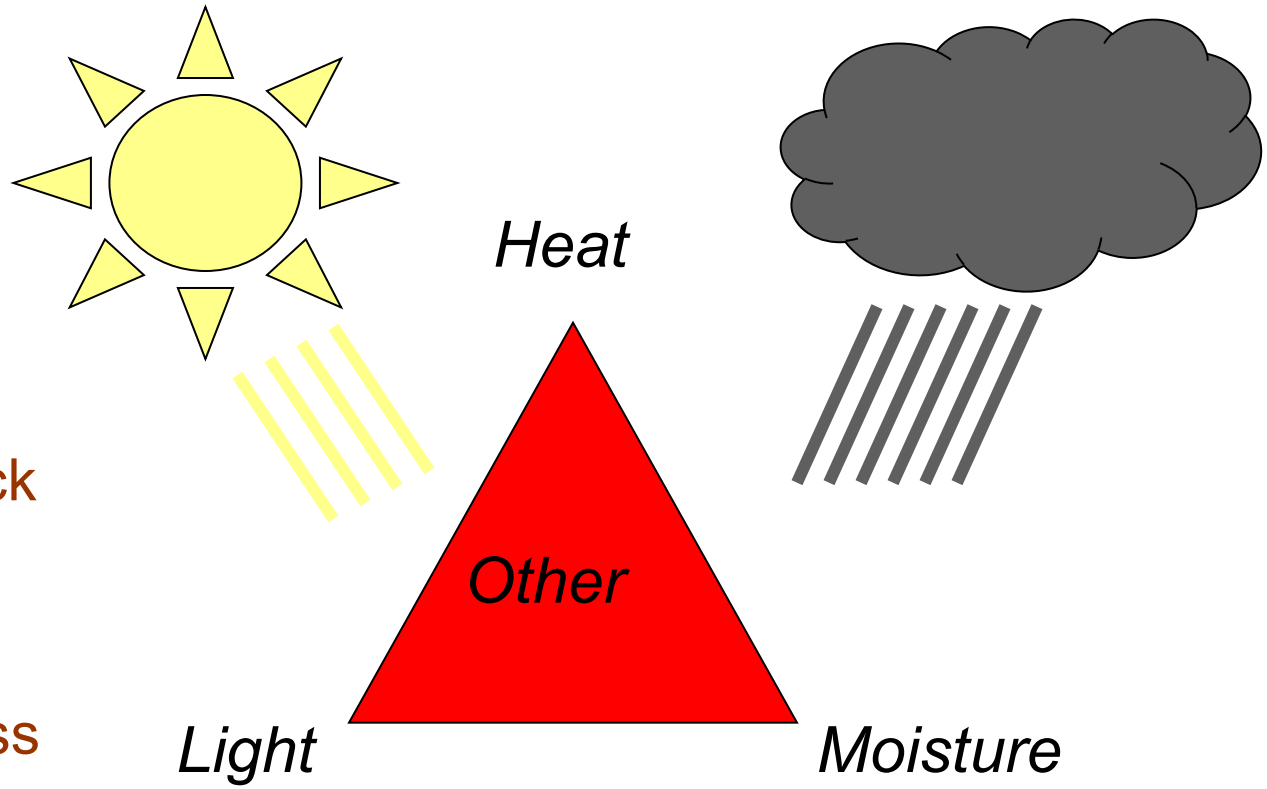


Issues with ALT

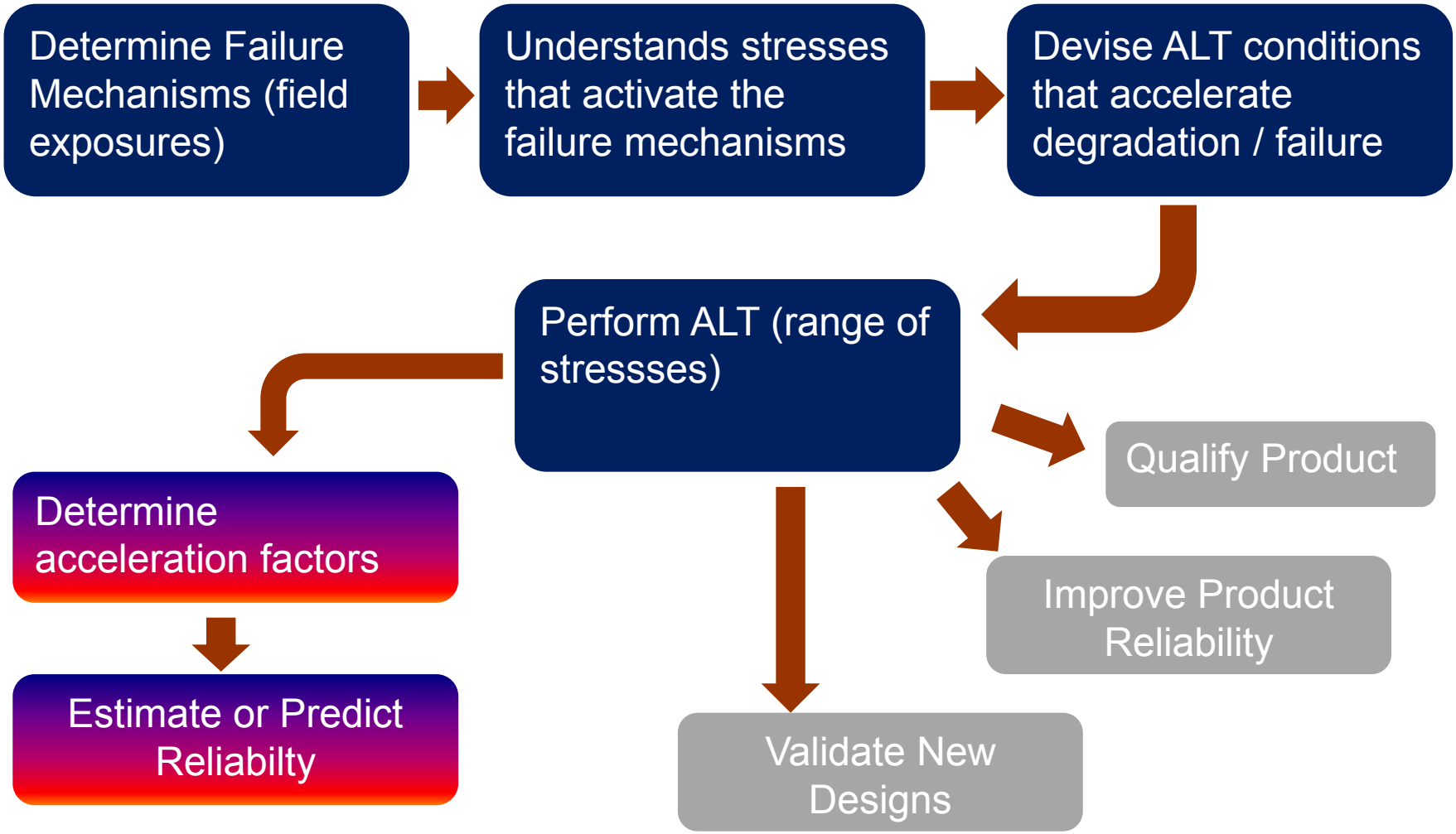
- Unknown failure mechanisms
- Unknown / variable use environment
- Changing mechanisms as function of environmental stress
- Difficult to control and characterize defects
- Long duration experiments
- Evolving / improving technology

What are the likely stresses that lead to Inverter Failure?

- Voltage
- Temperature
- Thermal cycling
- Thermal Shock
- Vibration
- Mechanical Shock
- Humidity
- Contamination
- Mechanical Stress
- ???
- ???

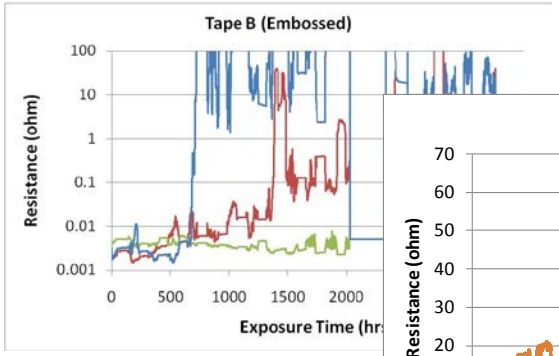


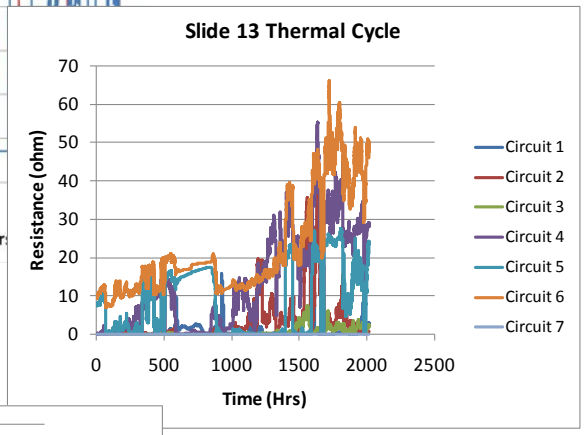
How do we apply ALT to predicting end-of-life (wear out)?

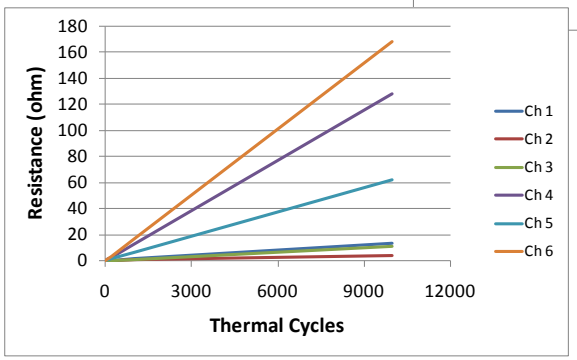


Analysis of metal foil tape degradation

Generate ALT data



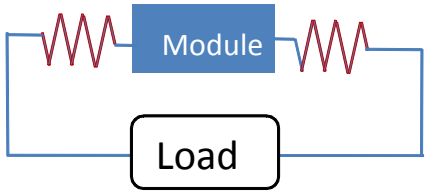




Develop "acceleration factors"

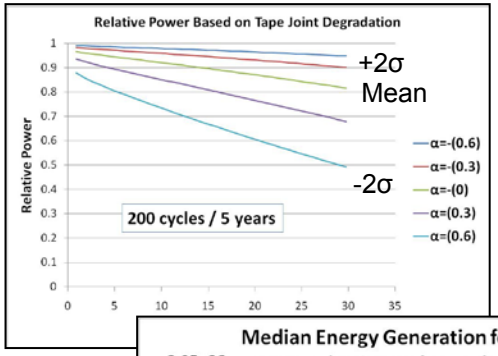
$$R = 10^{(0.028(\sqrt{t})+\alpha)}$$

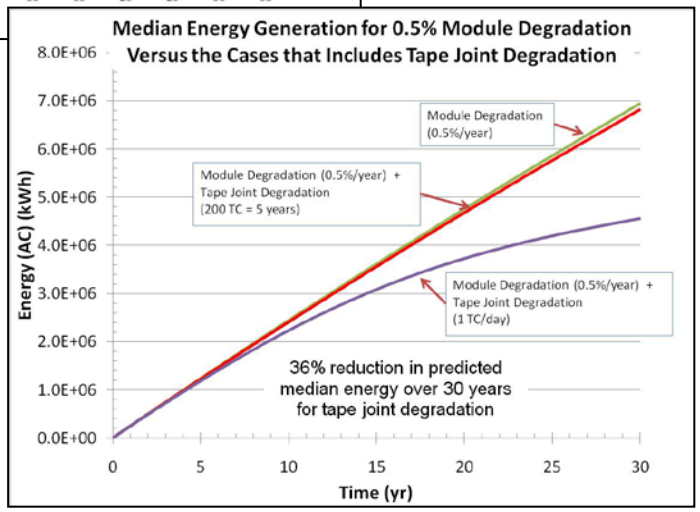
Determine performance effect



$$E = I \times R$$
$$P = I \times V = I^2 \times R$$

Apply acceleration factors to field





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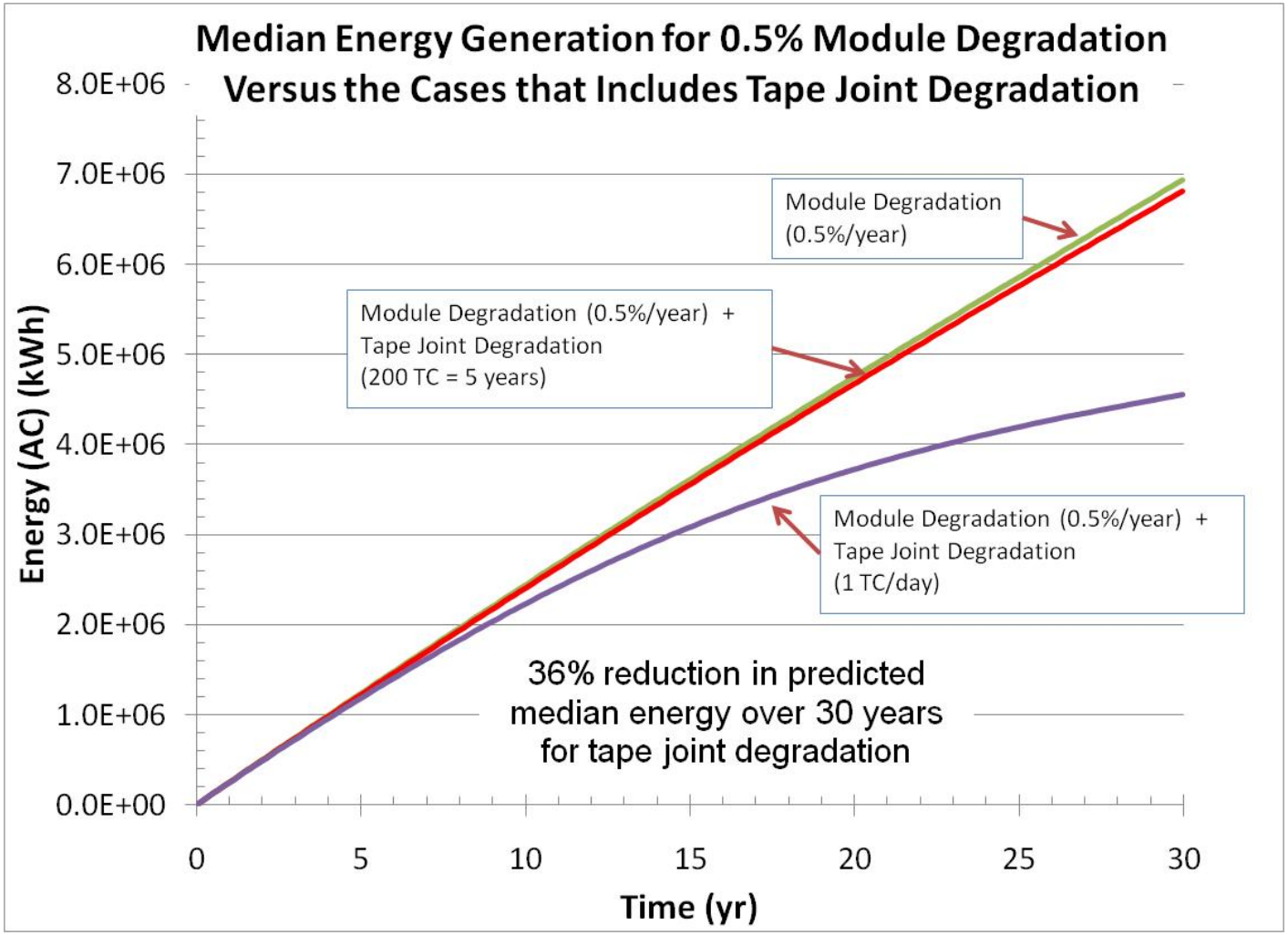
Use the ALT data to predict long-term performance degradation (wear-out???)



Summary

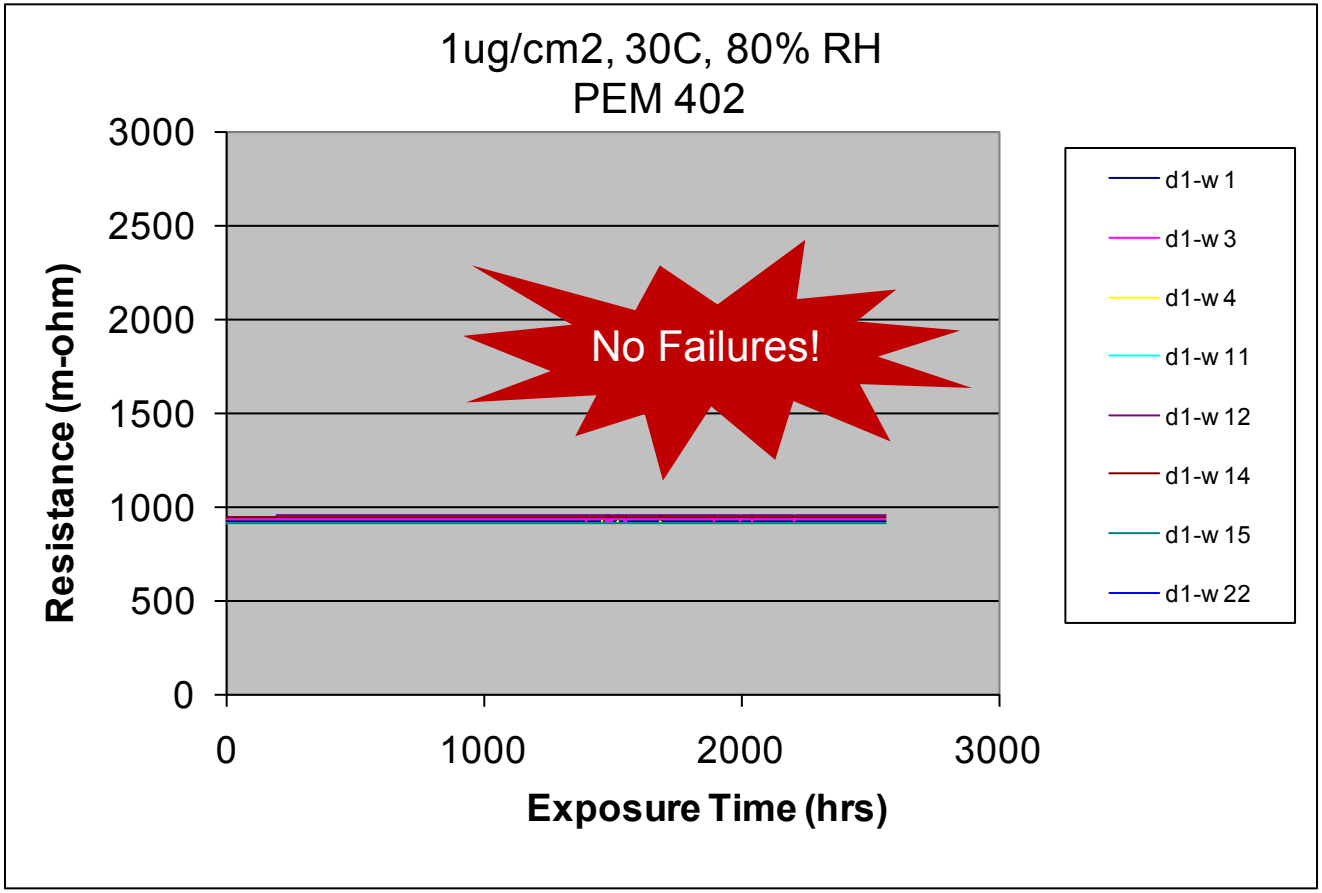
Accurate prediction of reliability is complex

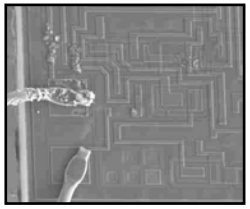
- Requires understanding of degradation processes
- Data Driven
  - Field data
  - Accelerated testing
- Effect on performance (what is failure?)
- Includes uncertainty

Extra Slides

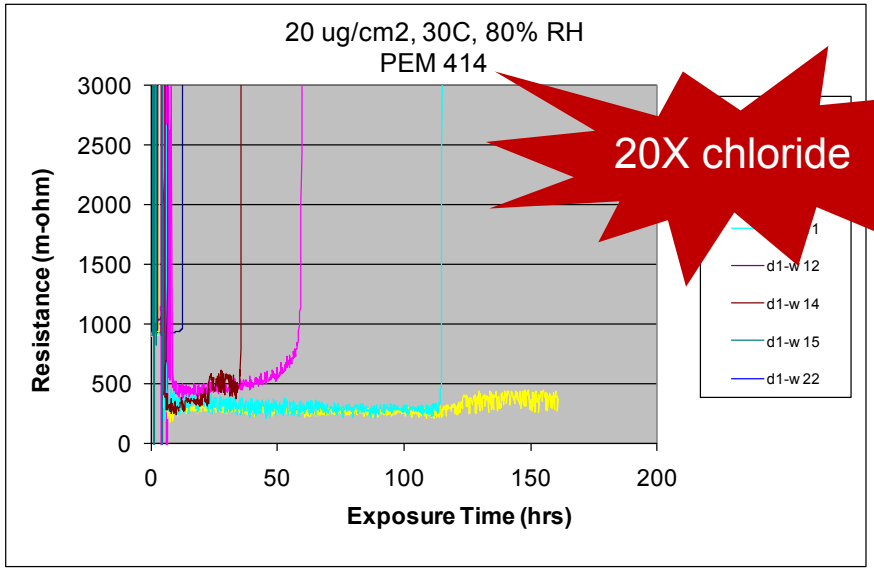
Example: Al bondpad corrosion: corrosion requires moisture and contamination & is accelerated by temperature.

Three environmental variables (T, RH, [Cl])





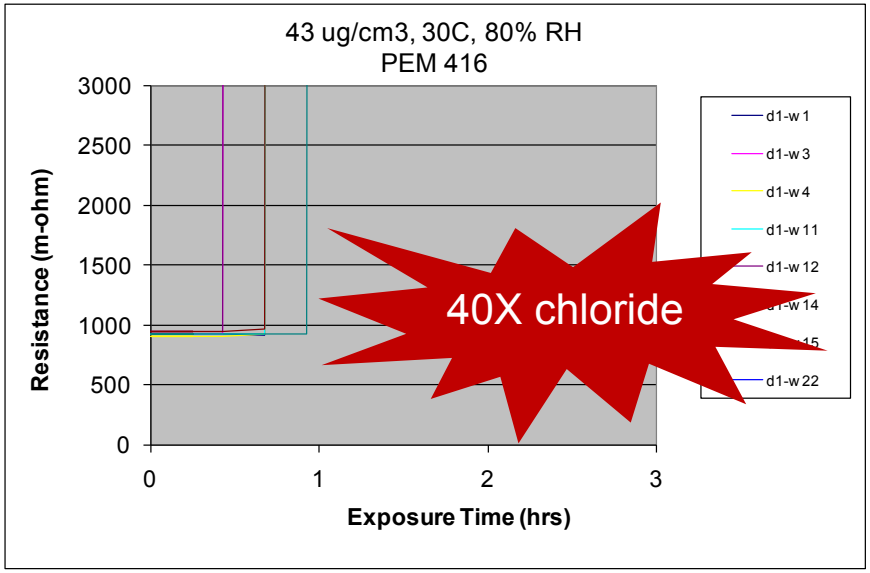
Increasing contaminant level causes failure.



Distribution of failure times

Not all failed

Clear effect of [Cl]



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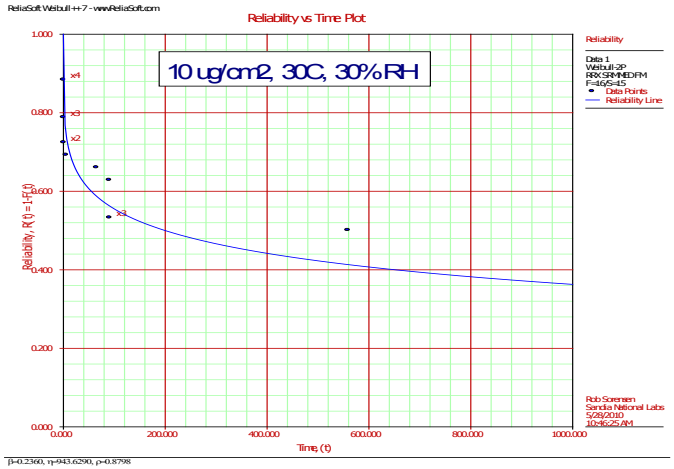
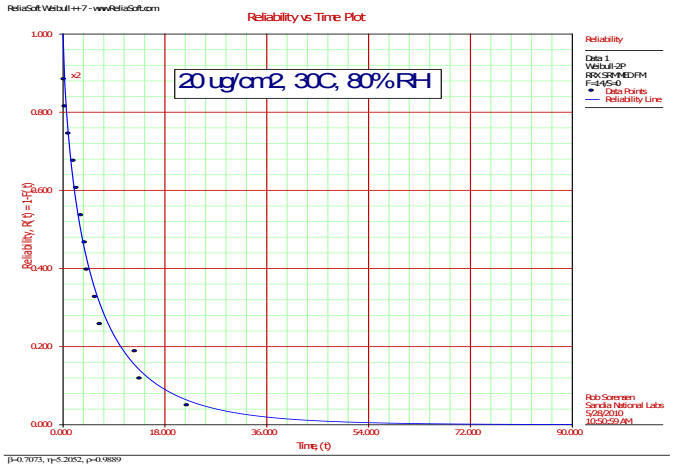
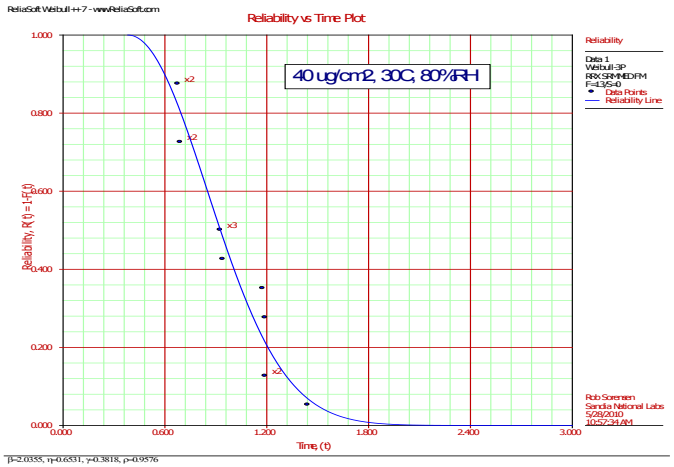
Statistical treatment (life-data analysis) provides a means of analyzing the bondpad data







$$AF = \left(\frac{MTTF_{field}}{MTTF_{test}} \right)$$

- Provides distributions
- Includes suspension results
- Basis for models {Pfail = f(T, RH, [Cl])}

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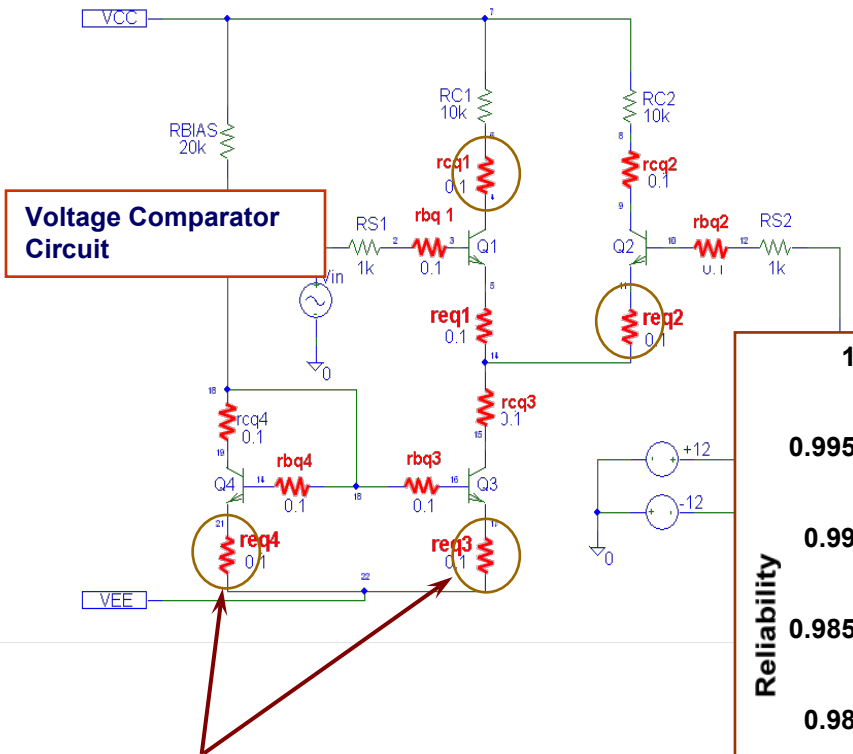
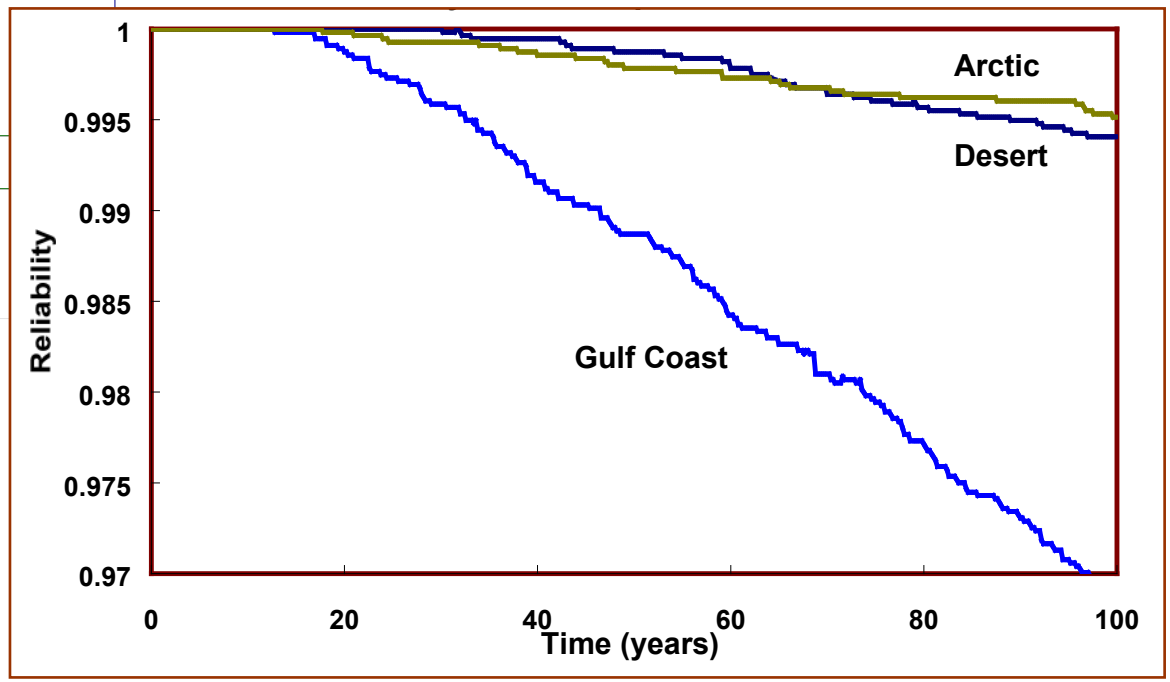
The distributed wirebond property (probability of failure) is input into an electrical system model & other component outcomes (reliability, performance threshold) can be determined

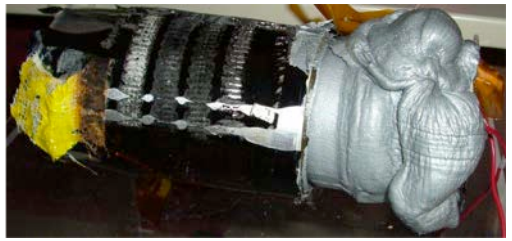


Bondpad corrosion is modeled as an additional series resistor

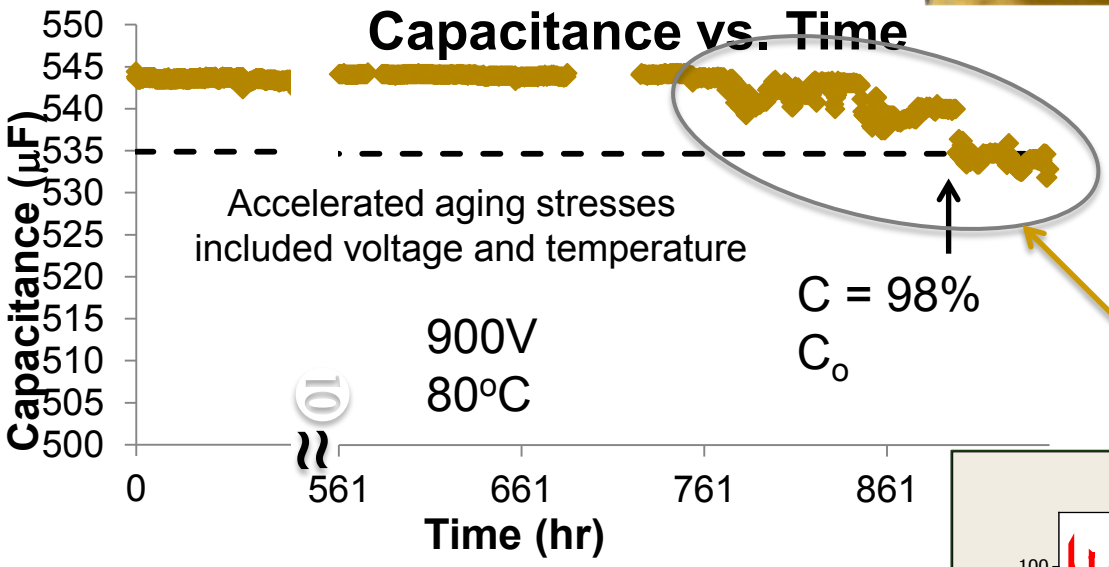
Prediction of the effect of corrosion on reliability as f(storage location)



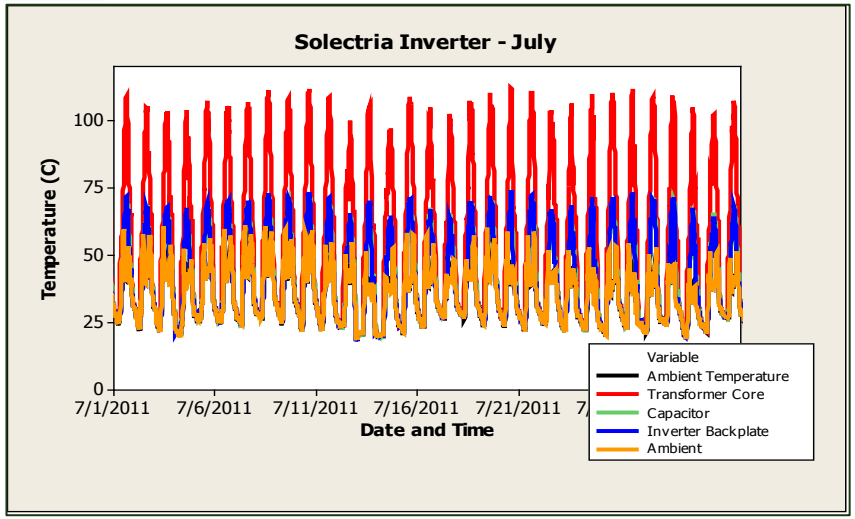
Accelerated aging induced capacitor degradation.



Capacitor failed in accelerated testing



Pre failure signature



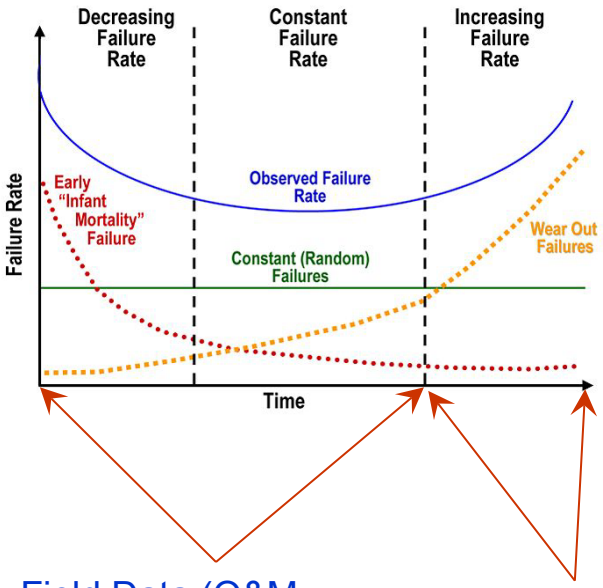
Accelerated Aging

Voltage & Temperature

Capacitor failure

Failure pre-cursor (decreased capacitance)

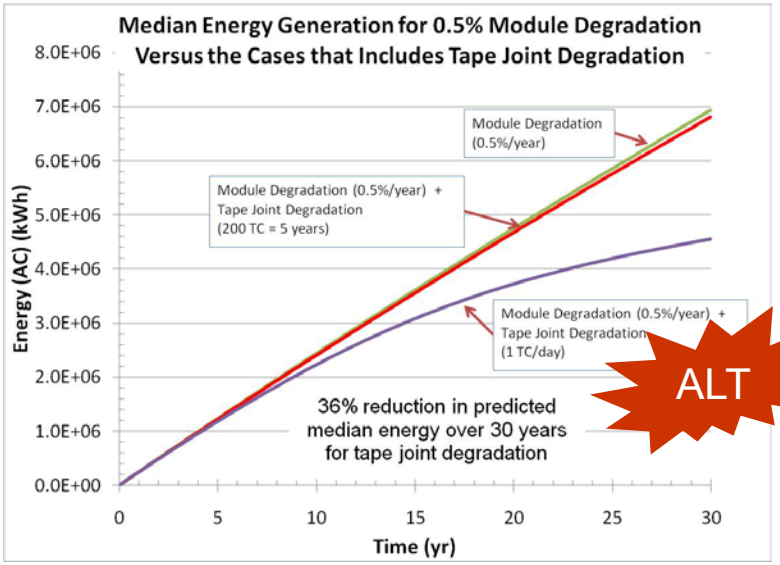
Laboratory testing provides vital information for PV system reliability

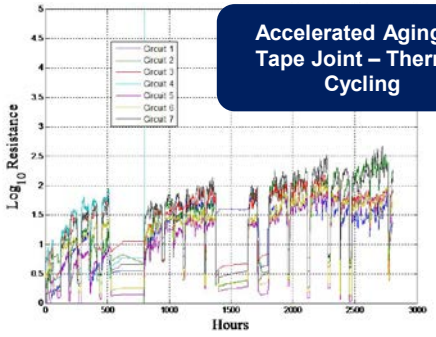


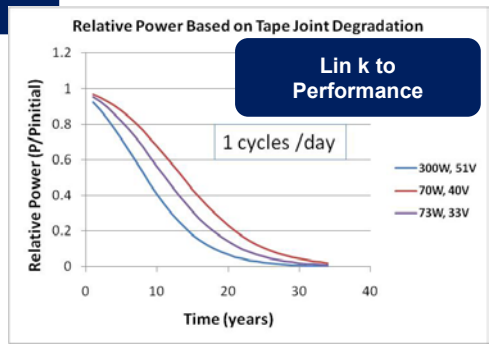
Field Data (O&M, Failures, …)

Accelerated Testing / Lab Tests

System performance model must include wear out (end of life) information





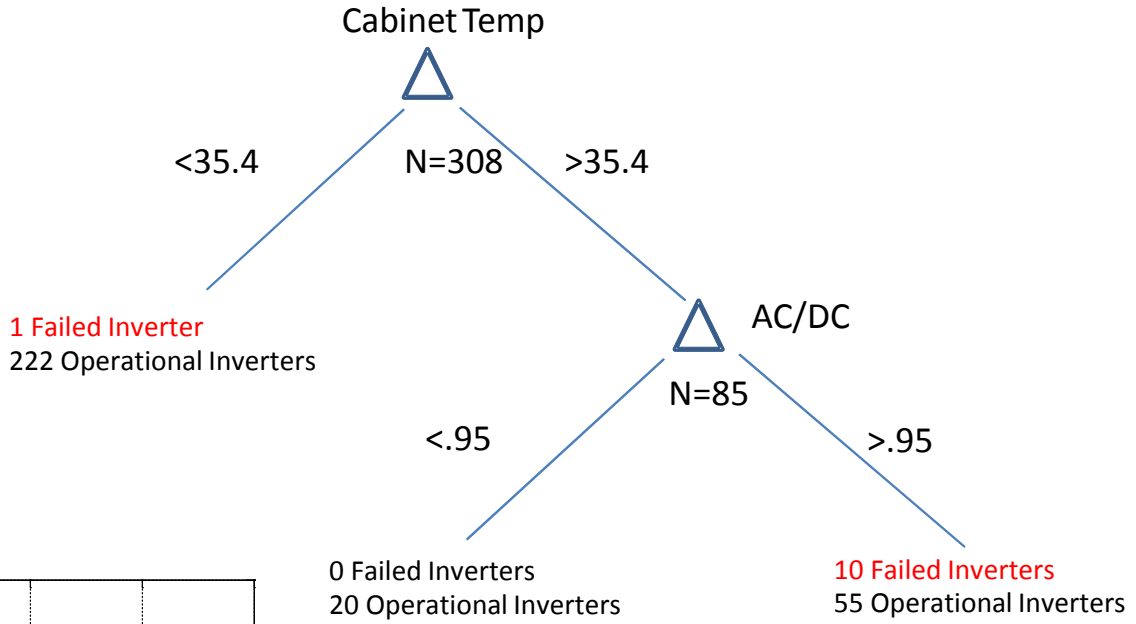


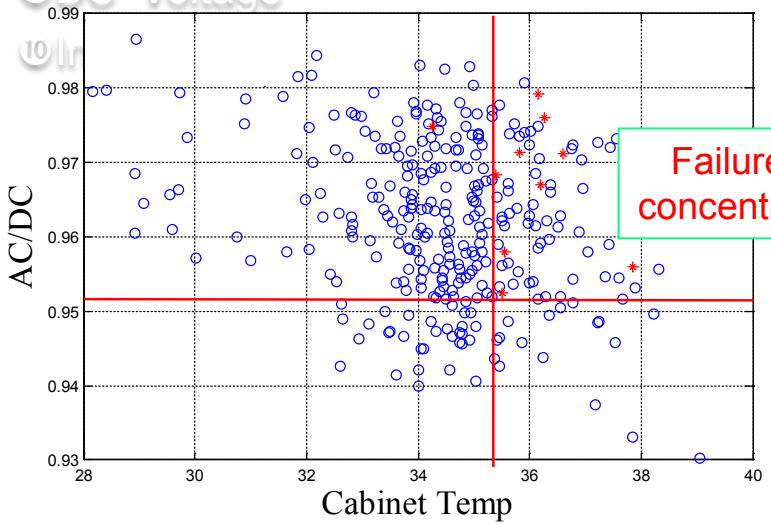
Acceleration Factors

Field failure data from very large plants indicate correlation between temperature and failure

Predictor Variables

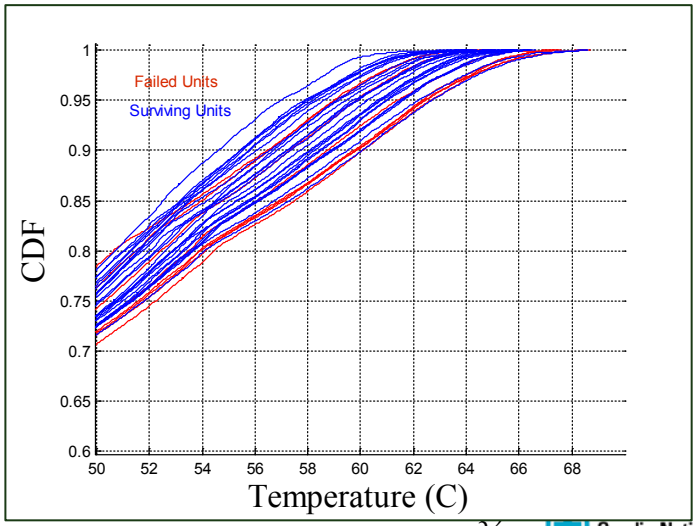
- AC_Power
- Cabinet_Temp
- Coolant_Temp
- DC_AC
- DC_Current
- DC_Power
- DC_Voltage
- In





Failures concentrated here

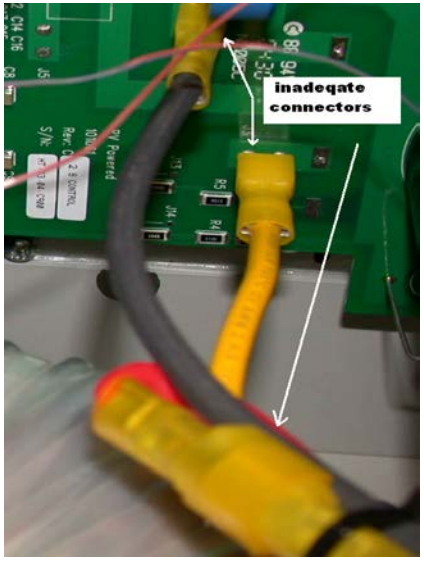
Data from large plant

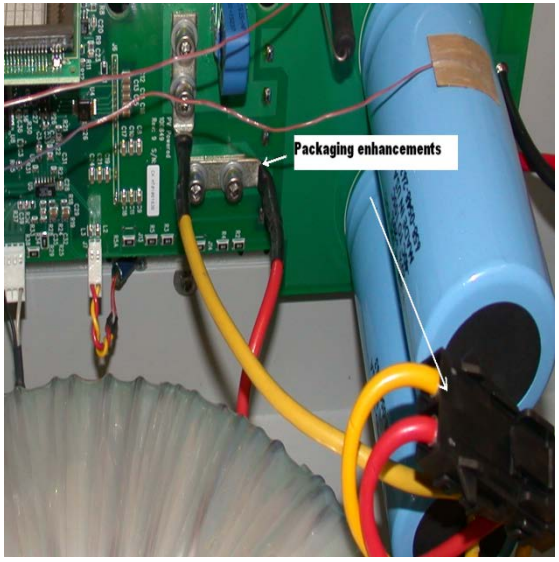


Sandia National Laboratories

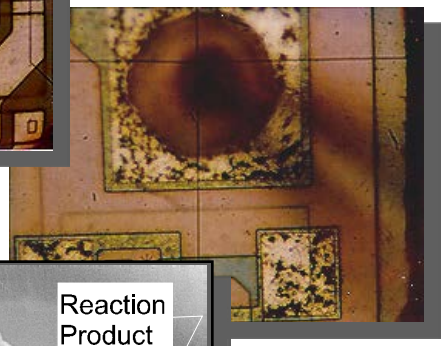
Accelerated Aging for Inverter Development

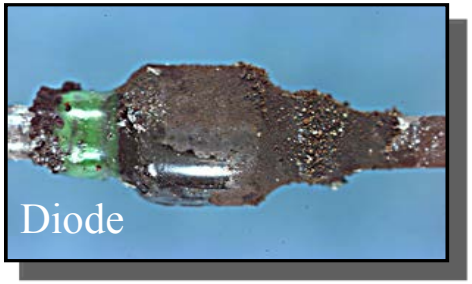
- No PV specific industry standard exists
- HALT testing is spotty; independently applied
- Separate needs identified for residential and commercial scale inverters
- Failure modes identified but not in a uniform program applicable across the industry
- System predictive models will require inputs for inverters

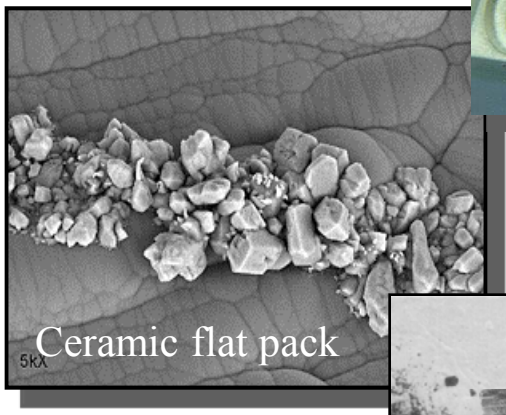


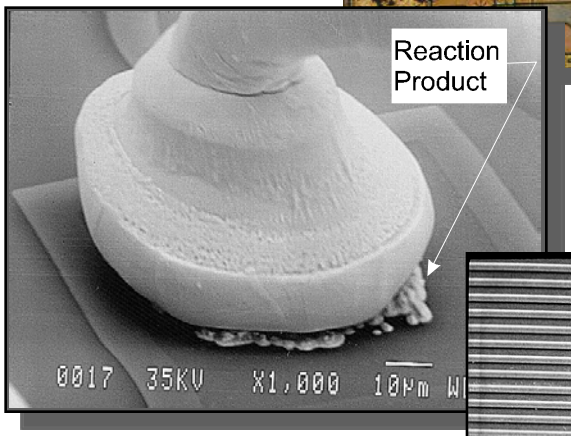


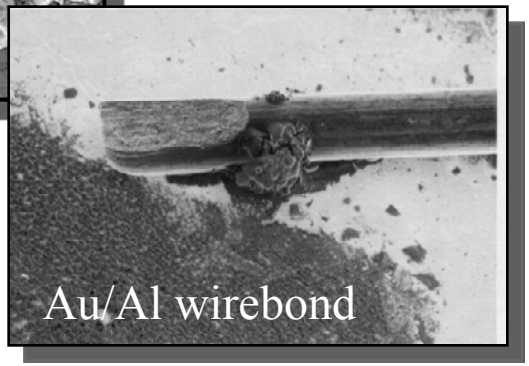
Atmospheric Corrosion





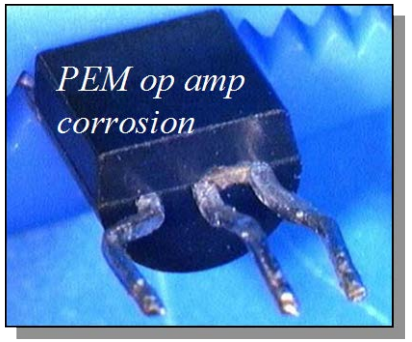






Examples of electrolytic migration

- LF amplifier - Puerto Rico
  - high humidity
  - seacoast environment (NaCl)
  - powered system
  - Ag used in ground plane
- Printed wiring boards
  - cyclic humidity
  - flux residue (activator)
  - powered electronics
  - Sn/Pb solder



DfR Solutions

reliability designed, reliability delivered

Nanocoatings: The Solution to All of Our Environmental Protection Problems?

2015 NREL Photovoltaic Module Reliability Workshop

February 25, 2015

Presented by Greg Caswell – DfR Solutions

Introduction

- Applying conformal coating or potting to provide environmental protection to electronics in outdoor applications is a very well-known and heavily used technique. This is especially true in solar and other green applications due to the severe environment (desert and tropical climates) and long-life expectations (25 years).
- A new class of nano-thin coatings that provide superhydrophobic capabilities have entered the marketplace with great fanfare. Superhydrophobicity is defined as having a wetting angle greater than 90 degrees and some materials have measured wetting angles exceeding 150 degrees.

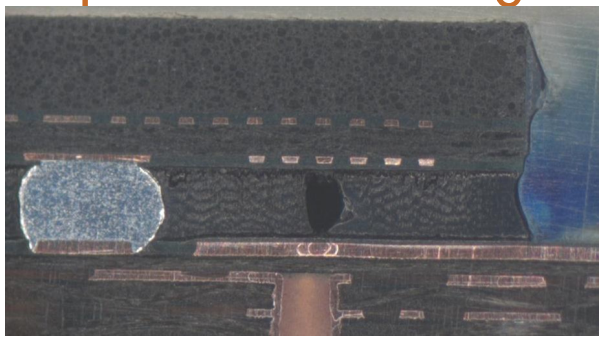
What's Wrong With Current Materials?

- Current conformal coatings all have their pros and cons
- Drives users to potting materials to compensate

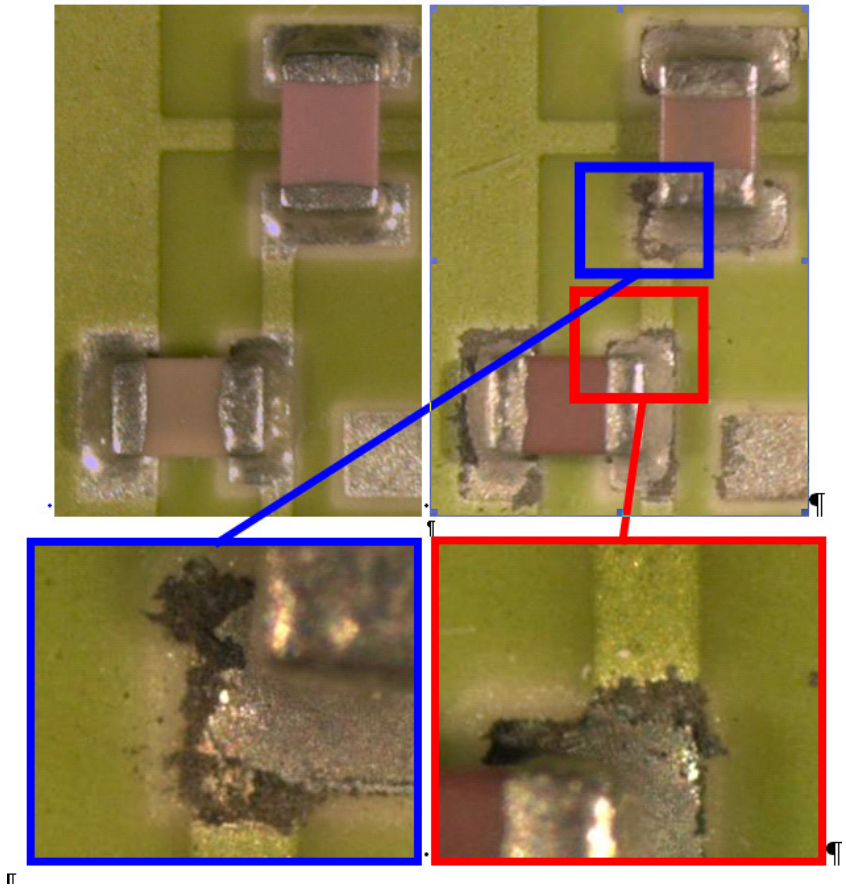
	Properties	Comments
Epoxy	Good adhesion Excellent chemical resistance Acceptable moisture barrier	Difficult to rework Needs compliant buffer Not widely used
Urethane	Good adhesion High chemical resistance Acceptable moisture barrier	Difficult to rework Widely used Low cost
Acrylic	Acceptable adhesion Poor chemical resistance High moisture resistance	Easy to rework Widely used Moderate cost
Silicone	Poor adhesion Low chemical resistance Excellent moisture resistance	Possibility of rework Moderate usage High cost
Paralyne	Excellent adhesion Excellent chemical resistance Excellent moisture resistance	Impossible to rework Rarely used Extremely high cost

Some Issues

- Coating getting under components – causing lifting



- Coatings are NOT hermetic – moisture will diffuse through

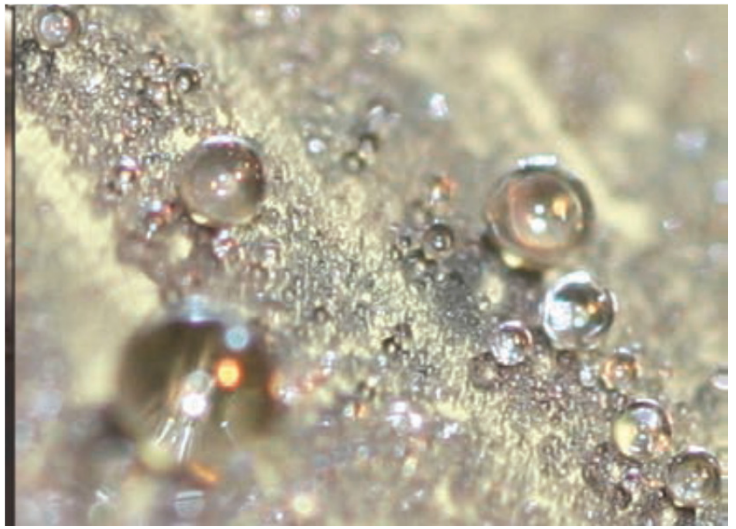


Sulfur penetration of Silicone – resulting in corrosion

DfR Solutions

Super Hydrophobicity

- Definition: Wetting angle far greater than the 90 degrees typically defined as hydrophobic
  - Can create barriers far more resistant to humidity and condensation than standard conformal coatings



- How to get there?
  - Deposit materials with existing high surface tension (e.g., Teflon)
  - Replicate the surface of the Lotus Leaf

Nanodeposition of High Surface Tension Materials

- Several companies currently focused on the electronics market

- The key technology for each company is the process, not necessarily the materials

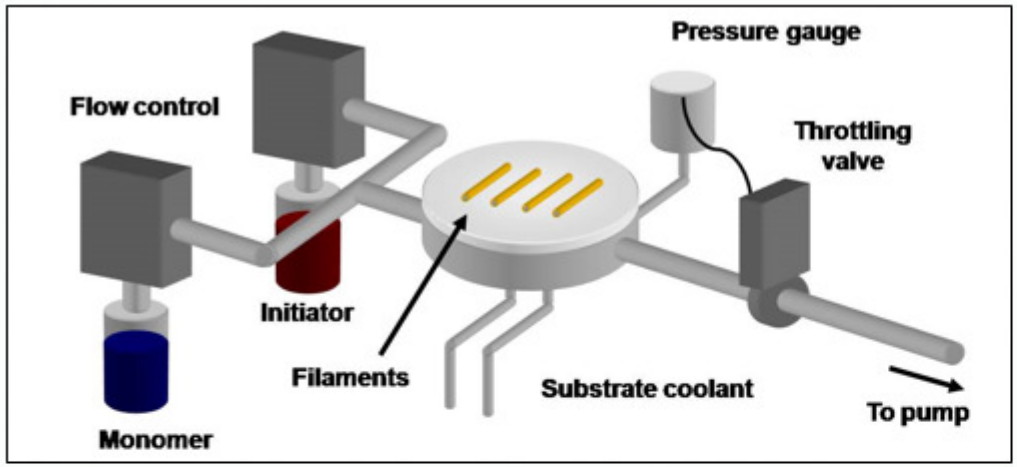
Nanocoating Companies

- GVD: Founded in 2001. Spinoff from MIT
  - Key technology is initiated chemical vapor deposition (iCVD) and PTFE and Silicone
- Porton Plasma Innovations (P2I): Founded in 2004. Spin off from UK MOD Laboratory and Durham University
  - Key technology is pulsed plasma and halogenated polymer coatings (specifically, fluorocarbon)
- Semblant: Founded in 2009. Spin off from Ipex Capital
  - Key technology is plasma deposition and halogenated hydrocarbon
- Barrian (Dry Surface) – Key technology is the integration of nanoparticles into existing conformal coating material to achieve superhydrophobicity
- ACT Nano Inc. -Key Technology is Advanced nanoGuard (ANG) that they say can be applied by dipping and is permanent because it is abrasion proof.

Process Technology

- Hydrophobicity tends to be driven by number and length of the fluorocarbon groups and the concentration of these groups on the surface
- The key points to each technology are:
  - Some are chemical vapor deposition (CVD) processes, with low vacuum requirements, Room Temperature Deposition Process
  - Variety of Potential Coating Materials (with primary focus on fluorocarbons)
  - Some incorporate nano-particles into a conventional conformal coating

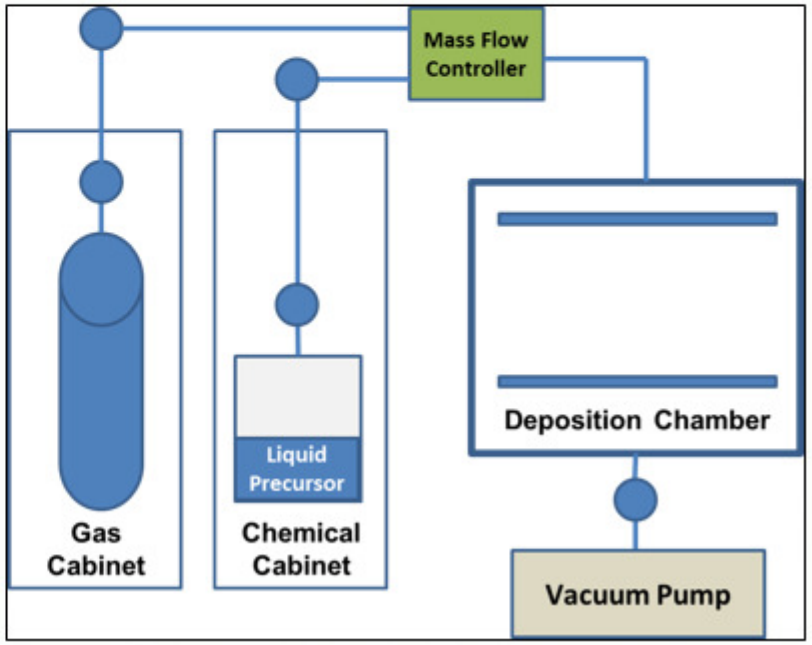
Semblant Process



http://web.mit.edu/gleason-lab/research.htm

- iCVD uses a chemical initiator to breakdown the monomer

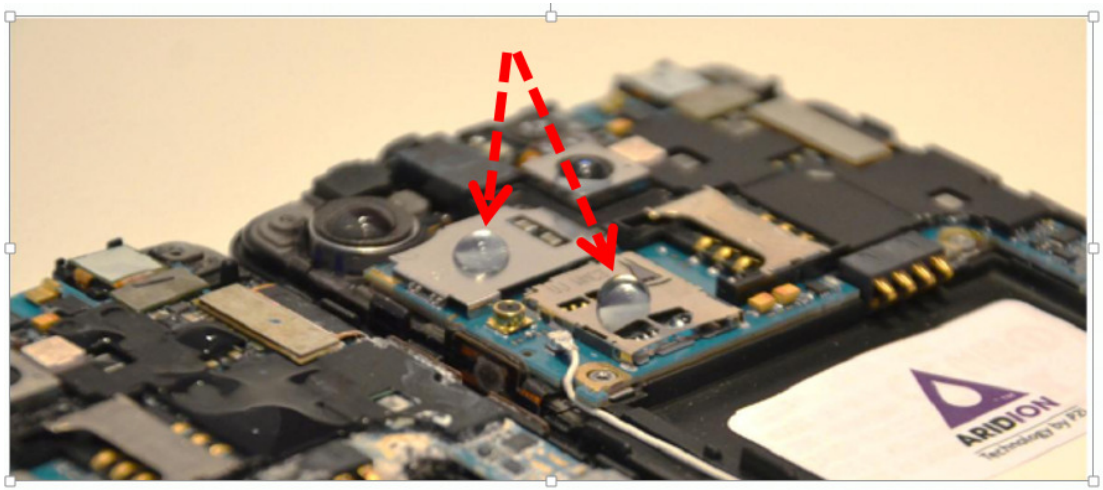
- Plasma-Enhanced CVD (PECVD) uses plasma to breakdown the monomer



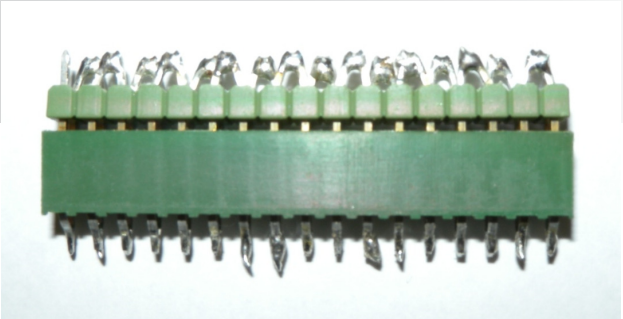
Benefits (especially compared to Parylene)

- These are truly nanocoatings
  - Minimum Parylene thickness tends to be above one micron (necessary to be pinhole free)
  - These coatings can be pinhole free at 100 nm or lower

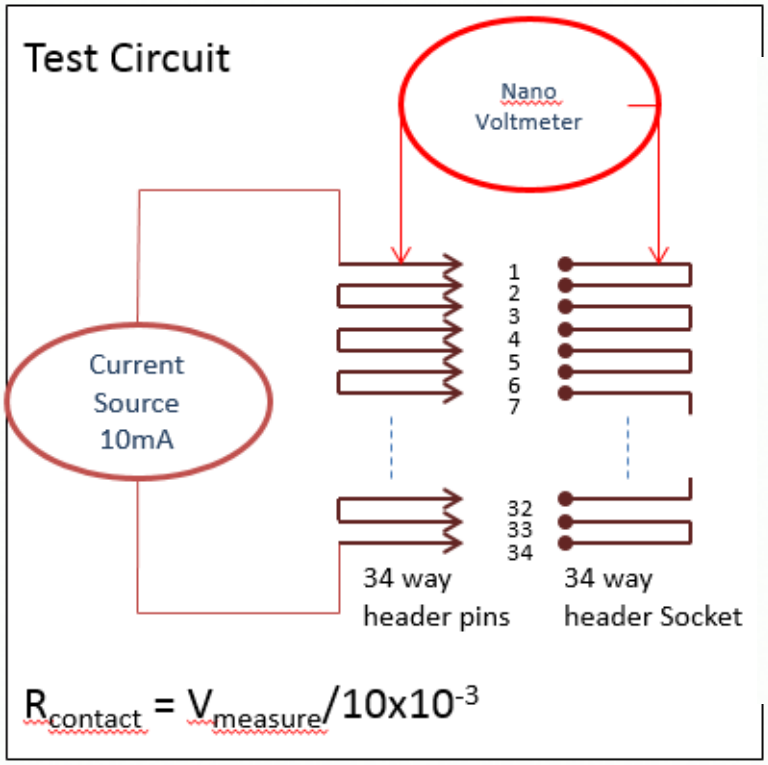
- Nanocoating allows for
  - Optical Transparency
  - RF Transparency
  - Reworkability
  - Elimination of masking

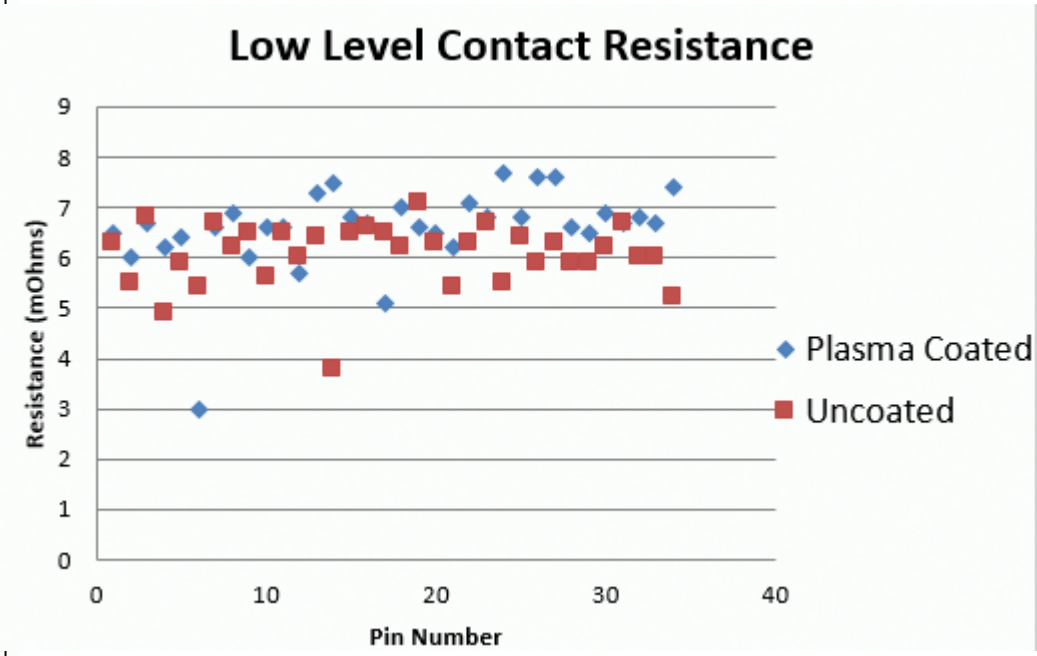


No Masking



LLCR Measurements
Current (A)
0.01
V comp (V)
0.1
Connector Male
34way Pin Header Au over nickel contact (TE Connectivity 1-215307-7)
Connector Female
34way Socket Header Au over nickel contact (TE Connectivity 1-826632-7)





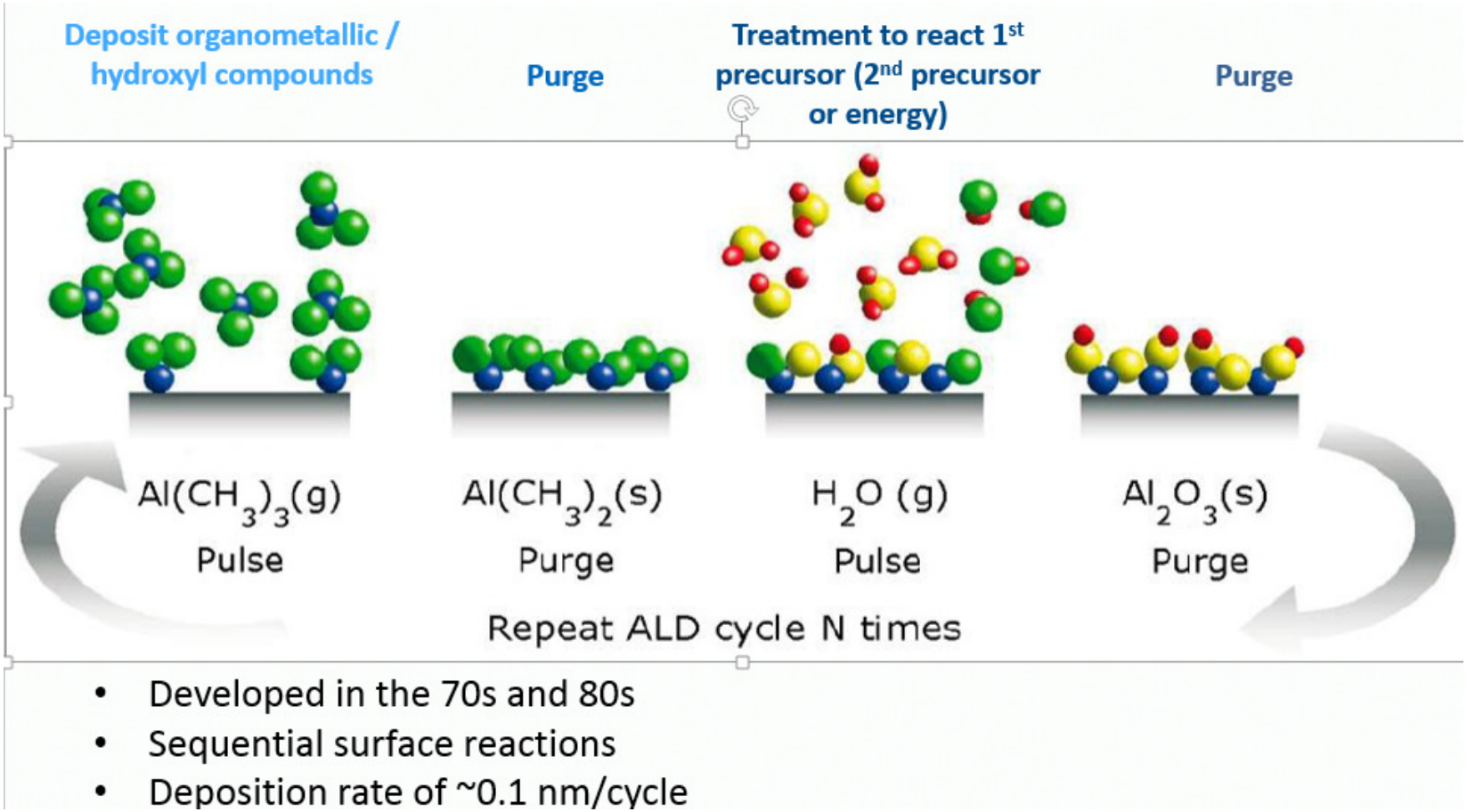
Courtesy of Semblant

DfR Solutions

Risks

- Voltage Breakdown
  - Levels tend to be lower compared to existing coatings (acrylic, urethane, silicone)
  - Can be an issue in terms of MIL and IPC specifications
- Optically Transparent
  - Inspection is challenging
- Cost
  - Likely more expensive than common wet coatings
  - However, major cell phone manufacturer claims significant ROI based on drop in warranty costs
- Throughput
  - Batch process. Coating times tend to be 10 to 30 minutes, depending upon desired thickness
  - However, being used in high volume manufacturing

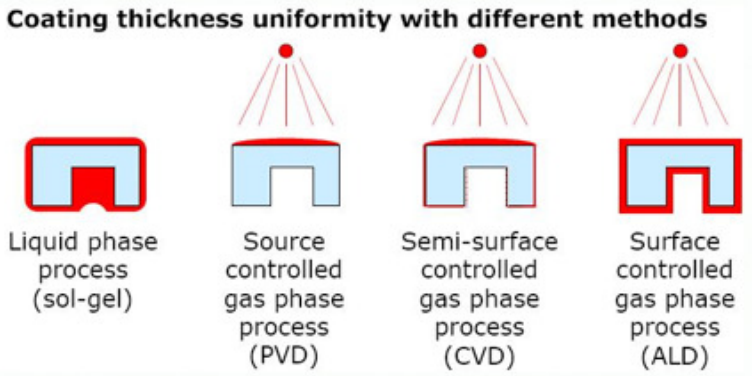
Atomic Layer Deposition (ALD)



- Developed in the 70s and 80s
- Sequential surface reactions
- Deposition rate of ~0.1 nm/cycle

ALD Continued

- Advantages
  - Deposition at low temps (80-150C)
  - Not line of sight (conformal)
  - Precise thickness control
  - Large area
  - Less stringent vacuum requirements (0.1 – 5 mbar)
  - Multilayer and gradient capability (it can be tailored)



- Northrop Grumman / Lockheed Martin estimated cost reductions of 50% vs. traditional hermetic approaches

Atomic Layer Deposition (ALD) Coatings for Radar Modules, DMSMS 2012

Risks

- The process can be very slow
  (100nm thickness can take over an hour)
- Not reworkable
- There have been challenges in regards to compatibility of ALD with existing electronic materials and manufacturing process
  - Clean surfaces with similar coefficient of thermal expansion (CTE) work best
  - De-adhesion and cracking sometimes observed when applied to metals, polymers, and surfaces with flux residue (requires some tailoring)

Barrian – Dry Surface

- Water droplets remain perched on the peaks in well-formed beads that can't adhere to the surface. Barrian duplicates this amazing waterproofing action by creating a microstructure of silica glass peaks. This precise surface geometry, combined with advanced low-surface-energy chemistry, results in optimal water beading that accelerates the flow of water over the surface, rendering the surface and the structure below it virtually unwettable

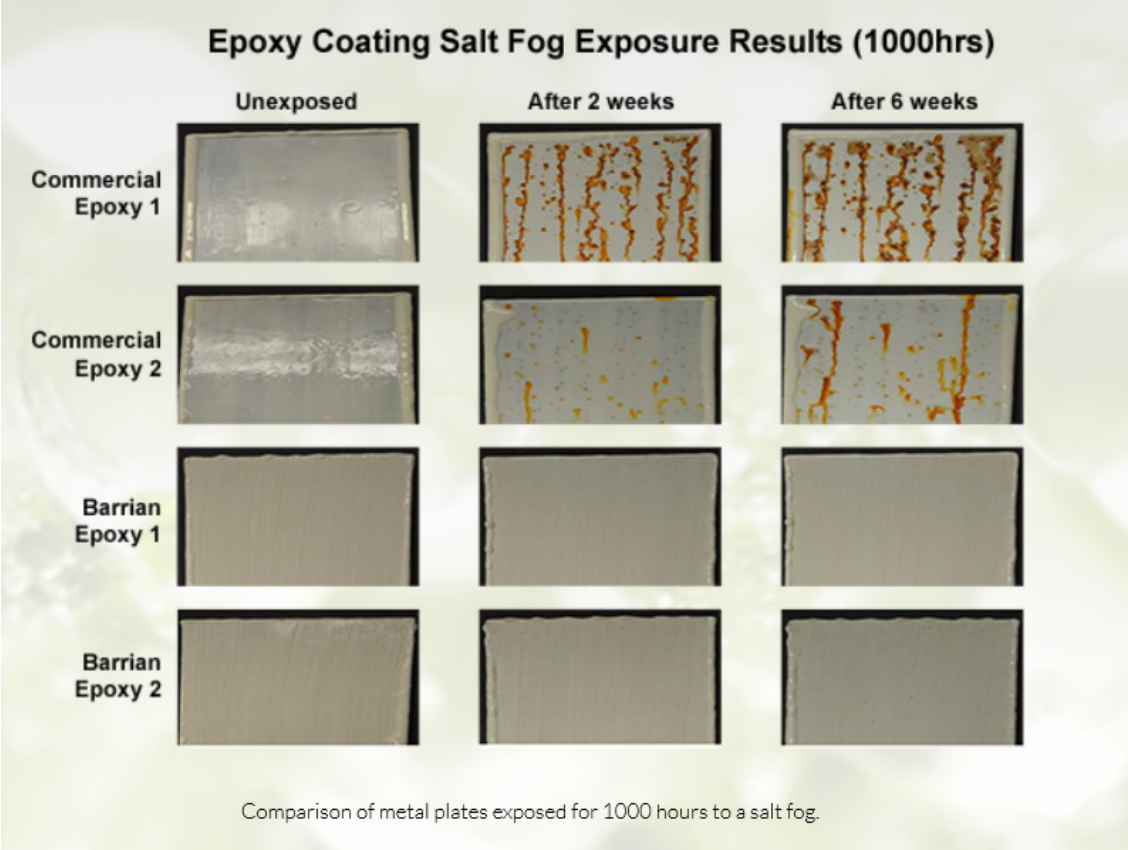
Photographs of water droplets on the surface of the 16F-7% after 54 sanding cycles (CA 153o±2).

The coating remains superhydrophobic as the coating is sanded away…all the way to the metal substrate!

DfR Solutions

Barrian

- Their process uses current conventional conformal coating materials like acrylic and integrates their proprietary nano particle formulation into the coating



Comparison of metal plates exposed for 1000 hours to a salt fog.

DfR Solutions

ACT Nano

- ACT states that their material can take many forms and be applied more than once. Their focus seems to be on repelling water.

- No Masking of conductive Parts
- Can be integrated into Production lines

THANKS

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SUNPOWER®

PV Inverter Accelerated Testing for High Humidity Environments

T Paul Parker and Sander Caldwell | February 25, 2015

PV Inverter Reliability Workshop

© 2015 SunPower Corporation

Introduction

- What standards are available for accelerated reliability testing of PV inverters?
- Are PV module humidity test standards applicable to inverters?
- Should we borrow from humidity test standards used in other industries?
- What failure mechanisms are we targeting?
- How do we model acceleration factors?
- How does the product react to the test environment?
- What next?

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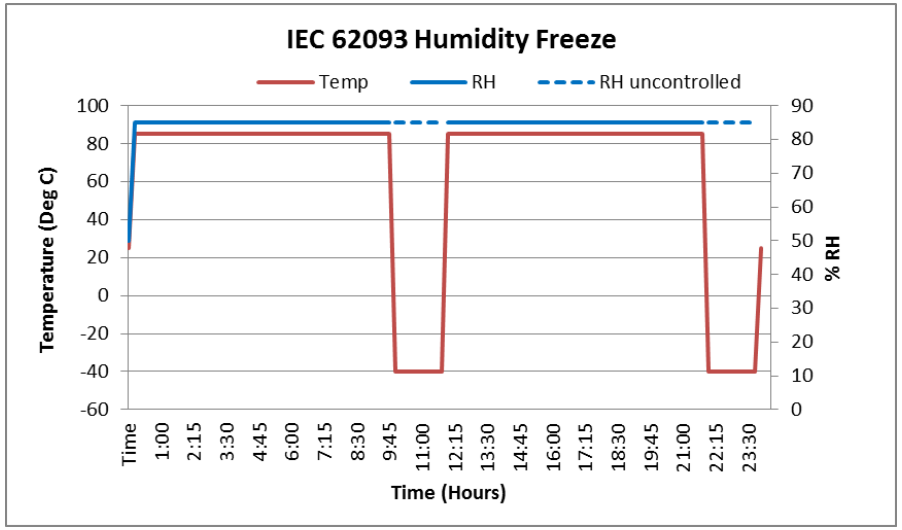
Industry standards for PV inverters

- IEC 62093 (draft)
  - Damp Heat
    - Powered, monitored, light load to reduce internal heating
    - 85C / 85% RH, 1000 hours (42 days)
  - Humidity Freeze
    - Powered, monitored, light load
    - 85C / 85% RH, 10 hours; followed by -40C, 2 hours
    - 20 cycles (10 days)
- ANSI TUV-R 71830 (DOE PREDICTS draft)
  - Microinverters / DC-DC converters
  - Similar to IEC 62093 DH / HF stress levels, duration TBD



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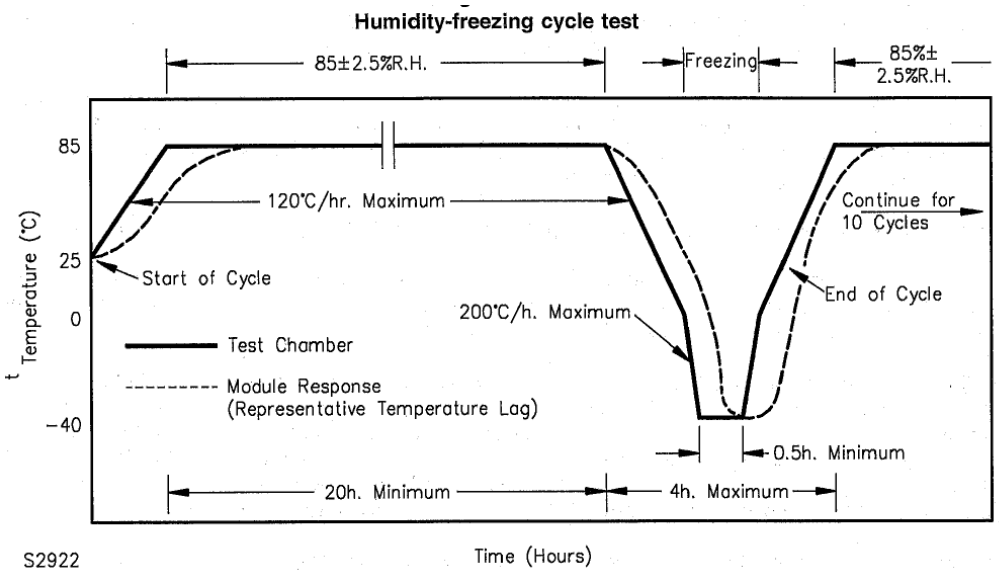
Other standards

- PV Module Standards
  - Damp Heat (IEC 61215)
    - 85C / 85% RH, 1000 hours
  - Humidity Freeze (UL 1703 / IEC 61215)
    - 85C/85%, 20 hrs ; -40C, 4 hrs; 10 cycles
- Telecom Power Supplies (IPC 9592)
  - Temperature, Humidity and Bias (THB) *
    - 85C / 85% RH, 1000 hours

* Similar to IEC 60068-2-67



Reference: UL 1703, Figure 36.1

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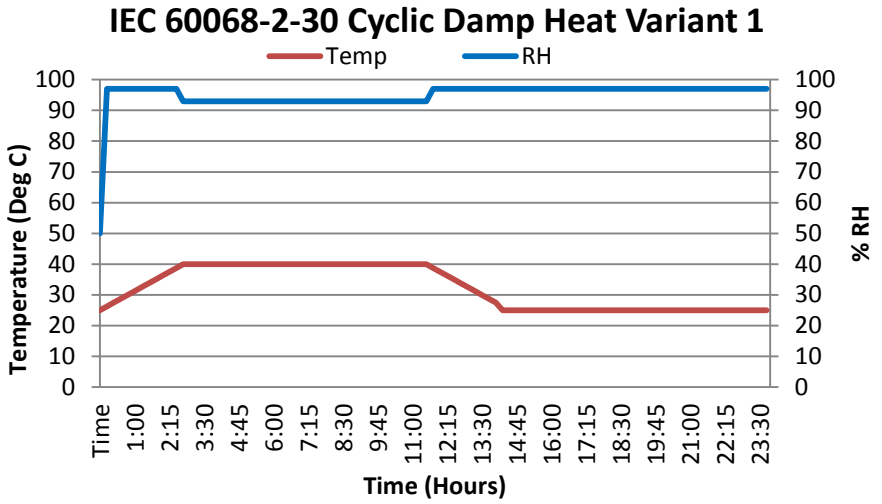
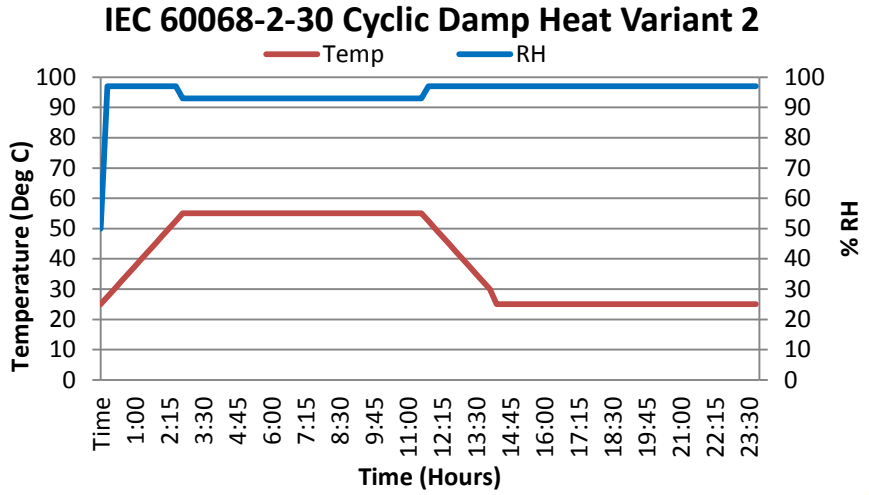
Other IEC standards

- General Industry
  - Damp Heat (IEC 60068-2-78)
    - 40C / 93%; 1 to 56 days
  - Damp Heat, cyclic (IEC 60068-2-30)
    - Variant 1:
      - 40C / 93%; 12 hr to 25C/97% 12 hr (24 hour cycle) ;
      - 2 to 56 cycles (days)
    - Variant 2:
      - 55C / 93%; 12 hr to 25C /97% 12 hr;
      - 1 to 6 cycles (days)





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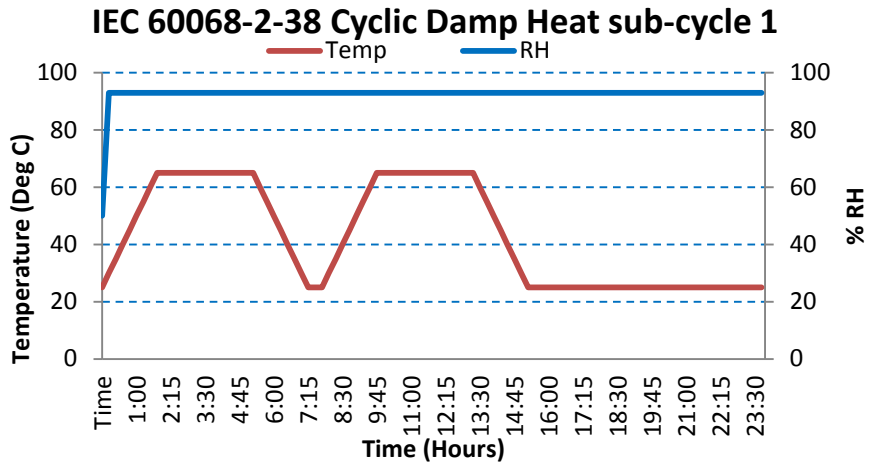
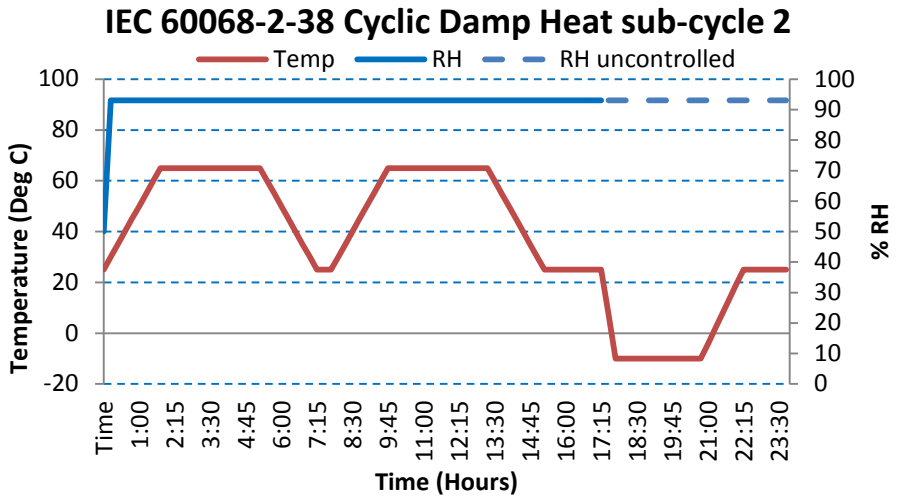
Other IEC standards

- General Industry
  - Damp Heat, cyclic (IEC 60068-2-38)
    - Sub-cycle 1:
      - 65C / 93% to 25C / 93% - 8 hour cycle
      - 2 cycles
      - 25C / 93% - 8 hours
    - Sub-cycle 2
      - 65C / 93% to 25C / 93% - 8 hour cycle
      - 2 cycles
      - 25C / 93% to -10C / uncontrolled RH – 8 hour cycle
    - Each sub-cycle repeated 5 times
    - Test duration – 10 days





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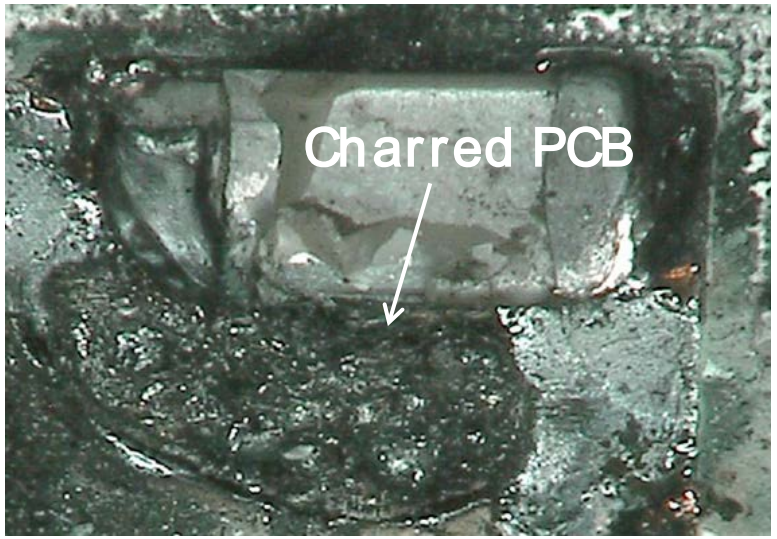
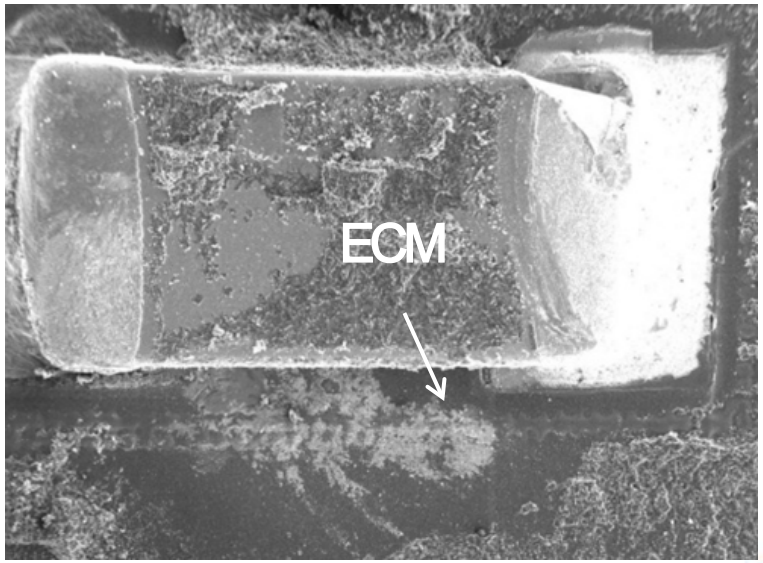
Moisture Assisted Failure Mechanisms

- Electrochemical Migration (ECM) – Dendrite*
  - Metallic ions migrate from anode to cathode, forming treelike structure growing back toward anode
    - Dissolution of Sn, Cu, Ag in the presence of moisture / contaminates
    - Requires Power (Voltage), typically > 1V/mi
  - Typically occurs at PCB surface between 2 conductors joined by an electrolyte medium such as adsorbed moisture
  - Can be highly intermittent, difficult to diagnose, especially in potted assemblies
  - Dependent on available power, evidence can be destroyed
  - Mitigated by cleaning, conformal coating or potting
  - Challenge to model due to hard to predict variables:
    - Amount of moisture adhered to surface of PCB
    - Nature and chemical activity of contaminates, especially flux

*References 1-3





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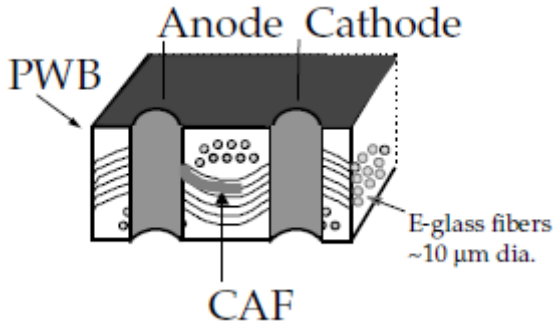
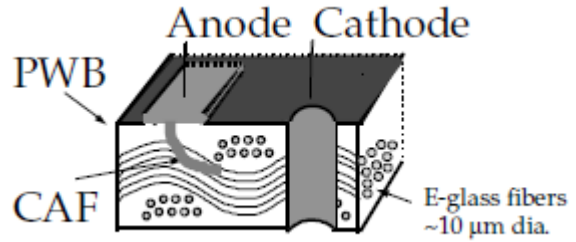
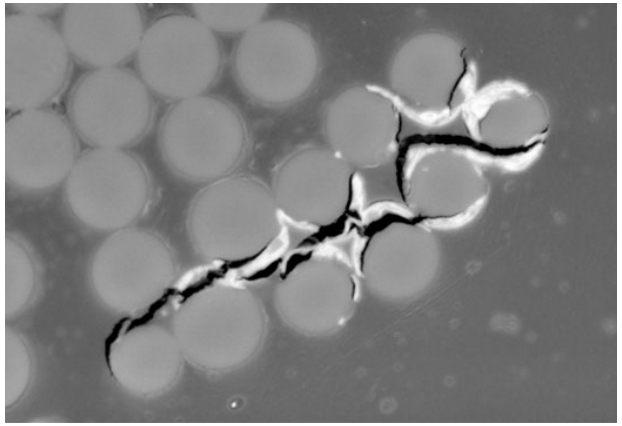
Failure Mechanisms (cont.)

- ECM –Conductive Anodic Filament (CAF) *
  - PCB inner layer only
  - Requires path between points of different potential
  - Path typically provided by glass fiber to resin separation
  - Higher risk in Pb-Free assemblies
  - Similar to dendrite, Cu++ dissolution at anode, migrates along path toward cathode.
  - Can be highly intermittent, often leads to PCB thermal damage
  - Mitigated by proper selection of laminate material, conservative internal spacings
  - Challenge to model due to hard to predict variables:
    - Moisture content of PCB before and after reflow
    - Quality of laminate
    - Process variant: PCB hole drill quality, PCBA reflow profile

* References 4-6







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Failure Mechanisms (cont.)

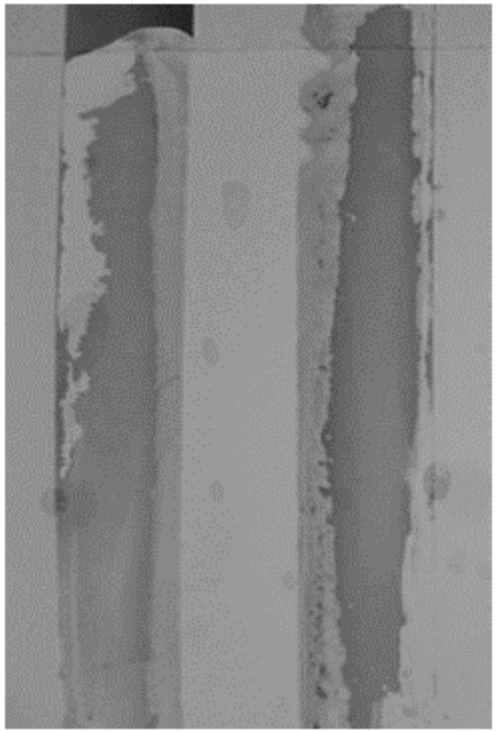
- Film Capacitor corrosion *
  - Corrosion reaction attacking thin metal electrode
  - ZnAl electrodes react with oxygen and water to form non conducting area, reducing capacitance

$$2\,Zn^{\circ} + O_2 + 2\,H_2O \rightleftharpoons 2\,Zn(OH)_2$$

  - Highly accelerated by temperature / RH / voltage
  - Mitigated by with appropriate selection of capacitor case material / pottant
  - Empirical models available from capacitor manufacturers

* References 7-8

Before



After

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Modeling – AF: Accelerated Test vs Field Use Conditions

- Identify a region you for which you wish to predict AF
  - Miami Average use environment: 24C / 73% RH (**Reference 9**)
- Identify accelerated test condition:
  - 85C / 85% RH
  - 65C / 85% RH
- Select model: ex: Peck Model (**Reference 10**)
  - $A_T(E_A = 0.7) = 106$
  - $A_H = (85/24)^{2.66} = 1.5$
  - $A_T(E_A = 0.9) = 400$
  - **AF = A_{TH} = 158 – 600x**
- For 25 year life, 50% on time (109.5 khr)
  - Req'd. test time for 85C/85% = 183 – 691 hours
  - Req'd test time for 65C/85%= 1026 – 2647 hours

$$A_T = Exp\left\{\frac{E_a}{K_B}\left[\frac{1}{T_{Use}} - \frac{1}{T_{Stress}}\right]\right\}$$

$$A_H = \left(\frac{R_{Stress}}{R_{Use}}\right)^m$$

$$A_{TH} = A_T A_H$$

$$Ln(t_f) = C + \frac{E_a}{K_B T} - m\ Ln(R)$$

Notation

A_H	= Humidity acceleration Factor
A_T	= Temperature acceleration factor
A_{TH}	= Temperature-Humidity acceleration factor
RH_{stress}	= Relative humidity of test
RH_{use}	= Nominal use relative humidity
T_{stress}	= Test temperature
T_{use}	= Nominal use temperature
m	= Humidity constant
E_a	= Activation energy
t_f	= Time to Fail
C	= Constant

Peck Model

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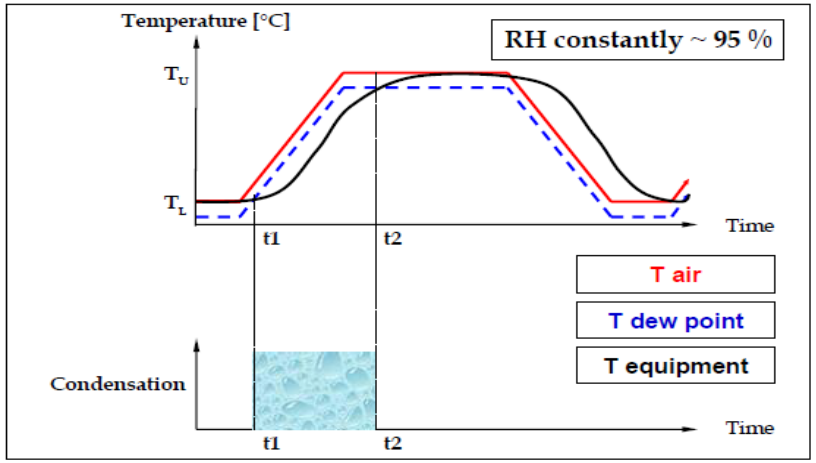
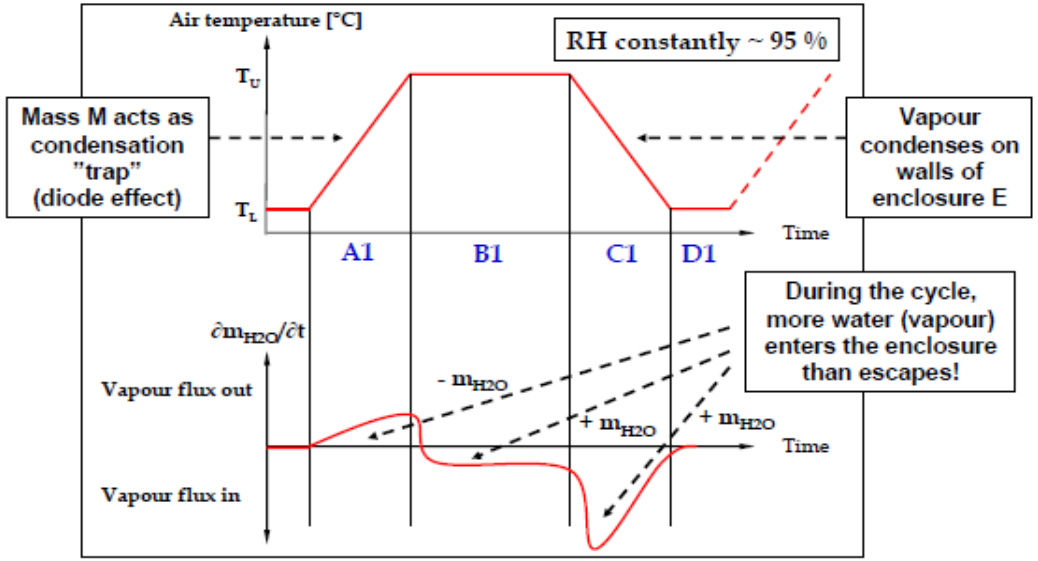
Design Response to T/RH Conditions

- Unsealed, unpotted assemblies track environment closely
  - For cyclic humidity testing, condensation during temperature ramp up
  - Potential for significant Insulation Resistance (IR) drop
- Sealed, unpotted assemblies vulnerable to “pumping” or “water diode” phenomena
- Potted and conformally coated assemblies may be at risk
  - poor adhesion
  - High moisture content
  - Fast vapor diffusion rate





Reference 11

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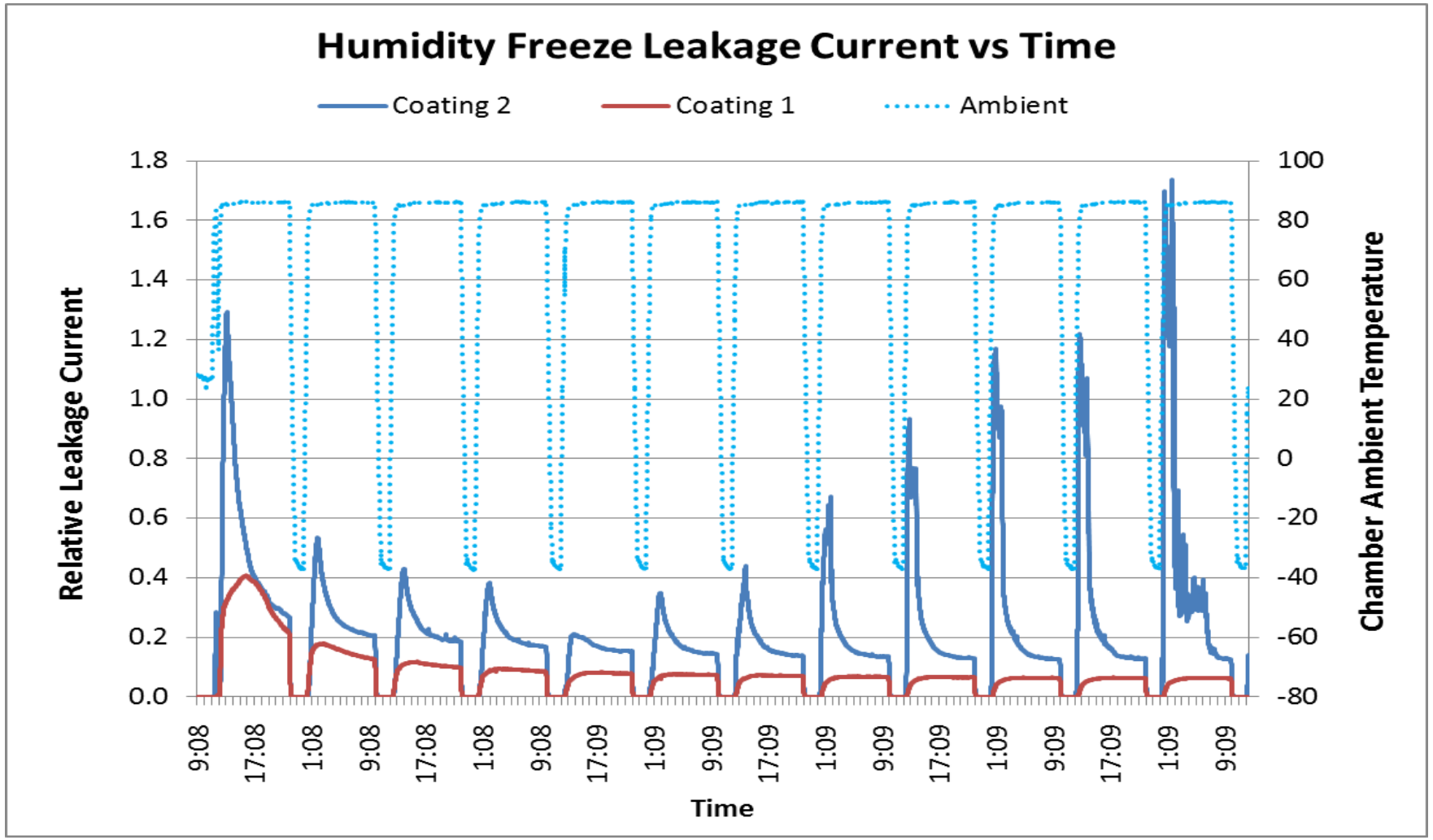
Real Time Monitoring of Leakage Current / Insulation Resistance



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Next Steps

- Survey PV inverter manufacturers for existing humidity test best practices

- Differentiate requirements of Test standard
  - Qualification Test – Pass requirement, no failures allowed
  - Accelerated Life Test– Test to fail, model based on failure mechanism

- Support standards efforts
  - IEC – 62093 needs to be resurrected
  - ANSI TUV-R 71830 (PREDICTS) – See Jack Flicker

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References

- ECM: Dendrites
  - (1) C. Hillman, “Contamination and Cleanliness – Developing Practical Responses to a Challenging Problem”, IMAPS – Nordic, June, 2010
  - (2) E Bumiller, et.al , “ A Review of Models for Time-to-Failure due to Metallic Migration Mechanisms”, DfR Solutions
  - (3) X. He, et.al, “Evaluation of Electrochemical Migration on Printed Circuit Boards with Lead-Free and Tin-Lead solder”, Journal of Electronic Materials” June, 2011

- ECM: CAF
  - (4) L Zou, et.al,” How to Avoid Conductive Anodic Filament (CAF), National Physical Lab, January, 2013. Technical Webinar, www.npl.co.uk/ei
  - (5) W.J Ready and L.J Turbini, “ Conductive Anodic Filament Formation: A Materials Perspective”, Proceedings of the 3rd Pacific Rim International Conference on Advanced Materials and Processes, 1998
  - (6) L. J Turbini, “Electrochemical Migration and Conductive Anodic Filament (CAF) Formation”, Tutorial 2, SMTA, October, 2013

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References

- Film Capacitor Corrosion
  - (7) M. Michelazzi, et.al, “RFI X2 Capacitors for High Humidity Environments”, 2014 CARTS International
  - (8) HJC White Paper, “Accelerated Lifetime Test for Metallized Film Capacitors”, http://www.hjc.com.tw/cap/pv.pdf

- Modeling
  - (9) NREL “Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors” – Data collected from 239 weather stations from 1961 to 1990. Miami, p 57.

Average Climatic Conditions

Element	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Temperature (°C)	19.6	20.3	22.1	24.0	25.9	27.4	28.1	28.2	27.7	25.7	23.1	20.6	24.4
Daily Minimum Temp	15.1	15.8	17.9	19.9	22.3	23.9	24.6	24.8	24.4	22.3	19.3	16.4	20.6
Daily Maximum Temp	24.0	24.7	26.2	28.0	29.6	30.9	31.7	31.7	31.0	29.2	26.9	24.8	28.2
Record Minimum Temp	-1.1	0.0	0.0	7.8	11.7	15.6	20.6	20.0	20.0	10.6	3.9	-1.1	-1.1
Record Maximum Temp	31.1	31.7	33.3	35.6	35.0	36.7	36.7	36.7	36.1	35.0	31.7	30.6	36.7
HDD, Base 18.3°C	49	28	8	0	0	0	0	0	0	0	3	23	111
CDD, Base 18.3°C	87	83	123	170	236	273	303	307	282	229	147	93	2332
Relative Humidity (%)	73	71	69	67	72	76	75	76	78	75	74	72	73
Wind Speed (m/s)	4.3	4.7	4.9	4.8	4.4	3.8	3.7	3.7	3.8	4.4	4.5	4.3	4.2

  - (10) D.S Peck, “Comprehensive Model for Humidity Testing Correlation, IRPS, 1986.

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References

- Humidity Technical Discussion
  - (11) A.B. Kentved, “Humidity Testing of Electronics and Mechanics – How to Select the Right Test Method”, Delta Electronic White Paper, Delta SPM-176, 2008. http://spm-erfa.dk/

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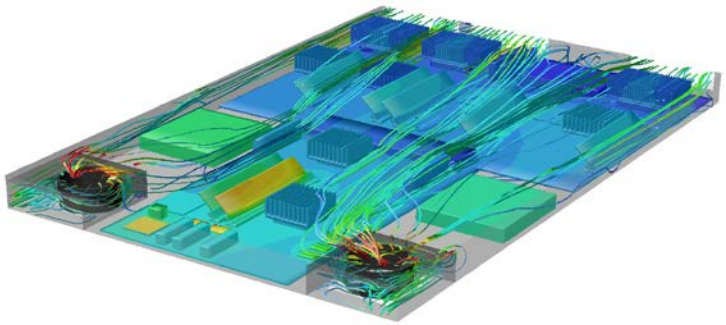

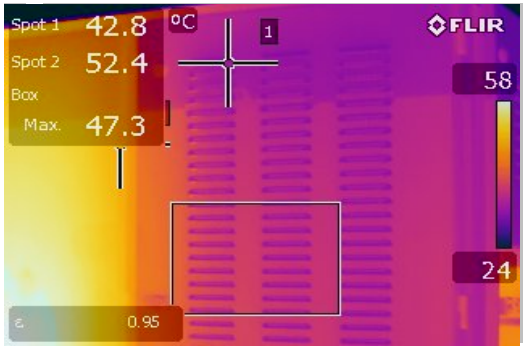

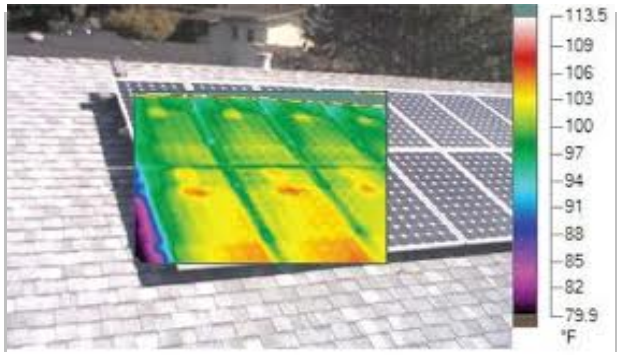

Inverter Electro-Thermal Modelling

Kenneth M. Armijo & Olga Lavrova

Sandia National Laboratories – Photovoltaic and Distributed Energy Dept.

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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Sandia National Labs: PV Systems Reliability Program

Sandia National Laboratories

Overview

- PV system investment is driven by initial price, system performance over time, and system reliability/availability to adequately assess risk.
- Poorly understood Reliability decreases confidence in PV technology and increases LCOE
- Need to understand WHOLE SYSTEM reliability, not only PV modules

Methodology

- Develop and apply reliability tools for use throughout the PV supply chain, not only PV module
  - Failure Modes and Effects Analyses
  - Accelerated Testing and Diagnostics
  - Real-time testing of systems
  - In-depth reliability and availability models
- Focus is on system reliability, inverter reliability, O&M strategies

Program Objectives

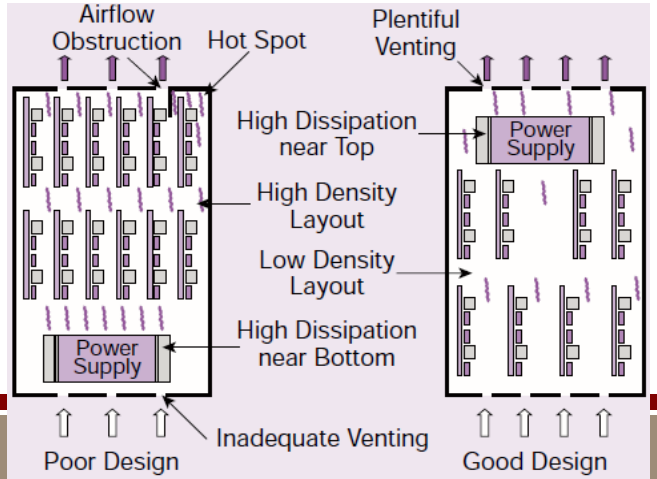
- Reduce LCOE by providing information needed to:
  - Improve BOS lifetime, reliability, safety, availability and performance
- Help investors to quantify bankability, quantify risks and reduce the costs of project financing

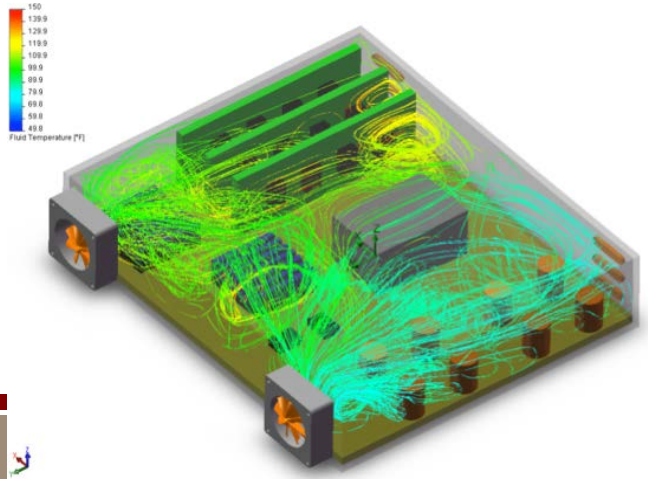
Challenges

- Constantly evolving technologies, manufacturing processes, and materials
- Increasingly complex systems functions
- Short time-to-market demands
- Risk to owners and underwriters, and associated cost implications

Overview & Need for Electro Thermal Modeling

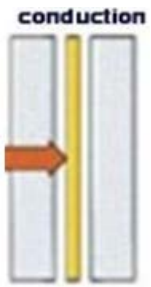
- Decreasing size & growing complexity of power transistors (i.e. MOSFETS and IGBTs) & IC systems, power dissipation is a critical concern.
- Thermal influence upon an electrical system caused by each transistor's self-heating and tightly coupled thermal interaction with neighboring devices cannot be neglected.
- PV inverters continue to have reliability challenges for achieving LCOE. Coupled electro-thermal issues contribute to these issues, especially for advanced inverter functionality.
- Rigorous, non-ideal, and transient electro-thermal models are required for robust development.





Thermal Heat Transfer

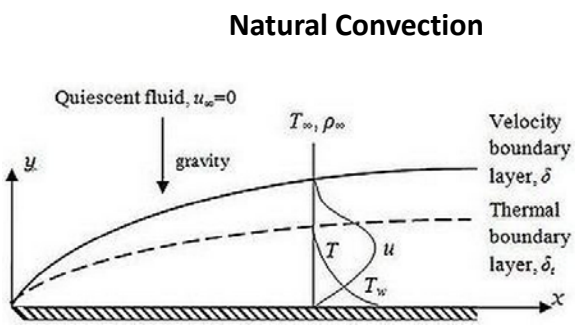
- Heat Transfer & Thermal Management
  - Modes for Electronic Design: Conduction, Convection & Radiation

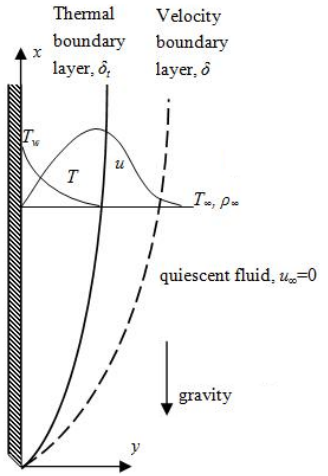


$$\dot{Q}_{Cond} = kA\frac{\Delta T}{\Delta l}$$

$$\dot{Q}_{Conv} = hA\Delta T$$

$$\dot{Q}_{Rad} = \varepsilon\sigma A(T_s^4 - T_\infty^4)$$



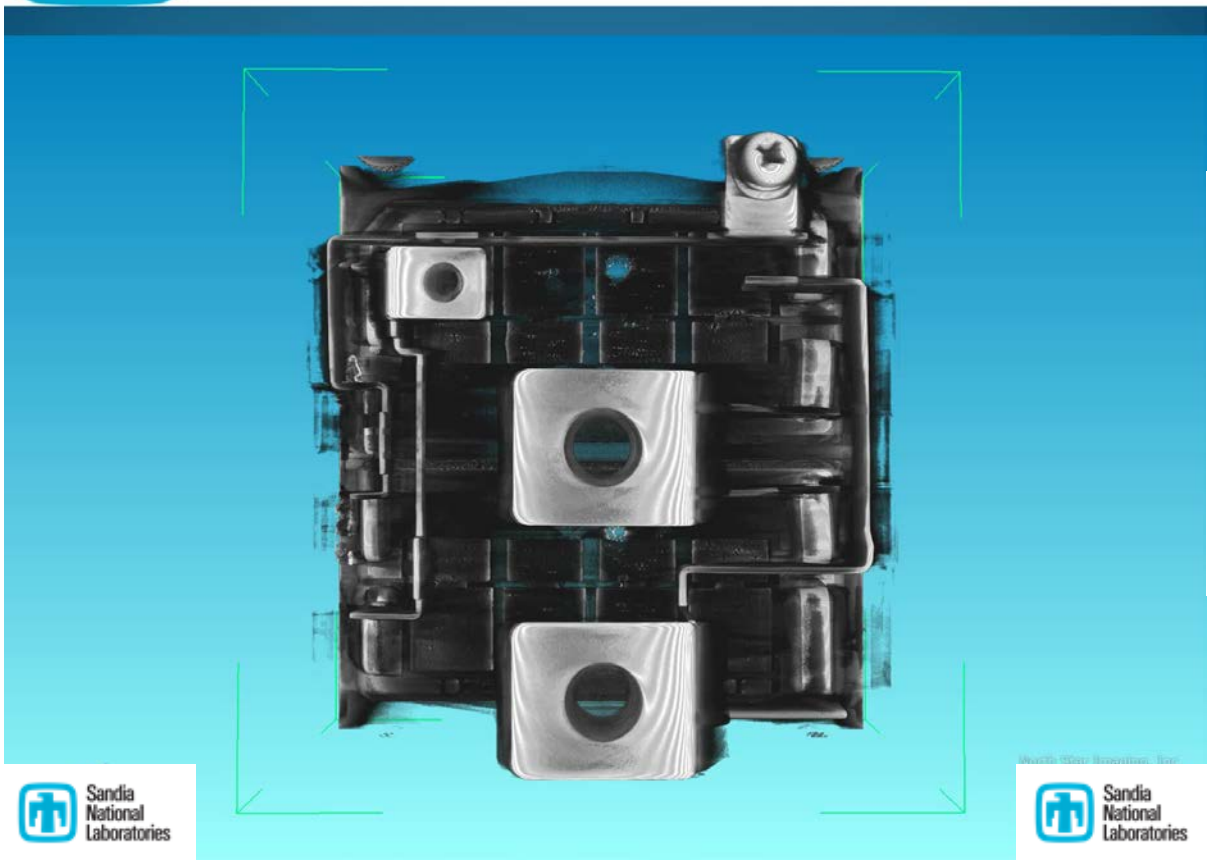


(Incropera and Dewitt, 2002)

- Inverter Thermal Considerations
  - Thermally Sensitive Electronics
    - Passive vs. Active Cooling
  - Temperature Sensing & Controls
    - Derates & Aging/Failure Modes
- Power Electronics Considerations
  - Conduction HT to case & heat sink
  - Radiation HT only ~1-2%

Process	h [W/m^2-K]
Natural Convection	
Gases	2-25
Liquids	50-1000
Forced Convection	
Gases	25-250
Liquids	100-20,000
Convection with Phase Change	
Boiling or Condensation	2,500-100,000

Sandia National Laboratories



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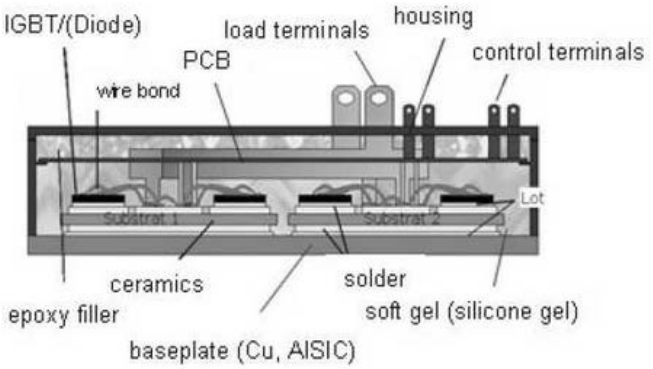
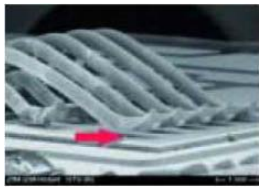


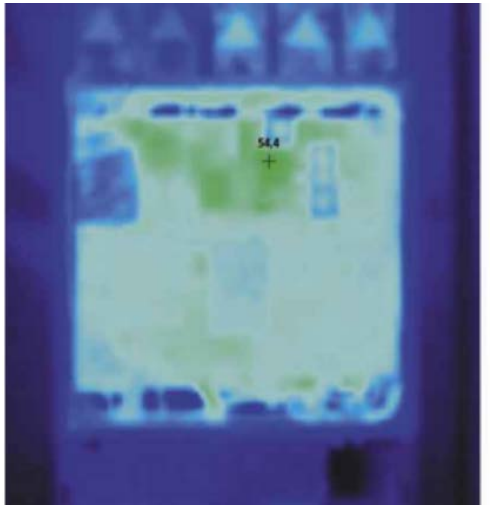
Construction of an IGBT module

Thermal Design Considerations

- Critical Thermal Management Components
  - IGBT's/MOSFET's (Flicker et. al, 2012)
    - Latch-Up
    - Bond Lift-Off
  - Capacitors

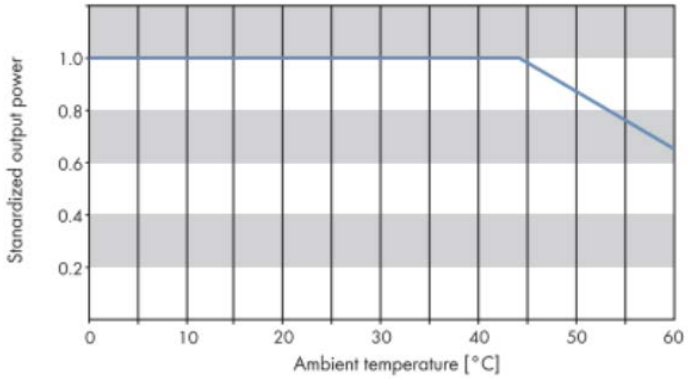


(Saddik, 2013)

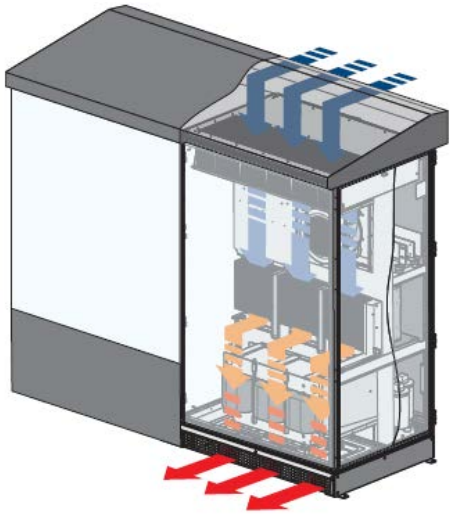


- Direct Active Cooling Issues
  - Dust, Salt Build-Up and Fouling

- Conjugate Heat Transfer Issues
- Derate Operation



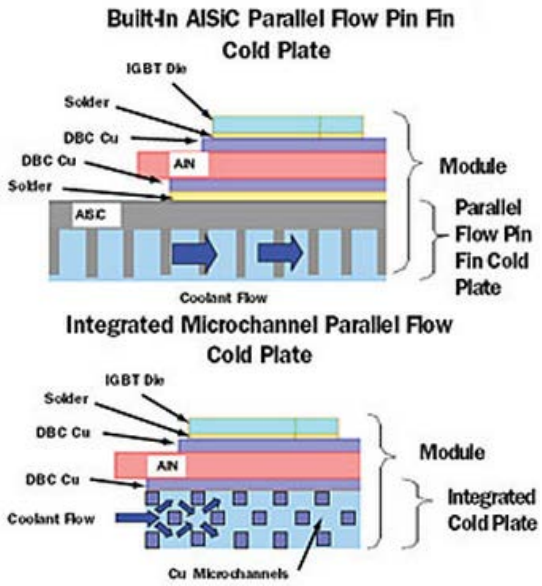
(Saddik, 2013)

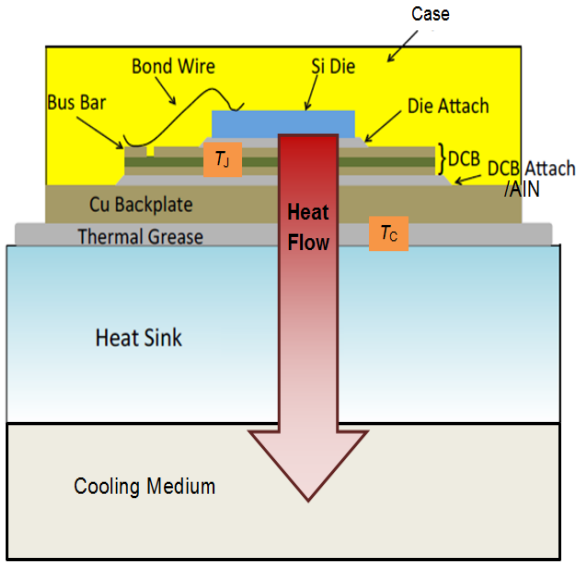


(http://www.sma.de)

Power Electronics

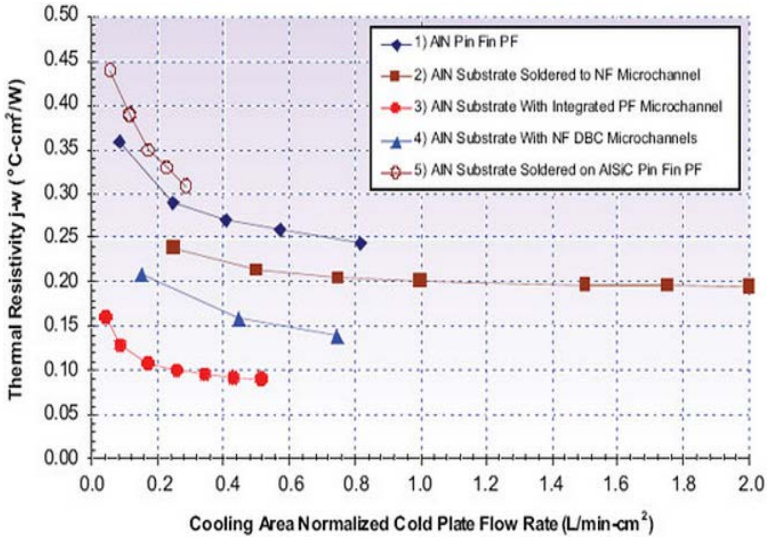
- Greater Number of Layers Increases R_{th} with Standard Configurations Capable of Thermal Dissipation Densities Up to 250-300 W/cm^2
- Power Cycling Degradation Impacts
  - Material Degradation and Micro-Fracturing
- CTE Mismatch Impacts
- Power Diss. = $Loss_{Switching}$ + $Loss_{Conduction}$





(Leslie et. al., 2013)

Layer	Thermal Conductivity (W/mK)	Thermal Resistivity (°C-cm^2/W)
Silicon (100°C)	100	0.025
Solder	36	0.036
Top DBC on Aluminum Nitride	393	0.008
Aluminum Nitride	170	0.037
Bottom DBC on Aluminum Nitride	393	0.008
Solder	36	0.035



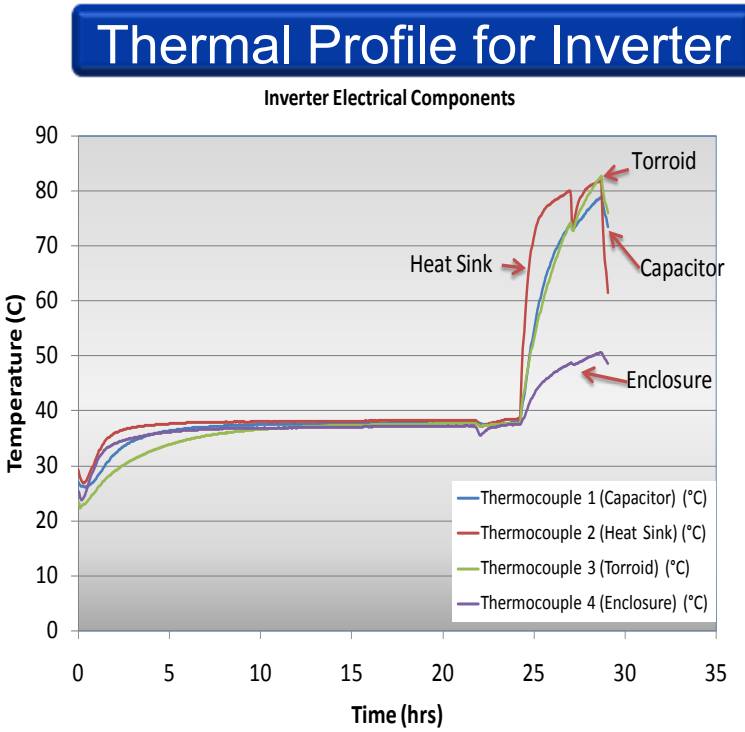
Accelerated Testing

- Thermal cycling
  - Determines the ability of parts to resist extremely low and high temperatures, as well as their ability to withstand cyclical extremes. Stress resulting from cyclical thermomechanical loading accelerates fatigue failures.
- Humidity Freeze
  - This test serves as a mechanical strength test to ensure the reliability of a device/system from failure due to stress and water ingress
- High Temperature Operating Bias (HTOB)
  - It consists of subjecting the parts to a specified bias or electrical stressing, for a specified amount of time, and at a specified high temperature.

