NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Photovoltaic Module Reliability Workshop 2014

Golden, Colorado

February 25–26, 2014

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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.

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

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In 2014, the PVMRW was held in Golden, Colorado, February 25–26. Workshop participants shared more than 100 presentations and posters, covering topics such as the physics of failure, inverter reliability, accelerated testing, and quality management.

The workshop was chaired by Nick Bosco.

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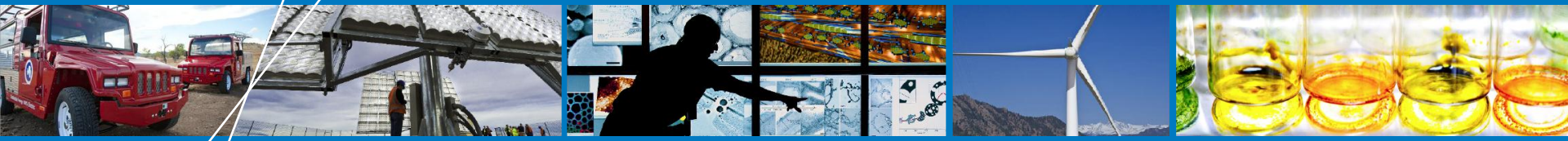
Expanding Solar Investment:

Accessing Low Cost Financing Thru Standardization, Best Practices, and Risk Scoring



PV Module Reliability Workshop

February 25th, 2014

Michael Mendelsohn, 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.

NREL Finance Team Activities

- **Develop models**
- **Publish research reports and market insights:**
  - *Financing best practices*
  - *Capital market investment*
  - *Tax-equity and depreciation complexities*
- **Conduct project-specific analysis**
- **Organize industry to facilitate U.S. capital market investment and bank lending:**
  - *Advanced Financing to Achieve SunShot*
  - *Principles adopted by finance working group for Clean Energy Ministerial**
- **Offer content & assets on financeRE.nrel.gov**

* Informally accepted by DOE International

Engaging Capital Markets: Project History

NREL Goal

Expand availability of capital

Lower cost of capital

Reduce transaction cost, time to access capital

3 Yr. DOE Award:

Advanced Financing to Achieve SunShot

Organize the industry around:

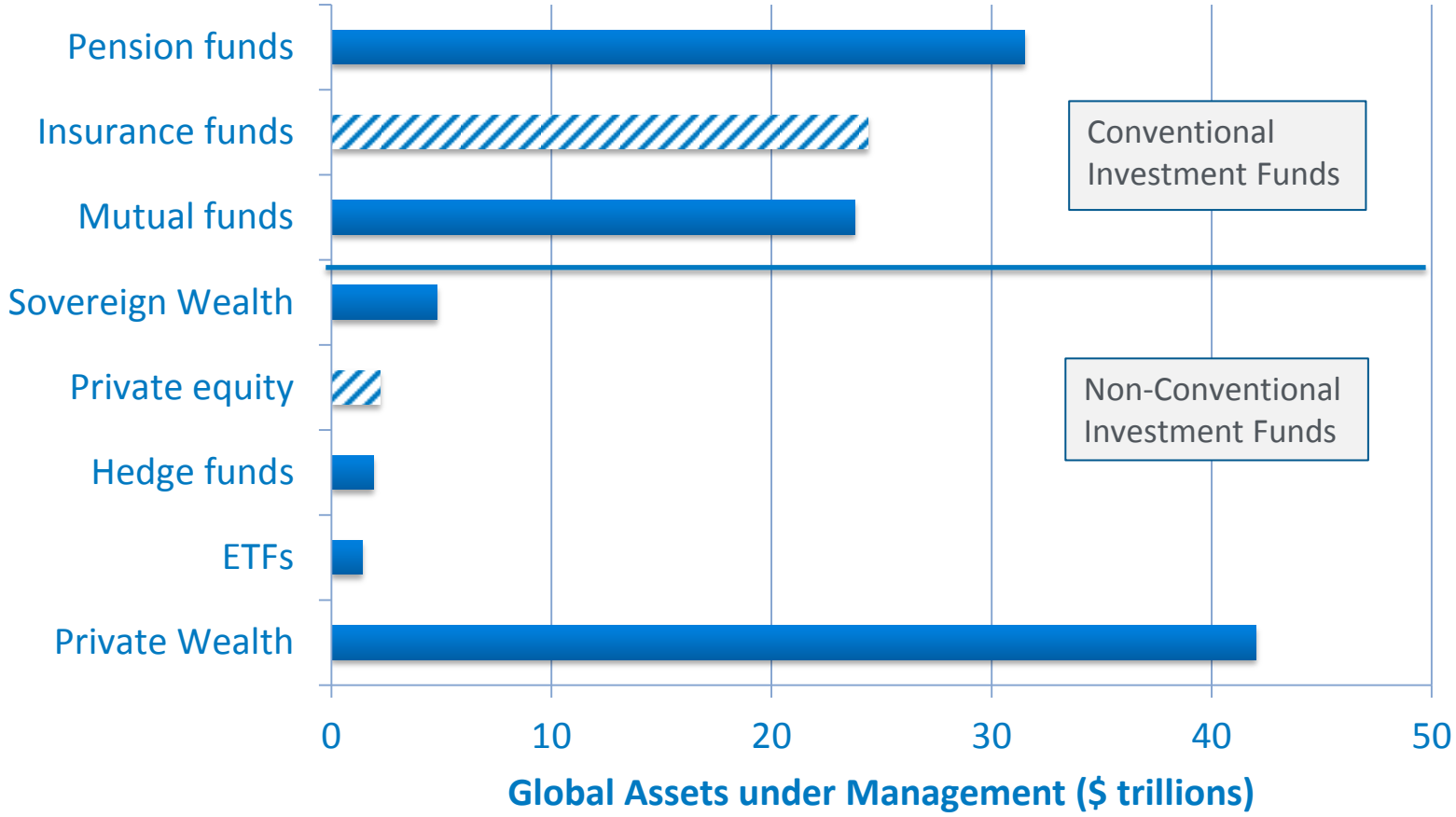
- Standard documents
- Best Practices
- Robust datasets

Conduct analysis to comprehend opportunities and barriers

Promote adoption by developers, financiers, law firms, etc.

Value: Expand the Availability of Capital

Most managed funds do not invest in renewable energy.
To tap this capital, investors need a liquid, tradable product priced by the market



Hatched sources of capital currently invest in RE, but not necessarily from all investment buckets

Source: The CityUK

Solar Access to Public Capital (SAPC) Working Group

Goal

Expand availability and lower the cost of solar through by improved access to public capital:

- Asset-backed Securities (ABS)
- Real Estate Investment Trusts (REITs)
- Master Limited Partnerships (MLPs) and Synthetic MLPs
- Yieldcos

How

By standardizing the project development process in order to:

- Lower risk perception and due diligence requirements
- Pool project cash flows & facilitate investment scale economies

SAPC: Approx. 175 Participant Entities

Developers	Legal	Investment	Advisory	Manuf. / Other
Affordable Solar	Akin Gump	B of A Merrill Lynch	Black & Veatch	Enphase
Altus Power	Bingham McCutchen	Barclays	Citi Trust Services	Hanwha Q-Cells
Amicus Solar	Chadbourne & Parke	CalCef	CohnReznick	KACO
Borrego Solar	Chapman & Cutler	Citi	Corelogic	SMA
CleanPath	Cooley	Clean Power Finance	First Associates	Solectria
Distributed Sun	Coronal Mgt	Credit Agricole	GL Garrad Hassan	Energi
Enfinity	Covington	Credit Suisse	Katten Muchin	CleanPath
Duke Energy	Dechert	Deutsche Bank	Kroll Bond Ratings	Skystream Markets
HelioPower	DLA Piper	Energy One Finance	KPMG LLP	PV Evolution Labs
Main Street Power	Hunton & Williams	Foresight Group	Lease Dimensions	Solar Electric Power Ass.
NextEra	K&L Gates	Global Capital Finance	Locus Energy	Global Cool Cities
OneRoof	Kramer Levin	Hannon Armstrong	Mercatus	Demeter Power
PsomasFMG	Milbank	KeyBanc	Moody's	Ballard Spahr
Recurrent	McCauley Lyman	kW Financial	Novogradac	Standard Solar
Rosendin	Nixon, Peabody	Macquarie	Power Factors	Amp Solar
SolarCity	Orrick, Herrington	MorganStanley	PwC	Department of Energy
SPG Solar	Patton Boggs	Nord LB	Rocky Mtn. Institute	SunSpec
Sungevity	Perkins Coie	PNC	SAIC	Birch Tree Capital
SunPower	Sidley Austin	Rabobank	Sol Systems	C2ES
SunRun	Skadden Arps	Seminole Financial	Standard and Poor's	Underwriters Laboratory
Vivint Solar	Stoel Rives	Union Bank	Trepp	Assurant
Wiser Capital	Troutman Sanders	US Renewables Group	TUV Rheinland	Mayer Brown

SAPC Activities

- **Standard Contracts – first set available and in use:**
  - Residential Lease (aggregated, disaggregated)
  - Commercial PPA
- **Develop Best Practices**
  - O&M
  - Installation
  - Independent Engineering
- **Develop *mock* filing to rating agencies**
- **Build Performance Dataset: oSPARC**
- **Promote to Solar & Investor Communities**

Standard Contracts and Best Practices

- **Benefits of Adoption:**
  - Facilitate cash flows to be pooled into securities to access capital market investment
  - Improve confidence among investors and regulators
  - Lower transaction costs
  - Speed deployment
  - Improve customer protection
  - Enable market liquidity of projects

Best Practices

- **Installation, O&M, Independent Engineering**
- **To build investor confidence systems are well-built and well-maintained.**
- **Build connection to PV quality assurance efforts**
  - What stamp of approval can assure systems will produce expected energy and cashflows over the life of the security

NREL's oSPARC Data Initiative

Will be first major publicly available database of system performance

Datasets from:

- California Solar Initiative crossed with weather data
- Monitoring entities*
- Solar developers w/ financier approval*

** Numerous offers but concerns over first mover risk*

Mock Securitizations

- **Several planned:**
  - Residential vs. Commercial
  - Pre vs. Post Recapture (i.e., Tax Equity ownership)
  - Various iterations of tranching, overcollateralization & priority of payments
- **First suite presented to rating agencies:**
  - Pool of residential leases, Senior/Sub structure
  - Detailed legal term sheets
  - Structuring and cash flow analyses

Banking on Solar – new FY14 Activity

- **Designed to facilitate direct lending for solar deployment**
  - Community banks
  - Credit Unions
  - Regional / National Banks
- **Proposed Activities:**
  - Standardize loan documents
  - Build consensus on underwriting principles
  - Develop educational materials on technology and loan performance for lenders & regulators
  - Educate on PACE program benefits / opportunity
  - Promote to retail banking industry

Next Steps

- **Expand pool of potential investors**
  - *Structured Finance Industry Group (SFIG)*
  - *Socially responsible investors (Ceres, others)*
  - *Insurance Companies (also for credit enhancements)*
- **Finalize best practices, next suite of standard contracts, oSPARC data acquisition**
- **Develop mock securitization for commercial portfolio, find structures that can incorporate tax equity**
- **Promote adoption of standard contracts, other assets**
  - *Developers*
  - *Investors*
  - *End-users (MUSH, large commercial, non-profit)*
- **Engage bank regulators on loan docs, underwriting practices, etc.**
- **Replicate internationally, leverage assets developed**

Glossary

- ABS – Asset-Backed Securities
- CDO – Collateralized Debt Obligations
- CLO – Collateralized Loan Obligations
- ETF – Exchange Traded Funds
- MBS – Mortgage-Backed Security
- MLP – Master Limited Partnership
- oSPARC – open Solar Performance and Reliability Clearinghouse
- REIT – Real Estate Investment Trust

Thank You

Michael Mendelsohn
National Renewable Energy Laboratory
michael.mendelsohn@nrel.gov

Reliability Evaluation of PV Power Plants:

Input Data for Warranty, Bankability and Energy Estimation Models

ARIZONA STATE UNIVERSITY
PHOTOVOLTAIC RELIABILITY LABORATORY

G. TamizhMani (Mani); manit@asu.edu

- Thanks to the hard work of ASU-PRL staff and students!
- Thanks to the SRP-R&D team and Bill Kazeta for the technical support!
- Thanks to SRP and DOE/SERIIUS for the funding support!
- This presentation material is based on two MS theses (available for free downloading at: repository.asu.edu)

ARIZONA STATE UNIVERSITY

Focus of this Presentation

Bankability of solar PV projects involves a 5-step process:

1. Site Assessment (SA)
2. Design Optimization (DO)
3. Component Procurement (CP)
4. Installation & Commissioning (IC)
5. **Operation & Maintenance (O&M)**

Focus of this Presentation

From PV module perspective:

Operation ~ **degradation rate**
Maintenance ~ **Failure rate**

} Used to calculate production generation risk

Production generation risk can be calculated if **DEFINED METRICS** for the degradation and failure rates are available. The focus of this presentation is to define the metrics and apply these defined metrics on the field measured data so they **can be used for warranty insurance, bankability and energy estimation calculations**.

Presentation Outline

- Importance to stakeholders
  - Reliability evaluations in the field

- METRIC definitions (from users perspectives)
  - Safety failures, reliability failures and durability/degradation losses

- Application of definitions in field evaluation
  - Quantitative determination of safety failures, reliability failures and degradation rates of aged PV power plants

- Application of the defined metrics on data processing
  - Failure and degradation modes and rates
  - Distribution between safety failures, reliability failures and degradation rates
  - Soiling losses *(see the poster for details)*

- Conclusions

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PV Power Plant Evaluation: O&M

Project Developer Perspective:

To secure low interest loan without risk premium adders. There are three risk premium adders.

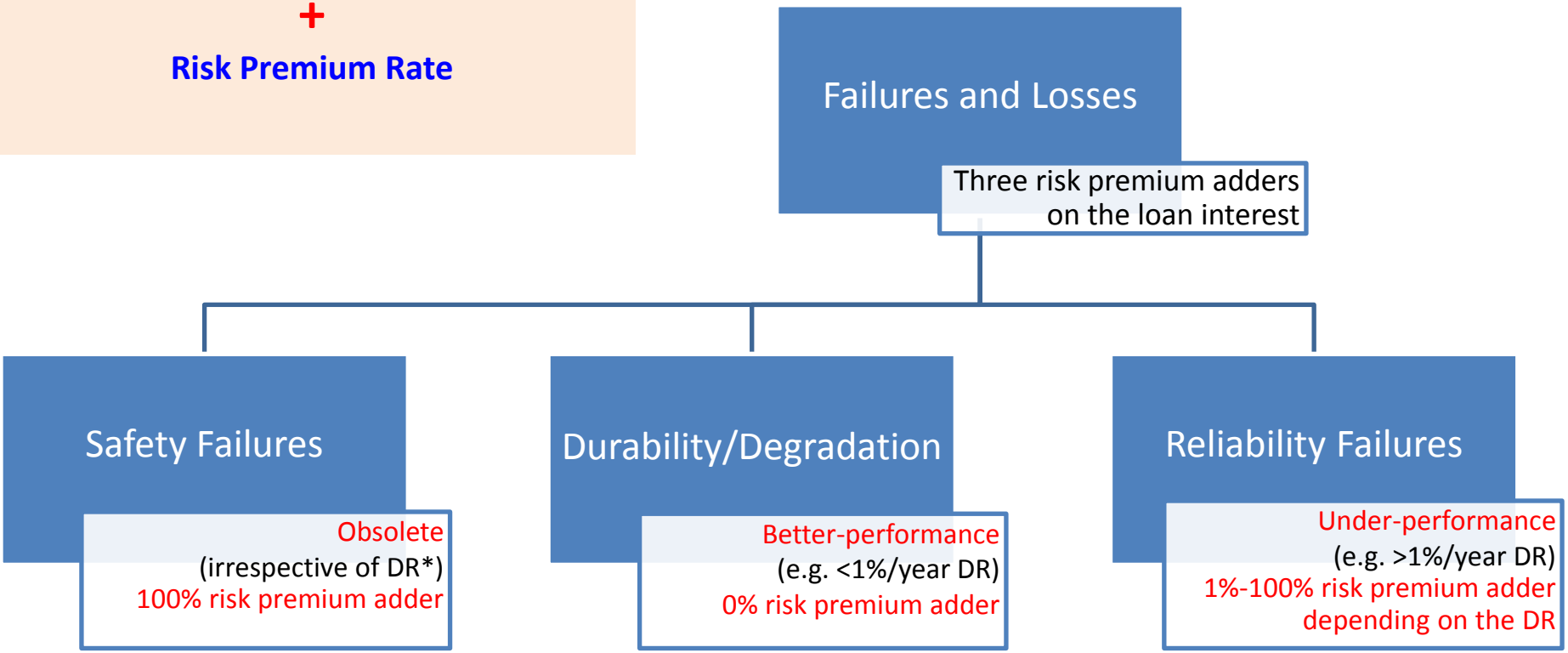
Interest Rate

=

Interest Rate @ Zero Risk

+

Risk Premium Rate



*DR = Degradation Rate

Source: ASU Photovoltaic Reliability Laboratory (ASU-PRL)

Goal: Number of modules which will have safety and reliability risks needs to be determined

PV Power Plant Evaluation: Importance to Stakeholders

Repairing or Decommissioning Decision Perspective:

To decommission the power plant when annual kWh generation declines below an acceptable level. The kWh value is dictated by three factors: safety failures over time, reliability failures over time and degradation loss over time.

kWh

is dictated by

- **Safety failures (SF) over time**
  (obsolete; qualifies for warranty returns)
- **Durability/Degradation loss (DL) over time**
  (better-performance; <1%/year degradation; does not qualify for warranty claims)
- **Reliability failures (RF) over time**
  (under-performance; >1%/year degradation; qualifies for warranty claims)

Goal: Number of modules which do not effectively contribute to kWh generation needs to be determined

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- Conclusions

ASU-PRL's METRIC Definition of Failures and Degradation

Defects (D) with Safety Issues = Safety Failure (SF)

> 1% dr/y − SF with >1% dr/y = Reliability Failure with or without cosmetic defects (RF)

< 1% dr/y − SF with <1% dr/y = Durability Loss with or without cosmetic defects (DL)

SF = Safety Failure (Qualifies for safety returns)

RF = Reliability Failure (Qualifies for warranty claims)

DL = Durability Loss with or without Cosmetic Defects (Does not qualify for warranty claims)

Presentation Outline

- Importance to stakeholders
  - Reliability evaluations in the field

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  - Distribution between safety failures, reliability failures and degradation rates
  - Soiling losses *(see the poster for details)*

- Conclusions

Field Evaluation of PV Modules:

Application of ASU-PRL's Definitions on Field Failures and Degradation Determinations

Review:
Module Construction, Full I-V curves (STC and LowEs), Previous Reports, System Layout, Metered kWh and Weather Data

Visual Inspection:
All modules per NREL checklist

Megger Tests:
All safety failed modules

Thermal Imaging:
All modules

IV & Megger Tests:
All hotspot modules

Diode Test:
All modules

IV & Megger Tests:
All diode-failed modules

Safety and Reliability Evaluation
Primary Goal: Identification of Safety Failures (SF) and Reliability Failures (RF)

ASU PRL

Durability and Reliability Evaluation
Primary Goal: Identification of degradation rates (DR)
[Reliability Failure (RF) = if DR>1%/y; Durability Loss (DL)= if DR<1%/y)]

I-V Test and SunEye:
All strings
(before cleaning)

I-V Test:
All modules in the best, worst and median strings
(before cleaning)

I-V Test
(1000, 800 and 200 W/m^2):
All modules in the best strings (after cleaning)

PID Current Test:
All modules in the best strings (after cleaning)

Cell-Crack Test:
All modules in the best strings (after cleaning)

Presentation Outline

- Importance to stakeholders
  - Reliability evaluations in the field

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  - Safety failures, reliability failures and durability/degradation losses

- Application of definitions in field evaluation
  - Quantitative determination of safety failures, reliability failures and degradation rates of aged PV power plants

- Application of the defined metrics on data processing
  - Failure and degradation modes and rates
  - Distribution between safety failures, reliability failures and degradation rates
  - Soiling losses *(not presented here; see the poster for details)*

- Conclusions

Four PV Plants Evaluated

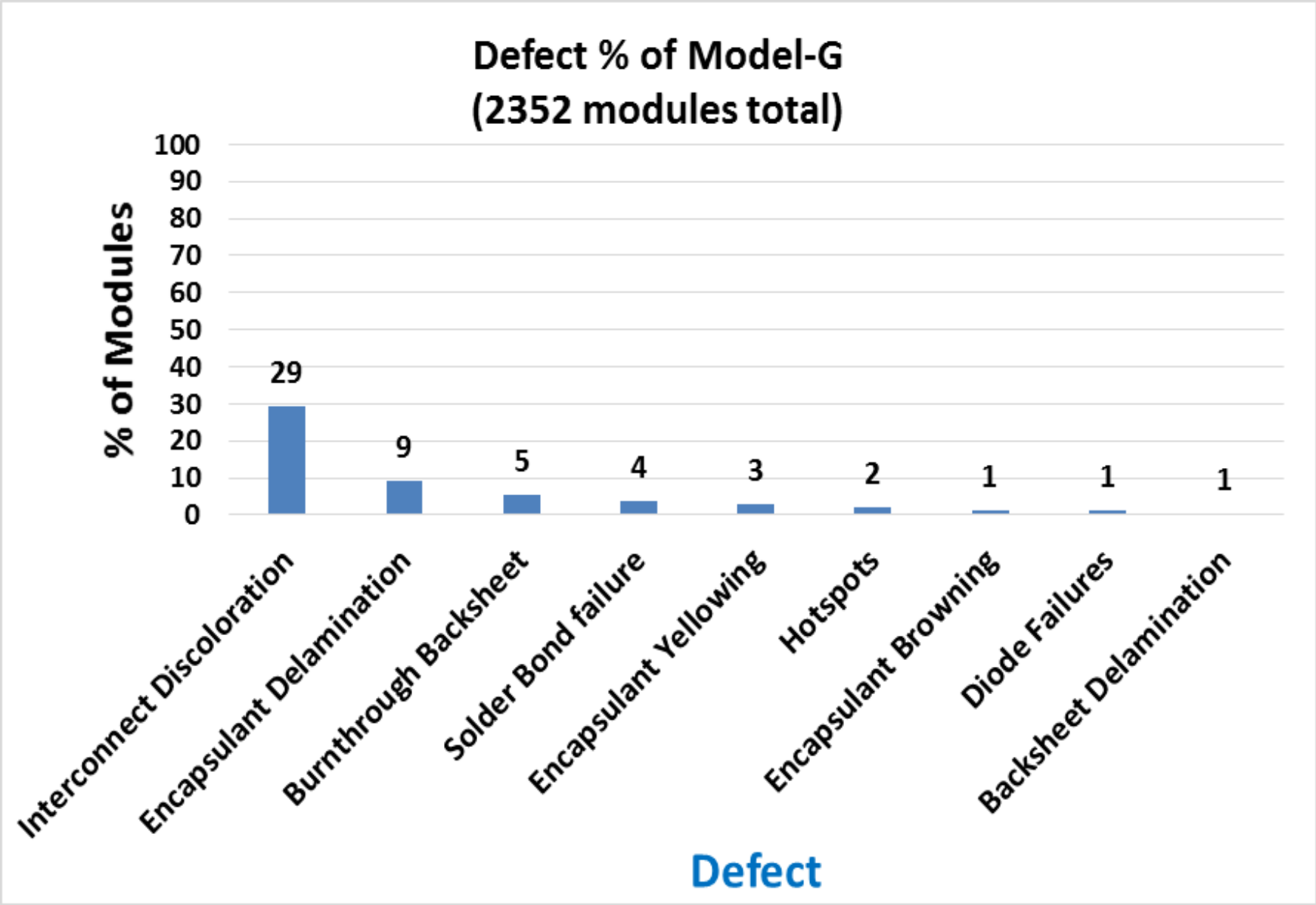
Hot-Dry Desert Climate

Four PV Power Plants Evaluated *(mono-Si; Glass/Polymer; 6656 modules)*

- **Due to time limitation, only one plant (Model G) data is presented here.**

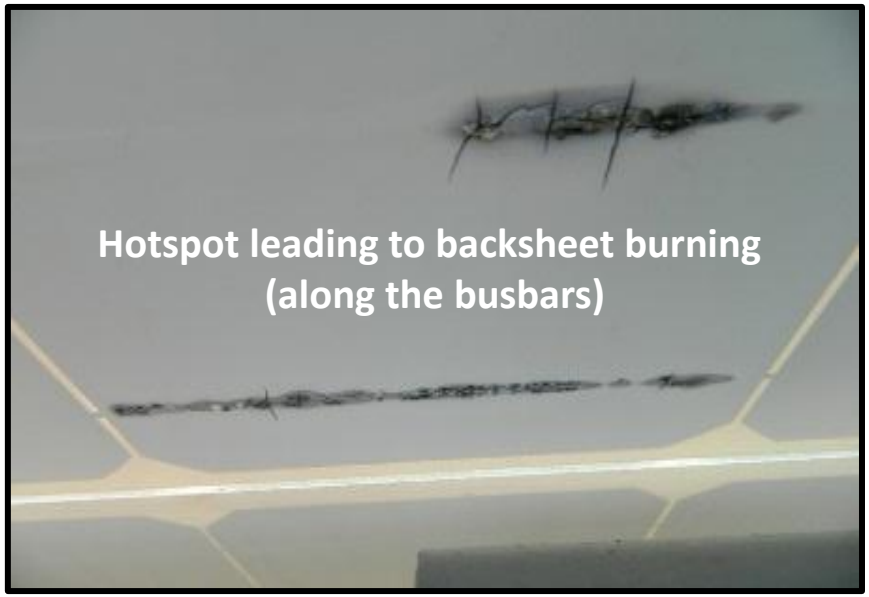
- **Data for the other three plants is made available in the appendix of this presentation.**

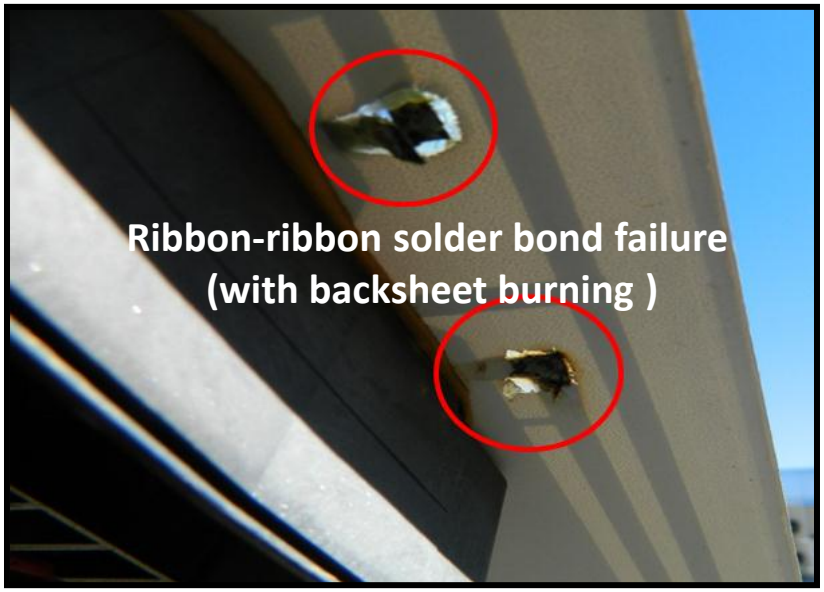
Defects Including Safety Failures (*Model G – Site 3*)

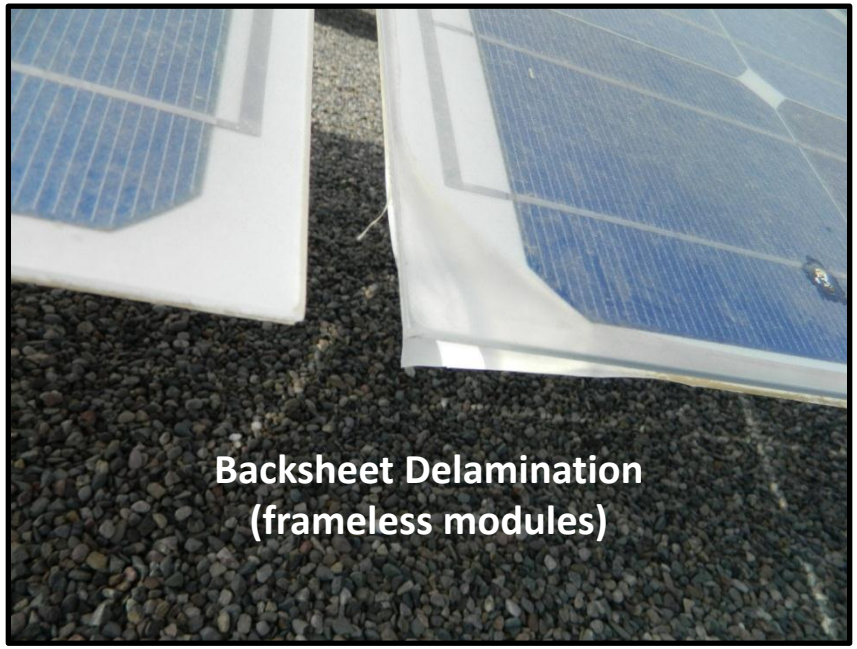


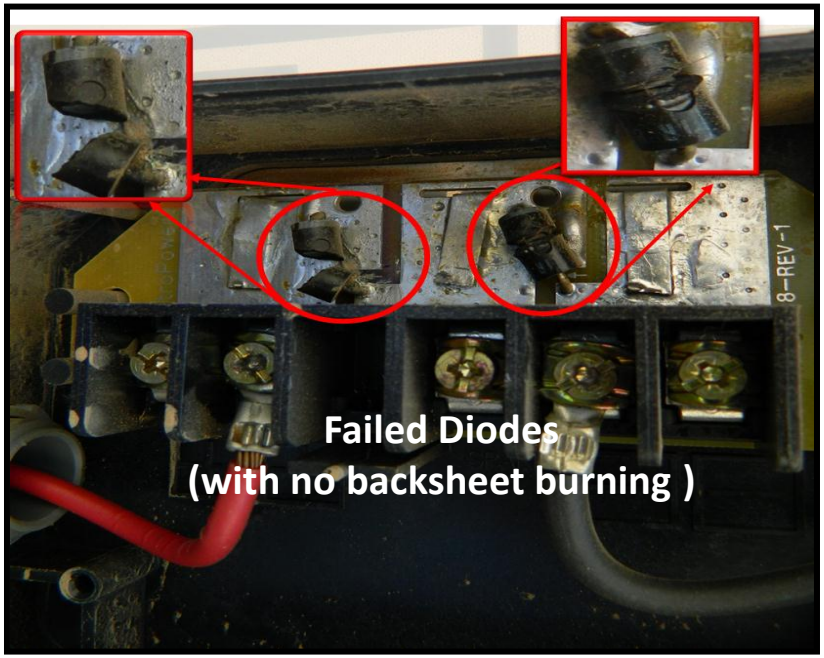
Safety Failures (*Model G – Site 3*)

12 Years – 1-axis Tracker





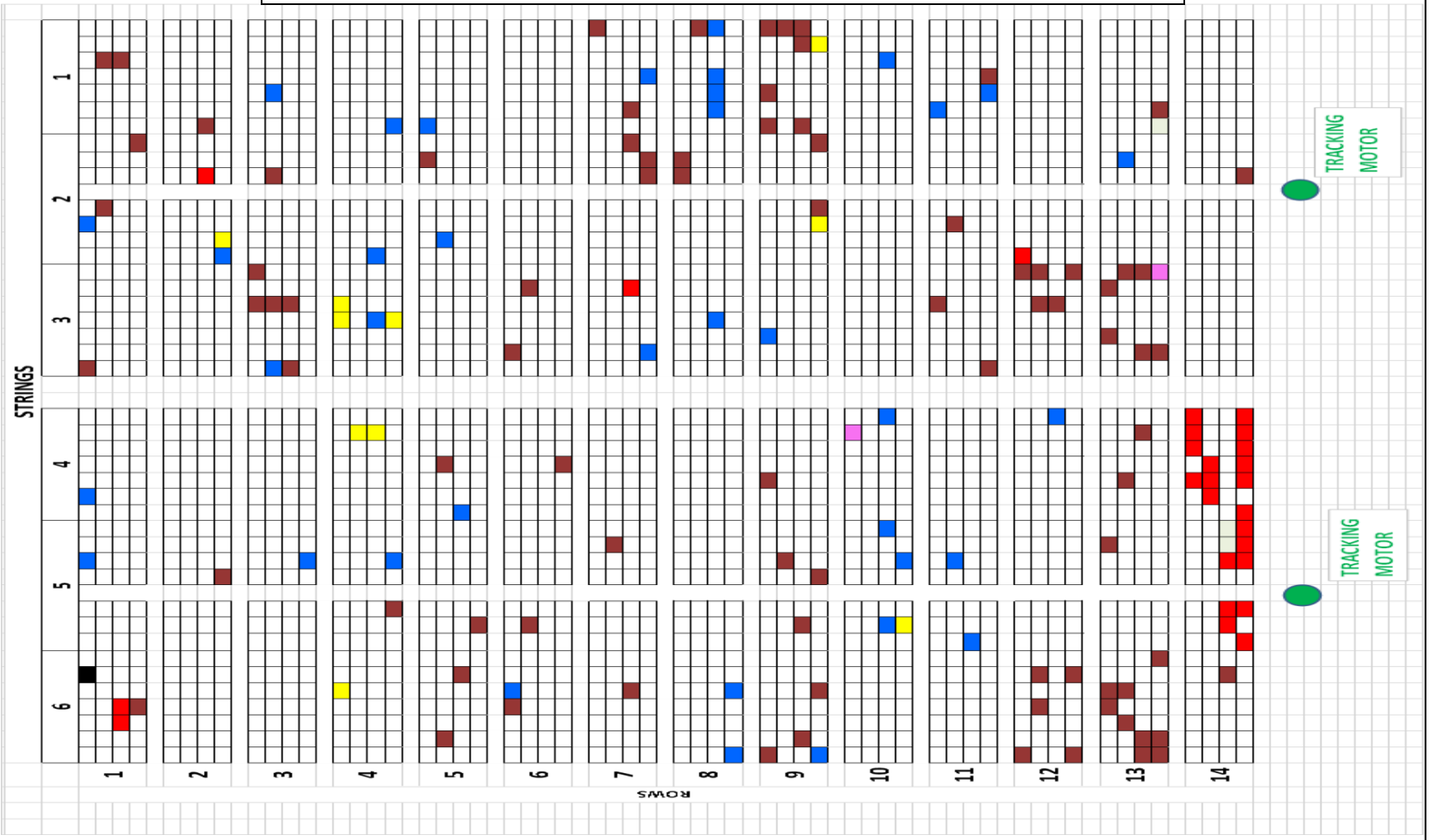




Mapping of Safety Failures (*Model G – Site 3*)

Framed - 12 Years – 1-axis Tracker

Safety failure rate at the plant level = 162/2352 = 7%

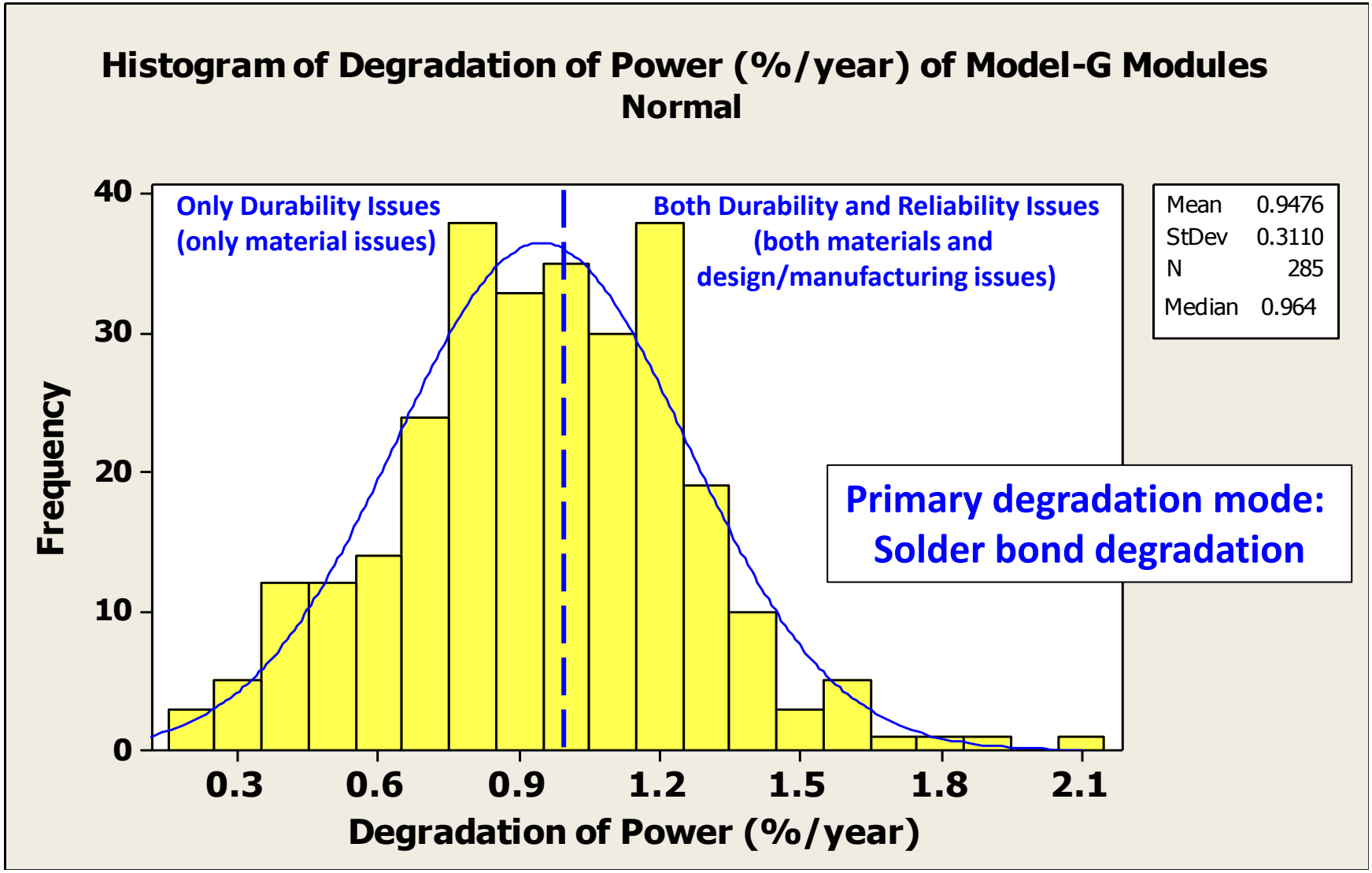


Primary failure mode:
Ribbon-ribbon solder bond failure with backskin burning

- Hotspot issues leading to backsheet burn (37/2352)
- Ribbon-ribbon solder bond failure with backsheet burn (86/2352)
- Failed diode wih no backsheetburn (26/2352)
- Hotspot issues with backsheet burn + Ribbon-ribbon solder bond with backsheet burn (1/2352)
- Backsheet Delamination (10/2352)
- Backsheet Delamination + Ribbon-ribbon solder bond failure (2/2352)

Distribution of Reliability Failures and Degradation Losses (*Model G – Site 3*)

12 Years – 1-axis Tracker



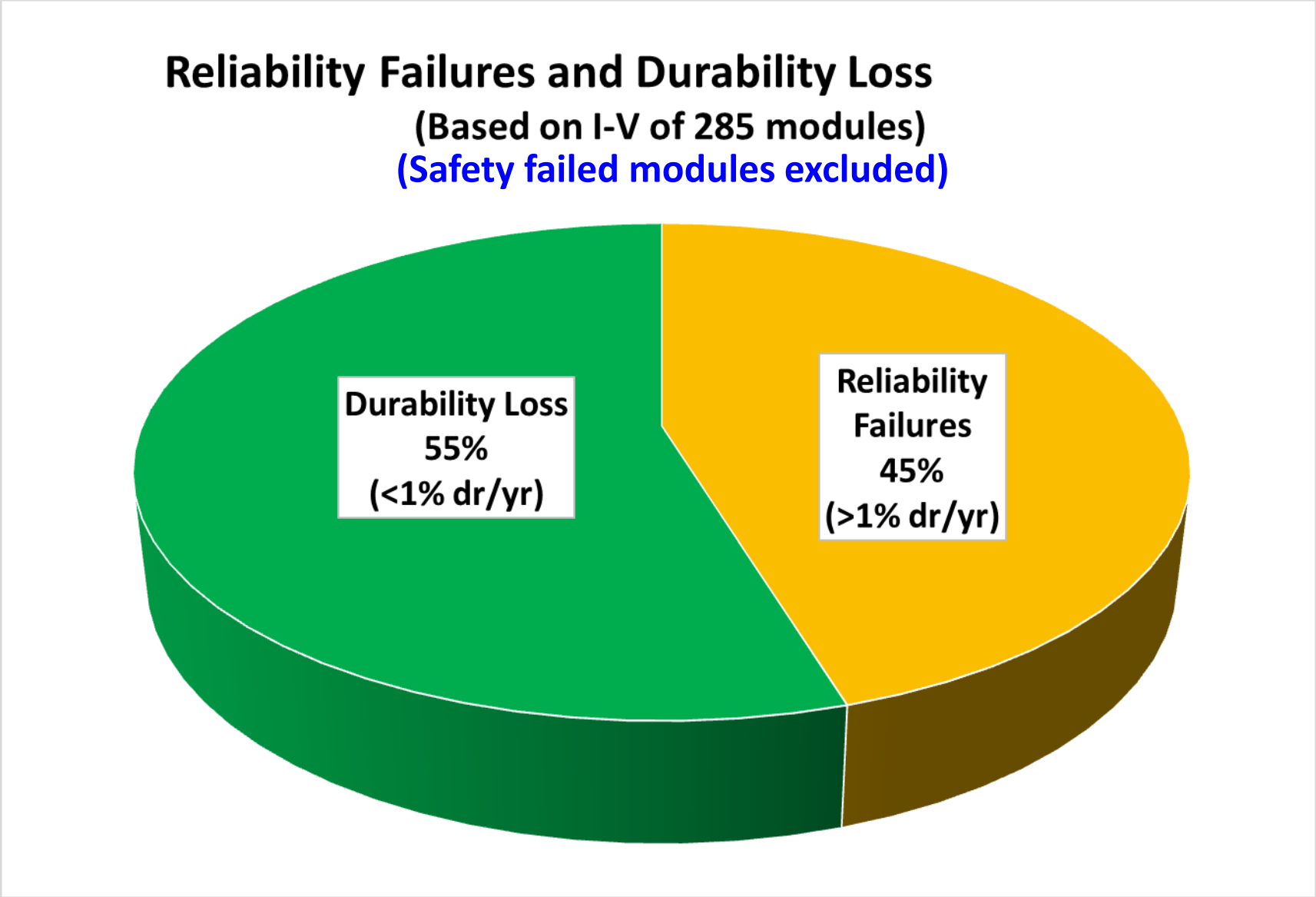
Total number of modules = 285 (safety failed modules excluded)

Mean degradation = 0.95%/year

Median degradation = 0.96%/year

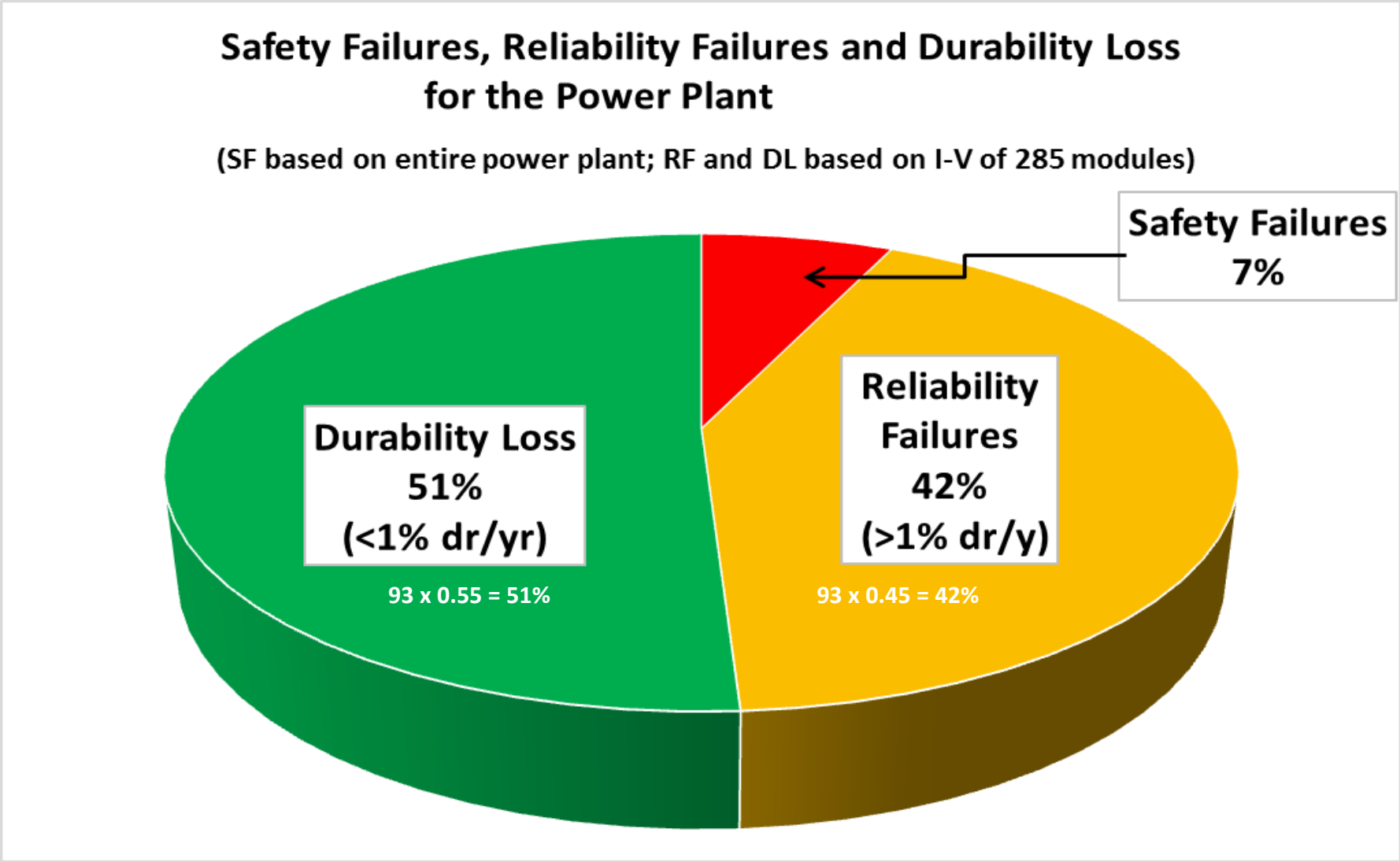
Distribution of Reliability Failures and Degradation Losses (*Model G – Site 3*)

12 Years – 1-axis Tracker



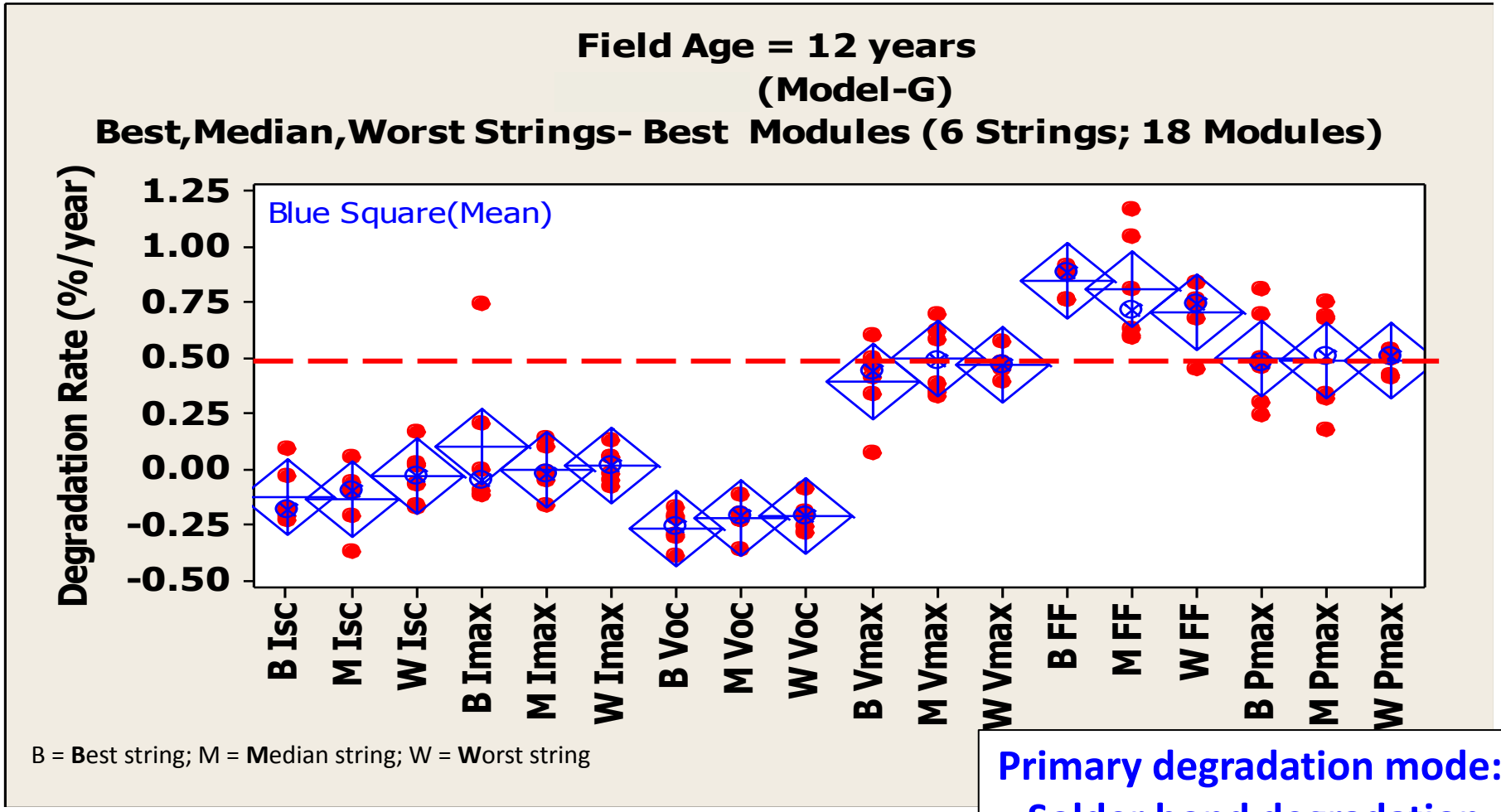
Distribution of Safety Failures, Reliability Failures and Degradation Losses (*Model G – Site 3*)

12 Years – 1-axis Tracker (combination of previous two slides)



Best Modules Experienced Only Durability Issues (*Model G – Site 3*)

1-axis Tracker



Primary degradation mode: Solder bond degradation

Pmax loss → FF loss → Rs increase

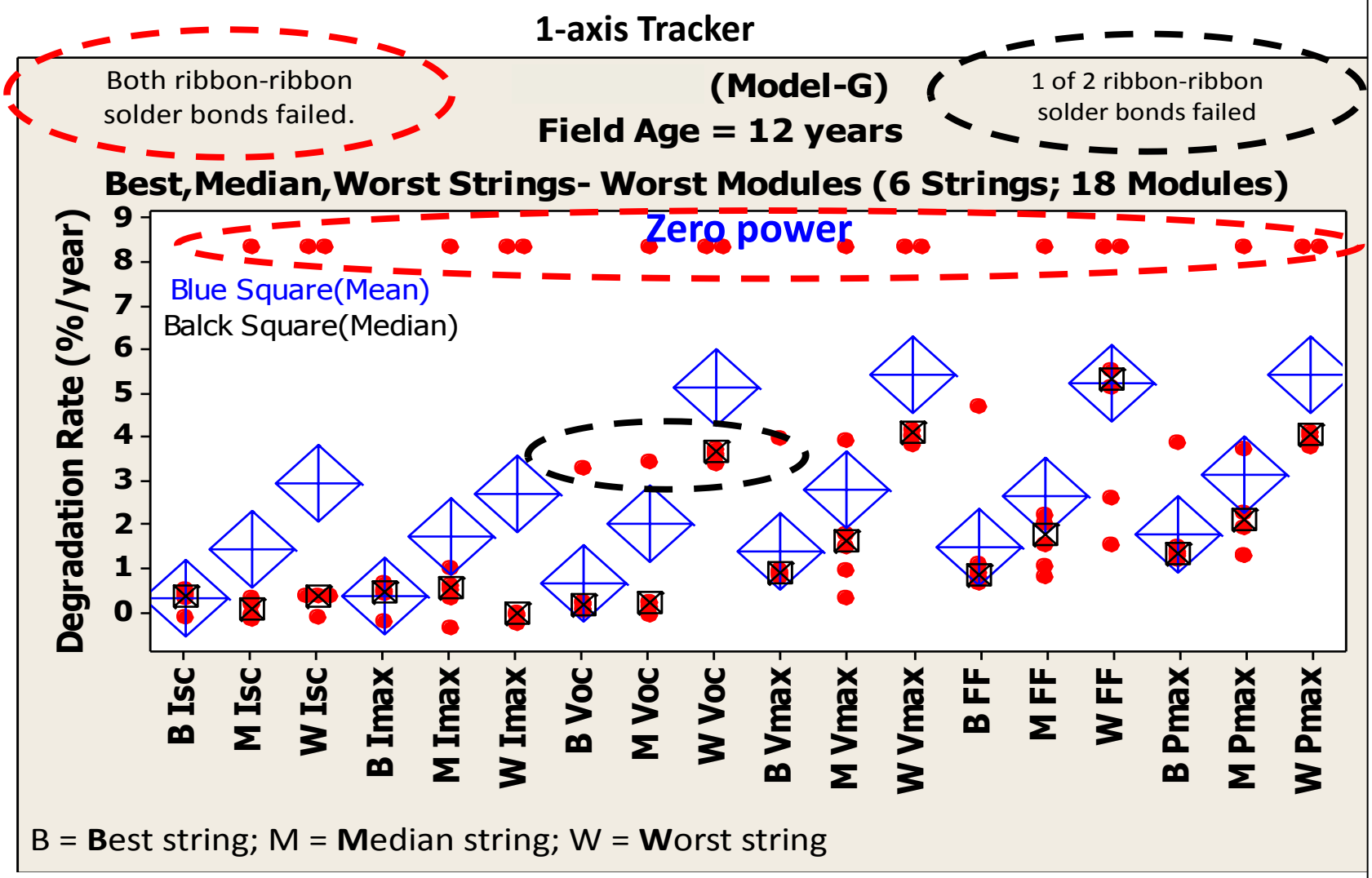
BEST modules = 18 (safety failed modules excluded)

Mean degradation = 0.5%/year

Median degradation = 0.5%/year

Due to only intrinsic (materials) issues contributing to real wear out mechanisms

Worst Modules Experienced Both Reliability and Durability Issues (*Model G – Site 3*)



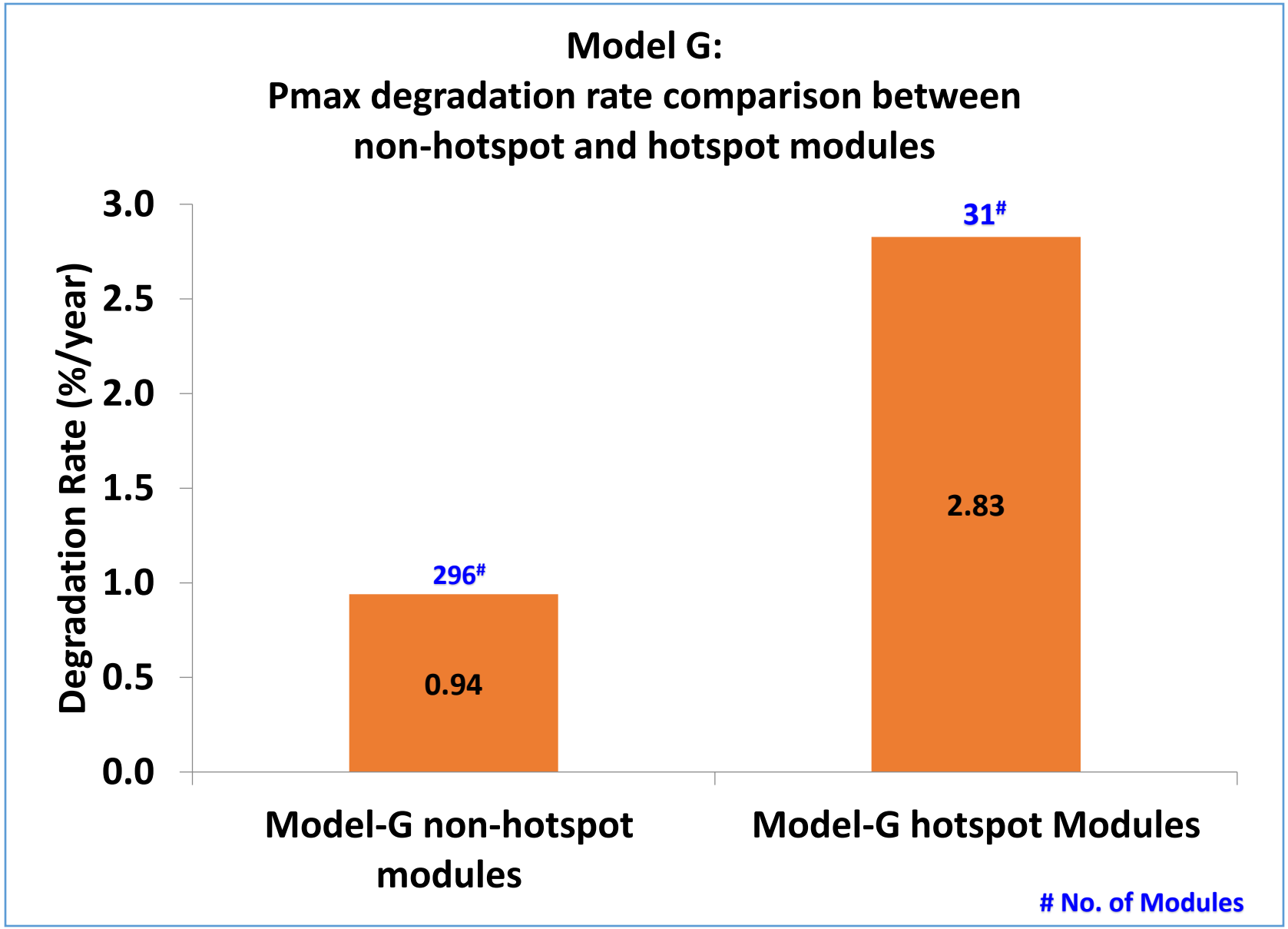
Primary failure mode: Ribbon-ribbon solder bond failure with backskin burning

WORST modules = 18 (safety failed modules included)

Mean degradation = 1.8-5.6%/year
Median degradation = 1.4-4%/year

Due to both intrinsic (materials) and extrinsic (design/manufacturing) issues

Hotspot modules degrade at higher rates (>3 times) (*Model G – Site 3*)



Summary: Model G (Site 3) – 1-axis Tracker – 12 years

- Average degradation rate = 0.5%/year for the BEST modules and 0.95%/year for ALL the modules (excluding the safety failed modules). On an average, the modules meet the typical 20/20 warranty expectations.

- Primary safety failure mode is the ribbon-ribbon solder bond failures/cracks leading to backskin burning.

- Primary degradation mode and reliability failure mode may potentially be attributed to thermo-mechanical solder bond fatigue (cell-ribbon and ribbon-ribbon) leading to series resistance increase.

- Average soiling loss of 1-axis tracker based Model G modules is 6.9%

- 7% of the modules qualify for the safety returns under the typical 20/20 warranty terms

- 42% of the modules qualify for the warranty claims under the typical 20/20 power warranty terms

- 51% of the modules are meeting the typical 20/20 power warranty terms

Presentation Outline

- Importance to stakeholders
  - Reliability evaluations in the field
- METRIC definitions (from users perspectives)
  - Safety failures, reliability failures and durability/degradation losses
- Application of definitions in field evaluation
  - Quantitative determination of safety failures, reliability failures and degradation rates of aged PV power plants
- Application of the defined metrics on data processing
  - Failure and degradation modes and rates
  - Distribution between safety failures, reliability failures and degradation rates
  - Soiling losses *(not presented here; see the poster for details)*
- Conclusions

Conclusion
(Hot-Dry Desert Climate)

- **Primary degradation/failure modes & Degradation rates of the four power plants presented in this work**

- **Linking degradation and failure metric definitions withrisk premium rate calculation**

Primary degradation/failure modes & Degradation rates of the four power plants presented in this work

Average degradation rate - BEST modules:

- 0.41%/year (Model G; 12 years; 1-axis)
- 0.50%/year (Model H; 4 years; 1-axis)
- 0.85%/year (Models BRO1 & BRO2; 16 years; 1-axis and horizontal)

Average degradation rate - ALL modules:

- 0.95%/year (Model G; 1-axis)
- 1.00%/year (Model H)
- 1.1%/year (Models BRO1 & BRO2)

Primary safety failure modes:

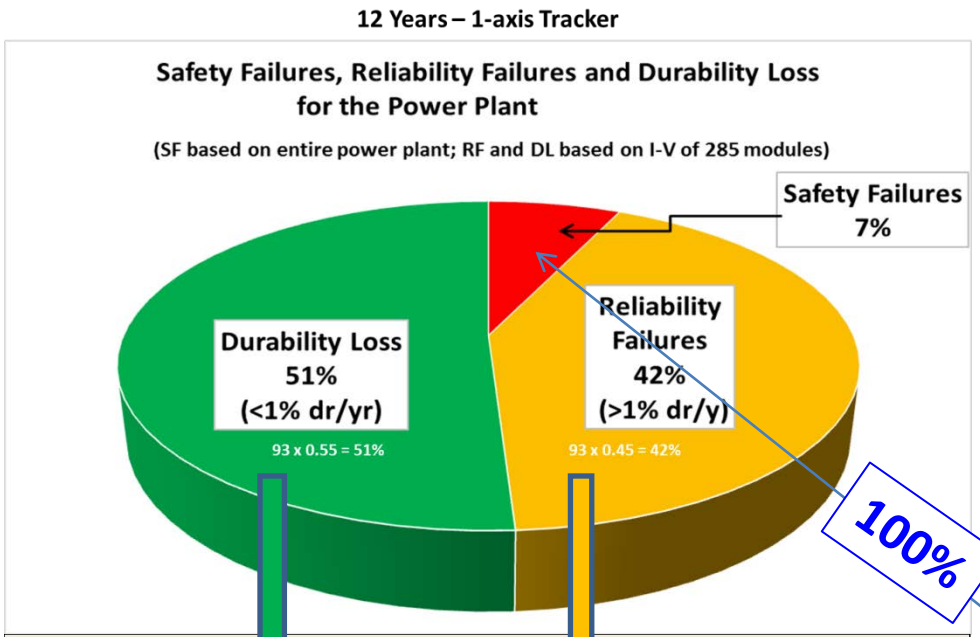
- **Backsheet delamination** (frameless modules; Models BRO1 & BRO2, and Model G)
- **Backsheet burning** (only Model G) and none (Model H)

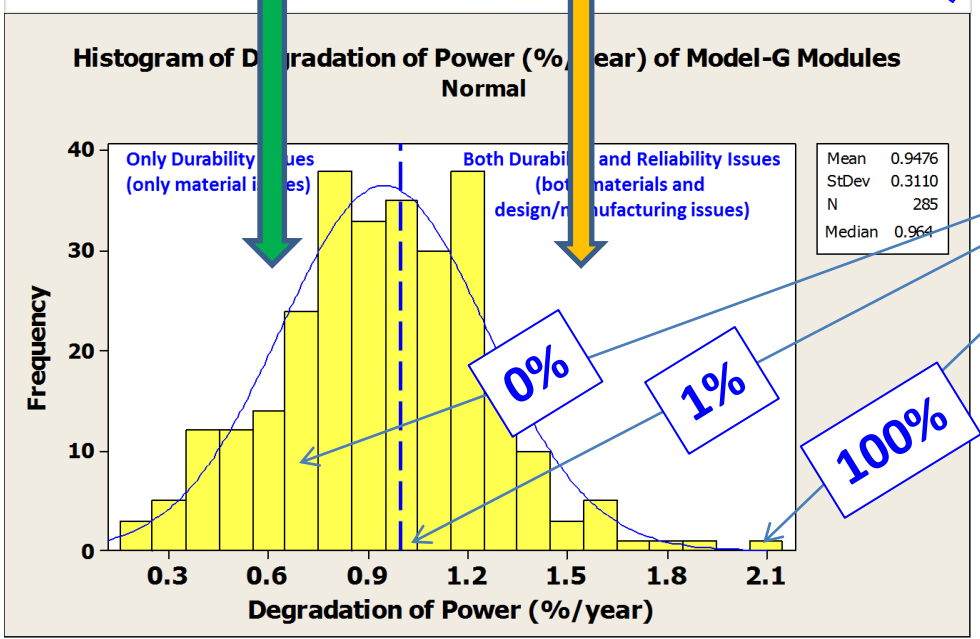
Primary degradation mode and reliability failure modes:

- Encapsulant **browning** leading to transmittance/current loss (only Models BRO1 & BRO2)
- Thermo-mechanical **solder bond fatigue** leading to series resistance increase (all models: G, BRO1, BRO2 & H).

Linking Failure and Durability Definitions with Risk Premium Rate Calculation

A Conceptual Representation





100%

0%

1%

100%

Interest Rate

=

Interest Rate @ Zero Risk

+

Risk Premium Rate

Thank You!

ARIZONA STATE UNIVERSITY
PHOTOVOLTAIC RELIABILITY LABORATORY

G. TamizhMani (Mani); manit@asu.edu

Appendix

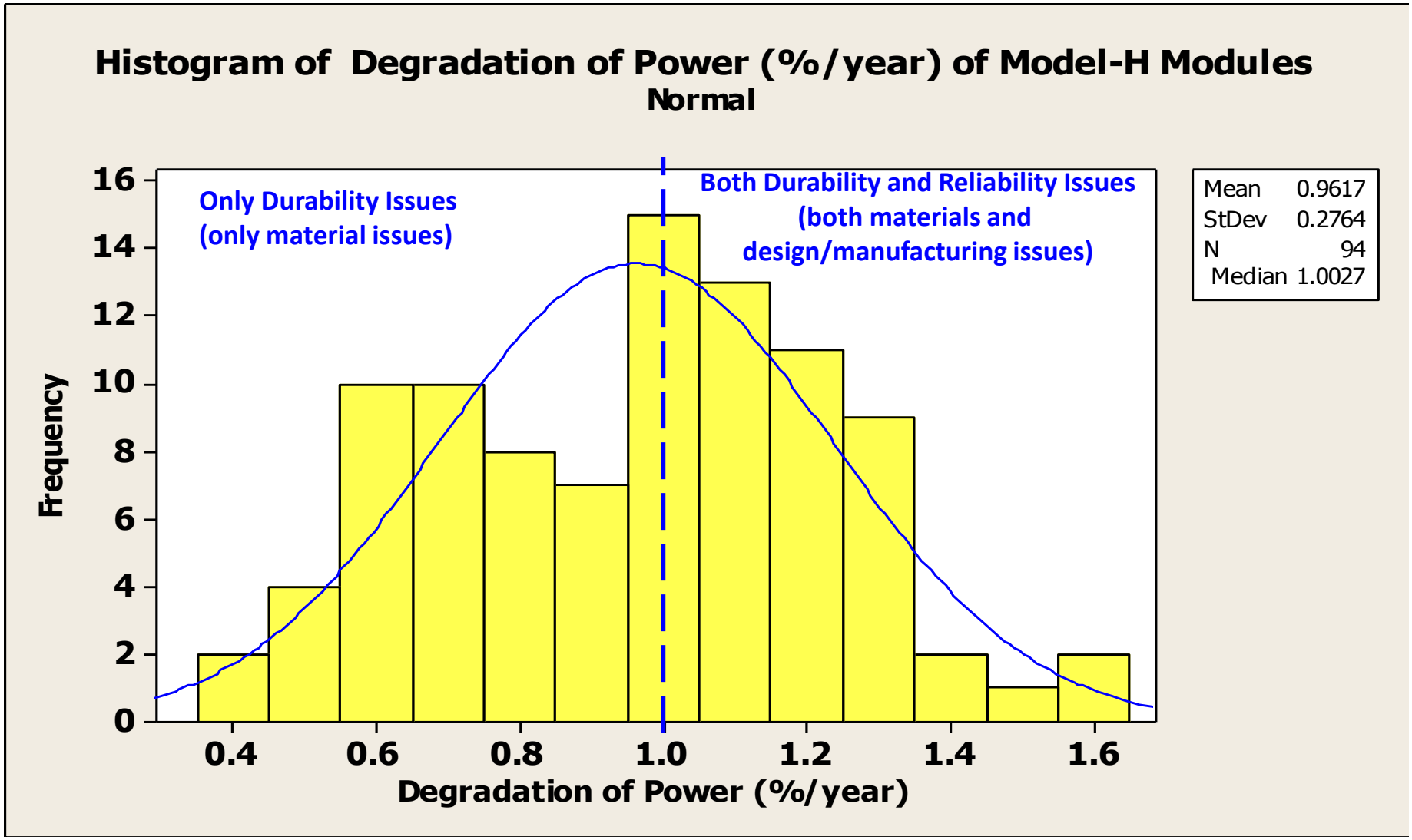
Model H

(Site 4C)

Mapping of Safety Failures (*Model H – Site 4C*) Framed - 4 Years – 1-axis Tracker

Distribution of Reliability Failures and Degradation Losses (*Model H – Site 4C*)

4 Years – 1-axis Tracker



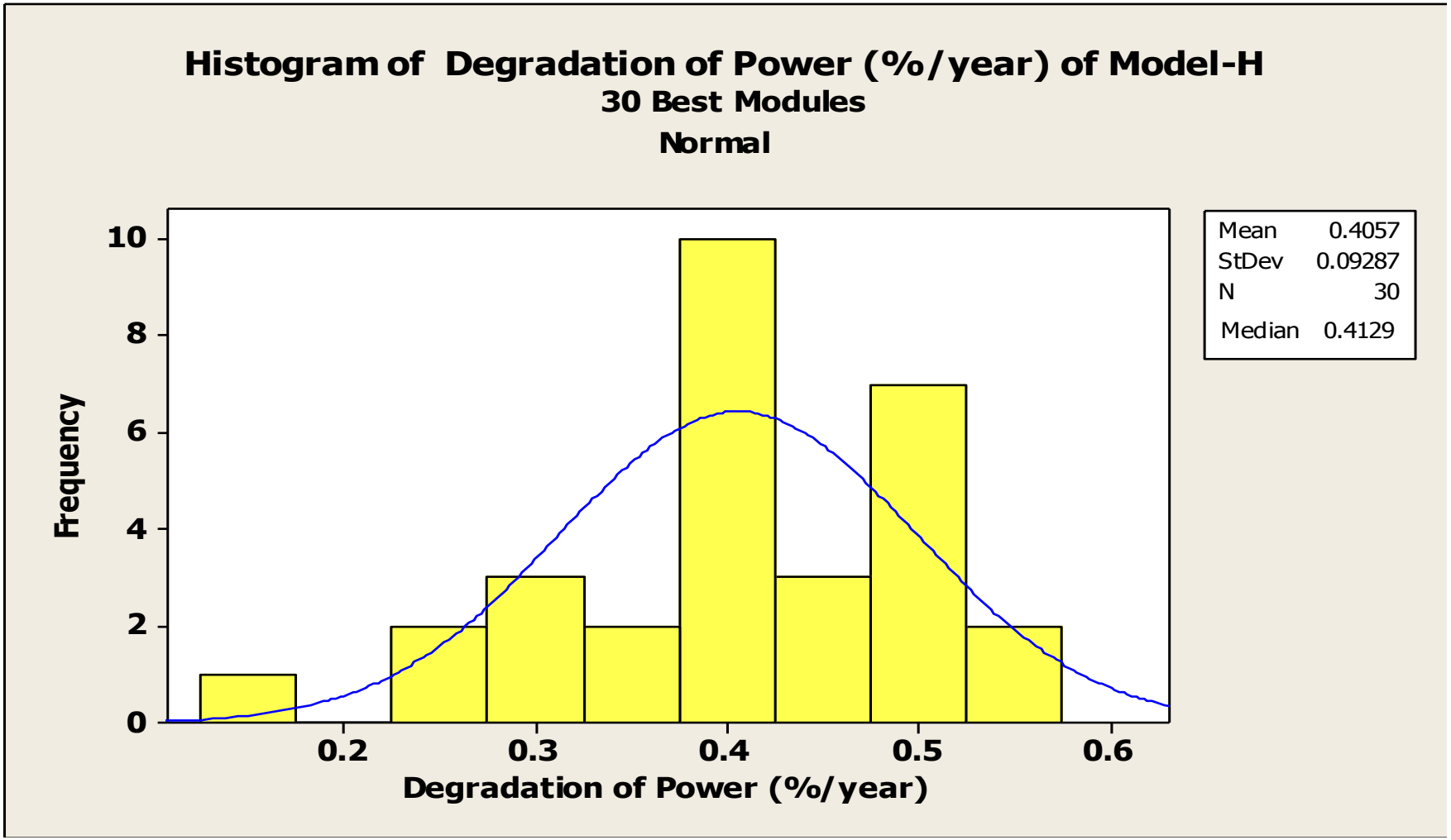
Total number of modules = 94 (safety failed modules excluded)

Mean degradation = 0.96%/year

Median degradation = 1.00%/year

Degradation Distribution of Best Modules (*Model H – Site 4C*)

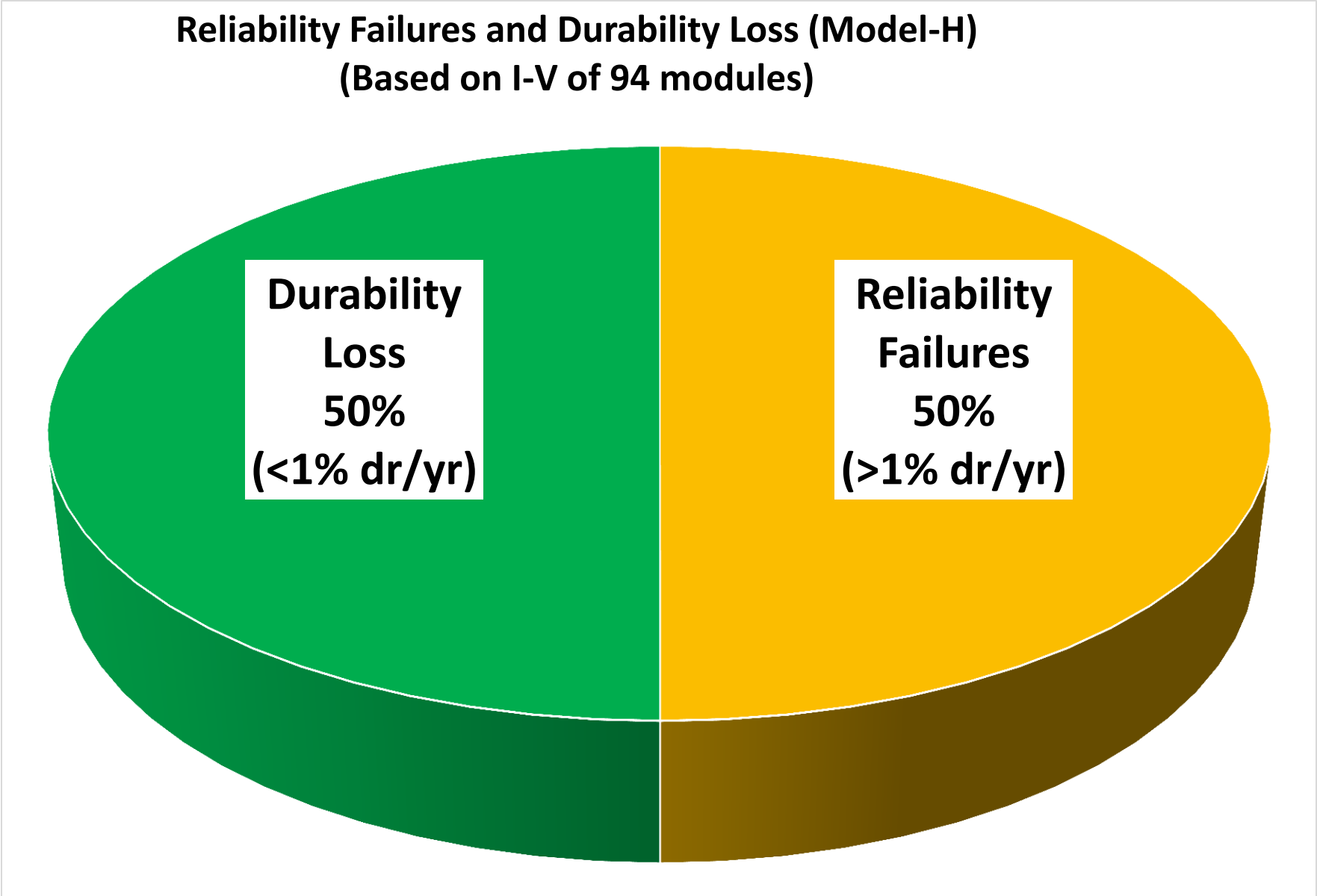
4 Years – 1-axis Tracker



Total number of BEST modules = 30 (safety failed modules excluded)
Mean degradation = 0.41%/year
Median degradation = 0.41%/year

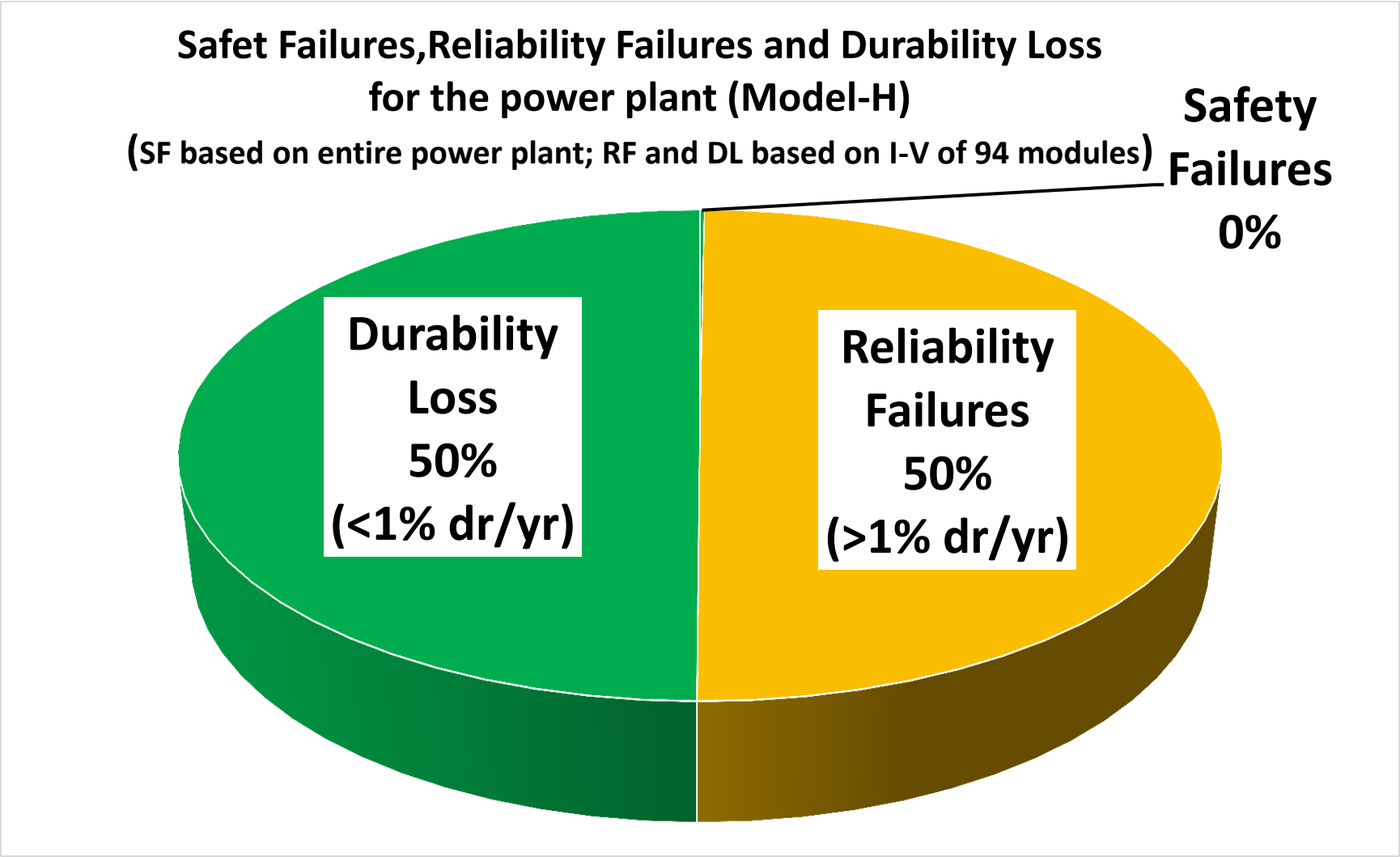
Distribution of Reliability Failures and Degradation Losses (*Model H – Site 4C*)

4 Years – 1-axis Tracker



Distribution of Safety Failures, Reliability Failures and Degradation Losses (*Model H – Site 4C*)

12 Years – 1-axis Tracker



Summary: Model H (Site 4C) – 1-axis Tracker

- Average degradation rate = 0.41%/year for the BEST modules and 1.00%/year for ALL the modules (excluding the safety failed modules). On an average, the modules meet the typical 20/20 warranty expectations.

- Practically, no safety failures have been detected.

- Primary degradation mode and reliability failure mode may potentially be attributed to thermo-mechanical solder bond fatigue (cell-ribbon and ribbon-ribbon) leading to series resistance increase.