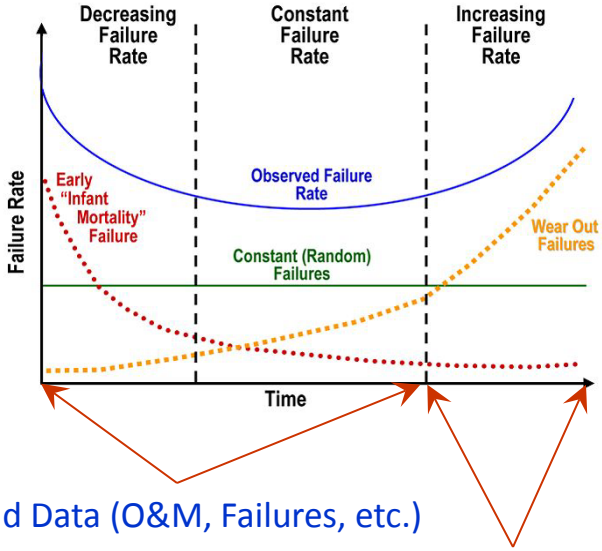
System Element	Failure Mechanism	Accelerated Test
Enclosure/Interconnect	Mechanical Deformation, Moisture Ingress, Corrosion, Dielectric Breakdown	Thermal cycling (TC)/Humidity Freeze (HF)/Damp Heat Test/UV Precondition
PCB/Solder system	TCE Mismatch, Electromigration. Corrosion	Thermal Cycling/humidity Freeze/ Damp Heat Test
Passive components	Dielectric/Insulation Breakdown	Humidity Freeze/Thermal Cycling/ UV Degradation
Active Components	Mechanical Wear-Out, etc.	Thermal Cycling/Damp Heat Test/Extreme Temperature Exposure/Integrated Power Cycling
Integrated Circuit Devices	Hot Carrier Injection (HCI), Time-Dependent Dielectric Breakdown (TDDB), etc.	Thermal Cycling/Humidity Freeze/Damp Heat Test

Accelerated Testing (AT)

- Accelerated Lifetime Testing (ALT)
- Accelerated Stress Testing (AST)
- Highly Accelerated Life Testing (HALT)
- Highly Accelerated Stress Screening (HASS)
- All of the above allow us to correlate to degradation signatures and predictions, as well as to validate novel diagnostic, screening and testing methods.
- Tests include:
  - Thermal Shock (TS), Thermal Cycling (TC), Highly Accelerated Thermal Shock (HATS), Damp Heat (DH) ,Humidity Freeze (HF)



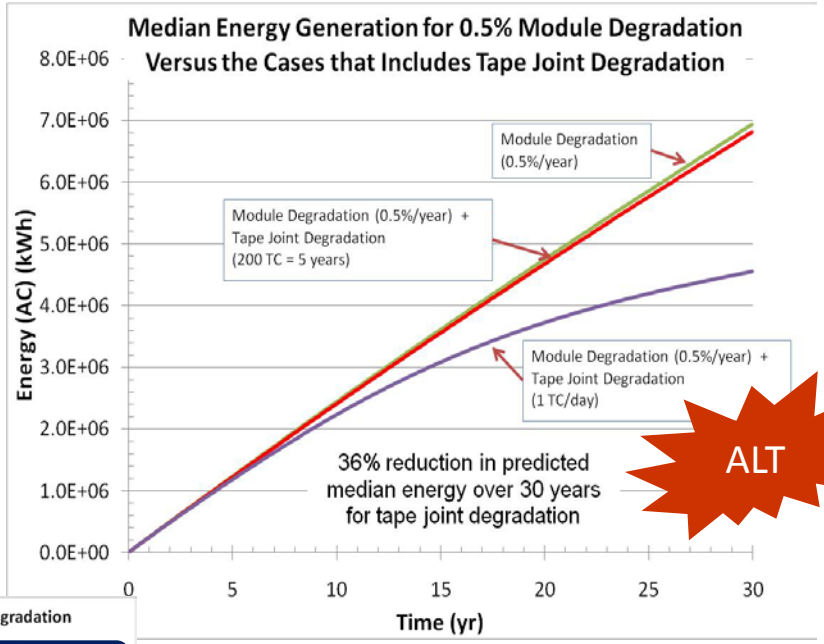
Laboratory testing provides vital information for PV system reliability

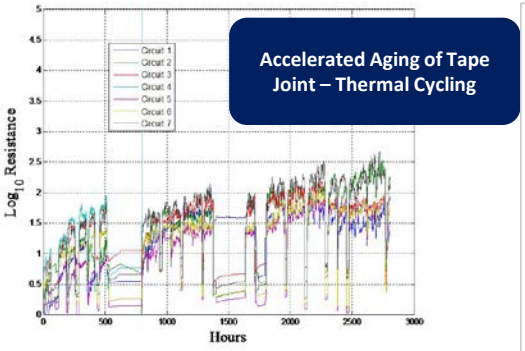


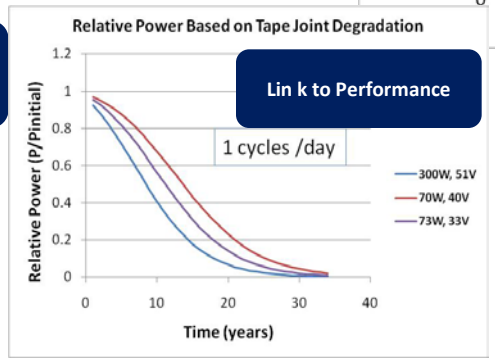
Field Data (O&M, Failures, etc.)

Accelerated Testing / Lab Tests

System performance model must include wear out (end of life) information



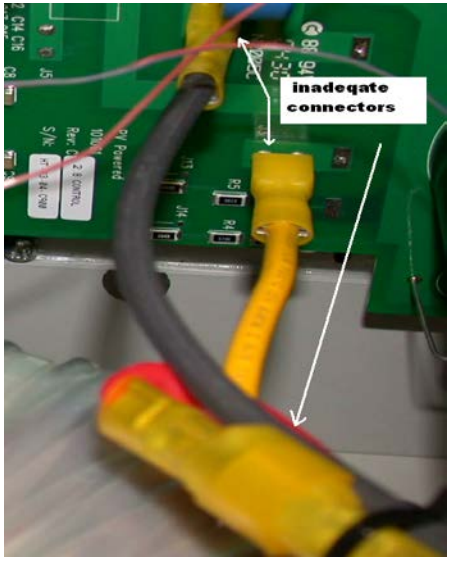


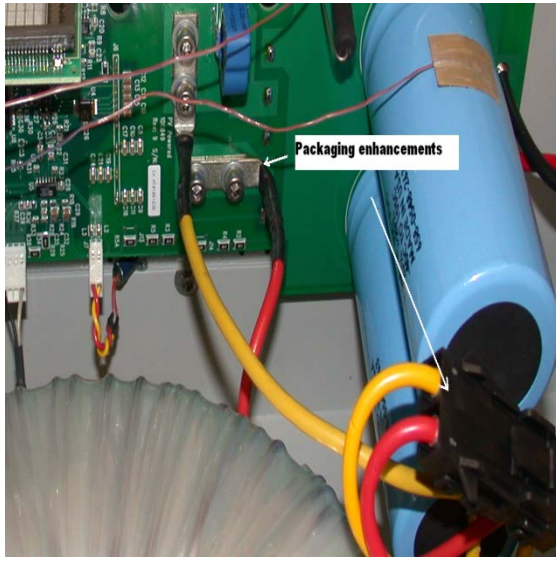


Acceleration Factors

Accelerated Aging for Inverters

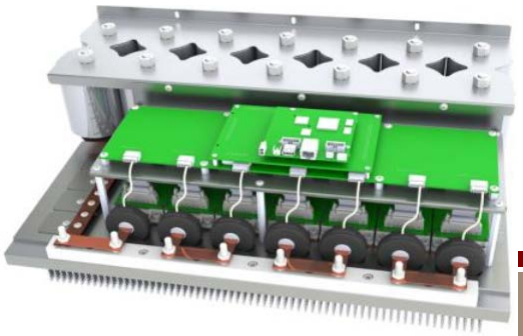
- No specific industry Qual standard exists
  - IEC 61215 is the “de-facto” spec
- HALT testing is spotty; independently applied by inverter manufacturers
  - Data in most cases proprietary
- Separate needs identified for residential and commercial scale inverters
- Failure modes identified but not in a uniform program applicable across the industry
- System predictive models will require inputs for inverters

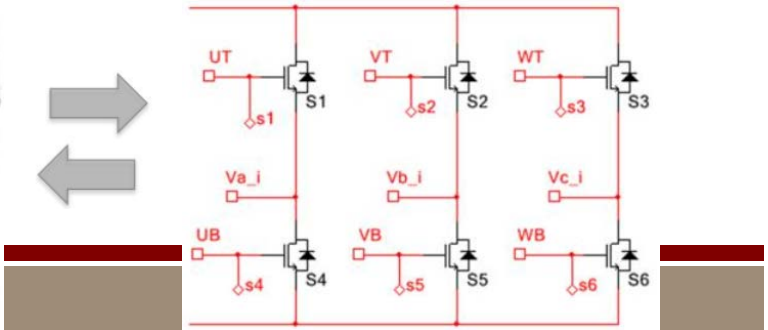


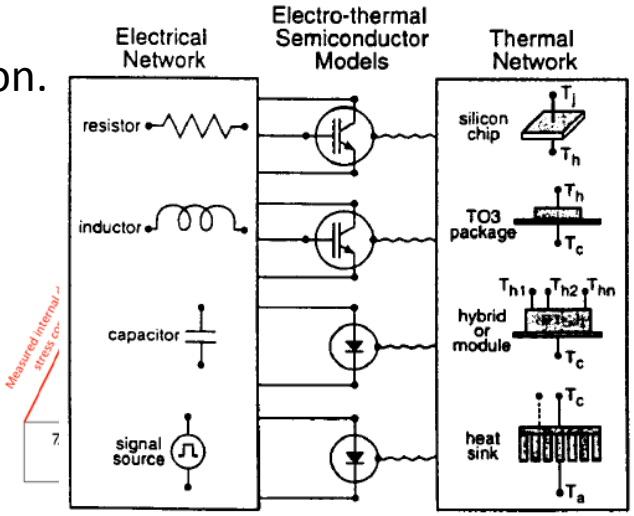


Electro-Thermal Modelling Platforms

- SPICE
  - General electronic circuit simulator, used for design & to check behavior.
- PLECS
  - Idealized power electronics simulator, used in conjunction with look-up tables.
- COMSOL/ANSYS
  - FEA-level circuit simulation based on fundamental principles.
- Matlab/Simulink
  - SimPowerSystems
    - Graphical block-diagram paradigm to create models of dynamic systems.
  - SimElectronics
    - SPICE-Level Modelling with Non-Ideal Characterization.







Inverter Modelling Platforms

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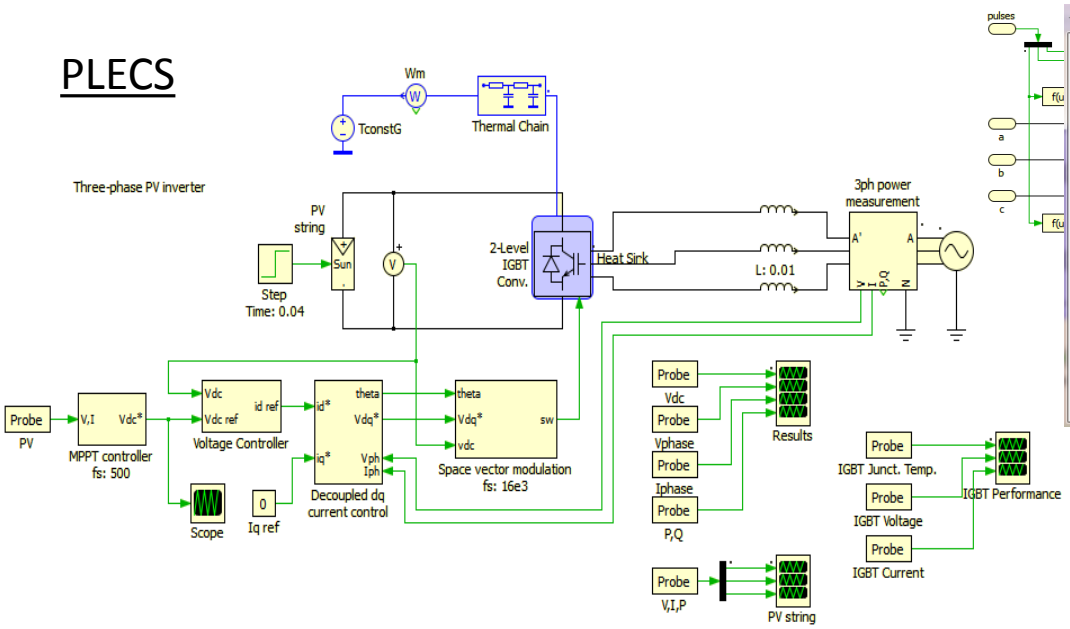
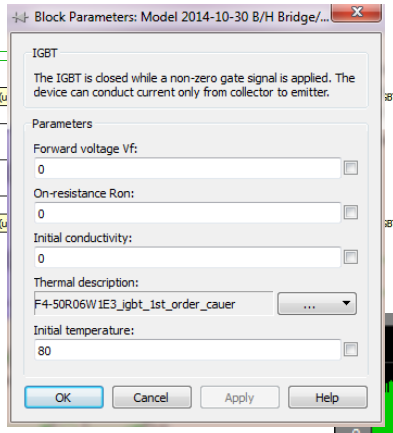
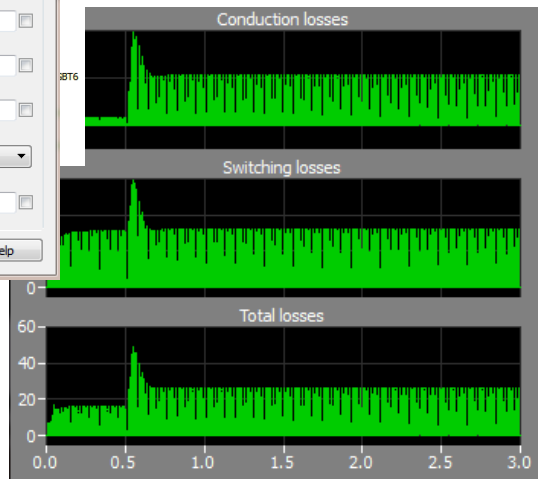
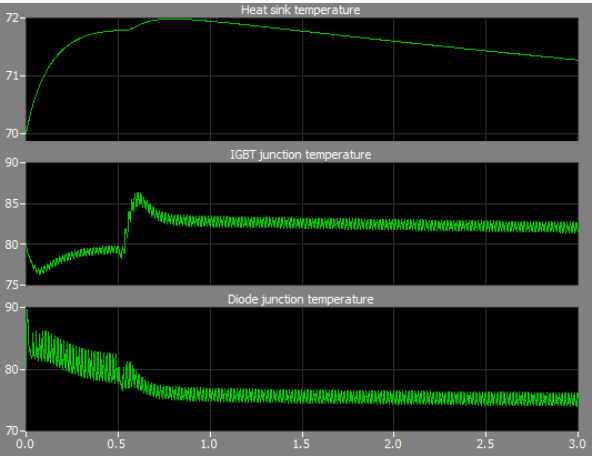
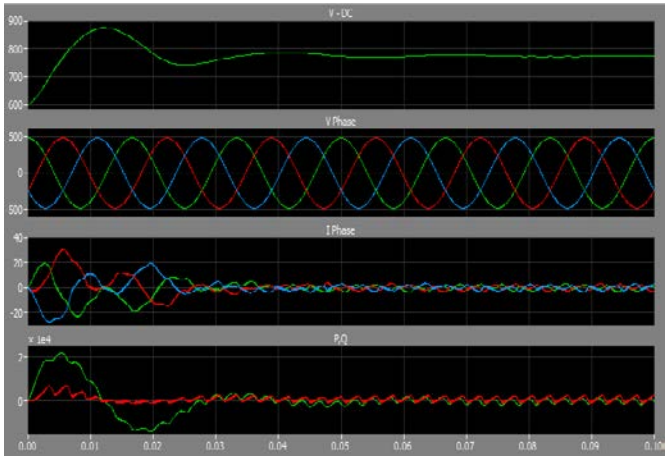
PLECS





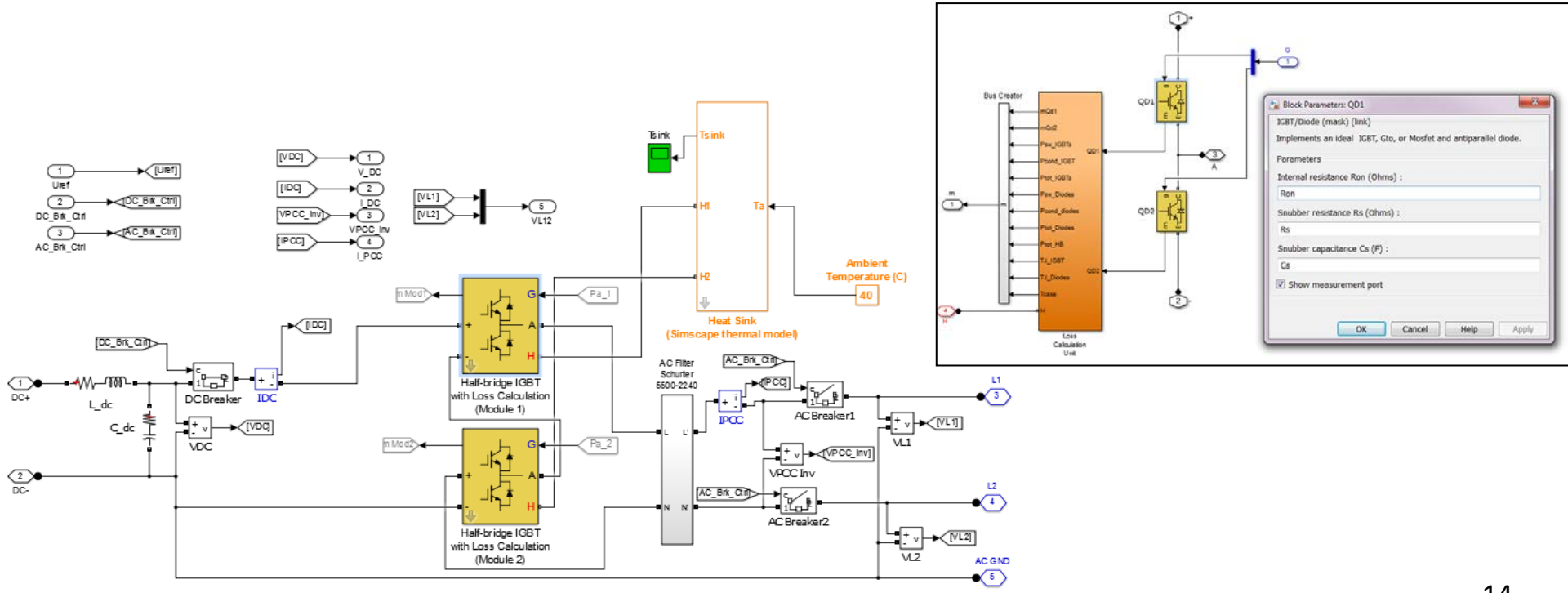






Matlab/Simulink SimPower Systems

- Simulink
  - Block-Diagram Platform for analyzing continuous, multi-rate, discrete systems
- SimPower Systems PV Examples
  - Electrical – System simulation described by a combination of basic functions, connected using lines representing common variables.
  - Thermal – Modelling based on resistor and capacitor thermal circuits



SimElectronics Model

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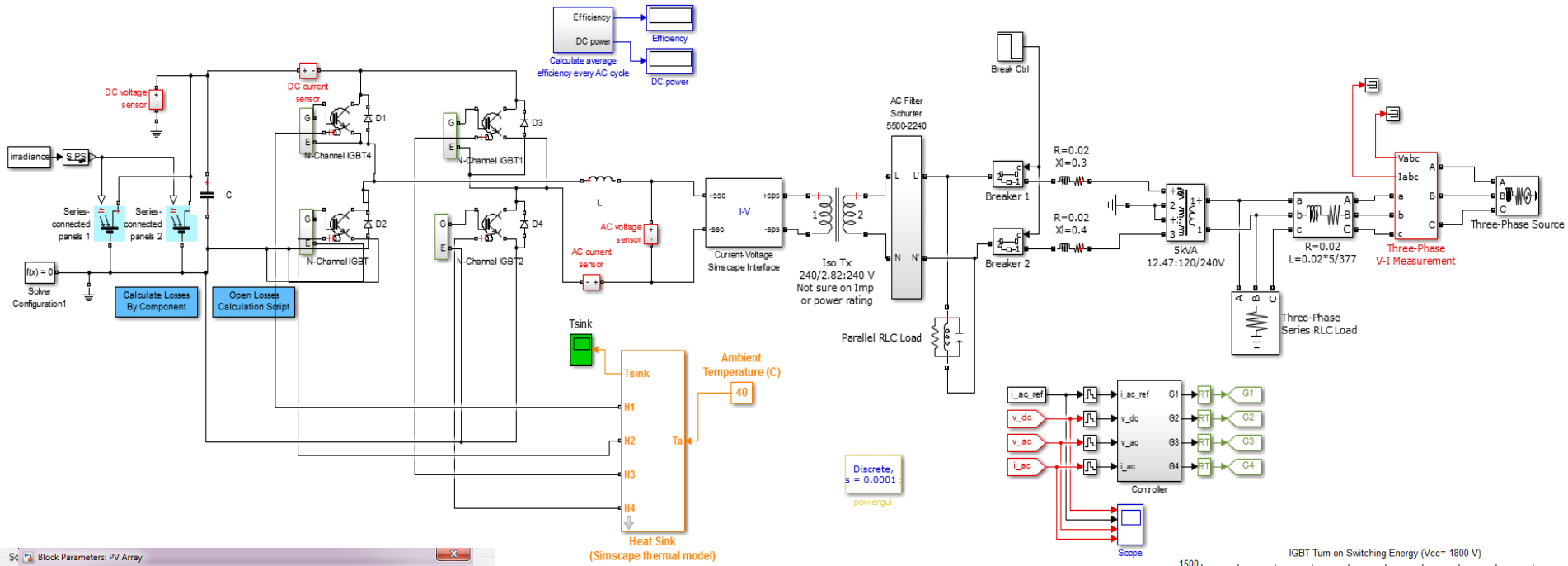
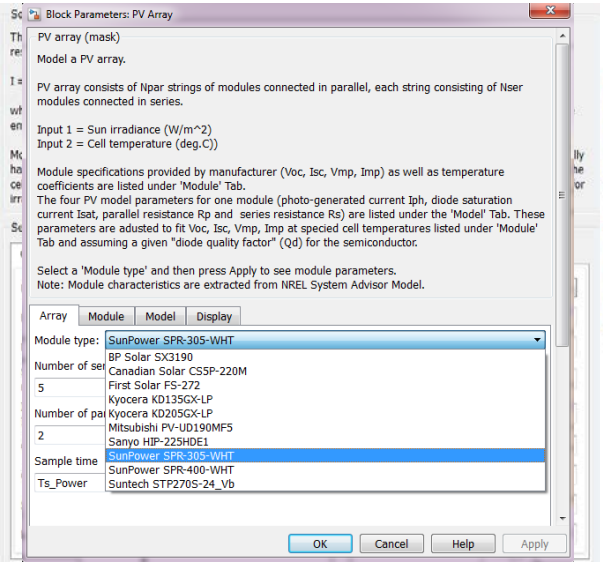
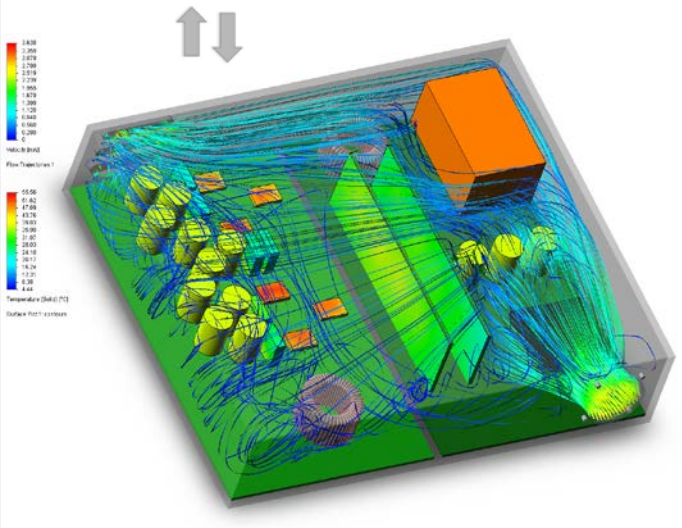
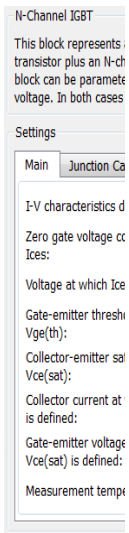
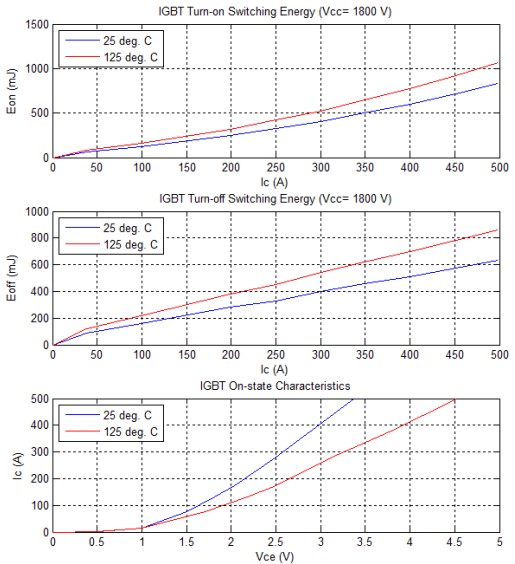




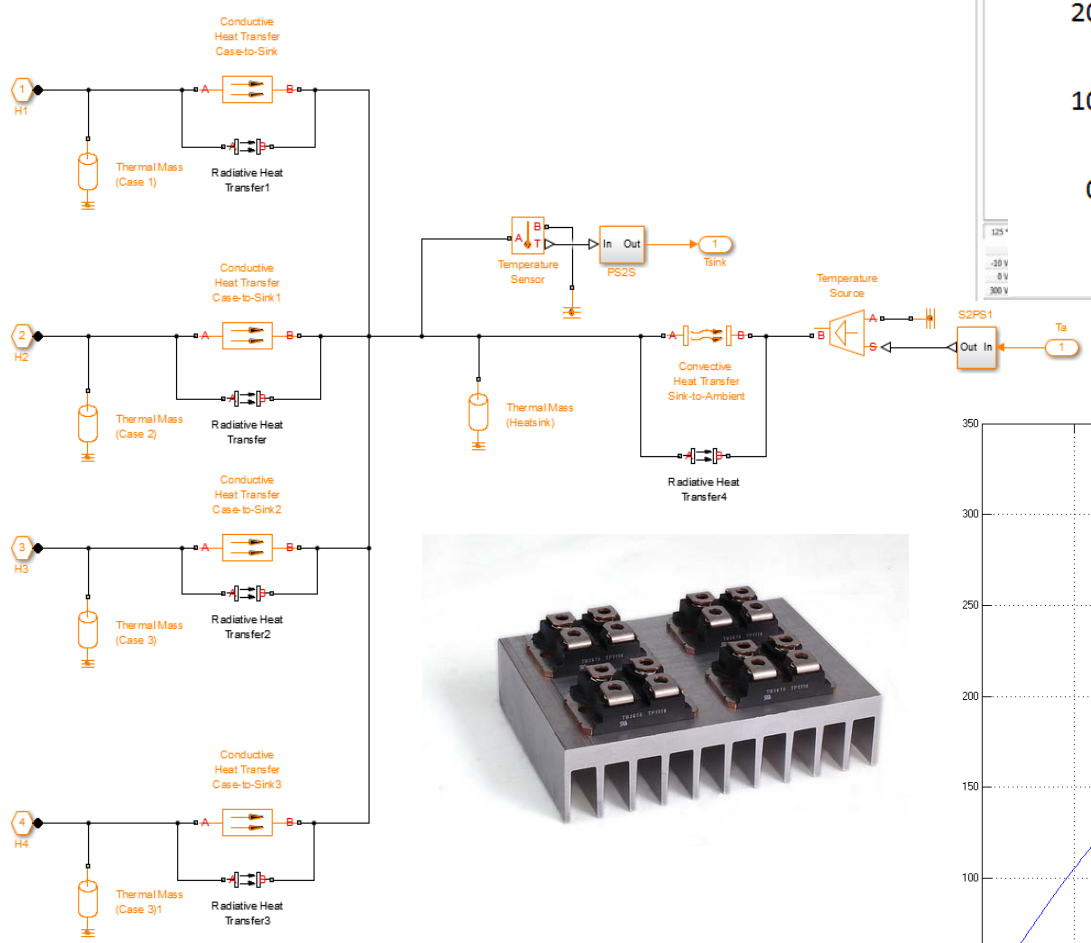


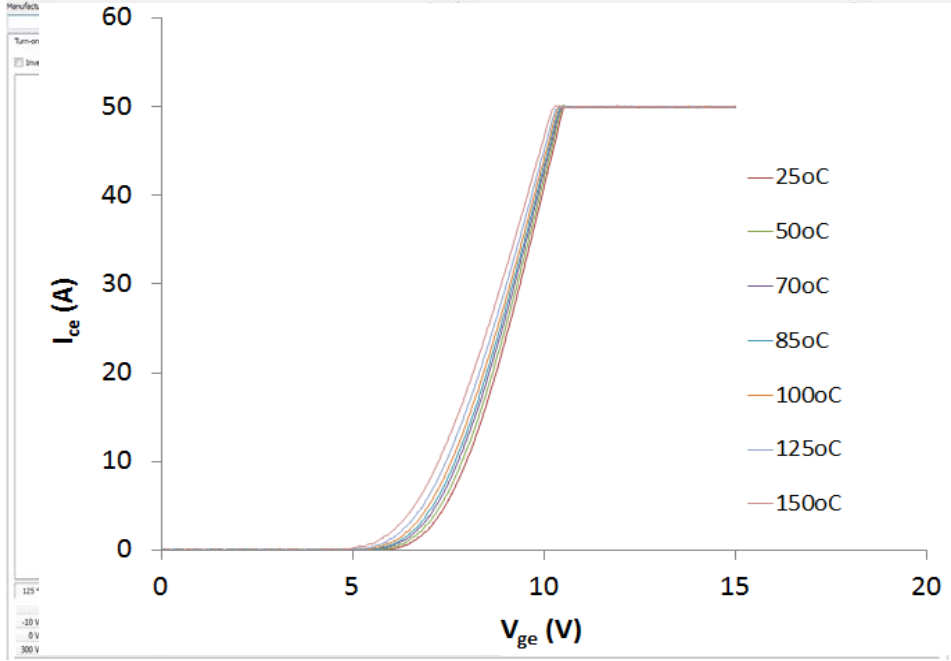




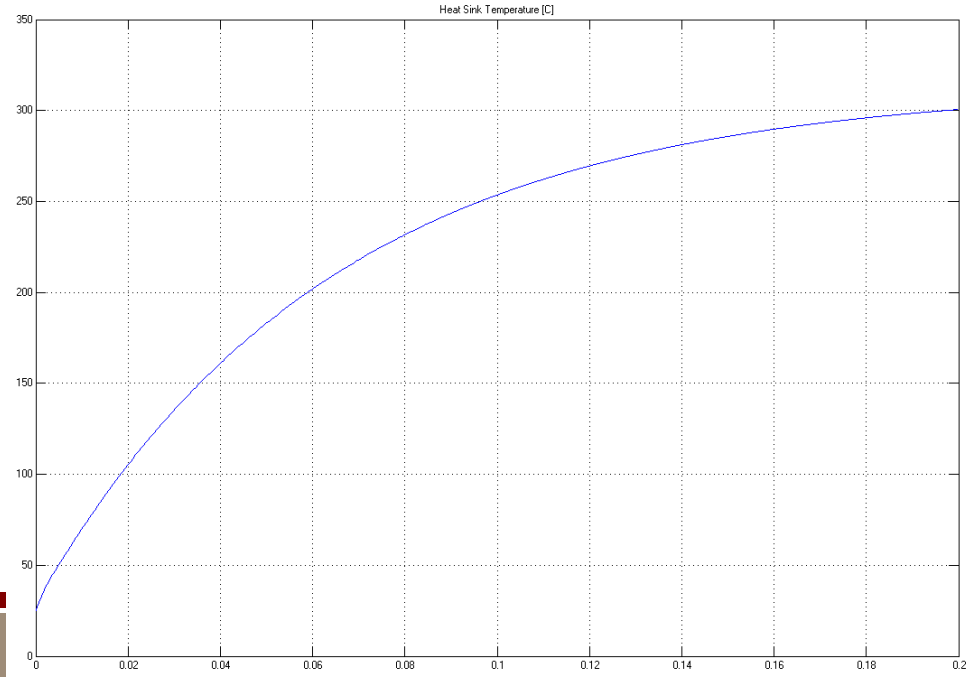
Thermal Sub-Model

Heat Sink Thermal Model





Heat Sink Thermal Profile Results



Fielded Studies Validation

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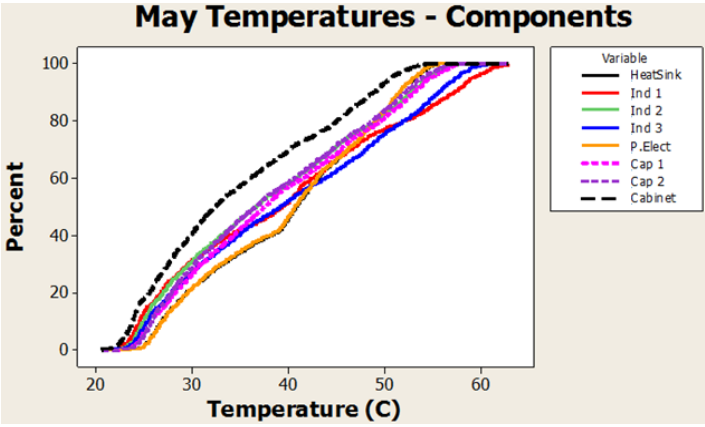
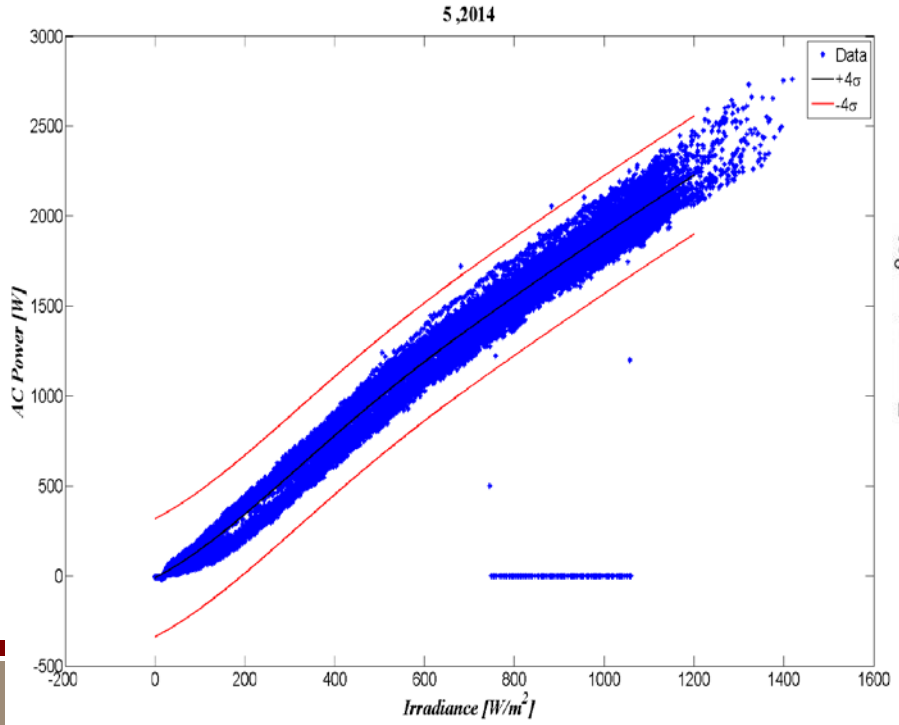
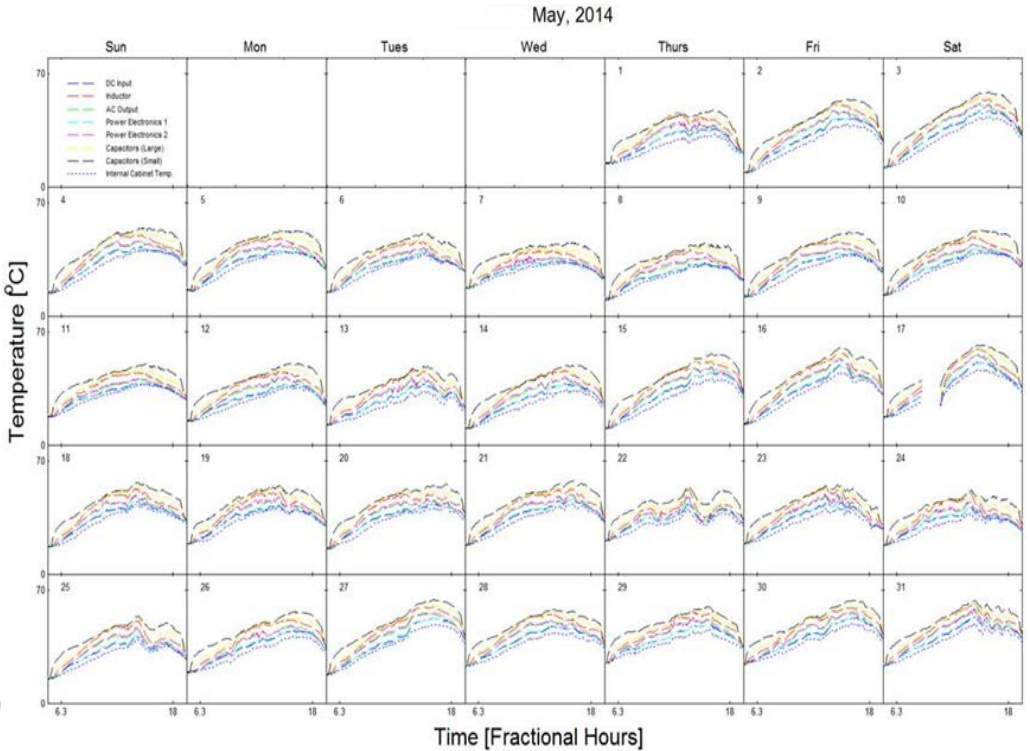
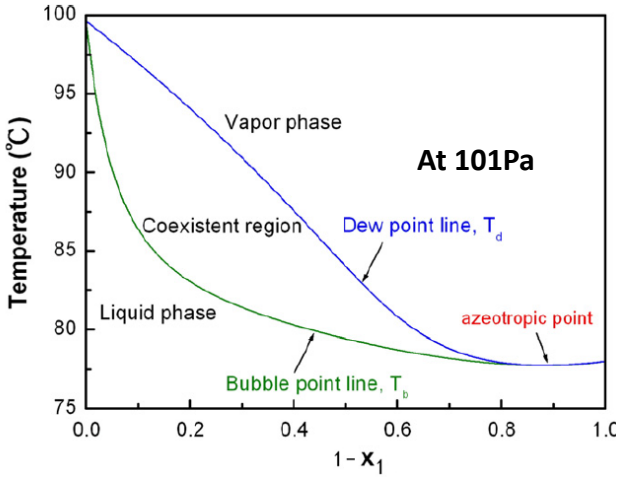


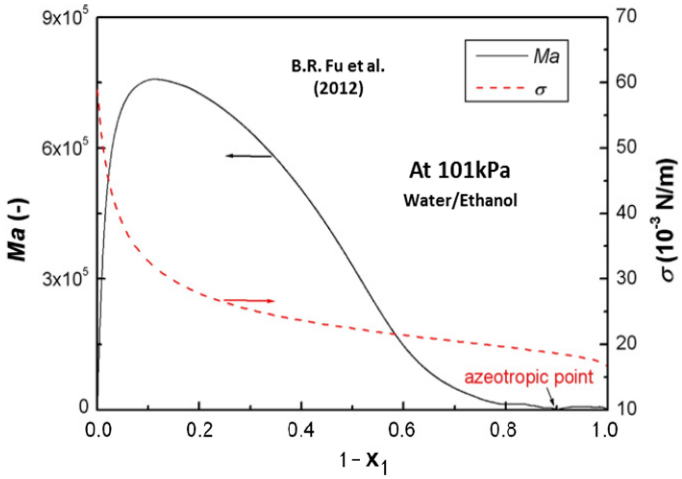


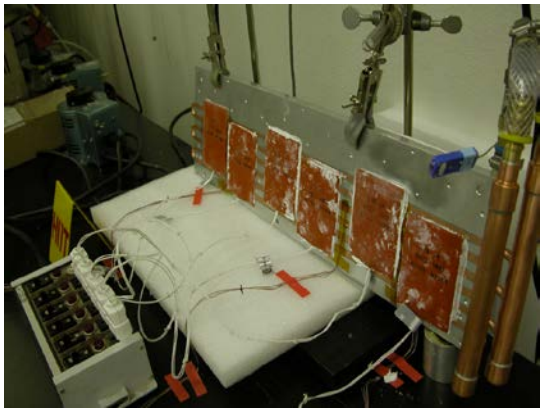


Heat Exchanger Cooling Plate

- Current Work Evaluating Heat Transfer Capability of Binary Mixture Working Fluids to Improve Heat Exchanger Performance
  - Isopropanal/Water – Leveraging Marangoni Effects
  - Propylene-Glycol (PPG)/Water
  - Ethanol/Water
  - Pure Components
- Alternative Adhesives Durability/ Performance Evaluation







Conclusions

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- Reliability issues still remain with inverters, especially with larger inverter systems.
- Enhanced power electronics have new thermal management challenges.
- Newer topologies & electronics densities are creating new reliability challenges.
- Various methods for accelerated testing:
  - ALT
  - HALT
  - HASS
  - Etc.
- Various electro-thermal modelling platforms exist with limitations.
- SimElectronics interfaced with CFD analysis has much potential!

Exceptional service in the national interest

Sandia National Laboratories

Thank You

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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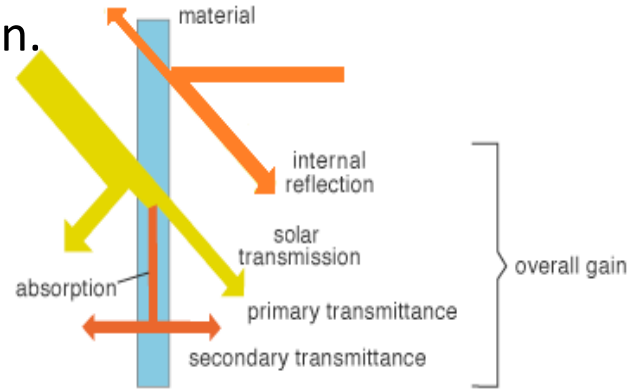
Extra Slides

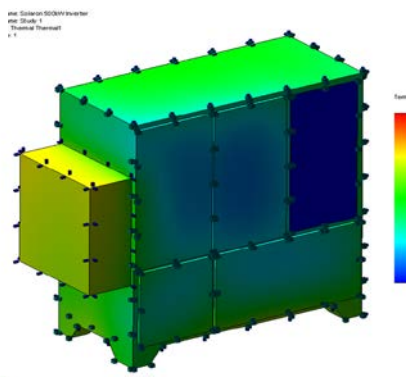
Solar Gain & Thermal Gain

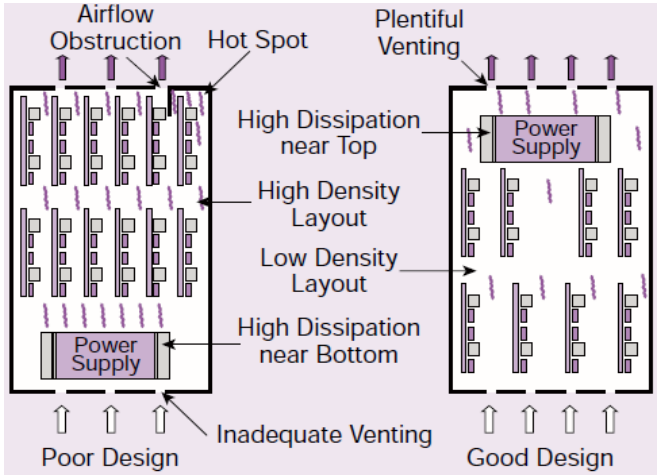
- Thermal gain from solar radiation in an object, space or structure, which increases with the strength of the sun, and with the ability of any intervening material to transmit or resist radiation.

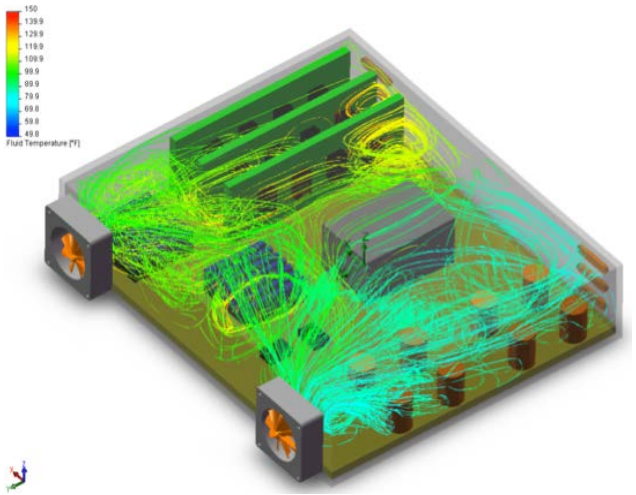
Radiative Energy Balance:



- FEA/CFD Impact Analysis of Internal Comps.







Overview & Need for Electro-Thermal Modeling

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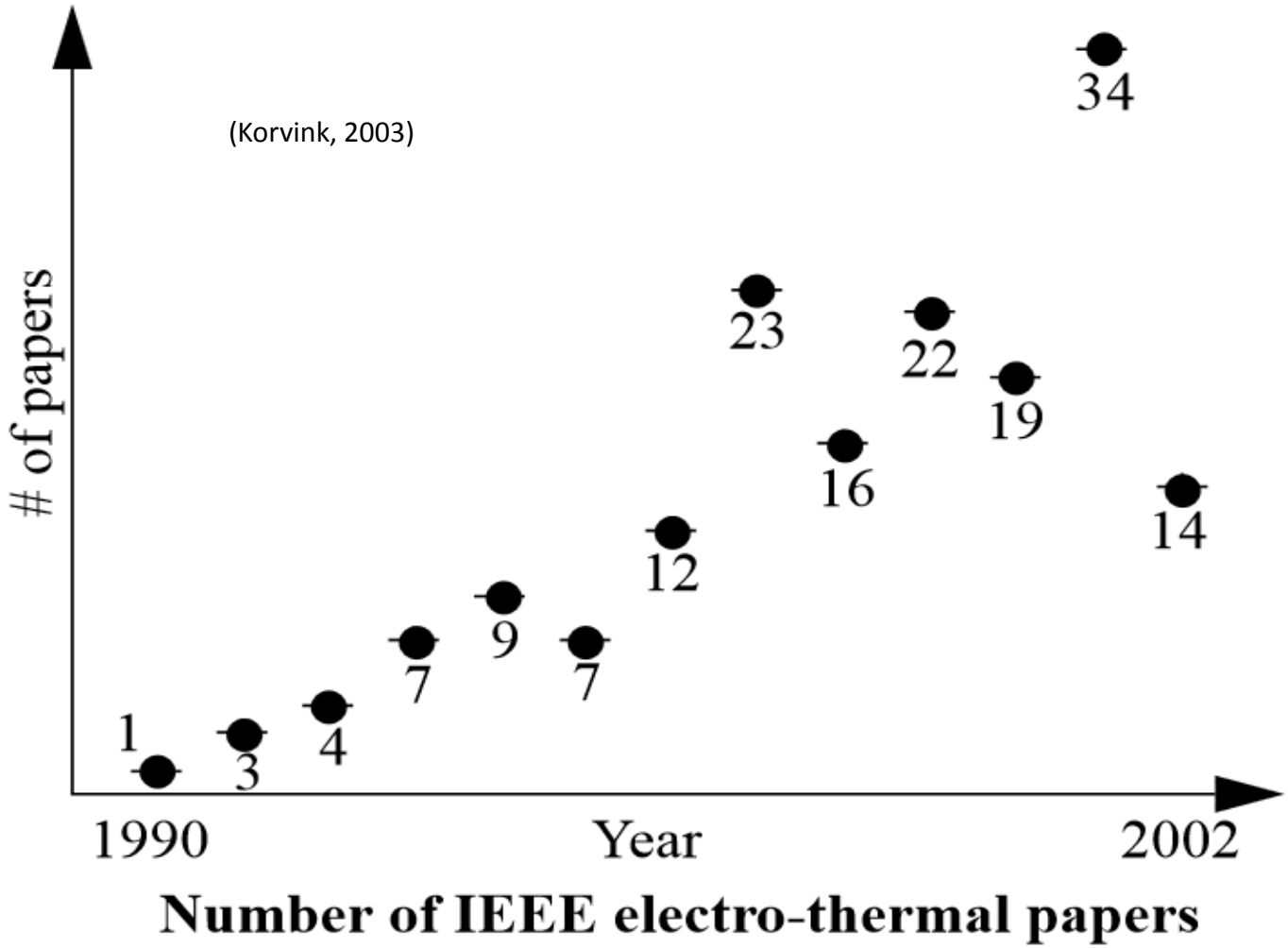
- **Research Goal:** Develop robust, reliable non-ideal electro-thermal model for an inverter and PV system.
- **Purpose:** Provide an overview of heat transfer challenges and design/operational solutions using fast, comprehensive, transient modelling tools.
- **PV Inverter Reliability:** PV inverters continue to be an area of reliability challenges for achieving levelized LCOE. Electro-thermal issues still contribute to these issues, especially for advanced inverter functionality. Rigorous, non-ideal, and transient electro-thermal models are required for robust development.
- **Sandia Reliability Program:** Sandia's historical and unique capabilities with power electronics, computing resources and PV fundamental science, as well as distinctive experimental platform laboratories and field-sites, provide distinction for electro-thermal modelling.

Necessity of an Inverter Thermal-Performance Model

Sandia National Laboratories

- Just like the electronics industry, inverters are reaching performance limitations.
- Need for a scalable model to determine heat transfer modes occurring at respective residential and utility-scale operations.
- Higher power conversion designs are creating an industry push to leverage liquid-cooled heat exchangers, from traditional fan-cooling
- Industry need for a standardized inverter thermal performance model for determining appropriate thermal management design options that will balance costs
- Knowledge gaps exists concerning inverter failure rates vs. cooling rates and impacts on IGBT switching and overall inverter performance

Title


(Korvink, 2003)
# of papers
1
3
4
7
9
7
12
23
16
22
19
34
14
1990
Year
2002
Number of IEEE electro-thermal papers

What is ALT & why? Issues with ALT:

What?

- Component life tests
- High stresses
  - Single or combined
  - Activate “appropriate” failure modes
  - Measureable
- Failure analysis

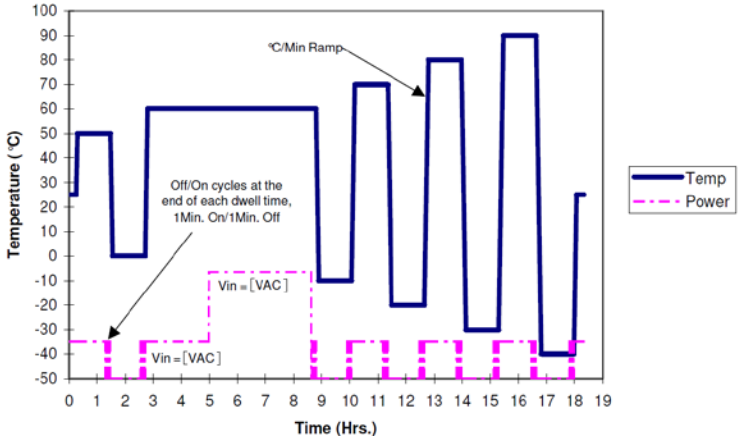
Why?

- Time
- Full system is expensive and complicated

- Unknown failure mechanisms
- Unknown / variable use environment
- Changing mechanisms as function of environmental stress
- Difficult to control and characterize defects
- Long duration experiments
- Evolving / improving technology

Accelerated Testing

- HALT – Highly Accelerated Life Testing
  - Stress tests not meant to simulate the field env., but find weaknesses in design
  - Stresses are stepped up to well beyond the expected field environment until "fundamental limit of the technology" is reached
  - General Procedures for HALT Testing:
    - 1. Attach thermocouples, & monitor line input Vac, output Vdc, and other signals.
    - 2. Perform temperature cycling
    - 3. Perform functional test
    - 4. Determine root cause of any failures, implement corrective action (if required), and repeat test (if required).



$$A.F. = e^{(\frac{E}{K})(\frac{1}{T_1}-\frac{1}{T_0})}$$

T_1 = Normal Ambient Temp. (298 °K)

T_0 = Elevated Ambient Temp (°K)

E = Activation Energy (eV, Typ.)

K = Boltzman's constant

Faraz Ebneali Phone: 520-370-3047 Email: faraz.ebneali@renesola.com

Sustainability Through Product Quality and Compliance

Objective

Standard Development

The codes and standards, protocols and testing methods of solar energy products family are being developed /updated to ensure suppliers will continue providing the products that can meet the product specification, performance and specified warranty obligations.

Overview of new standards

The present article was aimed at providing an overview of important developed and under development standards and test methods that will result in higher durability and reliability of photovoltaic modules, inverters and stability of grid networks.

Quality and Price Trend

PV module prices have dropped 60 to 65 percentage over the last couple years. According to the SunShot vision study (DOE 2012), the target total cost of systems will drop about 75% till 2020(1). This simply indicates the solar hardware manufacturers must lower the prices while increasing the quality by applying new standards and regulations.

The price-quality relationship has a low-high trend, as the prices drop the quality should increase. With that in mind, the consumer behavior has also changed and customers demand higher quality products. In fact, not only do they demand quality products, but they would also like to verify it through extra testing, inspections and going above and behind the existing standards to ensure the specified level

Summary of Plan

As shown in Figure 1, an estimate of ten new changes are expected to occur until 2017-2018. Six are module related standards and testing procedures:

I. Qualification plus testing protocol
II. IEC 62882 dynamic mechanical load testing (DMLT)
III. IEC 62804 Test Method for Detection of Potential Induced Degradation (PID)
IV. IEC 62852 connectors for DC application in photovoltaic systems
V. IEC 62790 junction boxes of photovoltaic modules are being developed for modules
VI. UL1703 new edition

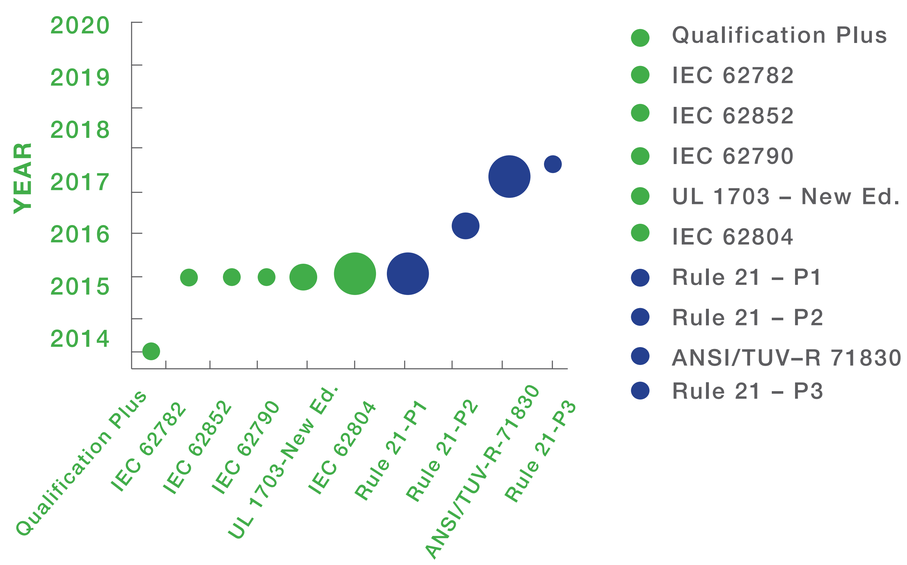


Figure 1- Trajectory of under development standards and testing procedures till 2017-2018

	Existing Qualification Test	Qualification Plus
Component Test		
UV Exposure of Encapsulant	UV-dose of 15 kWh/m2	UV-dose of 224 kWh/m2
UV Exposure of Backsheet	UV-dose of 15 kWh/m2	UV-dose of 320 kWh/m2
UV Exposure of Cables & Connectors	UV-dose of 15 kWh/m2	New-Standard - EN 50521 & IEC 62852
UV Exposure of Junction Box	UV-dose of 15 kWh/m2	New-Standard - EN 50548 & IEC 62790
Bypass Diode and Junction Box Thermal Test	1 hr	95 hours
Module Test		
Thermal Cycling	200 cycles	500 cycles
Dynamic Mechanical Load Test	State Mechanical Load	Dynamic Mechanical Load - IEC 62782
Enhanced Hot Sport Test	IEC 61215	ASTM E2481-06
Potential Induced Degradation	N/A	96h/60ºC ±/85%RH or 168h/25°C/60%RH
Quality Management		
PV - Specific Quality Management	N/A	Quality Management System
Sample Selection Method		
Number of Samples	2	5
Selection Method	Design or Engineering Line	Production Line

As shown in Figure 1, six new inverter related standards and testing procedures are on the way:

I. Rule 21 phase 1, 2, 3
II. ANSI/TUV-R 71830 microinverters and microconverters design qualification and type approval for utility interactive inverters

Table 1 shows the side-by-side comparison of the existing qualification test versus the proposed qualification plus.

Table 1- Summary of the existing qualification test vs. proposed qualification plus

Conclusion

ReneSola, as a leading international solar energy components supplier, is validated as a SATELLITE laboratory. ReneSola has a solid R&D on product optimization and new standard implementations to guarantee high performance and quality that help investors to achieve the fastest and safest possible return on investment.

ReneSola supports the intention of strengthening the quality control and standardization of the solar energy components as the new standards are scientifically approved and developed

Competitiveness qualification tests and new standards can help to identify the top-quality and performing products and differentiate between the quality driven manufacturers from a purely compliance driven one

The costs and time associated with the new standards should be carefully evaluated. Given these facts, although the solar family products will subject to the longer testing hours and additional standards but the outcome ensures a more reliable and efficient, low-risk and defect-free products which results in higher investment in solar sector that will benefit everyone.

This presentation contains no confidential information

2015 IECRE: PV System Certification Workshop

IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE System)

NREL PV Reliability Workshop

26 Feb 2015

Chair: George Kelly (Sunset Technology)

Today's Program

- Background and Current Status of the IECRE System (Sandy Butterfield, REMC Chairman)
- Current Status of the PV Sector of IECRE (G. Kelly)
- Stakeholders Perspectives
  - Financers/Investors/Owners
  - Certifying Bodies/Test Laboratories
  - Manufacturers/EPCs/ O&M Providers
- Survey Results (G. Ball)
- **Lunch**
- Review of PV Rules of Procedure
  - Participants rotate in 4 groups
- Issues to be Resolved (John & Alex)

IECRE PV Survey

- The goal of this workshop is to gather wide input from the PV community, leading to acceptance of the new system by all involved.
- **The survey is intended to solicit input on how a PV certification scheme can help meet your needs.**
- Please complete a paper copy if you didn't fill out the survey online when you registered.

Survey Questions Overview

#	SURVEY SECTION	INTENT
1	PV Plant Application	To help scope out whether the standards should govern different types and sizes of PV systems or just one size fits all
2	PV Power Plant Installation Scope	To help identify the governing boundary of the standard i.e., From which point in the plant stage till where
3	PV Plant Certification	Establish *certification types and requirements* for the certification bodies to follow within the standard's scope
4	Safety and Security of Power Plant	To help identify whether safety and security are areas to address. If so what specifically should be included
5	Performance Verification and Validation	To identify items regarding performance that should be included in standard and how verification is done on data accuracy, assumptions, and metrics on ongoing basis
6	Financial Performance	To identify the factors which contribute most to the successful operation of the asset

Introduction to IECRE

IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE System)

NREL PV Reliability Workshop

26 Feb 2015

Sandy Butterfield

PV-OMC Status

Solar PV Operating Management Committee

IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE System)

NREL PV Reliability Workshop

26 Feb 2015

George Kelly

IECRE PV Forum

- 18-Sep-2014 in Boulder, CO
  - Participation by 28 individuals representing 6 member body countries, including 4 officers of TC 82
- Initiated activities of PV OMC (per REMC Decision 12/2014) pending election of OMC officers
  - Call for nomination of officers issued in October
- Formed 1 permanent Working Group and 3 temporary Task Groups
- Made 2 formal recommendations to REMC

PV OMC Recommendations to REMC

- Recommend WG001 should include as many common issues as possible in the RE system rules of procedure.
- Recommend REMC should engage in outreach to financial stakeholders

  (e.g., PV OMC is planning a series of workshops in Asia, Europe and North America to collect input that can be used to guide future activities)

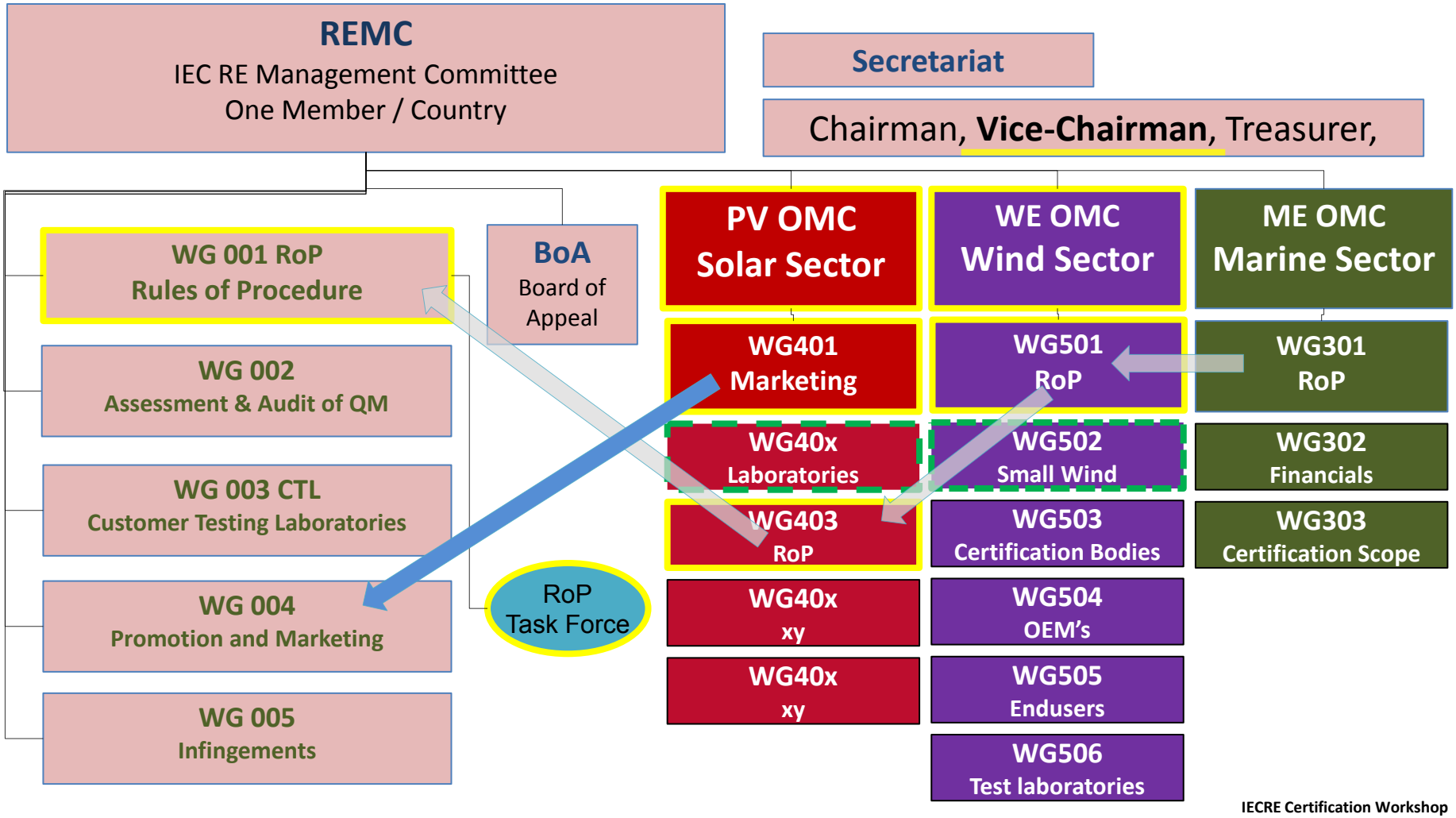
PV OMC Task Groups

- Three temporary task groups for creation of sector documents (task leaders in parentheses):
  - TG401: Terms of Reference and Scope for PV Rules of Procedure (R. Bedi)
  - TG402: PV Rules of Procedure and applicable standards to be considered for assessments (G. Kelly)
  - TG403: Assessment procedures and documentation required for initial acceptance of CB/TL in the PV sector (S. Rai)
- Documents to be presented for review at next PV OMC meeting

PV OMC Working Group

- PV OMC formed permanent WG401 on Market Surveillance with the following scope:
  - to collect information about problems observed in existing PV systems and
  - to develop statistics over time to analyze trends
- Call for nomination of convenor and WG members circulated to NCs in October
- Some confusion about scope and numbering

Defined Structure of IEC RE
REMC + Committees + Working Groups



WG401 Activities

- Market Surveillance:
  - To collect information about problems observed in existing PV systems and to develop statistics over time to analyze trends
- Marketing:
  - To promote use of the system within the PV industry

- Agreement to **do both** for now
  - Split into 2 WGs later if needed

PV OMC
Officer Elections

- PV OMC Chairman:
  - Adrian Häring (Germany)
- PV OMC Vice-Chairman:
  - Sewang Yoon (Korea)
- Next meeting planned for May 5-6
  - Cologne, Germany
  - Hosted by TUV Rheinland

PV OMC Members

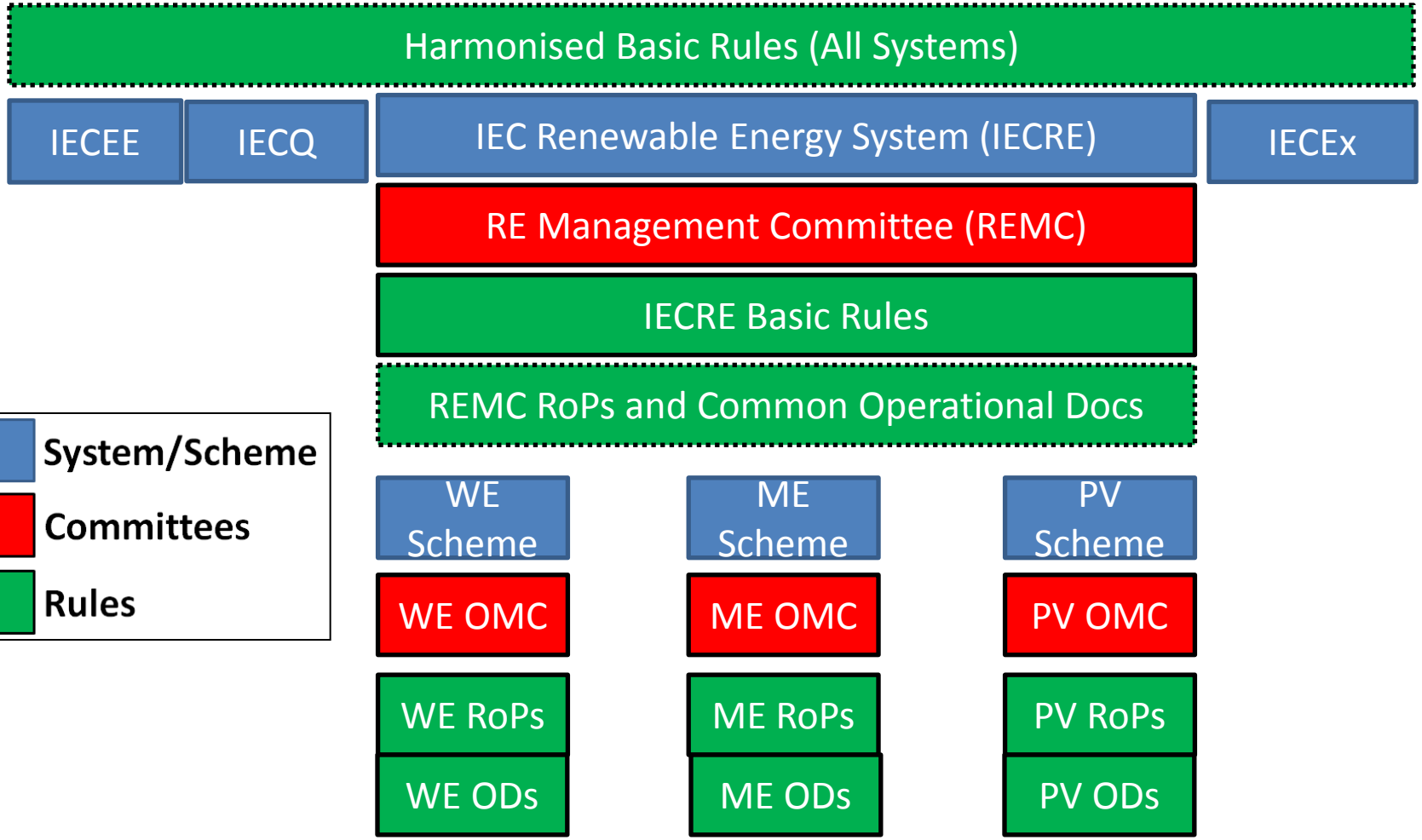
11 National Committees as of 17-Feb

Country	Member Body Name
Canada	CANC/IEC
China	Certification and Accreditation Administration of the People's Republic of China (CNCA)
Egypt	New & Renewable Energy Authority (NREA)
France	LCIE by delegation from the IEC NATIONAL COMMITTEE of FRANCE
Germany	IEC National Committee of Germany
Hungary	TÜV Rheinland InterCert kft.
Japan	IEC National Committee of Japan
Korea, Republic of	IEC National Committee of Korea, Republic of
Spain	IEC National Committee of Spain
United Kingdom	IEC National Committee of the United Kingdom
USA	USNC/IECRE

USNC/IECRE Status

- Established as standing committee of USNC/CAPCC (like other IEC systems)
- Kickoff teleconference 9-Jan
  - ~100 participants from 3 industries
- Discussed draft of USNC/IECRE rules
  - Final version to be balloted in March
- Election of officers closes 27-Feb
- Next meeting 8-9 April
  - Hosted by NEMA (Rosslyn, VA)
  - Contact Joel Solis, USNC Secretary

IECRE Hierarchy



IECRE-PV Documents

- PV Rules of Procedure (RoP)
  - Specific requirements for certification of PV power plants
  - First draft circulated in March 2014
  - Will combine work of all 3 TGs
  - Final version to be approved by REMC later in 2015
- PV Operational Documents (OD)
  - Administrative details for processing requests, record-keeping, etc.

Operational Documents

- OD 001 (Draft) Procedures for the Issuing of IECRE-PV Certificates of Conformity, IECRE-PV Test Reports and IECRE-PV Quality Assessment Reports

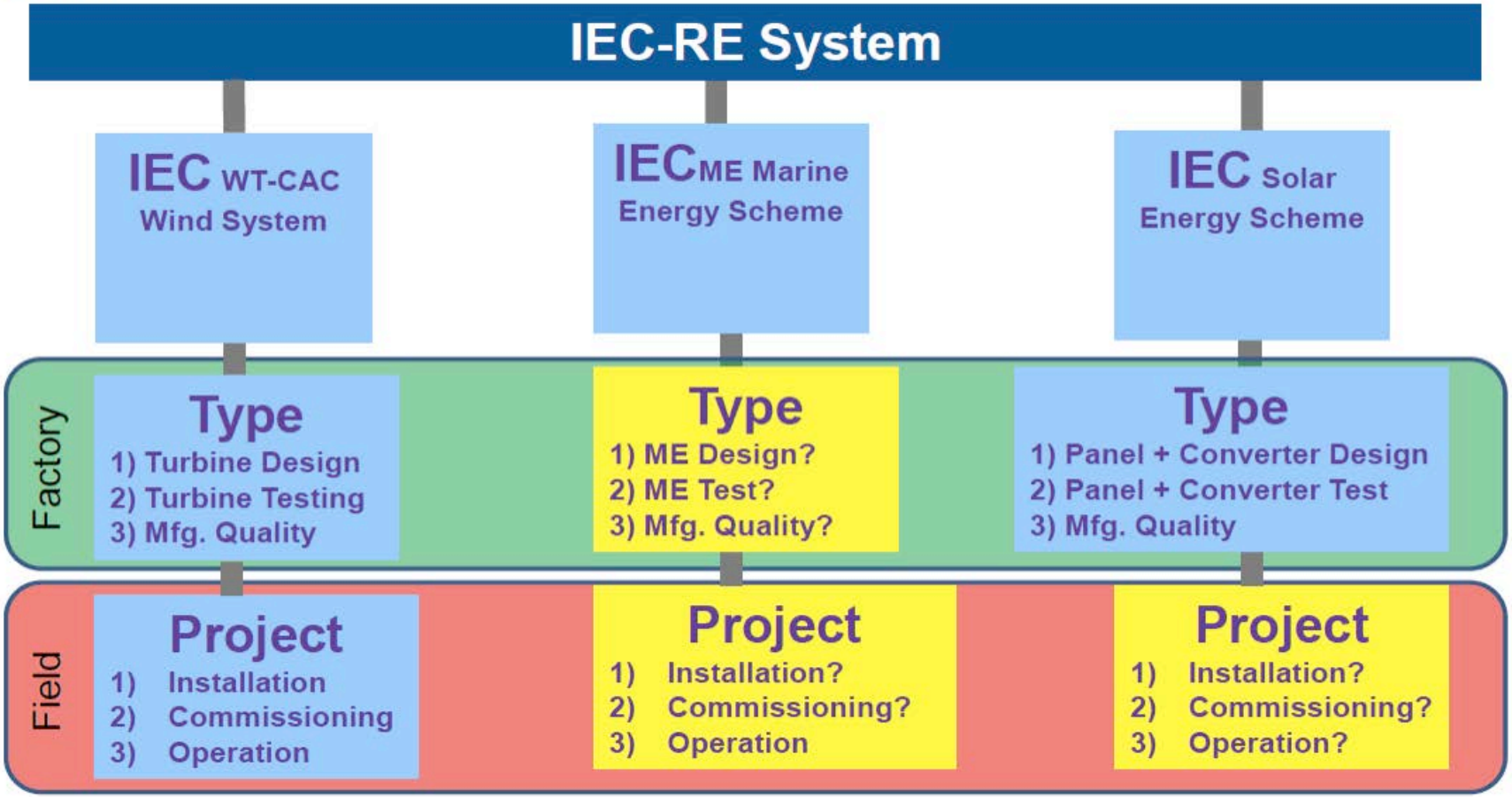
- OD 002 IECRE-PV Scheme rules
- OD 003 Certificate of Conformity rules
- OD 004 IECRE-PV Scheme Fees
- OD 005 IECRE-PV “On-Line” system
- OD 006 Qualification of PVCB auditors
- OD 007 IECRE-PV Test certificates

- Etc., Etc. Copy from IECEx wherever possible

PV Rules of Procedure

- Scope (TG401)
- Normative references (TG403)
- Terms and definitions (TG401)
- Acceptance of certification bodies (TG402)
- Management of the certification system (TG402)
- Extent of certification (TG401)
- Aspects of certification (TG401/403)
- Final evaluation (TG403)
- Plant certificate (TG402)

RE System Common Elements



Aspects of Certification

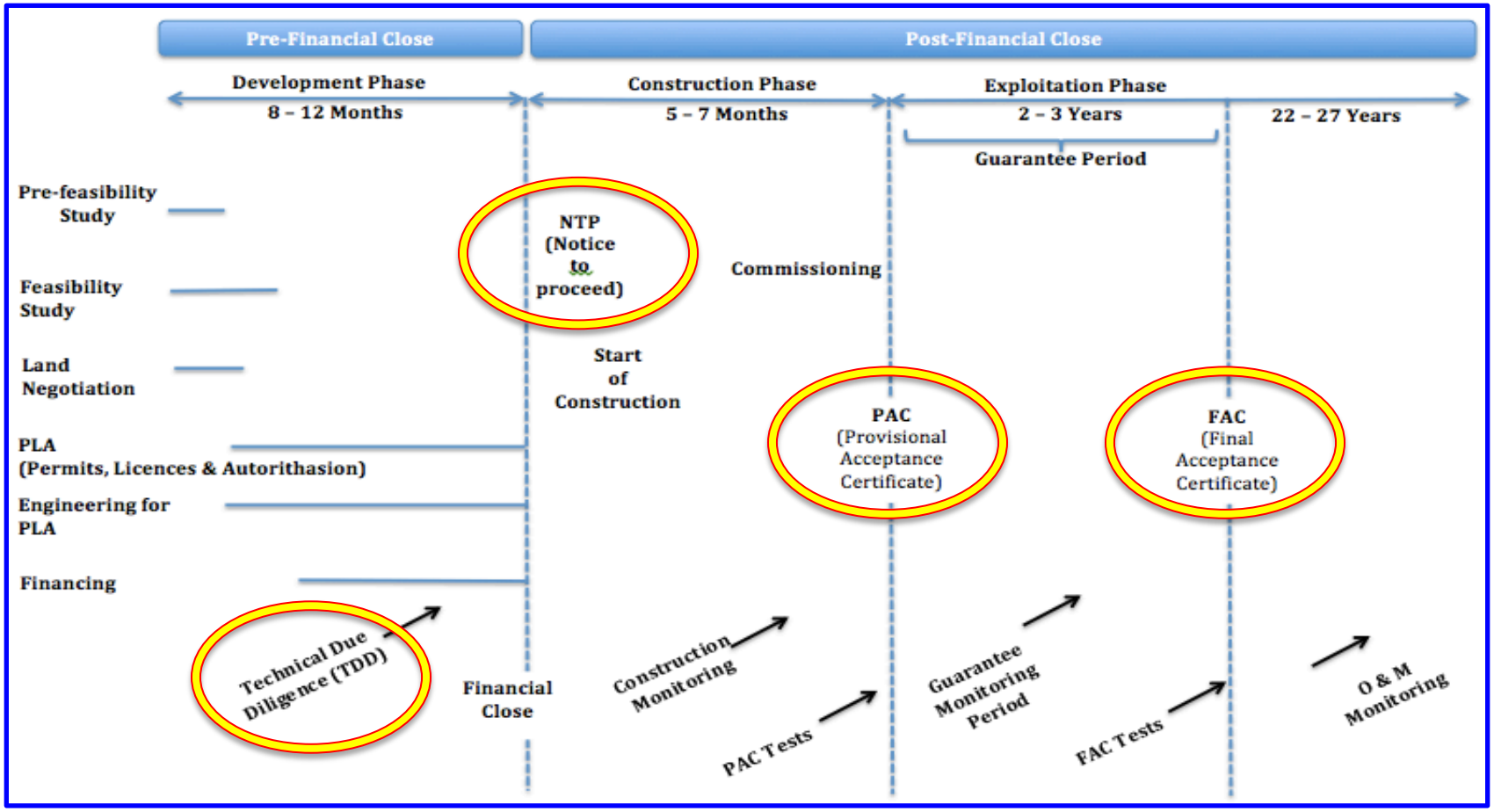
- Conformity assessment will be performed and certificate issued for an individual PV power plant on a specific site

- Design Phase
  - General
  - Site conditions evaluation
  - Design evaluation
  - Equipment evaluation
  - Structural and electrical evaluation

- Implementation Phase
  - Installation surveillance
  - Output characteristics measurement
  - Commissioning surveillance
  - Operation and maintenance surveillance

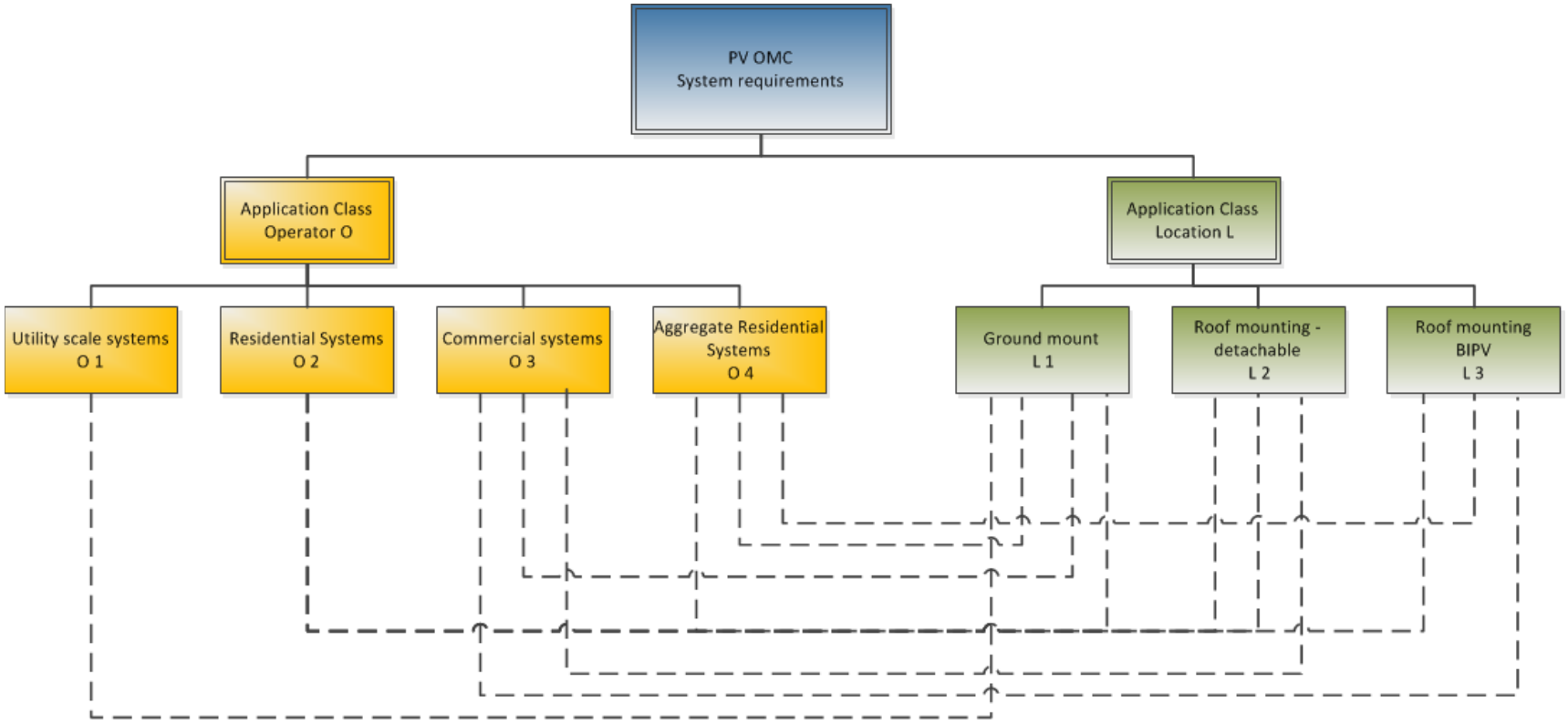
PV System Lifecycle

- Different audits may be required at different stages

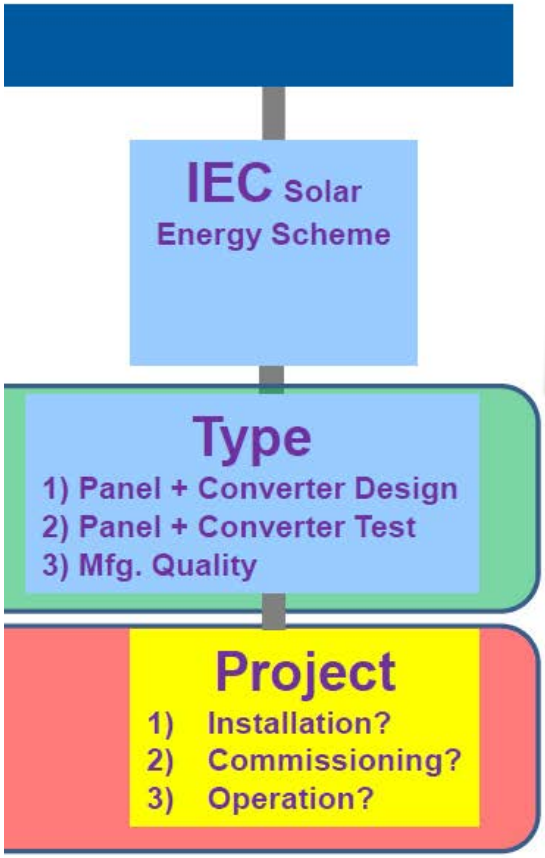


System Categories

- Requirements may depend on Operator Class (O) and Location Class (L)



PV Standards for Assessment



Module - 61215 / 61730
Inverter - 62109 / 62891
BOS - 62093 + others

Manufacturing Quality
– 62941 (Committee Draft)

System Design - 62548 / 62738
Installation – local codes
Commissioning - 62446 / 61829
Operation – 61724 + TBD
Maintenance – WG3 NWIP

IEEE PVSC – June 2014

Ensuring the reliability of PV systems through the selection of International Standards for the IECRE Conformity Assessment System

George Kelly, Sunset Technology, USA
Ted Spooner, UNSW, Australia
Guido Volberg, TUV Rheinland, Germany
Greg Ball, DNV GL, USA
Jonas Bruckner, VDE, Germany

Hardware Assessment

- PV Modules
  - IEC 61215 Design Qualification
  - IEC 61730 Module Safety
- PV Inverters
  - IEC 62891 Inverter Performance
  - IEC 62109 Inverter Safety
- Mounting Hardware
  - UL 2703 Mounting, Clamping, & Grounding Devices
  - TUV PfG 1794 Mounting Systems
- BOS Components
  - IEC 62093 BOS Qualification
  - Multiple IEC, EN & UL standards

QMS Assessment

- Guideline for Manufacturing Consistency
  - NWIP developed by PV QA Task Force (PVQAT)
  - Drafted by collaboration of 4 regional teams; collection of best practices from across the industry
  - Refers to basic requirements of ISO 9000, plus…
- Focus on PV-specific manufacturing processes and procedures to ensure quality and consistency
  - Defines key metrics and capabilities needed for PV
  - Modules produced this way will be more likely to perform according to warranty (25+ years)

System Design Assessment

- IEC/TS 62548 PV Array Design Requirements
  - PV system architectures
  - Mechanical design
  - Safety issues
  - Selection and erection of electrical equipment
  - Marking and documentation
- Needs to be coordinated with IEC 60364 series
  - Basic standards for low-voltage electrical installations
- New standard IEC 62738 under development
  - Specific to utility-scale plants

Installation Assessment

- Installation
  - No international standard (partly covered in IEC 62548)
  - Typically controlled by local government requirements
    - NFPA 70 US National Electrical Code
    - IEC 60364 series in Europe
    - Multiple building and fire codes (IBC, IFC, etc.)
    - ASTM E2766 for Steep-sloped Roofs
- Commissioning
  - IEC 62446 covers the most important requirements
  - System output measurement
    - IEC 61829 & 61724
    - ASTM E2848 & E2939

O&M Assessment

- Operation
  - IEC 61724 - guidelines for performance monitoring
  - Solar ABCs report on O&M Fundamentals
  - Sandia Labs O&M working group
  - ASTM Task Group (ICOMP)
    - Comprehensive guideline to available standards
    - Focus on power plant operation
- Maintenance
  - NWIP started in TC82 Working Group 3
    - Includes preventative and corrective maintenance
    - Both safety-related and performance-related
    - Troubleshooting and documentation of results

RoP Standards Matrix

Rules of Procedure IECRE PV	phase / aspect									
Applicable Standards	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.11		
Doc #	site conditions	design	equipment	struct/elect	installation	commissioning	plant output	ops & maint	responsible group	document status
IEC 60269		x	x						IEC SC32B	published
IEC 60364-5-52		x		x	x				IEC TC64	published
IEC 60721-2-1	x	x	x						IEC TC104	published 2013
IEC 60891							x	x	TC82 WG2	published 2009
IEC 60904-1							x	x	TC82 WG2	ed.3 CDV in process
IEC 60904-2							x	x	TC82 WG2	published 2015
IEC 60904-3							x	x	TC82 WG2	ed.3 FDIS in process
IEC 60947-1		x	x	x	x				IEC SC121A	published 2014
IEC 60947-2		x		x					IEC SC121A	published 2013
IEC 61215 series			x						TC82 WG2	ed.3 CDV in process
IEC 61439-1		x		x	x				IEC SC121B	published 2011
IEC 61683						x			TC82 WG6	published 1999
IEC 61724-1		x				x	x	x	TC82 WG3	ed.2 CD in process
IEC 61724-2		x				x	x	x	TC82 WG3	NWIP in process

RoP Standards Matrix

Rules of Procedure IECRE PV	phase / aspect									
Applicable Standards	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.11		
Doc #	site conditions	design	equipment	struct/elect	installation	commissioning	plant output	ops & maint	responsible group	document status
IEC 61724-3		x					x	x	TC82 WG3	CD in process
IEC 61727		x			x	x		x	TC82 WG3	published 2004
IEC 61730-1			x						TC82 WG2	ed.2 CDV in process
IEC 61730-2			x						TC82 WG2	ed.2 CDV in process
IEC 61829							x	x	TC82 WG3	ed.2 CDV in process
IEC 61853-3		x	x						TC82 WG2	FDIS in process
IEC 62093			x						TC82 WG6	ed.2 CD in process
IEC 62109-1			x						TC82 WG6	published 2010
IEC 62109-2			x						TC82 WG6	published 2011
IEC 62116						x			TC82 WG6	published 2014
IEC 62124			x			x	x	x	TC82 WG3	published 2004
IEC 62446-1						x		x	TC82 WG3	ed.2 CDV in process
IEC/TS 62548		x							TC82 WG3	ed.2 CDV in process
IEC 61724-3		x					x	x	TC82 WG3	CD in process

RoP Standards Matrix

Rules of Procedure IECRE PV	phase / aspect									
Applicable Standards	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.11		
Doc #	site conditions	design	equipment	struct/elect	installation	commissioning	plant output	ops & maint	responsible group	document status
IEC/TS 62727			x						TC82 WG7	published 2012
IEC/TS 62738		x							TC82 WG3	ed.2 CD in process
IEC 62790			x						TC82 WG2	published 2014
IEC 62817			x						TC82 WG7	published 2014
IEC 62852			x						TC82 WG2	published 2014
IEC 62891						x	x		TC82 WG6	FDIS in process
IEC/TS 62941			x						TC82 WG2	CDV in process
IEC 62446-2								x	TC82 WG3	draft NWIP
IEC/TS 6xxxx	x	x				x	x	x	TC82 WG3	draft NWIP
ASTM E2766					x				ASTM E44	published
ASTM E2848							x	x	ASTM E44	published
ASTM E2939							x	x	ASTM E44	published
ASTM WK43549	x	x	x	x	x	x	x	x	ASTM E44	ballot in process

RoP Standards Matrix

Rules of Procedure IECRE PV	phase / aspect									
Applicable Standards	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.11		
Doc #	site conditions	design	equipment	struct/elect	installation	commissioning	plant output	ops & maint	responsible group	document status
EN 50618				x					CENELEC	draft 2014
NFPA 70		x	x	x					NFPA CMP	2017 ed. In process
Solar ABCs								x	Solar ABCs	published
TUV 2PfG2305			x						TUV-R	published
TUV 2PfG1794/10.10			x		x				TUV-R	published
UL 489B		x		x					UL STP	published
UL 2703		x		x					UL STP	published
VDE AR-N 4105		x				x			VDE	published
O&M Cost Model		x				x		x	SAPC (E44?)	wish list
O&M Best Practices	x	x				x	x	x	SAPC (WG3?)	wish list
Installer Best Practices				x	x	x			SAPC (WG3?)	wish list
Inverter QMS			x						TC82 WG6?	wish list

Gaps to be Closed

- International Standards Needed:
  - Installation
  - Operation
  - Maintenance
- Standards Development in Process:
  - IEC TC82 – WG2, WG3
  - ASTM E44 - ICOMP
  - UL, TUV-R, VDE
  - SunSpec, Sandia, others

TC82 Areas of activity

- WG2 on Modules
  - Manufacturing quality system guidelines CD
  - Reliability & comparative testing CDs
- WG3 on Systems
  - System commissioning & documentation CDV
  - System operation & maintenance NWIP
- Coordination with ASTM E44
  - Installation, Commissioning, Operations & Maintenance Process (ICOMP)

IEEE PVSC – June 2015

Ensuring the reliability of PV systems through the formation of the IECRE Conformity Assessment System and the development of new International Standards

George Kelly, Sunset Technology, USA
Adrian Häring, SMA, Germany
Ted Spooner, UNSW, Australia
Greg Ball, DNV GL, USA
Sarah Kurtz, NREL, USA

Thank you for your attention

Questions?
Suggestions?
Concerns?

Contact george@sunset-technology.com

Stakeholders' Perspectives

IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE System)

NREL PV Reliability Workshop

26 Feb 2015

Chairs: G. Tamizhmani (TUV/PTL)

and Govind Ramu (SunPower)

Stakeholders' Perspectives

- Financers/Investors/Owners
  - Jon Previtali, Wells Fargo
  - Mike Roy, Hartford Insurance Group
- Certifying Bodies/Test Laboratories
  - Peter Bostock, VDE
  - Matthias Heinze, TUV Rheinland

10-10:30 COFFEE BREAK

Stakeholders' Perspectives

- Certifying Bodies/Test Laboratories
  - Tadashi Obayashi, JET
- Manufacturers/ EPCs/ O&M Providers
  - Sumanth Lokanath, First Solar
  - Rue Phillips, True South Renewables
  - Joe Cunningham, Centrosolar
  - Eric Daniels, Field Energy Operations

IECRE PV Survey

- Results presented by Greg Ball (DNV GL)

- **Reminder:**

  Posters will be on display during lunch break

  12:00–1:30

2015 IECRE: PV System Certification Workshop

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NREL PV Reliability Workshop

26 Feb 2015

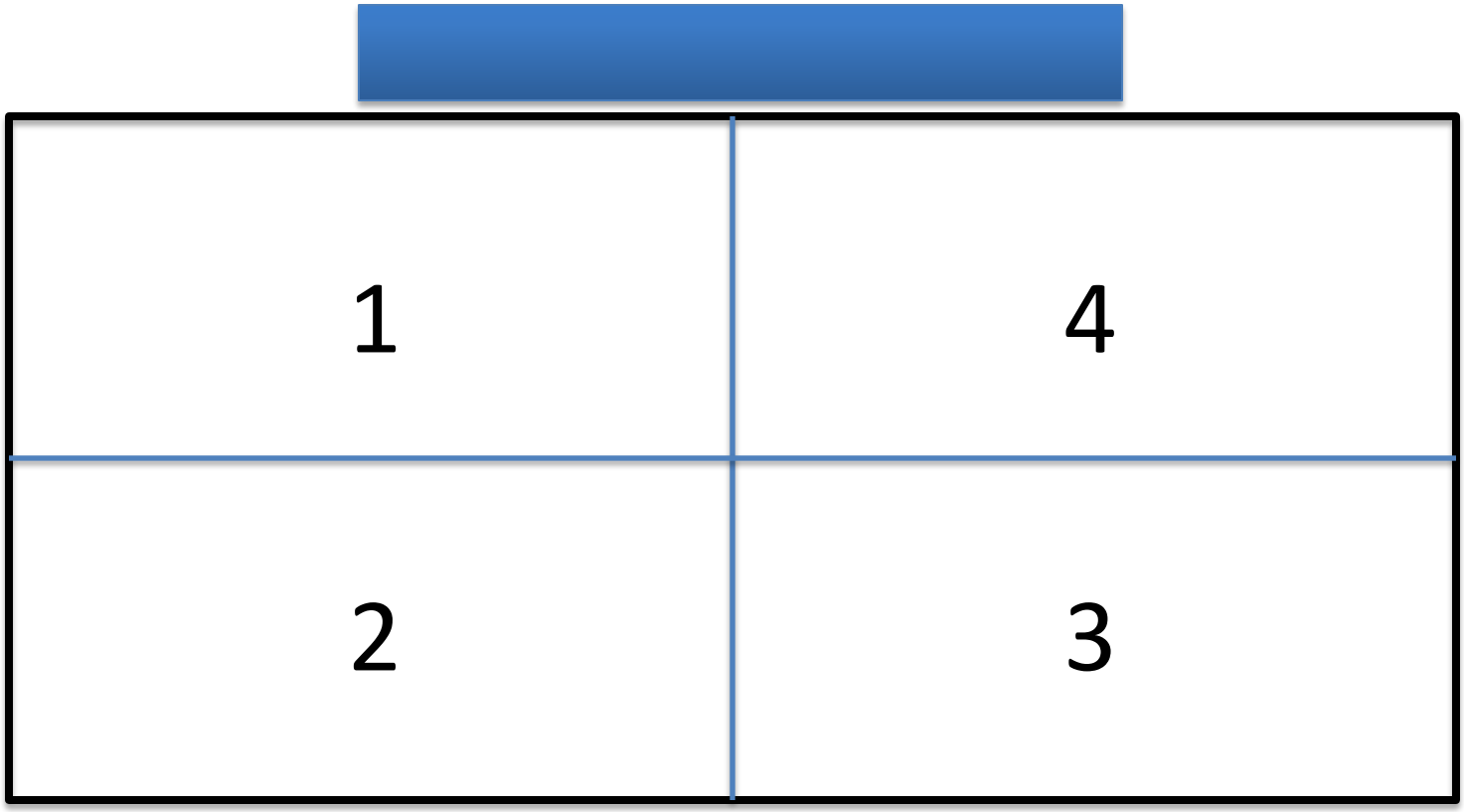
Chair: George Kelly (Sunset Technology)

Review of PV Rules

- Participants will rotate in small groups covering key topics:

1. Scope of Certification—Raj Bedi, First Solar
2. Applicable Standards—George Kelly, TC82
3. Mutual Recognition—Sunny Rai, Intertek
4. Personnel Certification—Don Warfield, NABCEP (thrown into the mix by popular demand)

Small Groups



Discussion

- **John Wohlgemuth (NREL), Alex Mikonowicz (Powermark), and George Kelly (Sunset Technology)**

- **"How can the certification system we are proposing be most successful in reducing stakeholders' risk?"**

- *Are we successfully addressing the issues identified by the participants? What are we missing? What are concerns with the approach? Are we trying to do too much?*

Review of PV Rules

- Small group discussions:

1. Scope of Certification—Raj Bedi, First Solar
2. Applicable Standards—George Kelly, TC82
3. Mutual Recognition—Sunny Rai, Intertek
4. Personnel Certification—Don Warfield, NABCEP (thrown into the mix by popular demand)

Summary

- Alex's List

Thank you for your participation

Contact george@sunset-technology.com

Introduction to IECRE

IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE System)

NREL PV Reliability Workshop 26 Feb 2015

Sandy Butterfield

President - Boulder Wind Consulting

TC88 Chairman

IECRE Chairman

IECRE System

- Industry need for international conformity assessment of Renewable Energy systems
  - Originally conceived for large projects
  - Interest in additional schemes for smaller systems and RE tech in developing countries

IECRE Background

- Industry Growth
  - Demand increasing 20%+ per year
  - Significant increase in large RE power plants
- Concern for Quality / Bankability
  - Doubts about adequacy of existing standards
  - Need for improved understanding of reliability
  - Validation of product lifetime for investors
- Need for Conformity Assessment
  - Assurance of security of investments in RE

Conformity Assessment

- Evaluation against international standards
  - May use national or regional standards if no international standard is available
- Improved quality and performance
  - Assurance that power plant will operate as designed for its expected lifetime
- Increased confidence for investors
  - Financial return meets expectations
  - Risk is reduced

Benefits of Conducting Conformity Assessment thru IEC

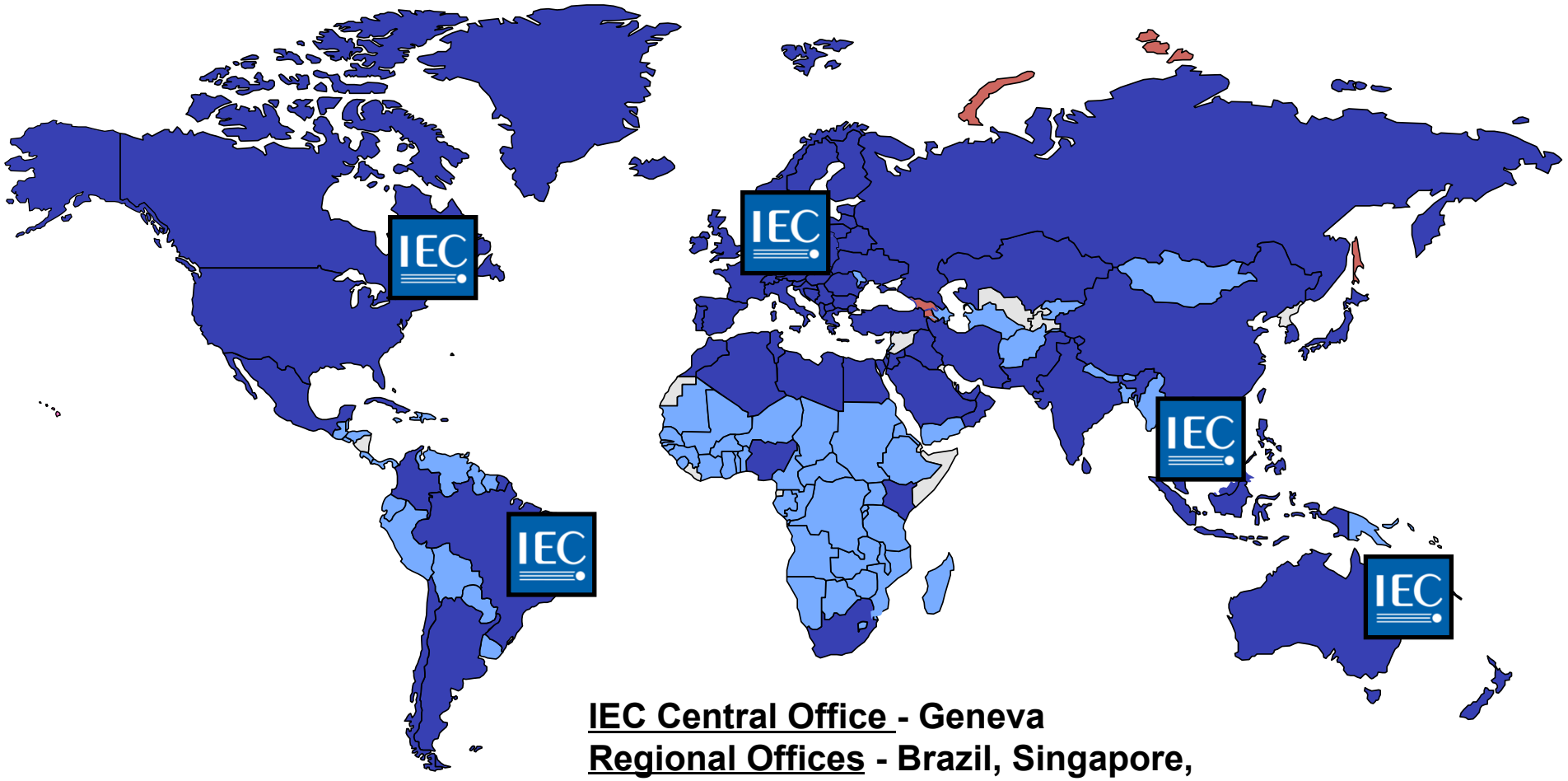
- IEC Brand
  - Global recognition – multiple industries
  - International recognition (e.g. WTO + UN)
  - IEC Reports and Certificates used nationally
- Open and Transparent Process
  - Clear Rules in process and results
  - Consistency in processes among participating Certification Bodies & Test Labs
- Industry and market provide direct input
  - CA systems driven by market demand

Key Demand Drivers

- Removal of costly duplication of testing at local level & delays in accessing markets
- Confidence among Industry, Regulators & Stakeholders
- Level playing field for CBs and TLs
- Portability of assessment results & certificates
- CA Services & Personnel Certification generally not covered elsewhere
- Instant access to information, including “On-Line” Certificates = instant checking

IEC Family: Global Reach

83 Members **83 Affiliates**

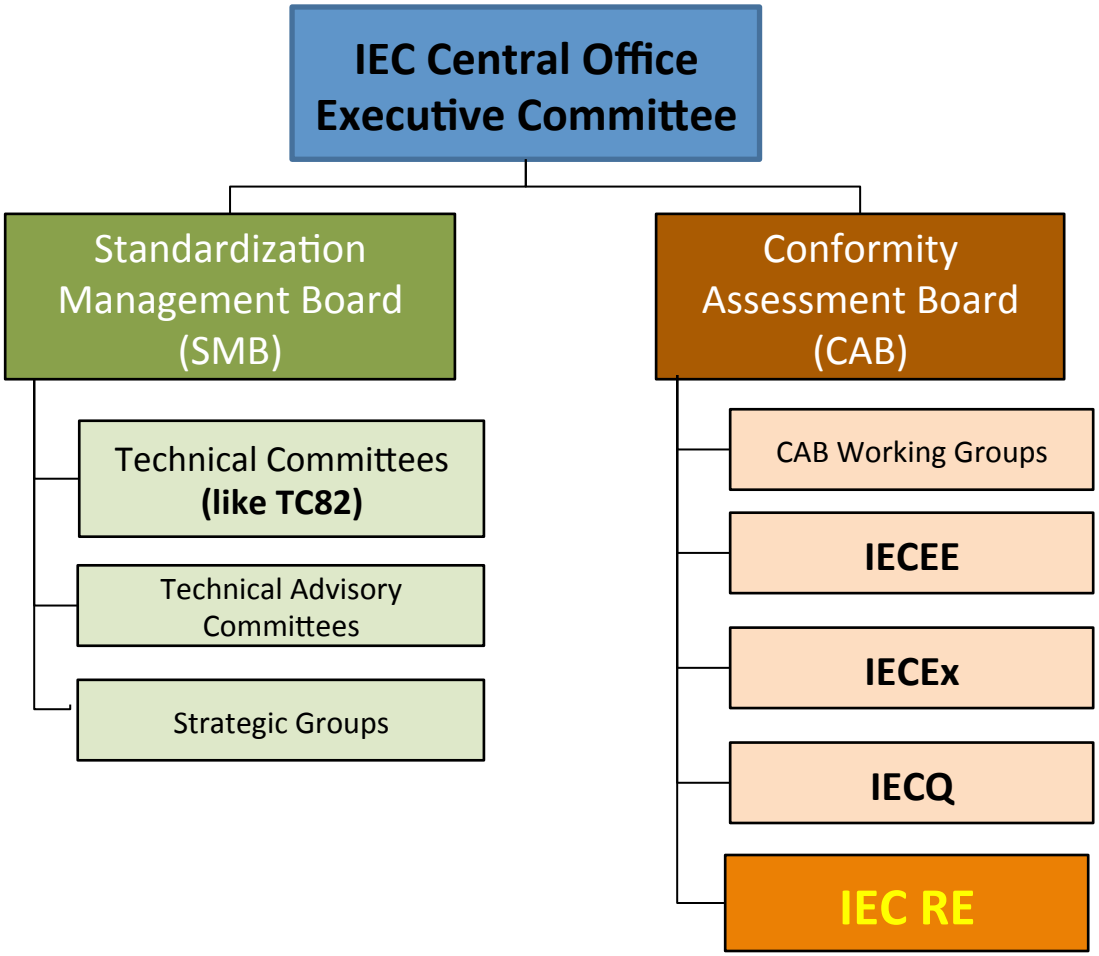


IEC Central Office - Geneva
Regional Offices - Brazil, Singapore, North America and Australia

IEC Roles & Responsibilities

- Standards Management Board (**SMB**)
  - Technical Committees => Write the standards
  - Manage nomination of experts and voting by National Committees (Member Bodies)
- Conformity Assessment Board (**CAB**)
  - Assessment Schemes => Evaluate implementation of standards in specific situations
  - Manage accreditation of Certifying Bodies

IEC Organization



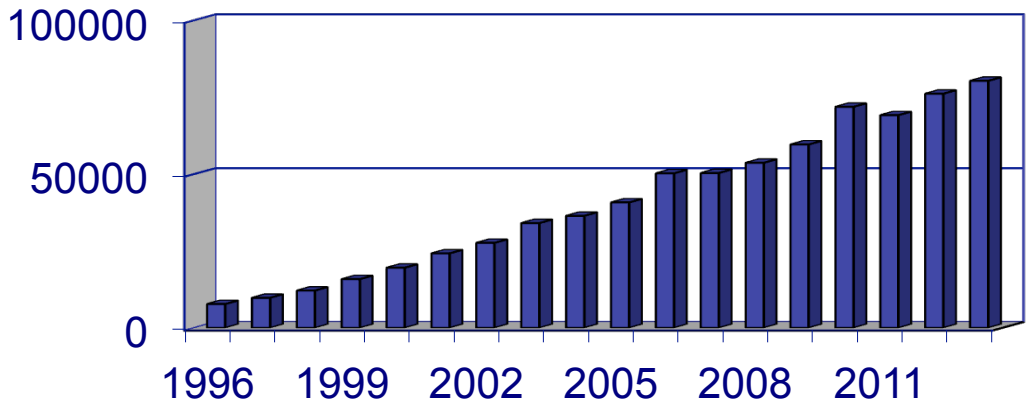
Existing CA Systems

- **IECEE**
  - System for conformity testing and certification of electrotechnical equipment (specific categories including PV modules)
  - Oversees the Certification Body (CB) Scheme and recognizes CB Testing Laboratories (CBTL)
- **IECEx**
  - Conformity assessment for equipment operating in explosive atmospheres
- **IECQ**
  - Quality assessment system for electronic components and associated materials

IEC CA Statistics

	IECEE	IECEx	IECQ	IECRE
Member Countries	**56**	**33**	**14**	**16**
Certification Bodies	**74**	**78**	**28**	**tbd**
Test Laboratories	**447**	**50**	**n/a**	**tbd**

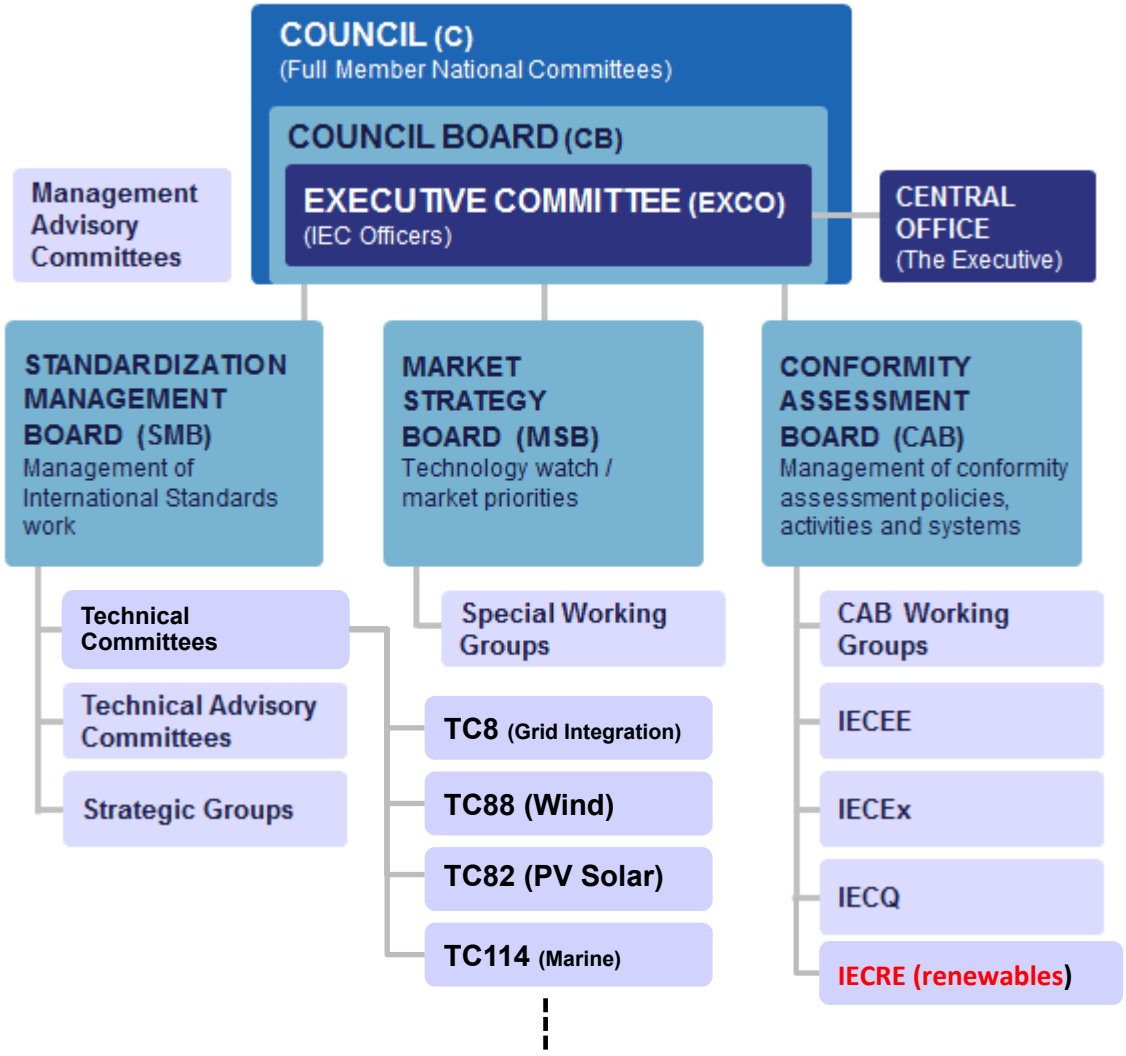
IECEE Certificates Issued



Standards / Certification Landscape

International Electrotechnical Commission (IEC)

- SMB manages 122 technical standards committees
- CAB manages conformity assessment four systems, including the newly formed IECRE
- TC8 leads grid integration
- Subcommittee 8A under TC8, sets renewable integration standards
- TC88 leads wind plants
- TC82 leads PV Solar
- TC114 leads Marine Energy



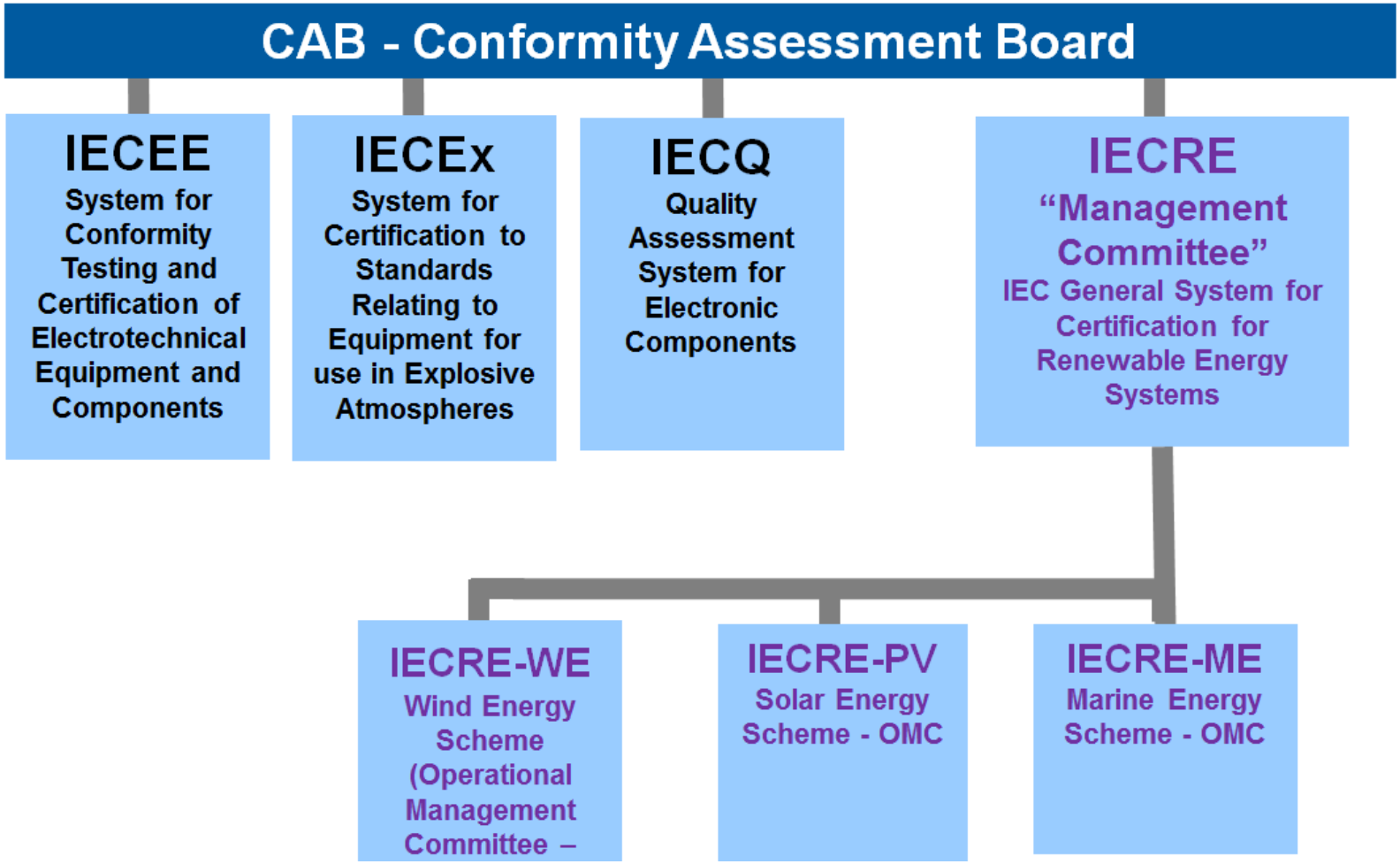
TC 88 - Wind Turbines

- Wind industry identified need to standardize "system aspect" of large complex projects
- Not addressed by any existing CA scheme
- Formation of Wind Turbine Conformity Assessment Committee (WT-CAC)
- Requirements written into IEC 61400-22
  - Type Certification
  - Project Certification
  - Management of certification system
  - Acceptance of operating bodies

Problem with WT-CAC

- IEC structure / policy requires separation of standardization and CA activities
  - TC88 crossed the line, but with strong industry support
  - WT-CAC allowed to exist temporarily as industry matured
  - Parallel infrastructure with CAB was not sustainable
- Concept developed for new CA system (IECRE)
  - Similar requirements exist for Marine Energy projects as well as large PV power plants
  - Specific differences and details apply for each industry

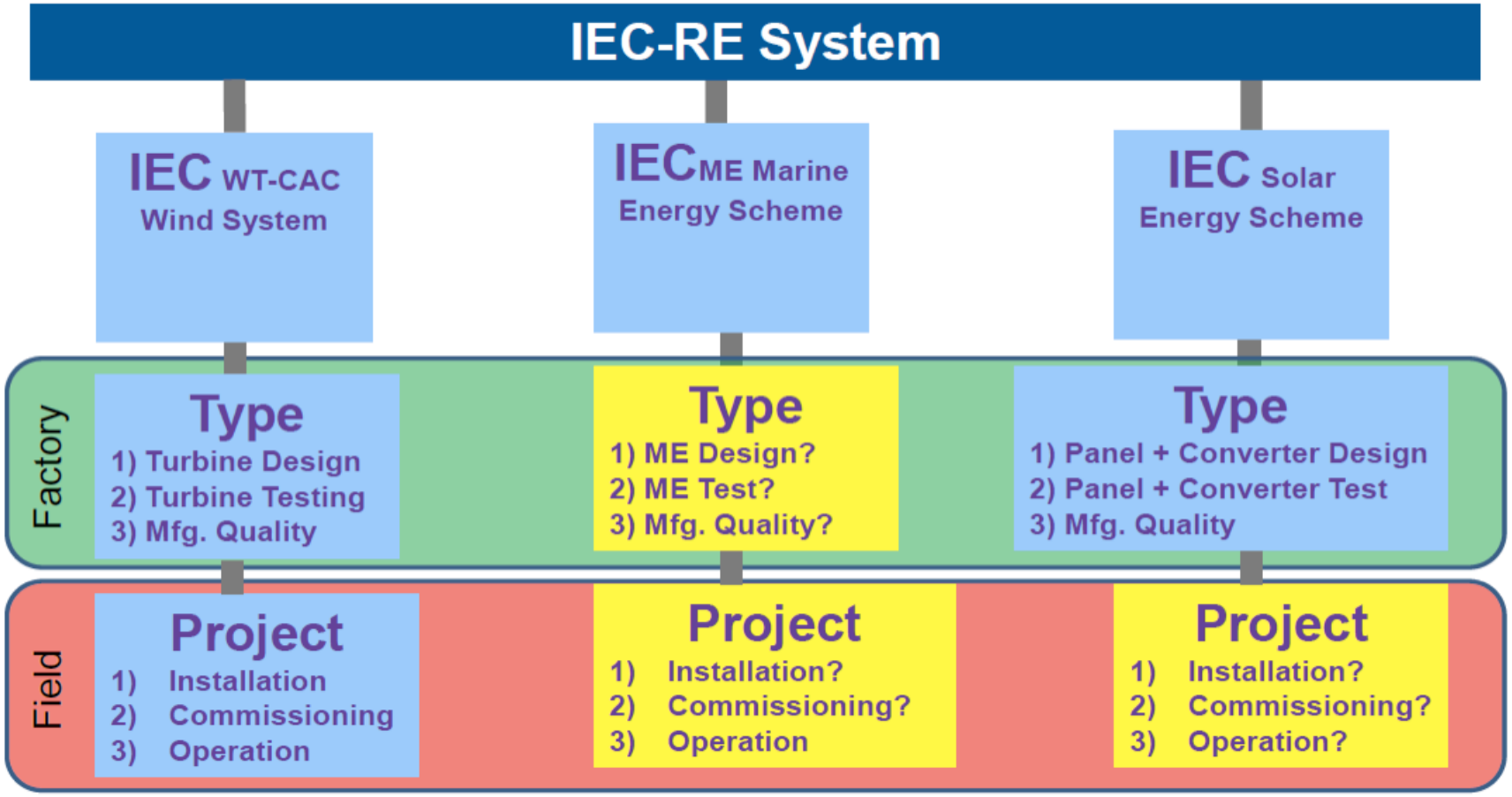
IECRE Concept



CAB Decisions

- Proposal for a new RE System was endorsed along with the recommended next steps
- June 2013
  - CAB approves creation of CA system for Renewable Energy industry sectors with common elements
  - Establishes working group to draft Basic Rules
- June 2014
  - CAB approves Basic Rules
  - Appoints K. McManama (IECEE) to head IECRE
  - Authorizes first REMC meeting (Sept 16-18 in US)

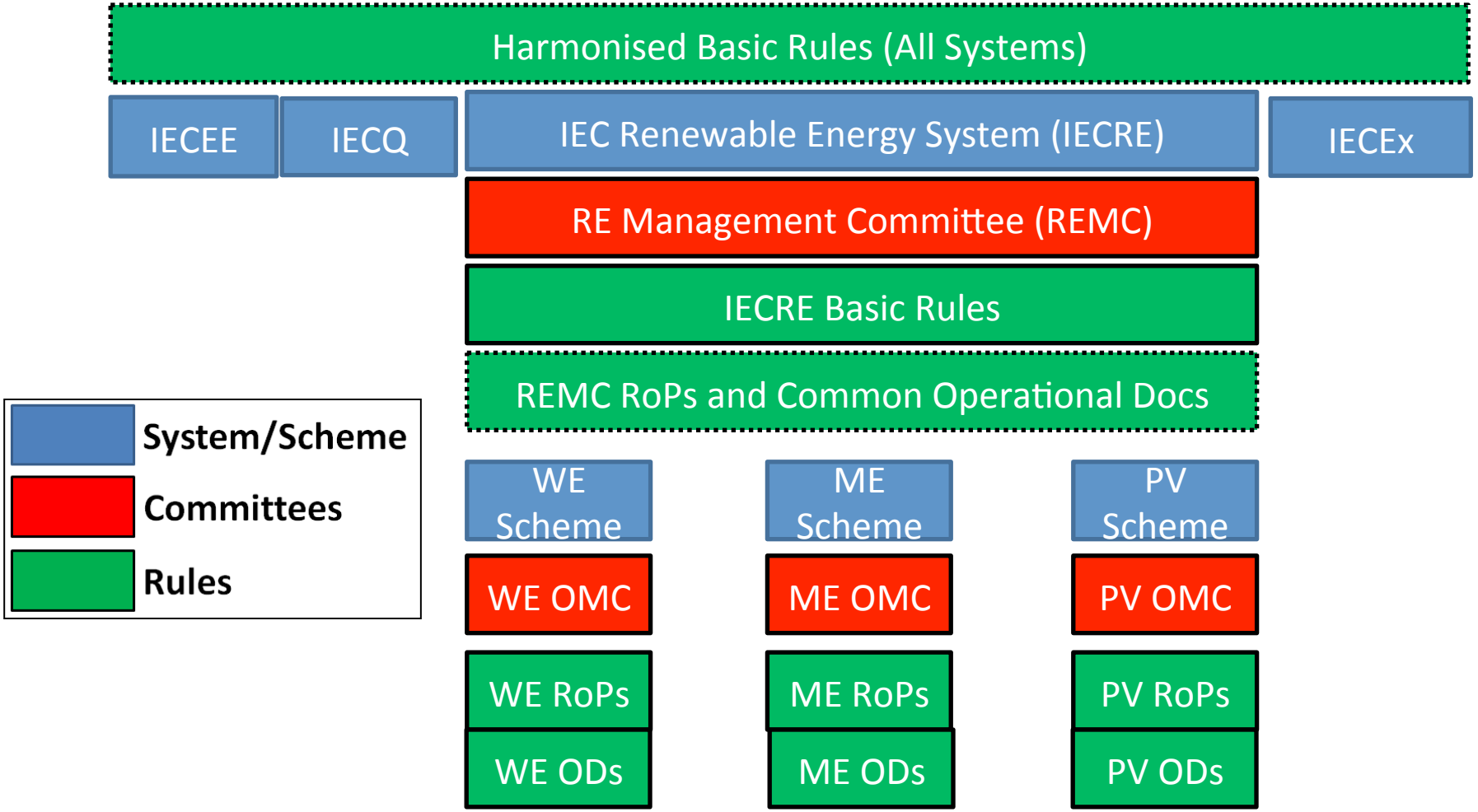
RE System Common Elements



IECRE kickoff meeting

- Oct-2013 in Aarhus, Denmark
  - Participation by TC82 (PV), TC88 (Wind Turbines) and TC114 (Marine Energy)
    - Working to include TC117 (Solar Thermal)
  - Working group (RE Forum) assigned to draft Basic Rules and Rules of Procedure for IECRE
    - Basic Rules are common to all
    - Rules of Procedure are partly common and partly industry-specific

IECRE Hierarchy



IECRE Basic Rules

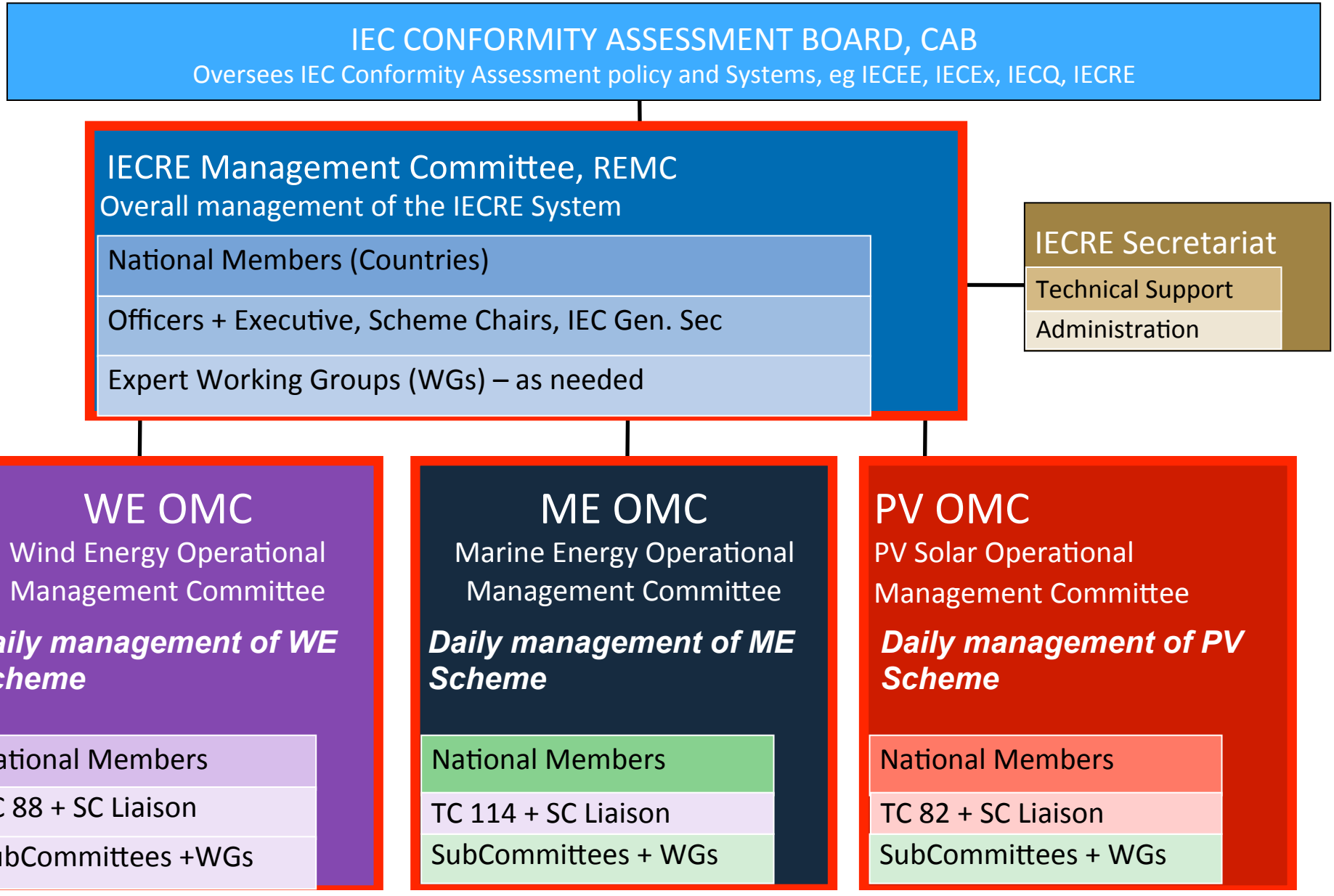
- Scope
- Governing documents
- Membership
- Organization
- RE Management Committee
- Officers, Executive and administration
- Committees reporting to the MC
- Legal provisions
- Standards
- Voting
- Finance
- Dissolution of the IECRE System

- Final draft of Basic Rules was approved by CAB in June 2014

REMC 1st Meeting

- Boulder, CO 16-17 Sept 2014
  - Hosted by USNC (ANSI)
  - 14 member countries attending
- IECRE Basic Rules confirmed
  - Chairman – S. Butterfield (TC88)
  - Formed 7 Working Groups
  - Authorized industry sector OMCs to begin work immediately

IECRE Structure



New Committees and Officers

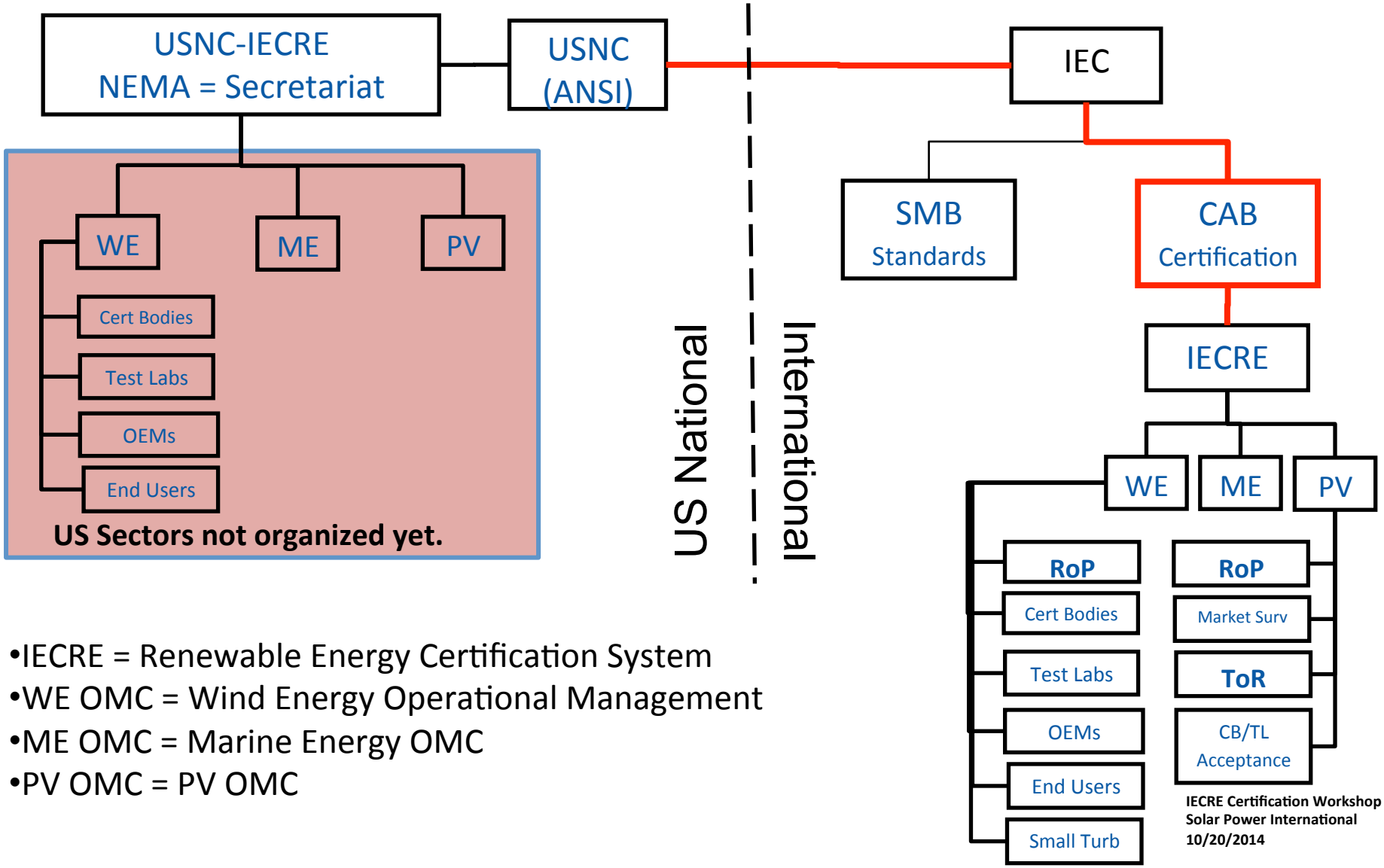
Committee	Title	Chairmen ("Convener" for WGs)	vice Chair	members
IECRE REMC	RE Management Committee	Sandy Butterfield (US-confirmed)	(multiple pending)	
RE WG001	Rules of Procedure	Jonathan Colby (US-Confirmed)		Sumanth Lokanaph
RE WG002	QA Assessnment & Audit	open		US Members needed
RE WG003	Customer Testing Laboratories	open		US Members needed
RE WG004	Promotion & Marketing	open		US Members needed
RE WG005	Infringements	open		US Members needed
RE WG006	Finance & Budget	Lars Sitzki (DE-Confirmed)		George Kelly
WE OMC	Wind Sector	Frank Ormel (DK confirmed)	(multiple pending)	
WG501	WE Rules of Procedure	Leo Jensen - DK (acting)		Toby Gillespie (GE)
WG506	Test Lab	Jeroen van Dam (US Nomination?) (NREL)		Jeroen van Dam (NREL)
WG503	Certification Bodies	open		US members needed
WG504	OEM	open		US members needed
WG505	End Users	Dan Brake (US Nomination?) (NextEra)		Dan Brake (NexEra)
WG502	Small Turbine	open		Trudy Frosyth (consultar
PV Solar OMC	PV Solar Sector	Adrian Haring (DE-confirmed)	Sewang Yoon (Korea-confirmed)	
PV Task Group 1	Terms of Reference	Rajan Bedi (US Nomination)		US members needed
PV Task Group 2	Acceptance of CBs and TLs	Sunny Rai (US Nomination)		US members needed
WG 402	Market Surveillance	open		US members needed
WG 401	Rules of Procedure	Miguel Martinez (Spain nomination likely)		US members needed
ME OMC	Marine Energy Sector	Jonathan Colby (US-confirmed)	Rebecca Sykes (UK-confirmed)	
WG301	ME Rules of Procedure	Peter Davies (UK nomination likely)		US members needed
WG302	Finance	open		US members needed

orange = immediate nominations or endorsements needed from the US

Yellow = anticipated open possitions that do not require immidiate nominations

Green = USNC IECRE nomination and endorsement ACTION Required)

How US Companies Engage with IECRE Certification System.