- Average soiling loss of 1-axis tracker based model H modules is 5.5%

- 0% of the modules qualify for the safety returns under the typical 20/20 warranty terms

- 50% of the modules qualify for the warranty claims under the typical 20/20 power warranty terms

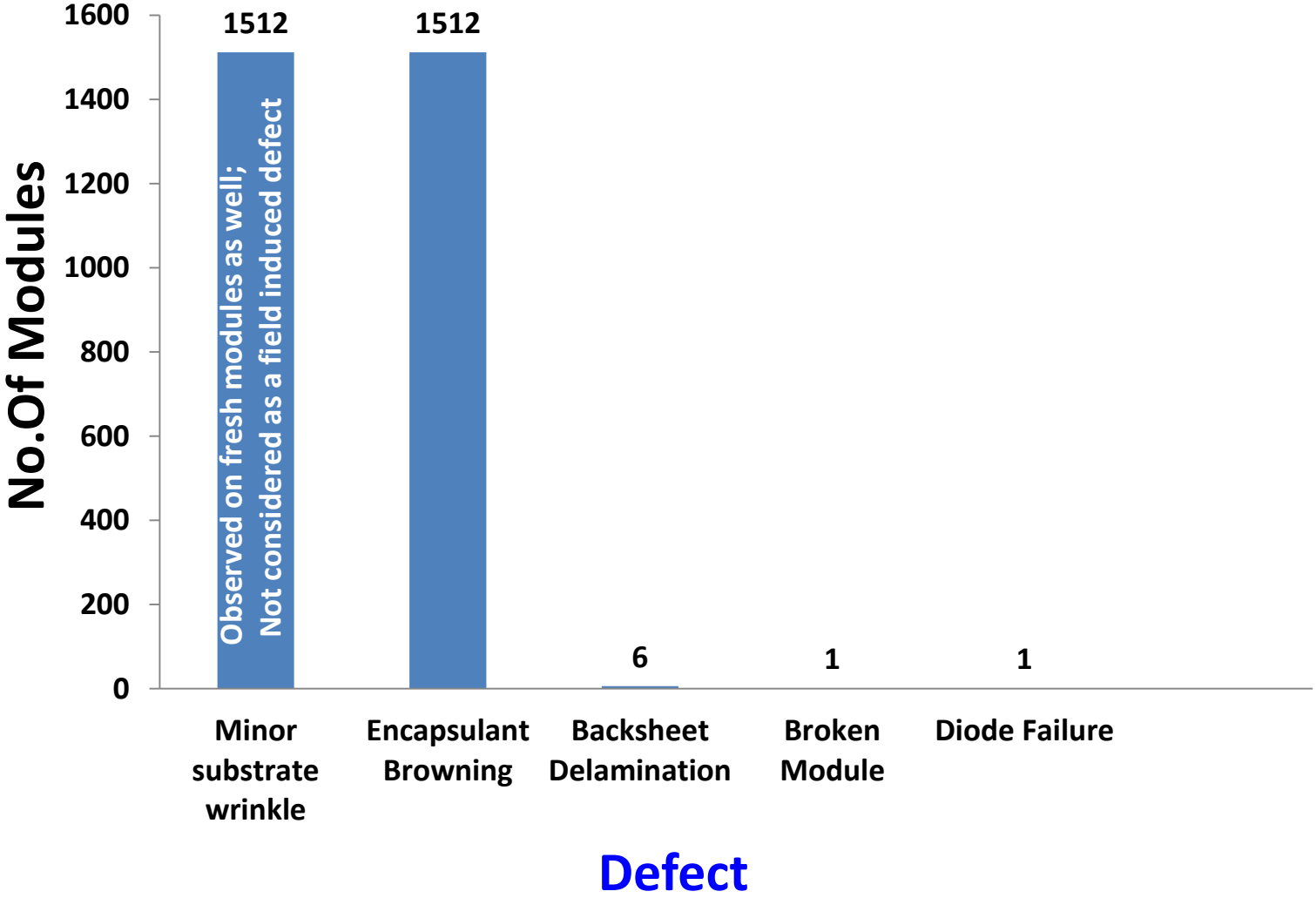
- 50% of the modules are meeting the typical 20/20 power warranty terms

Model BRO1 & BRO2

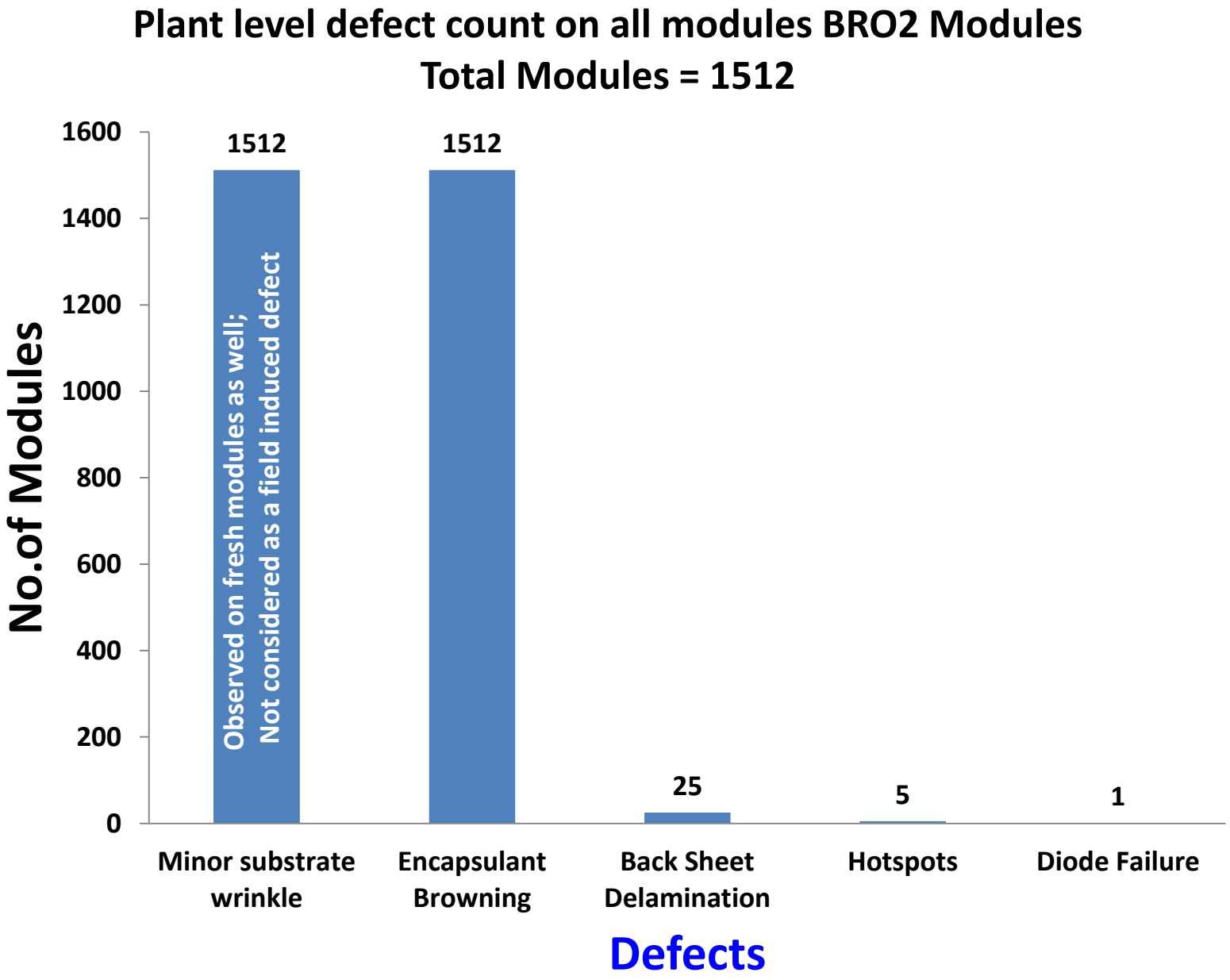
(Site 4A & 4B)

Defects Including Safety Failures (*Model BRO1 – Site 3*)

Plant level defect count on all BRO 1 modules
Total Modules = 1512



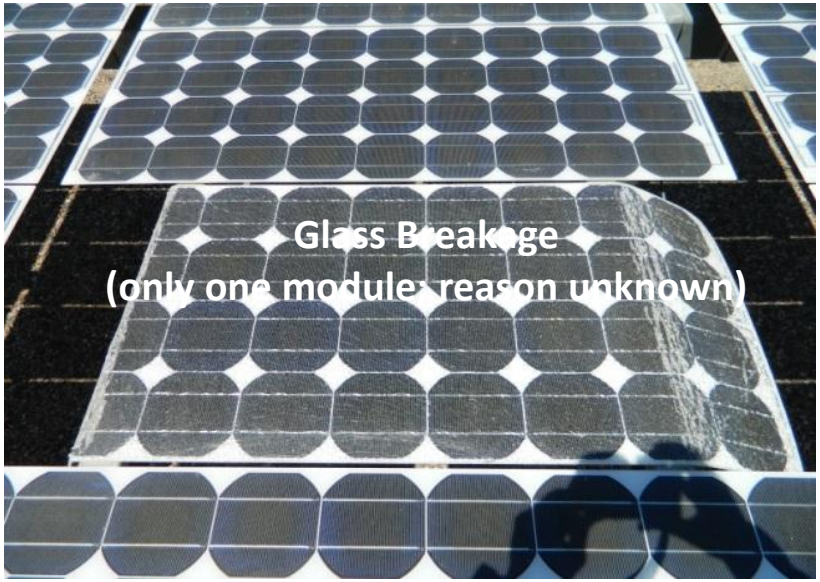
Defects Including Safety Failures (*Model BRO2 – Site 3*)

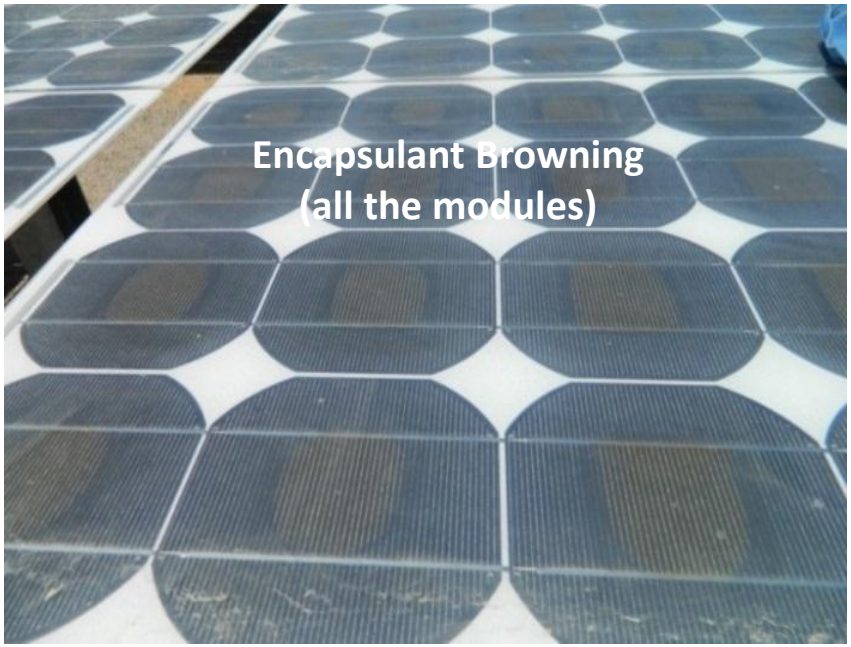


Safety Failures and Reliability Failures (*Models BRO1 & BRO2– Site 4A & 4B*)

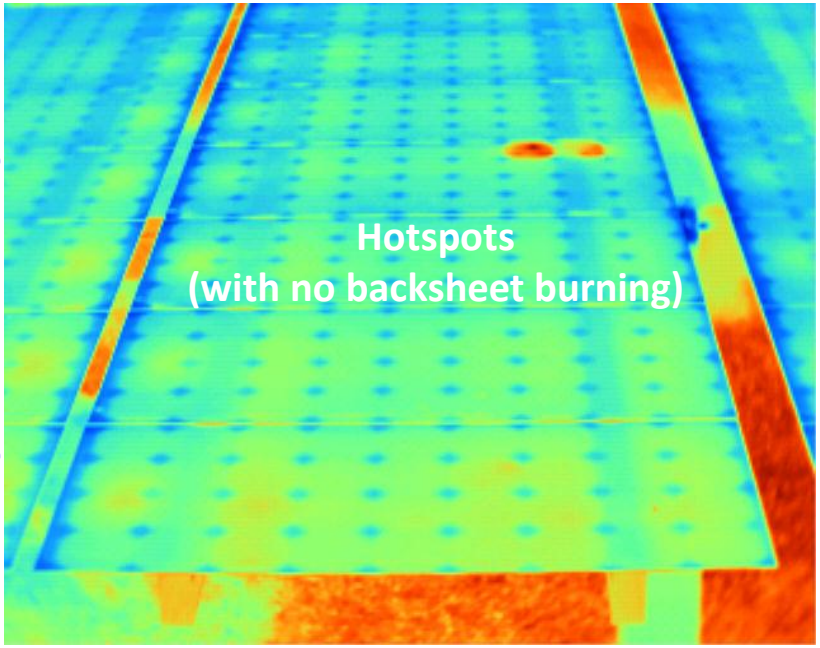
16 Years (7 years – 1-axis; 9 years – horizontal tilt)

Safety Issues





Durability and Reliability Issues

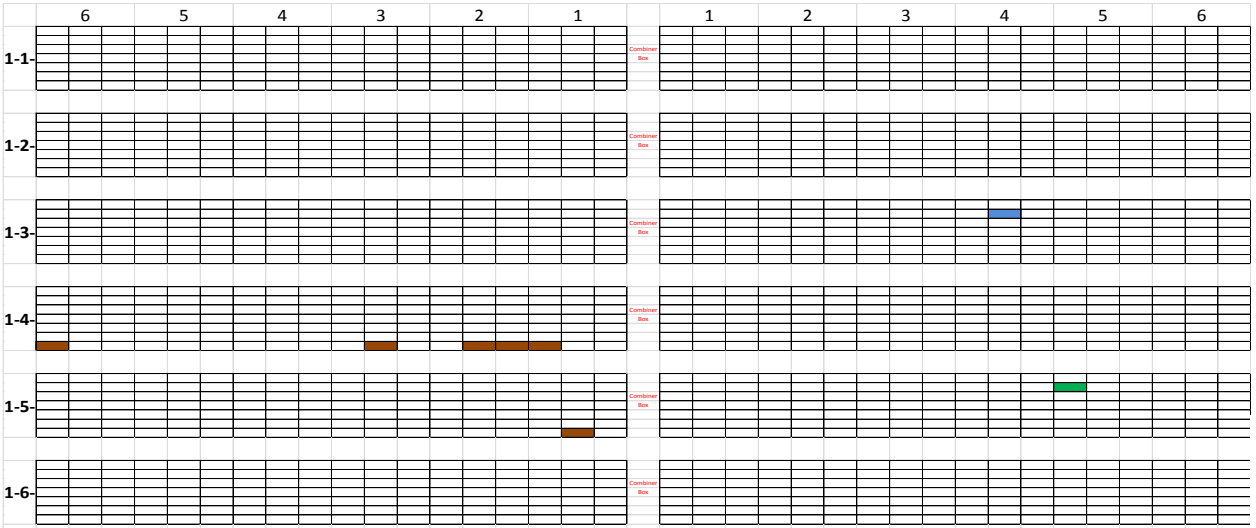


Mapping of Safety Failures (*Models BRO1 & BRO2 – Site 4A & 4B*)

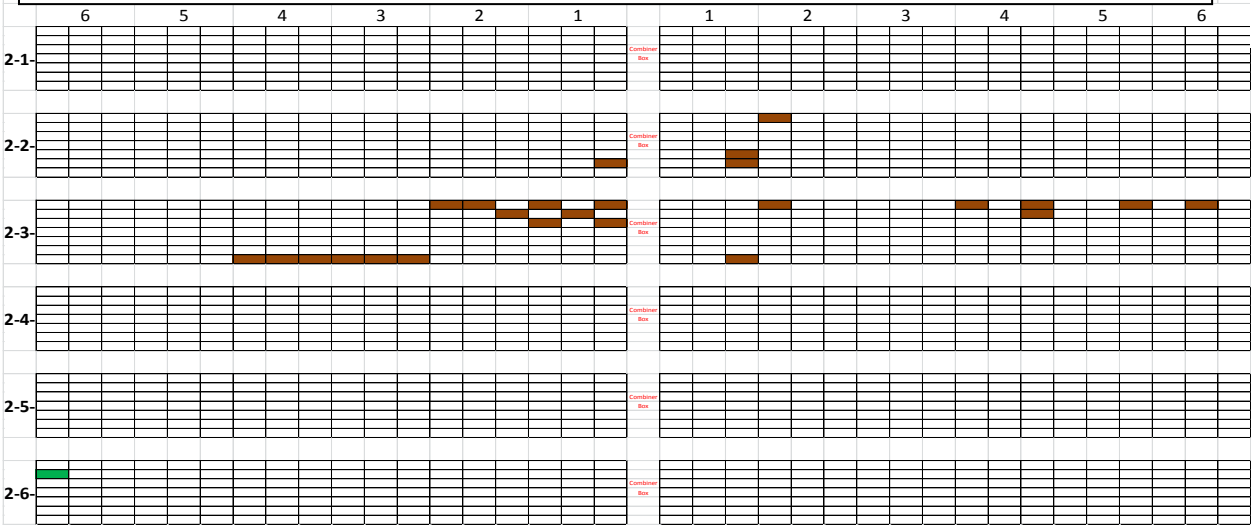
Framed - 16 Years

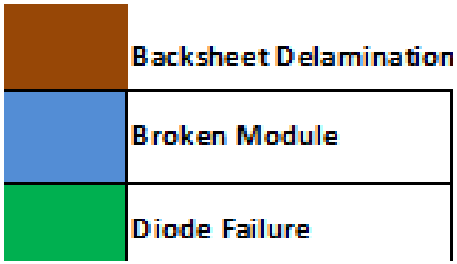
(7 years 1- axis; 9 years horizontal)

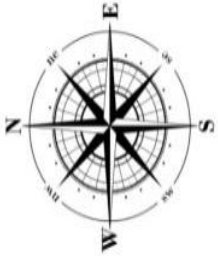
BRO1: Safety failure rate at the plant level = 8/1512 = 0.5%



BRO2: Safety failure rate at the plant level = 26/1512 = 1.7%

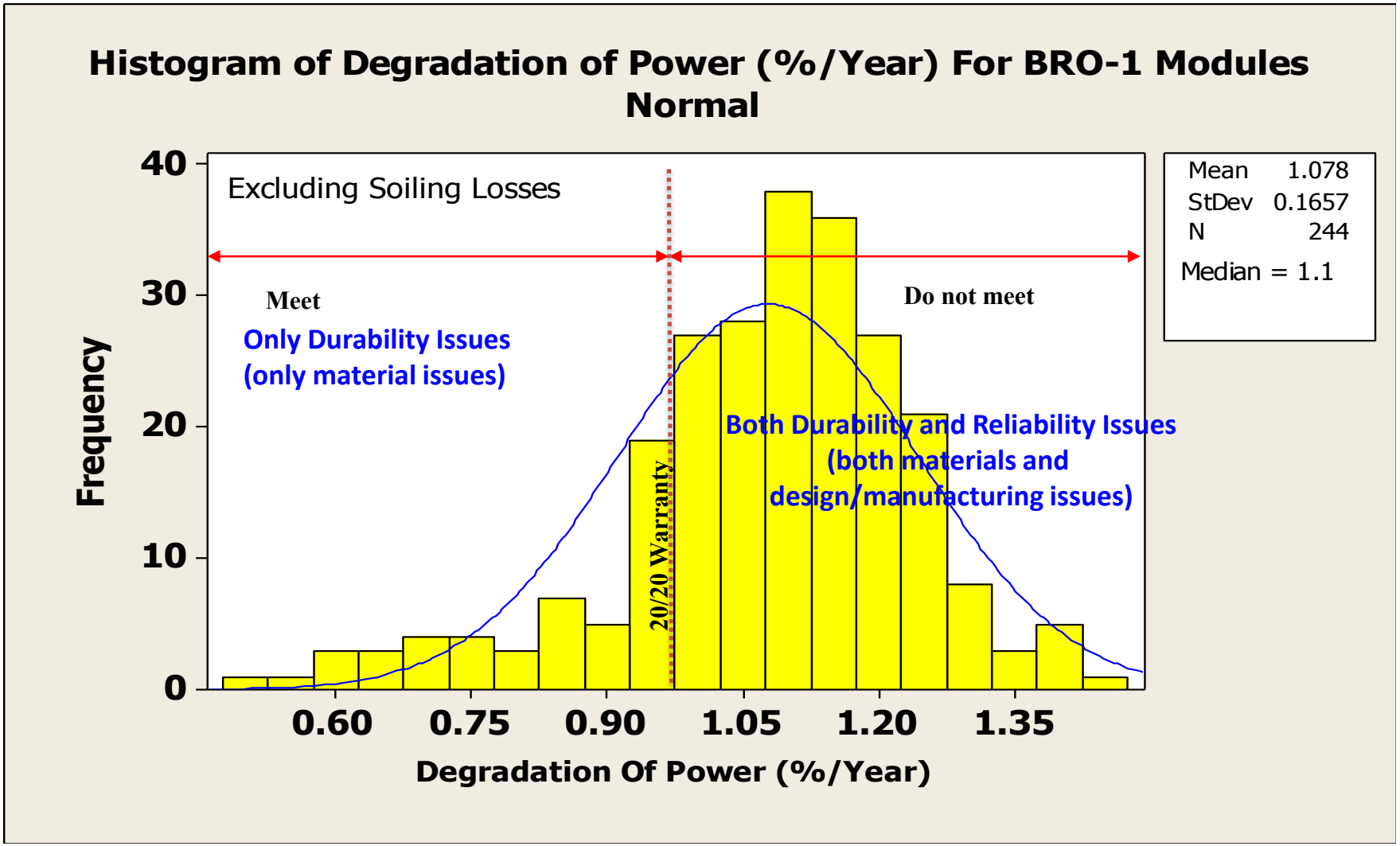






Distribution of Reliability Failures and Degradation Losses (*Model BRO1 – Site 4A*)

16 Years – 1-axis tracker for first 7 years and horizontal tilt for 9 years



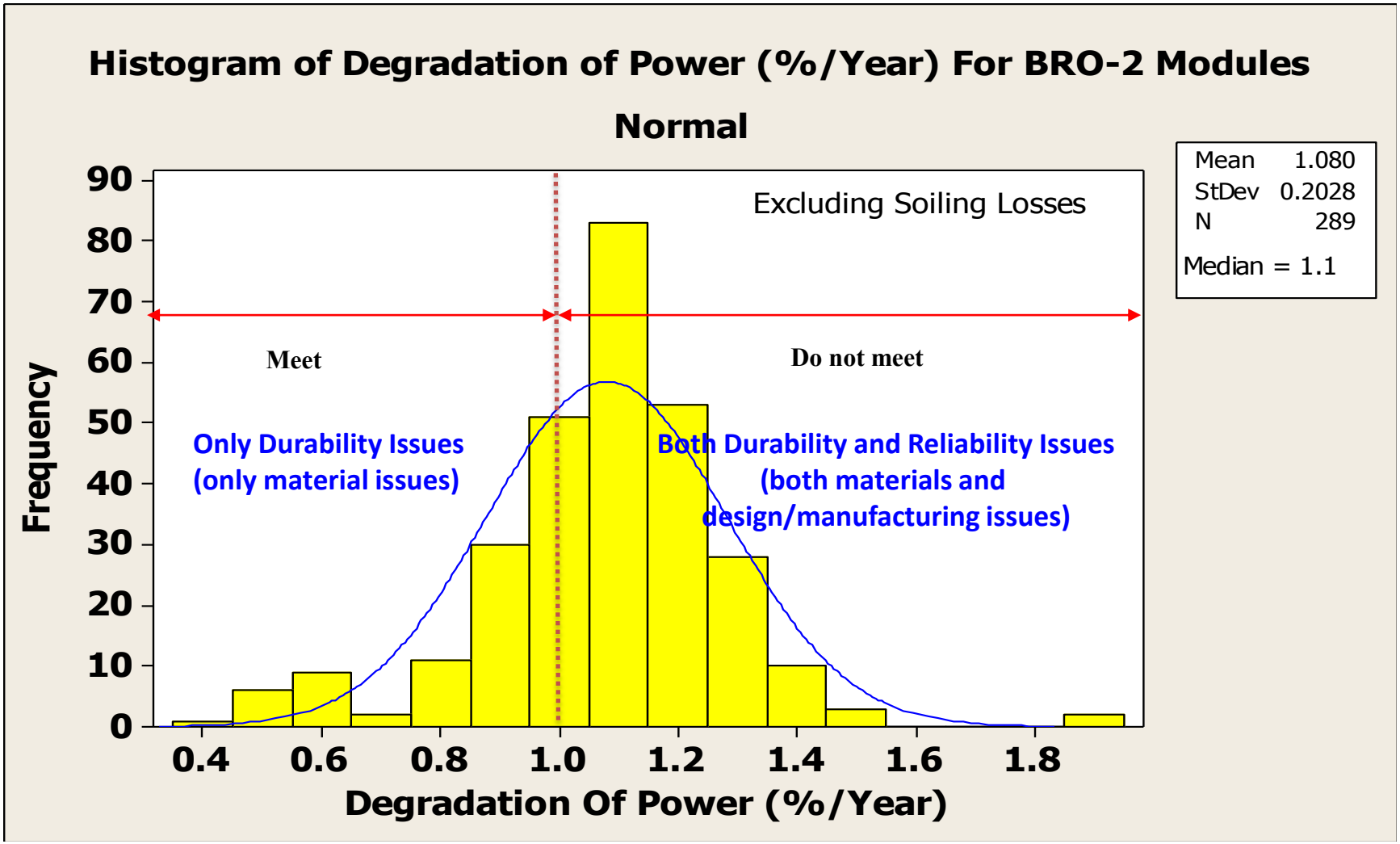
Total number of modules = 244 (safety failed modules excluded)

Mean degradation = 1.1%/year

Median degradation = 1.1%/year

Distribution of Reliability Failures and Degradation Losses (*Model BRO2 – Site 4B*)

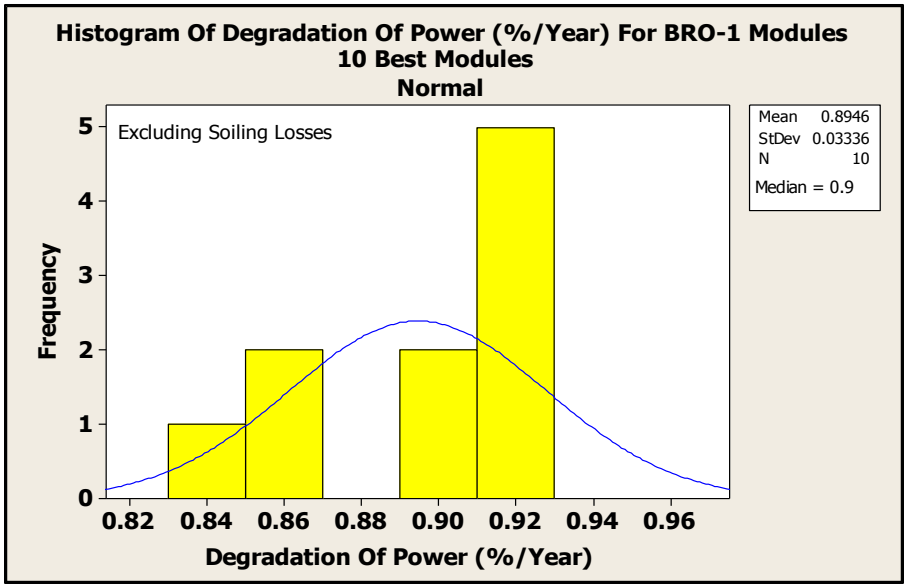
16 Years – 1-axis tracker for first 7 years and horizontal tilt for 9 years

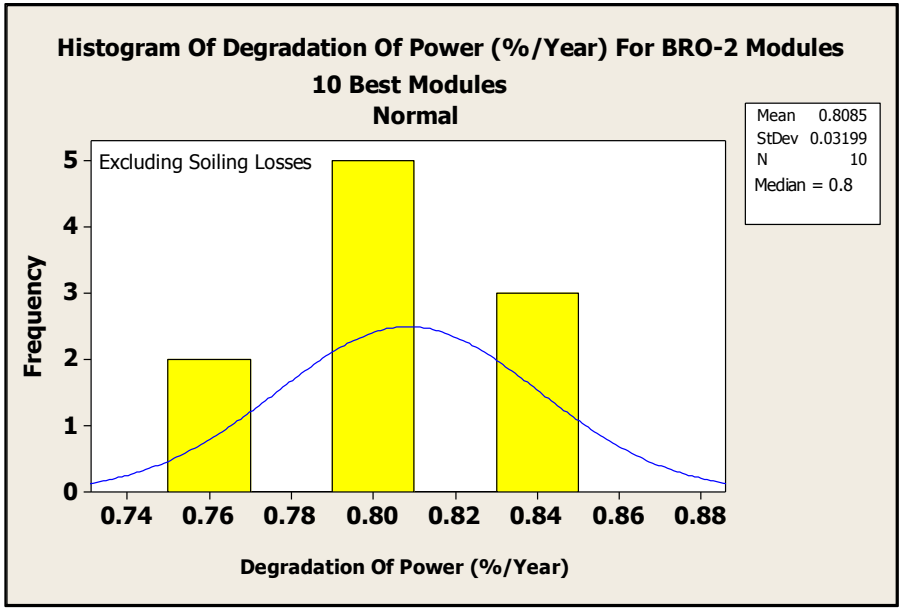


Total number of modules = 289 (safety failed modules excluded)
Mean degradation = 1.1%/year
Median degradation = 1.1%/year

Degradation Distribution of Best Modules (*Models BRO1 &BRO2 – Site 4A & 4B*)

16 Years – 1-axis Tracker for 7 years and horizontal tilt for 9 years

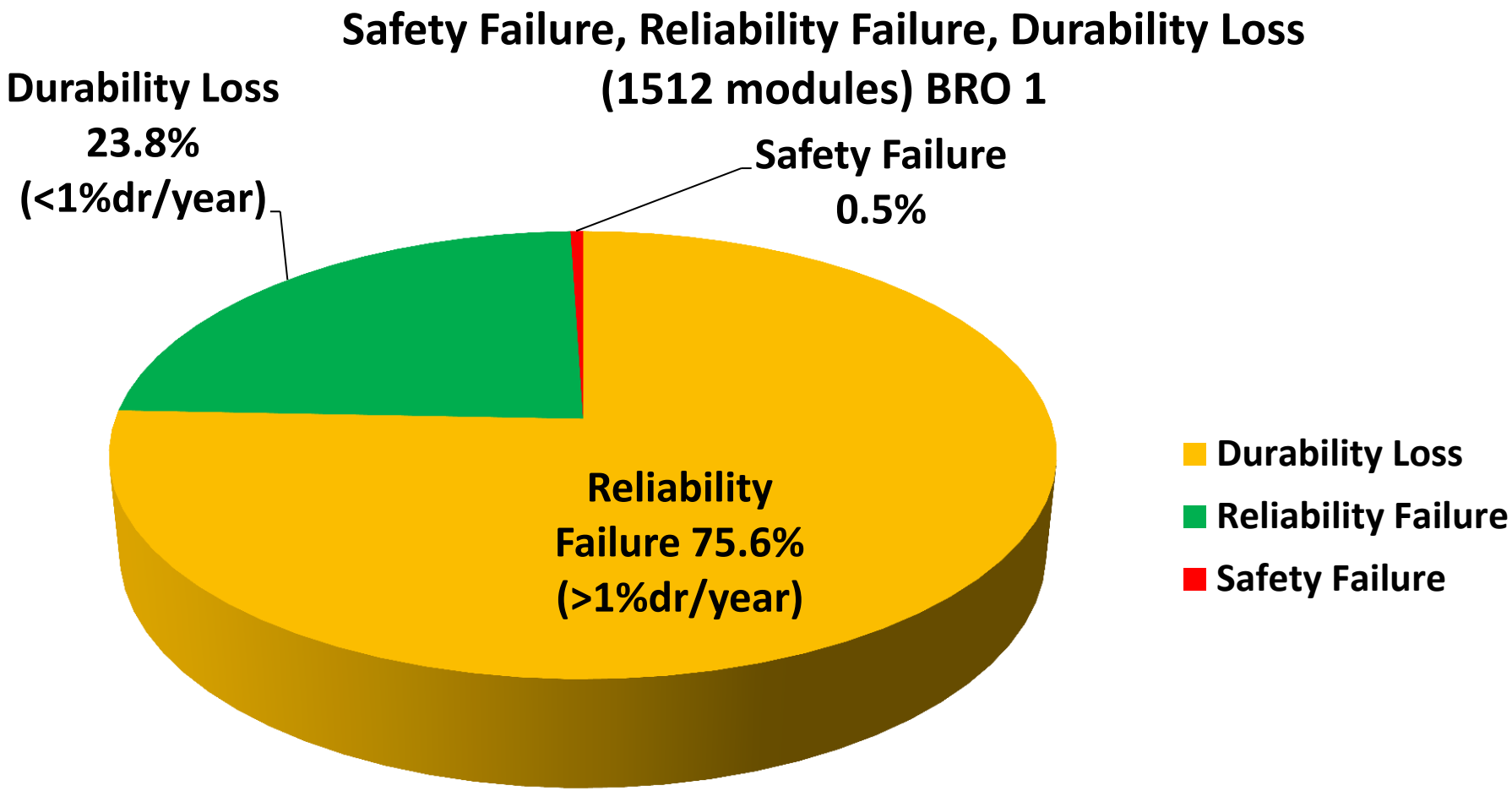




Total number of BEST modules = 20 (safety failed modules excluded)
Mean degradation = 0.8-0.9%/year
Median degradation = 0.8-0.9%/year

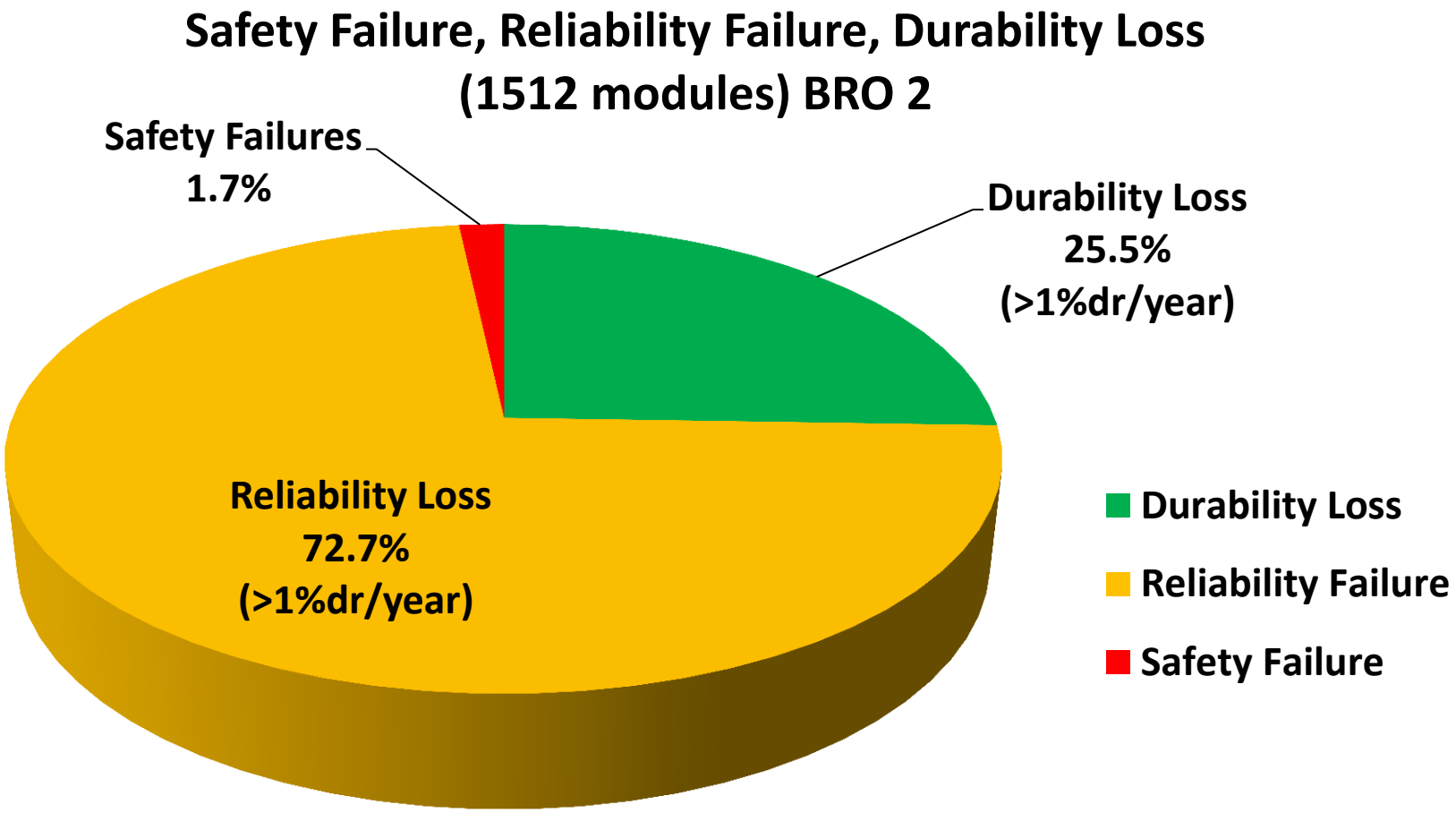
Distribution of Reliability Failures and Degradation Losses (*Model BRO1 – Site 4A*)

16 Years – 1-axis Tracker for 7 years and horizontal tilt for 9 years

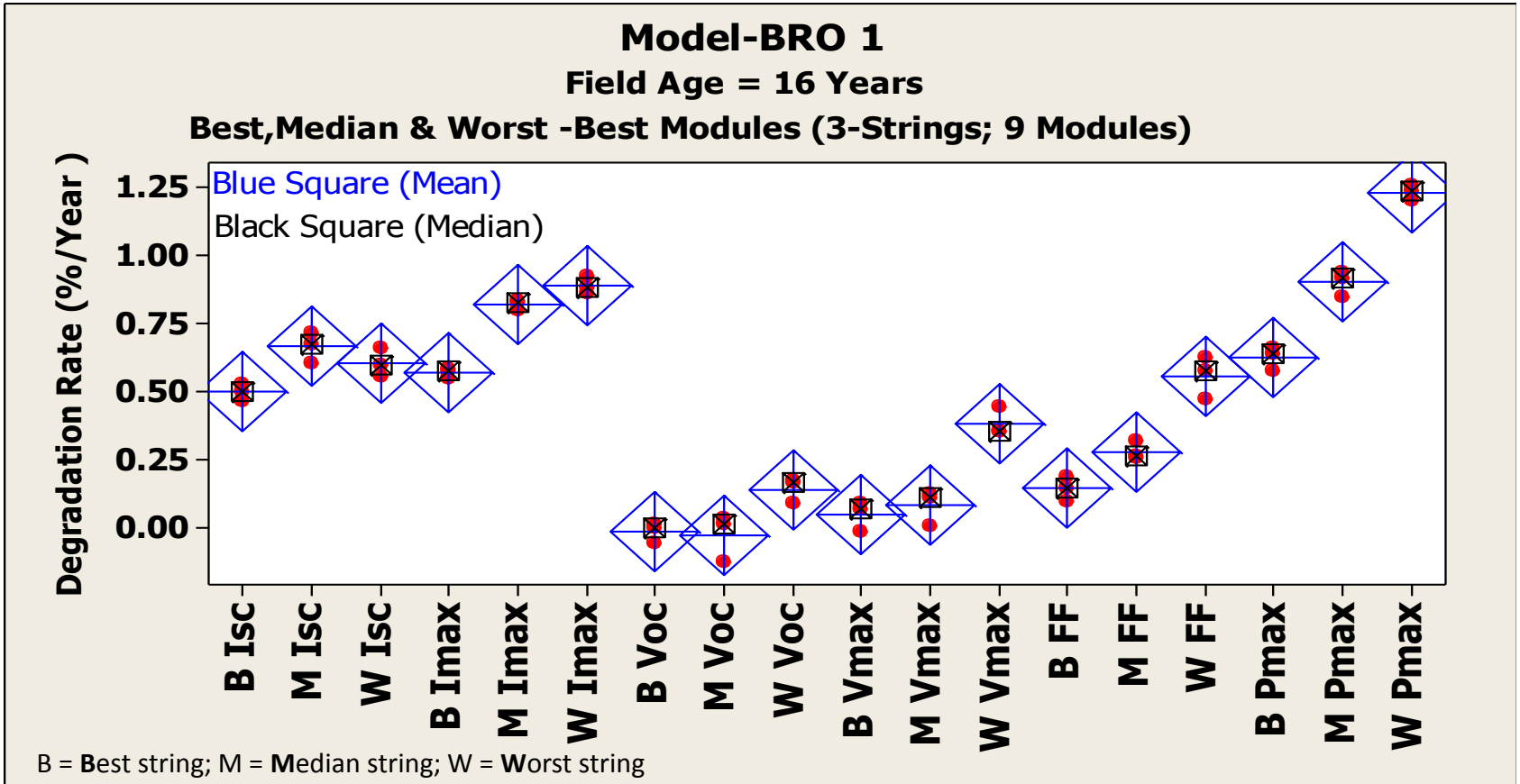


Distribution of Reliability Failures and Degradation Losses (*Model BRO1 – Site 4A*)

16 Years – 1-axis Tracker for 7 years and horizontal tilt for 9 years



Best Modules Experienced Only Durability Issues (*Model BRO1*)



Primary degradation modes:
Encapsulant browning & solder bond degradation

Pmax loss → Isc loss (encapsulant browning) & FF loss (solder bond degradation)

BEST modules = 9 (safety failed modules excluded)
Mean degradation = 0.85%/year

Summary: Models BRO1 & BRO2 (Sites 4A and 4B) – 16 years (7 years on 1-axis tracker and 9 years horizontal tilt)

- Average degradation rate = 0.85%/year for the BEST modules and 1.1%/year for ALL the modules (excluding the safety failed modules). On an average, the modules do not meet the typical 20/20 warranty expectations (due to two degradation modes: solder bonds and browning).

- Primary safety failure mode is the backsheet delamination though it is small (less than 1.7%)

- Primary degradation mode and reliability failure mode may potentially be attributed to encapsulant browning leading to transmittance/current loss and thermo-mechanical solder bond fatigue (cell-ribbon and ribbon-ribbon) leading to series resistance increase.

- Average soiling loss of horizontal tilt based modules is 11.1% (nearly double vs. 1-axis)

- 0.5-1.7% of the modules qualify for the safety returns under the typical 20/20 warranty terms

- 73-76% of the modules qualify for the warranty claims under the typical 20/20 power warranty terms

- 24-26% of the modules are meeting the typical 20/20 power warranty terms

Overall Conclusions

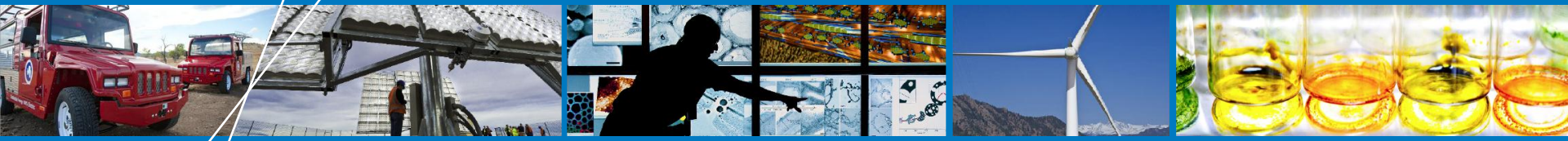
(for all four power plants)

Overall Conclusions for All the Modules – Hot Dry Desert Climates

- Metric definitions for safety failures, reliability failures and degradation rates are provided
- Metric definitions were applied on the power plant evaluations
- Metric results obtained in this work can be used to perform bankability calculations
- Degradation rate - BEST modules: Average Degradation = 0.41%/year (Model G; 12 years; 1-axis), 0.50%/year (Model H; 4 years; 1-axis) and 0.85%/year (Models BRO1 & BRO2; 16 years; 1-axis and horizontal)
- Degradation rate - ALL modules: Average Degradation = 0.95%/year (Model G), 1.00%/year (Model H) and 1.1%/year (Models BRO1 & BRO2)
- Safety failure modes: Primary modes are backsheet delamination (frameless modules; Models BRO1 & BRO2, and Model G), backsheet burning (only Model G) and none (Model H)
- Degradation mode and reliability failure modes: Primary modes are encapsulant browning leading to transmittance/current loss (only Models BRO1 & BRO2) and thermo-mechanical solder bond fatigue leading to series resistance increase (all models: G, BRO1, BRO2 & H).
- Soiling loss: Average soiling loss is 5.5% (Model H; 1-axis; urban surrounding), 6.9% (Model G; 1-axis; rural surrounding) and 11.1% (Models BRO1 & BRO2; horizontal; urban surrounding)

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Recent Photovoltaic Performance Data in the USA



Golden, CO

Dirk Jordan, Sarah Kurtz

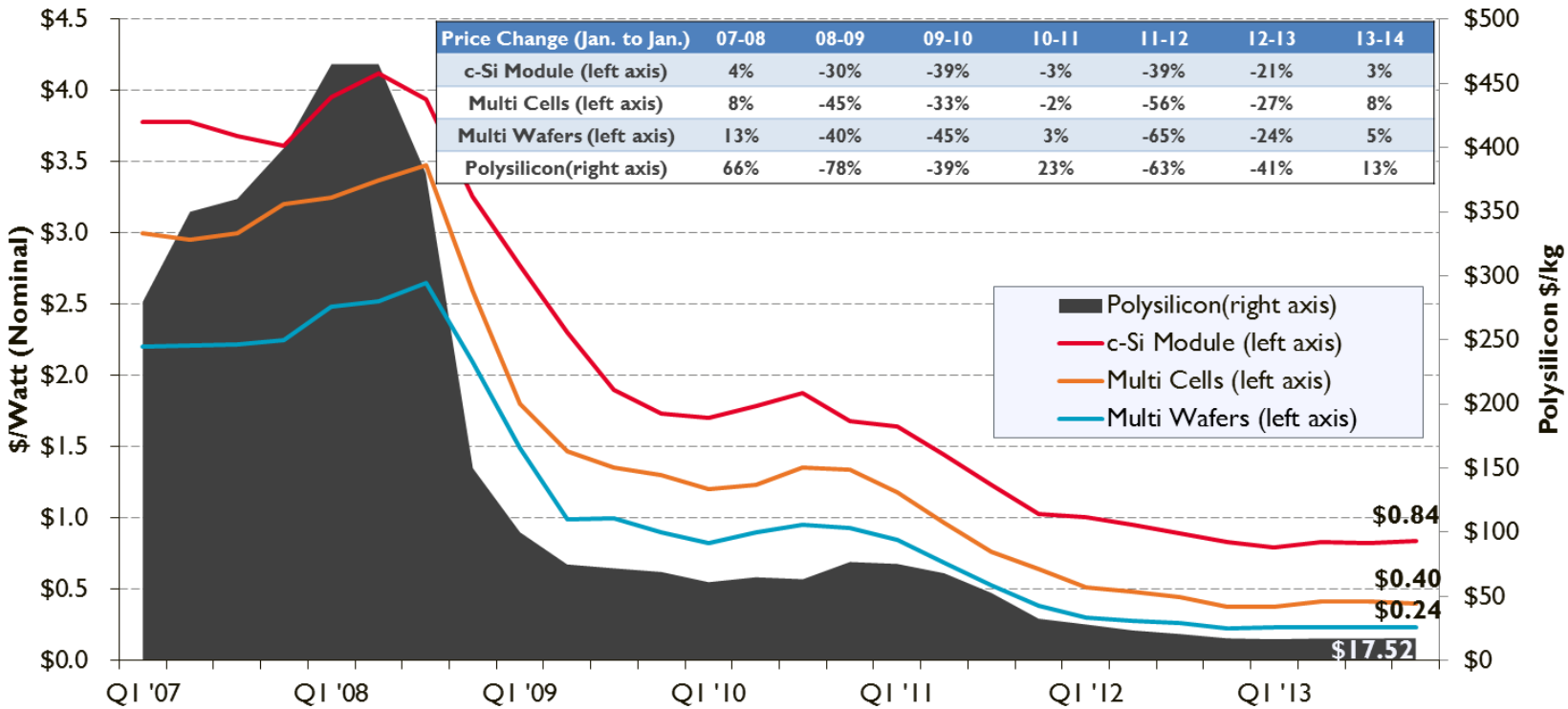
2/25/2014

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

- Introduction
  - American Recovery & Reinvestment Act data
  - Performance relative to predicted
  - Reliability categories
  - First geographic trends
  - Impact of reliability categories
- Conclusion

Has the recent PV price decline led to reliability issues?



Price Change (Jan. to Jan.)	07-08	08-09	09-10	10-11	11-12	12-13	13-14
c-Si Module (left axis)	4%	-30%	-39%	-3%	-39%	-21%	3%
Multi Cells (left axis)	8%	-45%	-33%	-2%	-56%	-27%	8%
Multi Wafers (left axis)	13%	-40%	-45%	3%	-65%	-24%	5%
Polysilicon(right axis)	66%	-78%	-39%	23%	-63%	-41%	13%

D. Feldman et al., Q3 2013 /Q4 2013 Solar Industry Update, 2014 Edition

Recent Negative Headlines about Solar Industry

Quality issues threaten to give solar a black eye, PVTECH , F.Carus, 15 January 2013

How Bad Is PV Panel Performance?, IEEE Spectrum, B. Sweet, 30 May 2013

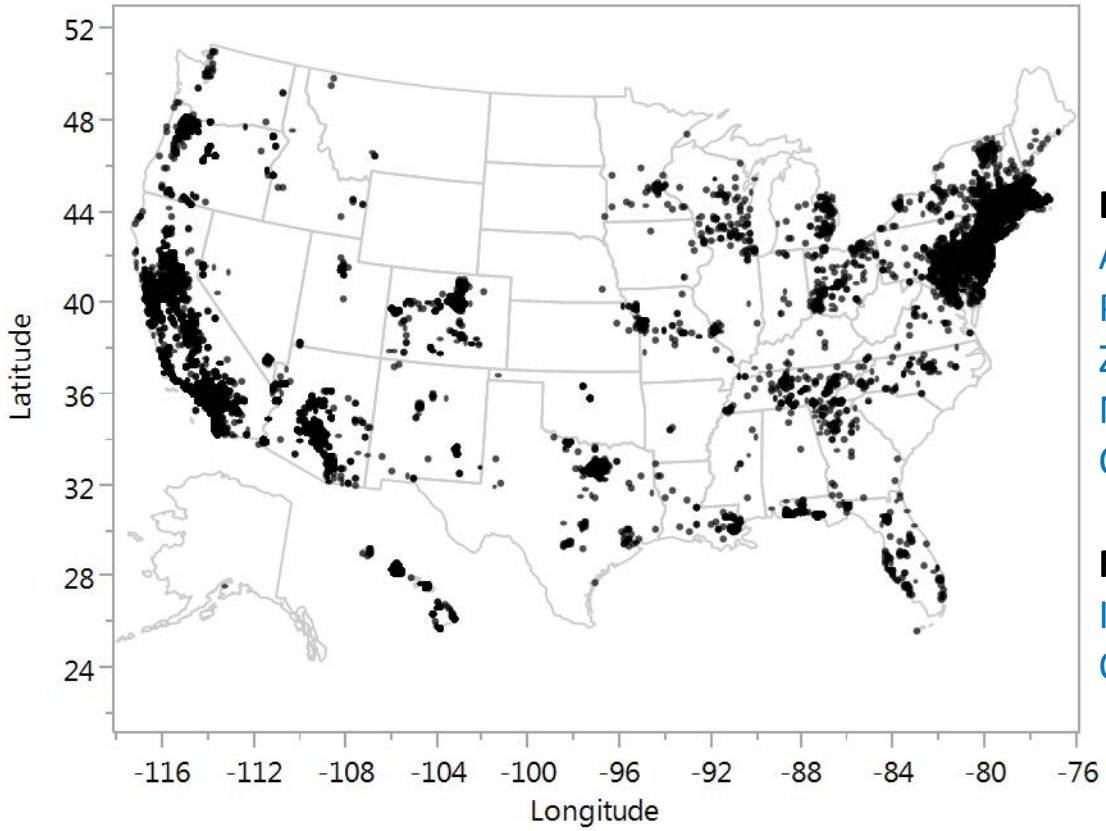
Solar Industry Anxious Over Defective Panels, New York Times, T. Woody, May 28, 2013

→ Documenting field performance data, especially on a large scale

Geographic Distribution of Systems

American Recovery & Reinvestment Act, Section 1603

50,000 Systems
1.7 Gwatts capacity
Up to 4 years of data



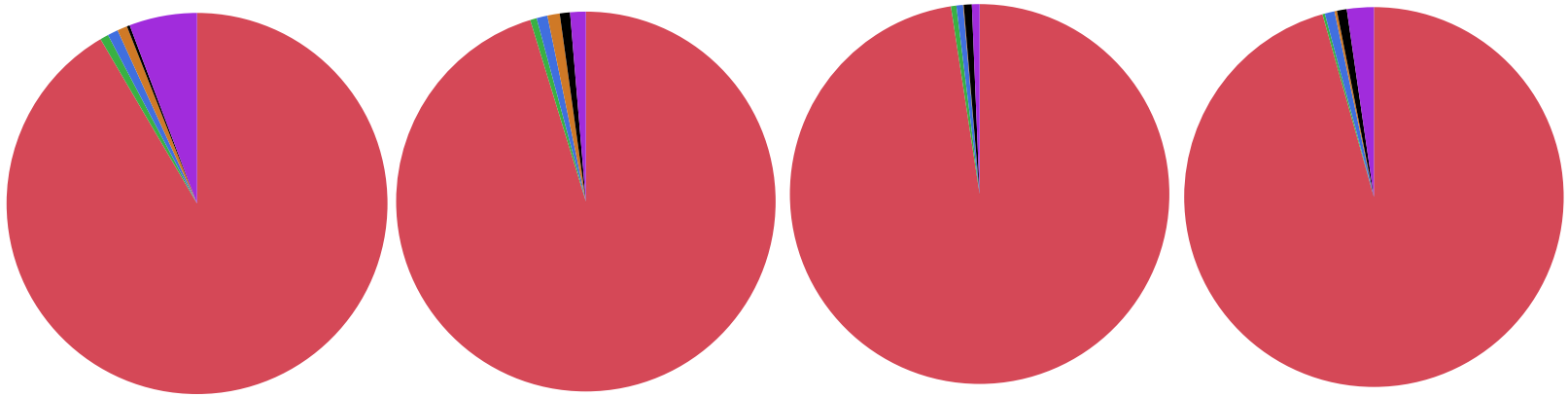
Data available:
AC production,
Predicted AC production
Zip code location
Nameplate
Comments

Not available:
Insolation
Orientation

Data filtering rules:

- Nameplate=production year1,2,3,4 → reject production years
- Predicted capacity factor: Predicted AC energy/(24*365*DC rating)*100= 3-40%
- Year1 production = Year2 production → reject year2 entry
- Annual production = predicted production → reject

No Evidence of Massive failure

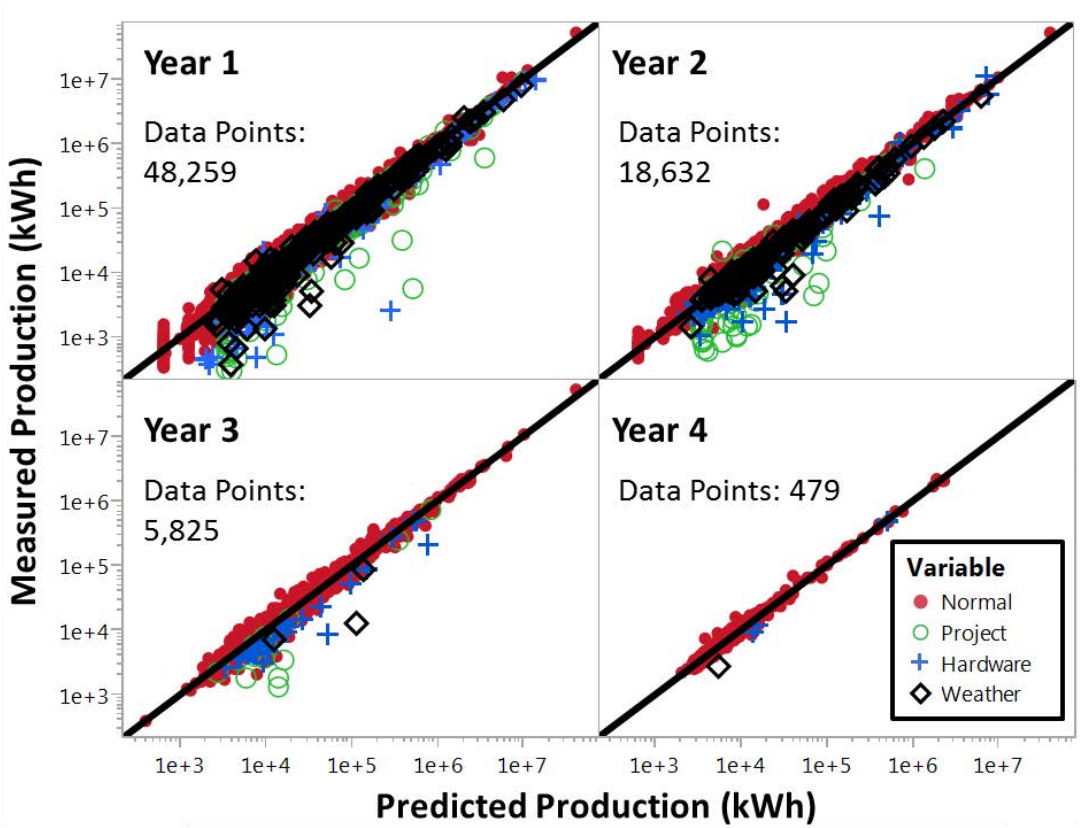


Year of Operation:	Year 1	Year 2	Year 3	Year 4
Data Points:	48,259	18,632	5,825	479
Normal	91.5	95.3	97.6	95.8
Project	0.7	0.6	0.5	0
Weather	0.8	1.0	0.1	0.2
Data Collection	5.8	1.3	0.7	2.3
Hardware	0.9	0.9	0.6	0.8
No information	0.2	0.9	0.7	0.8

Project/Site: Delay, grid interconnection, construction etc.
Weather: Snow, soiling, lightning, hurricanes etc.
Data Collection: Data acquisition, less than a year of data, etc. (not performance related)
Hardware: Inverter, module, breaker, fuses etc.

Most systems produce as expected

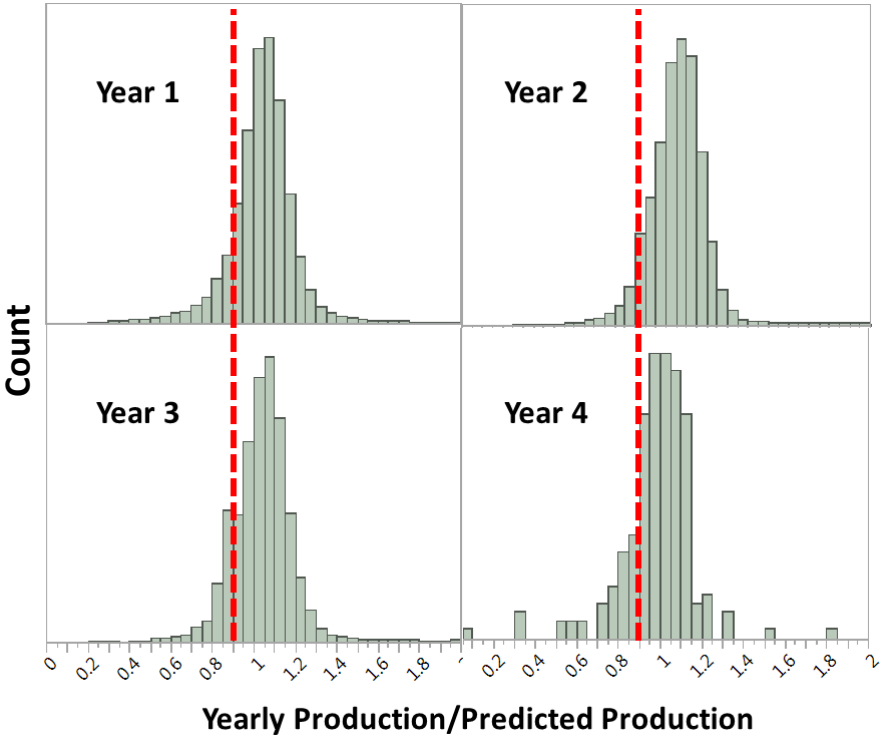
Measured vs. predicted production for all operation years



Project issues data points tend to be farther away from unity line →
They don't occur that often (previous slide) but if they do they tend to have larger impact

90% of normal data produce at least 90% of predicted

Normal data



Ratio: measured production/predicted production

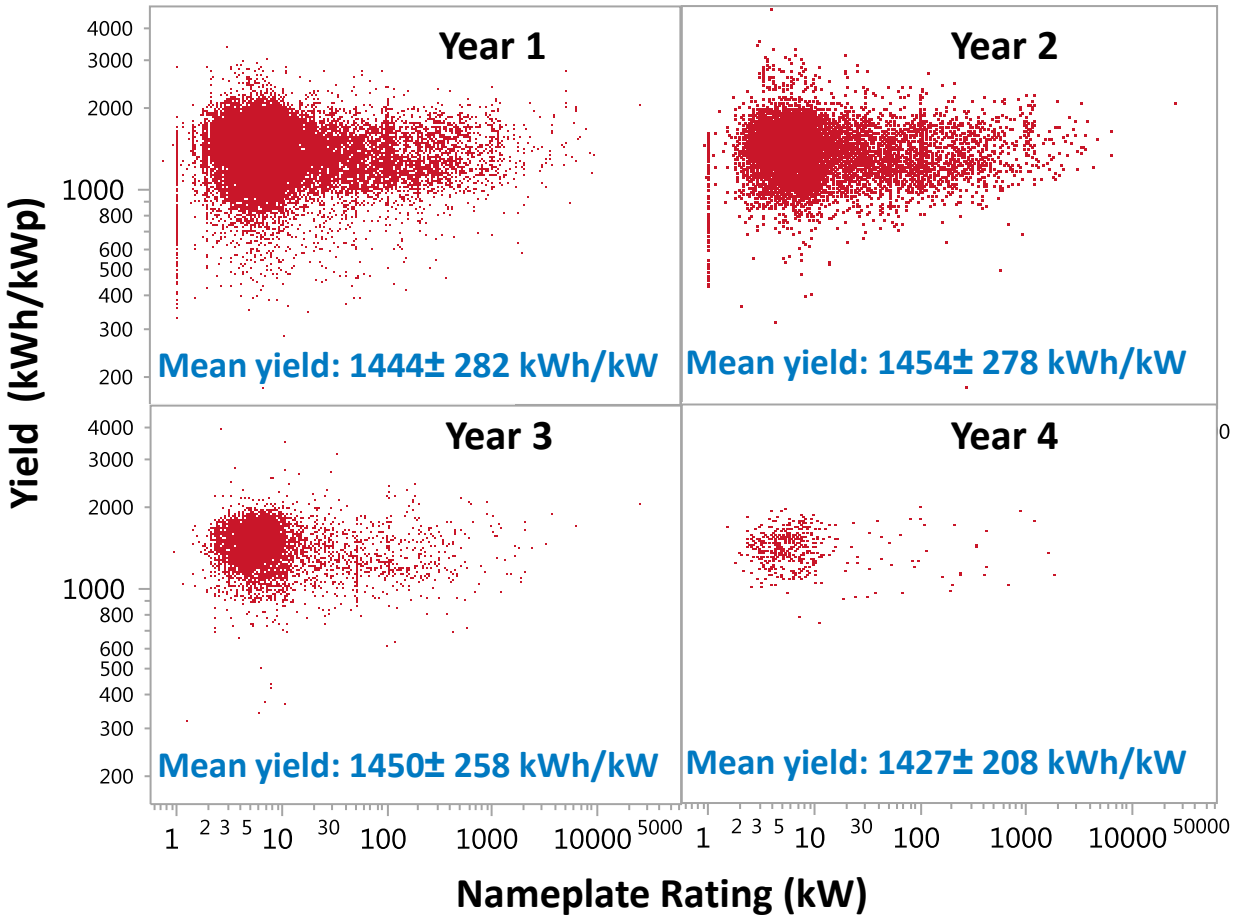
Median / Stdev	Year1	Year2	Year3	Year4
Normal	1.05 ± 0.14	1.06 ± 0.14	1.04 ± 0.14	1.03 ± 0.13
Project	0.84 ± 0.24	0.61 ± 0.37	0.29 ± 0.36	-
Data Collection	0.90 ± 0.41	0.76 ± 0.35	0.71 ± 0.21	0.65 ± 0.19*
Hardware	0.86 ± 0.23	0.77 ± 0.24	0.74 ± 0.18	0.74 ± 0.42*
Weather	0.87 ± 0.22	0.78 ± 0.20	0.45 ± 0.29*	-
No information	0.25 ± 0.37	0.48 ± 0.47	0.50 ± 0.16	0.54 ± 0.12*

* Indicates less than 10 data points

Normal data produce a few percent more than expected
→ may have significant impact on performance based incentive programs

No trend with nameplate rating

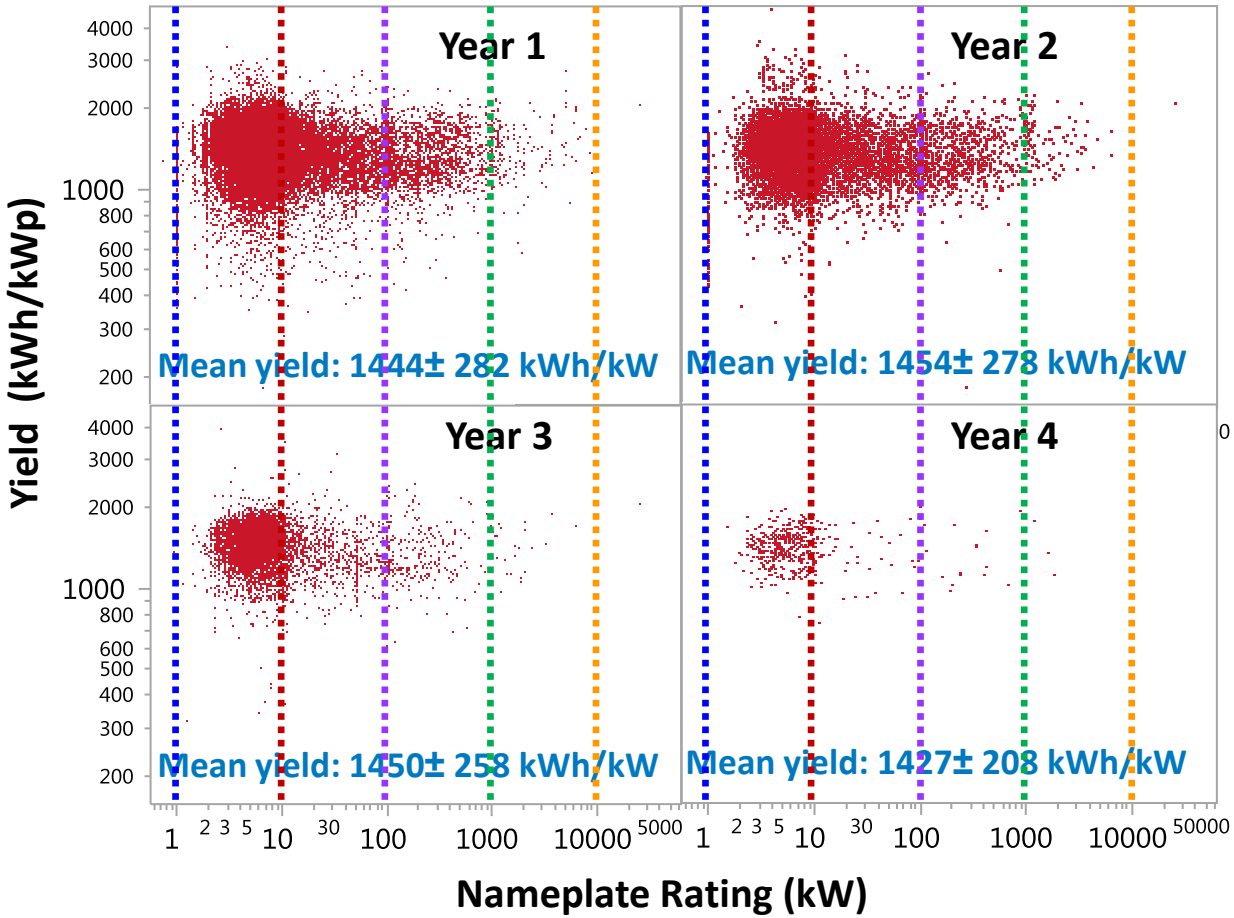
Yield (AC energy/nameplate rating) vs. nameplate & year



Yield appears wider for smaller systems → caused by higher point density

No trend with nameplate rating

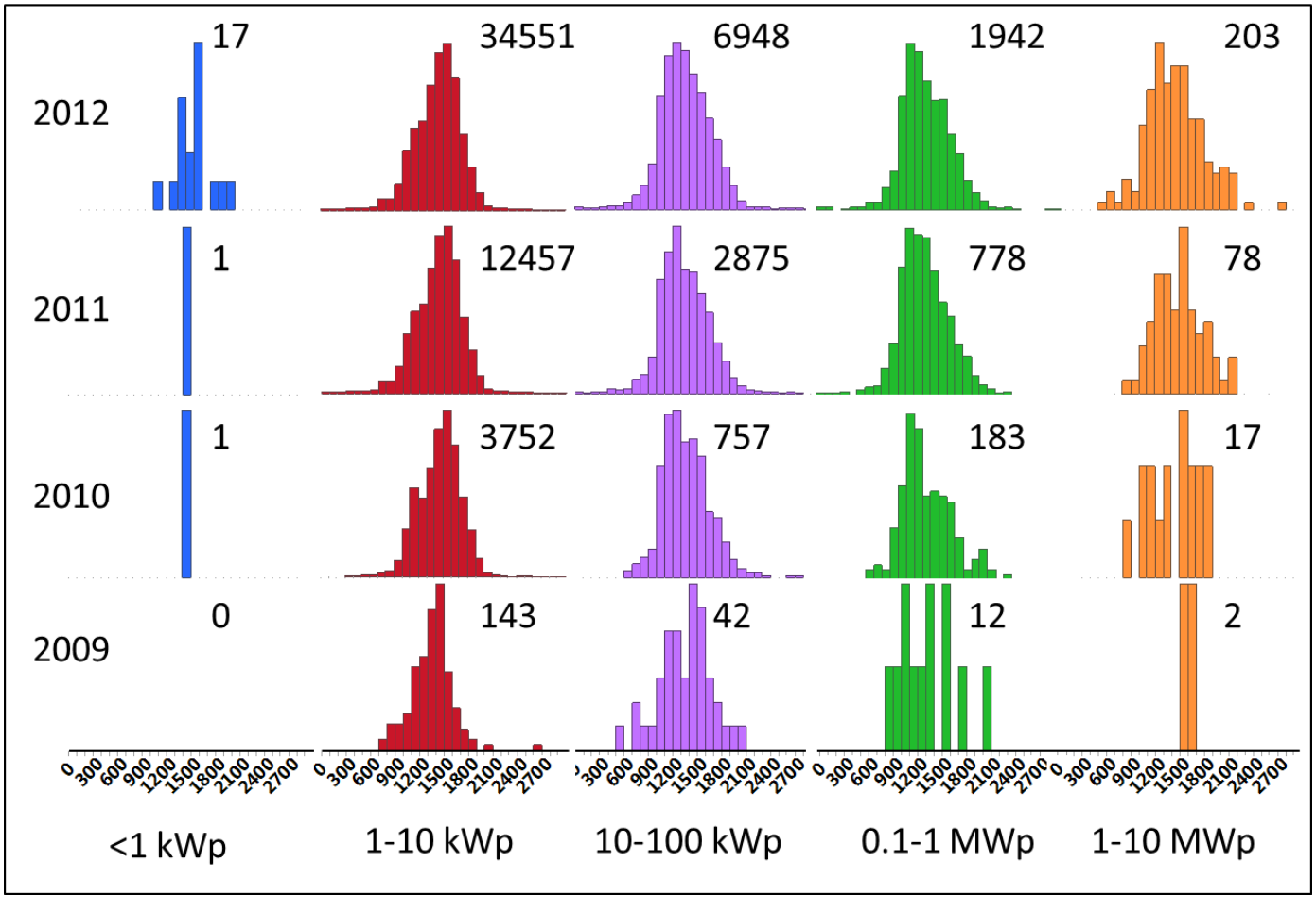
Yield (AC energy/nameplate rating) vs. nameplate & year



Yield appears wider for smaller systems → caused by higher point density

Yield distributions similar for different system size

Note: individual histograms have different count scales



AC yield

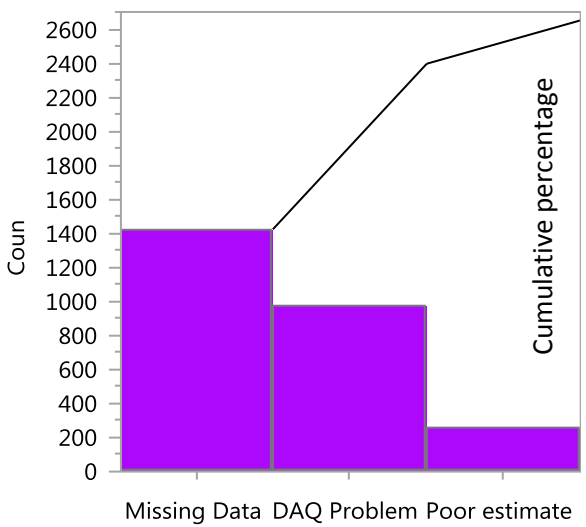
Nameplate rating

Distribution shapes for the AC yield for different rating bins as a function of year

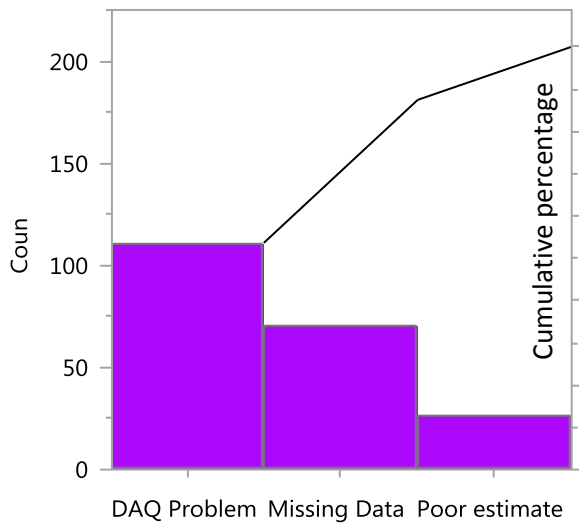
Data collection issues fall by order magnitude

Data collection-related issues

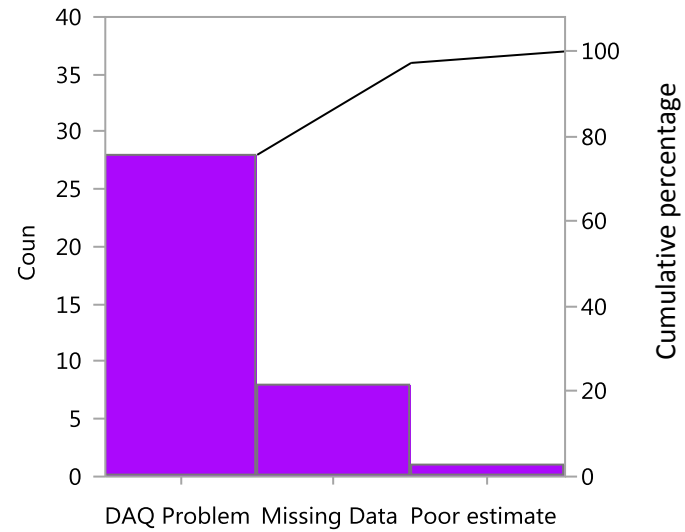
Year 1



Year 2



Year 3

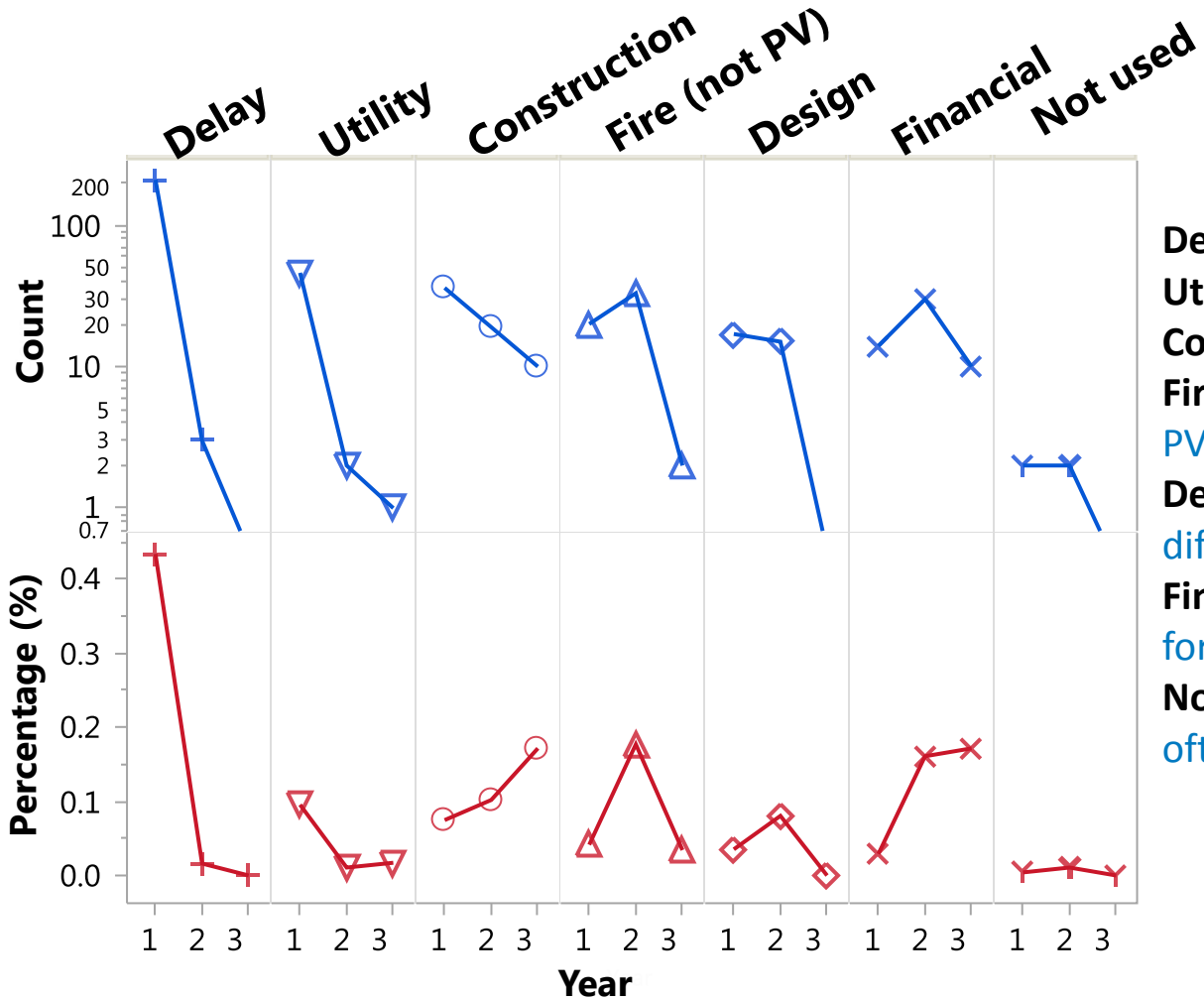


DAQ: data acquisition problem such as data transmission problem, internet outage etc.
Missing data: Less than a year before data were entered

Mean missed time (months)

Less than 1 year:	2.1	Less than 1 year:	2.2	Less than 1 year:	2.1
DAQ Problem:	3.5	DAQ Problem:	4.5	DAQ Problem:	5

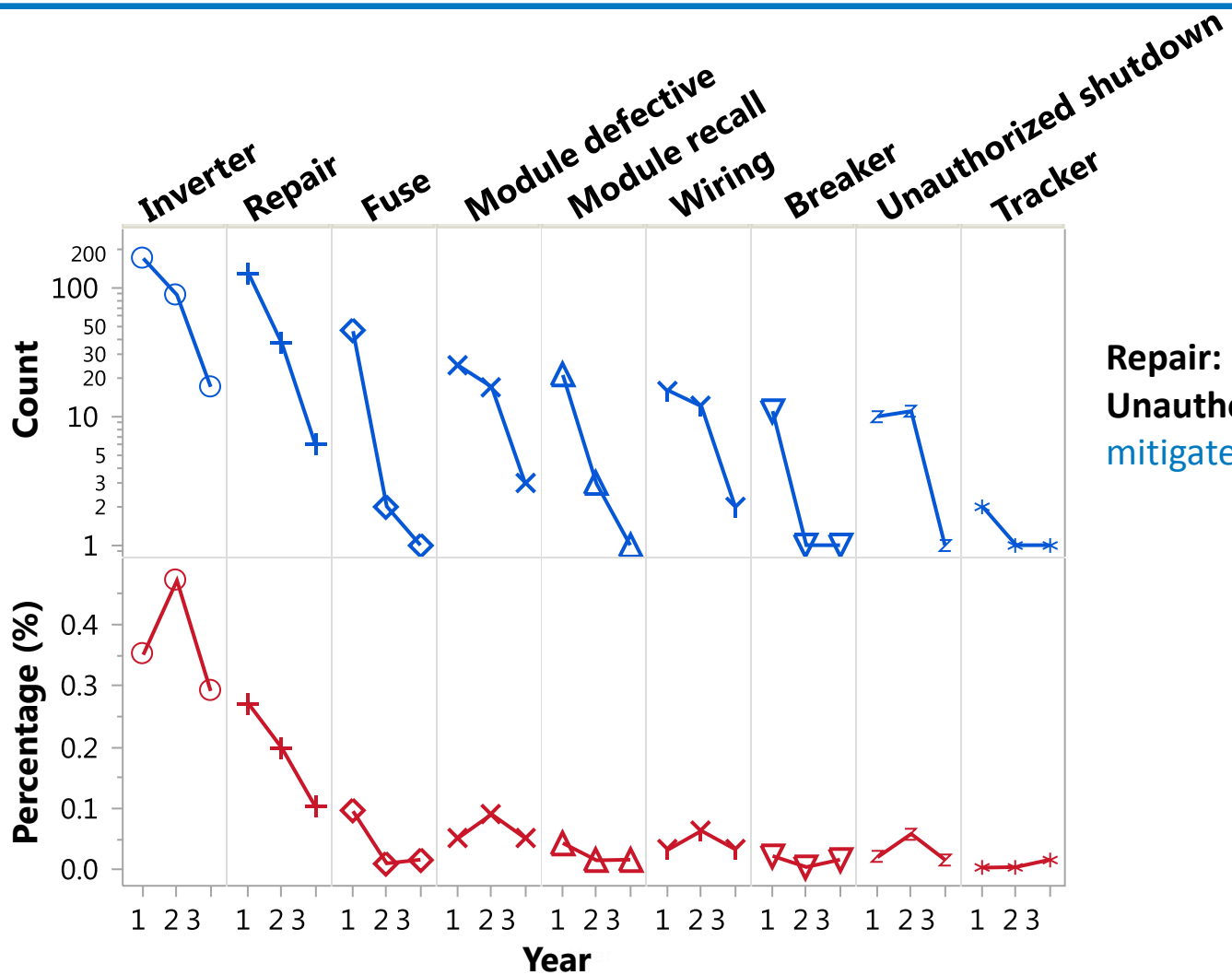
Project-related issues are dominated by delays



Delay: Permitting & construction
Utility: Grid interconnection
Construct.: Roof repair, remodeling…
Fire: fire at site not caused by PV → PV was turned off as precaution
Design: addition of new part-array @ different orientation
Financials: shutdown due to foreclosure
Not used: PV system not used as often

- Delay & grid interconnection dominates 1st year, rapidly declines in subsequent years
- Construction shows small percentage increase over years
- Fire can have broader impact due to precautionary PV system shutdown
- Financial reasons correlated to states with large housing price cycles

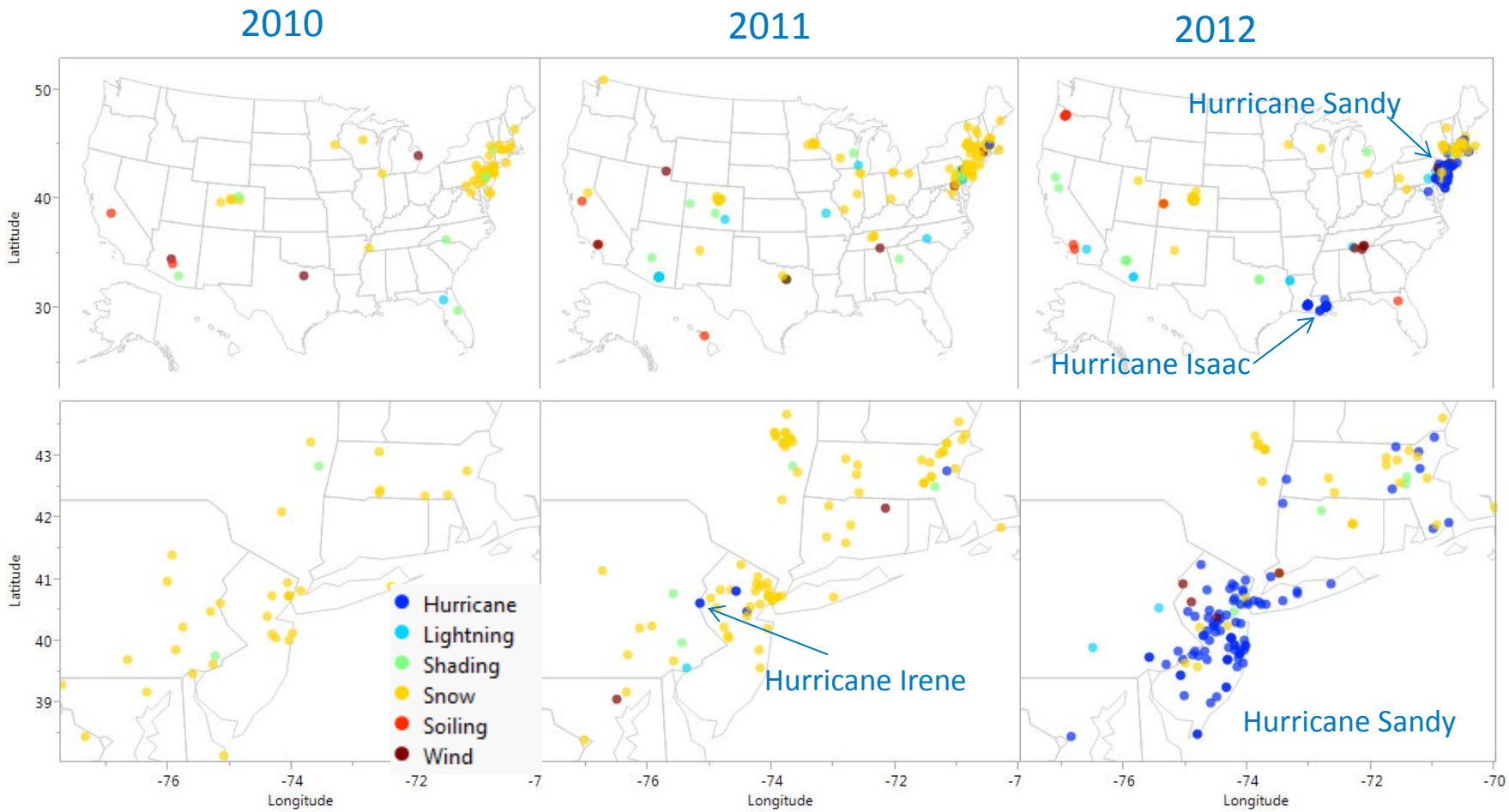
Hardware-related issues are dominated by inverter



Repair: Unspecified repair & outages
Unauthorized shutdown: May be mitigated by interconnect locks

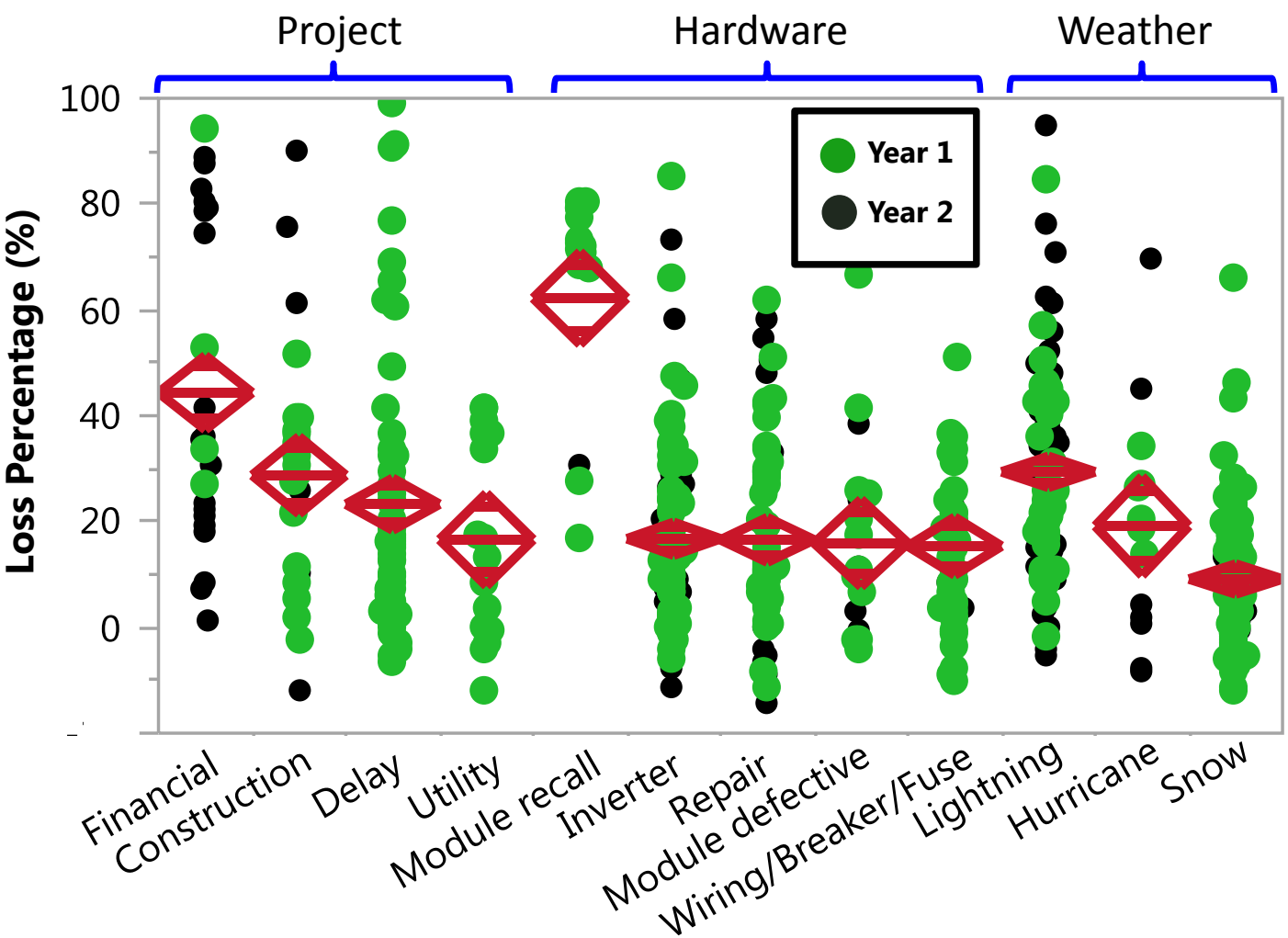
Less than 0.1% are due to defective modules

Weather-related issues dominated by snow & hurricanes



Hurricane: Typically, down time due to grid outage, not because of damage to system
Lightning: Not direct hits to PV system but transformer

Annual loss impact (%) of different categories



Performance in anomalous year compared to normal year → loss estimation due to cause of anomaly (assumes the same annual production)

Diamonds: 95% confidence interval
Crossbar: Mean

Module recalls do not occur often but if they do they can have large impact

Conclusion

- Analyzed field performance of 50,000 PV systems
- More than 90% of normal systems produce at least 90% of expected
- Project problems may not occur as often but have large impact
- Project-related problems are dominated by delays in the first year of operation, then rapidly declines in subsequent years.
- Hardware issues dominated by inverter, particularly in the first year of operation
- Less than 0.1% are due to defective or underperforming modules
- Module recalls can lead to significant annual production losses
- Weather-related issues are dominated by snow and hurricanes

Acknowledgments

Thank you for your attention

National Renewable Energy Laboratory
15013 Denver West Parkway, MS 3411
Golden, CO 80401, USA
dirk.jordan@nrel.gov

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ANALYSIS OF PHOTOVOLTAIC INSTALLATIONS: A COMMERCIAL OWNER PERSPECTIVE ON PV PLANT OPERATION AND OPTIMIZATION

Alexander Bradley, John Reimers, Babak Hamzavy, James Kopchick

DUPONT PHOTOVOLTAIC SOLUTIONS

February 25, 2014

NREL Reliability Conference

Introduction

- Review and analysis of commercial installations provides insight and learning to help the industry's continued growth
- Address technical risk to commercial/industrial projects, from design through decommission
- Simple quality management actions/processes minimize safety and performance risks and improve financial returns
- Identify and share learnings and best practices regarding distributed generation projects
- Gather data to identify durability challenges and trends
- Observed degradation and failure modes associated with module/material design, manufacturing, installation, weather, and operation & maintenance (O&M).
  - The importance of module material design and manufacturing consistency is critical

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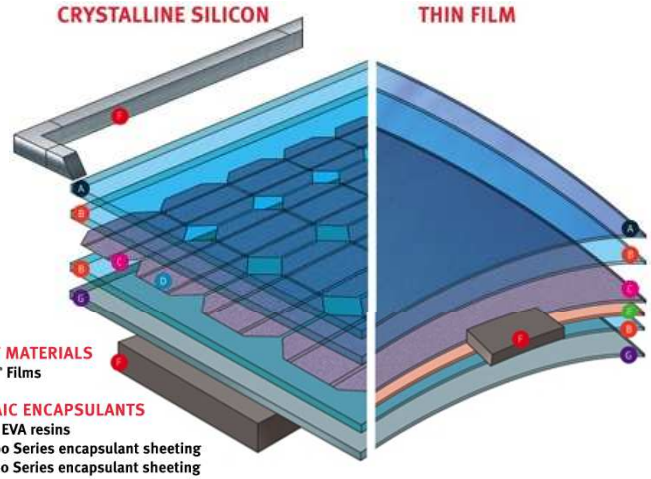
DuPont Role in Photovoltaics

Broadest materials portfolio in the PV industry



A FRONTSHEET MATERIALS
DuPont™ Teflon® Films

B PHOTOVOLTAIC ENCAPSULANTS
DuPont™ Elvax® EVA resins
DuPont™ PV5200 Series encapsulant sheeting
DuPont™ PV5300 Series encapsulant sheeting
DuPont™ PV5400 Series encapsulant sheeting
DuPont™ PV8600 Series encapsulant sheeting

C PHOTOVOLTAIC METALLIZATIONS
DuPont™ Solamet® photovoltaic metallizations

D SILICON DOPING TECHNOLOGIES
DuPont™ Innovalight™ silicon inks

E THIN FILM SUBSTRATES AND SUPERSTRATES
DuPont™ Kapton® polyimide films

F ELECTRICAL AND STRUCTURAL COMPONENT MATERIALS
DuPont™ Rynite® PET thermoplastic polyester resins

G BACKSHEET MATERIALS
DuPont™ Tedlar® PVF films

SODIUM METAL FOR POLY-SILICON MANUFACTURING
DuPont™ Niapure® and Niapure® Select sodium metal

WET-ETCH ADDITIVES FOR PV MANUFACTURING
DuPont™ Capstone® fluorosurfactants

HIGH PERFORMANCE PARTS
DuPont™ Kalrez® perfluoroelastomer parts
DuPont™ Zalak® high performance seals
DuPont™ Vespel® parts

System owner & PV electricity consumer

Shenzhen, China
Rooftop Thin Film

Taoyuan, Taiwan
Rooftop c-Si

Hyderabad, India
Rooftop Thin Film & c-Si

Waimea, HI
Ground Mount c-Si

Tlalnepantla, Mexico
Ground Mount TF

Parlin, NJ
Ground Mount c-Si

Wilmington, DE
Ground Mount c-Si

Wilmington, DE
Rooftop Thin Film

Wilmington, DE
Rooftop c-Si

3 Continents and 7 Countries
7 kW to 5 MW

Provide a unique industry perspective: largest material supplier and growing PV system owner

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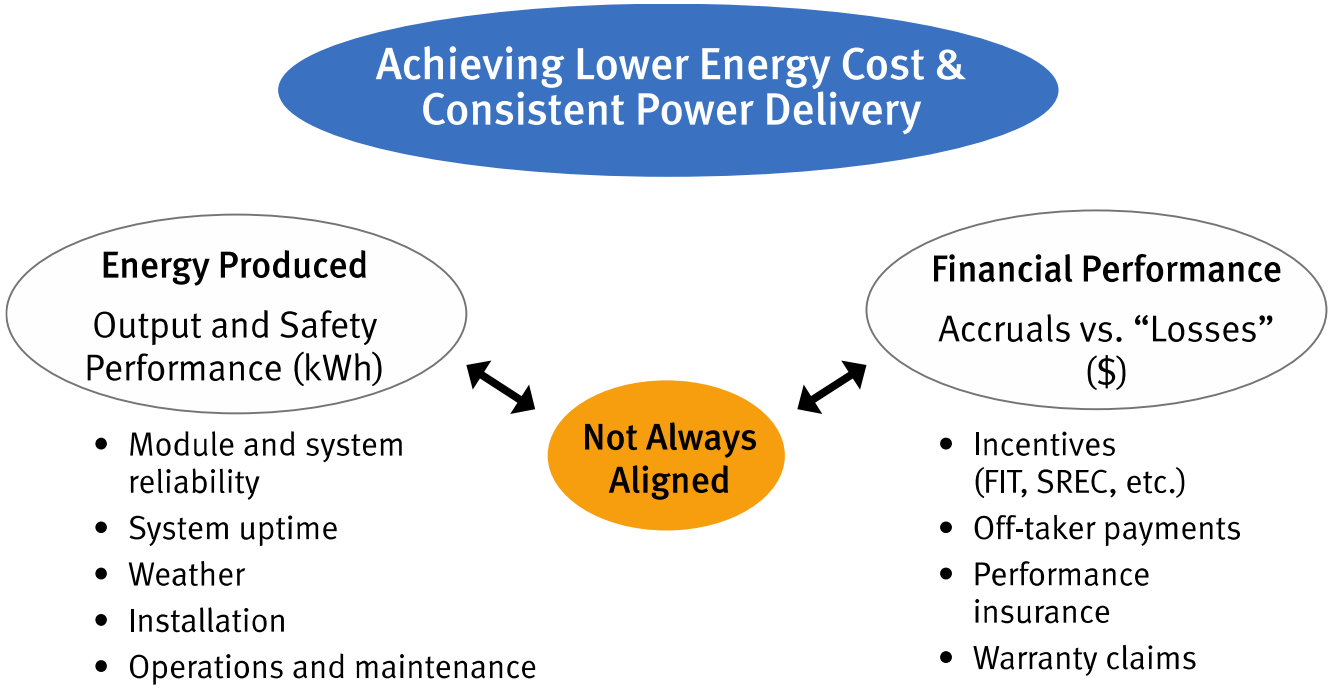
System Owners Recognize Lifetime is as Important as Cost and Incentives

Achieving multiple objectives of economics, energy output and scale requires careful planning and execution



Risks are distributed among several stakeholders and vary depending on role in value chain.

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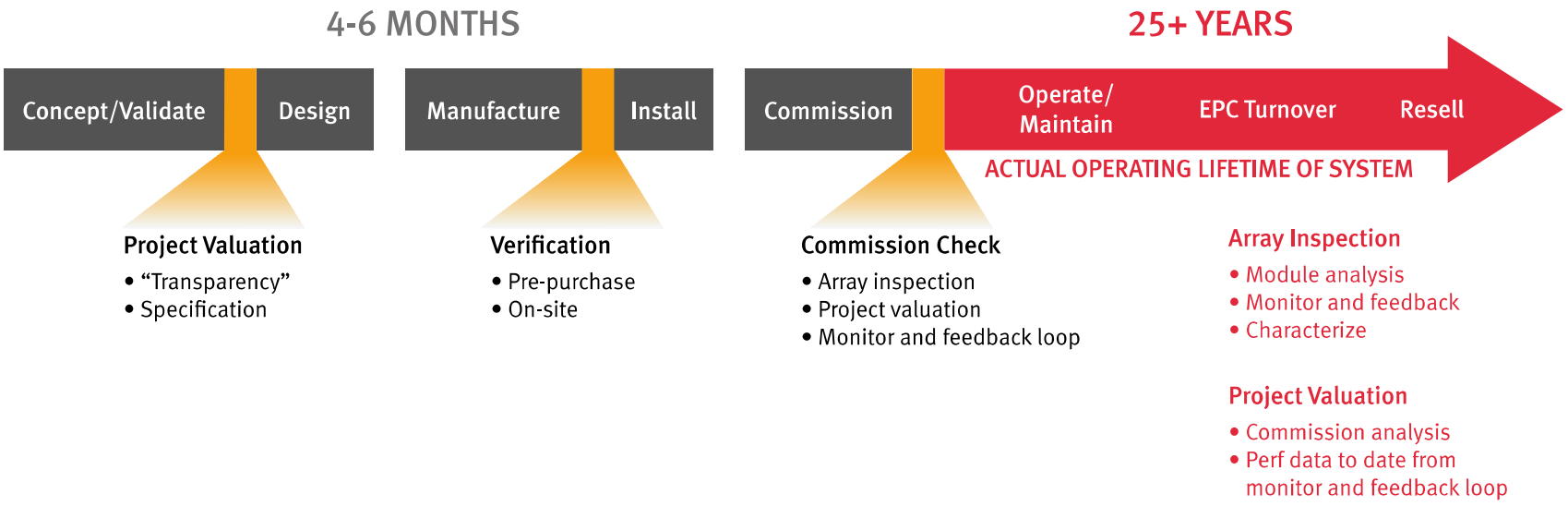
Project Lifecycle: Risk Assessment and Valuation Over Time

- Performance and safety over 25 years needs appropriate upfront consideration
- Importance of PV system optimization increases as subsidies are reduced



Risks are distributed among several stakeholders and vary depending on role in value chain.