- IECRE = Renewable Energy Certification System
- WE OMC = Wind Energy Operational Management
- ME OMC = Marine Energy OMC
- PV OMC = PV OMC

Next Steps

- Form the USNC IECRE / PV OMC shadow committee
- Call for more USNC PV-OMC shadow committee members
- Call for more US participation in REMC and OMC subcommittees
- REMC & OMCs Rules of Procedure need to be developed and harmonized.
- IECRE Budget and dues structure
- USNC/IECRE budget and dues structure
- Next REMC meeting: Beijing, September 8-9. not confirmed.
- Next PV OMC meeting: Likely Beijing, September 10-11?

Why Engage in IECRE:

Standards and Certification help Maturation Industries

- Public / investor confidence
  - Design compliance verification to consensus standards (implied reliability)
  - Credible performance verification
  - Permitting requirements clarity (international harmonization)
  - Credible community impact measures
- Technology development
  - Standardized (accurate / consistent) testing techniques
  - Defined design process
  - Design verification testing
  - Common definition of external conditions
  - Design goals (20 – 30 year life, safety systems, etc)
  - Level playing field in international market
  - Common design vocabulary (design load cases, coordinate systems, safety factors, etc)

Thank You

C.P.Butterfield@Gmail.com

A Banker's Perspective on IECRE

Jon Previtali
Wells Fargo Environmental Finance
NREL PV Reliability Workshop
February 2015

A Banker's Perspective on IECRE

How the new IECRE conformity system should work?

- **Timing** is everything. As much should happen well in advance of construction, ideally at the design and procurement stage.
- **Ease of use** is key. How can we empower both checkers and those being checked to use this quickly and easily?
- A **checklist is good**. Make it a free **online tool** – **a wizard**.
- **Market it brazenly** to everyone.
- **Distinguish** it from NEC and separate standards. The whole is greater than the sum of its parts.
- Position it as a **competitive advantage** and encourage it as a requirement.
- And… somehow allow for a **contingency plan:** Don't want to encourage it, but what can people do when they fail? Adjust production estimate and reduce project price, perhaps?

A Banker's Perspective on IECRE

What problems it will address?

- **Safety** and **performance** issues, particularly **long-term**.
- A material amount of time and money spent arguing about **what to do**.

How would my organization be involved?

We would include it as a **Conditions Precedent** (CP) to funding and put it in advisors' scopes of work:

- factory inspectors
- test lab
- independent engineers
- attorneys (to ensure conformation to "documents").

A Banker's Perspective on IECRE

A few more reactions:

- The key financial metric for banks is the **Debt Service Coverage Ratio**:
  - Revenue-Expenses (aka EBITDA)/Debt Payments (lease, loans, etc).
- **Air planes** are a good analogy for solar power projects -- they're complicated, run continuously and leased. Don't know if there's an equivalent standard to IECRE for planes.
- **Probably people's initial reactions:**
  - We're doing fine with the NEC (and implicitly NESC).
  - IEC is European and thus too stringent. It's true most power plants work as advertised.
- Position it as **NEC, plus IEC for solar?** *The sum is > the parts.*
- Do a **market research survey** to get people's perspectives.

A Banker's Perspective on IECRE

Possible areas for addition or more detail?

- Civil Engineering
- Geotech
- PAN file creation/verification
- MCP for met data
- Wire Management (possibly the most common installation issue)
- Location=specific tests: modules *and inverters*
- Module factory tests (during assembly)
  - Soldering (possibly the most common issue)
- Location-specific O&M scope of work
- CAISO SCADA Requirements (to anticipate nationwide adoption)
- Percentage of arrays inspected periodically
- Specific long-term energy test (performance ratio is probably easiest)
- Degradation test? (ala Dirk Jordan)

Arcing in L Conduit Fittings:

A safety issue the industry should know about.

The Scenario: LB fittings run DC outside a building. Probably built circa 2007-9. Failed megger test last year.

Inside: Insulation shavings left from abrasion caused by thermal expansion and contraction of conduit. Use of protective plastic cuff unknown.

The Fix: A box replaces LB fittings and new cables are installed. I consider this a partial fix because LB fittings are still present -- those runs probably passed the megger test…

Thank you!

Jon Previtali
Wells Fargo Environmental Finance
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jonathan.m.previtali@wellsfargo.com

PHOTOVOLTAIC POWER PLANT
AN INSURER'S PERSPECTIVE

Hartford Steam Boiler

2015 IECRE: PV System Certification Workshop

i h RE

PV Exposures
Property Risk

- Equipment Breakdown
- Fire – Internal and External
- Wind – Panels can act like sails
- Lightning – protection should be integrated
- Snow Loading – Typical design for about 5.5 ft of snow
- Hail – typical design is to withstand 1 inch hailstone
- Flooding – Depth of flooding determines damage
- Earthquake – 100% PD

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Exposures

Business Interruption

- Additional cost to purchase power
- Utility Penalty?
- Is there a “Power Purchase Agreement”?
- Renewable Energy Certificates
- Who owns the equipment?

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Key Elements of an Engineering Review

Hartford Steam Boiler

i h RE

NLE

Normal Loss Expected

What **Often** Happens

PML

Probable Maximum Loss

What is **LIKELY** to happen.

MFL

Maximum Foreseeable Loss

What **COULD** happen

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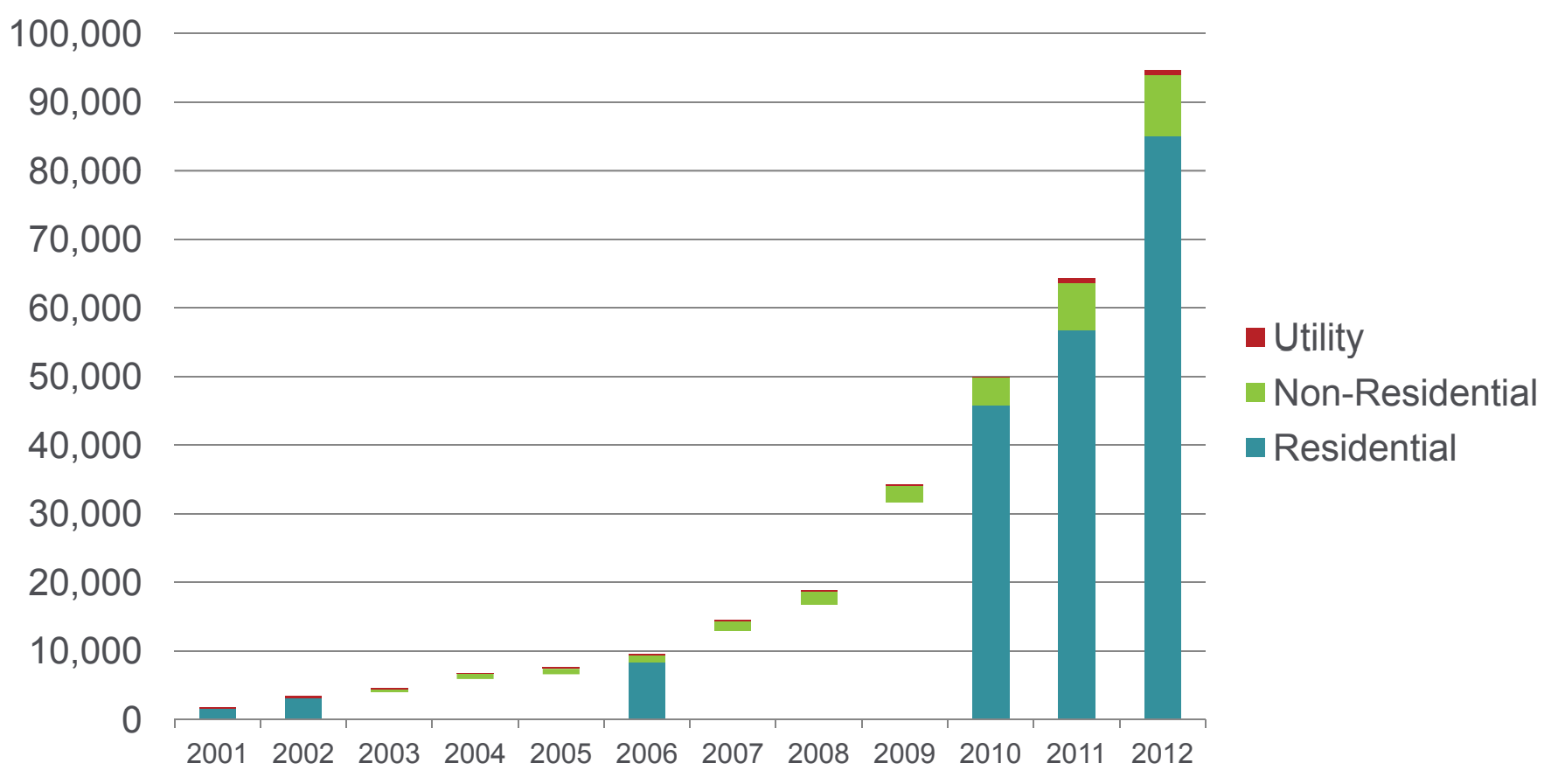
Solar Photovoltaic is an Emerging Exposure

Number of Installations



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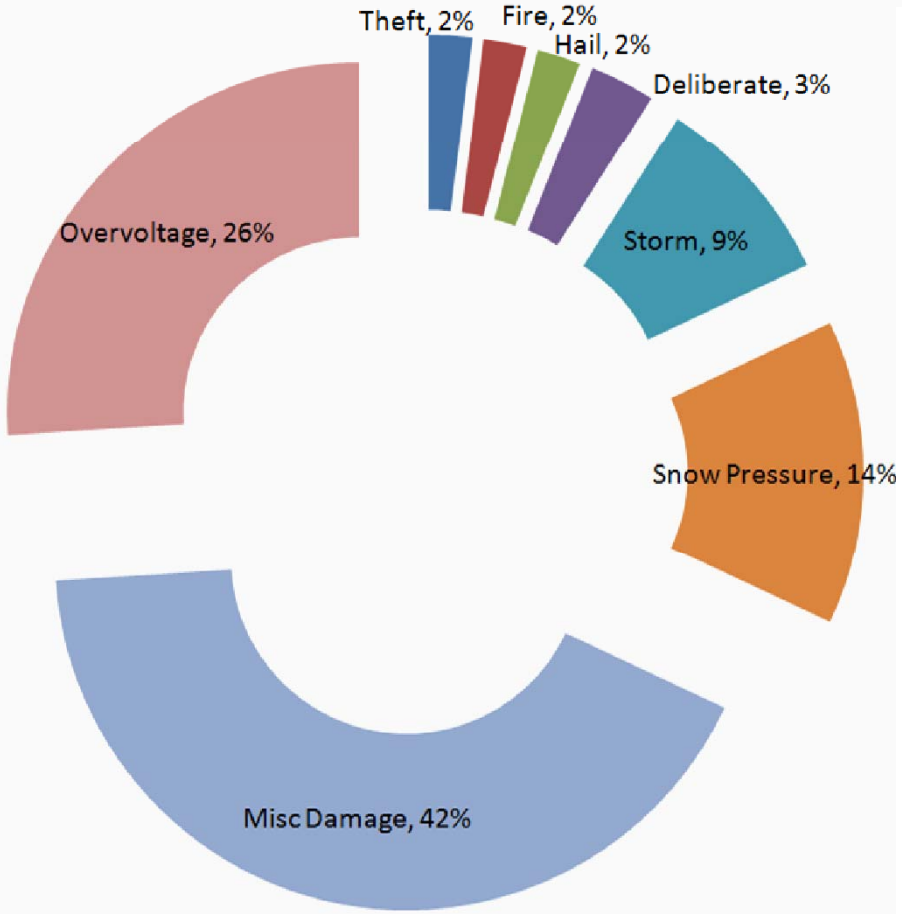
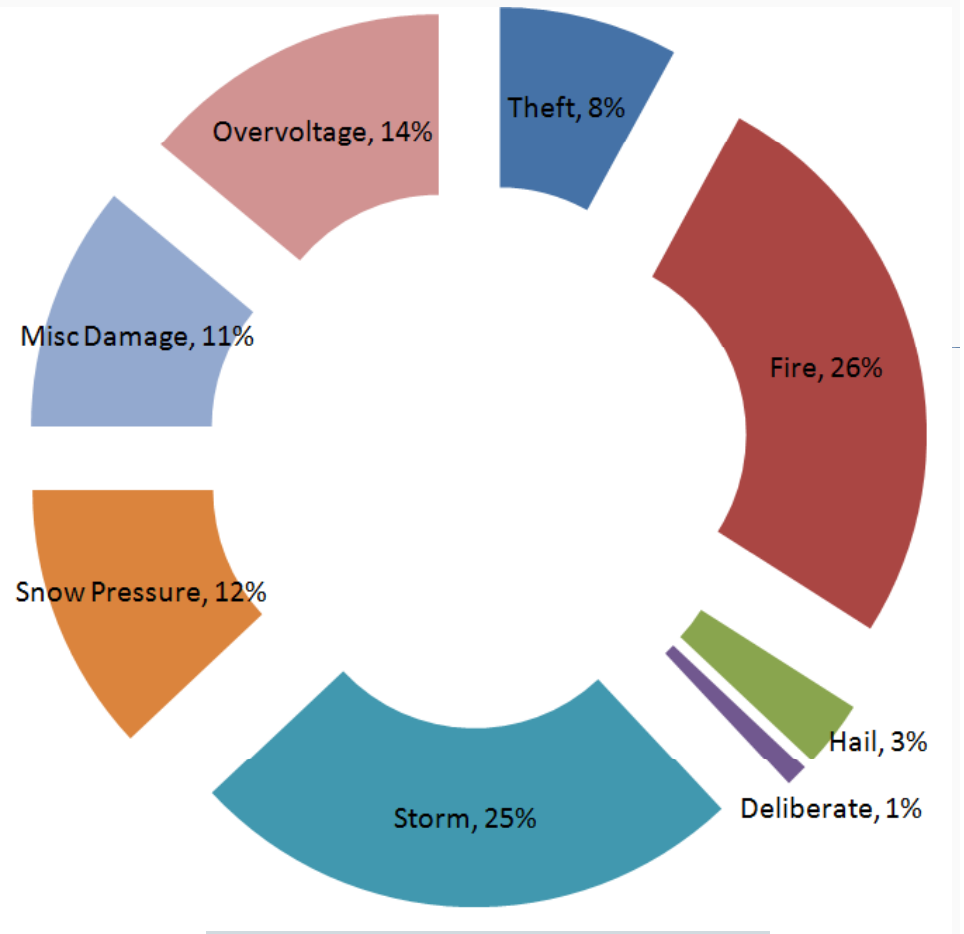
PV Loss Data
Property Damage Exposures - Frequency



Frequency, #



Severity, $

Chart Source: Renewable Energies, Survey, German Insurance Association

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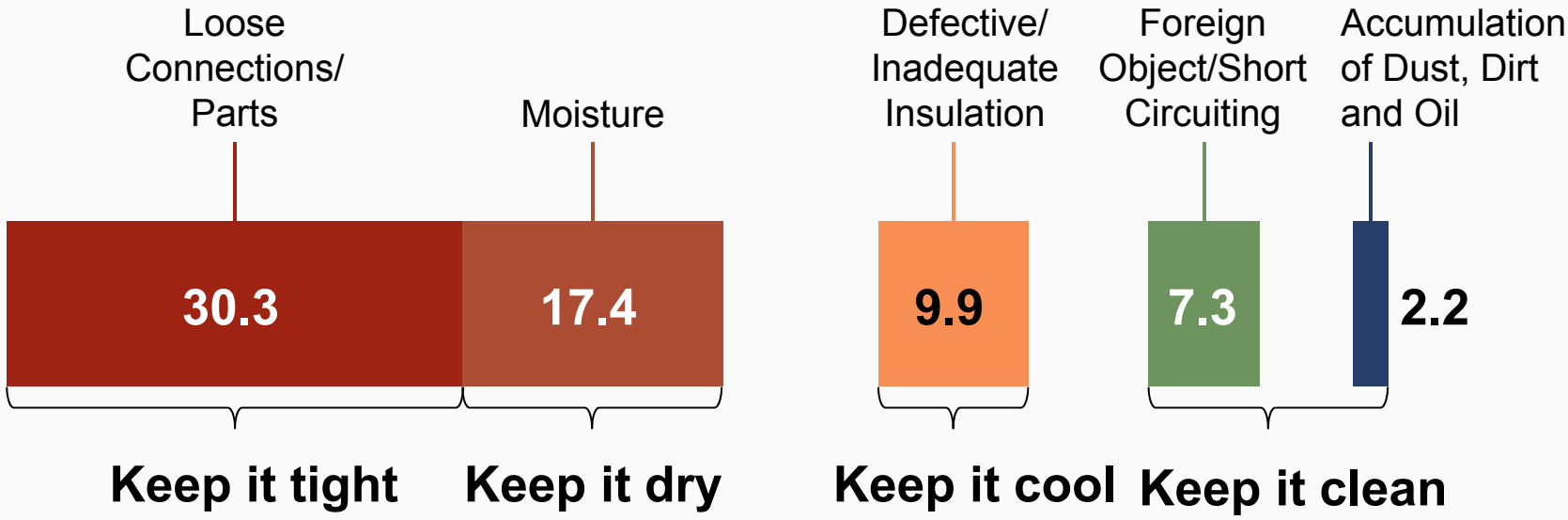
Primary Causes of Electrical Failures



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PV Exposures
Property Risk - Fire

System Layout

- Try and obtain diagrams showing layouts
- Groups of inverters and transformers are exposed to a fire starting in one of the units
- In this example; 2 inverters and 1 transformer here are exposed to same fire event.

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PV Exposures
Property Risk - Fire

Rooftop fires

- Fire departments hesitant to access roof
- Possible electrical hazards

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Causes of Loss
Snow Pressure

Source: Munich Re

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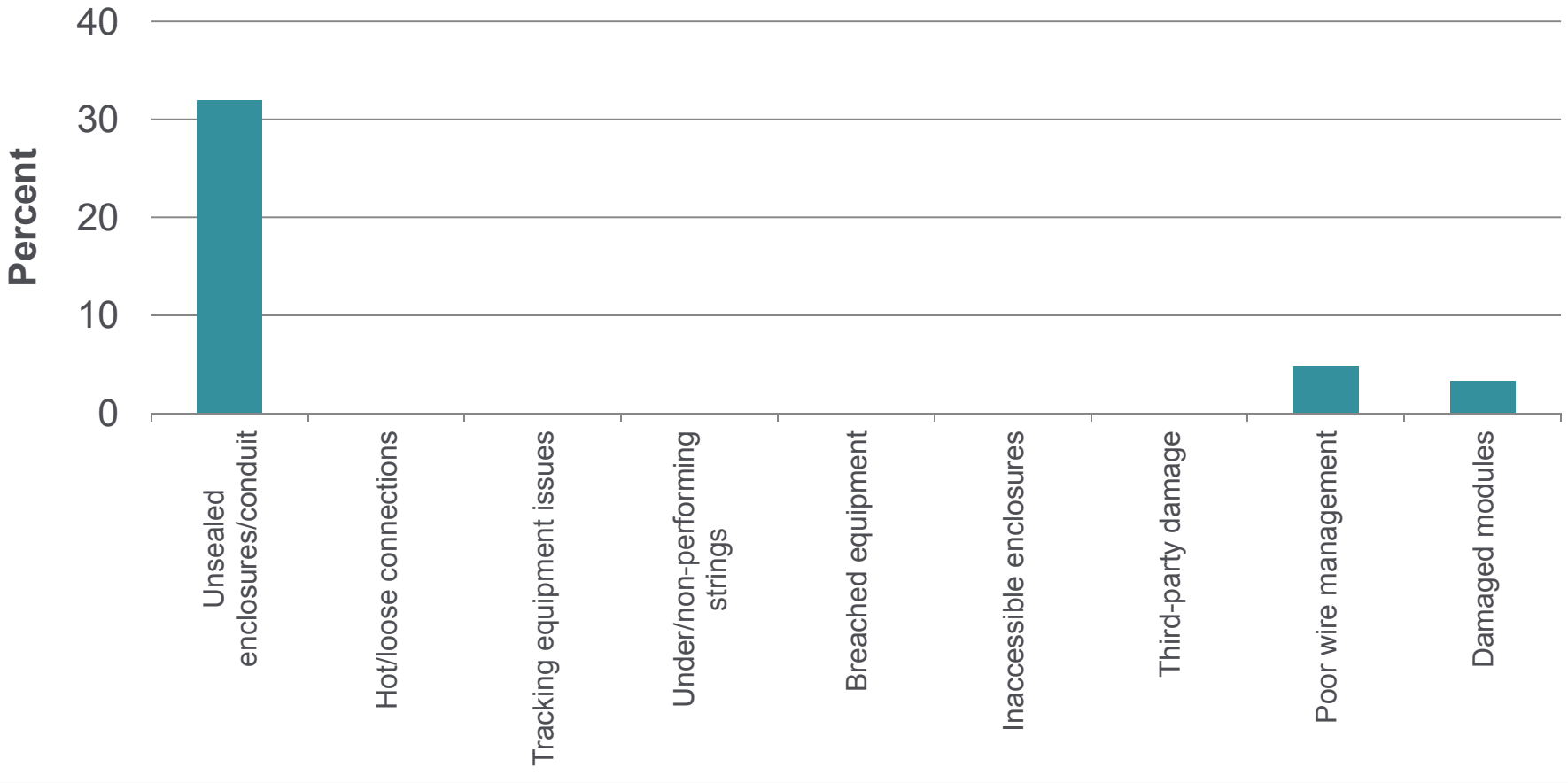
Causes of Failures

Analysis of O&M Findings



Courtesy of Advanced Energy Inc.

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Keys to Reducing Exposure

- Experienced installers
- Established manufacturers
- No experimental, prototype
- New equipment under Warranty
- Some sort of Service Agreement, regular inspection
- Equipment is visible and accessible
- Properly designed for climate (temperature, lightning, wind)

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PV Power Plant Certification

VDE Testing & Certification Institute

What is a Certification Body

- Certification needs to be performed by appropriately accredited certification body within purview of the standard
- Example VDE accredited by DAkks per regulation 765/2008 and ISO/IEC 17011 across the PV field….. competence, impartiality, performance
- Transparent process… public interest assured, trusted certification and test reports etc.

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Plant Level Certification Already Being Applied

- VDE in collaboration with our partner Fraunhofer ISE has developed a comprehensive set of technical requirements for plant level certification
- Macho Springs, a 50MW plant designed and built by First Solar in Luna County New Mexico was the first plant in the US to receive certification towards the end of last year
- Anticipating IEC standards developed by IECRE working groups

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Objective Plant Level Certification

- Reduce risk by providing internationally recognized and understood certification
- Covers asset quality as built and expected performance e.g. over 20 year life

VDE Prüf- und Zertifizierungsinstitut

ZERTIFIKAT
CERTIFICATE

First Solar Inc.
350 West Washington Road Suite 600, TEMPE AZ 85281
USA

ist berechtigt, für ihr Produkt /
is authorized to use for their product

Solar Kraftwerk
PV-Power Plant

in den Ausgaben/in the editions:

Macho Springs Solar, Deming NM

die hier abgebildeten markenrechtlich geschützten Zeichen zu benutzen /
the legally protected Mark as shown below

VDE Quality Tested — ID: 40040833

VDE Quality Tested — ID: 40040833

Weitere Informationen
Further Information

Siehe Produktdatenblatt
See Product Data Sheet

Bewertungsgrundlage:
Base of assessment

VDE_QT-SP-001:2012/12

VDE Prüf- und Zertifizierungsinstitut GmbH
VDE Testing and Certification Institute
Zertifizierung Produkte / *Certification Products*

Gültig bis: 2015-10-31
valid until

2014-10-15

Dieses VDE Zertifikat ist nur gültig bei Veröffentlichung unter:
This VDE Certificate is valid only when published on:

VDE VERBAND DER ELEKTROTECHNIK
ELEKTRONIK INFORMATIONSTECHNIK e.V.

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Scope of Plant Level Certification

- Technical not financial
- Defined requirements for documentation, component selection, overall design, **safety**, execution, commissioning report protocol, yield forecast, O&M procedures etc.
- As an example, VDE QT certification is a 300 point specification including detailed site visit, module through grid connect level performance confirmation and projection etc.
- Scope is scale dependent but minimum requirements for all

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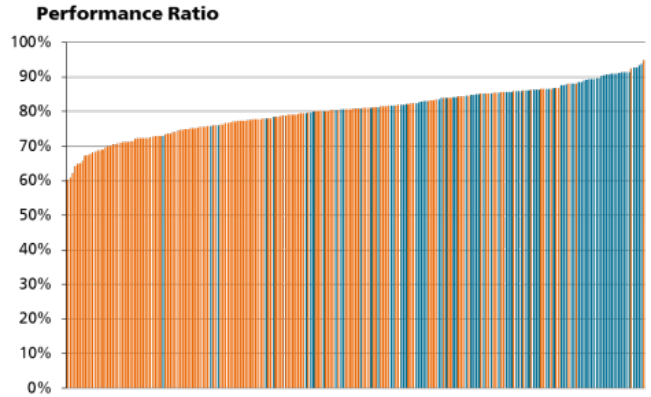
Performance Reporting & Measurement

- Performance checks
  - ✓Module performance using modules taken from the field. e.g. irradiance and temperature dependence
  - ✓String level performance at the combiner box
  - ✓Soiling/O&M effectiveness
  - ✓Monitoring Equipment
  - ✓Etc.
- Net result is yield assessment and performance ratio – including uncertainty



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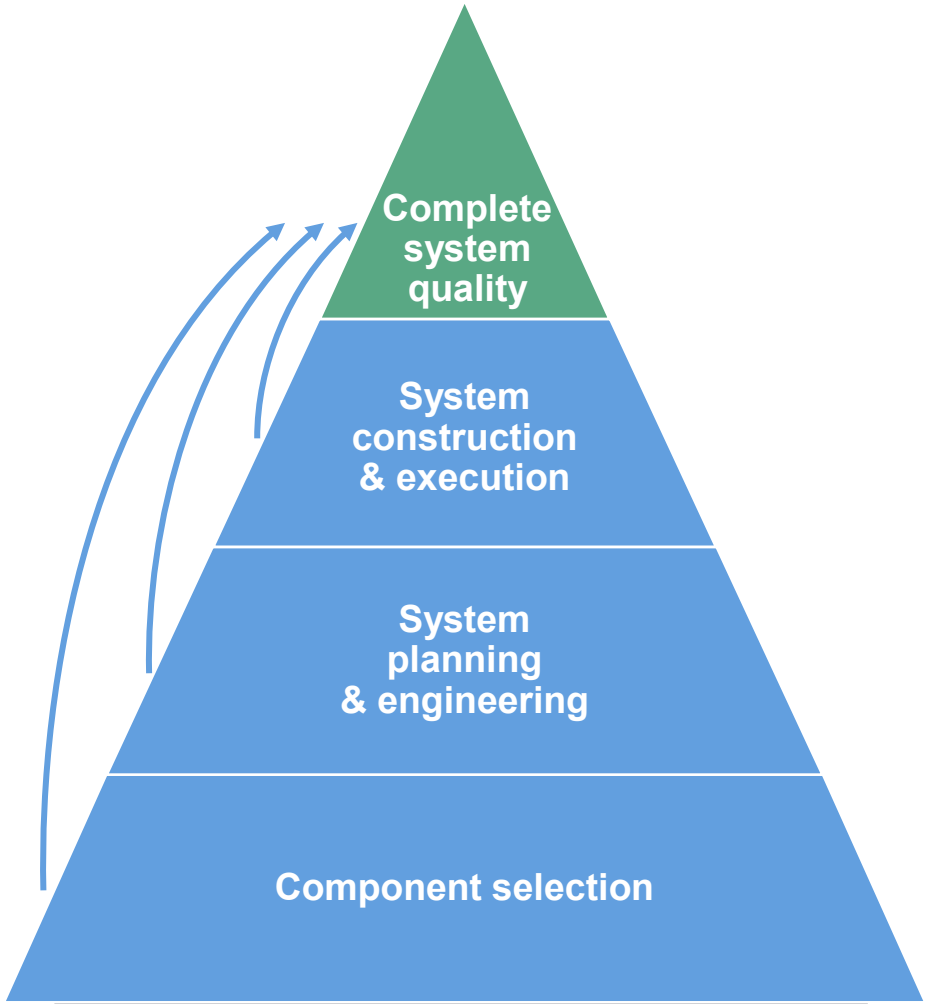
Achieving Invest-ability Through Certification

Achieving invest-ability needs:

- A professionally designed, **comprehensive quality assurance concept**
- Covers the core requirements of lenders, investors and insurers
- Leverages synergies in stakeholder requirements in a **streamlined** way
- Must verify other important aspects e.g. planning, engineering and, if applicable, training of installers



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Scope of Plant Level Certification

- Unambiguous and understood set of technical requirements and performance assessments
- Simple pass fail criteria and certified parameters

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It’s all About Return on Investment

- You can’t add cost you have to reduce costs
  - Confirm known quality standard c.f. module
  - Reduce risk and increase asset value,
  - Provide initial and ongoing cost savings – catch mistakes early, avoid overlaps QA
  - Increase confidence in yield over asset life
  - Reduce cost of capital and insurance as more entities willing to participate
  - Improve ROI for all participants

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Questions & Discussion

NREL Reliability Workshop
Peter Bostock Ph.D.
Vice President, Technical Marketing
VDE Americas
San Jose, California USA
Peter.Bostock@VDE.com

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IECRE OMC PV WG402
“Marketing”
Status February/2015

Matthias R Heinze

Note “This presentation contains no confidential information."

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Precisely Right.

BF Solar / Fuel Cell Technology (P.06).
IEC RE stakeholder view

PV system competitiveness

Facing	Banks	▪Improve finance ratio & confidence-KWh estimate ▪Reduce 3rd party cost & save time
Facing	Insurance	▪Improve warranty terms & dispute ▪Reduce warranty cost
Facing	Asset owner	▪Improve asset yield, reduce O&M cost ▪Improve residual value
Facing	Government	▪Improve financial transparency (cost of incentive) ▪Off-load responsibility (technical)
Facing	Developer	▪Reduce management effort ▪Reduce financing risk ▪Improve terms
Facing	Manufacturer	▪Reduce uncertainty (IE objectivity) ▪Reduce cost of compliance

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Motivation

Why Marketing is relevant?

- Original workgroup title from webpage: “Marketing”
- Marketing is a identified activity for IEC RE
- Value proposition document identifies the upside potential of the IEC RE to **investors**: “Investors which do not have a “Power Utility approach” generally have an upside margin in improving the management of their energy asset”
- investment in PV generation is different from that for Wind or Marin energy generation
  - The audience is different even if located under one roof
  - The technology differences require different justifications for certification services
  - The manufacturers are different
- More then ascertaining need, need is generated by innovation (of services)
- Data gathering and statistics are complementary to marketing

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Precisely Right.

Scope

Proposal

- The Marketing Working Group continuously monitors and assesses industry trends to provide market validation for new areas of interest to IEC RE members.
- It works with the IECRE PVOMC to identifying new specification through surveys, market research and market surveillance.
- Development of communication and education programs for members, potential members and the market on issues critical to the IECRE PVOMC future success. This may include: Tradeshow promotions, Booth Opportunities, Events & Speaking Opportunities, Public Relations.
- It promotes the acceptance of the IECRE PVOMC standards in the target market segments of the PV system financial stakeholders including: rating firms, investment funds, private equity investors, insurance companies, consumers, governmental entities.
- It coordinates its work with REMC WG 004

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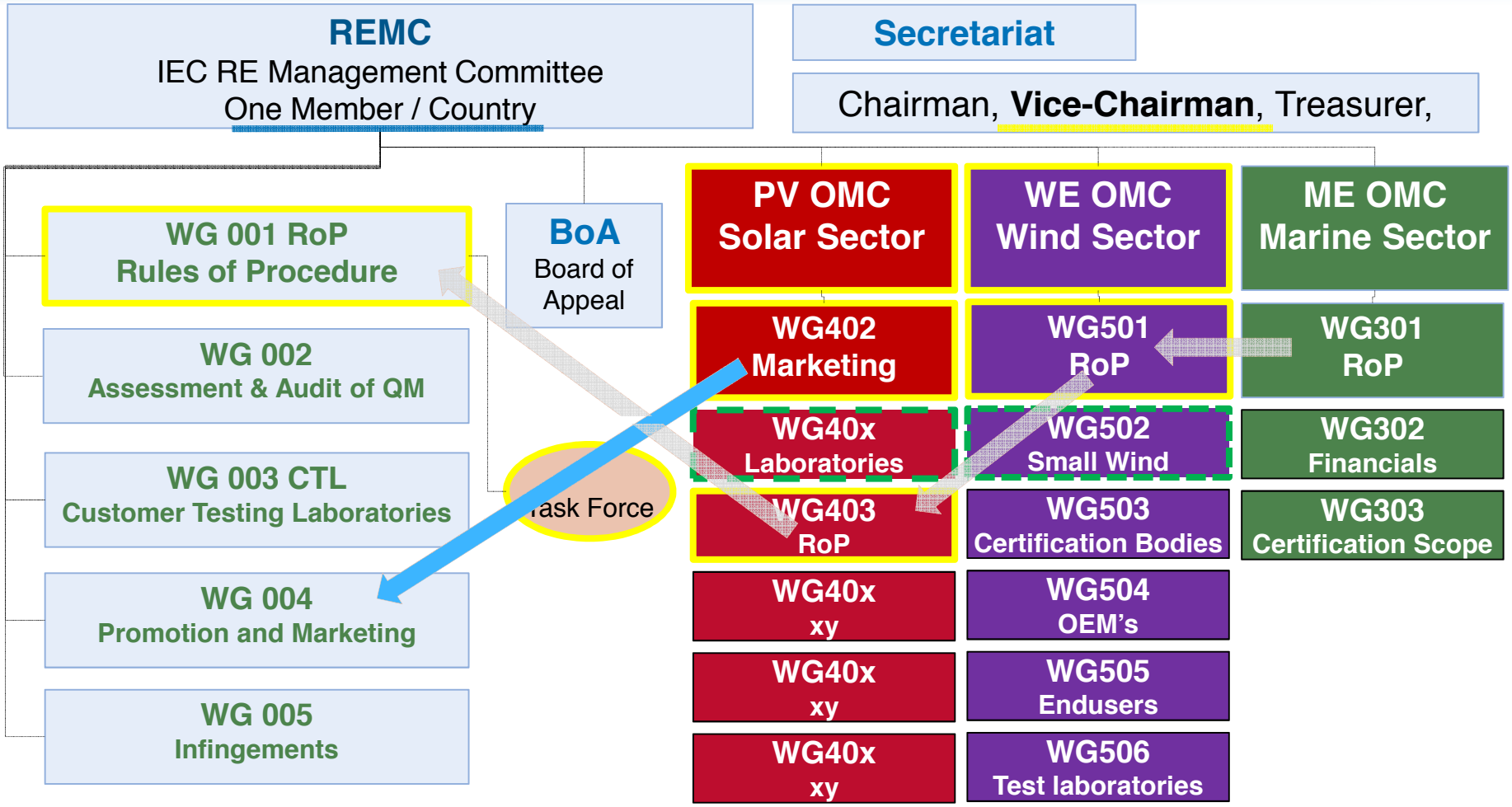
Defined Structure of IEC RE
REMC + Committees + Working Groups



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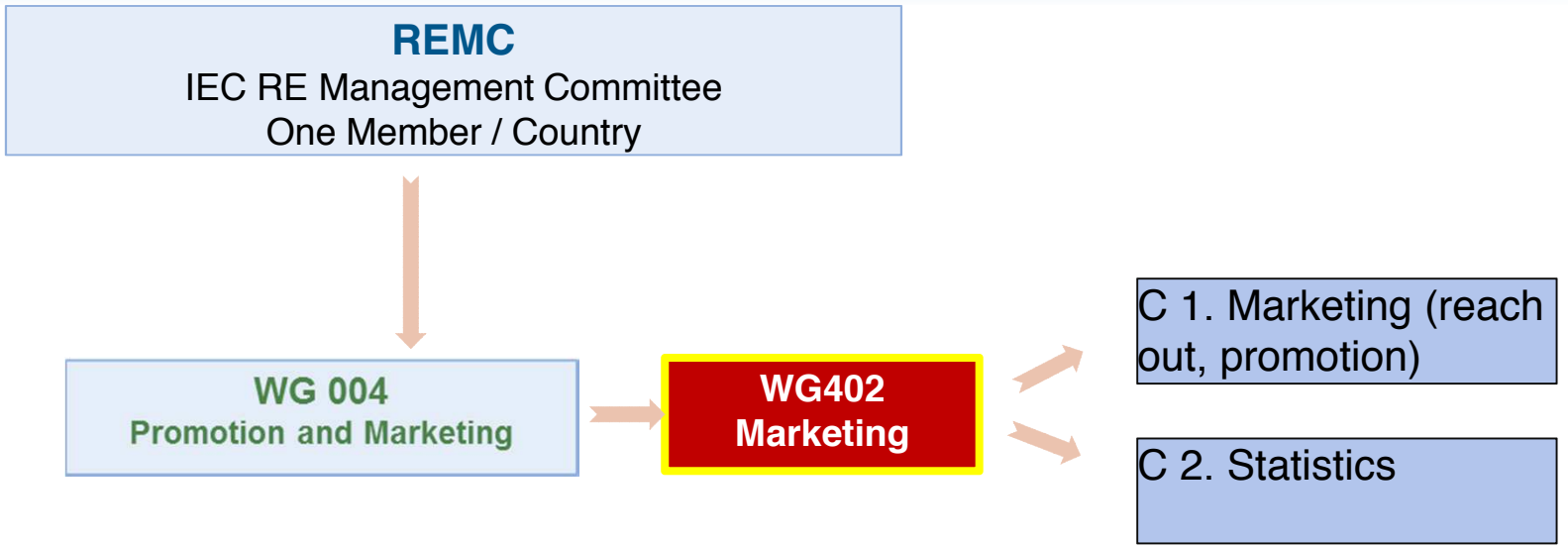
Structure



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Members

IEC RE PV OMC WG 401							
Attendance roster							
		C 1	C 2			Jan. 14	Febr. 10
Name	National Body	1 (marketing)	2 (market statistics)	Email	Phone		
Matthias Heinze	Hungary	x	x	mheinze@us.tuv.com		x	x
George Kelly	USA			solarexpert13@gmail.com		x	x
Ian Gregory	USA			igregory@solarbuyer.com		x	
Sarah Kurtz	USA		x	Sarah.Kurtz@nrel.gov			x
Rajan Bedhi				RBedi@FIRSTSOLAR.COM			x
Sumanth Lokanath				Sumanth.Lokanath@FIRSTSOLAR.COM			x
Wang Sicheng	PRC			wangsc@eri.org.cn			
Deukyoung Jeong	DRK			jj1102dy@naver.com			
Honggu Kim	DRK			kimhk@bokuk.co.kr			
Yeonji Kim	DRK			kimyj21@gmail.com			
Dohyon Baek	DRK			dbaek1973@hotmail.com			
Adrian Haering	Germany			Adrian.Haering@sma.de			
Bence Thurnay	Hungary			thurnay@hu.tuv.com			

TÜVRheinland®
Precisely Right.

Call for Next Meeting

- Fill C 1 and C 2 with members
- Identify events to gather statistics
- Identify events that are suitable for sponsorship
- Invite WG 004 to contribute

TÜVRheinland®
Precisely Right.

Introduction of PV related business of Japan Electrical Safety & Environment Technology Laboratories (JET)

2015 PV Module Reliability Workshop
Golden, Colorado, Thursday, February 26, 2015
Tadashi Obayashi, Research & Business Development Center

Japan Electrical Safety & Environment Technology

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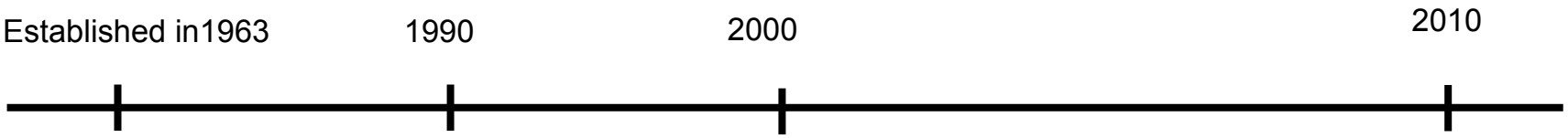
JET's History



Safety

1963 Testing, Inspection and Certification services of electrical appliances

1995 S-JET mark Testing, Inspection and Certification services as a third party

1977 Testing, Inspection and Certification services of electrical components

Testing services on Request (EMC, LED, etc.)

Renewable Energy

2003 PV modules Certification services

1993 Certification services of Power Conditioners

Certification based on Laws

Water Supply equipment
Consumers' items
Medical equipment
JIS items
Wireless equipment wearable to household equipment

Management System

1993 ISO9001, ISO14001, ISO50001, OHSAS18001, etc.

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JET's Activities

Japan Electrical Safety & Environment Technology Laboratories (JET) has supported **Safety, Quality and Environment Conservation** of electrical equipment and facilities.

JET has the largest share of electrical appliances certification services with about 60% of S mark certification, and covered all of the categories in Japan.

JET's PV modules certification has been required for Government's subsidies as the most reliable one. Its labels are attached to most of household PV modules.

JET has been acting as NCB and CBTL since 1998.

JET has the large share of certification services on dental electrical equipment and electronic massager.

JET is the first on certification of Li-ion battery with the largest share.

JET is the first and only one as testing body that is registered by JNLA on LED light performance test.

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Introduction of PV related business

< PV Certification Related >

- Grid Connection Certification (1993 -)
  - Confirmation service for domestic grid connection requirements (Low pressure interconnection)
  - Regarding Solar Cells, JET is in process to transfer to new system (multiple interconnection)
- Provision of Basic Devices (2002 -)
  - Supports to assure the traceability of Solar Cell output measurement values.
  - Bridging role for AIST toward national standard regarding cell/module output
- Module Certification (2003 -)
  - National & International certification by IEC standard
  - Rapid growth of overseas customers while mainly dealing with Japanese companies
- QMS Certification (2012-)
  - Under the objective to assure the long term quality of PV modules, JET added QMS certification (JIS Q8901) in 2012.

< Research Business (National project) >

- Data collection regarding long term reliability (2001-)
  - Long term outdoor exposure data/indoor test data
  - Started to participate NEDO commissioned business and METI subsidized business

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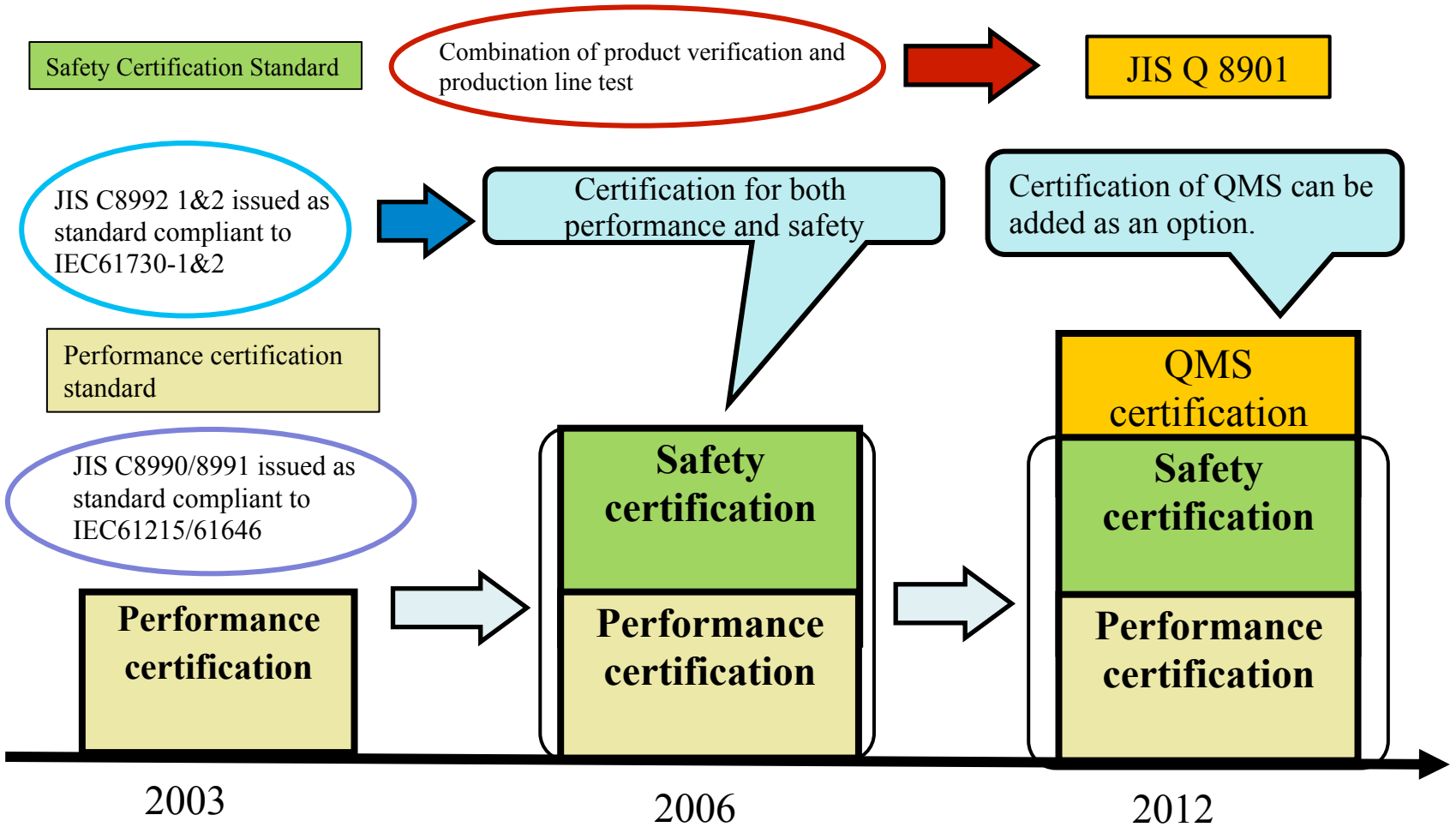
Short History of JET's PVm Certification

JET added safety certification to their JETPVm certification series in 2006. Then in 2012, they added QMS certification (JIS Q8901) for assuring the long term quality of PV modules.



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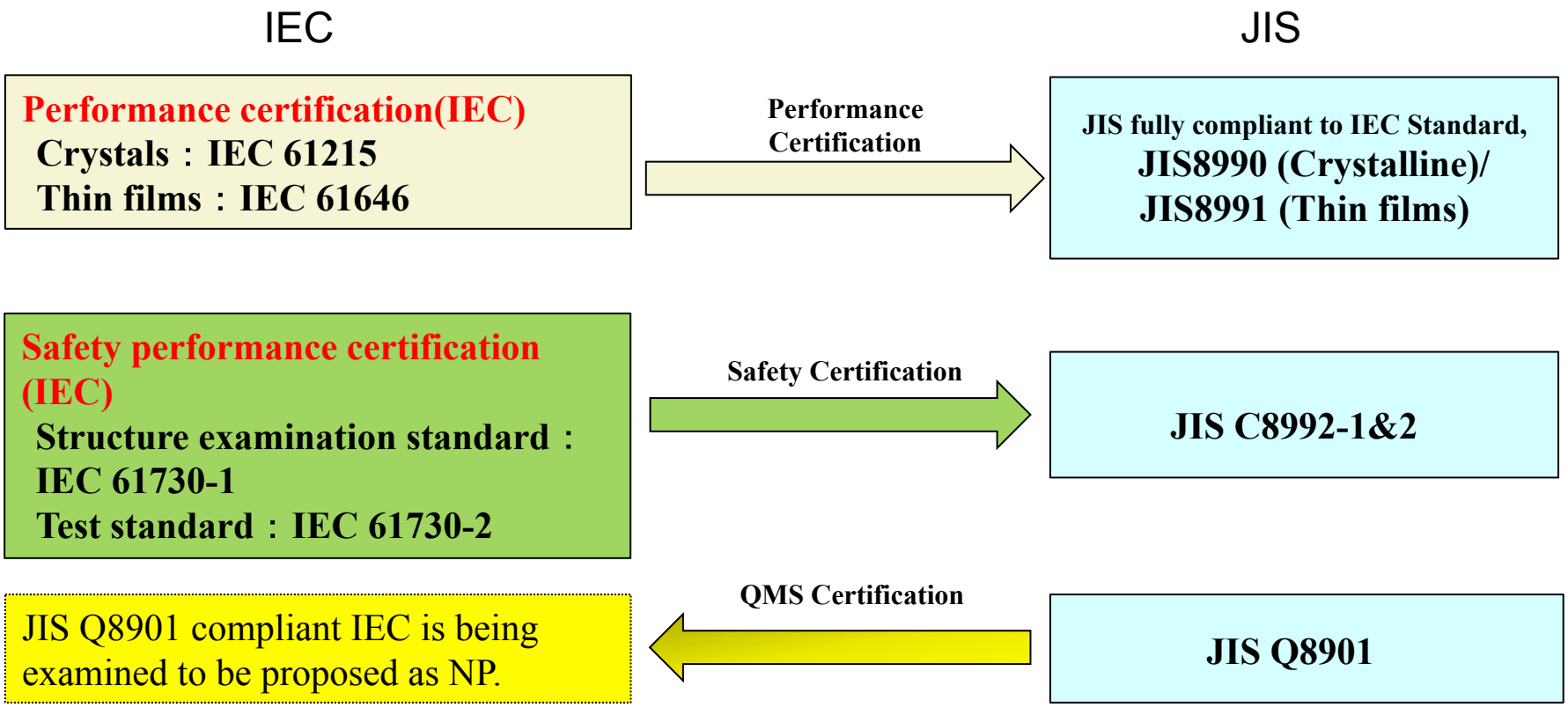
Performance/Safety/QMS Certification for PV Modules

Correspondence of IEC standards and JIS standard is as follows.



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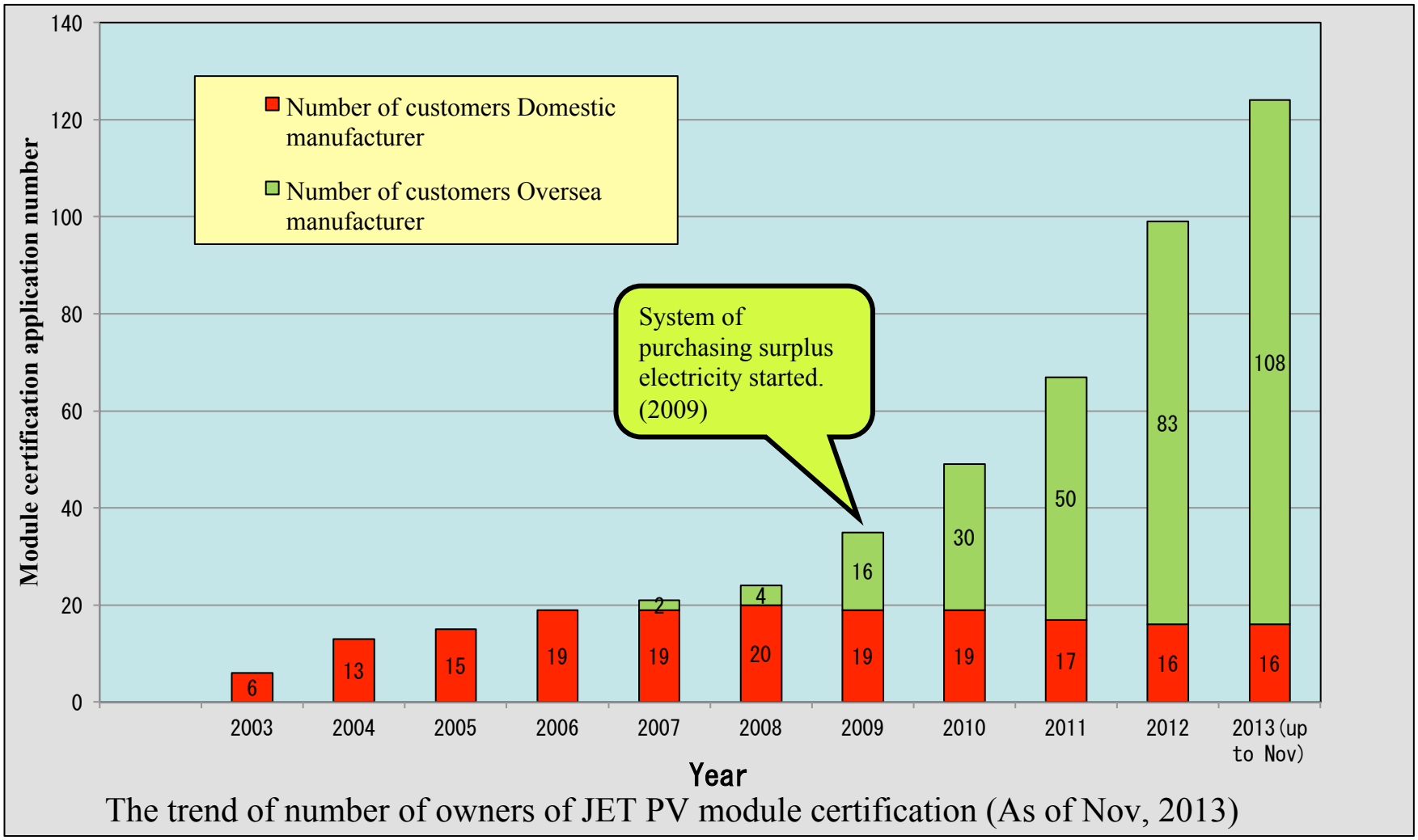
Trend of Number of JET Certification Owners for PV Modules

PV awards by JET are largely influenced by the government policy toward PV. The number of overseas customers requesting JETPVm has increased since 2009.



The trend of number of owners of JET PV module certification (As of Nov, 2013)

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PV Module Certification Test standard and Equipment

<Test standard>

International Certification Standards Applicable to PV Modules

- Performance Certification:
  JIS C8990 (IEC61215), 8991 (IEC61646)
- Safety Certification:
  JIS C8992-1, 2 (IEC61730-1, 2)
- QMS Certification: (JIS Q8901)

<Certification Test Equipment>

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Test Items for Performance Certification Standard (IEC 61215)

カテゴリー(Category)	規格に定められた試験項目(Test items defined in the standard)	
機能チェック (Functional check)	10.1	目視検査(Visual inspection)
	10.2	最大出力の決定(Pmax determination)
	10.3	絶縁試験(Insulation test)
	10.15	湿潤漏れ電流試験(Wet leakage test)
特性 (Characteristics)	10.4	温度係数(temperature coefficients)の測定
	10.5	公称動作セル温度(NOCT)の測定
	10.6	基準状態(STC)及びNOCTにおける特性
	10.7	低放射照度(low irradiance)における特性
前処理／予備的試験 (Preconditioning/Preliminary test)	10.10	紫外線照射試験(UV preconditioning test)
	10.8	屋外曝露試験(Outdoor exposure test)
長期耐久性 (Long term durability)	10.11	温度サイクル試験(Thermal cycling test)
	10.12	結露凍結試験(Humidity freeze test)
	10.13	高温高湿試験(Damp heat test)
さまざまな運用ストレスに対する耐久性 (Durability to various operating stress)	10.18	バイパスダイオード温度試験(Bypass diode thermal test)
	10.9	ホットスポット耐久試験(Hot spot endurance test)
	10.14	端子強度試験(Termination robustness test)
	10.16	機械的荷重試験(Mechanical load test)
	10.17	降雹試験(Hail test)

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Test Items for Safety Certification Standard (IEC61730-2)

カテゴリー(Category)	規格に定められた試験項目(Test items defined in the standard)	
感電危険(Electrical shock hazard)	10.2	接近性試験(Accessibility test)
	10.3	切断性試験(Cut susceptibility test)
	10.4	接地連続性試験(Ground continuity test)
	10.5	インパルス電圧試験(Impulse voltage test)
	10.6	耐電圧試験(Dielectric withstand test)
火災危険(Fire hazard)	10.7	温度試験(Temperature test)
	10.8	火災試験(Fire test)
	10.9	逆電流過負荷試験 (Reverse current overload test)
機械的ストレス(Mechanical stress)	10.10	衝撃破壊試験(Module breakage test)
部品(Component)	11.1	部分放電試験(Partial discharge test)
	11.2	配線管曲げ試験(Conduit bending)
	11.3	端子ボックスノックアウト試験(Terminal box knock out)

10.9 through 13 and 10.16 and 17 of Performance Certification Test items (environment test/mechanical strength test) are conducted as the preprocessing of 10.2, 3 and 5 of Safety Certification Test.

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Certification Test and Equipment

10.11 Thermal cycling test (IEC61215)

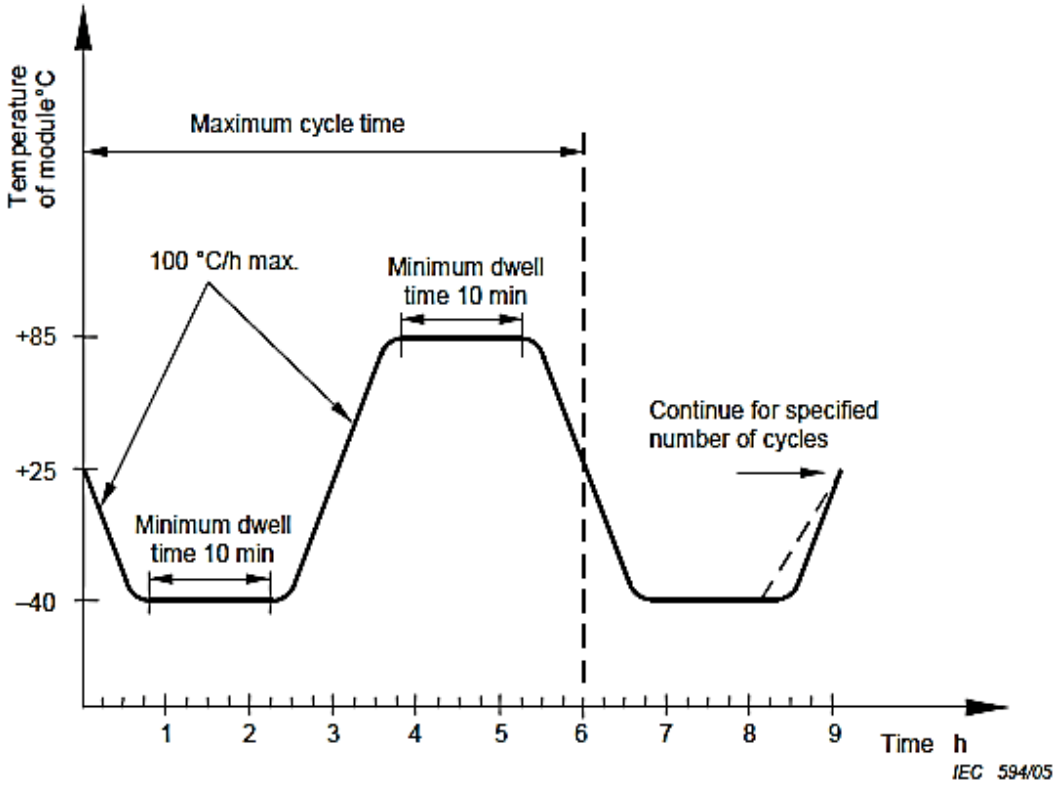

Figure 11 – Thermal cycling test

Temperature cycling test from -40ºC to +85ºC is conducted for 50 times and 200 times.

*In this cycle test, crystal samples shall receive STC peak output current for 200 times.

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Certification Tests and Equipment

10.12 Humidity freeze test (IEC61215)

Condensation/Freezing Chamber
(-40°C ↔ 85°C, 85%RH)

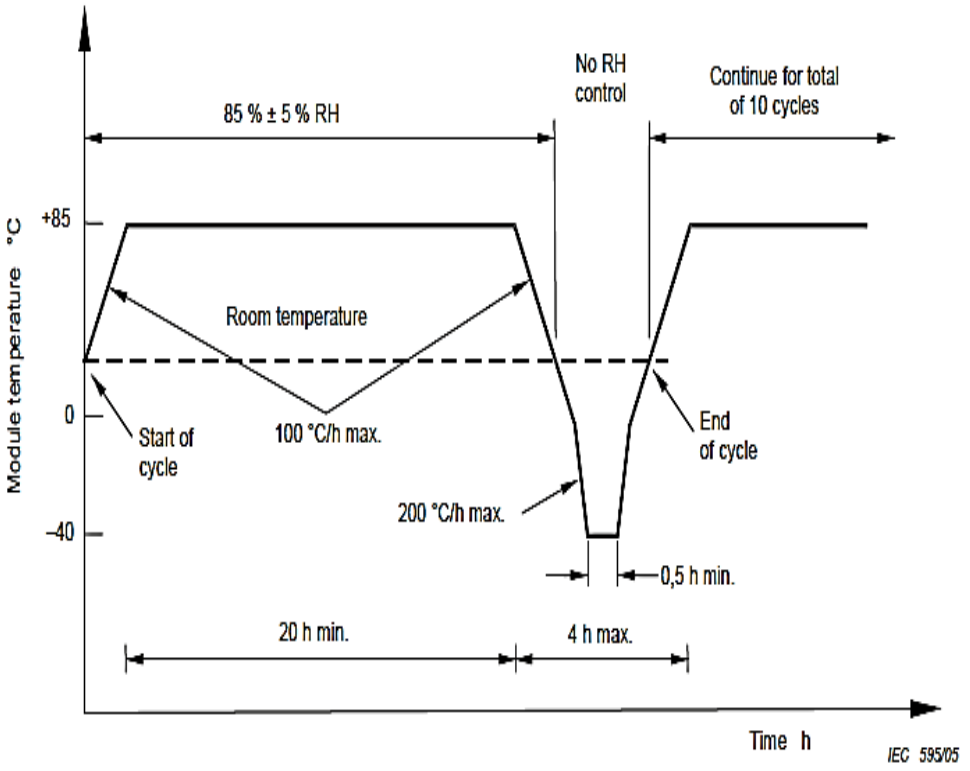

Figure 12 – Humidity-freeze cycle

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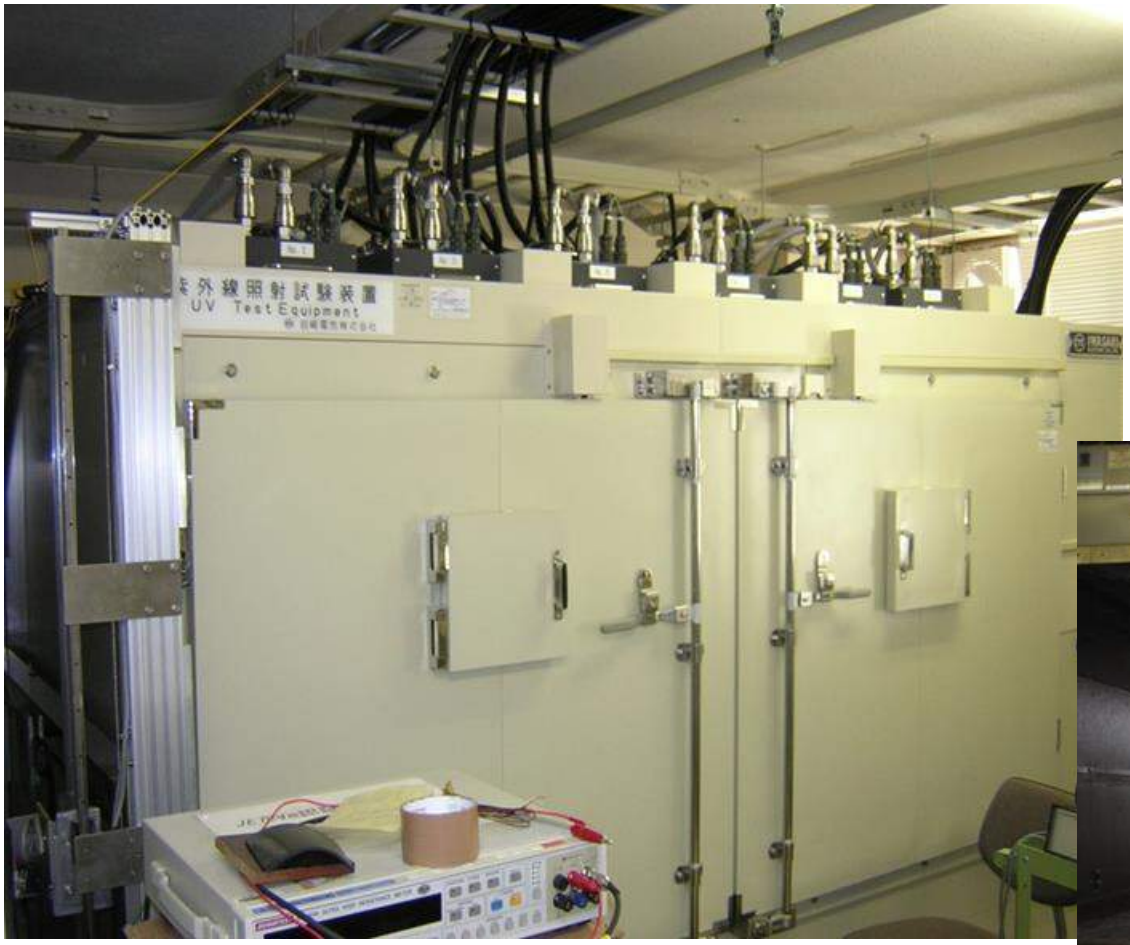
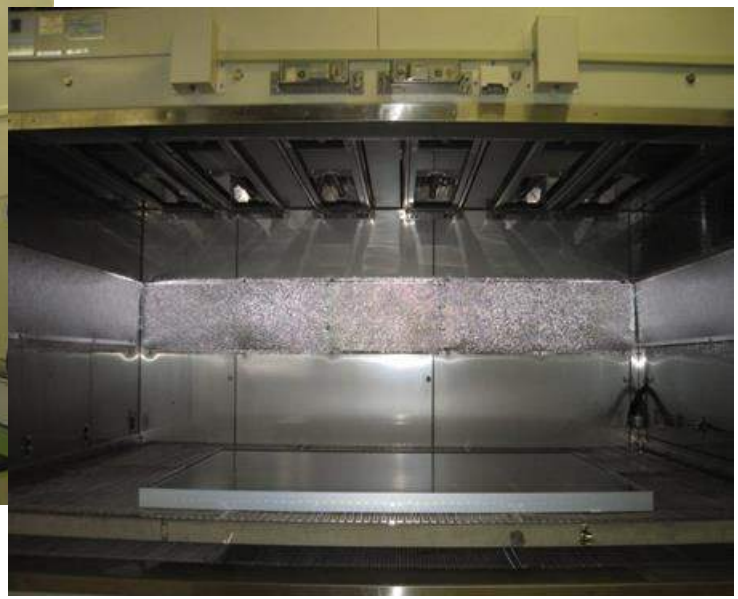
Certification Test and Equipment

10.10 UV preconditioning test (IEC61215)



10.10.1 Purpose: To precondition the module with UV radiation before thermal cycle / humidity freeze tests

10.10.3 Procedure:
Wavelength range: 285–385 nm and < 250 $W \cdot m^{-2}$ (i.e. ≈ 5 suns)
Module temperature: 60 °C ± 5 °C
Total irradiation: 15 $kWh \cdot m^{-2}$ and ≥ 5 $kWh \cdot m^{-2}$ at 280–320 nm



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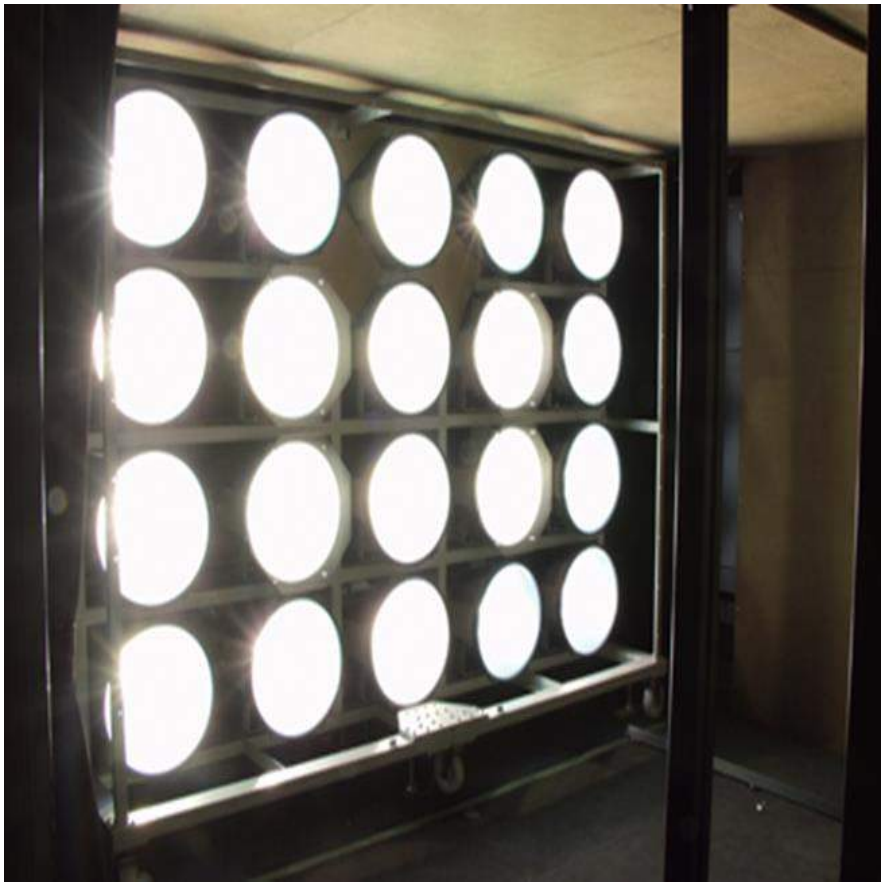
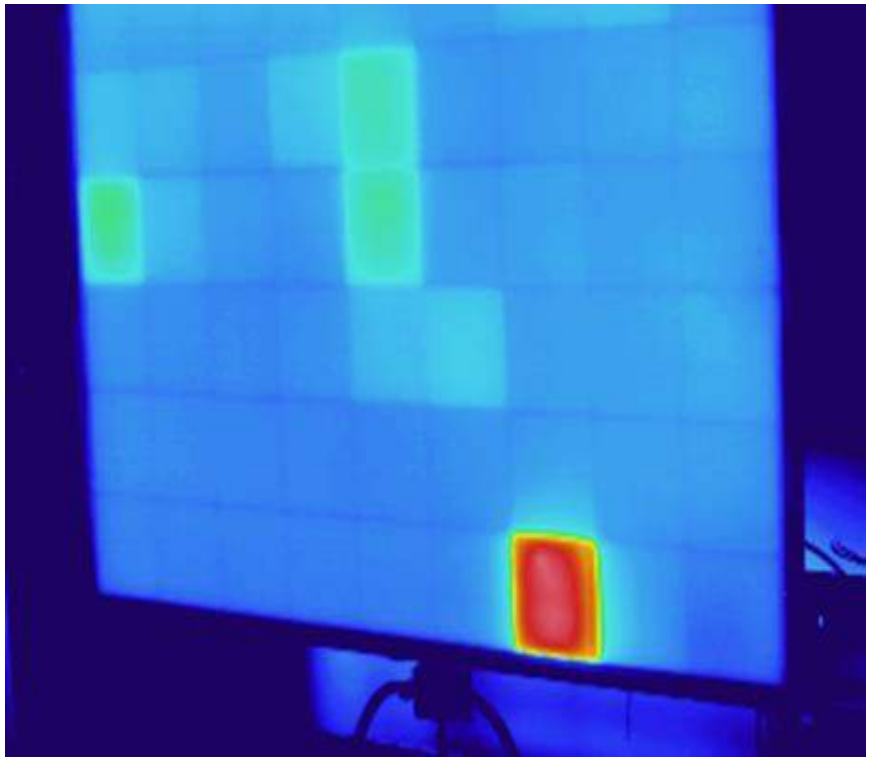
Certification Test and Equipment

10.7 Temperature test(IEC61215)



Ambient light solar simulator

10.9 Hot spot endurance test(IEC61730-2)



Shielding the cells

When there is uneven cell output, leaves stay on a module, or building shadow is cast to a module, cells will be in a severe condition. The test reproduces such conditions and examines the resistance of the module.

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Certification Test and Equipment

10.17 Hail test (IEC61215)

10.10 Module breakage test(IEC61730-2)

Impactor: 45.5 kg Height: 30, 45, 122 cm

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Certification Test and Equipment

10.13 Damp heat test (IEC61215)

+85°C. 85%RH for 1000h

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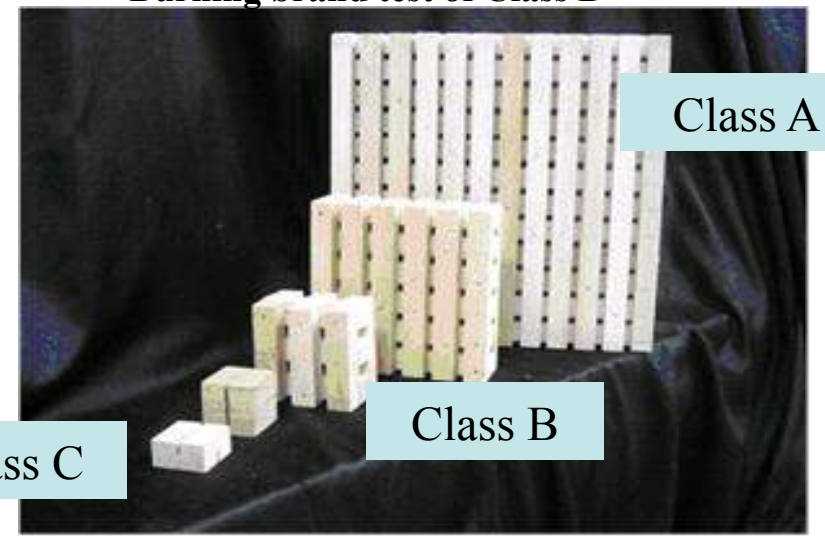
Certification Test and Equipment

10.8 Fire test(IEC61730-2)

Spread of flame test of Class C

Burning brand test of Class B



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QMS Certification (JIS Q 8901)

This Certification is for Reliability Assurance System for Ground Mounting

The scheme largely contributes to long term reliability of PV by configuration and operation of quality management system in three-phases such as design, manufacturing and after-sales services. This leads to winning the reliability and expectation of customers through such issues as long- term indebtedness.

QMS Certification (JIS Q 8901)

The manufacturer has the following liabilities.

(1)Functional service life (designed target period during which a PV module exhibits the specified performance under the specified conditions) and Assured performance period (period in which a PV module exhibits the assured performance by such services as module replacement, compensation in money and repair) can be confirmed (by the corroborating test methods or documents) in the product.

(2)Manufacturing of PV modules conforming to JIS Q9001 is maintained.

(3)The integrity of Functional service life, Assured performance period and actual Output performance assurance is secured, and the service system is in place.

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Aims of JIS Q8901 Certification

JIS Q8901 Certification was initiated in July, 2012, in accordance with FIT system in Japan. This certification can provide several competitive advantages to PV module manufacturers.

JIS Q 8901 Certification Overview

- (1) Additional requirements to existing IEC61215, IEC61646 certification
- (2) To be conducted by expanding the factory audit of IEC61215, IEC61646
- (3) Assumed as Third Party Certificate in FIT scheme.

This was enacted in June, 2012, and following four organizations support the certification.

JET	TÜV Rheinland Japan
UL Japan	VDE Global Service Japan

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Test Standard for System/BOS

IEC Standard

- Construction/safety requirements of PV system: IEC TS 62548 (Enacted), IEC60363-9-1(CDV) is being examined in TC64.
- Cables: 20/1441/NP (Electric cables for Photovoltaic system) is being examined in TC20
- Connectors: No standard. There is some movement intending to bring EN standard (EN 50521) to fast track.

Current status of local standards

<North America>

- System: NEC (National Electrical Code)
- Cables: UL 854, UL Subject 4703
- Connectors: UL 1703/489

<Europe>

- System: Requirements vary by country
- Cables: EN standard, VDE-AR-E 2283-4:2011-10 (Established as Requirements for cable for PV systems.)
- Connectors: EN 50521

<Japan>JET Certificate cables Connectors,Back sheet,Junction box)

- **Systems：JIS C 8954 (Electric circuit design standard for PV arrays), 8955 (the same as above, Supporter design standard), 8956 (Structure system design and construction method for residential solar cell arrays (for roof top type))**
- **Cables：JCS 4517 (Japanese Electric Wire & Cable Makers' Association Standard), Electric Appliance and Material Safety Law, Electric Utilities Industry Law**
- **Connectors： Substantially using the requirements for module components (IEC 61730-1 Section 7.3.)**
- **Back sheet(IEC 61730-1 Section 5.1/5.4)**
- **Junction Box(61730-1 Section 5/7/10)**

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Grid Connection Certification

⇒ Confirmation service for domestic grid connection requirements(Low pressure interconnection)

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Inverter Test

IEC Standard

・Product safty standard：IEC 62109-1&2 (Recently enacted (2010/4 and 2011/6))
・EMC Standard：IEC 61000 Series
・Grid connection standard：IEC 61727 (General requirements：Specific requirements accept the local rules.)

Current status of local standards

<North America>

・Product safety standard：UL 1740
・EMC standard：FCC Standard (IEC(CISPR)integrated)
・Grid connection standard：IEEE 1547-1&2, Rule21

<Europe>

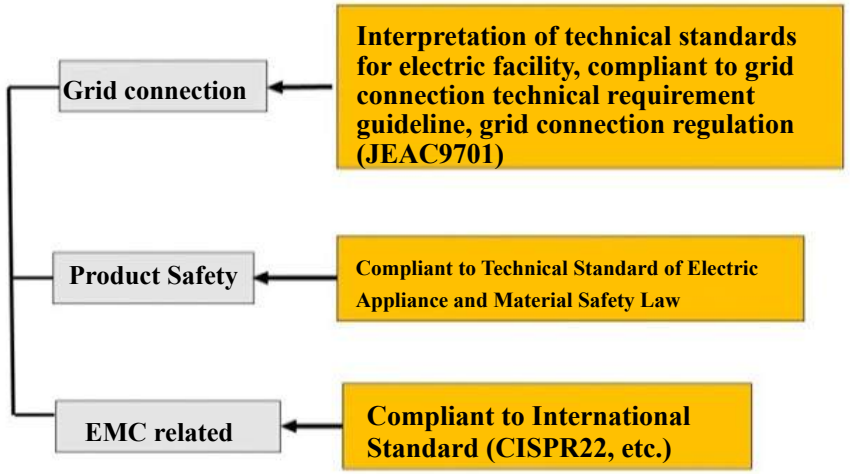
・Product safety standard：EN 50178 (IEC 62103：General requirements for power electronics products)
・EMC standard：EN 61000 Series
・Grid connection standard: Subject to requirements of each country (Germany: DIN/VDE 0126-1-1, UK：Distribution Code / Engineering Recommendation G83/1 etc.)

<Japan>

①Grid connection standard : Grid connection rule (JEAC 9701), Interpretation of electric facility engineering standard, technical requirement guideline for grid connection related to power quality

②Product safety standard : Chapter 8 of Technical criteria for electric products is used in JET certification.

③EMC standard : JIS 61000 Series



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Certified Cases for Grid Connection

Applied tests

Product aftys: Such tests as structure test, insulation performance test, ambient environment resistance test and durability test are conducted.

Protection function tests necessary for grid connection: Confirms that voltage and frequency are normal, and checks if protection level and operation time of single operation prevention are within specified limits.

Other tests (including EMC):

Confirms that product will not adversely affect environment or wiring system, and will not malfunction by influence from environment or wiring system through such tests as stationary characteristics test, transient response test, external accident test, environmental adaptation test and electric environment resistance test.

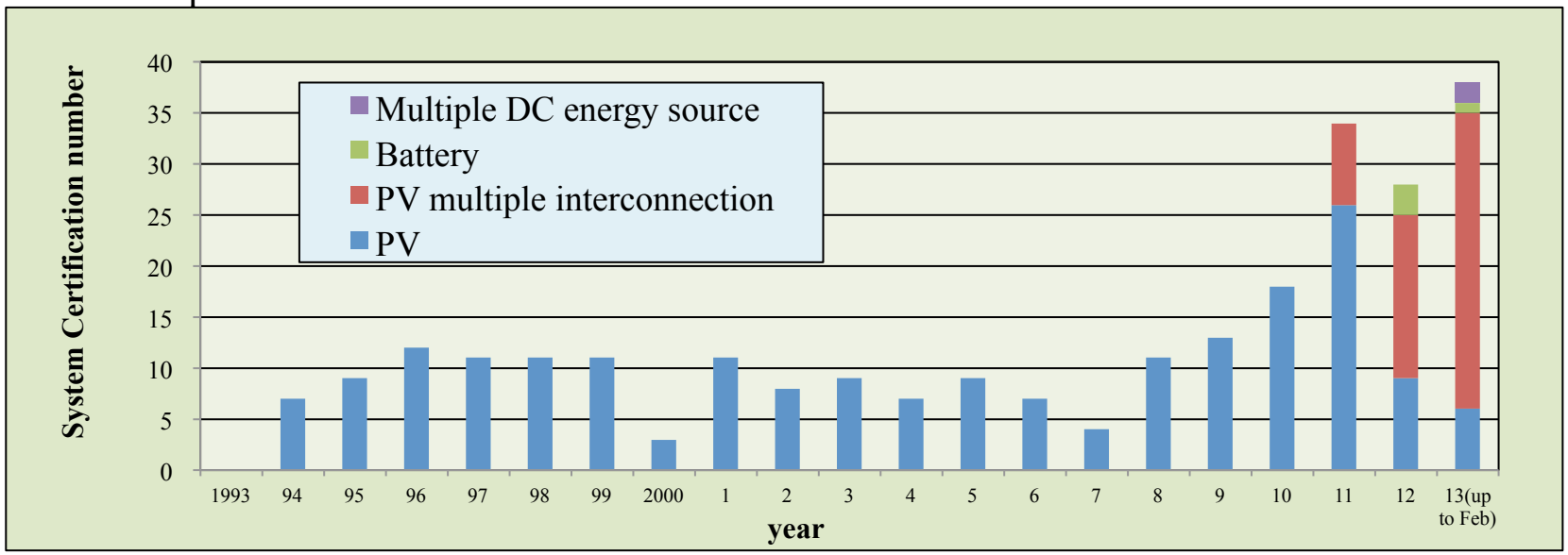

Figure: Grid connection achievement

Single unit 9: 90 models installation, multi units: 50 models installation (as of the end of Jan, 2014)

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Visit our site for model list.: http://www.jet.or.jp/

Thank you for your attendance.

First Solar Perspectives on PV Conformity Assessment

Sumanth V. Lokanath

Corporate Quality & Reliability

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First Solar at a Glance

Over 10GW installed worldwide and a 2.8GW contracted pipeline

Wide range of PV energy solutions

Partner of choice for leading utilities and global power buyers

Driving innovation across entire value chain and plant solution

Largest Solar O&M provider - 3.2GWdc under operation + multi GW pipeline

Strongest financial stability & bankability in the industry

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First Solar Provides More Value and Less Risk

TECHNOLOGY

Lower LCOE

Energy Performance

Sustainability

Local Jobs/ Content

Grid Integration & Forecasting

SERVICES

Reliability

Seamless Integration

Performance Guarantee

Predictable Energy

Time-to-Power

Less Price Volatility

Bankability

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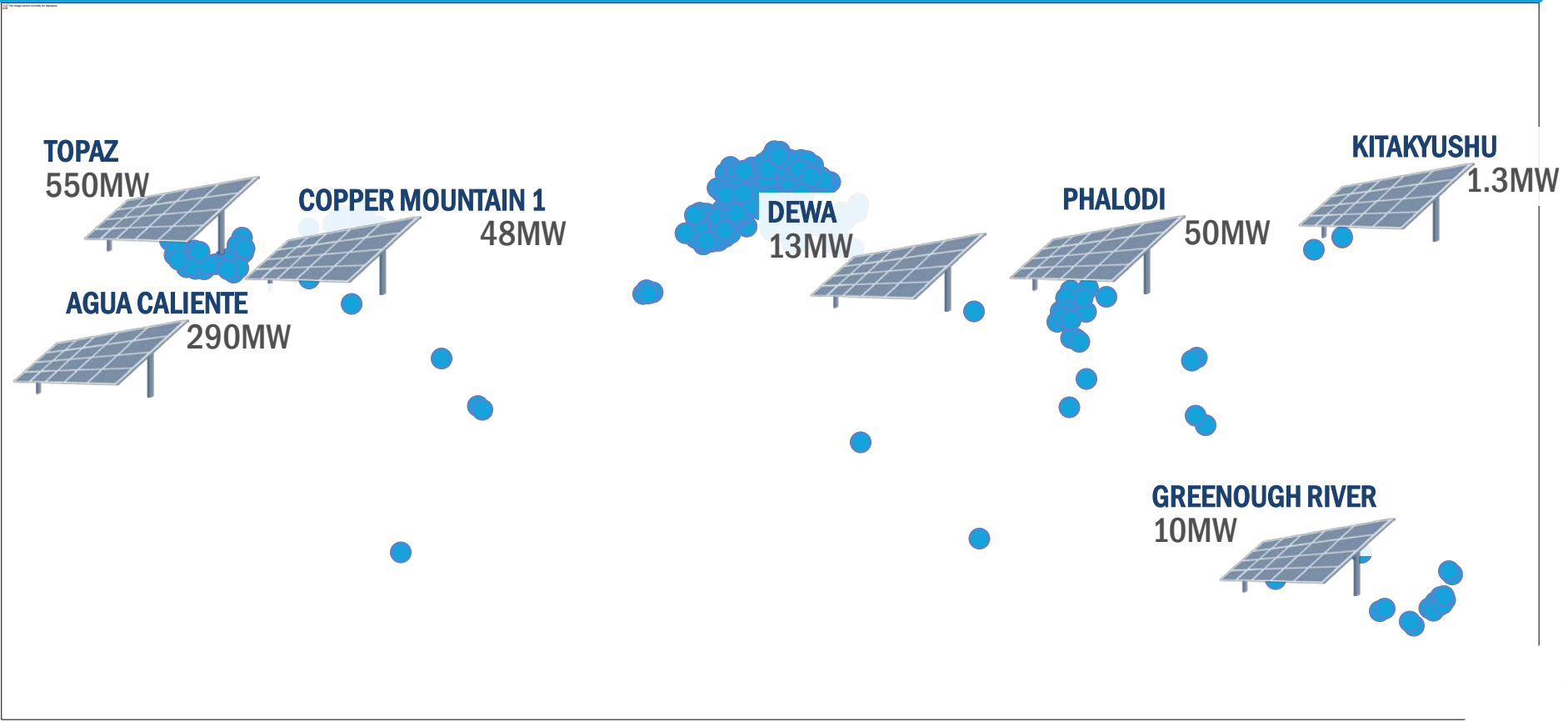
Featured Projects



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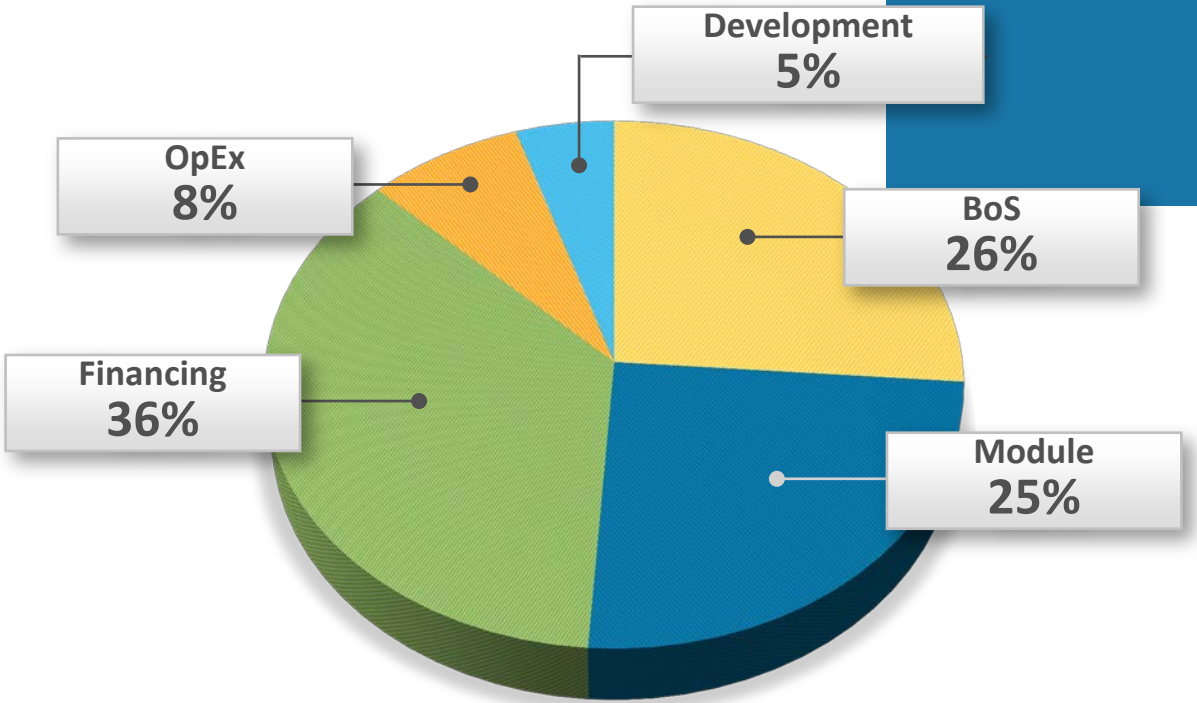
Project Costs

- Project Finance significantly impacts total cost of ownership
- Project finance is the single-largest contributor to the levelized cost of electricity (LCOE), far more than the module, balance of system, project development, or operating costs
- Obtaining low cost financing and access to capital markets is critical to reducing the total cost of ownership and accelerating solar adoption worldwide



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Partnering with Leading Global Power Buyers

> "We are very proud to be working with First Solar, who has a reputation for the delivery of world class renewable energy projects internationally."

Michael Librizzi, General Manager Midwest for WBHO Civil

Track record of delivering to leading utilities and energy investors

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First Solar Project Finance

- Strongest balance sheet and cash position amongst all solar competitors
- Unparalleled use of First Solar modules in debt financed projects around the world
- Financial institutions worldwide support First Solar technology

First Solar is BANKABLE

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Conformity Assessment - Value

- Improve Project bankability and IRR→ Goal is to enable certification as a pathway to
  - Reduce risk perception
  - Reducing solar financing costs
- Quality differentiation
  - Demonstrating best in class plant components, design, optimization and configuration.
  - With financial returns diminishing, assure quality of solar plants to perform as predicted
- Facilitate faster project implementation with global relevance
  - Lack of standards/Multiple standards and certification bodies not on par globally
  - Create block certifications or product level certifications to provide additional flexibility and keep industry costs down
- Common audit & test criteria for global assessment bodies – Reduce Audit overhead
- Establish & Enable benchmarking for System Design, EPC, O&M, field performance etc.

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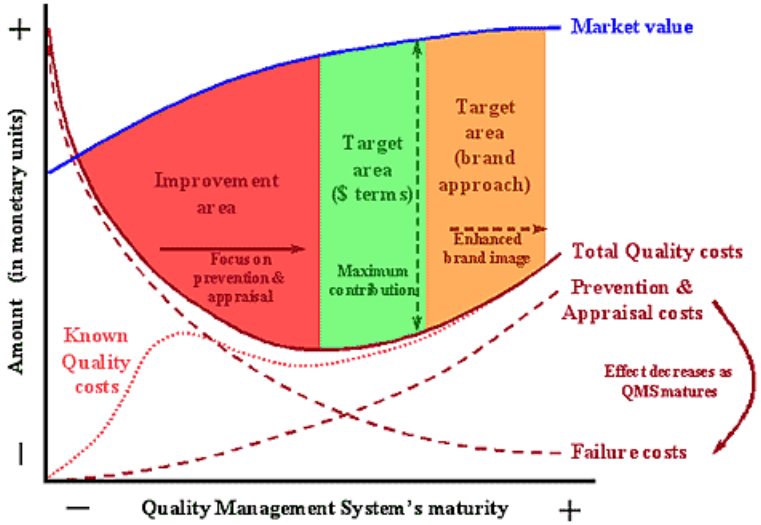
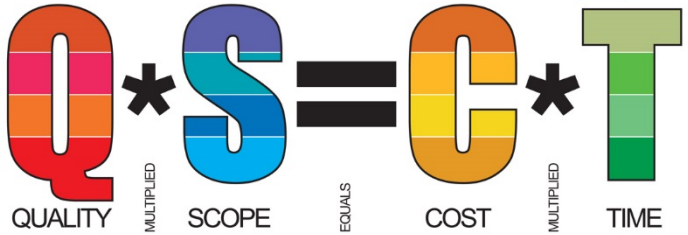
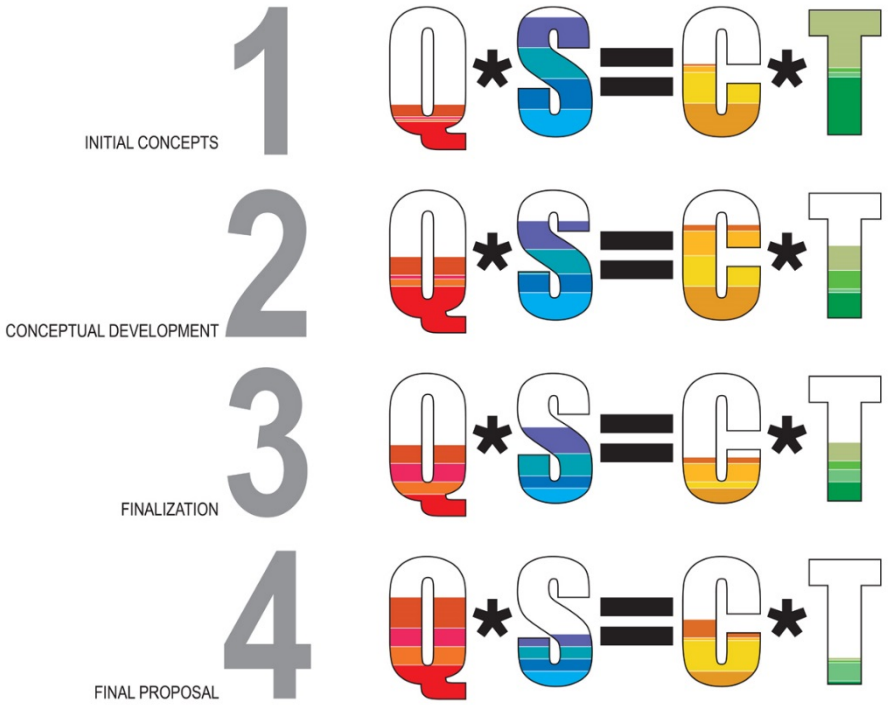
The Implementation Challenge







http://alexgreenhut.com/index.php?/fifthyear/logistic-drawings-and-diagrams/, http://www.qualitydigest.com/inside/twitter-ed/facing-crisis-through-quality-back-basics.html#

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2014 FSLR Module Manufacturing Plant Site Visit Summary

2014
Site Visits

Site	Factory Tours	Customer Audit	Technical Audit	Certification Audit	Totals
US - Perrysburg	8	7	3	7	25
Malaysia -Kulim	3	3		7	13
Total	11	10	3	13	38

Visit Description

Factory Tours - Visits to get overview of First Solar

Customer Audit - Formal assessments by Customers [1-2 days]

Technical Audit - Third Party Engineering for technical product endorsements [2-3 days]

Certification Audits - Compliance for Certifications on Site Standards or Product (i.e. ISO, UL, IEC..) [1 day]

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Conformity Assessment – Concern Areas

- Aligning to project execution velocity
  - Detailed understanding of the design by auditor prior to site visit
  - Have them review RFIs prior to visit so they understand some spec changes
  - Align inspection/audit schedule with project schedules.
- Uncertainty with Project Schedules (Shift Left scenario)
  - Need to clearly understand scope of inspections, auditable artifacts and criteria upfront.
  - Need to have prior agreement on regional code & standards basis for inspections.
    - NEC 2014 versus NEC 2011; Base criteria on AHJ requirements.
  - Need to have prior understanding of what calculations, drawings need to be reviewed (Sub Contracts)
- Arbitration procedure for Grey Areas
  - What the audit agency things is valuable versus what EPC/Customer values?
    - Ex: lightning protection, cable routing, wire management
  - Provide justified basis for audit findings to avoid debate and drawn out project closure.
  - Governance on how to classify major and minor findings?

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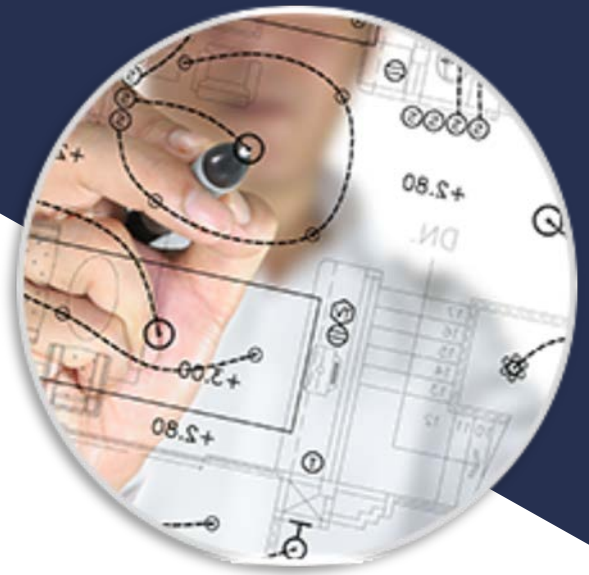


True South Renewables INC

The Renewable Energy O&M Solution

Rue Phillips, CEO, Co founder

26 February 2015

Presentation: NREL PV Performance Lab

NREL

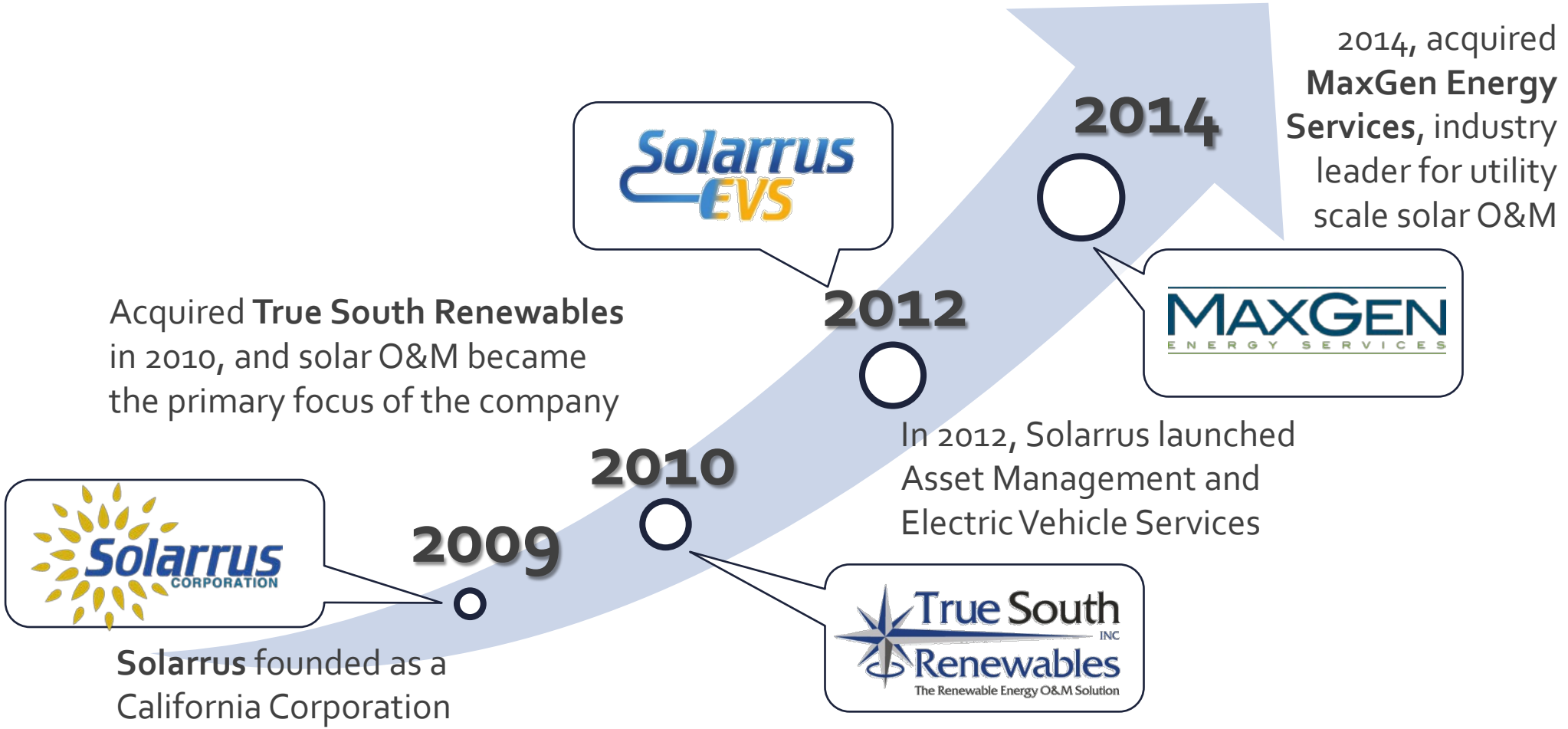
NATIONAL RENEWABLE ENERGY LABORATORY

Vision & Mission

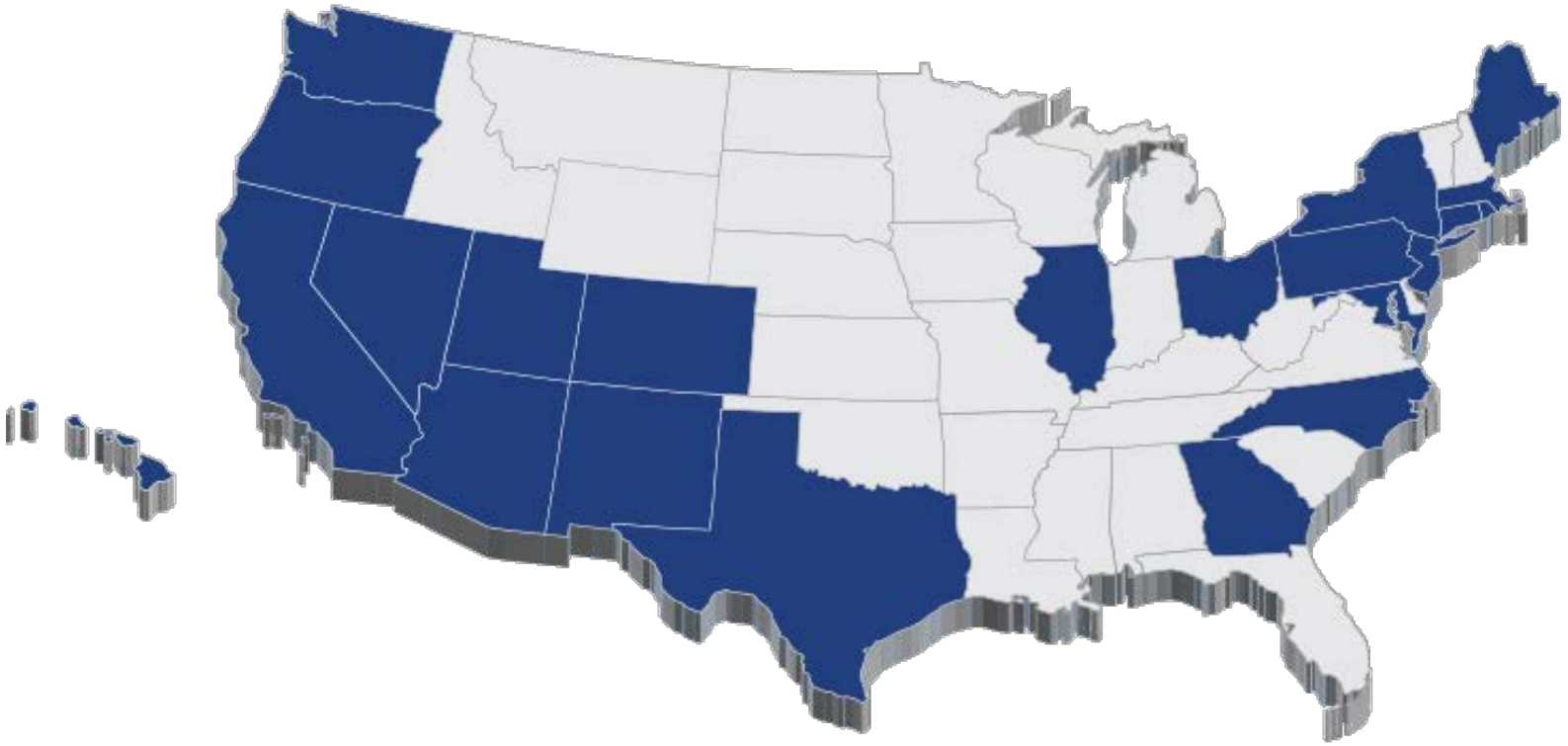
- **Vision**
  - Dedicated to developing, maintaining, and operating infrastructure that supports alternative energy technologies

- **Mission**
  - Leverage our capabilities to meet our customers' requirements, in order to mitigate risk, optimize performance, and offer a better return on their capital

About Solarrus



About Solarrus – Nationwide Coverage



True South INC Renewables

True South INC Renewables
The Renewable Energy O&M Solution

MAXGEN
ENERGY SERVICES

Solarrus EVS

Range of Services for the Solar Industry

Technical expertise and field services to support all phases of projects

Development

- Design and engineering
- Peer reviews
- Site viability evaluations

Installation

- Oversight
- Independent system commissioning
- Performance validation

Operation

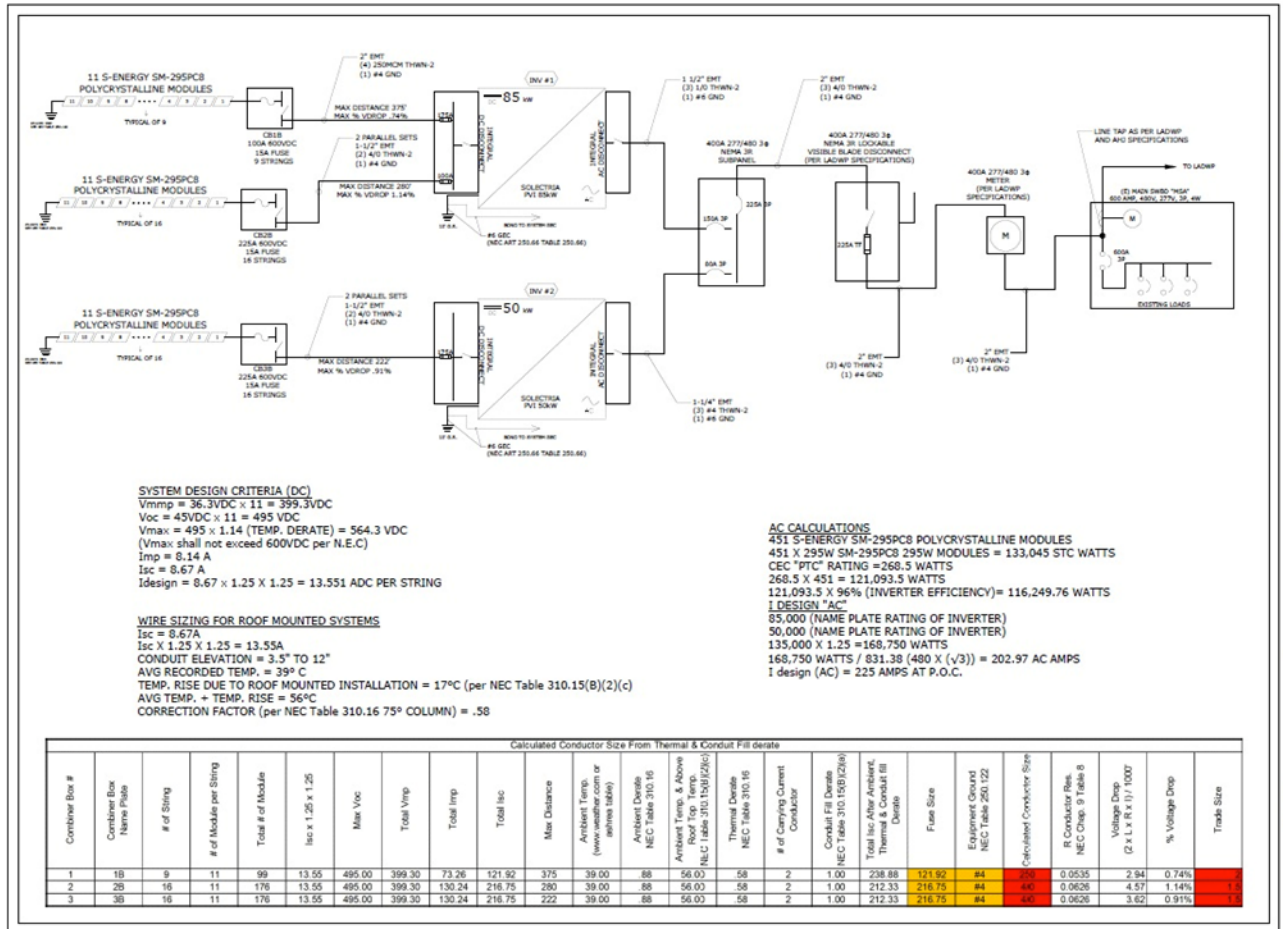
- Proactive O&M
- Array cleaning
- Asset Management
- Warranty Fulfillment

TSR is ***NOT*** an installer, developer, or EPC

Operations & Maintenance – Independent Industry Leader

- First mover in the market and leading reputation in the industry
- More than doubling in size with existing customers, and adding new customers as the industry grows – 89 customers now +2000 sites
- Customers are market leaders
- TSR helps set industry standards
- Focus on quality, performance, and safety in the field

Design & Engineering Services



Combiner Box #	Combiner Box Name Plate	# of String	# of Modules per String	Total # of Module	Isc x 1.25 x 1.25	Max Voc	Total Vmp	Total Imp	Total Isc	Max Distance	Ambient Temp. (www.weather.com or asthrea table)	Ambient Derate NEC Table 310.16	Ambient Temp. & Above Roof Top Temp. NEC Table 310.15(B)(2)(c)	Thermal Derate NEC Table 310.16	# of Carrying Current Conductor	Conduit Fill Derate NEC Table 310.15(B)(2)(a)	Total Isc After Ambient, Thermal & Conduit fill Derate	Fuse Size	Equipment Ground NEC Table 250.122	Calculated Conductor Size	R Conductor Res. NEC Chap. 9 Table 8	Voltage Drop (2 x L x R x I) / 1000	% Voltage Drop	Trade Size
1	1B	9	11	99	13.55	495.00	399.30	73.26	121.92	375	39.00	.88	56.00	.58	2	1.00	238.88	121.92	#4	#10	0.0535	2.94	0.74%	1
2	2B	16	11	176	13.55	495.00	399.30	130.24	216.75	280	39.00	.88	56.00	.58	2	1.00	212.33	216.75	#4	#6	0.0626	4.57	1.14%	1.5
3	3B	16	11	176	13.55	495.00	399.30	130.24	216.75	222	39.00	.88	56.00	.58	2	1.00	212.33	216.75	#4	#6	0.0626	3.62	0.91%	1.5

- **In house design and engineering capabilities**
  - PE, electrical engineer, and team of CAD technicians
    - Over 300MW engineering experience
    - Utility, commercial DG, and Residential projects
    - Peer Reviews
    - Permit Packages, PE + CE Stamp
    - Conceptual & Design Packages
    - Site Feasibility Analysis
    - PVSyst Analytics
    - Owner's Representative / Construction Monitoring
    - Medium voltage design & field expertise

True South Renewables INC
The Renewable Energy O&M Solution

True South INC Renewables

Utility-scale Experience

- **Long Island Solar Farm**
  - 37.5MW, fixed tilt
  - 164,312 solar modules
  - Largest project on East Coast
  - Powers 4,500 homes

- **Webberville Solar Farm**
  - 35MW, single axis tracker
  - 127,000 solar modules
  - First utility scale project in Texas
  - Powers 5,000 homes

Utility-scale Experience

pv magazine
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Solarrus acquires MaxGen, expands O&M operations

02. OCTOBER 2014 | APPLICATIONS & INSTALLATIONS, GLOBAL PV MARKETS, INDUSTRY & SUPPLIERS, MARKETS & TRENDS | BY: EDGAR MEZA

The alternative energy services company says the inclusion of MaxGen dramatically enhances its asset management capabilities for utility-scale solar clients. Solarrus will now be able to offer services across all project sizes.

Utility-scale Experience

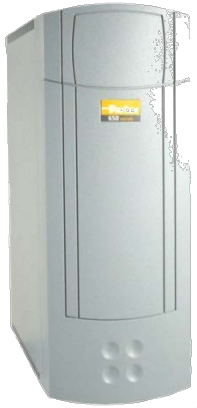
- Leader in utility-scale solar O&M and Asset Management Services
- Currently operating over ~300MW of solar PV, growing to ~600MW in 2015
- Specialize in commissioning services, plant operations, plant maintenance, and asset management services
- Experts with over 2GW of power plant experience (solar & wind)

Markets Served – Inverter Equipment

Solar Inverter

ABB

Battery Energy Storage



Parker

EV Service Equipment

NISSAN

Industrial Lift Vehicle Charger

PosiCharge™ AeroVironment

The same technology that is fundamental to maintaining solar inverters is applicable to other industrial applications

- *Same training*
- *Same equipment*
- *Same manufacturers*
- *Multiple markets*

Capabilities to handle advanced energy technology requirements for design, installation, operation, and ongoing service needs

Charging Equipment Infrastructure Services

- Aligned with companies shaping this market
- Industry leaders rely on Solarrus as part of their own infrastructure capabilities
- Growing faster than solar
- Industry leading with multiple OEMs, standards, and technologies
- Focus on quality and performance in the field

Battery Energy Storage Systems (BESS)

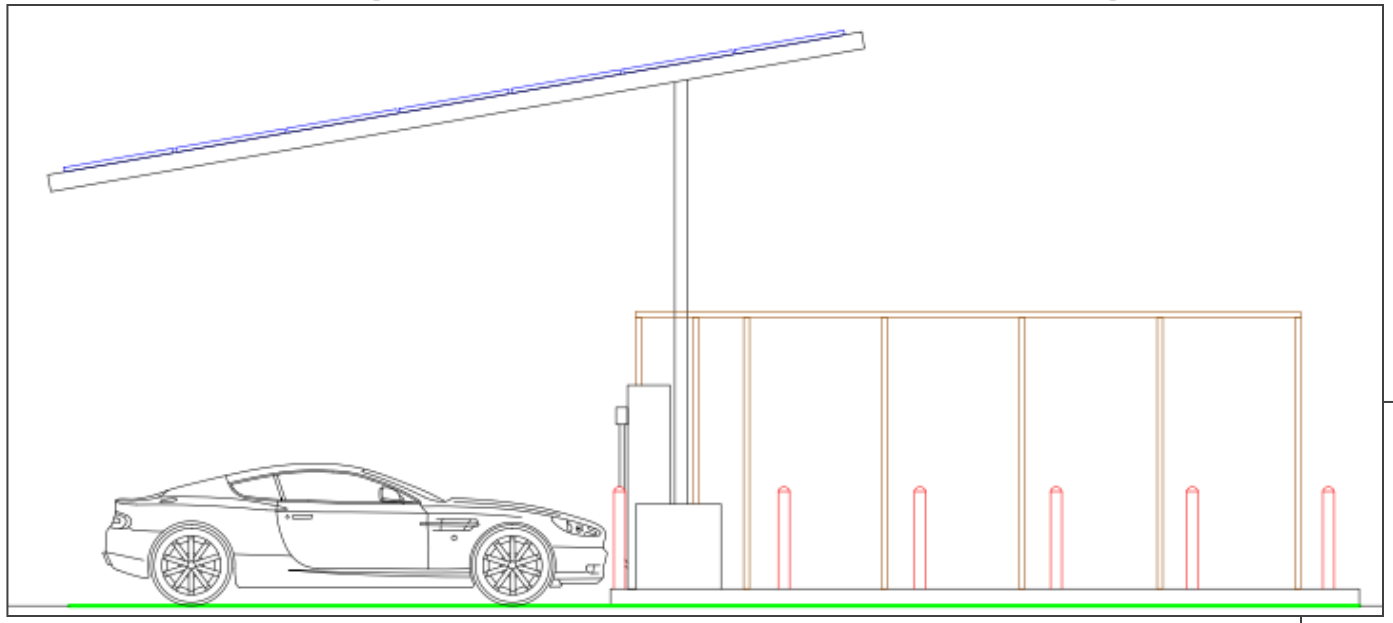
Peak Demand

Renewable Support

EV to Grid

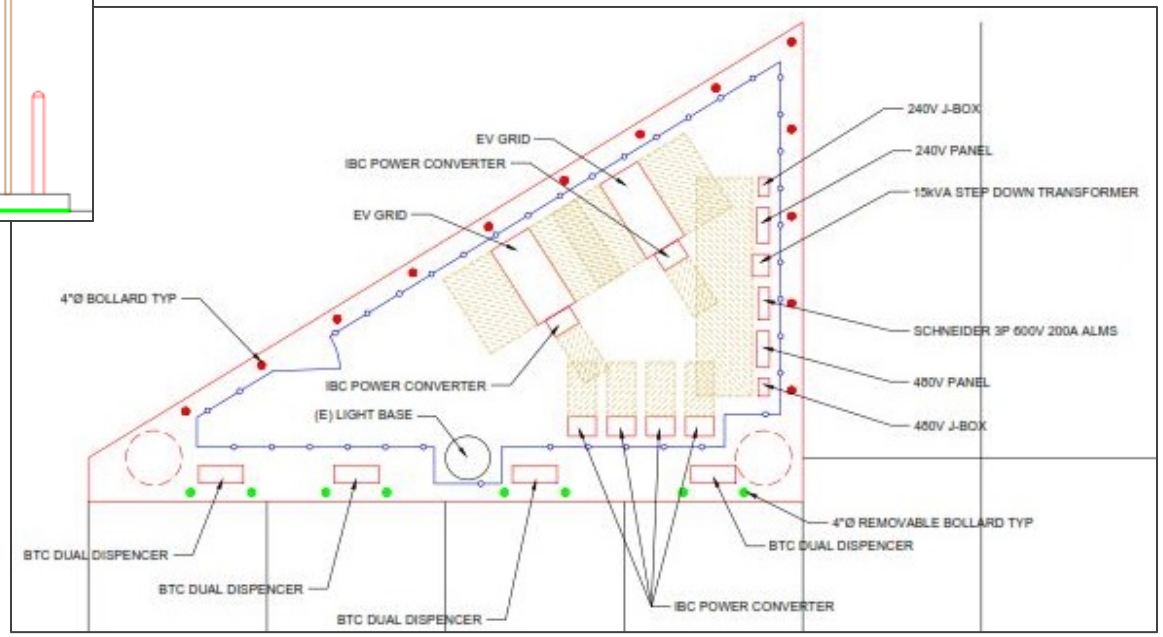
Leveraging expertise from our capabilities for design/engineering, solar operations and maintenance, and electric charging equipment

Convergence of Technologies



Integration of technology to evaluate means to lower operating costs of public infrastructure by eliminating peak demand charges

- *20kW solar canopy*
- *40-60kW Level 3*
- *24kWh storage batteries*



Commissioning.

Certification.

Acceptance.

Performance.

Testing.

What do they mean ?

Commissioning

- What is Commissioning ?

  A full mechanical and electrical system test upon substantial completion or COD of a solar asset to check the functionality, operation of a system to compliment AHJ or EOR inspection.

- What are the standards and protocols ?

  ASTM, IEC, Sandia, NREL, True South !

- Who performs ?

Third Party independent testing company. Established Engineering companies. EPC's !!

- For whom ?

Asset owner such PPA's, financial institutions, large EPC or IPP's

- Issues ?

The industry has mistaken commissioning for all other testing of solar assets, is is not a statement of the good health of a solar asset merely a test function at the end of construction in order to move from construction to operation and further testing. Further commissioning of system (particularly unstable plants bought on line) should have additional commissioning until the plant is stable in its operation as a solar generating plant.

Acceptance Testing

- What is Acceptance Testing ?

At test or protocol to officiate hand off from one stakeholder to the next. EPC to OEM, PPA to new equity owner

- What are the standards and protocols ?

Lots of work within the industry needed here with an emphasis to established organized such as IEC, ASTM, NREL , SANDIA

- Who performs the test?

Independent third party agent on behalf of the stakeholder. Banks, Engineers, O&M companies

- For whom ?

Stakeholders such as banks, PPA's , IPP's , Yield Co's, O&M companies

- Issues ?

Market is dangerously moving faster than the protocols and adopted standards

Validation of Assets

- What is Validation of assets ?

A comprehensive and analytic test of a solar asset towards its design, installation, operation, code compliance, permit admin, functionality, 'BENCHMARK' performance setting, stability, and warranty status.

- What are the standards and protocols ?

More work needed here ! Market is way ahead of the protocols.

- Who performs the validation ?

An engineering discipline and representative Stakeholder such as O&M service provider.

- For whom ?

Owners, banks, IPPS, PPA's, OER, AHJ's

- Issues ?

Standards are not conclusive, often a verbal acceptance of an asset is enough 'legally' to validate the system, or one years monitoring data is used for such a test !!!!

Performance Testing

- What is performance testing ?

A comprehensive analysis of a solar PV systems performance in reference to its design, financial model and actual deliverable energy production

- What are the standards and protocols ?

ASTM E2848 / E2939. IEC. NREL. EPRI, Sunspec Alliance

- Who performs the performance tests ?

Stakeholders or their service providers such EOR, O&M. this is a new and open market

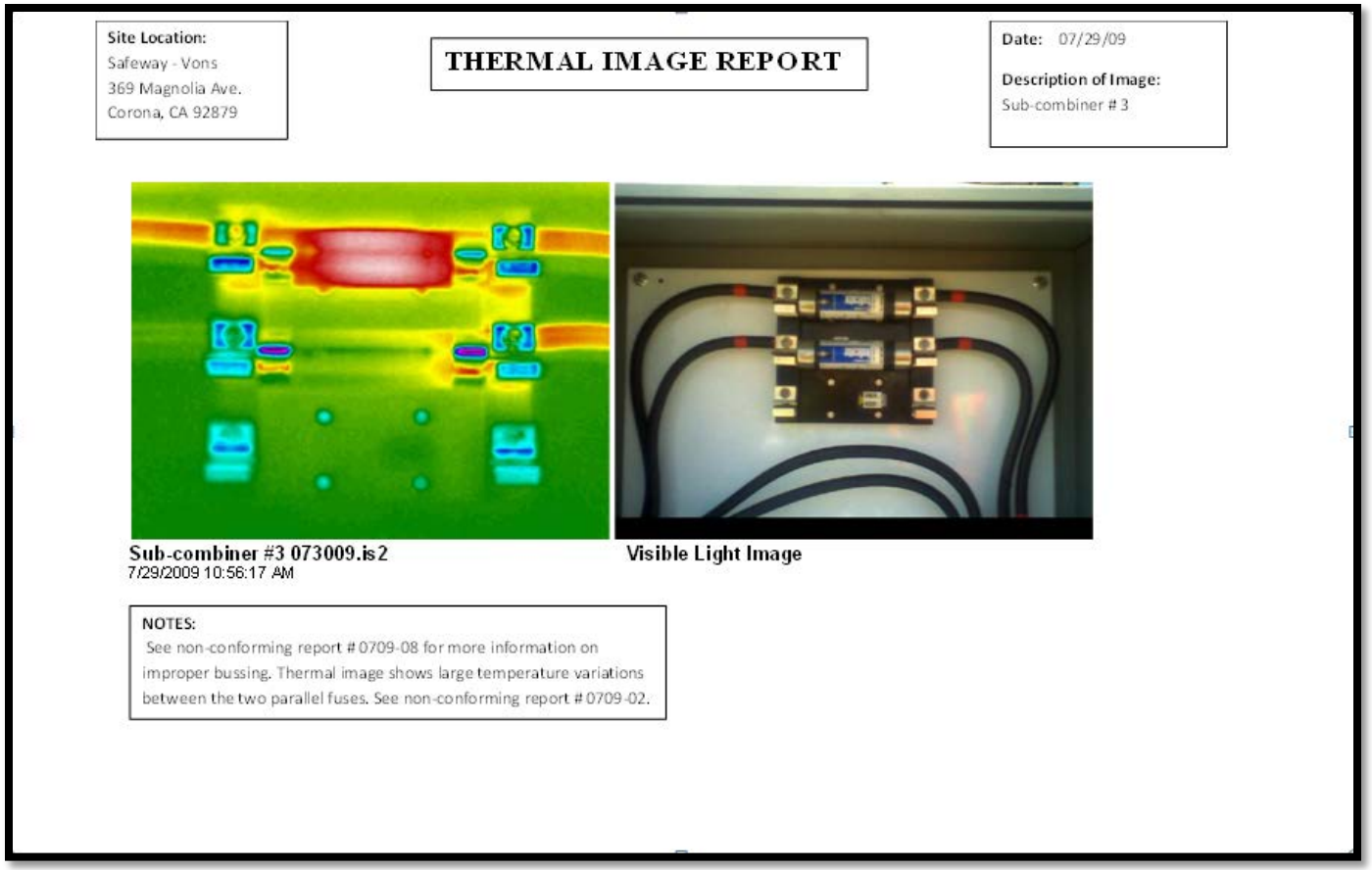
- For whom ?

Stakeholders and potential asset acquisition parties, PPA, bank yield co's

- Issues ?

If the asset is new then the test is merely a snapshot in time and NOT a guarantee that the system will function (without O&M) as it should

Commissioning



Site Location:
Safeway - Vons
369 Magnolia Ave.
Corona, CA 92879

THERMAL IMAGE REPORT

Date: 07/29/09

Description of Image:
Sub-combiner # 3

Sub-combiner #3 073009.is2
7/29/2009 10:56:17 AM

Visible Light Image

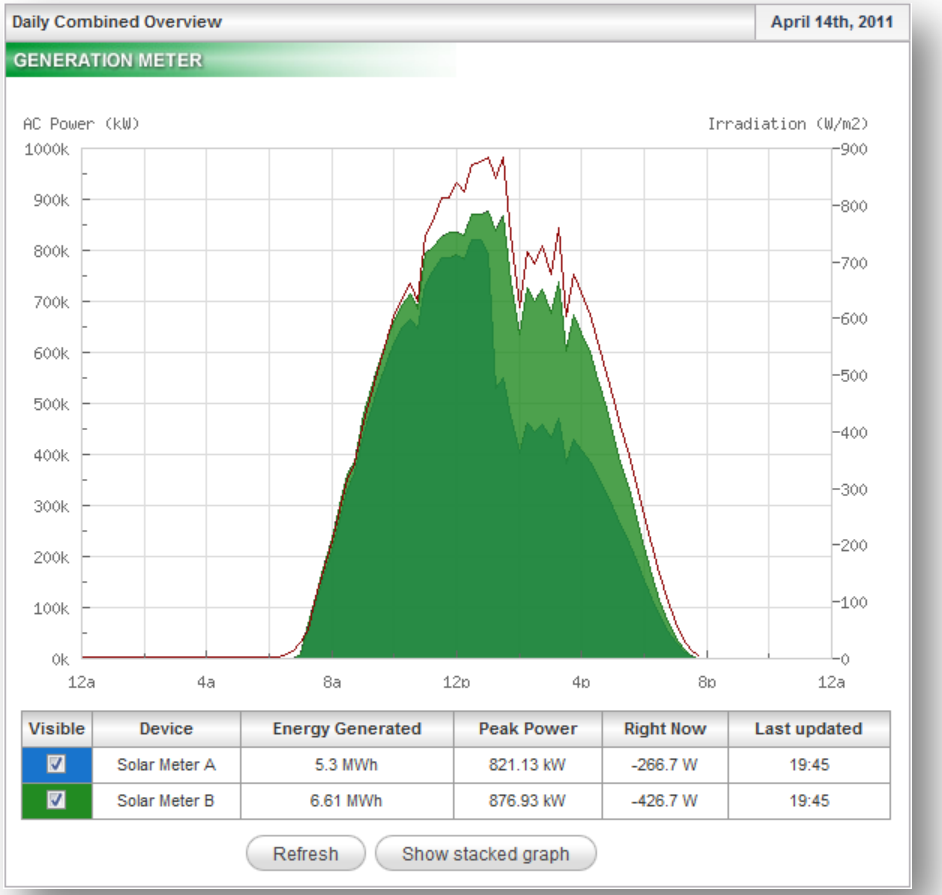
NOTES:
See non-conforming report # 0709-08 for more information on improper bussing. Thermal image shows large temperature variations between the two parallel fuses. See non-conforming report # 0709-02.

Common faults. Bad connections, wrong specifications of BOS. Poor workmanship. A through and comprehensive commissioning check should be mandatory on all solar assets

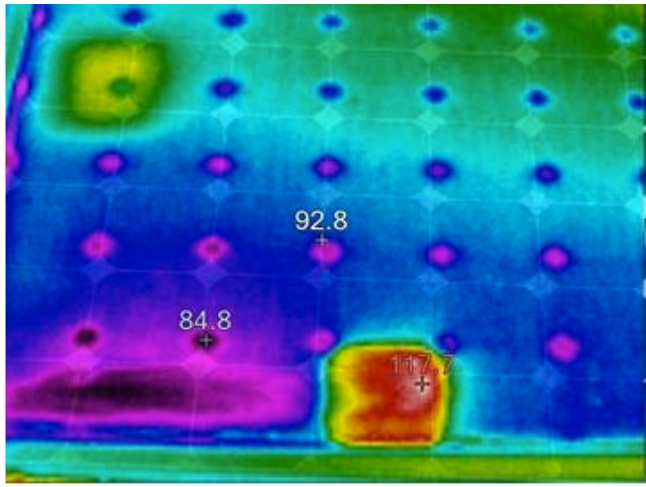
Validation of Assets

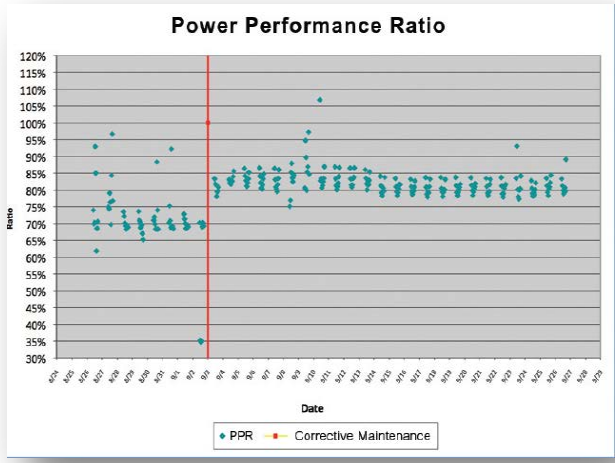
True South verifies the value of your solar electric facility with a full system appraisal. Our technicians perform an intrinsic audit of all mechanical and electrical components throughout your solar power plant.

Performance testing



We're in the business of ensuring your solar system's performance modeling withstands the testament of time. That is why the foundation of our success is built upon raising performance ratios and increasing total energy generation.





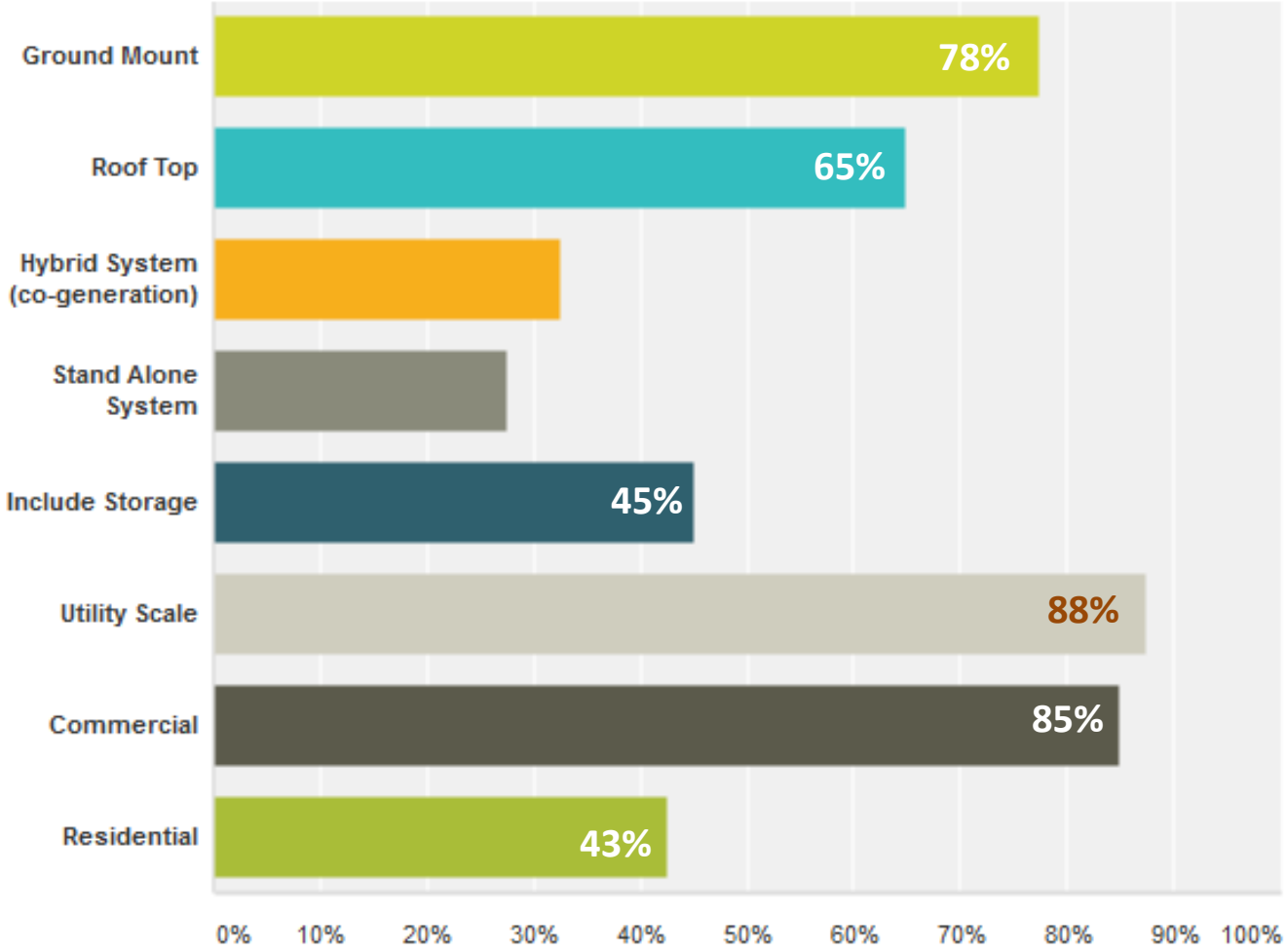
This system could have been a $6M solar asset being monitored by a sophisticated and reputable asset management team and technology. Full system checks are required annually in order to fully protect the asset !

IECRE PV System Certification Survey Results

Greg Ball
DNV GL
Co-Convenor, TC 82 WG6
2015 IECRE Workshop
February 26, 2015

IECRE Systems Certification Workshop – Survey Results

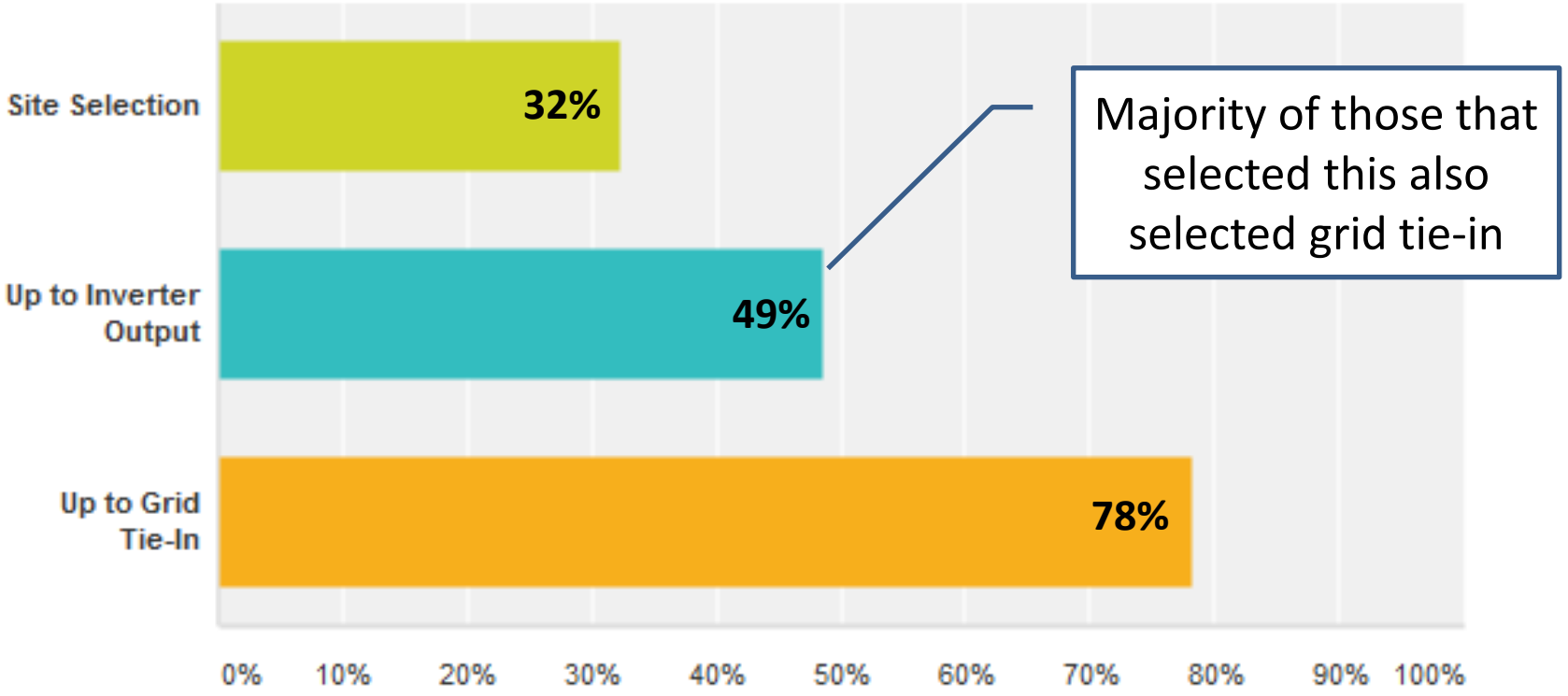
PV Power Plant Application - What types of plants would you include in a IECRE PV Plant certification standard?



PV Power Plant Application - What types of plants would you include in a IECRE PV Plant certification standard?

- Ground mount seems to be a given – whether commercial or utility scale
- Commercial and rooftop score high – are there size or project cost (financing) thresholds?
- How do we structure the scope (and cost) of a certification for large plants vs. small commercial or even residential systems?
  - Minimum certification cost may be too much for single residence
  - Could however apply to residential portfolio
- Need additional expertise and reference standards to address storage

PV Power Plant Installation Scope - What do you think the IECRE PV Plant certification standard should cover?



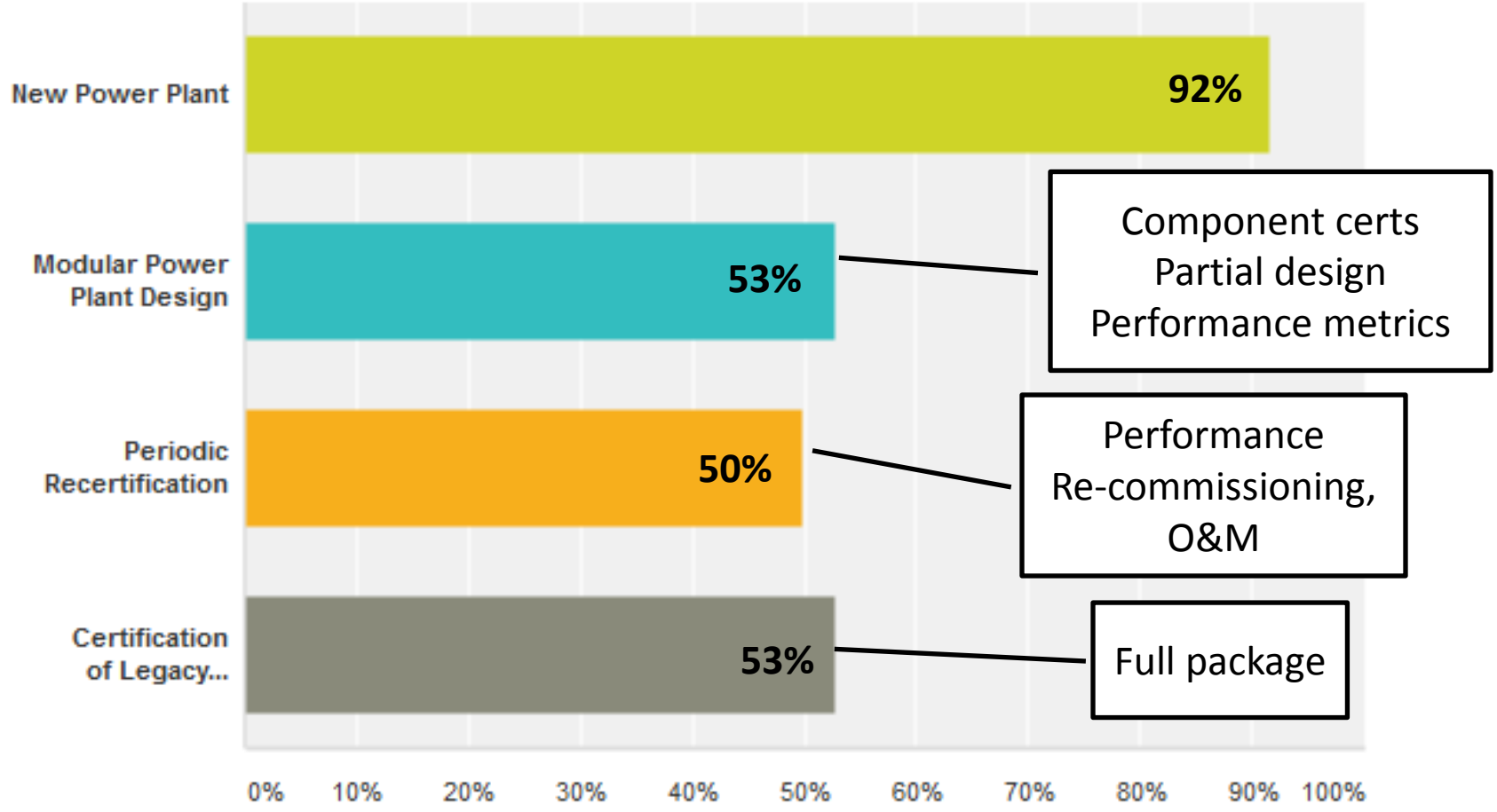
IECRE Systems Certification Workshop – Survey Results

Site Selection (Project Development)	• Site assessment – soils or other structural evaluation • Utility interconnect and access hurdles • Energy prediction – preliminary design
Component Certifications	• Module standards IEC 61730, 61215, etc. • Inverter standards 62109, **62093**.. • **Miscellaneous BOS safety standards**
Project Execution	• Design – IEC 62548, **62738** • Performance and Monitoring - 61724 series • Commissioning and **maintenance** – 62446 series
Additional to include Interconnection	• Basic local code and utility requirements • **MV transformer, MV installation** • **Substation design, installation** • **SC 8A, State or ISO, NESC requirements, for example**

What is the wind energy group in IECRE doing for this?

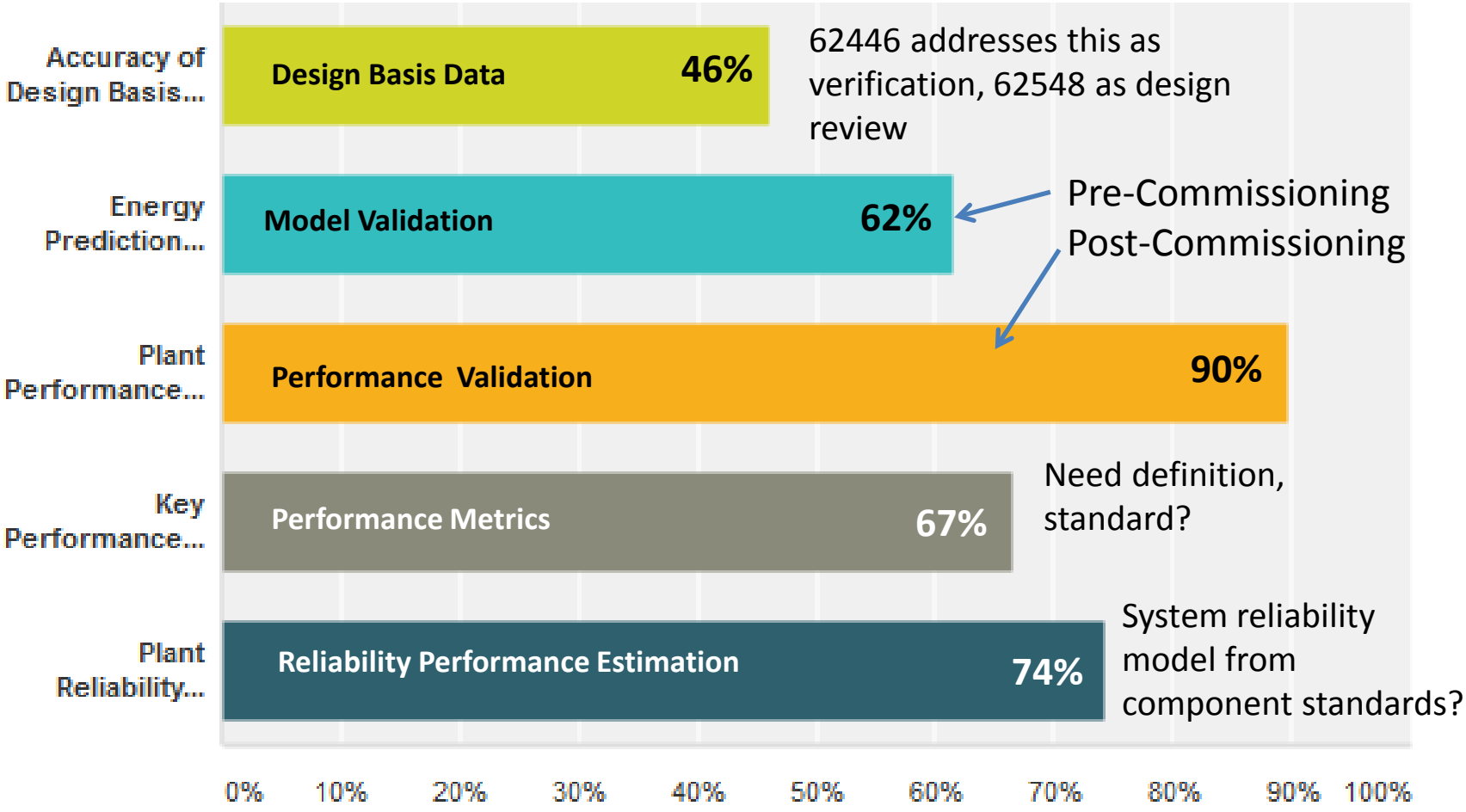
IECRE Systems Certification Workshop – Survey Results

PV Plant Certification - What types of certification should be governed by the IECRE standard?



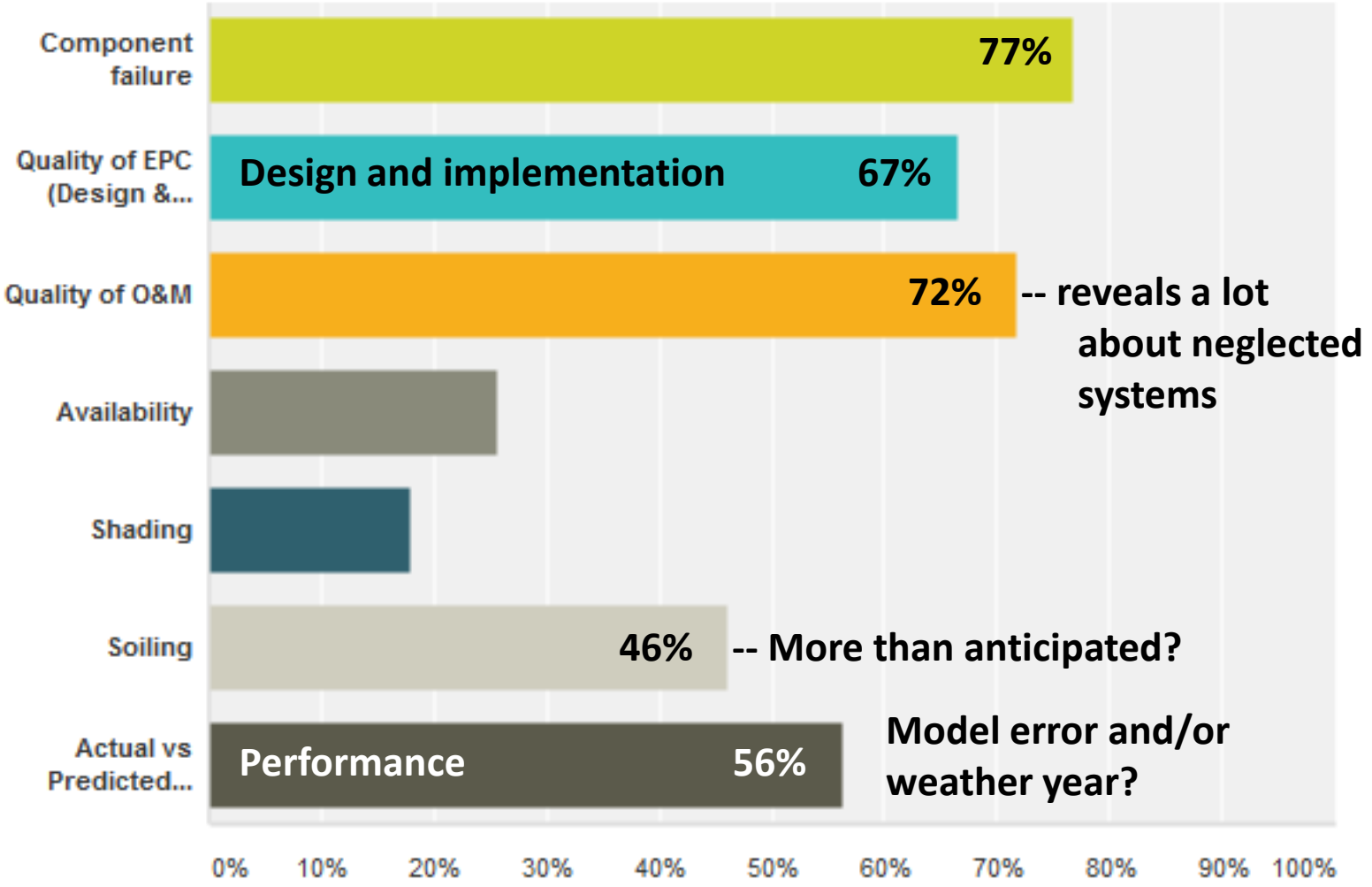
IECRE Systems Certification Workshop – Survey Results

Performance Verification and Validation- What aspects are important to you to assure performance of the power plant?



IECRE Systems Certification Workshop – Survey Results

Based on your experience, which of the following have a large effect on the financial performance of the asset?



IECRE Systems Certification Workshop – Survey Results

What are you most concerned about or what is it that you have the least confidence in?

Module Issues

- Module degradation
- Module design faults not well covered by standards, like cell cracks
- High accuracy models for long-term product durability or accelerated testing methods.
- Direct replacements for older failing modules
- Polymers, reliability due to extreme weather & earthquakes.

BOS Durability and Reliability

- BOS suppliers' quality, reliability and maturity. Lack of standardization, accountability of performance measures across industry.
- High accuracy models for long-term product durability or accelerated testing methods.
- I have the least confidence in the long term reliability of the plant
- Good standard development is hampered by the fact that manufacturers and distributors/dealers would likely prefer to deal with quality and reliability as a proprietary matter rather than helping less-experienced competitors gain more market share.

IECRE Systems Certification Workshop – Survey Results

What are you most concerned about or what is it that you have the least confidence in?

System Level Design and Engineering

- While there are individual standards for each component, the optimal interaction between system components at the prevailing environmental conditions on site is often enough not fully understood by system integrators.

Project Execution and Commissioning

- Much damage can be done during transport and installation that will not show up for years after commissioning. Not therefore caught by "certification."
- Quality of workmanship.
- Skill of field techs
- Current commissioning standards do not go deep enough into the most critical items which affect PV system performance at the time of commissioning and in the future.

IECRE Systems Certification Workshop – Survey Results

What are you most concerned about or what is it that you have the least confidence in?

Performance

- Predictability of yield
- Inaccuracy of the system
- The definition and use of PV performance metrics have not been standardized.
- Grading of installed power plants for state-of-health based on numerically obtained results through field evaluation.

O&M

- Inverter parts availability;
- High quality O&M tech skill;
- Enough money in the O&M and asset management budgets.
- Bankruptcy of solar companies, not supporting warranties - need independent, inexpensive, means to validate

Additional Insights from Survey Taken at IEC Workshop at 2014 IEEE PVSC

- Nearly identical results on:
  - Types of plants included
  - Scope of certification
- Less emphasis on certification of legacy plants
- Less variation on aspects of performance validation
- Quality of EPC ranked 1st in financial impact

NEXT STEPS

- Good responses and direction from survey
- Additional discussions on the priorities and their practical implications
- Draft detailed framework for certification of different kinds of plants:
  - Content and sequence of certification steps
  - Develop thresholds for defining the rigor of assessments
  - Define core assessment with optional add-ins (e.g. project development stage
- Emphasis on core competency aspects of assessment (TC82 specific standards) to get things rolling sooner.

NABCEP™

Raising Standards. Promoting Confidence.

NABCEP PV System Inspector Job Task Analysis

NREL PV Reliability Workshop /
IECRE PV System Certification Workshop
February 26, 2015
Golden, CO

Presented by: Richard Lawrence, NABCEP Executive Director

This presentation contains no confidential information

History

- The North American Board of Certified Energy Practitioners (NABCEP) was founded in 2002 as a non-profit 501 (c)(6) corporation with a mission “to support, and work with, the renewable energy and energy efficiency industries, professionals, and stakeholders to develop and implement quality credentialing and certification programs for practitioners.”
- NABCEP’s voluntary credentials are the most widel recognized and respected in the US solar industry.
- The NABCEP PV Installation Professional ™ and NABCEP Solar Heating Installer ™ certification programs are accredited to ISO/IEC 17024 by ANSI.

NABCEP's Current Schemes

- PV Installation Professional Certification
- PV Technical Sales Professional Certification
- Solar Heating Installer Certification
- PV Entry Level Exam
- Solar Heating Entry Level Exam

- PV Installation Company Accreditation

Job Task Analysis Development Process Overview

Role Delineation Study

Draft Job Task Analysis (JTA) created by Committee of SMEs during 2-day meeting

Industry Validation Study

Broad stakeholder input sought via online survey to refine and validate Draft JTA

Final Job Task Analysis Published

NABCEP Board of Directors approves final version of JTA developed by the Committee

PV System Inspector (PVSI) Target Audience

- Primary Audience
  - Individuals performing inspections of PV systems for an Authority Having Jurisdiction (AHJ), I.E. Town Electrical Inspector, to ensure code compliance
- Secondary Audience
  - Individuals performing inspection services for utilities to ensure compliance with interconnection requirements
  - Individuals performing inspection services for incentive programs, I.E. State or utility rebate programs, to ensure quality workmanship and performance
  - Individuals performing inspections of systems installed through a finance mechanism (loan, lease, PPA, utility program, ..)
  - **Individuals inspecting systems to the IECRE standard?**

PVSI Program Objectives

- Increase the quality of PV System Inspections to improve the reliability of PV Systems, protect the reputation of the PV Industry, and ensure safe operations
- Facilitate training of PV System Inspectors by providing an industry validated Job Task Analysis upon which curriculum can be based
- Provide employers and customers of PV System Inspectors with a tool to evaluate their competence at performing the job

PVSI Timeline

Q3 14	• Technical Committee Formed
Q4 14	• Role Delineation Study Performed • Draft Job Task Analysis Developed
Q1 15	• Industry Validation Study Conducted
Q2 15	• Final JTA Approved and Published • Examination Committee Formed
Q3 15	• Examination Questions Developed • Examination Form(s) Created and Passing Score Study Completed
Q4 15	• Credential Scheme finalized • First Exams Administered

Domain I: Inspecting Electrical Components and Systems

Domain I: Inspecting Electrical Components and Systems	
Task 1: Visually verify system labeling meets applicable codes to ensure safety.	
Subtask 1.1: Confirm AC interconnection point is properly labeled.	**Critical**
Subtask 1.2: Confirm labels are of sufficient durability to withstand the environment involved.	**Critical**
Subtask 1.3: Confirm DC raceways are properly labeled.	**Important**
Subtask 1.4: Confirm DC disconnects are properly labeled.	**Important**
Subtask 1.5: Confirm AC disconnects are properly labeled.	**Important**
Subtask 1.6: Confirm the main service panel is properly labeled.	**Important**
Subtask 1.7: Confirm the inverter or other power conditioning units are properly labeled.	**Important**
Subtask 1.8: Confirm labels pertaining to the ungrounded system are in place (if applicable).	**Important**
Subtask 1.9: Confirm the rapid shutdown system is properly labeled (if applicable).	**Important**
Subtask 1.10: Confirm labels are the proper color and in legible print (not handwritten).	**Useful**

Domain I: Inspecting Electrical Components and Systems Cont.

Domain I: Inspecting Electrical Components and Systems	
Task 2: Visually and physically verify installed components match those on the approved plans and adhere to applicable codes and standards.	
Subtask 2.1 Verify working clearances on components.	**Critical**
Subtask 2.2 Ensure all components are listed, labeled, and identified for use.	**Critical**
Subtask 2.3 Verify model numbers of components.	**Important**
Subtask 2.4 Confirm the number of PV modules.	**Important**
Subtask 2.5 Verify the National Electrical Manufacturer's Association (NEMA) rating (indoor/outdoor/hazardous environment).	**Important**
Subtask 2.6 Confirm the location of components matches the plans.	**Important**
Task 3: Visually and physically inspect conductors and raceways to ensure safety and compliance to applicable codes.	
Subtask 3.1 Verify conductor ampacity is appropriate for circuit current.	**Critical**
Subtask 3.2 Verify the conductor type is suitable for the location and environment.	**Critical**
Subtask 3.3 Verify the conductor voltage rating for the circuit.	**Critical**
Subtask 3.4 Verify installation of conduit expansion joints based on length.	**Critical**
Subtask 3.5 Ensure raceway connections are suitable for the location and environment.	**Critical**
Subtask 3.6 Verify conductor color is correct.	**Important**
Subtask 3.7 Verify conduit size is suitable based on conduit fill.	**Important**
Subtask 3.8 Verify raceway type is suitable for the location and environment.	**Important**
Subtask 3.9 Ensure raceways are secured and supported properly.	**Important**

Domain I: Inspecting Electrical Components and Systems Cont.

Domain I: Inspecting Electrical Components and Systems	
Task 4: Assess conductor terminations for integrity and compatibility of components to ensure safety.	
Subtask 4.1 Verify conductor size and type are appropriate for the terminal.	**Critical**
Subtask 4.2 Verify the conductor and terminal materials are compatible.	**Critical**
Subtask 4.3 Verify the connection is secure.	**Critical**
Subtask 4.4 Verify the termination device is rated for the voltage and current of the circuit.	**Critical**
Task 5: Ensure the integrity of the grounding system by visually and physically verifying continuity to ensure safety and compliance with applicable codes.	
Subtask 5.1 Ensure all non-current carrying metallic components are grounded.	**Critical**
Subtask 5.2 Ensure the grounding electrode is properly installed.	**Critical**
Subtask 5.3 Check the inverter or power conditioning unit for ground fault error when in operation.	**Critical**
Subtask 5.4 Ensure the equipment grounding conductor (EGC) is appropriately sized.	**Important**
Subtask 5.5 Ensure the grounding electrode conductor (GEC) is continuous and appropriately sized.	**Important**

Domain I: Inspecting Electrical Components and Systems Cont.

Domain I: Inspecting Electrical Components and Systems	
Task 6: Visually and physically inspect the point of PV system interconnection with the utility grid for compliance with applicable codes, following standard electrical safety practices.	
Subtask 6.1: Verify the interconnection devices are appropriate for use.	**Critical**
Subtask 6.2: Verify the maximum current fed to the busbar does not exceed code limitations.	**Critical**
Subtask 6.3: Verify the proper installation of the overcurrent protection device for the supply-side interconnection.	**Critical**
Subtask 6.4: Confirm the location of interconnection devices.	**Important**
Task 7: Verify proper sizing and ratings of overcurrent protection devices per applicable codes and standards to ensure safety.	
Subtask 7.1: Confirm voltage limitations of the overcurrent protection devices.	**Critical**
Subtask 7.2: Confirm circuit current calculations.	**Critical**
Subtask 7.3: Confirm characteristics of existing electrical distribution system.	**Critical**
Subtask 7.4: Confirm the allowable interrupting current ratings of overcurrent protection devices.	**Critical**
Subtask 7.5: Confirm the selection of overcurrent protection enclosures.	**Important**
Subtask 7.6: Confirm current limits of overcurrent protection devices.	**Important**

Domain II: Inspecting Energy Storage Components and Systems

Domain II: Inspecting Energy Storage Components and Systems	
Task 1: Verify PV array design and control per applicable codes and standards to ensure safety.	
Subtask 1.1: Verify conductor sizing is appropriate for array and charge controller ampacity.	**Critical**
Subtask 1.2: Verify the size and rating of overcurrent protection devices (OCPD) for array and charge controller conductors.	**Critical**
Subtask 1.3: Confirm the charge controller is suitable for the type of storage used.	**Important**
Task 2: Verify the energy storage system design and installation adheres to applicable codes and standards to ensure safety.	
Subtask 2.1: Verify the mechanical enclosure is sufficient to support the weight of the battery bank.	**Critical**
Subtask 2.2: Verify the grounding of any metal structures.	**Critical**
Subtask 2.3: Verify proper working clearance around batteries.	**Critical**
Subtask 2.4: Verify the battery enclosure has appropriate ventilation when required.	**Critical**
Subtask 2.5: Confirm the battery conductors and terminals are compliant and conductor insulation is appropriate.	**Critical**
Subtask 2.6: Verify seismic structural requirements meet applicable codes and standards.	**Important**
Subtask 2.7: Ensure the provision for the containment of battery acid if appropriate.	**Important**
Subtask 2.8: Verify the battery disconnect location.	**Important**
Subtask 2.9: Verify the battery overcurrent protection device(s) (OCPD) are appropriate for inverter output.	**Important**
Subtask 2.10: Verify code-compliant labeling.	**Important**

Domain II: Inspecting Energy Storage Components and Systems Cont.

Domain II: Inspecting Energy Storage Components and Systems	
Task 3: Verify the operation of the multi-mode inverter complies with applicable codes and standards to ensure safety.	
Subtask 3.1: Verify the proper installation and usage of the multimode inverter.	**Important**
Subtask 3.2: Verify the proper interconnection of system components.	**Important**
Task 4: Verify the inverter AC connections comply with applicable codes and standards to ensure safety.	
Subtask 4.1: Verify the proper AC overcurrent protection devices (OCPD) and conductors.	**Critical**
Subtask 4.2: Verify the overcurrent protection device is sized properly for bidirectional current flow at grid connection.	**Critical**
Subtask 4.3: Verify the installation and rating of the critical load panel.	**Critical**
Subtask 4.4: Verify proper generator sizing and interconnection as required.	**Important**

Domain III Inspecting Mechanical / Structural Components

Domain III: Inspecting Mechanical/Structural Components	
Task 1: Inspect roof-mounted components and systems to verify integrity and compliance with applicable codes to ensure longevity and safety.	
Subtask 1.1: Verify quantity and type of attachment points for racking.	**Critical**
Subtask 1.2: Verify the integrity of structural members.	**Critical**
Subtask 1.3: Verify the proper use of any dissimilar metals to avoid corrosion and deterioration.	**Critical**
Subtask 1.4: Verify ballast weights and placement.	**Critical**
Subtask 1.5: Inspect flashing and weather sealing.	**Critical**
Subtask 1.6: Verify module attachments meet listing requirements.	**Critical**
Subtask 1.7: Verify equipment is installed securely and meets listing requirements.	**Critical**
Subtask 1.8: Verify junction boxes and disconnects are mounted securely and meet listing requirements.	**Critical**
Subtask 1.9: Verify the racking system is properly mounted and meets listing requirements.	**Critical**
Subtask 1.10: Inspect modules for physical damage.	**Critical**
Subtask 1.11: Verify the rooftop array configuration meets setback requirements as defined by applicable codes and standards.	**Critical**
Subtask 1.12: Verify the location of attachment points.	**Important**
Subtask 1.13: Verify the integrity of attachment points into/on the structure.	**Important**
Subtask 1.14: Verify the array structure is level and plumb.	**Useful**

Domain III Inspecting Mechanical / Structural Components Cont.

Domain III: Inspecting Mechanical/Structural Components and Systems	
Task 2: Inspect ground-mounted components and systems to verify integrity and compliance with applicable codes to ensure longevity and safety.	
Subtask 2.1: Verify the proper use of any dissimilar metals to avoid corrosion and deterioration.	**Critical**
Subtask 2.2: Verify module attachments meet listing requirements.	**Critical**
Subtask 2.3: Verify equipment is installed securely and meets listing requirements.	**Critical**
Subtask 2.4: Verify DC conductors are not readily accessible.	**Critical**
Subtask 2.5: Confirm foundation inspection documentation if applicable.	**Important**
Subtask 2.6: Verify the ground-mounted array location meets setback requirements as defined by local jurisdictional requirements.	**Useful**

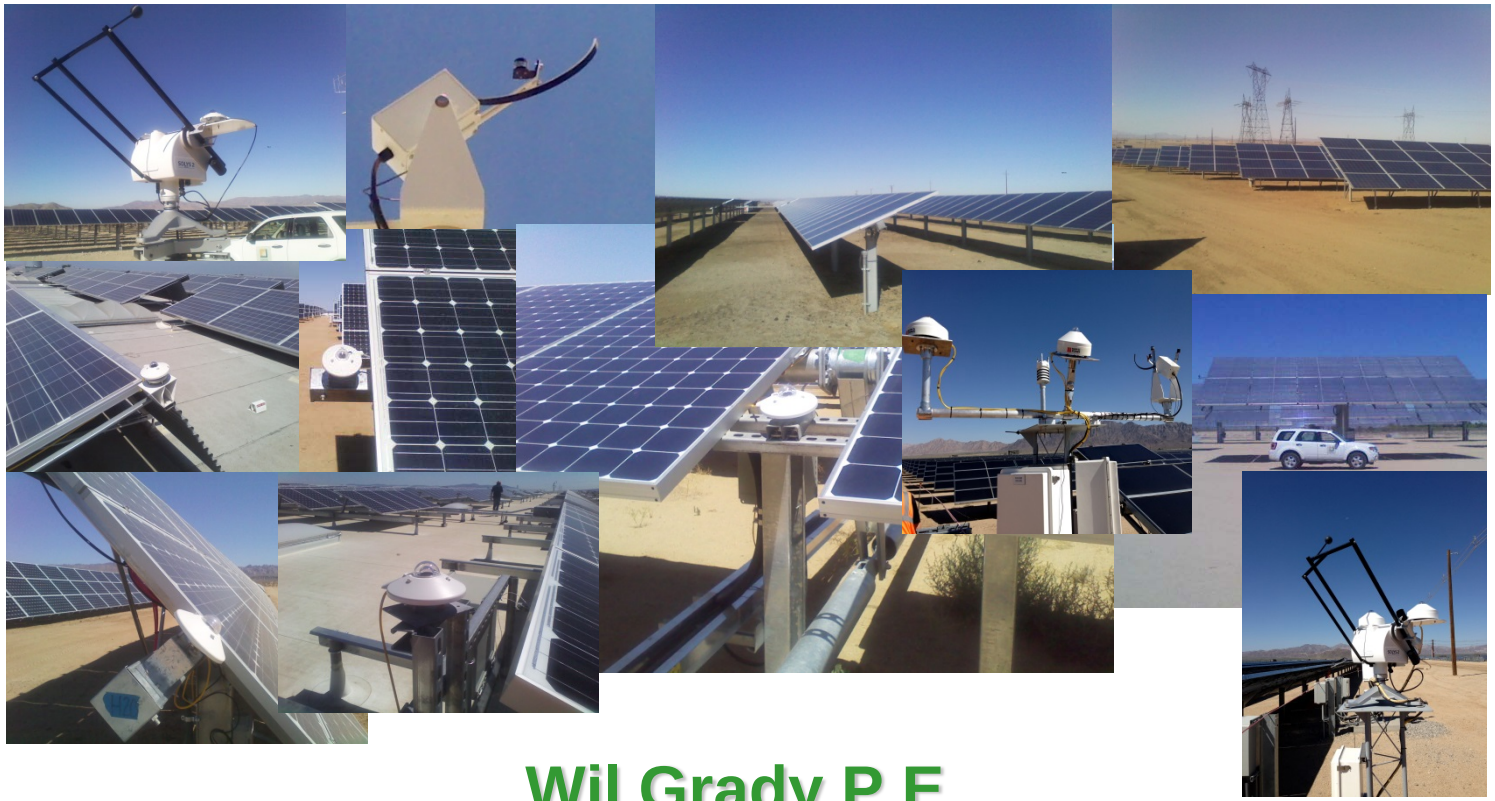
Domain IV: Documentation for the System Inspection

Domain IV: Documentation for the System Inspection	
Task 1: Review permit package for accuracy, completeness, and compliance with applicable codes to ensure a safe and functioning system design.	
Subtask 1.1: Verify a site diagram includes the location of major components.	**Important**
Subtask 1.2: Verify the electrical diagram includes information on electrical components, wiring methods, and electrical connection to the utility service.	**Important**
Subtask 1.3: Verify string sizing for compatibility with the inverter or other power conditioning unit.	**Important**
Subtask 1.4: Ensure the permit package includes the specification sheets for major components.	**Useful**
Subtask 1.5: Verify the permit plans identify an array that is mounted on a code-compliant and permitted structure.	**Useful**
Subtask 1.6: Verify the permit plans identify a mounting system.	**Useful**
Task 2: Quantify and report deviations of the installed system from design documentation and applicable codes and standards for various stakeholders.	
Subtask 2.1: Report any deviation from the manufacturer's specifications.	**Critical**
Subtask 2.2: Report any code violations.	**Critical**
Subtask 2.3: Report any deviation from submitted design documentation.	**Important**
Subtask 2.4: Present supporting documentation (e.g., photographs, measurements, technical documents, code reference).	**Important**

PVSI Validation Study

- NABCEP will be conducting an Industry Validation Study of the Draft PV System Inspector Job Task Analysis in March/April 2015.
- To access the survey during this time and provide feedback on the DRAFT PV System Inspector JTA please visit www.nabcep.org or e-mail info@nabcep.org to request an invitation.

Solar Resource Measurement Importance



Wil Grady P.E.
Southern California Edison
Power Supply

NREL PV Solar Resource Workshop Denver 2015

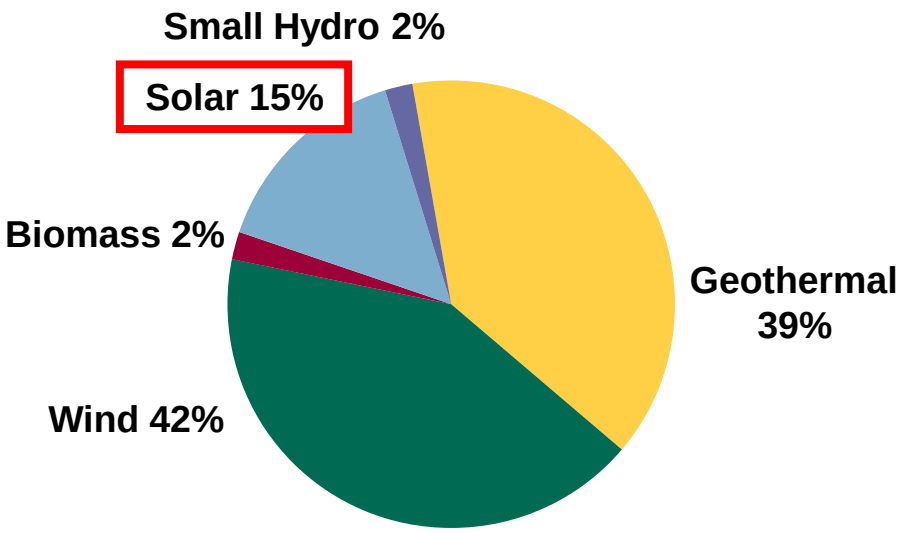
Overview of SCE

- Large service territory
  - 14 million residents
  - 4.9 million customer accounts
  - 50,000-square-mile service area
- National leader in environmental solutions
  - Energy efficiency
  - Renewable energy procurement
  - Electric transportation
  - Advanced meters
  - Smart grid

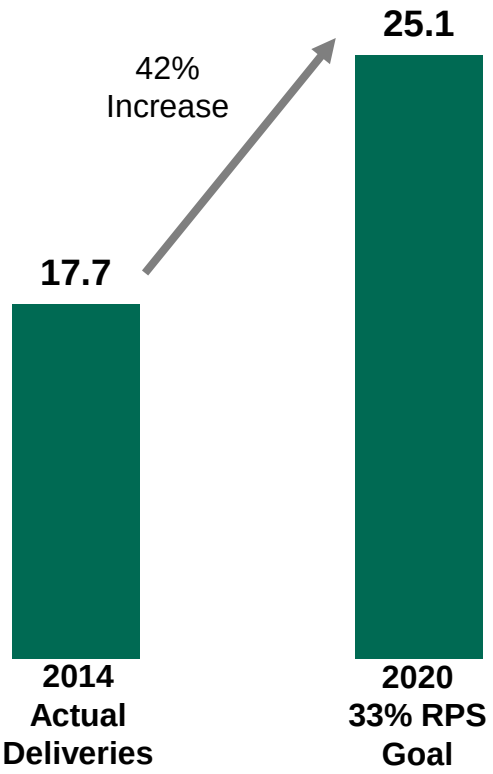
SCE's Solar Programs

SCE's Renewable Portfolio

Actual 2014 Renewable Resources:
23.4% of SCE's portfolio



Renewable Resources
(billion kWh)



In order to meet the 33% RPS requirement,
SCE will need to increase its renewable purchases by about 42%.
A large amount of this increase will be with solar resources.

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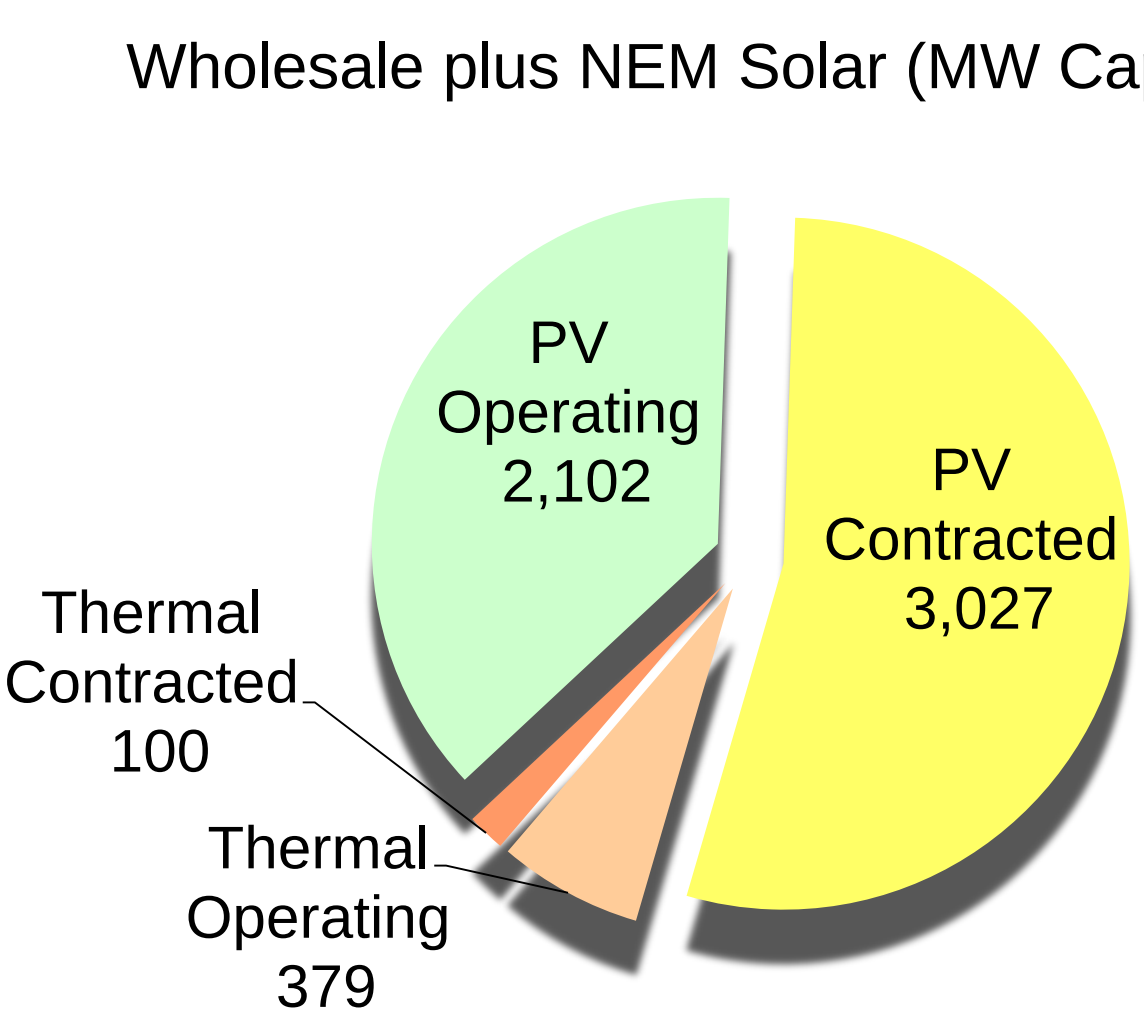
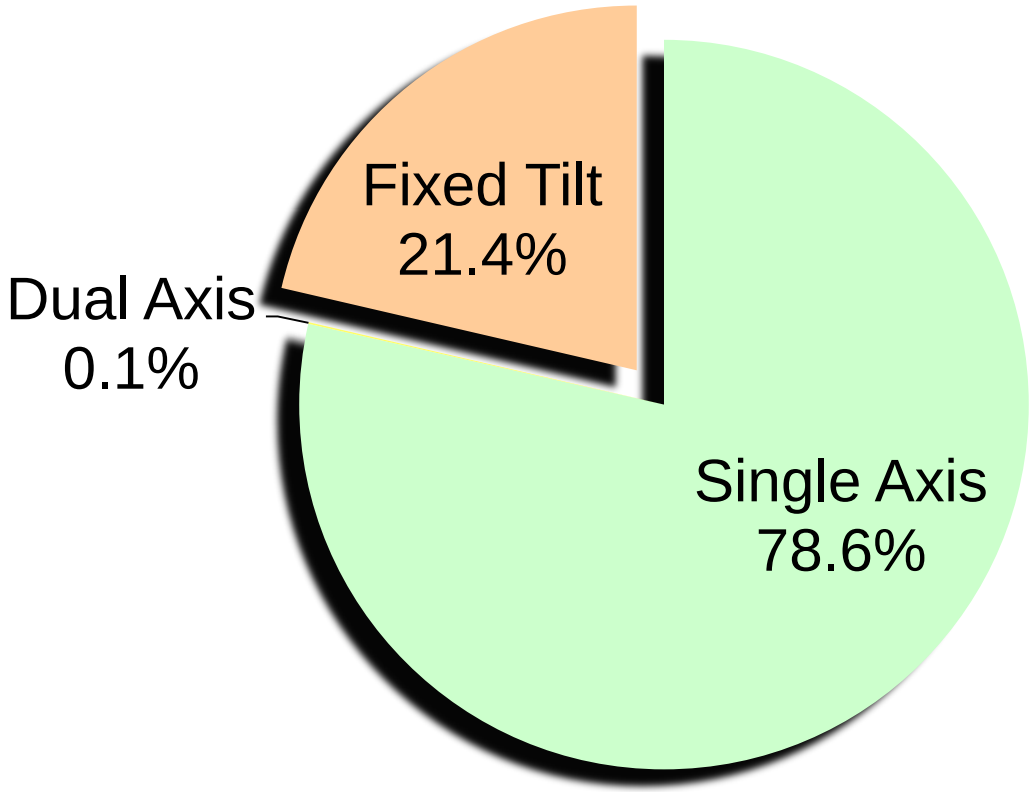
SCE Solar Portfolio as of December 2014



Solar PV Mounting Arrangements, SCE Portfolio

SCE's Solar PV portfolio is increasingly made up of single-axis tracking projects.



Observations

- SCE has been conducting renewables solicitations since 2002, and received its current competitive RPS proposals on February 2, 2015.
  - The majority of contracts recently executed by SCE have been Solar PV.
  - The domination of tracking solar arrays requires increased attention to the plane of array measurement.

- Solar Resource measurements are vital to solar project development and performance monitoring.
  - Poor measurements can directly impact a project's economics.
  - Consideration of the needs for true plane of array irradiance measurements must acknowledge model results can never replace direct measurements.

The Importance of Solar Resource Measurements

Solar resource measurements feed directly into the development, design and operational phases of a project's life-cycle:

Development & Design

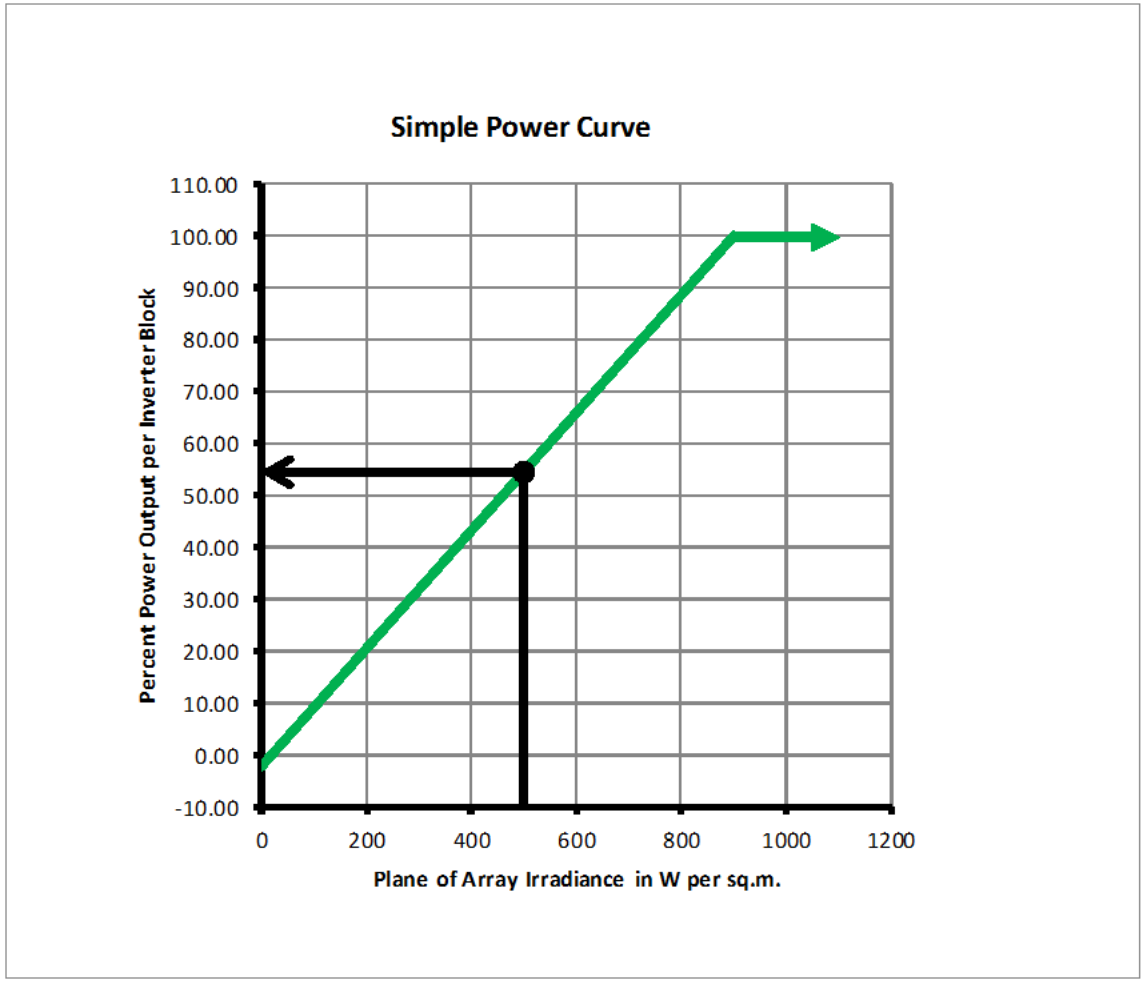
- ❑ Solar Resource Report
- ❑ Site Selection
- ❑ Equipment Selection
- ❑ Performance Models
- ❑ Performance Obligations
- ❑ Forecasted Revenues

Operation

- ❑ Energy Forecasts
- ❑ Performance Monitoring
- ❑ Cost Responsibility for Energy Deviations
- ❑ After the Fact Analysis of Delivery Obligations

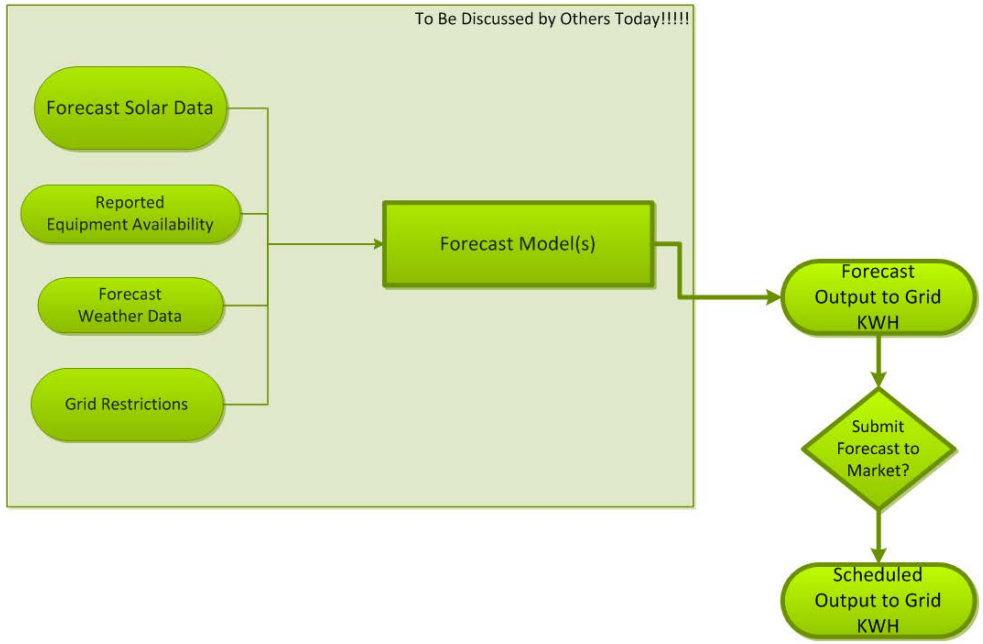
The Simple Power Curve

Input: Plane of Array Irradiance > Output: Electricity



Energy Forecasts in Organized Markets

Organized markets require accurate energy forecasts in order to optimize supply and cost-effectively meet demand.



Many Power Purchase Agreements (“PPAs”) include provisions requiring a minimum level of forecasting accuracy, and may penalize projects for over- or under-producing.

After the Fact Analysis ("AFA") of Plant Performance

Many PPAs include provisions guaranteeing a minimum level of energy production each year, and may include shortfall penalties.

- Production guarantees are generally a function of (i) energy yield factors (in kWh AC per kWp DC per year), and (ii) installed DC ratings, and may be adjusted for equipment degradation.
- Guarantees may be compared to actual recorded production, as adjusted for certain "lost output" events as defined in the PPA. Such events may include:
  - Grid outages
  - Curtailment orders
  - Uncontrollable forces (volcanic eruptions, wildfire, tornados, etc.)
- Measured solar irradiance and production model(s) are used to help make these adjustments, by determining what would have been produced but for the lost output event.

Accurate solar measurements are critical to accurate AFA, and could be the difference between meeting performance or incurring a penalty.

Summary

- Solar Resource measurements are vital to solar projects!
  - Measurements used for the development cycle impact site selection and project equipment design.
  - Production models need accurate solar and weather data.
  - Performance monitoring of projects demands accurate and reliable data to inform Operating and Maintenance decisions.
  - Power Purchase Agreements have performance obligations tied directly to the Solar Resource measurements.
  - Poor measurements can directly impact a project's economics, both hour to hour and at year-end.

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Questions?

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Southern California Edison
Contract Compliance and Technical Services
Power Supply
wil.grady@sce.com

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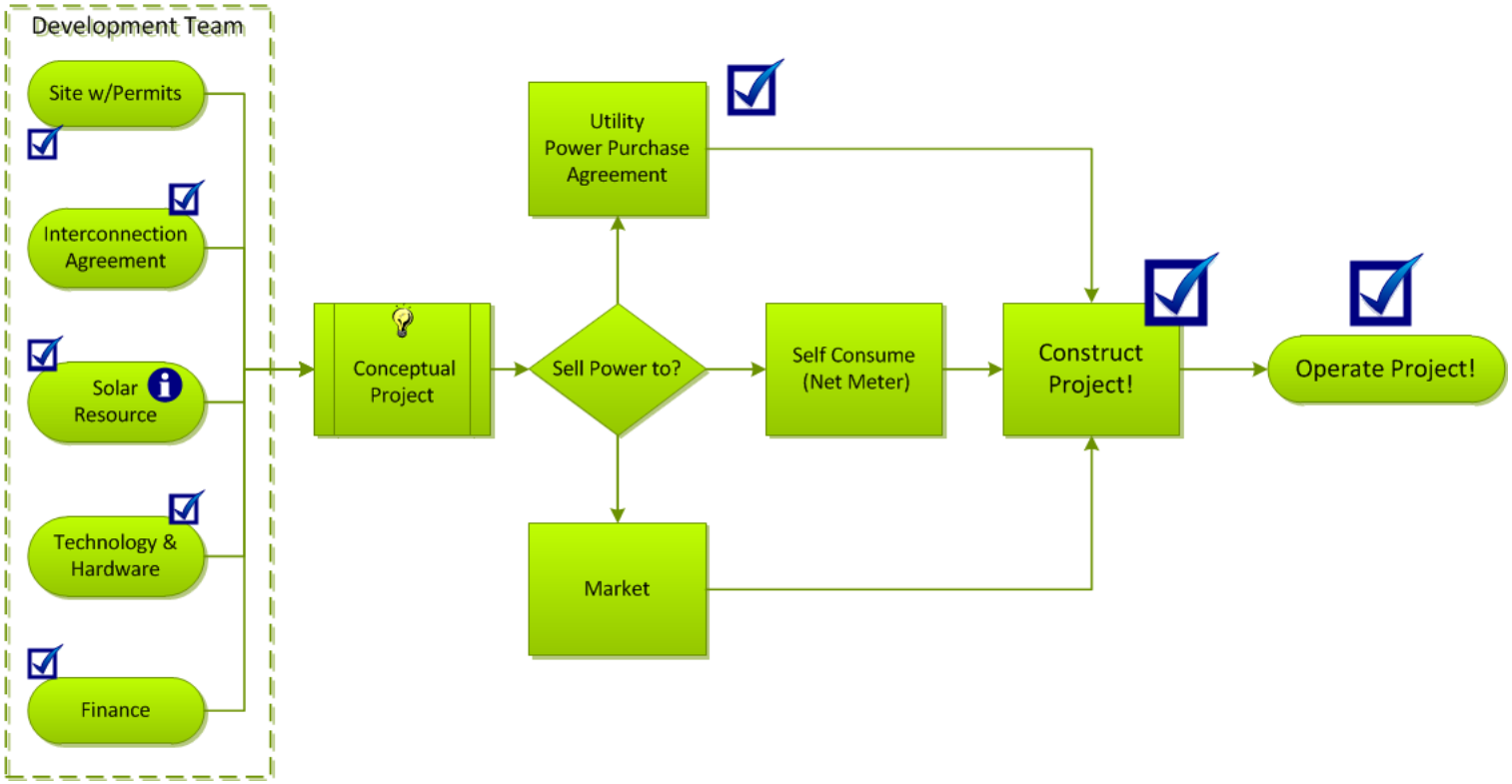
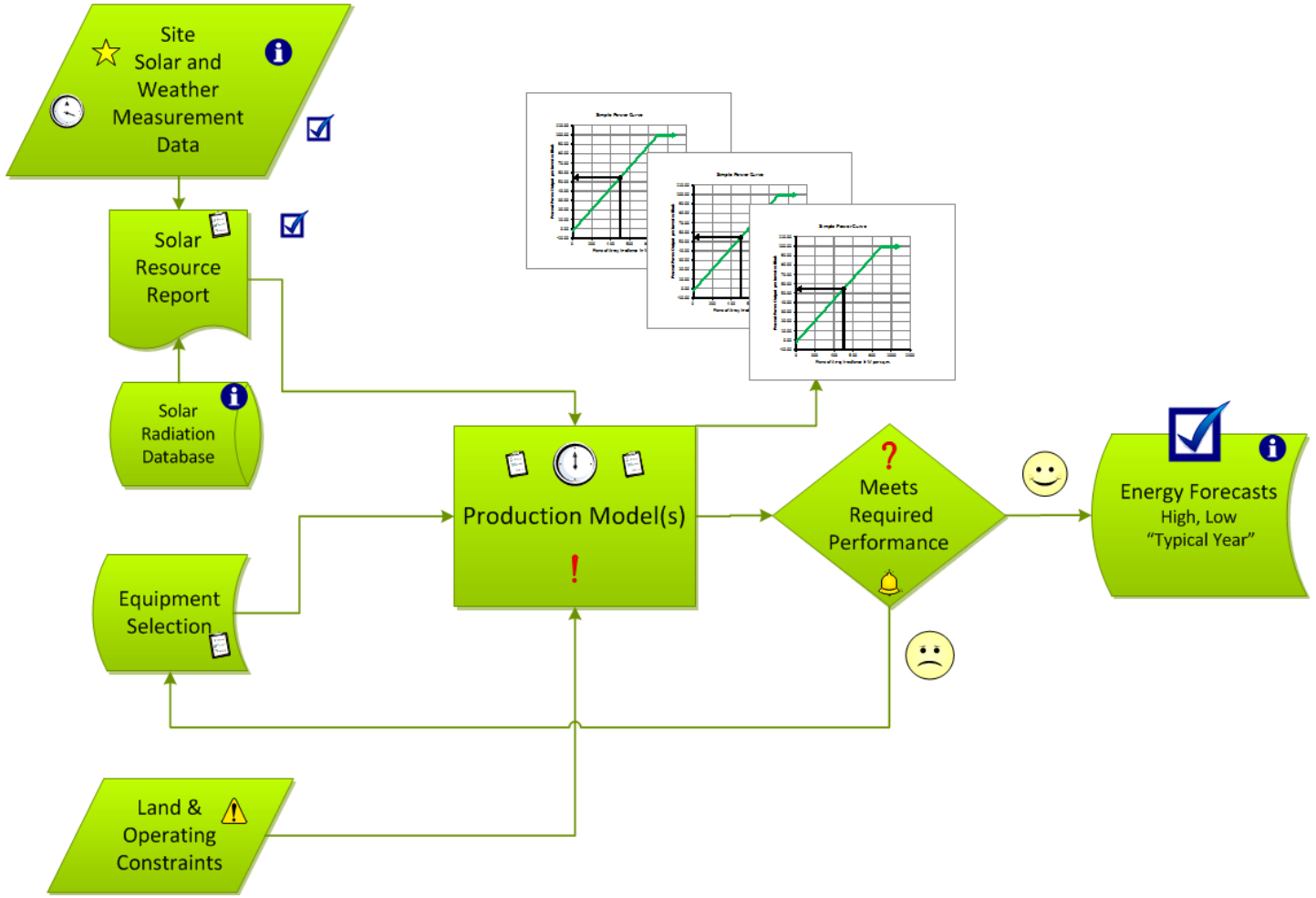
Back-up Slides

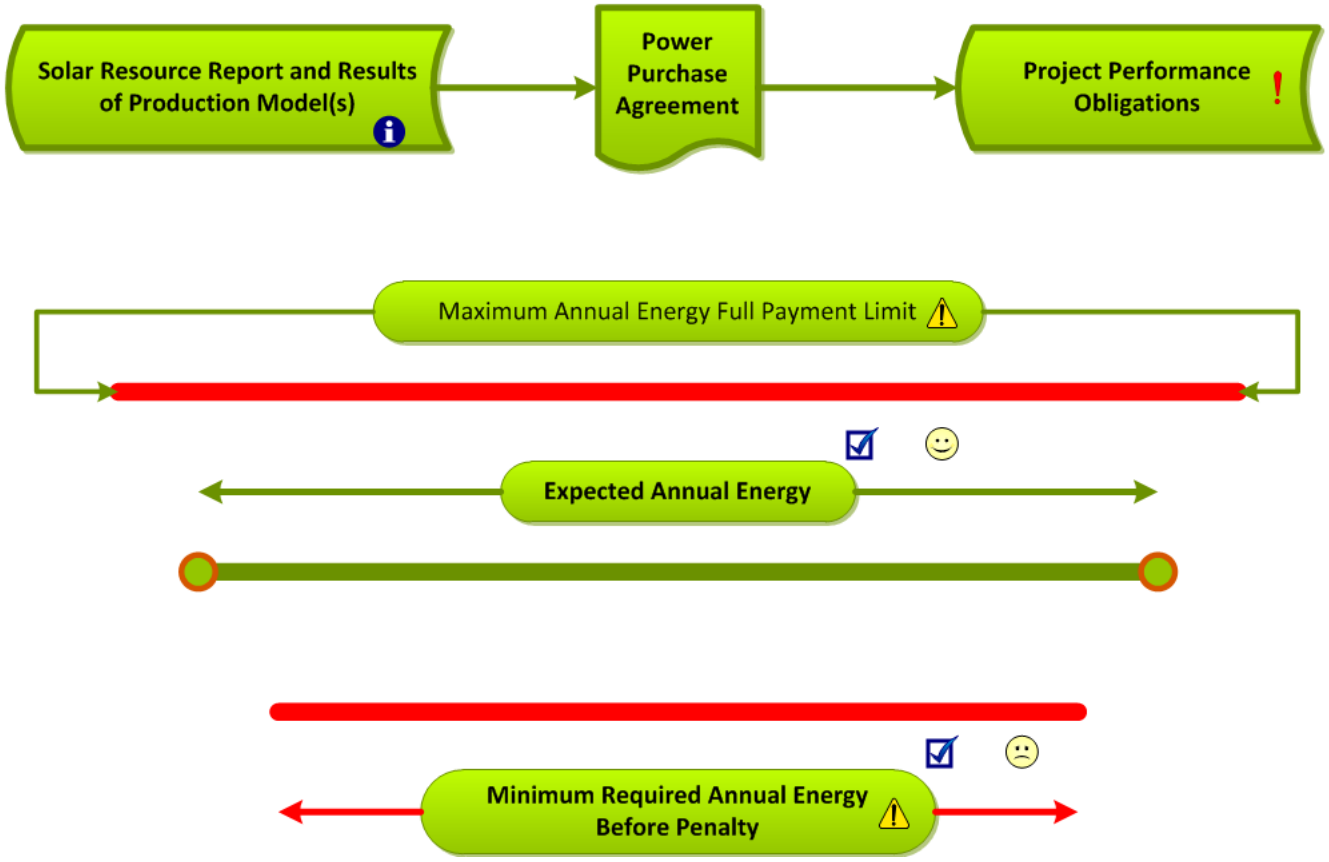
Project Development Process



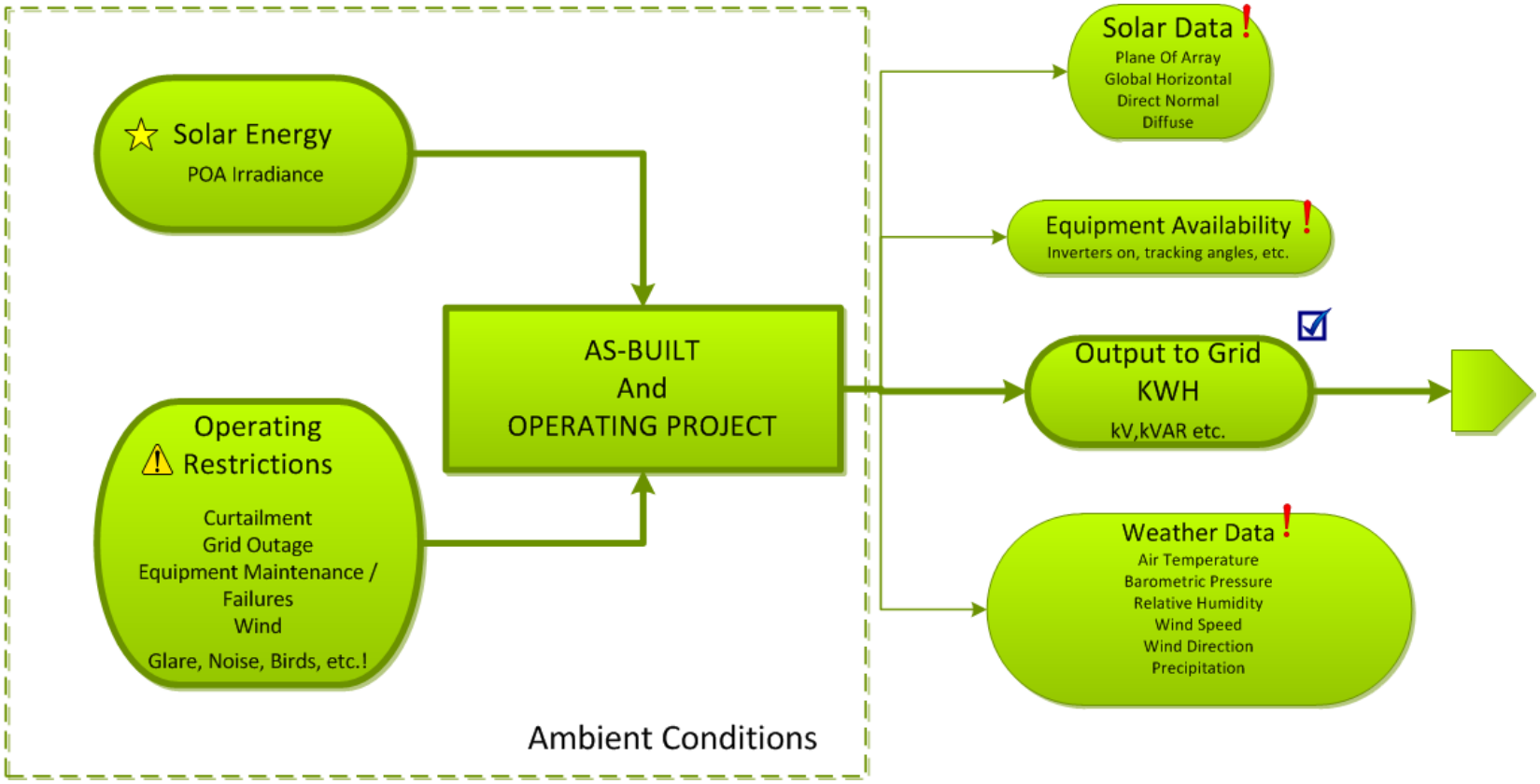
Energy Forecasts and Design Must Have Solar Resource Measurements



Power Purchase Agreements have Performance Obligations Tied Directly to the Solar Resource Report and Modeling Energy Predictions



Solar Energy + Equipment = Electricity



CYPRESS CREEK

RENEWABLES

Next Steps to Reduce Resource Uncertainty– Evan Riley

About Cypress Creek Renewables

- Cypress Creek is a developer and long-term owner of solar power plants with development assets in markets across the United States.
- Our business focus is on 2-20 MW ground mount utility scale solar projects
- Cypress Creek completed 46 MW in 2014 with another 300 MW slated for completion in 2015.
- Cypress Creek has a pipe line of over 1 GW to be deployed in the next 24-36 months.

First bond issuance back by revenue from a solar farm MEHC's 550 MW Plant: A Black & Veatch IE engagement

BLACK & VEATCH

- **10,000 person international engineering firm based in Overland Park, KS, founded in 1915.**
- **Majority of work in energy sector.**
- **Ranked *Number One in Power* by Engineering News-Record for last two years.**
- **Significant expertise in solar power:**
  - Performance testing, technical due diligence, contract review, construction monitoring, detailed design, policy, integrated resource planning.
  - Independent Engineer for investors financing over 4000 MW of utility scale PV projects.
  - Independent Engineer for investors financing several giant distributed rooftop portfolios, 1000+ MW -- 170,000+ systems!
  - Technical adviser to multiple utilities purchasing utility scale PV plants and energy from PV plants

Outline

Solar Resource 101

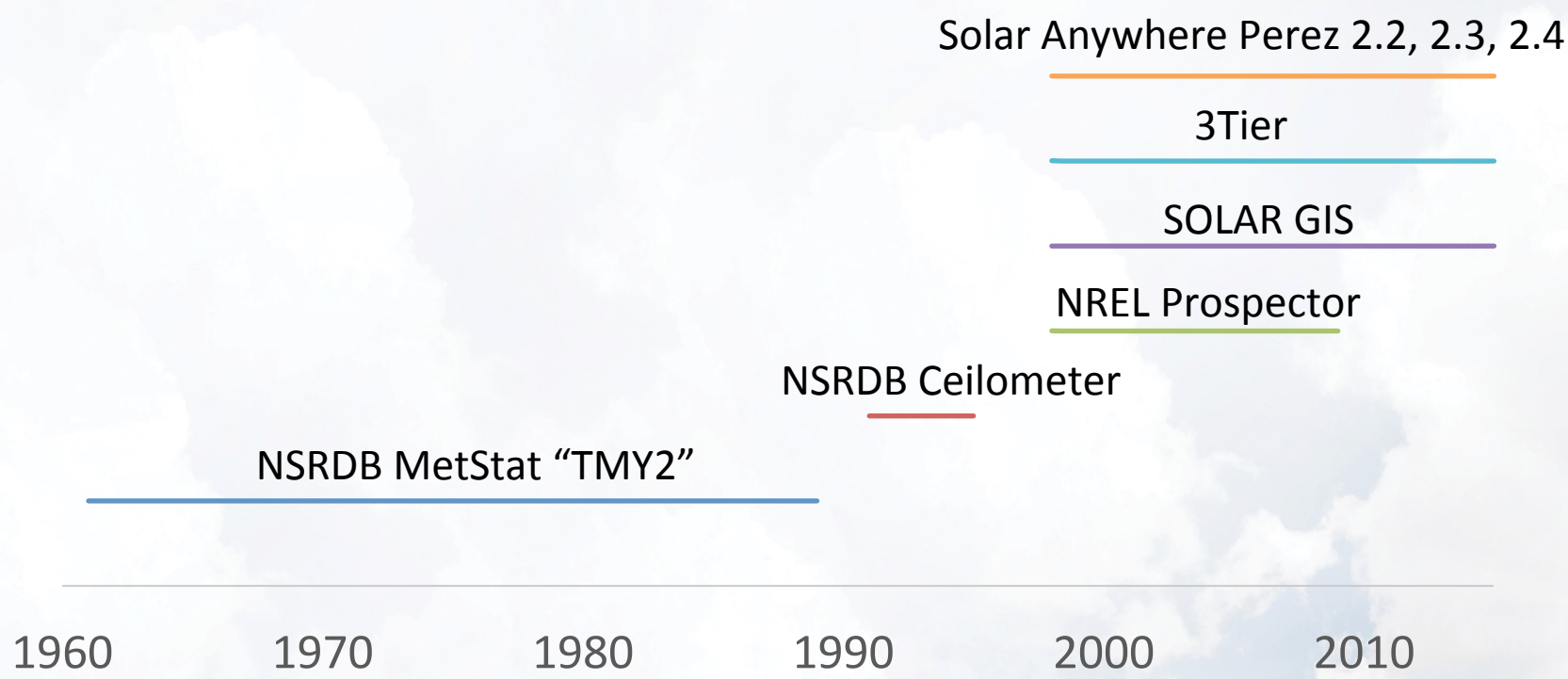
Reducing Uncertainty during Prospecting

Reducing Uncertainty during Operations

The Lowest Fruit - Transposition Uncertainty

Resource Uncertainty when Performance Testing

A History of Solar Resource in the US



- “Measured” long term GHI models include diffuse, method to derive diffuse is often not transparent
-The trade off of long term record vs. more accurate data is not clear anymore
-Most important measure of uncertainty is annual residual of plane of array, which is rarely reported.

A History of Solar Resource in the US

Typical Years:

- Typical Meteorological Year 2 (TMY2)
- Typical Meteorological Year 3 (TMY3)
- Typical Direct Normal Incident Year (TDY)
- Typical Global Horizontal Year (TGY)
- Wait……. why are we using typical years?

A History of Solar Resource in the US

Summary

1. There is no consistent method by which historic resource has been measured
2. Few datasets clearly communicate annual residuals of GHI or POA
3. All predominant datasets include global horizontal incident
4. All predominant datasets include diffuse
5. Few datasets explain how diffuse was derived
6. Most often only typical years are utilized – time of delivery!

Outline

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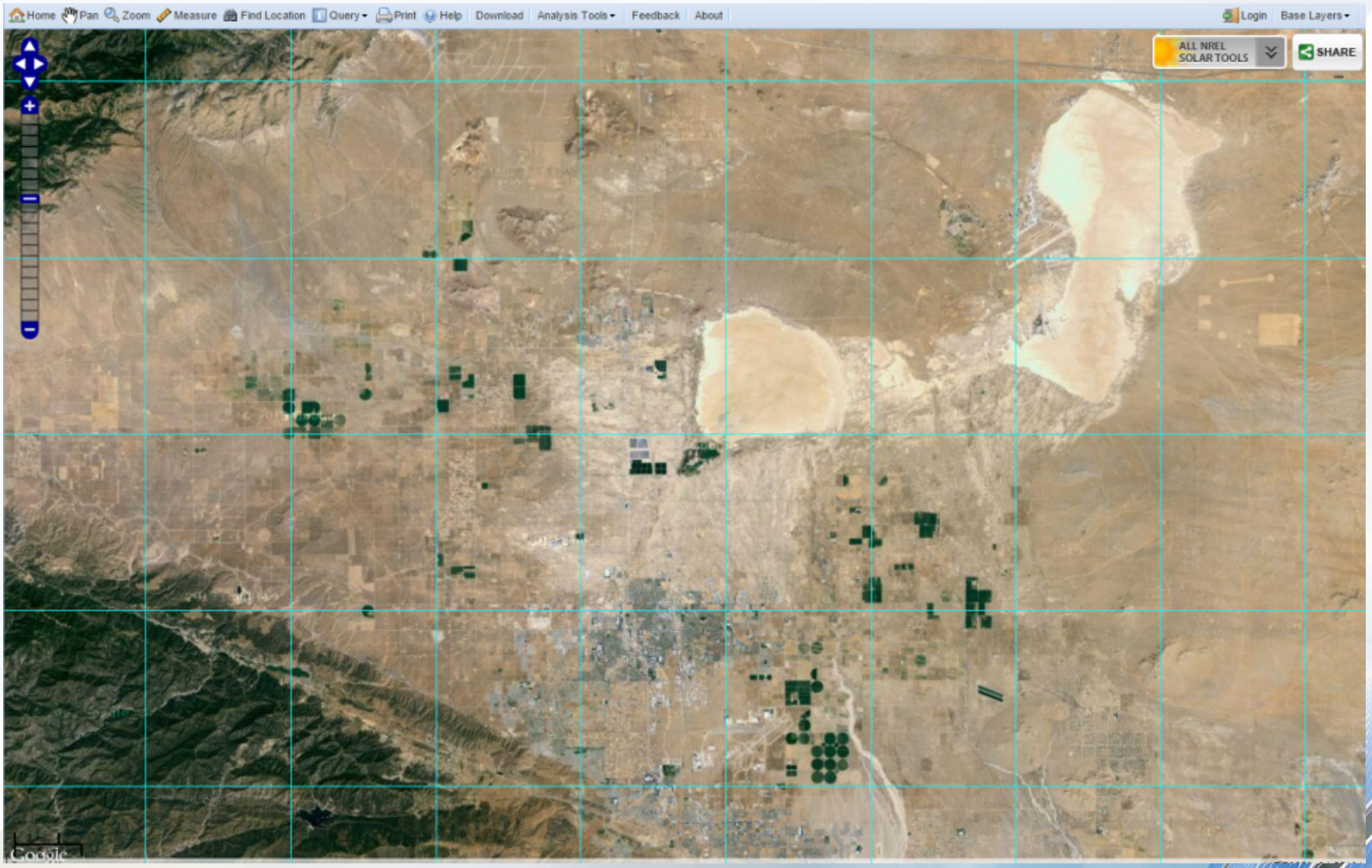
Reducing Uncertainty During Prospecting



Outline

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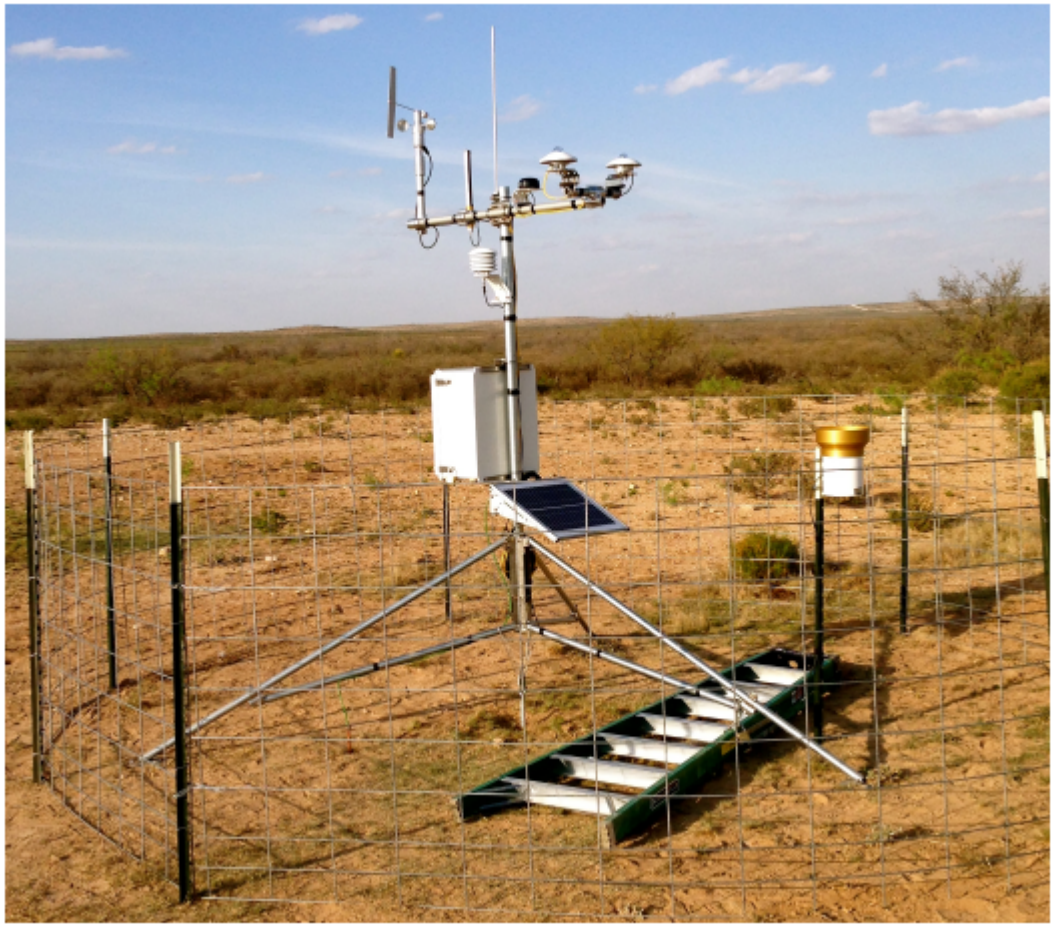
Reducing Uncertainty during Operations



Outline

Solar Resource 101

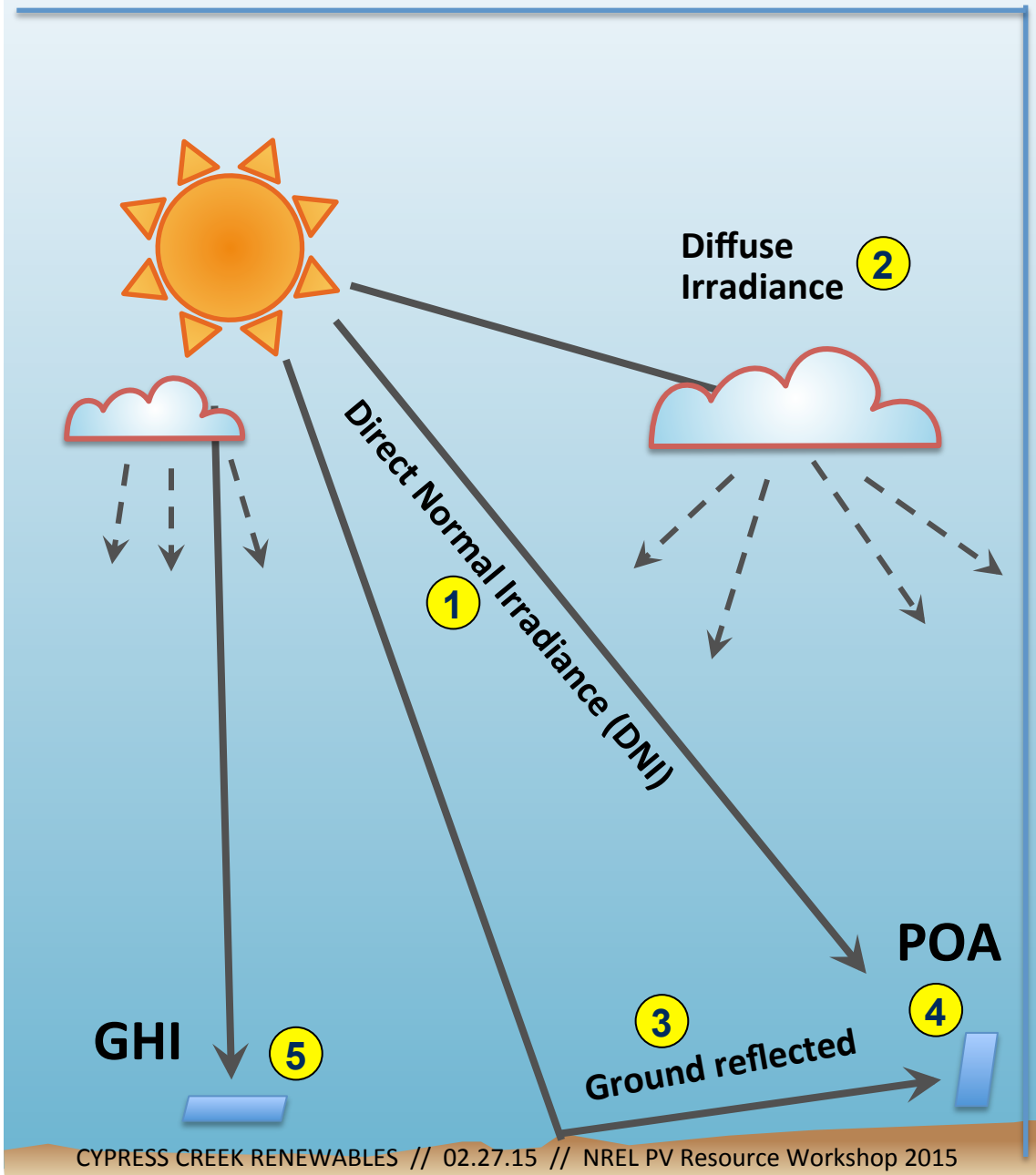
Reducing Uncertainty During Prospecting

Reducing Uncertainty by using Ground Measurements

The Lowest Fruit - Transposition Uncertainty

Resource Uncertainty when Performance Testing

Transposition – A Review



1. Direct radiation: incident solar radiation direct from the sun, without having been reflected or scattered, measured in the normal plane, (no cosine losses)

2. Diffuse irradiance: isotropic and forward scattered: incident solar radiation that has been scattered by aerosols such as water droplets or dust

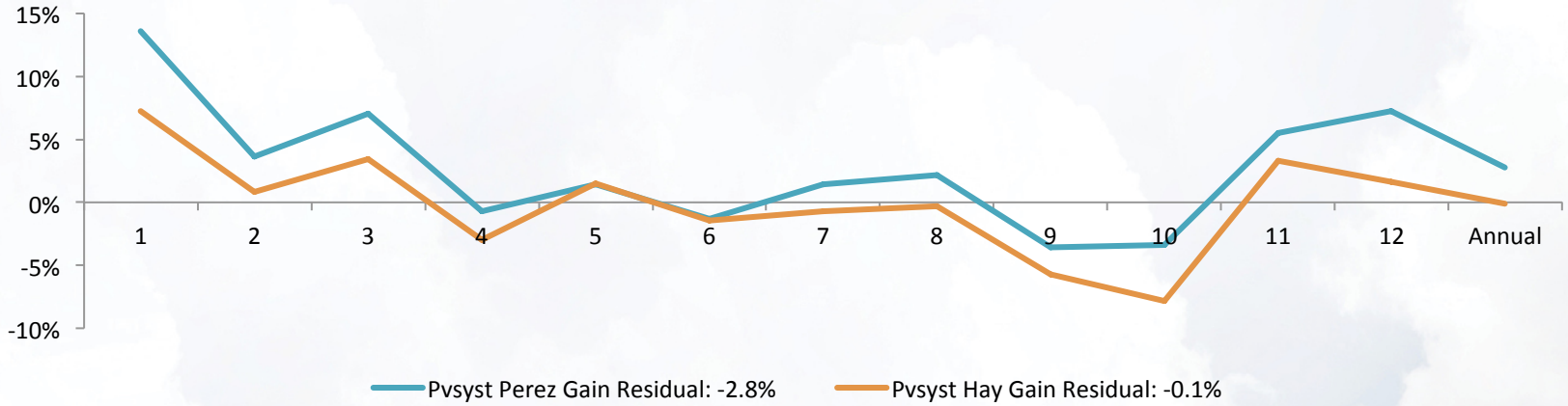
3. Ground Reflected: incident solar reflected from the ground

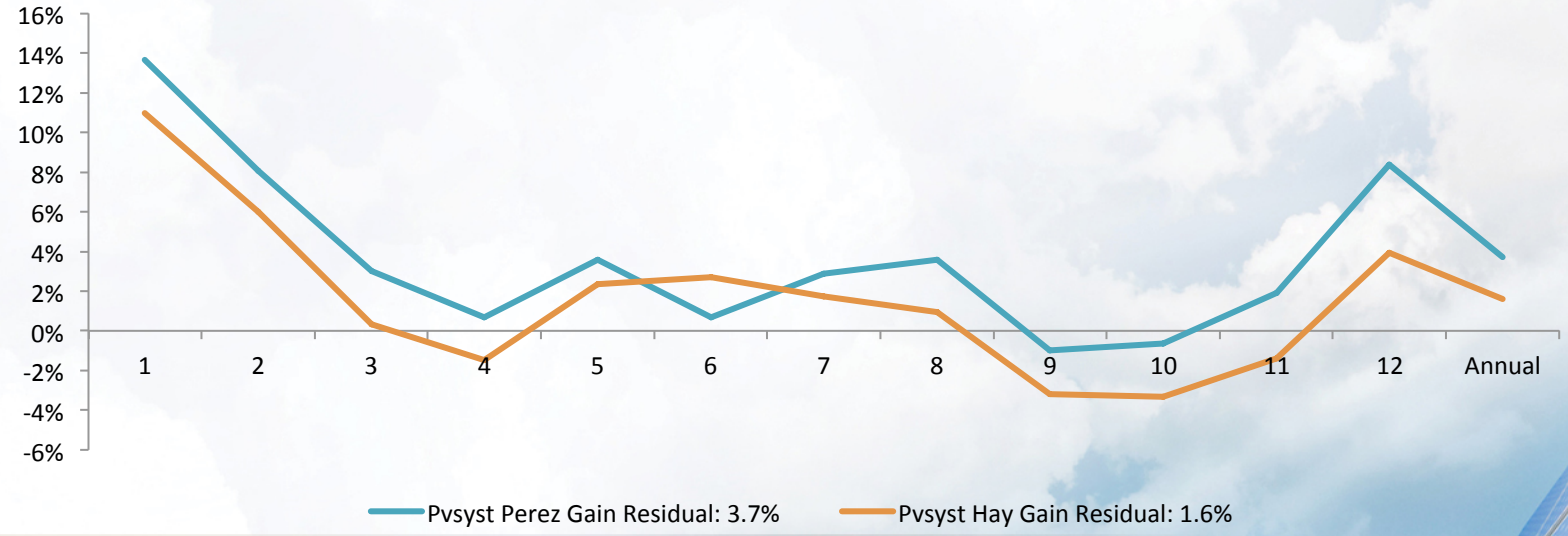
4. Plane of Array: The sum of all incident resource. What is available for conversion.

5. Global Horizontal Incident: This is the measurement orientation of most historic long term datasets.

Transposition Uncertainty

Courtesy of Tejas Tirumalai and Charith Tammineedi of Black & Veatch





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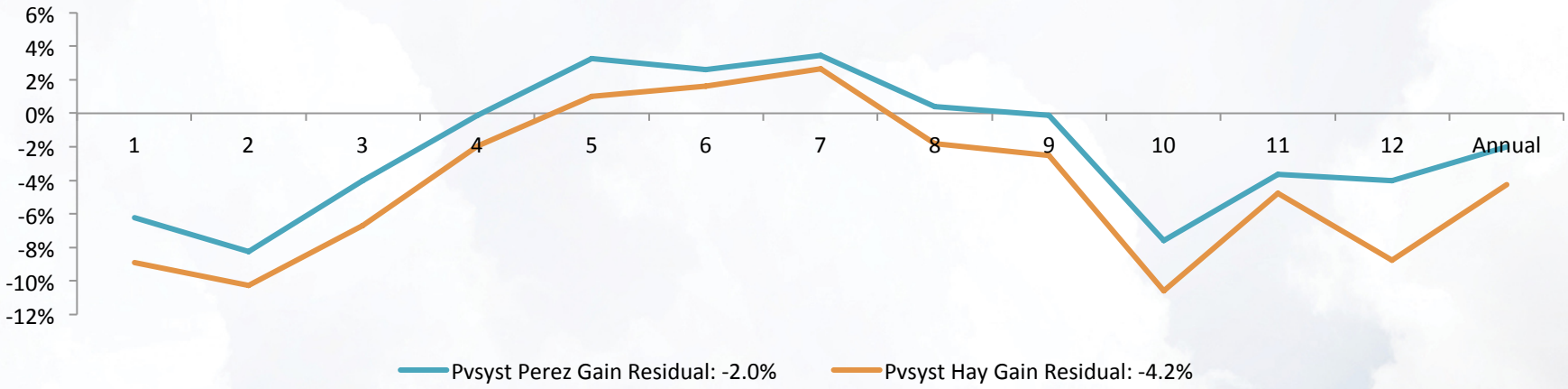
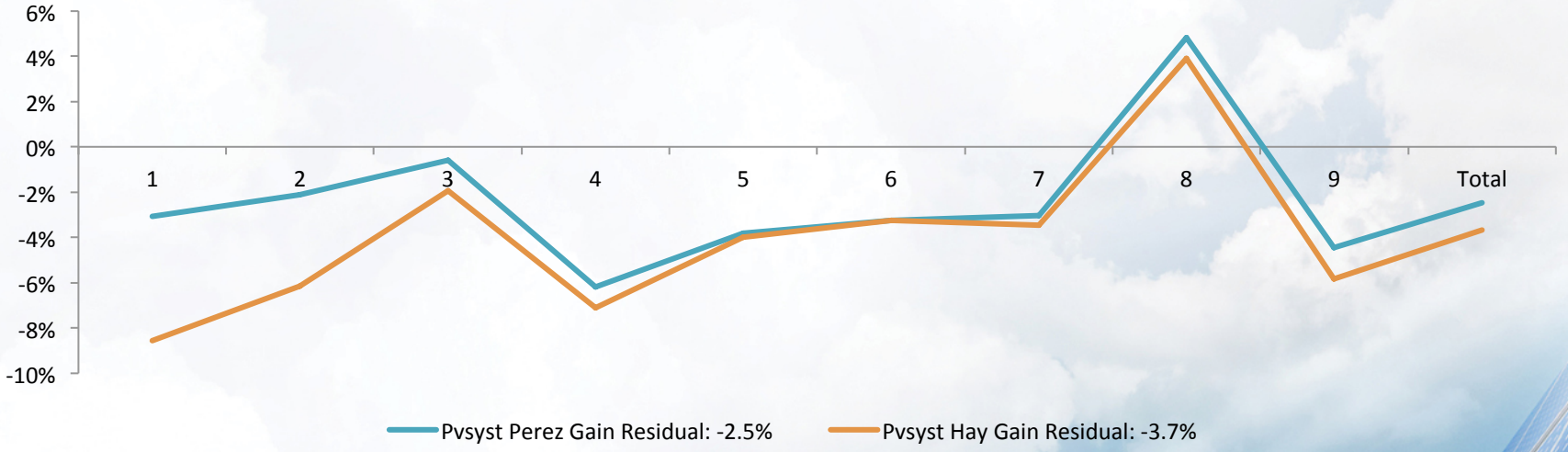




Outline

Solar Resource 101

Reducing Uncertainty During Prospecting

Reducing Uncertainty by using Ground Measurements

The Lowest Fruit - Transposition Uncertainty

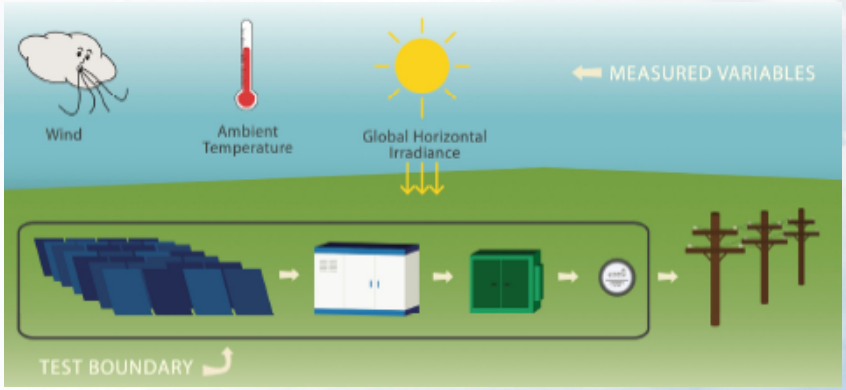
Resource Uncertainty when Performance Testing

Resource Uncertainty when Performance Testing

1. Nobody wants it
2. Everybody ends up taking it when it is not well understood, measured and parsed

Goal: Consistency with forward looking energy forecast using historic data

Challenges: Want most accurate measurement that is consistent with historic measurement methodology



Thank you!