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Overview

Background

- Inspected/Characterized >30 global installations (>100MW) in NA, EU, & AP ranging from newly commissioned to 30 years to gain technical learnings
- In last 36 months lab analyzed > 300 modules from service environment
- Observed and characterized over 30 different degradation modes
- Partnered with over 25 installers, developers, EPC, utilities, financial and academic institutions

Observations

- Module overcapacity and race to grid parity is driving dramatic changes
- Safety and performance issues are typically underreported, but are arising and being identified through industry publications.
- A proliferation of new materials combined with multivariate stresses and concurrent phenomena requires careful analysis and assessment.
- Once commissioned options for mitigation are limited

Recommendations

- Better understanding of product quality and qualification is needed
- Development of enhanced durability test methodology is required
- Use best practices and processes to optimize in-field performance
- Adopt improved risk mitigation strategies and technical specifications

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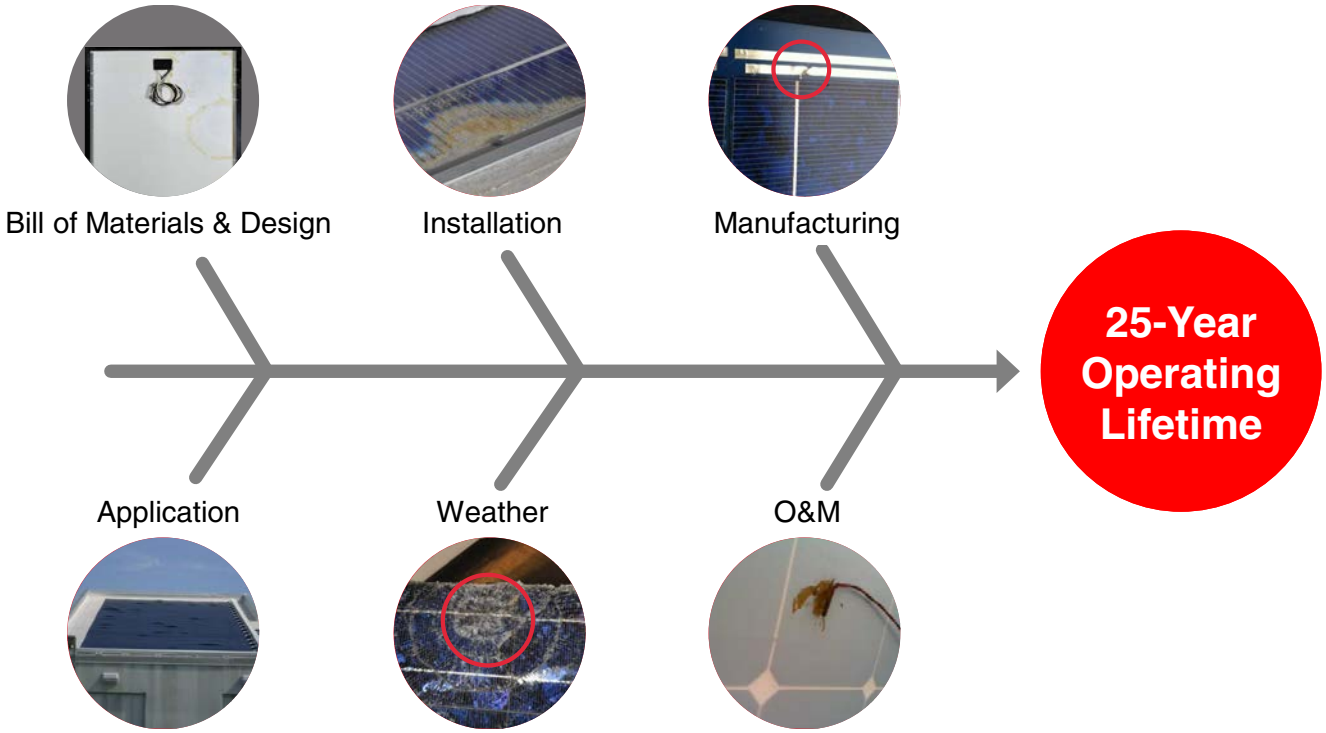
Quality Management Process: Storyboard the Performance Risk Issues

Identify and catalog degradation modes: mitigate risk with control plans



"Lifetime-prediction tests appropriate for full-sized modules would be possible only when a final module design is defined, all failure modes are identified for that module design, and acceleration parameters for each relevant environmental stress are known.

The development of a universal 30-year pass/fail certification for all PV module types cannot be expected."

Module 30 Year Life: What Does it Mean and Is it Predictable/Achievable?
T. J. McMahon, G. J. Jorgensen, R. L. Hulstrom, D. L. King and M. A. Quintana

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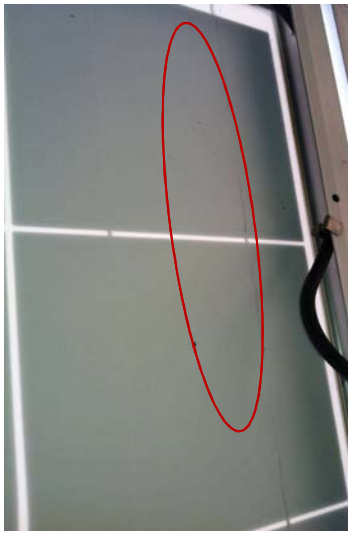
Identify and Catalog Degradation Modes:
Bill of Materials & Design

Material durability issues are widespread in modules less than 5 years in operation in the service environment

- Outer backsheet polyester cracked and delaminating
- 2.3 MW field estimated that ½ the field or approximately 5,000 modules in the park affected
- 2-year warranty on materials and workmanship elapsed, with no replacement of the panels



- Backsheet with embrittlement, cracking, and erosion of outer FEVE coated surface
- 1% of modules indicated early signs of degradation or gross damage after 3 years in service

- Inner backsheet PE tie-layer discoloration (PVDF backsheet)
  - 5 different countries (>10MW)
  - 5 different manufacturers
  - Different certifying agencies

Backsheet and Module Durability and Performance and Comparison of Accelerated Testing to Long Term Fielded Modules.
Gambogie, W., et. al. EUPVSEC 2013.

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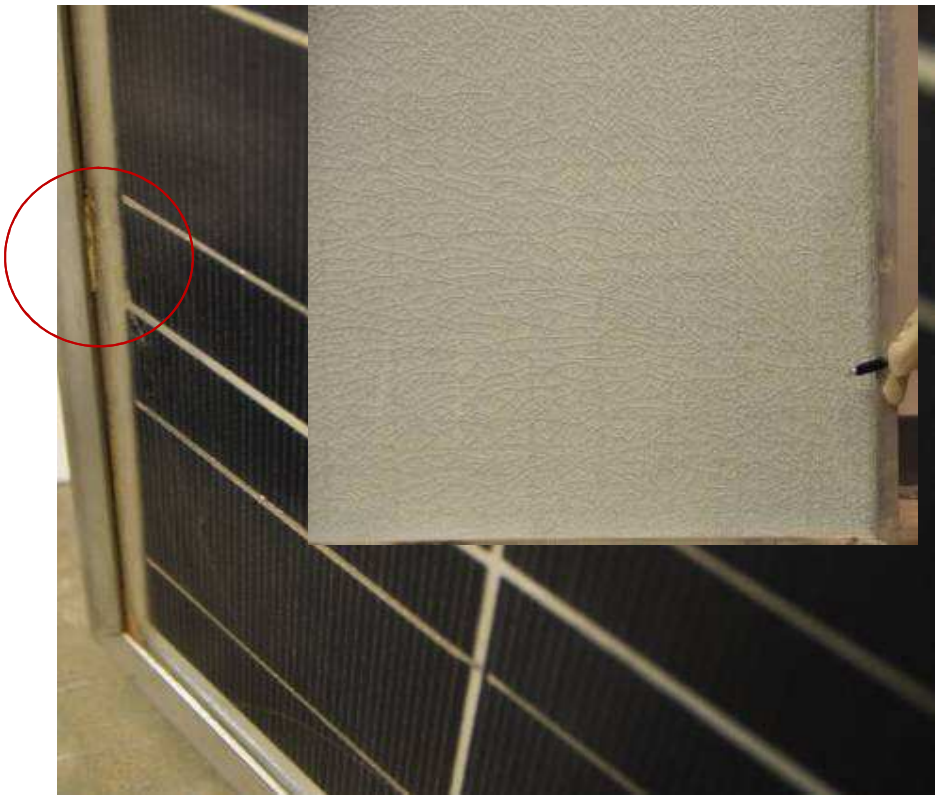
Identify and Catalog Degradation Modes: *Installation*

Errors due to improper installation methods are typically localized



Shim between glass and frame

Extra drill hole at grounding bar

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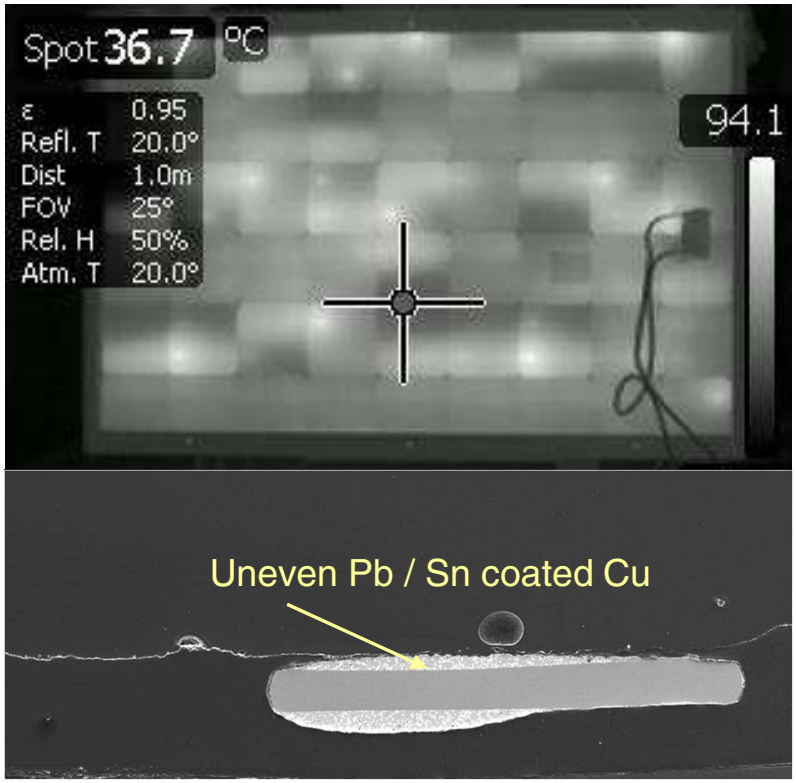
Identify and Catalog Degradation Modes: *Manufacturing*

Safety and performance issues due to inconsistent manufacturing

Bent bus bar and misaligned cells



Non-uniform solder

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Identify and Catalog Degradation Modes: *Application Environment*

Varied site-specific requirements present different operating environments for distributed generation

BIPV/BAPV delamination

Ground mount, open vs. closed rack, operating temperature differences

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Identify and Catalog Degradation Modes: *Weather*

Wide range of issues from instantaneous catastrophic failure to slow degradation

Hail damage

Soiling (temporary)

Glass Etching (permanent)

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Identify and Catalog Degradation Modes:
Operation & Maintenance

Remote monitoring systems are needed in combination with thermal imaging and visual inspection

Thermal imaging used to identify underperforming modules: Average backside cell temperature is not always representative.

Visual inspection: Necessary, but not sufficient.

E. Kaplani, Detection of Degradation Effects in Field-Aged c-Si Solar Cells through IR Thermography and Digital, Image Processing.
International Journal of Photoenergy (2012).

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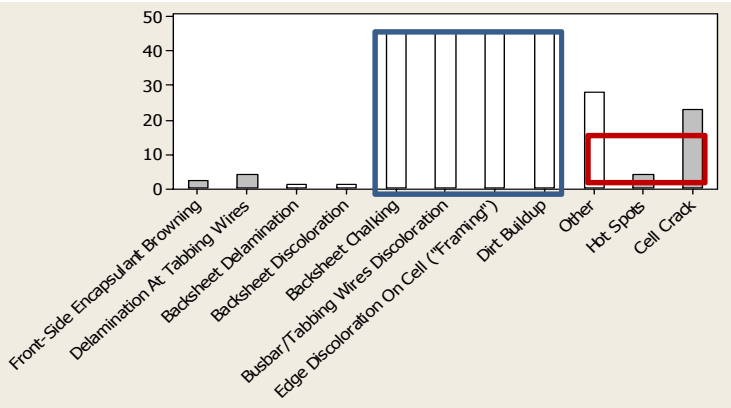
Quantitative Assessment: DuPont PV Installation Case Study 1

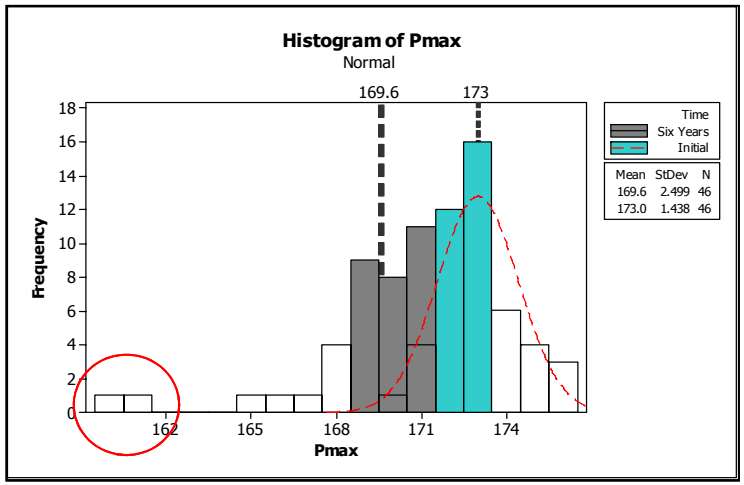
Project evaluation & documentation after six years



Pareto process & criticality analysis

- Degradation (Blue) modes with high frequency show a low degree of severity
- Degradations (Red) with low frequency have high degree of severity
- Ability to detect enhanced through thermal imaging

46.7 kW System



Performance: Pmax distribution

- Minimal power loss
- Mean change in power is -3.4 W (-2% drop); 95% confidence
- Degradation rate = 0.3% per year (assumed linear)

Safety: Electrical Insulation

- EVA encapsulant and TPE backsheet maintained electrical insulation

Safety and Performance Analysis of a Commercial Photovoltaic Installation. Bradley, A. Z., et. al. SPIE 2013.

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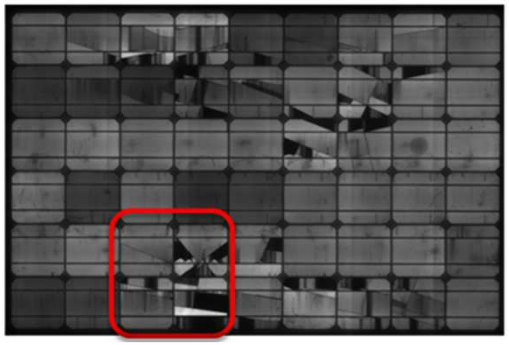
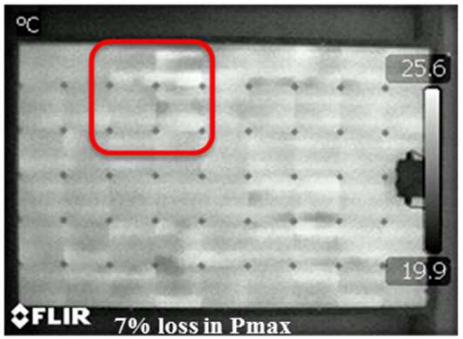
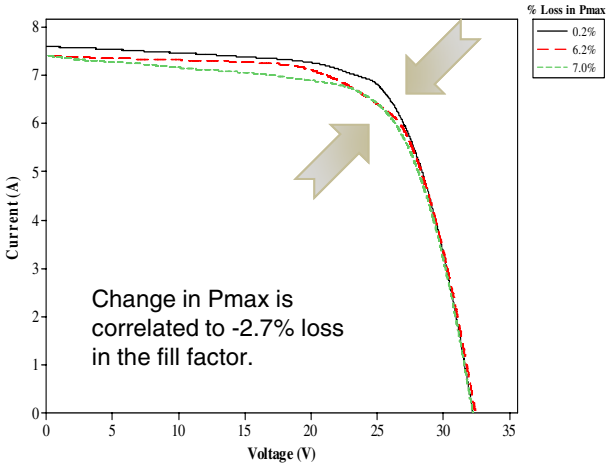
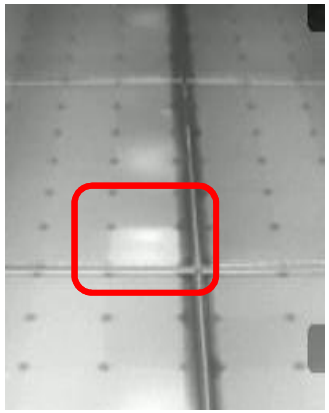
Electroluminescence and Thermal Imaging of Modules Indicated Different Degradation Modes Yield Similar Power Loss

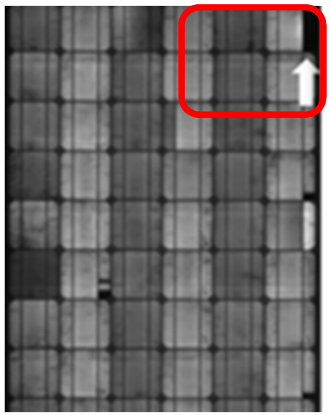


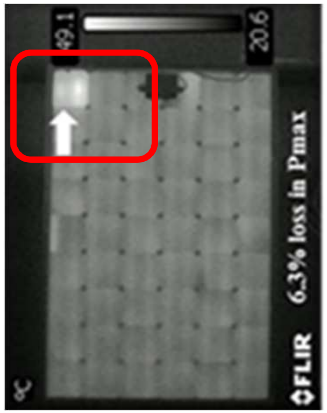


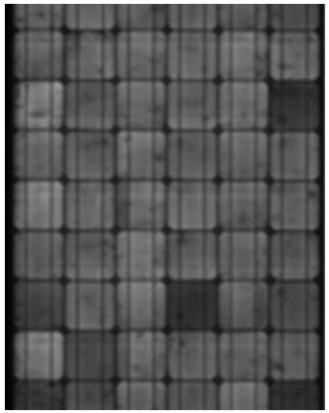
Some cracks are identifiable in the thermal image
(damage location is at an elevated temperature)











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Qualitative Assessment: DuPont PV Installation Case Study 2

- Reliability issue (37.8 kW system): Six 180W modules out of 210 have broken glass (2.8% broken) after 3 years
  - Mechanical/structural issues associated with installation
  - Broken interconnect on cells

- Current situation: Developer, module and inverter manufacturer are all out of business

- Mitigation: Cannibalize a smaller string of the array (6.6% decommissioned)

- Control plan: Semiannual inspection and thermal imaging

Analysis of Photovoltaic Installations: A Commercial Owner Perspective on PV Plant Operation and Optimization; Bradley, A., et. al. EuPVSEC, 2013.

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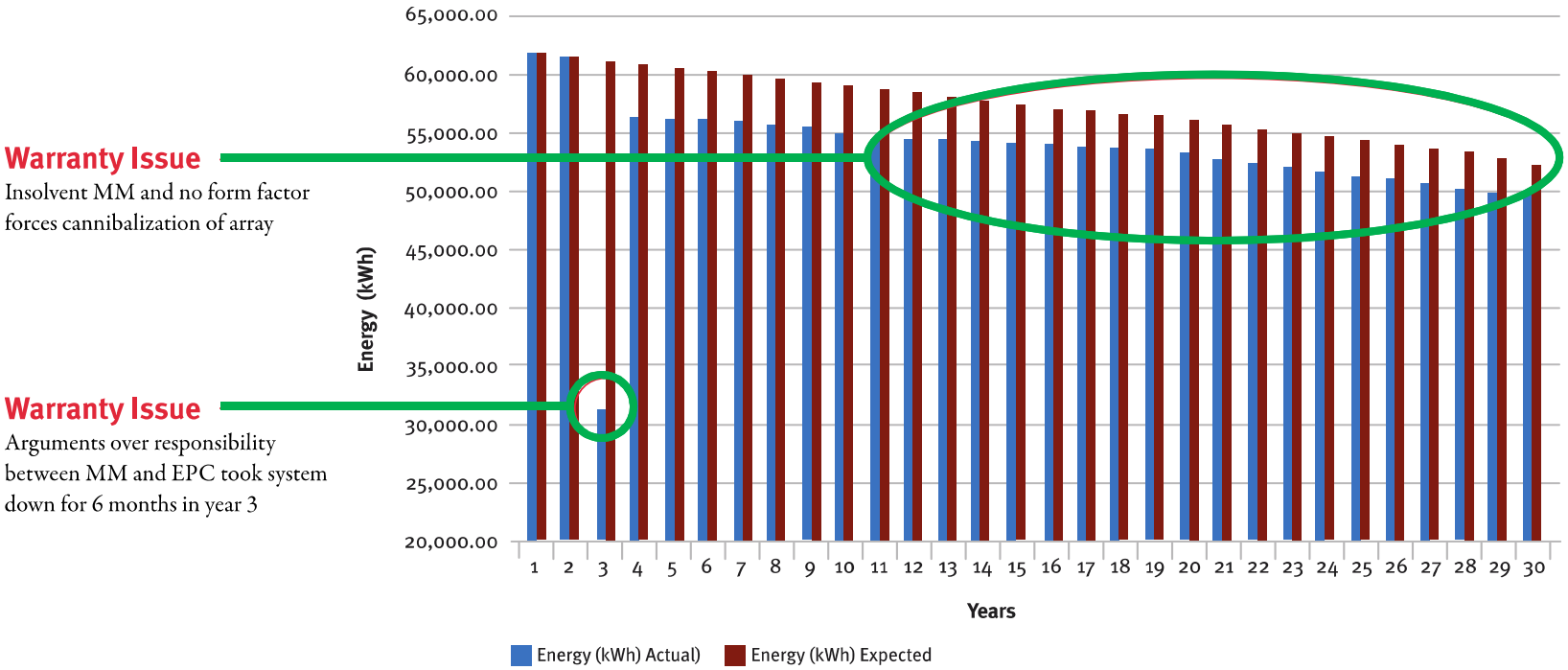
O&M is Not a Fixed Cost and Can Dramatically Increase Over the Lifetime of the System

- O&M costs were up 235% in year 3 due to system issues
- Revenue loss due to system availability (short term) & kW size (long term)



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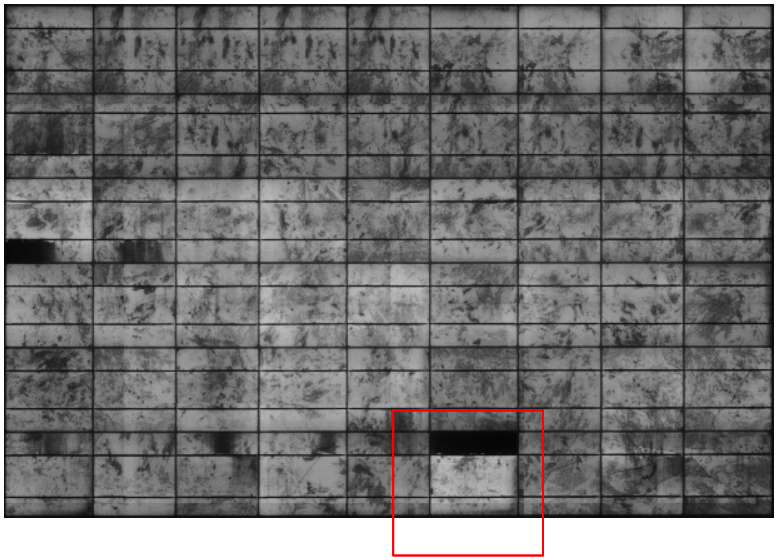
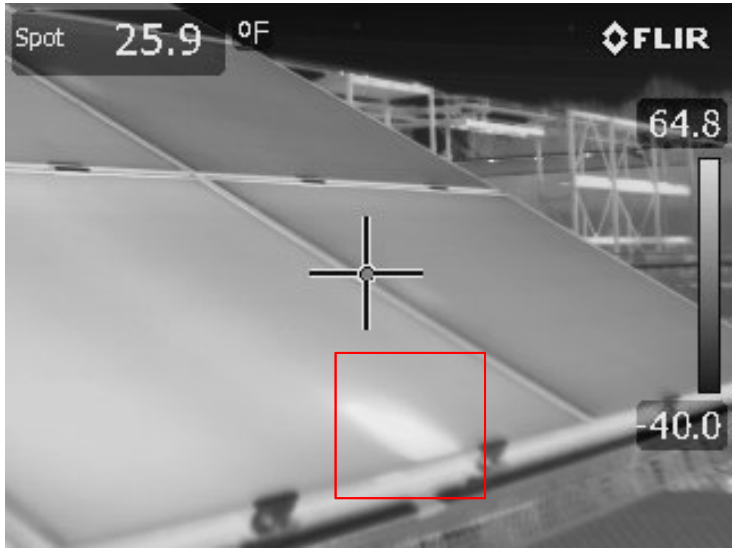
Thermal Imaging Assessment: DuPont PV Installation Case 3



EL image of replacement module before installation



Hot spot identified immediately after installation

- Reliability issue (43 kW System): Seven 205W modules out of 210 have cell hot spots (3.3%)
  - Safety: Overheated cells accelerate degradation of encapsulant and backsheet materials
  - Performance: The use of thermal imaging is critical to the inspection process and has been instituted as a best practice to improve safety and performance

- Remote string level monitoring combined with thermal imaging identified underperforming modules
  - One percent of modules do not meet performance warranty after 3 years.

- Poor manufacturing initially characterized by EL imaging detected as a hot spot using thermal imaging

Bradley, A.Z. submitted SPIE 2014

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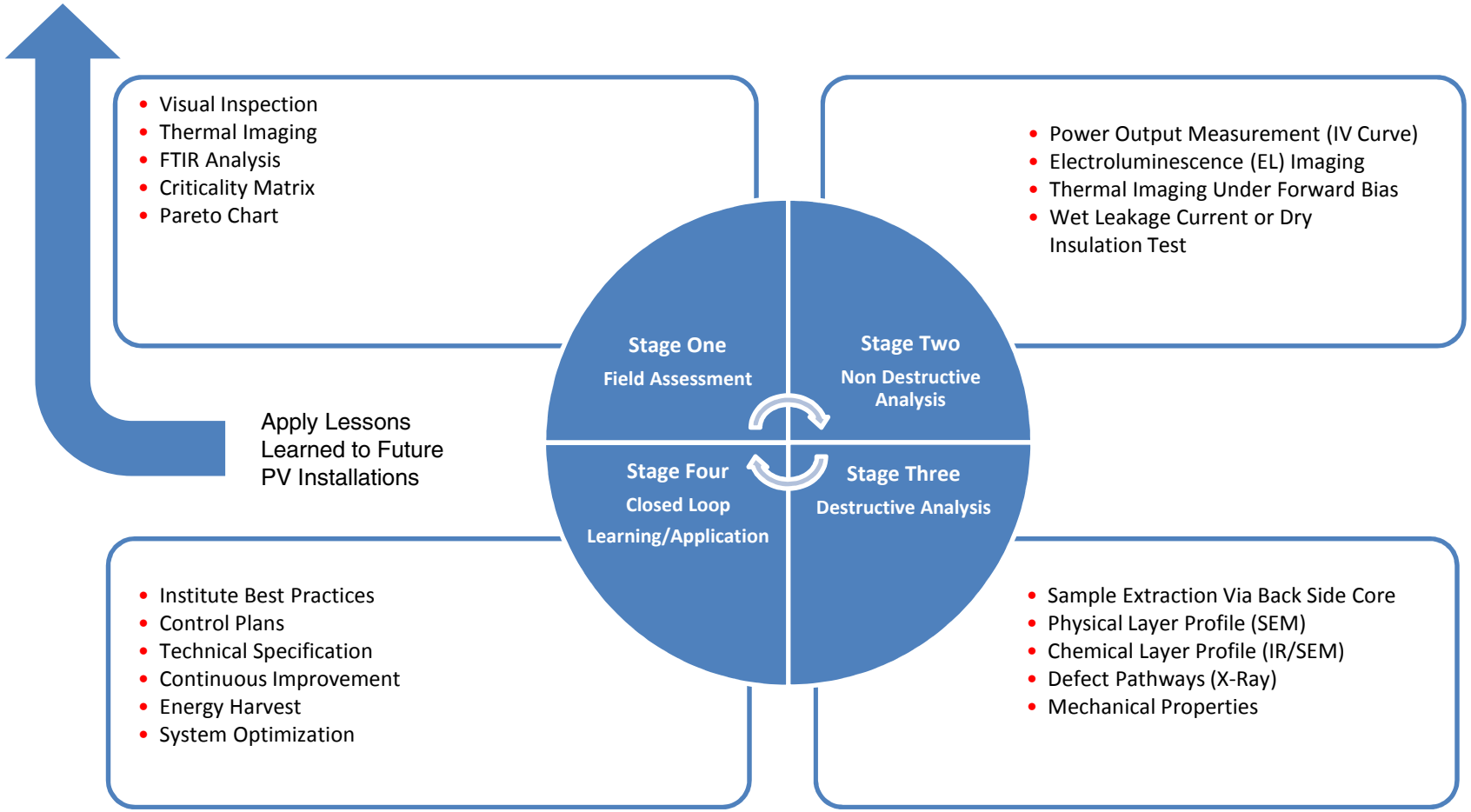
Minimizing PV Performance Risk and Optimizing Energy Harvest



Failure Modes and Effects Analysis used to improve component and system design.

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There are Straightforward Options to Mitigate Risk

	PV System Best Practices	Key Actions
Project Design	**Ensure Selection of Quality Modules**	Specify a **proven module BOM** that eliminates common module failure modes (e.g. electrical insulation materials)
		Require **transparency** of BOM to be provided in project solicitations
		Specify **Manufacturing Process Controls** that ensure design consistency, BOM & Process conditions
		Require **Letter of Conformance** & closed loop verification of modules vs. proposed/contracted
Contracting	**Assess Contractor Experience & Ensure Quality Asset Optimization Management**	Improve visibility of **contractor past performance** (beyond 5 years & problem resolution capabilities)
		Require/develop detailed plan for **long-term optimization & management** of the asset in project solicitations
Commissioning	**Enable Ongoing Safety & Performance Monitoring of the Asset**	Require **open access** to the facility, BOMs, plant designs and records
		Project Commissioning process to ensure conformance & establish baseline performance
		Ongoing data analysis of system (requirement of weather collection system to normalize data)

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Summary

Documented material durability and module manufacturing issues in systems less than 5 years in operation in the service environment

O&M is not a fixed cost and can be significant

Difficult to standardize distributed generation systems – no one size fits all approach to global commercial/industrial installations

Simple best practices and quality management actions/processes minimize risk, optimize safety/performance, and improve financial returns

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Alexander Z. Bradley, Ph.D.
DuPont Photovoltaic Solutions
(302) 999 4734
alexander.z.bradley@dupont.com

Acknowledgments
T. John Trout, James Berry, Corey Phillips, William Griswold, Lucie Garreau Iles, William Gambogi, Kate Stika, Eric Romano, Conrad Burke, Jill Cohen

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February 25, 2014

FIELD OBSERVATIONS OF MODULE FAILURE AND DAMAGE

DR. RALPH ROMERO
DIRECTOR
MANAGEMENT CONSULTING DIVISION

GREG GREENMAN
ASSISTANT MANAGER
CONSTRUCTION MONITORING SERVICES
ENERGY DIVISION

BLACK & VEATCH
Building a world of difference.

PRESENTATION SUMMARY

- Black & Veatch's PV Qualifications
- Module Failure and Damage Case Studies
- Q&A

B&V PV SOLAR SERVICES

- Independent Engineering (IE) for investors and lenders
- Owner's Engineering (OE) for power producers & utilities
- More than 4,000 MW of on-site construction monitoring experience worldwide
- Projects in United States, Canada, Mexico, South Africa, Puerto Rico, Thailand and India

MODULE FAILURE AND DAMAGE CASE STUDIES

CASE STUDY #1: SNAIL TRAILS

Snail trails and microcracks observed on installed modules.

Lesson Learned: The causes of snail trails should be investigated, monitored, and mitigated by the manufacturer.

CASE STUDY #2: MODULE GLASS CRACKING

- Cracks in thin film module glass were observed in one project in a desert climate.
- Possible cause: Excessive module deflection at high temperatures.
- No thermal breakage seen in crystalline Si modules.

Lesson Learned: The effects of thermal expansion on racking and modules should be carefully considered in the system design.

CASE STUDY #3: MODULE DAMAGE DURING SYSTEM OPERATION

Module back glass cracked due to rock from mowing equipment.

Broken modules due to growth of tree under modules.

Lesson Learned: Diligent O&M oversight and security is critical in preventing module damage.

CASE STUDY #4: IMPROPER MODULE STORAGE DURING CONSTRUCTION

Water accumulation in modules caused corrosion in junction boxes and connectors.

Lesson Learned: Consider storage environments when designing packaging.

FINAL OBSERVATIONS

- **The vast majority of the modules that we have observed operate properly and do not show damage.**
- **We speculate that less than 0.5 % of modules require replacement before system commissioning.**

THANK YOU & QUESTIONS

Dr. Ralph Romero

(757) 903- 7528

RomeroR@bv.com

Greg Greenman

(415) 290 - 2946

GreenmanG@bv.com

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The PV Reliability Operations Maintenance Database – Current Efforts by Sandia Labs and EPRI to Improve PV System Reliability

Geoffrey T. Klise Sandia National Laboratories – Earth Systems Analysis, P.O. Box 5800, MS 1137, Albuquerque, NM 87185 Contact: gklise@sandia.gov
Contributions by Colin Hamman and Peter Kobos - Sandia National Laboratories

Sandia National Laboratories

SAND2014-1451C

Abstract

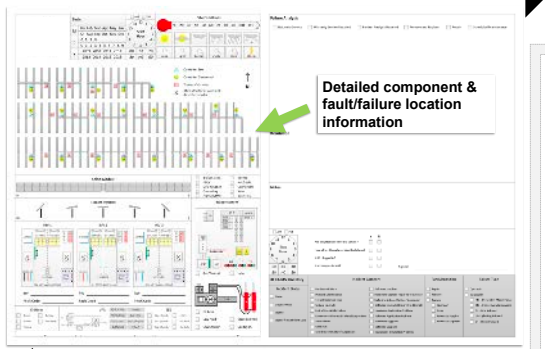
Sandia National Laboratories, in coordination with the Electric Power Research Institute (EPRI) is currently working with solar PV system operators to develop a standardized data entry, analysis and reporting framework as part of the PV Reliability, Operations Maintenance (PVROM) database initiative. Data collected on system faults and events will be used to inform the solar industry of current O&M related challenges with an eye towards continual improvement of O&M practices. Most importantly, this information can be used in coordination with industry to help develop both best practices and consensus standards that when implemented, will improve current and future PV system design and result in decreased financial exposure risk at various stages in the PV system's lifetime. PVROM database elements and analysis results will be presented and mapped to areas where Sandia and others are leading best practice and standards activities.

Benefits to partners:

- Secure access to XFRACAS® platform on Sandia's Open Network
- Data anonymity enforced by a Sandia-generated NDA
- Determine impacts to system performance based on actual and projected events
- Better understanding of system costs and cost-benefit of multiple O&M approaches based on various factors

What Feeds Into PVROM

PV Systems Field Data: Failures, Events, Performance

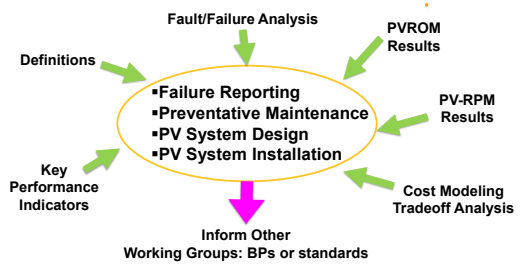


Detailed component & fault/failure location information

Data input from **field form, paper** or **web-based**

Working Groups - Best Practices

Lead to more reliable PV systems through improved data collection, analysis, design and installation



The PVROM Framework

Data input, aggregation, collection, storage

i – Set up "Bill of Materials" serialized data input

Level	Part Number	Part Description	Part Version	Serial Number
1	SGSSS	SGS Solar System Power Block		SGS-1
2	TXL	480V/34.5kV Transformer		SCL-2
2	TXS	208V/480V Transformer		TXS-1
2	ADS	AC Disconnect Switch		ADS-1
2	DDS	DC Disconnect Switch		DDS-1
2	ECON	Array Electrical Connections		ECON-1
2	INV	Inverter		INV-1
2	LIGHT	Lightning Event		L-1
2	MOD	PV Module		M-U1-1
2	MOD	PV Module		M-U1-2
2	MOD	PV Module		M-U1-3

ii – Enter historic incident data

Unique Identifier (20 characters)	Incident ID (100 characters)	Incident Title (20 characters)	Reported By (Date/Time)	Occurrence Date (Date/Time)	Reporting Date (Number)	Repair Duration

Clock Hours (Number)	Number of Starts (Number)	kWh Loss (Number)

BOM Level 1 Part Number (20 characters)	Level 1 Part Version (20 characters)	Level 1 Part Serial Number (20 characters)	BOM Level 2 Part Number (20 characters)	Level 2 Part Version (10 characters)	Level 2 Part Description (75 characters)	Under Warranty (Y or N)	Customer Requested Feedback (Y or N)	Service Response Date (Date/Time)

Responsible Individual (100 characters)	Incident Status (50 characters)	System Status (50 characters)	Incident Category (50 characters)	Report Type (30 characters)	Audience Restriction (50 characters)	Description of Incident (2000 characters)

Target Date (Date/Time)	Restored to Duty Date (Date/Time)	Incident Resolution (2000 characters)	Target Date (Date/Time)	Service Completed Date (Date/Time)	Initiating Event (2000 characters)	Target Date (Date/Time)	Completed Date (Date/Time)	Additional Comments (2000 characters)	Commis-sioning Date (Date/Time)	Completed Date (Date/Time)

iii – …and how it was repaired or replaced

Unique Identifier (20 characters)	Incident ID (Number)	Item Order (20 characters)	Old Part Number (10 characters)	Old Part Version (100 characters)	Old Serial Number (50 characters)	Failure Type

Disposition (50 characters)	RMA (50 characters)	Sales Order Number (Date/Time)	RMA Date Received (20 characters)	New Part Number (10 characters)	New Part Version (100 characters)	New Serial Number (Number)	Quantity

iv – Enter new Incident Data and how it was repaired or replaced

(Blank version of completed incident report shown here)

Incident status & summary

Incident component detail

Incident high level detail

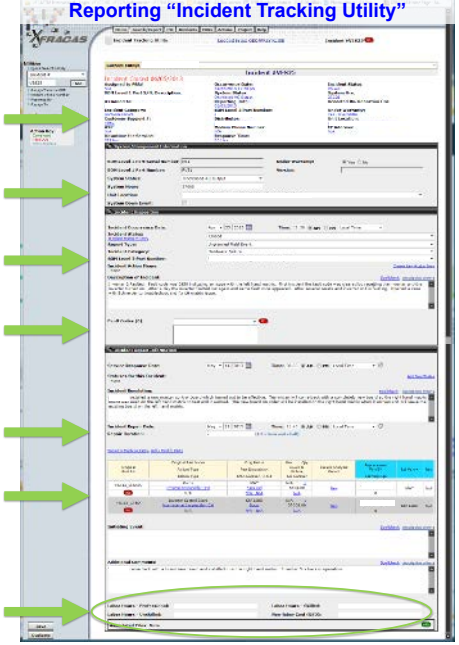
Different fault codes can be categorized

Incident repair date & duration

Replacement part information

Labor and repair costs can be entered

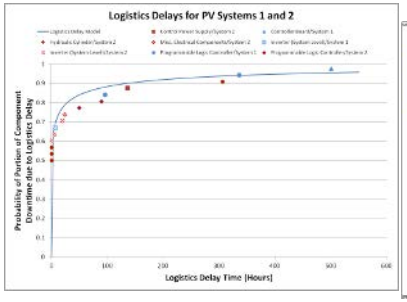
Failure Reporting Analysis & Corrective Reporting "Incident Tracking Utility"



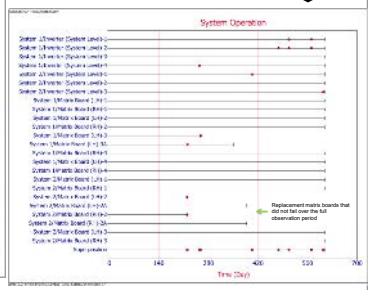
Data Analysis & Results

Incident frequency, repair duration, root cause analysis, down time, labor, replacement costs, lost production

Statistical Analysis Tools



All logistic delays for two similar PV systems revealing which components had the longest delay time before repair. System 1 faults are in blue and System 2 faults are in red



Inverter events, based on system operation time. Faults/failures represented by red circle and operation time represented by line. Most all matrix board faults resulted in board replacement. The bottom line shows all faults/failures

PVROM results – inform working groups

PV-RPM results – inform working groups

Comp-onent Failure Rates

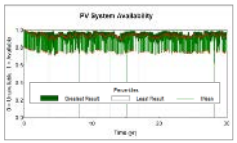
One Step Further – Combine Reliability and Performance Modeling

Cost & Labor Data Results

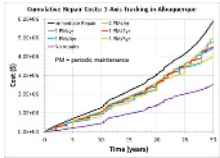
PV Reliability Performance Model (PV-RPM)

Ties *reliability* metrics to a *PV system performance* model. O&M & performance impacts for cost modeling

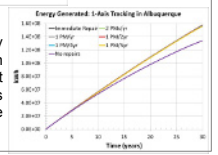
http://energy.sandia.gov/?page_id=6367



Grid, and system availability based on stochastic inputs over 30-year analysis period. 83% modeled cumulative production loss due to grid and system unavailability



Lifetime system costs of different repair scenarios. Looking at no repairs, to periodic, to immediate



Expected energy generation as a function of different maintenance options presented above

SunShot U.S. Department of Energy

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U.S. DEPARTMENT OF ENERGY

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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Results of I-V Curves and Visual Inspection of PV Modules Deployed at TEP Solar Test Yard

Peter McNutt, John Wohlgemuth, David Miller, Blaise Stoltenberg – NREL

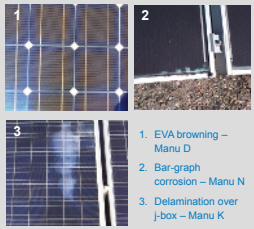
Background

- The purpose of the PV Service Life Prediction project is to examine & report on how modules fielded 5 or more years are holding up
- Testing performed January 13-16, 2014
- NREL compared test results to 2012 testing performed by University of Tucson (Kopp, et. al.) as well as against STC nameplate ratings
- Details of module tests from three manufactures are presented
- Present the common problems crystalline-silicon and thin-film modules exhibit

Tucson Electric Power Solar Test Yard

Test Method

- Perform visual inspection (per Packard 2012 paper)
- Take IR images
- Take photos
- Take I-V traces



1. EVA browning – Manu D
2. Bar-graph corrosion – Manu N
3. Delamination over j-box – Manu K

Test Equipment

- **Solmetric PVA-600 PV analyzer**
- **600 Vdc and 20 Adc**
- **Capacitive load**
- **Operating temperature -0°C to 50°C**
- **~ $5000**

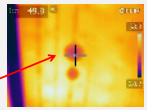
- Type K thermocouple
- 1.0°C resolution and accuracy
- Range -100°C to 200°C
- Wireless connection to PVA-600
- Field measurements include performance factor of PV modules or strings (measured / expected)

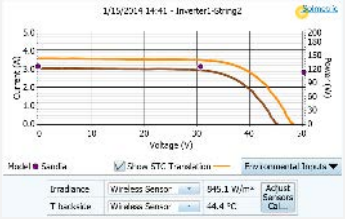
- *Reference cell – IMT Solar*
- *monocrystalline*
- *cell embedded in EVA between glass & Tedlar*
- *active temperature compensation*
- *0 to 1500 W/m² range*
- *Operating temperature -20°C to 70°C*
- *+/- 5% typical accuracy*
- *Wireless connection to PVA-600*

- ***FLIR T440 IR camera***
- ***320 x 240 pixel resolution***
- ***< 0.045 thermal sensitivity***
- ***Temperature range -20°C to 1200°C***
- ***7.5 to 13um spectral range***
- ***~ $11,000***

Manufacturer A

- Crystalline Si
- Deployed ~ 2003
- Glass superstrate and polymeric backsheet
- All 16 modules have bubbles in backsheet
- Discoloration pattern around j-box, parallel bus lines, and cell edges



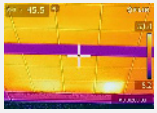


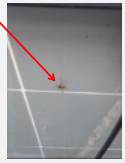
- In 2014, measured values divided by nameplate ratings were 44% and 94% for 2 modules
- In 2012 Kopp paper, the rating ranged from 44% to 94% for 8 modules

- Module Nameplate Ratings:
- Pmp = 180 W
- Imp = 3.33A
- Voc = 66.4V
- Vmp = 54V
- Isc = 3.65A

Manufacturer C

- Crystalline Si Module
- glass superstrate and polymeric backsheet
- *Deployed 2006*
- String I-V performance ranged between 78% to 89% (measured 2 strings of 9 modules – range was 58% to 89% in 2012 Kopp paper measuring 9 individual modules)
- Observed hot spots on 2 out of 18 modules





- 65% of nameplate rating I-V trace – 9 module string

- String STC Nameplate Ratings (9 modules):
- Pmp = 1521 W
- Imp = 4.77 A
- Voc = 388 V
- Vmp = 311 V
- Isc = 5.46 A

Major Visual Observations

Crystalline-Silicon modules

most have glass superstrates and polymeric backsheets

(manufacturer)

D. 9 modules, deployed 2004 - 8 modules have typical EVA browning (1 recent replacement); All have loose j-box lids; Labels have fallen off all modules. Output (I-V) of 3 modules ~ 82% of nameplate rating (see photo 1)

E. 10 modules, deployed ~ 2003 – 10 modules show no visible signs of defects. 2 modules ~ 76% of nameplate.

F. 8 modules, deployed ~ 2000) – all show typical EVA browning. No I-V taken.

G. 15 modules, deployed 2009 - 1 module had burn mark on the back; all modules have frame adhesive oozing out of frames onto module front No I-V taken.

H. 9 modules, deployed 2003 – no visual defects. 2 modules ~ 72% of nameplate.

I. 8 modules, deployed 2003 - All modules had some bubbles and ridges between cells in backsheet; EVA discoloration. 3 modules ~ 72% of nameplate.

J. 20 modules, deployed 2000 - Typical (but not pronounced) EVA discoloration. 3 modules ~ 69% of nameplate.

K. 72 glass-on-glass modules, deployed ~2001 - All have delamination above j-boxes; 6 modules have delamination in a corner or at an edge with subsequent corrosion of metallization. No I-V taken. (see photo 3)

Thin-film modules

L. CIS, glass-on-glass, (deployed ~ 2003) – 2 of 20 modules removed (due to broken glass); Remaining modules had no visual defects. 2 modules ~ 76% of nameplate

M. CIGS, polymeric front & backsheet with discreet cells (deployed ~ 2003) - Some curling of substrate and delamination of superstrate. 1 module ~ 76% and 1 module ~ 55% of nameplate.

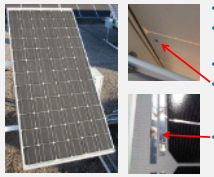
N. a-Si, glass/glass (deployed ~ 2004) - 1 of 150 had broken back glass; Corrosion around junction box contact feed through area on all modules; About 2/3rds of the modules had bar graph corrosion in lower corners. 4 module ~ 63% of nameplate. (see photo 2)

References

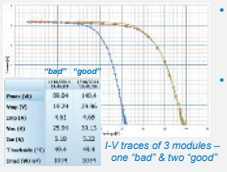
- TEP Solar Test Yard PV Site Visit - 2013/2/05), David Miller, NREL, April 2013.
- I-V Curves and Visual Inspection of 250 PV Modules Deployed over 2 Years in Tucson, Emily S. Kopp et al, University of Arizona, Tucson, 2012
- Development of a Visual Inspection Data Collection Tool for Evaluation of Fielded PV Module Condition, Corrine Packard et al, NREL, August 2012.
- PV SYSTEM REPORTS AT THE TEP SOLAR TEST YARD – available at http://uapv.physics.arizona.edu/pdfs/teptestyard_field_IVcurves.pdf
- Historic data for the TEP Solar Test Yard site is also available on the website http://uapv.physics.arizona.edu/dlpvdata.php

The authors would like to thank Adria Brook (U of AZ) and Randy Hunsberger (NREL), Work done under DOE Agreement # DE-AC36-08GO28308

Manufacturer B



- *Crystalline Si Module –*
- *glass superstrate and polymeric backsheet*
- *deployed 2005*
- *1 out of 18 modules had burn mark on back which was also visible on front of cell*
- *Evidence of overheating at output lead solder bond (6 out of 18)*



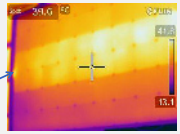
I-V traces of 3 modules – one "bad" & two "good"

- *IR image detected module with 2 rows of hot cells – I-V trace found module output to be 56% of expected*
- *Performance range for this module was not reported in 2012 Kopp paper*

comparison of "bad" (56%) and "good" (88%) modules

- Module STC Nameplate Ratings:
- Pmp = 170 W
- Voc = 44 V
- Isc = 5.4 A
- Imp = 4.9 A
- Vmp = 34.7 V

hot spot at j-box & 2 rows of hot cells



Conclusions

- *IR images quickly detect problems*
- *Visual inspection after IR image usually determines the exact cause of problem*
- *Testing should be done by teams of two or more people working closely together*
- *Best procedure would be to scan arrays & modules first with an IR camera, then take visual photos and I-V traces*
- *Major visual defects included EVA browning, delamination, burn marks, oozing adhesive, backsheet bubbles, and broken glass.*
- *Some modules show no signs of visual defects*
- *Overall, after being deployed from 4 to 12 years, the modules were found to be operating fairly well, still delivering from 55% to 82% of their nameplate rating*

- *NREL is looking for other older PV systems to do testing & analysis*
- *Contact: Peter McNutt | peter.mcnutt@nrel.gov | 303 384 6767*

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Data Science Approach to Time Series Analysis of Real-World PV modules

Yang Hu[1], Mohammad A. Hossain[1], Yifan Xu[2], Timothy Peshek[1], Jiayang Sun[2], Roger H. French[1]
[1]Solar Durability & Lifetime Extension Center, Material Science and Engineering, Case Western Reserve University, Cleveland OH, USA
[2]Center for Statistical Research, Computing and Collaboration (SR2c), Department of Epidemiology and Biostatistics, Case Western Reserve University OH, USA 44106

CASE WESTERN RESERVE UNIVERSITY EST. 1826 — think beyond the possible
GREAT LAKES ENERGY INSTITUTE
SDLE — SOLAR DURABILITY AND LIFETIME EXTENSION CENTER

Motivation

Photovoltaics capacity exceed 100 GW in 2012

In the US, a solar project will be installed, on average, every 4 mins.

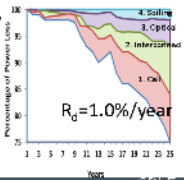
Lifetime & Degradation Science for PV Modules
- Convened by U. S. DOE, Basic Energy Sciences

Current warranty 25 year
- Degradation rate R_d less than 1.0%/year

Qualification testing not sufficient for reliability
- Does not guarantee lifetime

Quantify influence of each stress in real-world
- Requires better understanding of degradation mechanisms
- Lead to more sensible testing protocol

Outdoor testing is vital !
- It is the typical environment PV systems work with
- It is the only way of correlating real-world degradation mechanisms to indoor accelerated test



Case study of 60 modules on SDLE SunFarm

60 modules of 20 brands
- Distributed on 6 sites
- Three samples from each brand
- Same brand on the same site
- Brand name A–T

Observation period:
- November 25, 2012
- To May 31, 2013

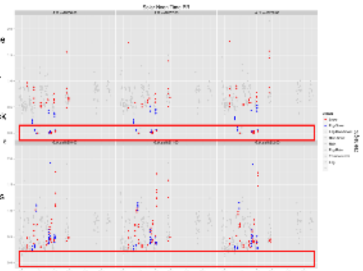
Purpose:
- Interpreting the information
- Develop a data cleaning and data munging procedure
- Integrate analytic procedure with Energy CRADLE
- Improve experimental design
- Evoke interests of further analysis

Analytical methods
- Raw data validation
- Exploratory data analysis
- Data assembly for performance metrics
- Subsampling of data
- Clustering

Snow covered PV module

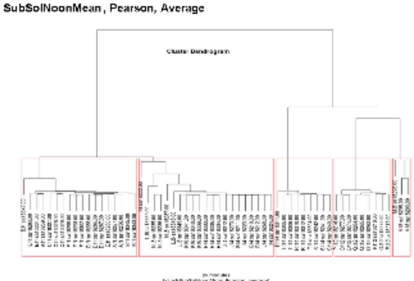
Snowy days
- Plot PR
- As a function of time
- Colored Snowy days data
- PR was very low or zero
- Snow cover mostly appear on fixed rack
- Also seen on stopped trackers

Snow cover
- Partially uncover help melting snow
- Arise thermal stress in PV module
- Potentially one of the degradation causes



Hierarchical clustering of 60 modules

SubSolNoonMean, Pearson, Average

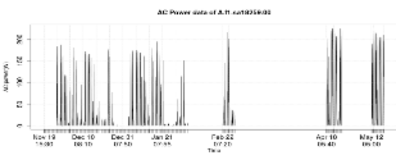


SunFarm Network

S-DLE Center SunFarm
Cleveland, OH
Lakeview 1MW SunFarm
Cleveland, OH
Under construction
Replex SunFarm
Mt. Vernon, OH
AEP Dolan Center SunFarm
Columbus, OH
Q-Lab (Existing)
Arizona
Dsh
Florida
Aw
Taiwan - UL
Taitung
Luihu
India – Gujarat
IIT gandhinagar

Raw data validation

1. **Baseline I-V characteristics**
   - SPIRE solar simulator 4600
2. **Power data**
   - Enlighten micro-inverter user interface
   - Three "gaps" in data collecting due to unexpected grid disconnection and human error
   - 99 days' data out of 183 days power data was collected.
3. **Weather data**
   - Global Horizontal Irradiance (GHI) data from Nov. 2012 to May. 2013 Sampling rate 1 min
   - Covert to plane of array (POA) irradiance
4. **Data alignment**
   - Align power data and weather data



Snow covered irradiance sensor

Irradiance sensor cross check

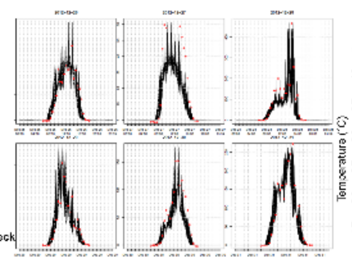
Sensor 1:
- Horizontal
- Sampling rate 1min
- Black curve

Sensor 2:
- Horizontal
- Sampling rate 30mins
- Red dots

Data alignment

Visually determine
- "2012-12-27"
- "2012-12-28"
- "2012-12-30"
- "2013-01-04"
- "2013-01-25"

Redundant sensors and sensor cross check are needed !

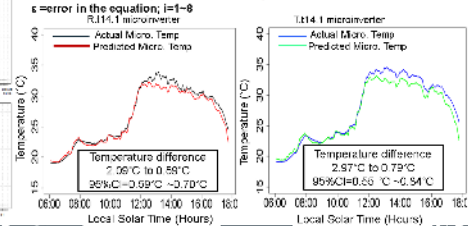


Predictive Model based on Linear regression

A linear regression model was used to develop an equation to predict the microinverter temperature

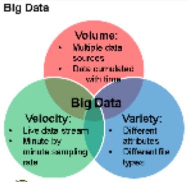
$$Micro.T_i = \sum_{j=1}^{6}\beta_{0j}x_{ij} + \left(\sum_{j=1}^{6}\beta_{1j}x_{ij}\right)Ambient.T_i - \left(\sum_{j=1}^{6}\beta_{2j}x_{ij}\right)Module.T_i + \left(\sum_{j=1}^{6}\beta_{3j}x_{ij}\right)Irradiance_i + \left(\sum_{j=1}^{6}\beta_{4j}x_{ij}\right)Power_i + \varepsilon$$

ε = error in the equation; i=1~6



Data Science Approach

Big Data



hadoop
- Open-source software framework
- Storage and large scale processing of data
- On clusters of commodity hardware

Energy-CRADLE
- Data Sources
  - SunFarm Network
- Data Acquisition
  - Local pre-storage
- Data Processing
  - Hadoop Distributed File System (HDFS)
  - HBase non-relational, distributed database
- Data Representation
  - Energy-MiMi, web interface

R language
- Free software programming language
- Statistical computing and graphics
- Well developed packages for statistical analysis

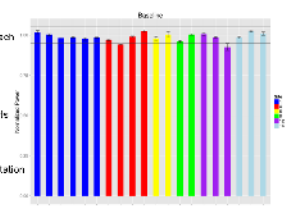
Exploratory data analysis on integrated performance

Baseline

Evaluation of each module
- 16 I-V curve were taken for each module
- Maximum power output(P_{max})
- Corrected to Standard Test condition
- According to IEC 60891
- Deviations of 16 measurements between 0.04%-0.9%

Evaluation of 20 brands
- Means of three samples
- +/- 5% common market expectation
- Brand H and Q didn't reach

Help decision making
- Power plant owner
- Module price based on nominal power
- Deviation also influence modules performance in strings



e.g.

Brand	Initial $/W	Baseline	Final $/W
A	0.82	101%	0.812
Q	0.80	92.5%	0.865

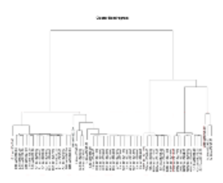
Hierarchical clustering of 60 modules

Data set:

Subseted SolarNoon Mean
- PR time series data of 60 modules
- Subtract snow covered days
- There are 85 days in common

Distance metric:
- Euclidean, ordinary distance in 85 dimensions
- **Pearson, Pearson Correlation measures the similarity in shape between two profiles.**
- Dynamic time warping, measuring similarity between two temporal sequences which may vary in time or speed. Widely used in Time series analysis
- Data was aligned, Euclidean, Pearson are applicable

Linkage criteria:
- Distance between sets of observations as a function of the pairwise distances
- Single : shortest distance
- Complete : longest distance
- **Average: average distance**



Conclusions

Enabled remotely diagnostic of PV system performance in the field
- Will be applied to Energy CRADLE

Data analytics procedure was built
- Including raw data validation
- data alignment
- sensor data cross check
- data assembly
- data sub-sampling

Data clustering
- Observed potential groups in data, conformed with clustering analysis.
- Solar noon time PR found malfunctioning brands and trackers
- Distinguished fixed rack and trackers

Future Work

Improve SunFarm metrology and study design
- Irradiance metrology and redundant sensors

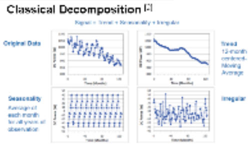
Predictive model
- Identifying major contribution stressors to the over all system performance lost
- Feature selection

Time Series Analysis (TSA)

Continuous data monitoring:
- **Photovoltaic for Utility Scale Application(PVUSA)**
  Power data, ambient T, wind speed
  Estimated module temperature
  Correct to PVUSA test condition (PTC)
- **Performance Ratio (PR)**
  Compare real-world performance to performance under standard test condition(STC)
  Quantitatively compare the system performance of systems with different configurations at different locations
- **DC/POA Temperature corrected**
  "Total uncertainty fluctuates somewhat from dataset to dataset – DC/POA Temp-corr best performing"[1]

Point in time measurements:
- **Indoor I-V curve**
  With indoor solar simulator
- **Outdoor I-V curve**
  With portable solar simulator
  Both methods need to disconnect module from array

Classical Decomposition [2]



ARIMA + Decomposition [3]

AutoRegressive Integrated Moving Average (ARIMA)

References:
[1] Jordan, Dirk C. and Sarah R. Kurtz. "Photovoltaic degradation rates—an analytical review." Progress in Photovoltaics: Research and Applications 21.1 (2013): 12-29.
[2] S.G. Makridakis et al., "Forecasting", New York: John Wiley & Sons 1998.
[3] Jordan, Dirk. Methods of Analysis of Outdoor Performance Data. National Renewable Energy Laboratory, 2011.

Data assembly

Performance metrics
- In order to quantitatively compare the system performance of systems with different configurations at different locations,

Normalized instantaneous quantities

$Y_r = POA/G_0, G_0 = 1kW/m^2$

$Y_{DC} = P_{DC}/P_0$

$L_c = Y_r - Y_{DC}$

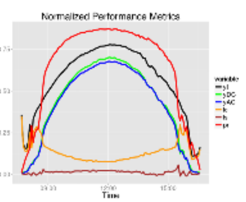
$Y_{AC} = P_{AC}/P_0$

$L_s = Y_{DC} - Y_{AC}$

$PR = Y_{AC}/Y_r = (P_{AC}/POA)/(P_0/G_0)$

Solar time
- Convert performance metrics
- From local time to solar time

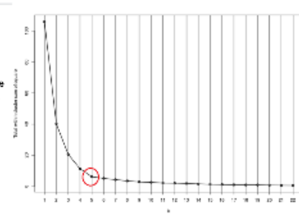
Data filtering
- PR of +/- 15 min solar noon time
- Seven data points for each



Kmeans Clustering

Number of clusters k.

Within Cluster Sum of Squares (WCSS)
- Assign each observation to k clusters such that the total WCSS is minimized.
- Plot WCSS as a function of K
- WCSS always decrease
- "Elbow point"
- Adding more cluster doesn't give a much better modeling of data



K-mean clustering indicate that the number of clusters is 5

Partition the hierarchical clustering result into 5 groups

Acknowledgement

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Department of Material Science and Engineering:

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Mohammad A. Hossain
Daniel Dryden
Nicholas Wheeler
Dr. Timothy Peshek
Prof. Roger French

Department of Epidemiology and Biostatistics

SR2c Center:
Dr. Yifan Xu, Prof. Jiayang Sun

Department of Electrical Eng. & Computer Sci.

Division of Biomedical Informatics:
Yashwanth R. Gunapati, Yi Hou, Prof. G.Q. Zhang

this presentation contains no confidential information

PV Performance and Energy Harvest over Time for Utility and Rooftop Systems

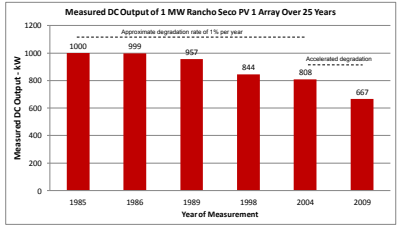
Obadiah Bartholomy, TJ Vargas, Megan Simone, Sacramento Municipal Utility District

Rancho Seco Utility PV Performance Measurements over 25 Years

Rancho Seco PV was installed in 1984 with a nameplate capacity of 1.18 MW DC. The system operated consistently for 27 years, with regular maintenance primarily associated with tracker operation and periodic replacement of PV modules and other inverter and array components.

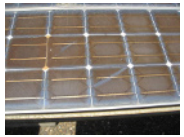
Rancho Seco PV System Attributes

Age	27 Years of operation (1984-2012)
Location	Sacramento, CA
System Size, Type	1.18 MW DC Nameplate, Single Axis Tracker
Module Type	Arco M52N
# Modules	28,672
Backsheet	Tedlar®/PET/Tedlar® ("TPT™")
Climatic Conditions	Temperate / High Desert



Measurements were taken using an IV curve tracer on all 56 half-source circuits as well as current and voltage measurements on each of 16 subfield strings Measurements were taken by Southwest Technology Development Institute in 1985, 1986, 1989, 1998, and 2004, and by Sunedison, LLC in 2009

Module Quality and Related Issues



Images and Descriptions summarized from SunEdison, LLC 2009 inspection and testing report

Darkened EVA encapsulant occurred early on in life of array, did not appear to impact performance. Cell cracking more prevalent in later years, effecting approximately 5% of array in 2009 inspection

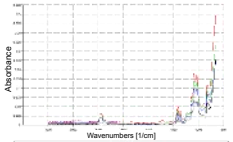
Less Commonly found Issues affecting a very small number of modules

Water Ingress resulting in cell corrosion and some cells showing internal arcing — Unsealed J-box missing plug, a few were missing sealant — Arcing at back of module — Severe cracking of cells

DuPont Testing on Module Backsheet Tedlar® for Arco M52N Modules

Images and Descriptions provided by DuPont based on tests performed on removed and spare modules

Visual inspection shows essentially no appearance difference for backsheet between exposed and unexposed modules



Material analysis and characterization of Tedlar® material compares favorably to modules installed at SMUD PV1 in 1984

Demonstrated consistent field performance of Tedlar®-based backsheet

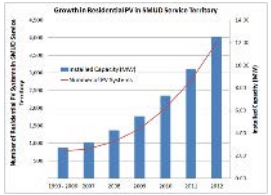
"We were very clearly specifying what we wanted to buy." SMUD laid down the criteria for the design of the modules along with the type and level of quality assurance required*

*Source: *Electric Light and Power*, 62/8, 1984

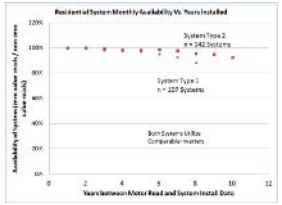
Measuring Performance of Groups of Residential PV Systems

SMUD's residential PV programs began in the early 1990's with a utility-owned approach to minimize risk to customers of the relatively new technology. Transitioning to customer-owned, utility aggregated programs and then strictly utility incentivized programs occurred between 2000 and 2007.

One unique aspect of these programs is that SMUD required separate meters for monitoring production of the systems. With the switch to smart-metering, there are now opportunities to understand a variety of system performance issues remotely and more completely.



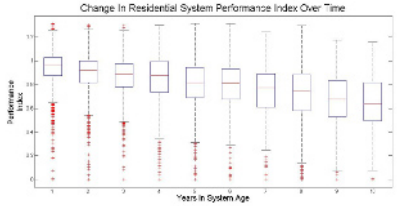
Despite some of the lowest electricity rates in the state of California, and a top tier rate of approximately $0.18 per kWh, PV growth has been steady and accelerating



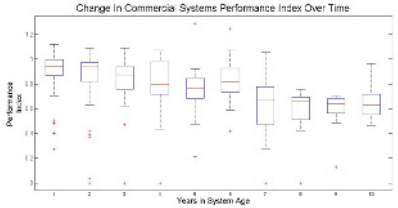
System Availability

System availability for these purposes was determined from examining 'zero' reads from monthly measured data. For those reads that were zero for an entire month, they were assumed to be unavailable for the month. Partial month or partial day availability was not examined for this exercise.

The data show for two similar vintage, modern multi-crystalline module technologies with inverters produced from the same manufacturer, a fairly substantial decline in availability for both system types after 6-8 years, indicating value in both monitoring and follow-up system checkups



Using Satellite based irradiance measurement and individual PV system modeling provided by Clean Power Research, and comparing to actual metered monthly values, these charts demonstrates observed drops in performance index for residential systems over time. Commercial systems showed less degradation, but also had fewer systems in some of the year-bins, limiting ability to make robust conclusions. However, it is also intuitive that the commercial systems would have lower degradation in system energy harvest rates due to there being less shading and a higher likelihood of system monitoring. The most significant performance factor impacting residential PV systems is most likely shading, followed by component level failure. Further analysis of hourly metered data should provide more robust shade impacts assessment.



Powering forward. Together.

SMUD™

Regional Influence on Module Design Quality:
Qualification Testing Failure Rate Results from Six Regional Labs of TUV Rheinland around the World

TÜVRheinland® Precisely Right.

G. TamizhMani[1], B. Li[1], B. Shisler[1], C. Monokroussos[2], C. Dreier[2], S. Lim[3], CS. Kamalaksha[4], S. Sugita[5] and E. Janknecht[6]

[1]United States, [2]China, [3]Korea, [4]India, [5]Japan, [6]Germany

TÜVRheinland® Precisely Right.

1. MOTIVATION

Between 2011 and 2013, there was an immense price pressure/competition on/between the PV module manufacturers and this price pressure has steered many manufacturers to cutting corners with poor quality materials or introducing unqualified materials. This paper analyzes if these changes influence the module design quality from two perspectives:

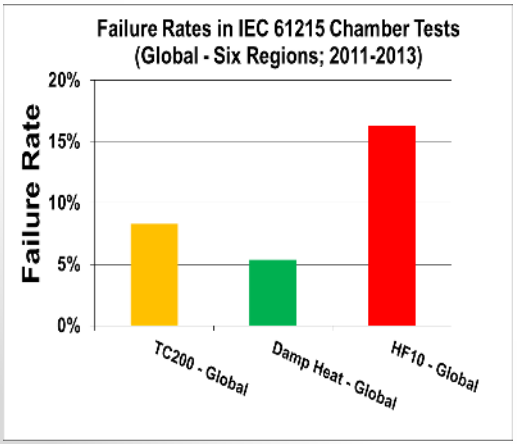
(i) is the failure rate in the 2011-2013 period dependent on the specific regions of the world where the modules were produced and tested?

(ii) is the failure rate in the 2011-2013 period dramatically changed as compared to the prior failure reported between 1997 and 2011?

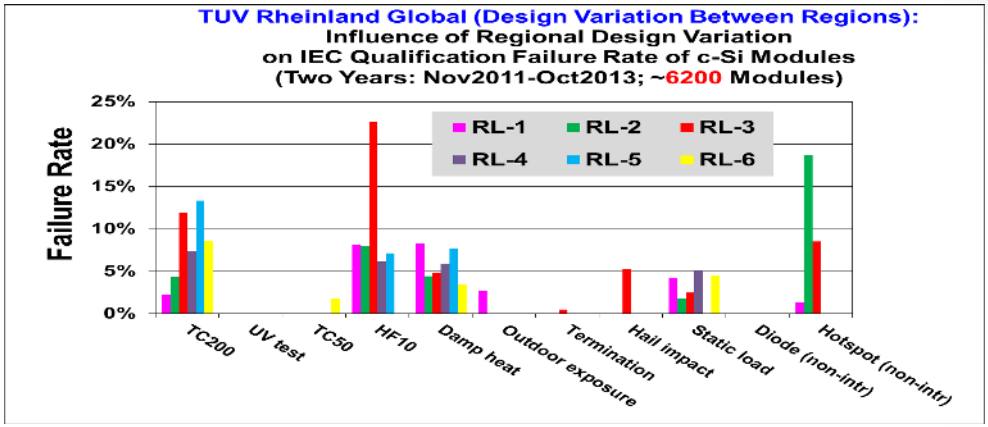
2. DATA ANALYSIS APPROACH

- To uphold a country-blinded approach for this publication, the locations of the six TUV Rheinland's Regional Laboratories (RL) are identified by the following randomly assigned codes:
  RL-1, RL-2, RL-3, RL-4, RL-5, RL-6.
- Only the failure rate analysis of crystalline silicon technologies is presented in this paper.
- The failure rate reported in this paper is calculated using the following formula: Failure Rate (%) = Number of modules failed in a specific test in a specific period ÷ Total number of modules tested in the specific test in the specific period.

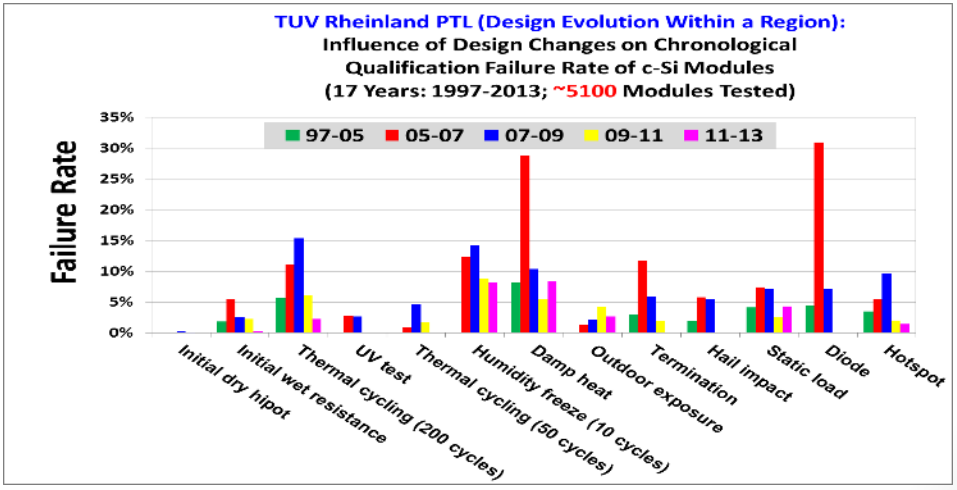
3. FAILURE RATES IN IEC 61215 CHAMBER TESTS (Global-Six Regions; 2011-2013)



4. DESIGN VARIATION between the REGIONS (all tests of IEC 61215 considered; 2011-2013)



5. DESIGN EVOLUTION within a REGION (all tests of IEC 61215 considered; 1997-2013)



6. CONCLUSIONS

- Between Regions - Regional variation influence on the design quality: Stark regional dependence on the failure rates has been observed for the three stress tests of thermal cycling (metallic material issue?), humidity freeze (polymeric material issue?) and hotspot (cut-cell issue?).
- Within a Region - Regional evolution influence on the design quality: Encouragingly, the test results obtained at TUV Rheinland PTL (United States) over the past 17 years indicate that the failure rates are generally lower in almost all the stress tests of qualification testing for the latest period of 2011-2013. To differentiate these products "Qualification Plus" testing, "PV+" Testing and/or "Comparative " testing are needed.

Contact (Mani): gtamizhmani@tuvptl.com

Initiation of Reliability Studies At GREEN-IPUC/PUCMINAS, Brasil

Antonia Sônia Alves Cardoso Diniz
Study Group of Energy – GREEN-IPUC, Polytechnical Institute - IPUC
Pontifical Catholic University of Minas Gerais - PUCMINAS
Rua Dom José Gaspar 500, CEP:30000, Belo Horizonte, Minas Gerais, Brasil
asacd2012@gmail.com; asacd@pucminas.br

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. An important area of GREEN solar is testing photovoltaic BOS and solar heating water systems for the Brazilian Labeling Program - PBE / INMETRO (with which GREEN has been involved since 2004).

Reliability Studies at GREEN-IPUC

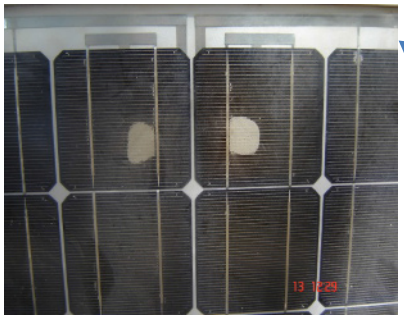
The PV reliability research started at GREEN Solar in 2013, with a project in this new PV area named "Evaluation of Field Failure and Degradation Rate of Installed PV Modules and Systems in Minas Gerais, Brasil" and funded by the Minas Gerais State Science Foundation – FAPEMIG, and PUCMINAS. The ***objective*** of the project is to evaluate field performance and degradation of PV modules, and isolated and small-scale grid-connected PV systems installed in Minas Gerais by CEMIG (Energetic Company of Minas Gerais).

In the first-phase of the project, ***visual inspections*** of the PV modules and systems were undertaken. Initial results have shown that the main failure modes found in PV *modules* are: *light corrosion, encapsulant delamination, broken glass, hotspots, and junction box and connector failures*—indicated the the "Examples" on this poster.

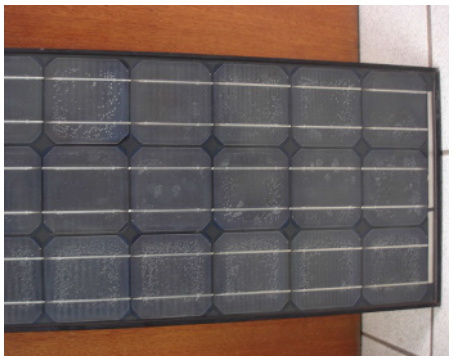
Additionally***, improper storage*** had led to CEMIG's loss of 2000 PV modules because the glue cardboard packing adhered to front glass. In the PV systems area, a major inverter failure source was identified and corrected. This was associated with higher than expected temperatures internal to the installation cabinets and the lack of adequate forced ventilation for the inverters.

Examples: PV Module Degradation

Browning



Encapsulant Delamination



Summary

PV reliability research was intiated at GREEN Solar in 2013, complementing the solar-thermal testing/labeling program. This PV research enhances the capabilities of the Laboratory and is important for the bankability of PV projects as Brasil expands its PV investments.

(This presentation contains no proprietary information)

20-Year field exposed polycrystalline silicon PV modules: detailed visual inspection and analysis

Tony Sample and Alberto Pozza

European Commission, DG JRC, Institute for Energy and Transport, Ispra (VA), Italy

Introduction

70 polycrystalline glass-glass modules from Helios technology were installed in 1991 in the outdoor test field at the European Solar Test Installation in Ispra. The modules consisted of 36 series connected pseudo square solar cells, divided into two strings, of 19 and 17 cells. The modules were divided into two groups, each connected to an inverter, keeping modules in operation around their maximum power point. The system was field exposed without interruption from 1991 to 2010 in moderate subtropical climate, and the analysis of electrical parameters degradation as well visual inspection according to IEC 61215 has been published [1]. We present the results of detailed visual inspection performed according to the protocol proposed by Packard et al. [2] and the spatially resolved analysis using LBIC and electroluminescence techniques.

Visual inspection:

Visual inspection according to IEC 61215 was performed on the majority of modules in 2010. More than 90% of defects were due to 4 types:

- Cells discoloration
- Degraded cable feed through
- Delamination and bubbles formation
- Chipped or cracked glass (module front or back)

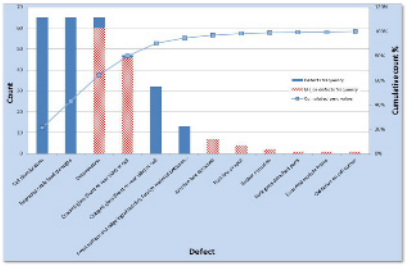


Fig.1: result of 2010 visual inspection

Visual inspection was repeated for all modules according to the protocol proposed by Packard et al. [2]. Part of the results together with the cumulative percentage of defects are reported in the graphs of fig.2

Characteristics of the graph:

- Height of columns: occurrence of each defect as a percentage of the total number of defects found with the visual inspection in all modules.
- Each defect type is divided into four severity levels corresponding to protocol indications eg.:
  - "cells dark discoloration": severity 4 = 75% - 100% discolored area
  - "cracked glass": severity 1 = 1 crack; severity 2 = 2 cracks; severity 3 = 3 cracks

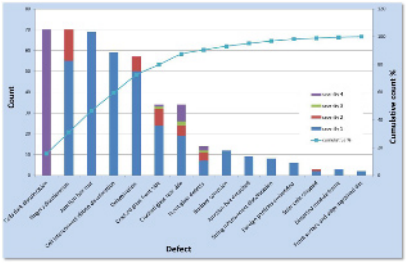


Fig.2: result of 2013 visual inspection

Figure 2 contains a selection of information useful to compare the results of the previous visual inspection.

Some defect types found in 2010 are not present in 2013 eg: "degraded cable feed throughs". This defect was not evident in 2013 as the cables were removed from modules in 2010 after visual inspection.

Comparison of the two methods:

- The new protocol contains more detailed description of defect types
- Each defect type is analyzed in more detail by "severity" classification

Electrical comparison:

Direct correlation between visual defects and electrical degradation was not found even taking into consideration defect severity as a parameter. This is due to the low average degradation rate (-0.24% P_{max} per year)

- Data analysis showed correlation between degradation of P_{max} (-0.24% /y) and I_{sc} (-0.15% /y) (fig.3).

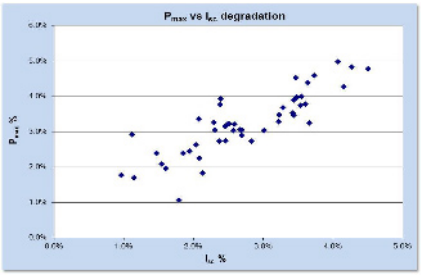
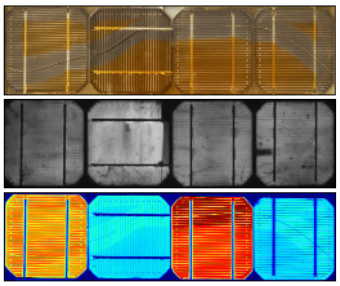


Fig.3: 1991–2010 P_{max} versus I_{sc} degradation

LBIC and electroluminescence analysis:

I_{sc} degradation was found to be related to extensive yellowing on all modules. Analysis was performed by means of visual, LBIC and electroluminescence inspections:

- LBIC: scan of the complete module with 633nm HeNe laser and lock-in amplifier
- EL: picture taken with injection of I_{sc}



Visual

Electroluminescence

LBIC (false colour image to enhance differences within the cell)

Fig.4: Visual, EL and LBIC images of the same module area

Visual: extensive EVA yellowing, extensive glass crack, no yellowing near cracked area (effect due to oxidative bleaching)

EL: several defects visible (cracked cell, finger interruptions, scratches). No difference between area with and without yellowing. Cells do not show damage by moisture ingress from glass crack.

LBIC: higher photogenerated current in the area without yellowing (optical coupling is limiting factor for current).With dark LBIC technique, only the difference of response inside a cell is to be considered. (Cell to cell comparison is not possible as the response is dependent on the complete string connection).

Conclusions:

Visual inspection:

- Quantitative information on defect types and occurrence available with new proposed protocol.
- Possibility to analyze more in depth the correlation of visual defects and electrical parameters degradation.

LBIC and electroluminescence analysis:

- Main degradation factor was found to be optical coupling degradation due to extensive yellowing, present in all modules, causing I_{sc} losses.
- Moisture ingress from glass crack did not cause cell degradation.

www.jrc.ec.europa.eu

The information contained here does not include confidential information and is suitable for public release

Joint Research Centre

[1] Polverini D. et al. "Polycrystalline silicon PV modules performance and degradation over 20 years", *Progr. Photovoltaic: Res. Appl.* 2013; 21: 1004-1015

[2] Corinne E. Packard et al. "Development of a Visual Inspection Data Collection Tool for Evaluation of Fielded PV Module Condition", *Technical Report* NREL/TP-5200-56154 August 2012

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Risk of PV fire caused by solder bond failure

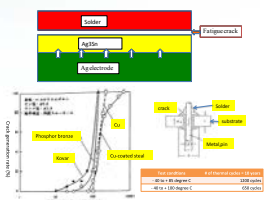
Ag dissolution into solder in the interconnection between Ag electrode and Cu ribbon

National Institute of Advanced Industrial Science and Technology
AIST

Uichi Itoh[1], Manabu Yoshida[1], Hideo Tokuhisa[1], Kohichi Takeuchi[2] and Yasuyuki Takemura[2]
1 National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305, Japan
2 Ites cooperation, Ritto, Shiga 520-3531, Japan

Motivation

- Ag dissolves into solder even in low temperature[1,2]
  - Solder bond connection on Ag electrode is not allowed in consumer electronic assembly when considering long term reliability more than 2 years.
  - Brittle Ag-Sn compound is formed when Ag dissolved into solder.
  - Cracks at the interface of solder and Ag-Sn compound >> arc discharge >> risk of fire
- Long-term solder bond failure
  - Metals composed of solder alloy tends to separate into individual metal grain for long term. Grain size becomes large when shaking.
  - Cracks generated at the boundary of grain with different mechanical character >> arc discharge >> risk of fire



Solder Bond Connection in Crystalline Si PV module

- Cu ribbon-solder-Ag electrode-Si Cell

- Cu ribbon-solder-Cu ribbon
- By-pass diode connection at junction box
- Circuit board at inverter

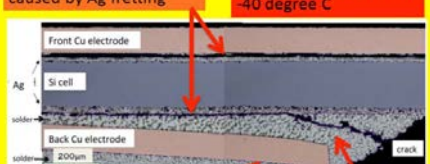
Background

Solder Bond Failure in Consumer Electronics

- CRT TV fire
  - ←crack at solder bond and insulation failure at fry-back transformer
- Fluorescent lamp fire
  - ←crack at solder bond at inverter. It may be caused by long-term thermal cycle of solder.
- Hot-water supply system leads city gas leak
  - ←crack at solder bond at sensor circuit. It induces to open the gas valve

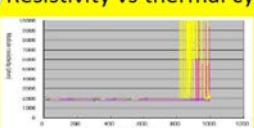
Crack at the interface of solder and Ag electrode caused by Ag fretting

Cross section view of Si solar cell after 1000 thermal cycles (+85 to -40 degree C

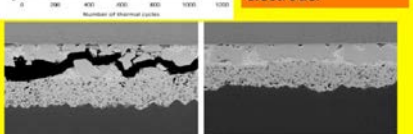


Solder bond failure due to growing metal grain induced by shaking caused by the large TEC difference of Si and Cu.

Resistivity vs thermal cycles of PV module



There are connecting and disconnecting areas at the interface of solder and Ag electrode.



Disconnecting area

Connecting area

Conclusion

- Ag dissolution into solder (PbSn, SAC) >> AgSn compound formed >> crack is generated at the interface of AgSn and solder >> hot spot [3]>> arc discharge >> risk of fire
- Metal grain of solder grows by shaking >> ununiformity of adhesiveness of solder grain>> crack is generated >> arc discharge >> risk of fire

Acknowledge

This work is supported by New Energy and Industrial Technology Development Organization (NEDO) project "Development of Next-generation High-performance Technology for Photovoltaic Power Generation System"

References

W.G.Bader "Dissolution of Au, Ag, Pd,Pt, Cu and Ni in a molten Tin-Lead solder" Welding Journal Welding Research Supplement, Dec (1969) p551s-557s.
[2] G. Cuddalorepatta1, A. Dasgupta1, S. Sealing, J. Moyer, T. Tolliver and J. Loman, "Durability of Pb-free solder between copper interconnect and silicon in photovoltaic cells" Prog. Photovolt. Res. Appl. 18, 168- 182 (2010)
[3] K. Kato, "PVRessQ! PV module failure observed in the field" Photovoltaic Module Reliability Workshop 2012.

the way to trust KCL 한국건설생활환경시험연구원
Korea Conformity Laboratories

Outdoor Exposure Testing for Glass-to-Glass PV module for Building Application in Korea

Hanbit Kang, Jonghwa Song

This presentation contains no confidential information

CONTENTS

INTRODUCTION

RELIABILITY TEST

INFRASTRUCTURE

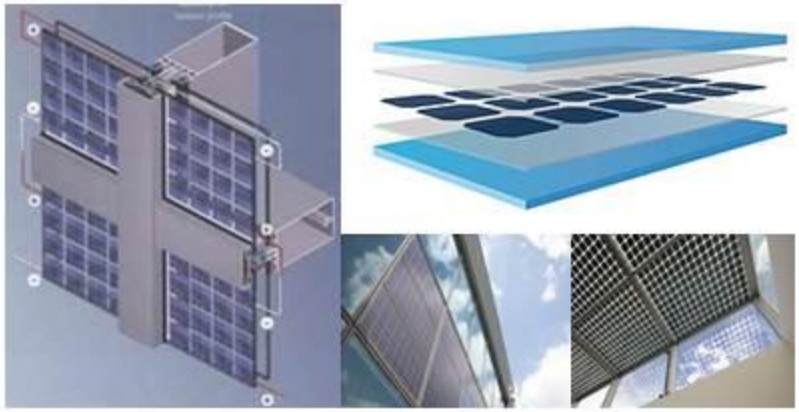
FUTURE WORKS

INTRODUCTION

Glass-to-Glass PV Module for Building

Conventional PV Module

Glass-to-Glass(G2G) PV Module



- Glasses on both sides of the module; **strong for severe environment, great thermal insulation performance.**
- G2G module transparency **creates a new aesthetic value of building**.
- System efficiency and output energy depends on the **module encapsulating materials**. [1]
- Development of life reliability test of G2G module as building materials is needed.

[1] Lasnier F, Gang-Ang T. Photovoltaic engineering hand-book. Bristol: Adam Hilger; 1990.

INTRODUCTION

OBJECTIVE

PV module

+

Glass(Curtain wall)

GtoG PV module

Performance Test

- IEC 61215(c-Si)
- IEC 61646(a-Si)

Reliability Test

- Accelerated life test
- Outdoor exposure test

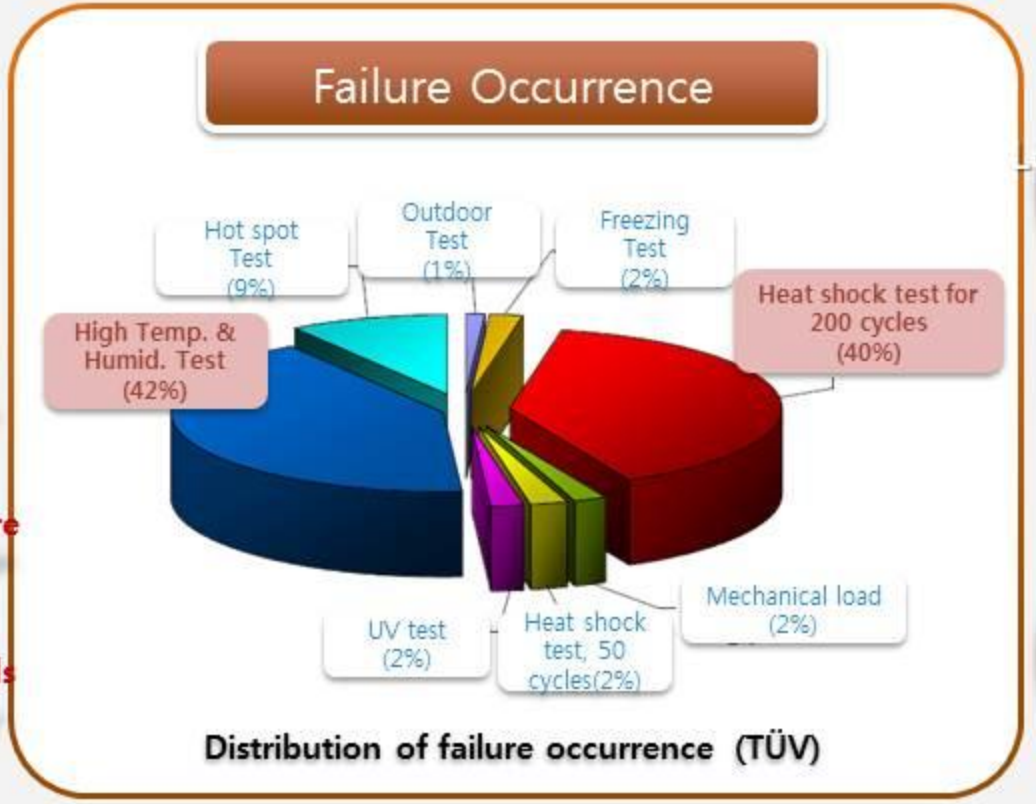
- **Glass :**
  - KS L 2002 (Tempered glass)
  - KS L 2004 (Laminated glass)
- **Building Materials**
  - ASTM E 283-04 (Air Leakage)
  - ASTM E 331-00 (Water Penetration)
  - ASTM E 330-02 (Structural Performance)

"Performance and Reliability Evaluation Method for G2G PV module

; Through Exterior Windows, Curtain Walls and Doors"

RELIABILITY TEST

Major Failures of Modules



Distribution of failure occurrence (TÜV)

Long-term stability of PV module components

Requirement of operation for 20 years

RELIABILITY TEST

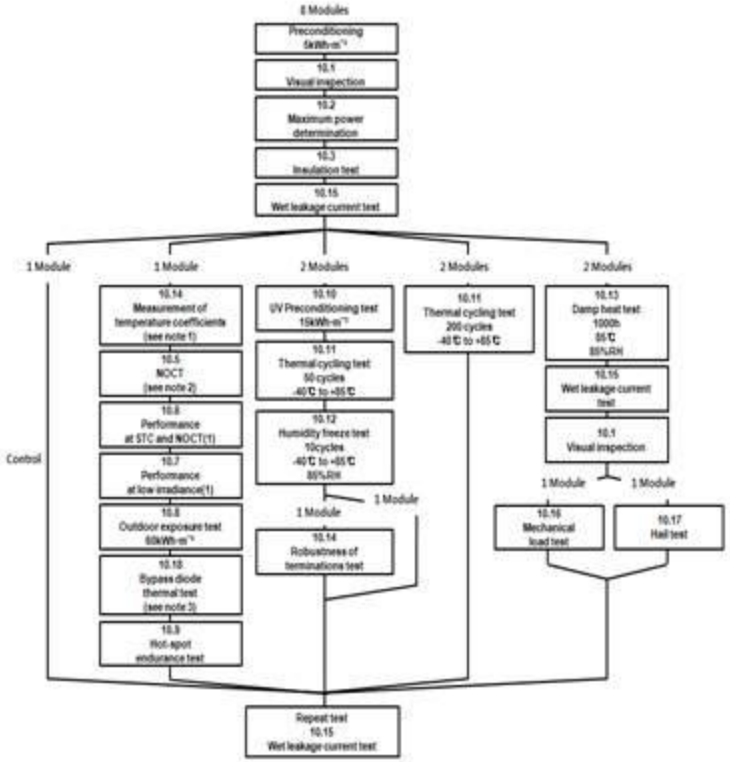
Development Process

한국건설생활환경시험연구원
Korea Conformity Laboratories

✓ IEC 61215/61646(c-Si, a-Si terrestrial PV module) + Construction Standards

➔ Degradation factor : **Irradiation**, **Temperature**, Humidity.