NV·GL

ENERGY

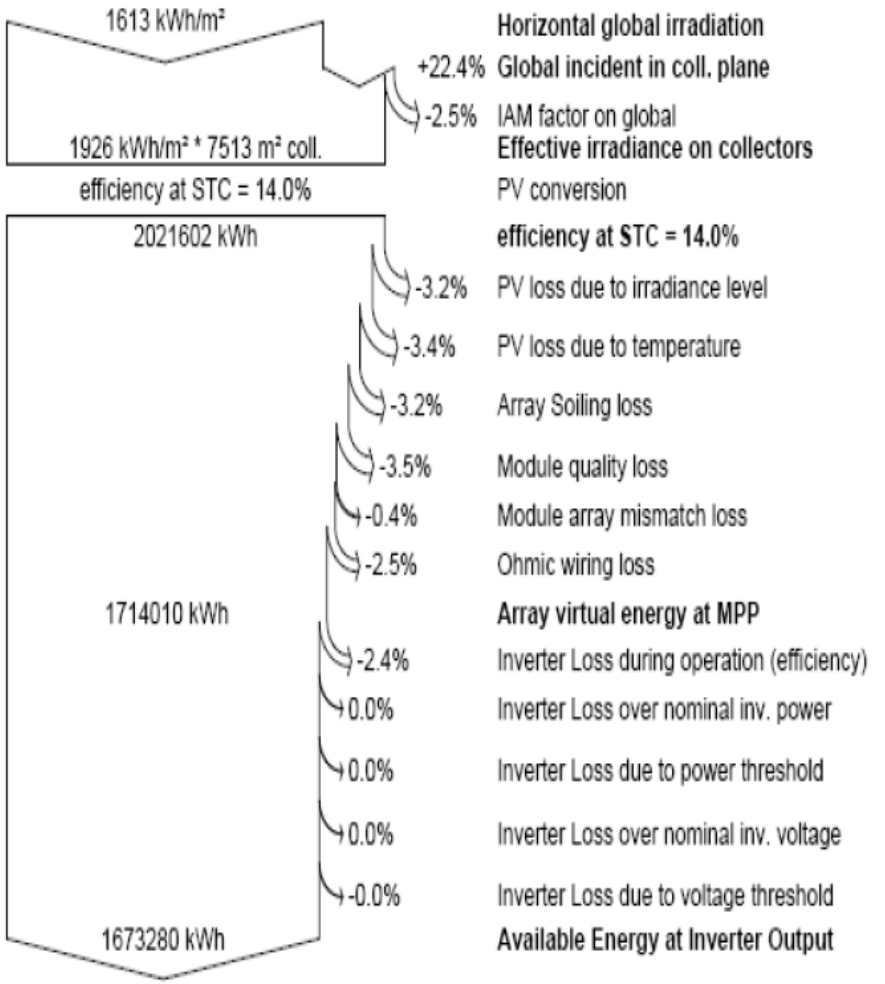
The Challenges of Selecting Solar Resource Data for a New Site

Jeff Newmiller

27 FEBRUARY 2015

Purpose

- Photovoltaic Power projects are financed based on
  - Expected value of energy production over the project life
  - Downside estimates of generation (e.g. P90)
- What goes into estimates of generation?
  - Global Horizontal Irradiance (GHI)
  - Diffuse Horizontal Irradiance (DHI) is measured (rarely) or modelled (in the database or within the PV performance modelling software)
  - DHI is combined with GHI and a transposition model to obtain Plane-of-Array (POA) irradiance
  - POA Irradiance is the dominant input
  - Ambient temperature is important as well

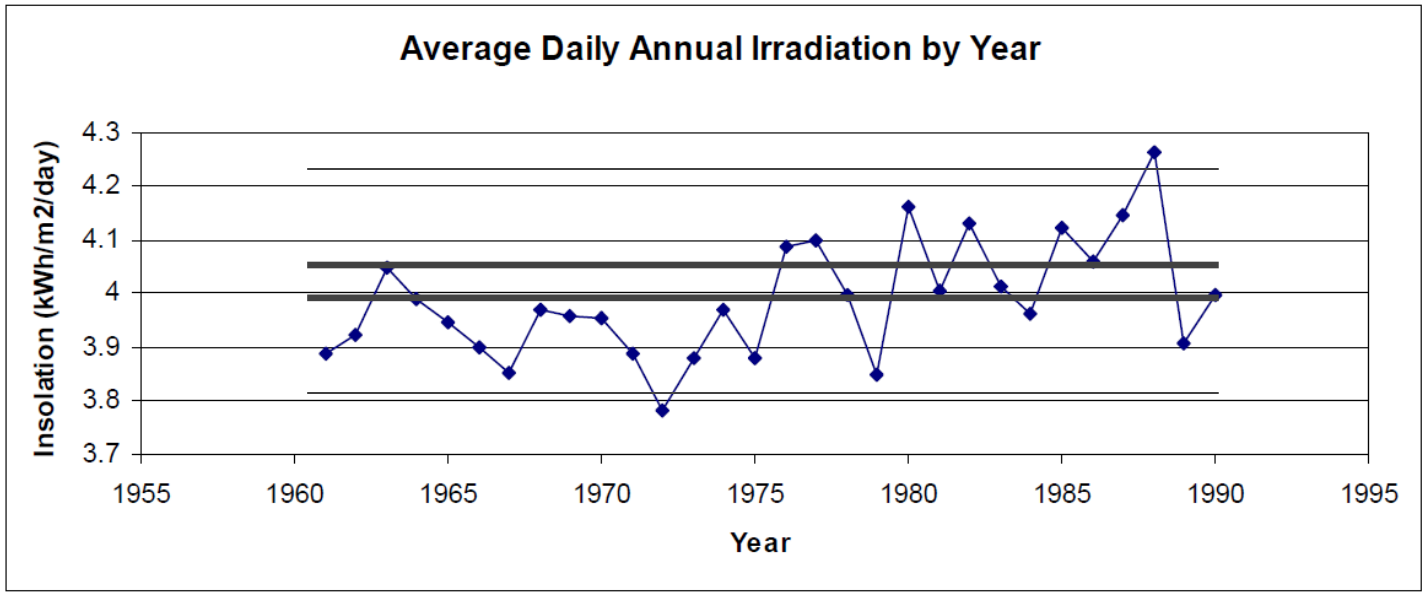


Sample Solar Resource Databases

- **NREL National Solar Radiation Database – NSRDB**
  - 30 years (1961-1990) hourly data, 239 sites, 56 primary Sites (have some ground measurements)
  - Secondary sites only have modelled data from reported cloud cover, humidity, etc.
- **NSRDB Update**
  - 15 years (1991-2005) hourly data, ~2000 sites, satellite images used to estimate cloud cover
  - Poor reliability 1991-1997
- **CIMIS**
  - 3-25 years (1985+) hourly data, California-only agricultural network with 200 stations
- **3-TIER**
  - 18 years (1997-current) daily data, 20km grid, ±66° latitude worldwide,
- **SolarAnywhere (NREL Solar Prospector contains a subset)**
  - 15 years (1997 to present), 10km or 1km grids, 1hr or 1min values
- **NASA-SSE**
  - 22 years (1983-2005) monthly data, 1degree grid
- **SolarGIS**
  - 29 years (1985-present) 15min samples, 0.09km at equator

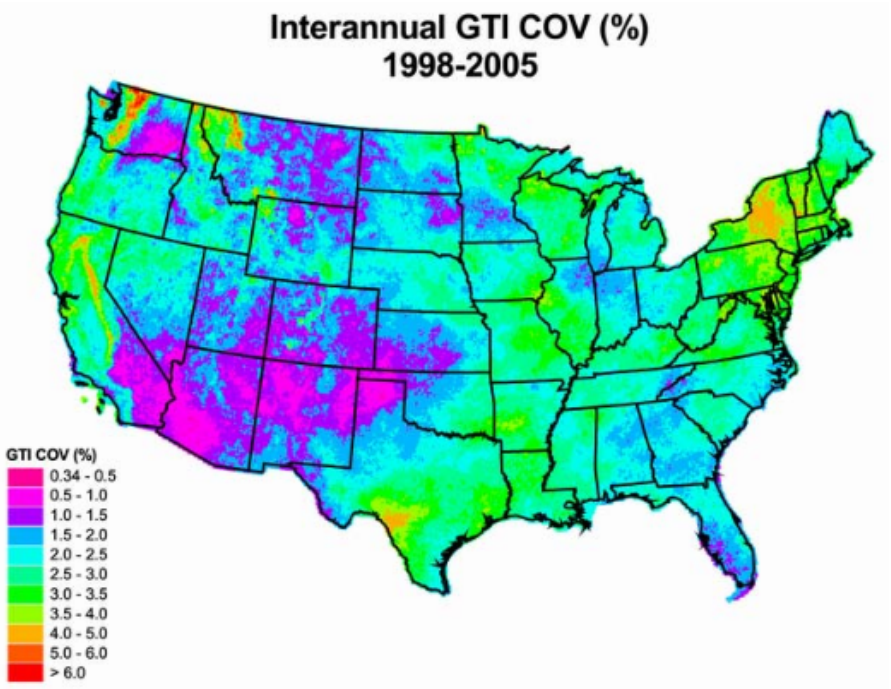
Variability

- Annual irradiation varies stochastically from year to year
- Even if you had a perfect instrument to measure the true value, you would still have to wait indefinitely to learn the true long-term average behaviour
- Instead, we use what data we have and bracket the long-term average with confidence intervals
- More years means smaller confidence intervals



Site-Specific Temporal Variability

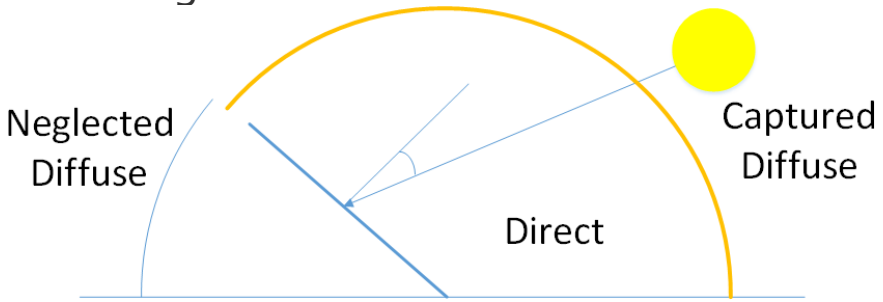
- Some areas have more variability than others.
  - Texas has surprisingly high variability over time
- Coincidentally (not), some locations in solar resource databases are more accurate than other locations
  - No one data source is likely to work in every location



(Gueymard and Wilcox 2009)

Orientation Affects Variability

- Keep in mind that tilted or tracking orientations:
  - Intercept more irradiation when the sun is out
  - Intercept LESS irradiation when the sky is cloudy
  - Bigger upside comes with a bigger (relative) downside!
- Site-specific, orientation-specific measurements need more years of data to get similar relative range of confidence as GHI
  - POA is valuable for monitoring installed PV equipment
  - For prospecting, there is a high risk that implemented orientation will change
  - GHI can be correlated with more alternate sources without introducing transposition modelling error

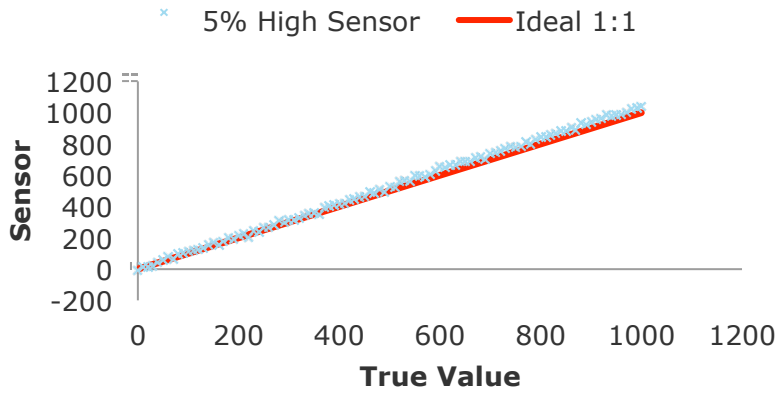


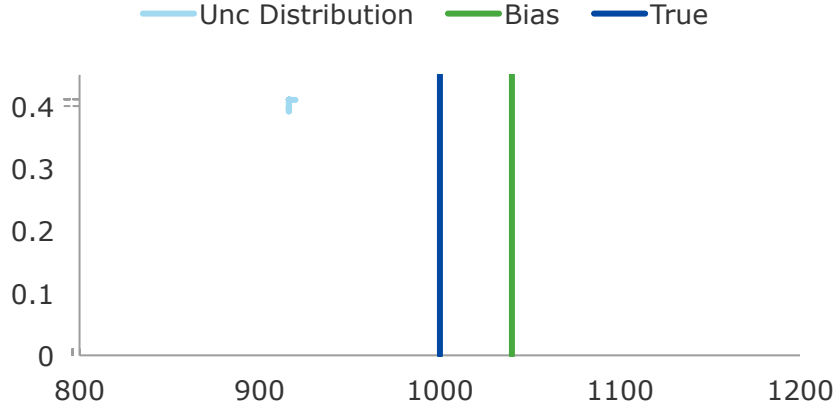
Onsite Measurements… Rarely Long Enough

- Sometimes a developer will start measuring irradiation before the project begins
  - Is one year enough? (perhaps)
  - How about 2 months? (unlikely)
- Alone, the usefulness of this data is constrained by the variability problem
- If low-accuracy equipment is deployed, or the instrument is not cleaned then it may also yield uncertain data
  - Maintenance is as important as equipment class

Uncertainty

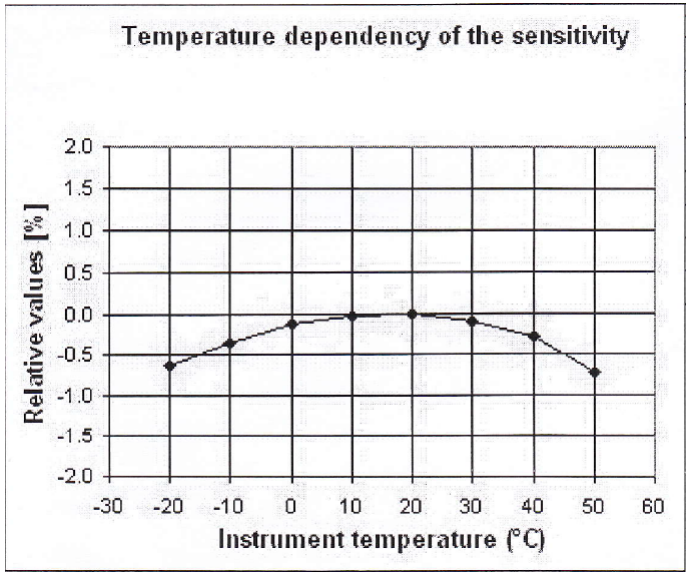
- How far is this measure likely to be from the right answer?
  - Typically expressed as a range which is expected to contain the right answer
  - Range should include an expression of confidence, because there is always some chance that the right answer is outside the specified range
  - Uncertainty should be provided by the source, but is not always
  - "Truth" is hard to compare with... normal practice is to calibrate an instrument against a more accurate instrument and estimate the uncertainty of the more accurate instrument

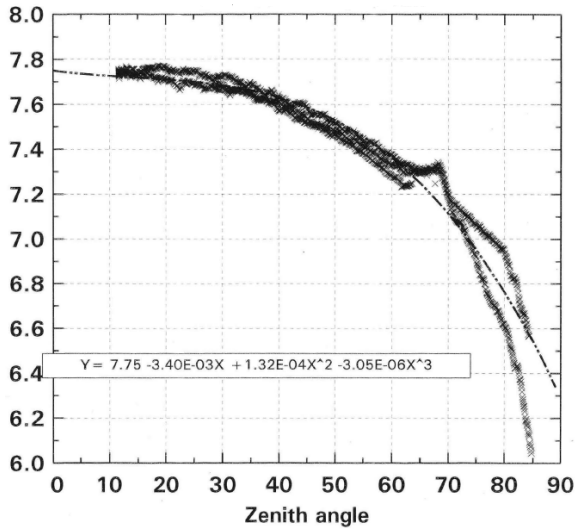




Uncertainty Is Not Necessarily the Same at all Times

- NSRDB quotes Hourly uncertainty values 6-25%
  - Includes incidence angle calibration sensitivity, which has been known to vary by 5% but the actual impact depends on time, latitude and diffuse fraction
  - Modern secondary standard instruments are not that sensitive to incidence angle (<2%), but First or Second Class instruments may be



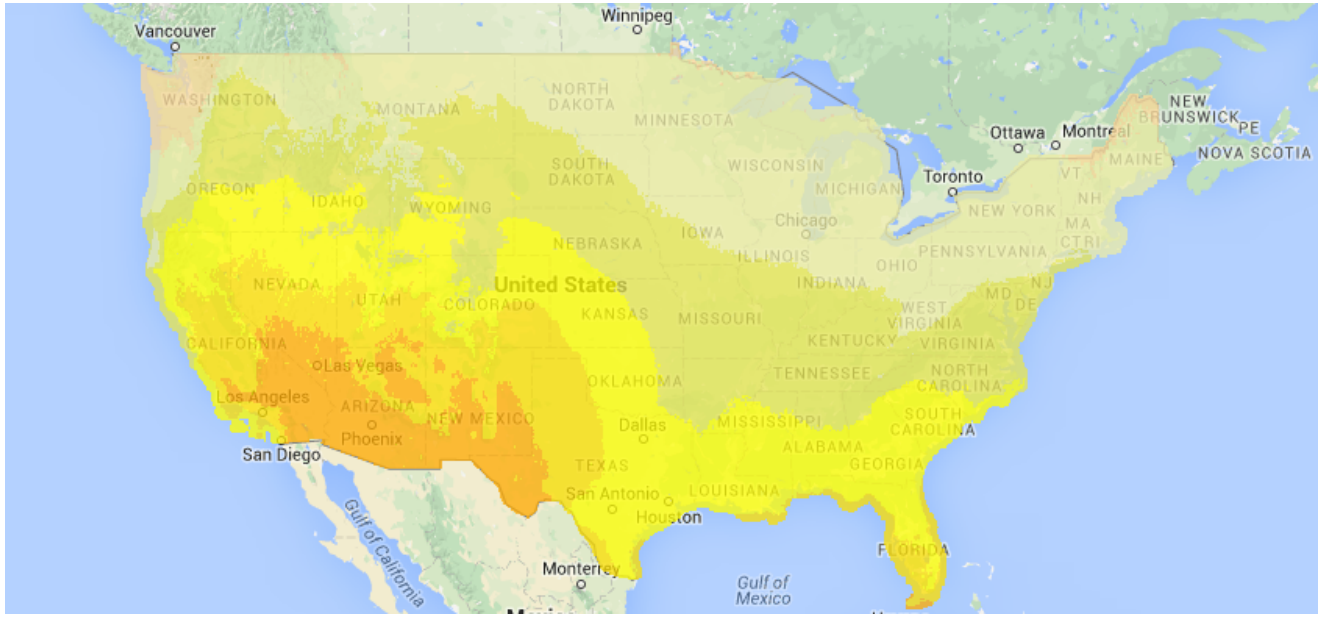


Uncertainty Over Time

- A short-term bias error can become a long-term variation that partly cancels out plus a bias that does not cancel out
- Estimates made over short intervals are likely to have higher uncertainty (10%) than estimates made over long intervals (6%?)
- How much of the hourly uncertainty is bias?
  - If bias error is small, then averaging helps (10% hourly → 3% annual)
  - If bias error is large, averaging is less helpful (10% hourly → 8% annual)
- Myers et. al. suggest bias can be small in some cases
  - Myers 1989 estimated 4% for laboratory grade outdoor measurements
  - Myers 2009 showed most instruments delivering bias less than 4% annually (at a manned facility)

Uncertainty Over Distance

- How far away does a measurement have to be before it is no longer useful?
- Depends on your local conditions
  - In many good sun locations spatial gradients in expected irradiation are small... hundreds of miles may be feasible
  - Near a mountain or coastline 5 miles may be the limit



Solar Prospector GHI Map

Spatial Averaging

- Satellite data sources provide estimates that apply to many square kilometers
- Ground sensors (and most PV arrays) are "point" measurements
- Primarily of concern in short duration data (i.e. forecasting), though mountains and coastlines can be a problem for historical data
- Can create artificial "step" changes at grid boundaries

Site-Specific Calibration

- Satellite data suppliers are accumulating a longer history
  - Weak on local calibration
  - Claimed strength in shape of historical trend and contemporary data collection
- Local ground-based measurements have short history
  - May be well calibrated
  - Can overlap in time!
- Use overlap to recalibrate satellite ground to calibrate satellite during overlap, assume calibration applies to all of history

Site-Specific Calibration Dangers

- Overfitting + Extrapolation
  - Ground measurement may easily be biased 2% high with good equipment
  - Satellite instrumentation may drift or be swapped out or albedo may change, with profile being 2% lower during the overlap than the rest of the profile
  - Estimated long-term value may be biased 4% too high!
    - ... Or not... but the uncertainty is difficult to eliminate because there are so many contributors.

No Magic Answer

- When all sources of error are considered, most data have
  - In specific cases, quality problems such as soiling, missing data, or large calibration shifts may be apparent in the trend... do not blindly compare such data with other sources
- Where the data sources are independent and show no obvious quality problems, errors should be uncorrelated
  - Central tendency of multiple sources of data should reduce uncertainty of estimate if the mean is used as the benchmark
  - To maintain correlation of weather variables, we normally choose one data source with irradiation near the mean of all valid sources
- As multiple new sources with lower uncertainty build history, older lower-quality sources may lose relevance.

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The Challenges of Selecting Solar Resource Data for a New Site

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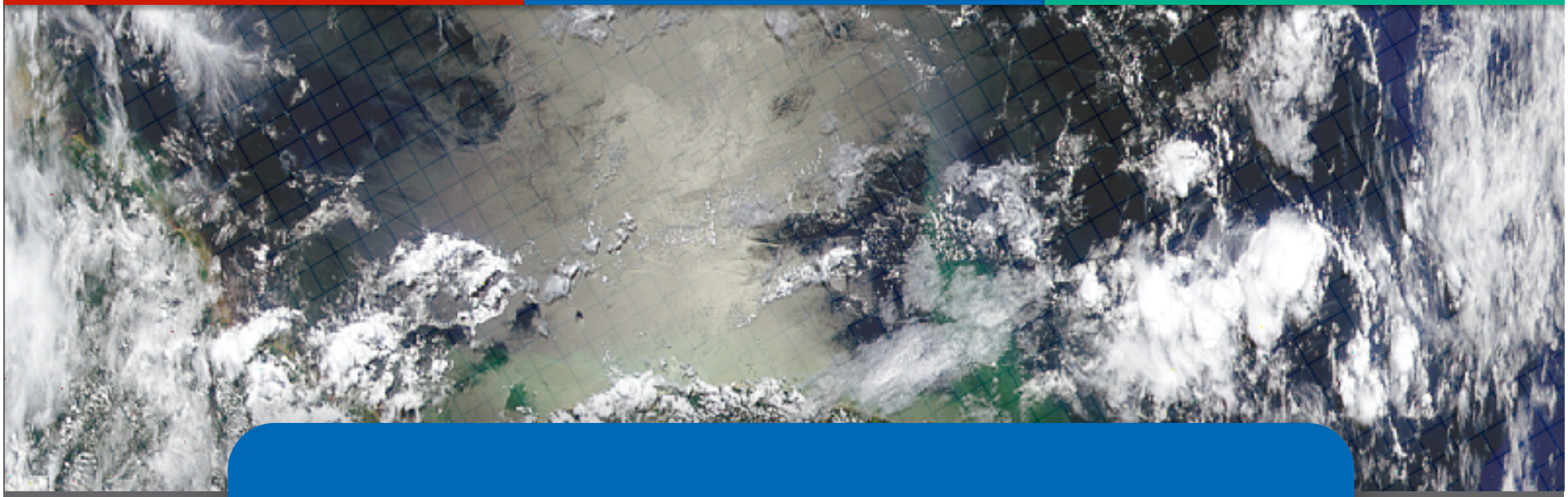
SAFER, SMARTER, GREENER



Combining Satellite and Ground Data: What Works & What Doesn't

Adam Kankiewicz
Clean Power Research
2015 NREL PV Solar Resource Workshop
Feb 27th, 2015

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Research Scientist

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Product Manager

Dr. Richard Perez
Research Professor
Atmospheric Sciences
Research Center

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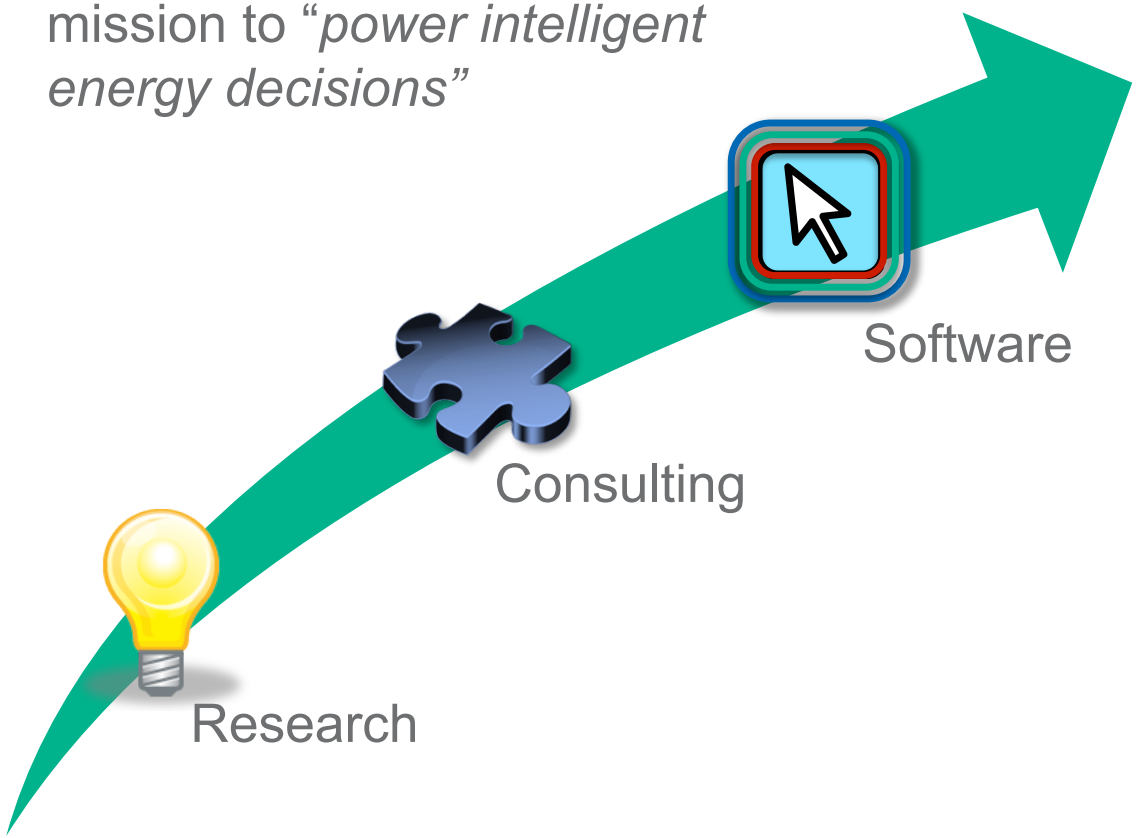
Founded in 1998 with the mission to "*power intelligent energy decisions*"



SOLAR PREDICTION

Most widely used solar resource database

PROGRAM OPTIMIZATION

~6.0 GW of renewable incentives processed

ENERGY VALUATION

>30 million solar estimations performed

Today's Discussion

- What Data Should I Use?
- Ingredients Needed for High-Accuracy Solar Resource Assessment
- Optimizing Ground & Satellite Data
  - Case study
  - What works and what doesn't
- Conclusions

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Which Dataset Should I Use? Conclusions from 2014 Sandia Conference

Use Cases	TMY/ TGY	Ground	Satellite
Initial Estimates	✓		
Siting & Financing of Utility Scale PV Systems		✓	✓
Production Guarantees for DG Lease Funds			✓
Real-time Monitoring		✓	✓

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Today's Discussion

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Ingredients Needed for a Dependable Solar Resource Assessment

- PV system details, near/far shading, soiling characteristics, etc. (site details)
- Solar resource (fuel)
- Ancillary inputs (air temperature, wind speed, precipitation (rain/snow), humidity, etc.)

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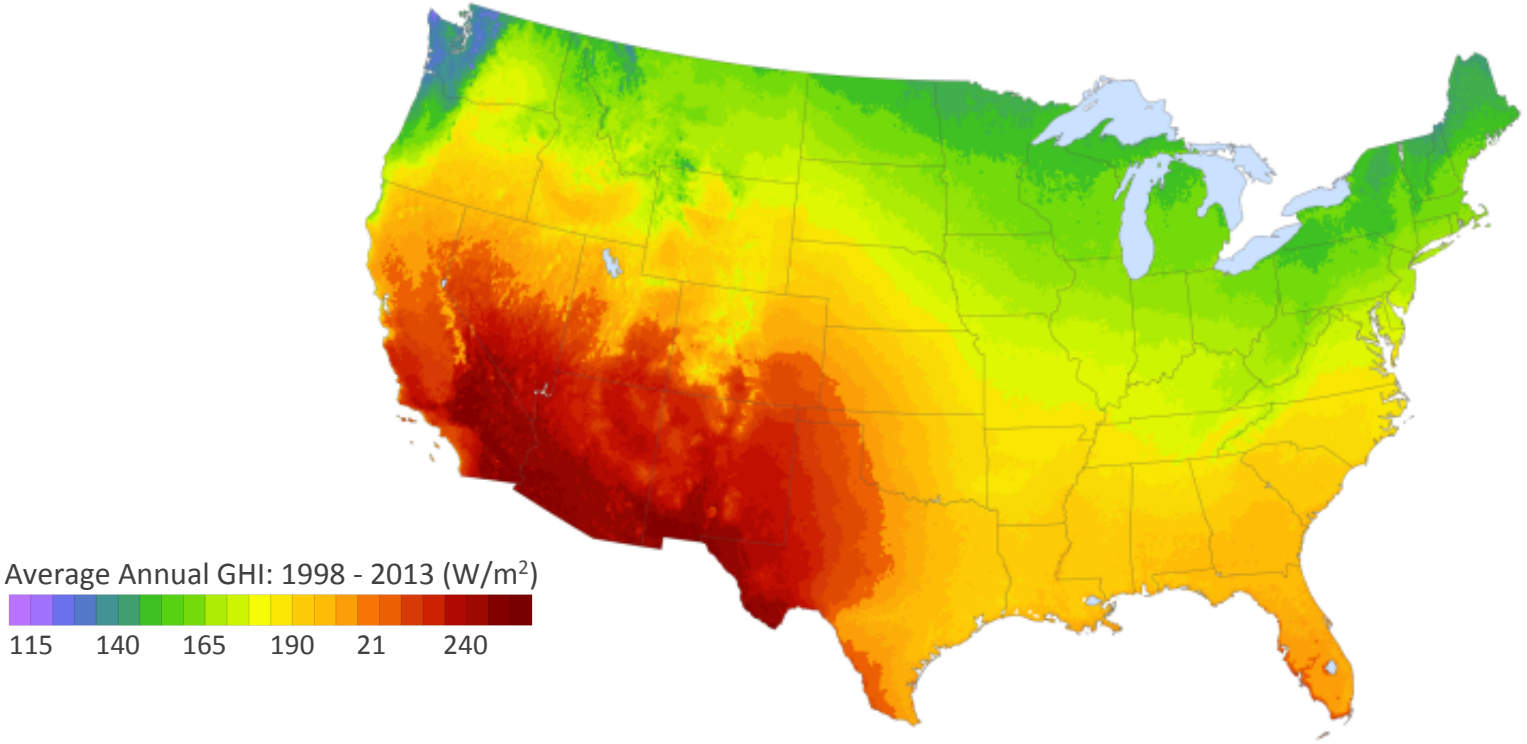
Solar Resource: Foundation for All PV System Simulations



Satellite-based solar irradiance models

Advantages:

- Continuous geographical coverage (1 km resolution)
- Temporally solid and consistent (17+ years)
- Up to 15 minute frequency observations
- Site-specific historical weather observations

Limitations:

- Lower accuracy (than high quality ground observations)

Value of Ground-based Solar Resource Monitoring

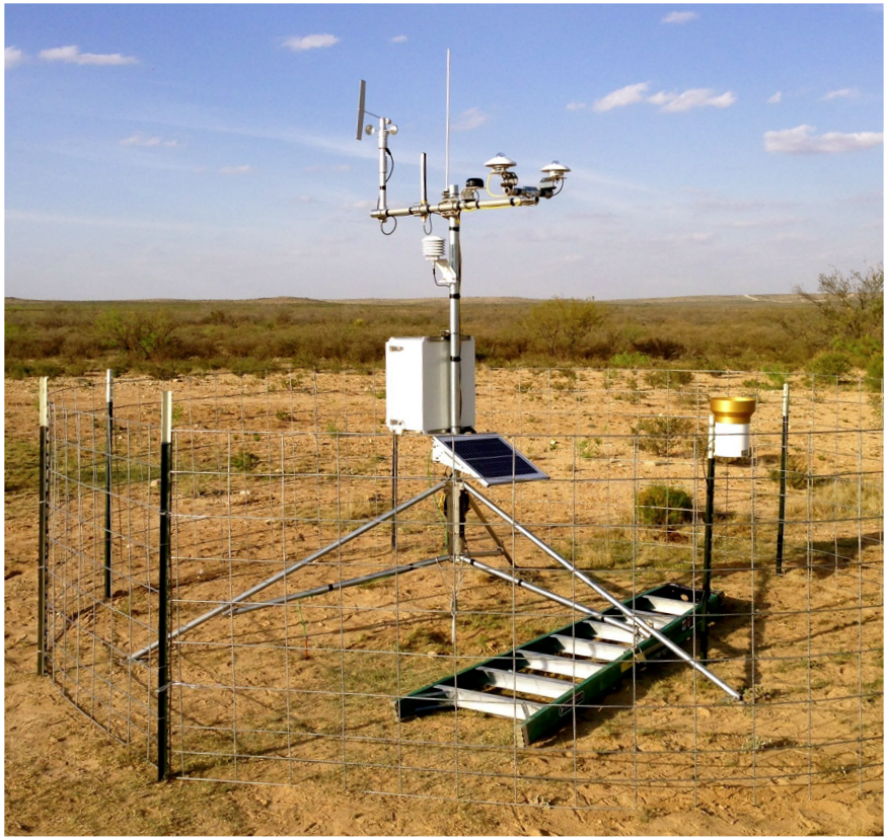


Image courtesy of GroundWork Renewables, Inc.

- High accuracy if properly maintained (dust, frost, snow, birds, event logging, etc.)
- Necessary to understand local variability effects
- Requires meticulous data QC
- Ground truth for tuning process
- Have to place into long term reference frame for proper resource context!

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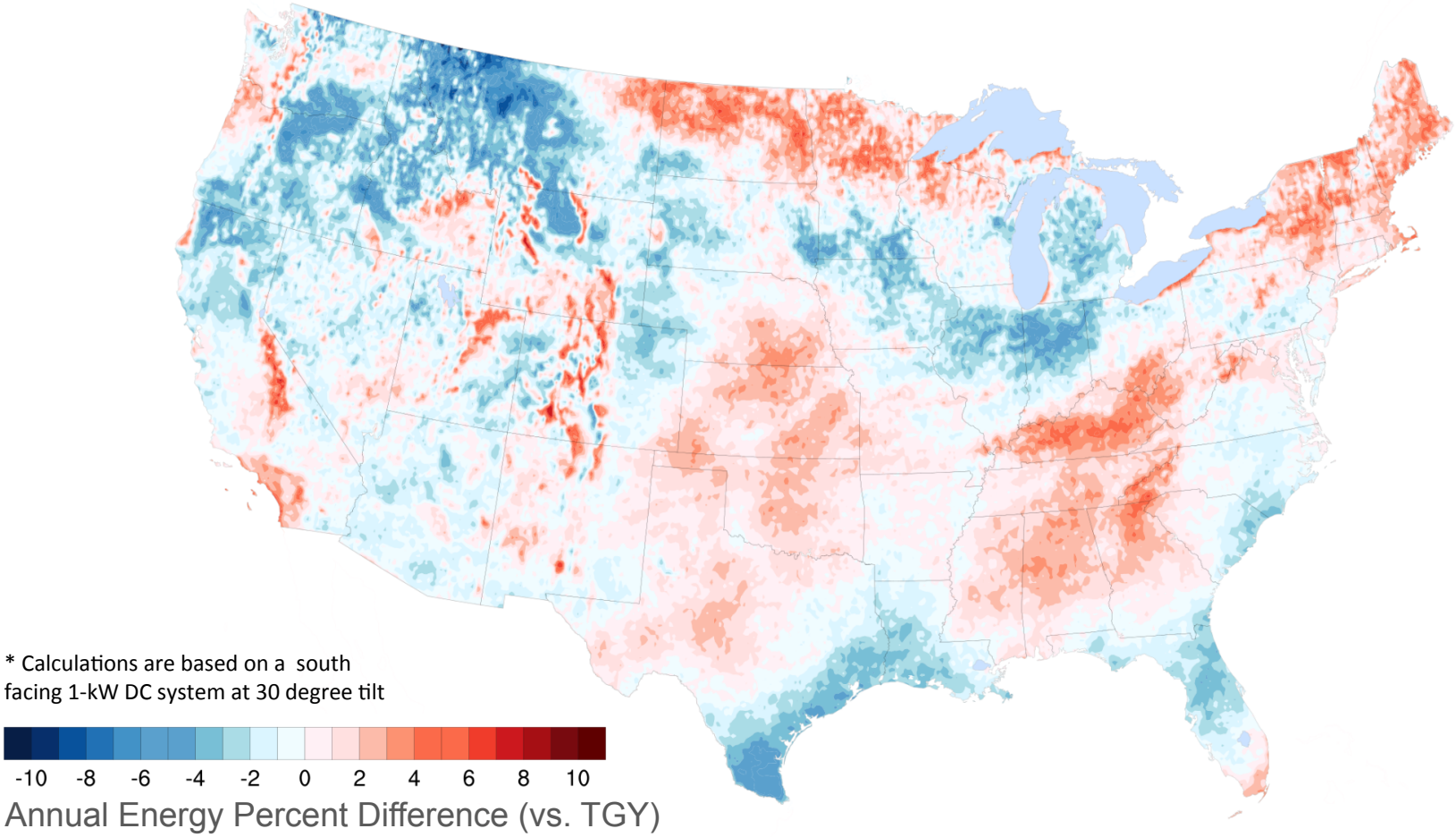
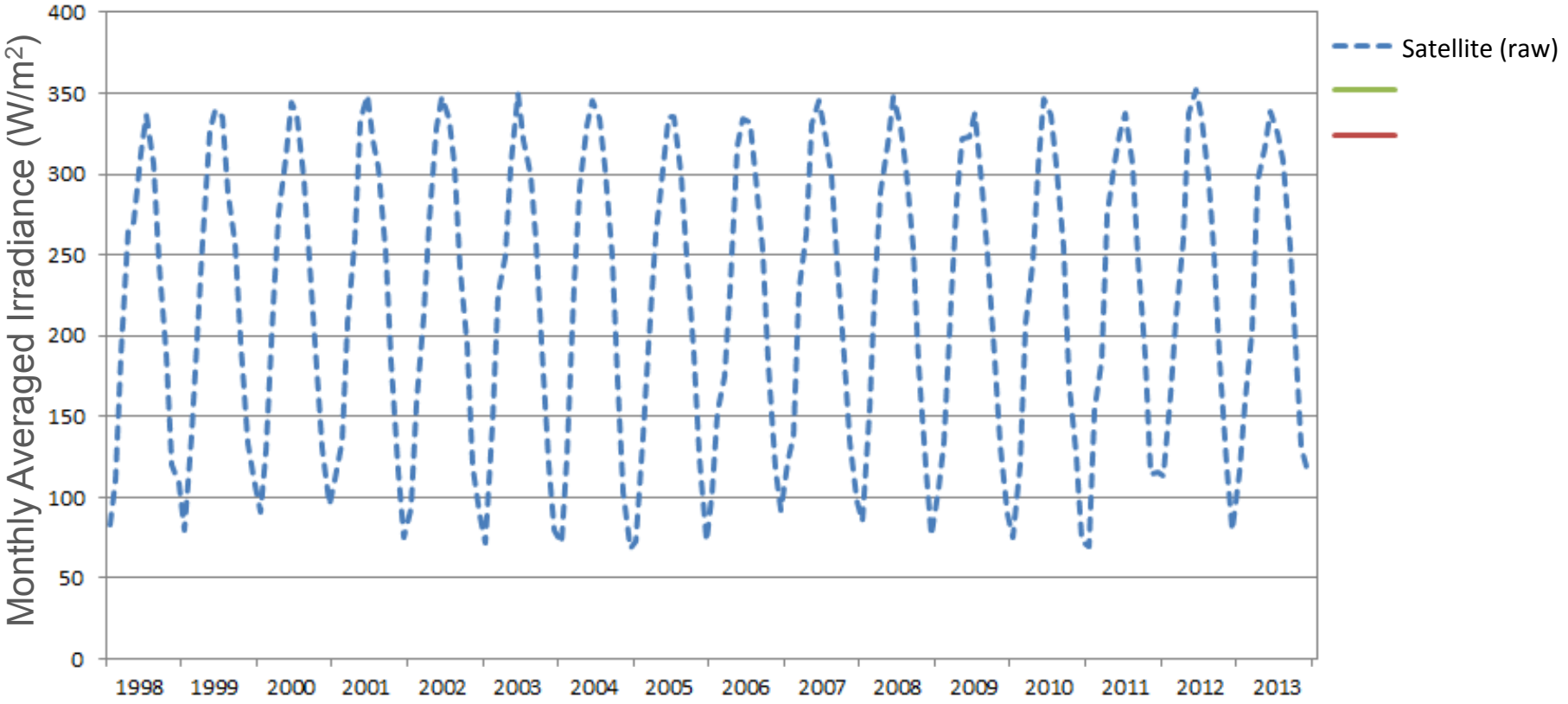
2014 Annual PV Production Variance*



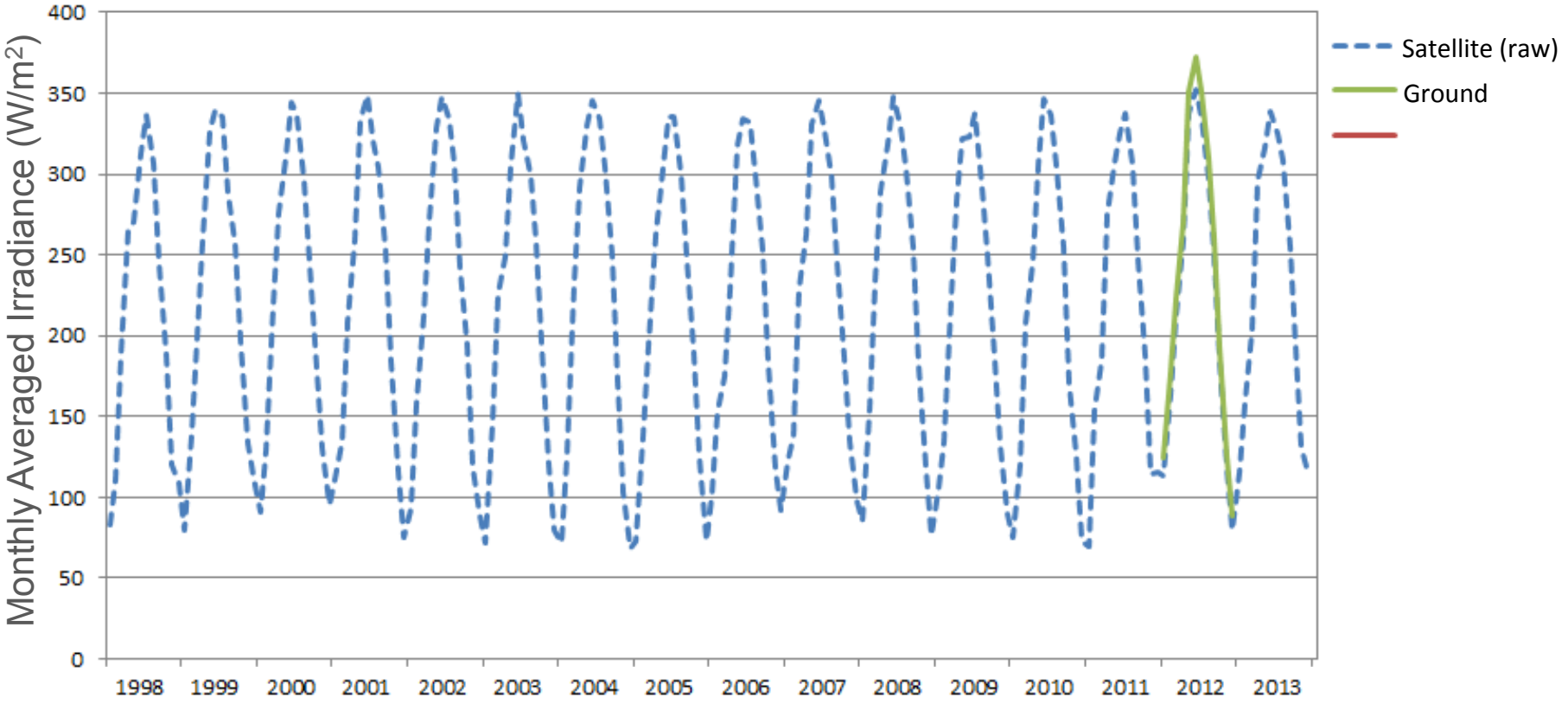
Need to place on-site measurements into long term reference frame due to year-to-year variability

Low-Uncertainty, Long-term Solar Resource Dataset



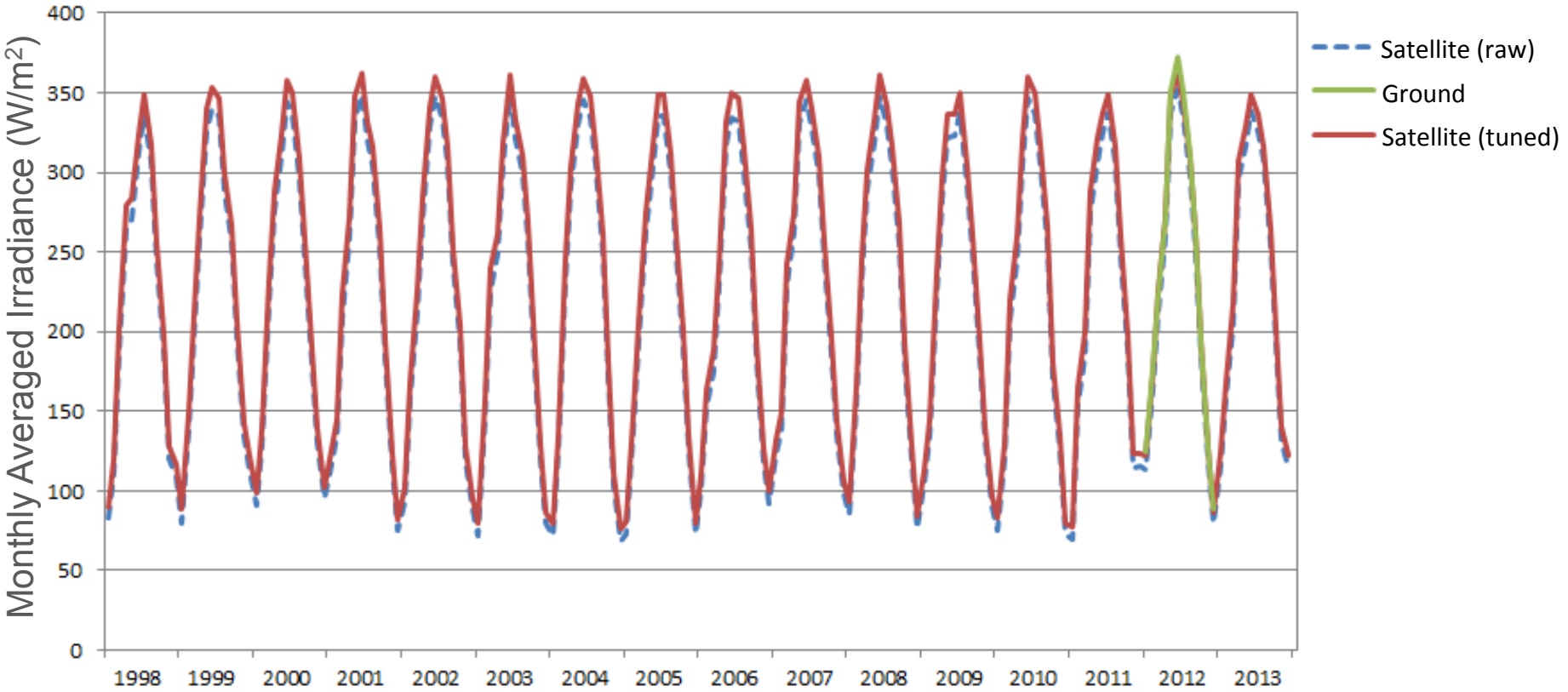
Satellite data

Low-Uncertainty, Long-term Solar Resource Dataset



Satellite data + quality ground data

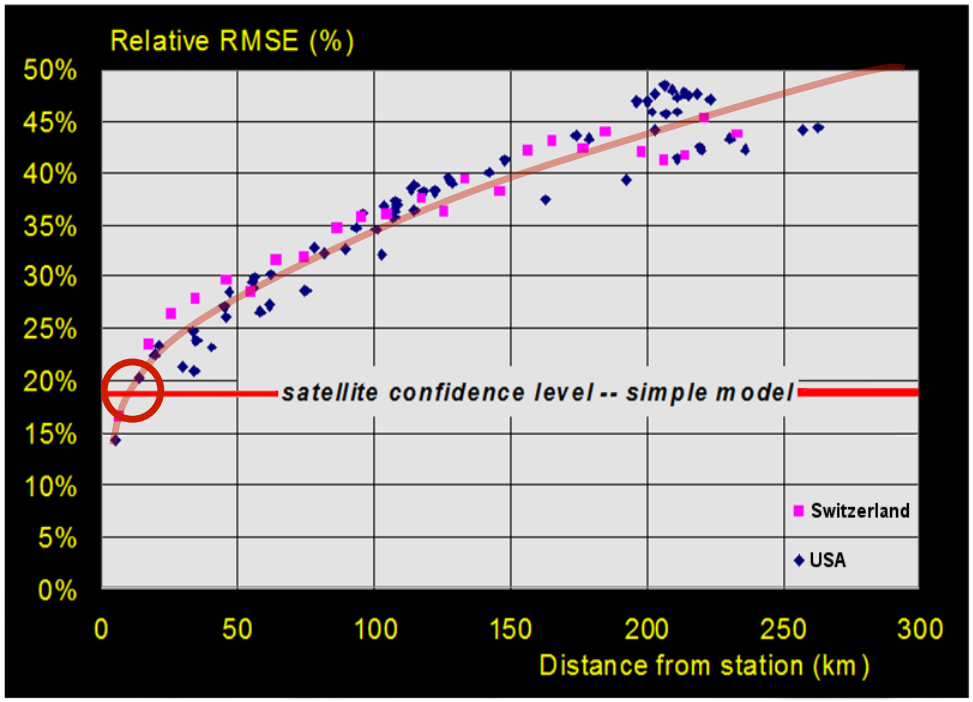
Low-Uncertainty, Long-term Solar Resource Dataset



Satellite data + quality ground data + intelligent tuning methodology
= most reliable long term solar resource

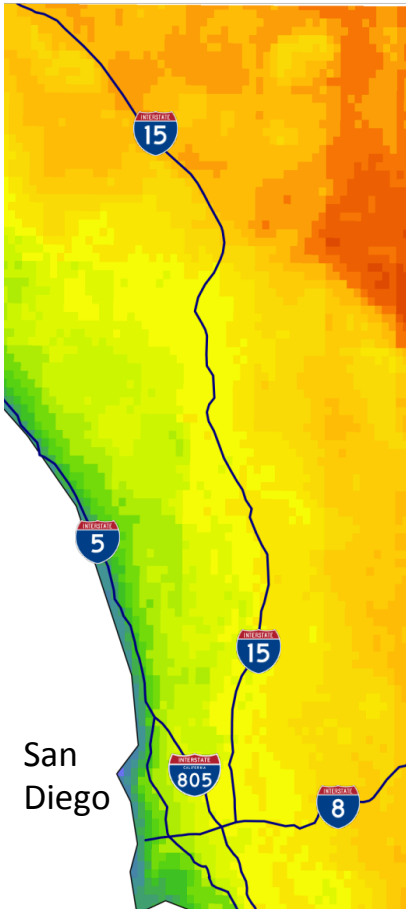
(P50, P90, inter-annual variability, etc.)

Ground Data Usefulness Degrades with Distance



Ground data are suitable at distances up to 10-25 km from project site (can be <5 km in regions with variable topography)

1 km SA TGY data



Average Annual GHI: 1998 - 2013 (W/m^2)

Today's Discussion

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- Conclusions

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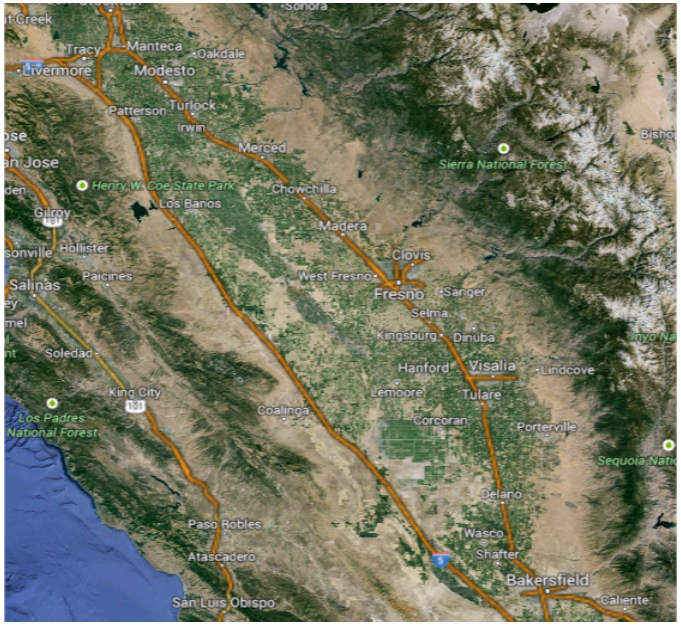
Case Study: PV Prospecting Site

Arid Desert Climate Site



High-Quality Ground Data (12 months)

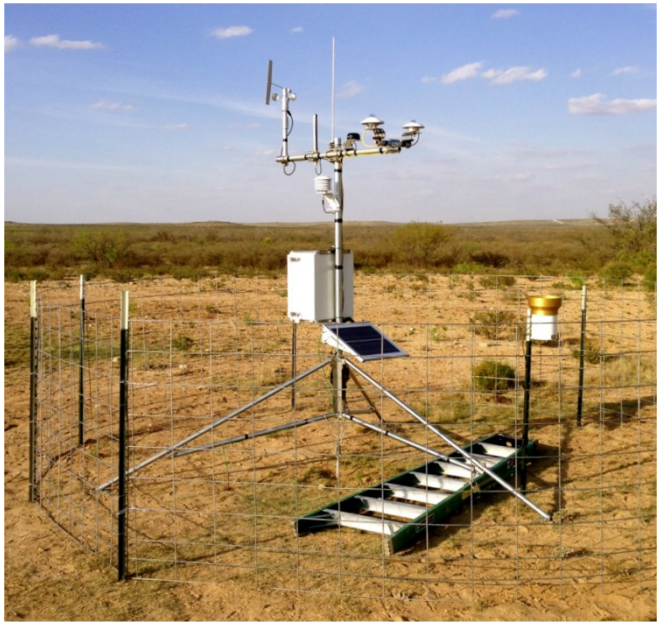


Image courtesy of GroundWork Renewables, Inc.

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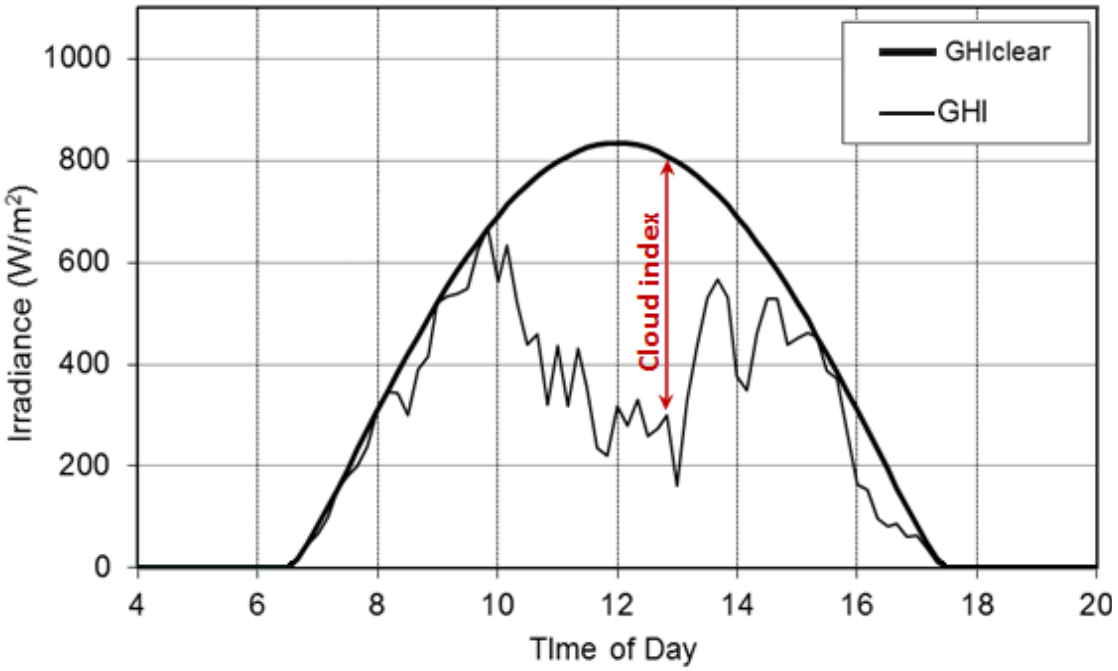
Understanding Differences: Satellite and Ground Datasets

Sources of satellite-model and ground irradiance differences:

- Clear sky bias (AOD, etc.)
- Seasonal (winter v. spring, etc.)
- Cloudy sky measurement error (satellite/ground mismatch, etc.)

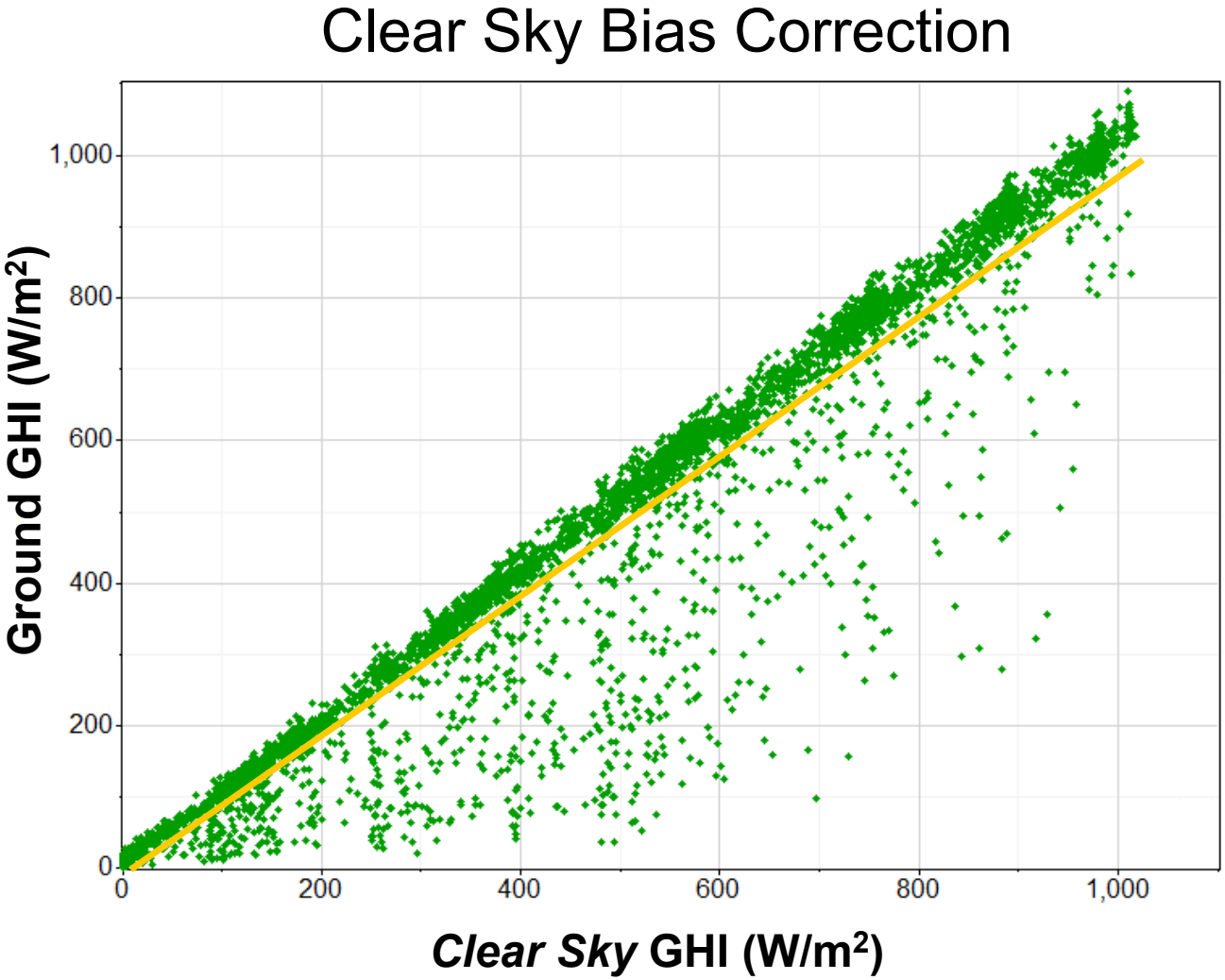
Other considerations:

- Irradiance rebalancing
- Ancillary data



Differences need to be targeted individually during the tuning process

Tuning Satellite Data with Ground Observations: Clear Sky Corrections



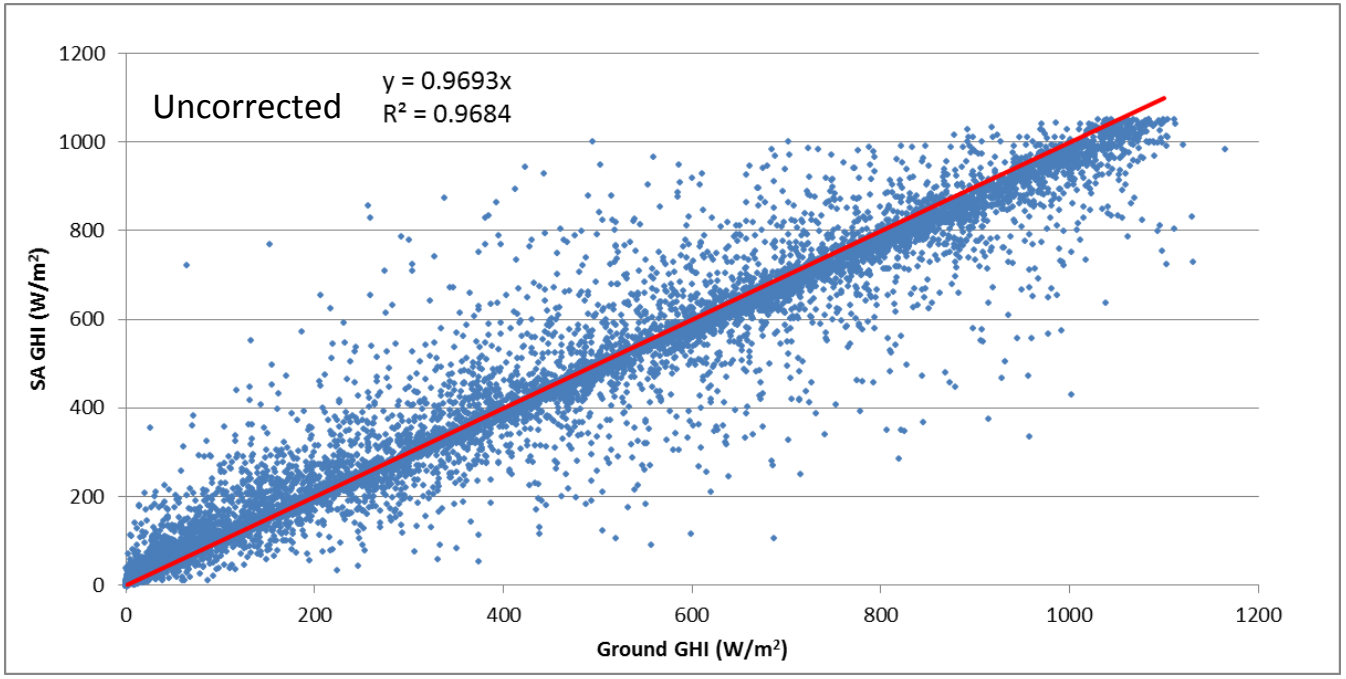
Overall Bias: 4.6%
Clear Sky Bias: 4.1%

Non targeted bias corrections would over correct in this situation

Addressing Clear Sky Bias Only

High quality ground data versus SolarAnywhere ("SA") satellite data

	rMBE
Overall	-0.59%
Clear Sky	-2.71%



Addressing Clear Sky Bias Only

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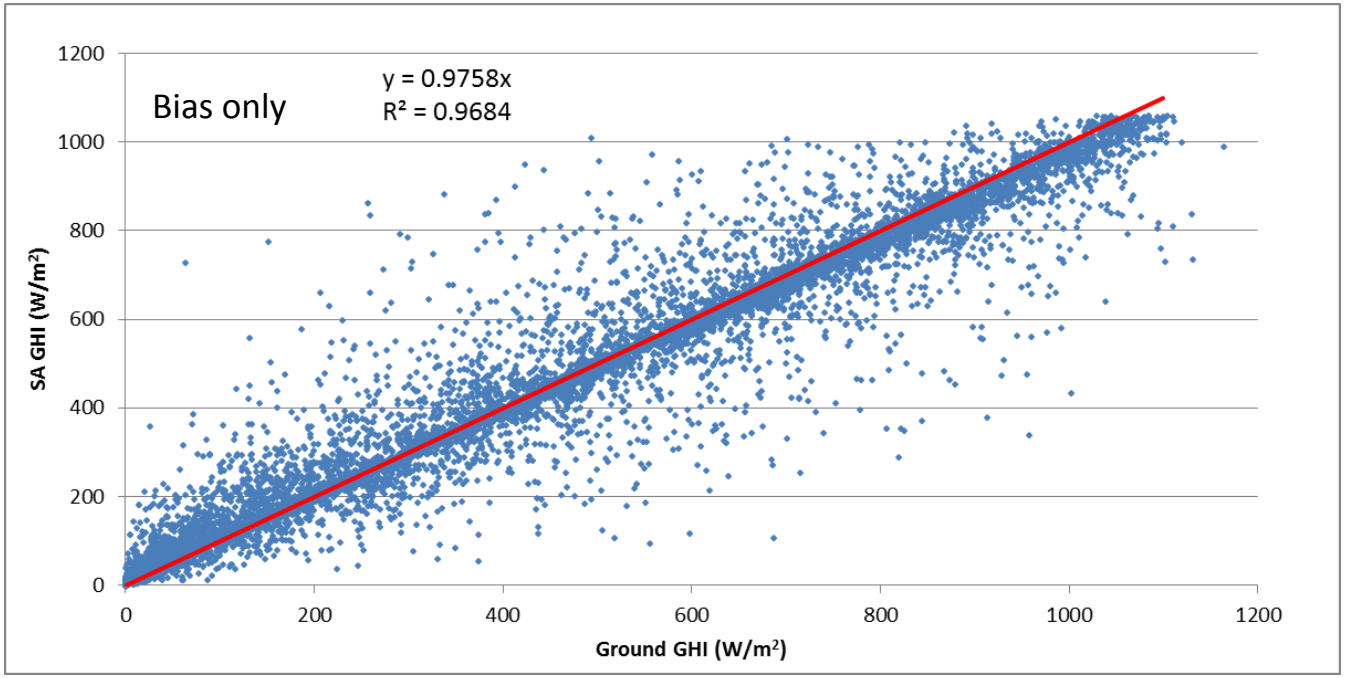

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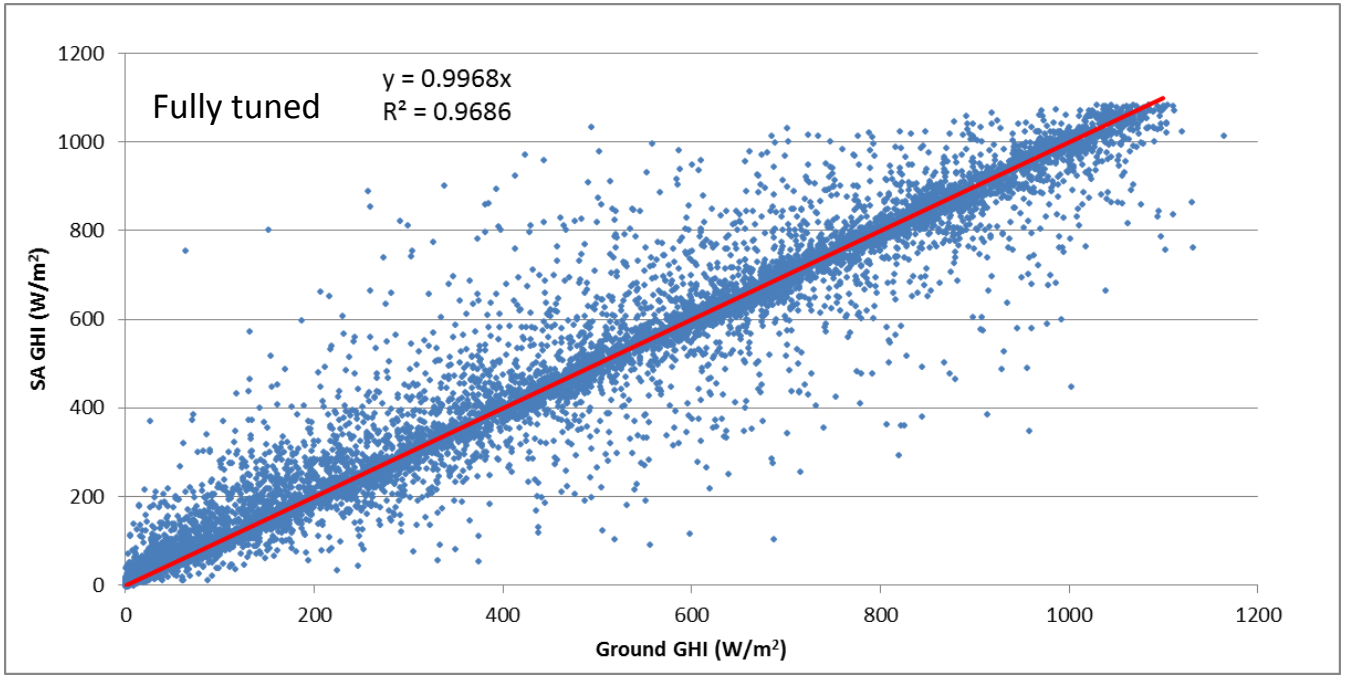
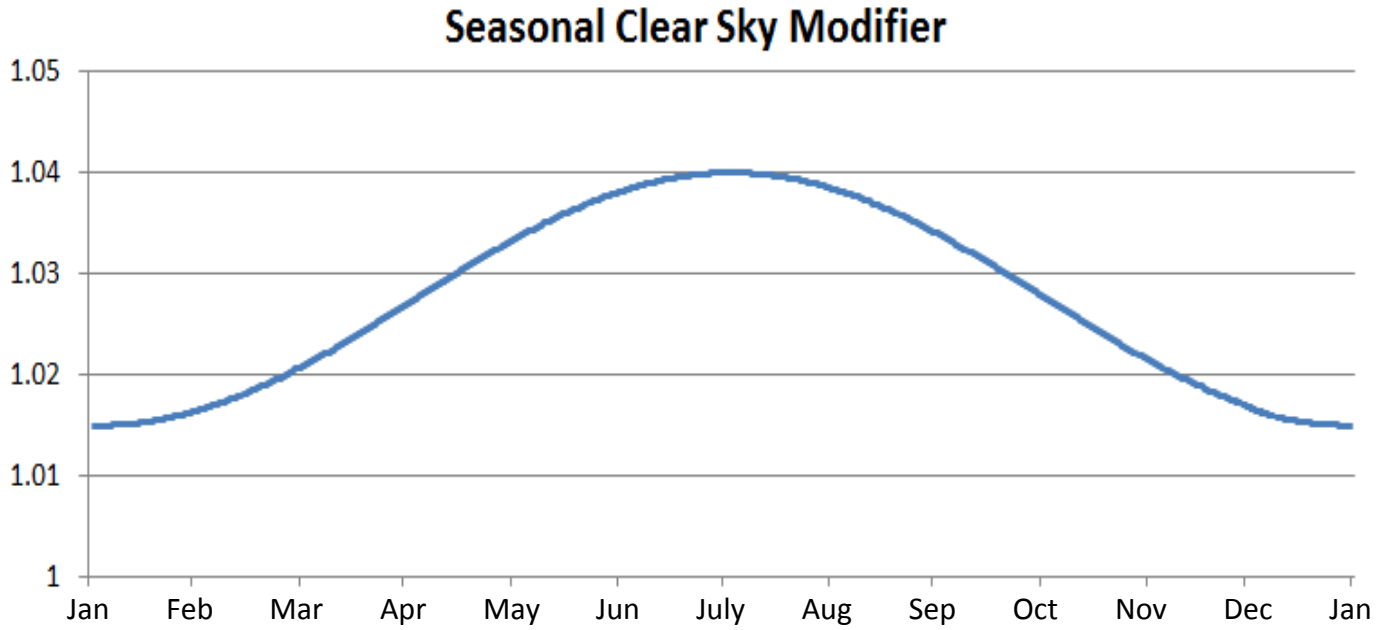


Targeting clear sky conditions addresses intrinsic measurement source errors

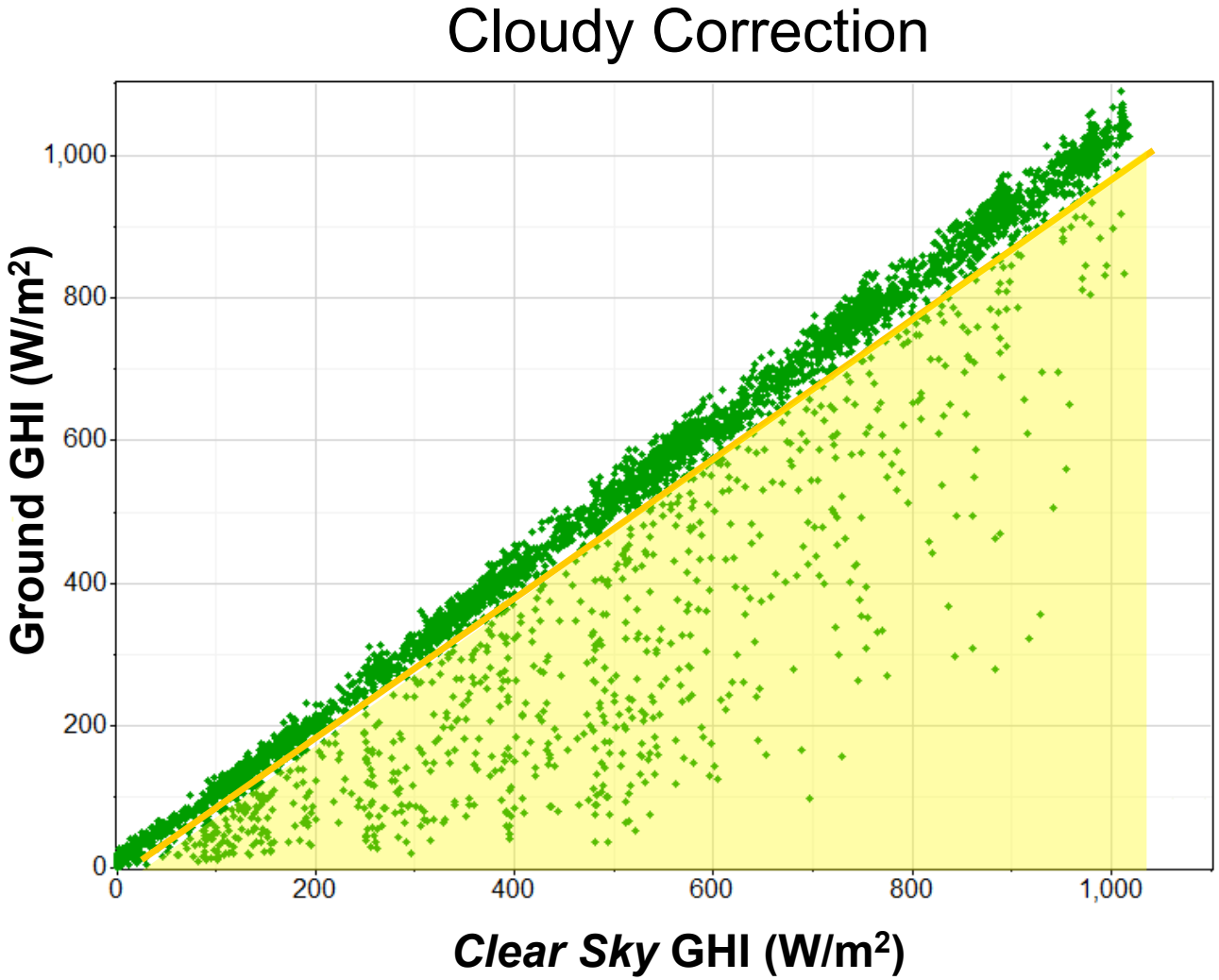
Tuning Satellite Data with Ground Observations: Seasonal Clear Sky Corrections

Can correct for seasonal clear sky biases with year+ of ground data observations



Seasonal impacts occur over the full year

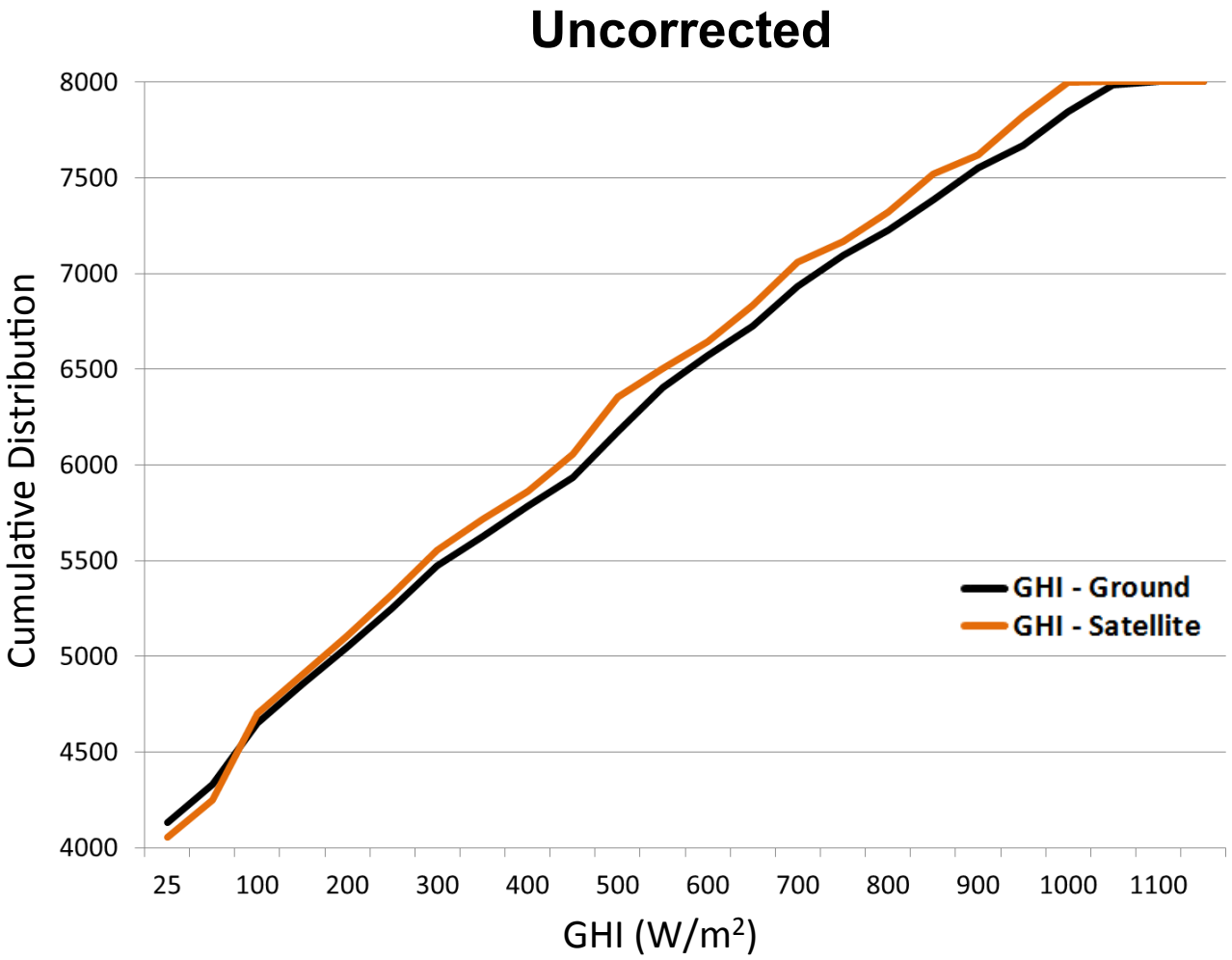
Tuning Satellite Data with Ground Observations: Cloud Measurement Error



Overall Bias: 4.6%
Clear Sky Bias: 4.1%

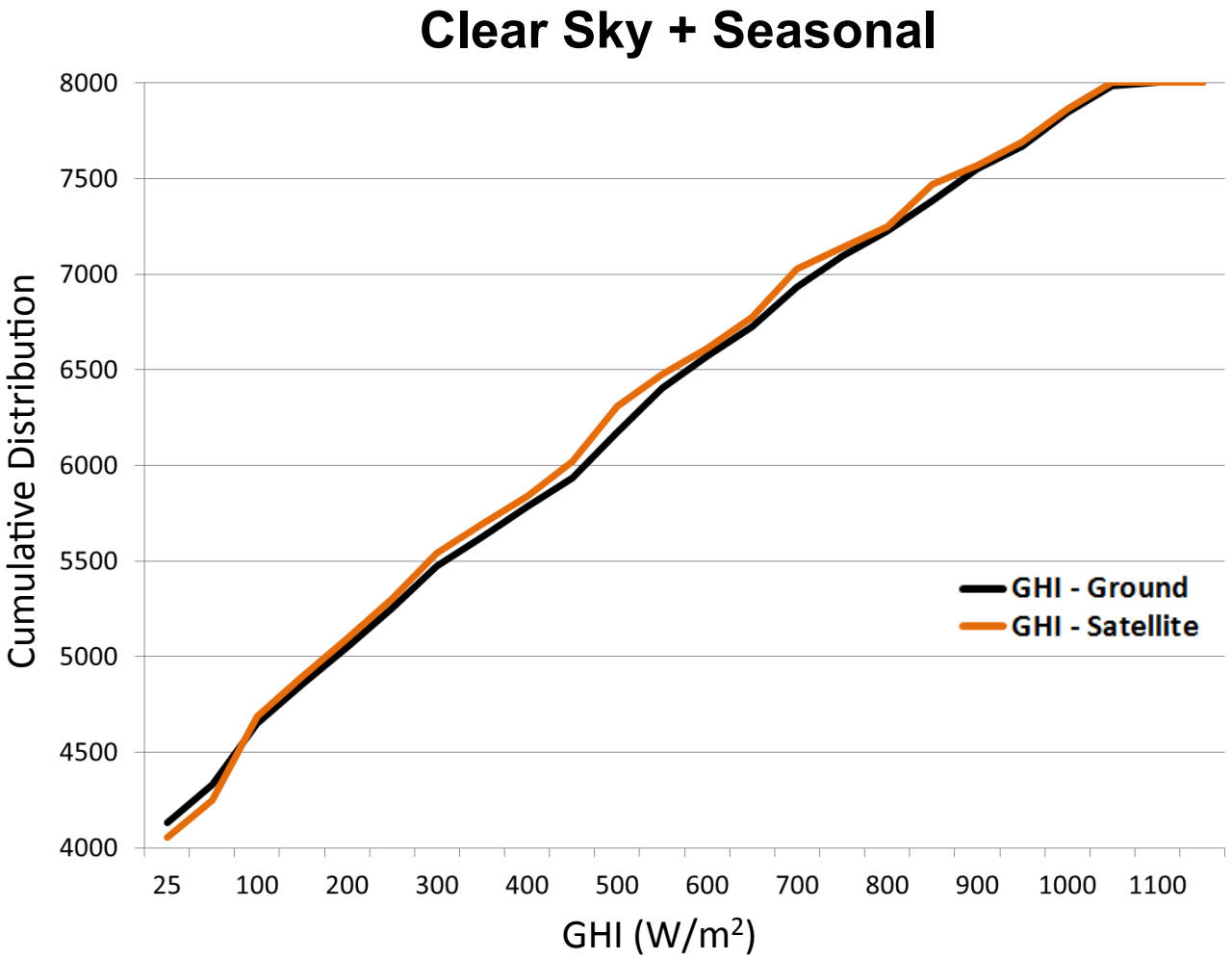
How do we target bias in the cloud measurements?

Tuning Satellite Data with Ground Observations: Cloud Measurement Error



Overall Goal: Minimize error (RMSE and KSI)

Tuning Satellite Data with Ground Observations: Cloud Measurement Error



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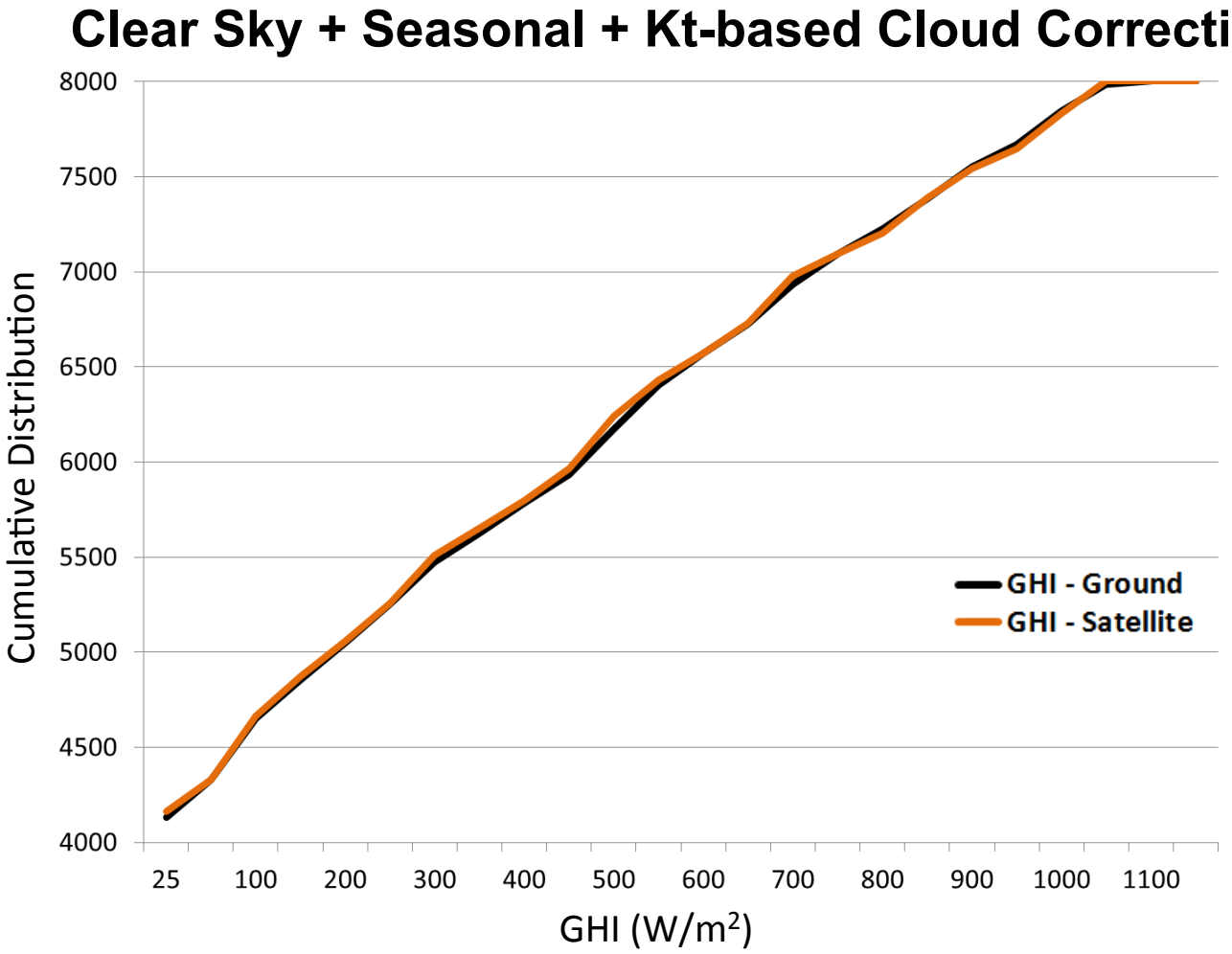
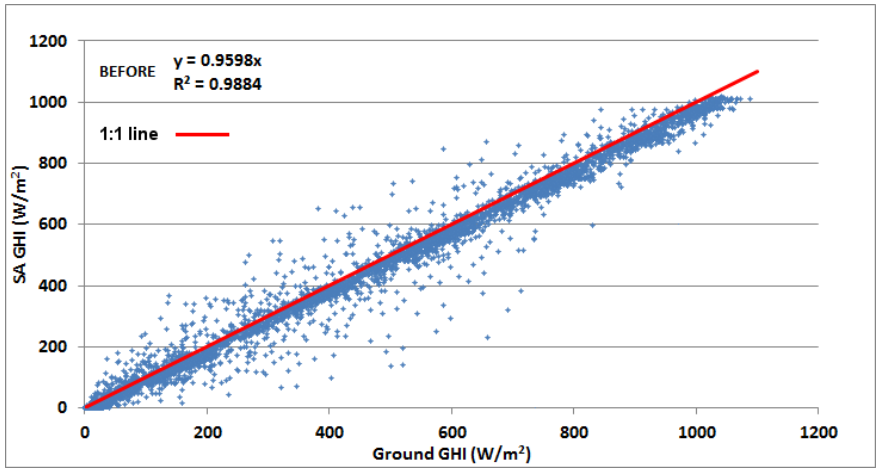
Tuning Satellite Data with Ground Observations: Cloud Measurement Error



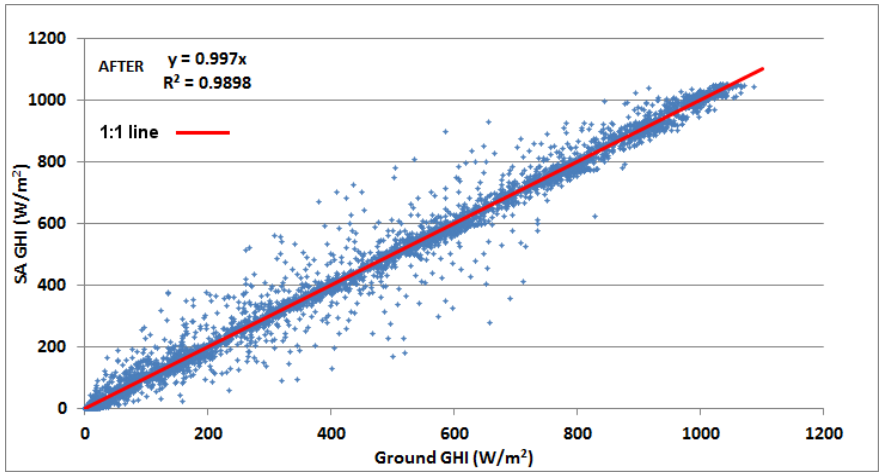
Overall Goal: Minimize error (RMSE and KSI)

Tuning Satellite Data with Ground Observations: Case Study Results

Ground/Satellite Tuning Results



Original Data

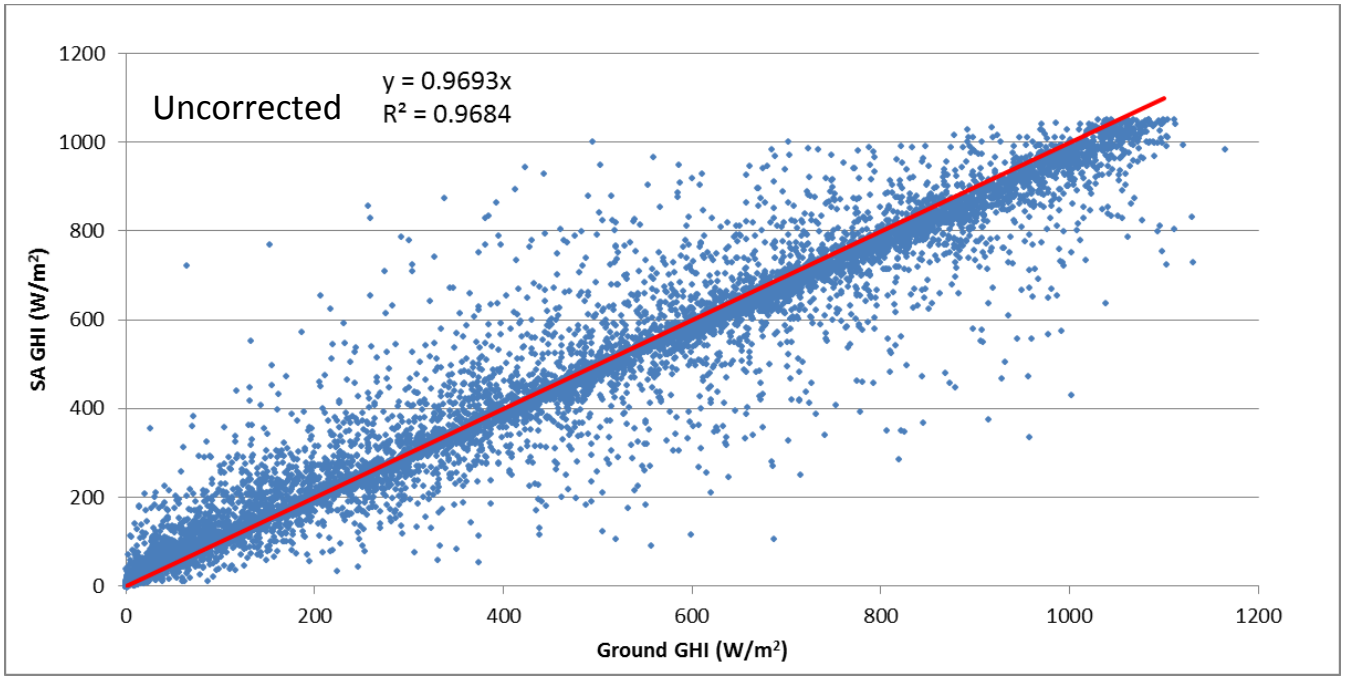


Final Tuned Data

Tuning Satellite Data with Ground Observations: Multi-year Validation

Two years of high quality ground data combined with SolarAnywhere ("SA") satellite data

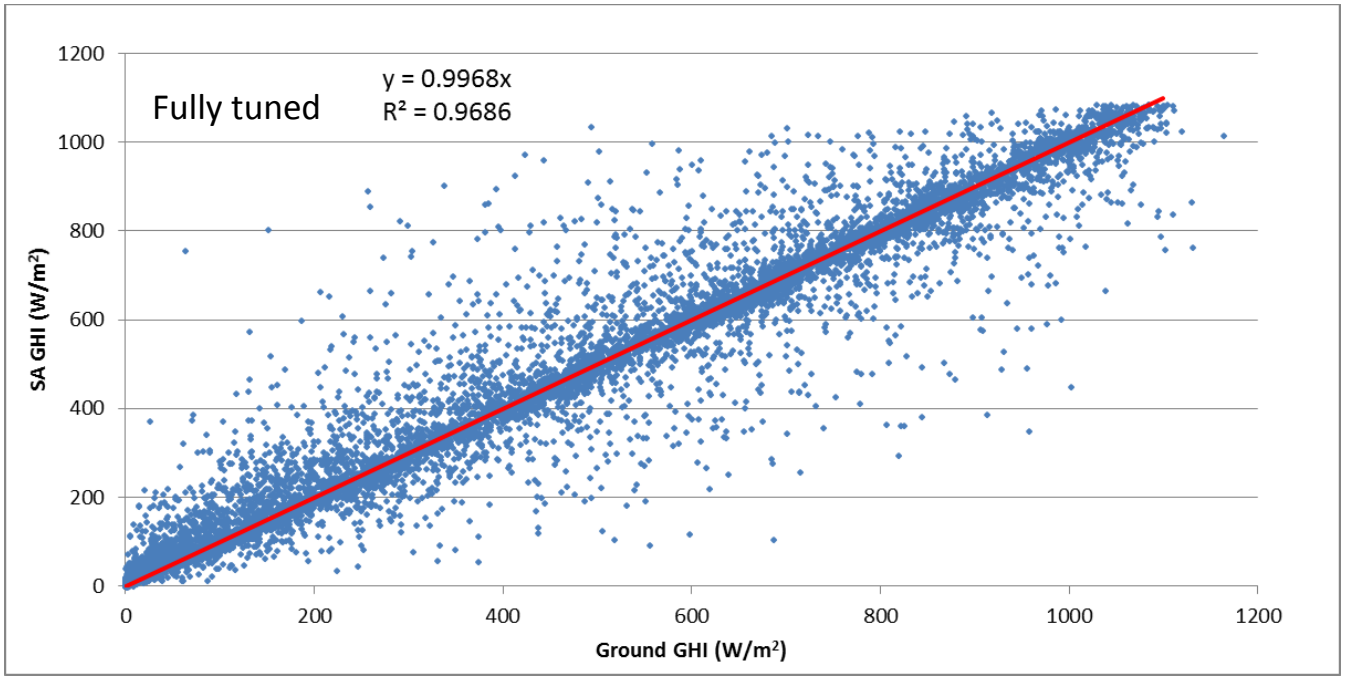
	Year 1 rMBE
Overall	-0.59%
Clear Sky	-2.71%



Tuning Satellite Data with Ground Observations: Multi-year Validation

Two years of high quality ground data combined with SolarAnywhere ("SA") satellite data

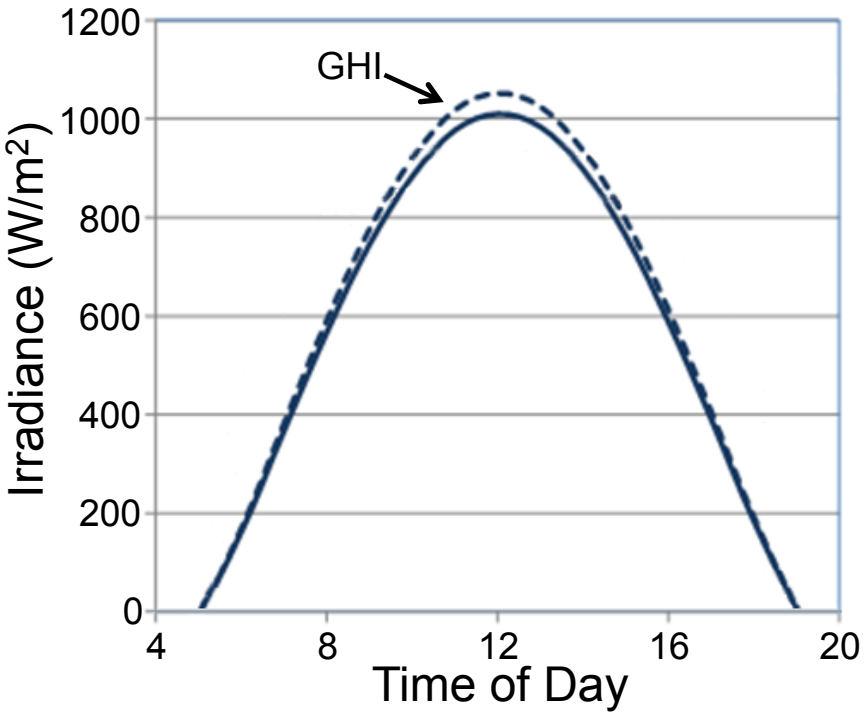
	Year 1 rMBE	Year 2 rMBE	Combined rMBE
Overall	-0.59%	-0.75%	-0.67%
Clear Sky	-2.71%	-3.16%	-2.93%



Targeted satellite tuning is reasonably consistent on a year-to-year basis

Other Considerations: Satellite DNI/DHI Rebalancing

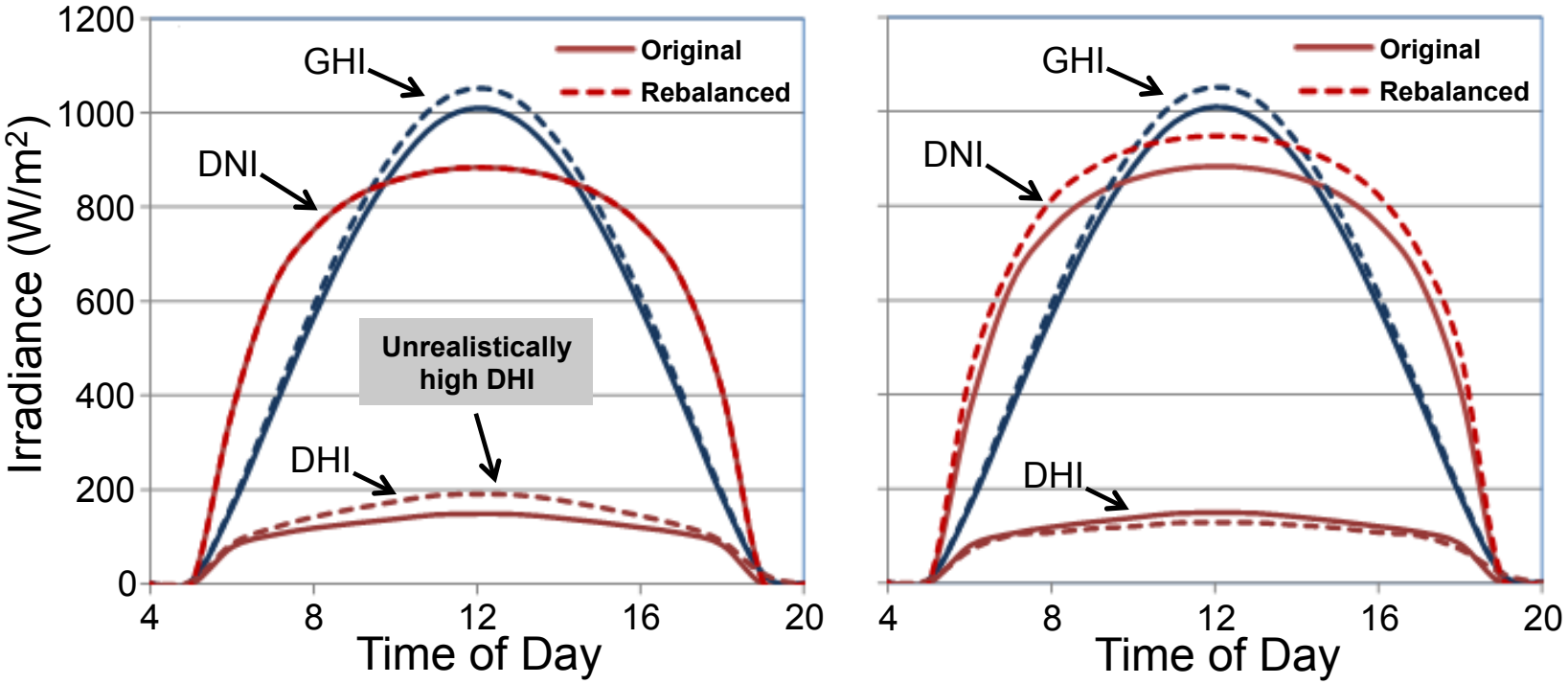
GHI = COS(Z)*DNI + DHI



Correction up in GHI needed due to modeled AOD inputs. What about DNI and DHI?

Other Considerations: Satellite DNI/DHI Rebalancing

GHI = COS(Z)*DNI + DHI



Improper rebalancing can skew PV energy simulations (PVsyst & SAM)

Simple corrections do not address clear/cloudy sky biases and DNI rebalancing needs

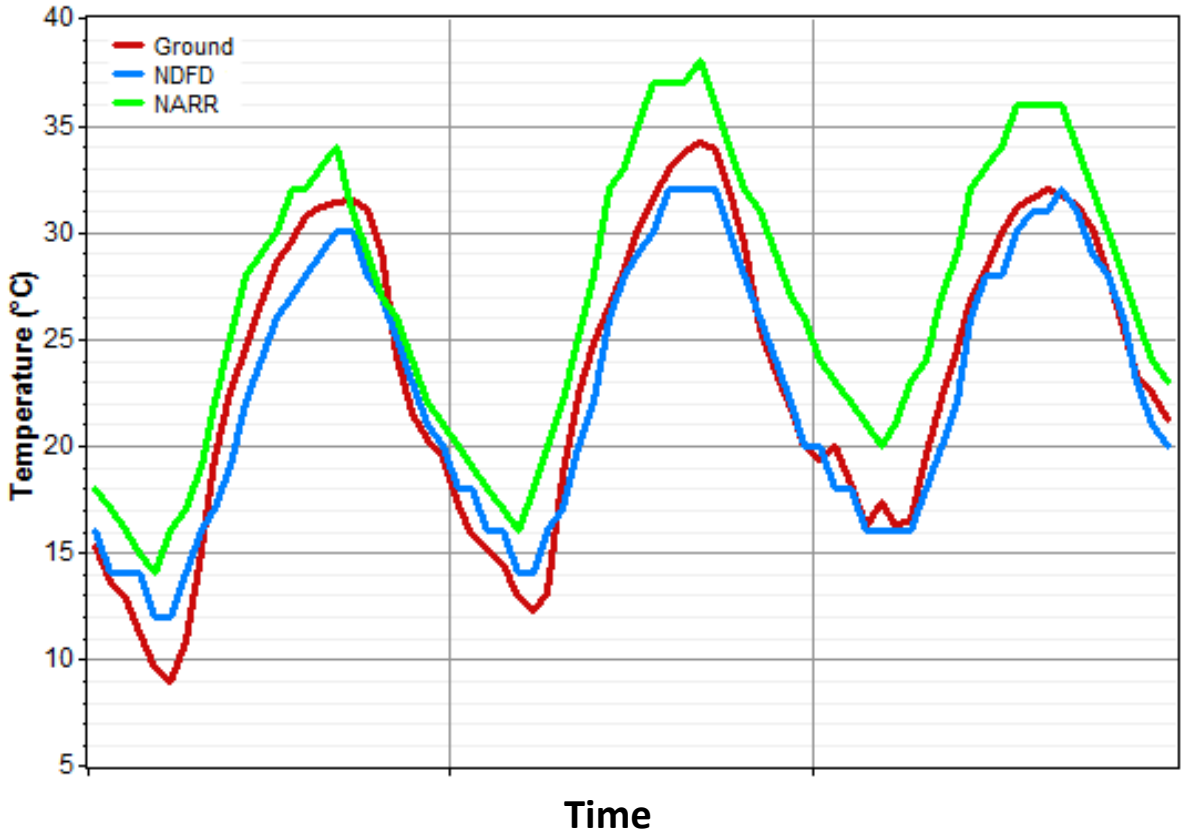
Other Considerations: Ancillary Meteorological Data Collection

NWS ASOS weather station (image credit: NOAA)

Standard surface observations are taken at 2 meters for dry bulb temperature and 10 meters for wind speed and direction.

Long term reference datasets (both observed and modeled) report 2 meter dry bulb temperature and 10 meter wind speed and direction data. PV site met observations taken at different levels will need to be reconciled with long term reference met sources

Other Considerations: Ancillary Meteorological Data Biases



Site Air Temperature Biases

NDFD (all)	NDFD (day)	NARR (all)	NARR (day)
0°C	-0.8°C	+2.9°C	+2.6°C

Need to correct for daytime-only biases in long term ancillary datasets

A +2°C swing in temperature results in a -1% swing in energy output in PVsyst for most PV modules

Conclusion: Ground + Satellite Data
"Better together when properly combined"

Run a well maintained and monitored ground campaign and collect 1+ year of high-quality ground data

Combine in ligently with
long-term reference sate e and ancillary met data

=

Results in lowest uncertainty and most reliable solar resource available for a solar project site

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Thank you

Please feel free to contact us for any details or clarification related to presentation

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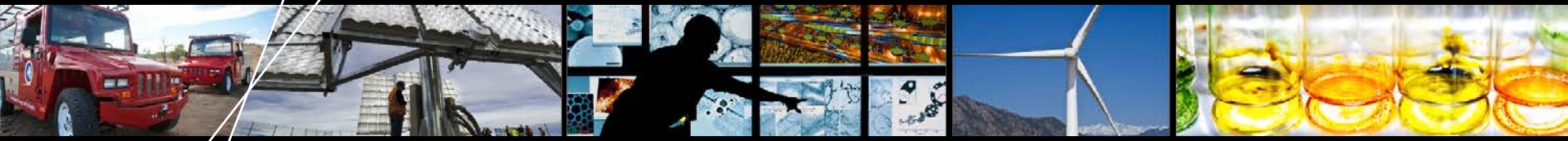
Delivering Data for the PV User from Physics-Based Satellite Models



Manajit Sengupta (NREL)
Aron Habte
Anthony Lopez
Yu Xi

PV Solar Resource Workshop

February 27, 2015

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.

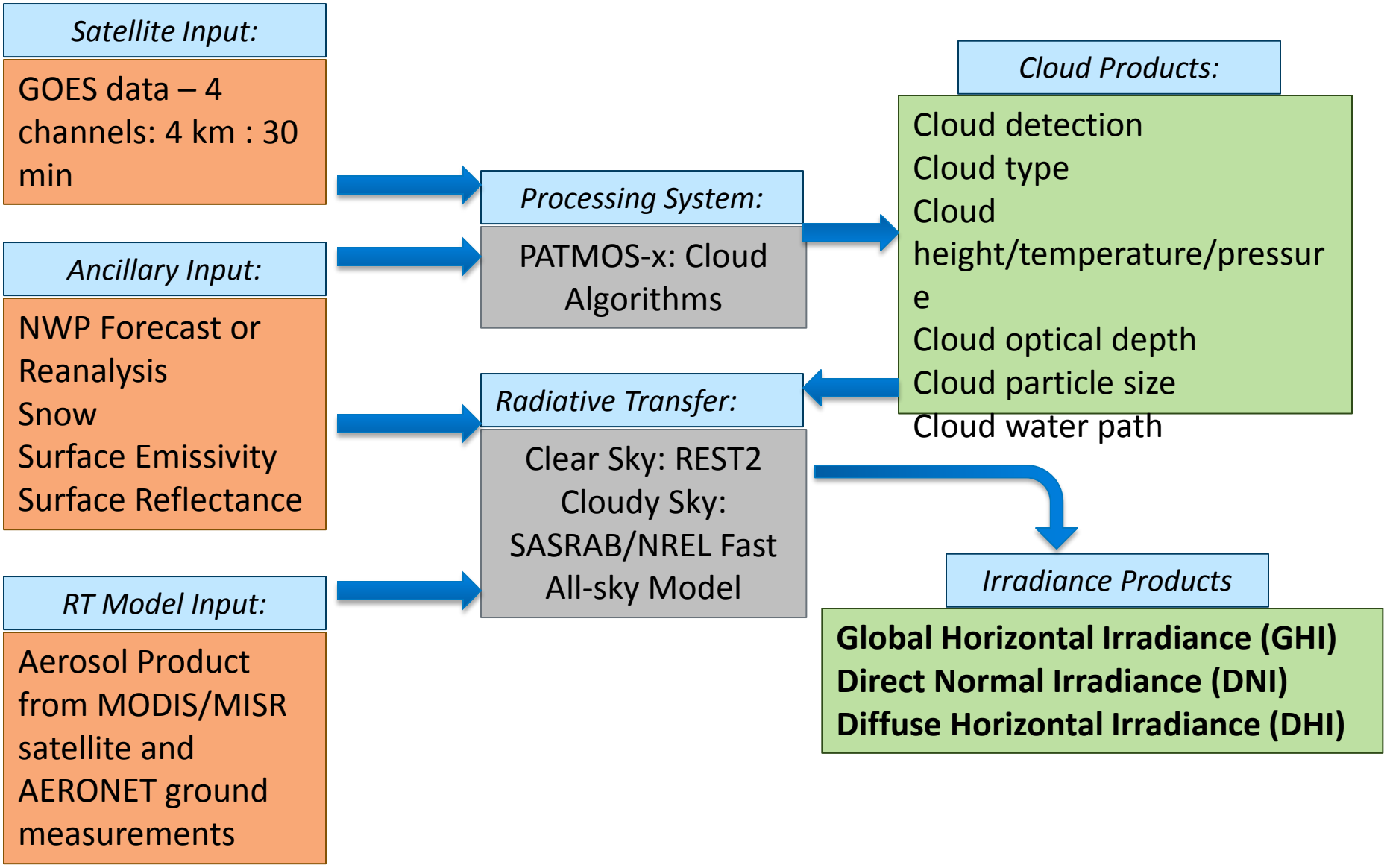
How do satellites model surface radiation?

- **Empirical Approach: (original)**
  - –Build model relating satellite measurements and ground observations.
  - –Use those models to obtain solar radiation at the surface from satellite measurements.

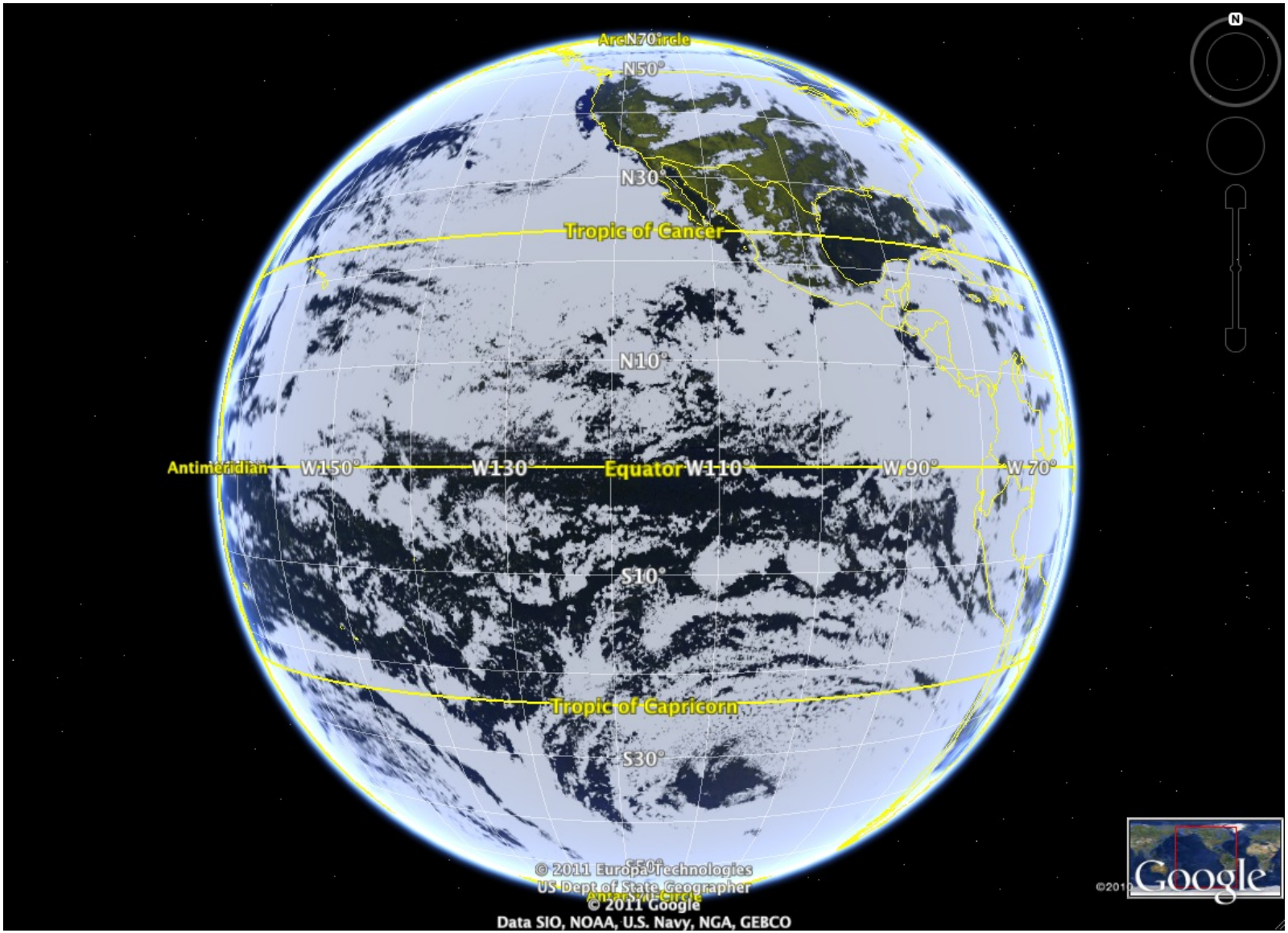
- **Semi-Empirical Approach: (current industry standard)**
  - –Retrieve “cloud index” using counts from visible satellite measurements
  - –Relate “cloud index” to “clearness index”
  - –Scale clear sky radiative transfer model output by “clearness index”

- **Physical Approach: (the new approach)**
  - –Retrieve cloud and aerosol information from satellites
  - –Use the information in a radiative transfer model

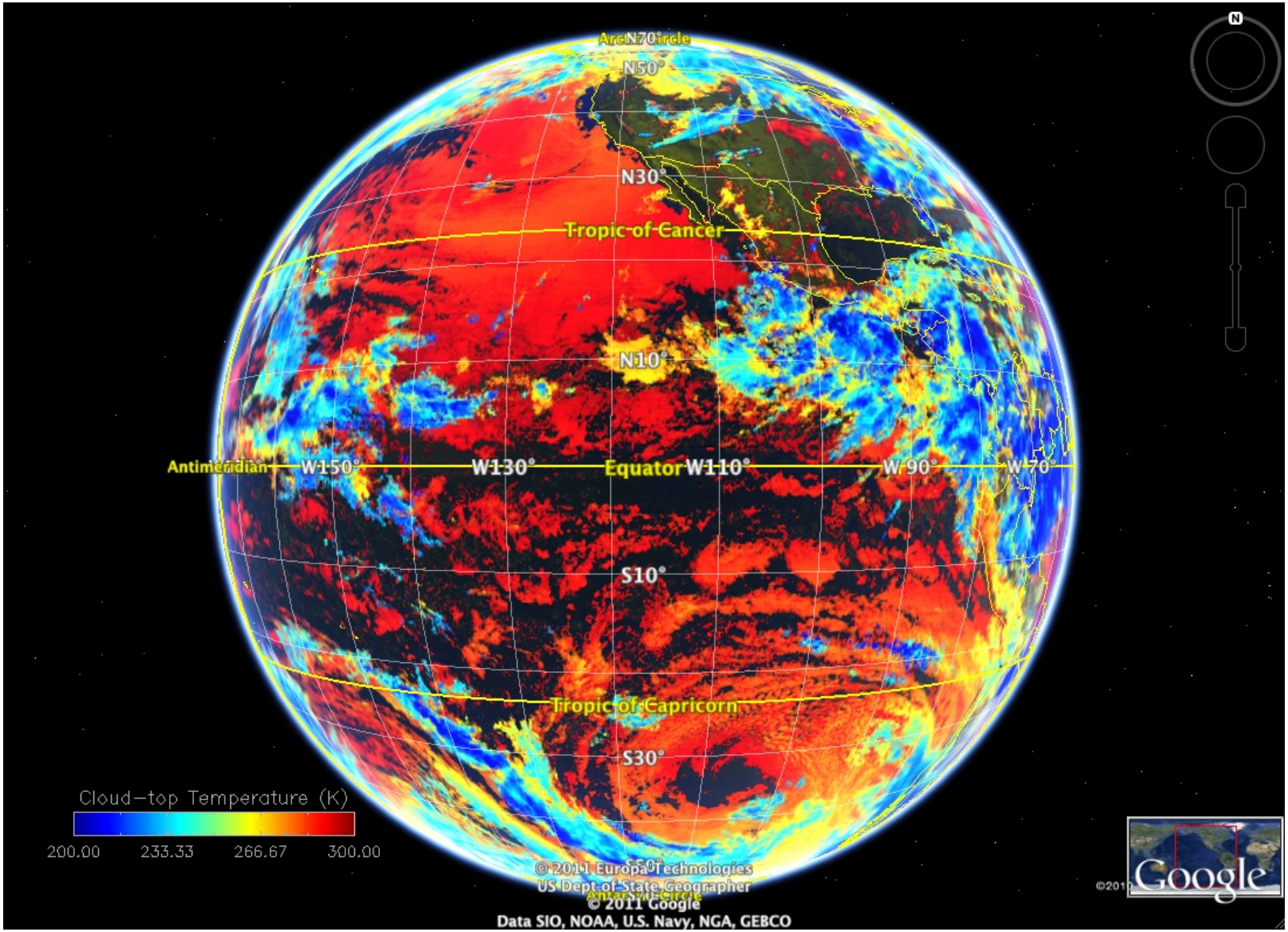
The Gridded NSRDB Product



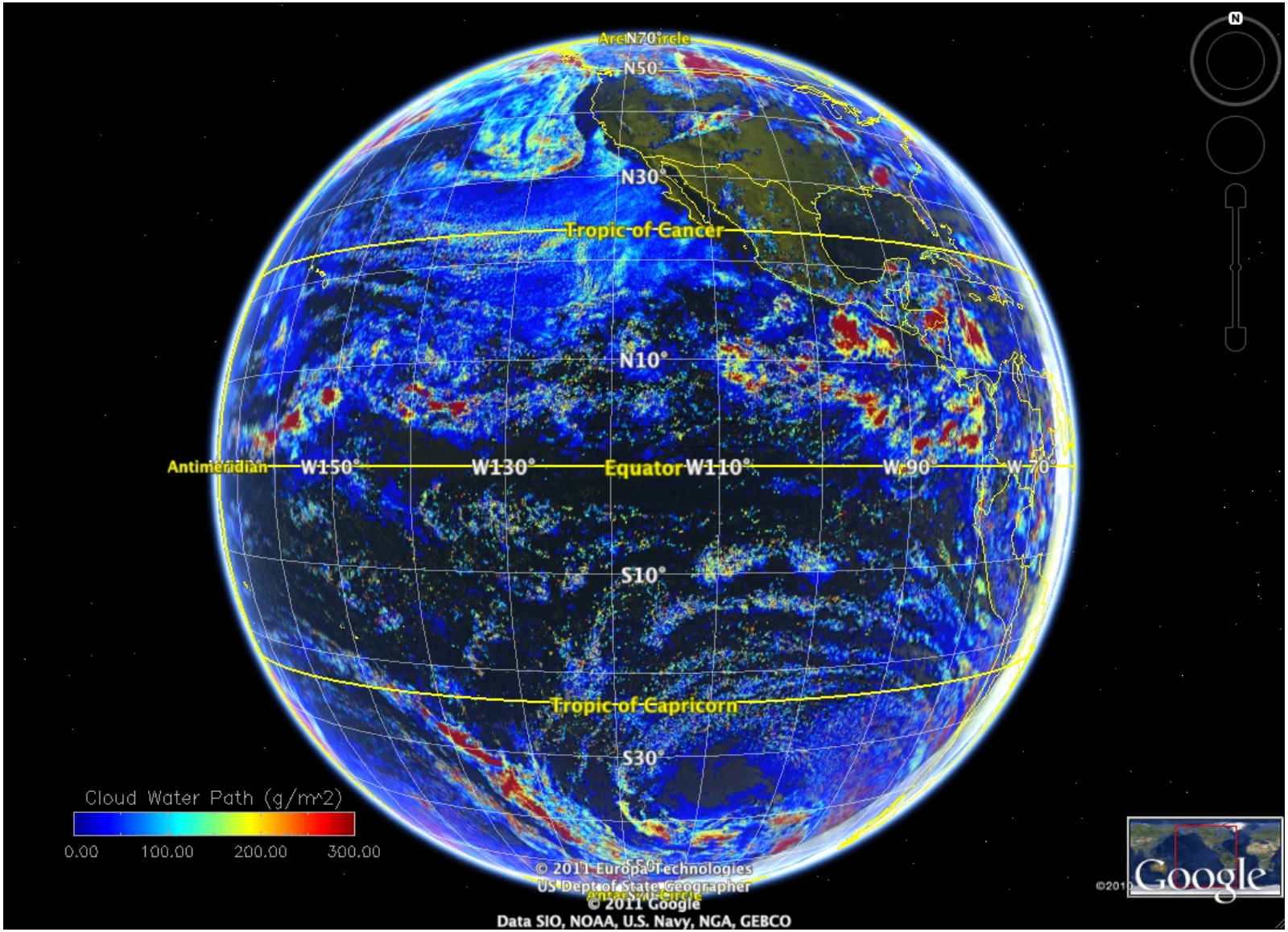
Cloud Algorithms: Cloud Mask



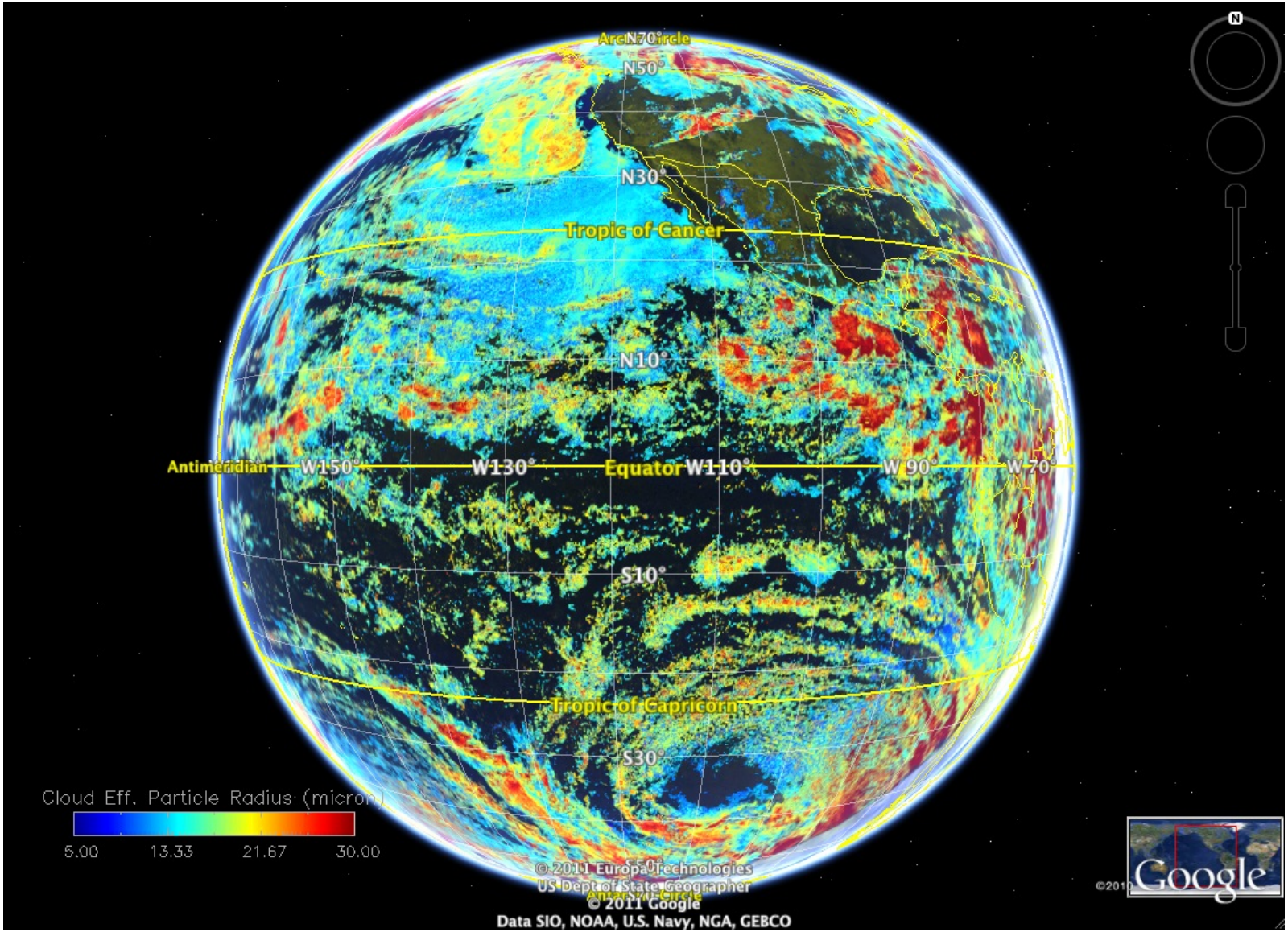
Cloud Algorithms: Cloud-top Temperature (K)



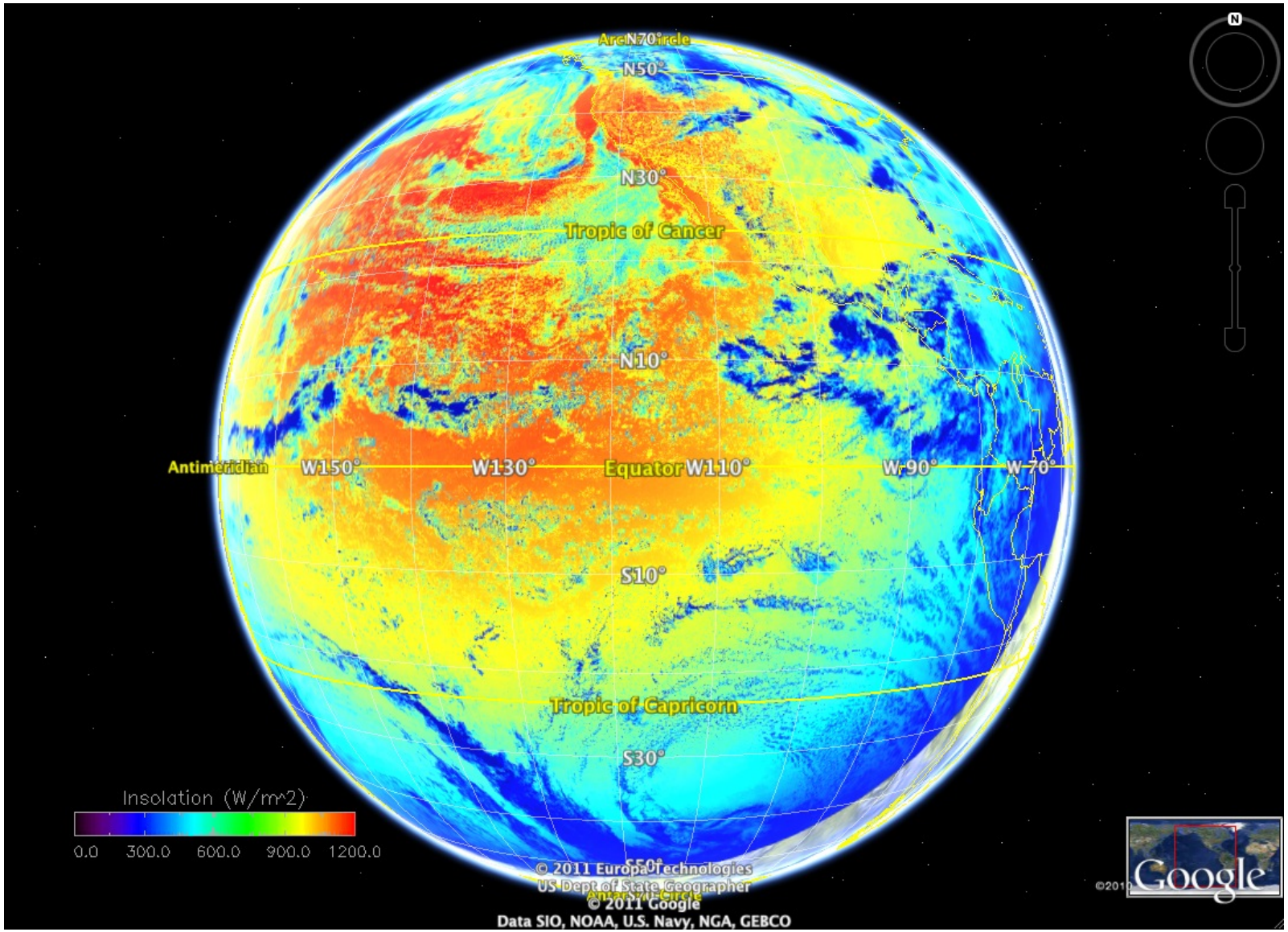
Cloud Algorithms: Cloud Water Path



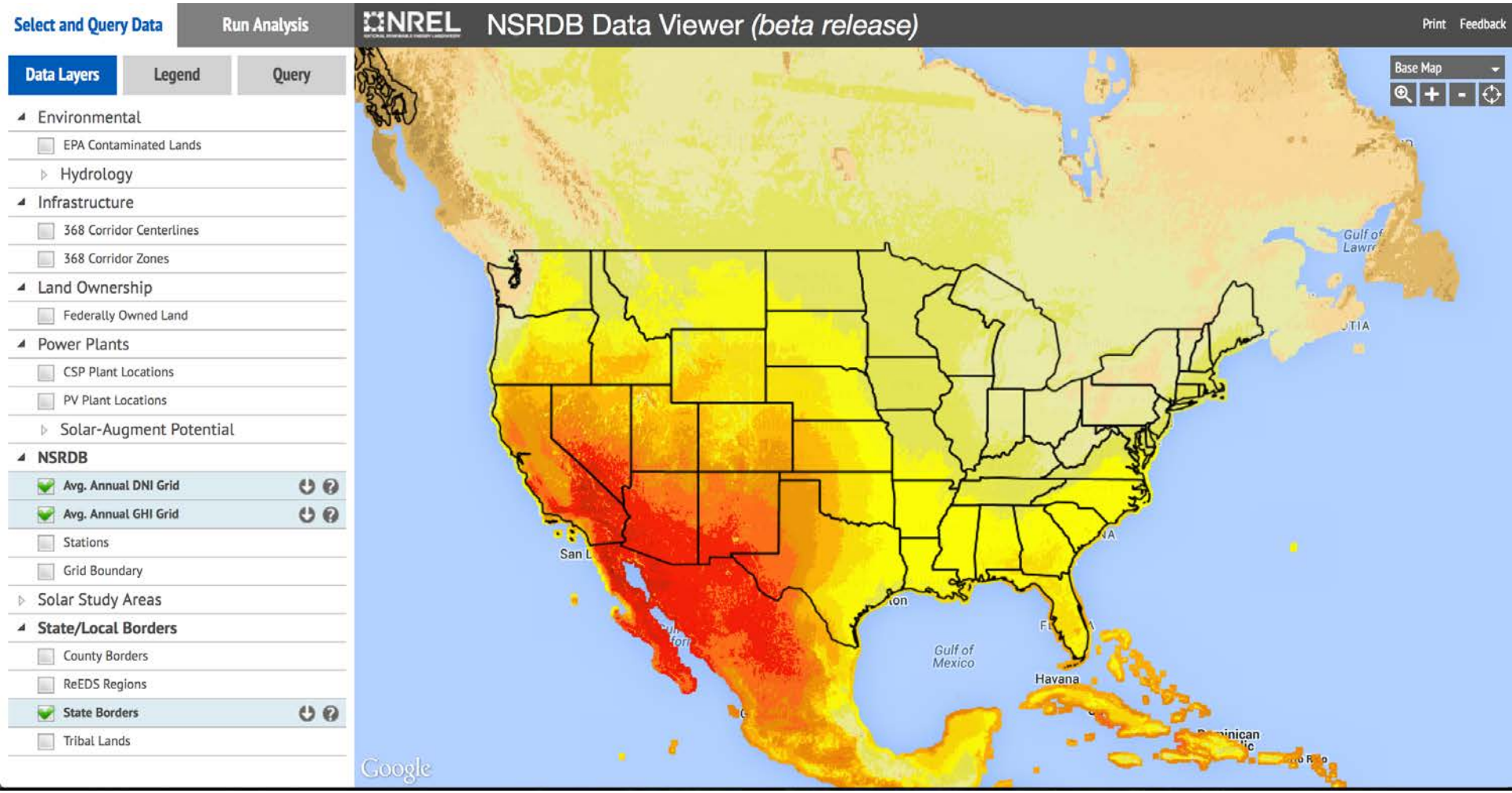
Cloud Algorithms: Cloud-top Particle Size



Radiative Transfer: Global Horizontal Irradiance



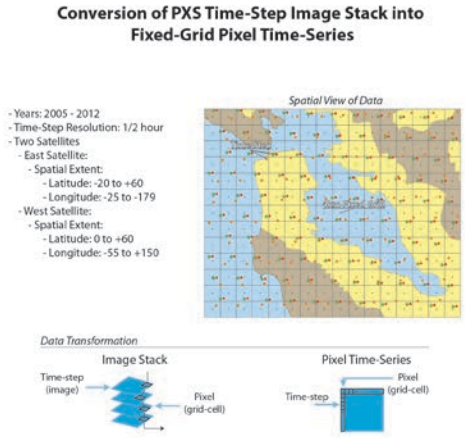
Accessing the NSRDB Data

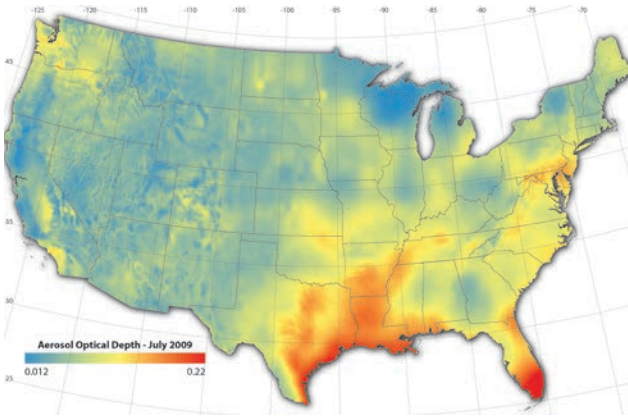


GIS based data access with web-service for multi-pixel download

Timeline

- **Beta product (2005-2012) available by March 2015**
- **Final Product (1998-2014) available by September 2015**
- **Typical Meteorological Year (TMY) product by September 2015**
- **Intermediate monthly update available after September 2015 (possible daily product)**
- **Annual dataset by following March (2015 onward) .**





Clear Sky Model Inputs- Measured at SURFRAD sites

7 sites – Data from 2009 used for the study

Aerosol	Water Vapor
Climatological	Climatological
Daily	**Climatological**
Daily	**Daily**

Not shown

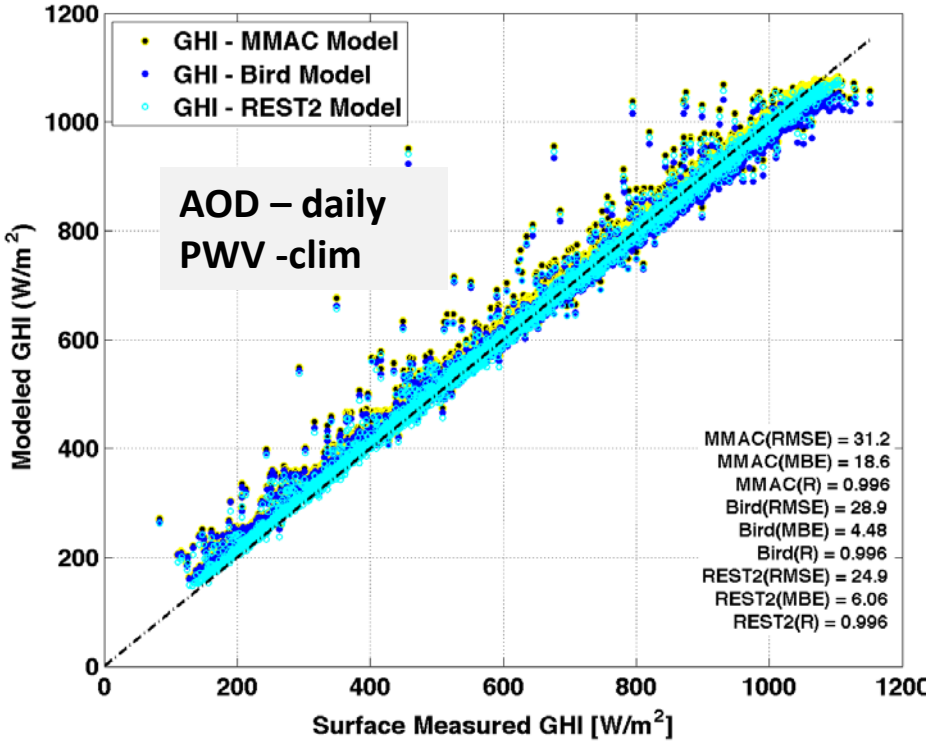
Climatological Values are annual averages

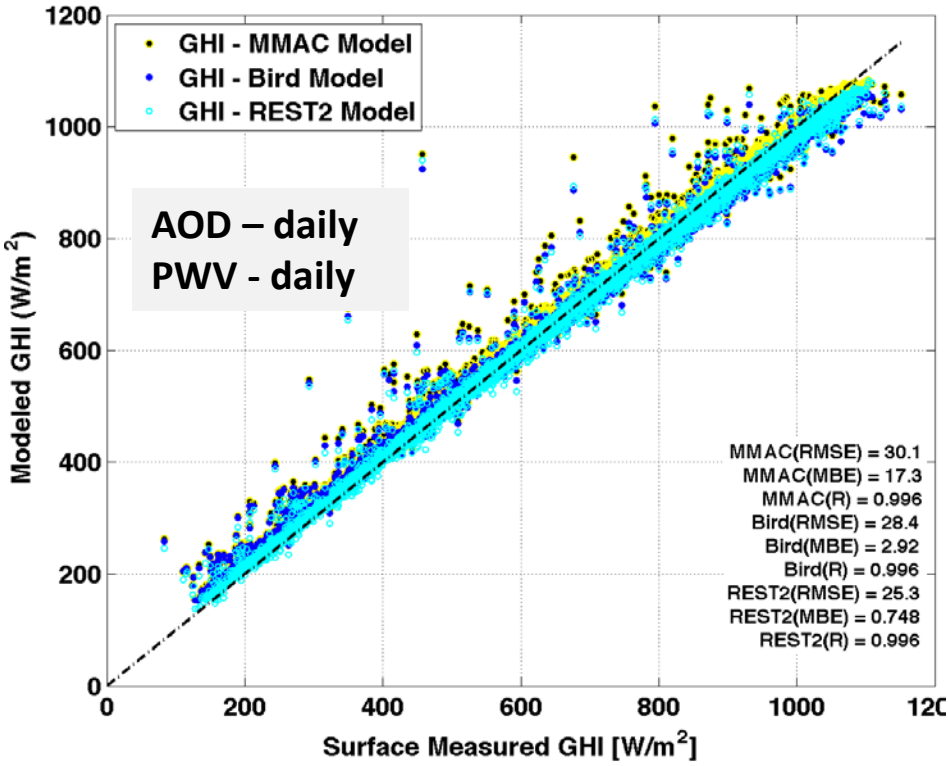
Source of Inputs:

AOD from MODIS/MISR/Aeronet

Water Vapor from CFSR

GHI -Desert Rock – NV - Clear Sky Comparison

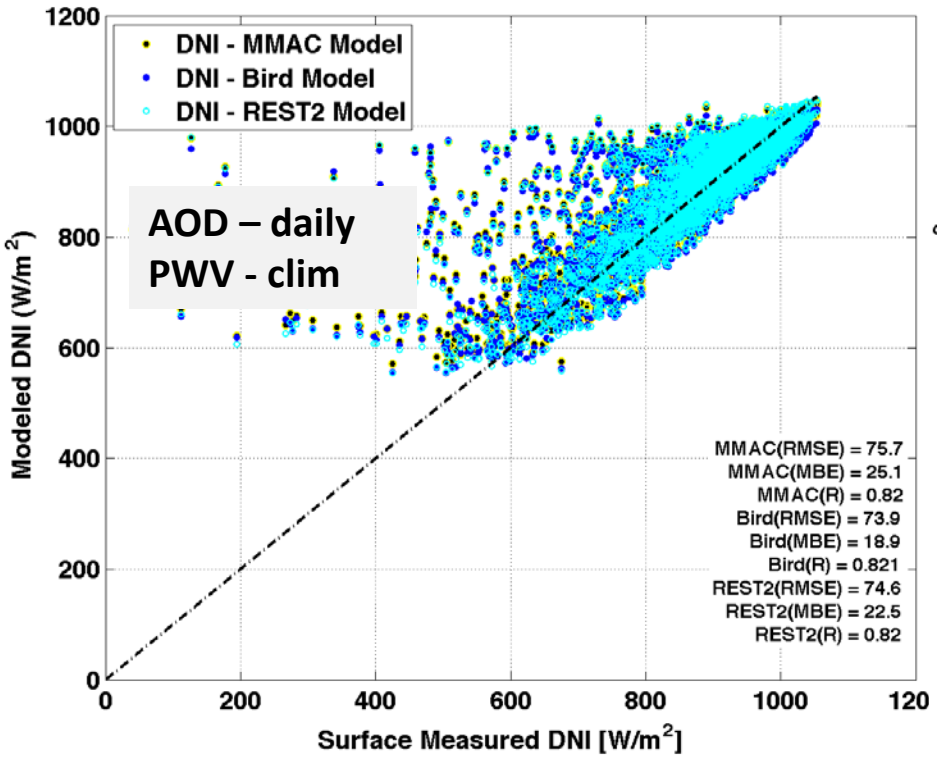


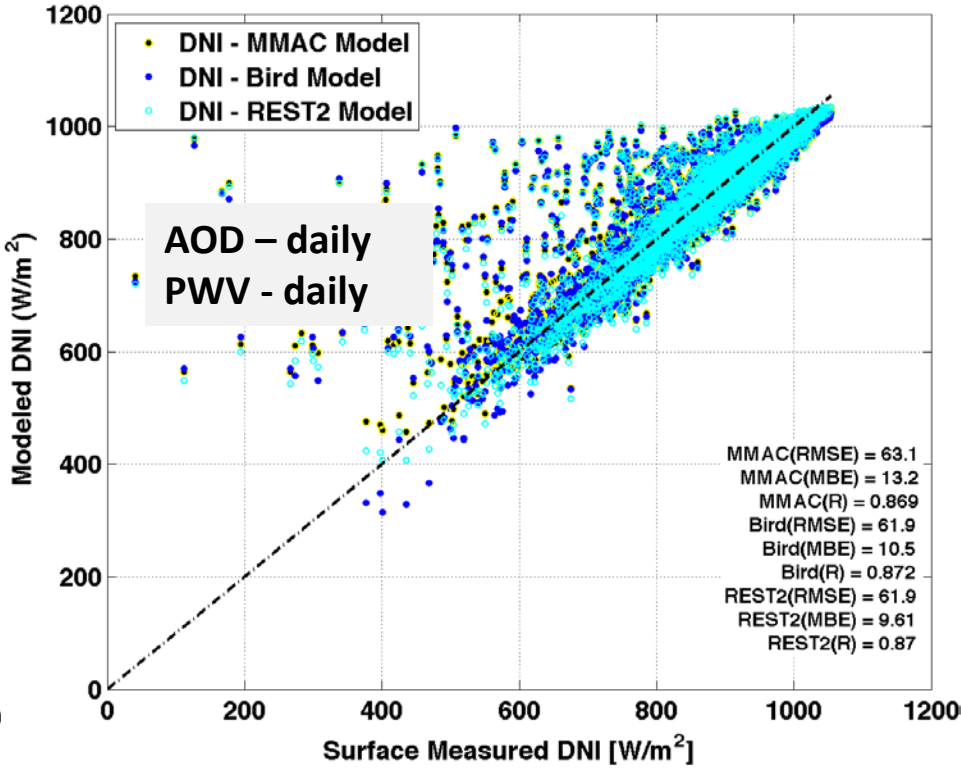


	RMSE (W/m^2)	MBE (W/m^2)	R
MMAC	31	19	0.996
Bird	29	4	0.996
REST2	25	6	0.996

	RMSE (W/m^2)	MBE (W/m^2)	R
MMAC	30	17	0.996
Bird	28	3	0.996
REST2	25	1	0.996

DNI -Desert Rock – NV Clear Sky Comparison



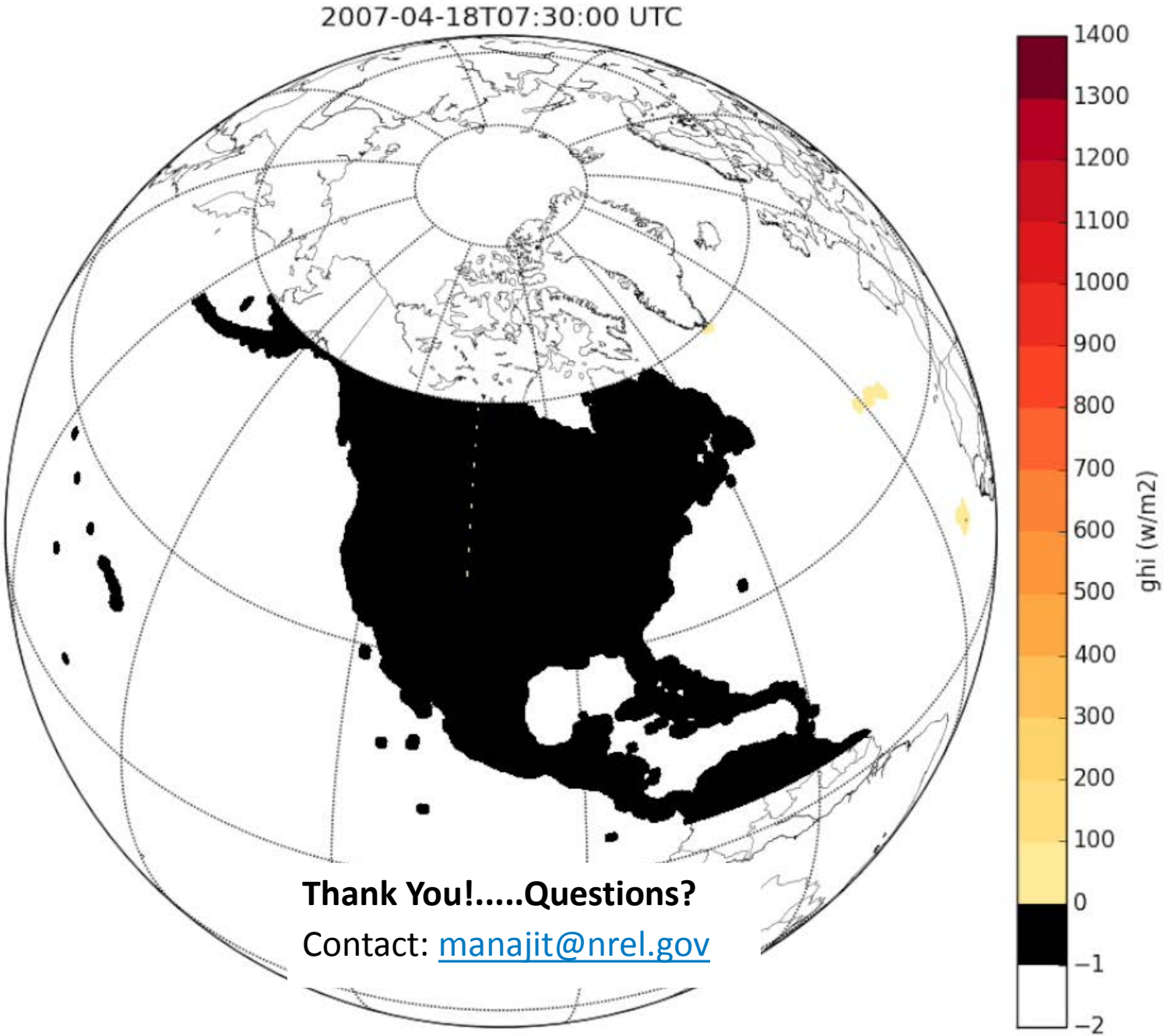


	RMSE (W/m^2)	MBE (W/m^2)	R
MMAC	76	25	0.82
Bird	74	19	0.82
REST2	75	23	0.82

	RMSE (W/m^2)	MBE (W/m^2)	R
MMAC	63	13	0.87
Bird	62	10	0.87
REST2	62	10	0.87

Conclusions

- **Clear sky GHI and DNI from the satellite is significantly accurate whether MMAC, REST2 or Bird models is used.**
- **Accurate aerosol and water vapor information is critical in properly modeling clear sky GHI and DNI.**
- **Accurate spatial and temporal satellite based spectral aerosol data are found to be the most important model input but most difficult to get right.**
- **MMAC is used in the beta version but we plan to use REST2 in future versions.**



Thank You!.....Questions?

Contact: manajit@nrel.gov

Exceptional service in the national interest

Sandia National Laboratories

GSIP Verification and Validation : Preliminary Results

Clifford W. Hansen

2015 PV Solar Resource Workshop

February 27, 2015

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

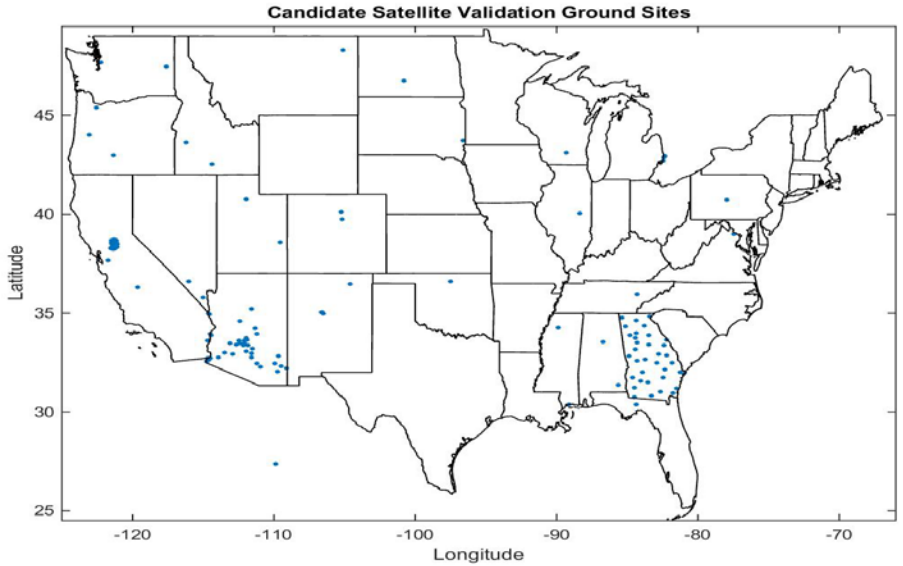
Questions to answer

- What confidence can be placed in GSIP?
  - →Compare with ground measurements
- What improvements can be made?
  - →Look for systematic differences, i.e., seasonal, geographical, and/or geometrical
- However, we are comparing a point-in-time spatial average (GSIP) to a time series at a point (ground measurement)

Quantity and quality data

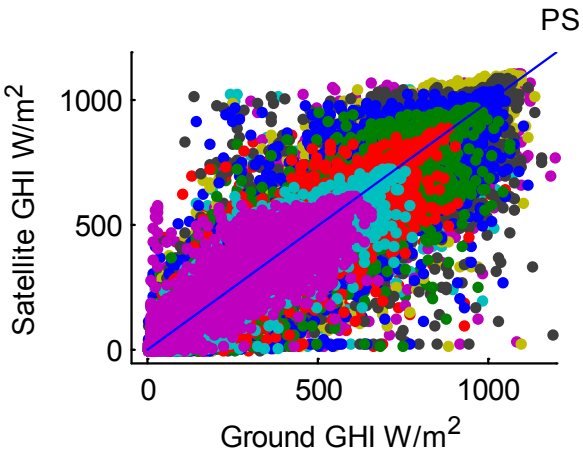
- Compare GSIP results with measured ground data
  - Avoid data used in GSIP development
  - Quantity and quality data approach
    - Many lower quality GHI instruments, some not maintained
    - Quality and self-consistency filters
  - Data at different spatial and time scales

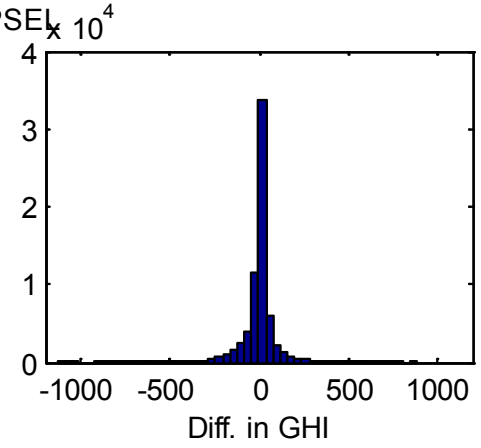
- 1 min data at ~15 locations across the US
- 60 and 15 min data for AZ and GA networks
- 1 min data for SMUD network (5km spacing)
- Time averaging of ground data

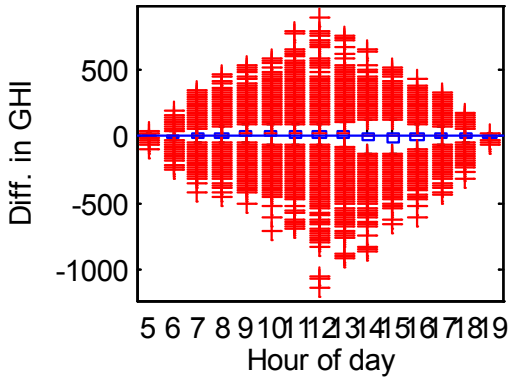


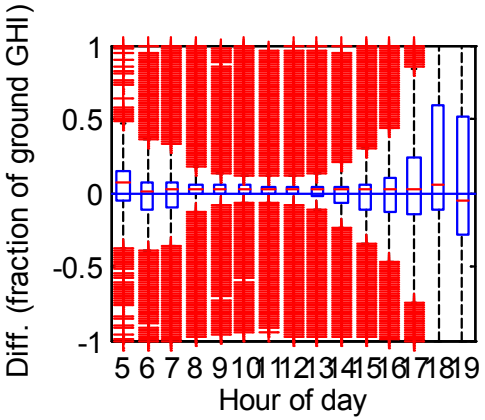
GSIP generally compares well

- 1 min data at SNL (05-12) reduced to 30 minute averages
- GSIP generally unbiased <u>at this location</u>
- Disparity between spatial and temporal scales causes most of the scatter

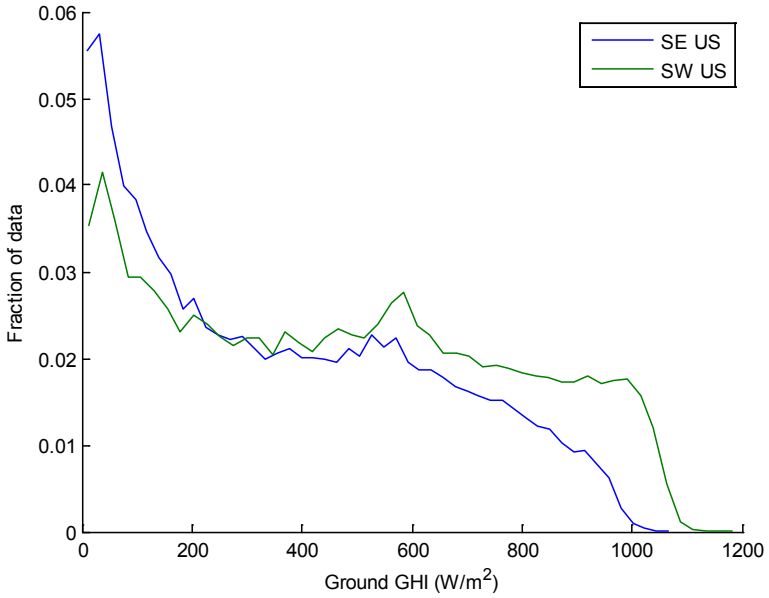


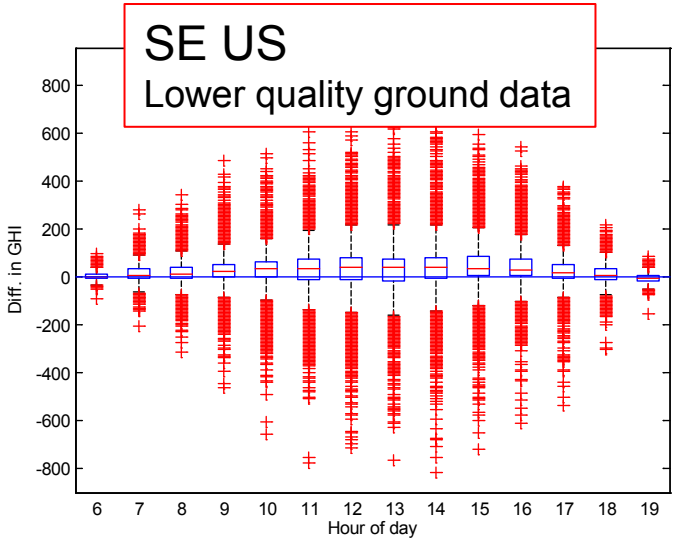


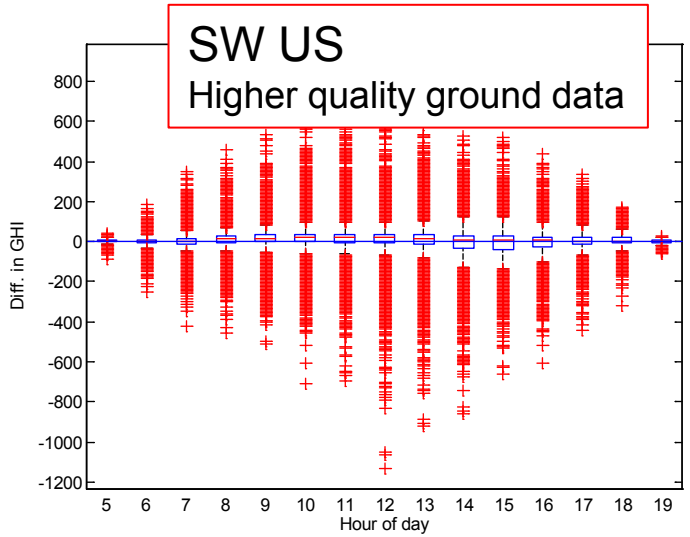




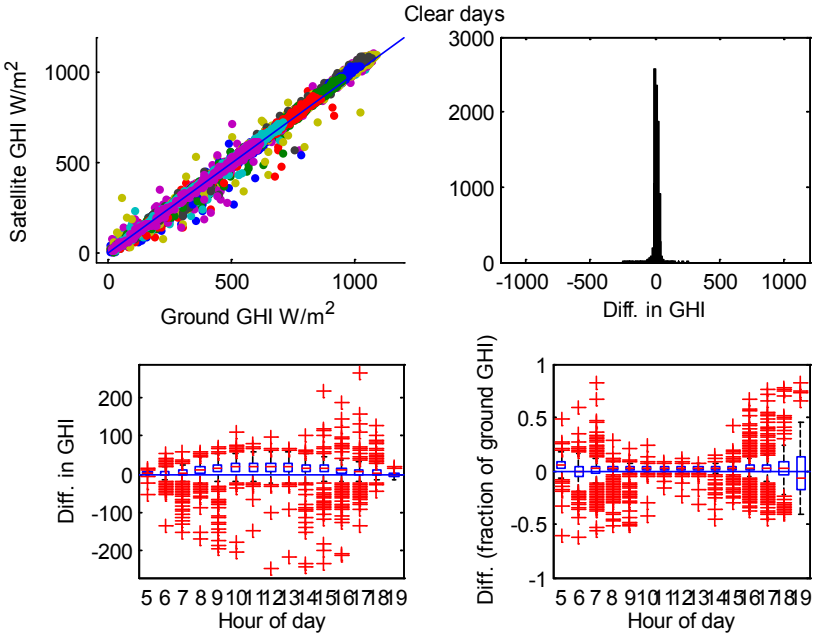
GSIP performance is similar in different climates, different quality of ground data



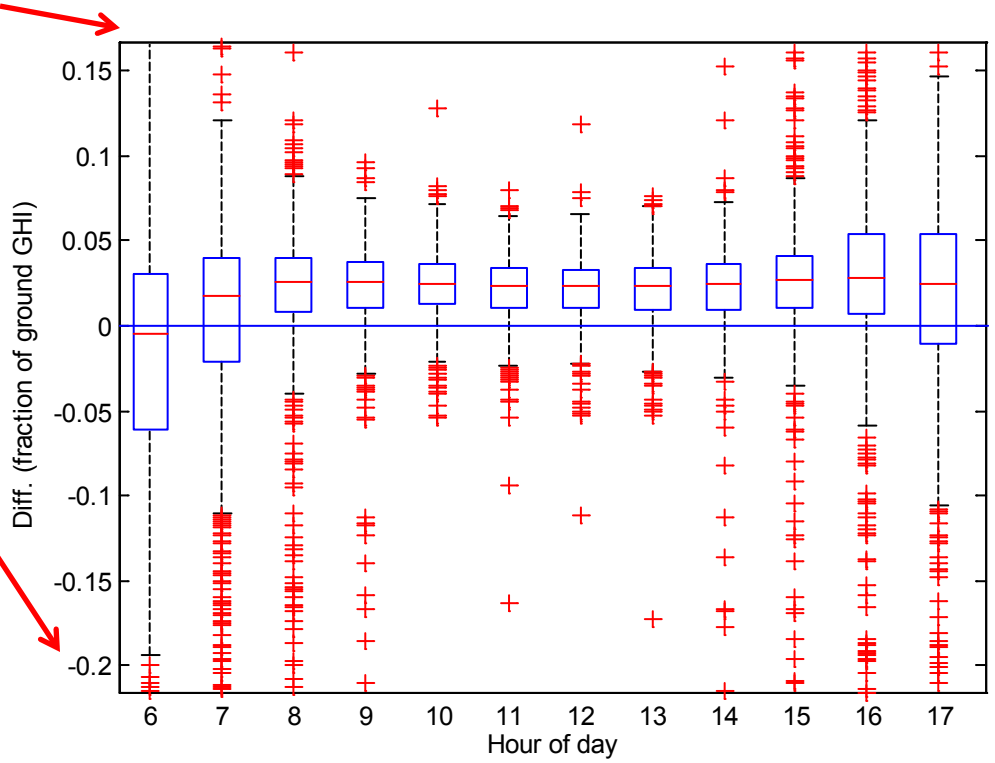




Clear sky days show evidence of bias



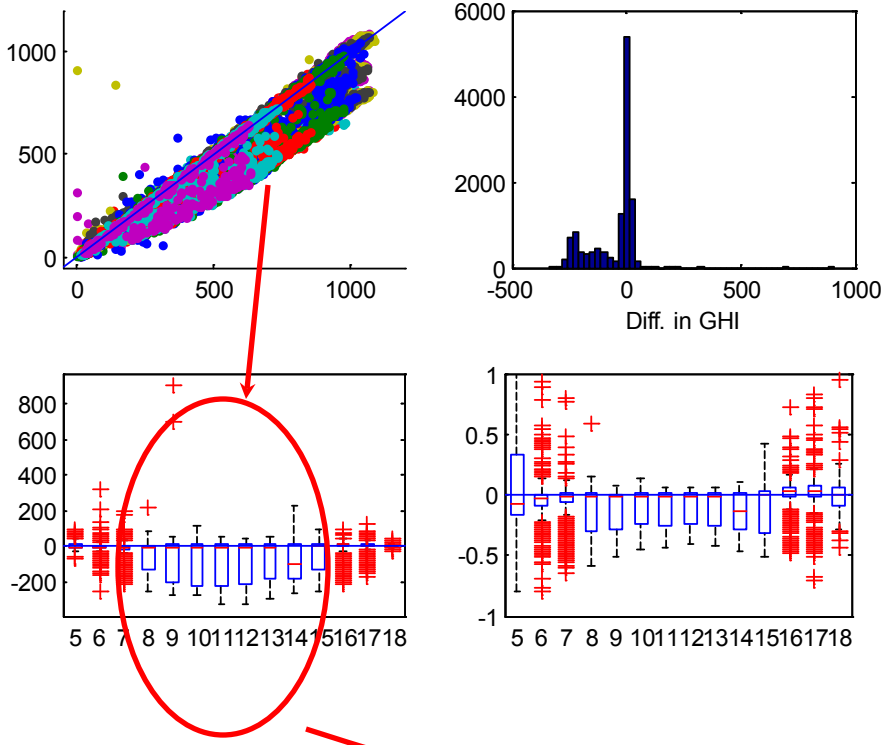
- Slight trend to overestimate GHI for clear skies
- Similar at many other locations

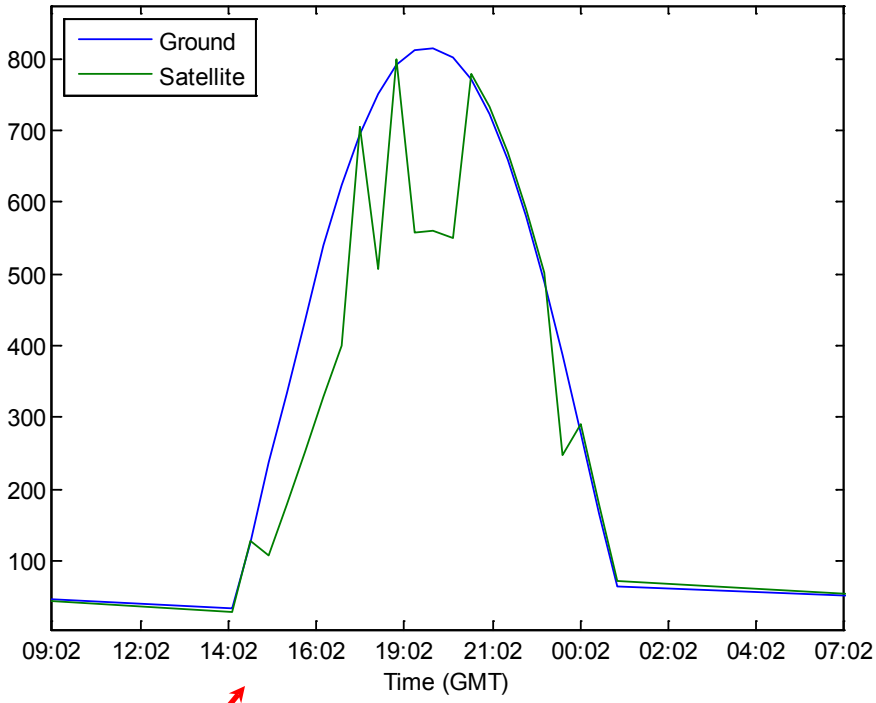


Clear sky for ground isn't always clear in GSIP

But perhaps an unavoidable result of comparing spatial average to time average

Clear days

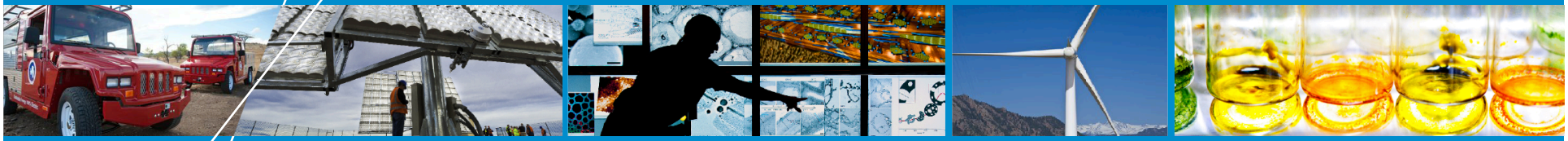




Ground > GSIP for most clear hours

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Deriving the Solar Resource Using PV Data



NREL PV Reliability Workshop

Bill Marion

February 27, 2015

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.

Goal

- **Can we use PV system performance data to determine the solar resource (direct and diffuse) which can then be used to model the performance of other PV systems?**
  - Provides source of data based on ground measurements with small incremental cost
  - Millions of micro-inverters have been deployed that are collecting performance data

Approach

- **Determine the plane-of-array (POA) irradiance from the PV system performance data.**
- **Determine the direct and diffuse horizontal irradiance from the POA irradiance.**

POA to Direct and Diffuse

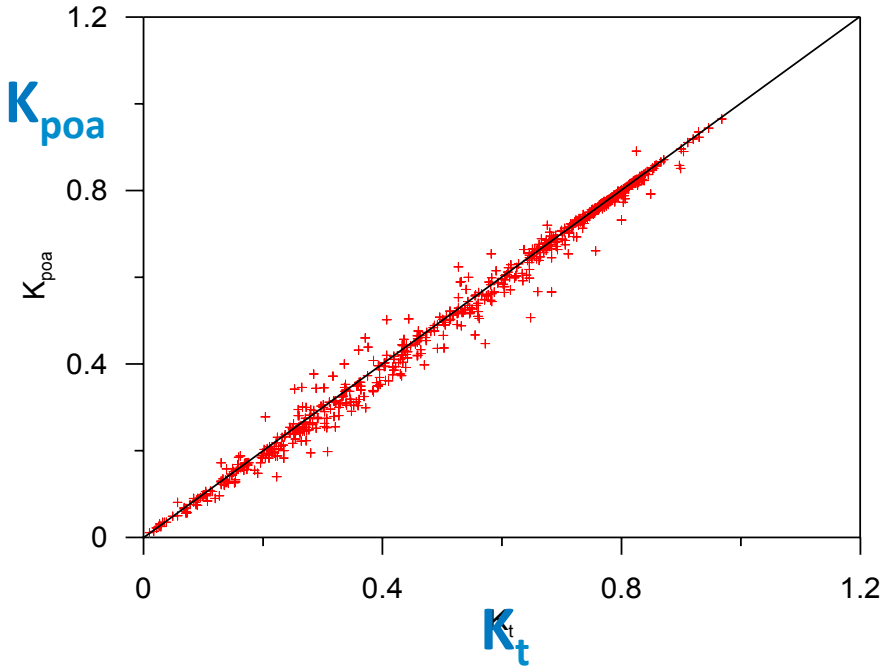
- **Problem is similar to using global horizontal irradiance (GHI) to estimate direct normal irradiance (DNI), for which we have solutions.**
  - Perez et al. (1992) modifications to NREL's DISC model
  - Key model parameter – GHI transmittance, K_t

$$K_t = GHI \div (I_0 \cdot \cos(\theta_z))$$

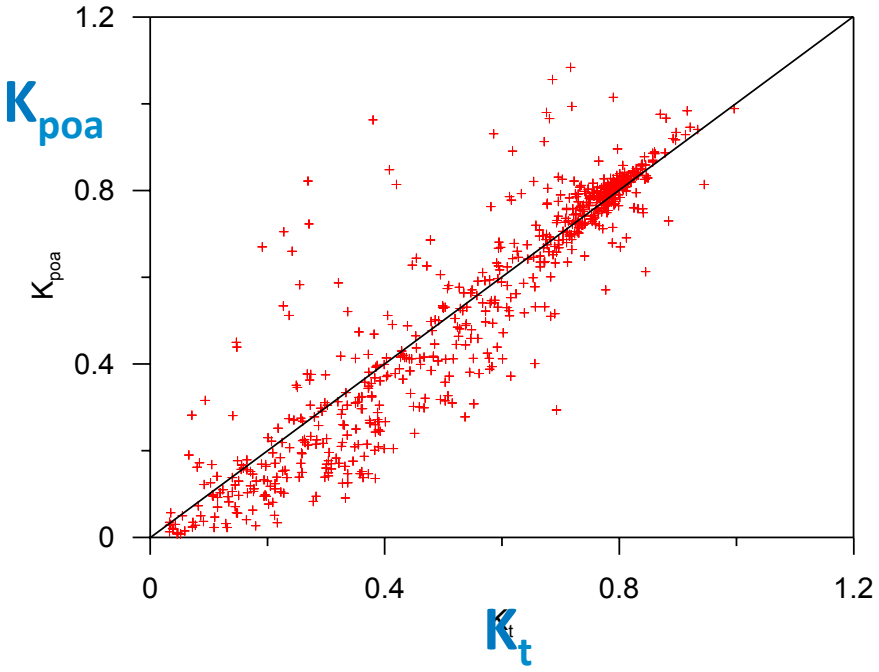
- **Substitute model parameter – POA transmittance, K_{poa}**
  - $$K_{POA} = POA \div (I_0 \cdot \cos(\theta))$$

K_t and K_{poa} Relationship Depends on Tilt

- **More similar for small tilt angles**



10 Degree Tilt



40 Degree Tilt

Method for POA to Direct and Diffuse

1. Substitute POA for GHI for input to Perez modified DISC model: model calculates K_{poa}, an DNI and diffuse horizontal irradiance (DHI).
2. Calculate error term as difference between measured POA and POA modeled using the DNI an DHI and the Perez et al. (1990) tilt irradiance model.
3. Add error term to POA input values, repeat steps an 2 t minimize error.

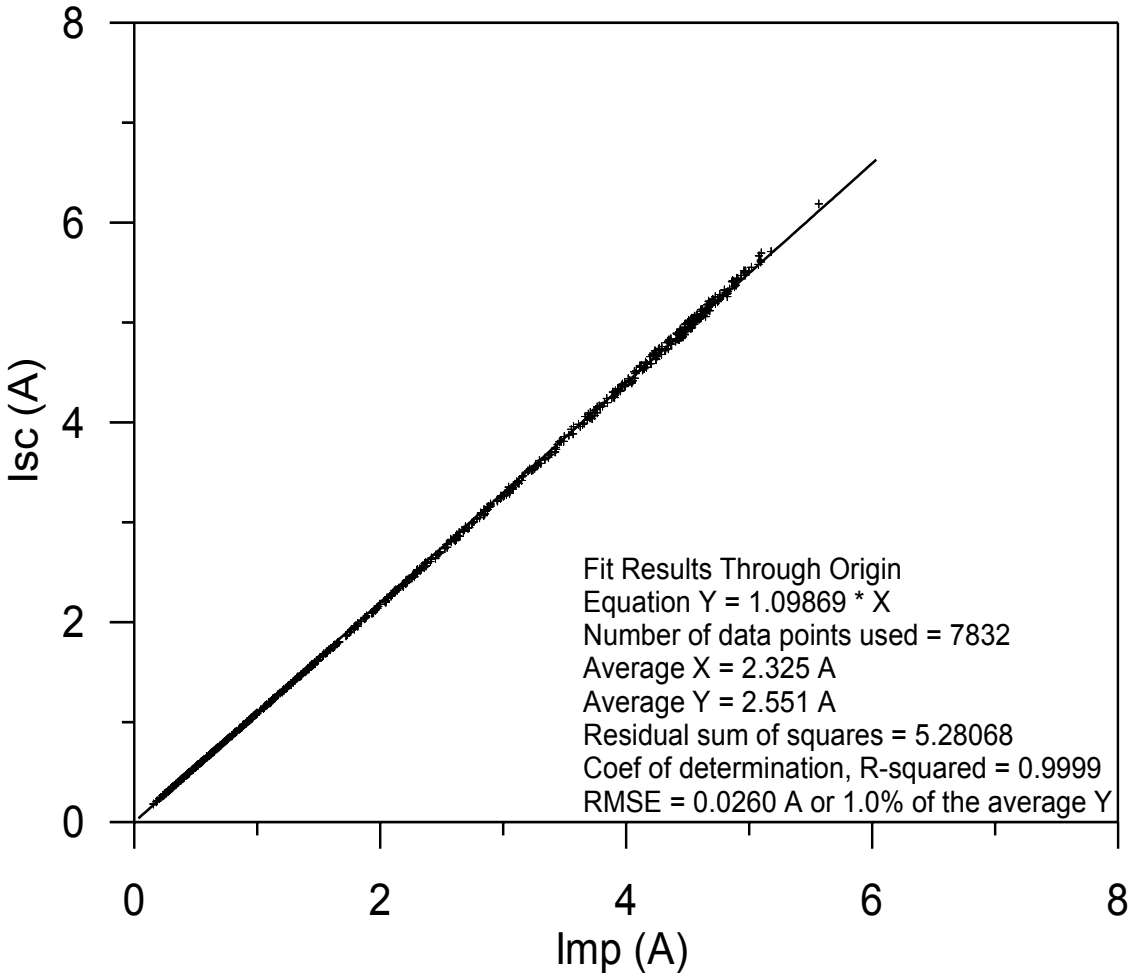
- Compared to using GHI, use of POA increases errors for modeled DNI and DHI, but when subsequently used to model POA, errors in modeled POA for same tilt are reduced.

POA from PV Performance Data

- Use operating current to determine POA irradiance (similar to using a reference cell)
- Correct for PV angle-of-incidence (AOI) effects for optimal application of the Perez models.

Relationship between I_{mp} and I_{sc}

- **Essentially linear for crystalline silicon**



Validation Data and Method

- PV modules at NREL with micro-inverters. Step 1: Measure PV module current and voltage for one PV module. Step 2: Determine POA and direct and diffuse radiation. Step 3: Use direct and diffuse radiation to model POA for other orientations.
- Direct, global, and diffuse horizontal irradiance measured at nearby Solar Radiation Research Laboratory (SRRL).

Preliminary Results - Using Measured POA

- **Measured with Kipp and Zonen pyranometers**
- **Evaluates POA to direct and diffuse method, and their use for modeling POA**

Parameter	MBE (%)	RMSE (%)	RMSE (W/m^2)
DNI	-1.4	24	108
DHI	2.5	35	56
10° Tilt POA	0.3	3	16
25° Tilt POA	0.7	2	10
40° Tilt POA*	-0.1	1	3
40° SW Tilt POA	-0.2	3	15
2-X Tracking POA	-0.2	15	95

*used for modeling DNI and DHI

Preliminary Results - Using Measured POA (cont)

- RMSE for DNI when using POA for input was about 20 W/m^2 greater than if GHI was used for input to the Perez modified DISC model.
- RMSE for fixed tilt POA irradiances generally within accepted RMSE for Perez tilt irradiance model when using measured DNI and DHI inputs (15 W/m^2)
- RMSE of 95 W/m^2 for the 2-X tracking POA irradiance is mostly attributed to the larger DNI RMSE.

Preliminary Results - Using Measured PV Data

Parameter	MBE (%)	RMSE (%)	RMSE (W/m^2)
DNI	-4.1	25	115
DHI	4.4	35	55
10° Tilt POA	-0.9	5	22
25° Tilt POA	-0.4	4	19
40° Tilt POA	-1.3	4	21
40° SW Tilt POA	-1.2	6	25
2-X Trking POA	-1.8	16	103
10° Tilt DC Pm	-0.5	4	
25° Tilt DC Pm*	-0.5	3	
40° Tilt DC Pm	-0.5	3	
40° SW Tilt DC Pm	-0.1	5	
2-X Trking DC Pm	1.0	16	

*used for modeling, POA, DNI, and DHI

Deriving the Solar Resource Using PV Data

Questions?

bill.marion@nrel.gov

2015 NREL Photovoltaic (PV) Solar Resource Workshop

Practical Issues with Quantifying Solar Resource for PV Systems

Justin Robinson

February 27, 2015

Acknowledgements

Kathleen E. Moore, Ph.D, iedat
Mark Blohnquist, Apogee Instruments
Jobie Carlisle, Utah Climate Center
Bart Kneff, Campbell Scientific Inc
Jonathan Wright, Met Spec Ltd

GroundWork Met Equipment and Services

Development or pre-construction
Plant build and acceptance testing
Operations and maintenance (O&M)
Asset turnover

GroundWork Services

System Design and Submittals
Equipment Supply, Fabrication and Testing
Installation and Commissioning
GroundWatch™ Data Quality Program
Rapid Response Field Work
Solar Resource Assessments through Clean Power Research
Program and Fleet Management

Practical Issues for Quantifying Solar Resource

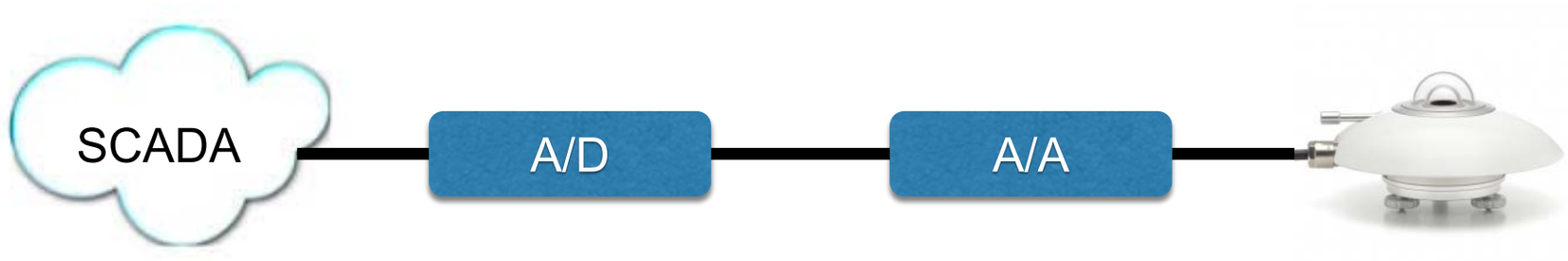
System Accuracy
Pyranometer Azimuth, Tilt, and Level
Siting Within Solar Plant
Ongoing O&M and Data Review
Ambient Temperature

Pyranometer specification list

Ref. no.	Specification	Pyranometer category		
		Secondary standard	first class	second class
1	Response time (time for 95% response)	< 15 s	< 30 s	< 60 s
2	Zero offsets response to 200 W/m² net thermal radiation response to 5 K/hr temperature change	 < 7 W/m² < 2 W/m²	 < 15 W/m² < 4 W/m²	 < 30 W/m² < 8 W/m²
3a	Non-stability (percentage change in responsitivity per year)	< 0.8 %	< 1.5 %	< 3 %
3b	Non-linearity (due to change in irradiance within 100 to 1000 W/m²)	< 0.5 %	< 1 %	< 3 %
3c	Directional response	< 10 W/m²	< 20 W/m²	< 30 W/m²
3d	Spectral selectivity	< 3 %	< 5 %	< 10 %
3e	Temperature response	< 2 %	< 4 %	< 8 %
3f	Tilt response	< 0.5 %	< 2 %	< 5 %

System Accuracy

Must account for all contributions to measurement accuracy
Estimate accuracy: square root of the sum of squares



System Accuracy Example

Analog to Analog Converter

Voltage Input: +/-0.1% = 2.9 W/m2

Current Output: +/-0.1 % = 2.9 W/m2

Analog to Digital Converter

Voltage Input: +/-0.07% = 2.03 W/m2

Pyranometer

Hourly: 2% = 22.3 W/m2 (ISO 9060)

Azimuth, Tilt, & Level

Proper azimuth, tilt, and level critical to accurate irradiance

Significant issues with proper azimuth alignment of POA pyranometers

Accurate alignment with compass difficult

Most technicians not equipped with accurate inclinometers

Azimuth, Tilt, & Level

Verify tilt and level with two-axis inclinometer

Verify azimuth with Magnetometer

Low cost

Easily integrated

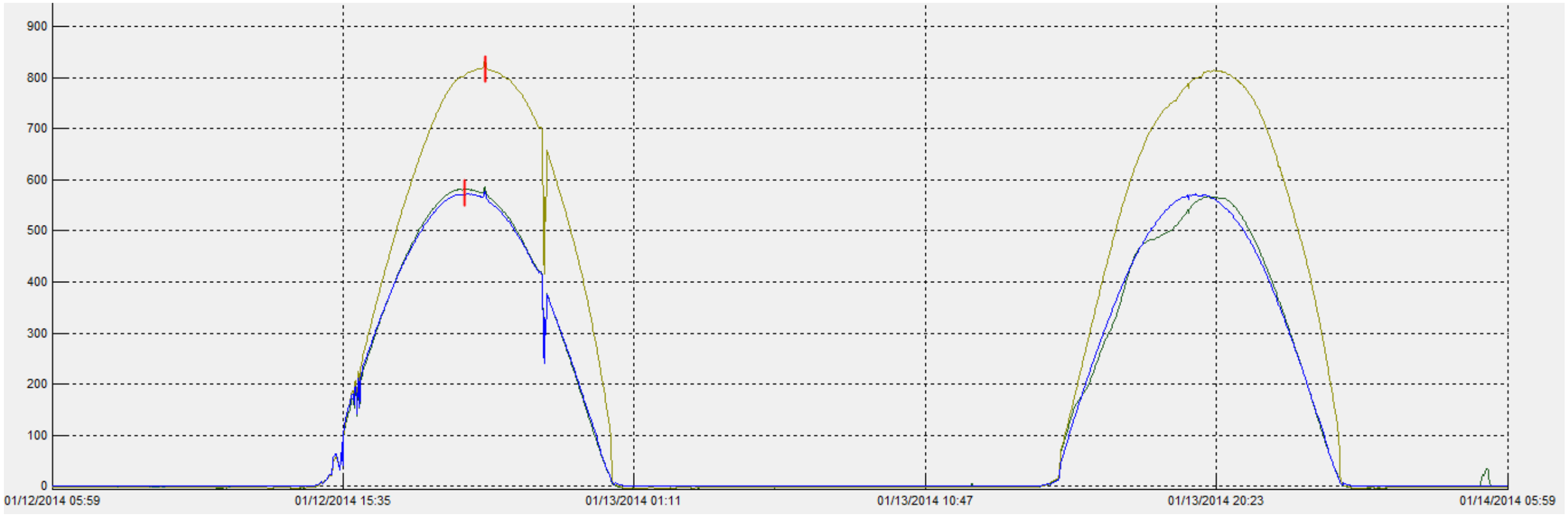
Bracket orientation only

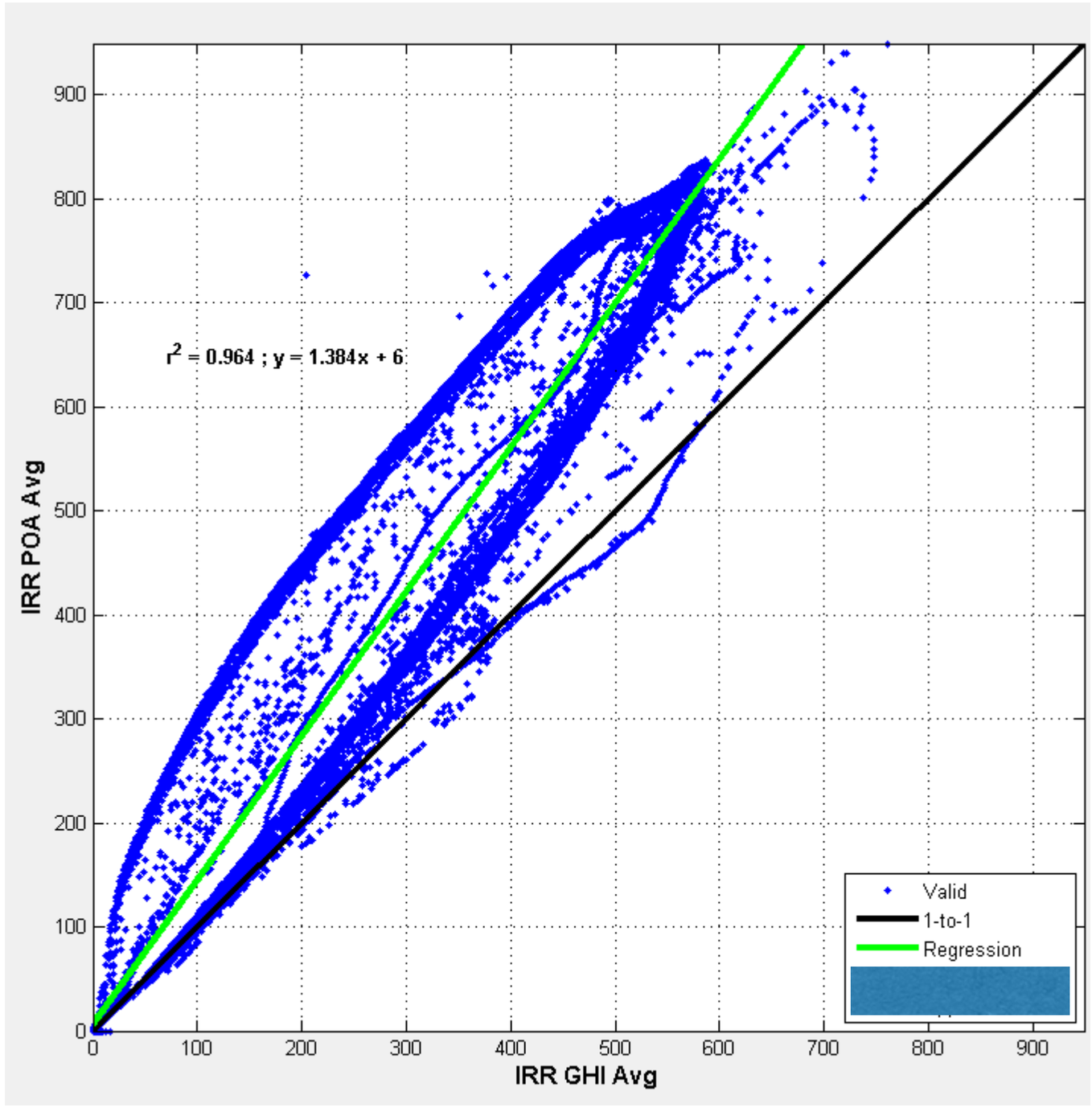
Option to embed in the pyranometer

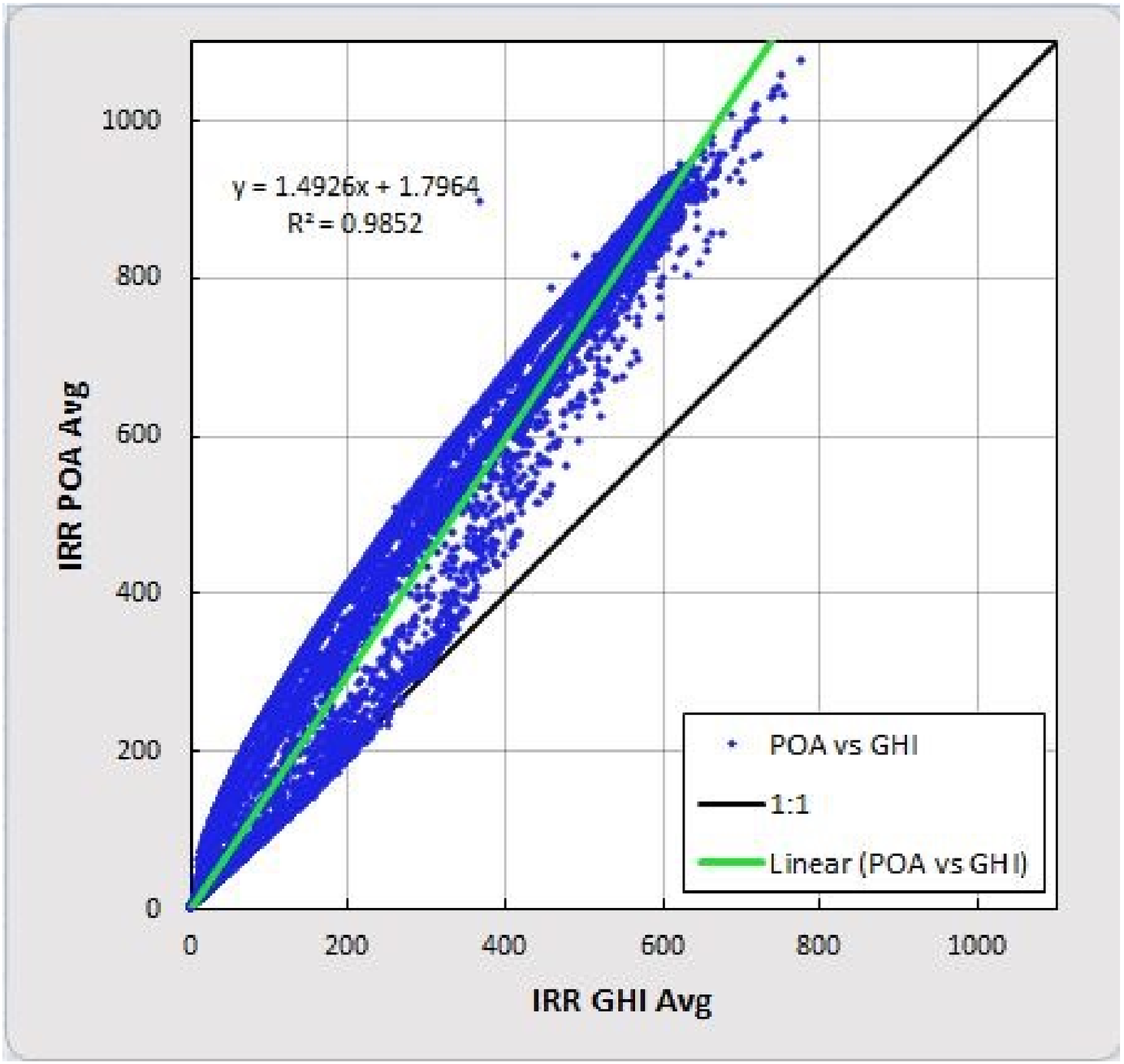
43°

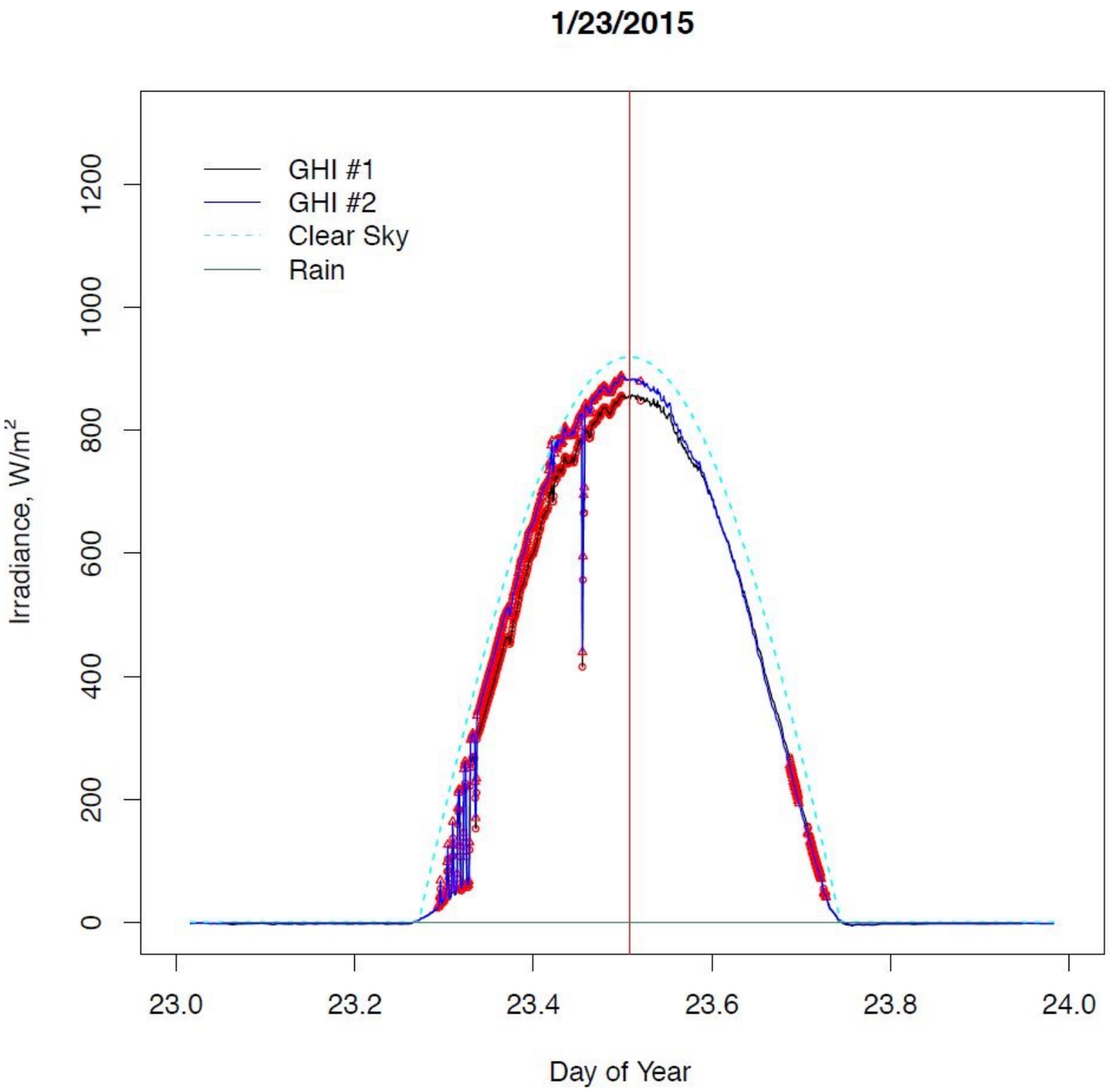
≠

HUSKY
Hold
On/Unit/Off
Reset


900
800
700
600
500
400
300
200
100
0
01/12/2014 05:59
01/12/2014 15:35
01/13/2014 01:11
01/13/2014 10:47
01/13/2014 20:23
01/14/2014 05:59


r^2 = 0.964 ; y = 1.384x + 6
IRR POA Avg
IRR GHI Avg
0
100
200
300
400
500
600
700
800
900
Valid
1-to-1
Regression


y = 1.4926x + 1.7964
R² = 0.9852
1000
800
600
400
200
0
0
200
400
600
800
1000
IRR POA Avg
IRR GHI Avg
POA vs GHI
1:1
Linear (POA vs GHI)


1/23/2015
GHI #1
GHI #2
Clear Sky
Rain
Irradiance, W/m²
0
200
400
600
800
1000
1200
23.0
23.2
23.4
23.6
23.8
24.0
Day of Year

Siting Considerations: Plant Design

Design plant to reduce field uncertainty of irradiance and met data

Minimize GPOA pyranometer cable lengths

Reduce EMF exposure

Avoid albedo and reflections on pyranometers

Design station for frequent pyranometer cleaning and leveling

Siting Considerations: Pyranometer Cable Length

High noise environment
Voltage drop negligible
uV output signal
Cable acts as antenna
EMF
Use shielded cable with drain
60 Hz signal conditioning
Over sample and average

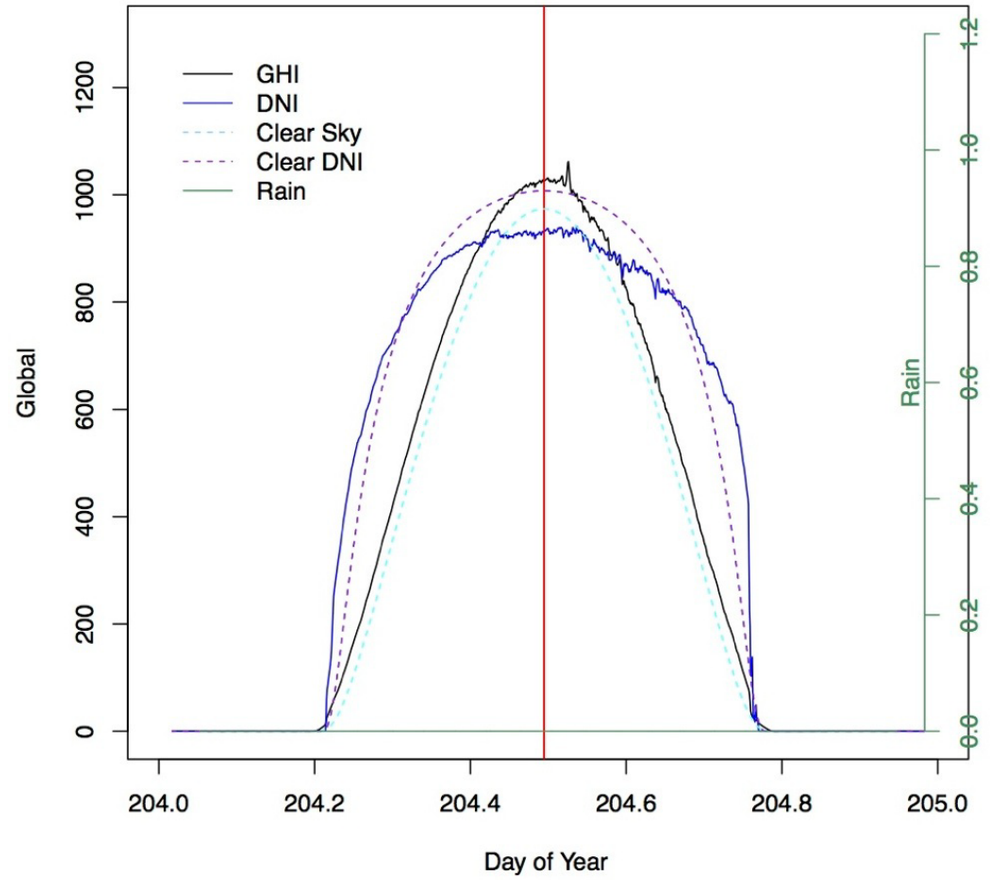
courtesy Swinerton Renewable Energy

Siting Considerations: Albedo and Reflections

Albedo is critical to accurate measured and modeled POA

Keep inverters, buildings, reflective surfaces out of sensor FOV

Reflections are hard to predict; must monitor data



Ongoing O&M and Data Review

Defined and frequent cleaning and leveling

Biennial service and pyranometer calibrations

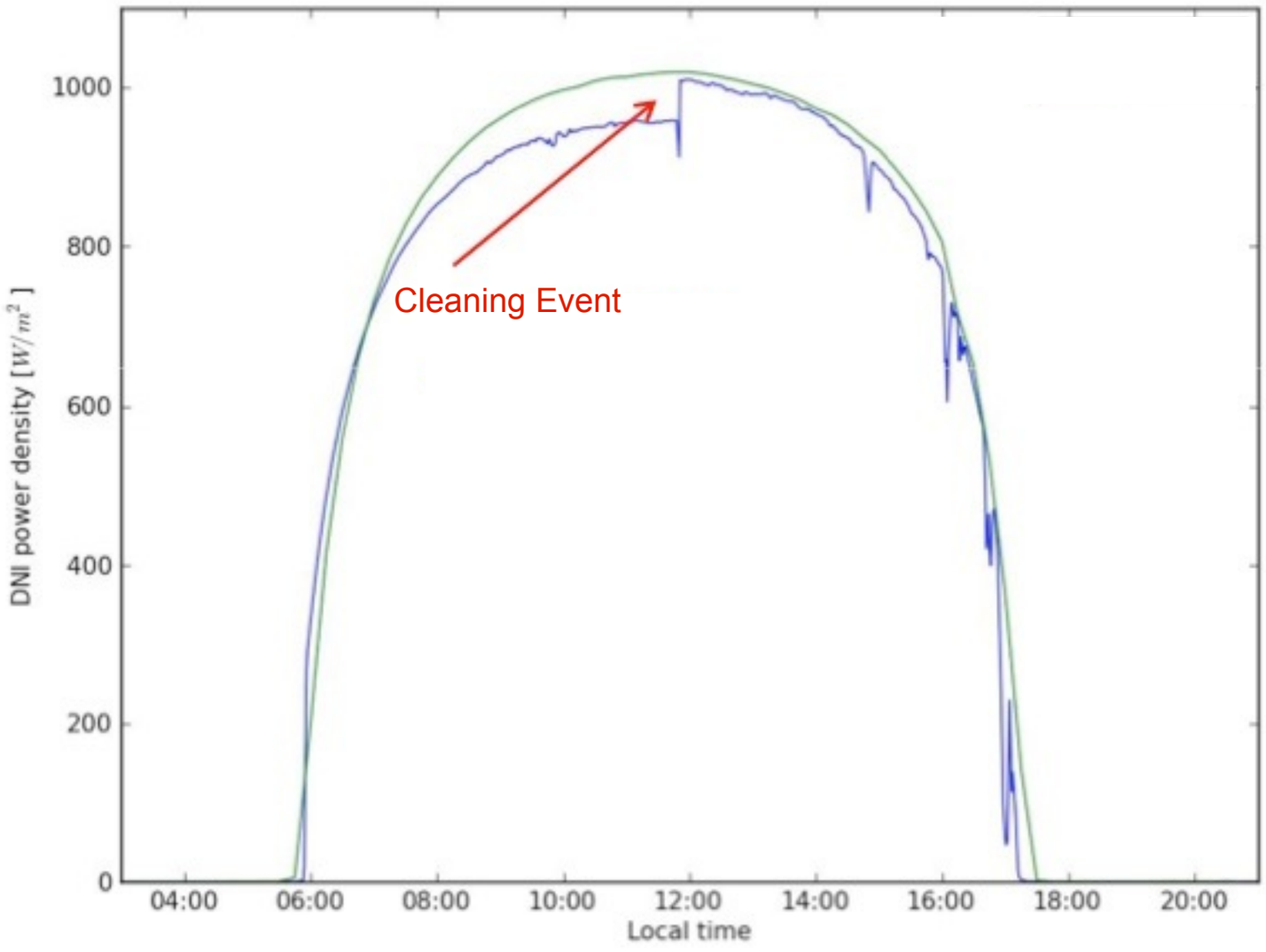
Daily automated analysis and plotting scripts

Correlate data with cleaning events

Compare redundant sensors and/or component sum values

Evaluate symmetry of irradiance curves

Compare clear sky transmittance indices (NREL SERI QC)


Cleaning Event
DNI power density [W/m^2]
1000
800
600
400
200
0
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
Local time

Ambient Temperature

Prevalent specification is passive gill ambient temperature shield

Maximum of 10℃ discrepancy between passive and active methods

Lin et al., 2001; Huwald et al., 2009

Impact of +/-10℃ temperature offset on power estimates?

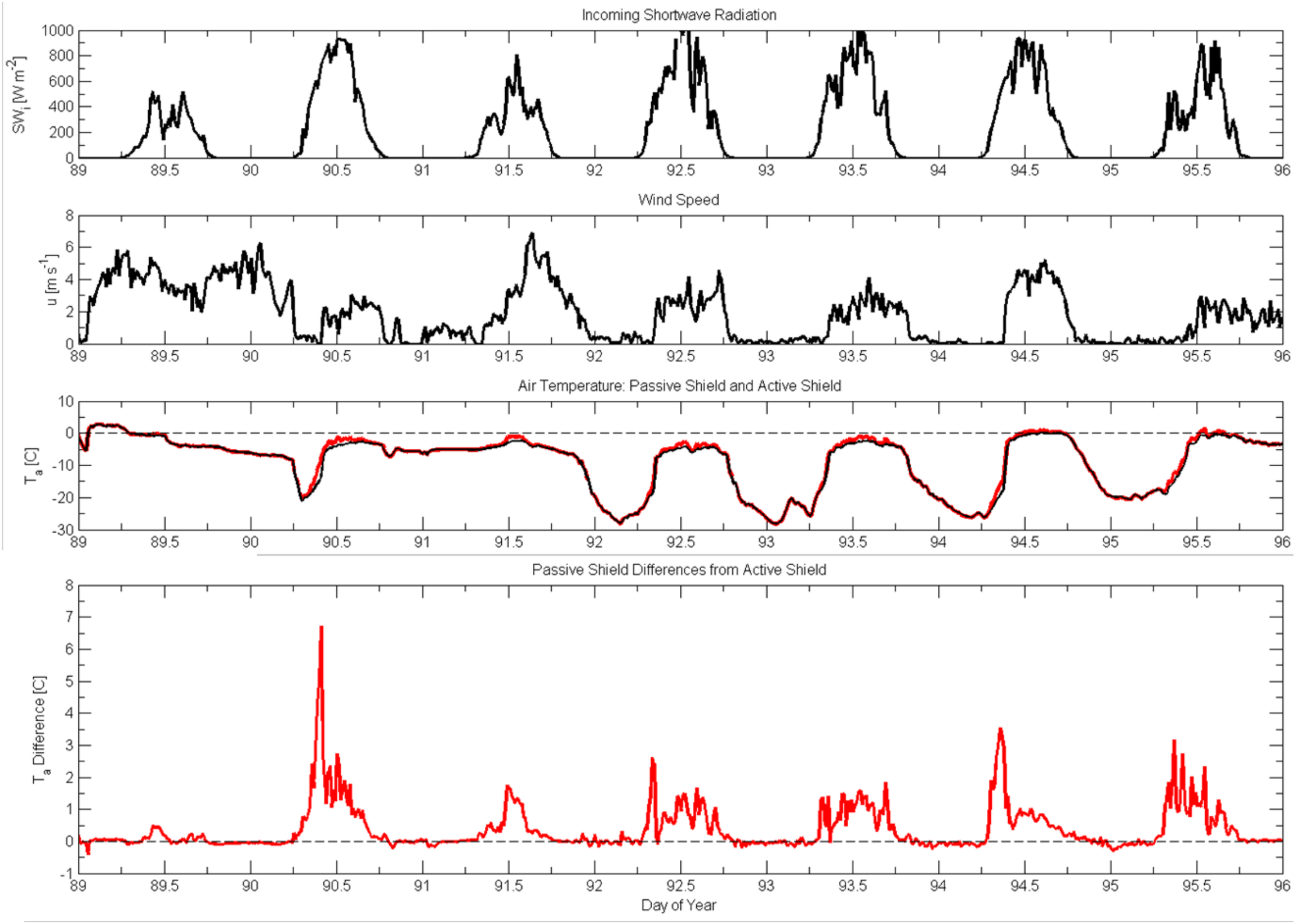
High Albedo Ambient Temperature: Peter's Sinks

15 Min Mean ambient temperature study

February 2013 through October 2014

One ventilated shield versus one 6-plate passive shield

Low thermal mass sensor design (0.1℃ accuracy)


Incoming Shortwave Radiation
SW_i [W m^-2]
1000
800
600
400
200
0
Wind Speed
u [m s^-1]
8
6
4
2
0
Air Temperature: Passive Shield and Active Shield
T_a [C]
10
0
-10
-20
-30
Passive Shield Differences from Active Shield
T_a Difference [C]
8
7
6
5
4
3
2
1
0
-1
89
89.5
90
90.5
91
91.5
92
92.5
93
93.5
94
94.5
95
95.5
96
Day of Year

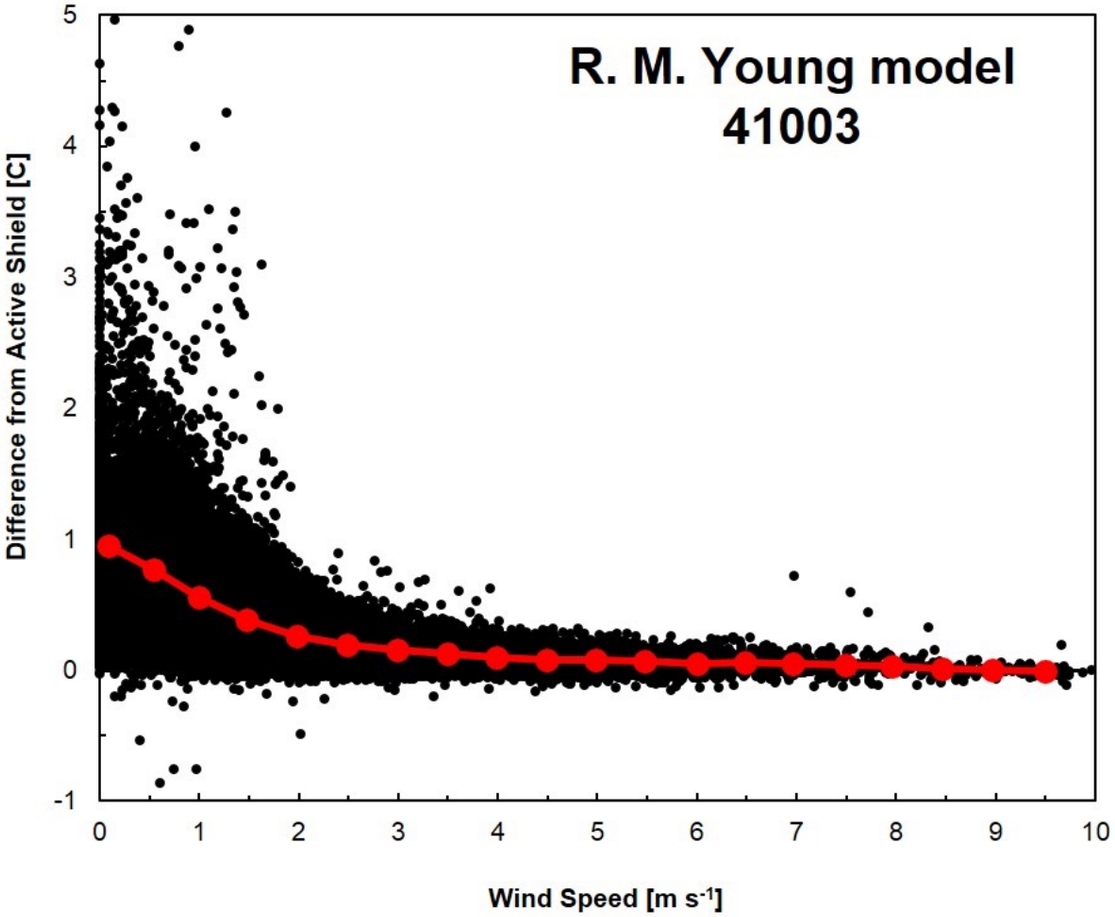
Ambient Temperature: Logan, UT

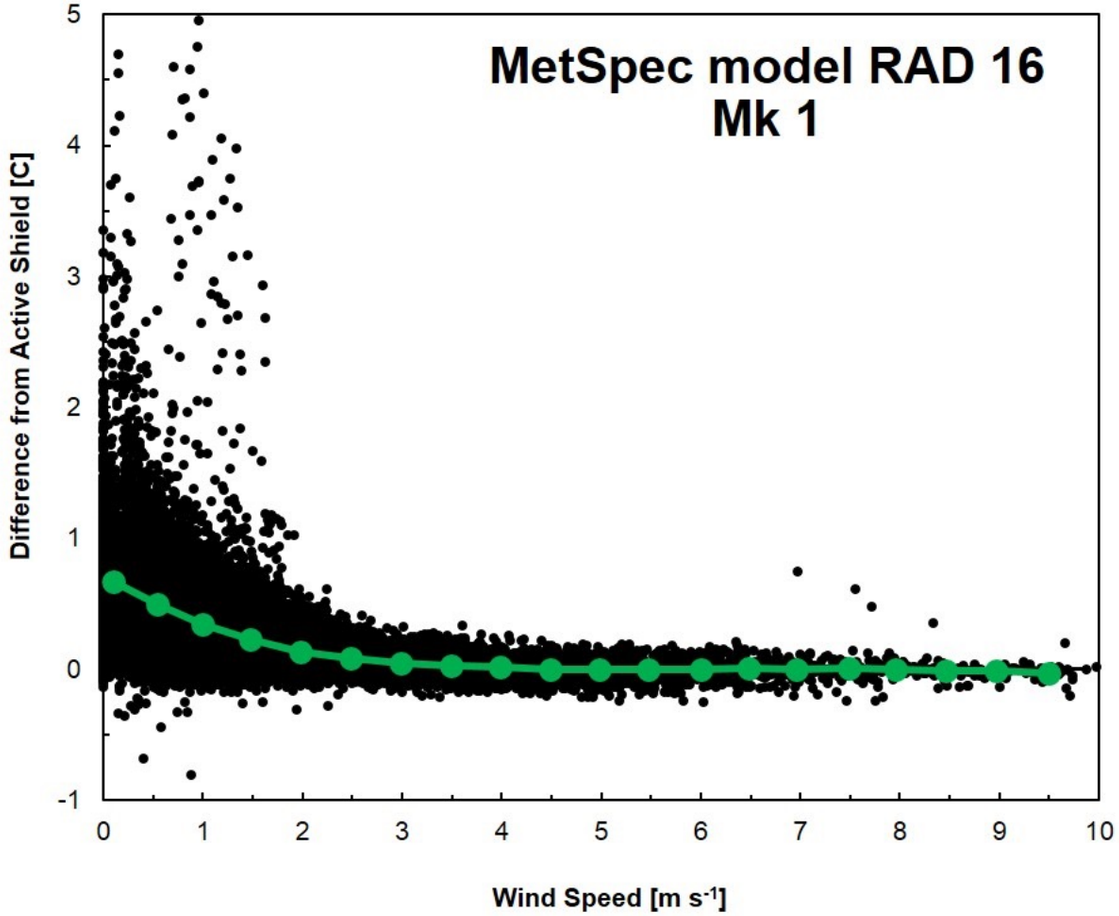
5 Min Mean ambient temp study

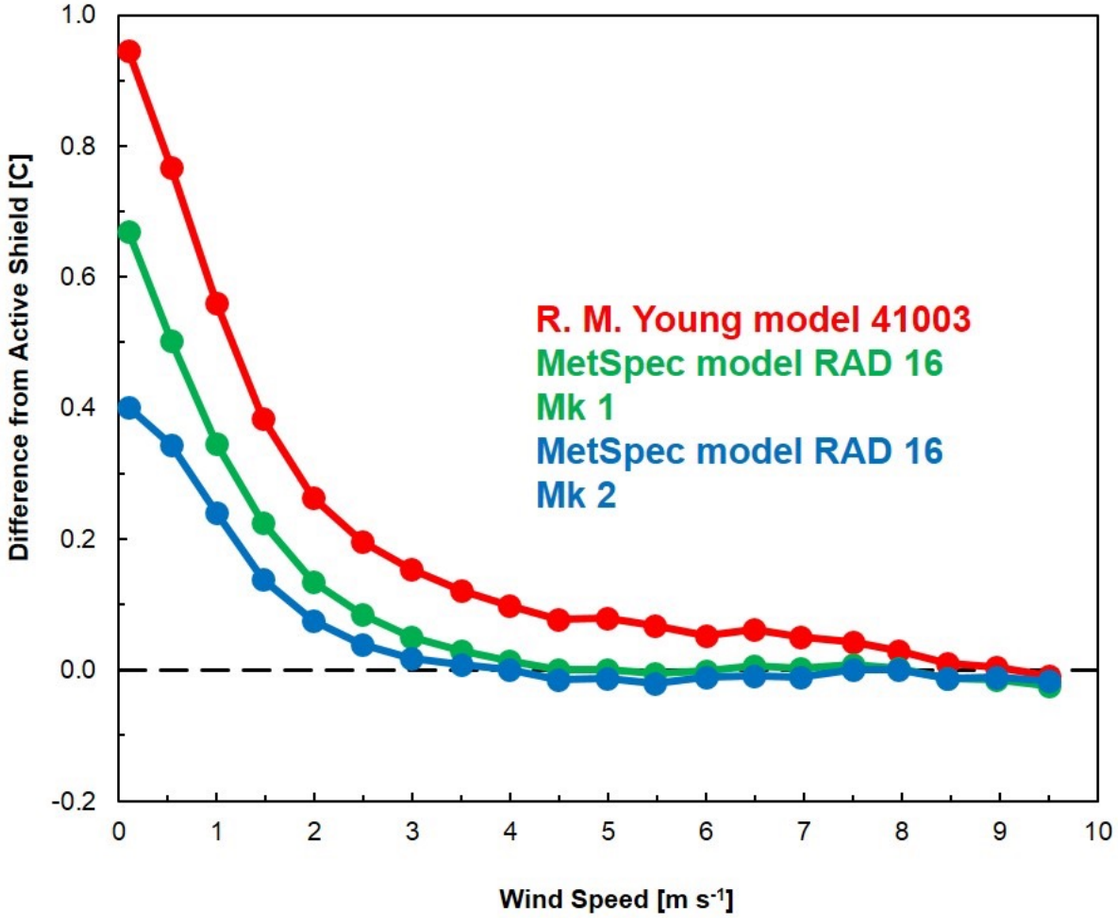
September 2013 to present

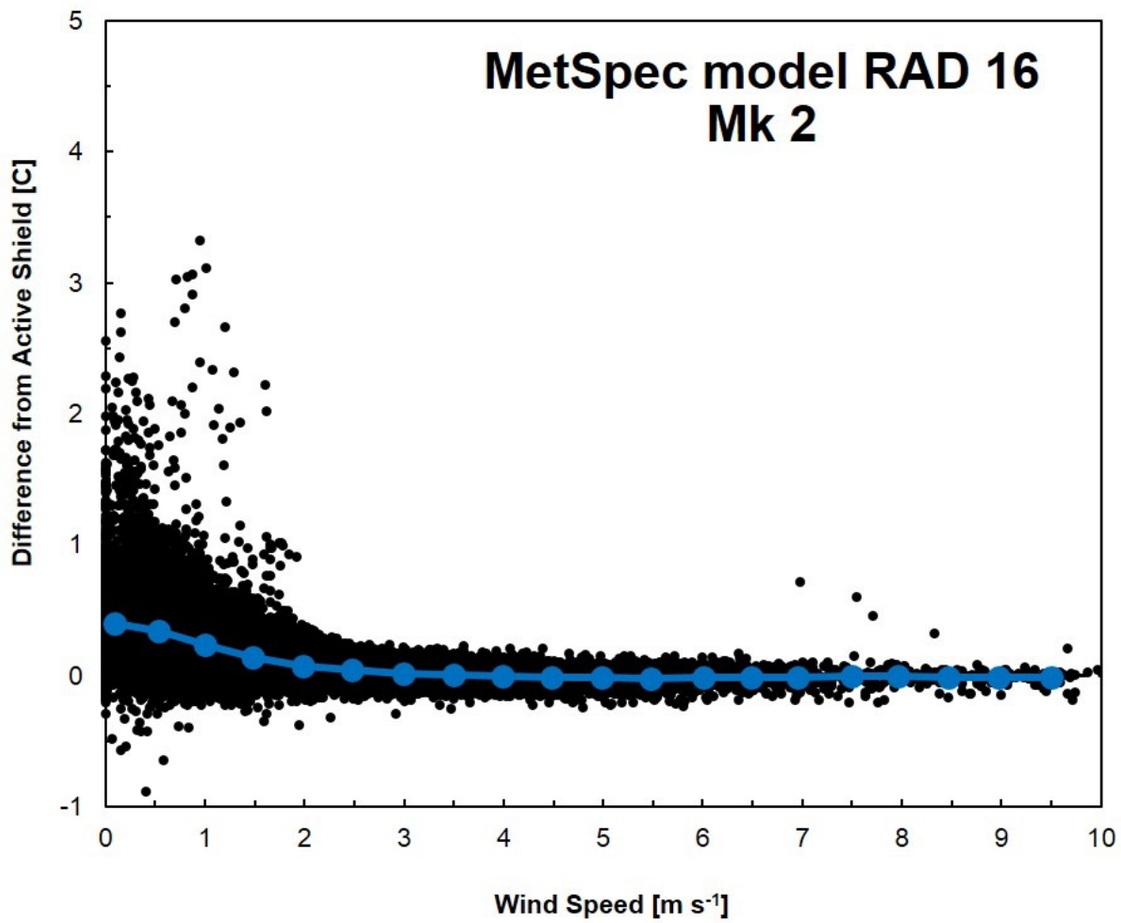
Two ventilated shields, six 10-plate passive shields

Low thermal mass sensor design (0.2℃ Accuracy)


R. M. Young model
41003
Difference from Active Shield [C]
Wind Speed [m s-1]


MetSpec model RAD 16
Mk 1
Difference from Active Shield [C]
Wind Speed [m s-1]


R. M. Young model 41003
MetSpec model RAD 16
Mk 1
MetSpec model RAD 16
Mk 2
Difference from Active Shield [C]
Wind Speed [m s-1]


MetSpec model RAD 16
Mk 2
Difference from Active Shield [C]
Wind Speed [m s-1]

Ambient Temperature: Shield Design Improvements

Enlarged internal space

Double louver plates

Black internal louver

Significant improvement over “Gill” style

Thanks!

CAUTION
GroundWork

Sensor Calibration: Standards

ISO 9847, ASTM E824 — Calibration Using Pyranometer

ISO 9846, ASTM G167 — Calibration Using Pyrheliometer

ISO 17025 — General Calibration Laboratory Requirements

Published Expanded Calibration Uncertainties

Sensor Calibration: Indoor

Typical solar applications

Traceable, standardized, quantifiable

Low cost and quick turnaround

Manufacturer credibility and coincident repairs

No time of year limitations

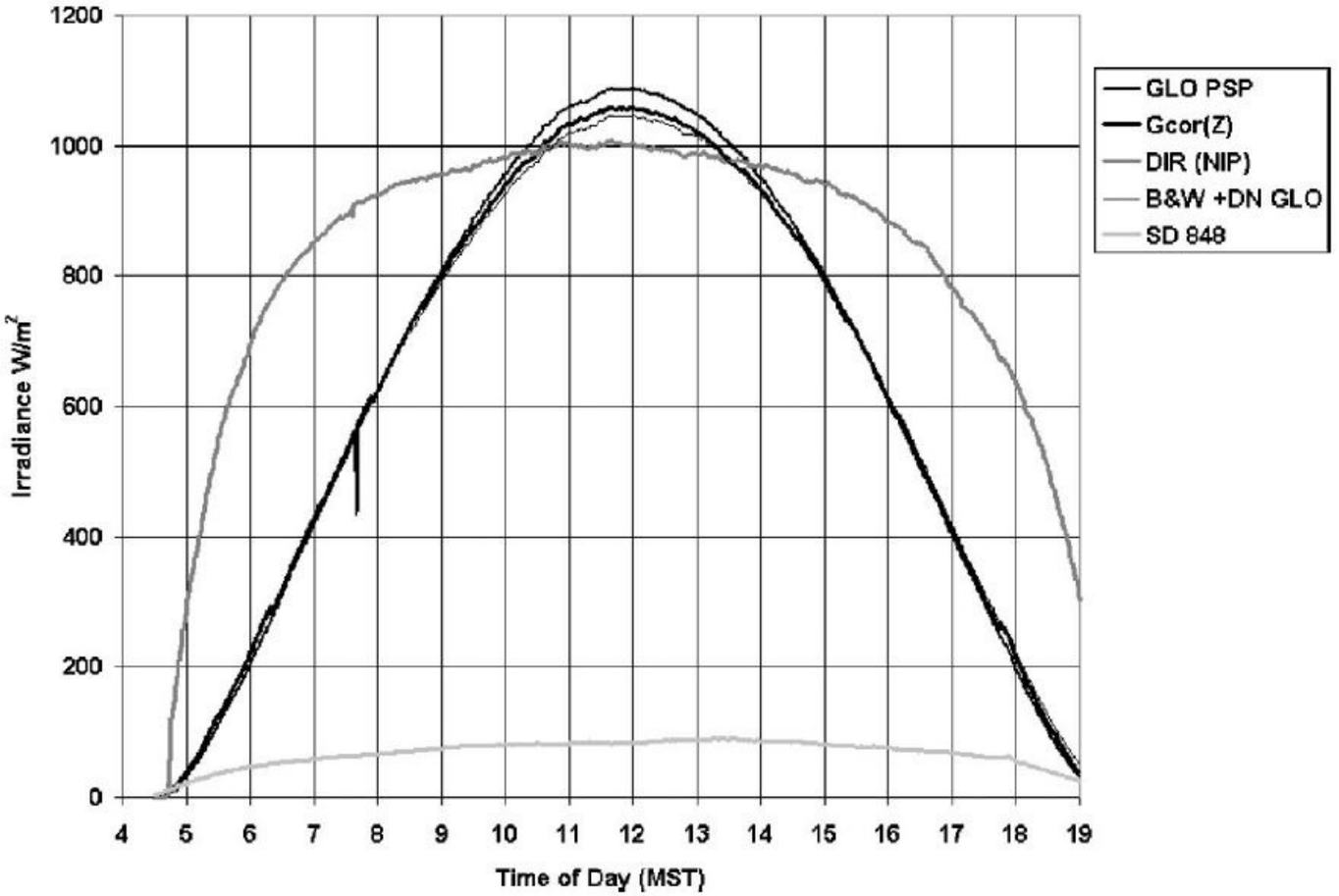
Non-ideal spectral distribution

Various bulb types

Normal incidence calibration

Sensor Calibration: Outdoor

- Typical solar applications, testing, research
- Traceable, standardized, quantifiable
- Ideal spectral distribution
- Calibrate at any deployment angle
- Typically 3rd party
- Calibration season limitations
- Higher cost and slower turn around



Myers et al., 2002

Sensor Calibration: NREL BORCAL

Transfer standards, research

Traceable, standardized, quantifiable

Ideal spectral distribution

Characterization full zenith 80° to 80°

Calibration function

Restricted calibration season

Higher cost and slow turn around

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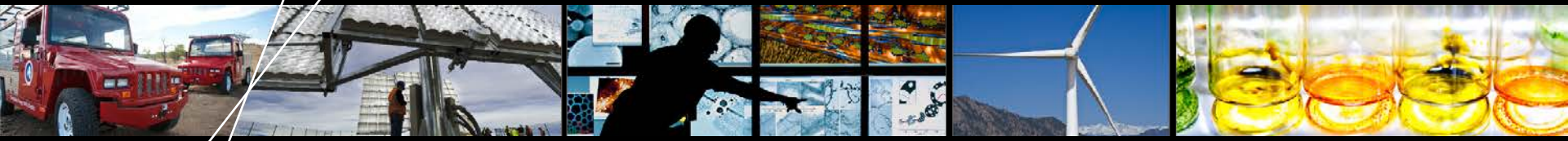
Quantifying Measurement Uncertainty in Thermopile Instrument



2015 PV Solar Resource Workshop, Golden, Colorado

- Aron Habte, NREL
- Manajit Sengupta, NREL
- Ibrahim Reda, NREL

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.

Motivation:

- To develop a consensus standard to estimate radiometric measurement uncertainty.
  - At present the tendency is to look at instrument datasheets and take the instrument calibration uncertainty as the measurement uncertainty.

Outline:

- Quantifying measurement uncertainty using the GUM method
- Inter-comparison of radiometric measurements from various instruments
- Developing consensus standards through American Society for Testing Materials (ASTM) International

Measuring Solar Radiation with Thermopiles

Direct Normal

Measured by a *Pyrheliometer* on a sun-following tracker

Global Horizontal

Measured by a *Pyranometer* with a horizontal sensor

Diffuse

Measured by a shaded *Pyranometer* under a tracking ball

Traceability of Radiometric Measurements

Uncertainty Increases

World Radiation Reference (WRR) ~±0.3%

International Pyrheliometer Comparison (IPC) ~±0.36%

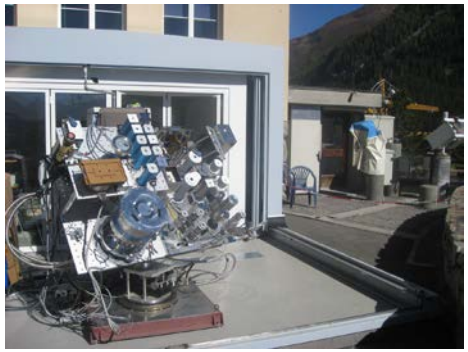
NREL Pyrheliometer Comparison (NPC) ~±0.4%

Calibrate Pyrheliometer (~±1%-2%)
Standards: BORCAL, ASTM E816, ISO 9059

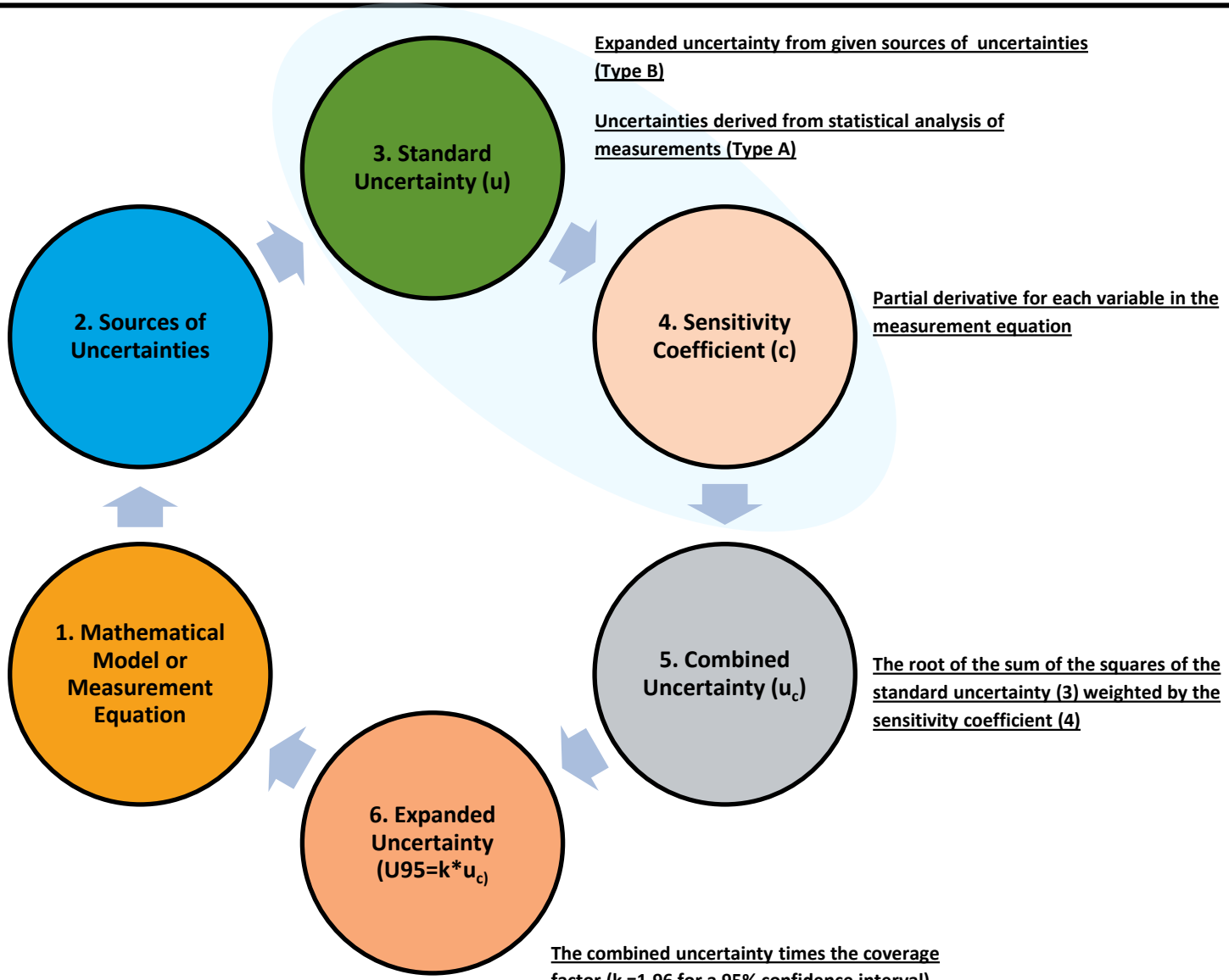
Diffuse Reference (Shade/Unshade) (~±3%+1W/m²)
Standards: BORCAL, ASTM G167

Calibrate Pyranometer (~±2%-3%)
Standards: BORCAL, ASTM G167, ISO 9846

Field deployment (~±3%-5%)



Steps for Measurement Uncertainty Estimation



Reda et al., 2011:http://www.nrel.gov/docs/fy11osti/52194.pdf; JCGM/WG 1. (2008). www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

Measurement Equation – Step 1

$$G = \frac{(V - R_{net} * W_{net})}{R}$$

where:

G is the calculated global solar irradiance in watts per square meter (Wm^{-2})

V is the pyranometer's thermopile output voltage in microvolts (μV)

R_{net} is the pyranometer's net longwave responsivity estimated or determined by blackbody characterization in $\mu V/(Wm^{-2})$

W_{net} is the net longwave irradiance measured by a collocated pyrgeometer in W/m^{-2} (Pyrgeometers are radiometers that measure atmospheric longwave irradiance)

R is the pyranometer's responsivity determined by calibration in $\mu V/(Wm^{-2})$.

Sources of Measurement Uncertainties – Step 2

- **In field deployments, add uncertainties in Measurement Equation Variables *(V, R_{net}, W_{net} and R)* due to**
  - Calibration (R)
    - NREL radiometer calibrations are done outdoors.
    - Calibration certificate reports the calibration results under specific environmental conditions that are different from conditions in the field.
  - Spectral Response (R)
  - Zenith Angle (R)
  - Maintenance----Soiling (dust, rain, bird droppings, etc.) (R)
  - Data logger uncertainty (V)
  - Temperature dependence (R)
  - Non-linearity (R)
  - Aging (R)

Quantifying Standard Uncertainty – Step 3

- **Type B uncertainties** - Method of evaluation of a standard uncertainty by means other than the statistical analysis of a series of observations such as, **manufacturers' specifications, calibration, and/or previous experience/literature estimates**
  - Example, **rectangular distribution** for a source of uncertainty with unknown distribution

where *U* is the expanded uncertainty of a variable.

$$u = \frac{U}{\sqrt{3}}$$

  - For **normal distribution**: $u = \frac{U}{2}$

- **Type A uncertainties** – A standard uncertainty is **derived from Measurements** using the statistical analysis of a series of observations.

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}}$$

Sensitivity Coefficient Calculations – Step 4

Measurement Equation

$$G = \frac{(V - R_{net} * W_{net})}{R}$$

Sensitivity Coefficient Calculations: e.g. (sensitivity coefficient of R)

$$C_R = \frac{\partial G}{\partial R} = \frac{-(V - R_{net} * W_{net})}{R^2}$$

Combined Uncertainty – Step 5

- The standard uncertainty (u) and sensitivity coefficients (c) are combined using the root sum of the squares method to calculate the **combined uncertainty**

$$u_c = \sqrt{\sum_{i=0}^{n-1} (u_i * c_i)^2}$$

Note: The combined uncertainty is applicable to both Type A and Type B sources of uncertainties.

Expanded Uncertainty (U_{95}) – Step 6

- The **expanded uncertainty (*U95*)** is calculated by multiplying the **combined uncertainty (u_c)** by a **coverage factor** (k=1.96, for infinite degrees of freedom), which represents a 95% confidence level, in W/m^2.

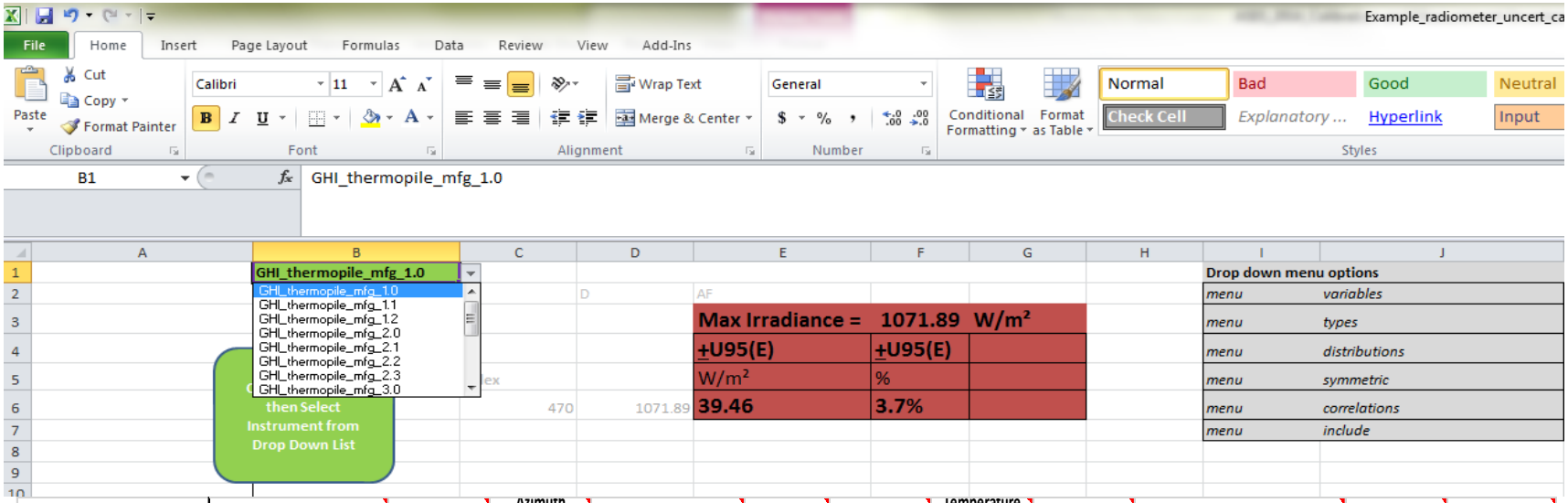
$$U_{95} = u_c * k$$

- The **expanded uncertainty U_{95}** as a percentage is then calculated as

$$U_{95} = \frac{U_{95}}{\text{Measured Irradiance}} * 100$$

Excel® spreadsheet- Radiometric Data Uncertainty Estimate Using GUM method

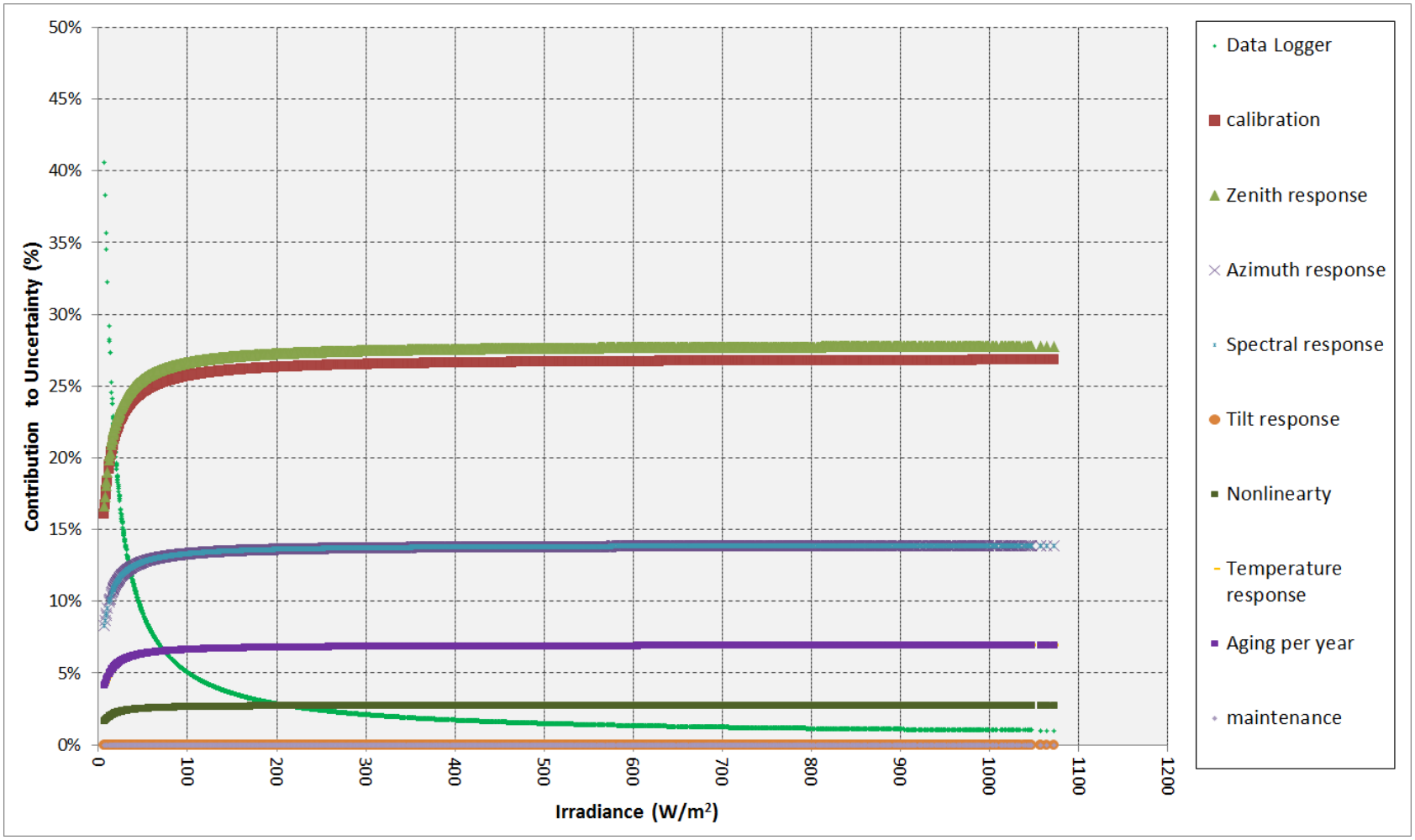
- **The spreadsheet provides a comprehensive estimation of measurement uncertainty associated with measurands using GUM method.**



uncertainty component	calibration	Zenith response	Azimuth response	Spectral response	Tilt response	Nonlinearity	Temperature response	Aging per year	Datalogger	maintenance	Directional Error
acts on input / output quantity	E	E	E	E	E	E	E	E	E	E	E
uncertainty type	relative	relative	relative	relative	relative	relative	relative	relative	relative	relative	relative
distribution	normal	rectangular	rectangular	rectangular	rectangular	rectangular	rectangular	rectangular	rectangular	rectangular	rectangular
symmetry	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric
include in analysis?	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
unit	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Expanded Uncertainty	2.85	2	1	4	0	1	1	2	Refer to Calculation_final Sheet	0	0
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Standard Uncertainty	1.43	1.15	0.58	2.31	0.00	0.58	0.58	1.15	#VALUE!	0.00	0.00
Rs @ 45 [uv/W/m^2]	13.475										

Link: http://www.nrel.gov/midc/srrl_bms/ and look for Excel® uncertainty spreadsheet at the bottom of the page.

Contribution of various sources of uncertainty to expanded uncertainty



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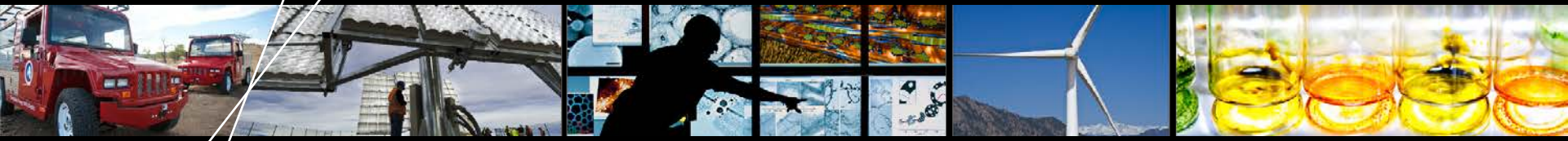
Evaluation of Radiometers Deployed at the National Renewable Energy Laboratory's Solar Radiation Research Laboratory



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

Purpose:

- **Comparing various radiometers to the best instrument**
  - Provides relative performance of instruments under test
  - Offers information in quantifying/understanding sources of uncertainties of a measurement
  - Assists in justifying measurement uncertainties

Available: http://www.nrel.gov/docs/fy14osti/60896.pdf

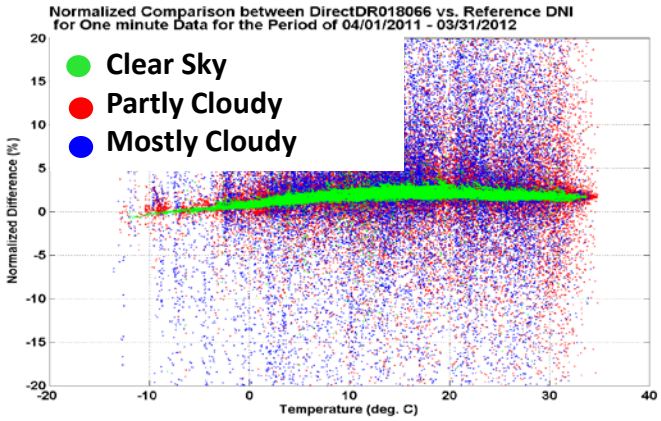
Method and Experimental Design:

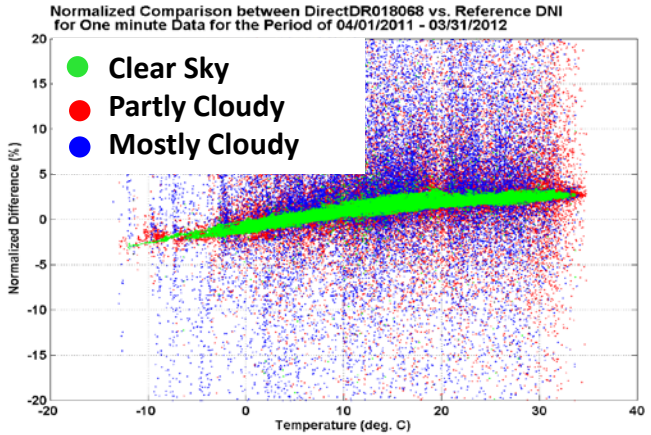
- Test Instruments: 32 Global Horizontal and 19 Direct Normal irradiance measuring radiometers
- Data was quality assessed
- Best practices for Operation and Maintenance of the instruments was followed.

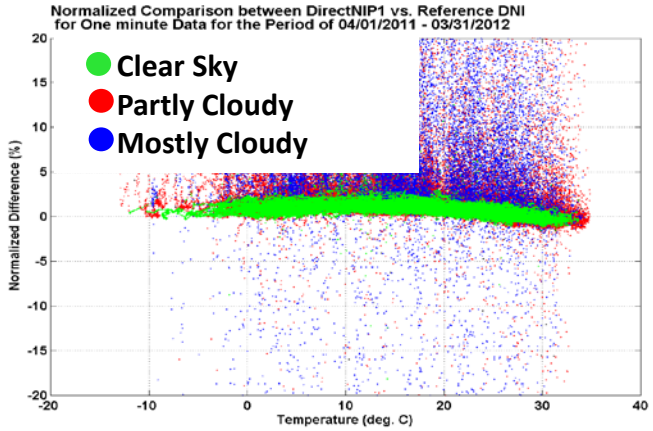
Reference Instrument Used for comparison

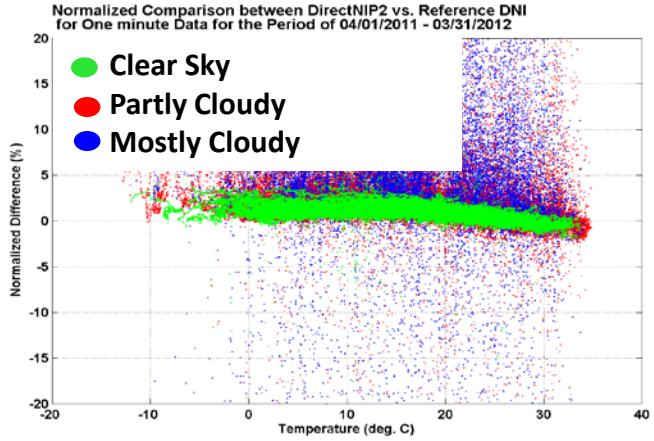
- **Reference Data**
  - **A Kipp and Zonen CH1 (DNI)** instrument and **an Eppley Laboratory, Inc., black-and-white model 8-48** (diffuse horizontal irradiance, or DHI) instrument
    - Traceable to SI through the World Radiometric Reference (WRR)
    - Lowest calibration and measurement uncertainties

Temperature dependence of DNI Instruments









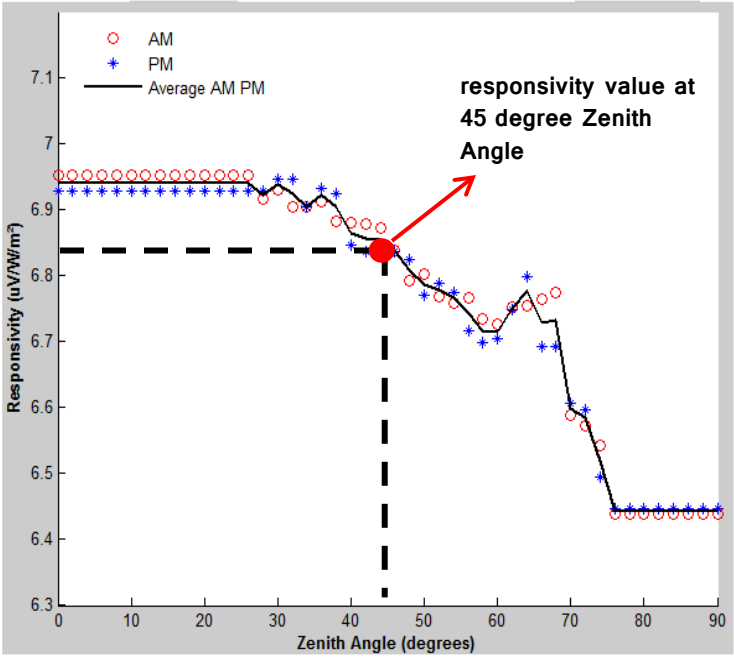
- The Hukseflux radiometer model number DR108068 had relatively more evident temperature dependence than model number DR108066.
- The two Eppley NIP radiometers tend to have less temperature dependence.

Effect of temperature on DNI measurement, (Top) Hukseflux radiometer and (bottom) Eppley NIP model

Evaluating Radiometric Measurements Using a Fixed 45° Responsivity and Zenith Angle Dependent Responsivities

MBE for the NREL EPPLEY PSP (28402F3)

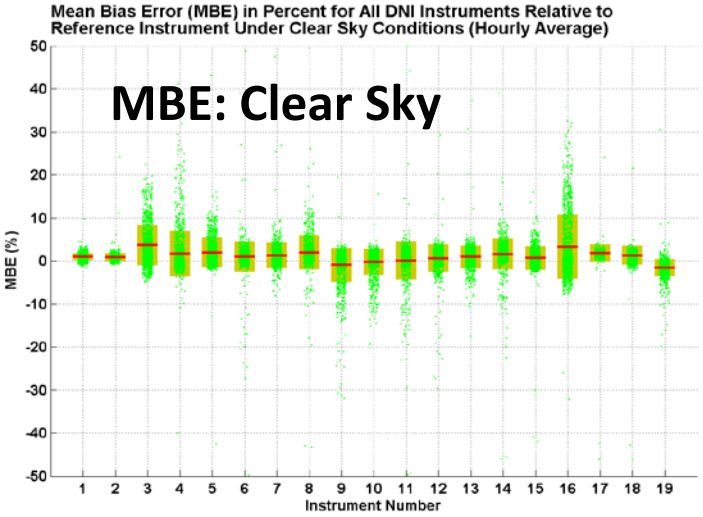
Solar Zenith Angle Bins	Responsivity using Zenith Function		Responsivity at 45 degree Zenith	
	MBE%	MBE in W/m^2	MBE%	MBE in W/m^2
10-20	-0.36	-2.77	3.01	22.12
20-30	-1.55	-4.62	1.77	19.61
30-40	-1.40	-5.04	1.93	17.47
40-50	-1.10	-4.15	2.25	16.04
50-60	-0.77	-2.74	2.58	13.13
60-70	-0.83	-2.99	2.52	8.60
70-80	3.03	3.68	6.48	9.97

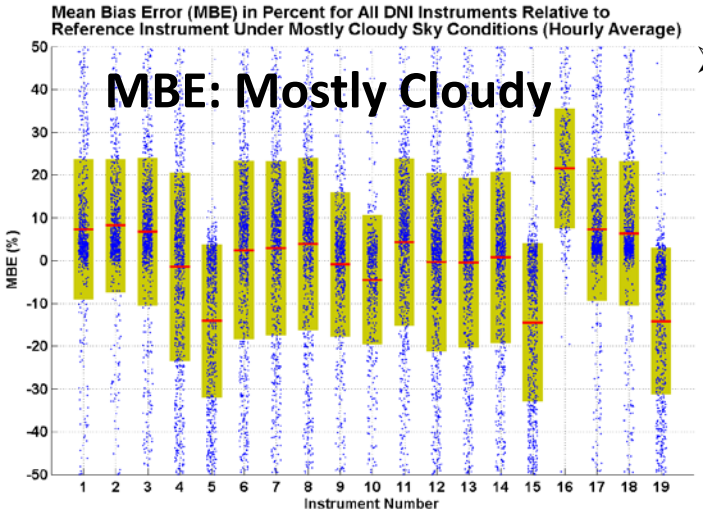


Solid line– shows the average and interpolated responsivity values for all zenith angles

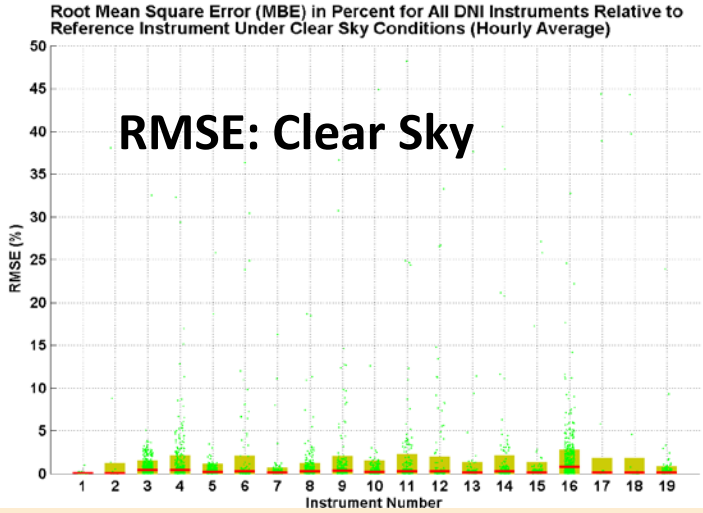
- **As stated in the above table using the responsivity function, the irradiance MBE decreased by more than 50%. This reduction is mostly attributed to the uncertainty reduction of the instrument's responsivity.**

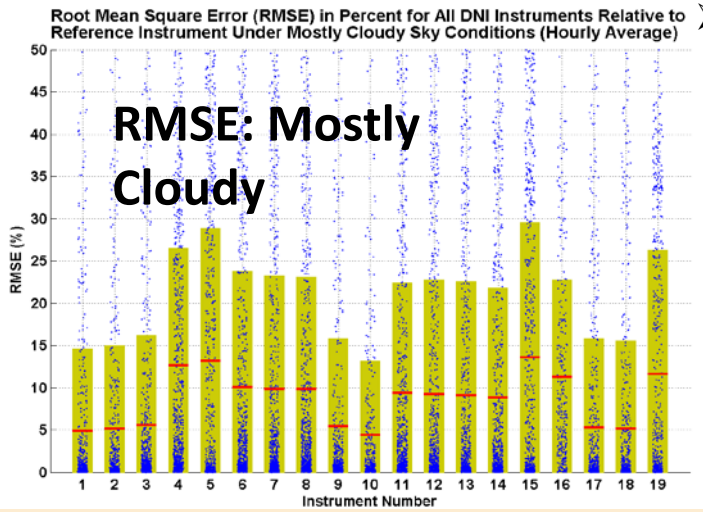
Result: DNI Dataset





➢ Relative differences are higher under cloudy sky conditions, some factors, such as temporal responsivity, field of view of the radiometers, and spectral response become an influence for these higher differences.