IEC 61215



Construction Standards

Glass Standards

- ✓ **Shot Back**
- ✓ **Bends & Curves**

Building materials Standards

- ✓ **Air Leakage**
- ✓ **Water Penetration**
- ✓ **Structural Performance**

Mock-up test

- ✓ **Application (Curtain Wall)**

INFRASTRUCTURE

Test Apparatuses in KCL

한국건설생활환경시험연구원
Korea Conformity Laboratories

Building Materials Test

Mock-up Test of large scale BIPV
Total performance test of Weathering

- **Energy Environment Technology Center**
  - Energy Efficiency and Insulation Test
  - Air Leakage/Water penetration/ Wind pressure Test
  - Fire Safety Test
  - Insulator Test
  - etc.
- **Outdoor Experimental Test Center**
  - Weathering Test
  - Outdoor Exposure test
  - Curtain Wall Mock-up Test

▶ Curtain Wall Mock-up

▶ Fire Test

▶ Thermal Transmittance

PV Performance Test

PV performance Test
KS C IEC 61215, 61646

- **Outdoor Experimental Test Center**

Photovoltaic Performance Test equipment

Solar Simulator

Mechanical Test

Hail Test

Outdoor exposure

I-V Curve

Bypass Diode

INFRASTRUCTURE

Outdoor Exposure Site

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Korea Conformity Laboratories

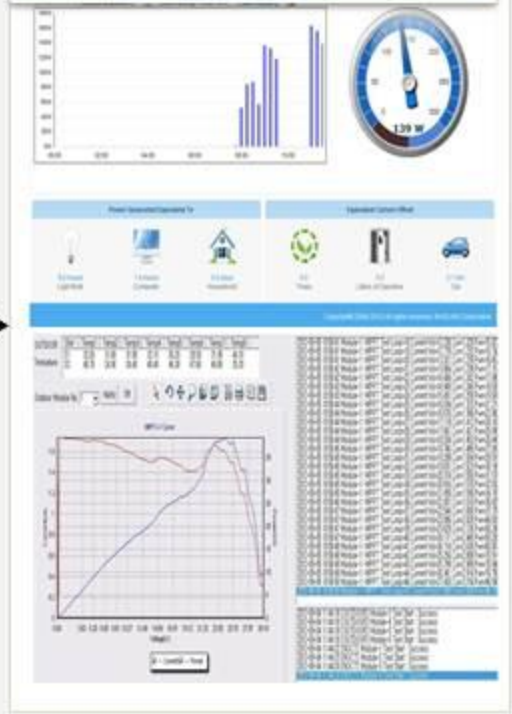
Outdoor Test Facility

Seosan in west sea, Korea (48,000 m2)
Area for PV module (5,200 m2)
Max Power : 500 kW (usable area)

Outdoor NOCT Testing

Field Failure Testing

Reliability D/B



Weathering data
(T, humidity, irradiation, etc.)
Electrical data
(I-V, Power, etc.)

INFRASTRUCTURE

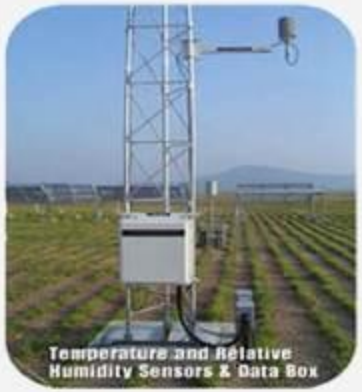
Environment Monitoring Site

Weathering Environment Monitoring Equipment

Real-time Data acquisition of temperature, humidity, rainfall, solar irradiance

UV Pyranometer
- Angle : 5, 30, 37, 45°

Total Pyranometer
- Angle : 5, 30, 37, 45°



Under Glass Pyranometer(UV&Total)
- Angle : 5, 30, 37, 45°

White Panel Temperature

Black Panel Temperature

Wet Time (젖음 시간)

< Salt measurement system >

<Acid rain measurement system>

FUTURE WORKS

Performance Comparison

| Module Performance |

Performance comparison between conventional PV module and G2G PV module

1 | Module Performance Testing |

Conventional PV module

Glass-to-Glass PV module

2 | Outdoor Exposure Testing |

c-Si G2G PV module a-Si G2G PV module

FUTURE WORKS

Performance Comparison

Building Application

Performance simulation for building application

Curtain Wall

- Installation angle : 90°

Roofing

- Installation angle : 45°

CONCLUSION

Summary and Conclusion

1. Main failure factors that examined by outdoor exposure test are solar irradiation and temperature, which could be degradation factors of G2G module reliability test.

2. Especially for G2G PV module, the test for laminated glass(KS L 2004) will be carried out as building materials.

3. Comparison tests ; ① module performance, ② installation type, have been implemented for building application.

4. As a result, standard 'Performance and Reliability Evaluation Method for G2G PV module' will be crystallized in KOREA.

Case Study of Using a Modified "DC/POA" Method in Determining PV System's Degradation Rate and the Impact of Data Filters

Wilson Zhang, Teck Cheng Tan, Nick Rose, REC Solar, Singapore

Abstract

Outdoor degradation rates of a PV system can be assessed remotely using DC power and plane of array (POA) irradiance measurements. In this work, a modified so-called "DC/POA" method is introduced to determine the degradation rates of several PV plants of less than 3 years by analyzing the meteorological and inverter hourly and sub-hourly time-series data collected from the data-logging equipment without conducting site inspections. Various filters are applied prior to the linear regression technique to reduce the outliers in the data which is caused by several known issues such as low-light behaviours, data irregularities and system outages. The degradation rates and confidence interval are presented; its relationships with various filters are also discussed. It is found out that the degradation rates are sensitive to data filters and further refinements are required to isolate module degradation rates from system degradation characteristics of the DC system.

Introduction

A robust method to determine the degradation rate of PV systems on site to serve as tool in monitoring the decline in performance of the PV modules installed in the field. Specific filters were applied to DC/POA method, which is recommend as most precise among other methods [1].

Method

Data Acquisition → Determine Filter Criteria → Filtering → Temperature Corrected Power, P_{25} → Linear Regression

- Data Acquisition: -Outdoor, inverter & Meteo. sensor time series; Hourly, Sub-hourly
- Filtering: -Irradiance, -Performance Ratio, -Module Temp.

→ System degradation over time is measured at the AC output of the inverter

→ Modified NREL method [2] filter guidelines :

- Daylight data only
- Removal of any record with missing data for any parameter
- Removal of any record with using Irradiance filter condition
- Remove any records using determined PR condition of site
- Include only records with module temperature within 0 to 50ºC range (minimise the thermal lag effects at extreme temperatures)

→ Module power is adjusted back to 25ºC equivalent via the following:

$$P_{25} = Power_{meas} \times [1 + \gamma(T_{mod} - 25°C)]^{-1}$$

→ Performance Indicator (PI):

$$PI = \frac{Power_{meas} \times 1000}{G \times Power_{rated} \times [1 + \gamma(T_{mod} - 25°C)]}$$

→ PI is plotted against time from the commissioning of the monitoring system

→ Linear regression of data post filtered dataset to determine Degradation Rate, Rd

Sites

Site	Location	System Size	Commissioning Date	Analysis Period	Module	Inverter	Irradiance Sensor
System A	Germany	725 kWp	Dec-10	37 Months	REC230PE	Refusol 630K	K&Z SMP11
System B	Germany	679 kWp	Dec-10	37 Months	REC210PE	Refusol 630k	K&Z SMP11
System C	Italy	992 kWp	Aug-11	26 Months	REC235PE	SMA 800CP	Silicon Sensor
System D	Italy	998 kWp	May-11	32 Months	REC235PE	SMA 800CP	Silicon Sensor

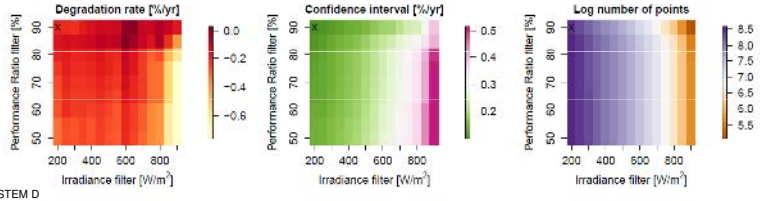
Uncertainties

Measurements	Sensor Accuracy
AC, DC Parameters	2%
K&Z SMP11 Pyranometer	1%
Silicon Irradiance Sensor	5%
PT1000 Module Temp. Sensor	1%

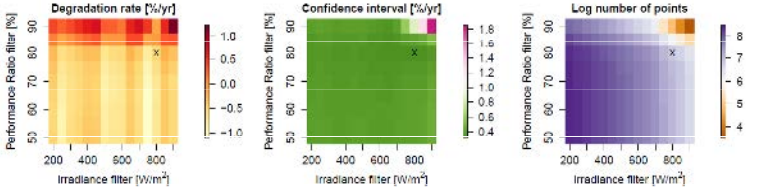
Impact of Filters

→ Filter: Performance Ratio and Irradiance vs Degradation Rate, Rd, & Confidence interval

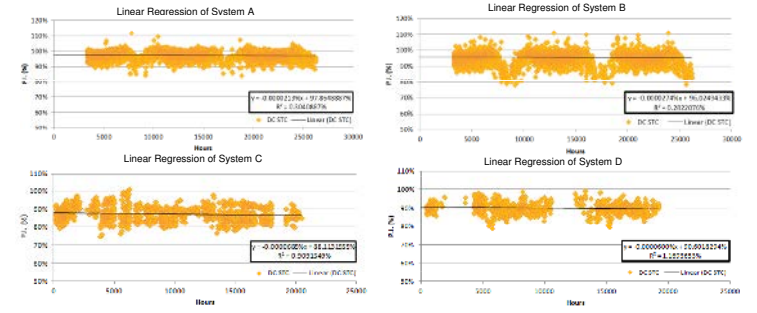
SYSTEM A



SYSTEM D



Results



Degradation Rates (%/year) of the four sites determined using this model below -0.6%/year; consistent with published data of multi-crystalline PV modules [3].

PV System	PR Filter	Irradiance Filter	Degradation Rate, Rd	Confidence Interval (95%)	Post-Filtered Data Points
System A	PR ≥ 90%	G ≥ 200	-0.19%/year	± 0.12%	4739
System B	PR ≥ 90%	G ≥ 200	-0.17%/year	± 0.10%	4313
System C	PR ≥ 75%	G ≥ 800	-0.60%/year	± 0.35%	1217
System D	PR ≥ 80%	G ≥ 800	-0.53%/year	± 0.31%	953

Discussion

→ Modified DC/POA method shown to be robust method

→ Filters to apply to exclude abnormities and non-linearity varies from site to site

→ The amount of filter also affects the confidence of the reported rate especially for PV plants with low data analysis period

→ Degradation rate determined using above method reported degradation rate below published rates

→ Mean soiling loss of PV plants reported to be between -2.4 to -8.3 x10^{-4} /day [4] ; Such soiling loss has not been excluded from reported Rd

→ Method needs to be improved to take soiling rate into consideration

Reference

[1] Jordan, D.C.; Kurtz, S.R. (2012). "Data Filtering Impact on PV Degradation Rates and Uncertainty." Presented at the *NREL PV Module Reliability Workshop*.

[2] Daryl Myers, "Evaluation of the performance of the PVUSA rating methodology applied to DUAL junction PV technology", *American Solar Energy Society Annual Conference*, Buffalo, New York, 11-16 May 2009.

[3] Jordan, D. C. and Kurtz, S. R. (2013), "Photovoltaic Degradation Rates—an Analytical Review", *Prog. Photovolt: Res. Appl.*, 21: 12–29

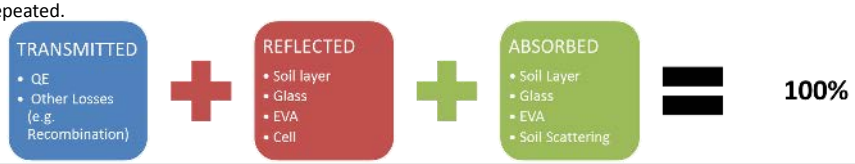
[4] Mejia, F. A. and Kleissl, J. (2013), "Soiling Losses for Solar Photovoltaic Systems in California", *Solar Energy*, 95: 357-363

PV Modules: Effect of Soiling on Quantum Efficiency, Spectral Reflectance and Incident Angle

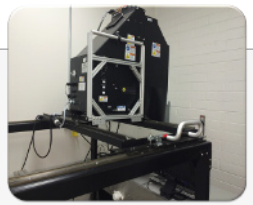
Jim Joseph John[1,2], Sai Tatapudi[2], and Govindasamy Tamizhmani[2]
[1]Indian Institute of Technology, Bombay, INDIA
[2]Arizona State University Photovoltaic Reliability Laboratory, USA

INTRODUCTION

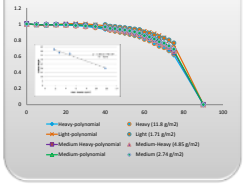
- Soil layer changes not only the irradiance level but also changes the spectral distribution and angle of incidence of the incoming solar radiation.
- Three soiled modules of varying soil layer thickness were used to study the influence of soiling thickness on the AOI effect
- Three soiled solar cells of varying soil layer thickness within a module were used to study the spectral reflectance (SRef) and quantum efficiency (QE) changes at various wavelengths. The three soiled solar cells were then cleaned using three different cleaning techniques – 60psi compressed air clean, brush assisted 30psi compressed air clean and water cleaned. The SR and QE measurements were repeated.



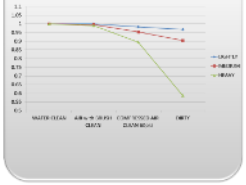
METHODOLOGY



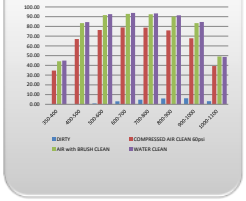
ANGLE OF INCIDENCE



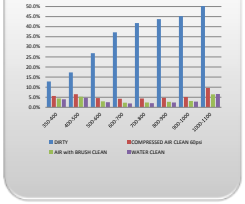
CURRENT VOLTAGE (I-V) MEASUREMENT



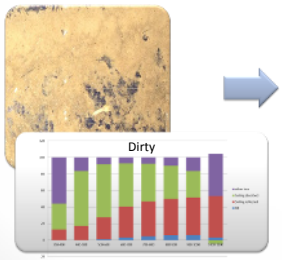
QUANTUM EFFICIENCY

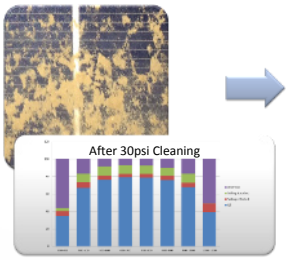


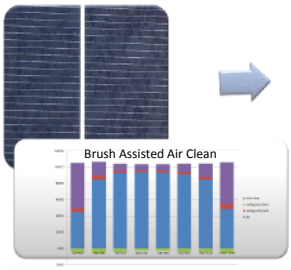
SPECTRAL REFLECTANCE



RESULTS



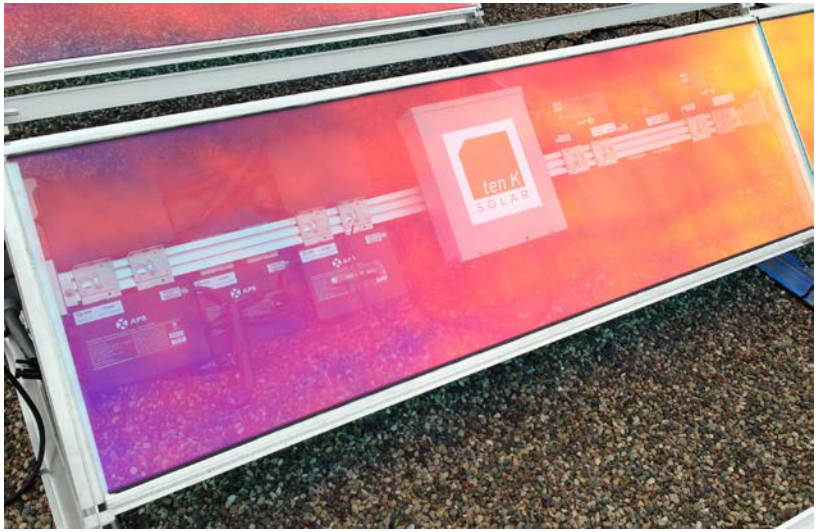




ACKNOWLEDGMENT

This study is based upon work supported in part under the US-India Partnership to Advance Clean Energy-Research (PACE-R) for the Solar Energy Research Institute for India and the United States (SERIIUS). Contact: Mani TamizhMani, manit@asu.edu, 480-528-4967

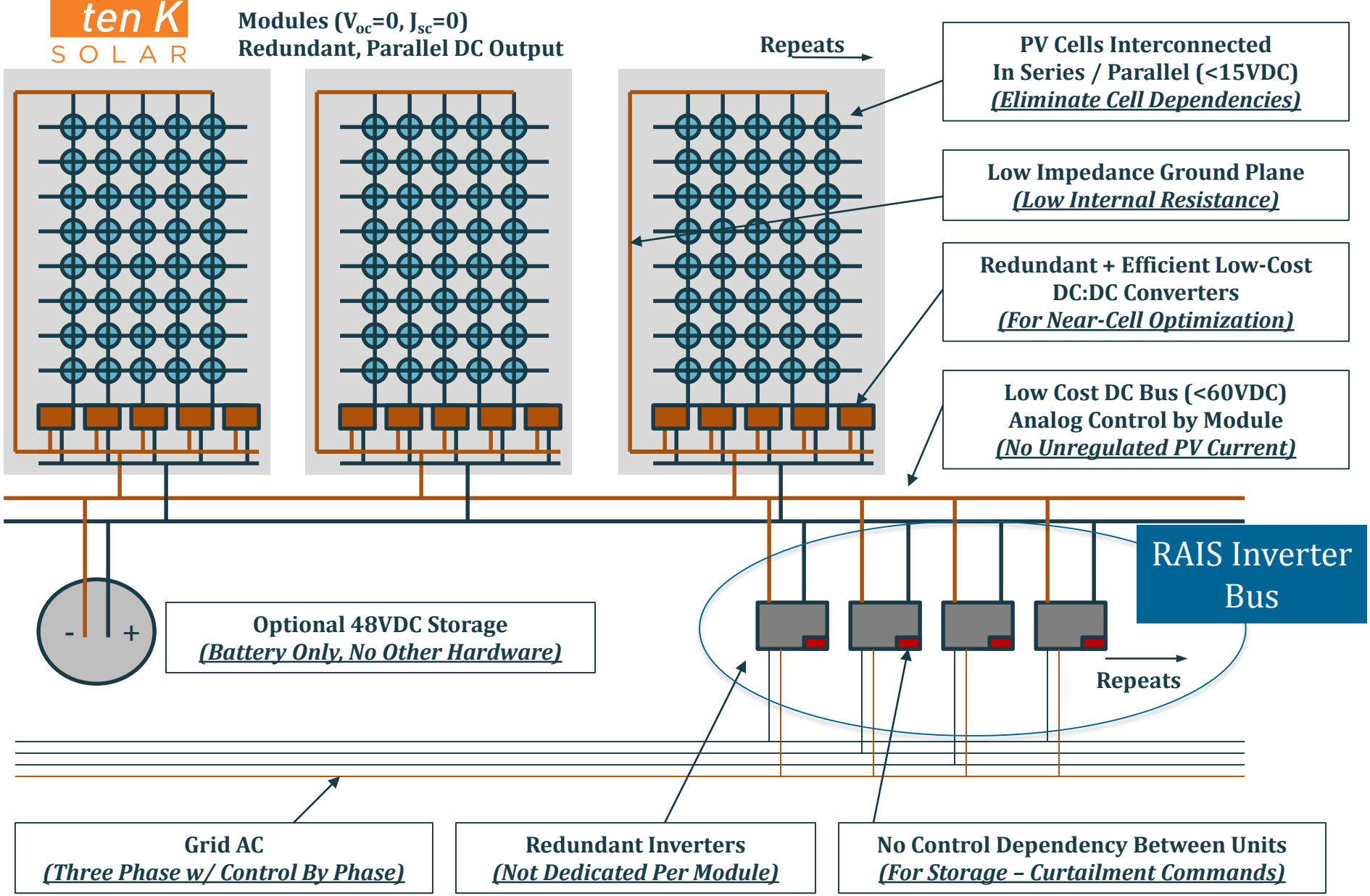
ten K
SOLAR



Highly Redundant Inverter Architecture

Tim Johnson

A Highly Redundant, Low-Voltage Solar Topology



RAIS Inverter Bus

AC Out

DC In

AC Out

RAIS Inverter Bus:

Unparalleled Inverter Reliability

Redundant Power Sharing Shatters Traditional Limits of DC/AC Reliability

500W and 1000W small inverters at low 50V bus voltage.

AC Power combines in 36 KW 3Φ blocks, Very very low cost rooftop electrical installation

All units share load, only power on as Needed. Duty cycle cut by ½.

Inverters are warranted for 25 years, run cooler and ½ the time on the tenK bus. Shared power bus design means any individual failure has nearly no impact on output.

Parallel, But No Comm Between Devices

System Response Shown to Left

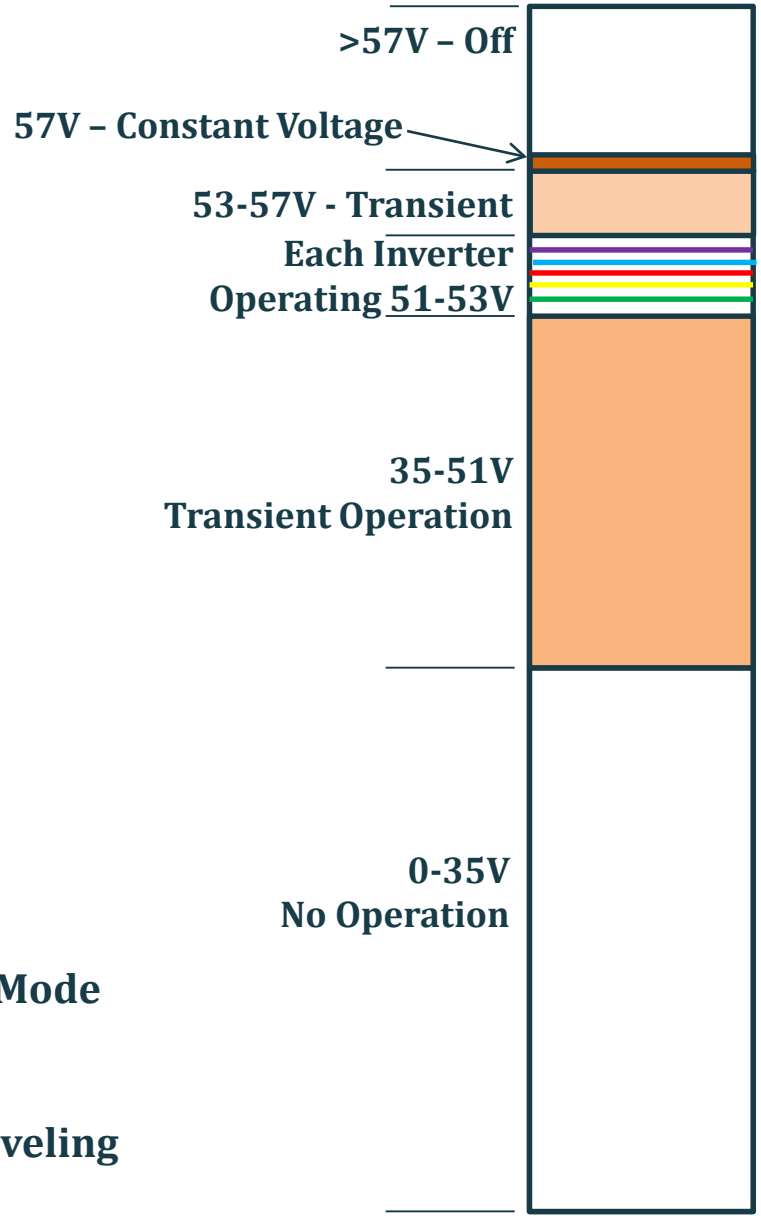
Modules Self-Start in AM
- Push System Voltage to 57V

One of Inverters on Bus
- Lowest Voltage Setpoint of Group
- Pulls Current From Bus
- System Voltage Falls to Setpoint

Once First Inverter Reaches Limit
- System Voltage Rises Slightly
- Second Inverter Starts – New Setpoint

Repeats For Each Inverter Until All At Max
- System Voltage Rises to 57V
- Some Modules Drop Into Constant Voltage Mode
- System Holds at 57V

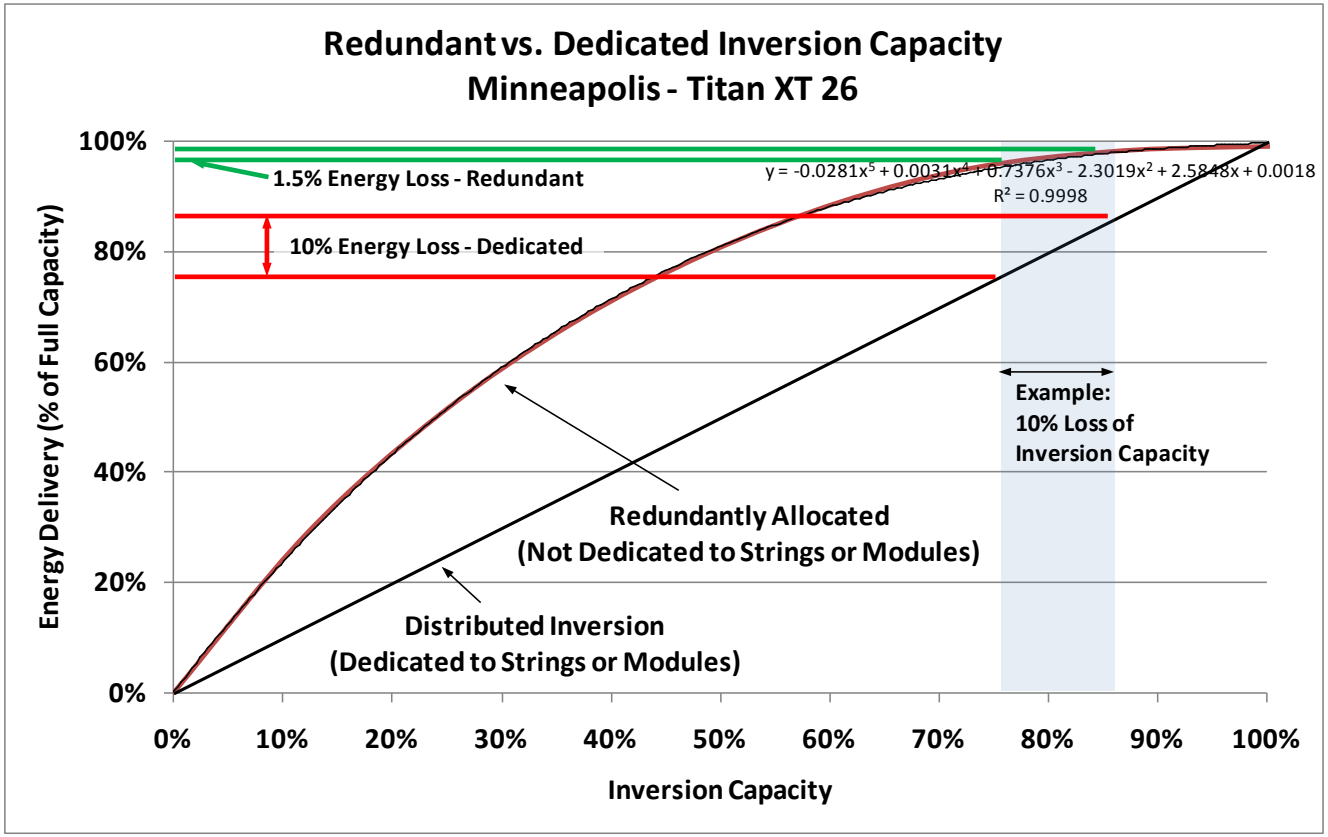
Randomize Inverter Setpoints Daily for Wear Leveling



Effect of Redundancy

First Consider Energy Loss Curve In Solar (i.e., Energy Delivery vs. Inversion Capacity)

Shared power bus design means any individual failure has nearly no impact on output. Result ➔ 88% or > energy guaranteed from system after 20 years with no maintenance.

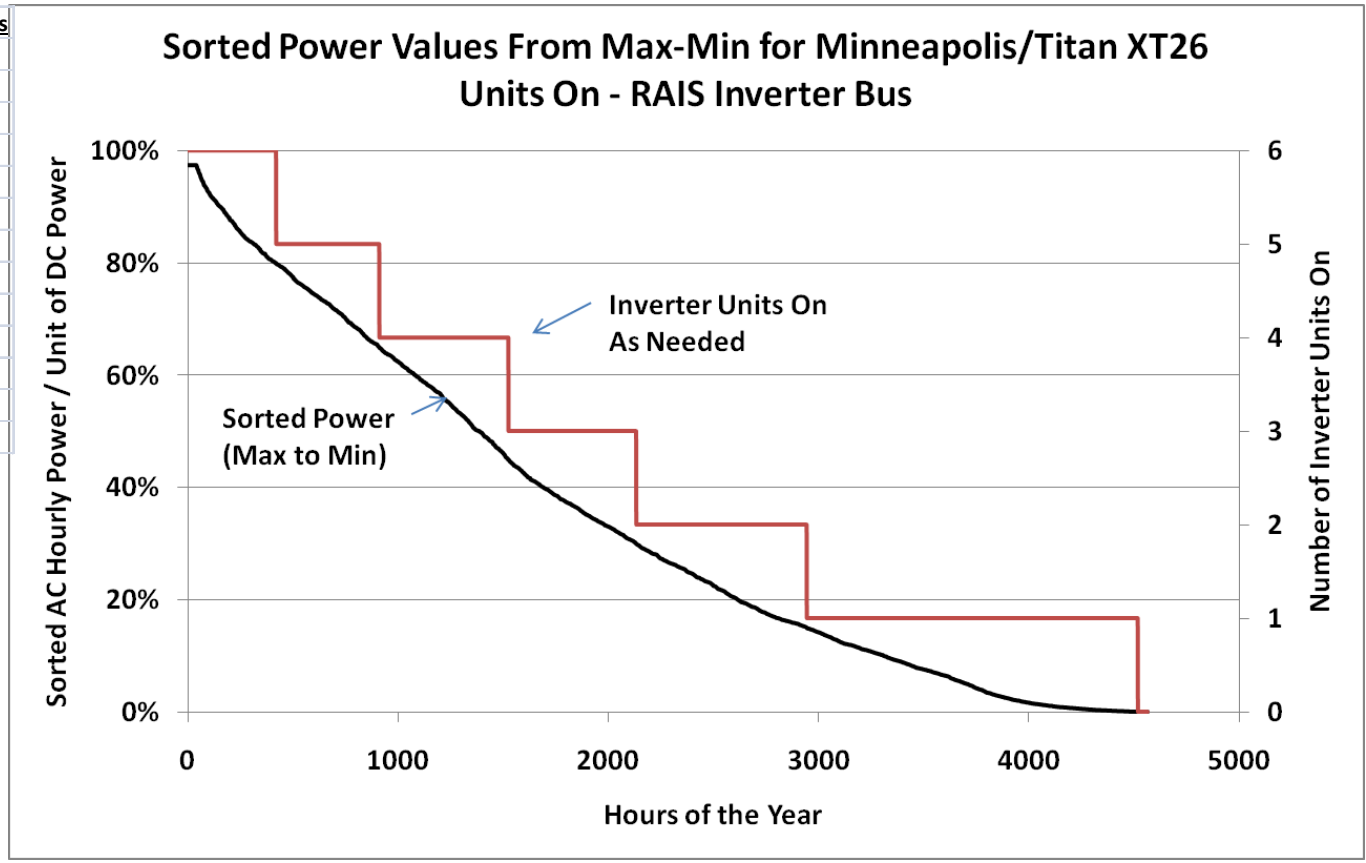


Duty Cycle Effects

Data Below is Solar Power Production in MN
Sorted From Highest to Lowest Through One Year

By Powering On What is Needed: Duty Cycle is 23.7%
Powering On All Units When Sun is Available: 51.6%

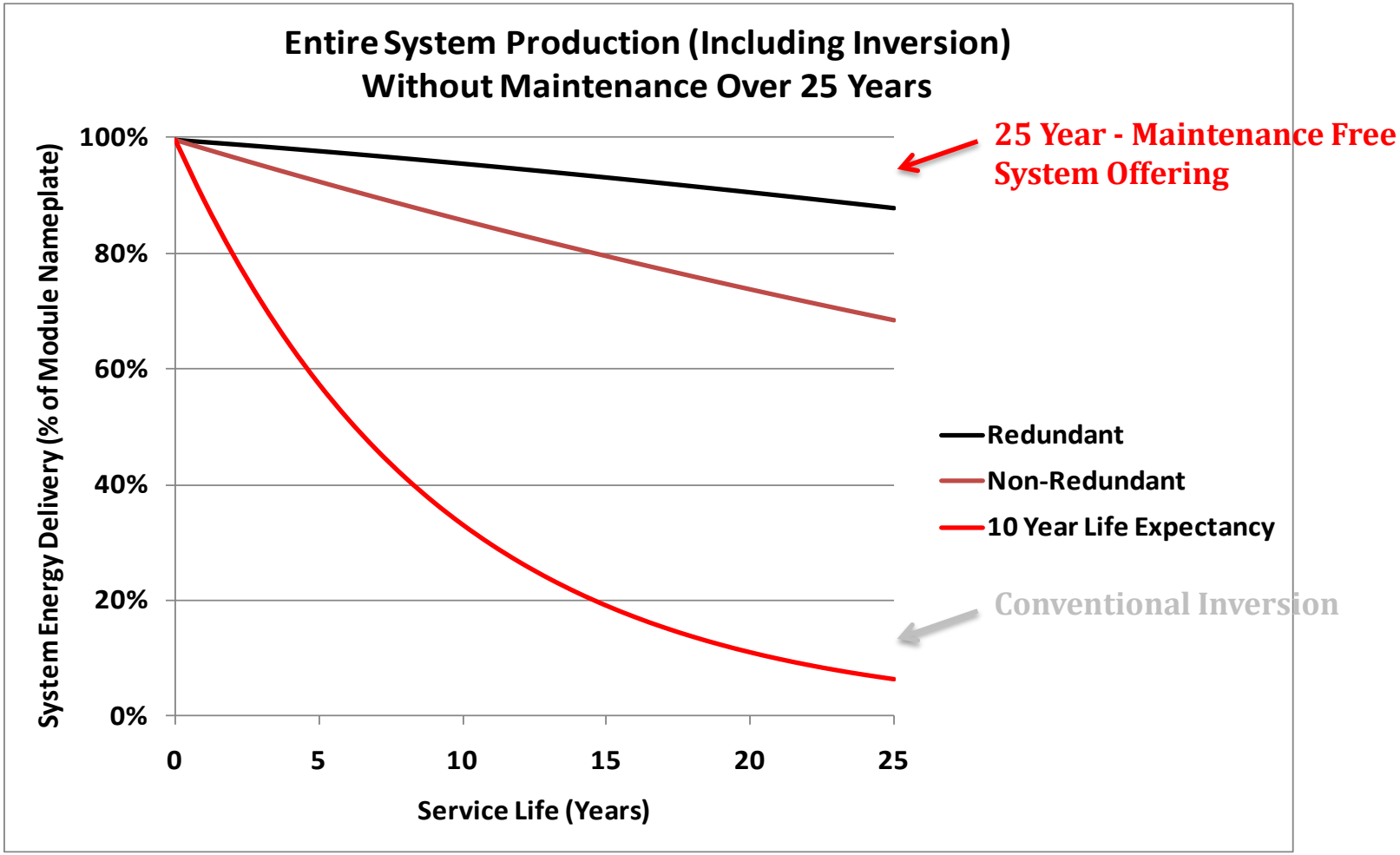
Units On	Hours	Units*Hours
6	421	2526
5	912	2455
4	1526	2456
3	2134	1824
2	2945	1622
1	4520	1575
0	0	0
Total		12458
Average Hours On		2076
Annual Duty Cycle		23.70%
Conventional (4520 Hours On)		51.60%



ten K SOLAR

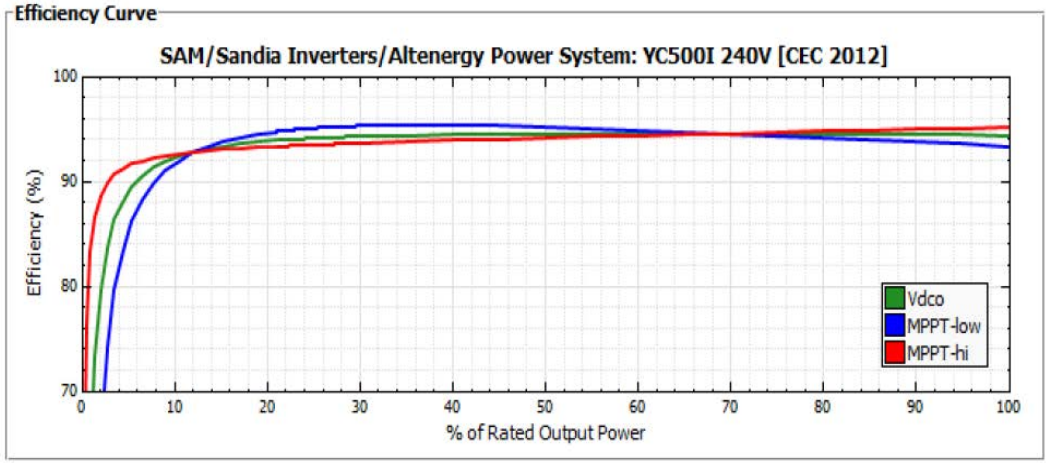
Effect of System Redundancy

1% AFR for Electronic Units (Module and Inverter)
and 0.2% / Year Module Degradation (Parallel Cell Interconnects)
(And Compared to 10 Year Life Conventional Inverter)

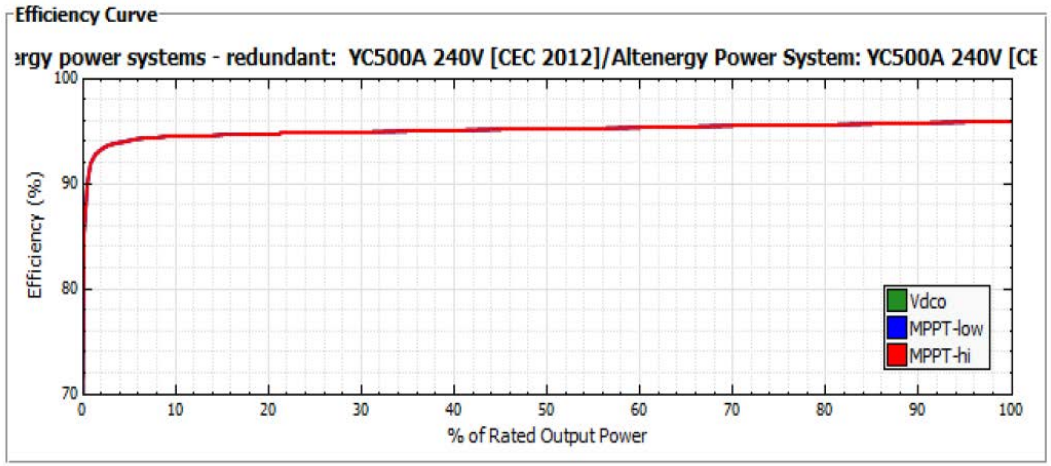


1% Higher Overall Efficiency when inverters share the load versus a Single Inverter Efficiency

Single Inverter Module



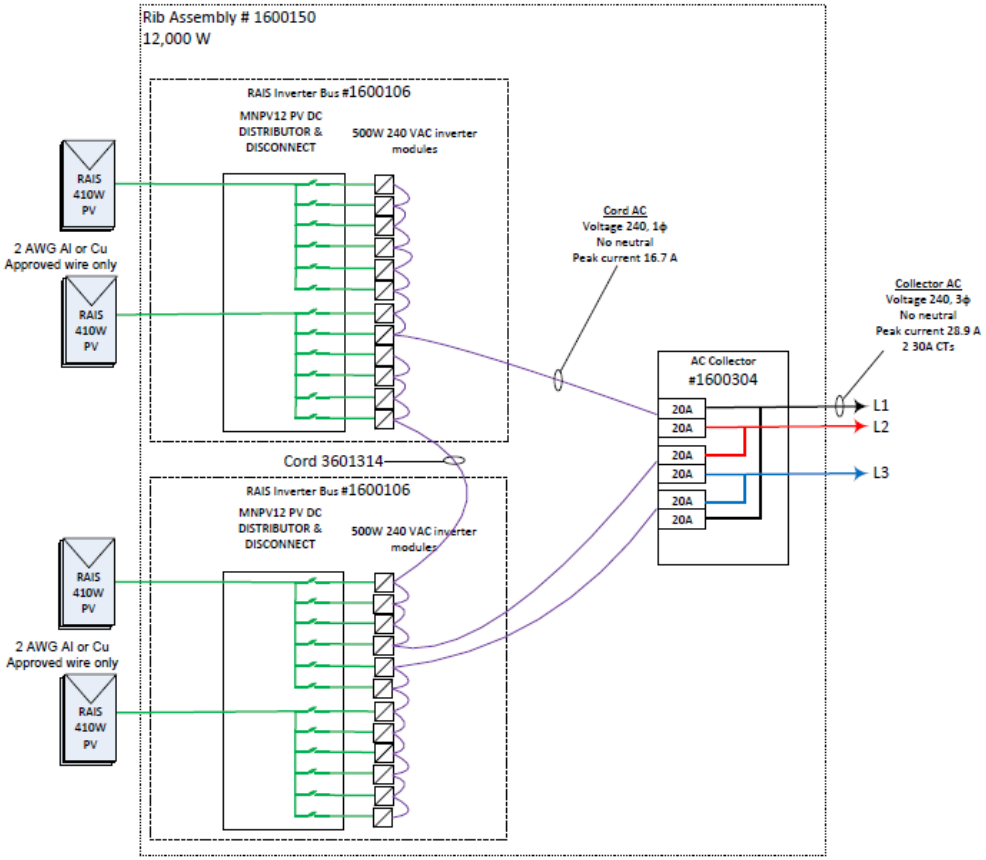
Multiple Inverter Modules Connected Via Bus



RIB – Electrical and Mechanical

Today: 12 kW Kit Installer Snaps Into Array – Single AC Connection Pre-Kitted and Shipped by tenK

Q1-2014: 24 kW Kit – Single AC Connection



Soiling Losses of Utility-Scale PV Systems in Hot-Dry Desert Climates: Results from 4-16 Years Old Power Plants

J. Mallineni, K. Yedidi, S. Shrestha, S. Tatapudi, B. Knisely
J. Kuitche and G. TamizhMani
Arizona State University Photovoltaic Reliability Laboratory (ASU-PRL), USA

INTRODUCTION

- Soiling: Major O&M expense in the power plants
- Typical 3% annual de-rating factor used in energy estimation models may not be valid for all site conditions and configurations as they are influenced by: tilt angle, surrounding (urban or rural), installation type (fixed ground mount, fixed rooftop mount or 1-axis tracking) and the season (dry, windy, humid or rainy).
- The data presented in this study could be used to determine an appropriate de-rating factor in the energy estimation models and as a tool to determine if module cleaning is an economically viable option.

METHODOLOGY

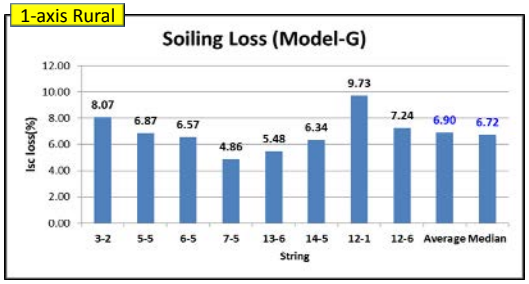
- I-V curves of soiled (existing operating state) string / module was individually measured.
- Water was used twice during the cleaning process (before and after using a mop)
- I-V curves were then taken after the string / module was completely dried without any trace of water or dirt.
- The curves were translated to STC and the percentage change between cleaned-string Isc and soiled-string Isc was then calculated.

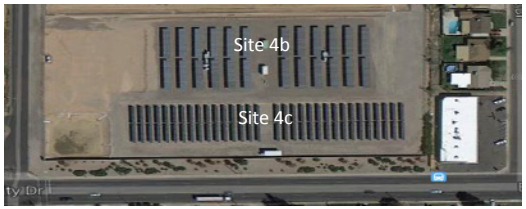
Plant site	Tilt / Orientation	Capacity (kW)	Surrou-nding	Field Age
Site 3 (Glendale)	1-axis tracking	243	Rural	12
Site 4b (Mesa)	Horizontal tilt (Ground)	113	Urban	16
Site 4c (Mesa)	1-axis tracking	250	Urban	4
Site 6 (Tempe)	Fixed 5° tilt (Rooftop)	97	Urban	8

RESULTS

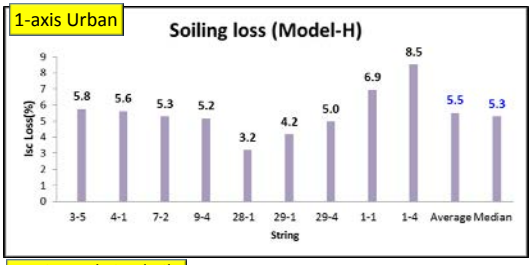
1-axis Rural

1-axis Rural

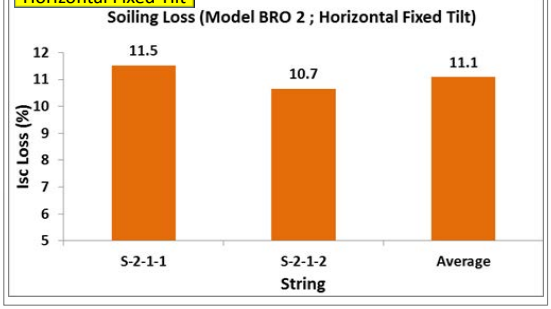




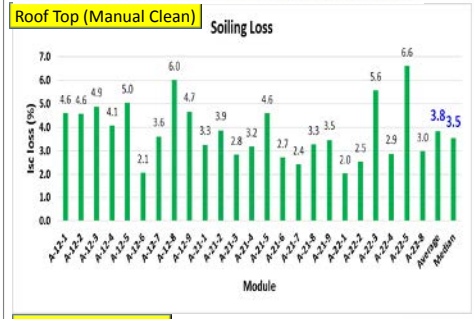
1-axis Urban



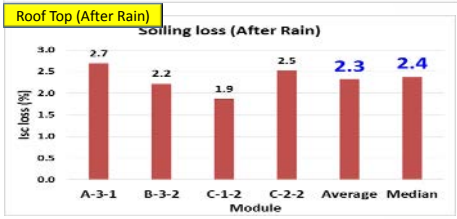
Horizontal Fixed Tilt



Roof Top (Manual Clean)



Roof Top (After Rain)



CONCLUSIONS

- The 1-axis tracker based modules in the rural surroundings have experienced a higher soiling loss (6.9%) as compared to the 1-axis tracker based modules in the urban surroundings (5.5% soiling loss).
- The horizontal tilt PV modules have experienced about two times (11% soiling loss) higher loss as compared to the 1-axis tracker based modules (5.5% soiling loss) for the same site (site 4).
- The rooftop mounted (even with near horizontal tilt) modules experience the lowest soiling loss (3.8%) as compared to the ground mounted modules.
- It appears that a few minutes of light rain (only about 0.04 inches) cleaning is only about 61% effective as compared to the manual cleaning for the (near) horizontal tilt modules.

ACKNOWLEDGEMENT

The extensive technical support rendered by Salt River Project (SRP) is gratefully acknowledged. The funding support of SRP and Department of energy through SERIIUS project is gratefully acknowledged.

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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Office of Energy Efficiency and Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC.

Uncertainty Analysis for Photovoltaic Degradation Rates

D.C. Jordan[1], S.R. Kurtz[1], C. Hansen[2]

[1]National Renewable Energy Laboratory, Golden, CO 80401, USA

[2]Sandia National Laboratories, P.O. Box 5800 Albuquerque, New Mexico 87185-1033

1 Introduction

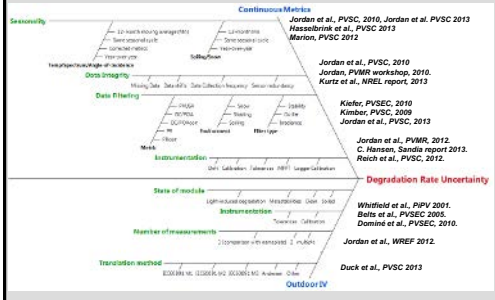
Long-term PV Performance

1. *Financially:*
   - *Cash flow*
   - *Uncertainty directly related to risk*
2. *Technically:*
   - *Lifetime prediction*
   - *Product improvement*

Need to determine degradation rates (R_d) accurately

2 Ishikawa Diagram

Sources of variations & strategies for degradation rate uncertainty



Jordan et al., PVSC, 2010, Jordan et al. PVSC 2013
Hasselbrink et al., PVSC 2013
Marion, PVSC 2012

Jordan et al., PVSC, 2010
Jordan, PVMR workshop, 2010.
Kurtz et al., NREL report, 2013

Kiefer, PVSEC, 2010
Kimber, PVSC, 2009
Jordan et al., PVSC, 2013

Jordan et al., PVMR, 2012.
C. Hansen, Sandia report 2013.
Reich et al., PVSC, 2012.

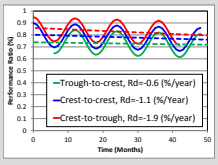
Whitfield et al., PIPV 2001.
Belts et al., PVSEC 2005.
Dominé et al., PVSEC, 2010.

Jordan et al., WREF 2012.

Duck et al., PVSC 2013

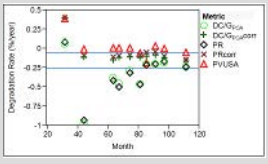
3 Seasonality & Metrics

Seasonality



Seasonality can lead to systematic deviations

Metrics



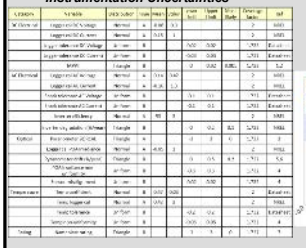
DC/G_{POA}: DC power/ plane-of-array Irradiance
DC/G_{POA}corr: temperature-corrected DC/G_{POA}
PR: Performance ratio
Prcorr: temperature-corrected PR
PVUSA: PVUSA regression methodology

Temp-corrected metrics: excellent agreement down to 3 ½ years.

Temperature-corrected metrics are preferred over non-corrected metrics.

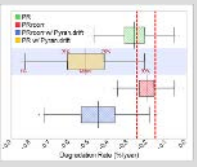
4 Total Uncertainty Simulation

Instrumentation Uncertainties



$$PR = \frac{E/P_0}{H/G}$$

PR=Performance Ratio
E=Net Energy output
P_0=Nameplate DC rating
H=In-plane Irradiance
G=Reference Irradiation



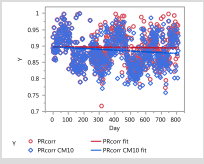
Even a small drift dominates other uncertainties

[1]R. Faranda, S. Leva, WSEAS Transactions on Power Systems, 2010.
[2]M. B. Strobel et al, Solar Energy Materials & Solar Cells 93 (2009) 1124–1128.
[3]D.R. Myers et al., 2004, NREL Conference Paper NREL/CP-560-36320.
[4]K. Mällejans et al., Meas. Sci.Technol. 20 (2009) 075101.
[5]D.C. Jordan et al., NREL PVMR Workshop, Golden CO, USA, 2013.
[6]N.H. Reich et al., PVSC, Austin, TX, 2012, 1551 – 1555.
[7]http://www.solarabcs.org/

Precision (relative accuracy) more important than absolute accuracy

5 Intentionally Drifting Pyranometer

Condensation film on dome



Pyranom.	R_d (%/year)	Uncertainty (%/year)
Regular	-0.18	0.38
High humidity	-1.15	0.36

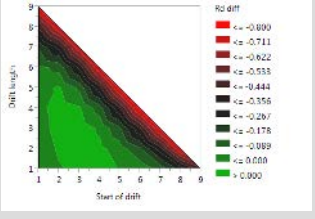
CM10 pyranometer (high humidity) drifted about 1%/year

Apparent high "R_d" due to drifting pyranometer

6 Drift Occurrence

Monte Carlo Simulation

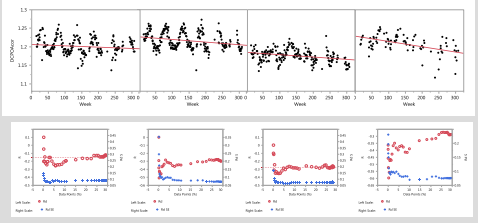
1. *1.4 kW multi-Si system*
2. *Use temperature-corrected Performance ratio (PR)*
3. *Use a drift of 1%/year on average (low: 0.5%/year, high: 1.5%/year, triangle distribution)*
4. *Let the drift have different length 1,2,3…years*
5. *Let the drift occur at different times of field exposure*
6. *1000 realizations, calculate R_d for each realization*



If drift occurs during middle of field exposure → negligible effect
If drift occurs at end of field exposure → may have large effect

7 Irradiance Source Strategies

Pyranometer mounted on system | *Median of 10 pyranometers at OTF* | *Precision pyranometer, ¼ km distant* | *RMIS: OTF weather station*



R_d=-0.15 %/year | R_d=-0.30 %/year | R_d=-0.28 %/year | R_d=-0.33 %/year

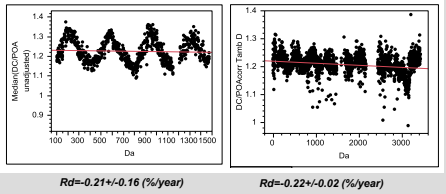
Instrumenting every system with pyranometer may not be necessary

Using Irradiance from nearby system may be adequate

8 Uncertainty for "Clean" Data Set

Multi-Si 1400kW system at NREL

1st 4 years | *All 9 years*



Rd=-0.21+/-0.16 (%/year) | *Rd=-0.22+/-0.02 (%/year)*

Uncertainties are only statistical uncertainty and do not include instrumentation

With a "clean" data set Rd can be determined to within 0.2%/year after 4 years of field data

9 Conclusion

- *Seasonality caused by temperature, angle-of-incidence, spectral effects can lead to systematic errors and higher uncertainties*
- *Temperature-corrected metrics are preferred over non-corrected metrics.*
- *Changes (drift) of instrumentation during field exposure is more critical than absolute accuracy*
- *Drift has significantly more impact at the end of the monitoring period than in the middle*
- *Nearby irradiance sensors may be used to determine degradation rate*

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

Determining PID-resistance based on accelerated tests extrapolated to field stress levels

Scope

- Not on mechanism – more on method!
- Not on quality – more on reliability!

- Business reality
  - Demands a high-degree of comfort with fielding modules in a floating array.
  - Acknowledges risk
    - Being wrong may result in MW-sized replacements in as soon as 1 year.
    - Banks and Independent Engineers are not happy with ambiguity.

- Observations from running nineteen ~2m^2 modules at a negative bias in an elevated temperature and humidity DOE.
  - Leakage current stability is an issue
  - Leakage current variability is not trivial
  - Resulted in a lower activation energy than other works and may support multiple current paths.

- Need - A consensus-driven approach to reliability from accelerated testing.

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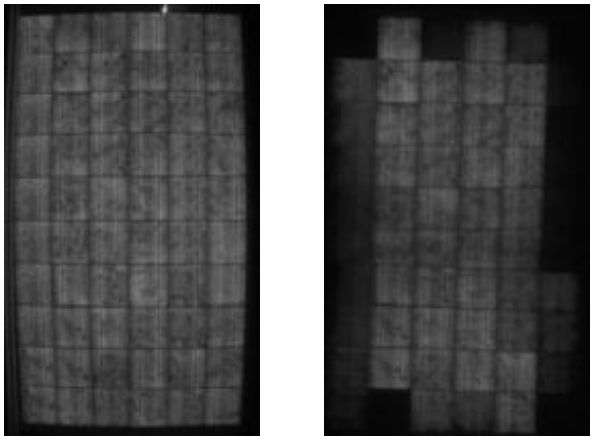
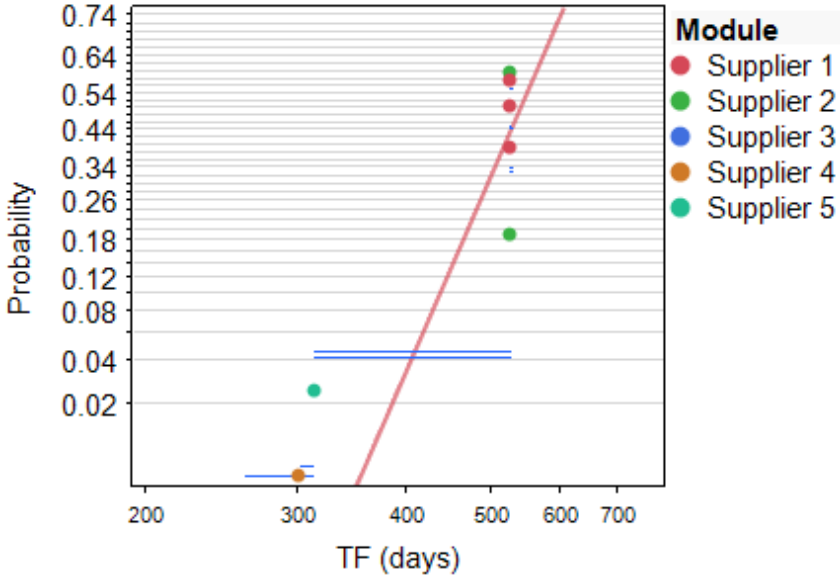
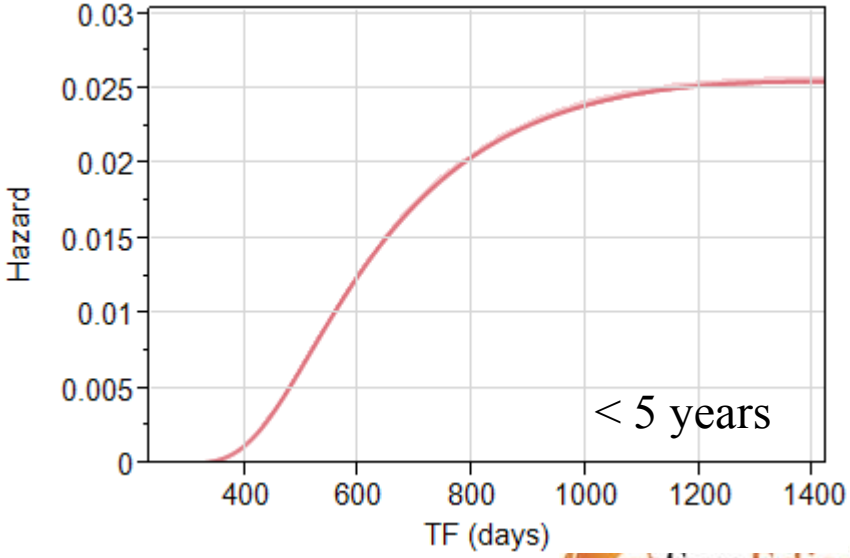
PID Reality

- PID from supplier modules
  - EL indicates cell damage near grounded frame.
  - High probability of occurrence in 2 years – if it is going to occur.

Pattern matters!

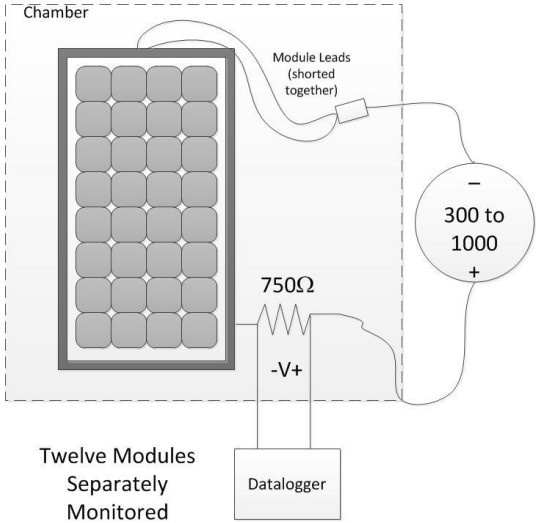






Plan

- "How long do I test the modules to ensure they are not at risk of developing PID?"
  - Characterize similar full-sized modules.
  - Design of Experiments: Vary T, RH, V and measure
    - Coulombs to failure
    - Leakage current
    - Extrapolate leakage current function to field stress levels and accumulate to a 5-year Coulomb value.
    - Run accelerated testing to 5-year Coulomb value and look for degradation levels >5% coincident with tell-tale signs of PID.
  - Answer requires several guesses
    - Issues with comparing Coulombs to fail
    - Accelerated tests affect all cells in the module
    - Implication of leakage current variability



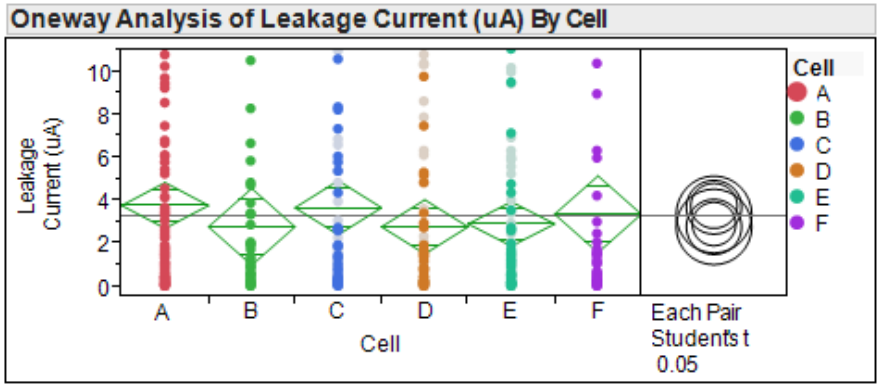
DOE

- 19 samples into a 4x3x3 + 1 + 1 condition study
  - 13→

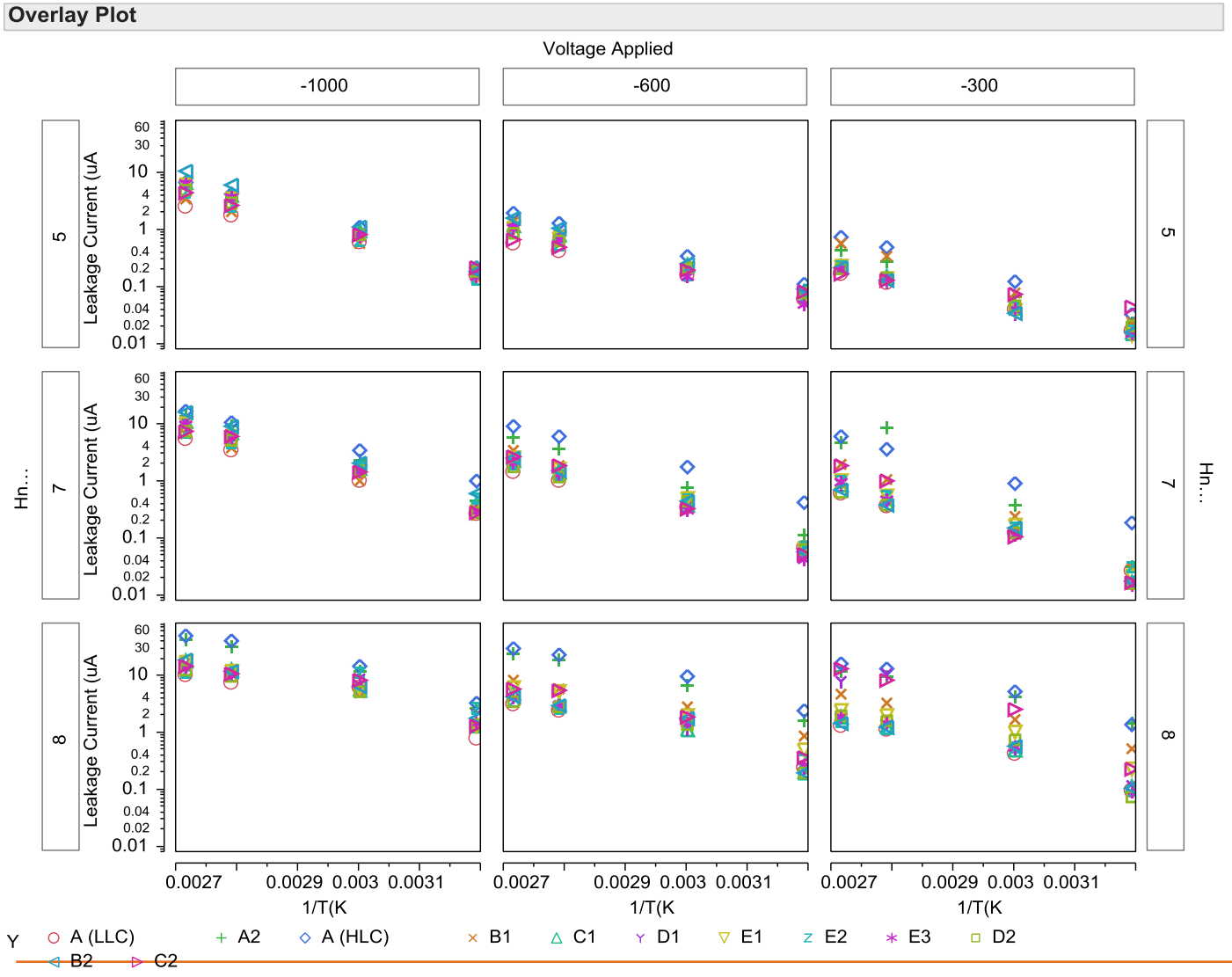
Temp. (°C) & Dwell (hours)	Humidity (%RH)	Voltage Bias (-V)
40 / 2	50	300
60 / 6	70	600
85 / 8	85	1000
95 / 8		

    - Added 90°C, 90%RH, -1000V for 48 hours
  - 6→85°C, 85%RH, -1000V for 1200+hours

- 72-cell monocrystalline Si p-type BSF, 3.2mm tempered ARC glass, EVA encapsulant, TPE backsheet, aluminum frame.
  - Different cells studied, however, leakage current did not correlate to cell and highest and lowest leakage current occurred within the replicates for one cell type.

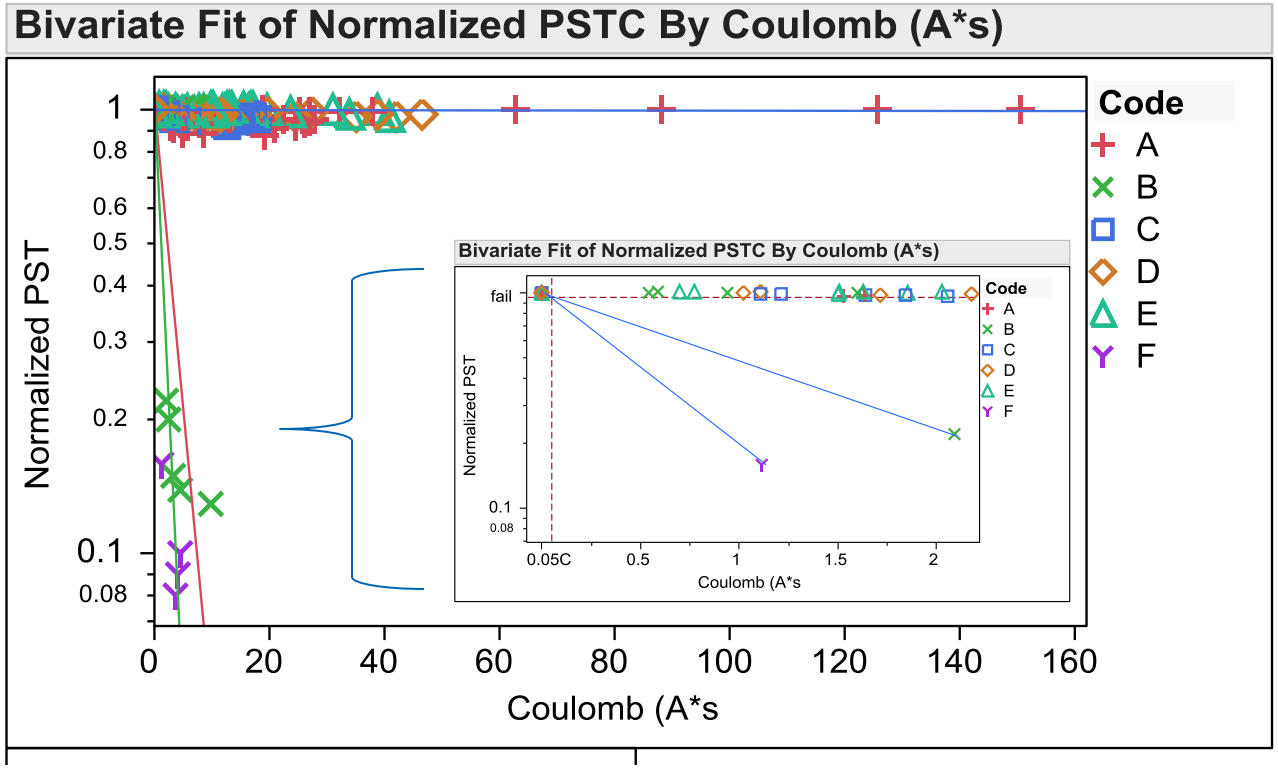


Leakage Current Results

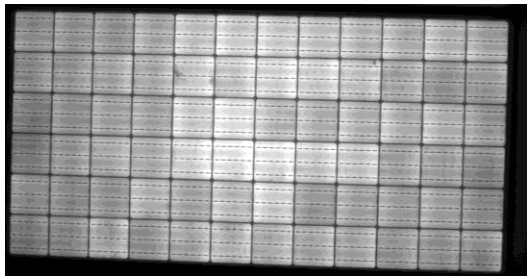


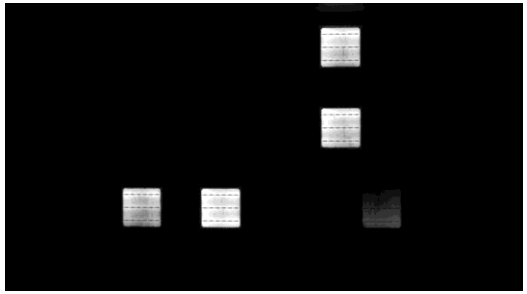
- Reasonable linearity.
- Rational voltage and humidity relationship.
- Large spread of leakage current results.

Coulomb Result



Pattern matters!





- At 85C/85%RH, -1000V failure occurs in a short time in test - consistent with other works.
- Pattern inconsistency with field → Affects Pmax degradation rate!
  - May contribute to Type 1 error; deemed conservative
- What about Coulombs? Data suggests as little as 0.05C for 5% drop.
  - 0.5C taken as a conservative limit.

Hoffmann and Koehl, 2012

What might 0.5C mean in the field?

- 0.2 C in 2 years @ -600V in the Canary Islands
- 0.5 C in ~ 3.3 years

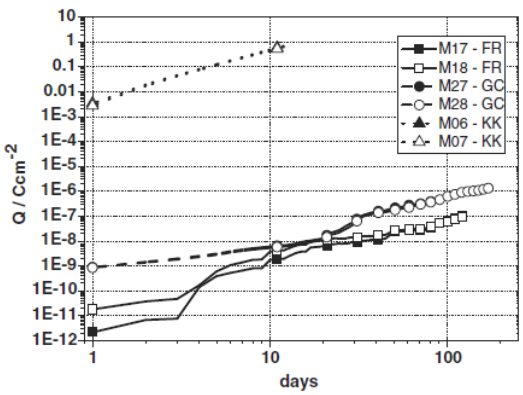
PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2012)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2238

RESEARCH ARTICLE

Effect of humidity and temperature on the potential-induced degradation

Stephan Hoffmann and Michael Koehl*

Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, D-79110 Freiburg, Germany



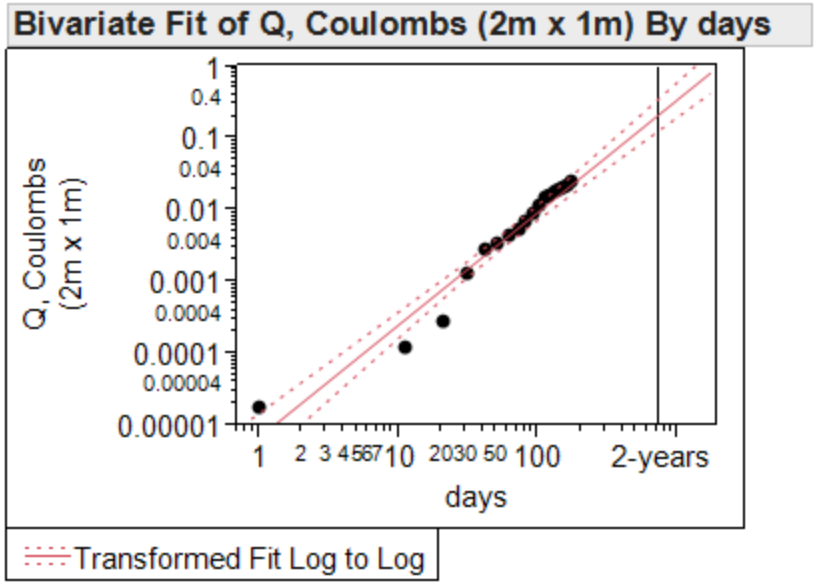


Figure 9. Cumulated leakage current as function of the time for exposure in Canary Island (circles and points), Freiburg (squares and straight line) and during damp-heat testing (85% relative humidity at 85 °C) (triangles and dashed line) for always two modules with different bias voltage of 600 V direct current (solid symbols) and 450 V direct current (open symbols).

Del Cueto and Rummel, 2010

Degradation of Photovoltaic Modules Under High Voltage Stress in the Field

Preprint

J.A. del Cueto and S.R. Rummel

To be presented at SPIE 2010 Optics and Photonics Conference
San Diego, California
August 1-5, 2010

Generally a lack of individual module leakage current measurements. More under fixed external bias.

0.5 Coulomb (in this work) was accumulated in ~ 1 year, for the portion of study where voltage was varied 10-600V.

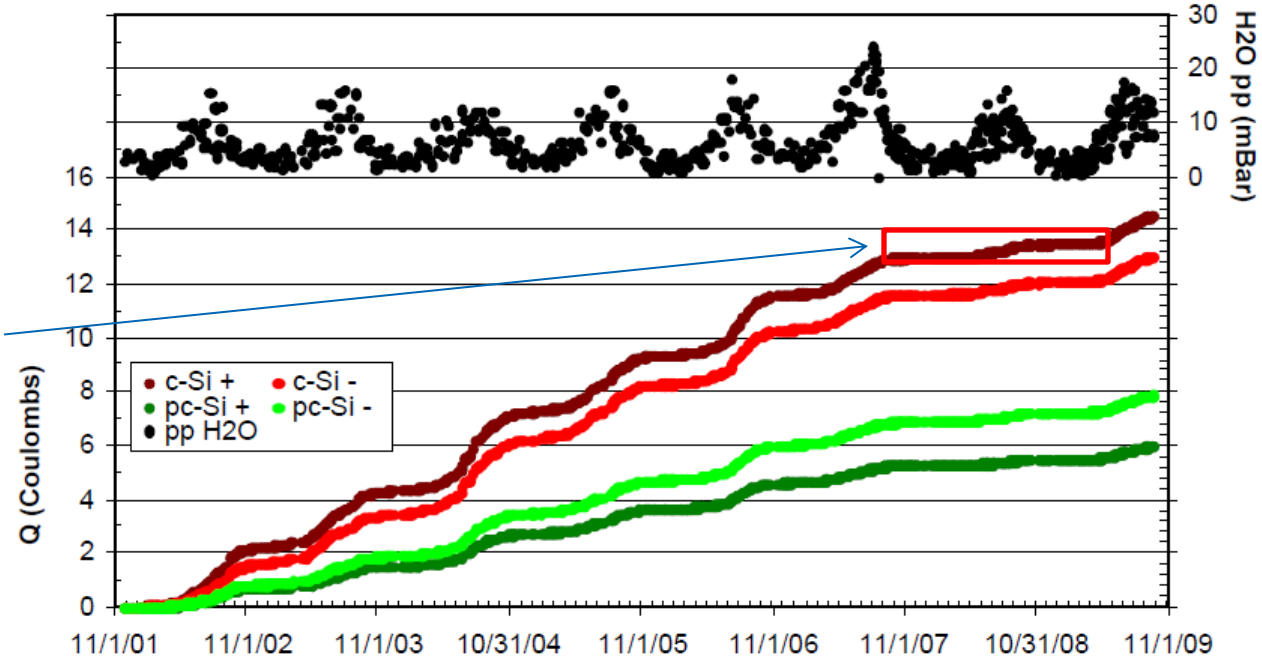


Figure 6. Integrated charge on c-Si and pc-Si modules read along the left-hand abscissae plotted vs. time; and partial pressure of water vapor in the atmosphere, read along the right-hand abscissae, also plotted vs. time.

Results in General

- Leakage current behavior not simple.
  - Suspicions:
    - Nature of leakage current paths through module may change as a function of test conditions. Not new.
    - Surface conductivity of glass strongly suspected to change the effective influence of the grounded frame over the biased cells. Not new.
    - Distances through EVA are NOT constant sample-to-sample. Not aware of this in other works.

- Dwell at test conditions is critical to repeatability.

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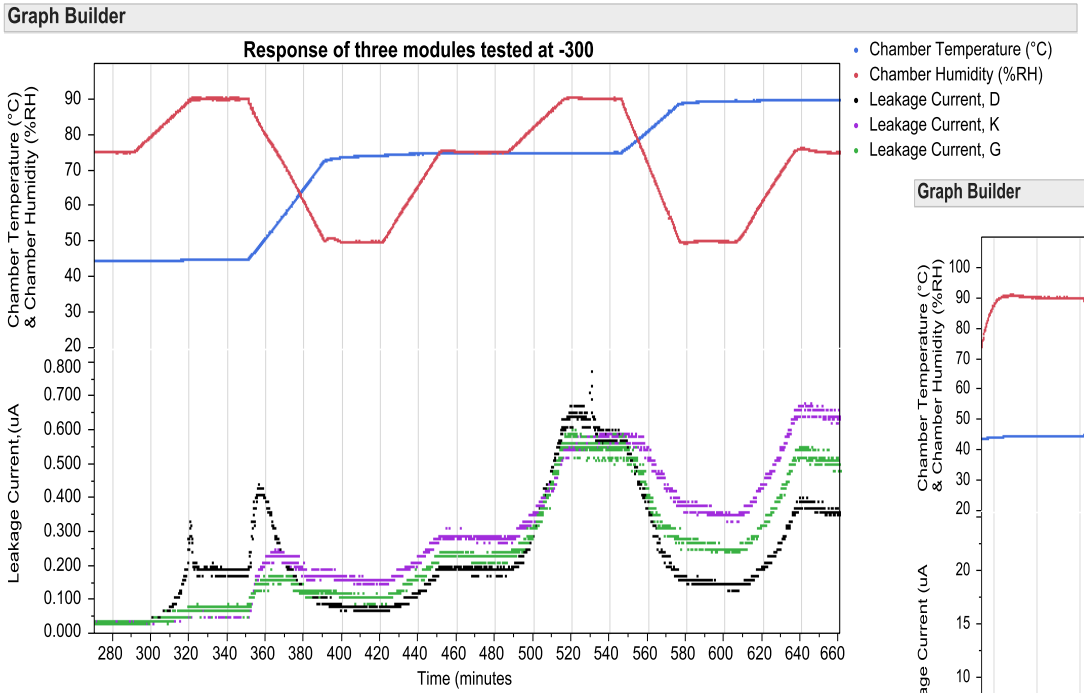
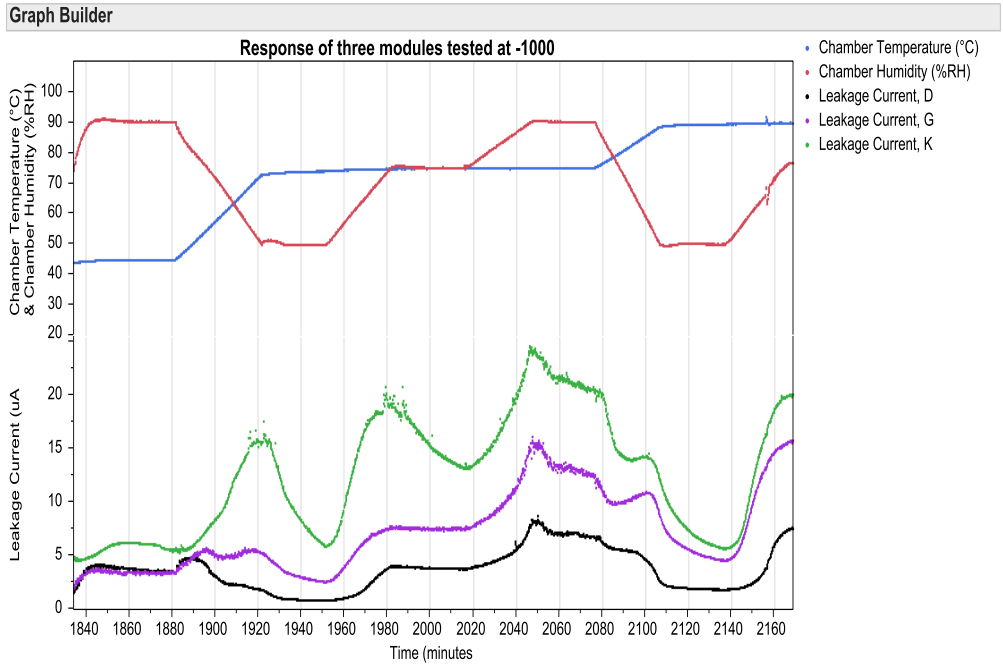
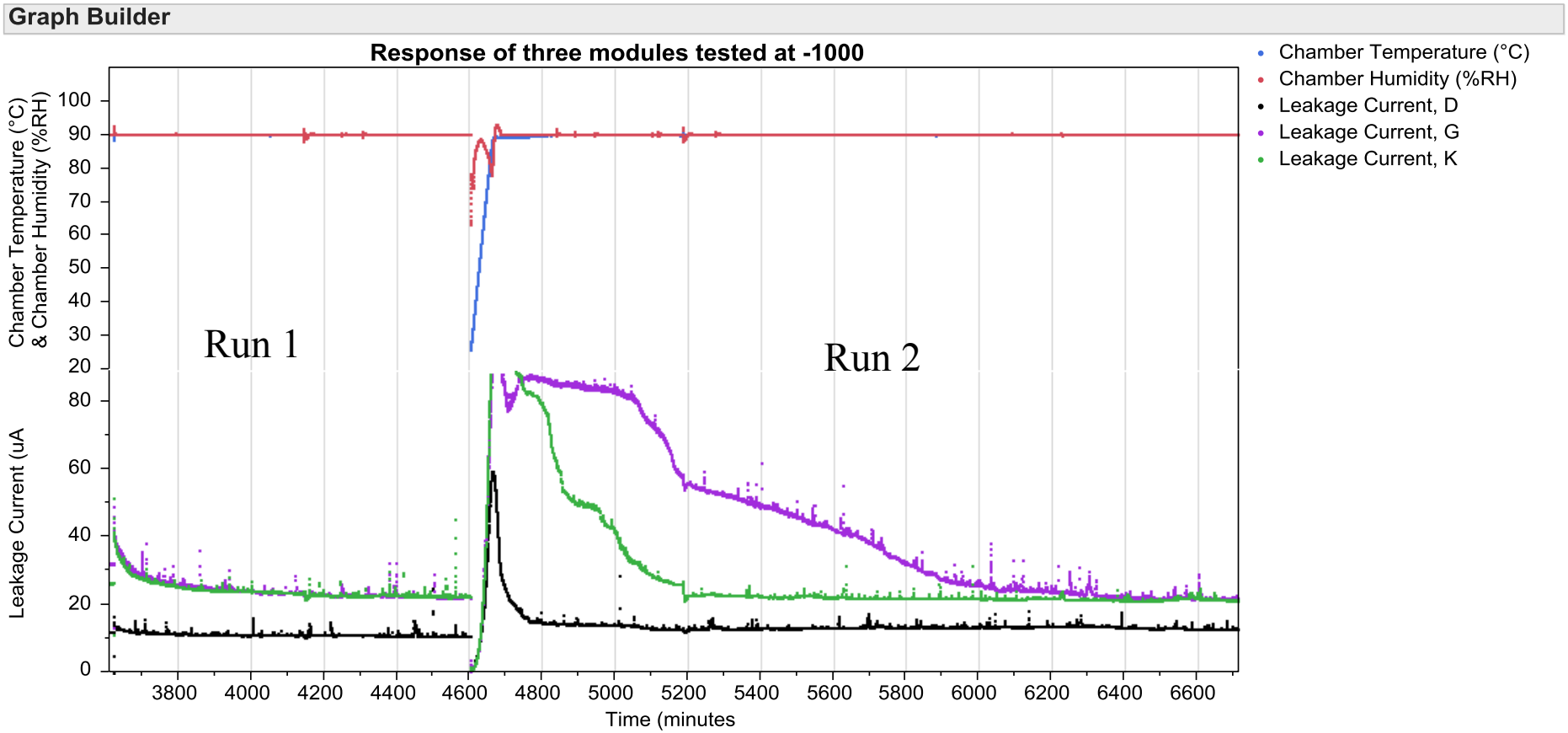
Leakage Current Stability





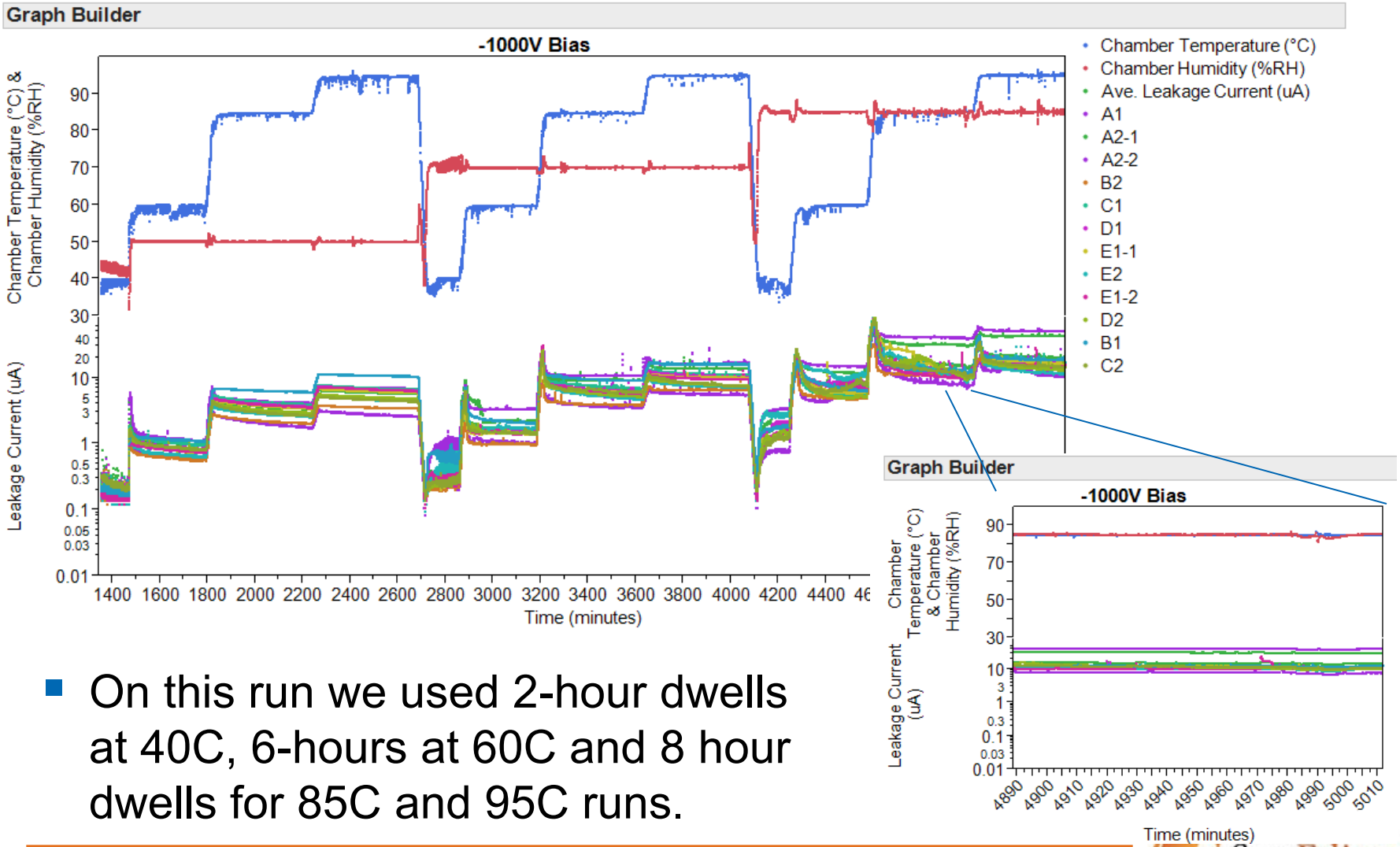
- Voltage has a strong impact on LC settling time.

Leakage Current Stability



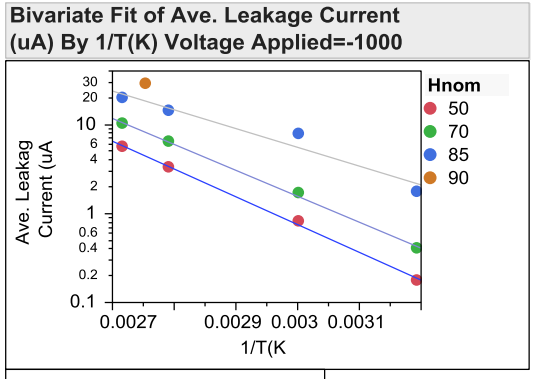
- Humidity at higher temperatures has a SIGNIFICANT effect on stability. Very pronounced at 85% and above.

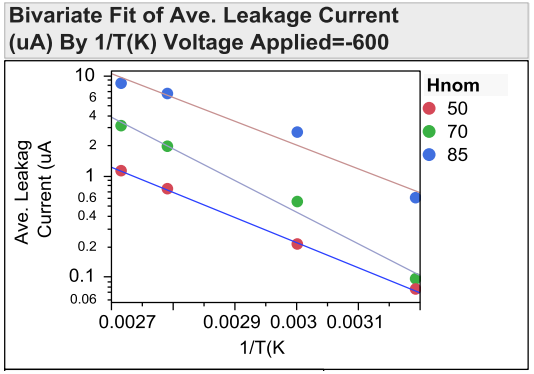
General Approach for Data Collection

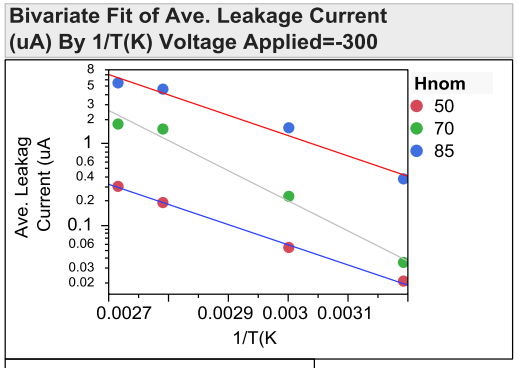


- On this run we used 2-hour dwells at 40C, 6-hours at 60C and 8 hour dwells for 85C and 95C runs.

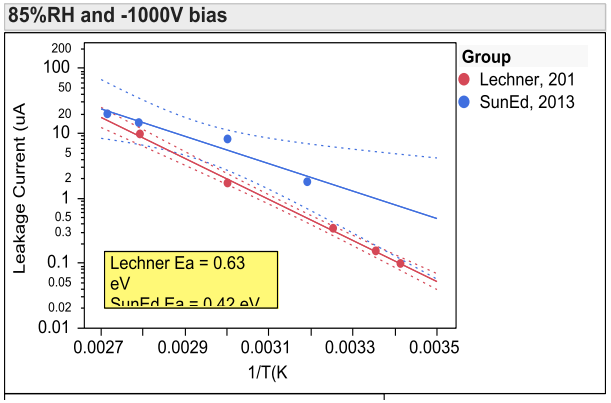
Runs Analyzed Individually

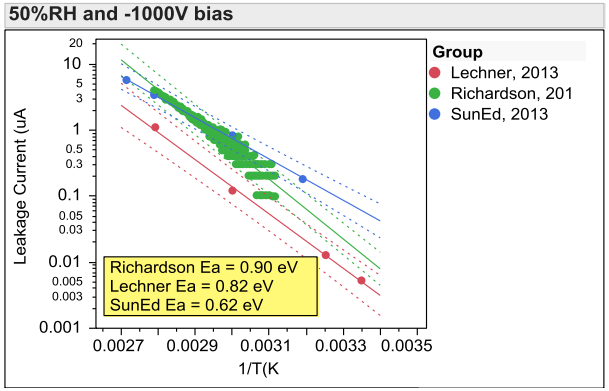






As compared to others, outcome was lower Ea





- Considerable variability, so remaining focus on best fit to highest LC dataset

		Average Leakage Current-Derived		Highest Leakage Current Sample	
Humidity (%RH)	Voltage (V)	Prefactor (A)	Ea (eV)	Prefactor (A)	Ea (eV)
50	-1000	1765	0.620	2238	0.620
50	-600	6.567	0.494	34.50	0.529
50	-300	1.416	0.488	58.34	0.575
70	-1000	875.7	0.579	149.0	0.507
70	-600	1165	0.623	337.3	0.551
70	-300	21340	0.729	2039	0.622
85	-1000	11.85	0.419	284.7	0.489
85	-600	24.69	0.468	54.32	0.454
85	-300	35.42	0.493	22.61	0.445

Nonlinear Regression to a Standard Model

- Already have an indication that thermal rate of change of Coulombs is not constant.
  - Presume that there exists a relationship between the significant independent variables that allows us to separately estimate apparent contributions to rate (i.e., LC) due to voltage, relative humidity and temperature.
  - Results are then interpreted as *apparent* activation energy.

- Many models exist (ref JEDEC JEP122C, also Hoffmann and Koehl)
  - Selected exponential corrosion model
    - Rate basis→ $R \propto LC = A \cdot e^{n \cdot RH} \cdot e^{\frac{-Ea}{k \cdot T}} \cdot f(V)$ and $f(V) \propto V$
  - Use nonlinear regression to seek unknowns using the highest leakage current (HLC) data set.

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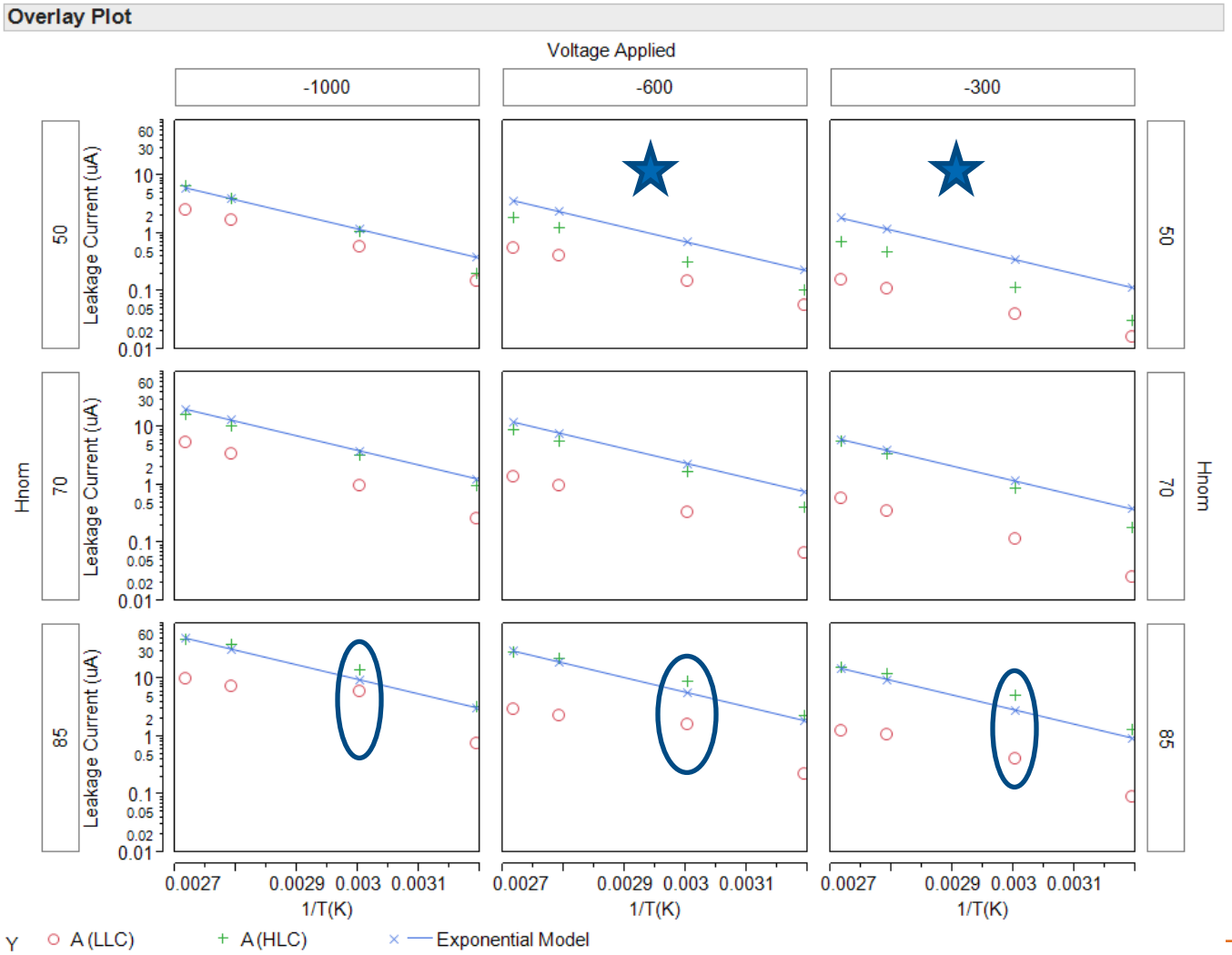
Model Result

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

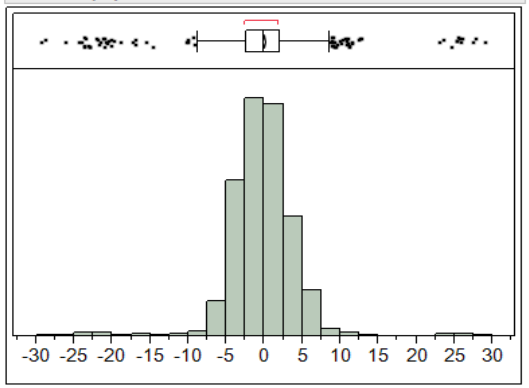


Model is considerably conservative to the data

Model under predicts at 60C for the 85%RH condition.

5-year Coulomb Modeling using TMY Input

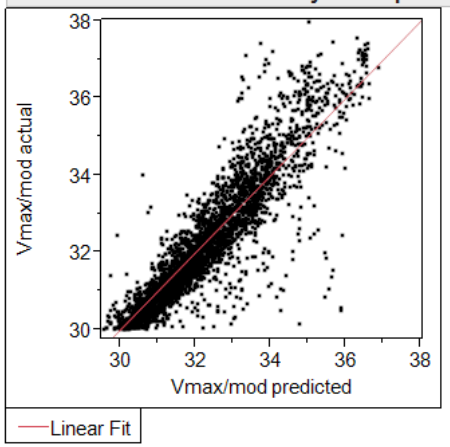
delta T (C)



Summary Statistics

Mean	-0.128375
Std Dev	4.1199455
Std Err Mean	0.0709492
Upper 95% Mean	0.0107324
Lower 95% Mean	-0.267483
N	3372

Bivariate Fit of Vmax/mod By Vmax predicted



Nonlinear Fit

Prediction Model

POA Irrad * Exp(a + b * WS)
+ Tambient

Response: Tmodule, Predictor: Model

Control Panel

Converged in Gradient

Criterion	Current	Stop Limit
Iteration	10	60
Obj Change	8.770905e-13	1e-15
Relative Gradient	8.5053269e-7	0.000001
Gradient	0.0000365869	0.000001

Parameter	Current Value	Lock
a	-3.262535366	☐
b	-0.073205032	☐

SSE 57274.761173
N 3372

Edit Alpha	0.050
Convergence Criterion	0.00001
Goal SSE for CL	.

Nonlinear Fit

Prediction Model

(b0 * Tmodule
+ b1 * Tmodule * Log(POA Irrad))
+ b2 * Log(POA Irrad)

Response: Vmax/mod, Predictor: Vmax predicted

Control Panel

Converged in Gradient

Criterion	Current	Stop Limit
Iteration	1	60
Obj Change	3888420.9008	1e-15
Relative Gradient	1.1430988e-9	0.000001
Gradient	7.54943e-9	0.000001

Parameter	Current Value	Lock
b0	0.6377882383	☐
b1	-0.114189087	☐
b2	5.7443317286	☐

SSE 1823.282725
N 3372

Edit Alpha	0.050
Convergence Criterion	0.00001
Goal SSE for CL	.

1. Estimate module temperature from irradiance, ambient temperature and wind speed.
2. Estimate maximum module voltage based on module temperature and irradiance. *Needs to be translated to a system voltage.*
3. Assume an isobaric heating approximation for module effective humidity.

$$RH_{\text{module}} = \frac{RH_{ambient} \cdot P_{sat}(T_{ambient})}{P_{sat}(T_{\text{module}})}$$

Results

DONE: Determines 5-Year Coulombs in a specific location. Can also estimate how long the test runs for a high-leakage current sample.

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

Re-running the model with the lowest leakage current data helps establish how long the test might take.

$$LLC(\mu A) = 1319(\mu A/V)\cdot V_{sys}(V)/2\cdot e^{0.046/\%\cdot RH_{\text{module}}(\%)}\cdot e^{\frac{-0.5eV}{k\cdot T_{\text{module}}}}$$

- Basic forward stepping numerical integration over the course of a typical year.

	Five-Year Coulombs (Target Value to Complete Test)	HLC Estimated Testing Time at 85°C, 85%RH, -1000V	LLC Estimated Testing Time at 85°C, 85%RH, -1000V
Bangkok, Thailand	8.6	72	399
Miami, FL	8	67	371
Boston, MA	4.6	38	213
Munich, Germany	4.3	36	199
Denver, CO	2	17	93
Phoenix, AZ	1.8	15	83
Riyadh, Saudi Arabia	1.5	13	70

Conclusions

- Field data of PID failures have occurred in less that two years.
  - Definition of failure selected to be >5% degradation with EL indicating PID within a five-year service time in the field.

- Data from modules tested
  - Indicate PID failure in < 0.5C with others showing stability to > 50C.
    - 1 to 3.3 field years based on others' works consistent with our failure definition
  - Generally conforms to an expanded exponential corrosion model that can be extrapolated to field conditions.
    - Allows for an accelerated test that is terminated based on accumulated charge related to time in the field.
      - 5-year Bangkok estimate 8.6C
      - Likely would take less than two-weeks of -1000V Damp Heat testing to achieve
    - Process believed conservative, however:
      - Variability of leakage current data at a fixed testing condition not well understood.
      - General lack of individual module leakage current data from actual floating arrays in the field to validate results.

- General process of extrapolating accelerated test results to use conditions is an area requiring consensus-driven procedures for PV modules.
  - Well developed in the semiconductor industry.
  - New effort underway for inverters.

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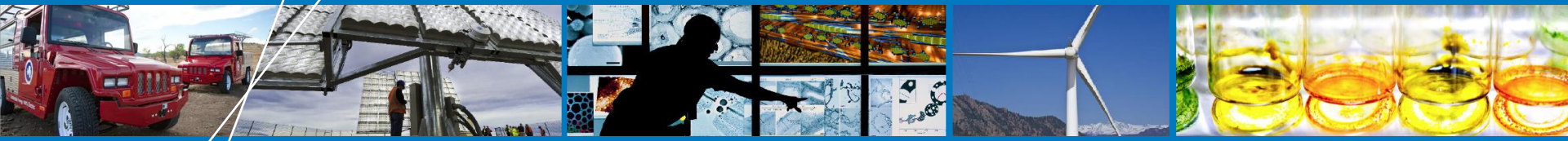
NATIONAL RENEWABLE ENERGY LABORATORY

Testing modules for potential-induced degradation– a status update of IEC 62804



Peter Hacke

National Renewable Energy Laboratory (NREL)

this presentation contains no confidential information

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.

Scope

Testing modules for potential-induced degradation– a status update of IEC 62804

- **Mechanisms**
  - Covers:
    - Measuring potential-induced degradation
    - Polarization
  - Does not cover:
    - Electrochemical corrosion
    - Combined effects with wear out, delamination, etc.
- **Materials**
  - Covers:
    - p-base and n-base Si cells (~89% of the market 2011)
  - Does not yet cover:
    - Thin film modules
    - No experiments so far in tandem or heterostructure devices

New in IEC 62804 project (key items)

- **IEC 62804 draft has been revised to be a method for test**

  TEST METHOD FOR DETECTION OF POTENTIAL INDUCED DEGRADATION OF PHOTOVOLTAIC (PV) MODULES

  - No pass/fail criteria
  - Contains a foil test and a damp heat test
  - Provides details on how to set up tests
  - Provides stress conditions for use as baseline allowing for comparisons
  - International task group
    - M. Koehl (Germany)
    - C. Liciotti (Italy)
    - F. Rummens (Belgium)
    - F. Fabero Spain)
    - K. Berger (Austria)
    - Y. Eguchi (Japan)
    - P. Hacke (USA)

Outline of talk

- Comparison of stresses and degradation rate for 25° C / foil and 60°C/85% RH damp heat test
- Illumination factor on PID rate
- Measurement techniques and stress levels discussion

Outline of talk

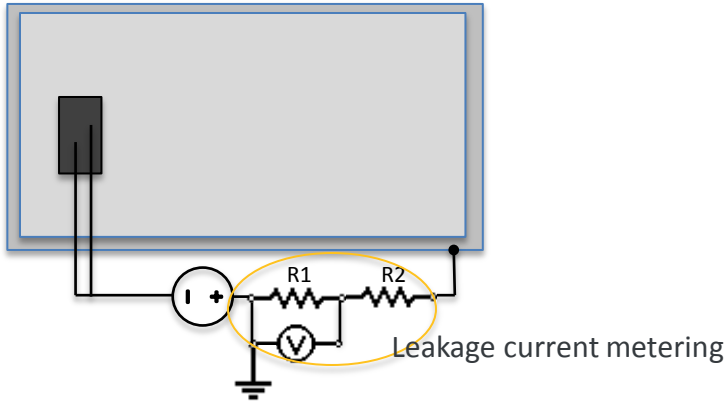
- **Comparison of stresses and degradation rate for 25° C / foil and 60°C/85% RH damp heat test**
- Illumination factor on PID rate
- Measurement techniques and stress levels discussion

Damp heat and foil methods – setup

Damp Heat

Foil

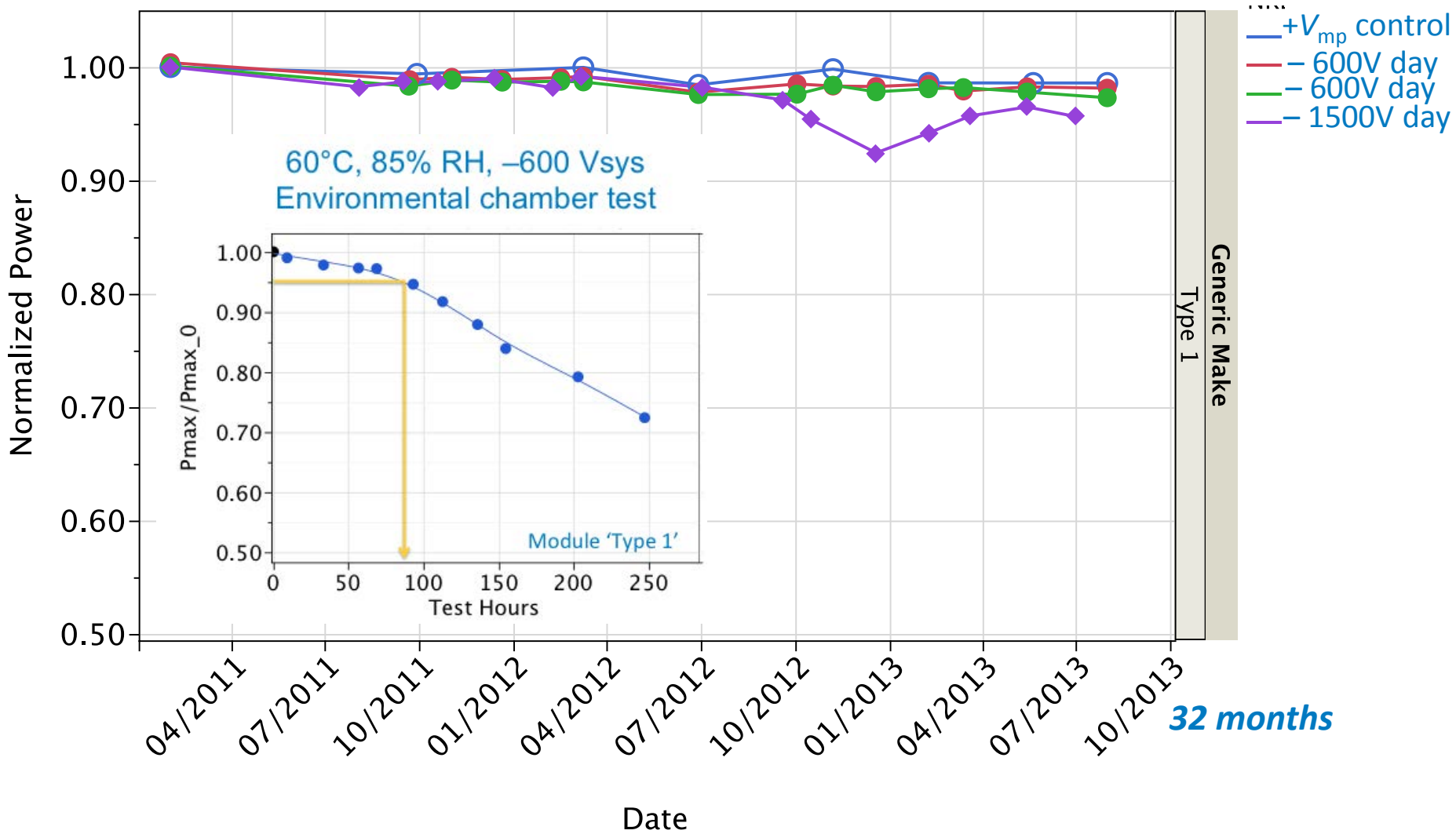
Bagdahn, Fraunhofer CSP
PV Japan, 5-7 Oct 2012



Damp heat and foil compared - background

- DH test (60°C/85%RH/96h/Vsys)
  - Does not defeat PID solutions based on the frame design
    - Rear rails, limited area edge clamps
  - Includes the environmental factor of humidity
    - Exposes effects of glass quality, texture, leakage current pathways, moisture ingress to an extent
- Foil test (25°C/168 h/Vsys)
  - Applies even grounding potential over the module surfaces
    - More representative of very heavy soiling
  - Favored by those seeking a simple test
- Tests are not comparable, stress state is different

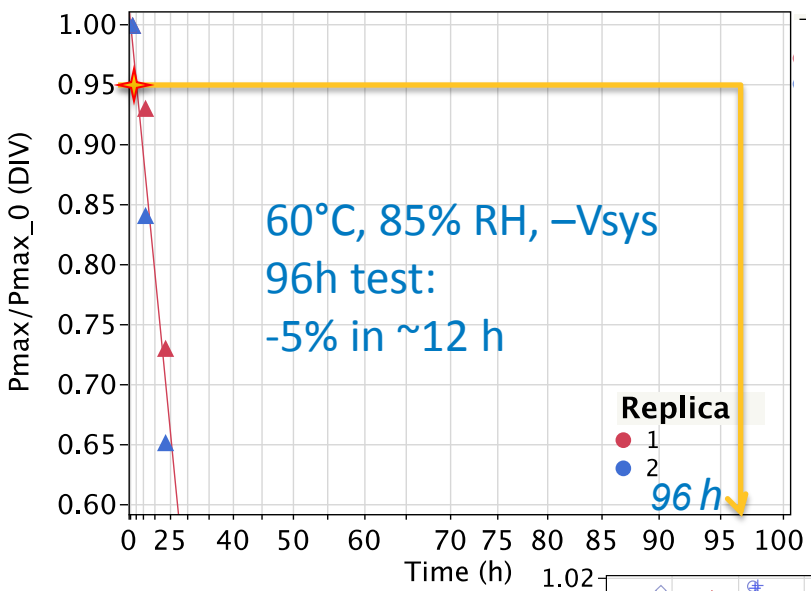
60°C/85%RH/96h/-Vsys stress condition origin



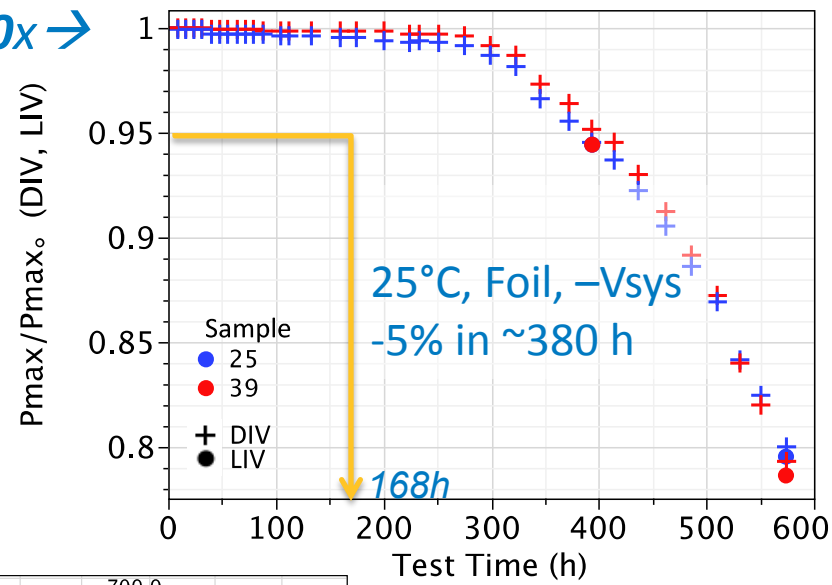
To date, chamber test successfully sorts 7 module designs (31 modules) for PID in the field

Hacke et al, 2013 E PVSEC (Paris)

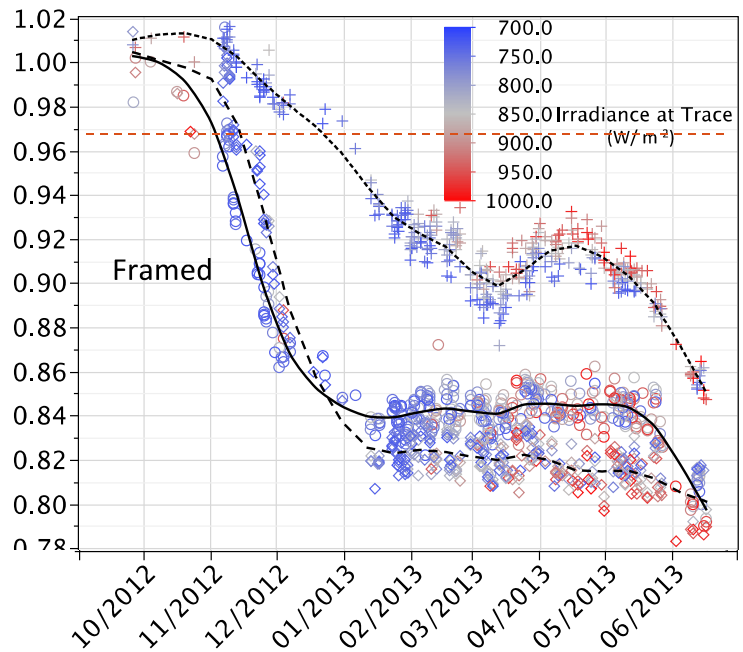
Damp heat and foil compared - 1



→30x→



Module replicas start fail in ~ 92 days under $-V_{sys}$ in Florida

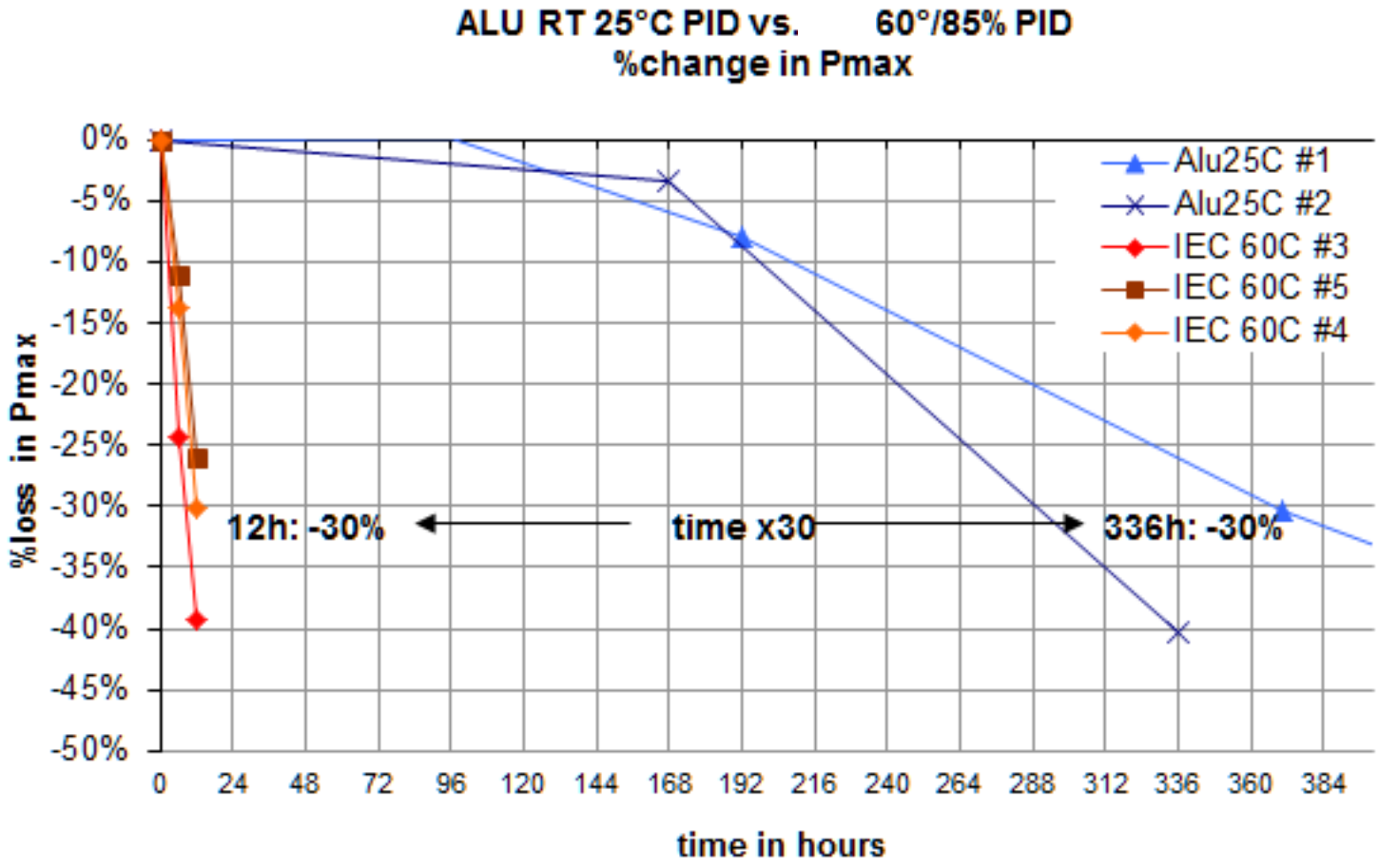


Framed, commercial mc-Si module

Hacke et al, 2013 E PVSEC (Paris)

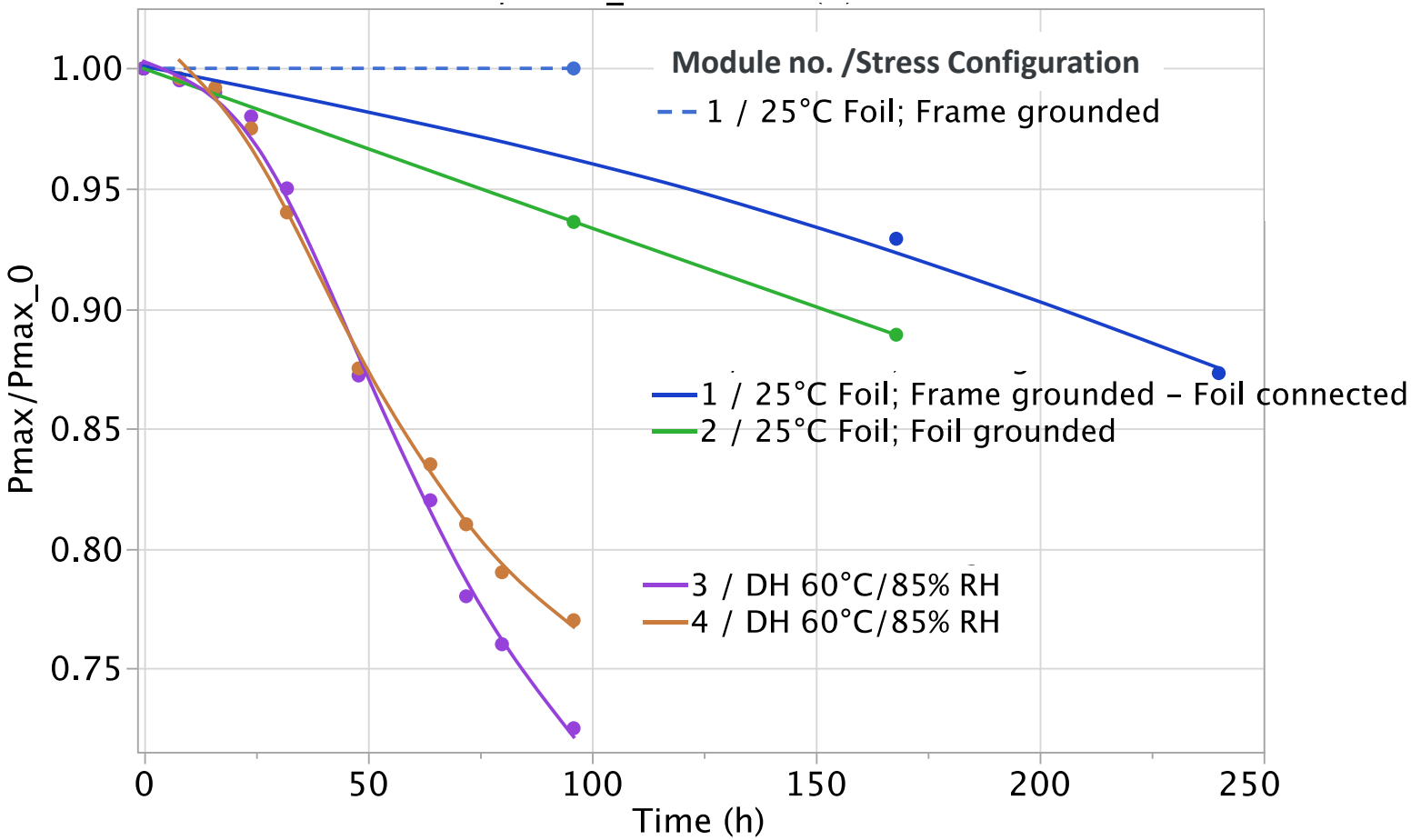
Damp heat and foil compared - 2

S. Janke. S. Pingle, SOLON, unpublished



Damp heat and foil compared - 3

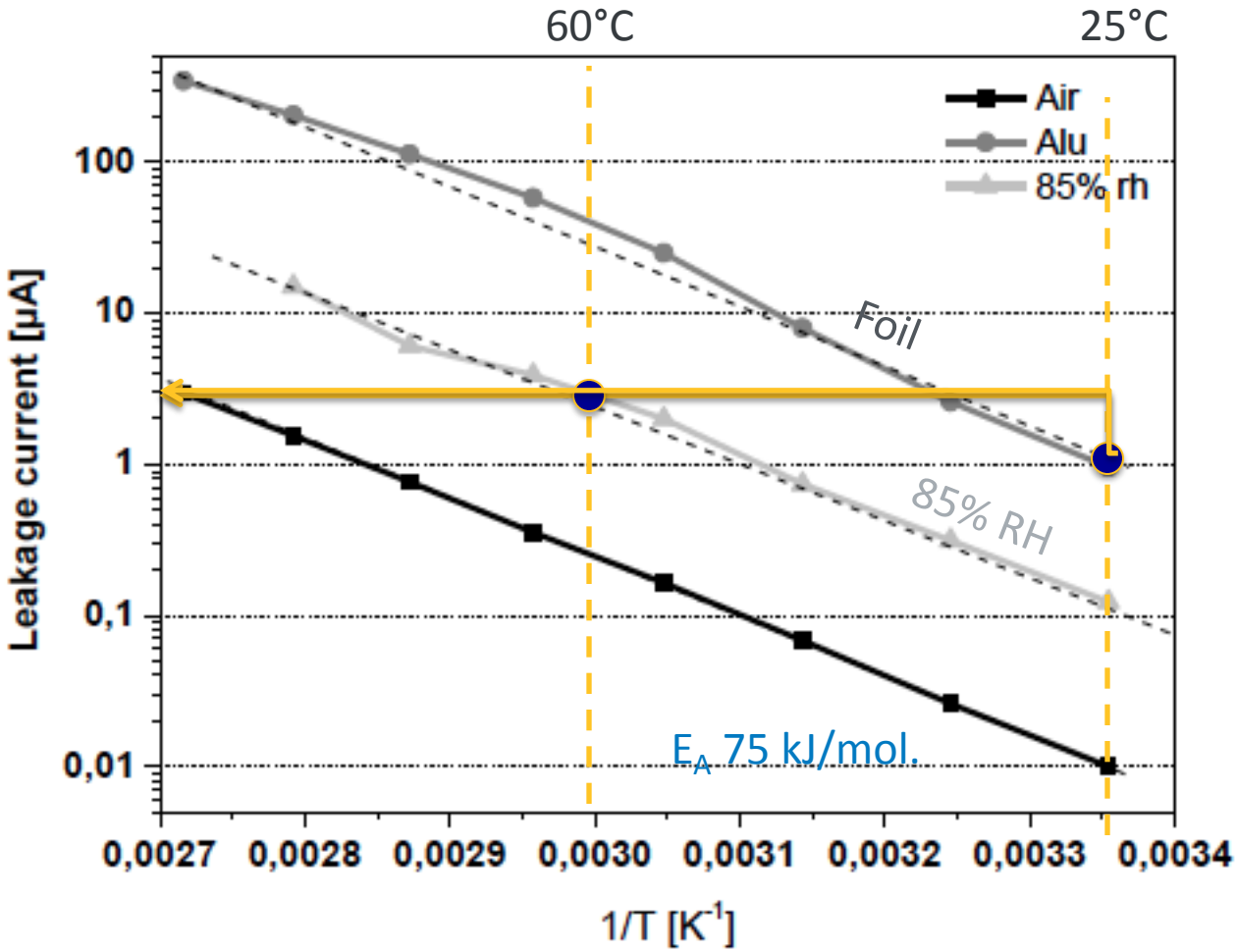
Prof. Mani, S.Tatapudi, C. Anderson (ASU), to be published



- **Significant boost in 25°C foil method PID rate by defeating insulating coating on frame; ie, removing frame anodization**
- **Al foil method still produces ~4 times slower degradation than the 60°C/85% RH condition**

Damp heat and foil compared - 4

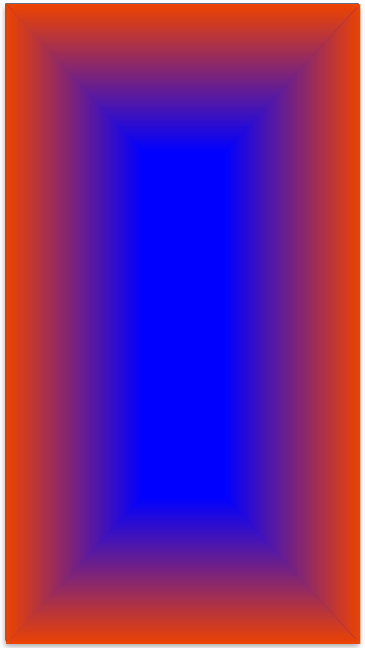
Hoffmann & Koehl, 27th E-PVSEC



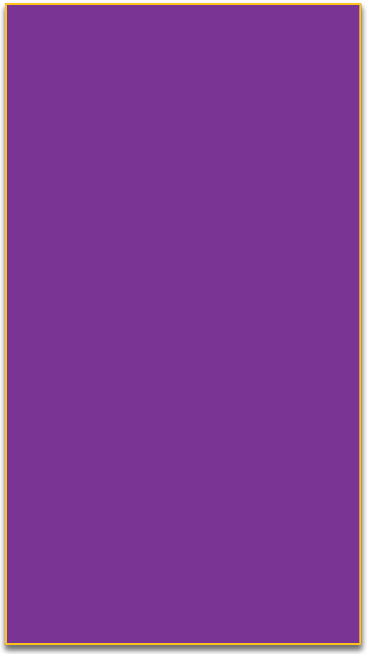
Leakage current at 60° C/85% RH approximately 3x that of 25° C Al foil

Different stress configurations of DH, foil

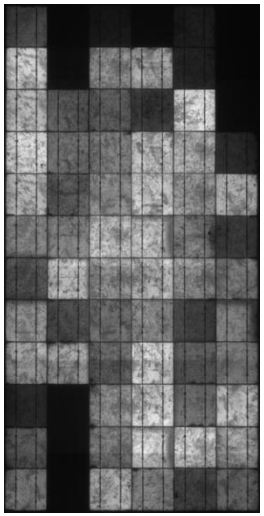
Damp Heat



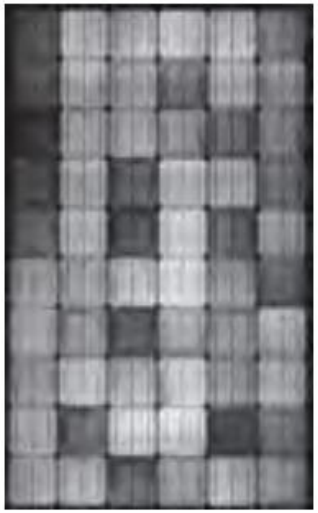
Foil



Damp Heat



Foil



CONCEPT

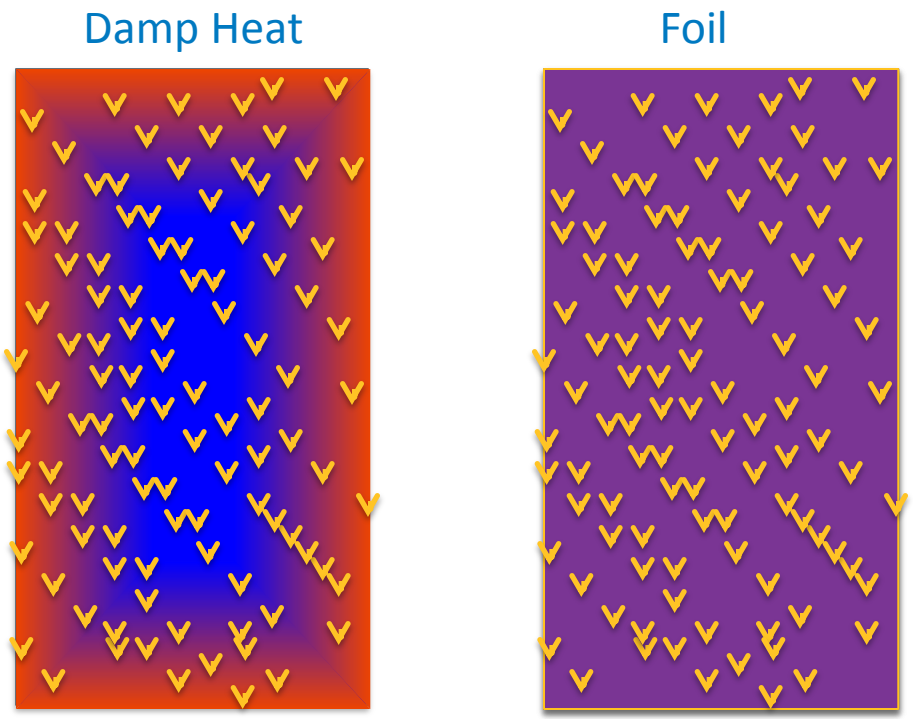
EL by Sascha Dietrich et al, Fraunhofer CSP

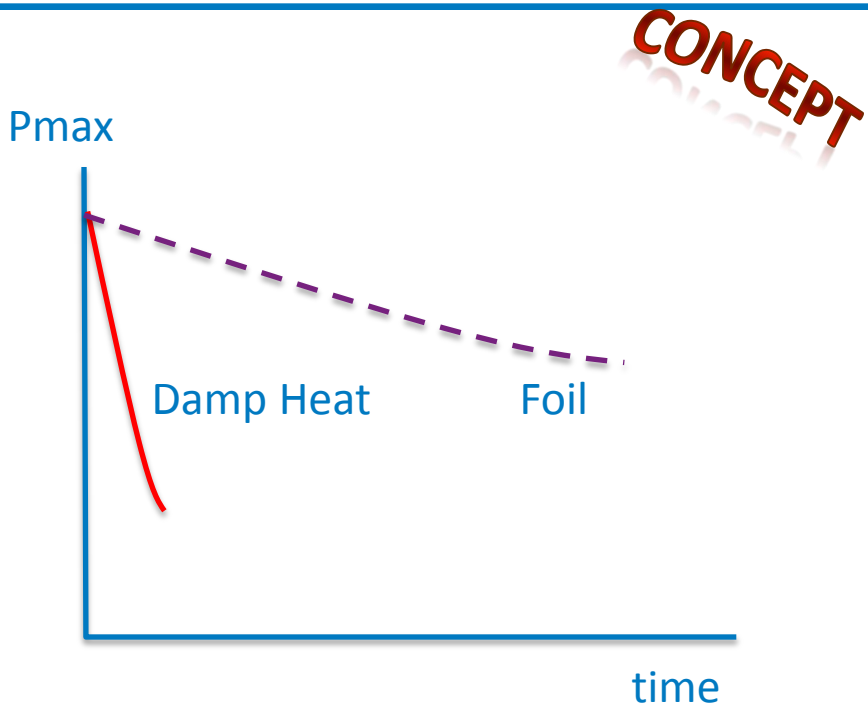
Low stress High stress

- Many defects, conductive encapsulant
- Many defects, resistive encapsulant
- Few defects, conductive encapsulant

Defects, V. Naumann model of Na at stacking faults:

Different stress configurations of DH, foil





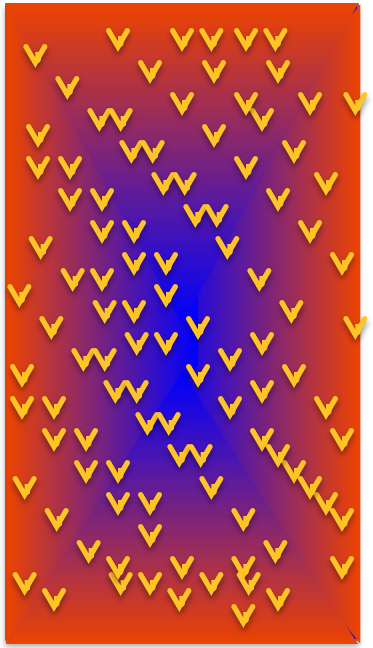
Low stress High stress

- ***Higher T overcomes activation energy***

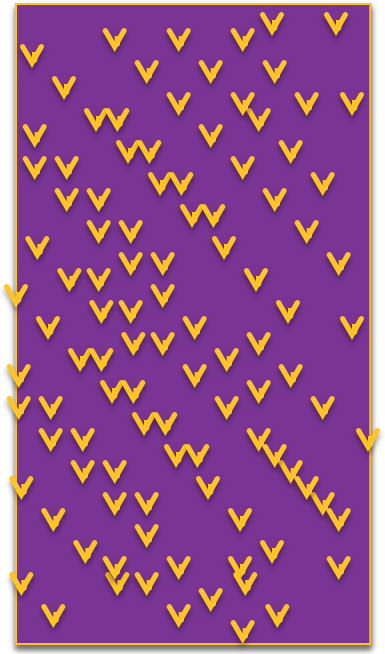
- **Many defects, conductive encapsulant**
- Many defects, resistive encapsulant
- Few defects, conductive encapsulant

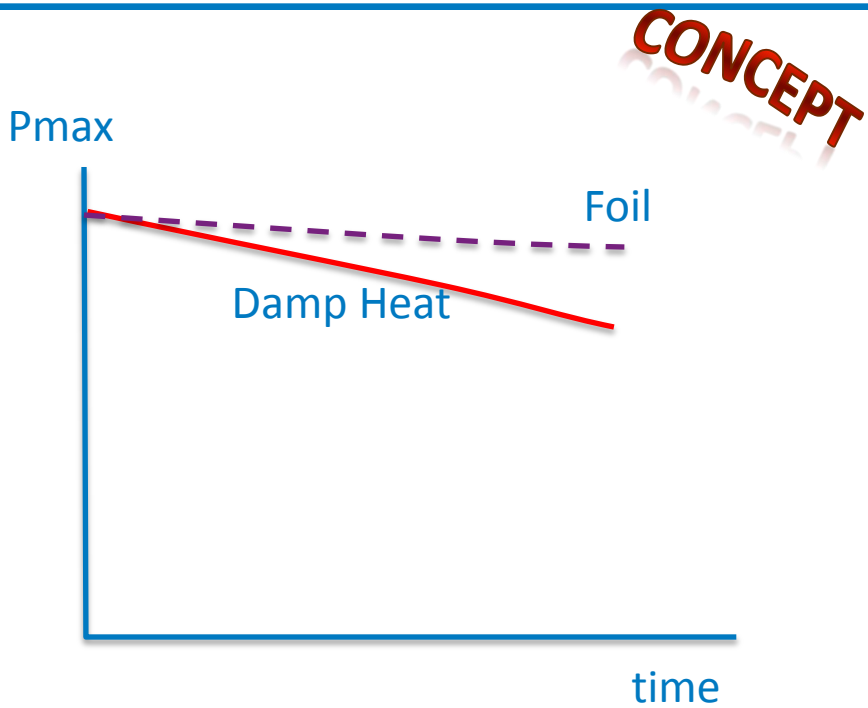
Different stress configurations of DH, foil

Damp Heat



Foil



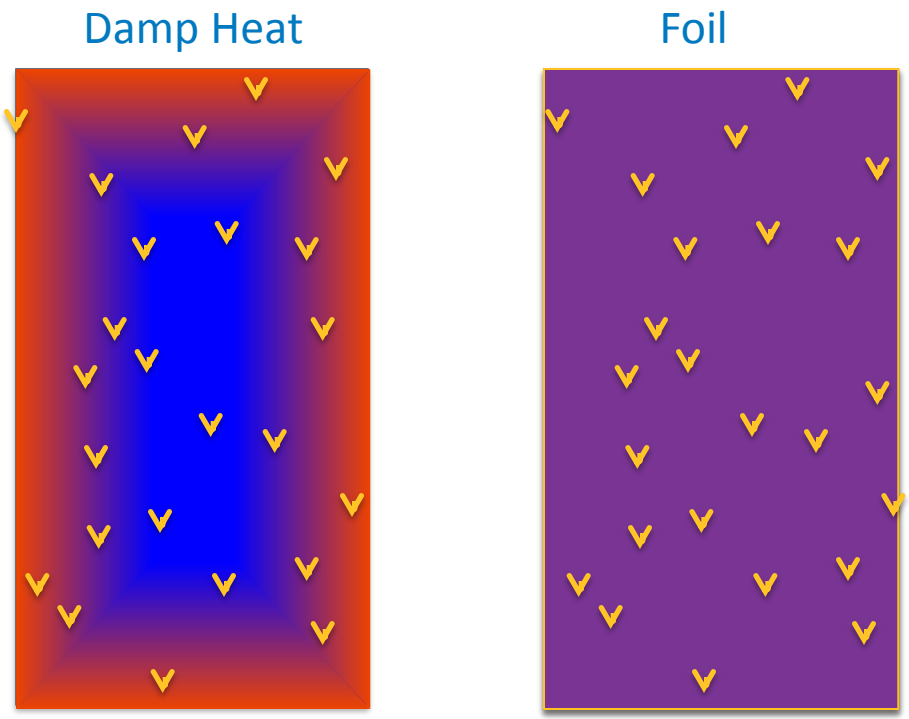


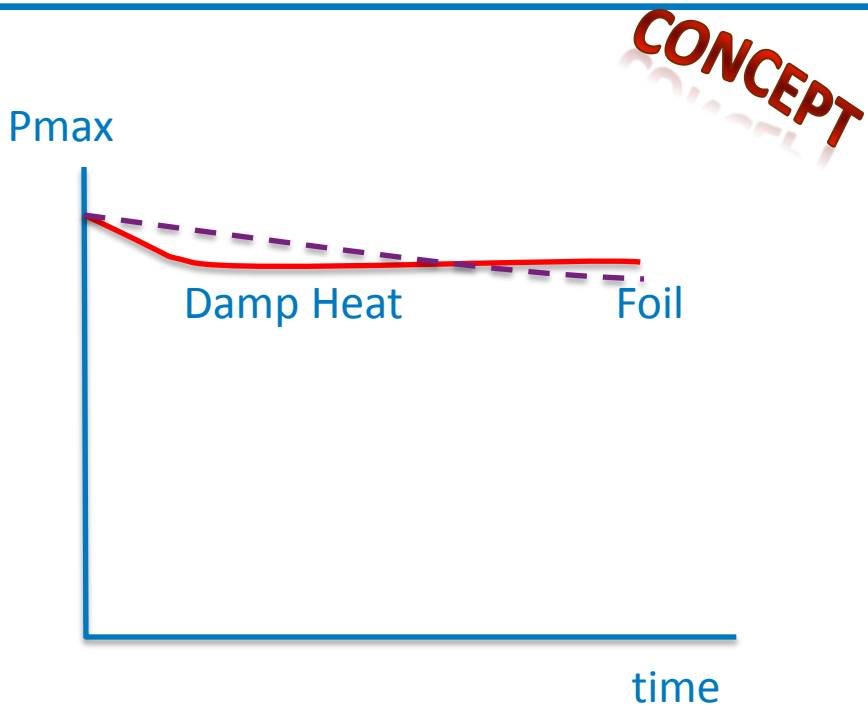
Low stress High stress

- Many defects, conductive encapsulant
- **Many defects, resistive encapsulant**
- Few defects, conductive encapsulant

- ***Higher T overcomes activation energy***
- ***Resistive encapsulant leads to more distribution in the grounding and stress (less charge transfer into the module)***

Different stress configurations of DH, foil





Low stress High stress

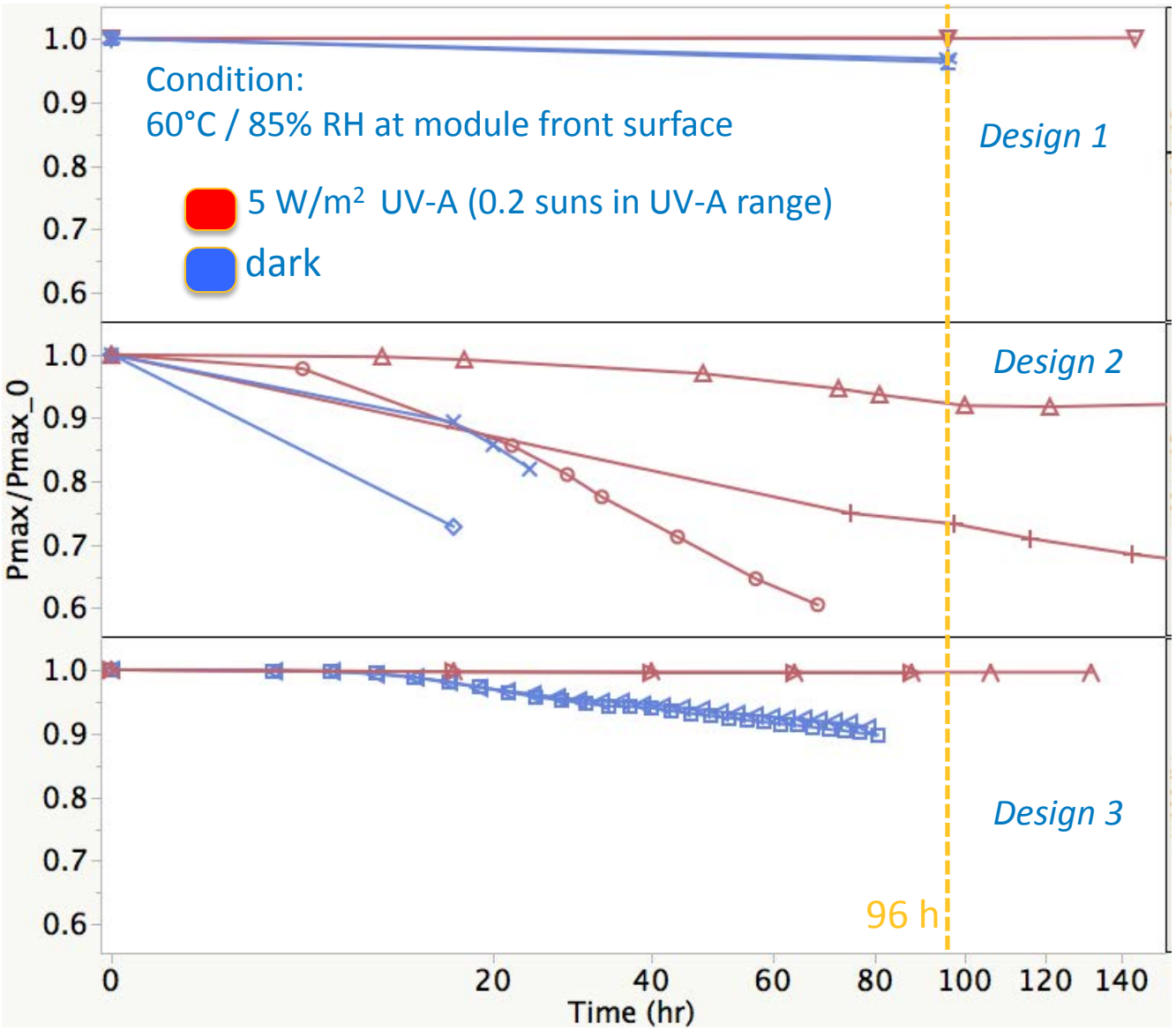
- Many defects, conductive encapsulant
- Many defects, resistive encapsulant
- **Few defects, conductive encapsulant**

- ***Higher T overcomes activation energy***
- ***Defects covered in 'high stress' region in DH saturate; foil however eventually reaches to all defects.***

Outline of talk

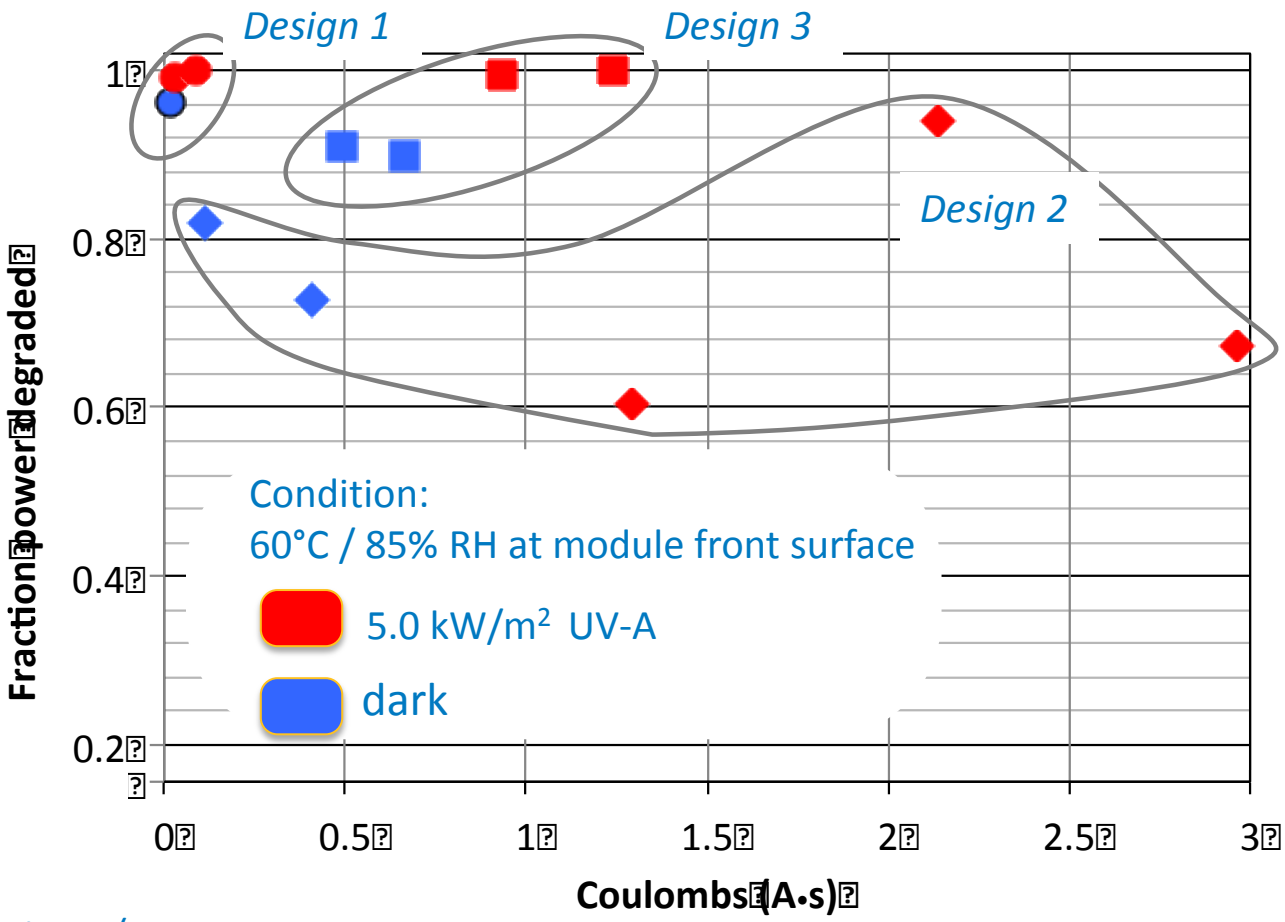
- Comparison of stresses and degradation rate for 25° C / foil and 60°C/85% RH damp heat test
- **Illumination factor on PID rate**
- Measurement techniques and stress level discussion

Chamber in-situ UV-A light: PID retardant



- T Chamber decreased and RH increased to maintain 60°C/85% RH on surface.
- Leakage current with UV at or above dark condition

Extent of PID with and without simultaneous 0.2 sun UV-A vs Coulombs



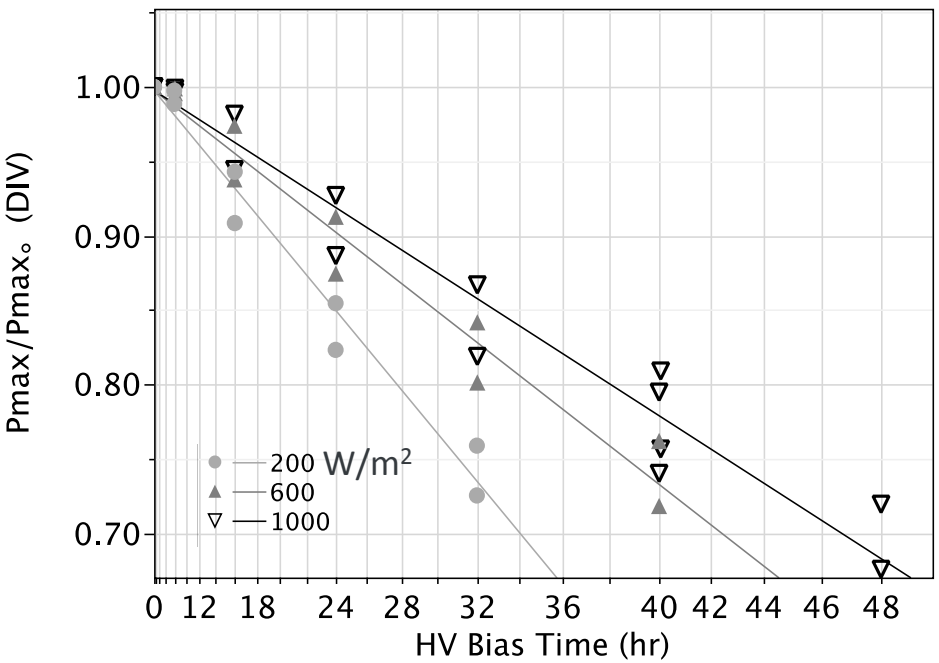
- With more stress (leakage current - time product) under illumination, there is the same or less PID.
- For a given leakage current charge measured in chamber, we expect less (possibly no) degradation under illumination, such as outdoors
- Focus then becomes how much they degrade outdoors, accelerated tests are just correlations, and leakage current not a universally representative indicator of degradation
- Possible mechanism: UV creates radicals that scavenge the most deleterious ions (e.g., Na^+)

Outline of talk

- Comparison of stresses and degradation rate for 25° C / foil and 60°C/85% RH damp heat test
- Illumination factor on PID rate
- **Measurement techniques and stress level discussion**
  - Power of module in low light undergoing PID
  - Removing non-equilibrium conditions and leakage current spikes in DH
  - Motivation for higher stress levels

Low light impact, chamber and field tests

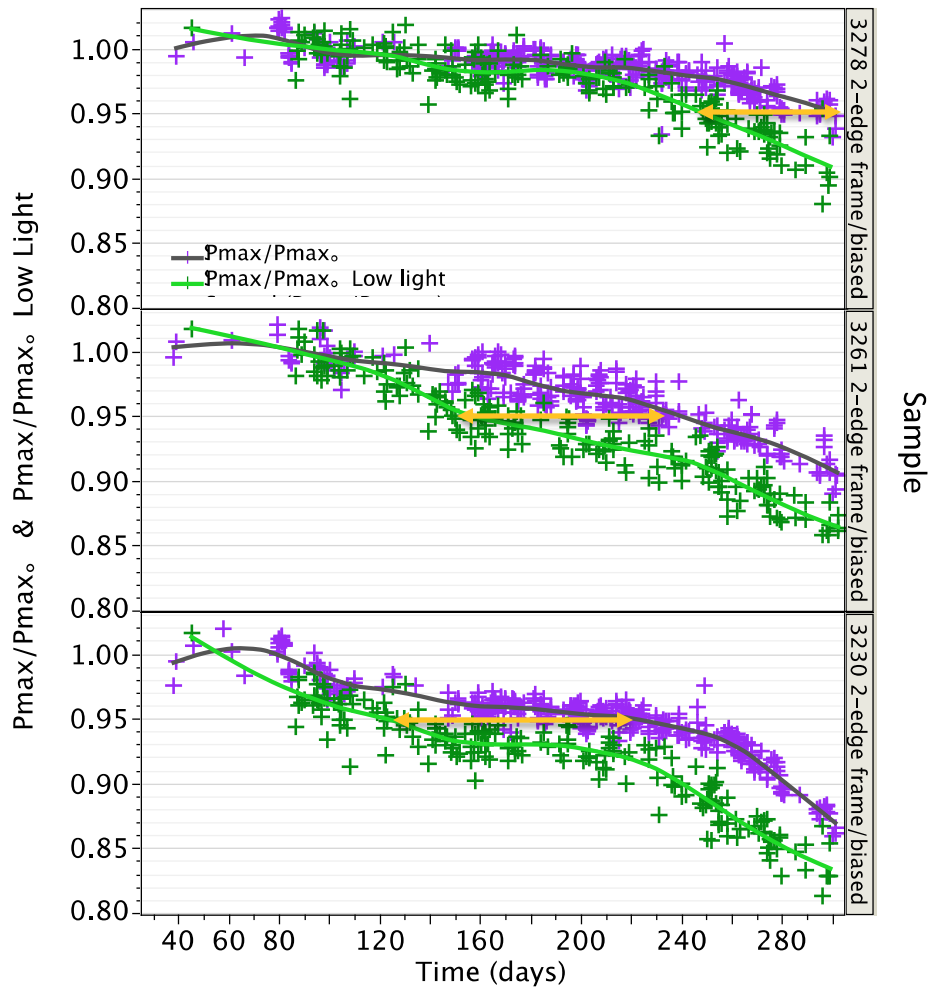
Indoor chamber tests



Time to 5% degradation in **28%** less time At 200 W/m² than at 1000 W/m²

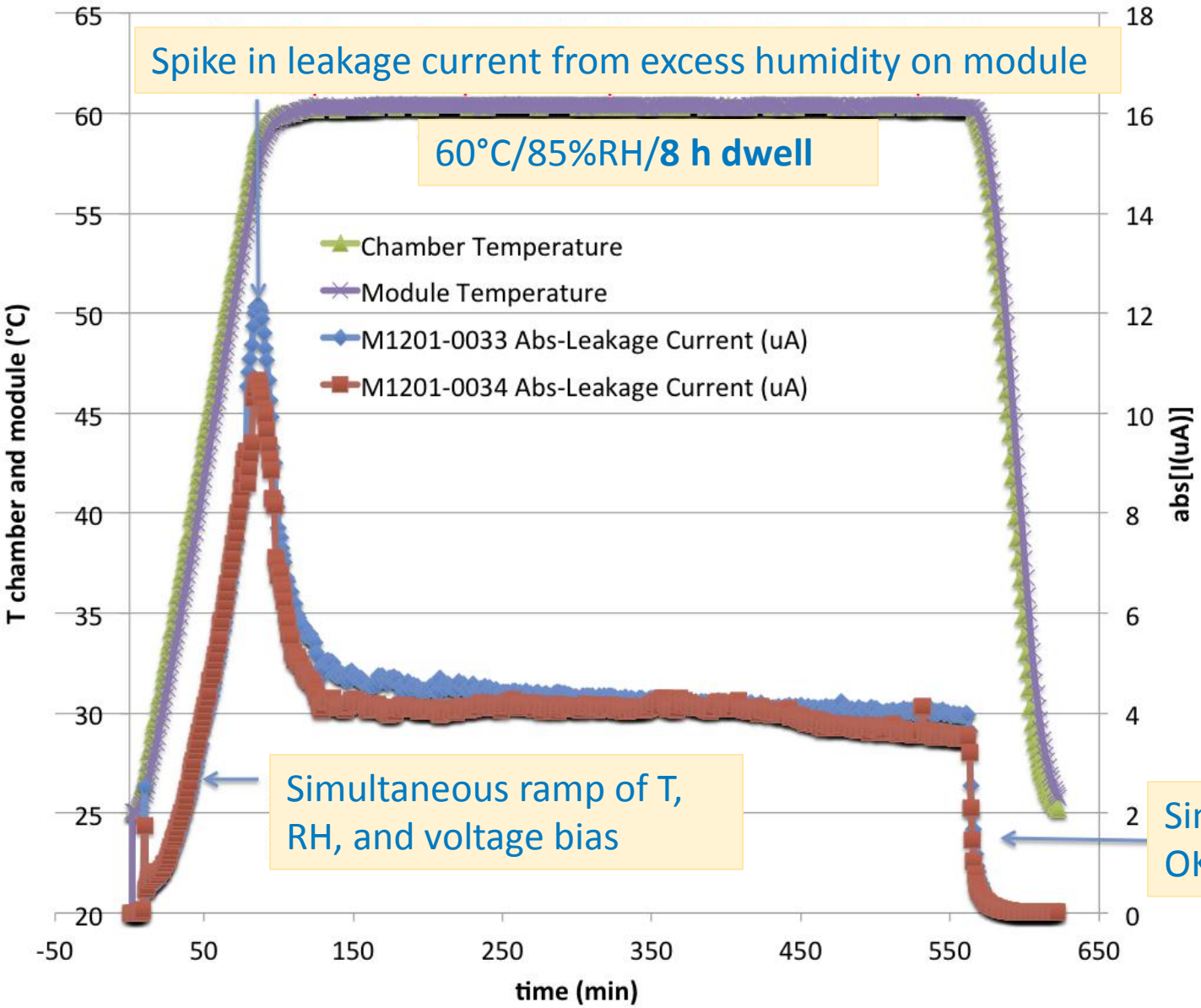
Also see:
G. Mathiak *et.al.*, TÜV-R
27th EU-PVSEC

Outdoor tests



Time to 5% degradation in **17%, 35%, and 42%** less time than the full light curves

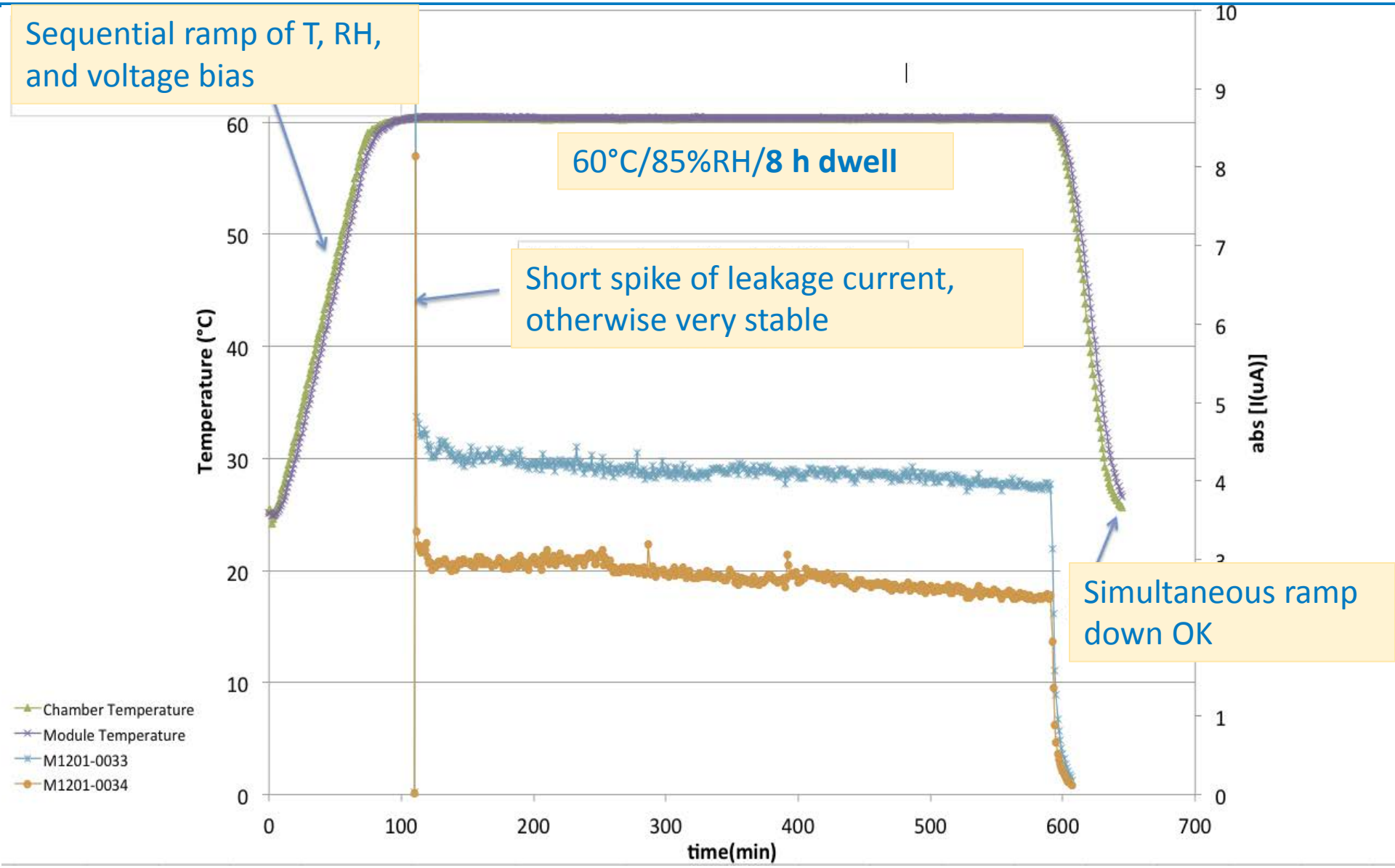
Voltage applied on start, then combined T, RH Ramps (early draft sequence)



Leakage current spike, if different from chamber to chamber could conceivably contribute to poorer reproducibility & excess stress

Also see: G. Mathiak, *et.al.* TÜV-R 27th EU-PVSEC

T ramp/dwell ➔RH ramp ➔V ramp (later draft sequence)

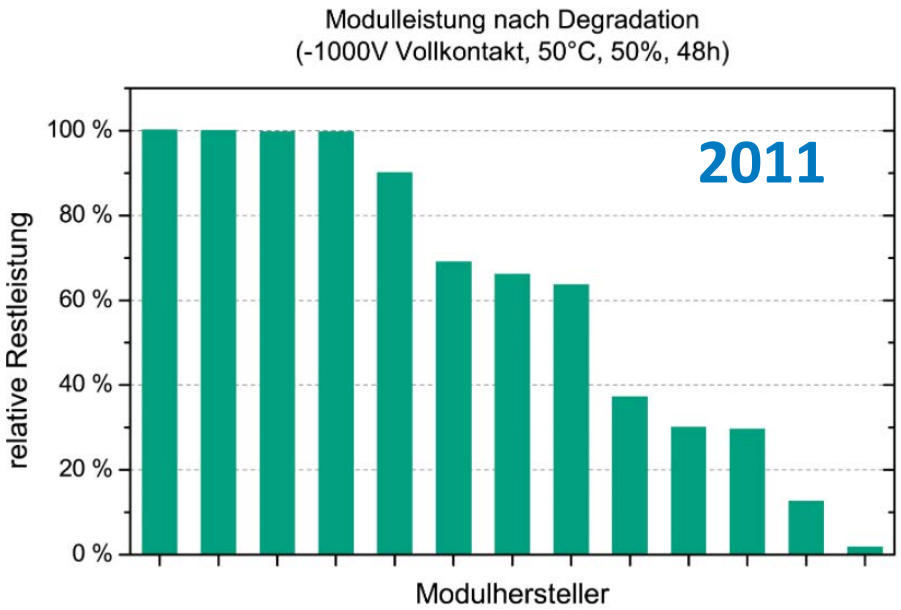


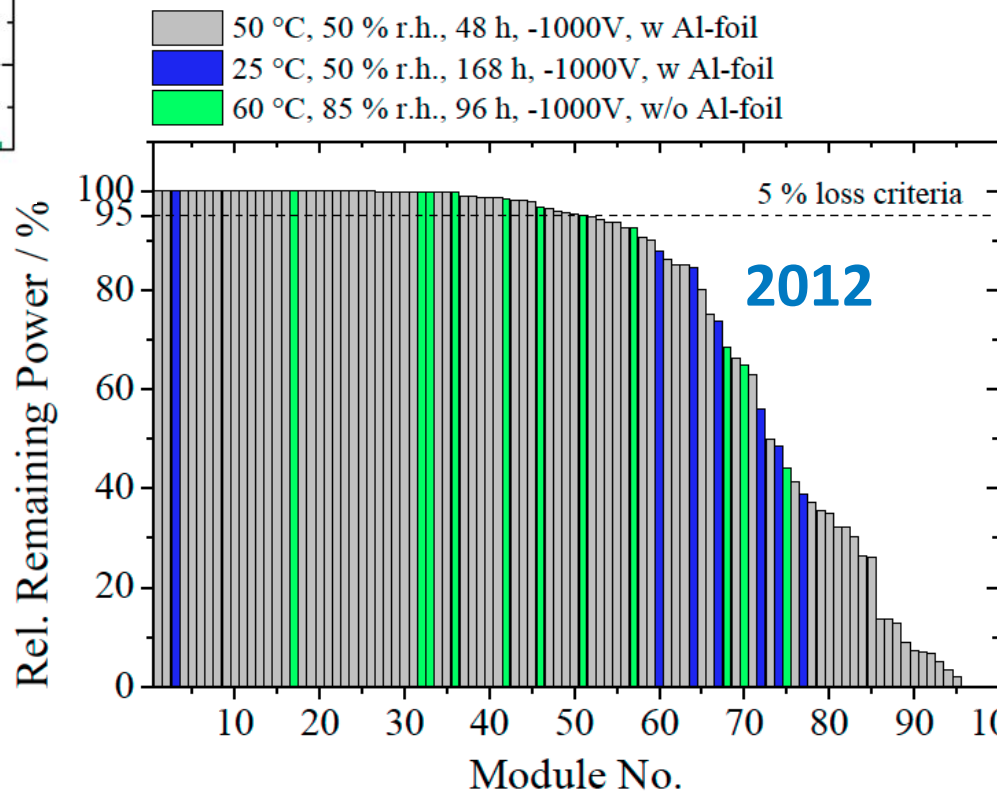
Possible futures of the stress level

- **DH PID test**
  - To detect low light degradation when it manifests in STC power, and to
  - add additional stress, making up for the removal of the excess humidity on startup
    - 1.35-1.5 X increase in nominal stress level
    - Damp heat test 60°C→65°C stress levels
- **Foil PID test**
  - *Minimum* 3x increase in stress level to bring it closer to 60°C DH test stress level
  - *Minimum* 4.0x to 4.5x increase in stress level to bring it to 65°C/ 85% RH
  - Must manually defeat the frame insulation to short the frame to the glass (what humidity would normally do)

MORE DATA NEEDED

PID in c-Si modules becoming the minority





2013, 2014 should be even better

Fraunhofer CSP data

PID in c-Si modules becoming the minority

- The ‘norm’ in China for qualifying PID resistance is 85°C/85%RH/96h/-Vsys for manufacturers paying attention to it
- Companies and labs frequently testing with foil at elevated (50°C -60 °C)temperatures
- Module manufacturers already moving beyond the proposed stress levels

Thank you for your attention

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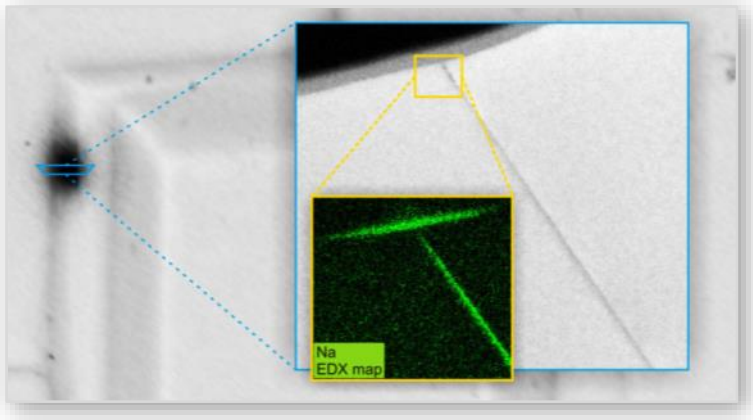
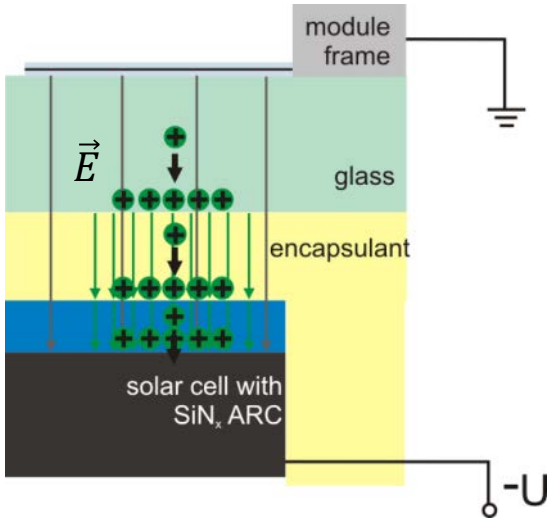
PID-shunting: Understanding from nanoscale to module level

PV Module Reliability Workshop 2014-02-25





Volker Naumann[1], Dominik Lausch[1], Klemens Ilse[1],
Otwin Breitenstein[2], Jan Bauer[2], Stephan Großer[1], J. Bagdahn[1], Christian Hagendorf[1]

[1] Fraunhofer Center for Silicon Photovoltaics CSP, Walter-Hülse-Str. 1, 06120 Halle, Germany
[2] Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle, Germany

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Outline

- Introduction: Potential-induced degradation of shunting type (PID-s)
- PID test for unlaminated solar cells and encapsulants
- The nature of PID-shunts
  - Local shunts
  - High resolution defect analysis
- Voltage divider model for solar module encapsulation
  - Measurement of leakage currents and voltage distribution
  - Explanation of approaches for PID prevention

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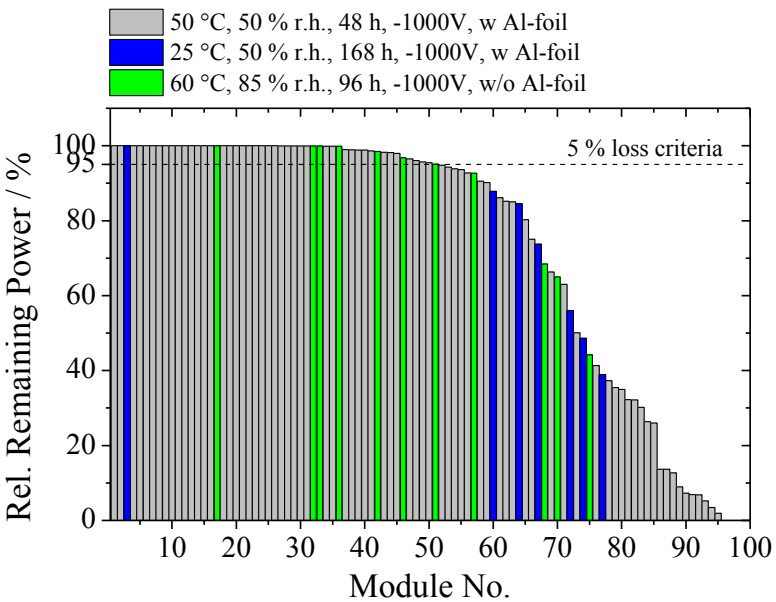
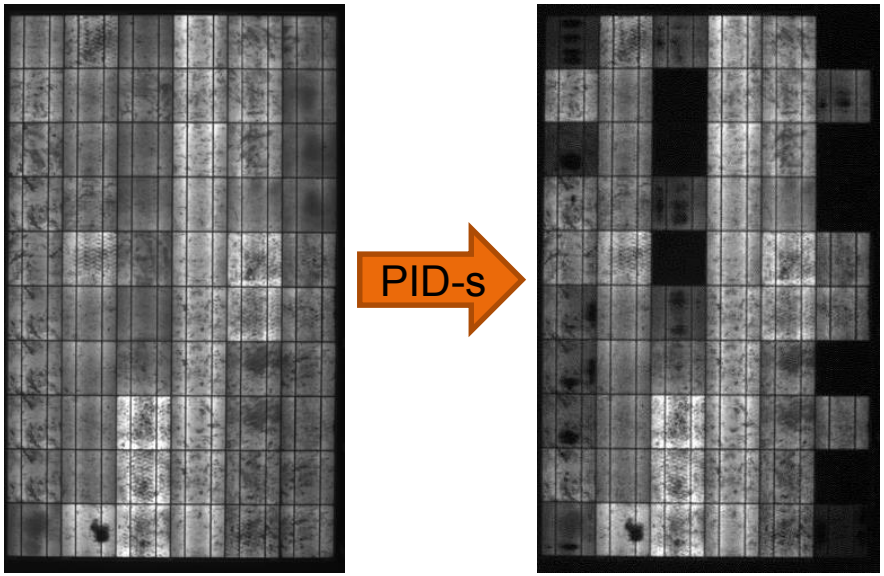
Potential-induced degradation of shunting type (PID-s)

- Large potential between front glass surface and solar cells
  → leakage current (cations, electrons) [1, 2]
- Massive reduction of the parallel resistance = shunting → PID-s
- Great efforts to achieve a test standard require a basic understanding



Relative power output after PID tests at 95 modules

S. Dietrich et al., Experiences on PID testing of PV modules in 2012, NREL PV Module Reliability Workshop 2013



Electroluminescence imaging reveals PID-s

[1] P. Hacke et al., Proc. of 25th EU-PVSEC, Valencia, Spain, 2010
[2] S. Pingel et al., Proc. of 35th IEEE PVSC, Honolulu, USA, 2010

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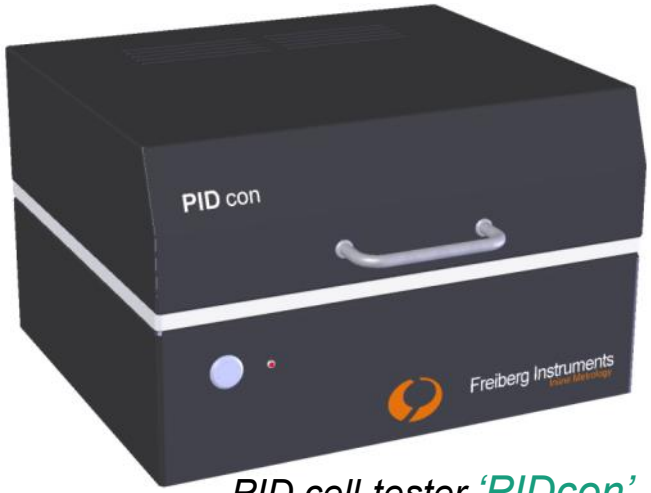
PID test for unlaminated solar cells and encapsulants

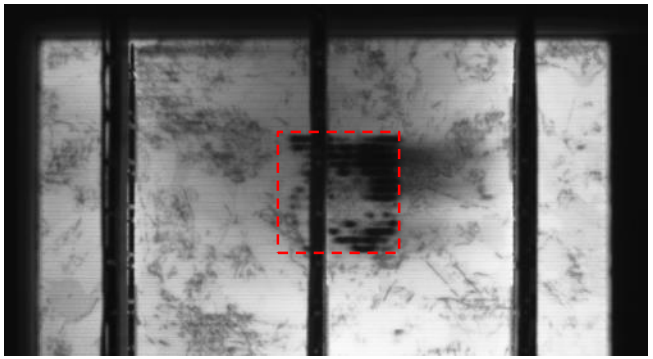
- PID test procedure for solar cells and module components (glass, polymer sheets)
- Use of standard encapsulation materials
- PID-testing without manufacturing of mini modules, no climate chamber necessary
- In-situ recording of R_p
- Patent pending
- Commercially available (Freiberg Instruments/Germany)

→ Fast and inexpensive quality check for cells

→ Flexible tool for R&D (cells, encapsulants)



PID cell-tester 'PIDcon'



EL image of a multicrystalline Si solar cell after PID test on an area of 4x4 cm² (shunted region)

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Comparison of PID test methods

	Time to result	Closeness to reality	Varia-bility	Control of test	Cost per test (incl. equipment)
In-field testing					
- ‘intelligent’ HV source	−−	++	o	o	−−
- permanent HV	−	+	o	+	−
Climate chamber					
- Standard modules	o	+	+	++	−−
- Mini modules	+	o	+	++	o
Corona test					
- of mini modules	+	o	+	−	+
- unlaminated solar cells	++	−−	−	−	++
PIDcon cell test	**+**	**o**	**+**	**+**	**++**

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Physical nature of PID-shunts

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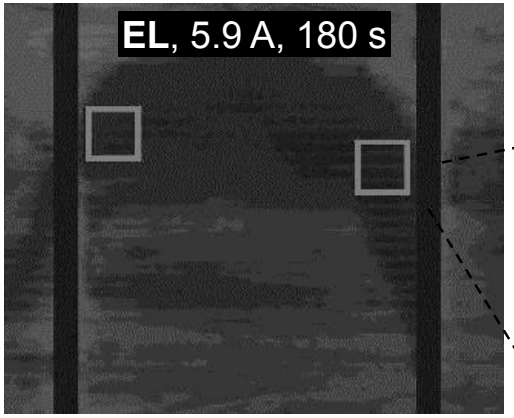
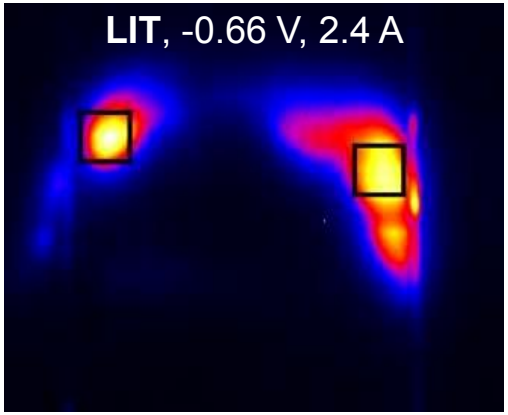
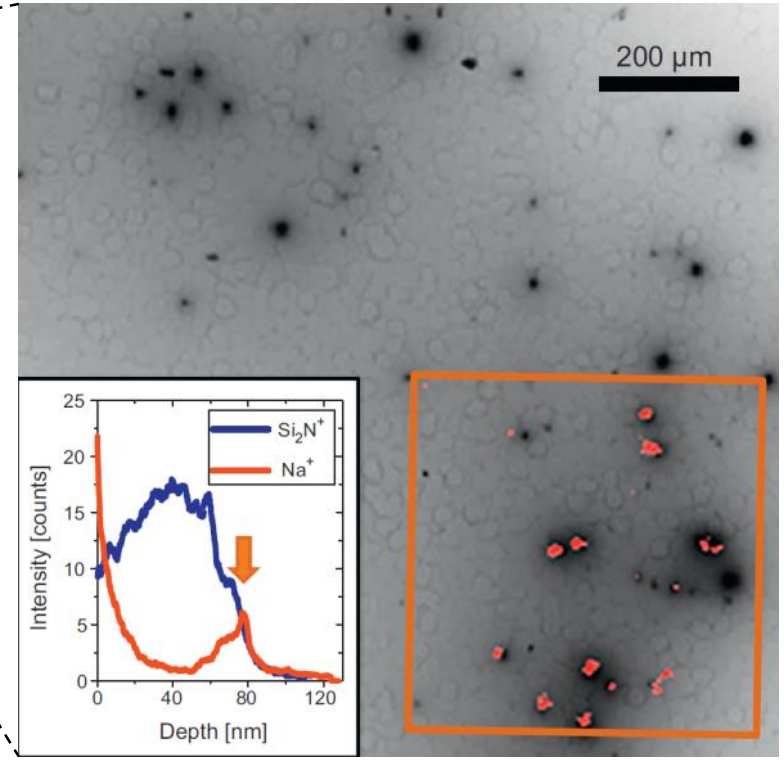
Physical nature of PID-shunts: local shunts