➢ The clear-sky conditions demonstrated tighter differences among the instruments.

Clear- and mostly cloudy sky condition: (top) MBE and (bottom) RMSE in percent for the hourly average for all DNI data under study.

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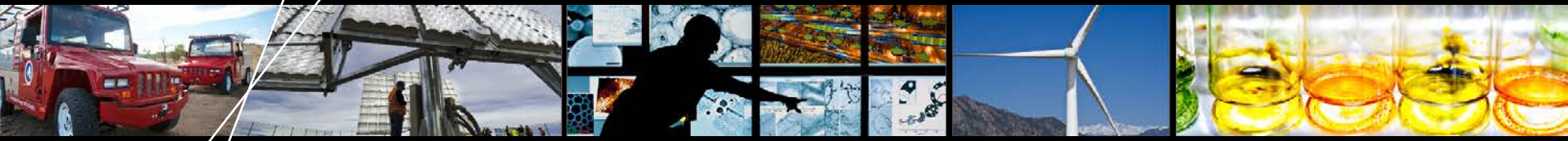


Overview of ASTM International Activities through Radiometry Subcommittee

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.

Current ASTM Radiometry Standard Development Activities

Two of the Proposed New Standards under Radiometry Subcommittee

- **WK36479 New Practice for uncertainty evaluation of calibration and measurements with pyranometers and pyrheliometers**
  - Standardized procedure according to GUM (Guideline to evaluation of Uncertainty in Measurement)
  - Standard is currently in balloting cycle
- **WK38983 New Guide for Performance Classification of Solar Radiometers**
  - Classification of radiometers serves as a reference for use in other standards to define what instruments are recommended for use, such as in solar energy system performance monitoring, material testing etc.,
  - A division in classes allows users with different target measurement uncertainties to easily make a choice between instruments at different cost price levels.

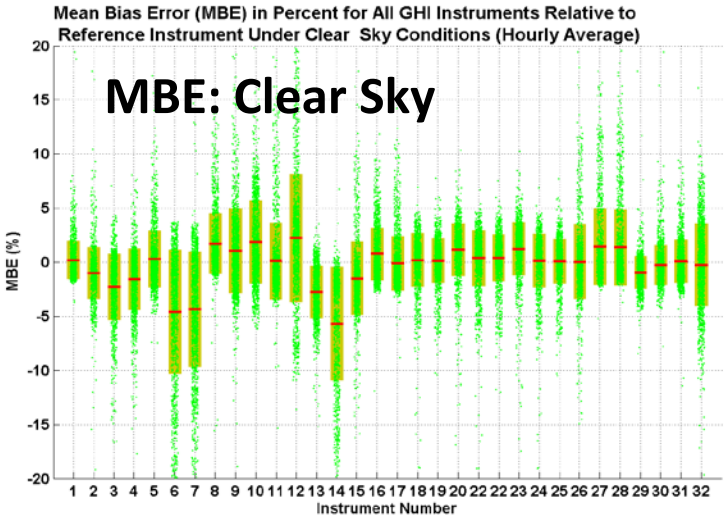
Summary

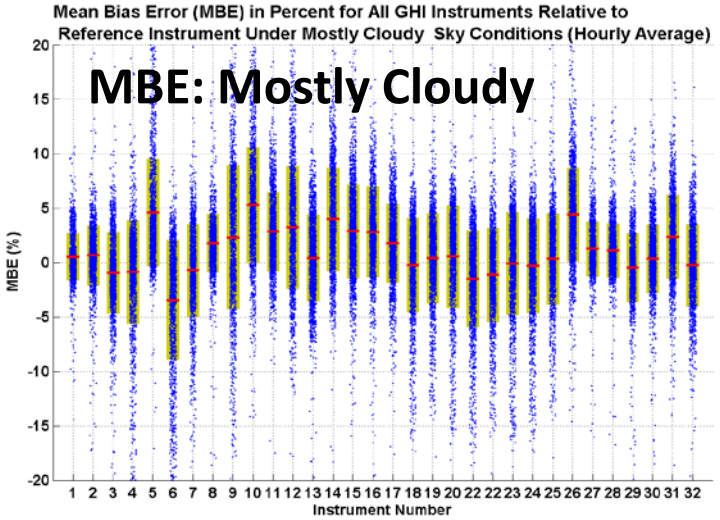
- Solar resource data with **known and traceable uncertainty** estimates are essential for the site selection of renewable energy technology deployment, system design, system performance, and system operations.
- **Comparison of the radiometric data** provides valuable information-differences due to the various instrument design characteristics for time response, spectral response, angular (cosine) response, field of view and temperature response, etc.
- Adopting such **standardized method** will ensure that the uncertainty quoted for data collected by radiometers can be compared based on documented methods of derivation and provides global uniformity and acceptance.

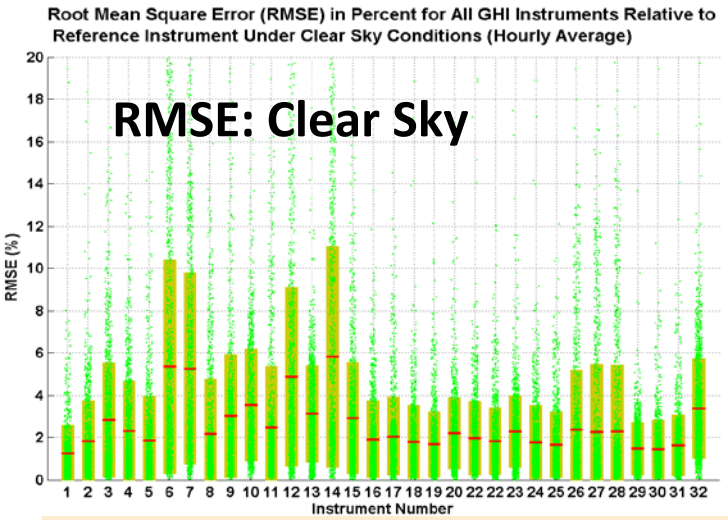
Thank You!

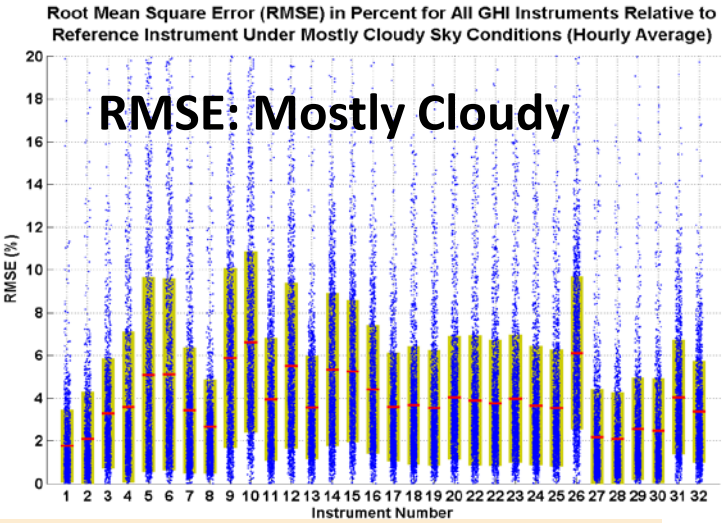
Questions?

Result: GHI Dataset









Clear and mostly cloudy sky condition: (top) MBE and (bottom) RMSE in percent for the hourly average for all GHI data under study. The red line signifies the mean value of the differences for the 95% confidence level.

Instrument List:

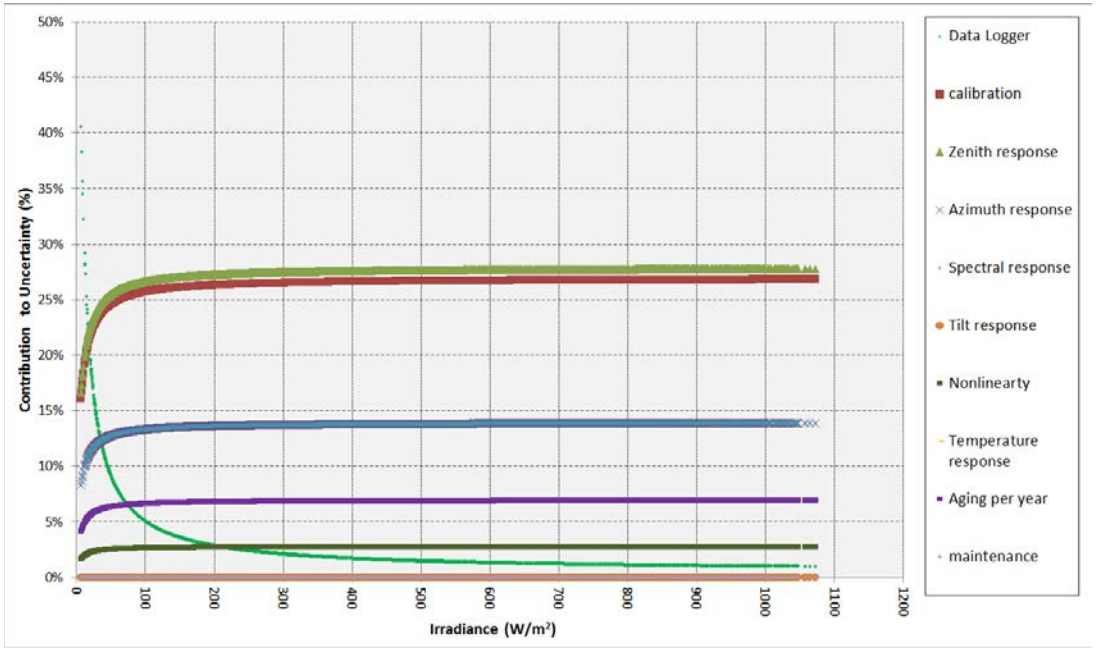
GHI Instrument List:

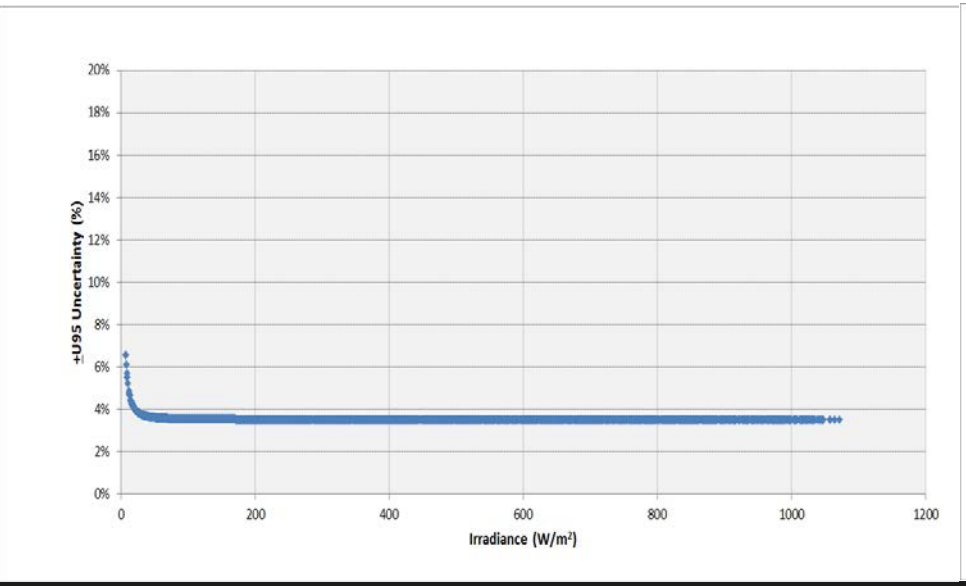
Instrument Number	Instrument Type	Model	Manufacturer	Instrument Number	Instrument Type	Model	Manufacturer
1	Thermopile	CM22	Kipp & Zonen	17	Semiconductor	RSP (secondary)	LI-COR
2	Thermopile	CM6b	Kipp & Zonen	18	Thermopile	TSR-590	YES, Inc.
3	Thermopile	CM3-CNR1	Kipp & Zonen	19	Thermopile	TSR-591	YES, Inc.
4	Thermopile	PSP	Eppley Laboratory, Inc.	20	Thermopile	TSR-592	YES, Inc.
5	Thermopile	PSP	Eppley Laboratory, Inc.	21	Thermopile	TSR-590-LH[a]	YES, Inc.
6	Thermopile	PSP	Eppley Laboratory, Inc.	22	Thermopile	TSR-591-LH	YES, Inc.
7	Thermopile	PSP	Eppley Laboratory, Inc.	23	Thermopile	TSR-592-LH	YES, Inc.
8	Thermopile	TSP-700	YES, Inc.	24	Thermopile	TSR-590-JM[b]	YES, Inc.
9	Thermopile	TSP-1	YES, Inc.	25	Thermopile	TSR-591-JM	YES, Inc.
10	Thermopile	SPN1	Delta-T	26	Thermopile	TSR-592-JM	YES, Inc.
11	Semiconductor	SPLite	Kipp & Zonen	27	Thermopile	SR11-7196	Hukseflux
12	Semiconductor	SP-110	Apogee	28	Thermopile	SR11-7242	Hukseflux
13	Semiconductor	LI-200	LI-COR	29	Thermopile	LP02-41120	Hukseflux
14	Semiconductor	P007	David Brooks	30	Thermopile	LP02-41272	Hukseflux
15	Semiconductor	ATI	Ascension Technology, Inc. RSR/LI-COR	31	Semiconductor	NREL-CRADA-RSR2	Irradiance Inc./LI-COR
16	Semiconductor	RSP	LI-Cor	32	Semiconductor	Solar-Mil.-CRADA-RSR	Solar Millennium AG./LI-Cor

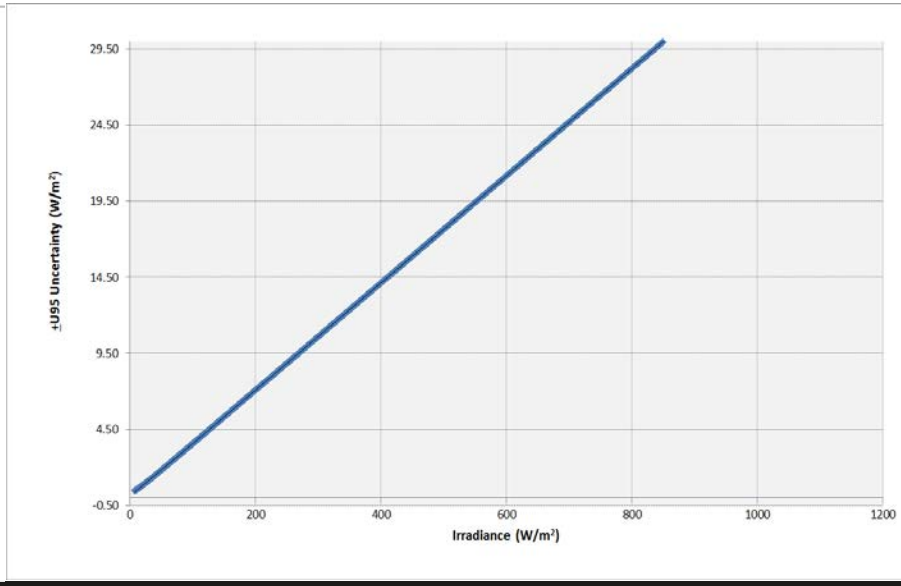
GHI Instrument List:

Instrument Number	Instrument Type	Model	Manufacturer
1	Thermopile	NIP2	Eppley Laboratory, Inc.
2	Thermopile	NIP1	Eppley Laboratory, Inc.
3	Semiconductor	LI-201	LI-COR
4	Semiconductor	ATI/LI-COR	Ascension Technology Inc./ LI-COR
5	Semiconductor	RSP/LI-COR	Irradiance Inc./LI-Cor
6	Thermopile	TSR-590	YES, Inc.
7	Thermopile	TSR-591	YES, Inc.
8	Thermopile	TSR-592	YES, Inc.
9	Thermopile	TSR-590LH	YES, Inc.
10	Thermopile	TSR-591LH	YES, Inc.
11	Thermopile	TSR-592LH	YES, Inc.
12	Thermopile	TSR-590JM	YES, Inc.
13	Thermopile	TSR-591JM	YES, Inc.
14	Thermopile	TSR-592JM	YES, Inc.
15	Semiconductor	NREL-CRADA-RSR2/LI-Cor	Irradiance Inc./LI-COR
16	Thermopile	SPN1	Delta-T
17	Thermopile	DR018066	Hukseflux
18	Thermopile	DR018068	Hukseflux
19	Semiconductor	Solar-Mil.-CRADA-RSR/LI-COR	Solar Millennium AG./LI-COR

Example Output Plots:







Example of Calibration and Field Measurement Uncertainty Sources:

Example Of Typical Calibration Type B Standard Uncertainties (U) For A Pyranometers

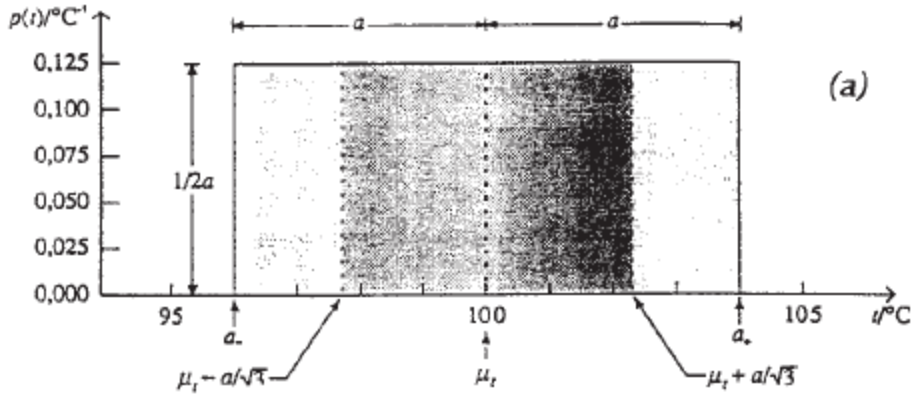
Sources of Uncertainties	Expanded Uncertainties of the Sources					Distribution	Degrees of Freedom	Standard Uncertainty (u)
Input Variable	Value and Units	U%	U	Offset	a=U+ Offset			
V	7930.3 uV	0.001	0.079 uV	1.0 uV	1.079 uV	Rectangular	∞	0.62 uV
R_{net}	0.4 uV/Wm^{-2}	10	0.04 uV/Wm^{-2}	--	0.04 uV/Wm^{-2}	Rectangular	∞	0.02 uV/ Wm^{-2}
W_{net}	-150 Wm^{-2}	5	7.5 Wm^{-2}	--	7.5 Wm^{-2}	Rectangular	∞	4.33 Wm^{-2}
N	1,000 Wm^{-2}	0.4	4 Wm^{-2}	--	4 Wm^{-2}	Normal	∞	2 Wm^{-2}
Z	20°	--	2. 10^{-5}	--	2. 10^{-5}	Rectangular	∞	1. 10^{-5}
D	50 Wm^{-2}	3	1.5 Wm^{-2}	1 Wm^{-2}	2.5 Wm^{-2}	Normal	∞	1.25 Wm^{-2}

Example Of Measurement Sources of Uncertainty for A Pyranometers

Uncertainty component	Quantity	Statistical Distribution	Uncertainty Type	Standard Uncertainty (u)	Expanded Uncertainty (U)*
Calibration	R	Normal	Type B	$\frac{U}{2} = 2.81\%$	5.62% (calibration done at 45 degrees)
Zenith Response	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 1.15\%$	2% (calibration done at 45 degrees)
Spectral Response	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 0.58\%$	1% (calibration done at 45 degrees)
Nonlinearty	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 0.29\%$	0.5%
Temperature Response	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 0.29\%$	1%
Aging per Year	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 0.58\%$	1%
Datalogger Accuracy	V	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 5.77uv$	10 µV
Maintenance	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 0.17\%$	0.3%

Measurement Equation and Sensitivity Coefficient Calculations :

MEASUREMENT EQUATION AND SENSITIVITY COEFFICIENT CALCULATIONS	
Calibration Sensitivity Equations	Field Measurement Sensitivity Equations
Equation: $$R = \frac{(V - R_{net} * W_{net})}{N * Cos(Z) + D}$$	**Equation:** $$G = \frac{(V - R_{net} * W_{net})}{R}$$
$$c_V = \frac{\partial R}{\partial V} = \frac{1}{N\,Cos(Z) + D}$$	$$c_R = \frac{\partial G}{\partial R} = \frac{-(V - R_{net} * W_{net})}{R^2}$$
$$c_{Rnet} = \frac{\partial R}{\partial Rnet} = \frac{-Wnet}{N\,Cos(Z) + D}$$	$$c_{R_{net}} = \frac{\partial G}{\partial R_{net}} = \frac{-W_{net}}{R}$$
$$c_{Wnet} = \frac{\partial R}{\partial Wnet} = \frac{-Rnet}{N\,Cos(Z) + D}$$	$$c_{W_{net}} = \frac{\partial G}{\partial W_{net}} = \frac{-R_{net}}{R}$$
$$c_N = \frac{\partial R}{\partial N} = \frac{-(V - Rnet\,Wnet)Cos(Z)}{(N\,Cos(Z) + D)^2}$$	$$c_V = \frac{\partial G}{\partial V} = \frac{1}{R}$$
$$c_Z = \frac{\partial R}{\partial Z} = \frac{N\,Sin(Z)\,(V - Rnet\,Wnet)}{(N\,Cos(Z) + D)^2}$$	
$$c_D = \frac{\partial R}{\partial D} = \frac{-(V - Rnet\,Wnet)}{(N\,Cos(Z) + D)^2}$$	


p(t)/°C⁻¹
0,125
0,100
0,075
0,050
0,025
0,000
1/2a
a
a
(a)
95
100
105
t/°C
a₋
a₊
μt − a/√3
μt
μt + a/√3

Standards, Specifications and Characteristics of Global Irradiance Sensors

Anton Driesse

PV Performance Labs

www.pvperformancelabs.com

Introduction

- User perspective
- PV system performance

- Want to achieve greater accuracy and quantified uncertainty in conclusions about PV system performance

- Need to better understand the accuracy/uncertainty of irradiance measurements and data sets

- Need to better understand instrument characteristics

Some years ago…

1981 - IEA Conference on Pyranometer Measurements

Goal 2: Determine ways to improve the measurement accuracies of pyranometers currently available by developing a more complete understanding of the instruments' performance characteristics.

1996 - IEA Solar Heating and Cooling Programme Task 9

Improved Measurements of Solar Irradiance by Means of Detailed Pyranometer Characterisation

Information Sources

- Manufacturer specifications
  - classification standards
  - testing standards

Characteristics

- Response time
- Zero offsets/thermal offsets
- Non-stability (long-term)
- Non-linearity
- Directional response
- Spectral selectivity
- Temperature response
- Tilt response

Non-Linearity

- Pyranometer: (WMO/ISO)
  - deviation from responsivity at 500 W/m²
  - irradiance range 100-1000 W/m²
  - 10/10 specified a maximum deviation
  - 1/4 manufacturer specified a broader irradiance range

- Photodiode:
  - 4/5 specified a maximum deviation
  - no indication how deviation was calculated
  - all chose different irradiance ranges

Non-Linearity

- Reference cell: (IEC 60904-10)
  - maximum deviation from a linear fit on output vs. G
  - irradiance range not specified (“range of interest”)
  - 1/7 specified a maximum deviation
  - no indication how deviation was calculated or over what range

Non-Linearity Correction ?

- Many sensors for other phenomena are non-linear, and linearity corrections are common

- Need a reliable linearity curve for the instrument or instrument type

Temperature Response

- Pyranometers (WMO/ISO)
  - maximum deviation over (floating) 50C range
  - 1-3% over 50C range
  - 1/10 products provided with graph, 1/10 with numerical data
  - 1/4 manufacturer chooses a wider temperature range
- Photodiode pyranometers
  - 5/5 provide % deviation per C
  - makes 2-10% over 50C range

Temperature Response

- Reference cells
  - 6/7 provide % or mV deviation per C
  - applicable over full operating range
  - makes 1-4% over 50C range

Temperature Response Correction ?

- Need instrument temperature
  - 2/10 pyranometers have built-in sensors
  - many (most?) reference cells have built-in sensors
- Need reliable temperature response curve or slope coefficient
  - 1/10 pyranometers provided with correction instructions
  - temperature correction for reference cells is common

Directional Response

- Thermopiles: (WMO/ISO)
  - maximum deviation in W/m² in any direction when normal irradiance is 1000 W/m²
  - 10/10 datasheets provide maximum errors
  - 1/4 manufacturers specifies angle limit
  - measurements at different instrument rotations are needed as well to assess non-symmetry

Directional Response

- Photodiodes:
  - 1/5 datasheets provides maximum error in W/m²
  - 4/5 datasheets provide maximum error in %
  - all datasheets specify angle limits
  - several datasheets provide graphs

- Reference cells:
  - 1/7 datasheets mentions angle limit
  - 0/7 datasheets provide maximum error

Directional Response Correction ?

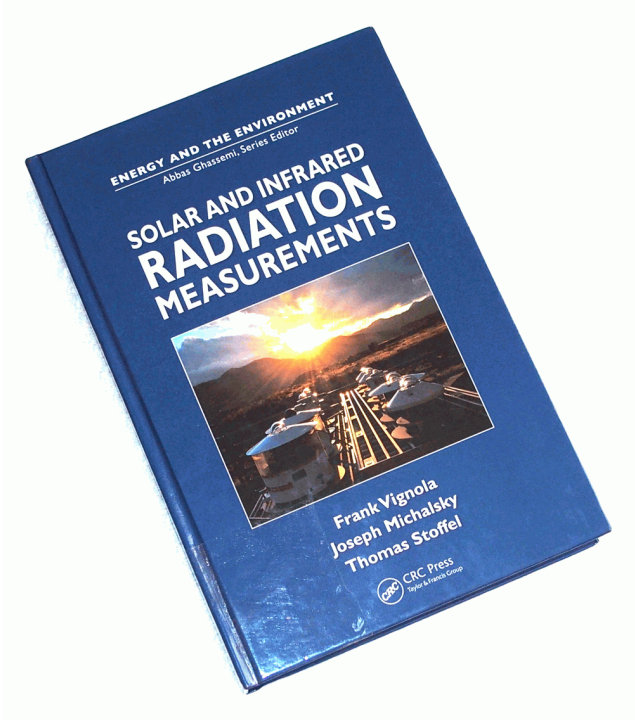
- Need sun position and diffuse fraction
- Need reliable directional response curve

More Corrections ?

- Pyranometer thermal offsets
  - correction based on IR measurements
- Photodiode or reference cell spectral response
  - correction using models based on air mass

Information Sources

- Manufacturer specifications
  - Classification standards
  - Testing standards
- Books
- Independent studies



Photon 2010

Solarstrahlungssensoren: Tageseinstrahlungssummen

Hersteller	Typenbezeichnung	Bauart	Abweichung zur Referenzmessung in %
Apogee Instruments Inc.	SP-215	Pyranometer mit Photodiode	15,15
EKO Instruments Co. Ltd.	MS-602	Thermosäulenpyranometer	4,26
Hukseflux Thermal Sensors BV	LP02	Thermosäulenpyranometer	2,88
IKS Photovoltaik GmbH	Iset Sensor (amorph)	Solarzelle (amorphes Silizium)	-1,08
	Iset Sensor (monokristallin)	Solarzelle (monokristallin)	-4,89
	Iset Sensor (polykristallin)	Solarzelle (polykristallin)	-3,19
Kipp & Zonen BV	CMP3	Thermosäulenpyranometer	-0,28
	SP Lite2	Pyranometer mit Photodiode	8,60
LI-COR Biosciences	LI-200SA	Pyranometer mit Photodiode	7,86
Mencke & Tegtmeyer GmbH	Si-02-Pt100-K	Solarzelle (monokristallin)	-3,75
	Si-10TC-K	Solarzelle (monokristallin)	-6,66
	Si-420TC-T-K	Solarzelle (monokristallin)	-4,26
NES Mess- und Meldesysteme, Lothar Viel	SOZ-03	Solarzelle (monokristallin)	-3,54
	SOZ-03 mit Verstärker	Solarzelle (monokristallin)	-2,61
Reinhardt System- und Messelectronic GmbH	Globalstrahlungssensor	Thermosäulenpyranometer	4,60
Skye Instruments Ltd.	SKS 1110	Pyranometer mit Photodiode	7,27
Soluzione Solare	Sunmeter	Solarzelle (monokristallin)	-7,56
Technische Alternative GmbH	GBS01	Photodiode (monokristallin)	-10,55
Tritec International AG	Spektron 200*	Solarzelle (monokristallin)	-8,38
	Spektron 210	Solarzelle (monokristallin)	-5,47
	Spektron 300*	Solarzelle (monokristallin)	-14,05
	Spektron 310	Solarzelle (monokristallin)	-1,16

-15 -10 -5 0 5 10 15 20

* wird nicht mehr hergestellt,
Referenzwert gemessen mit »Secondary Standard«-Pyranometer (Kipp & Zonen CM 21)

Messungen von November 2009 bis September 2010

Schultz et al 2010

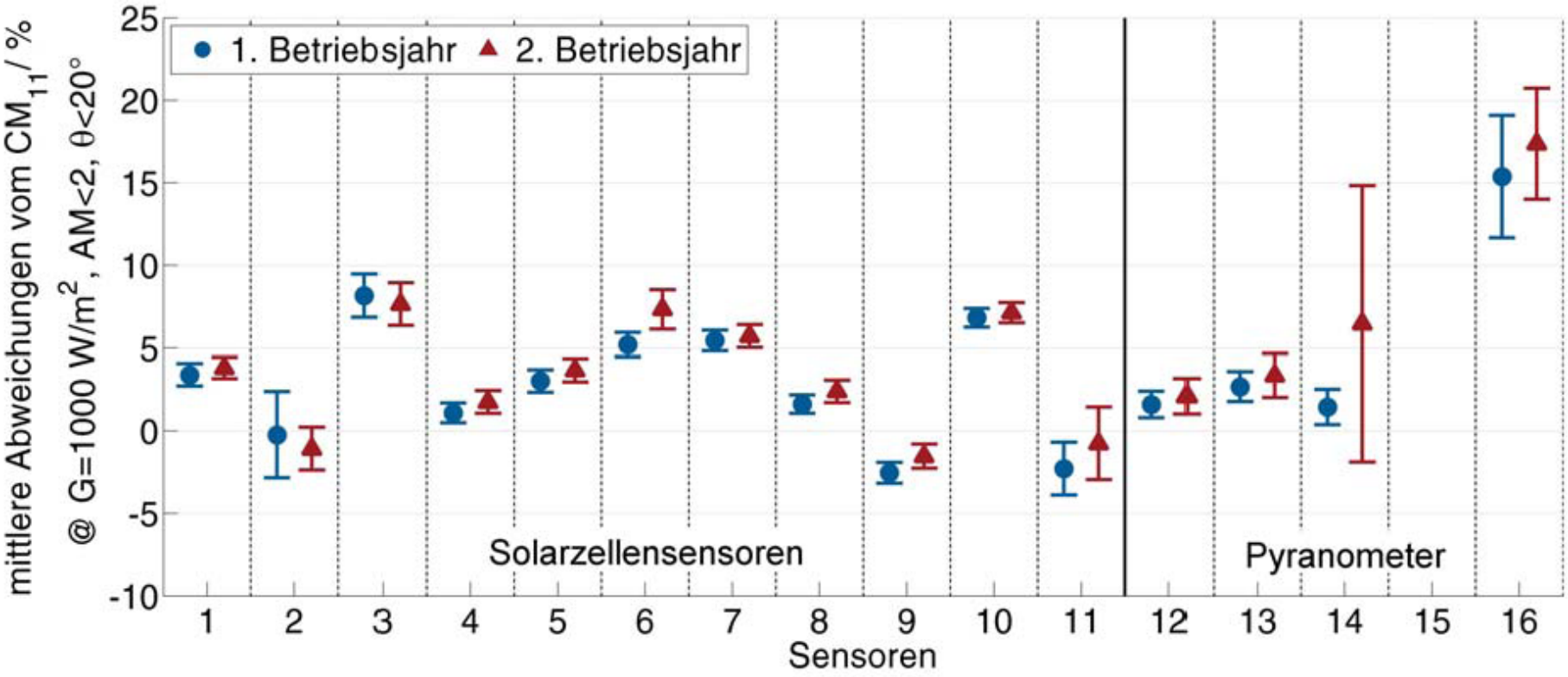


Abbildung 1: mittlere Abweichungen vom Thermosäulen-Pyranometer.

Schultz et al 2010

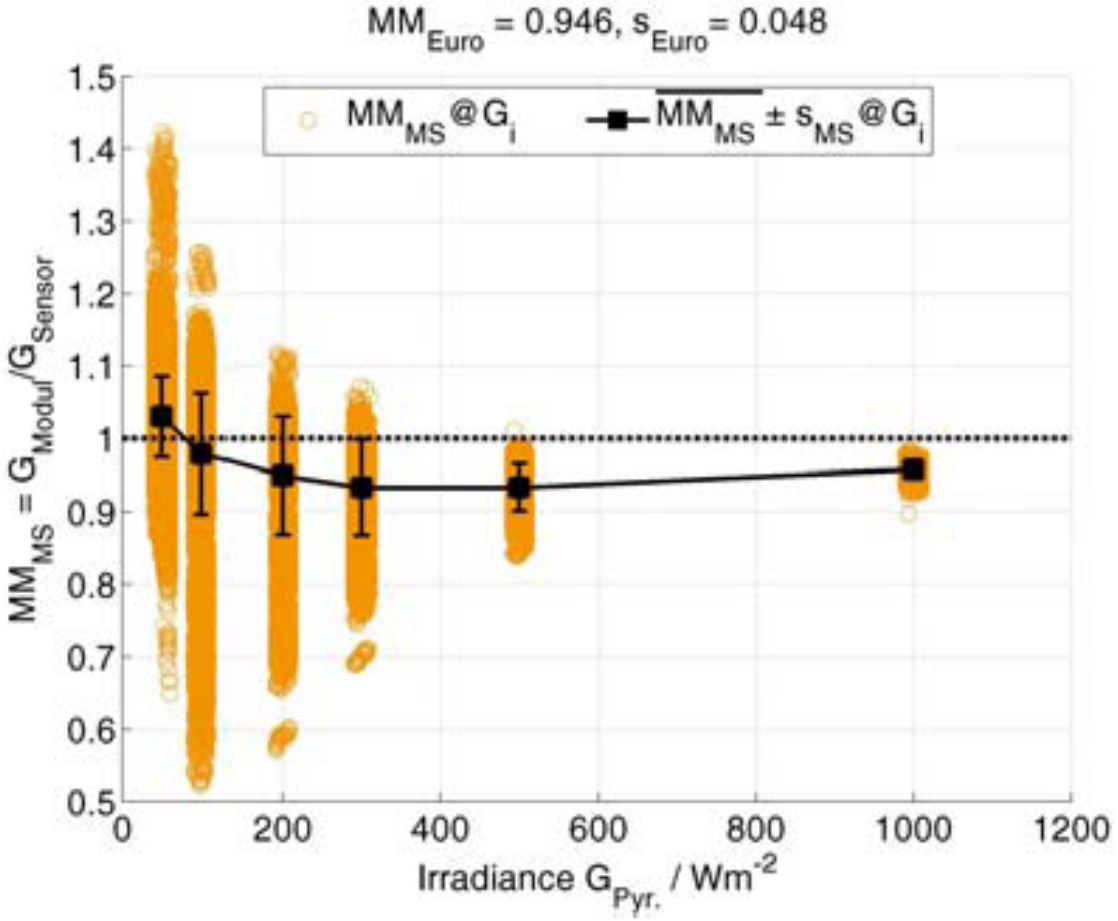


Figure 5: Mismatch between a monocrystalline PV module and a thermopile pyranometer (sensor 15)

EU PV Performance Project 2007

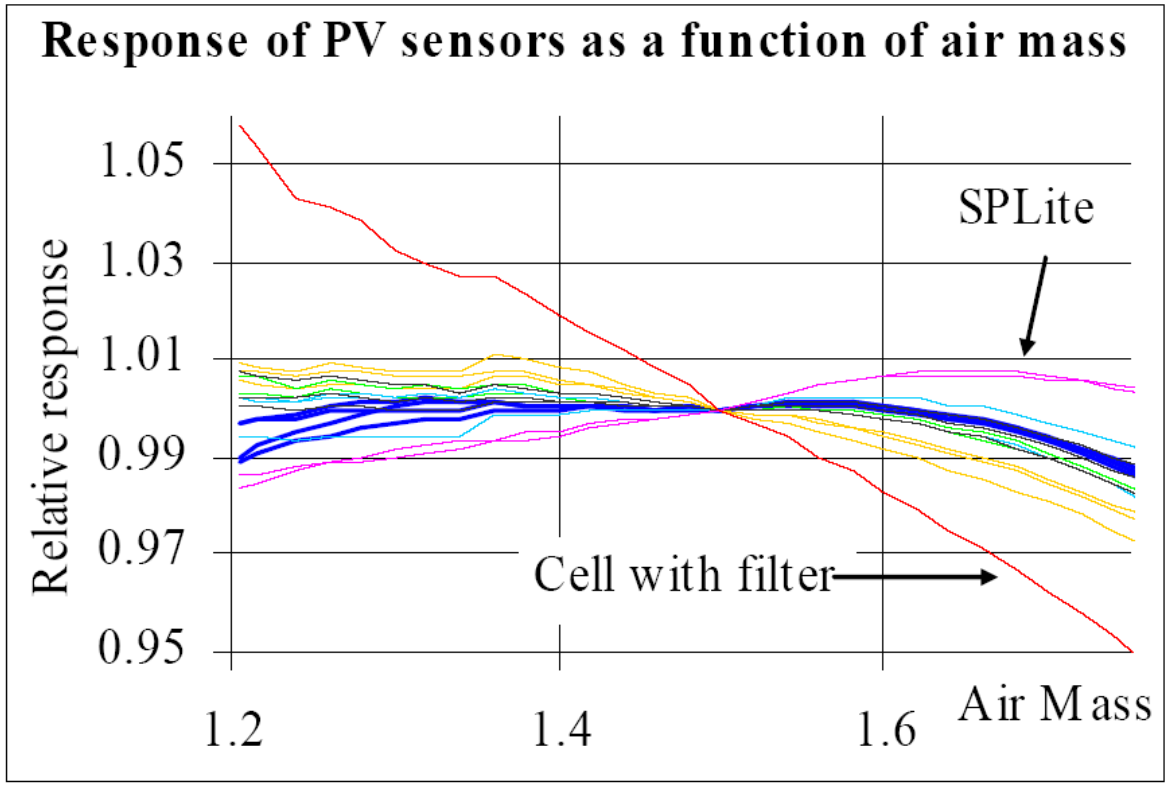


Figure 5: Relative response of reference cells as a function of air mass.

Wilcox and Meyers 2008

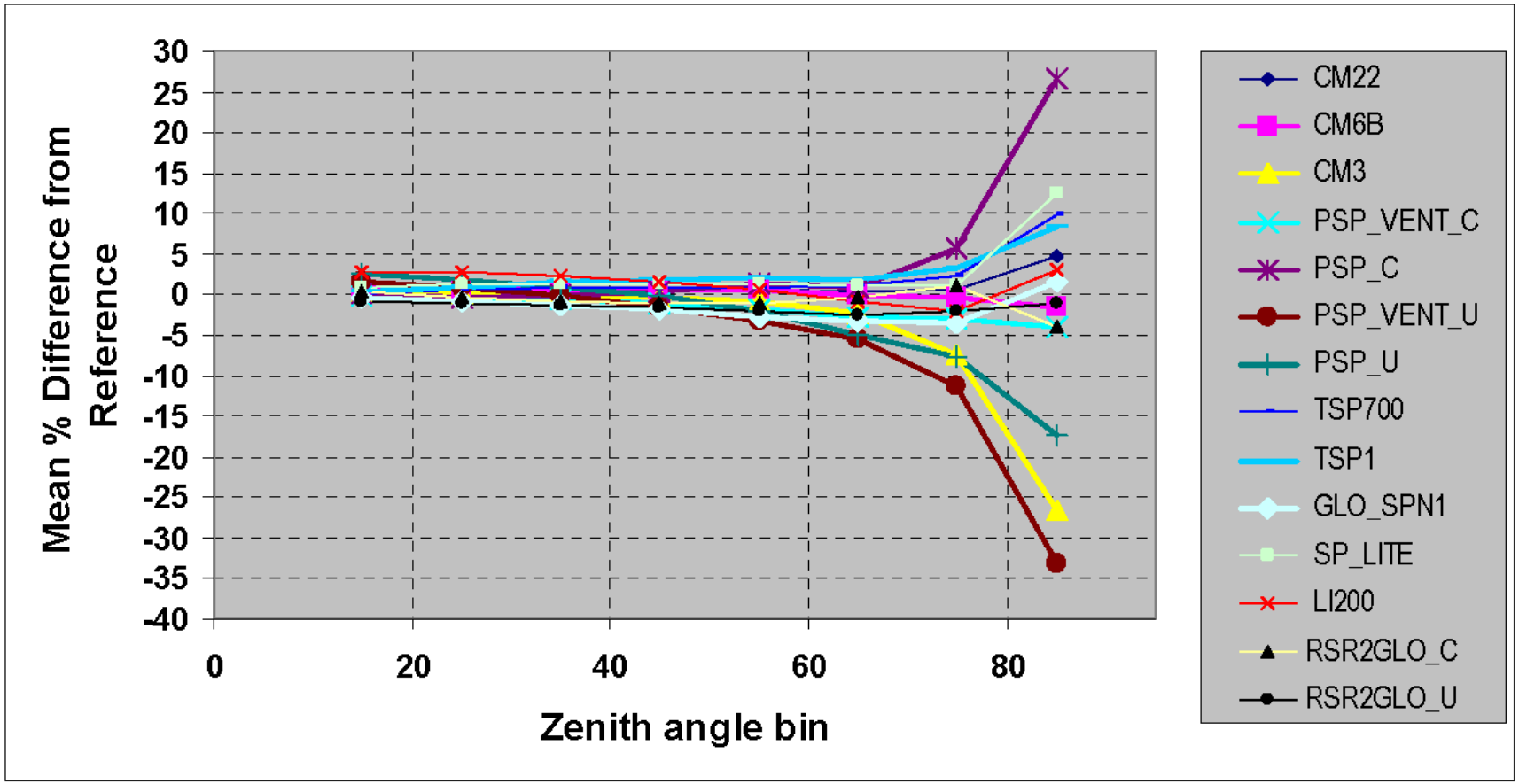


Figure 3-1. Mean percent differences from reference global irradiance for pyranometers as function of zenith angle. See Appendix A, Table A-1 for instrument list.

IEA Conf. Pyranometer Measurements 1981

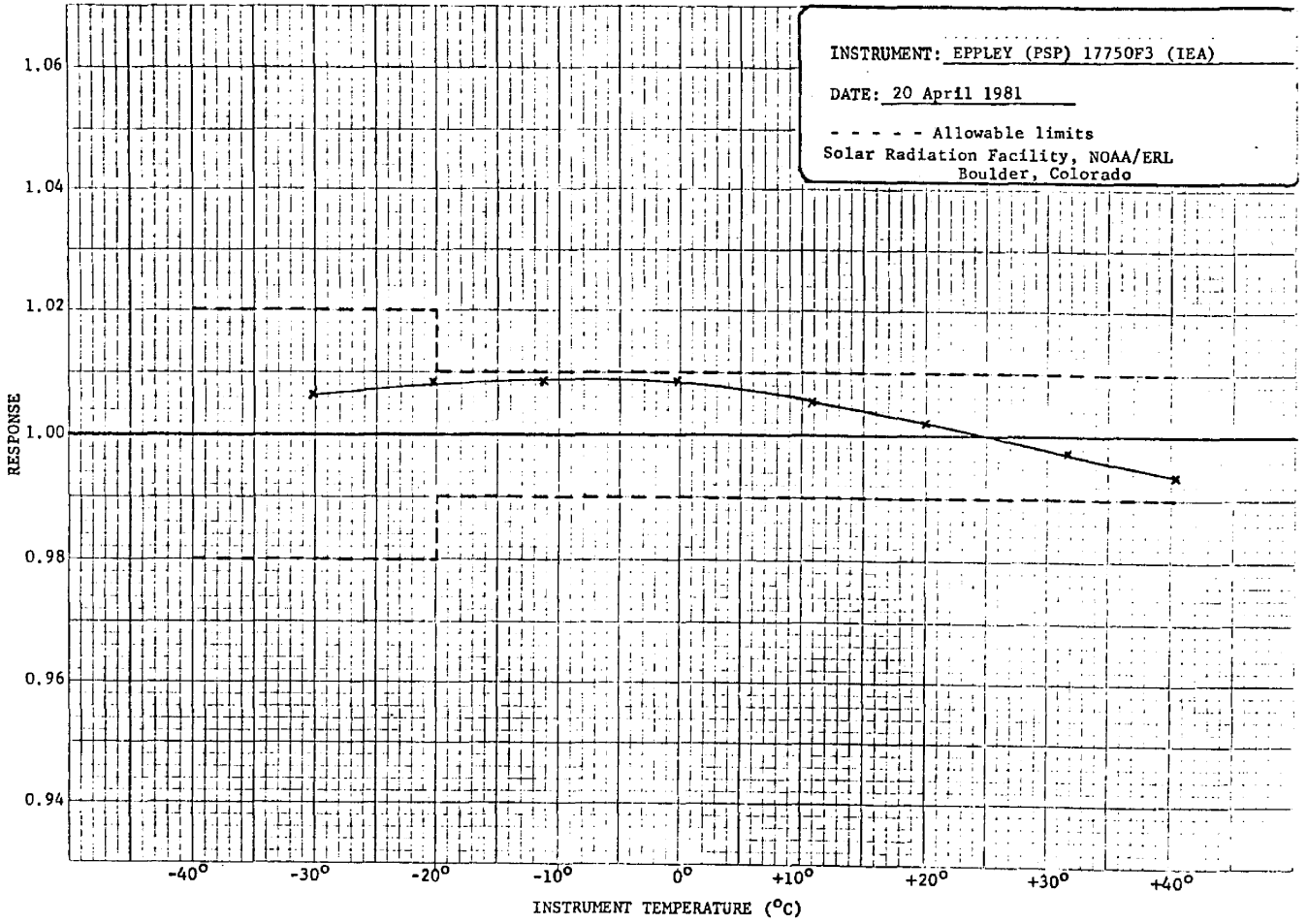
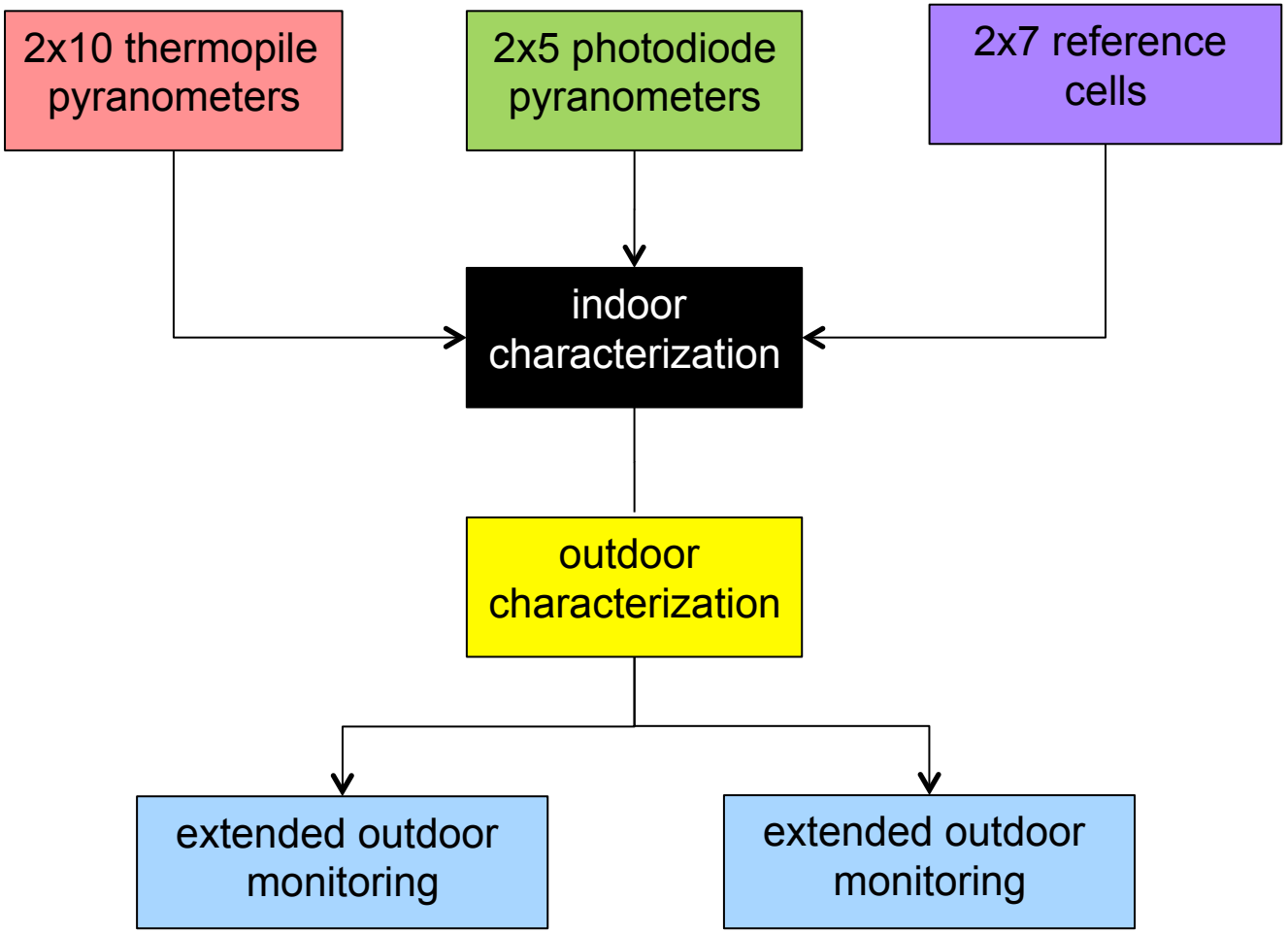


Figure 22: Temperature chamber test data for Eppley PSP 17750F3.

PVSENSOR 2014+



Expected Outcomes

- Detailed curves describing each instrument's response to the most important external influences
- Ability to apply corrections to and/or calculate uncertainties for individual irradiance measurements
- Ability to assess the suitability of instruments for different purposes
- Insights and recommendations for instrument test methods

Opportunities for Further Exploration

- Variability with instruments of the same type
- Additional characteristics: long-term stability, …
- Survey PV industry to find out what products have been and are currently being installed
- Identify potential instrument improvements to better meet the needs of the PV industry

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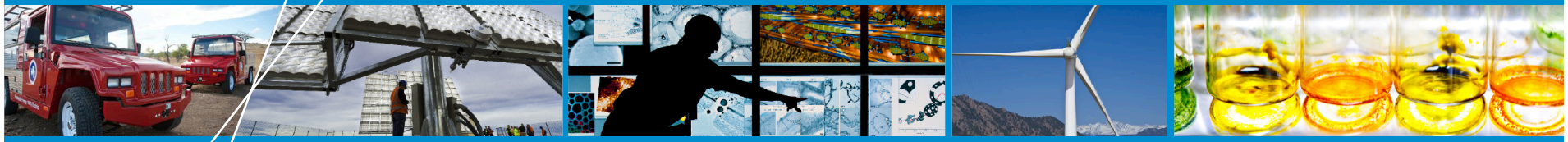
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Changing How We Look at Things:

Are There Opportunities That We're Overlooking?



Sarah Kurtz, Manajit Sengupta, Keith Emery

PV Solar Resource Workshop

February 27, 2015

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.

Outline

- **Goal: Reduce uncertainty in PV investments**
- **Options for quantifying irradiance data**
  - For predicting output of a future PV plant
  - For verifying output of an installed PV plant
  - Key question is horizontal vs plane-of-array irradiance
- **Can we avoid taking risk twice for the uncertainty of the transposition?**
- **Can we change the way we communicate historical data to enable more precise validation of PV plant performance?**
- **Solar resource vs PV resource – what would it take to change the paradigm?**

Investors want to know the ROI

- **If you buy a Certificate of Deposit, would you buy the one for**
  - 2%/year return or
  - 2.5%/year return?
- **When investing in PV, each reduction in uncertainty (risk) is valuable to the investor**
- **Risk is included in contract for**
  - The available sunshine
  - The plant performance

For a new project, what are options?

- **Quantify solar resource:**
  - Deploy sensors in the proposed location and configuration and wait 30 years

For a new project, what are options?

- **Quantify solar resource:**
  - Deploy sensors in the proposed location and configuration and wait ~~30 years~~ a year

For a new project, what are options?

- **Quantify solar resource:**
  - Deploy sensors in the proposed location and configuration and wait ~~30 years~~ a year
  - Use historical data sets derived from > 30 years of data (e.g. TMY = Typical Meteorological Year*) to provide horizontal (GHI, direct, diffuse) irradiance, transpose that to plane-of-array (POA) irradiance

*www.nrel.gov/rredc/

Why GHI rather than POA Irradiance?

- **Why not include POA irradiance in weather files?**
- **Practical questions for POA irradiance in weather data files:**
  - How many tilts and azimuths might we want data for?
  - When creating a POA irradiance data set,
    - What albedo would one assume?
    - What transposition model?
    - Isotropic or anisotropic diffuse radiation?
- **Conclusion: Horizontal data are easier to document (though less useful than POA data).**

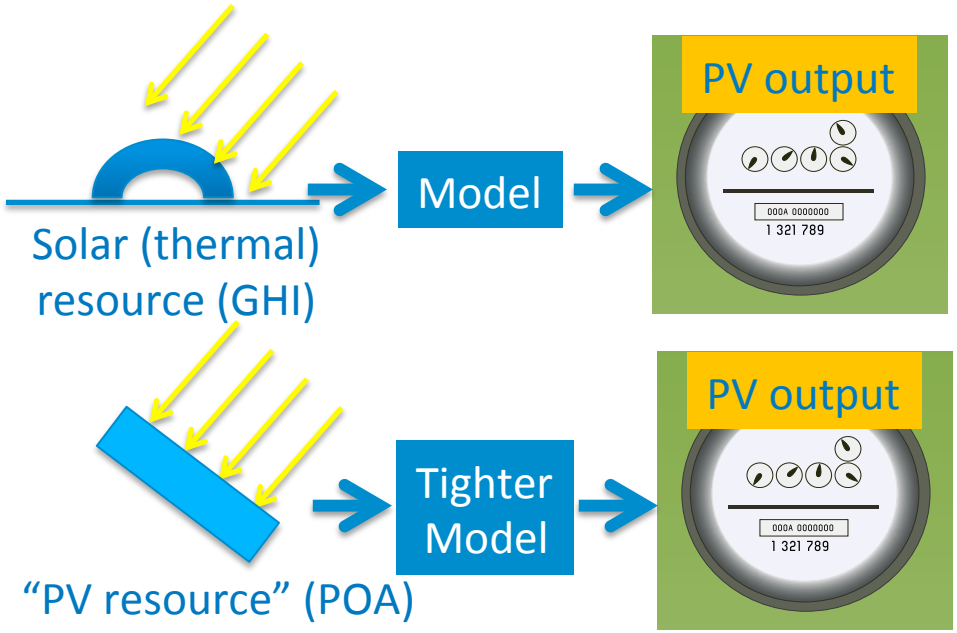
For monitoring plant operation, what options?

- **Quantify solar resource using:**
  - Thermopile in horizontal plane
    - This is consistent with the data used for the original prediction
  - Reference cell or module in POA
    - This is known to more closely correlate with system performance

For monitoring plant operation, what options?

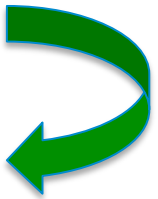
- **Quantify solar resource using:**
  - Thermopile in horizontal plane
    - This is consistent with the data used for the original prediction
  - Reference cell or module in POA
    - This is known to more closely correlate with system performance

- **Which is preferred?**
  - Some say that the only "correct" way is the thermopile



Double counting risk

- **Investor wants to know kWh at the end of the year. Risk includes:**
  - Accuracy of historical data
  - Sunny or cloudy weather relative to historical average
  - Accuracy of transposition to POA
  - Risk of plant performance relative to predicted for measured weather is transferred to installer
- **Installer's risk includes:**
  - Accuracy of measurement of GHI
  - Accuracy of transposition to POA
  - Plant performance relative to predicted for measured weather



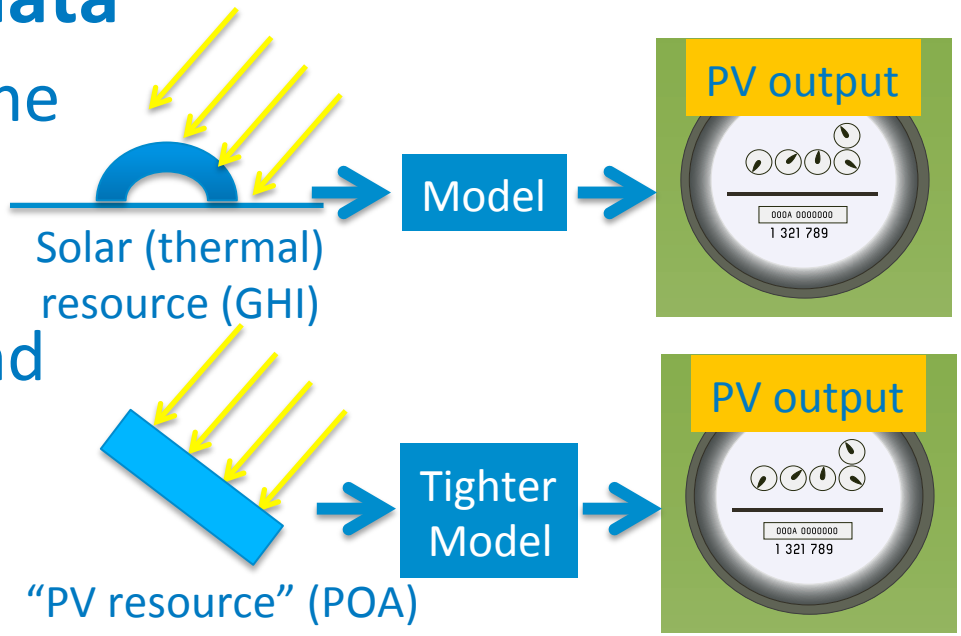
Double counting risk

- **Investor wants to know kWh at the end of the year. Risk includes:**
  - Accuracy of historical data
  - Sunny or cloudy weather relative to historical average
  - Accuracy of transposition to POA
  - Risk of plant performance relative to predicted for measured weather is transferred to installer
- **Installer's risk includes:**
  - Accuracy of measurement of horizontal irradiance
  - Accuracy of transposition to POA
  - Plant performance relative to predicted for measured weather

Both the investor and the installer often take risk for inaccurate transposition!

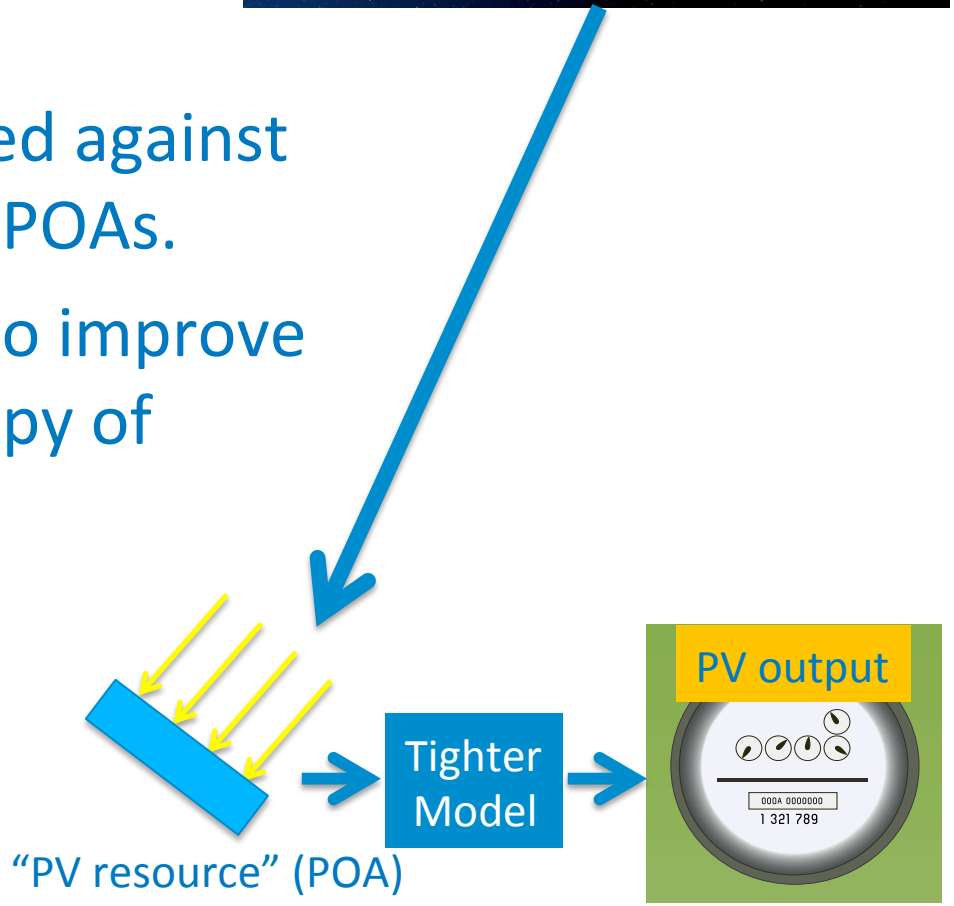
Can we use POA data to verify plant performance?

- **Reasons for using horizontal data**
  - Historical POA data is not available in many cases
  - POA may not be well defined
  - Performance model may use horizontal rather than POA irradiance
- **Reasons for using POA data**
  - Avoids double counting the risk for transposition
  - Allows a tighter contract between the investor and the installer

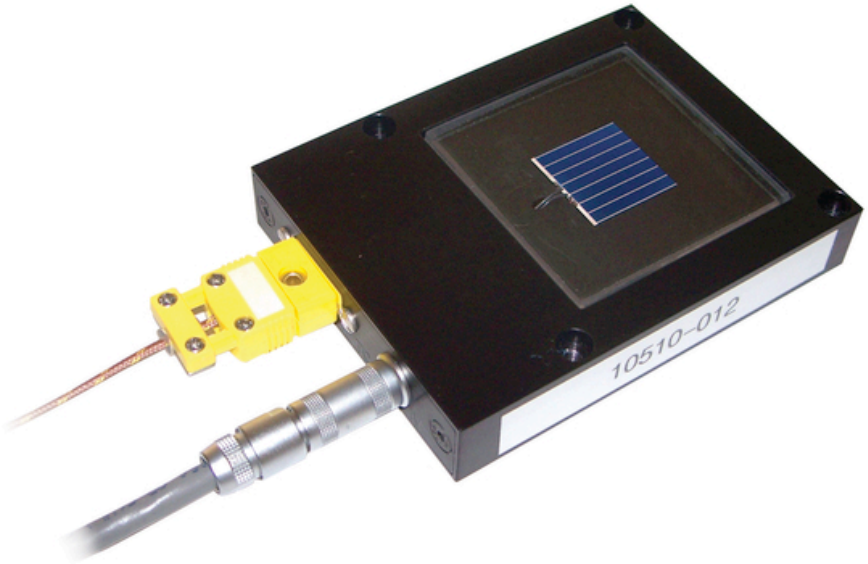


What if?

- **What if the satellite data could be used to create TMY files for any POA?**
  - Would need to be validated against ground data at a range of POAs.
  - May use satellite images to improve understanding of anisotropy of diffuse light
  - What if?????



What sensor for POA? Thermopile vs Reference cell vs ?

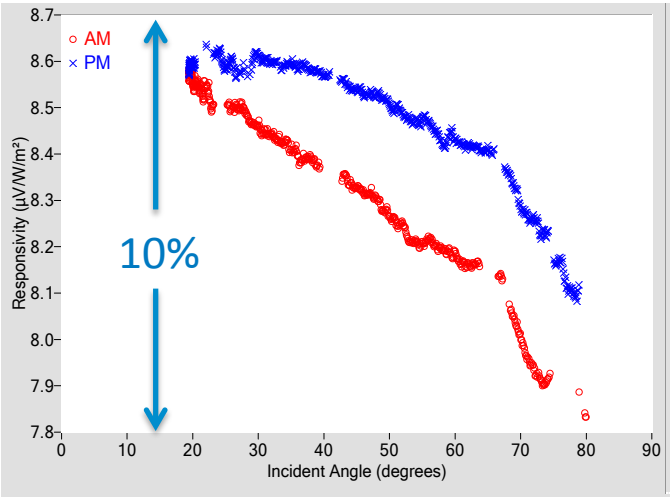


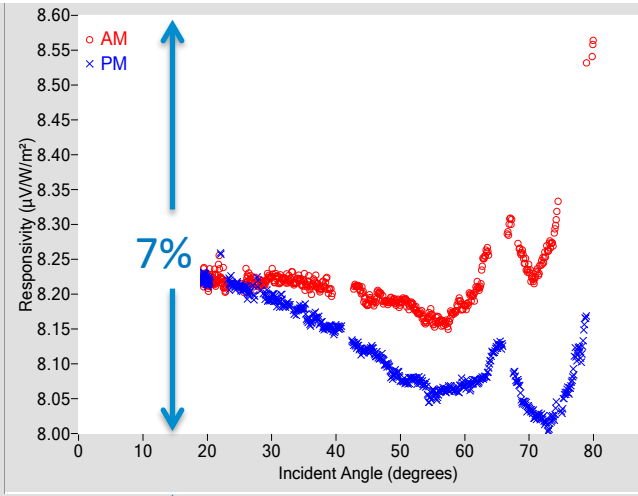
Many options for irradiance sensors.

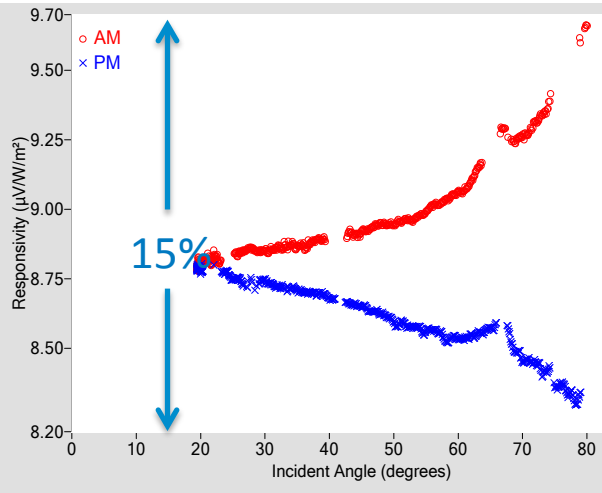
Which is the best for which purpose?

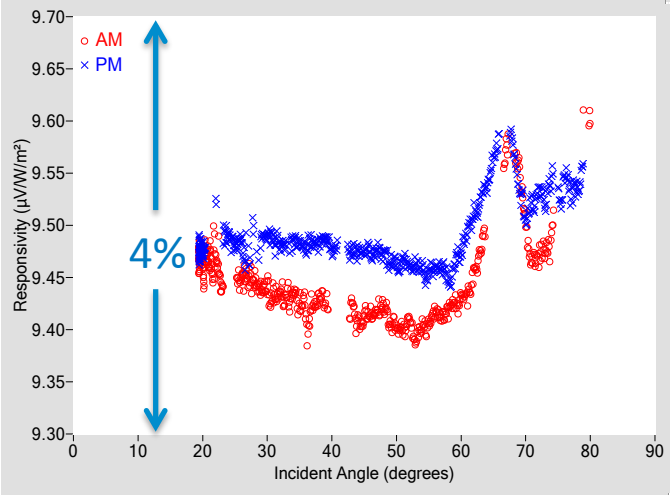
Do they differ enough for us to care?

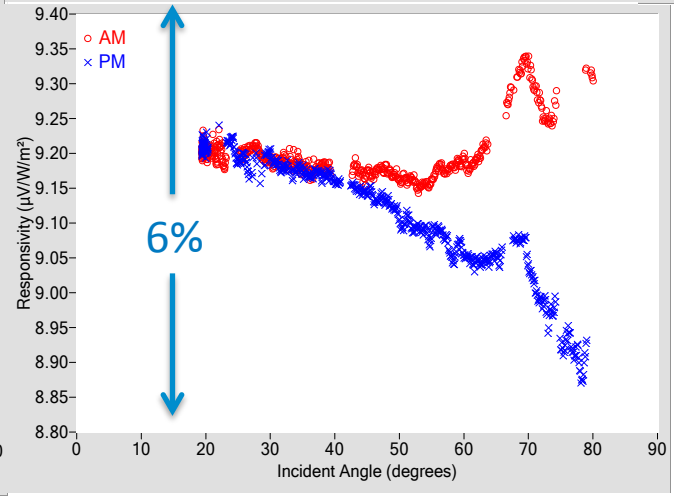
Calibration of Thermopiles – angular effects









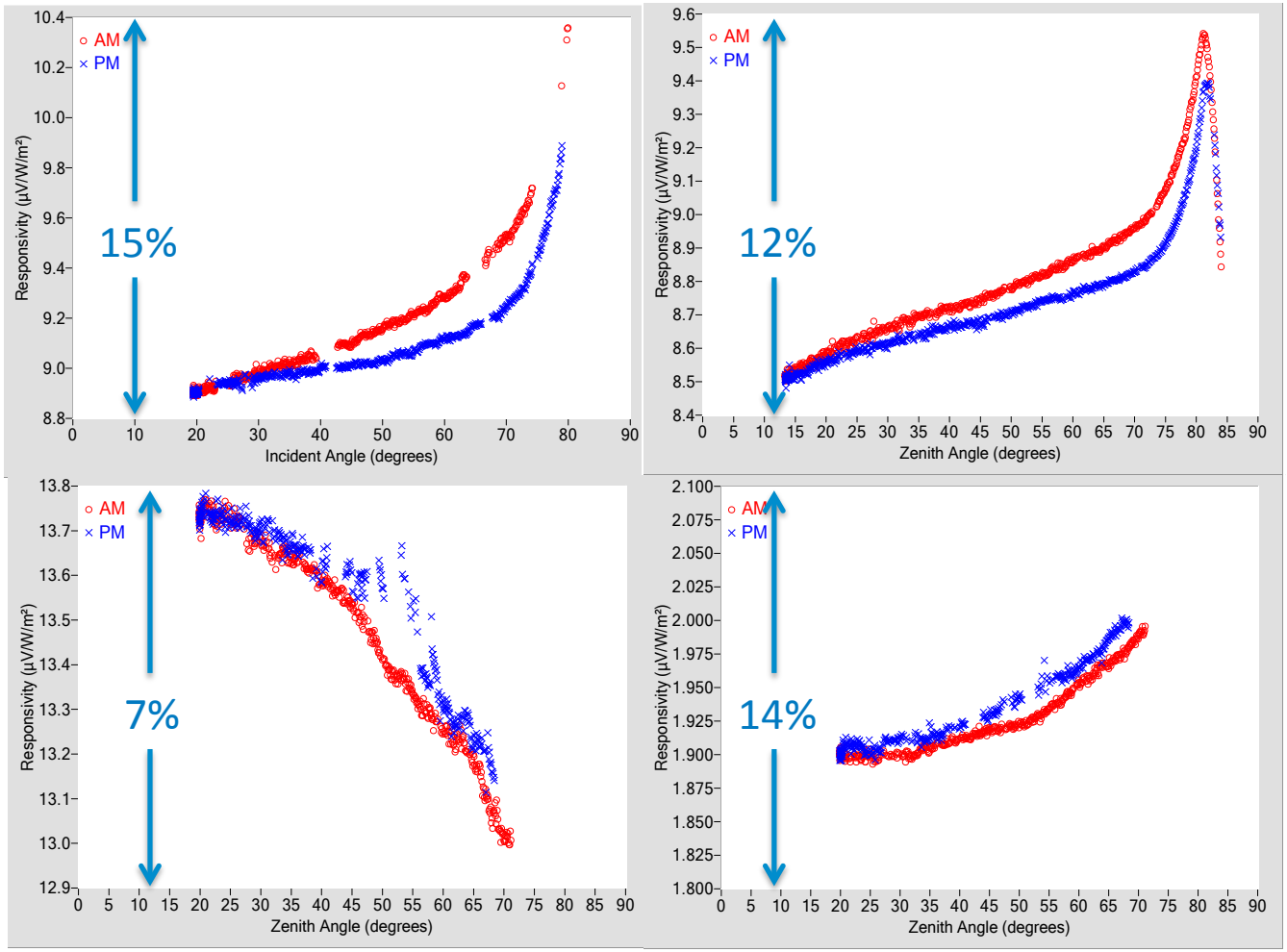


Thermopile calibrations can depend on angle of incidence by several per cent

How do we account for this during normal use?

BORCAL data from http://www.nrel.gov/aim/Calibrations/BORCAL/

Calibration of LI200,LI201 – angular effects



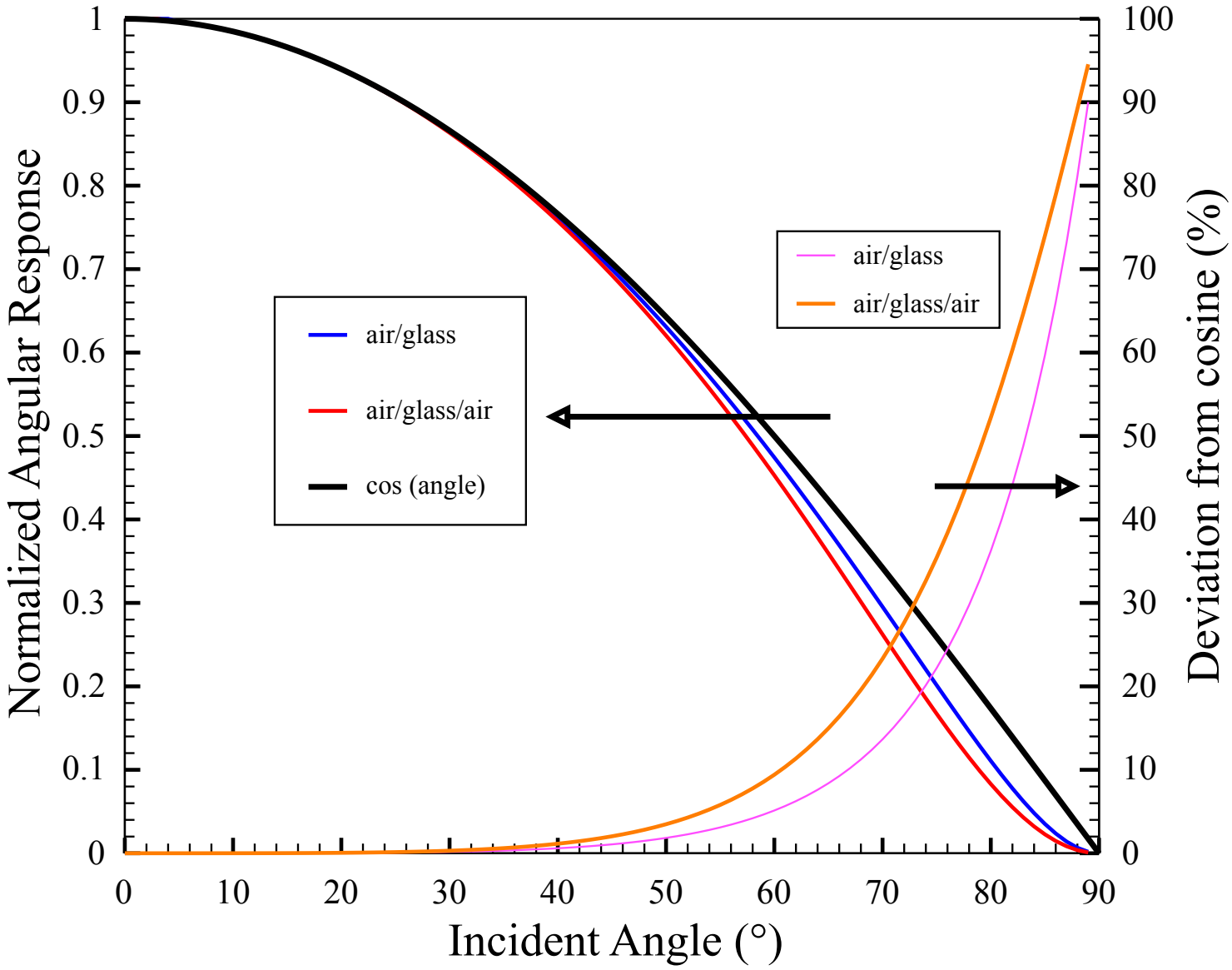
Almost ALL irradiance sensor calibrations depend on the angle of incidence by several per cent

How do we account for this during normal use?

Is this dependence from angle of incidence or spectral effects?

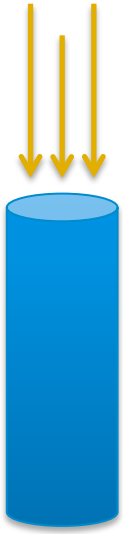
BORCAL data from http://www.nrel.gov/aim/Calibrations/BORCAL/

Angular response – depends on interface



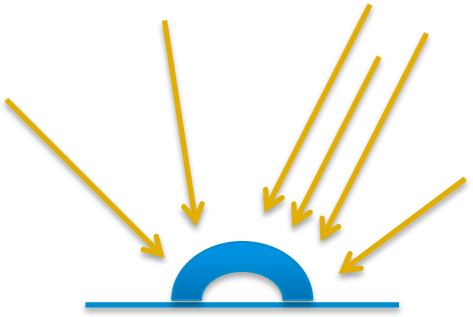
How should we calibrate irradiance sensors?

- **Normal incidence (collimated) light**
- **Diffuse light**
- **Mixture of diffuse and normal light?**



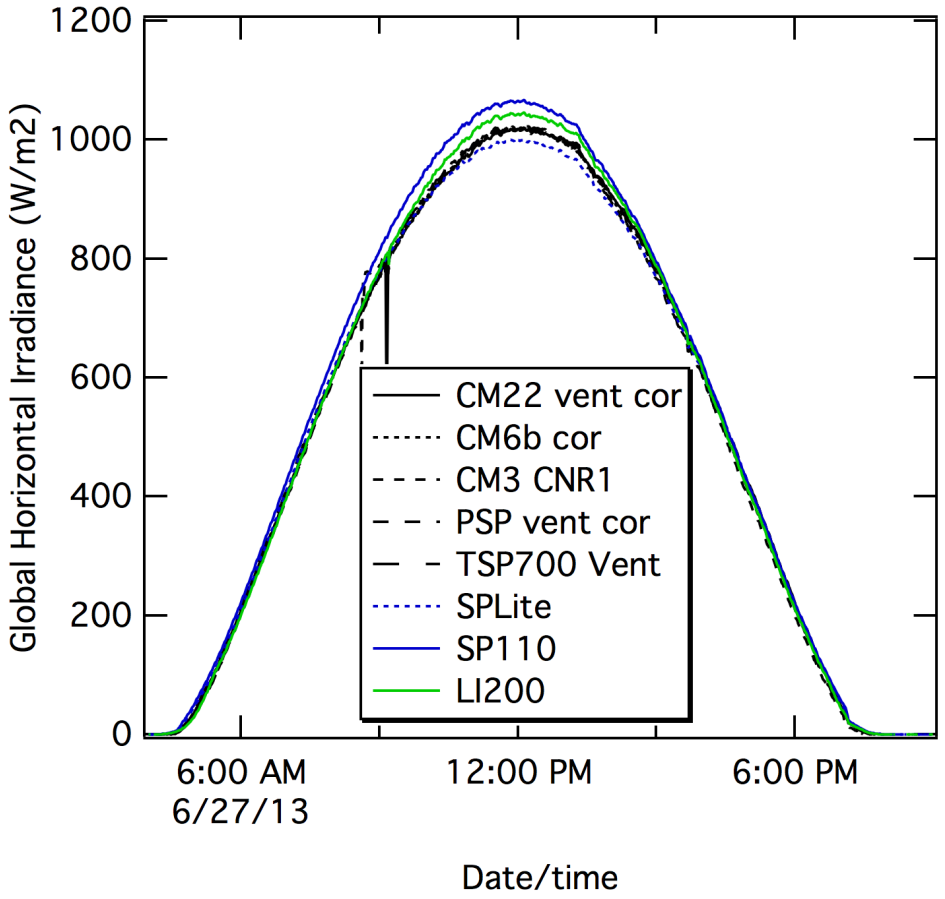
Reference cell calibration: normal incidence

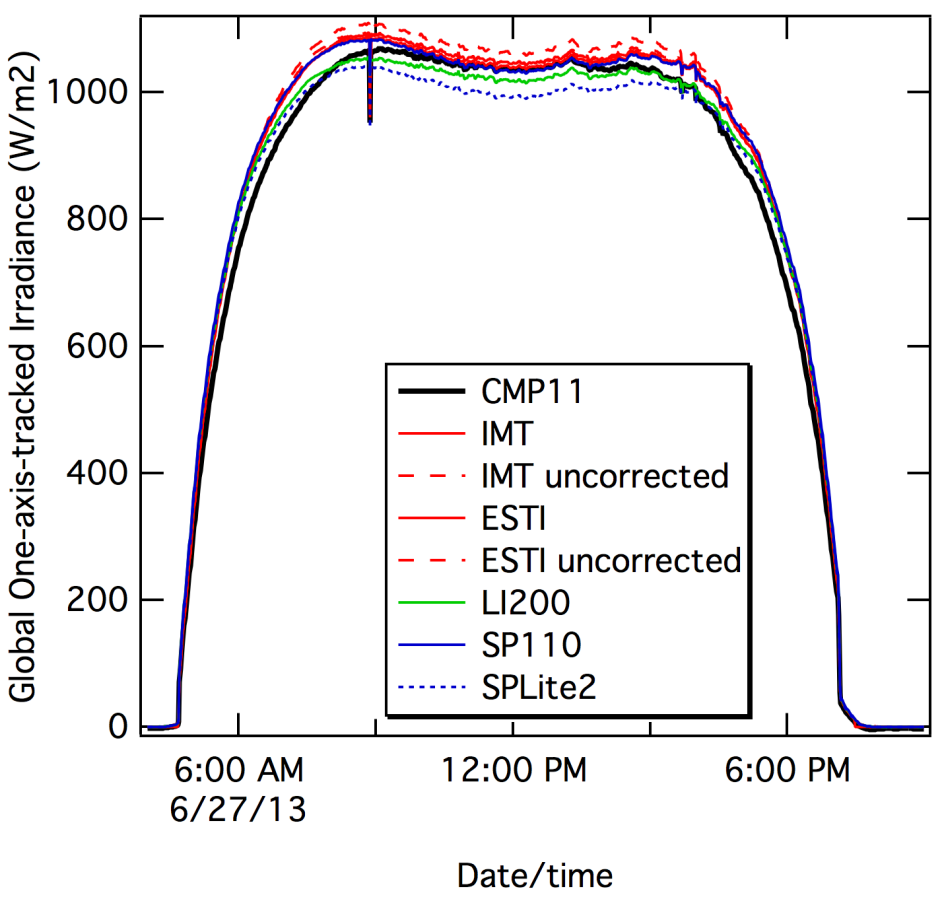
Winter, et al (25 EUPVSEC, pp. 4304-4306, 2010) reported 0.5%-1.2% error



Thermopile calibration: BORCAL uses variable angle; others use normal incidence

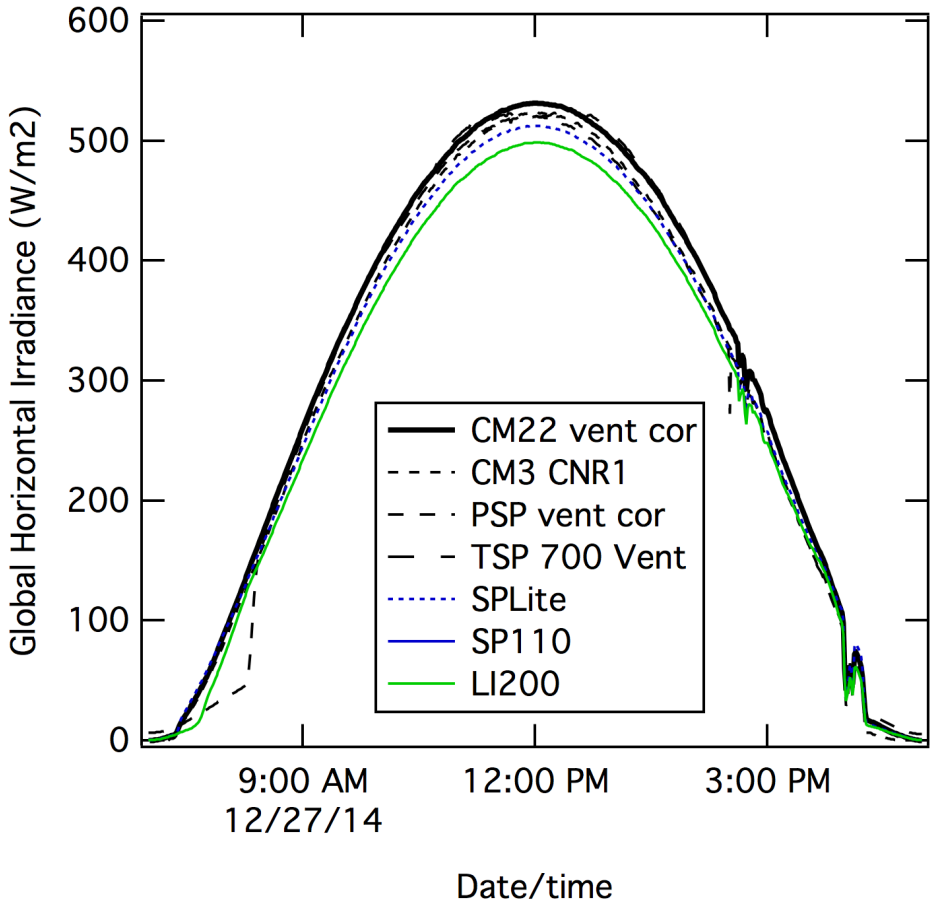
Irradiance sensors may respond similarly

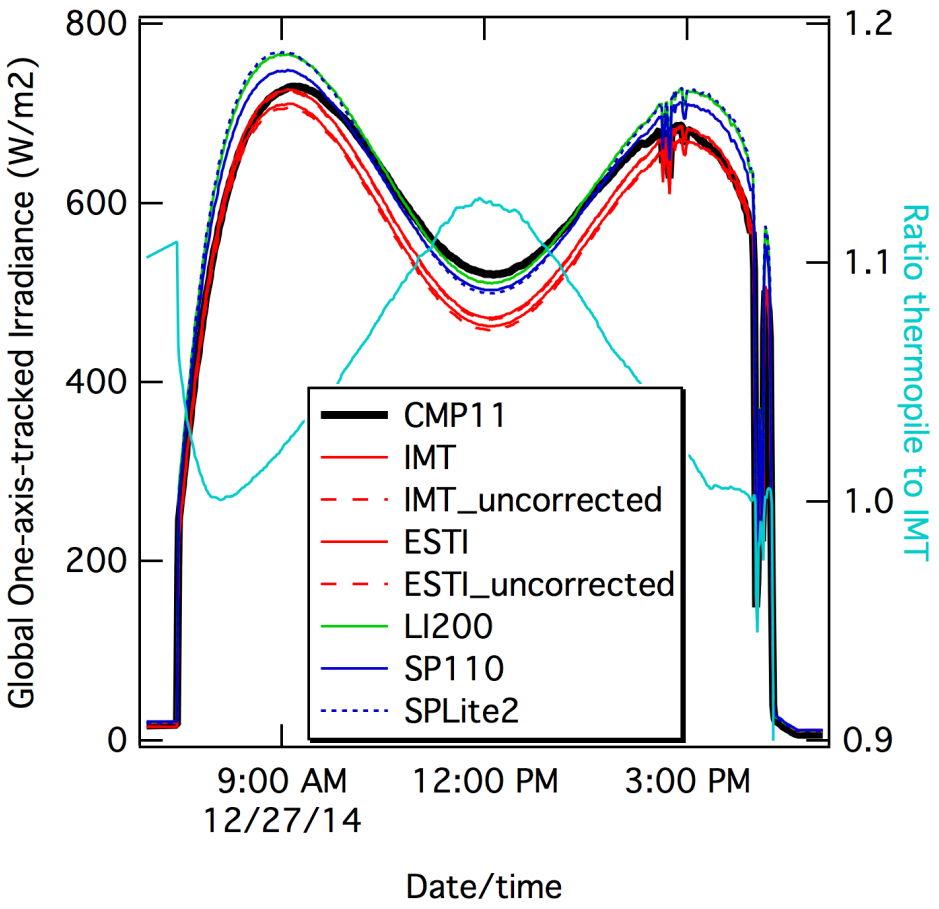




Collection of irradiance sensors give results, typically within ~5%

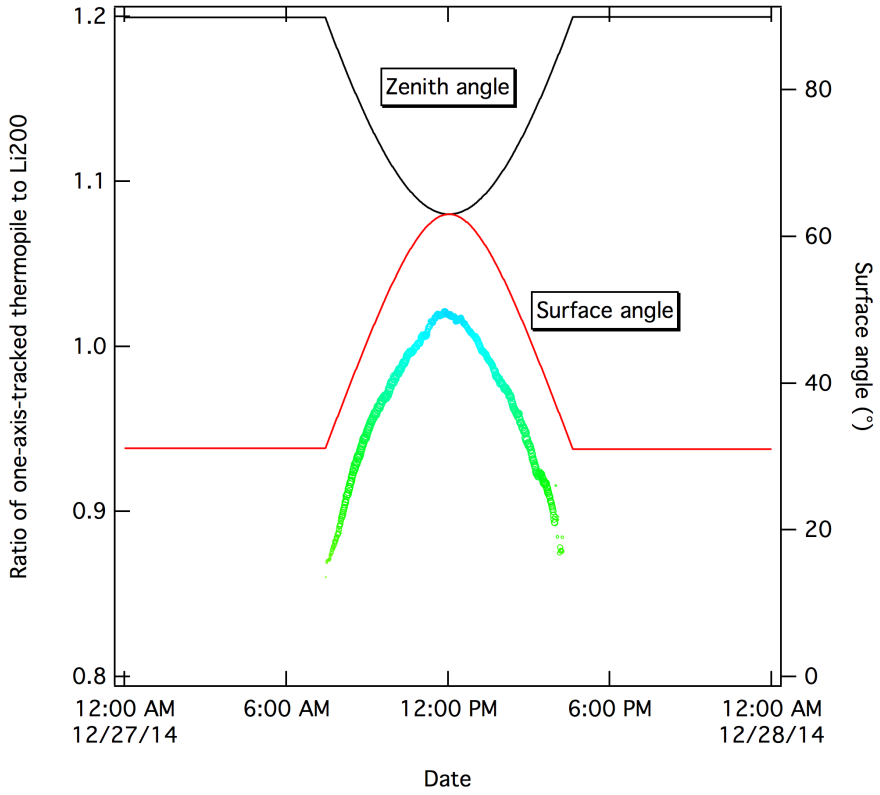
Irradiance sensors sometimes don't agree

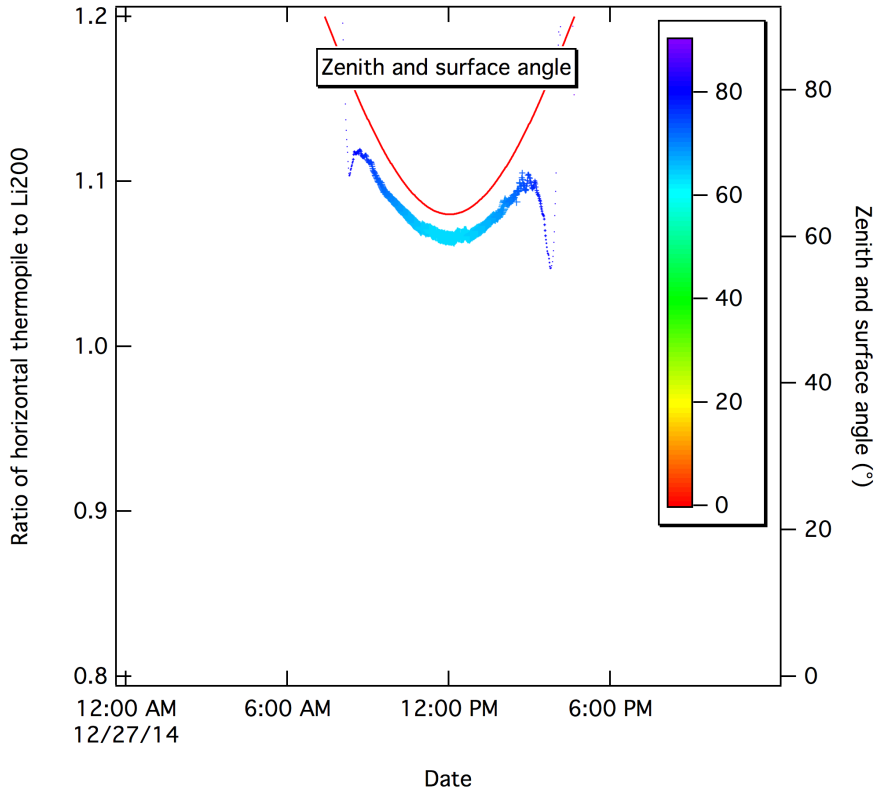




Ratio of thermopile to reference cell may vary by more than 10%!

Difference may be both angle and spectrum





Ratio of thermopile to Li200 may vary by more than 10%; Difference correlates with angle of incidence, but also depends on spectrum!

Solar Resource vs PV Resource

- Thermopiles measure W/m^2 – traceable to world reference standards

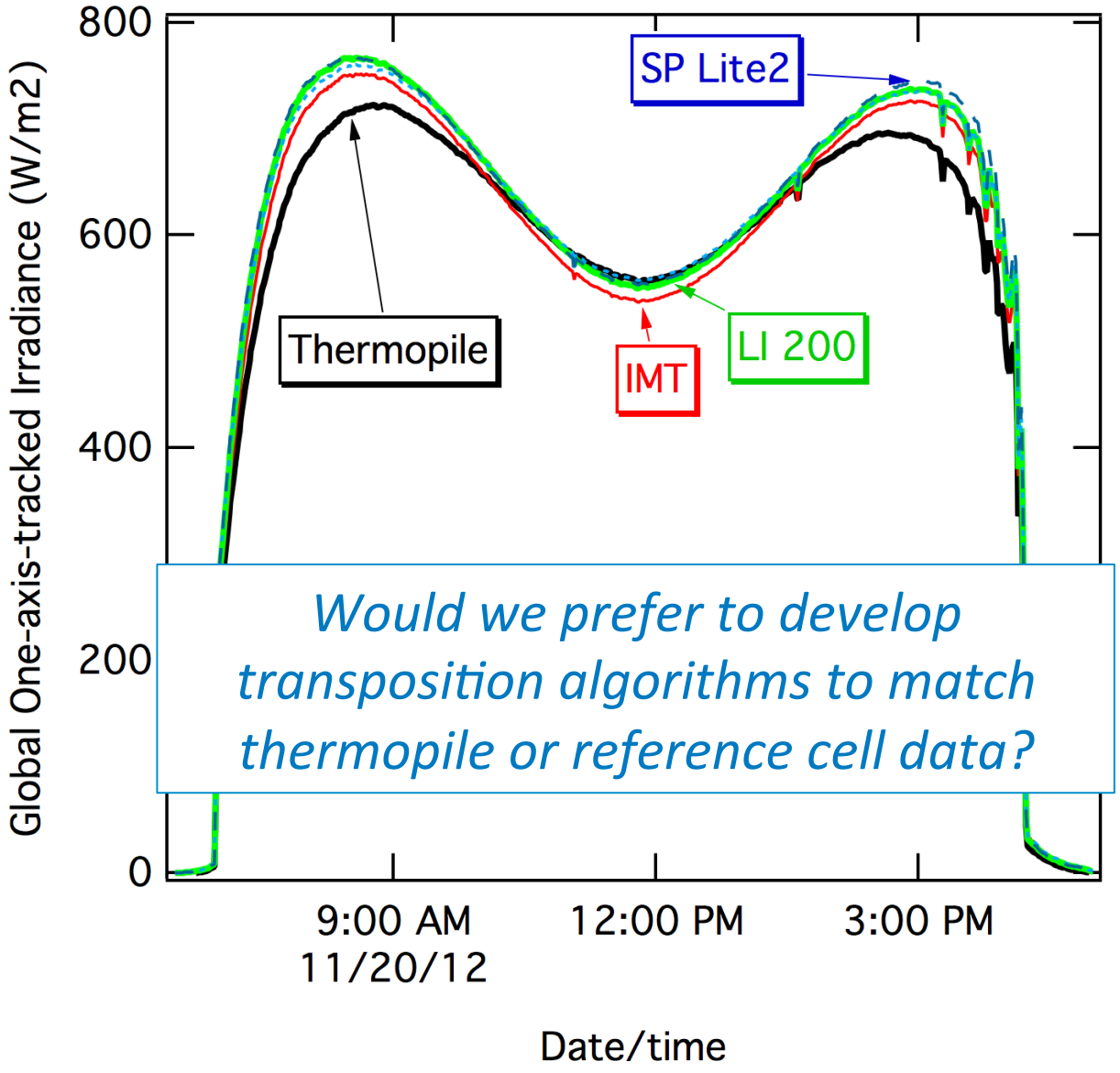
- What do reference cells measure?
- PV module power output measurements are adjusted to Standard Test Conditions – the actual W/m^2 during the measurement may differ from the thermal 1000 W/m^2 because of the spectral correction

Should we define a new unit?

- Irradiance as "total energy" = W/m^2
- Irradiance as "the eye sees" = Lumens
- Irradiance as "a PV cell sees" = "Solmens?" IEC calls this "effective" irradiance

- *Can we differentiate "Solar Resource" from "PV Resource" so that we are measuring the quantity most relevant to PV?*

Transposition to thermopile or reference cell?



Would we prefer to develop transposition algorithms to match thermopile or reference cell data?

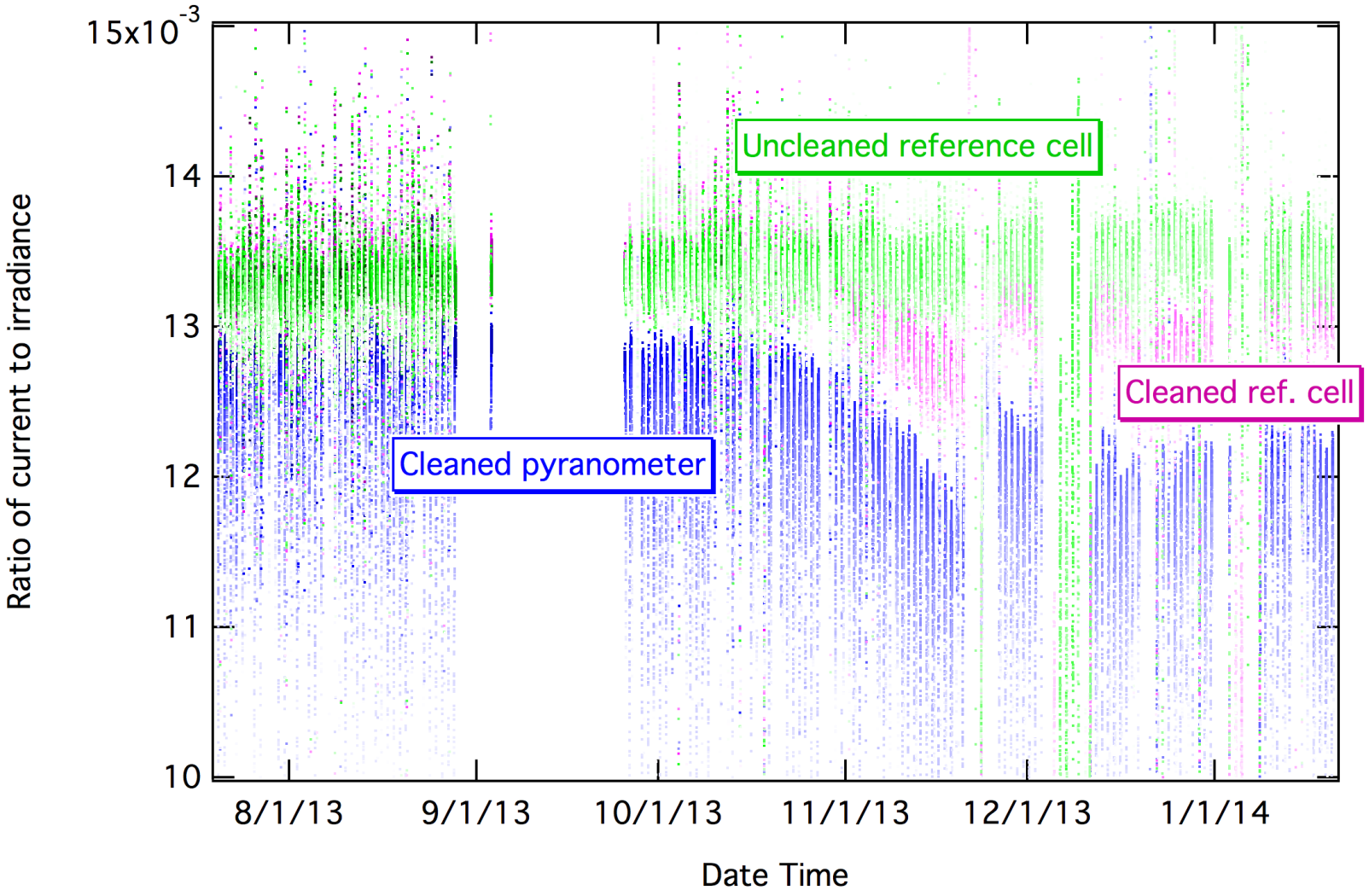
Do we calibrate PV modules and irradiance sensors similarly?

- **Angle**
  - Normal incidence (in collimating tube or using a solar simulator with a long path)
  - Typical global (clear-sky day with sun overhead)
  - Diffuse (cloudy day or some simulators)
  - If calibrated in one condition is adjustment made for different angles of incidence?
- **Spectrum**
  - Modules and reference cell measurements are adjusted for spectrum
  - Thermopile calibrations are independent of spectrum
  - When used outdoors, do we want to adjust for spectrum?

How do we measure irradiance? Depends!

- Module manufacturer: irradiance reaching cells (uncleaned reference cell)
- Investor expecting MWh consistent with original prediction: (thermopile for GHI)
- O&M provider: compare cleaned and uncleaned reference modules to determine need for cleaning
- Degradation rates: uncleaned reference cell?

Sensors for measuring degradation



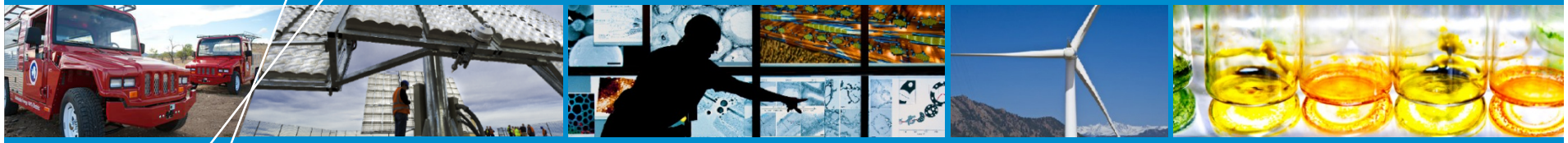
When measuring degradation, an uncleaned reference cell correlates most closely

Conclusions

- **What if?**
  - Satellite data could quantify irradiance on any POA with accuracy as good or better than what we can do now? Could we use this data as the basis for our predictions?
  - Spectra could be derived from satellite data to adjust for any reference cell?
- **Would it make sense to:**
  - Verify plant performance using POA data?
  - Model plant performance from POA rather than horizontal data?
  - Use matched or semi-matched reference cell data?
- **What would it take?**

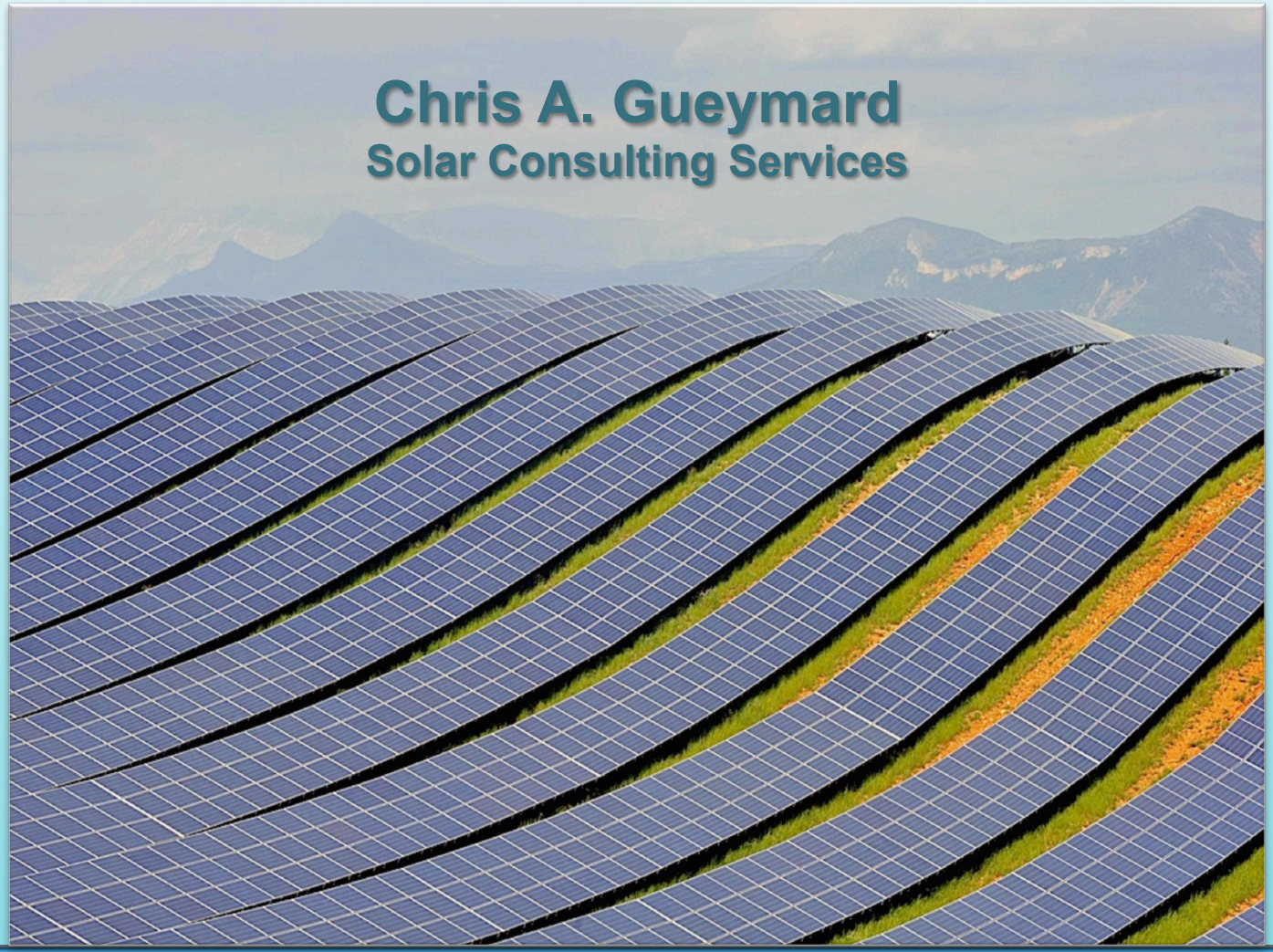
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Sarah.Kurtz@nrel.gov



Thank you. Questions?