Imaging of local PID-shunts with SEM/EBIC*



*Electron Beam Induced Current

ToF-SIMS Na^+-map

- PID-shunted regions consist of high numbers of local shunts
- Accumulations of Na at the SiN_x-Si interface correlate with shunt positions

[1] V. Naumann et al., Solar Energy Materials and Solar Cells Vol. 120 (2014), 383-389

- Lock-in EBIC system by point electronic

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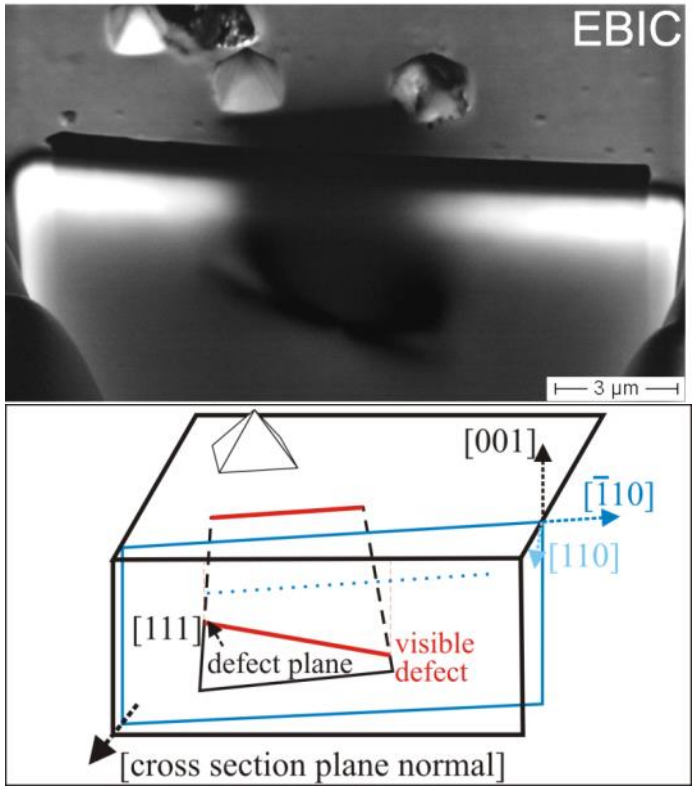
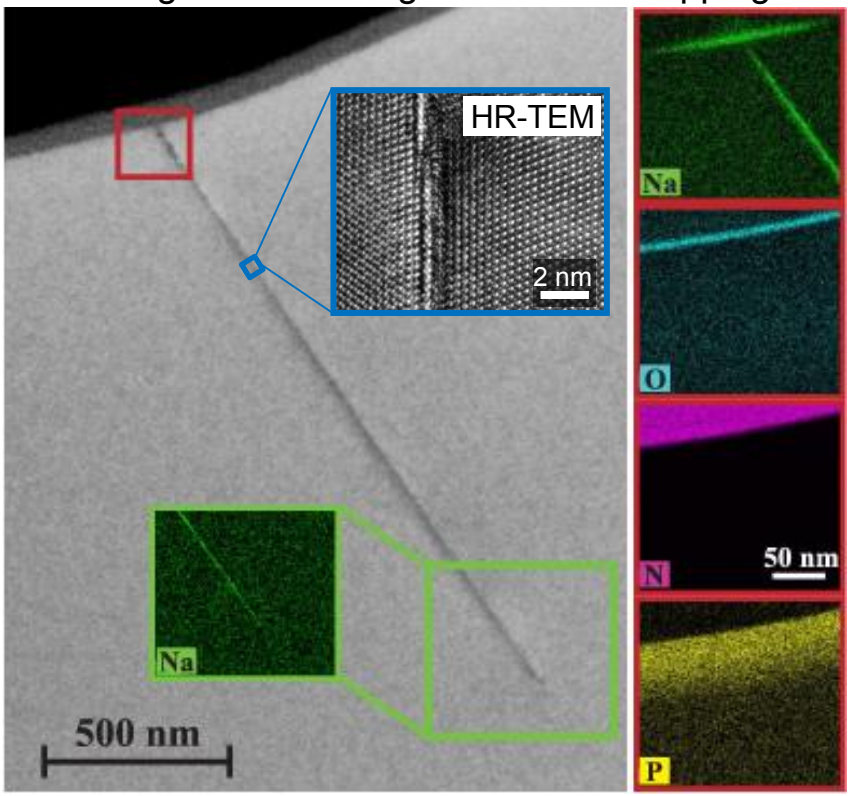
point electronic Fraunhofer CSP

Physical nature of PID-shunts: cross section

FIB cross section of a PID-shunt:



TEM image of a stacking fault + EDX mapping:



- PID-shunt = 2D crystal defect ("stacking fault") in Si, decorated with Na [1]
- Corona test → Na comes from the surface of the cell, not from the glass
- Assumption: voltage across SiN_x antireflective layer critical for Na^+ ion drift

[1] V. Naumann et al., Solar Energy Materials and Solar Cells Vol. 120 (2014), 383-389

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Voltage divider model for PID

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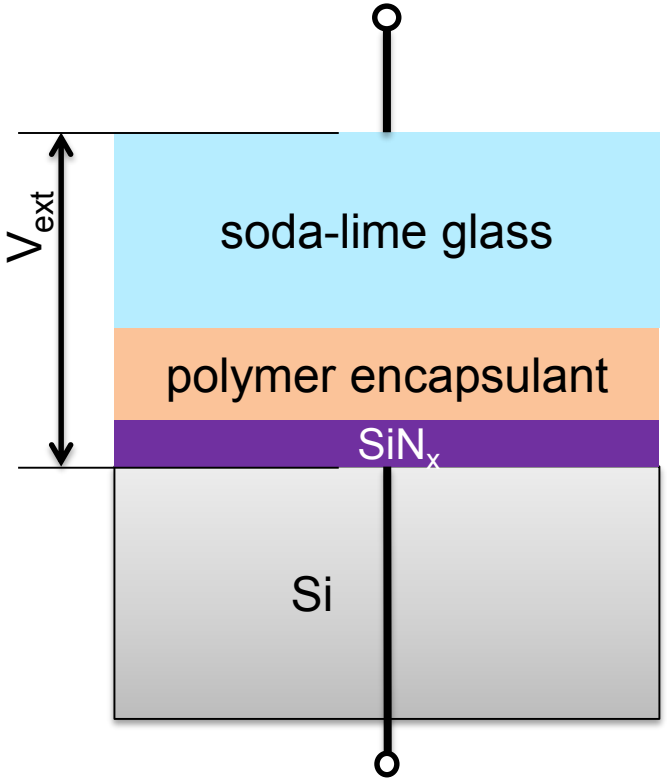
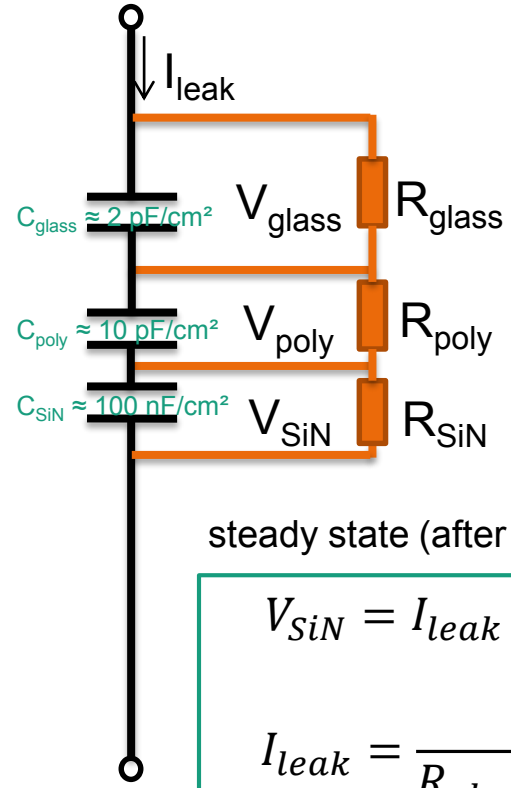
Voltage divider model for PID on module level





steady state (after charging of all capacitors):

$$V_{SiN} = I_{leak} \cdot R_{SiN}$$

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

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

- Critical parameter for resistance against PID:
  voltage across SiN_x layer (V_{SiN})

[1] V. Naumann et al.: On the discrepancy between leakage currents and potential-induced degradation of crystalline silicon modules, *Proc. 28th European Photovoltaic Solar Energy Conference and Exhibition,* 2013, pp. 2994-2997

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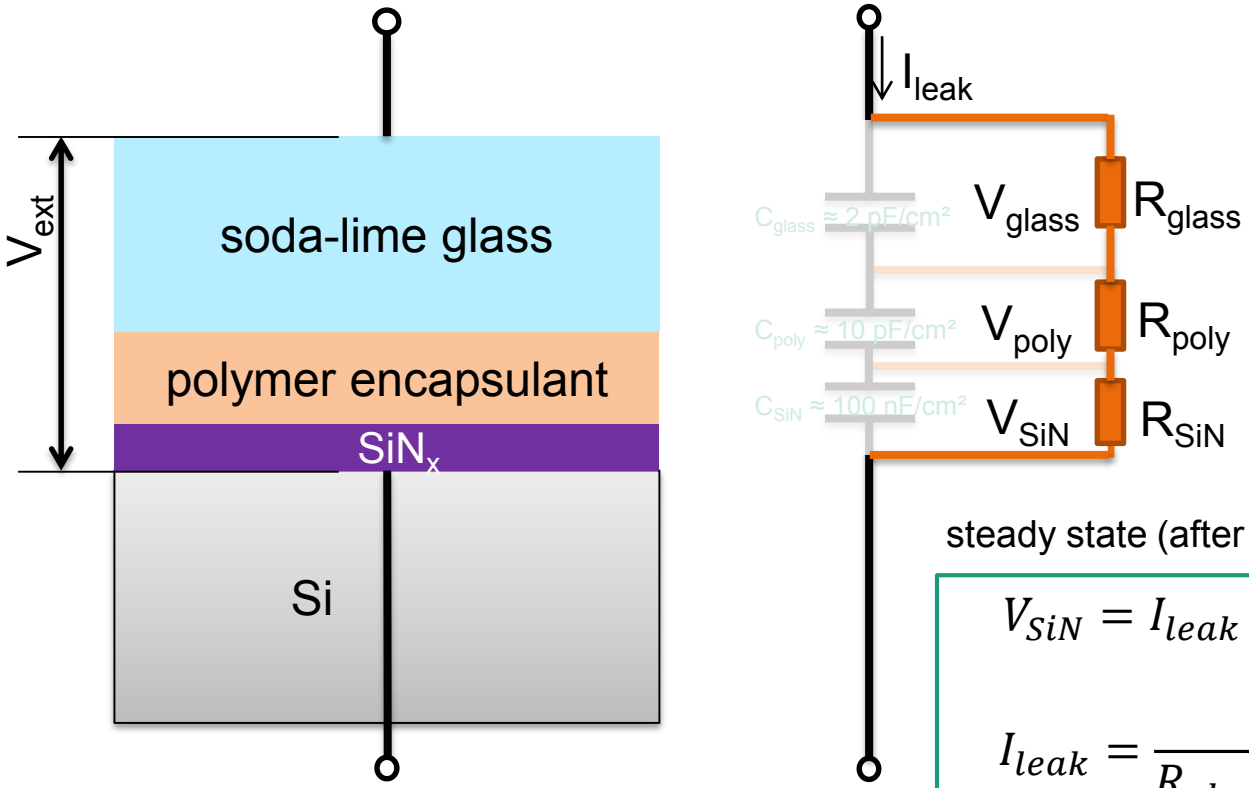
Voltage divider model for PID on module level



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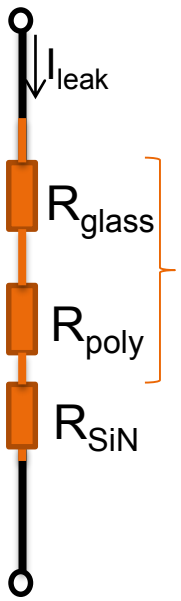
Voltage divider model

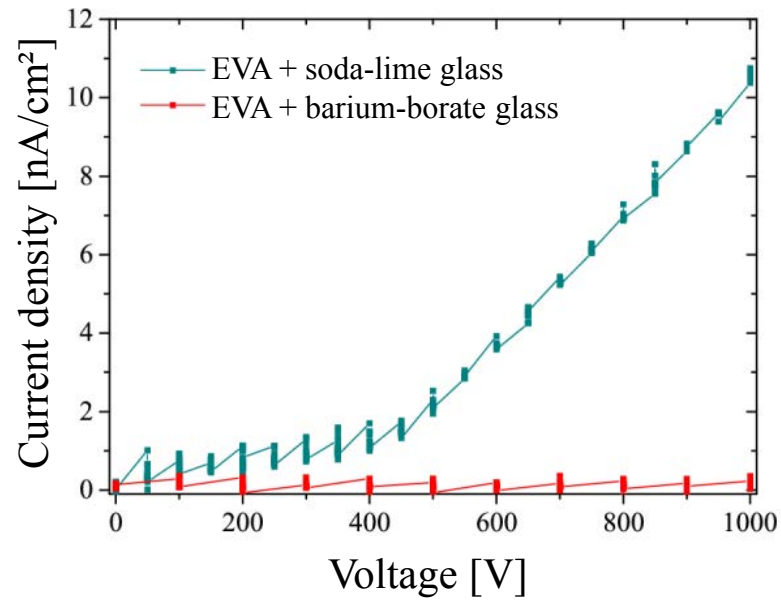
Case 1: control of the leakage current

$$V_{SiN} = I_{leak} \cdot R_{SiN}$$

- Reduced leakage current avoids PID-s
- Can be achieved through high resistance of encapsulation glass or polymer



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



Measurement of leakage current for different glass

[1] V. Naumann et al., *Proc. 28th European Photovoltaic Solar Energy Conference and Exhibition,* 2013, pp. 2994-2997

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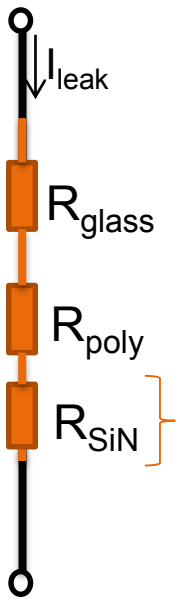
Voltage divider model

Case 2: control of the SiN_x properties

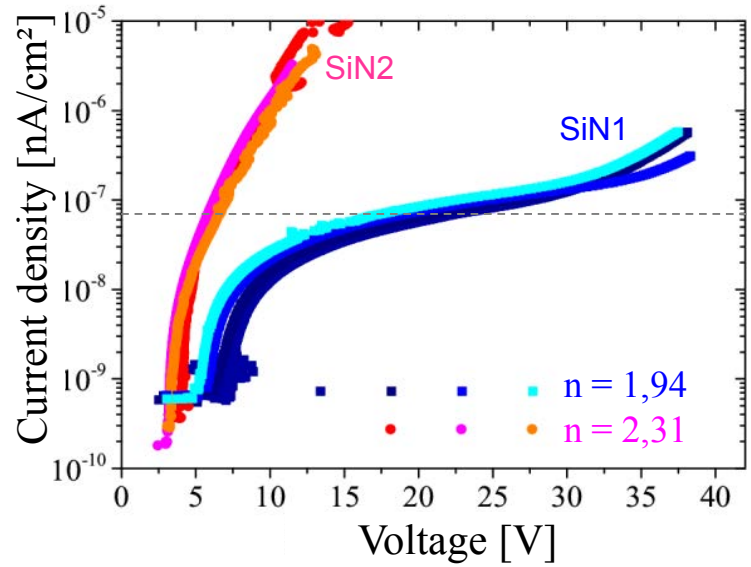
$$V_{SiN} = I_{leak} \cdot R_{SiN}$$

- Properties of SiN_x layer have no influence on the leakage current, but on the PID-s sensitivity
- Low resistivity of SiN_x at fixed leakage current gives reduced V_{SiN} and therefore less Na^+ ion drift across the SiN_x layer → avoids PID-s



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

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



Measurement of the voltage across SiN_x layer

[1] V. Naumann et al., *Proc. 28th European Photovoltaic Solar Energy Conference and Exhibition,* 2013, pp. 2994-2997

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Approaches for preventing PID(-s)

Explanation with voltage divider model

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

System level	
▪ Avoid high negative bias of cells in modules [1]	$V_{ext} \rightarrow 0$ → $I_{leak} \rightarrow 0$ → $V_{SiN} \rightarrow 0$
Module level	
▪ Front glass with less mobile ions (quartz glass) [2]	$R_{glass} \uparrow$ → $I_{leak} \downarrow$ → $V_{SiN} \downarrow$
▪ Encapsulants with reduced mobility of ions [1, 2]	$R_{poly} \uparrow$ → $I_{leak} \downarrow$ → $V_{SiN} \downarrow$
Cell level	
▪ Low potential across SiN_x layer through increased conductivity (refractive index ↑ [1, 3], doping [4])	$R_{SiN} << R_{glass} + R_{poly}$, $R_{glass} + R_{poly}$ = const. → I_{leak} = const., $R_{SiN} \rightarrow 0$ → $V_{SiN} \rightarrow 0$
▪ Modification of the Si surface before SiN_x deposition [5]	presumably not electrical effect

[1] S. Pingel et al., in: Proc. 35th IEEE Photovoltaic Specialists Conference, USA, 2010, pp. 2817–2822.
[2] P. Hacke et al., in: Proceedings 37th IEEE PVSC, Seattle, WA, USA, 2011, pp. 814–820.
[3] H. Nagel et al., in: Proceedings 26th EUPVSEC, Hamburg, Germany, 2011, pp. 3107–3112.
[4] Patent DE 10.2010.017.461.A1 2011.12.22.
[5] H. Mehlich et al., in: Proceedings 27th EUPVSEC, Frankfurt, Germany, 2012, pp. 3411–3413.

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Conclusion

Conclusion:

- PID cell test provides economic PID testing of solar cells and encapsulants
- PID-s: stacking faults in Si become conductive by decoration with Na
- PID degradation rate and final condition depend on voltage in the SiN_x layer, which is a function of leakage current and SiN_x layer's electronic conductivity

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Acknowledgements:

This work is partly supported by the BMBF project "xµ-Module" (03SF0400A) within Spitzencluster Solarvalley Mitteldeutschland.

The ToF-SIMS/EBIC correlation and first TEM investigations have been conducted under the project "FutureFab" (13N11446) within Innovationsallianz Photovoltaik.

Hanwha Q Cells is gratefully acknowledged for supply of non-standard monocrystalline solar cells.

GEFÖRDERT VOM

SOLARVALLEY Mitteldeutschland

Bundesministerium für Bildung und Forschung

FutureFab

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

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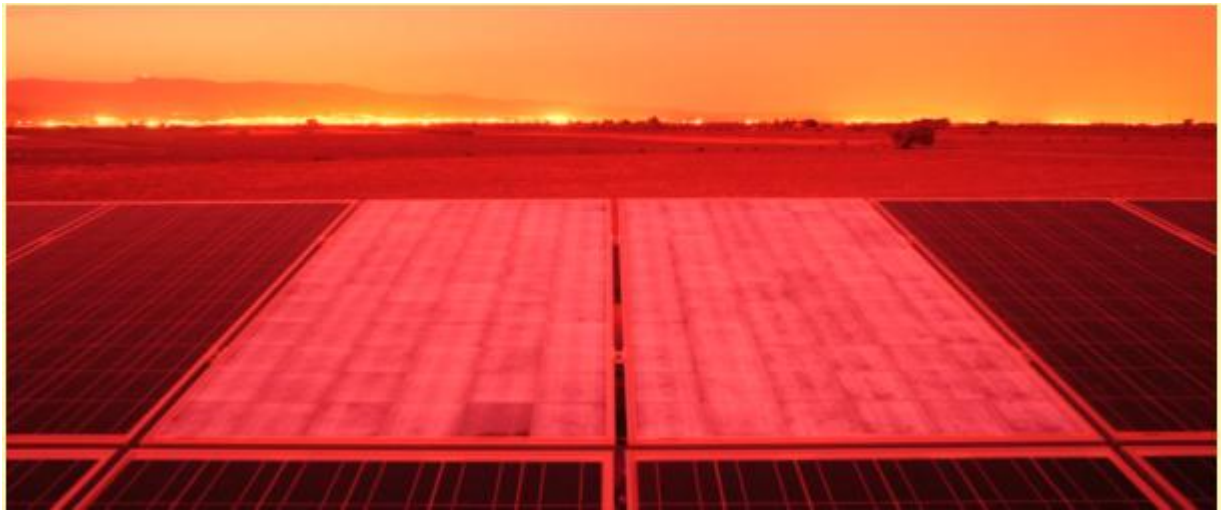


Towards a Predictive Model for Potential-Induced Degradation (PID) Based on Climate Data

Simon Koch,

J. Berghold, P. Grunow

PI Photovoltaik Institut Berlin AG

Photovoltaik-Modultechnologie

Testing | Consulting | Development | Research

Wrangelstr.100, 10997 Berlin, Germany

Overview

1. Introduction
2. Phenomenological PID model
3. Application examples
4. Current work
5. Summary

Introduction

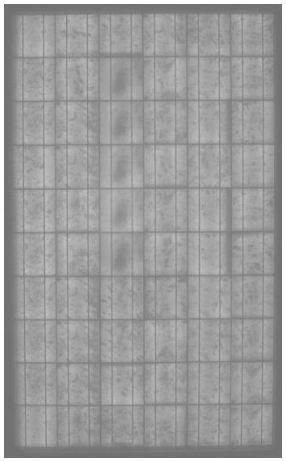
- PID is comparable to a growth process
- A growth process is usually limited
- There are countless examples of limited growth processes:
    - An epidemic which covers a city or a country
    - A product which is newly introduced in the market
    - Growth of a fungus in a petri dish
- A common feature of these growth processes is that they describe highly complex systems with a large number of influencing factors

- The current notion assumes that sodium ions accumulate into stacking faults and thus short-circuit the cell.
- A cell can therefore be regarded as a space with a finite number of stacking faults.
- More and more stacking faults are affected or „infected“ by sodium ions

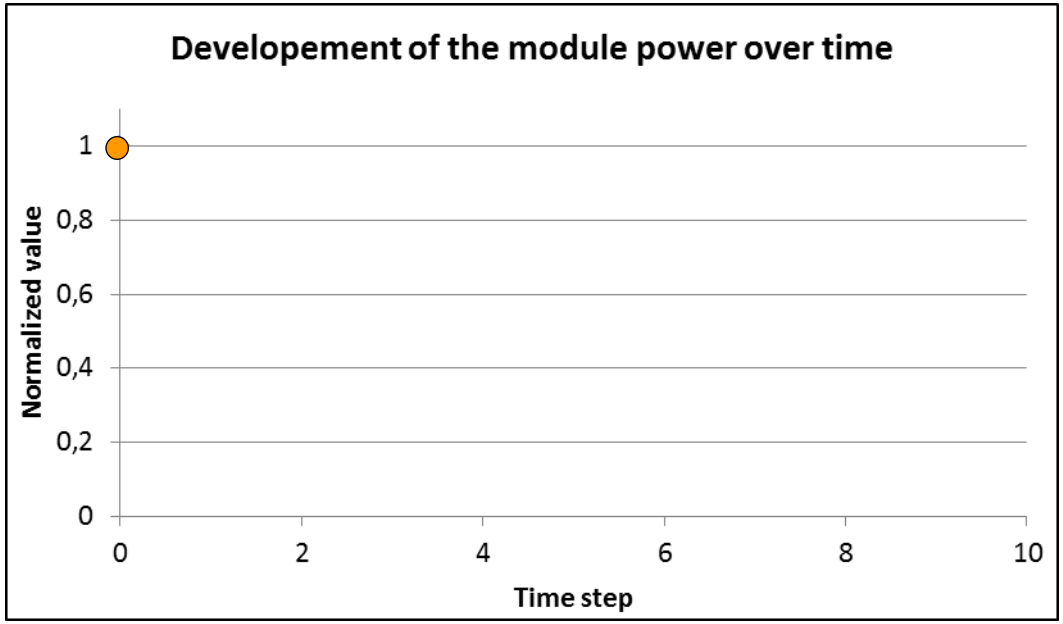
The potential induced degradation process

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

Electroluminescence



STC Power

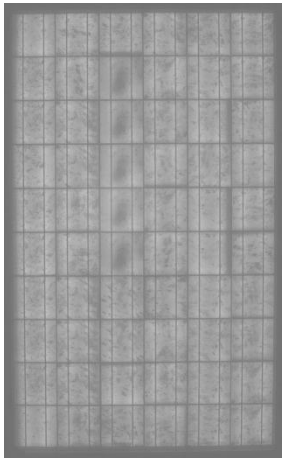


- Slow degradation at the beginning
- Develope to an exponentiale like grows in the middle
- Flattens at the end

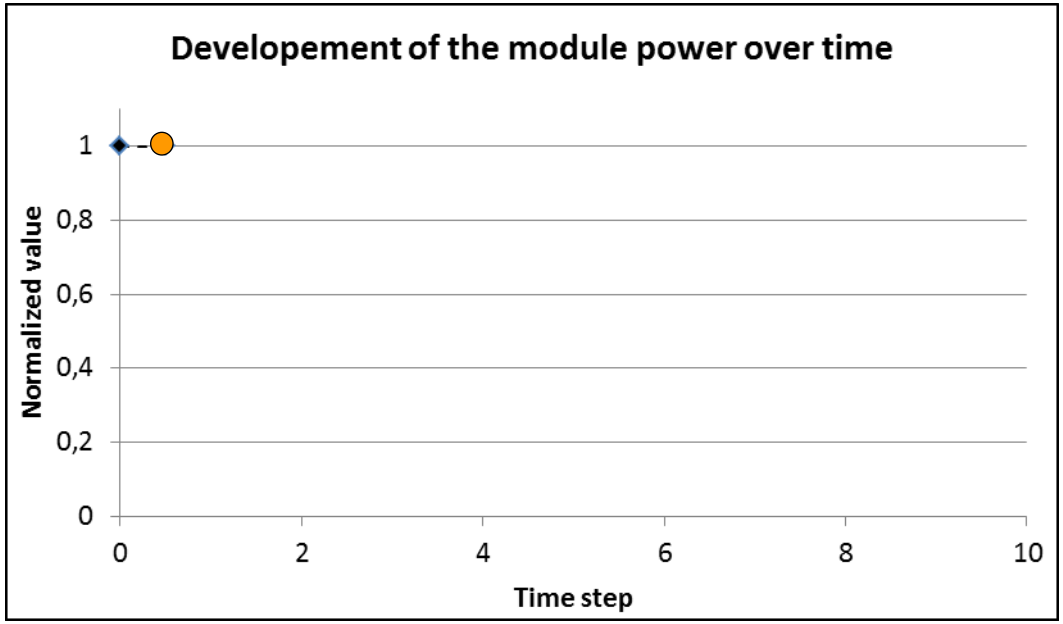
The potential induced degradation process

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

Electroluminescence



STC Power



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The potential induced degradation process

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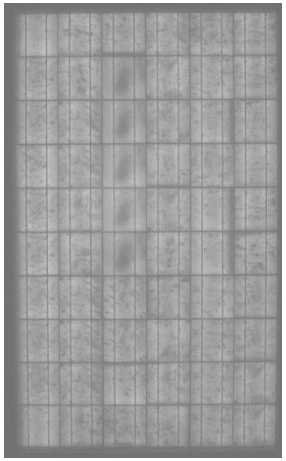
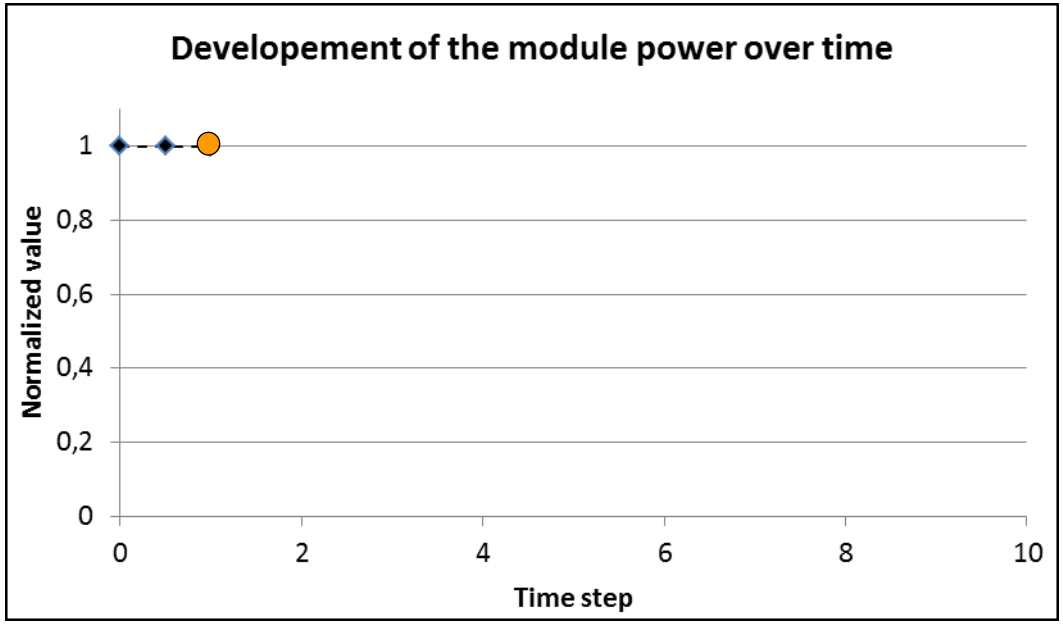


STC Power



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The potential induced degradation process

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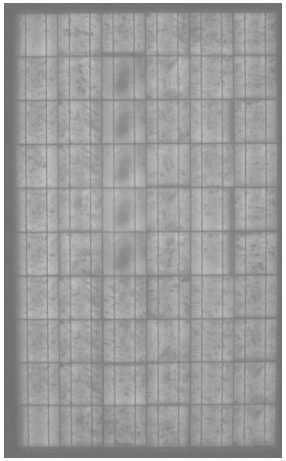
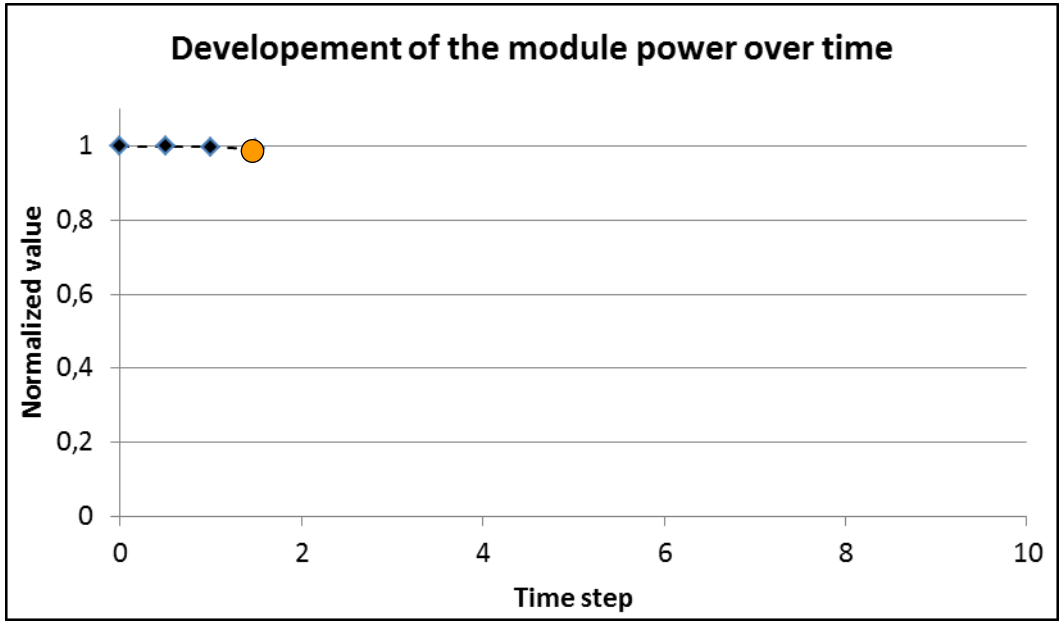
Electroluminescence



STC Power



- Slow degradation at the beginning
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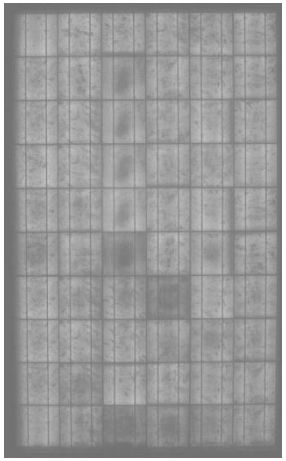
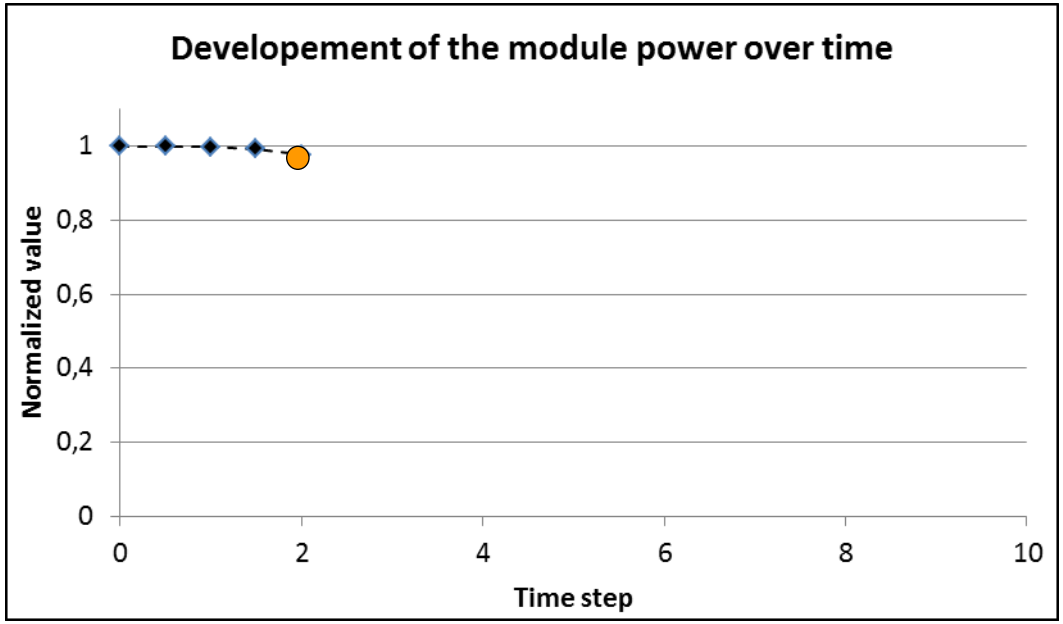
The potential induced degradation process

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

Electroluminescence



STC Power



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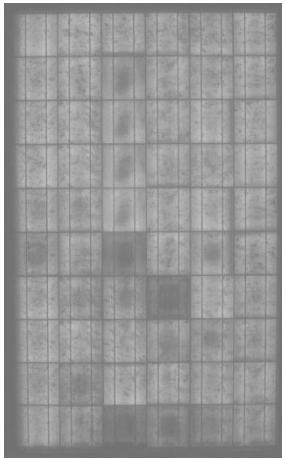
The potential induced degradation process

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

Electroluminescence



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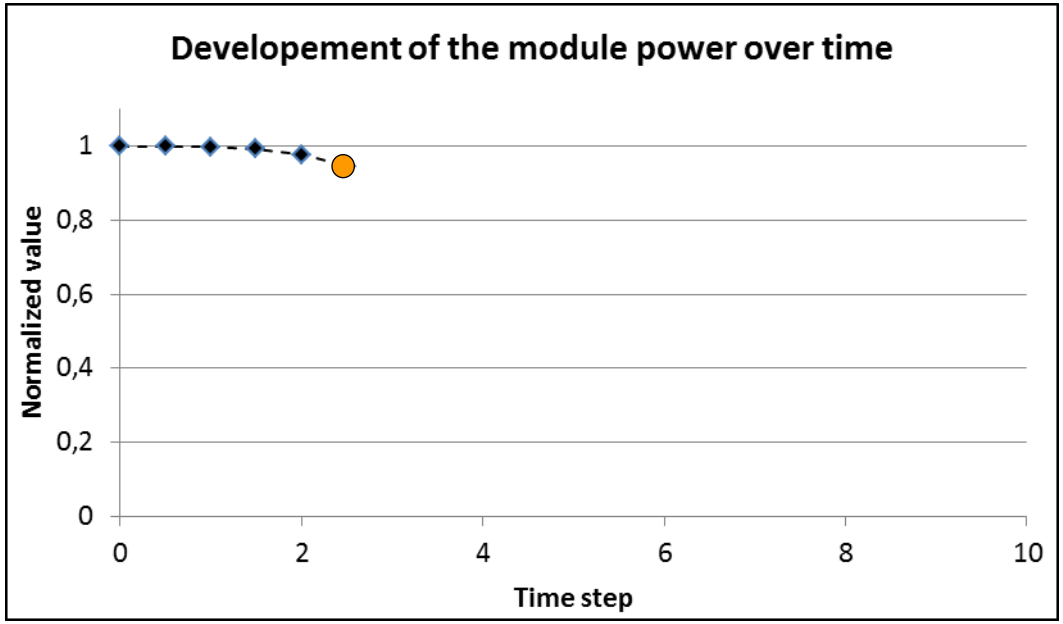

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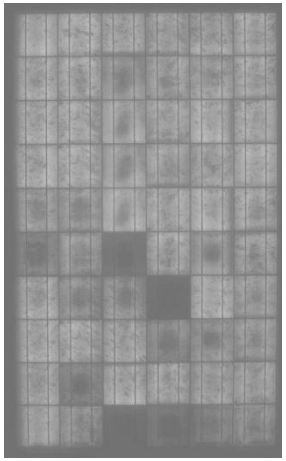

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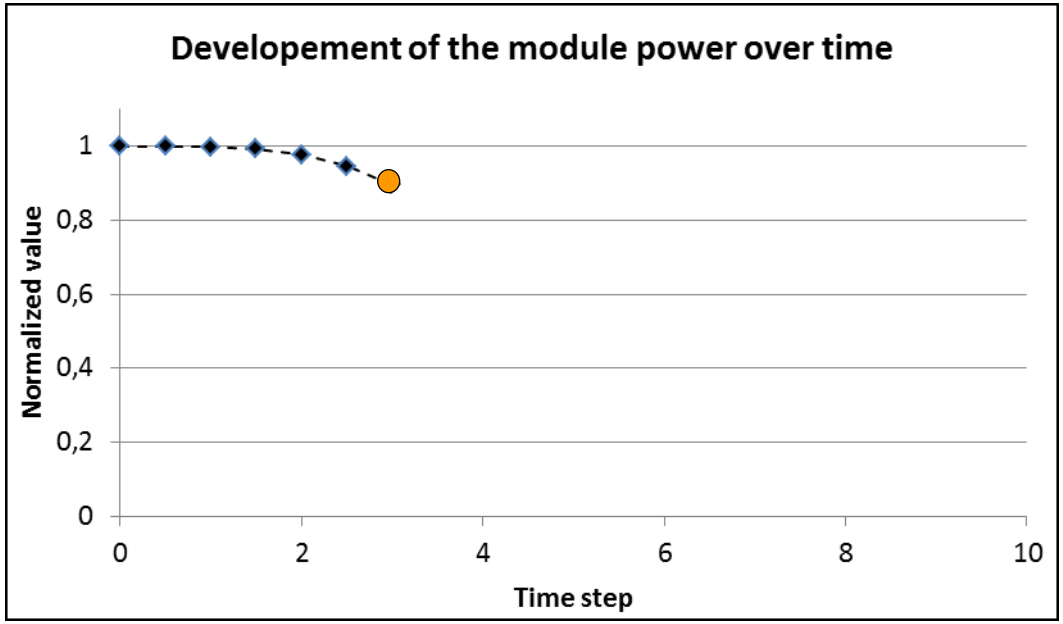

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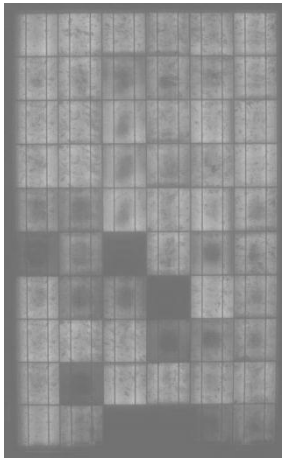

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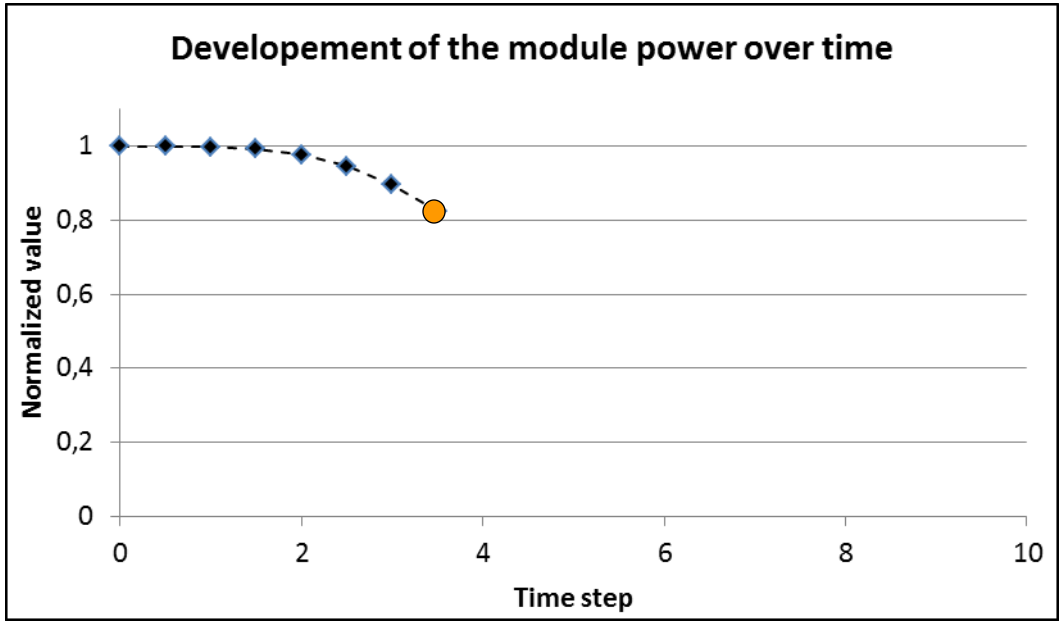

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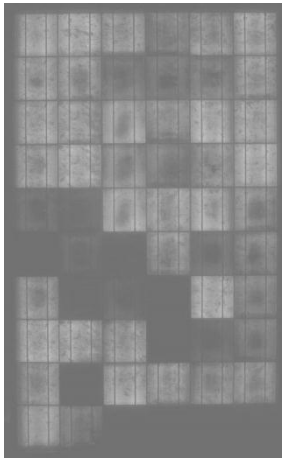

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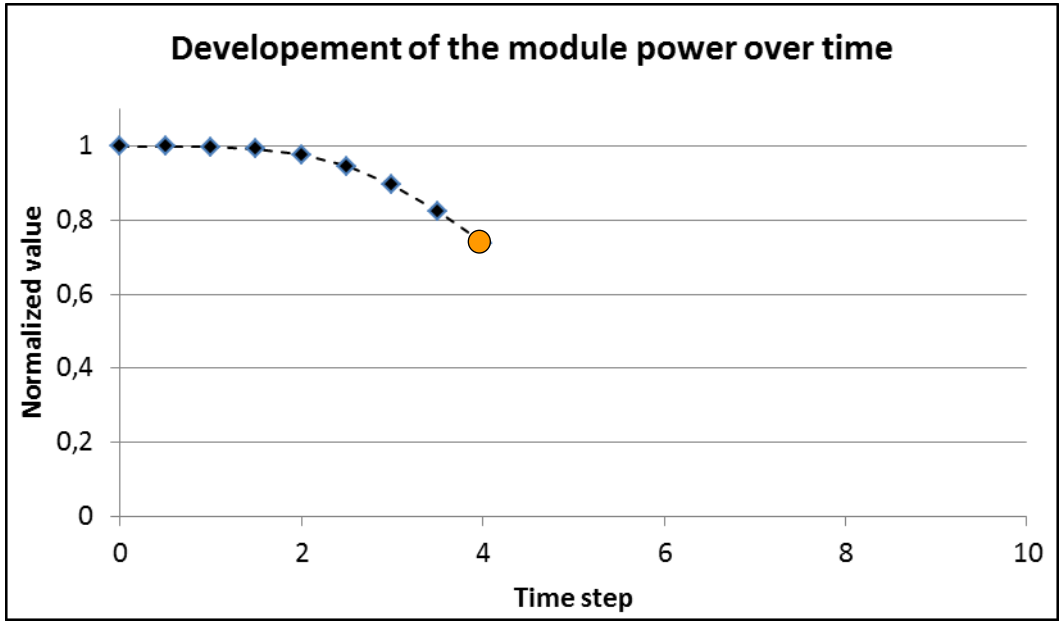

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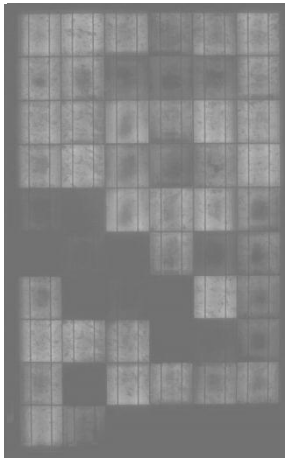

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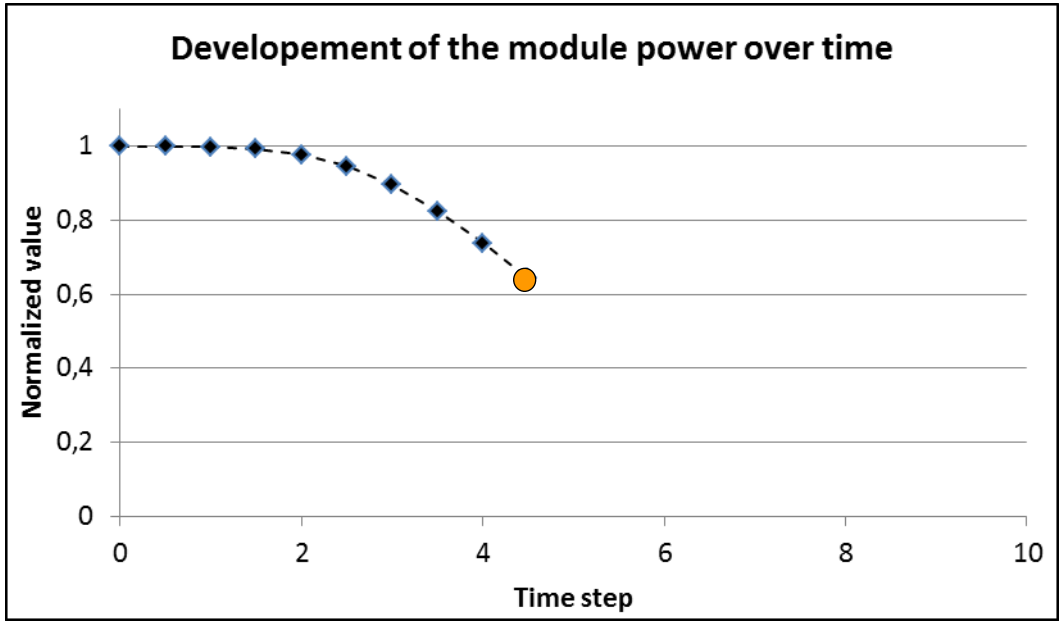

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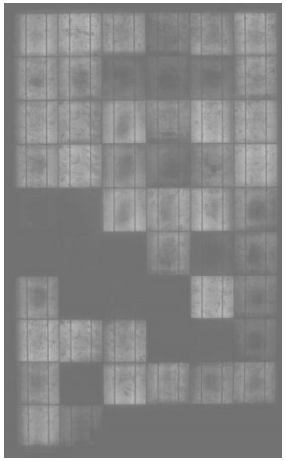

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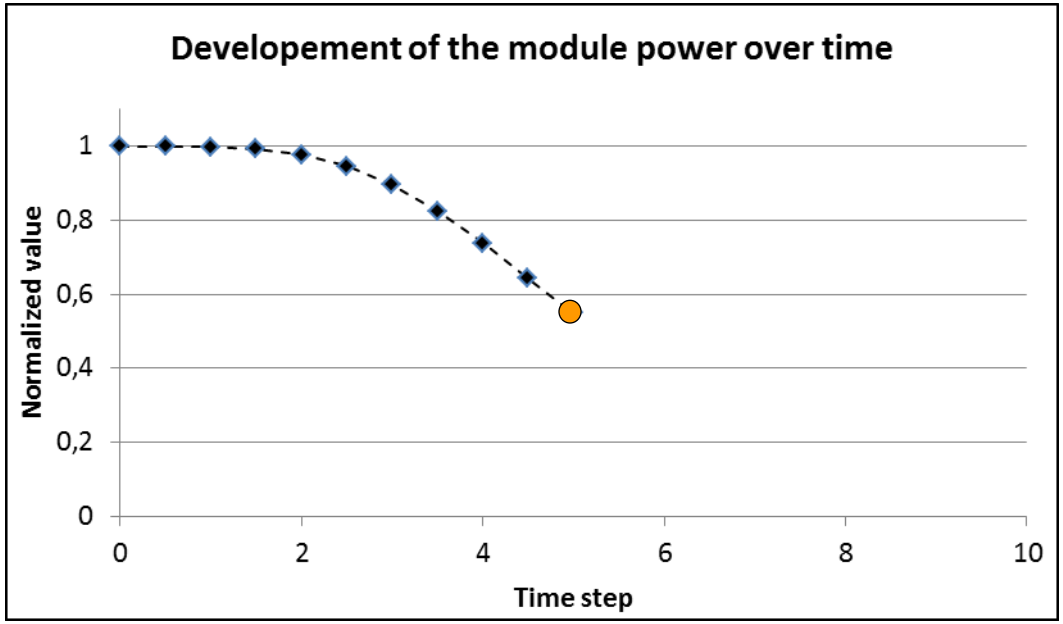

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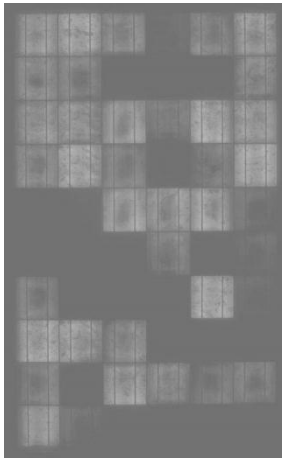

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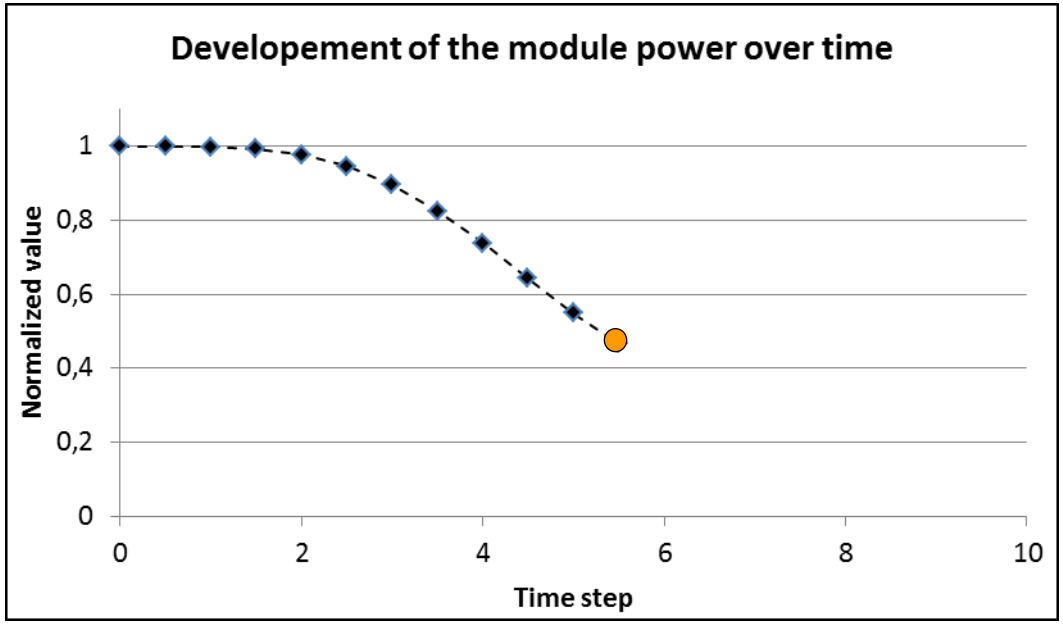

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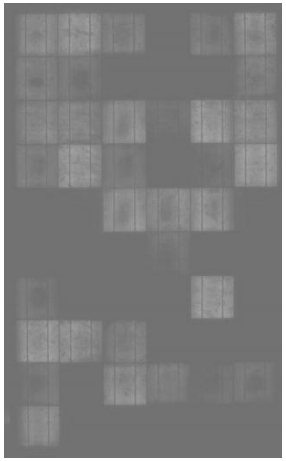

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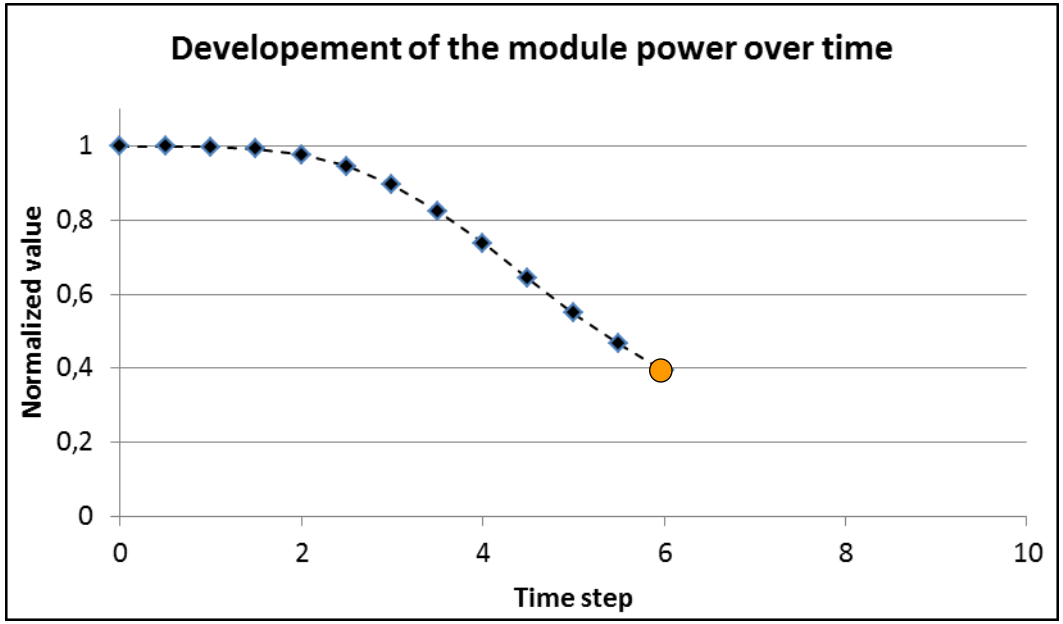

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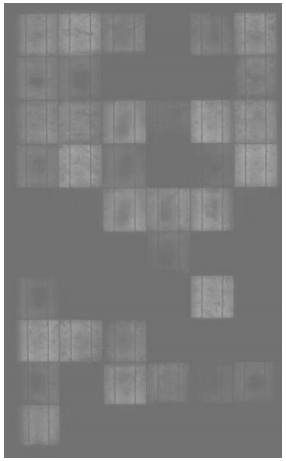

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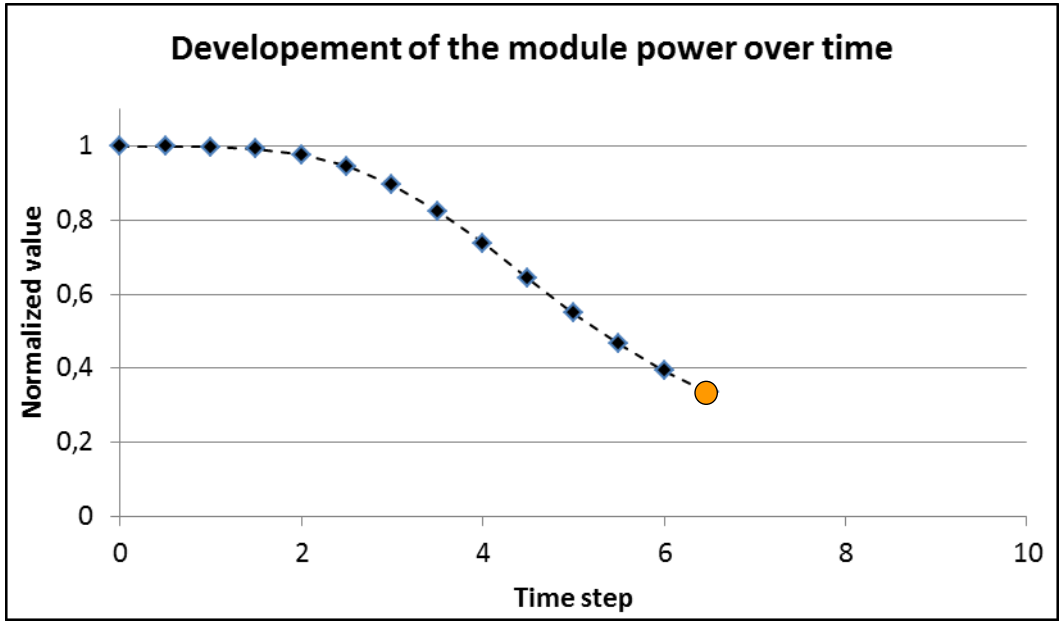

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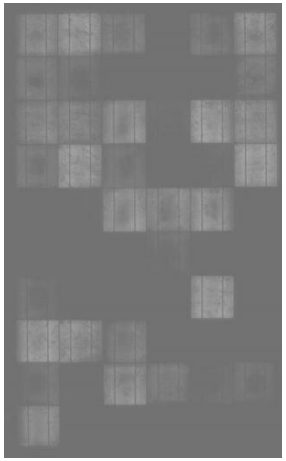

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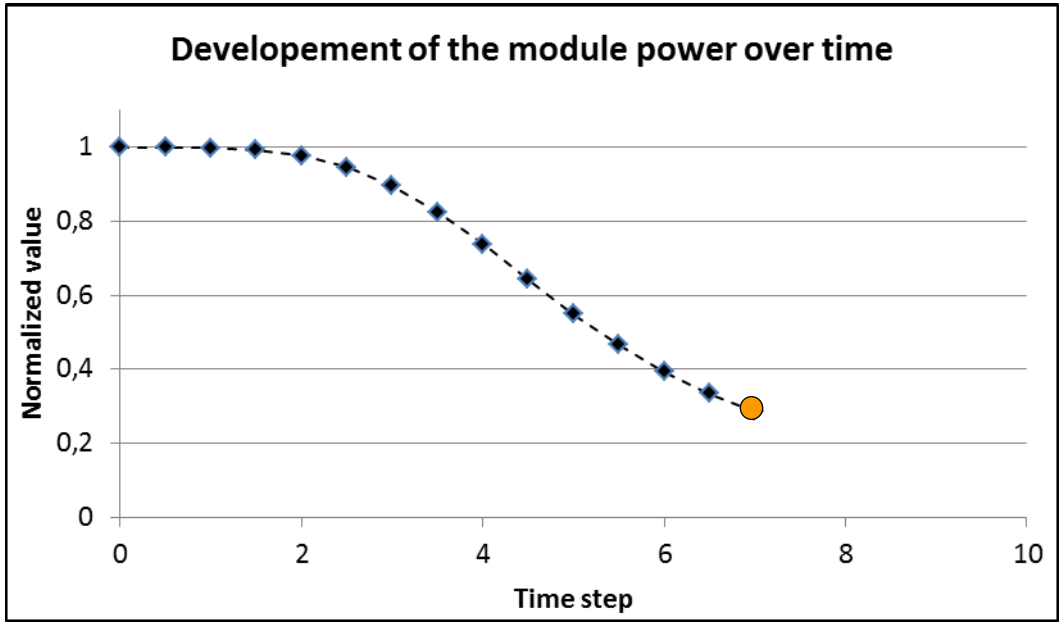

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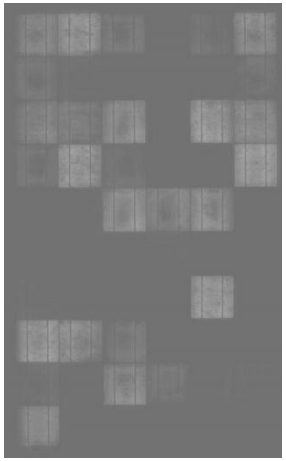

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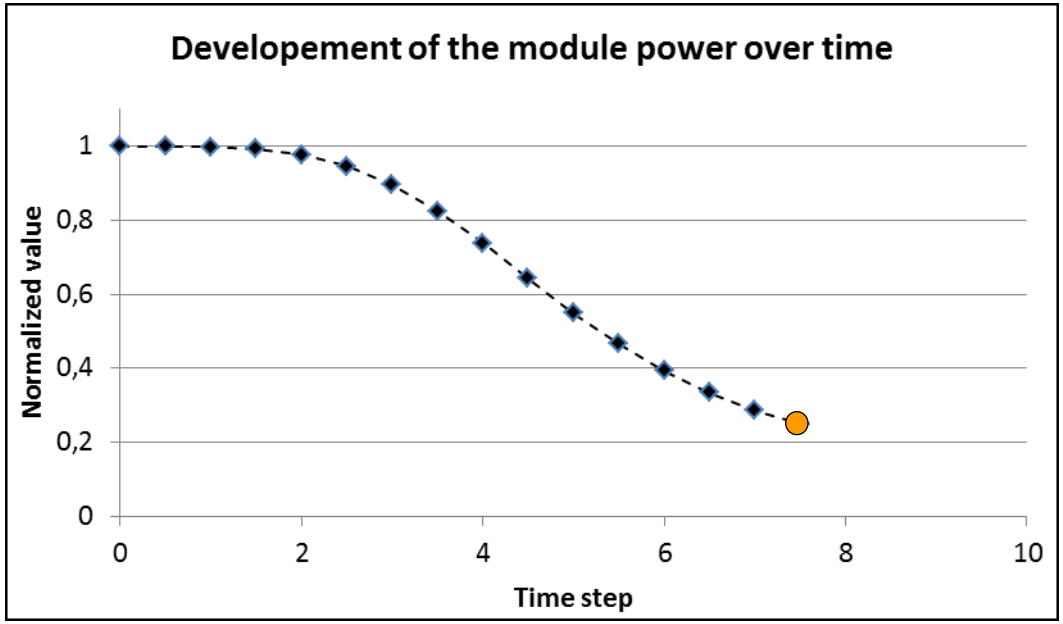

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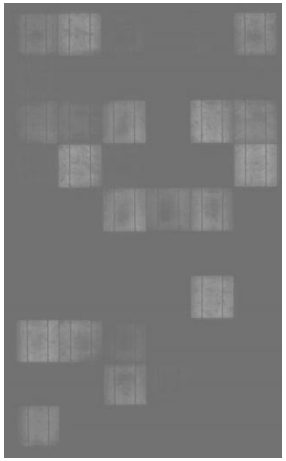

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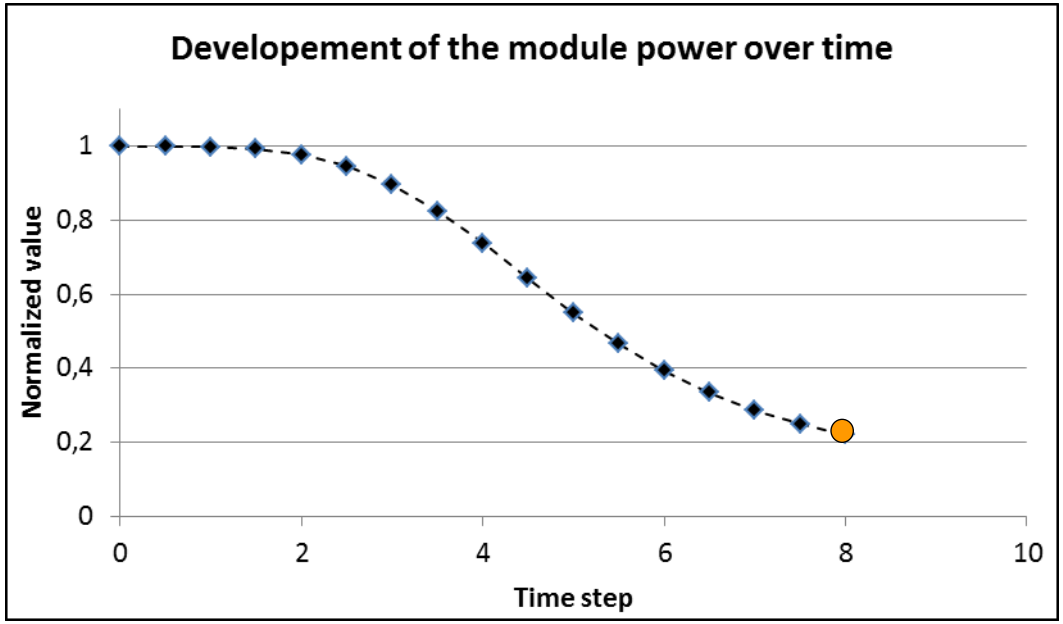

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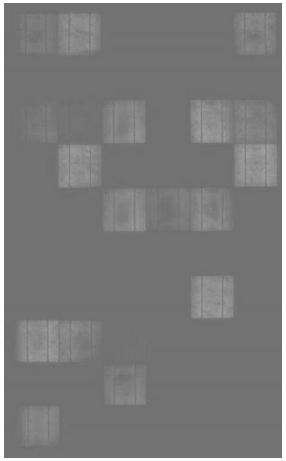

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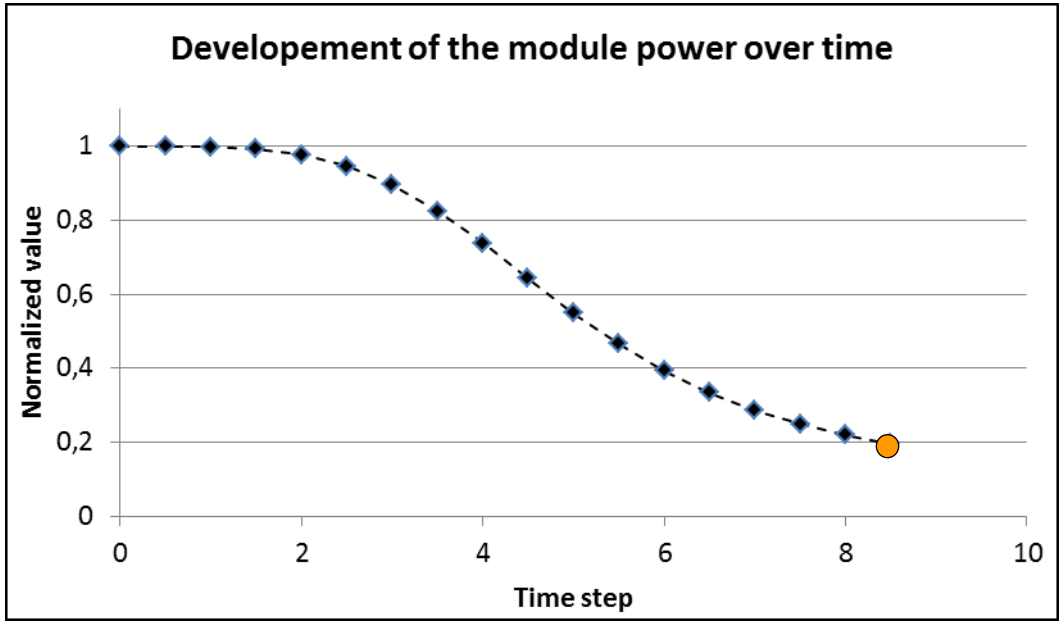

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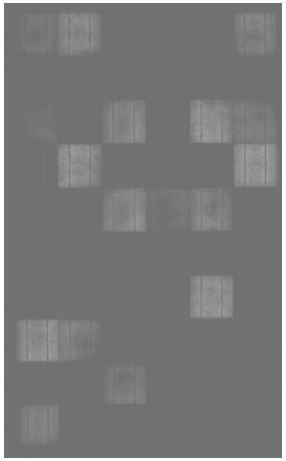

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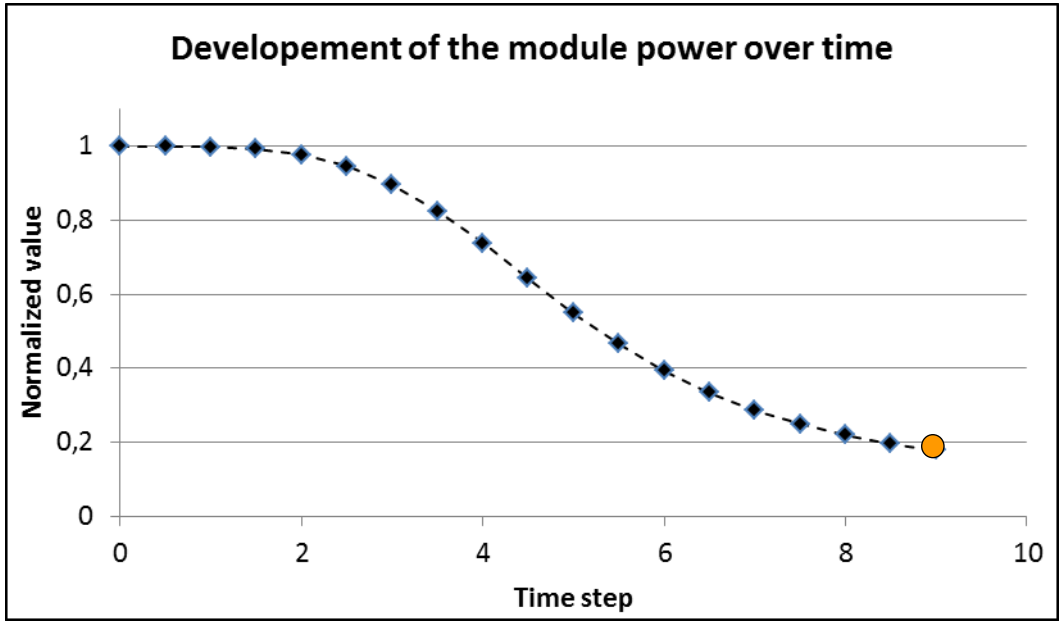

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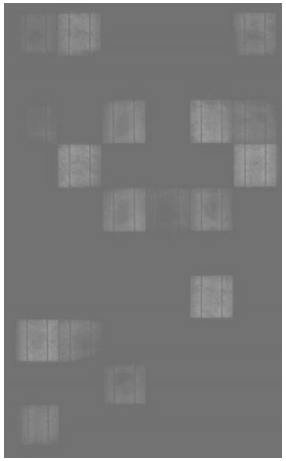

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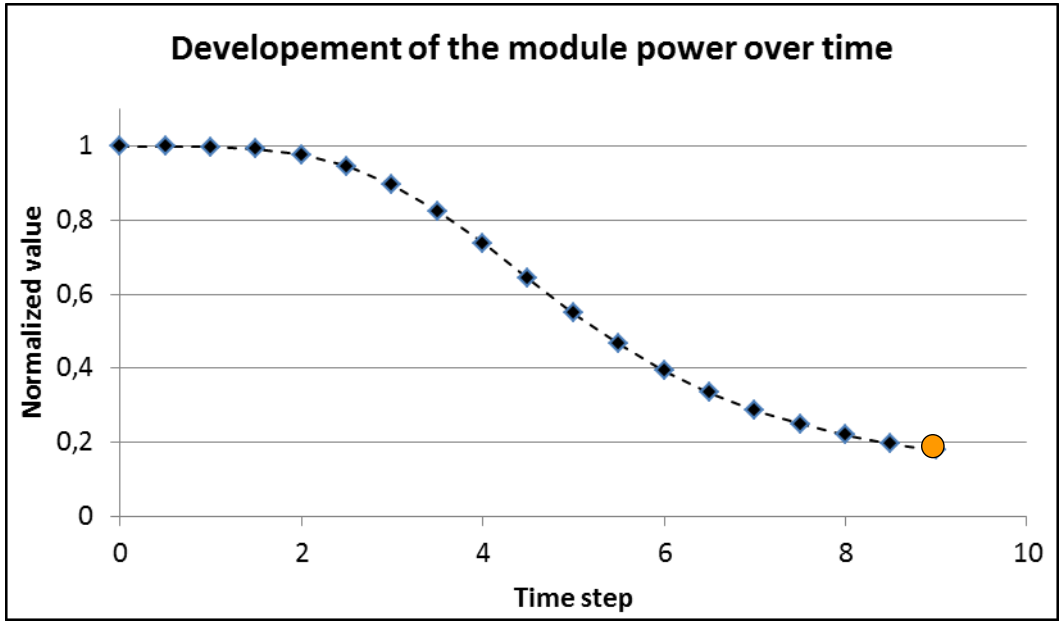

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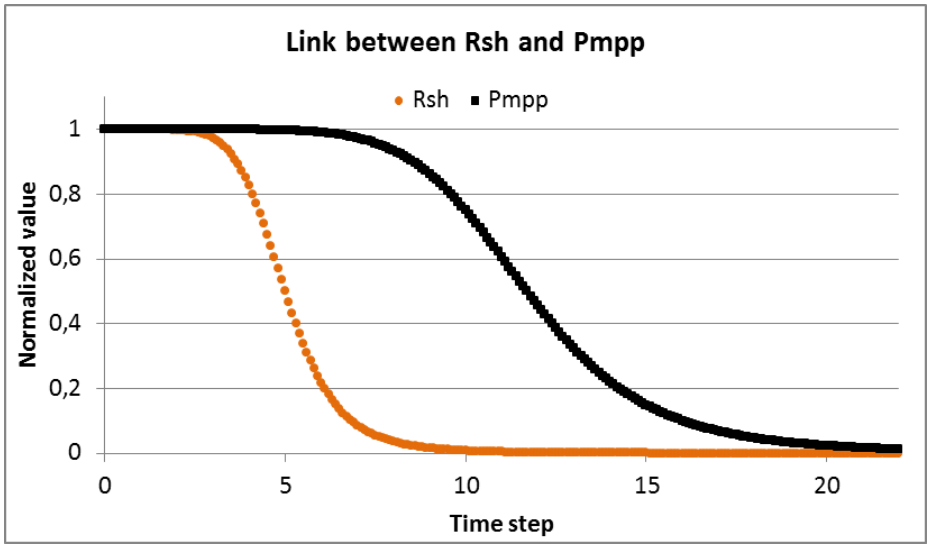
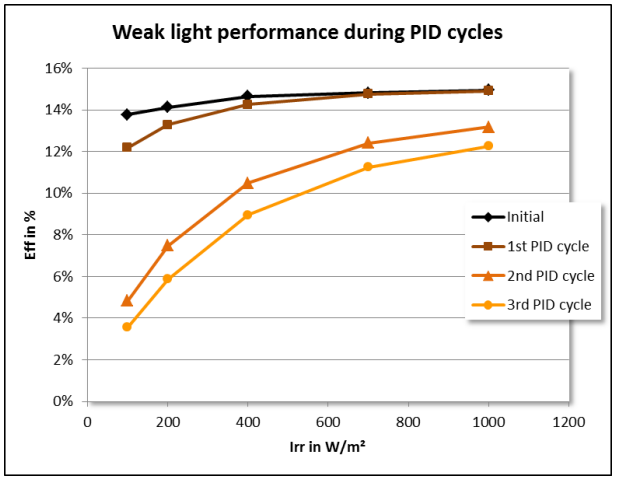
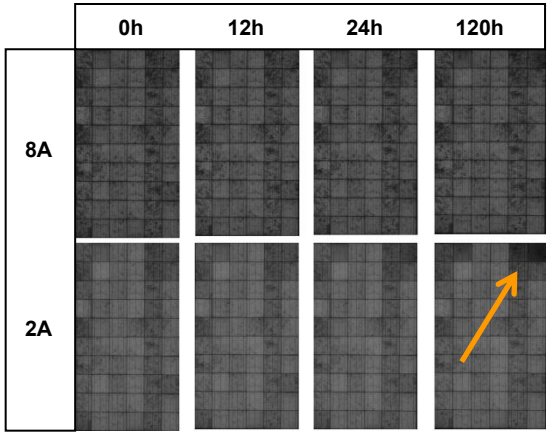
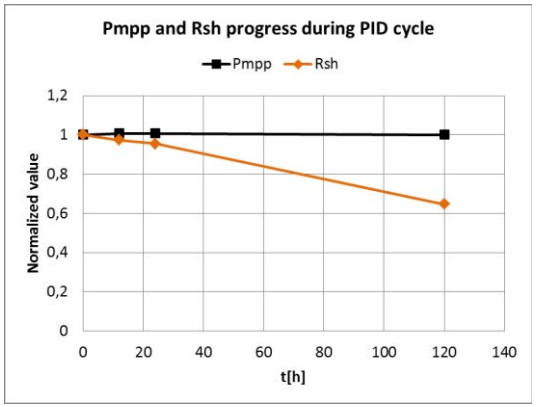
The link between Rsh and Pmpp



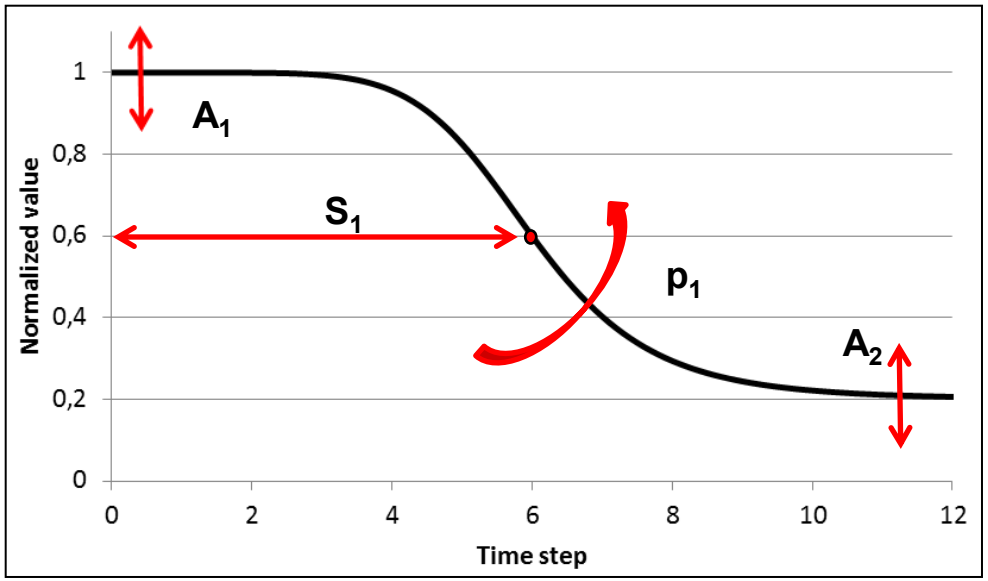
- Rsh is connected with the Pmpp of a cell or module according to the two diode model
- The Rsh is an indicator for PID
- This can be visualized with weak light graphs or electroluminescence images
- **Both progresses are following a logistic function**







The PID model based on a logistical function



$$f(x) = \frac{A_1 - A_2}{1 + (\frac{x}{s_1})^{p_1}} + A_2$$

Power function

Alternative notation:

$$f(x) = \frac{A_1 - A_2}{1 + e^{p_1 * (x - s_1)}} + A_2$$

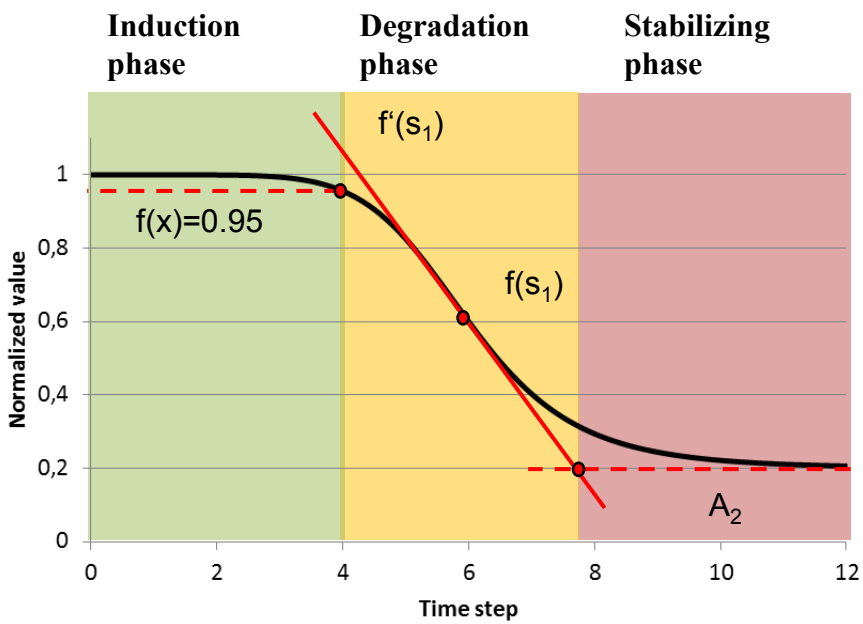
Exponential function

- First presented by Pierre Verhulst (1804 - 1849) to describe the grows of the population in Paris

Main characteristics of the functions

- A_1 gives the start value (it will be 1 when looking at normalized values)
- s_1 gives the position of the inflection point
- p_1 gives the power of the function
- A_2 gives the end value of the function
- $f'(s_1)$ gives the slope in the inflection point

The PID model based on a logistical function



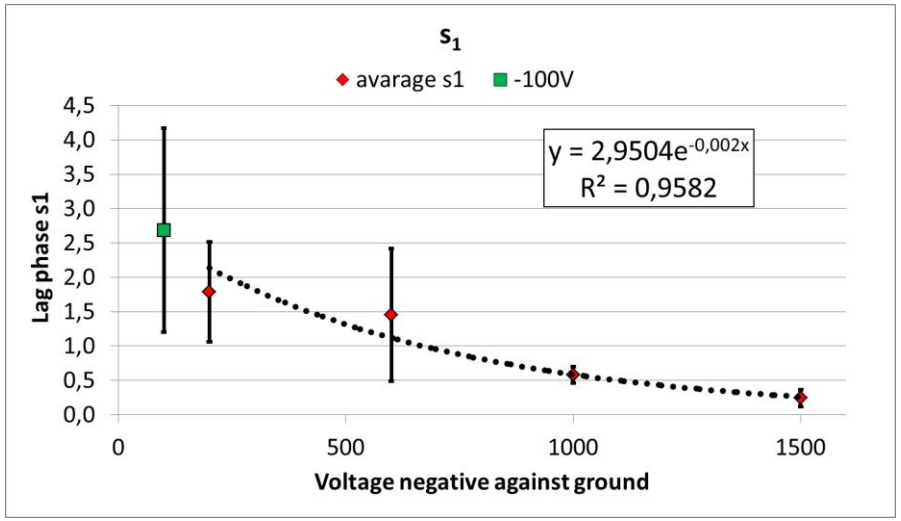
$$f(x) = \frac{A_1 - A_2}{1 + (\frac{x}{s_1})^{p_1}} + A_2$$

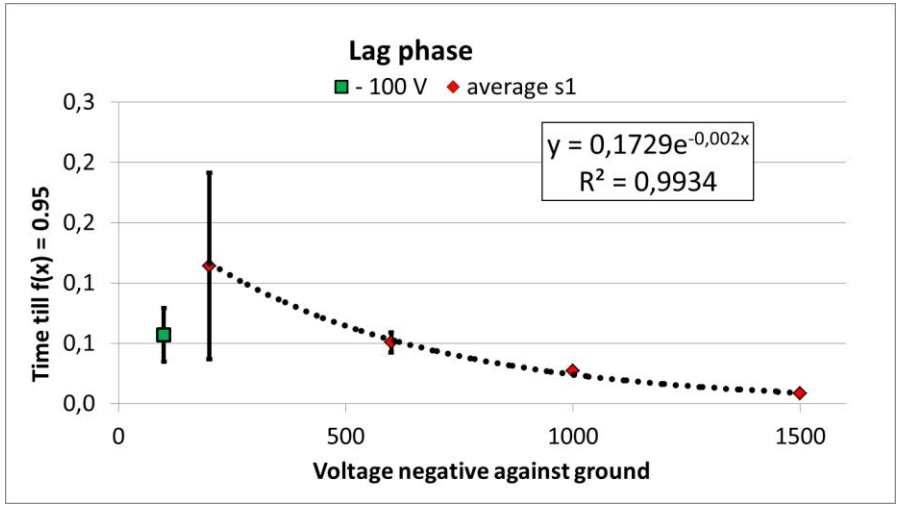
$$f'(x) = \frac{-(A_1 - A_2) \cdot p_1 \cdot (\frac{x}{s_1})^{p_1}}{x \cdot ((\frac{x}{s_1})^{p_1} + 1)^2}$$

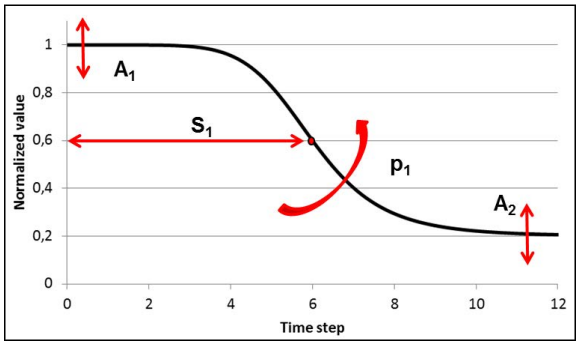
Derivative of f(x)

- The induction or **lag phase** is defined as the time till f(x) = 0.95
  - → The **lag phase** is mainly influenced by $\mathbf{s_1}$
- The **degradation phase** is defined as the time from f(x) = 0.95 till $f'(s_1)*x + a_0 = A_2$
  - → The **degradation phase** is influenced by $\mathbf{p_1}$ and $\mathbf{S_1}$
  - → The average **degradation velocity** is defined as $\mathbf{f'(s_1)}$
- The **stabilizing phase** is defined as the time after degradation phase
  - → The **stabilizing phase** is manly influenced by $\mathbf{A_2}$

Application example: Voltage and R_{SH}

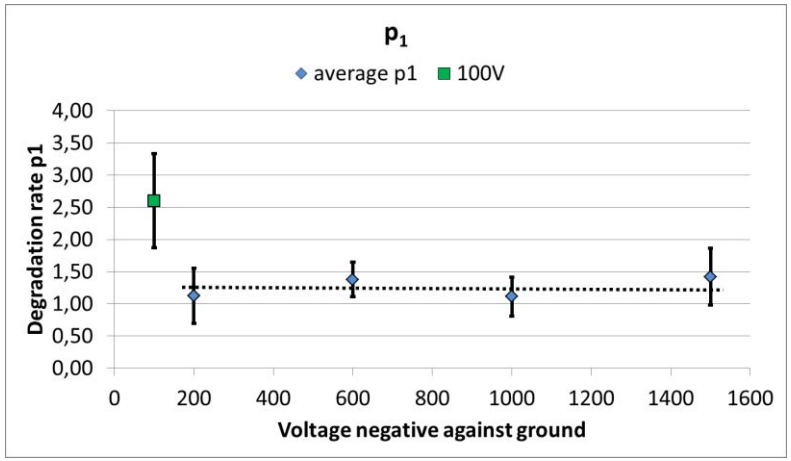


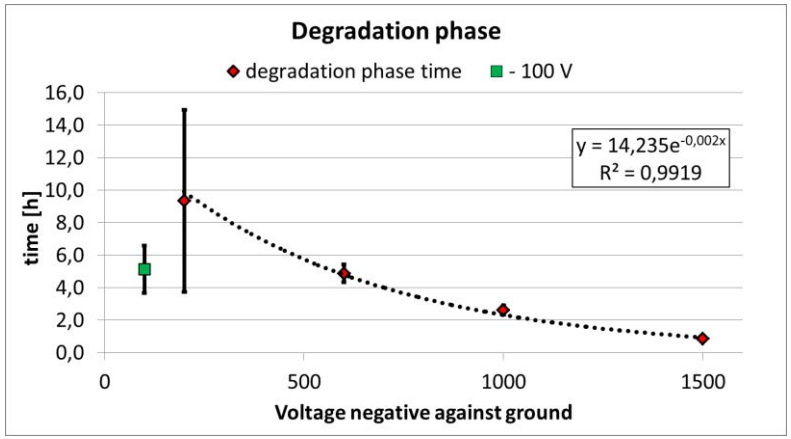


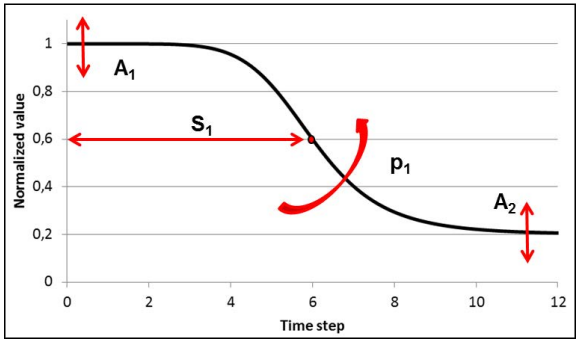


- The s_1 parameter is decreasing with the voltage
- The lag phase is decreasing as well and can be described by an exponential function
- It seems that the sodium ions need more time to reach the cell surface or to accumulate to a certain level
- The value for -100 V does not fit the other values

Application example: Voltage and R_{SH}



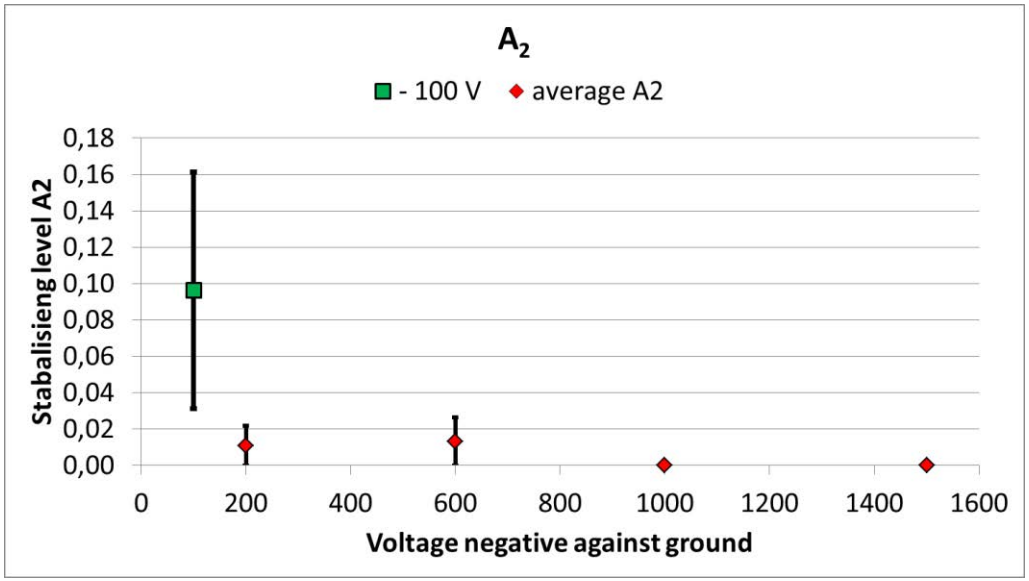


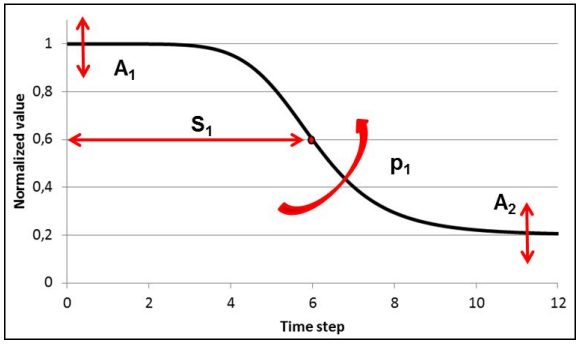


$$f'(s_1) = \frac{(A_2 - A_1) \cdot p_1}{s_1 \cdot 4}$$

- The degradation rate stays nearly stable for all voltages
- The degradation phase time is also following an exponential grows
- It seems that the accumulation along stacking faults is also highly influenced by the voltage
- The value for -100 V does not fit the other values

Application example: Voltage and R_{SH}

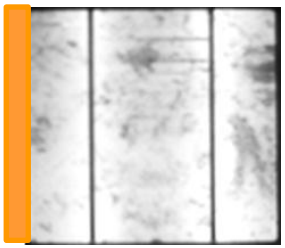




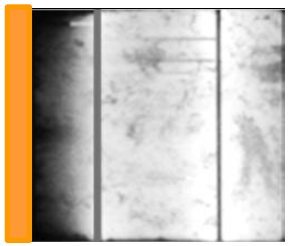
- The A_2 value is nearly zero for all voltages
- The A_2 value for -100 V does not fit the other values and the degradation progress can not readily be compared with the other voltages

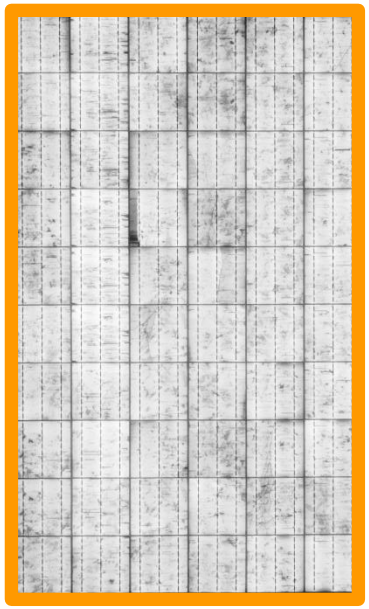
A closer look at A_2

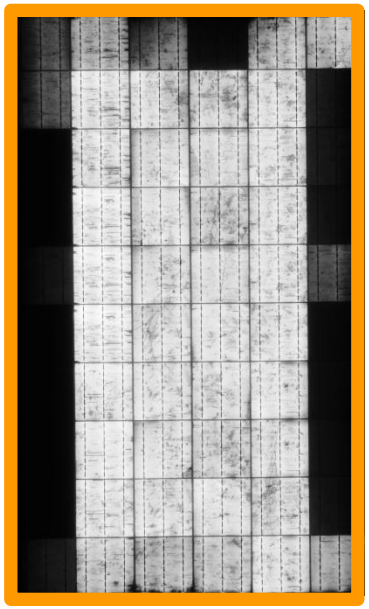
Bevore PID



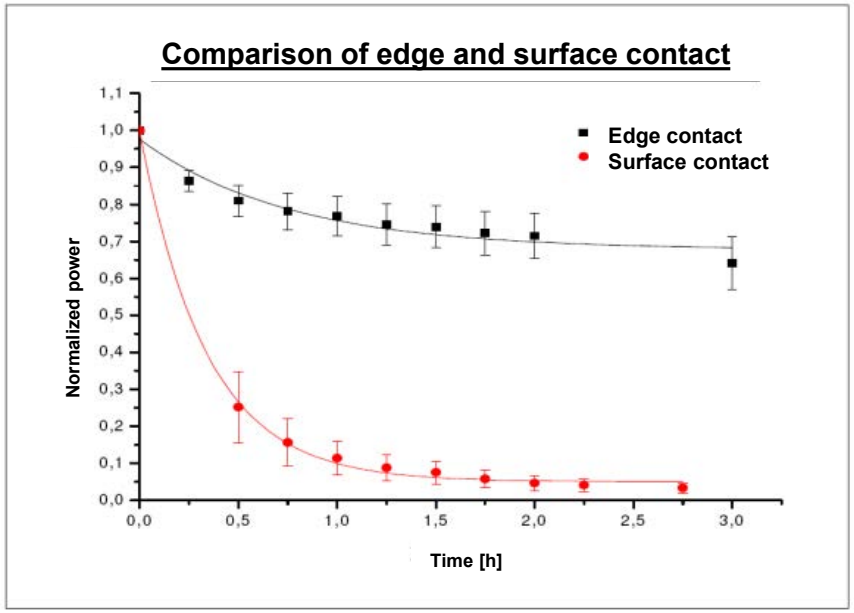
After PID degradation



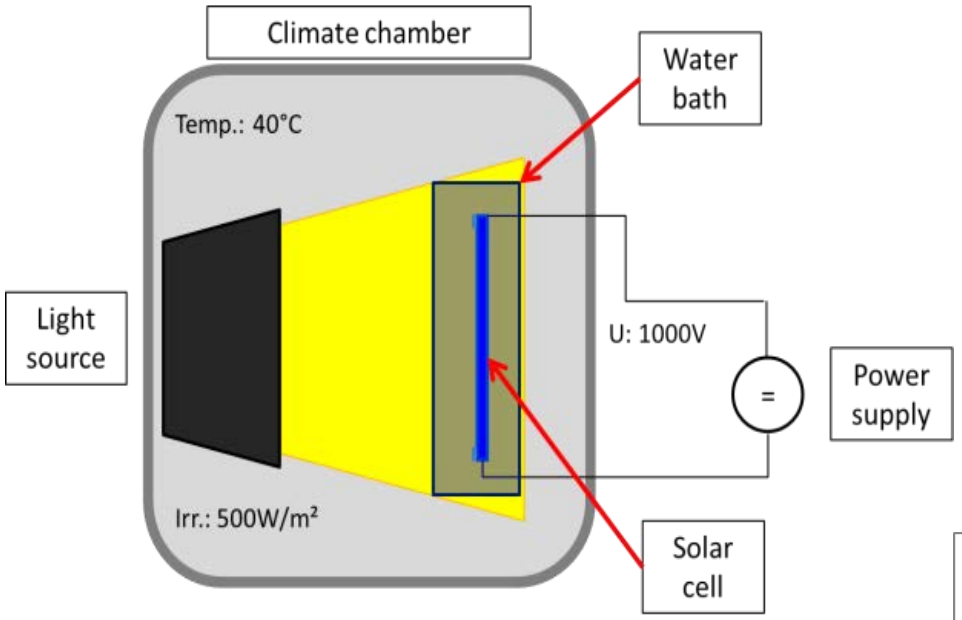




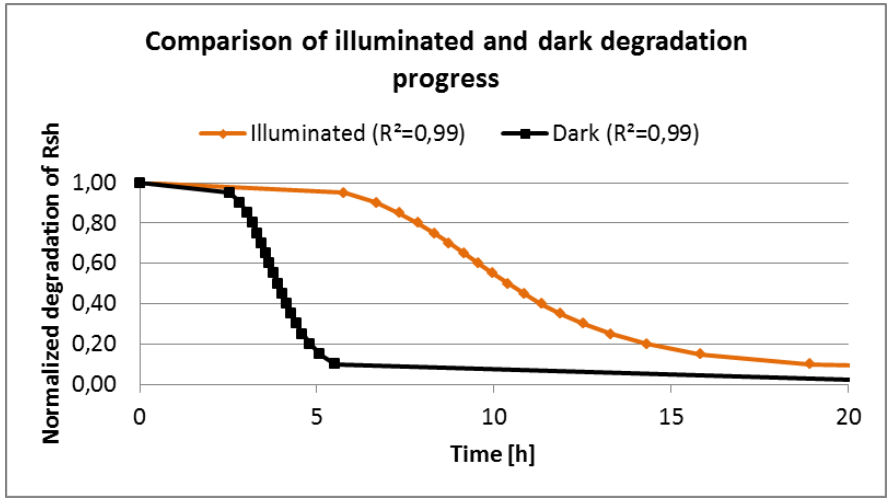
- A surface contact leads to full degradation ($A_2 = 0$)
- An edge contact leads to a degradation which stabilizes on a certain level ($A_2 > 0$)
- The voltage drops with the distance to the law of Coulomb (note: when surface is dry)



Application example: Irradiation and R_{SH}

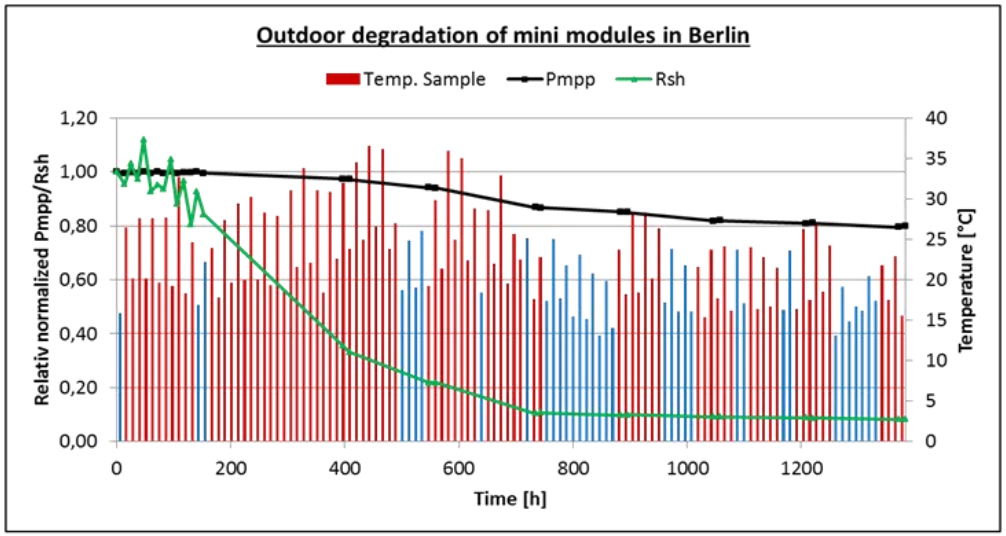


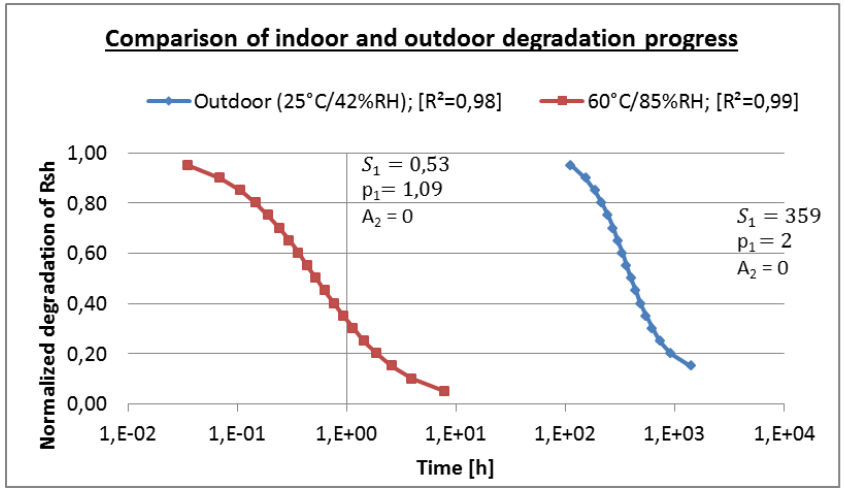
- The PID is decelerated by irradiation
- The s_1 value is 2.6 times higher
- The lag phase is 2.3 times longer
- The p_1 value is 0.7 times lower
- The degradation phase is 2.4 times longer



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

Outdoor degradation





- The outdoor degradation progress is also following a logistic function
- The acceleration between indoor and outdoor degradation was determined with 950 [note: the average module temperatures in Germany was 25°C]
- The goal of this model is to make an appropriate statement about the reliability by indoor test.
- **Indoor:** Stable temperature, humidity, contact, voltage
- **Outdoor:** Temperature gradient, humidity, changing contact area (rain, humidity, soiling), voltage relatively stable (fix string position), changing day duration
- **Additional regeneration:** Regeneration phase at night and deceleration due to irradiation

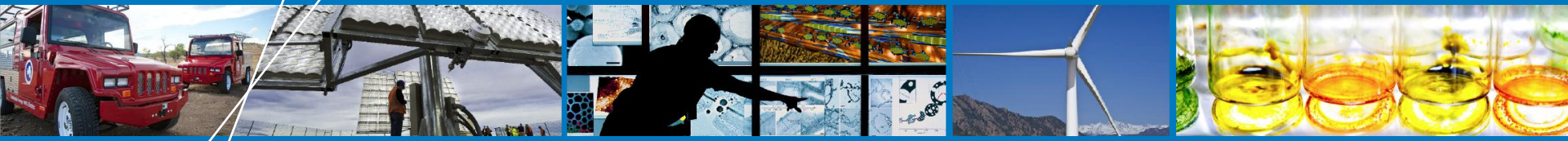
Summary

- A mathematical model which describes the degradation process was introduced
- Different degradation phases during PID were defined
- The influence of the voltage was investigated with the model
- It was shown that irradiation slows down PID
- Samples which are degraded under outdoor conditions fit also a logistic function

Thank you for you attention!

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Using Uncertainty Analysis to Guide the development of Accelerated Stress Tests



NREL PVMRW

Michael Kempe

Tuesday, February 25, 2014

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

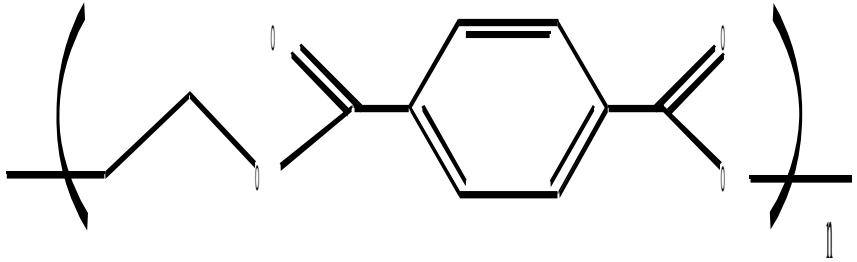
Introduction

- PV modules degrade in response to environmental stresses such as heat, humidity, UV irradiation, CTE mismatch, high voltage, and etc..
- Many degradation processes are driven by complex combinations of these stress factors.
- For generalized accelerated stress tests, a significant amount of uncertainty is inherent.
- A better understanding of the uncertainty in the relevant stress factors will aid in the development of accelerated stress tests.

Outline

- Look at the hydrolysis of a typical back-sheet made of PET as a case study for a material with an unusually high level of understanding of degradation.
- Apply kinetic models of paints and coatings degradation to backsheets.
- Discuss concerns with developing a single test for all degradation modes.

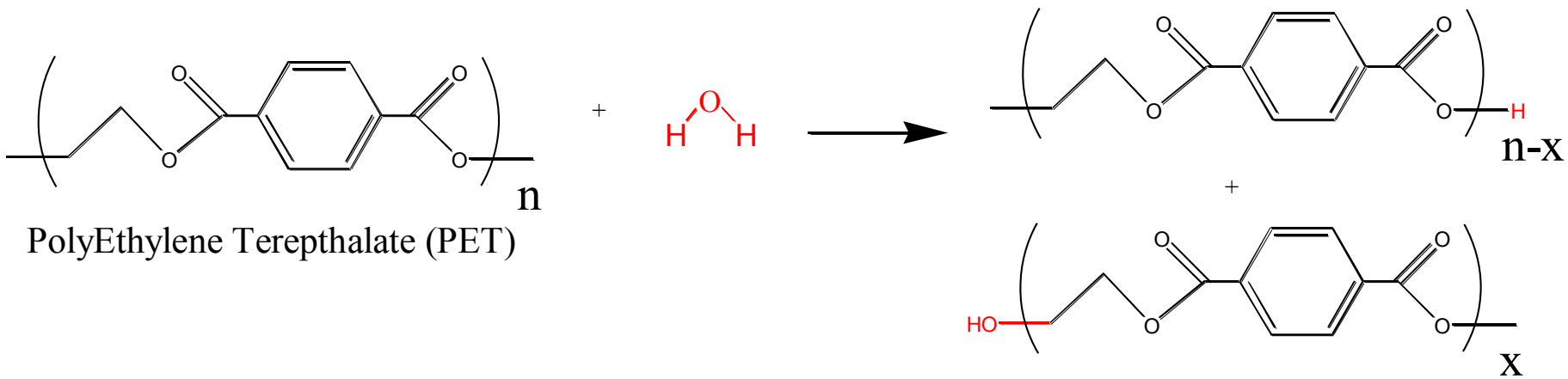
PET Hydrolysis Modeling



PolyEthylene Terepthalate (PET)

- **PET is commonly used in back-sheet materials:**
  - Low cost
  - Good electrical insulator
  - Long term track record
- **Hydrolysis results in embrittlement of PET which can lead to cracking and back-sheet failure.**
- **However, hydrolysis is only one potentially relevant failure mechanism, but it is extremely well understood.**

PET Hydrolysis Kinetics



PolyEthylene Terepthalate (PET)

$$t_{fail} = \frac{e^{\left(\frac{E_a}{RT}\right)}}{A[RH]^2}$$

Pickett *et. al***

Ea=129±3.4 kJ/mol

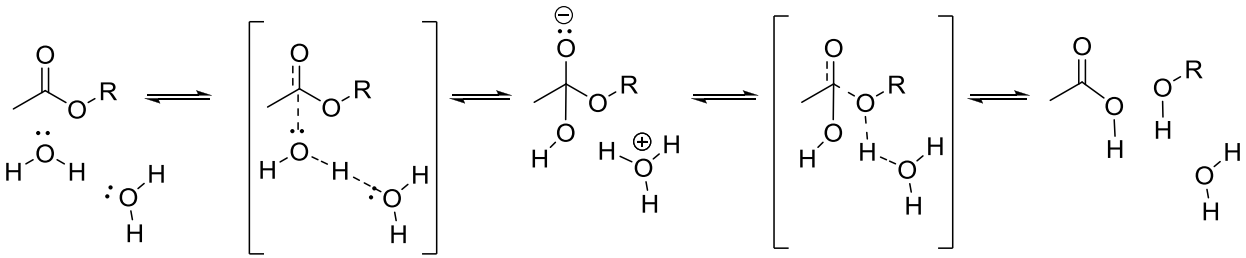
A=1.2·10^{17}±1.3·10^{17}h

RH expressed as a percentage.

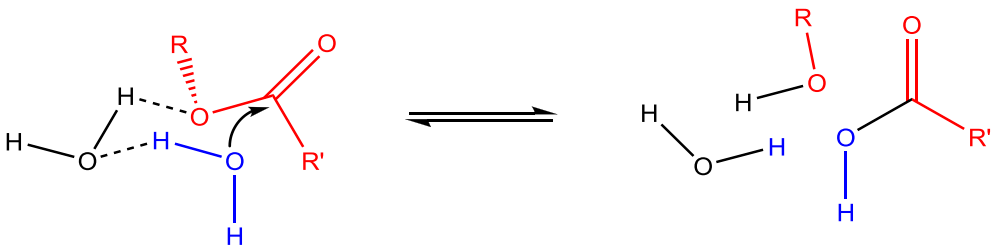
*PET becomes brittle (1/3 initial tensile strength) and "failed" when about 0.55% hydrolysis of ester bonds.

*W. McMahon, H. A. Birdsall, G. R. Johnson, and C. T. Camilli, "Degradation Studies of Polyethylene Terephthalate," Journal of Chemical & Engineering Data, vol. 4, pp. 57-79, 1959.
**J. E. Pickett and D. J. Coyle, "Hydrolysis Kinetics of Condensation Polymers Under Humidity Aging Conditions," Polymer Degradation and Stability, vol. 98, pp. 1311-1320, 2013.

Hydrolysis Mechanism is Well Understood



Scheme 4*



Scheme 6*

- **Picket *et. al** proposed these mechanisms and reaction intermediates as possible hydrolysis pathways.**

*J. E. Pickett and D. J. Coyle, "Hydrolysis Kinetics of Condensation Polymers Under Humidity Aging Conditions," Polymer Degradation and Stability, vol. 98, pp. 1311-1320, 2013.

**Shi Z, Hsieh Y-H, Weinberg N, Wolfe S. The neutral hydrolysis of methyl acetate—Part 2. Is there a tetrahedral intermediate? Can J Chem 2009: 87; 544-555.

Euranto EK, Cleve NJ. Kinetics of the neutral hydrolysis of chloromethyl chloroacetate. Acta Chemica Scand. 1963: 17; 1584-1594.

Site Specific Equivalent T and RH

$$t_{fail} = \frac{e^{\left(\frac{E_a}{RT}\right)}}{A[RH]^2}$$

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

RH_{WA} is an average effective relative humidity weighted towards higher temperatures where most of the damage occurs.

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

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

Uncertainty Propagation

$$\sigma_f{}^2 \approx \left|\frac{\partial f}{\partial a}\right|^2 \sigma_a{}^2 + \left|\frac{\partial f}{\partial b}\right|^2 \sigma_b{}^2 + 2\frac{\partial f}{\partial a}\frac{\partial f}{\partial b} COV_{ab} \ldots$$

Assumes f(a,b,…) has normally distributed uncertainties and ignores higher order terms.

$$T_{eq} = -\frac{Ea}{kln\left[\frac{\sum e^{\left(-\frac{Ea}{kT}\right)}}{N}\right]}$$

$$\sigma_{T_{eq}} = \left\{-\frac{1}{kln\left[\frac{\sum e^{\left(-\frac{Ea}{KT}\right)}}{N}\right]} - \frac{Ea}{k^2}\frac{\sum \frac{e^{\left(-\frac{Ea}{KT}\right)}}{T}}{\sum e^{\left(-\frac{Ea}{KT}\right)}}\right\}\sigma_{Ea}$$

Pet Hydrolysis Uncertainty

	Years to failure	Teq for Ea=129 kJ/mol	Effictive $RH_{W/A}$, at T_{eq}
	(y)	T	RH
		(°C)	(%)
Denver, Colorado	10500±1600	32.9±0.3	14.2±0.3
Munich, Germany	8400±1300	27.5±0.4	25.3±0.5
Albuquerque, New Mexico	7000±1100	36.7±0.3	12.6±0.2
Riyadh, Saudi Arabia	6400±1000	47.7±0.3	5.6±0.1
Phoenix, Arizona	2700±400	46.1±0.3	9.8±0.2
Miami, Florida	870±130	36.7±0.2	36.4±0.5
Bangkok, Thailand	530±80	40.9±0.2	33.4±0.5

- **The uncertainty in the service life was a function of the uncertainty in the prefactor A and Ea, with a significant correlation between the two.**
- **The uncertainty in all other terms is dependent only on σ_{Ea}.**
- **The uncertainty in the order parameter n was assume to be zero.**
- **The uncertainty in the weather, materials, microclimate, and etc was ignored.**
- **Thus this represents a minimal estimate of uncertainty.**

Pet Hydrolysis Uncertainty

	Years to failure	Teq for Ea=129 kJ/mol	Effictive RH_{WA}, at T_{eq}	Conditions for a test Equivalent to 25 y for Ea=129±3.4 kJ/mol and n=2, for a rack mounted system				
				1000 Hour Test				
				Thermal Only		50:50 Split		
	(y)	T	RH	$T_{100\%}$	Years	T	RH	Years
		(°C)	(%)	(°C)	(y)	(°C)	(%)	(y)
Denver, Colorado	10500±1600	32.9±0.3	14.2±0.3	69.3±-0.7	25±3.1	50.1±-0.1	54.5±1.2	25±1.4
Munich, Germany	8400±1300	27.5±0.4	25.3±0.5	62.5±-0.6	25±3.1	44±-0.1	97.4±2.3	25±1.3
Albuquerque, New Mexico	7000±1100	36.7±0.3	12.6±0.2	74.1±-0.7	25±3.1	54.4±-0.2	48.6±0.8	25±1.3
Riyadh, Saudi Arabia	6400±1000	47.7±0.3	5.6±0.1	87.9±-0.8	25±3.6	66.6±-0.2	21.7±0.5	25±1.8
Phoenix, Arizona	2700±400	46.1±0.3	9.8±0.2	86±-0.8	25±3.3	64.9±-0.2	37.7±0.7	25±1.5
Miami, Florida	870±130	36.7±0.2	36.4±0.5	74.1±-0.9	25±3.5	54.3±-0.3	140±2	25±1.7
Bangkok, Thailand	530±80	40.9±0.2	33.4±0.5	79.4±-0.9	25±3.6	59.1±-0.3	128±2.1	25±1.8

- **A 1000 h 25 y equivalent test can be designed by using only thermal acceleration.**
- **Alternatively, the acceleration can be split between higher temperature and higher humidity.**

Pet Hydrolysis Uncertainty

	Years to failure	Teq for Ea=129 kJ/mol	Effictive RH_{WA}, at T_{eq}	Conditions for a test Equivalent to 25 y for Ea=129±3.4 kJ/mol and n=2, for a rack mounted system														
				1000 Hour Test					6 Month Test					2.5 Year Test				
				Thermal Only		50:50 Split			Thermal Only		50:50 Split			Thermal Only		50:50 Split		
	(y)	T	RH	$T_{100\%}$	Years	T	RH	Years	$T_{100\%}$	Years	T	RH	Years	$T_{100\%}$	Years	T	RH	Years
		(°C)	(%)	(°C)	(y)	(°C)	(%)	(y)	(°C)	(y)	(°C)	(%)	(y)	(°C)	(y)	(°C)	(%)	(y)
Denver, Colorado	10500±1600	32.9±0.3	14.2±0.3	69.3±-0.7	25±3.1	50.1±-0.1	54.5±1.2	25±1.4	58.5±-0.3	25±2.2	45.2±0.02	37.7±0.6	25±0.9	47.5±0	25±1.1	40±0.16	25.2±0.3	25±0.3
Munich, Germany	8400±1300	27.5±0.4	25.3±0.5	62.5±-0.6	25±3.1	44±-0.1	97.4±2.3	25±1.3	52.1±-0.3	25±2.1	39.3±0.07	67.3±1.1	25±0.8	41.5±0	25±1	34.3±0.19	45±0.5	25±0.3
Albuquerque, New Mexico	7000±1100	36.7±0.3	12.6±0.2	74.1±-0.7	25±3.1	54.4±-0.2	48.6±0.8	25±1.3	63±-0.4	25±2.1	49.3±-0.02	33.6±0.4	25±0.8	51.7±-0.1	25±1	44±0.12	22.4±0.2	25±0.3
Riyadh, Saudi Arabia	6400±1000	47.7±0.3	5.6±0.1	87.9±-0.8	25±3.6	66.6±-0.2	21.7±0.5	25±1.8	75.9±-0.5	25±2.6	61.2±-0.07	15±0.3	25±1.3	63.7±-0.1	25±1.6	55.5±0.08	10±0.1	25±0.8
Phoenix, Arizona	2700±400	46.1±0.3	9.8±0.2	86±-0.8	25±3.3	64.9±-0.2	37.7±0.7	25±1.5	74.1±-0.5	25±2.3	59.5±-0.06	26.1±0.3	25±1	62±-0.1	25±1.2	53.9±0.09	17.4±0.1	25±0.5
Miami, Florida	870±130	36.7±0.2	36.4±0.5	74.1±-0.9	25±3.5	54.3±-0.3	140±2	25±1.7	63±-0.5	25±2.5	49.3±-0.14	96.8±1	25±1.2	51.6±-0.2	25±1.4	44±-0.0005	64.7±0.4	25±0.6
Bangkok, Thailand	530±80	40.9±0.2	33.4±0.5	79.4±-0.9	25±3.6	59.1±-0.3	128±2.1	25±1.8	67.9±-0.6	25±2.6	53.9±-0.15	88.7±1	25±1.3	56.3±-0.2	25±1.5	48.4±-0.01	59.3±0.4	25±0.7

- **A 1000 h test is suitable for screening tests or qualification tests.**
- **A 6 month test provides more flexibility in a reasonable amount of time.**
- **A 2.5 y test is an acceleration factor of 10× which provides reasonable accelerations for unknown processes.**

Reduced Uncertainty for Longer Test Times

Uncertainty in Equivalent Length of 25 y test for Rack Mounted System for PET Hydrolysis	Conditions for a test Equivalent to 25 y for Ea=129±3.4 kJ/mol and n=2, for a rack mounted system					
	1000 Hour Test		6 Month Test		2.5 Year Test	
	Thermal	50:50	Thermal	50:50 Split	Thermal	50:50
Denver, Colorado	3.1	1.4	2.2	0.9	1.1	0.3
Munich, Germany	3.1	1.3	2.1	0.8	1.0	0.3
Albuquerque, New Mexico	3.1	1.3	2.1	0.8	1.0	0.3
Riyadh, Saudi Arabia	3.6	1.8	2.6	1.3	1.6	0.8
Phoenix, Arizona	3.3	1.5	2.3	1.0	1.2	0.5
Miami, Florida	3.5	1.7	2.5	1.2	1.4	0.6
Bangkok, Thailand	3.6	1.8	2.6	1.3	1.5	0.7

- **This represents the smallest amount of uncertainty possible. It ignores variability from exposure, construction and other test specific sources, and assumes the failure mode is directly related to PET hydrolysis.**

Kinetics of Paints and Coatings Degradation

$$R_D \sim I^x \cdot (b + m \cdot TOW) \cdot T_f^{\frac{T - T_o}{10}}$$

*Fischer *et. al*

T_f=1.41±0.23 Acceleration per 10°C increase.

X=0.64±0.2 Irradiance acceleration exponent.

m=-0.0015±0.12 Time of Wetness (TOW) factor.

b=1.071±0.0026

- **50 coatings with respect to color shift, cracking, gloss loss, fluorescence loss, retroreflectance loss, adhesive transfer, and shrinkage.**

*R. M. Fischer and W. D. Ketola, "Error Analyses and Associated Risk for Accelerated Weathering Results," *Third International Service Life Symposium, Sedona, AZ February 2004,* 2004.

Modeling Assumptions for a PV Backsheet

- **Assume UV on back of rack mounted system is 0.5% of global horizontal irradiance.**
- **Ignore TOW**
  - Very high uncertainty with a low mean value indicating typically no effect.
  - Condensation is predominantly on the front making application of this effect dubious on the back.

Location Specific Effective Conditions

Rack Mounted Modules	I_{WA}		T_{oeq}
	(W/m^2 from 295 to 385)	($W/m^2/nm$ @340 nm)	(°C)
Munich, Germany	0.753±0.339	0.0095±0.0043	14.4±1.5
Denver, Colorado	1.17±0.48	0.0148±0.006	19.0±2.1
Albuquerque, New Mexico	1.44±0.55	0.0181±0.0069	24.0±2.0
Miami, Florida	1.01±0.36	0.0127±0.0046	30.8±0.8
Bangkok, Thailand	1.05±0.38	0.0131±0.0047	35.2±0.8
Phoenix, Arizona	1.52±0.57	0.0191±0.0071	34.6±2.0
Riyadh, Saudi Arabia	1.57±0.58	0.0197±0.0073	36.7±1.9

ASTM G173 has 35.6 W/m^2 between 295 and 385 nm

$$T_{oeq} = \frac{10}{ln(T_f)} ln\left(\frac{\sum T_f^{\frac{T}{10}}}{N}\right)$$

$$I_{WA} = \left[\frac{\sum I^x T_f^{\frac{T-T_{oeq}}{10}}}{N}\right]^{\frac{1}{x}}$$

Much Greater Uncertainty in 25 y Tests

Uncertainty in Acceleration Factor for Optimized Data			
Uncertainty in 25 y Equivalent Test	Accelerated Stress Test Duration		
	1000 h	6 month	2.5 y
Munich, Germany	27	18	7.3
Denver, Colorado	28	18	7.8
Albuquerque, New Mexico	28	19	8.3
Miami, Florida	29	19	8.9
Bangkok, Thailand	29	19	8.9
Phoenix, Arizona	29	19	8.4
Riyadh, Saudi Arabia	29	19	8.4

- **Temperature and irradiance optimized to minimize the uncertainty in a 25 y equivalent stress test.**

Optimal Exposure Conditions

Irradiance optimized Data						
Uncertainty in 25 y Equivalent Test	Accelerated Stress Test Duration					
	1000 h		6 month		2.5 y	
	T_o (°C)	(W/m²/nm @340 nm)	T_o (°C)	(W/m²/nm @340 nm)	T_o (°C)	(W/m²/nm @340 nm)
Munich, Germany	68	2.5	55	0.50	40.4	0.086
Denver, Colorado	74	3.6	61	0.71	46.4	0.12
Albuquerque, New Mexico	78	4.4	65	0.89	51.2	0.15
Miami, Florida	80	4.1	67	0.81	53.1	0.14
Bangkok, Thailand	85	4.2	72	0.83	57.7	0.14
Phoenix, Arizona	89	4.7	76	0.94	61.7	0.16
Riyadh, Saudi Arabia	90	5.0	77	1.01	63.2	0.17

- **ASTM G173 using 0.5018 W/m²/nm @340 nm**
  - 1000 h test - 5 to 10 UV suns
  - 6 month test - 1 to 2 UV suns
  - 2.5 y test - 0.17 to 0.33 UV suns

Conclusion

- **With an extremely good understanding of the degradation kinetics, one can design a 25 y equivalent test to within ~±1 y. Unfortunately, this is an unusual occurrence and produces results with a very narrow scope.**
- **For backsheet materials, a generic and long, ~2.5 y, test may yield reasonable uncertainties of ~± 8 y.**
- **Accelerated stress tests must be very targeted at specific materials and failure modes, or be of a very long duration.**
- **Estimates for irradiance for a 25 y backsheet test:**
  - 1000 h test - 5 to 10 UV suns
  - 6 month test - 1 to 2 UV suns
  - 2.5 y test - 0.17 to 0.33 UV suns

Acknowledgements

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Experimental evaluation of the acceleration factors and activation energies for humidity-based degradation phenomena in c-Si modules

Michael Köhl

Stephan Hoffmann

Fraunhofer Institute for

Solar Energy Systems ISE

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How to perform Accelerated Life Testing ?

Experimental Set-up:

5 different commercially available c-Si module types in the framework of National German project „PV-Zuverlässigkeit II“)

Different constant load tests

- Damp-heat-UV
- Damp-heat-humidity-freeze
- Temperature cycling
- Combi-tests
- **Damp-heat tests**

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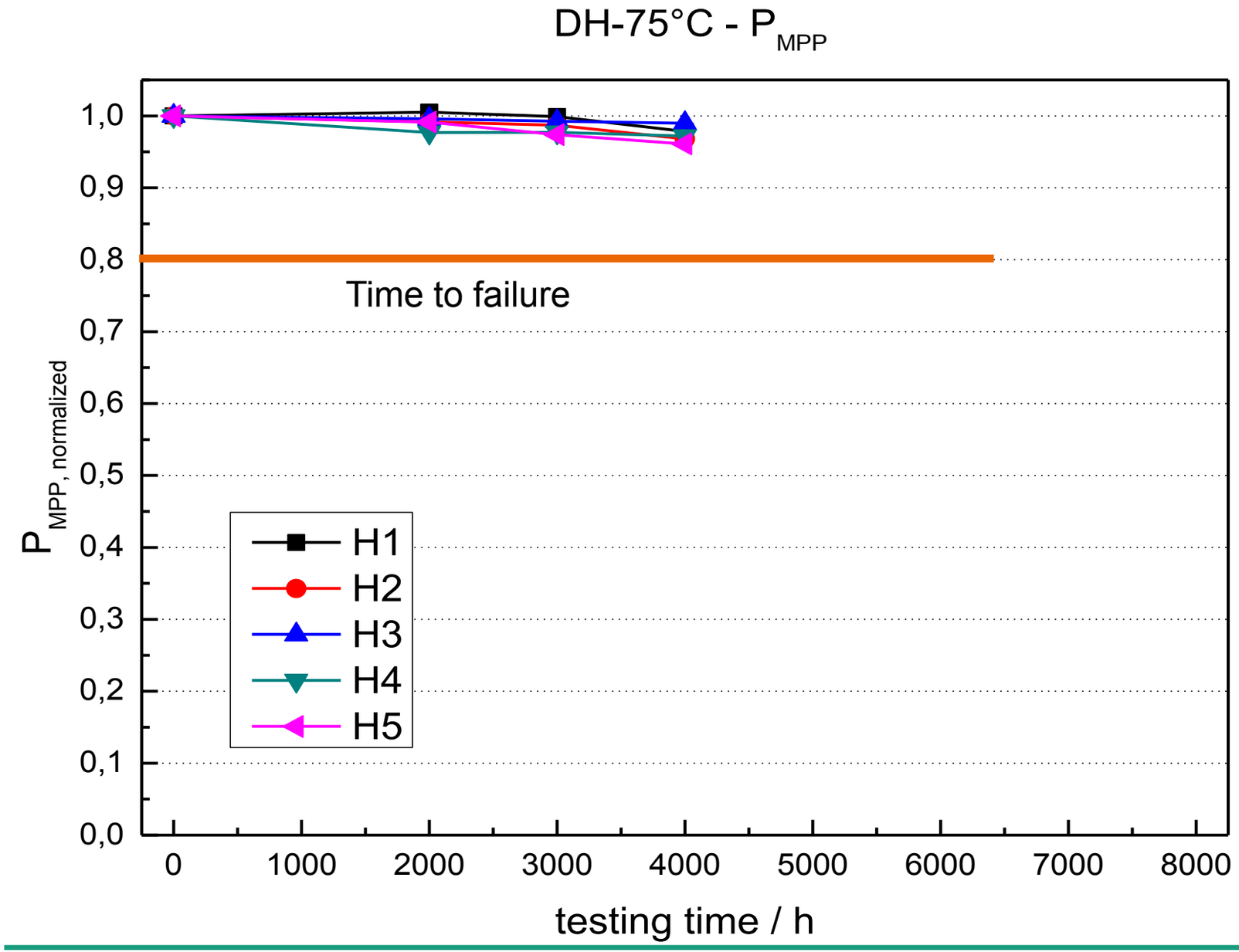
Evaluation of the parameters for time-transformation functions by ALT

Damp-heat testing at 85%rh of 5 different c-Si modules at 75°C



After half year:

no significant changes

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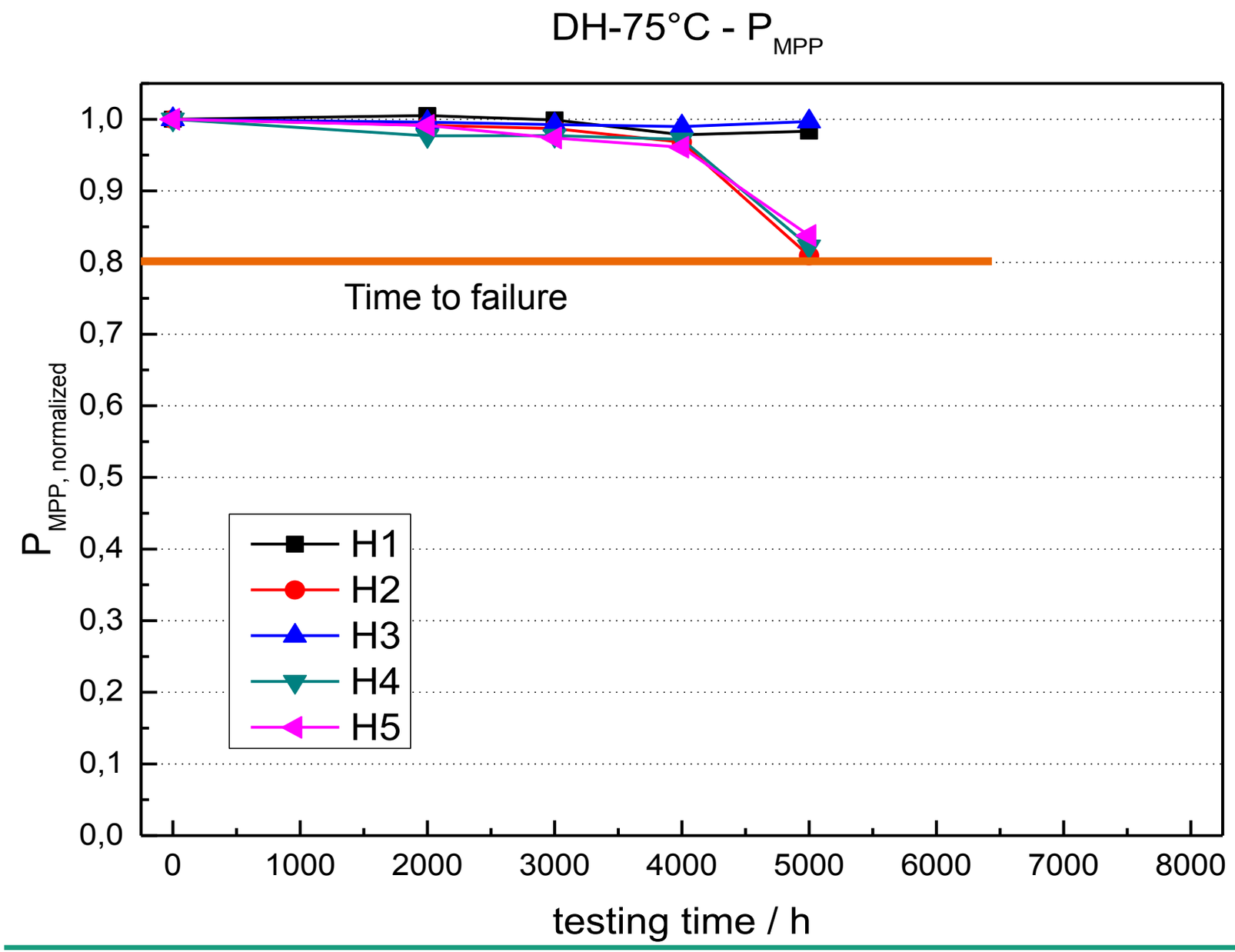
Evaluation of the parameters for time-transformation functions by ALT



H1, H3 no changes

H2, H4, H5 similar time to failure

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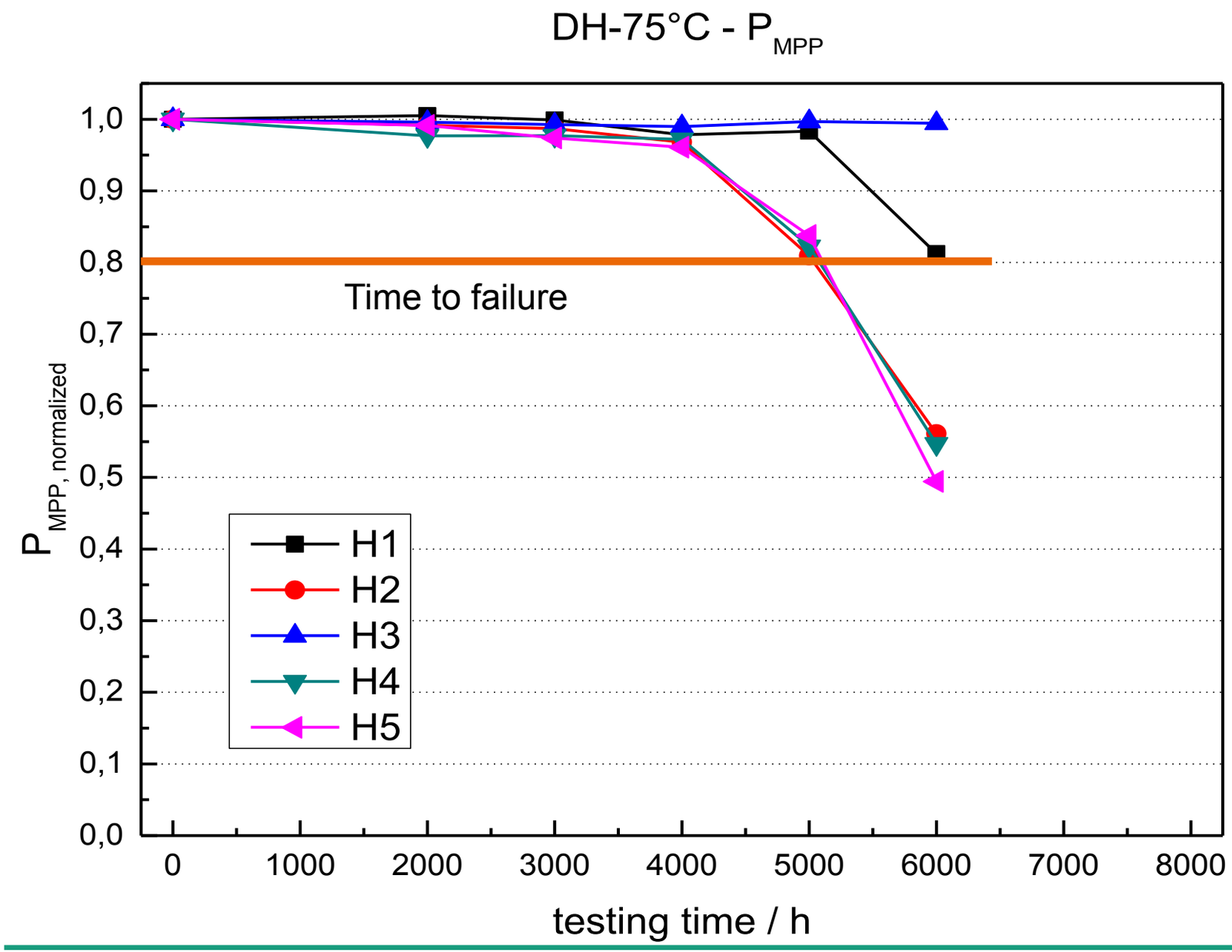
Evaluation of the parameters for time-transformation functions by ALT



H3 no changes

H1 longer time to failure

H2, H4, H5 similar

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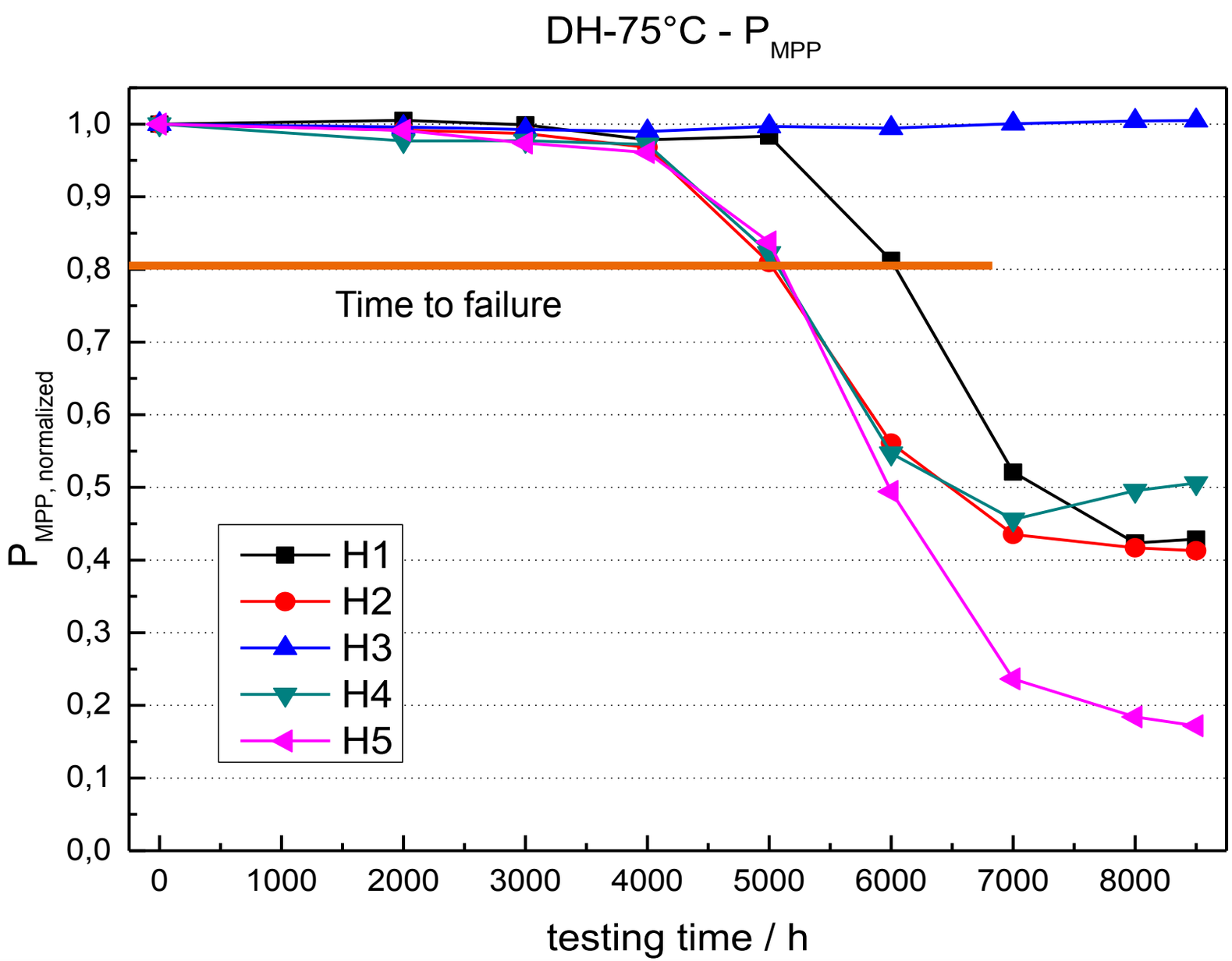
Evaluation of the parameters for time-transformation functions by ALT



After one year:

H3 no changes

H1 longer time to failure

H1, H2, H4 similar end

H5 more degradation

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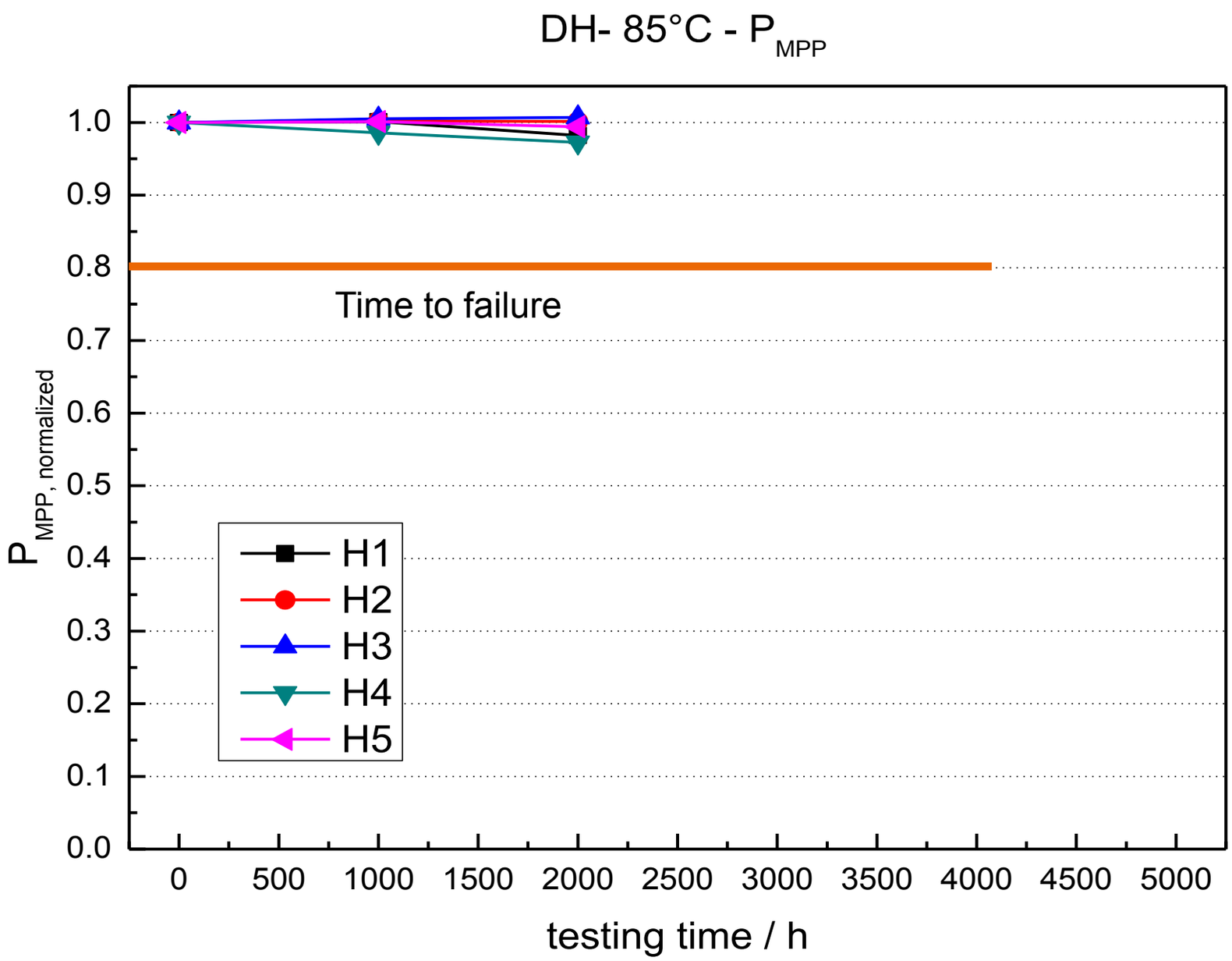

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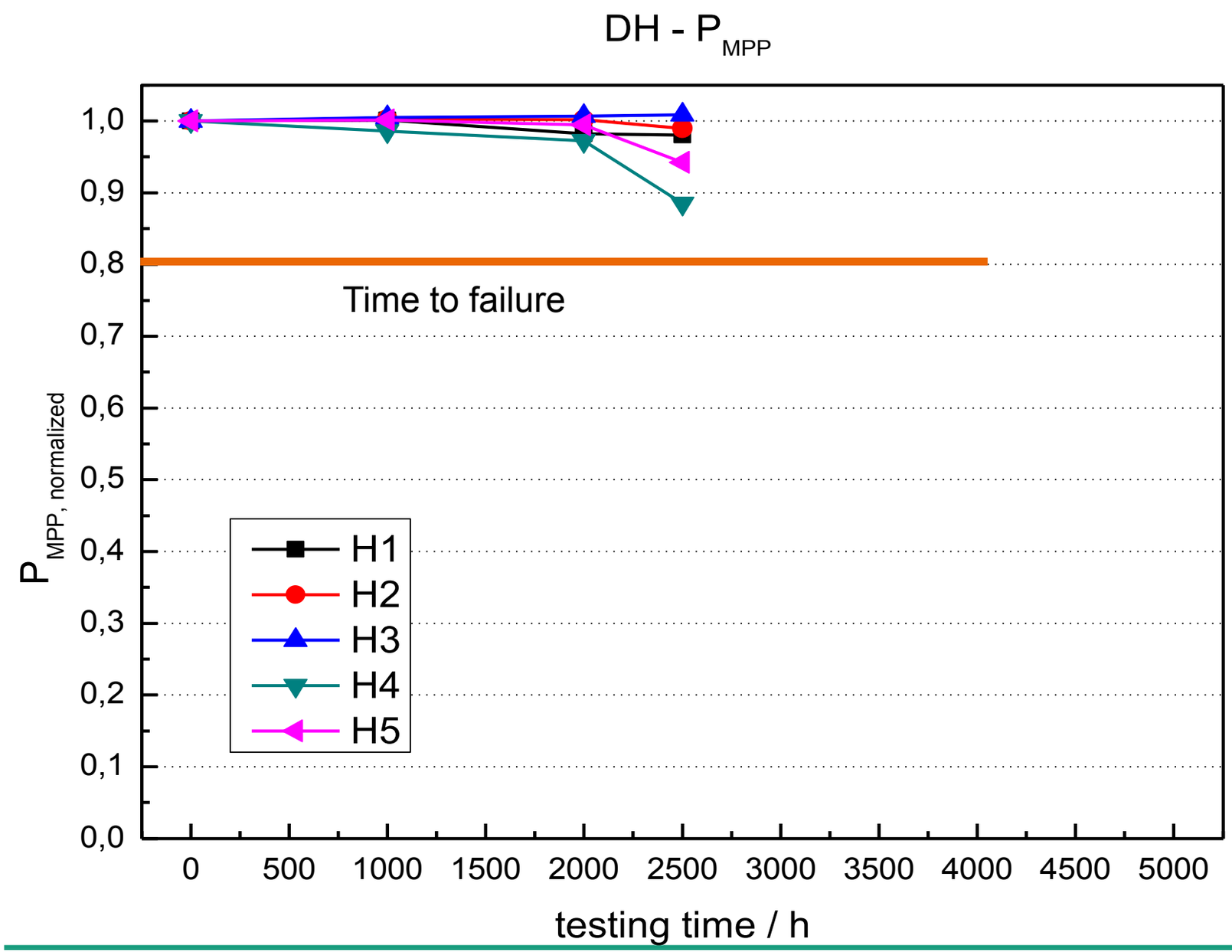

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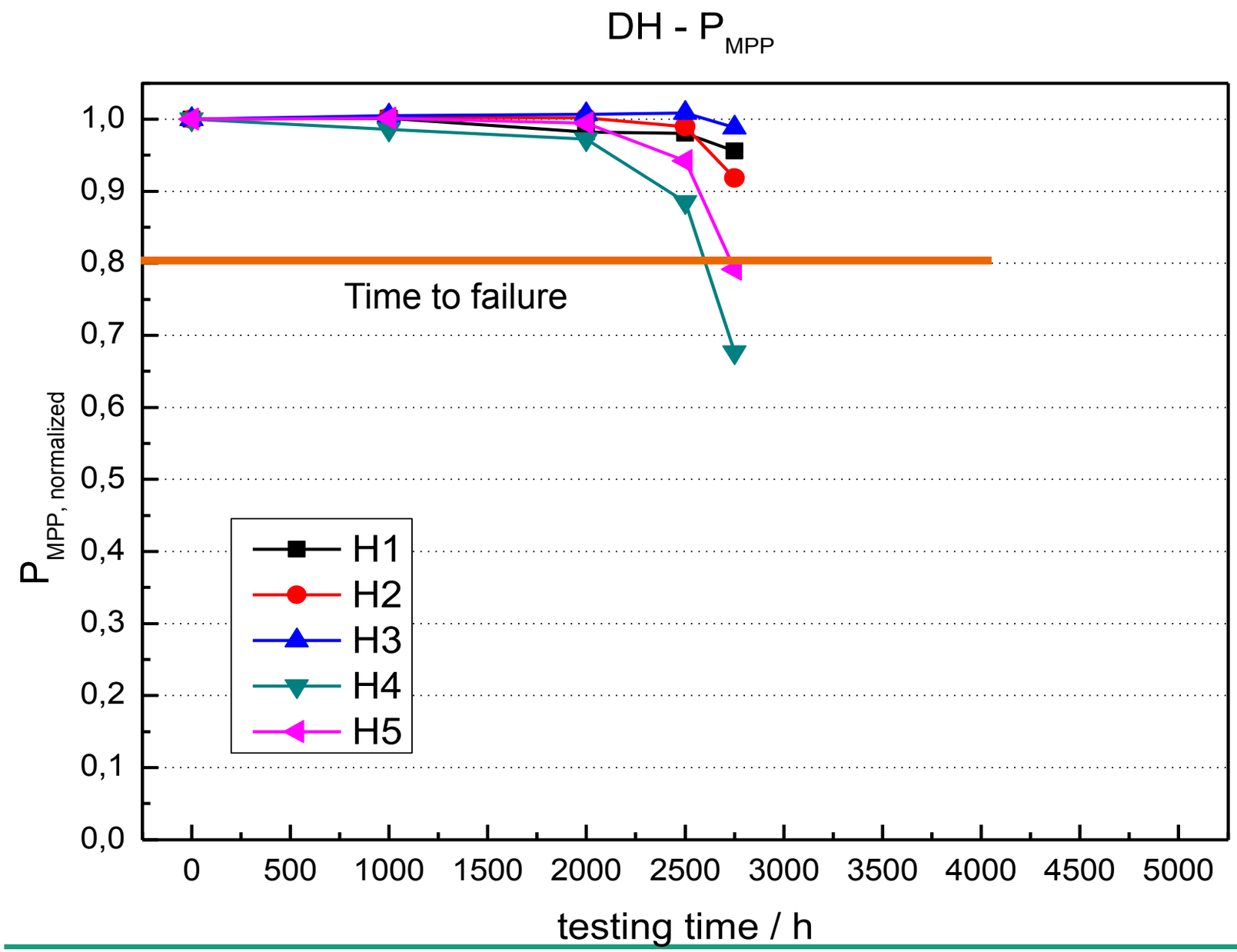

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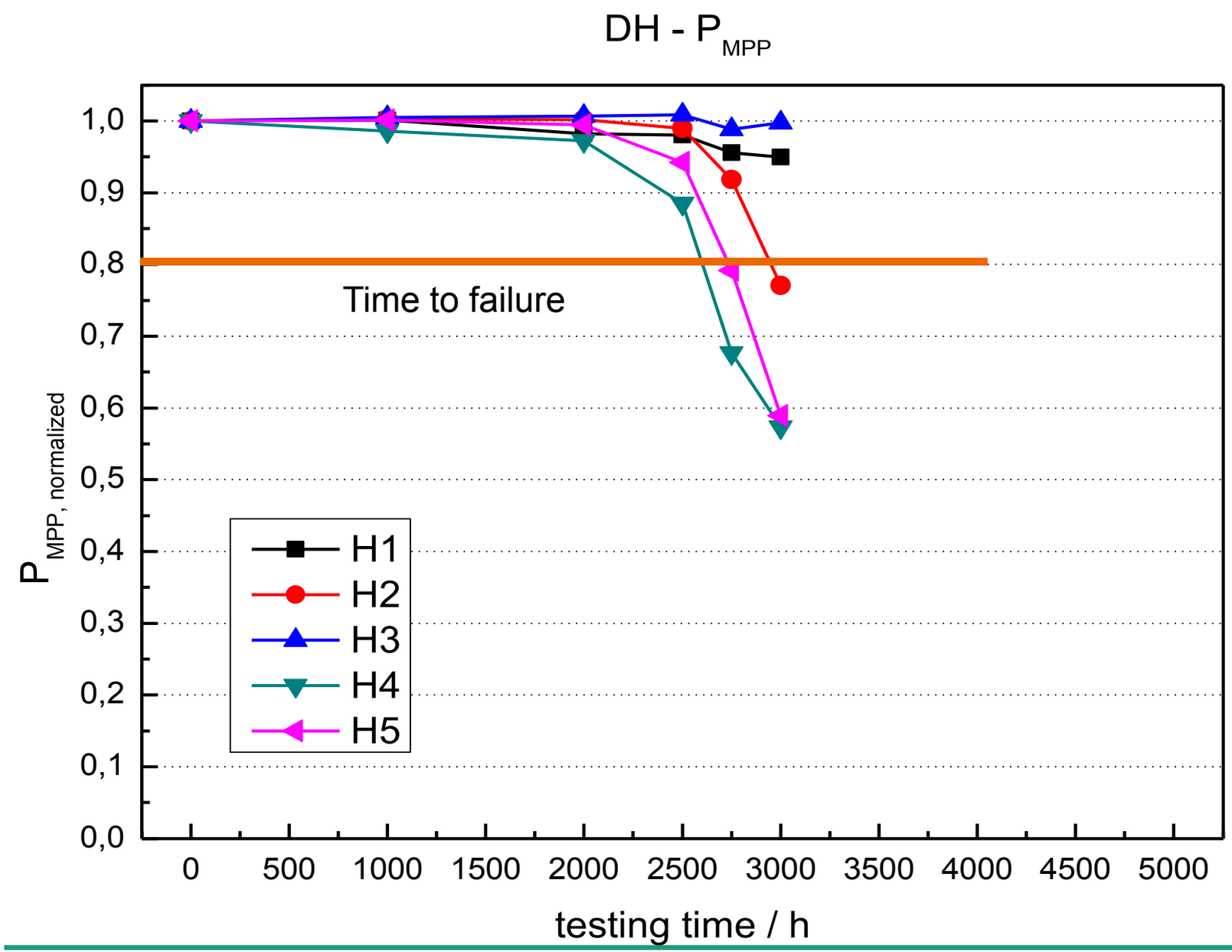

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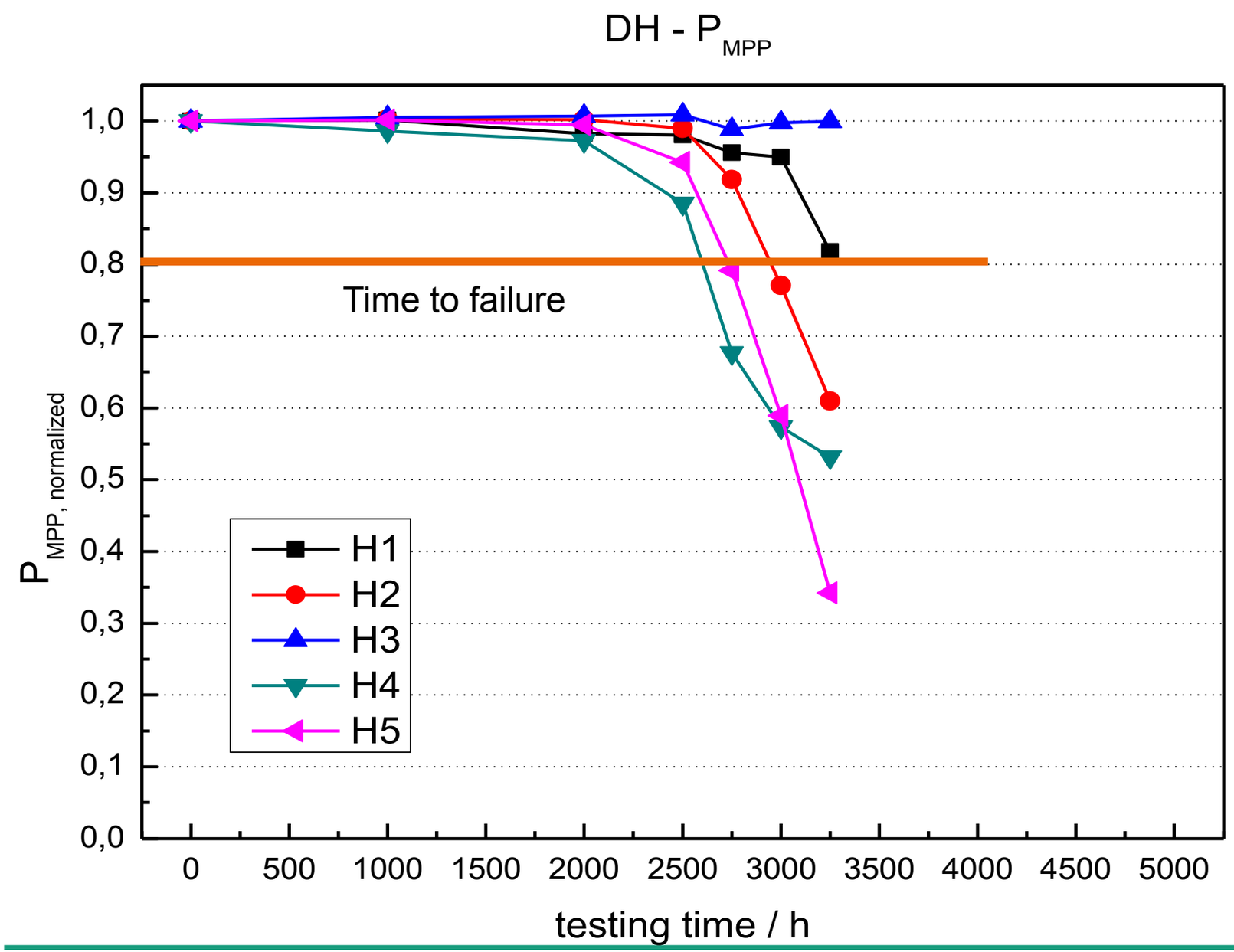

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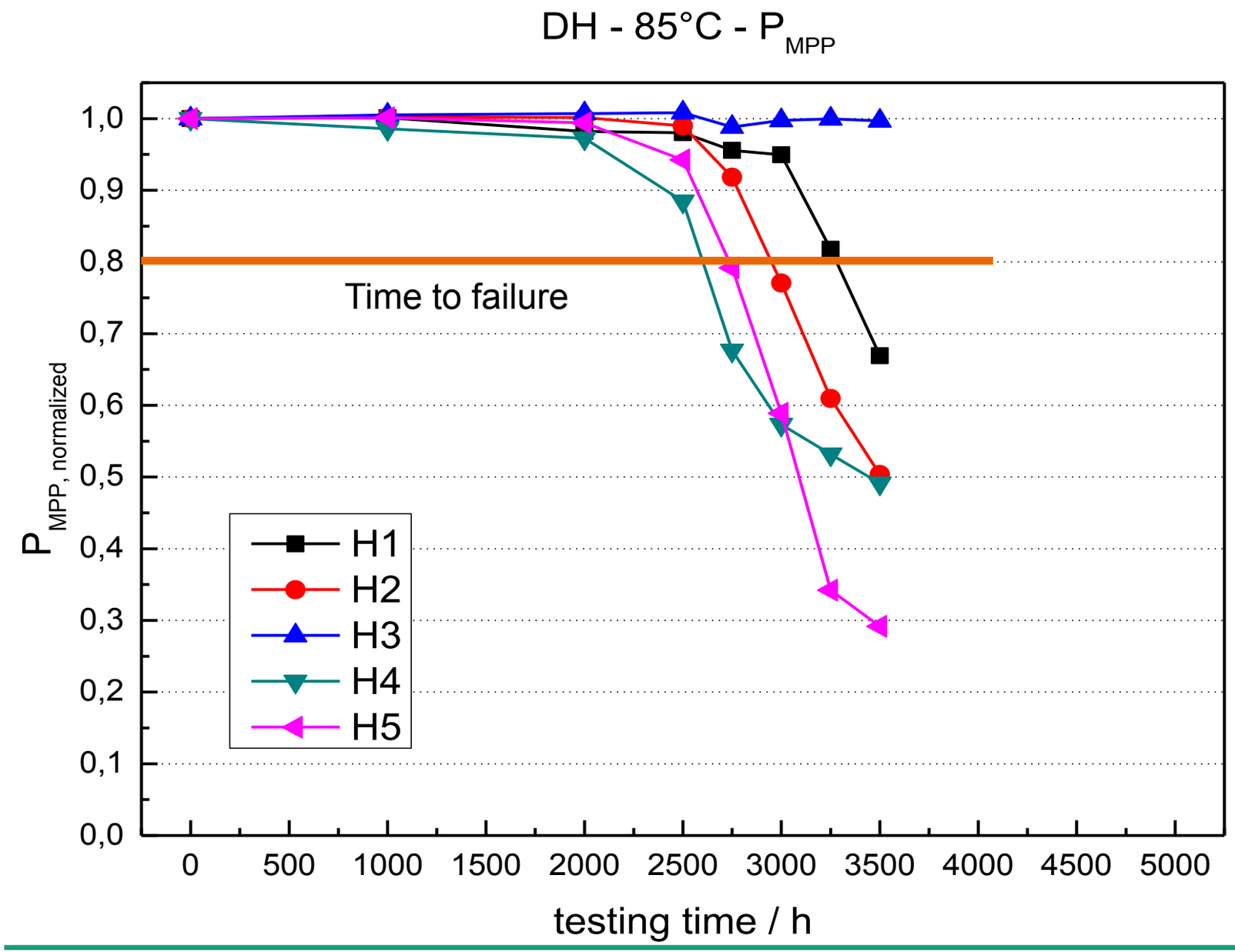

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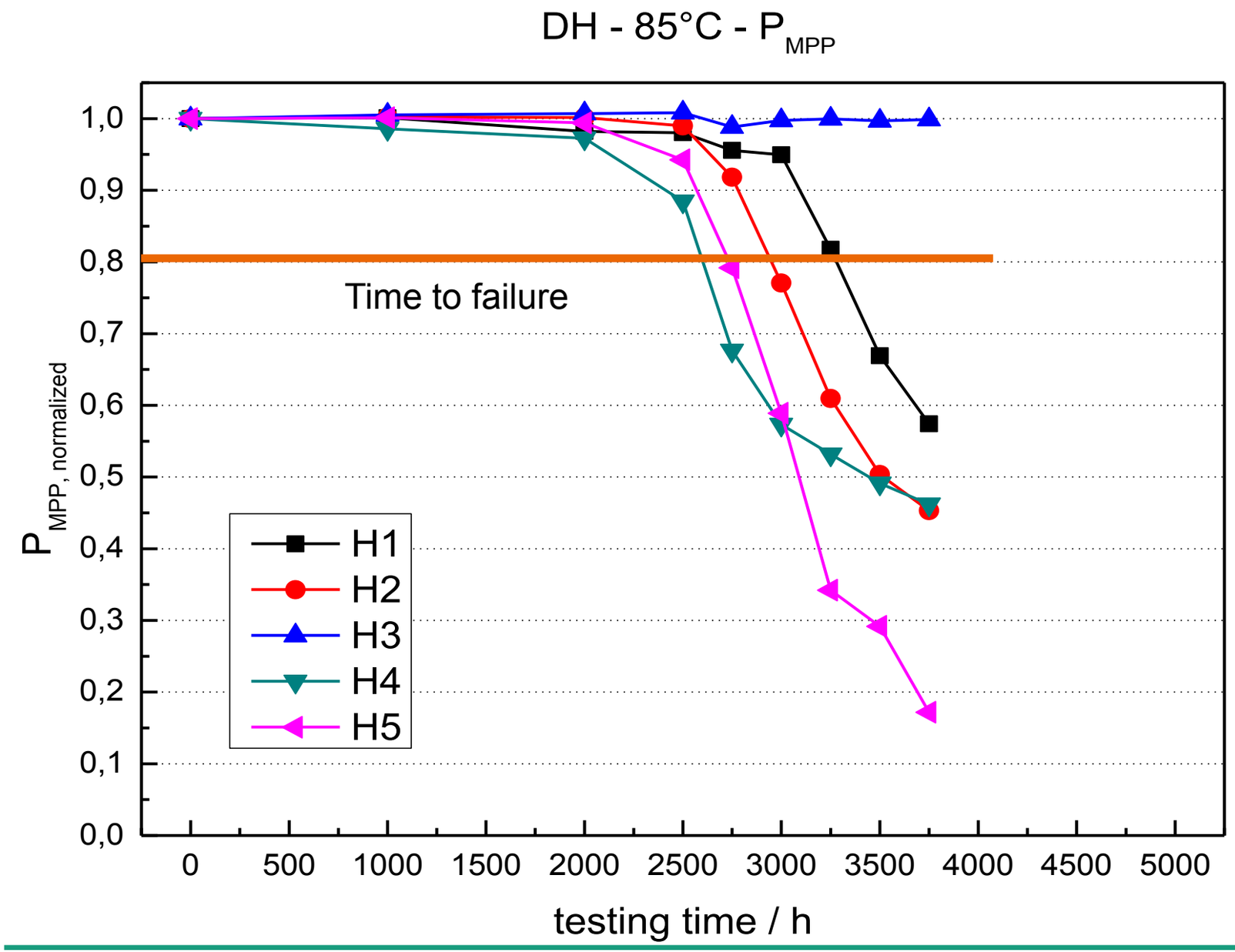

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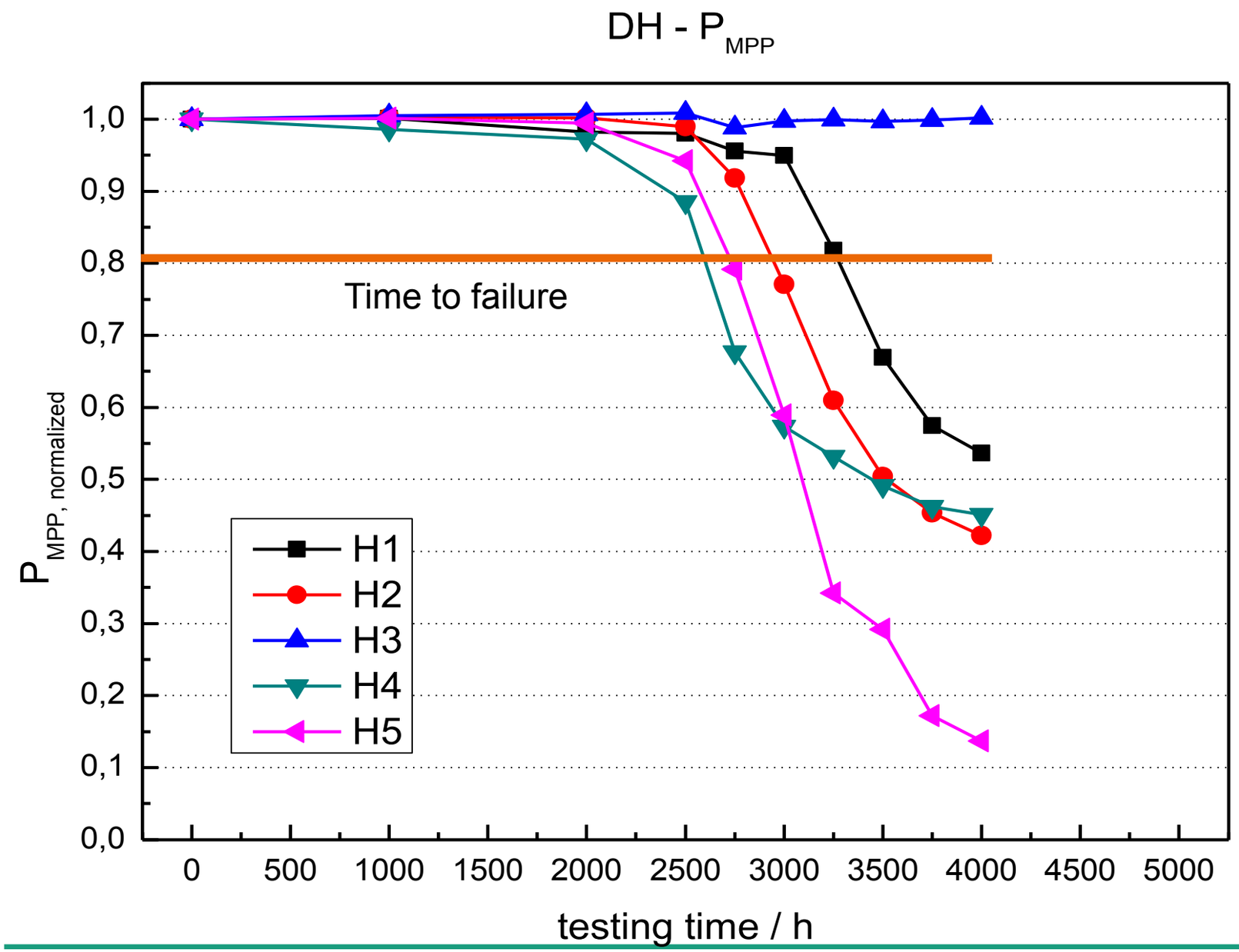

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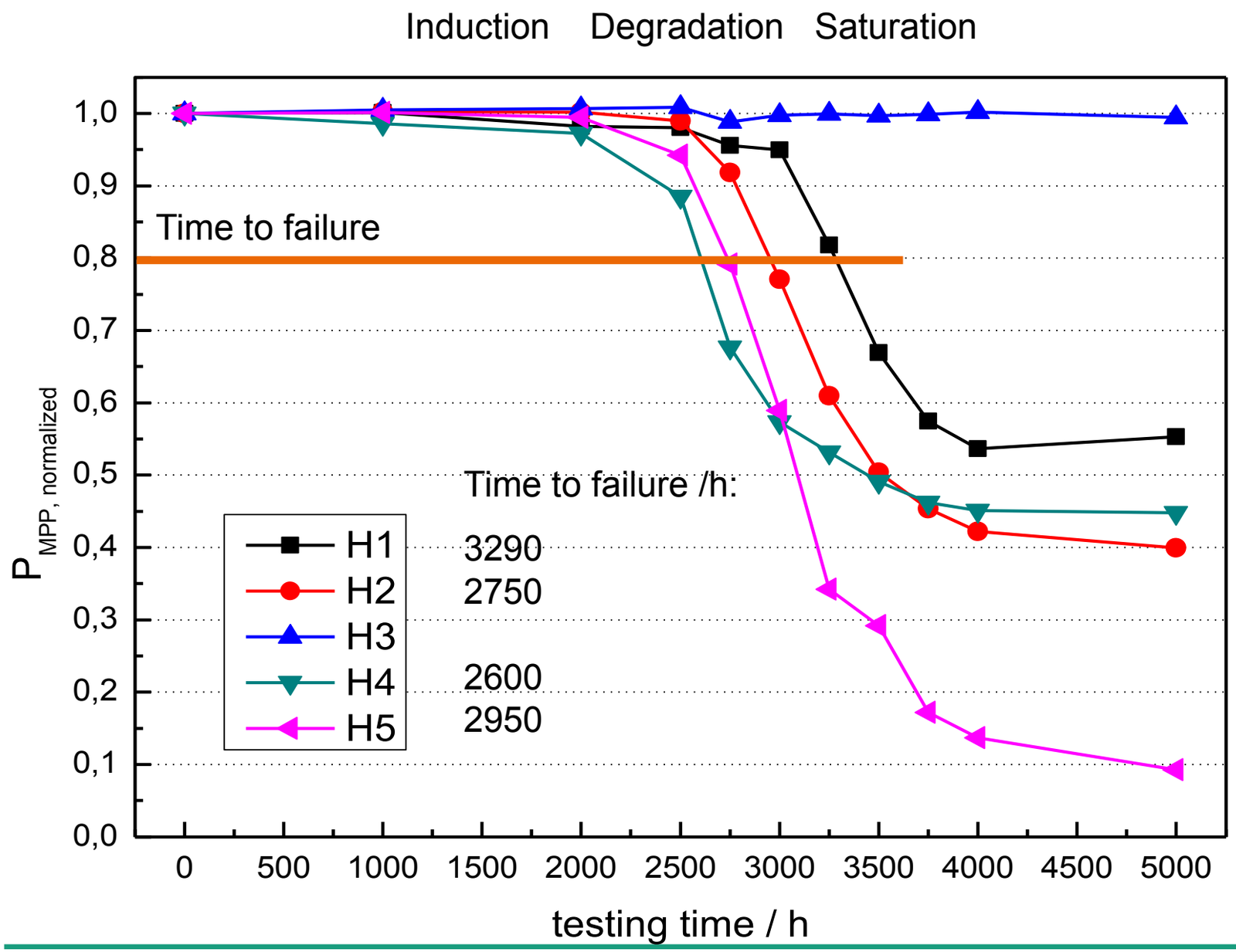

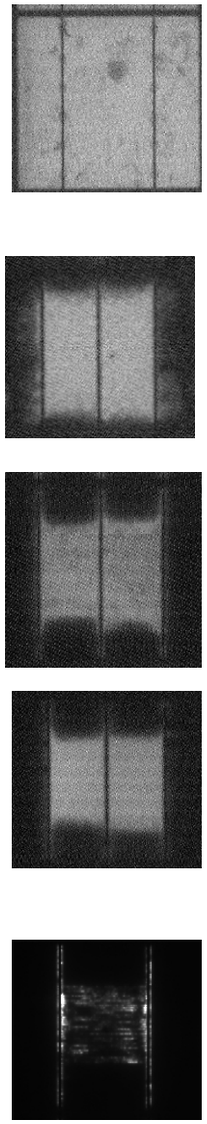

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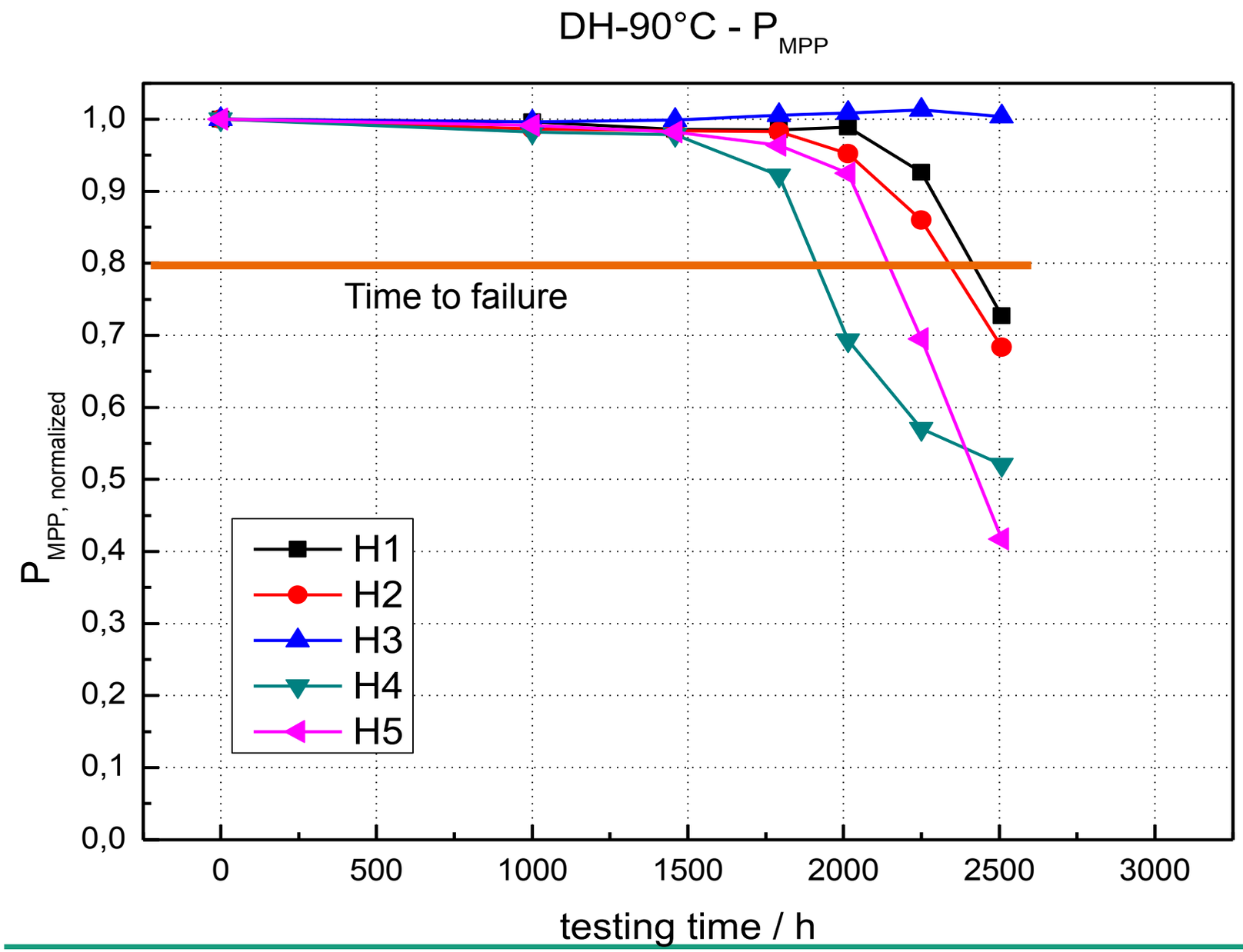

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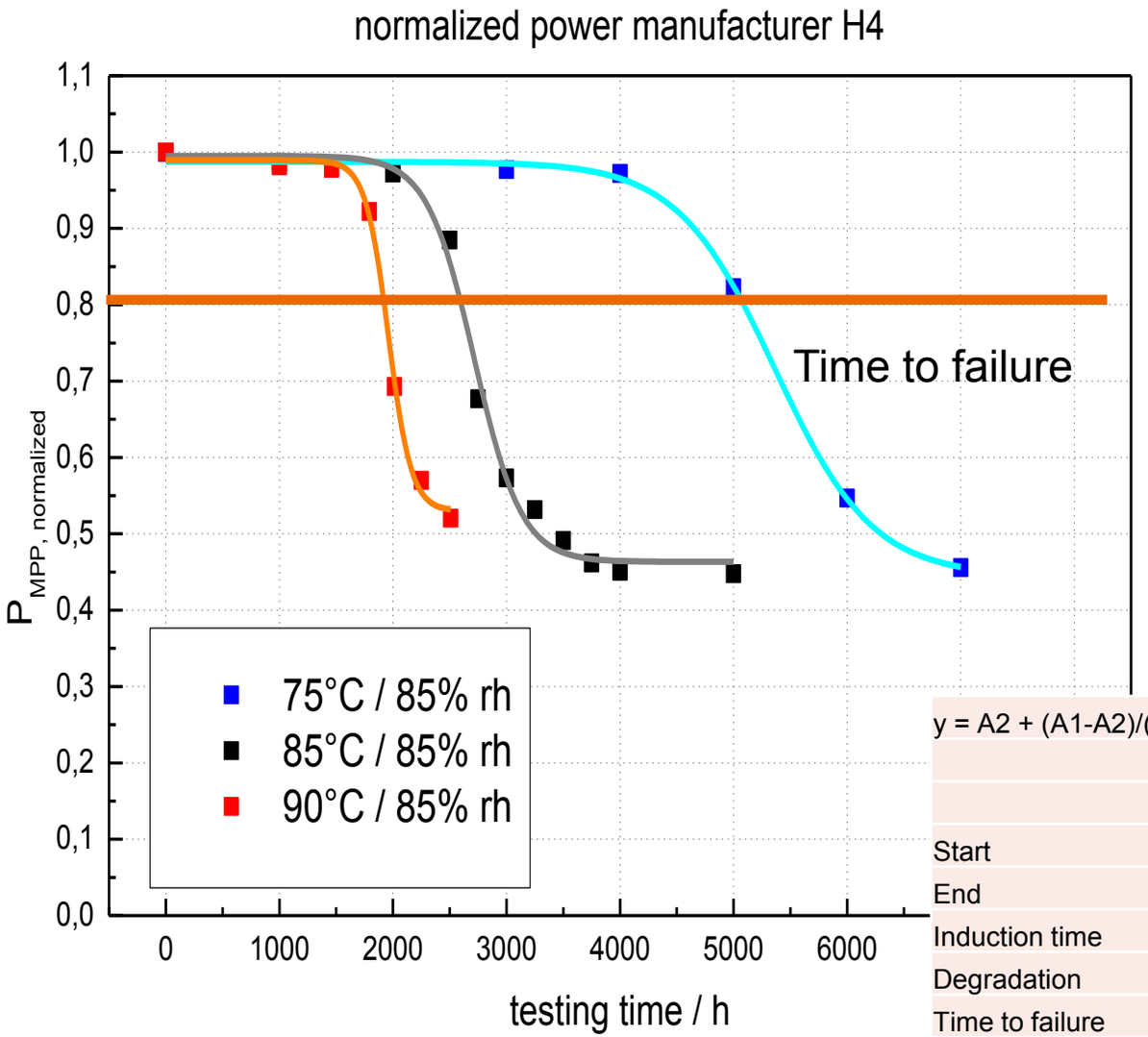
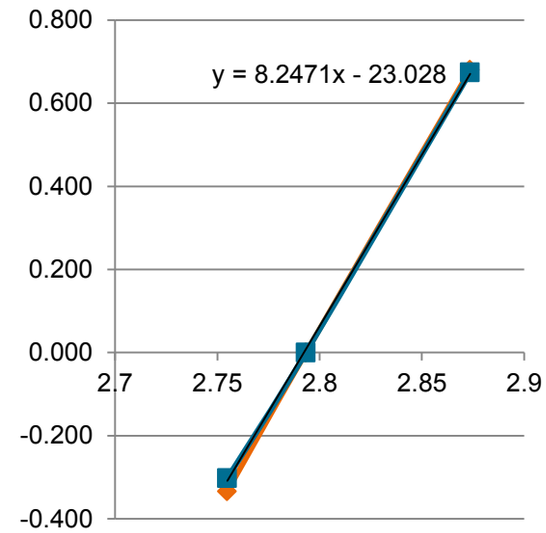
Evaluation of the parameters for time-transformation functions by ALT

Damp-heat testing at 85%rh@ 75°C, 85°C and @90°C





Arrhenius-Plot: Activation energy = 69 kJ/mol

y = A2 + (A1-A2)/(1 + exp((x-x0)/dx))		75°C		85°C		90°C	
		Value	Error	Value	Error	Value	Error
Start	A1	0,987	0,01	0,995	0,01	0,988	0,01
End	A2	0,445	0,01	0,463	0,01	0,556	0,01
Induction time	x0	5364	51,11	2717	30,84	1946	12,67
Degradation	dx	430	39,55	208	28,99	90	9,86
Time to failure	tlt	5117		2608		1928	
Acceleration a		0,51		1,00		1,35	