Uncertainties in Transposition and Decomposition Models: Lessons Learned

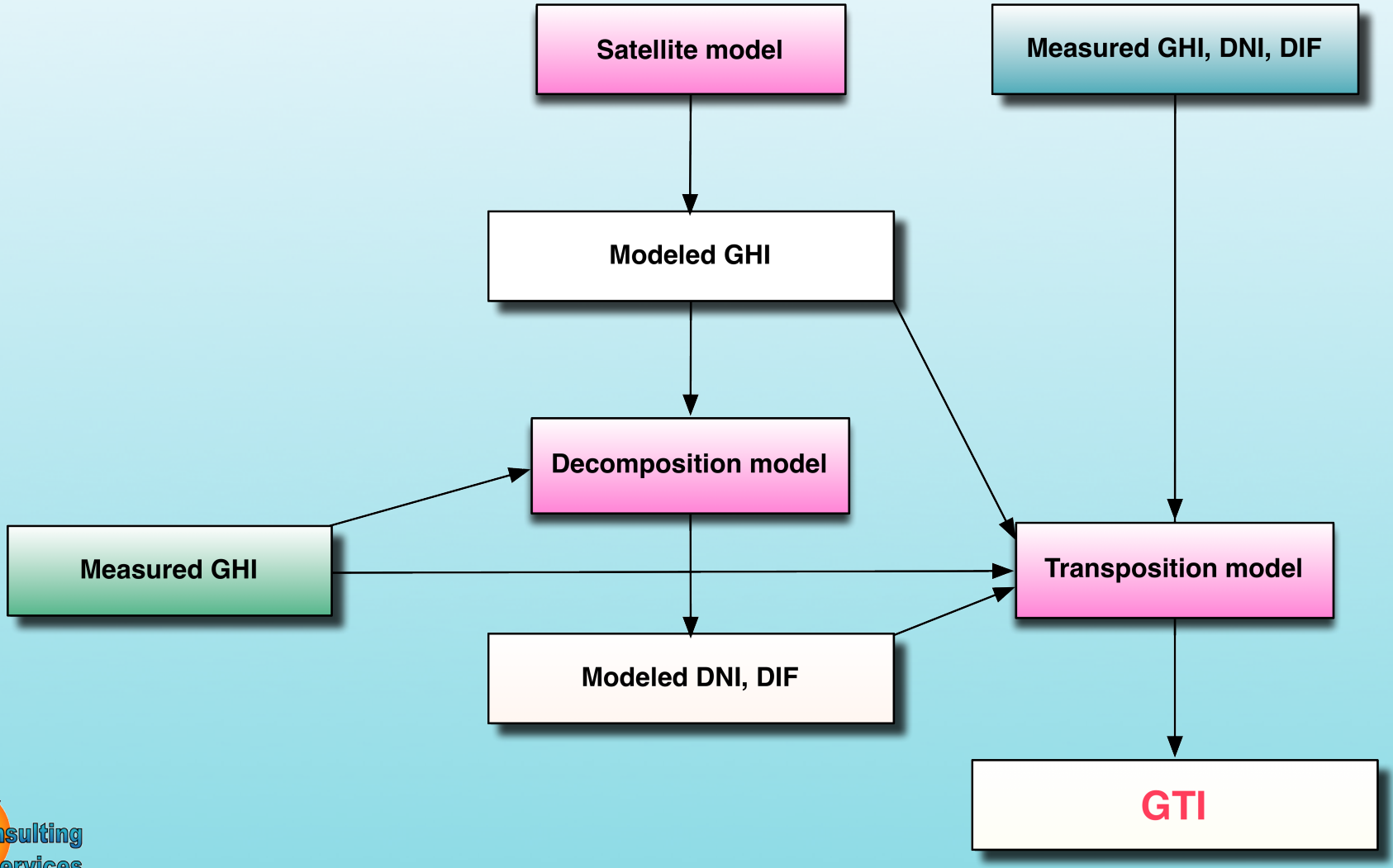


Solar Consulting Services

Expert Assistance in Solar Resource Assessment, Radiometry and Solar Radiation Data Analysis

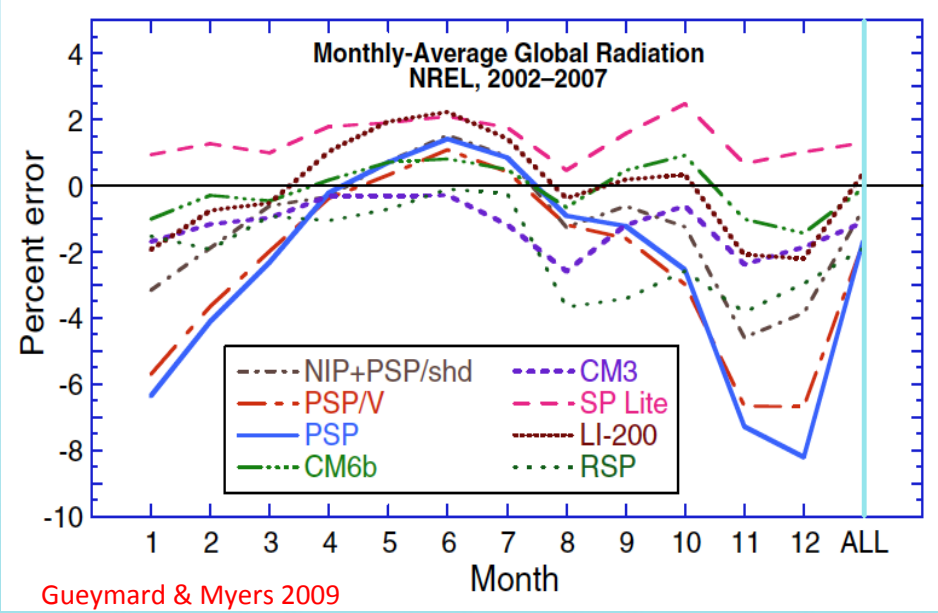
Overview

- How to obtain GTI (Global tilted irradiance on POA) if not measured?
- Three possible ways

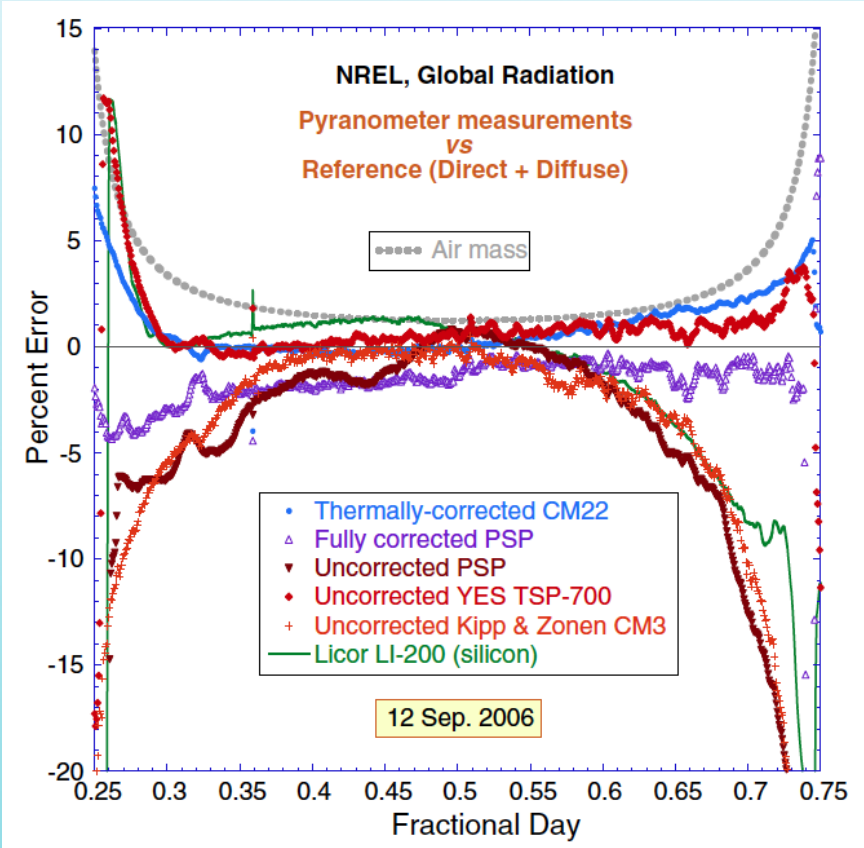


Experimental Issues—GHI

- Measuring GHI with a pyranometer is simplest but suboptimal
- A seasonal bias is likely, except with selected instruments
- Beware of thermal offset (e.g., PSP); requires appropriate correction

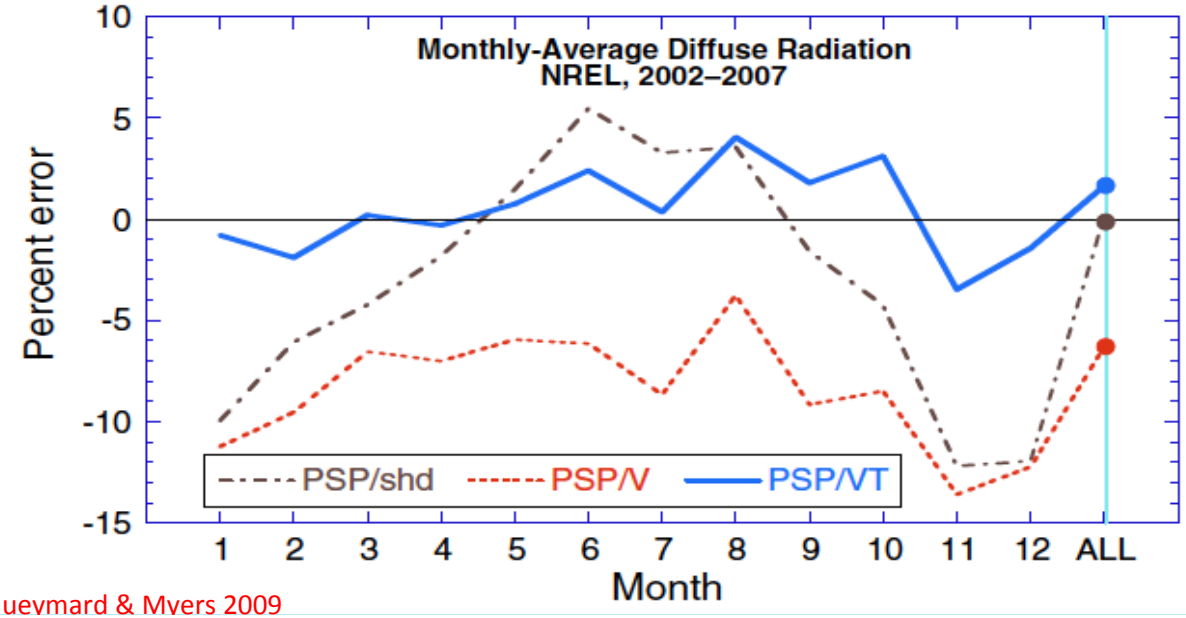


Gueymard & Myers 2009

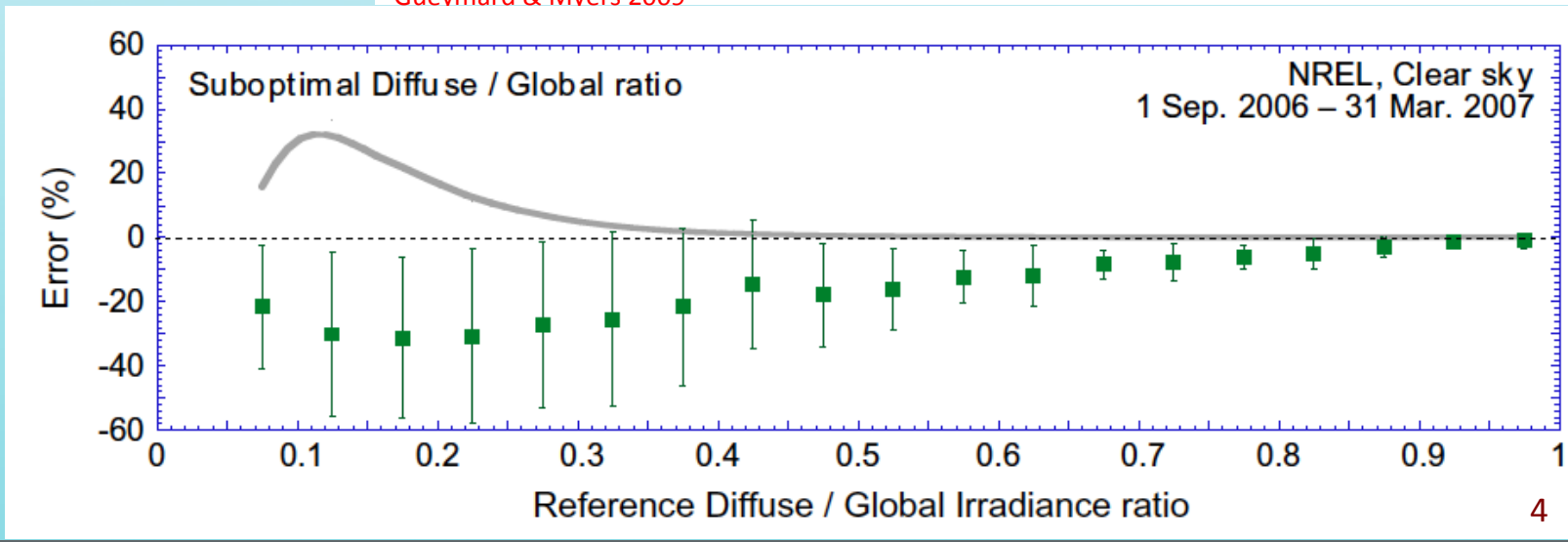


Experimental Issues—DIF

- Beware of thermal offset; may induce large bias
- Avoid shadowband

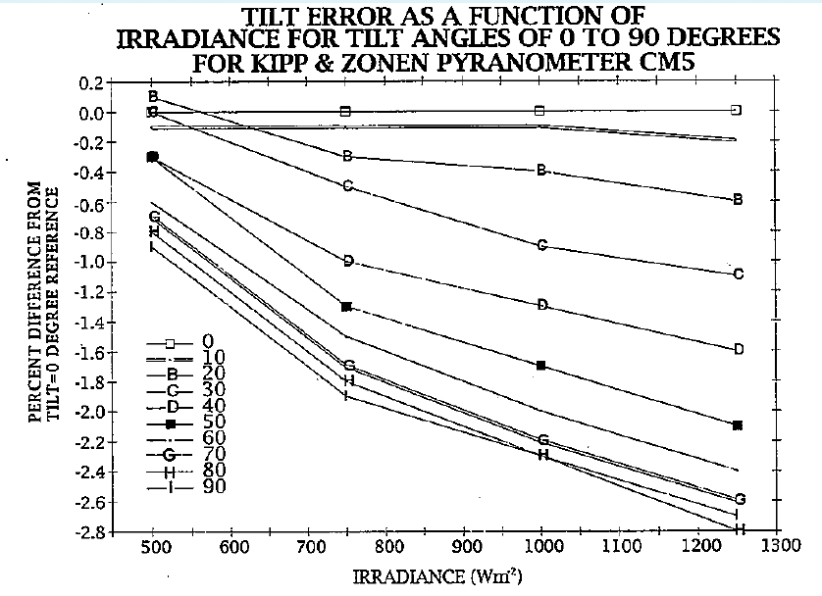


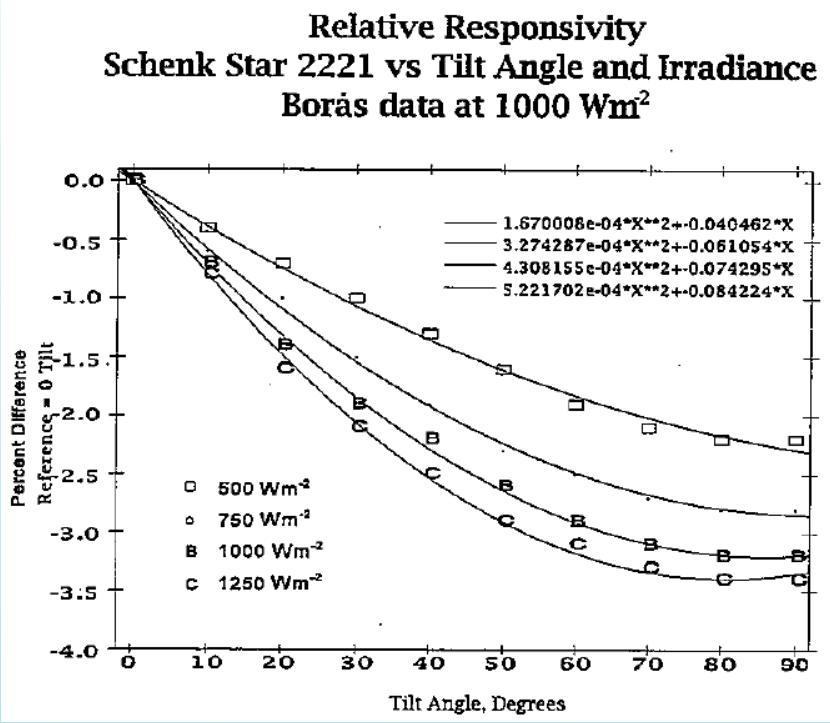
Guevmard & Myers 2009

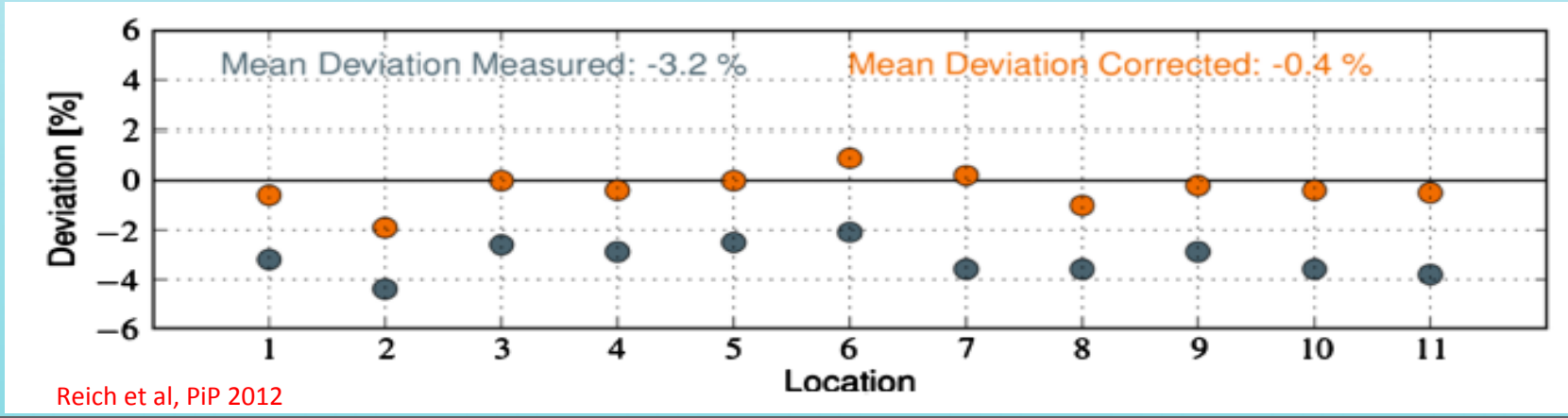


Experimental Issues—GTI

- Tilted pyranometers and photodiode sensors may require specific calibration
- Reference cells are convenient but induce bias (2–5% typical)







Reich et al, PiP 2012

Solar Consulting Services

Transposition

- Modeling **GTI**:

$$GTI = DNI \cos\theta + R_d\, DIF + f_s\, \rho\, R_r\, GHI$$

f_s Shading factor

ρ Surface albedo

R_r Ground view factor

- **21 models** tested for IEA-SHC Task 9 study (Hay, 1988) for hourly or sub-hourly data. This remains the most comprehensive study ever undertaken on this topic.
- **27 stations** were classified depending on setup:
  A. Artificial horizon, measured DNI (6)
  B. Measured albedo, measured DNI (6)
  C. Estimated albedo, measured DNI (3)
  D. Artificial horizon, measured DIF (6)
  E. Measured or estimated albedo, measured DIF (6)
- Study found 3 models with consistently best performance overall, but with varying ranking depending on station and geometry:
  Perez (1983), Gueymard (1983), Hay (1979)

Transposition Models Performance

Results for U.S. sites

ATLANTA

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
34S	33	48	31	45	33	48	36	51
Rank.1	2=	2=	1	1	2=	2=	4	4
Rank.2	2=	2=	1	1	2=	2=	4	4

GOLDEN

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
40S	48	73	47	73	55	86	56	86
90S	43	71	49	75	50	72	48	72
All	46	72	48	74	53	79	52	79
Rank.1	1	1	2	2	4	3=	3	3=
Rank.2	1	1	2	2=	4	2=	3	2=

LOS ALAMOS

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
45ESE	145	289	139	279	141	272	141	274
90S	136	285	123	265	127	247	126	249
All	141	287	131	272	134	260	134	262
Rank.1	4	4	1	3	3	1	2	2
Rank.2	4	4	1	3	3	1	2	2

SAN ANTONIO

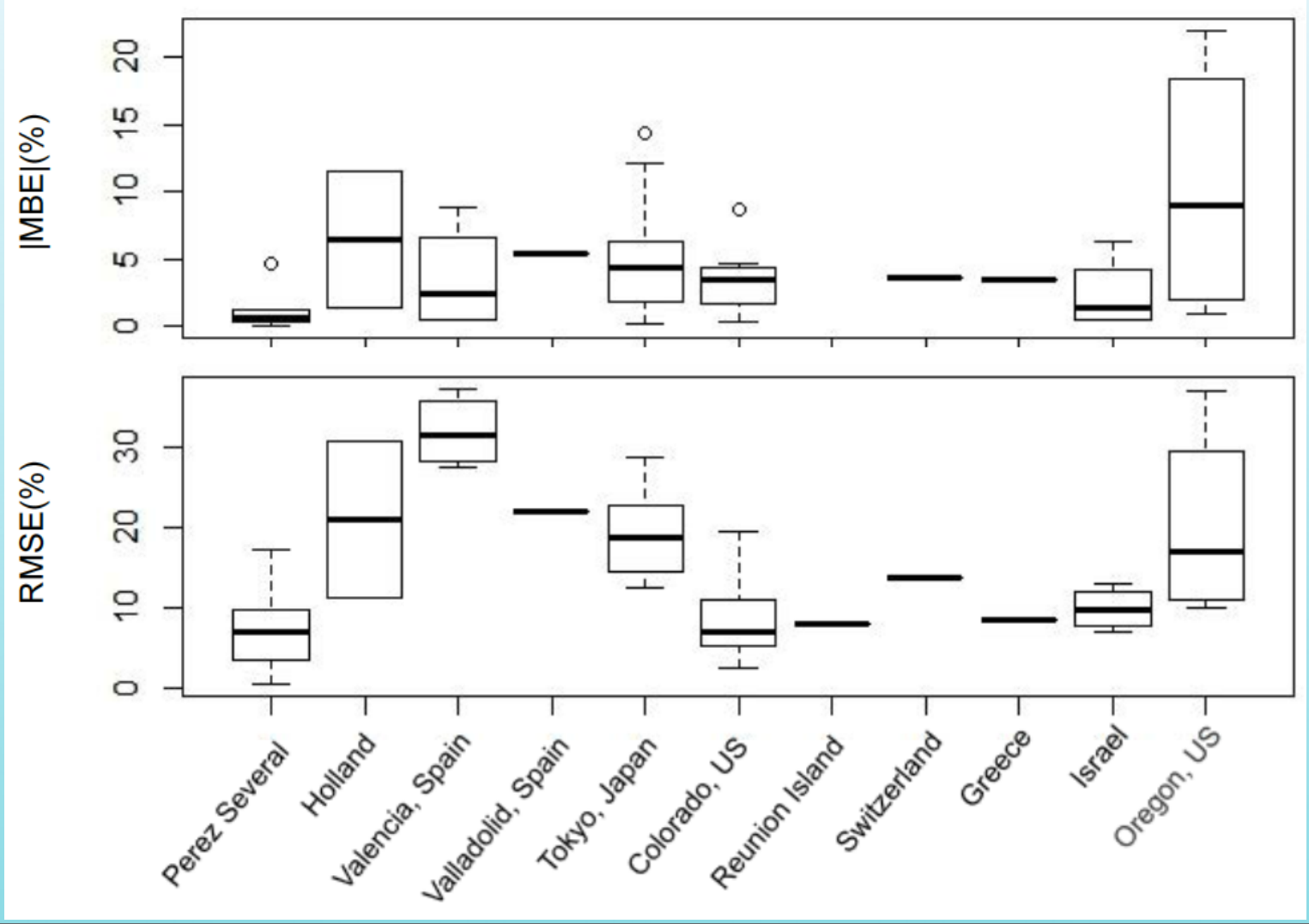
SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
20S	27	42	27	40	22	32	22	33
30S	35	53	37	54	25	37	26	39
40S	45	68	49	70	34	48	36	52
90N	51	72	88	120	49	69	53	74
90E	78	113	100	138	62	90	65	94
90S	75	106	99	136	64	87	68	93
90W	75	113	103	146	65	97	67	100
All	55	85	72	109	46	70	48	74
Rank.1	3	3	4	4	1	1	2	2
Rank.2	3	3	4	4	1	1	2	2

ALL LOCATIONS

SLOPE	GUEYMARD MAD	GUEYMARD RMSD	HAY MAD	HAY RMSD	PEREZ 1 MAD	PEREZ 1 RMSD	PEREZ 2 MAD	PEREZ 2 RMSD
All	55	97	63	103	54	92	53	91
Rank.1	3	3	4	4	2	2	1	1
Rank.2	3	3	4	4	2	2	1	1
Equatorward	56	99	60	101	54	94	54	93
Rank.1	3	3	4	4	1	2	2	1
Rank.2	3	3	4	4	1	1	2	2
Poleward	53	94	67	106	53	89	51	87
Rank.1	3	3	4	4	2	2	1	1
Rank.2	2	3	4	4	3	2	1	1

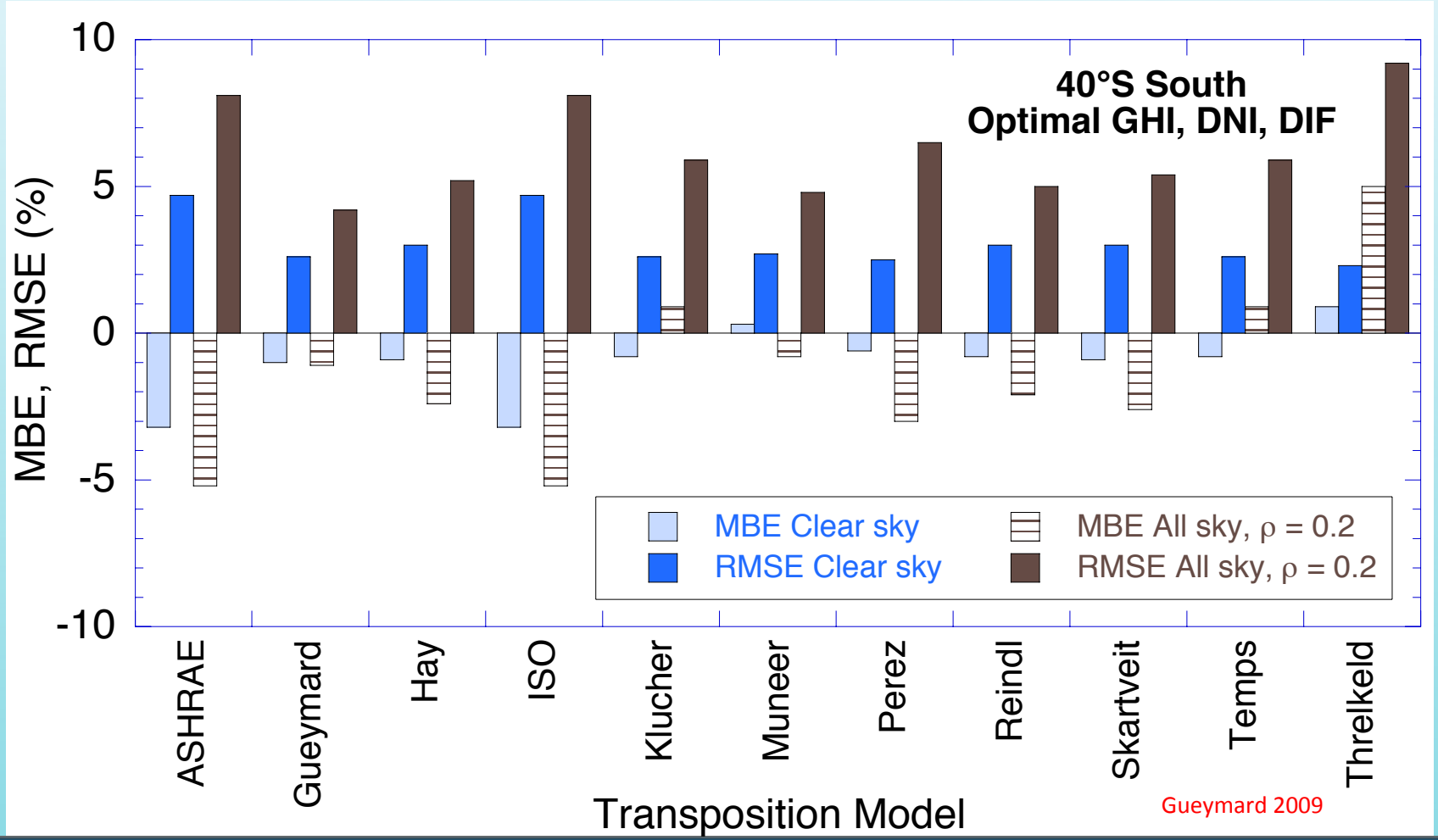
Transposition Models Performance

- Many more (but much more limited) studies followed
- Sun et al. (2014) showed variable bias and RMS for Perez model depending on site



Transposition Models Performance

- For Golden (NREL) and *optimally measured 1-min irradiances*, the lowest bias is obtained with the Muneer, Klucher, Temps and Gueymard models
- Best models under both clear-sky and all-sky conditions have low bias (<2%) and low RMS (<7%), even if albedo is assumed constant (0.2)

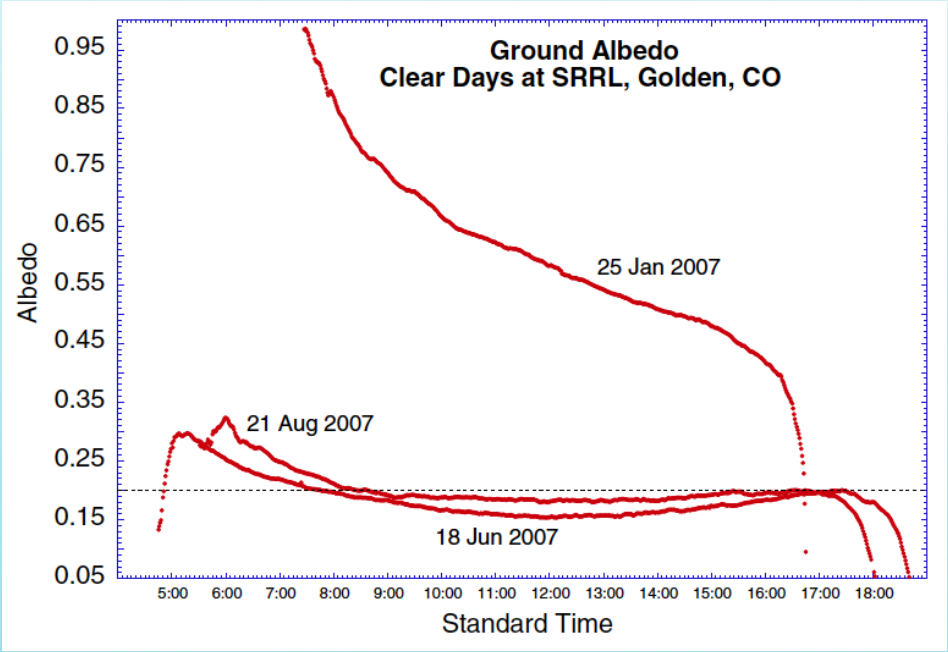


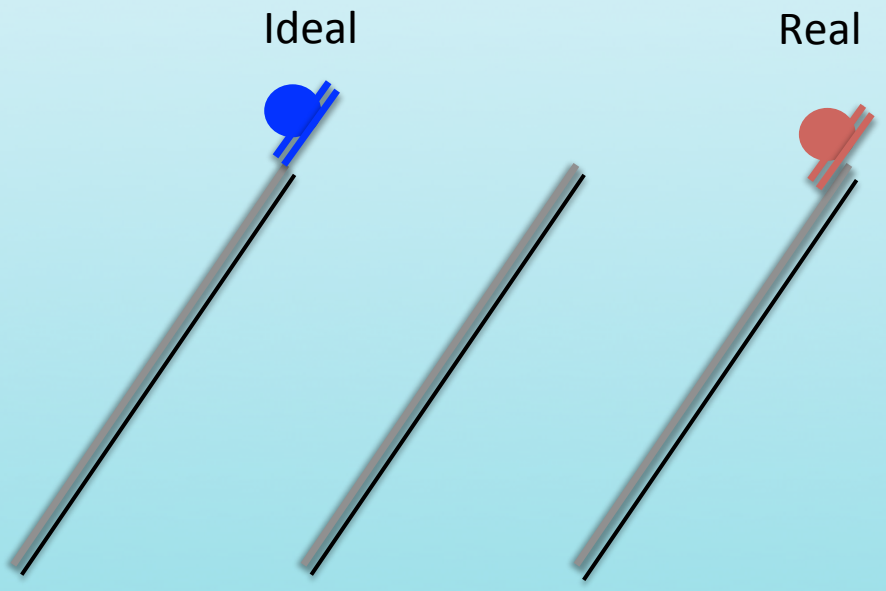
Gueymard 2009

Validation Issues

Sources of error:

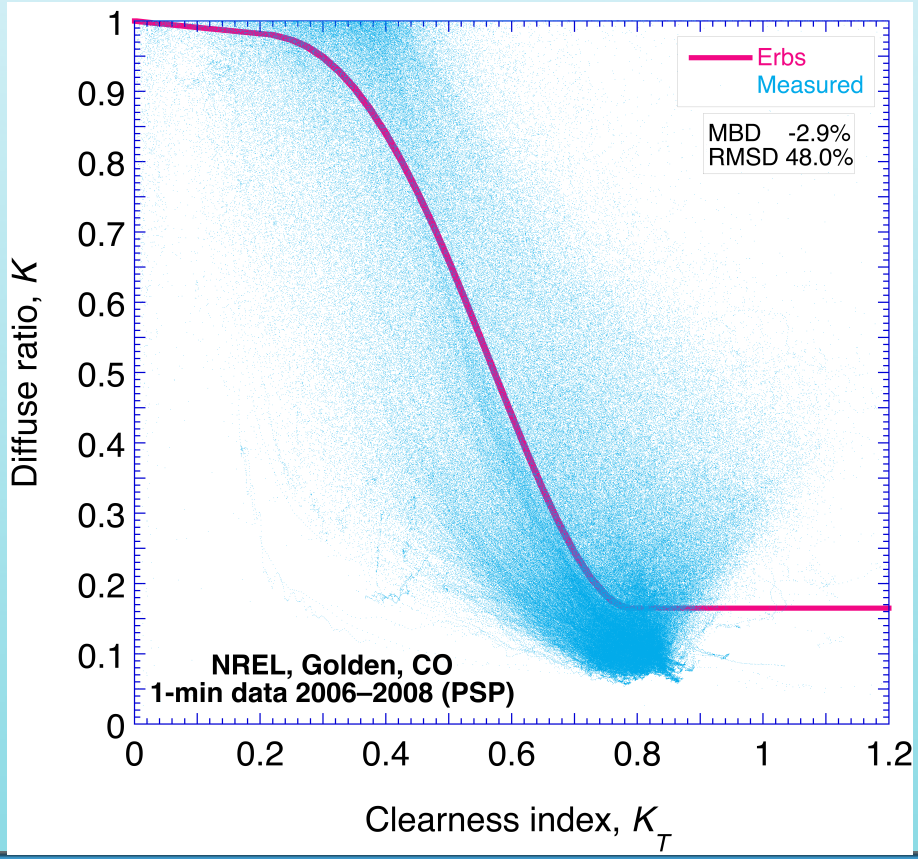
- Measured irradiances (DNI, GHI, DIF) may not be optimal
- Measured GTI may not be optimal (tilt-specific calibration?)
- Foreground may not be infinitely extended (R_r less than ideal value)
- Foreground may be shaded by e.g. back-panels (f_s less than 1)
- Surface albedo ρ is usually unknown; often assumed constant (0.2)





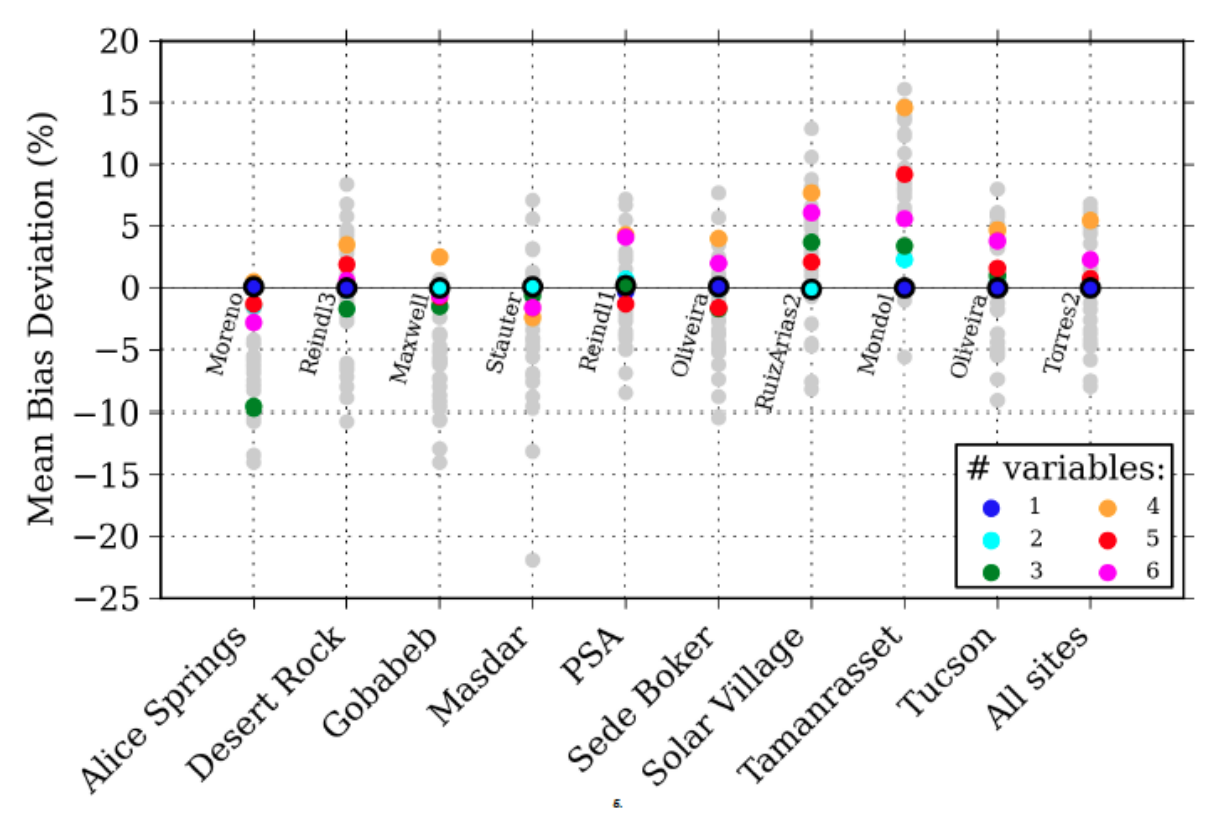
Decomposition

- Also referred to as *Separation*
- Many empirical models exist (>100), so which one should be used?
- Most are of the "diffuse fraction" type
- Many validation studies exist, usually just for some models at a few sites
- Random errors increase when time step decreases
- No known truly "universal" model
- 1-min DNI and DIF are desirable



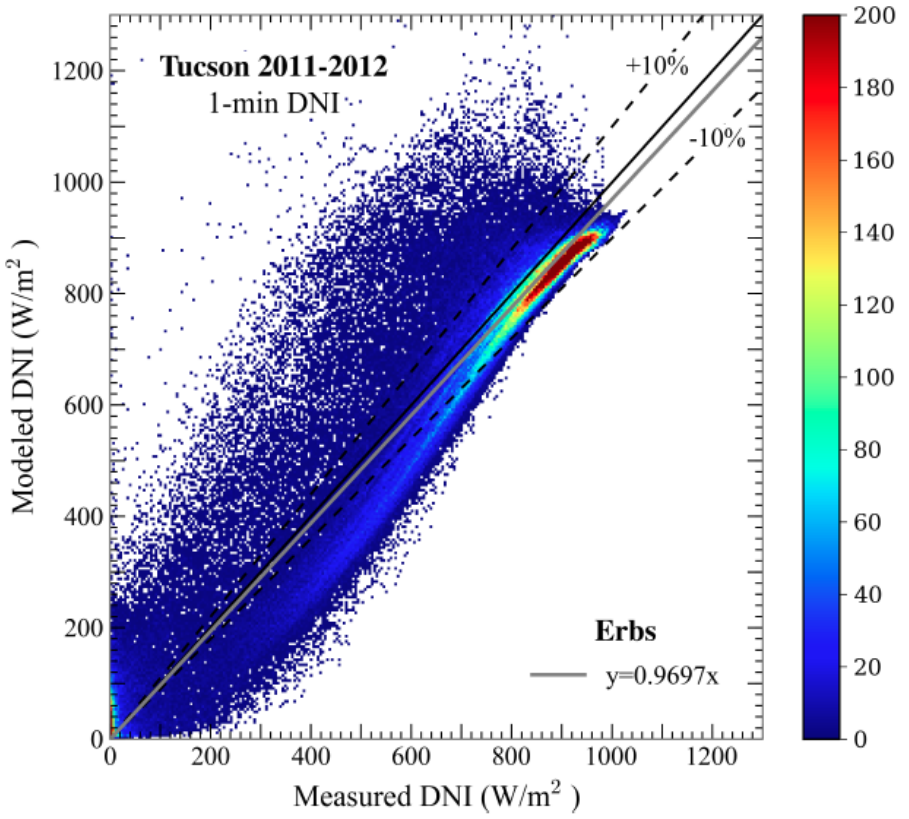
Decomposition

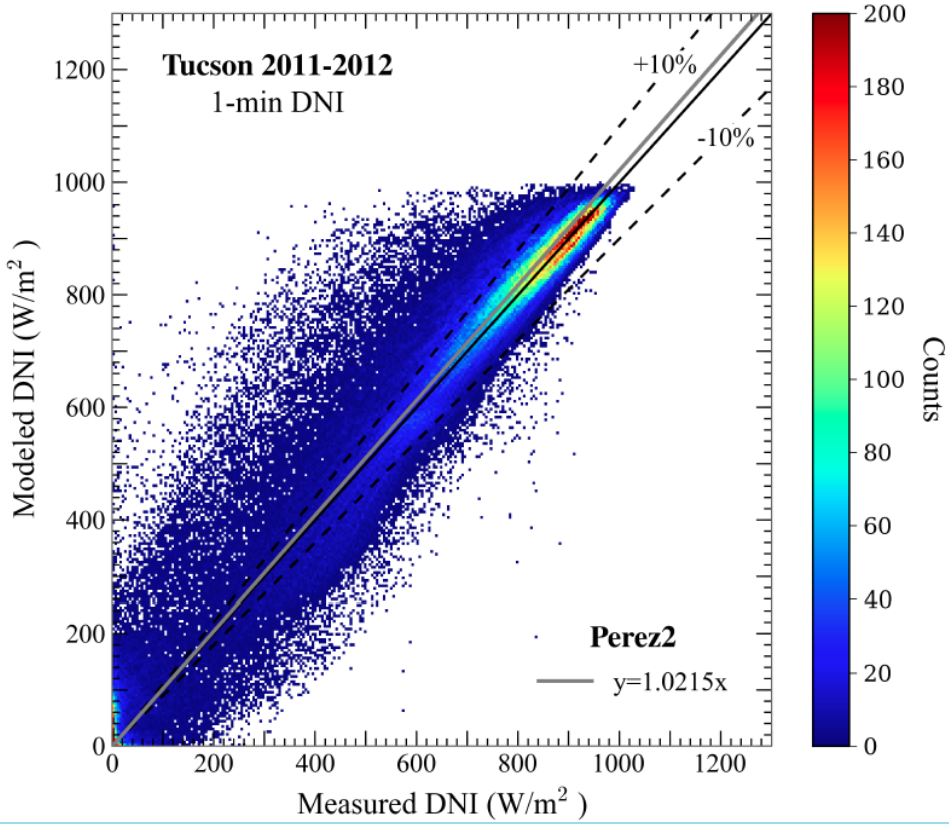
- Recent study by Gueymard & Ruiz-Arias (2014): 36 models tested at 9 arid sites, using 1-min data
- Models in 6 categories, based on number of predictors (*Kt, m*, etc.)
- Bias varies depending on model and site; significant impact of aerosols
- Adding predictors does not necessarily improve performance



Decomposition

- Issues found with Erbs, Louche and Perez
- Perez has lowest RMS most often, but systematic high bias (2–5% on average)





Decomposition + Transposition

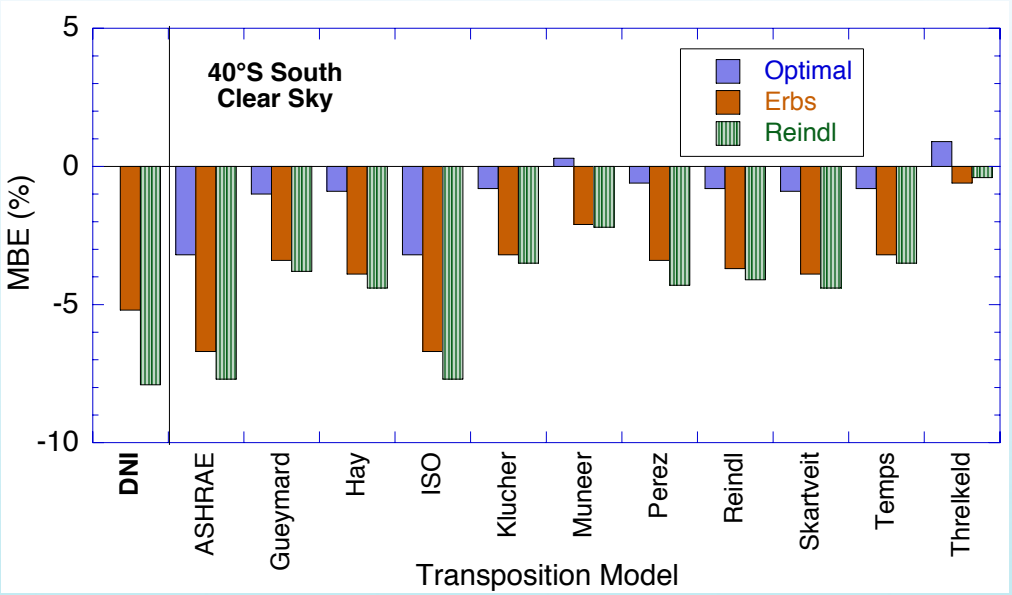
- Only a few studies have considered the overall process

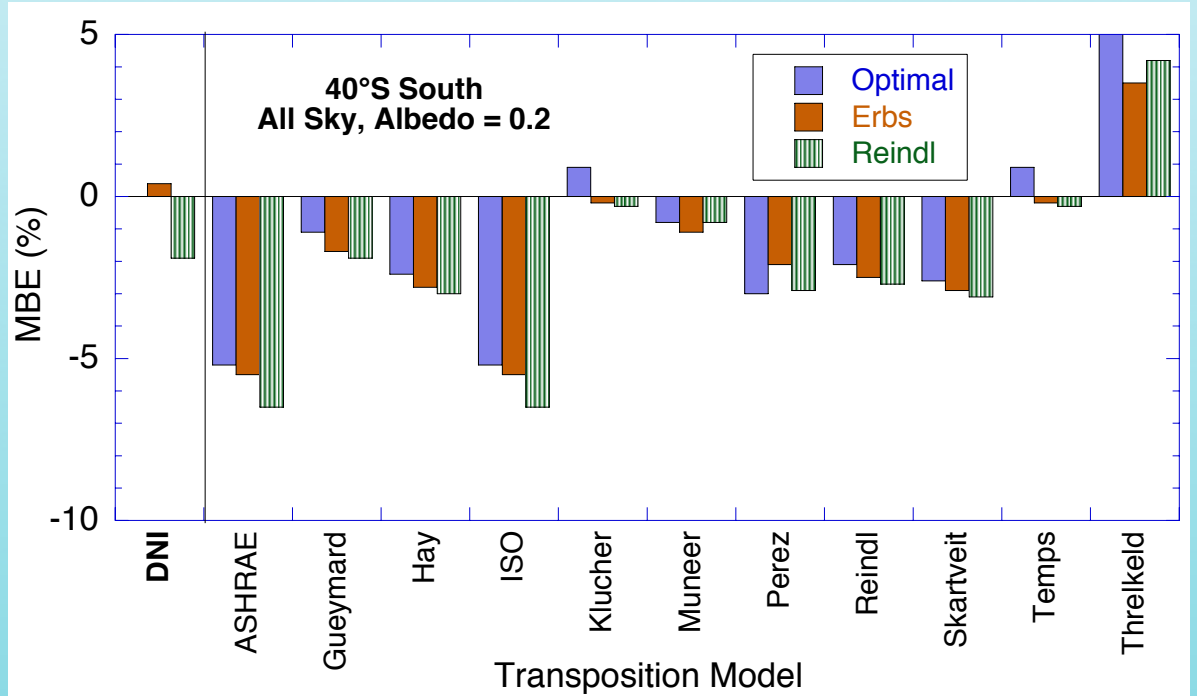
Author	Year	Decomposition	Transposition	Study Sites	Geometries
Gueymard	2009	4	10	1 (NREL)	40°, 90° S, 2AT
Orehounig et al.	2014	2	1	1 (Austria)	90° N, E, S, W
Prada et al.	2015	22	12	5 (Europe)	90° N, E, S, W
Lave et al.	2015	12	4	10 (USA)	15°, 25°, 35°, 40°

Decomposition + Transposition

Results from Gueymard (2009):

- Significant increase in bias due to using decomposition, mostly under clear skies
- Bias in GTI increases depending on the bias in estimated DNI
- Klucher, Muneer, Temps perform best with any decomposition

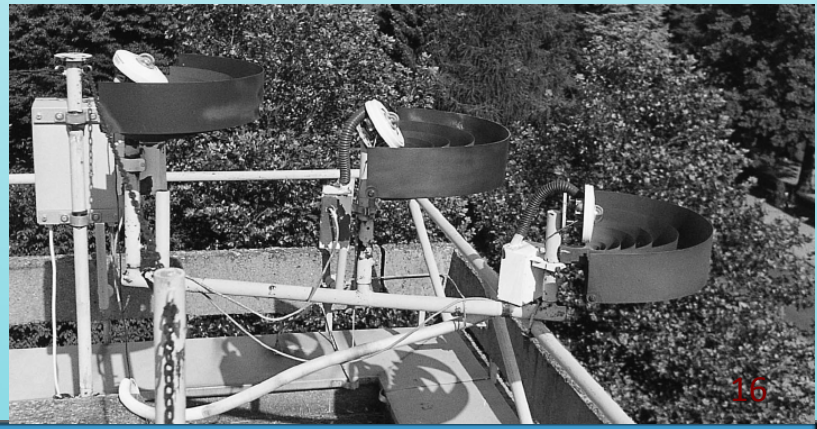




Solar Consulting Services

Conclusions

- Transposition is relatively accurate
- Surprisingly few transposition models have been considered by the industry (Perez, Hay). Lesser known models may perform as well or better (Gueymard, Klucher, Muneer, Temps…), depending on climate (cloudiness?)
- Decomposition may play a major role, depending on the generated bias in DNI, local conditions, associated transposition, etc.
- Best model combination still need to be found empirically (trial and error)
- Results by Gueymard (2009) and Lave et al. (2015) do not agree well about the bias resulting from model combinations at their common location (NREL)
- Combination studies need to be expanded to more sites, using better instrumentation, and more rigorously controlled conditions (sky shade; ground shade)
- Differences between ideal and realistic conditions must now be emphasized and better modeled (albedo, shading, limited foreground…), so that validation results can be correctly interpreted in the practice of PV performance simulations.



GroundWork

NREL and Sandia Photovoltaic (PV) Workshop
The Use of Shadowband Radiometer Data to Reduce POA Uncertainty
Justin Robinson
February 27, 2015

Use of RSR2 DHI for POA Modeling

Can measured RSR2 DHI reduce modeled POA uncertainty?

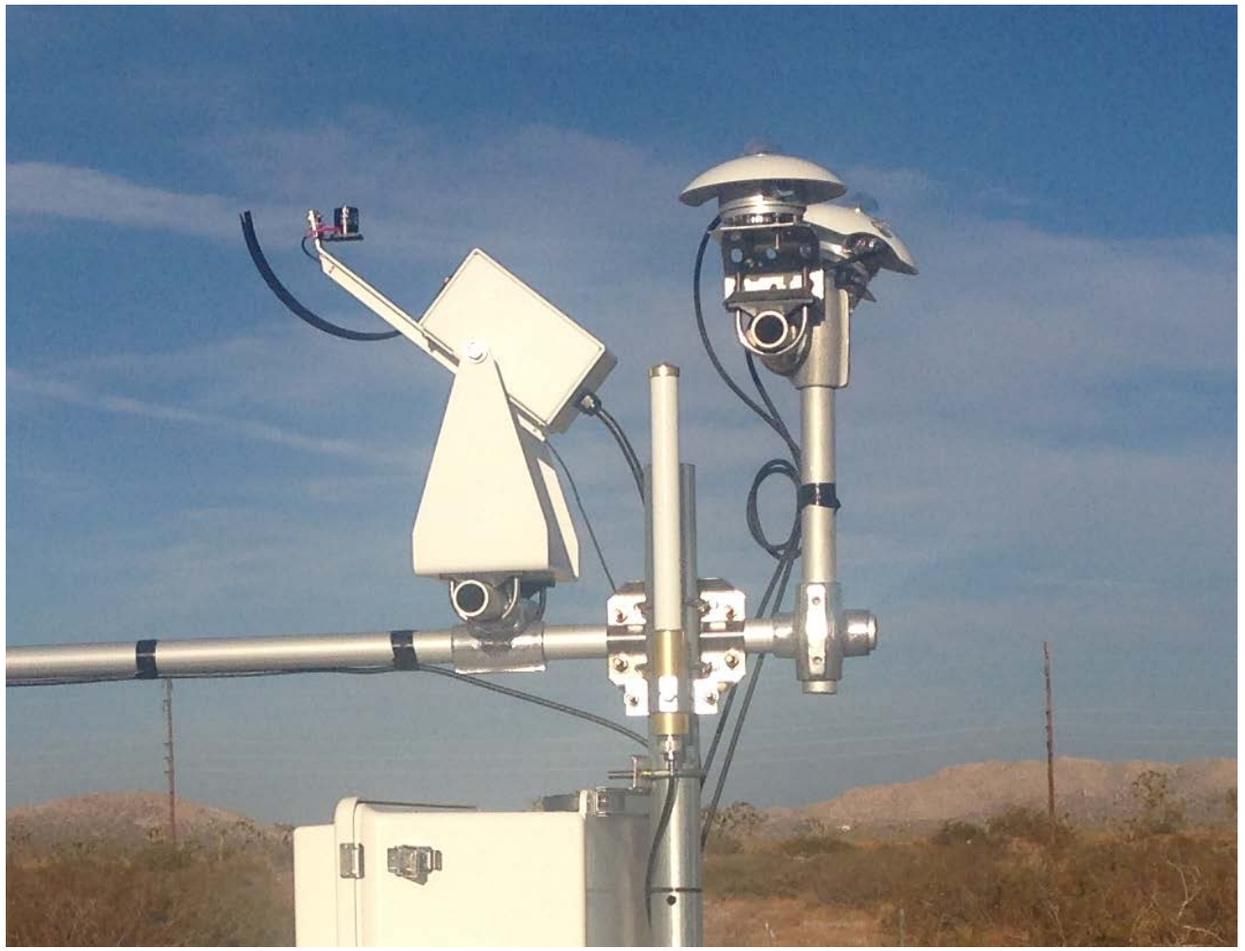
Solar community split

Concerns about measurement bias

PV developers struggle with mismatched datasets

Studies show that LI200 underestimate DHI by 20-30%

Limited characterization beyond NREL SRRL



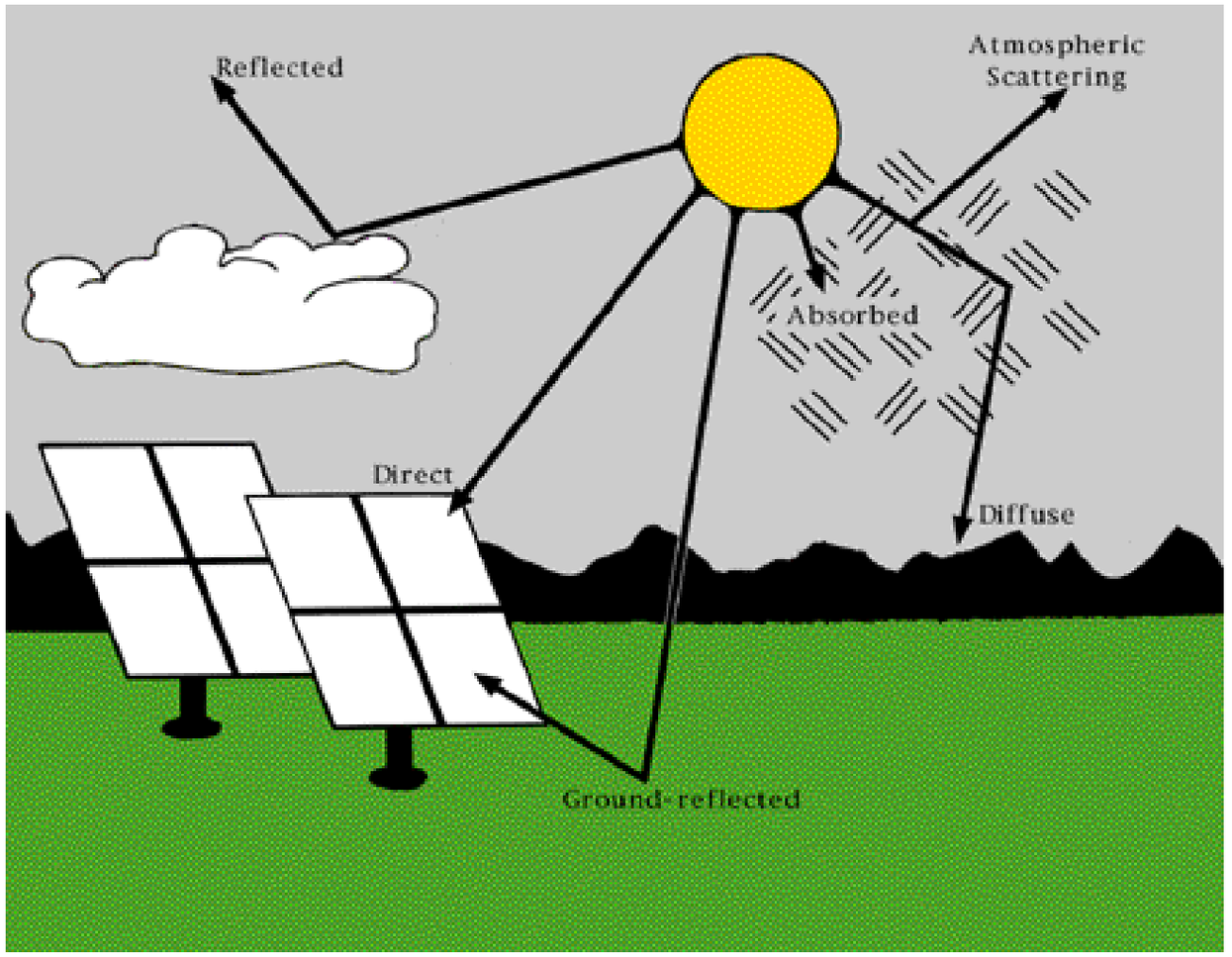
Solar Resource Assessment Methodology

Collect one year or more high quality ground based GHI

Tune satellite data with high quality ground based GHI

Model POA with tuned GHI

Use decomposition algorithm or measured DHI (predominantly RSR2)



http://rredc.nrel.gov

Decomposition Model Studies

Gueymard and Ruiz-Arias, 2014

“ an obvious conclusion is that a more efficient and truly “universal” model is necessary.”

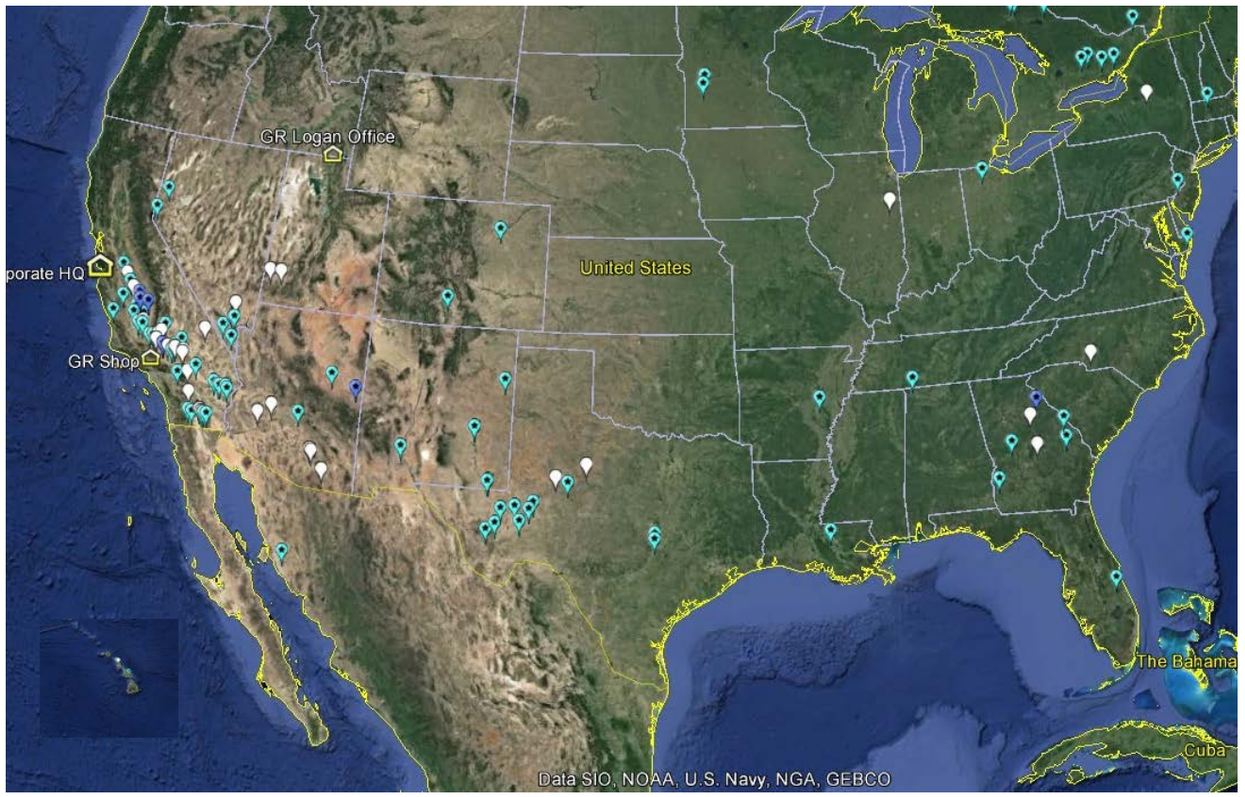
Lave et al., 2015

Evaluation of GHI Irradiance to POA Irradiance Models at Locations Across the United States.

Decomposition Models Performance Statistics

Table 3. Summary performance statistics (in percent of the overall mean DNI, 662.4 W/m^2) for all 36 tested models at all test sites combined. Best results in each category are in bold; best results overall are in bold italic and underlined.

Acronym	#Predictors	MBD	RMSD	MAD	Acronym	#Predictors	MBD	RMSD	MAD
BOLAND1	1	0.6	18.0	12.5	GONZALEZ	2	0.2	16.0	11.9
DEMIGUEL	1	-2.0	17.0	13.1	HELBIG	2	***0.0***	16.0	11.6
ERBS	1	-0.6	**16.9**	12.5	HOLLANDS2	2	-3.6	21.4	15.3
HOLLANDS1	1	2.0	18.7	12.6	MACAGNAN	2	1.2	18.6	14.1
LAM	1	-8.3	21.2	18.3	MAXWELL	2	4.3	**15.6**	**10.6**
LI	1	-4.9	18.6	15.4	POSADILLO	2	5.7	17.8	12.4
LOUCHE	1	5.0	17.4	**11.4**	REINDL2	2	-4.9	17.7	14.0
MONDOL	1	-7.7	18.8	16.0	RIDLEY1	2	-0.4	18.8	12.8
MORENO	1	6.7	19.3	13.0	RUIZARIAS2	2	-1.9	18.1	14.0
MUNEER	1	-4.7	17.9	14.1	SKARTVEIT1	2	-4.5	16.3	13.2
OLIVEIRA	1	**0.2**	17.2	13.0	STAUTER	2	-5.8	19.0	15.3
REINDL1	1	-0.4	**16.9**	12.5	SUEHRKE	2	-2.7	15.7	11.2
RUIZARIAS1	1	4.7	18.3	12.2	ZHANG	2	3.5	17.4	11.3
SANCHEZ	1	6.1	18.0	12.4	SKARTVEIT2	3	**-3.9**	**16.5**	**12.6**
TORRES1	1	-1.5	17.3	13.7	PEREZ1	4	5.3	14.7	9.7
TORRES2	1	**-0.2**	17.1	13.1	REINDL3	4	**-0.4**	***12.5***	**9.5**
					BOLAND2	5	**1.4**	**15.8**	11.0
					LAURET	5	4.3	17.4	11.3
					RIDLEY2	5	4.9	16.5	**10.5**
					PEREZ2	6	**2.1**	**13.8**	***9.3***



RSR2 Prevalence

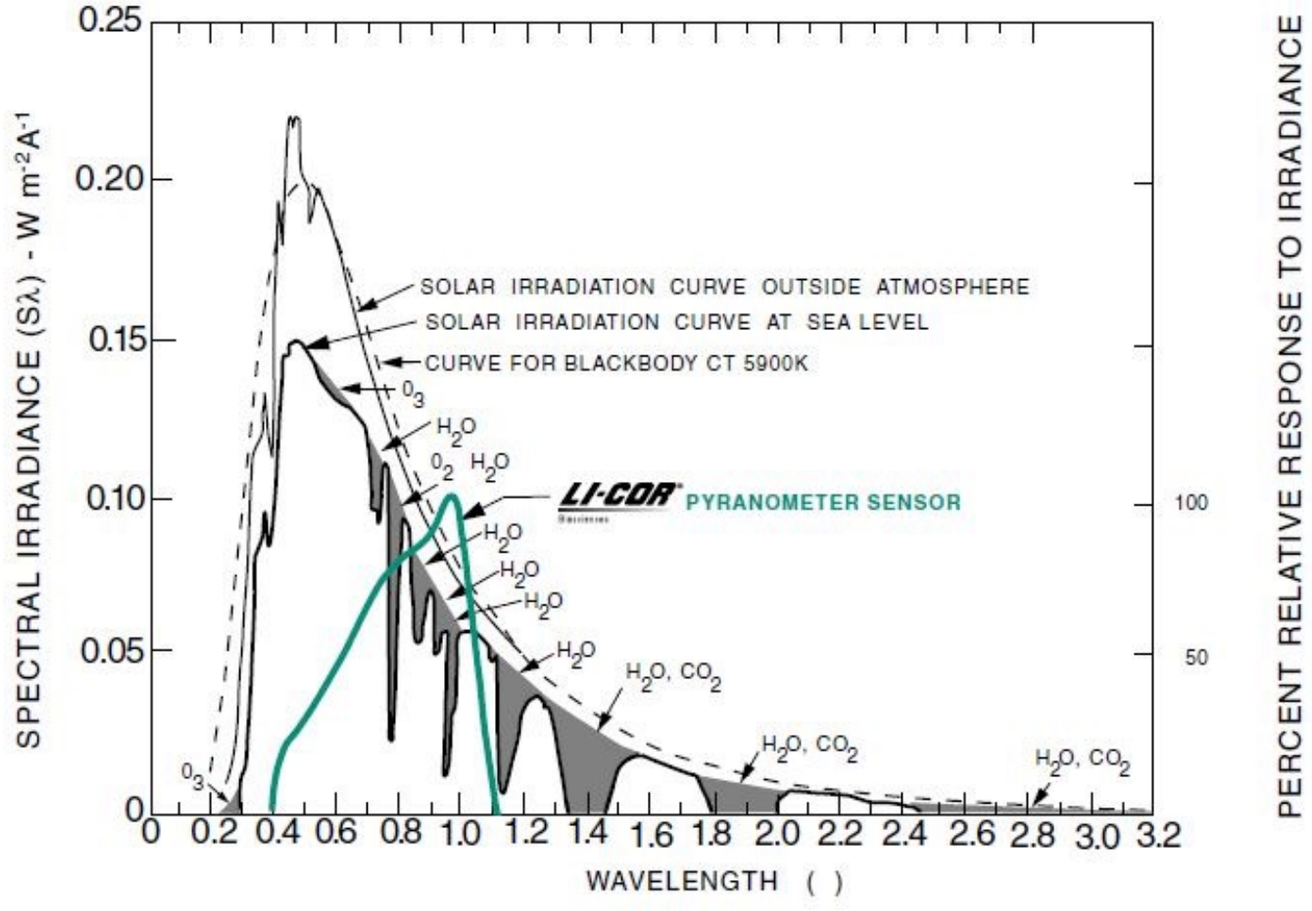
Over 800 units sold since 1991

RSR2 developed in 2007

Led by 2008 specification and adoption by NREL SOLRMAP

Lowest cost component sum irradiance station ~$15k

Accepted form of DHI for SCE



LI-COR Limitations

Si-Photodiode pyranometers underestimate diffuse

Si-photodiode calibration drift +/-2% per year

Instrument (see Table A1 in Appendix A)	Sub-hourly Uncertainty % (range of bins to 80° Zenith)		Mean Daily Total Uncertainty %	
	Bias % max / min	Standard Deviation %	Monthly Bias % (monthly bins) max / min	Annual Bias[+] %
CM22_Vent	+0.6 to +0.4	2 to 3	+0.77 to +0.18	+0.48
RSR2_C (Glo)**	+1.0 to -1.2	4 to 6	+0.53 to -2.54	-0.73
RSR2_C (Dir)**	-3.5 to -7.5	16 to 19	-0.59 to -8.81	-6.60
RSR2_C (Dif)	-0.2 to +3.0	5 to 6	-1.06 to +3.03	+1.00
RSR2_U (Glo)**	-0.8 to -2.5	4 to 6	-0.81 to -3.59	-2.17
RSR2_U (Dir)**	+1.3 to +0.5	17 to 20	-2.07 to +3.37	+1.04
RSR2_U (Dif)**	-12.0 to -15.0	13 to 16	-19.3 to -19.6	-14.1

RSR2 Data Uncertainty: Wilcox et al., 2008

MBE Hourly Average RSR2 GHI: Habte et al., 2013

Clear

Max: 2.5 % Min: -1.0 %

Mostly Cloudy

Max: 4.69 % Min: -0.52 %

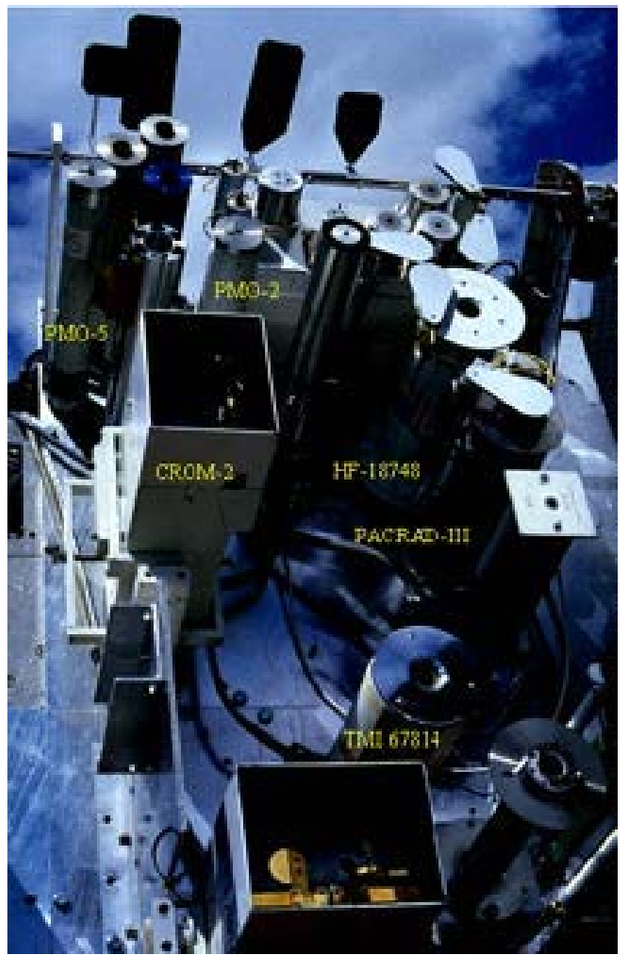
MBE Hourly Average RSR2 DNI: Habte et al., 2013

Clear

Max: 2.92 % Min: -0.52 %

Mostly Cloudy

Max: -23.68 % Min: -50.76 %



International Collaboration & Continued Research

- MeteoSwiss/U of O/WRR(PMOD/WRC)
  - Si-photodiode response to changing spectral distribution
  - Temperature dependence
  - Cosine response
- NREL SRRL
  - Long term characterization and further refinement

Areas of Further Improvement

Perform BORCAL calibrations of LI-CORs

Evaluate and incorporate Precipitable Water Vapor (PWV)

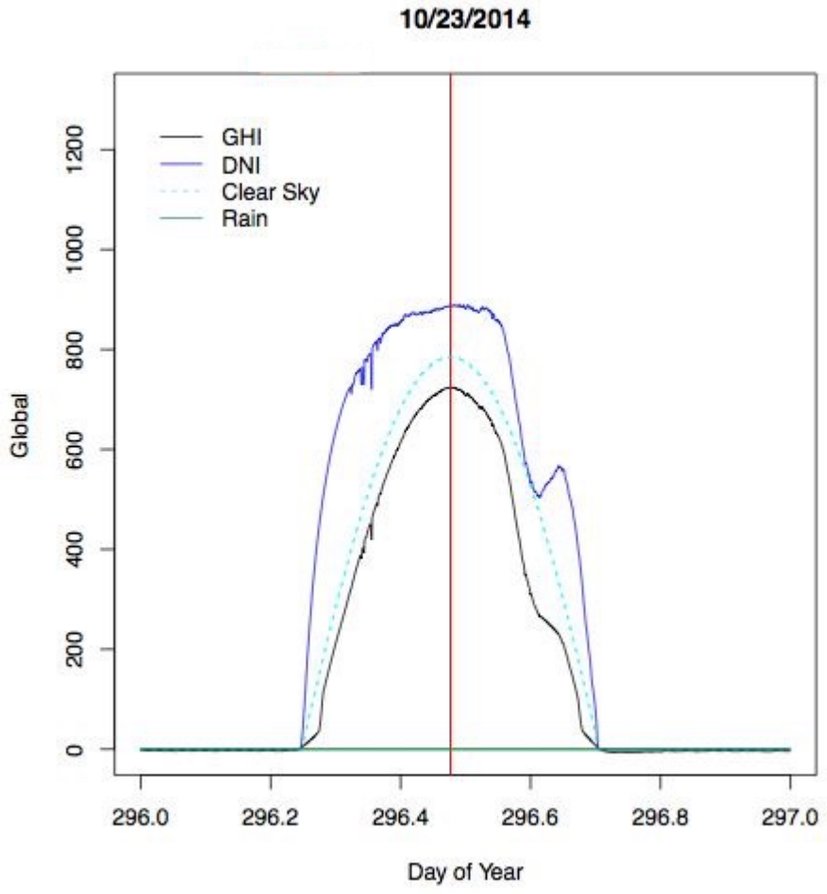
Develop fast response thermopile RSR

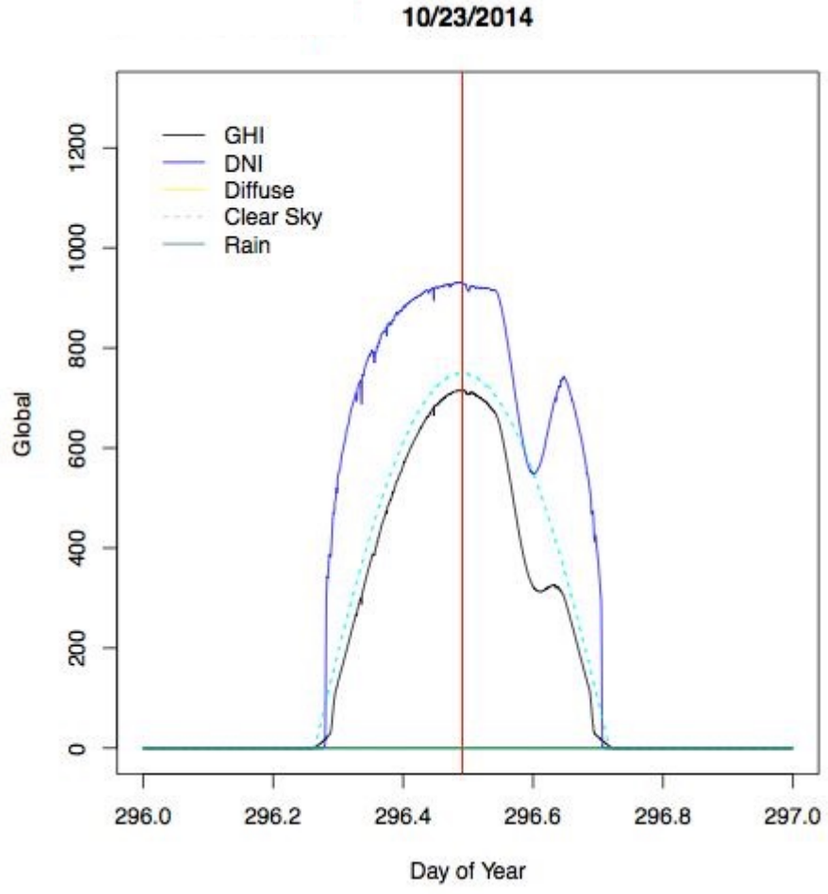
Increase frequency of arm rotations

Analyze shadowband across geographic and climatic regions

Validate against high quality DNI stations

Courtesy Bob King


10/23/2014
GHI
DNI
Clear Sky
Rain
Global
0
200
400
600
800
1000
1200
296.0
296.2
296.4
296.6
296.8
297.0
Day of Year


10/23/2014
GHI
DNI
Diffuse
Clear Sky
Rain
Global
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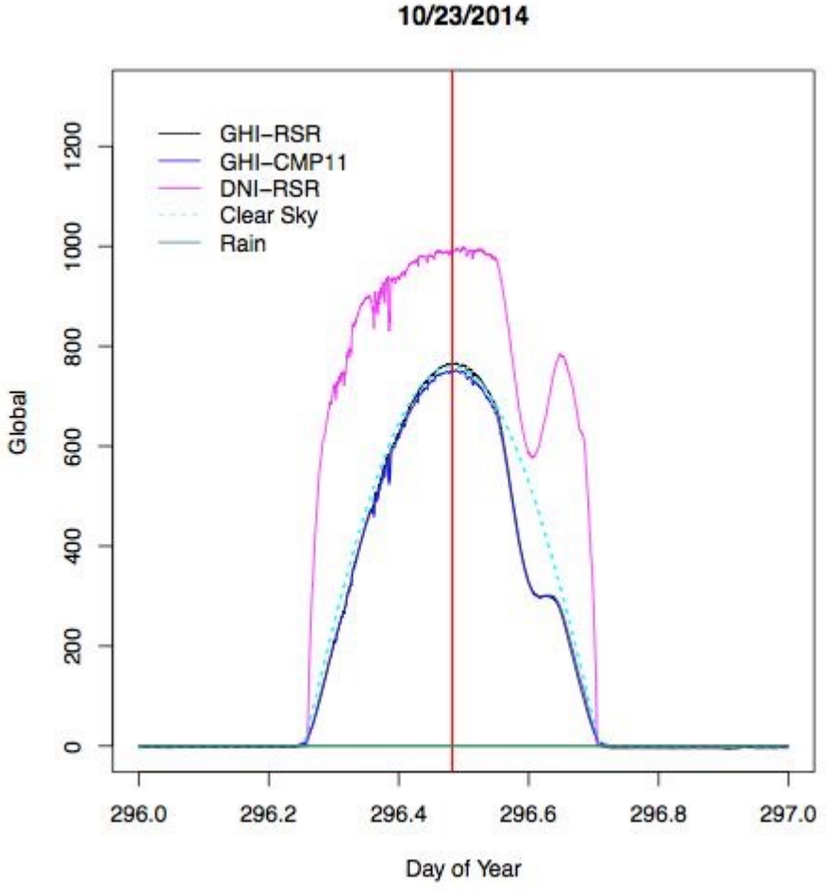
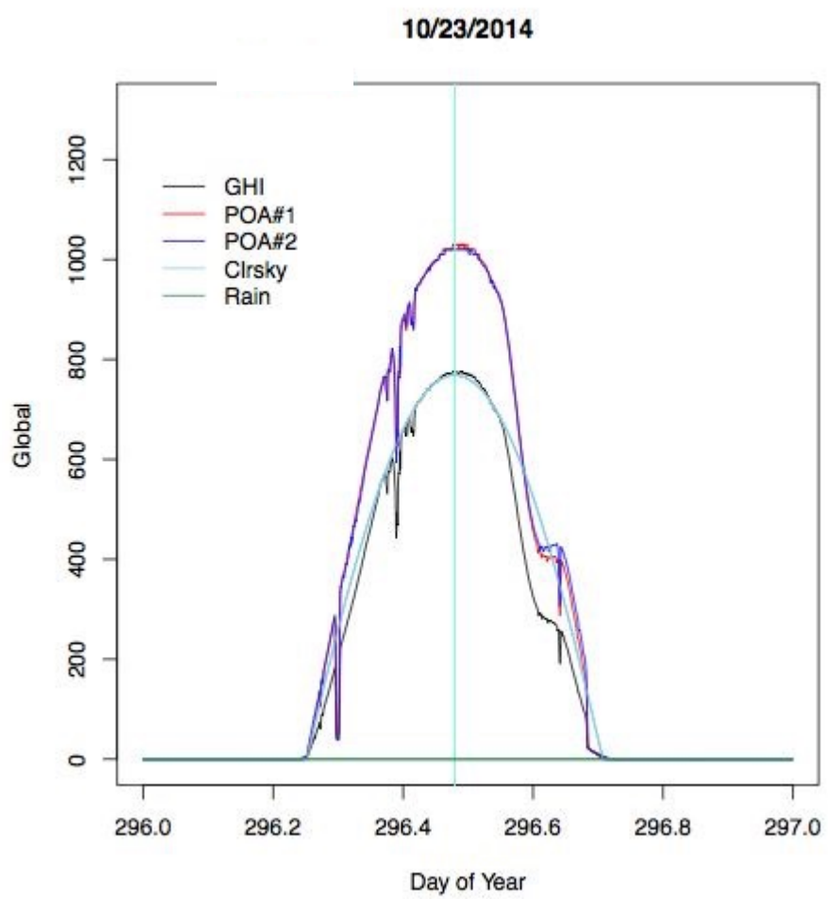
200
400
600
800
1000
1200
296.0
296.2
296.4
296.6
296.8
297.0
Day of Year


10/23/2014
GHI-RSR
GHI-CMP11
DNI-RSR
Clear Sky
Rain
Global
0
200
400
600
800
1000
1200
296.0
296.2
296.4
296.6
296.8
297.0
Day of Year


10/23/2014
GHI
POA#1
POA#2
Clrsky
Rain
Global
0
200
400
600
800
1000
1200
296.0
296.2
296.4
296.6
296.8
297.0
Day of Year

Thanks!

State of the Practice for Diffuse Solar Irradiance Measurements

Tom Stoffel
SOLAR RESOURCE SOLUTIONS, LLC

February 27, 2015

2015 PV Solar Resource Workshop

This presentation contains no confidential information

To Measure Is to Know

Solar Resource Solutions, LLC

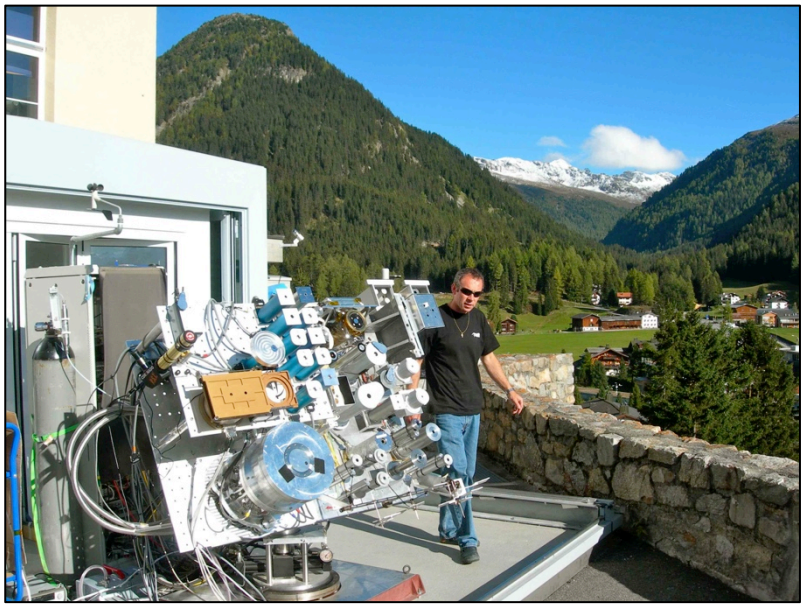
- Lord Kelvin (1824-1907)
- **Know Your Measurement**
  Tom Stoffel

Optical Radiometry

- The most **uncertain** measurement discipline
- **No absolute standard** for diffuse solar irradiance

World Radiometric Reference

- Only Internationally **Recognized** Measurement **Reference** for Solar Radiation
- **WRR** Uncertainty: **±0.3%**
  - **Detector-based** standard using **electrical** power equivalence and **area** measurements
  - Applies only to **Direct Normal Irradiance** > 700 Watts/meter^2

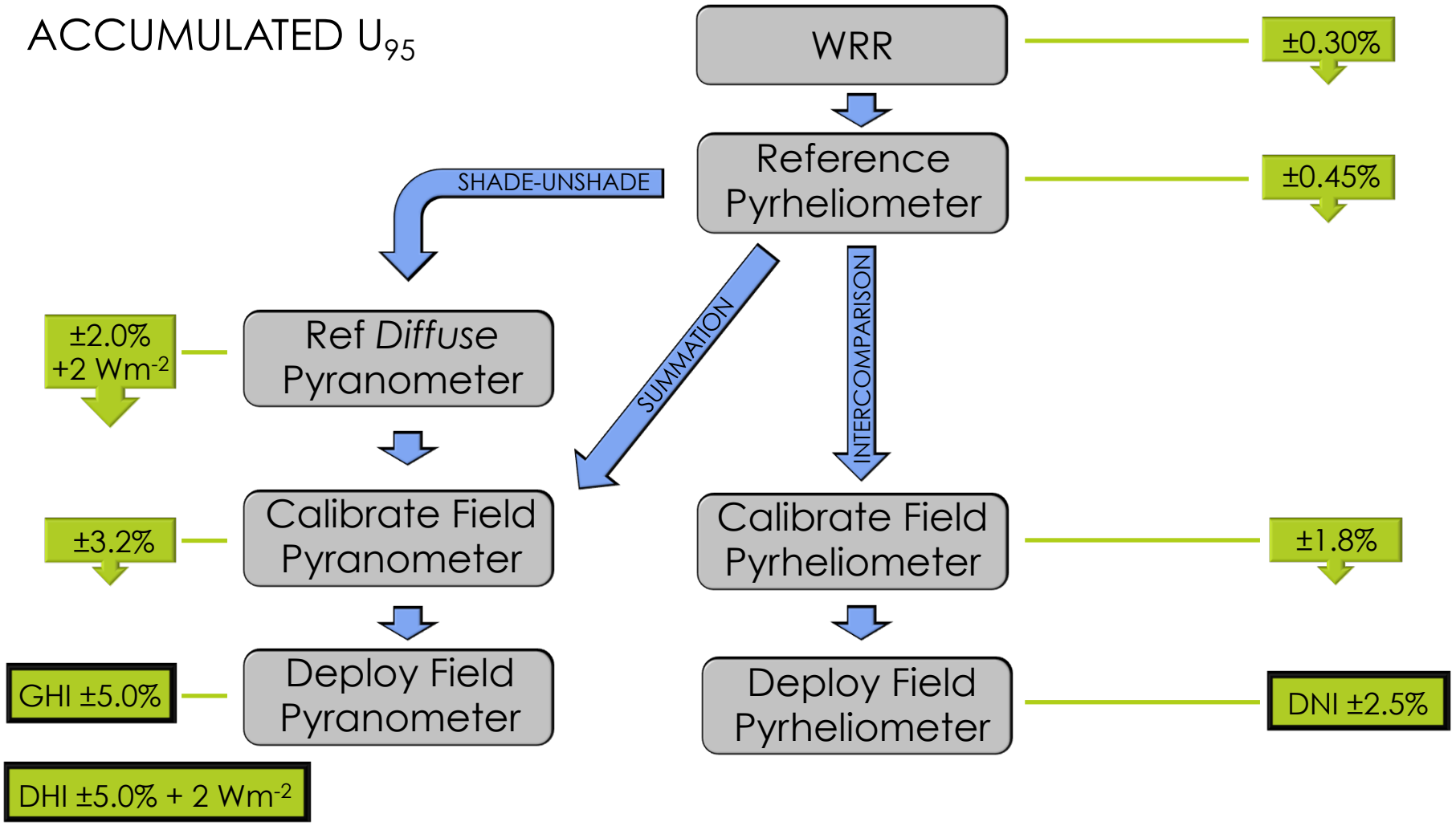


World Standard Group:
6 electrically self-calibrated absolute cavity radiometers

Physikalisch-Meteorologisches Observatorium Davos
World Radiation Center
www.pmodwrc.ch

International Pyrheliometer Comparison

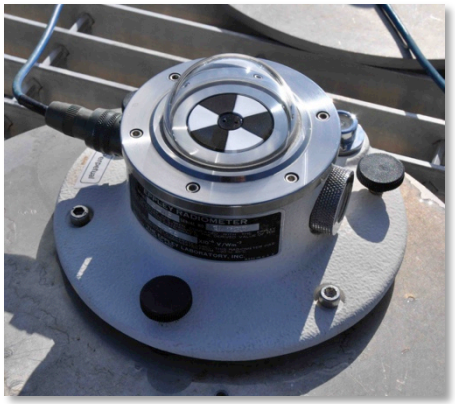
Uncertainty Tree

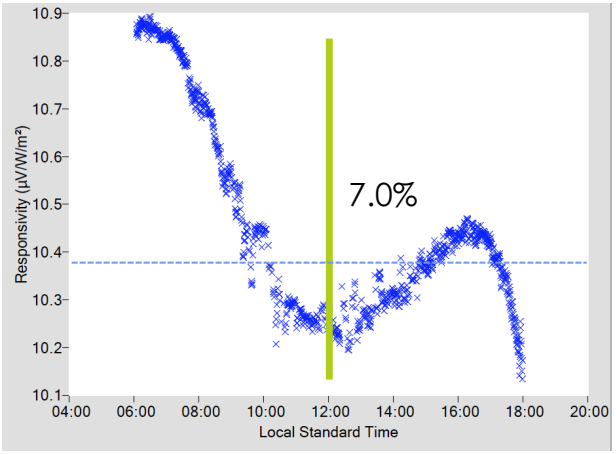


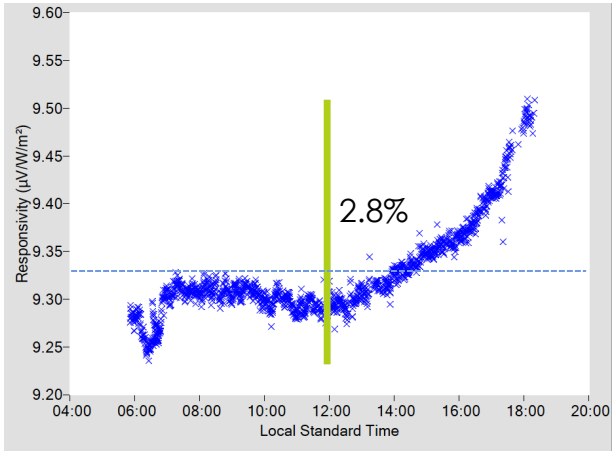
[After Sengupta, et al. 2015]

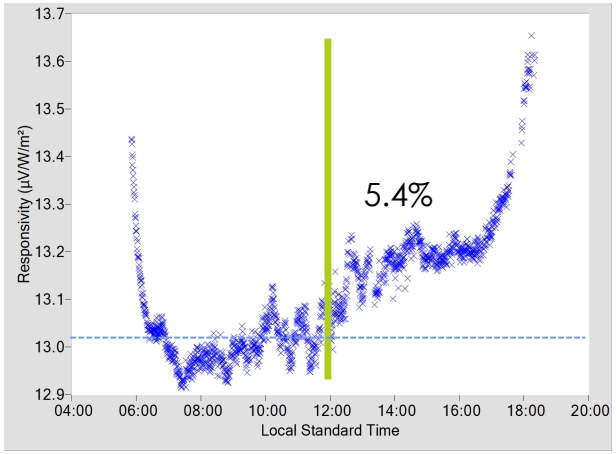
Outdoor Calibrations

Calibration Factors Vary Through the Day…









Model 8-48 Model CM22 Model LI-200

Responsivity (µV / Wm^{-2}) @ 45° solar zenith angle

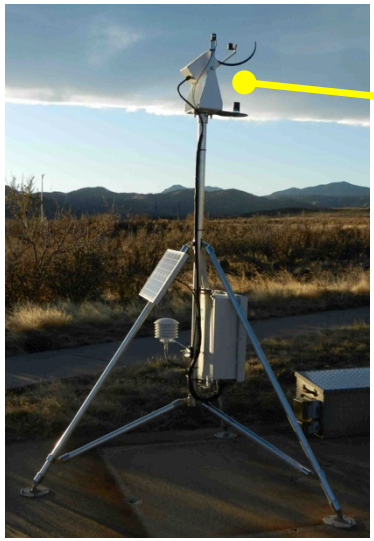
Measuring Diffuse Irradiance

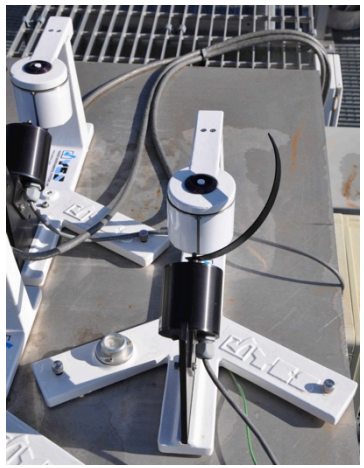
Shadowband

*

Shading Ball or Disk

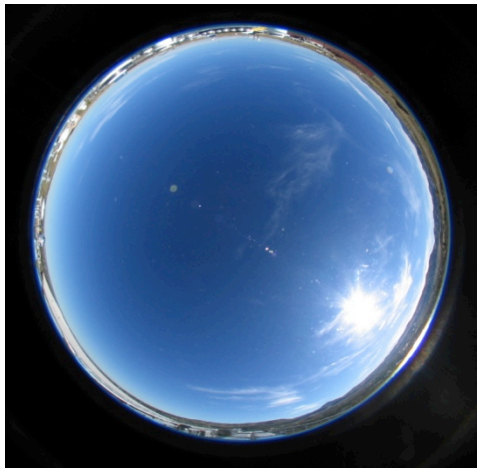
Rotating Shadowband Radiometers*





* Measures GHI & DHI for computing DNI

Getting to POA



Horizontal Plane

Plane of Array (?)

$$GHI = DNI \cos(Z) + DHI$$

$$POA^{1} = DNI \cos(\theta)/\cos(Z) + \text{<Direct-Sky}$$
$$0.5\ DHI\ [1-\cos(\beta)] + \text{<Diffuse-Sky}$$
$$0.5\ \rho\ DNI\ [1-\cos(\beta)] + \text{<Direct-Reflected}$$
$$0.5\ \rho\ DHI\ [1-\cos(\beta)] \quad \text{<Diffuse-Reflected}$$

[1] **Isotropic Model:**

θ = solar incidence angle
Z = solar zenith angle
β = panel tilt angle from horizontal
ρ = ground albedo

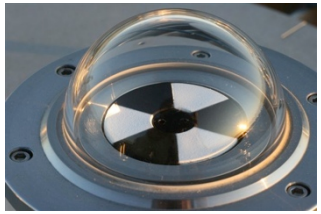
[After Myers, 2013 and Stoffel, et al., 1987]

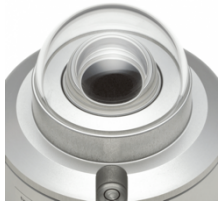
Key Measurement Issues

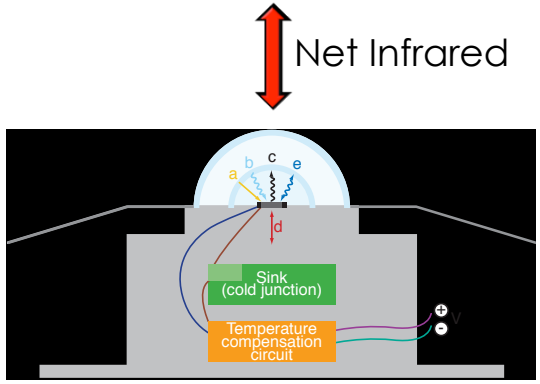
- Pyranometer Detector Types
- Spectral Irradiance Variations
- Temperature/Thermal Offsets
- Sky Radiance Distributions
- Orientation & Alignment

Photodiode

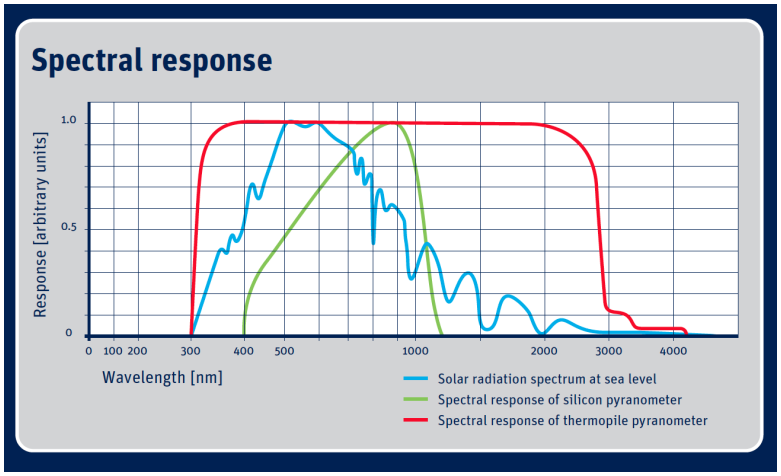
Thermopile







Thermal Offset Corrections
Needed for
Single-black thermopile
pyranometers UNDER measure
clear sky diffuse
(i.e., cold atmosphere)
by ~3 to 30 Wm^{-2}



From www.kippzonen.com

Pyranometer Measurements

Thermopile Pyranometers

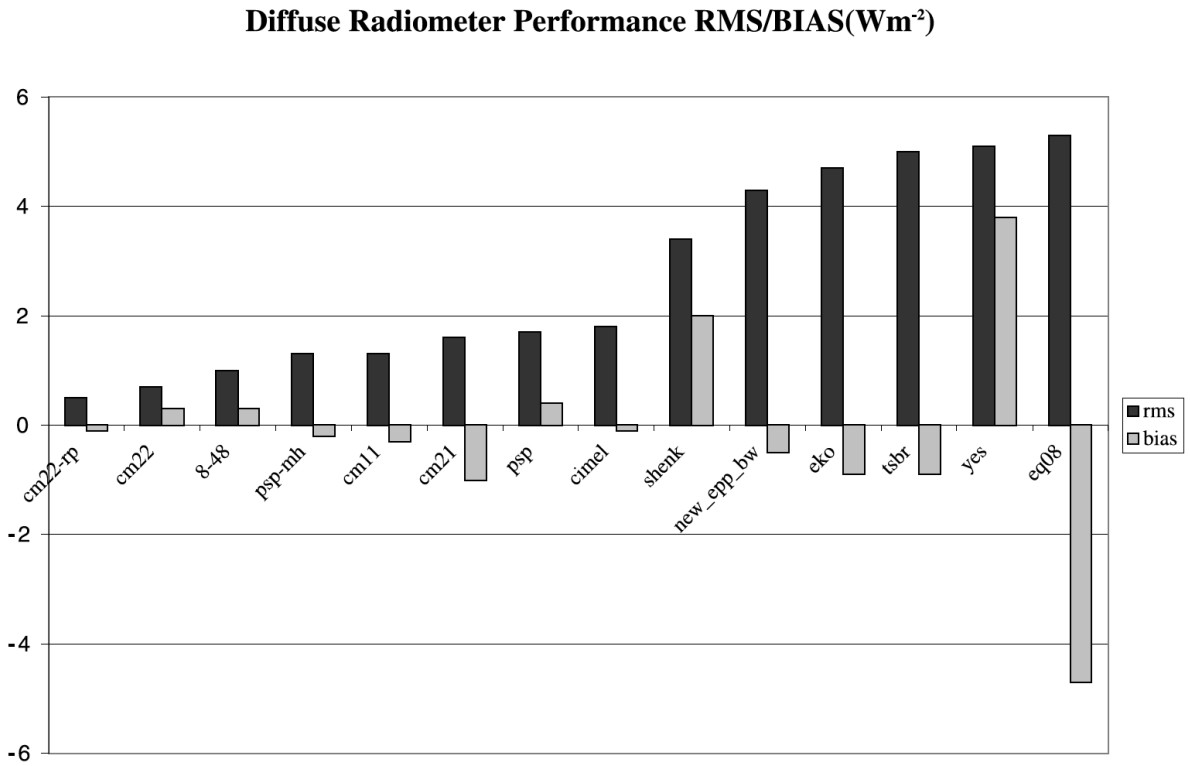
DOE/ARM:

Intensive Observational Period (Fall of 2001)

14 T.P. Pyranometers
- Shade/Unshade Calibrations
- Ventilated & Unventilated
- Tracking Shade Ball

2 Weeks of Data - mostly clear sky

Precision is within **2 Wm^{-2}** or ~2% @ ~100Wm^{-2} Diffuse



RMS & Bias (Wm^{-2}) wrt the *mean* of **5** most stable pyranometers *after correction* for thermal offsets

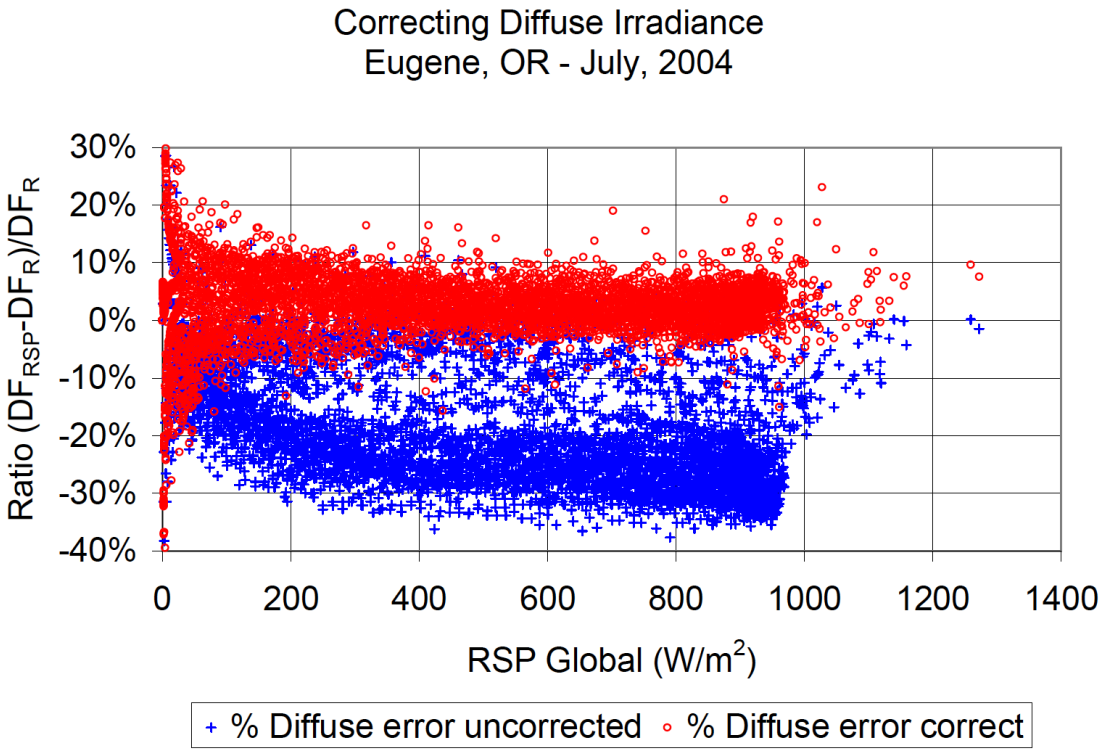
Pyranometer Measurements

Photodiode Pyranometers

- Temperature Response
  - ✓ Silicon PV
- Spectral Response
  - ✓ Under-measures "blue"
  - ✓ Blind to $\lambda > 1{,}100$ nm

Note: Calibrations are performed under clear-sky conditions. The manufacturers' Instructions clearly state, *For this reason, we do not recommend its use under artificial lighting, within plant canopies or to measure reflected radiation.*

Vignola Diffuse Correction
Applied to LI-200 measurements



[Vignola, 2006]

State of the Practice

± 30^{+}% Photodiode – No corrections for temperature or spectral response

± 10% Photodiode – Corrections for temperature and spectral response

± 5%* Thermopile – Single-Black detector with thermal offset corrections & mounted in ventilator (upper range)

± 2%* Thermopile – Black/White detector or Single-Black detector with thermal offset corrections & mounted in ventilator (lower range)

* Percentage of Reading + 2 Wm^{-2}

Conclusions

- How much **uncertainty** can you afford?

  There is a wide range of options for commercial instrumentation.

- **Model** accuracy is limited by the uncertainties of the **measurements** used for development and validation.

- Know your **pyranometer!**

- Observe **Best Practices** for Installation, O&M.

Acknowledgments

Thank You!

And for the mountains of work done by:

- ARM – Atmospheric Radiation Measurement Program (U.S. DOE)
- BSRN – Baseline Surface Radiation Network (WMO)
- DOE/NREL – Staff at the Solar Radiation Research Laboratory
- K.A.CARE – King Abdullah City for Atomic and Renewable Energy; Renewable Resource Monitoring & Mapping (RRMM) Program.
- NOAA/ESRL/GMD – Global Monitoring Division Radiation Group
- University of Oregon – Solar Radiation Monitoring Laboratory

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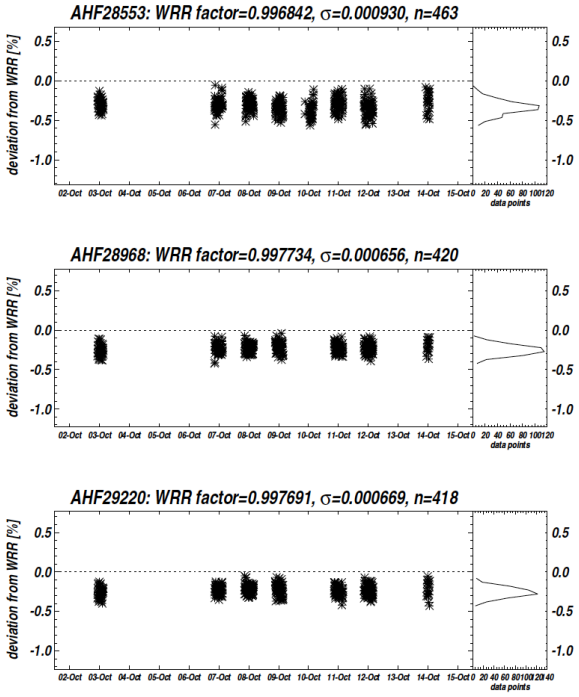
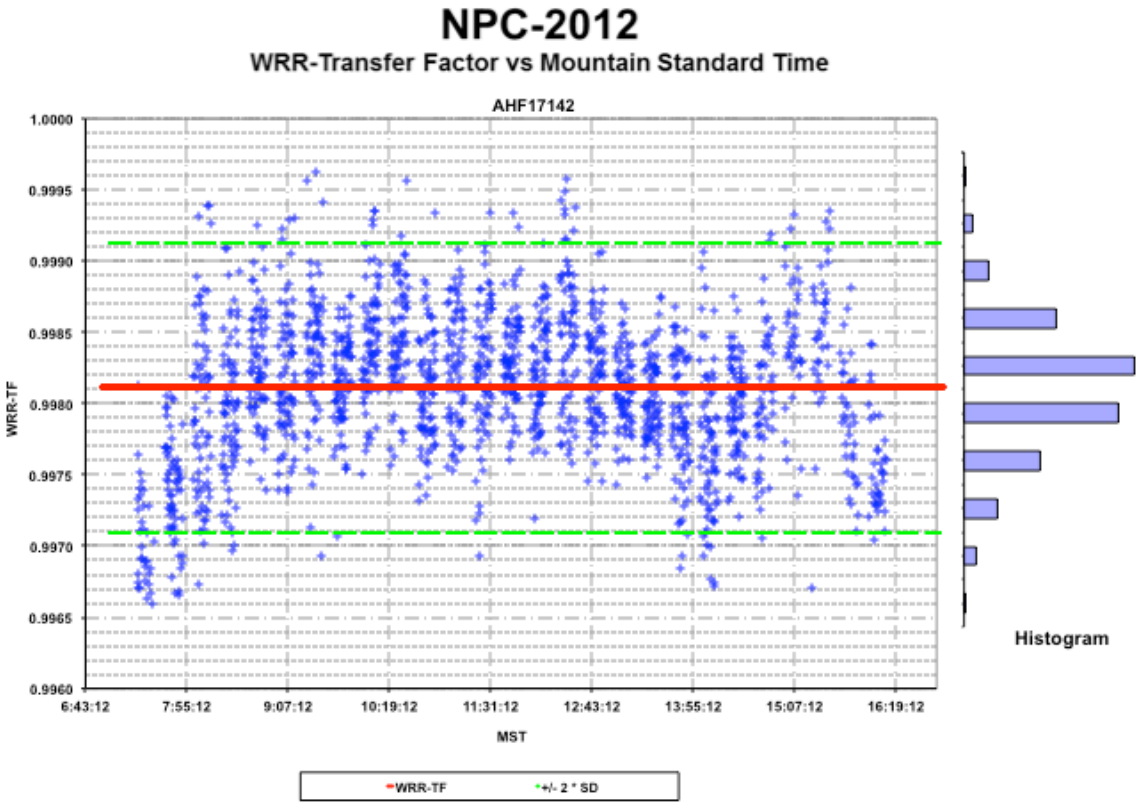
- Stoffel, T. L.; Maxwell, E. L.; Bird, R. E.; Myers, D. R. (1987). Solar Irradiance on Vertical Surfaces. Passive Solar Journal. Vol. 4(2), 1987; pp. 187-210. (based on a technical report: http://www.nrel.gov/docs/legosti/old/2525.pdf

- *Vignola, F.; (2006)*. Removing Systematic Errors from Rotating Shadowband Pyranometer Data, *Proc. of the 35th ASES Annual Conference, Denver, CO.* *http://solardat.uoregon.edu/download/Papers/RemovingSystematicErrorsfromRotatingShadowbandPyranometerData.pdf*

Comparison of Absolute Cavity Radiometers (4 instruments: - 0.1% to - 0.5% wrt WRR)

International Pyrheliometer Comparisons – IPC XI
+
NREL Pyrheliometer Comparisons – NPC 2012





Measuring Diffuse Irradiance on Vertical Surfaces

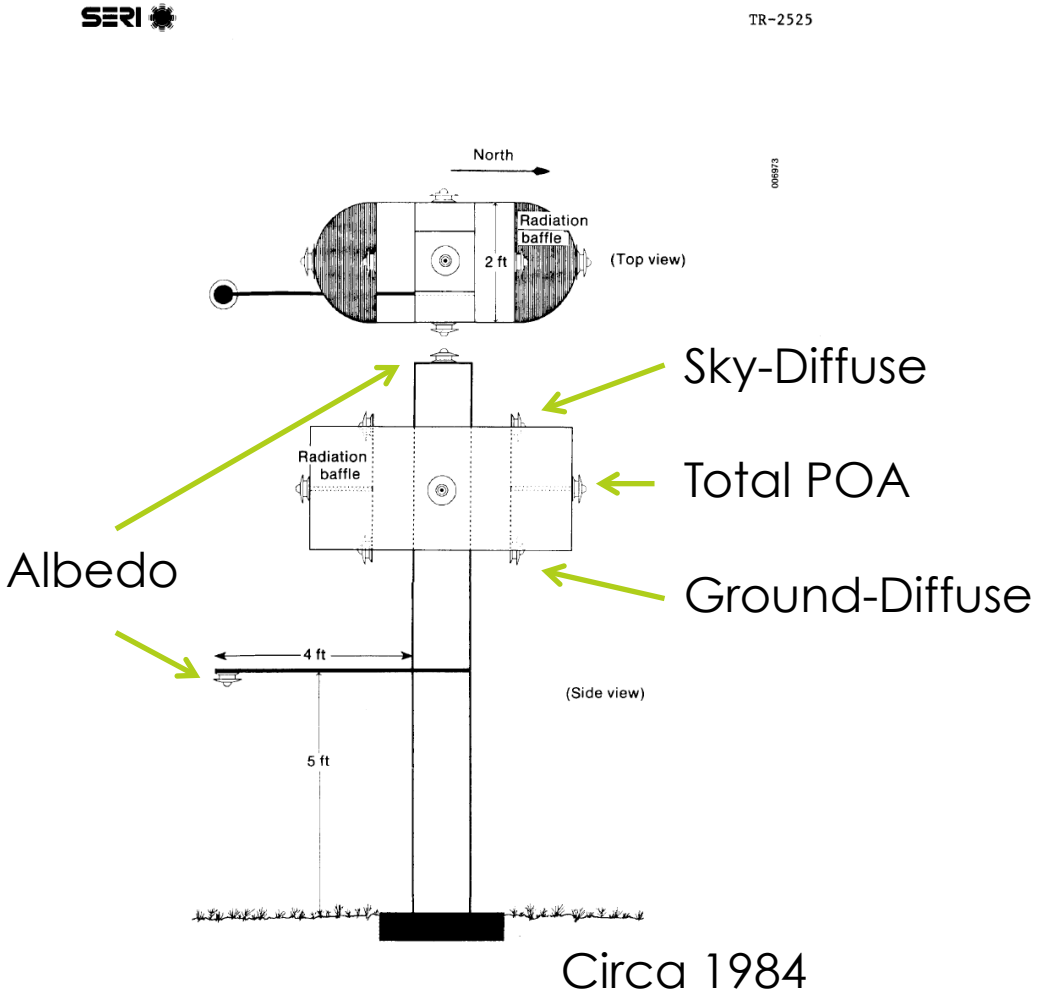


Figure 3-2. Locations of Pyranometers on Radiometer Tower for Measuring Solar Irradiance on Vertical Surfaces

Evaluated *5 Tilt Models*:

- Isotropic
- Temps and Coulson
- Klucher
- Hay
- Perez

North: 18% to 45% Overestimate

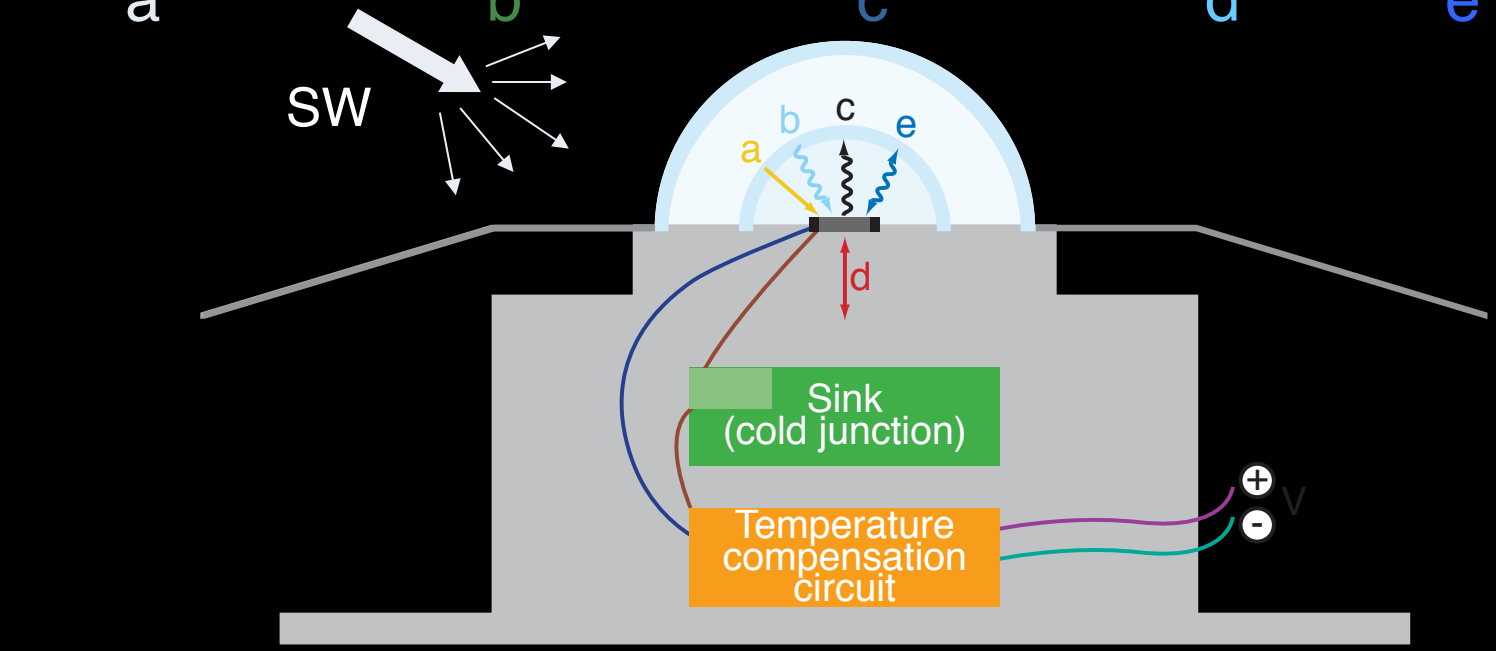
East & West: -3% to 23%

South: ± 5% (except ±10% T&C)

Heat Budget of Generic Pyranometer with Single Black Detector

$$SW\ t_g(1-\rho) + F_{gd}A_g\varepsilon_g\sigma T_g^4 - F_{dg}A_d\varepsilon_d\sigma T_d^4 - (T_d - T_s)k \pm Con = 0 \quad [1]$$

a b c d e



SW = shortwave solar
F = config factor (area=A)
k = heat conduction coeff.
d = detector surface

t = transmission of glass dome(s)
T = temperature (°K)
Con = convection &unwanted conduction
V = pyranometer output voltage (μV)

ρ = SW reflectance
ε = emissivity
g = glass dome
s = thermopile heat sink

Why Resource Matters:

Impacts of Preconstruction Resource Data on Long-Term Production Estimates and Project Finance

Paul Thienpont – Meteorologist, Marie Schnitzer – VP Consulting Services, Rebecca Tilbrook – Solar Services Team Lead

Abstract

Accurate resource and energy production assessments are needed to establish project revenues with confidence thereby sizing debt appropriately. However, when plant performance exceeds the pre-construction energy estimate, what are the financial implications?

This presentation will review the impacts of overproduction on tax equity and debt financing models, while evaluating the major variables that contribute to plants outperforming the pre-construction energy estimates, such as: solar resource input data, plant loss assumptions, and uncertainty.

Some developers are still relying on higher uncertainty or non-site specific solar resource data for inputs into energy simulation models. These datasets typically have a larger uncertainty band and are less accurate, either under-estimating or over-estimating the resource at the project location. When used in an energy simulation there are direct impacts on the forecasted energy production. Additionally accurate plant loss considerations are crucial to best represent the long-term production of the solar plant. When poor plant loss assumptions are made in conjunction with inaccurate and high uncertainty solar resource datasets, actual plant production may vary considerably from the pre-construction estimate.

Plant production and the associated revenue are key inputs into financial models used to size debt or tax equity contributions. Therefore, relying on a poor quality resource and energy estimate can lead to less than optimal debt sizing which can result in lower returns on investment for equity partners.

Objectives

- Determine how various sources of solar and meteorological data impact production estimates
- Determine how uncertainty of data sets inhibit the ability to leverage the project
- Determine how plant overproduction can lead to lost revenue
- Determine how plant overproduction can result in lower rate of returns for debt, tax equity, and cash equity finance partners

Investor Interests:

- Cash Equity Investors: Long-Term energy production estimates (Reliant on P50 analysis)
- Tax Equity Investors: Interests are greatest in the beginning of the project life-cycle (Reliant on P50 analysis)
- Debt Lenders: Interested in only the minimum ability to pay back loan (Reliant on P90/P99 analysis)

Financial Model Key Performance Metrics:

- Debt Ratio: Ratio of acquired debt to cash equity
- Tax Equity Contribution: Amount financed through tax equity investor
- Projected Internal Rate of Return (IRR): Estimated IRR for the cash equity investor when financing with each resource dataset
- Actual IRR: Realized IRR for the cash equity investor when running the actual ground measured resource data file through the financial model for the Satellite TMY and NSRDB TMY3

Methodology

Resource Inputs:

- To test the impacts of potential over-production AWST evaluated three geographically diverse sites across the United States , studying the impacts of how various resource inputs predict long-term resource versus a high quality ground reference. The sources of data included Typical Meteorological Year (TMY) from:
  - Satellite derived dataset
  - National Solar Radiation Database (NSRDB) TMY3 [1]
  - Ground measured data from the United States Climate Reference Network (USCRN) [2]
- The ground measurements from the USCRN sites were used as the baseline for all results and assumed to be representative of the actual irradiance on site.
- The three project sites selected were in:
  - Merced, California
  - Tuscon, Arizona
  - Millbrook, New York
- Uncertainty for each dataset were assessed utilizing AWST's standard approach.

Energy Analysis:

- Energy was simulated for each of the studied resource files using the PVSyst Software.
- All three sites were simulated using AWS Truepower standard loss assumptions.
- Basic plant designs are as follows:
  - 12.5 MW_{DC} / 10.0 MW_{AC} (DC/AC Ratio: 1.25)
  - Generic 300 W polycrystalline module
  - Generic 500 kW inverter
  - Row tilt optimized for each project location using PVsyst
  - Modeled without near shading
  - Plant loss assumptions were applied consistently for each project location and resource analysis

Uncertainty Analysis:

- Uncertainty around resource data, as a percentage of the resource data, is highly variable and dependent on the source of data, type of campaign, and accuracy of the sensors utilized.
  - Measurements: 1% - 5%, depending on the measurement campaign
  - Satellite Modeled: 5% - 10%, depending on the resolution of the model and the project location
  - NSRDB TMY3: 10% or greater, depending on the proximity of the dataset to the project location

Projected Revenue:

- Power Purchase Agreement (PPA) pricing for each project location was developed using Locational Marginal Pricing (LMP)[3]:
  - The Base Price was assumed to be 1.5 x the average LMP
  - Time of Day and Seasonal (TOD) multipliers were developed from the raw LMP prices
- Potential project revenue was estimated from the hourly net energy and the TOD PPA price
- Production thresholds were assumed within the PPA structure.
  - Guaranteed Energy was assumed to be the annual P50 estimate
  - Overproduction limitations began at 110% of the Guaranteed Energy and paid 75% of the TOD PPA price.
  - Default was assumed to occur at 70% of the annual P50

Financial Model:

- Traditional Debt financing and Tax Equity Financing structures were evaluated:
  - CAPEX: \$2.2/W_{AC} Installed Capacity
  - OPEX: \$25/kW_{AC}/year Installed Capacity
- Debt Sizing: sized using a DSCR of 1.0 and P99 production estimates
- Tax Equity Investment sized assuming an 8.0% IRR

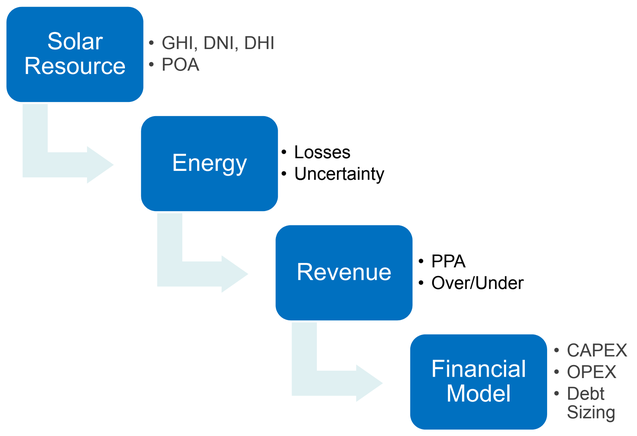


Figure 1. Flow Chart of Case Study Methodology

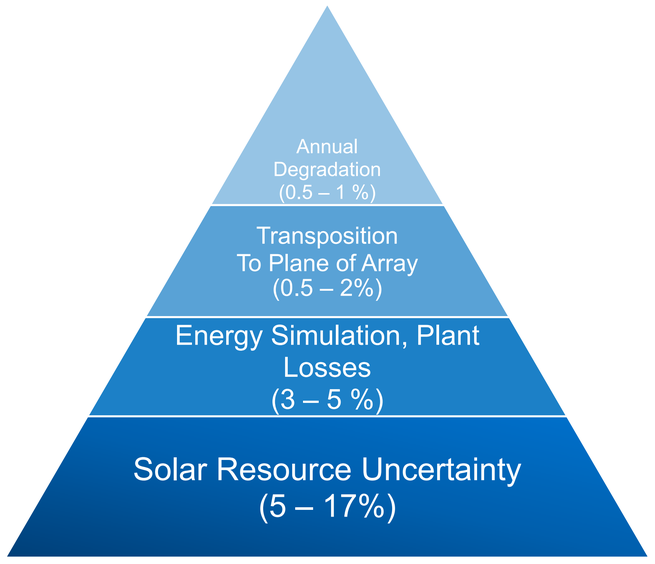


Figure 2. Sources of Energy Uncertainty

Results

- Figure 3 presents the gross energy yield and long-term net energy yield for the NSRDB TMY3 and Satellite modeled TMY for each case study location.
  - From this graph the most notable trend is that the NSRDB TMY3 under-predicts the energy yield when compared to the ground measured data at all three locations.
  - The Satellite Modeled TMY is more variable across each region.
- Figure 4 presents the projected revenue for the Satellite Model and the NSRDB TMY3 at the Merced, CA location where both estimates under-predicted the resource and energy
  - In both cases the projected revenue is lower than what the plant would actually produce.
  - For the NSRDB TMY3 the estimate is low enough that over the long-term the PPA overproduction threshold would be met, resulting in lost revenue of approximately 0.5%.

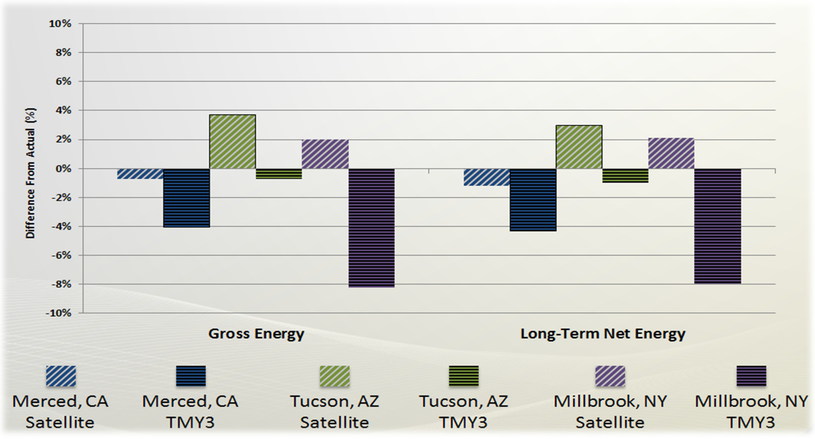


Figure 3 Project Energy Yield for all three case studies

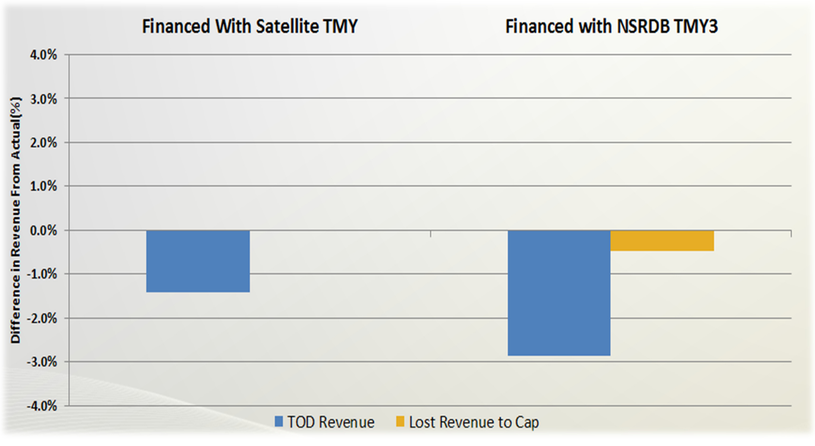


Figure 4 Project Revenue for the Merced, CA case study

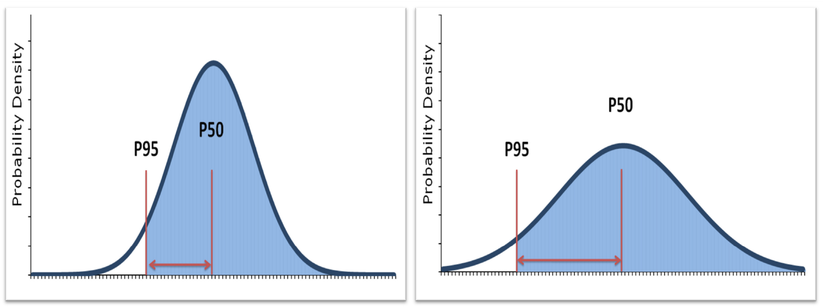


Figure 5 Example of low uncertainty (left) and high uncertainty (right)

- Figure 5 illustrates how energy estimates with larger uncertainty bands can impact the P90/P99.
  - When financing with debt, use of higher uncertainty resource datasets will limit the risk lenders are willing to take on.
- Figure 6 presents the Debt Ratio, Projected IRR, and Actual IRR for a traditional debt financing structure.
  - The results of financing with the Satellite Modeled TMY for the Merced, CA case study shows that the cash equity investor would have yielded an Actual IRR of 0.5% lower than if a higher quality resource dataset was used for financing. If we assume a \$10M cash equity investment over a 25-year project lifetime, the 0.5% IRR differential would have a cash equivalent of roughly \$1.3M of unrealized revenue potential.
  - The results from the NSRDB TMY3 analysis yield actual IRR losses of nearly double those of the satellite model, which is due to the larger uncertainty band around the resource data. This point Illustrates the importance of high quality resource input data to reduce the spread between P50 to P90/P99 estimates.
- Figure 7 presents the Tax Equity Contribution, Projected IRR, and Actual IRR for a tax equity financing structure.
  - The results of financing with the Satellite Modeled TMY for the Merced, CA case study shows that the cash equity investor would have yielded an Actual IRR of 0.5% lower than if a higher quality resource dataset was used for financing. As in the scenario above, for a \$10M cash equity investment over a 25-year project lifetime the cash equivalent is roughly \$1.3M left on the table.

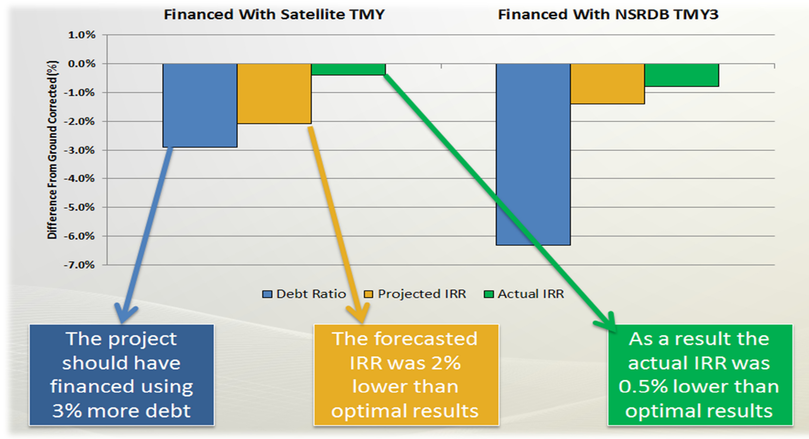


Figure 6 Debt Financing Structure Project Yields

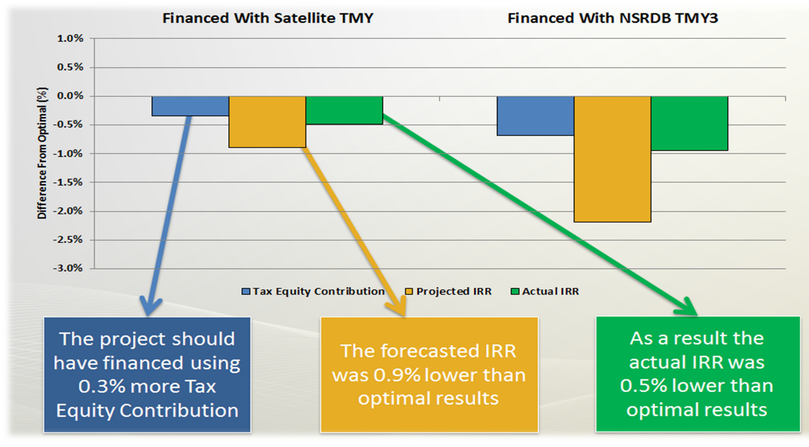


Figure 7 Tax Equity Debt Structure Project Yields

Conclusions

- Choosing an accurate and reliable source of solar resource data is critical for project financing
- Under-estimating solar resource can lead to plant overproduction and lost revenue to PPA caps
- Plant over-production can result in lower returns for lenders, tax equity, and cash equity finance partners

References

[1] National Solar Radiation Data Base "1991 – 2010 Update" http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2010/

[2] United States Climate Reference Network "Hourly Data" http://www1.ncdc.noaa.gov/pub/data/uscrn/products/hourly02/

[3] California ISO "Open Access Same-time Information System" http://oasis.caiso.com/

[4] Paul Thienpont, AWS Truepower "Is Solar Overproduction Costing You?" 18 November 2014 Webinar, https://www.awstruepower.com/knowledge-center/webinars/

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A NEW SILICON PHOTOVOLTAIC PYRANOMETER FOR MEASURING SOLAR IRRADIANCE IN METEOROLOGICAL AND SOLAR RESOURCE APPLICATIONS

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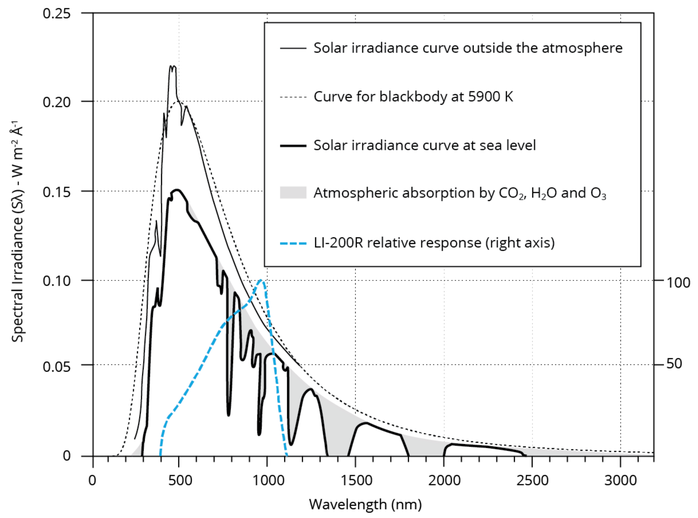
LI-COR Biosciences, Lincoln, NE, USA. *taylor.thomas@licor.com

INTRODUCTION

- LI-COR solar radiation measurements:
  - Designing solar radiation sensors for over 40 years
  - Sensors used at thousands of locations around the world
  - Used for solar resource assessment, photovoltaic efficiency monitoring, meteorological and agricultural studies
- Silicon photovoltaic design advantages of LI-200 Pyranometer:
  - Low-maintenance, proven field performance [2, 3]
  - Lower cost than thermopile designs
  - Lower sensitivity to dust and dirt compared to thermopile designs
  - Response time less than 1µS (2m cable terminated into 147 Ω load)

REFERENCE LI-200 PYRANOMETER



The LI-200SA Pyranometer spectral response along with the energy distribution in the solar spectrum. [1, 2]

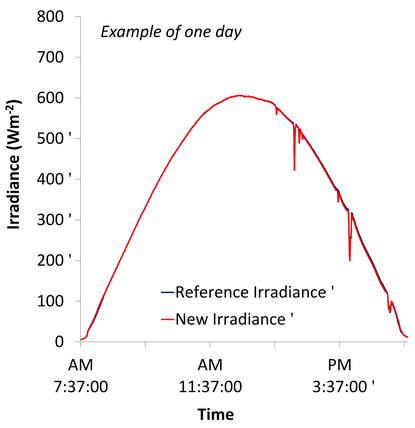
- In unobstructed daylight conditions, LI-200 Pyranometer compares well with thermopile pyranometers [1, 2, 3]
- LI-200: silicon photovoltaic detector, fully cosine-corrected miniature head, current output directly proportional to solar radiation

NEW LI-200R PYRANOMETER

- Detachable sensor head
- Easy removal for calibration w/o unwiring
- Larger drain for improved water shedding
- High-speed, fully cosine corrected
- Designed for continuous monitoring
- µA and mV (with adapter) output
- Sensitivity typically 90µA per 1000 Wm^{-2}

PERFORMANCE OF NEW vs OLD DESIGNS: LATEST RESULTS

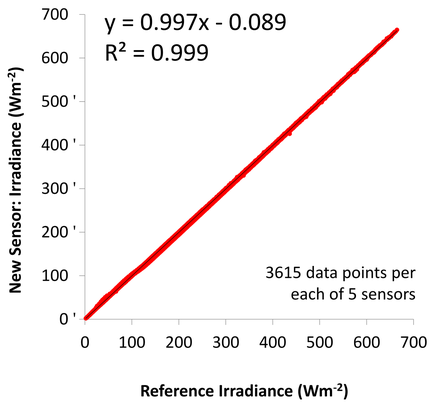
Daily Irradiance



Irradiance from new LI-200R and reference LI-200 sensors. Values represent an average of 5 pyranometers.

Under unobstructed daylight conditions, new LI-200R pyranometer compared well with reference LI-200

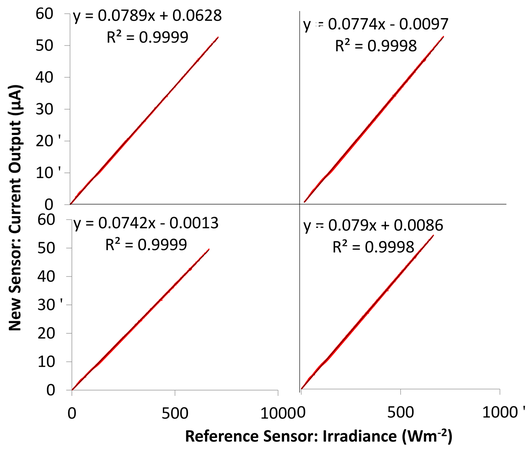
Irradiance Response



Irradiance from new LI-200R sensors plotted against irradiance values from reference LI-200 sensors

In 1:1 comparison, new LI-200R performed well vs reference LI-200 at 1 minute intervals with no averaging

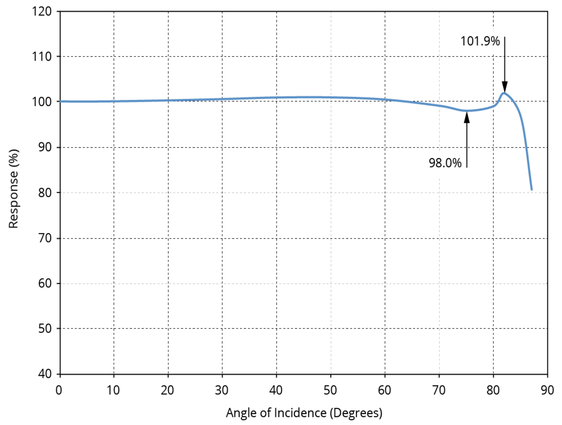
New Design Output vs. Reference



Current (µA) output from new LI-200R sensors as function of reference LI-200 irradiance (Wm^{-2})

New LI-200R performed well vs reference LI-200 (data for 1 minute intervals with no averaging)

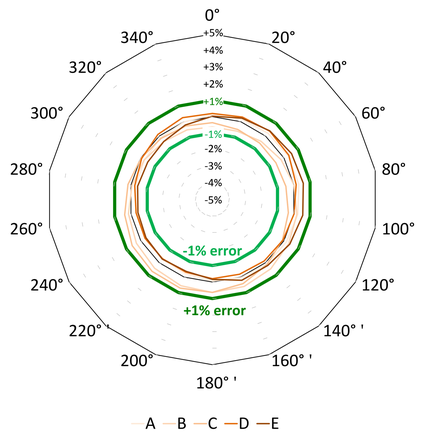
New Design Cosine Response



The sensitivity of new LI-200R sensors as a function of angle of incidence

Cosine response is corrected well up to 82° angle of incidence*

New Design Azimuth Response



Azimuth errors for a set of 5 new LI-200R sensors at 45° angle of incidence

Errors were below 1% in new LI-200R over 360° at 45°elevation

*A sensor without an accurate cosine correction can give a severe error at low solar elevation angles. The cosine error at angle 0 is the percent difference of the ratio of the measured output at angle 0 and normal incidence (angle 0°) as compared to the cosine of angle 0

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[1] Biggs, William W. (1984). Principles of Radiation Measurement. LI-COR, Inc. Lincoln, NE
[2] Kerr, J. P., Thurtell, G. W., & Tanner, C. B. (1967). An integrating pyranometer for climatological observer stations and mesoscale networks. Journal of Applied Meteorology, 6(4), 688-694.
[3] Weiss, A., & Norman, J. M. (1985). Partitioning solar radiation into direct and diffuse, visible and near-infrared components. Agricultural and Forest meteorology, 34(2), 205-213.

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