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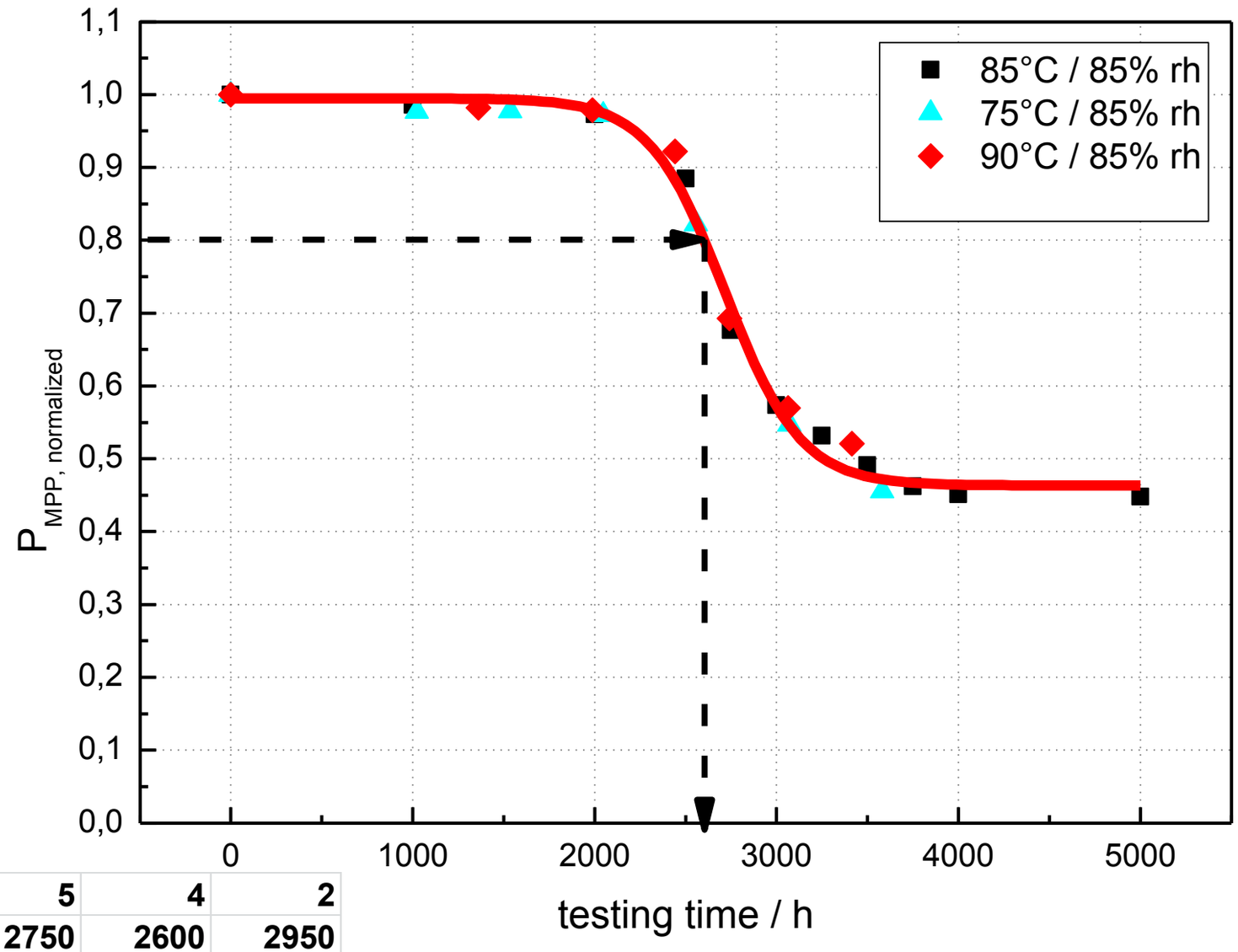
Evaluation of the parameters for time-transformation functions by ALT

$$a = \exp\left[-(E_a / R)\cdot(1/T_1 - 1/T_2)\right]$$



Module #	1	5	4	2
Lifetime @ 85°C/h	3290	2750	2600	2950
Induction time @ 85°C/h	3339	3105	2717	3033
Accelaration 75/85	1,85	1,85	1,95	1,7
Activation E / kJ/mol	64,5	63,7	69,2	55,0

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EU-FP7 project SOPHIA

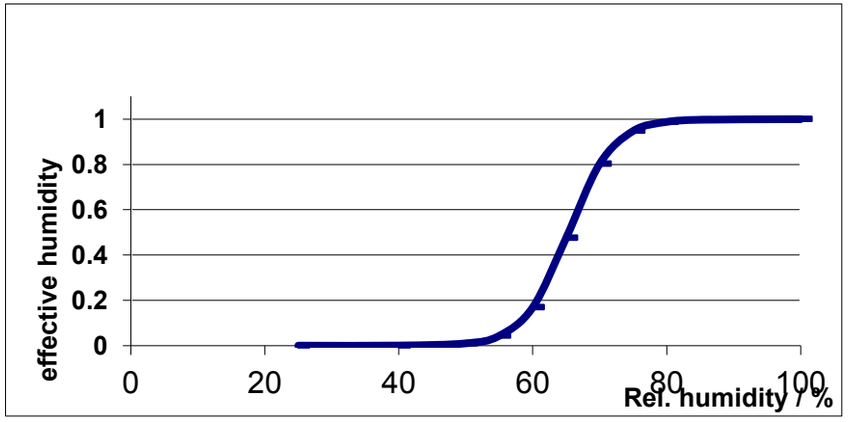
Work-sharing testing in different labs => poster by Jiang Zhu
Challenge: how to compare the results

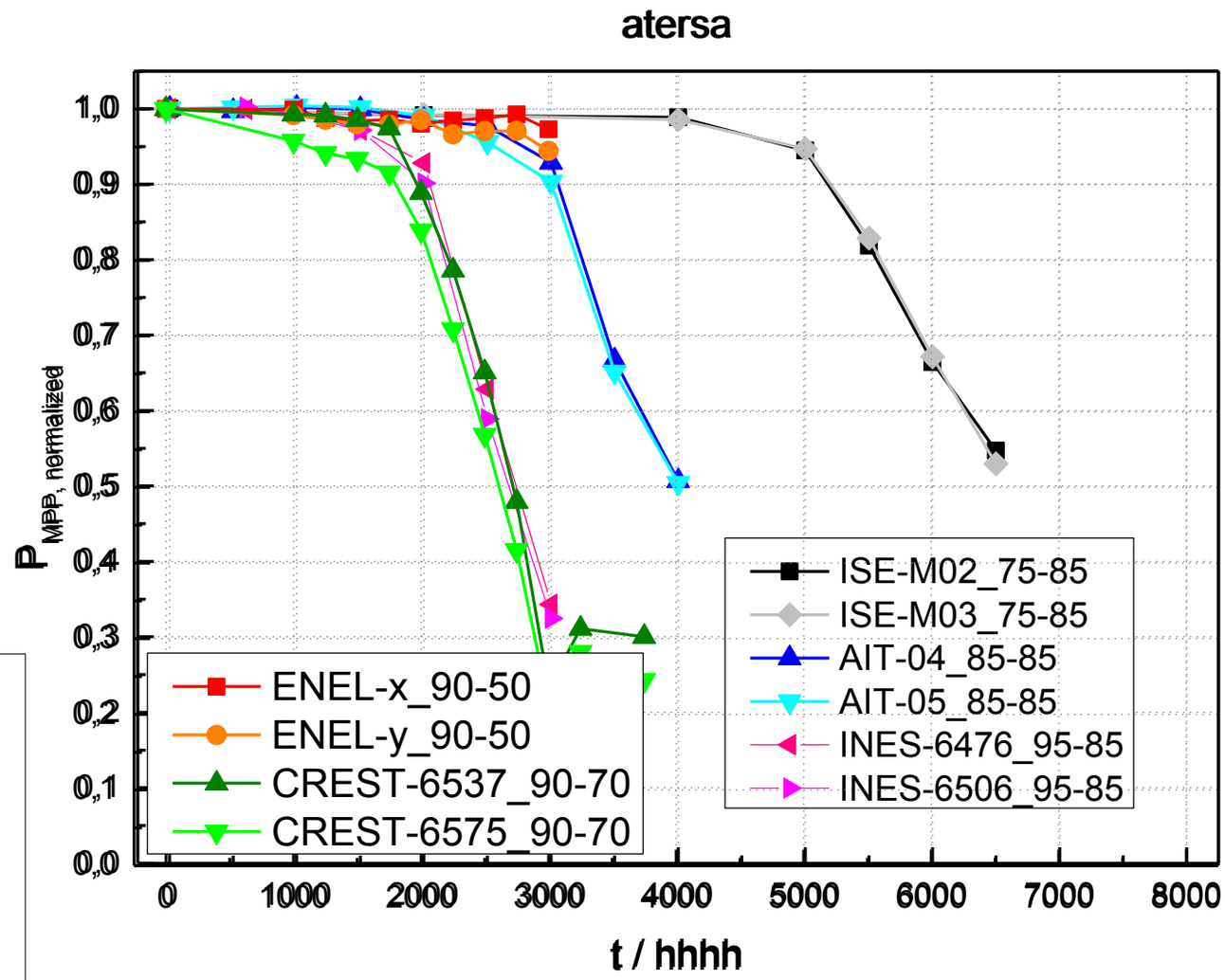
Average activation energy

50 kJ/mol

No serious degradation at 50%rh

Similar degradation at 70% and 85% rh: S-curve for eff. humidity





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Koehl et al: Solar Energy Materials & Solar Cells 99 (2012) 282–291

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What are the weathering stresses? => Monitoring climatic conditions

Ambient climate and sample temperatures as 1min averaged time series

Corrosivity, salt concentration as yearly or monthly dose

City or reference:

Freiburg Germany

Alpine

Zugspitze

Germany

Arid

Sede Boqer

Israel

Tropical

Serpang

Indonesia

(operated by TÜV Rheinland)

Maritime

Pozo Izquierdo

Gran Canaria

© Fraunhofer ISE

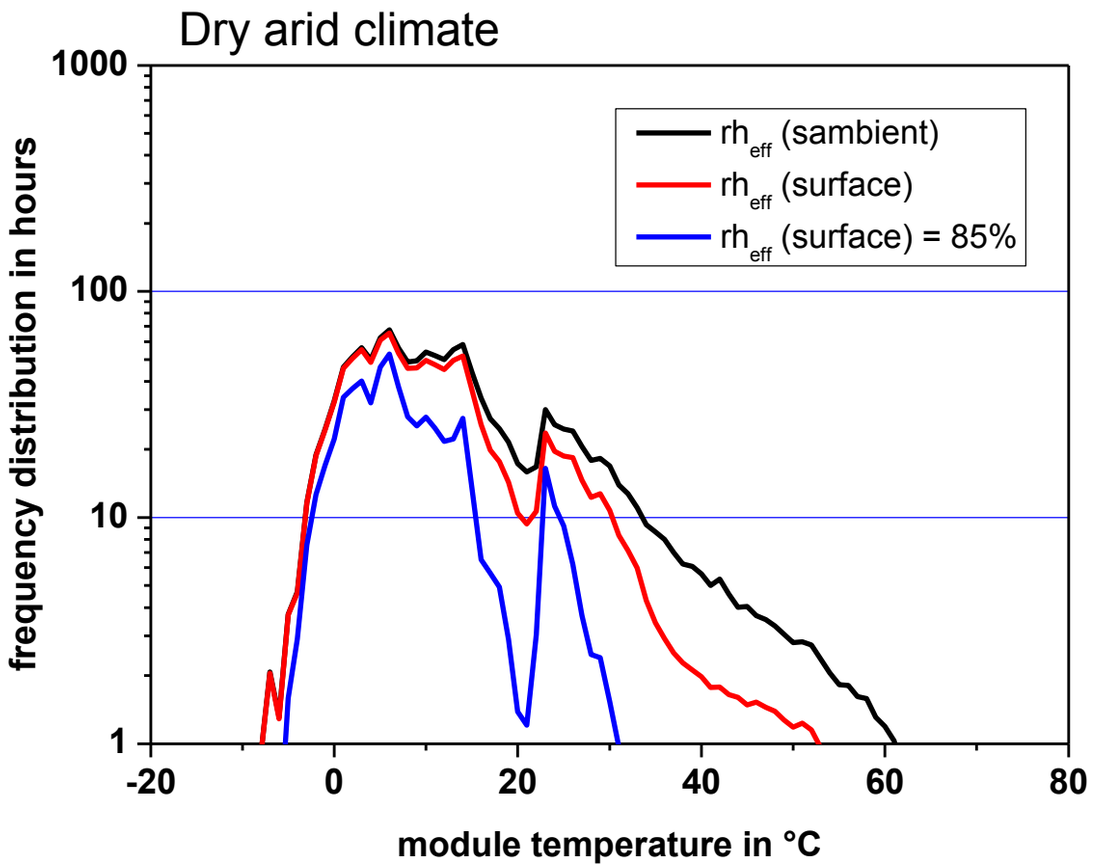
Modeling micro-climatic moisture stress factors for back-sheets and cell edges

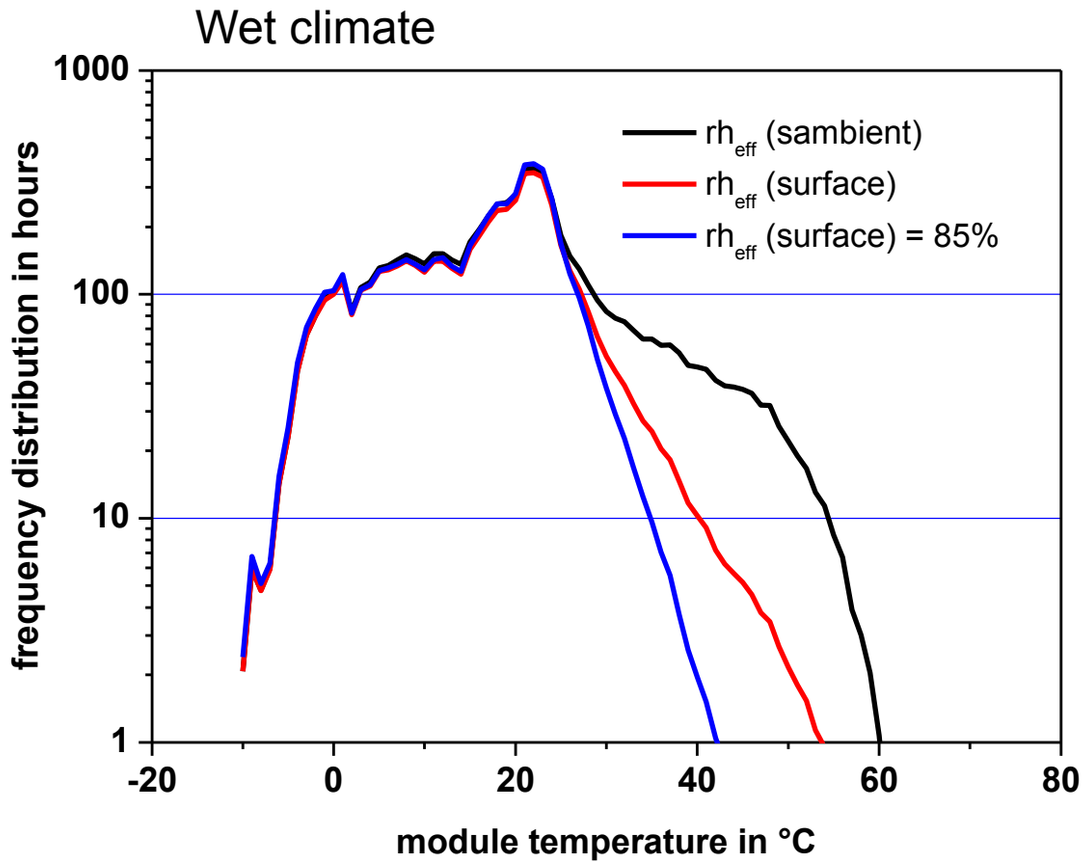
1.) $T_{mod} = T_{amb} + H/(u_0 + u_1 v)$ modeling the module temperature

2.) $rh(T_{mod}) = rh(T_{amb}) * P_{sat}(T_{mod}) / P_{sat}(T_{amb})$ takes into account the higher module temperature

3.) $rh_{eff} = 1/(1 + \exp(-s*rh) \cdot (1/0{,}01 - 1))$ effective humidity gives more weight to periods with high rh

4.) $\Delta t_{85} = \Delta t * rh_{eff} / 0{,}85$ relates to the moisture level during testing





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Time-transformation functions for major degradation processes

5.) Process kinetics depend on module temperature (Time Transformation Function):

$$t_{test} = \text{Lifetime (years)} \cdot \Sigma_i \{\Delta t_i(rh_{eff}, T_{mod,i}) \cdot \exp[-(E_a / R)\cdot(1/T_{test} - 1/T_{mod,i})]\}$$

E_a = activation energy for the rate dominating degradation process

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Evaluation of the service life time in different climates

Activation energy is more important than time to failure

E_a = 70 kJ/mol

For tropical climates

ALT time @ 85°C= 1500h

Time to failure = 2600h is longer

>> passed

E_a = 55 kJ/mol

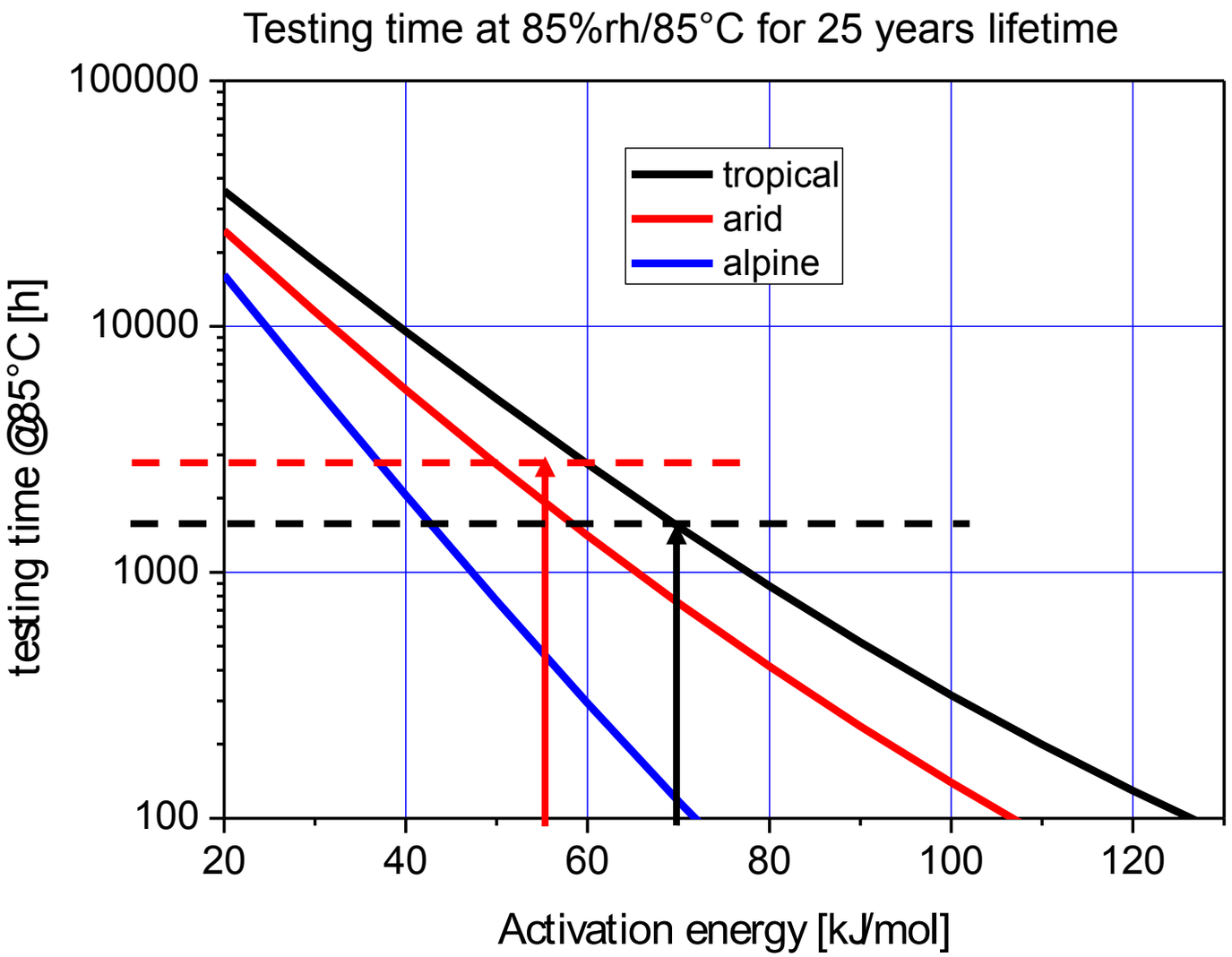
For tropical climates

ALT time @ 85°C: 3700h

Time to failure = 2950h is shorter

>> failed

But good enough for deserts



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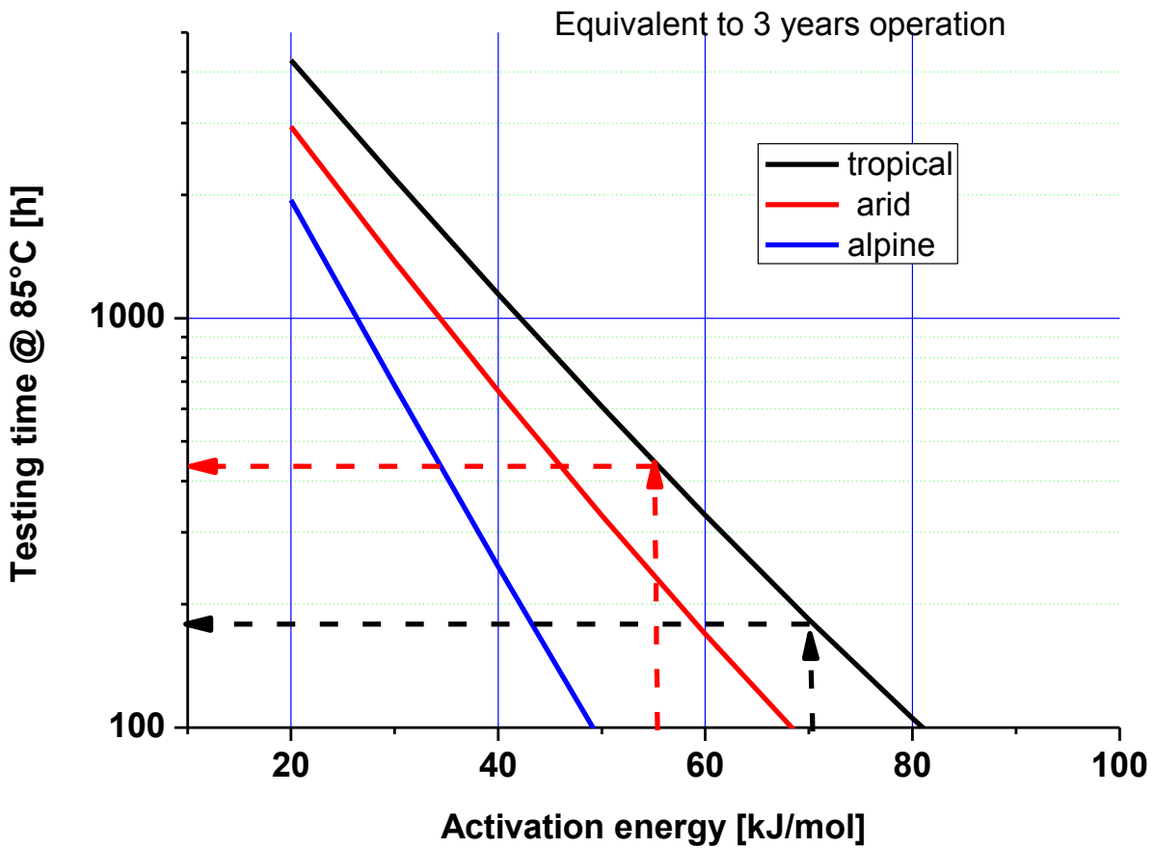
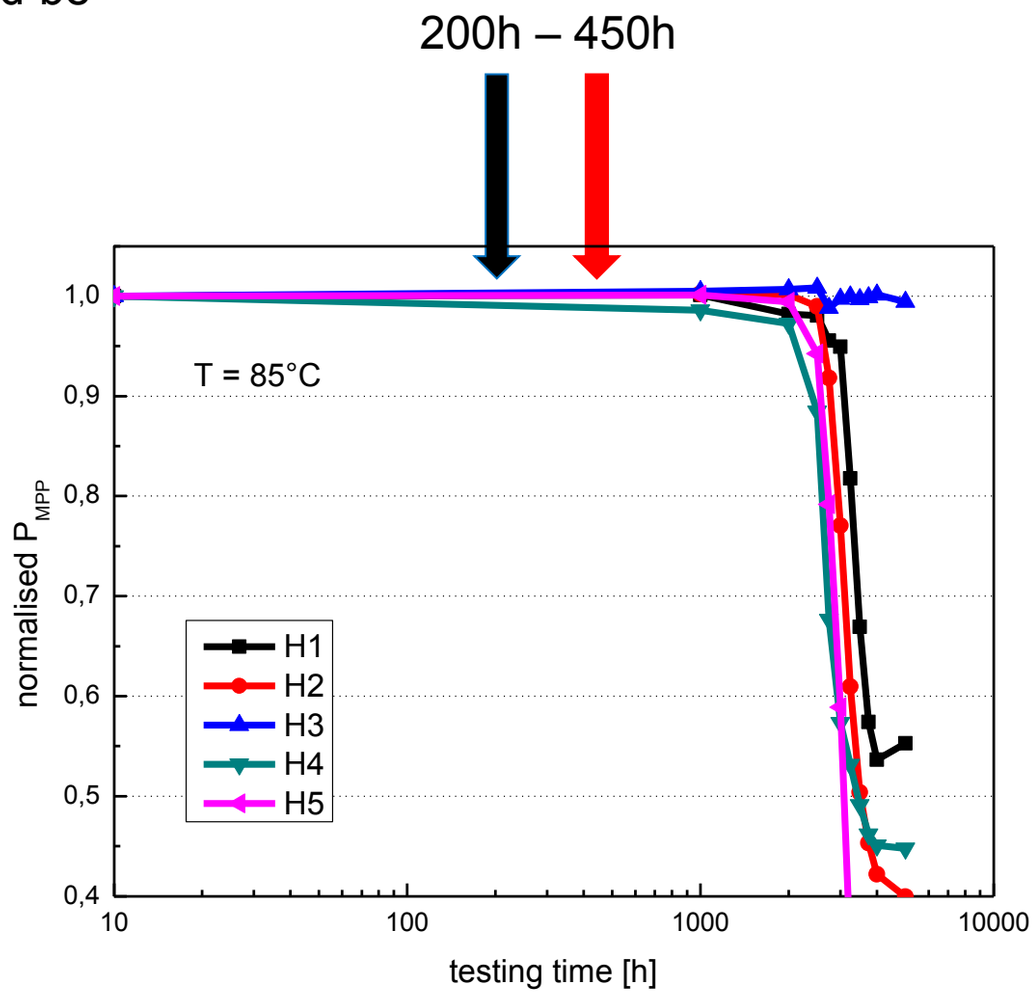
Modeling expected degradation for validation by outdoor exposure

Power reduction after 3 years outdoor exposure < 3%

Corresponding 85rh@85°C test for the tropical site would be 200h for 70kJ/mol and 450h for 55 kJ/mol





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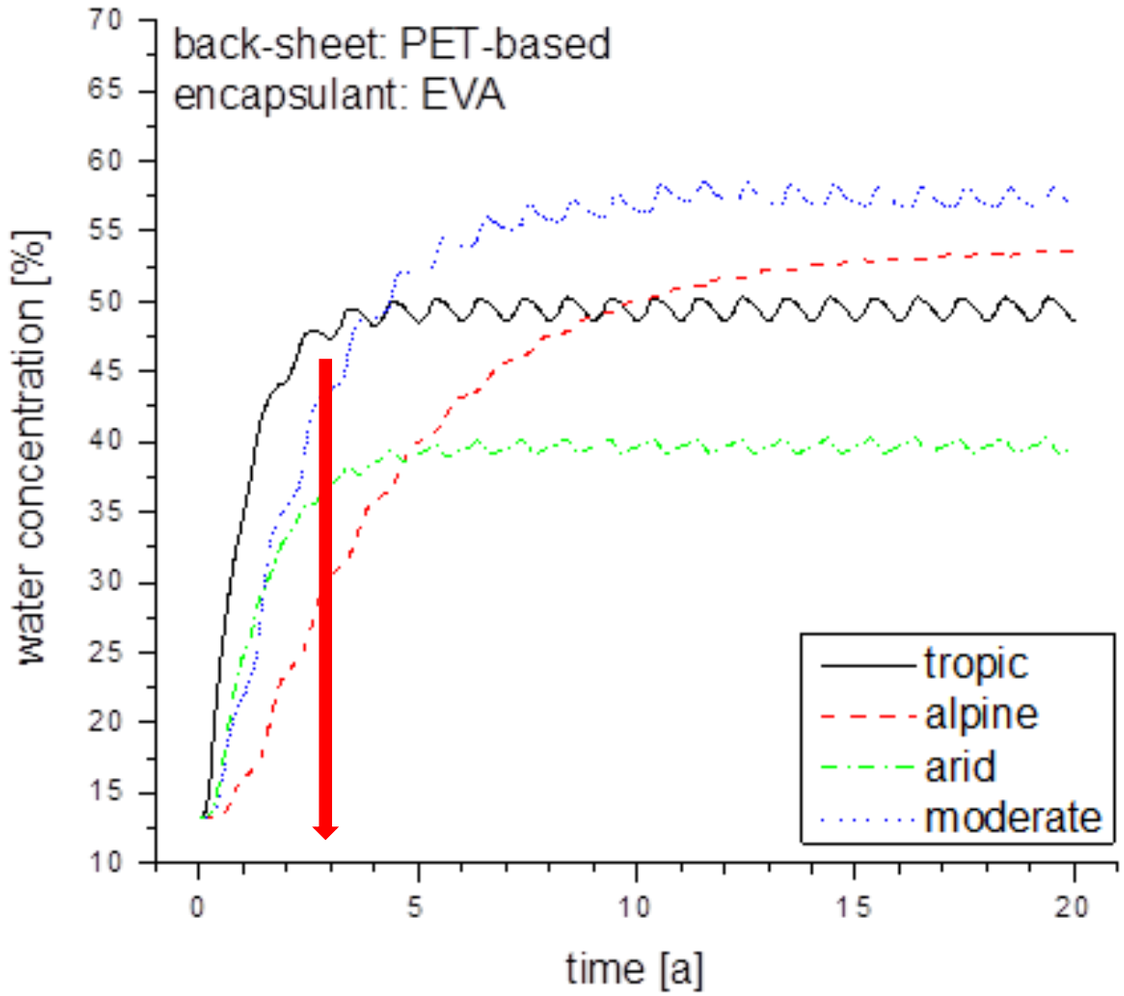
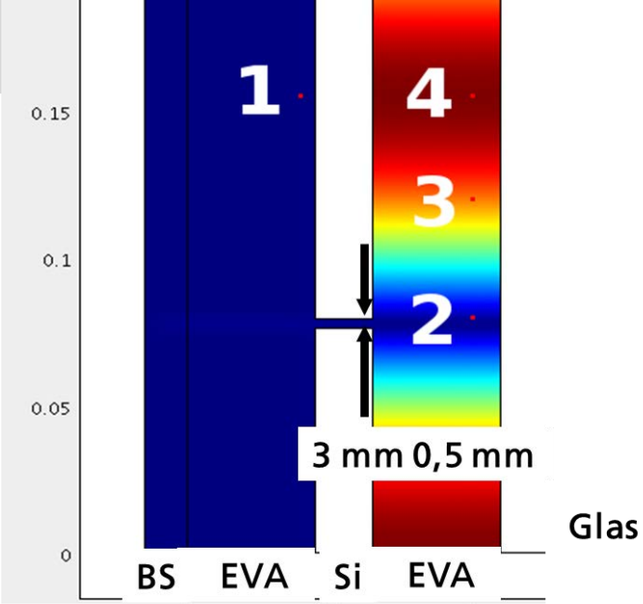
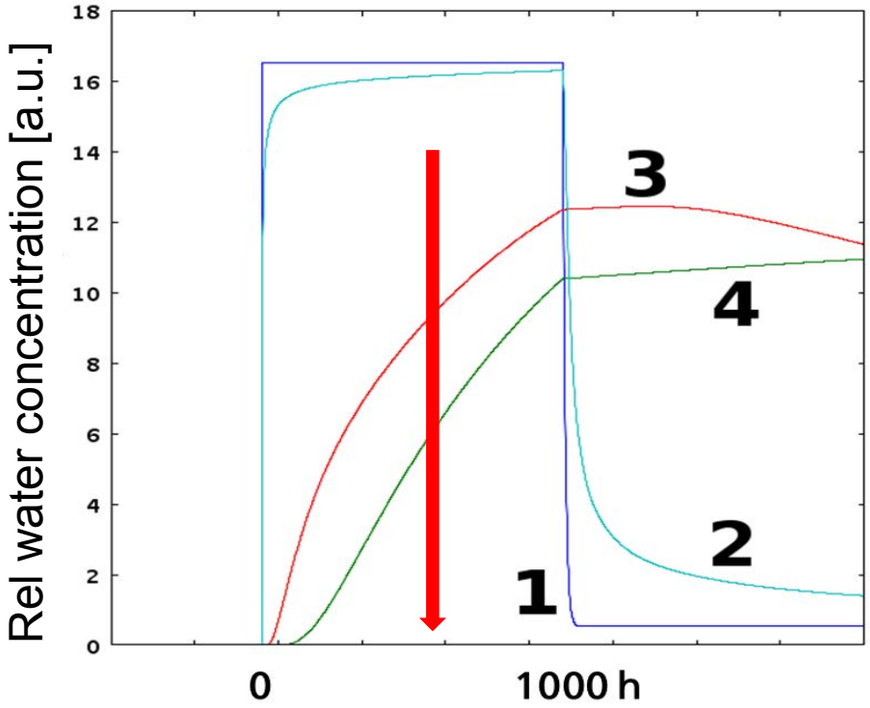
Modeling micro-climatic stress factors front-side

Simulation of module humidity by FEM based on measured temperature dependent permeation/diffusion coefficients







Damp-heat testing 85%rh @ 85°C

J. Wirth, Diploma Thesis, University of Freiburg, 2008.

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J. P. Hülsmann et al., "Simulation of Water Vapor Ingress into PV-Modules under Different Climatic Conditions," Journal of Materials, vol. 2013, doi:10.1155/2013/102691

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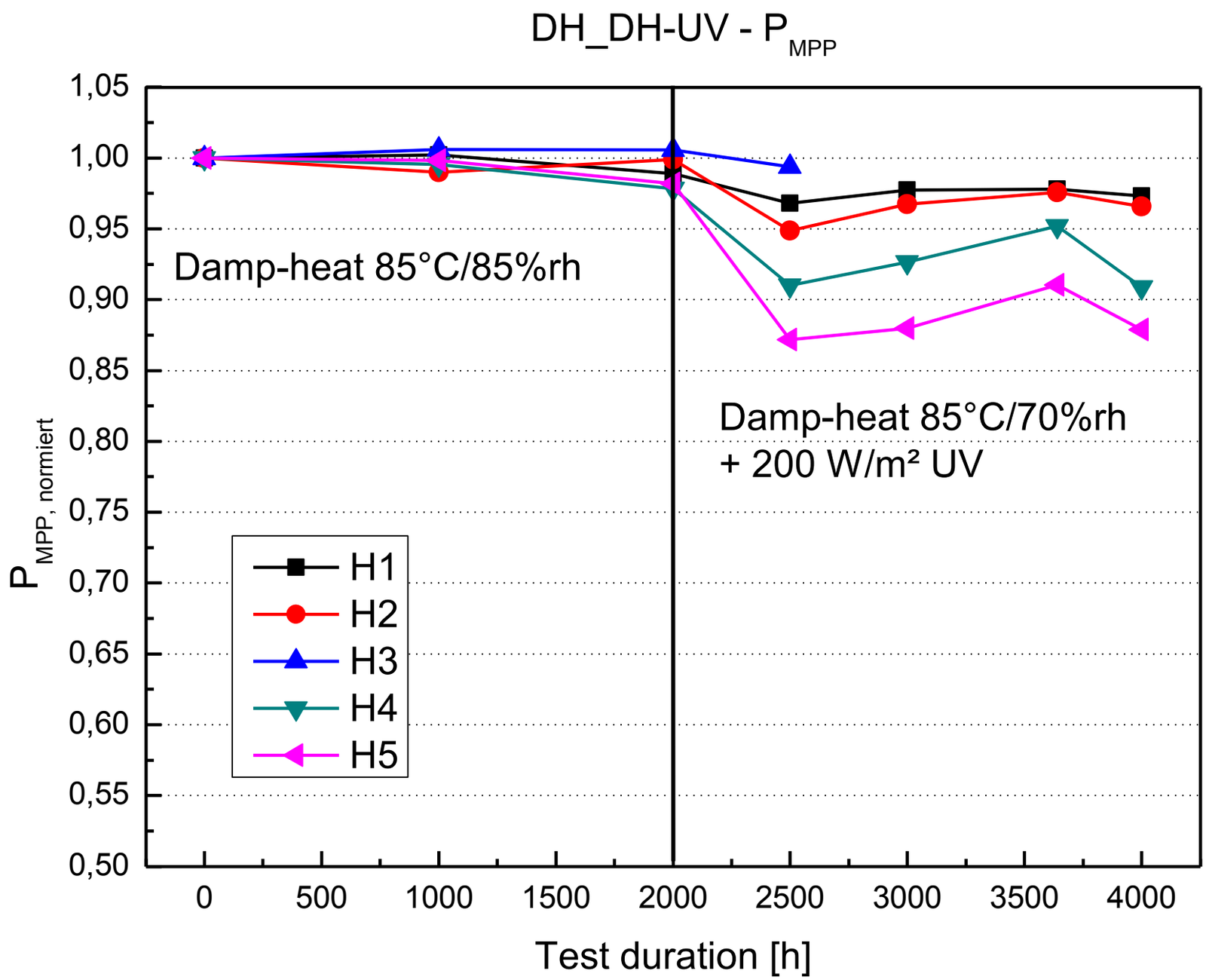

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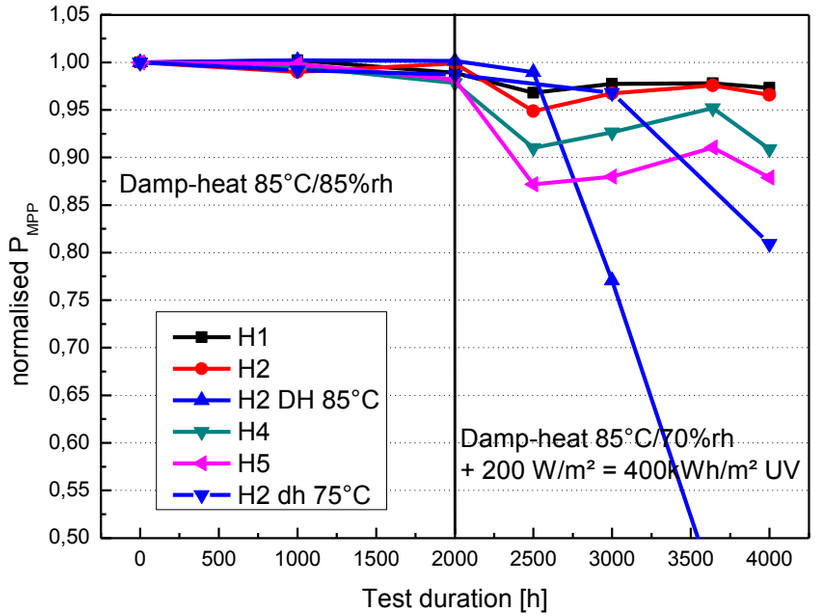
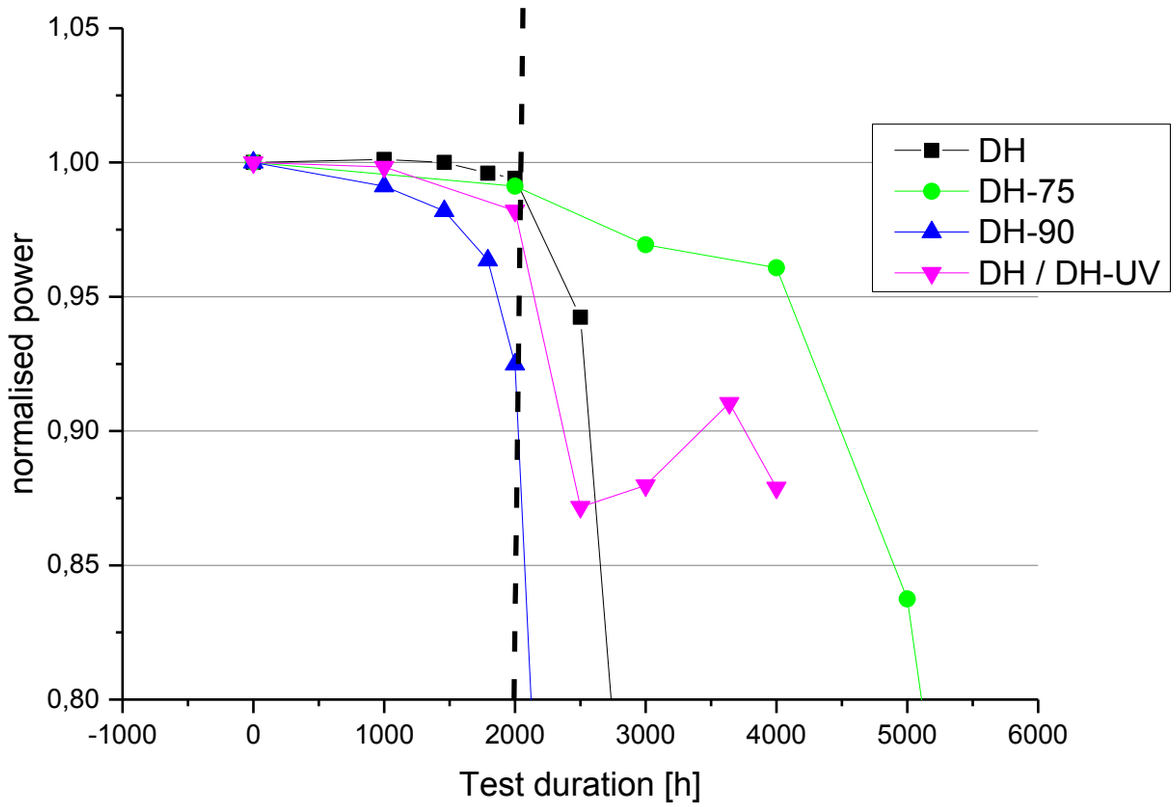


Is high humidity relevant?

Is irradiation healing?

Is constant load testing relevant?



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Thank you for your attention
Workshop to be continued:

SOPHIA Workshop PV-Module Reliability

June 3rd– June 4th, 2014, Freiburg (Germany)

From Type Approval to Accelerated Life Testing (ALT)

organized by Fraunhofer ISE (Michael Köhl) and JRC (Tony Sample)

www.pv-reliability.com

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European Commission

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POWERHOUSE™ DOW SOLAR

Development of reliable interconnect systems for photovoltaic modules

Abhijit Namjoshi, Dakai Ren, Lindsey Clark, Marty DeGroot, Rebekah Feist, Leonardo López

NREL PV Module Reliability Workshop

Feb 25 – 26, 2014

Golden, CO

Outline

Introduction

Problem statement

- Power degradation in reliability testing

Solution Approach

- Isolating the problem
- Understanding physics of failure
- Component level testing for process development
- Applying solution and validating improvements

Conclusions

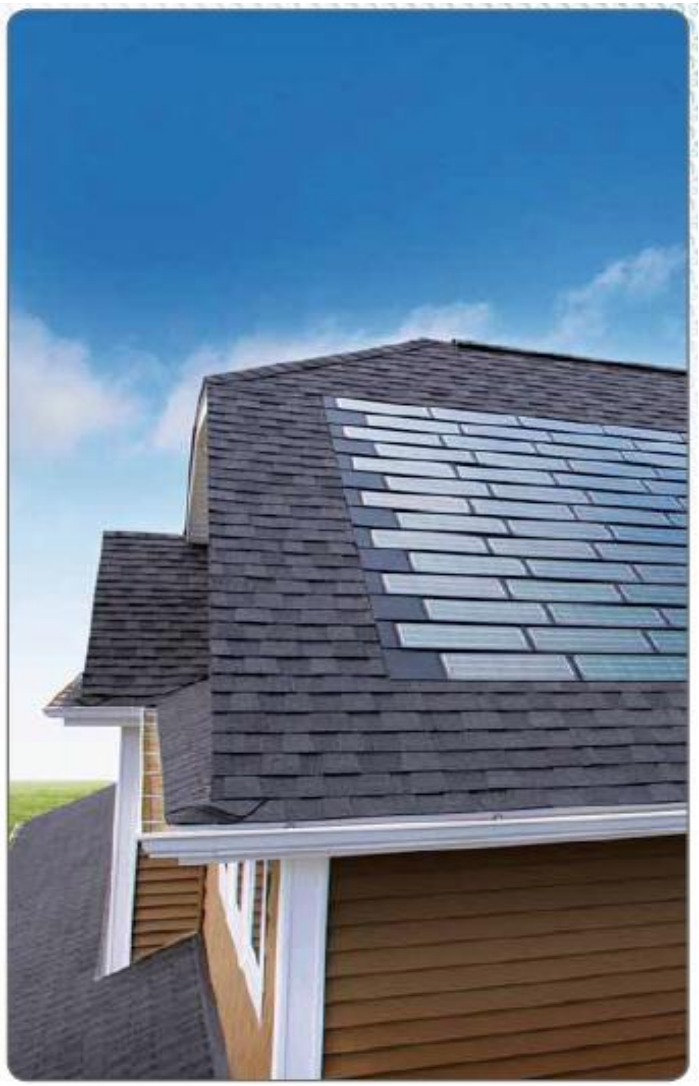
Introduction

Dow POWERHOUSE™ shingle – Reinventing the roof with unique BIPV product

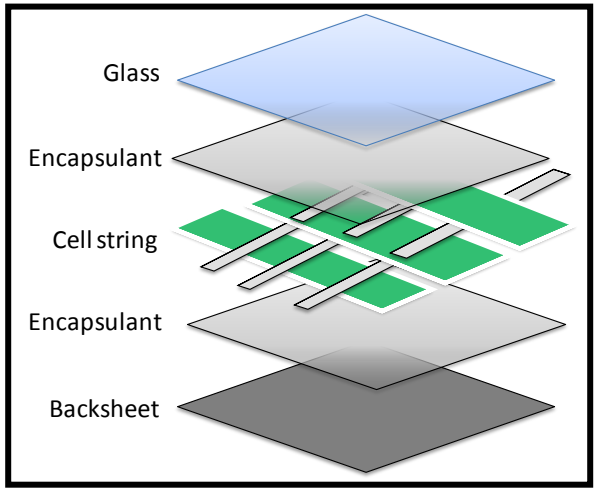
Safe, Durable and Reliable

Ease of Installation, aesthetically appealing

Empowering home owners with clean energy



Interaction between design and reliability performance

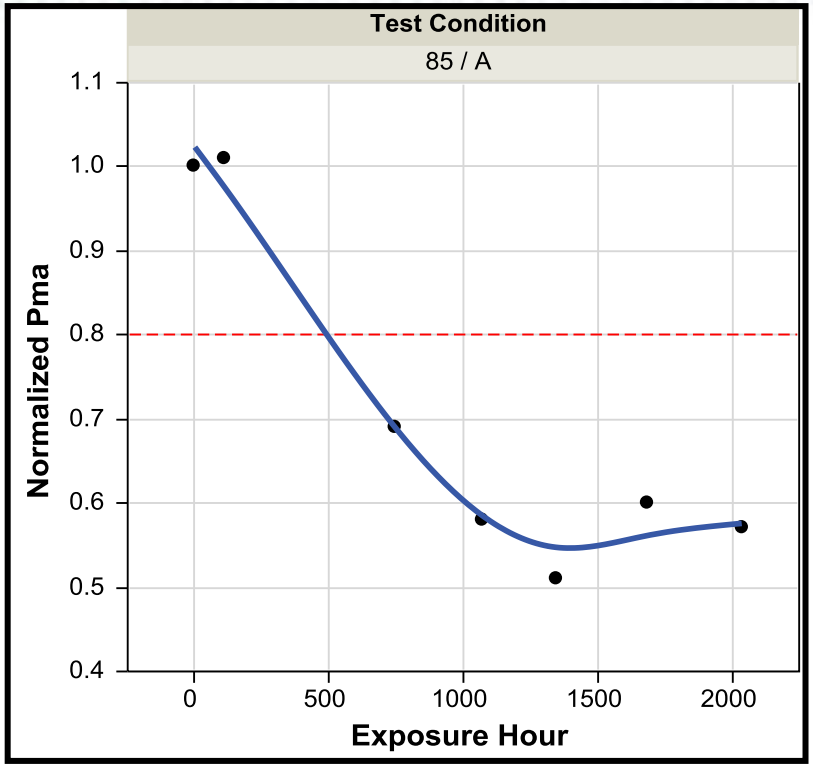


Design Considerations

Environmental Chambers
-Thermal Cycling
-Damp Heat
-Dry Heat etc.

Reliability Testing

Observed power degradation driven by Rs increase



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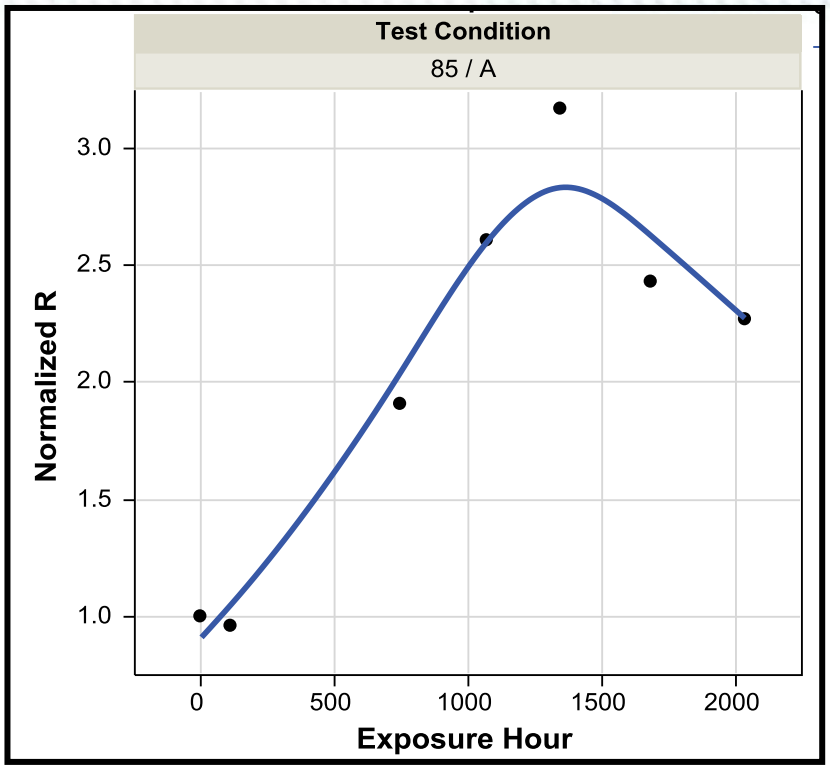
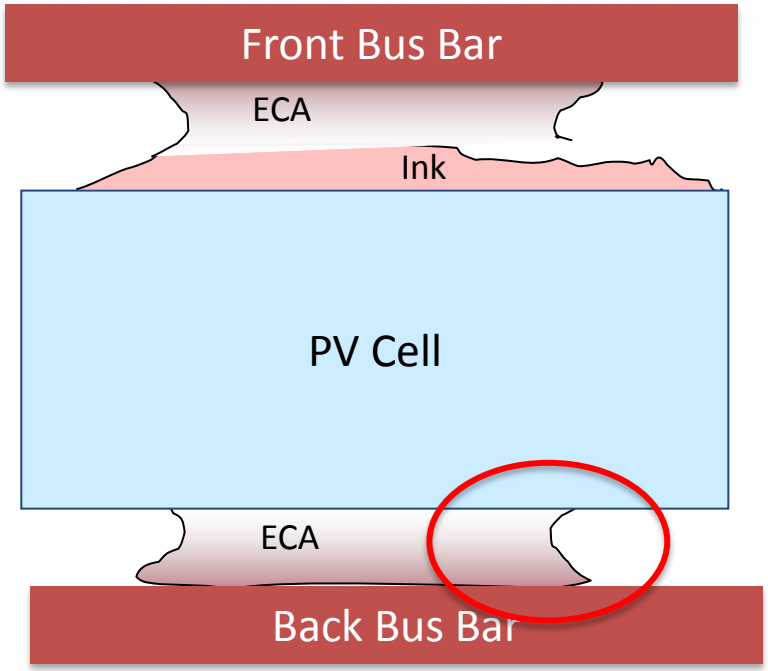


Location of Rs increase necessary to understand the problem

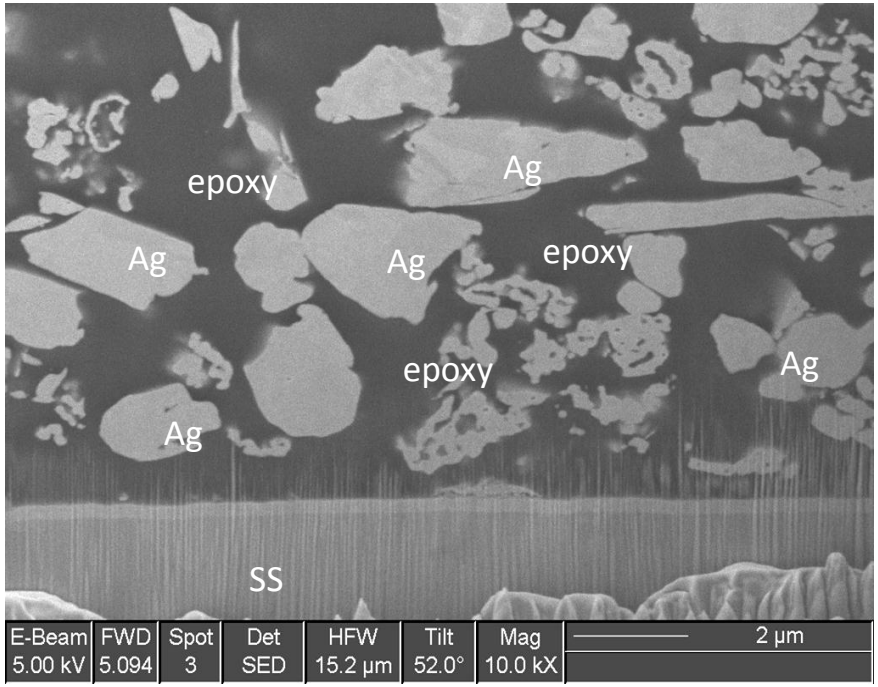
Several failure modes can contribute to Rs increase

- **Cell**
  - Junction
  - TCO
- **Interconnect**
  - ECA
  - Ink
- **Interfaces**
  - Front Bus – ECA
  - ECA – Ink
  - Ink – TCO
  - Within Cell
  - Cell back – ECA
  - ECA – Back Bus

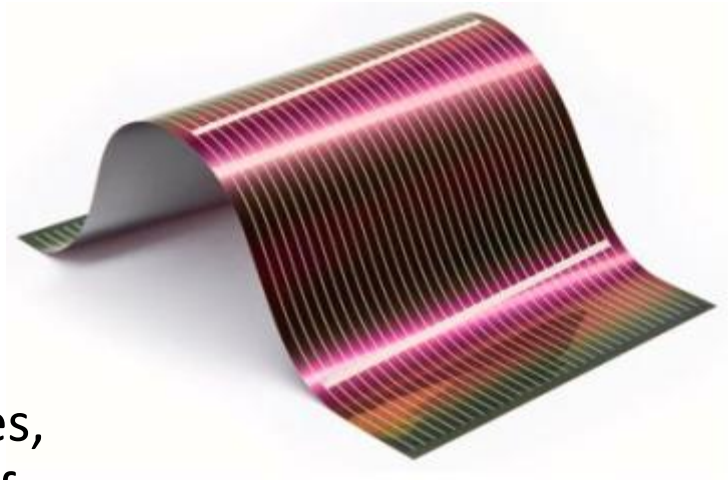


Component level testing helped identify back contact degradation as root cause

Electrically Conductive Adhesive (ECA)



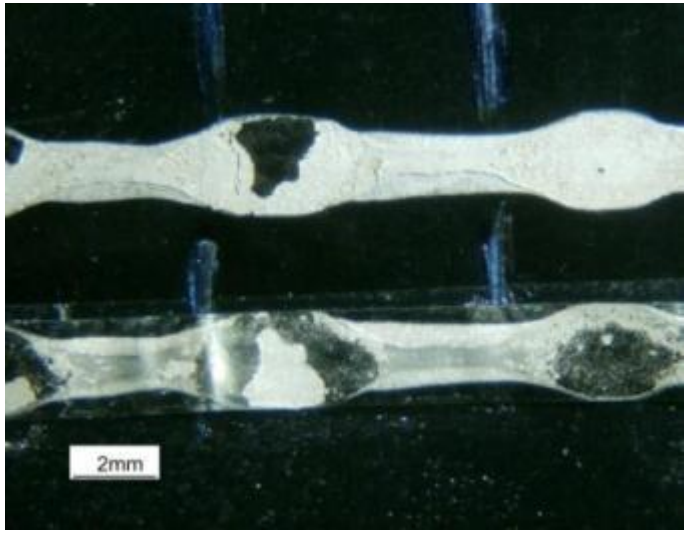
- Epoxy resin with more than 70 wt% silver flakes
- Provides mechanical bonding and conductive path
- Properties readily tailored



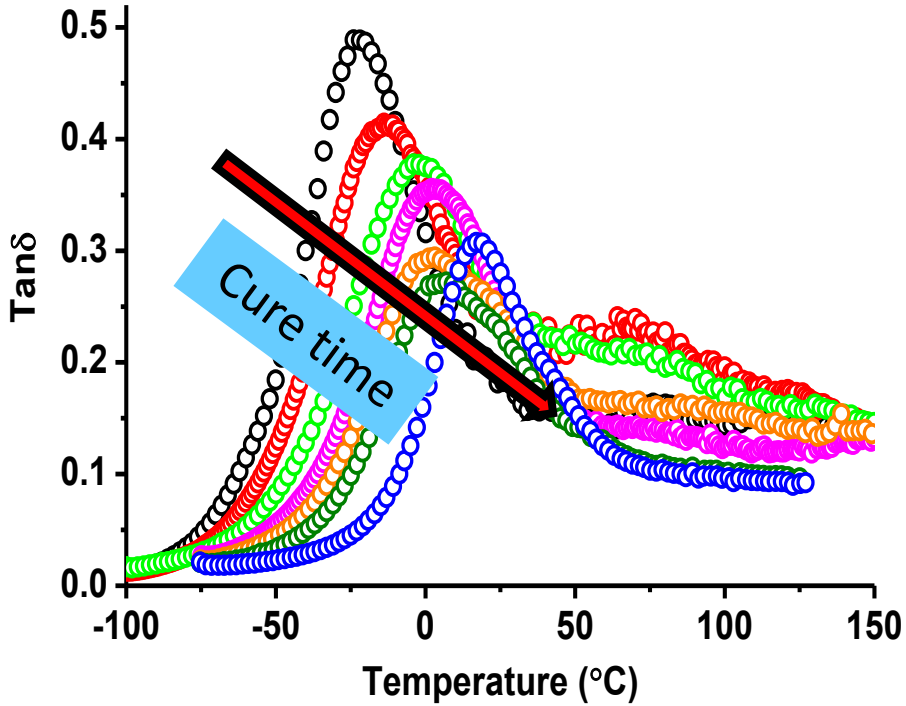
ECA selection considerations: product and process attributes, such as substrate surfaces, curing conditions, stresses, reliability, ease of dispense…

Used multi-pronged approach for issue resolution

- **Material Properties**
  - ECA selection
  - Surface treatment
- **Process Parameters**
  - ECA coverage
  - ECA cure
  - Bondline thickness
- **Performance Measurement**
  - Power & resistance measurement
  - Failure Analysis
  - Mechanical Testing
  - Environment aging



Established technique for *in situ* cure estimation



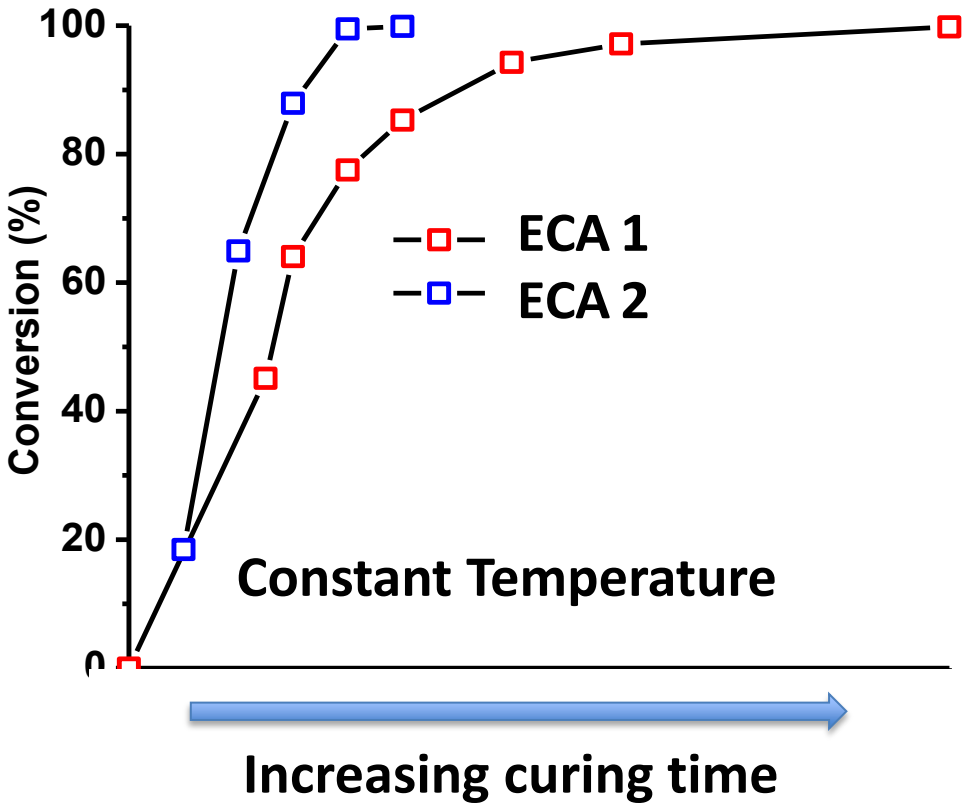
Torsional Dynamic Mechanical Analysis

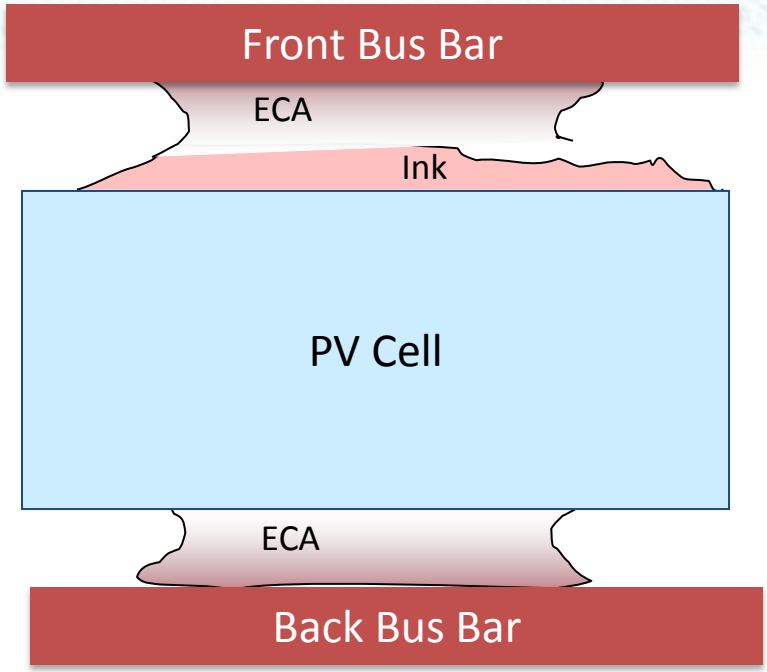
Developed DMA based techniques to understand evolution of ECA curing vs. process conditions

"Glass transition temperature as an *in situ* cure index of electrically conductive adhesives in solar photovoltaic module interconnect assemblies", Dakai Ren et al., Solar Energy Materials & Solar Cells 107 (2012) 403 - 406

ECA can be optimized differently for top / bottom

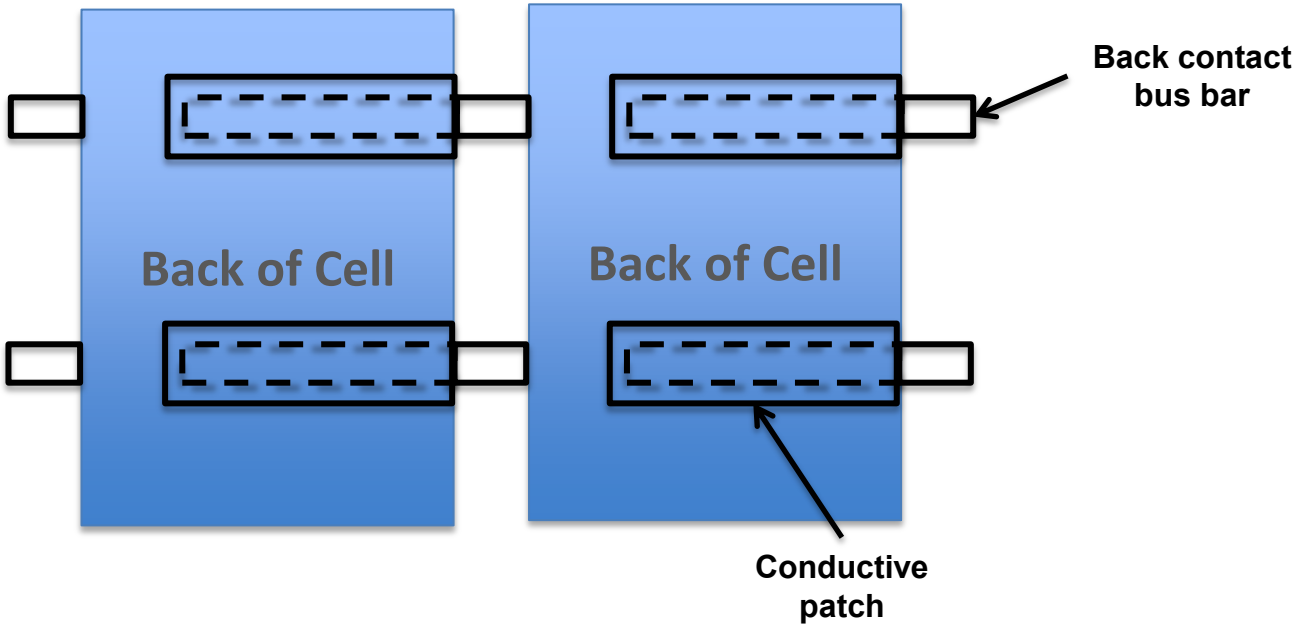
Need to optimize cure conditions





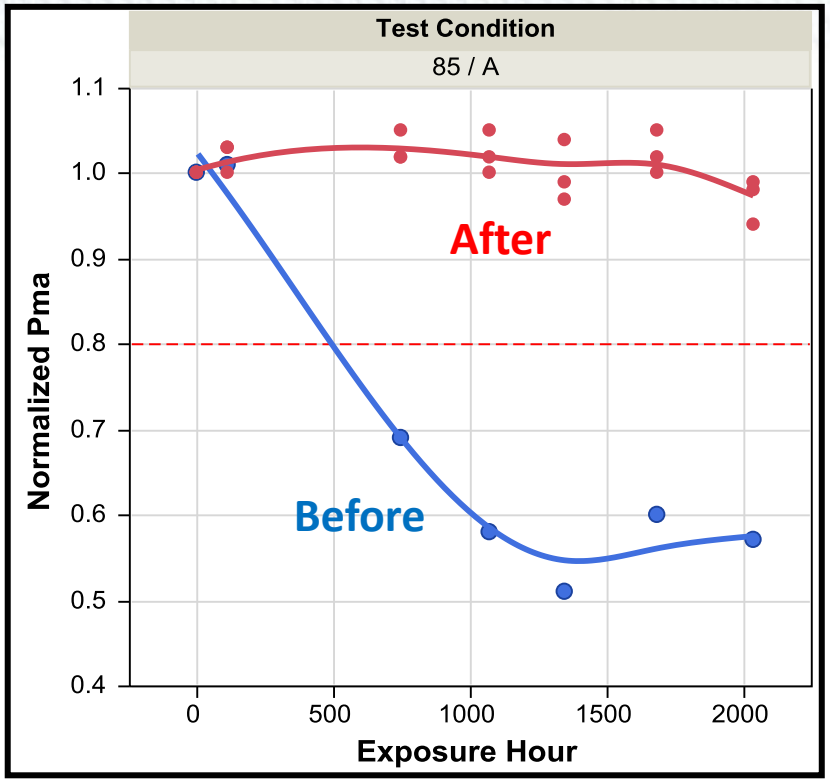
Challenge: balance the cure temperature profile for even cure performance

Conductive patch added on back of the back ribbon



Added “layer of protection” to minimize back contact degradation

Conductive fixes improve power performance



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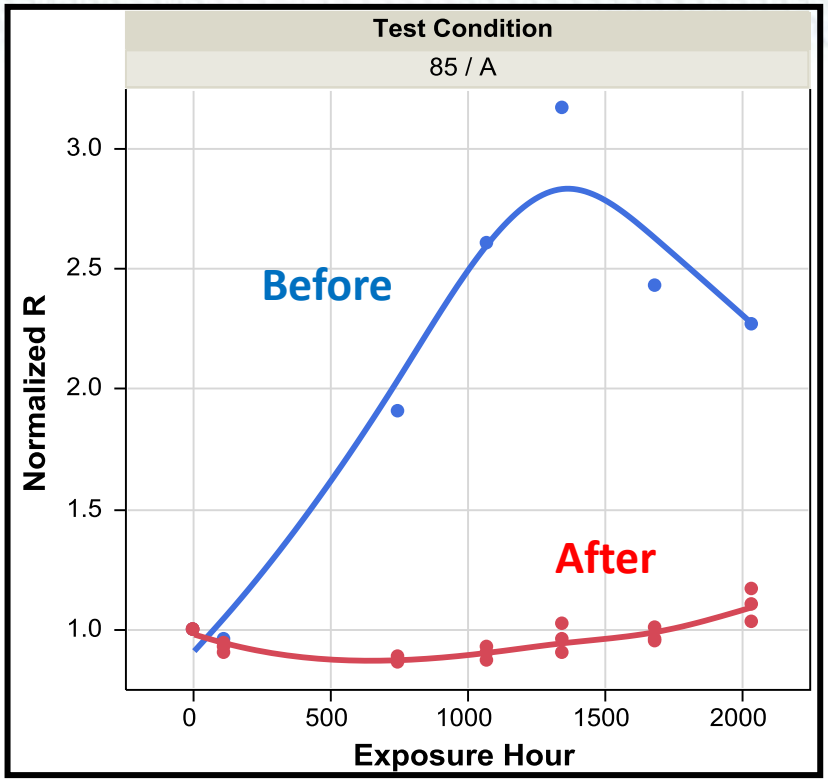


Stable power performance Pmax reflected in stable series resistance Rs

Conclusions

Technical:

Selection of appropriate ECA for performance is important

ECA cure important for performance… especially reliability

ECA adhesion important for reliability performance

Conductive fixes improved reliability performance

Problem solving:

Reliability demonstration takes time… start early

Proper isolation of problem location critical to narrow scope of investigation

Component level testing can accelerate mechanism identification

Understanding physics of failure key to improve reliability performance

Broadened thinking needed for timely "out of the box" solutions

Adhesion and Debonding Kinetics in PV Devices and Modules

Chris Bruner, Stéphanie Dupont, Ryan Brock (PV active layers)
Fernando Novoa, Warren Cui (encapsulation and optics)
Scott Isaacson, Tissa Mirfakhrai (ultra barrier films)

Reinhold H. Dauskardt (dauskardt@stanford.edu)

Adhesion and Debonding Kinetics in PV Devices and Modules

Collaborators:

Stephen Eglash / Stanford

David Miller and Sarah Kurtz / NREL

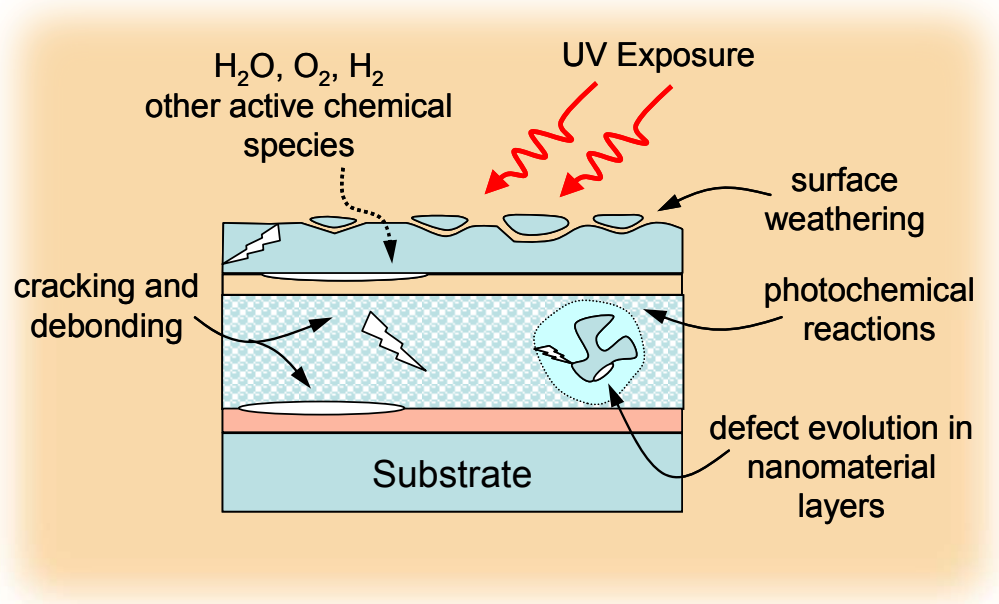
Mike Wiemer, Taner Bilir and Homan Yuen / Solar Junction

Peter Hebert and Jim Ermer / Spectrolab (Boeing)

Support:

DoE support through the Bay Area PV Consortium, Predicts CPV program through SunShot, and the CAMP-KAUST center.

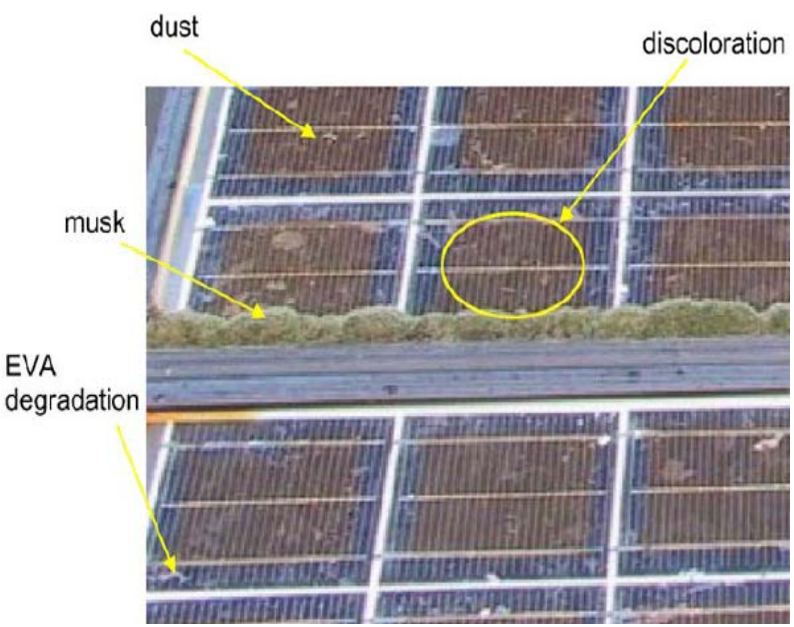
Degradation and Reliability of PV Devices and Modules



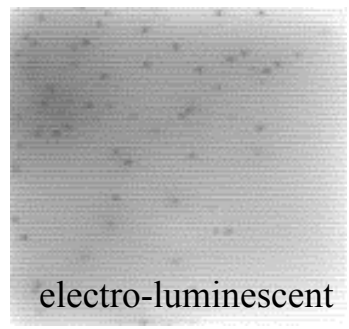
Severe operating environments:

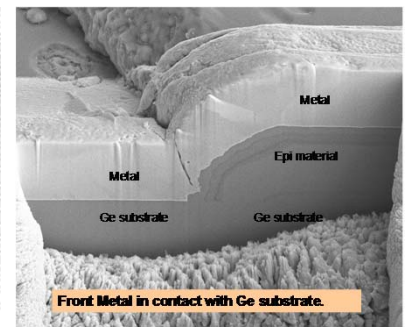
Thermal cycling, stress, moisture, chemically active environmental species, and solar UV.

Uncertain degradation kinetics and reliability models.



defects in semi-conductor layers





peeling metallized grids after thermal cycling

Device Reliability and Evolution of Defects

damage propagates if mechanical stresses are large enough so that

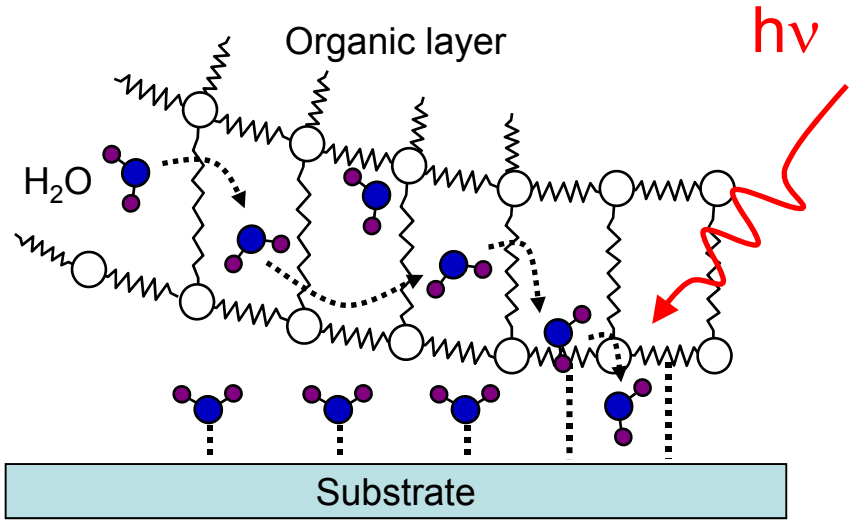
mechanical "driving force" $G \geq G_c \left[J / m^2 \right]$ *cohesion or adhesion*

presence of chemical species and photons, damage propagates even if

$G < G_c \left[J / m^2 \right]$ *environment and stress accelerates defect evolution*

Role of coupled "stress" parameters:

- *mechanical stress*
- *temperature*
- *environmental species*
- *photons (photochemical reactions)*



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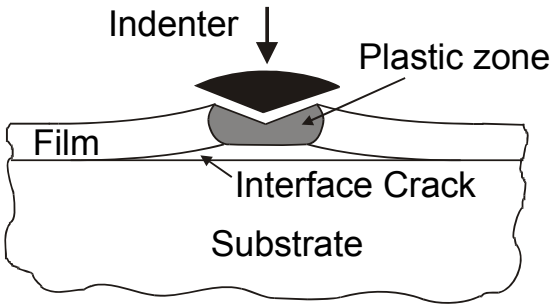
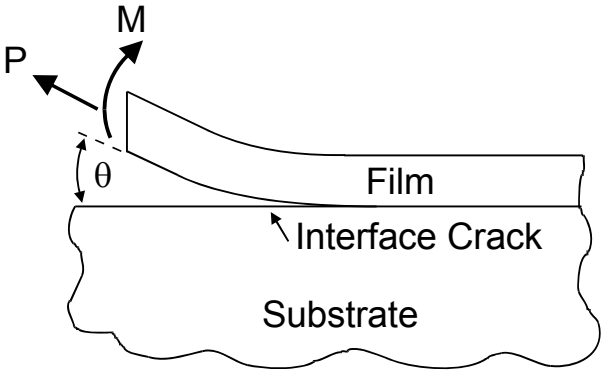
Limitations of Thin-Film Adhesion Tests

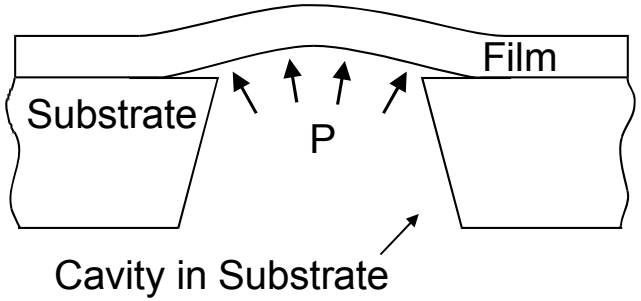
- Indentation/Scratch Test
  - complex stress and deformation fields
  - principally qualitative results
  - (nano) scratch test even less quantitative



- Peel/m-ELT Test
  - difficult to apply loads
  - plastic deformation of film
  - temperature complications in m-ELT



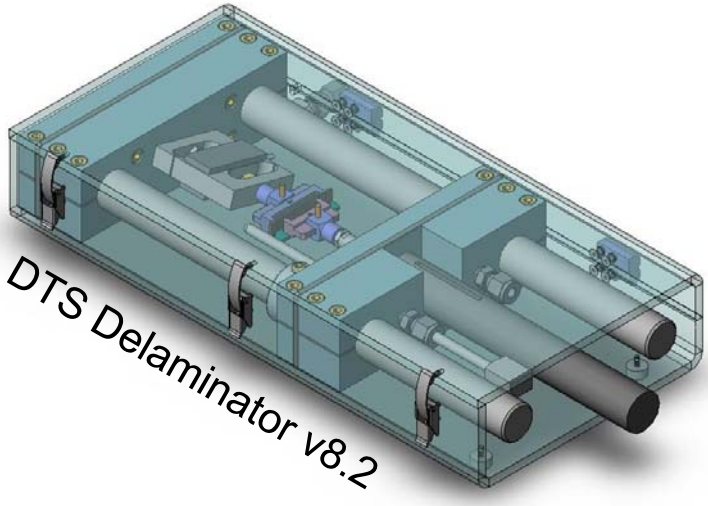
- Blister Test
  - compliant loading system
  - environmental effects
  - etching/machining of cavity difficult

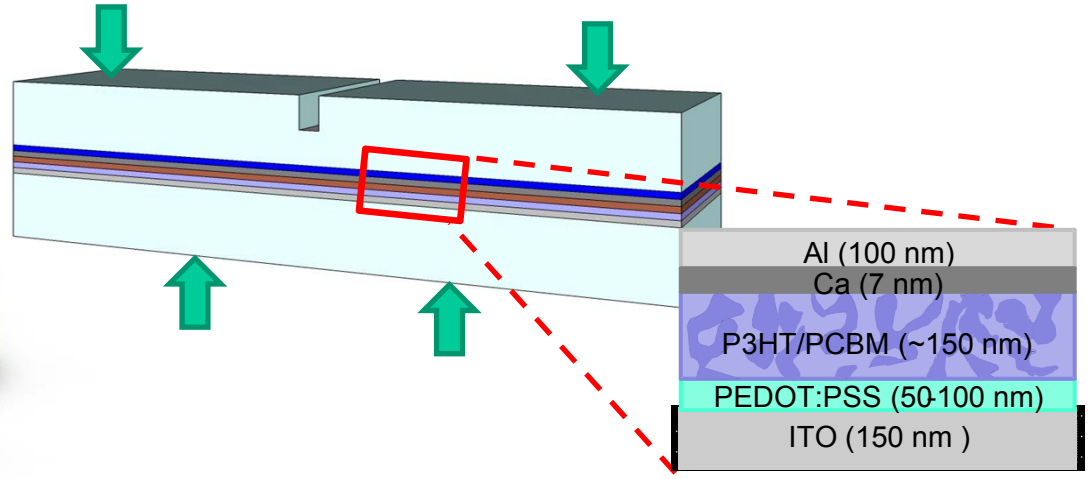


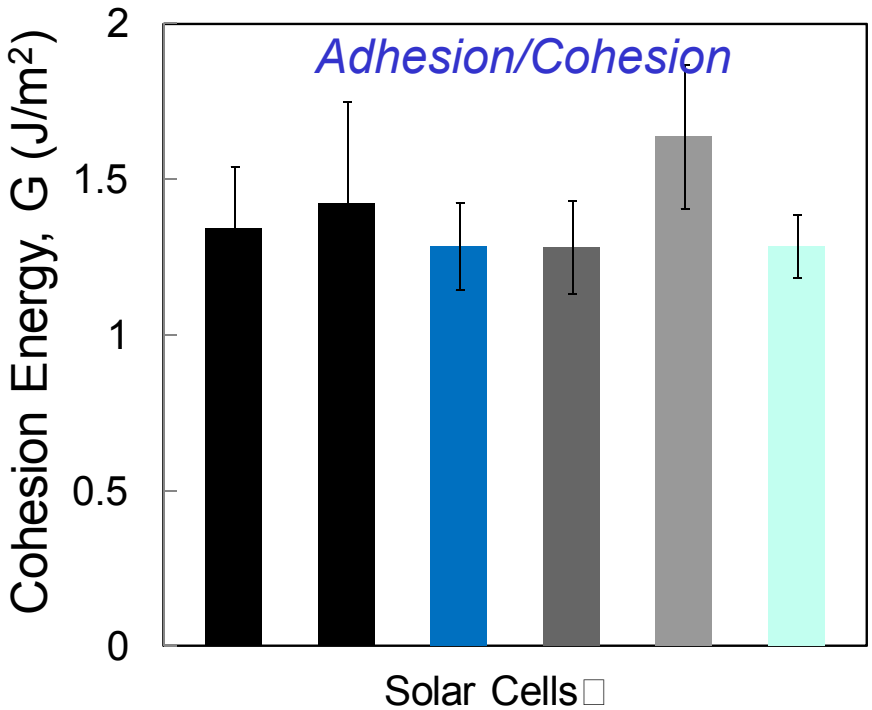
Major limitations: need detailed film properties, film stress relaxation and film plasticity

$\Rightarrow$ principally qualitative results for all above methods!

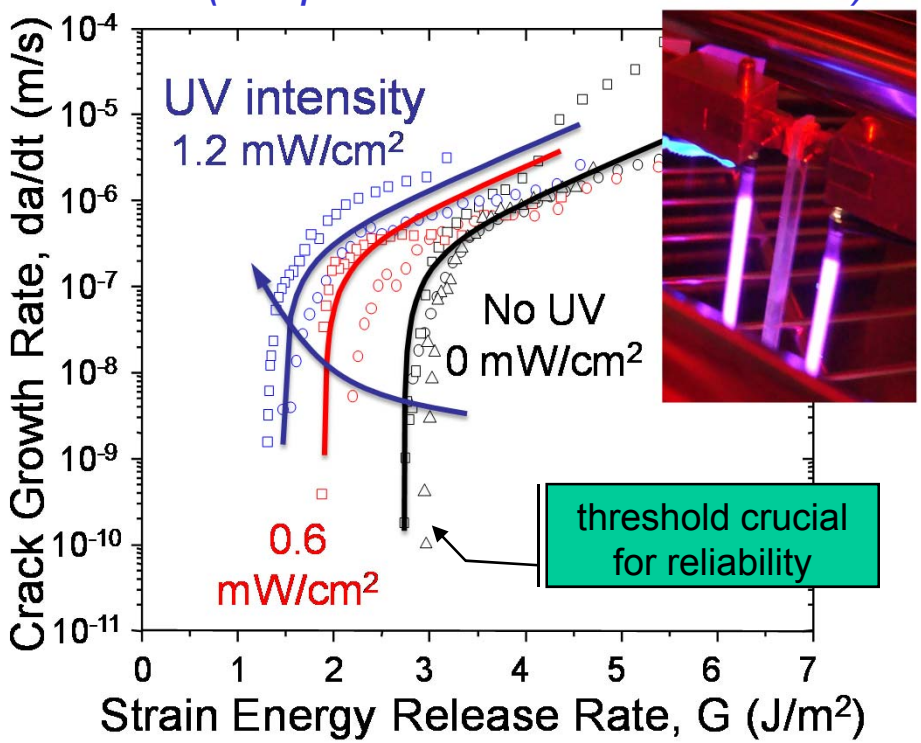
Quantitative Adhesion/Cohesion and Debond Kinetics







Degradation Kinetics
(temp/environment /UV effects)

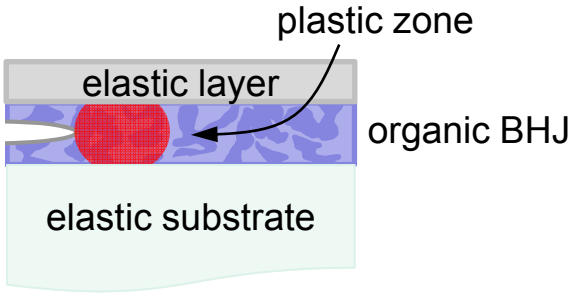


Outline

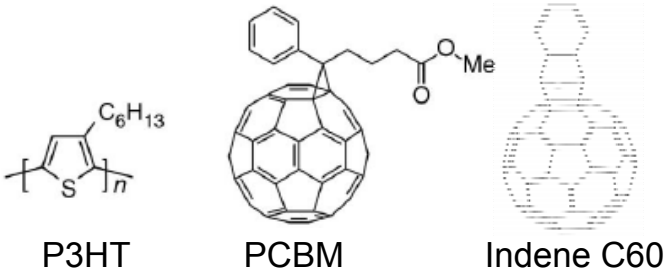
- Inherent Solar Cell Thermo-Mechanical Reliability
  - polymer / PCBM BHJ type devices
  - adhesion and cohesion properties in flexible systems
- Encapsulant and Ultra-barriers in Solar Modules
  - synergistic effects of multiple “stressing parameters”
  - kinetics and lifetimes

Factors Effecting Cohesion of BHJ Layers

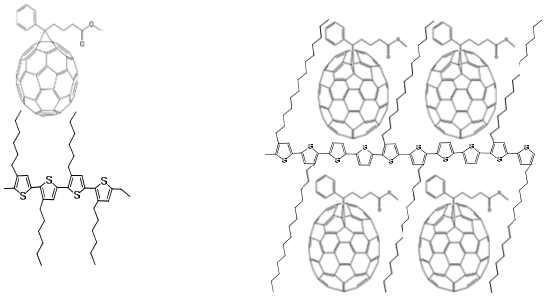
- Heterojunction layer thickness
  - is cohesion in organic layers sensitive to layer thickness?



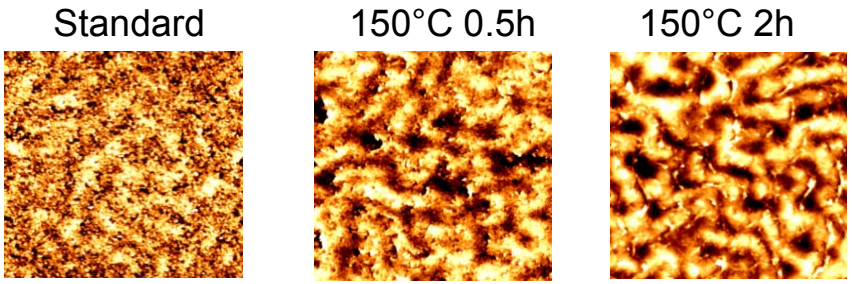
- Composition of the heterojunction layer
  - limited bonding to fullerene
  - polymer/PCBM ratio makes stronger layer



- Molecular intercalation
  - manipulating the types of intermolecular interactions



- Annealing
  - morphology of the BHJ layer changes with annealing



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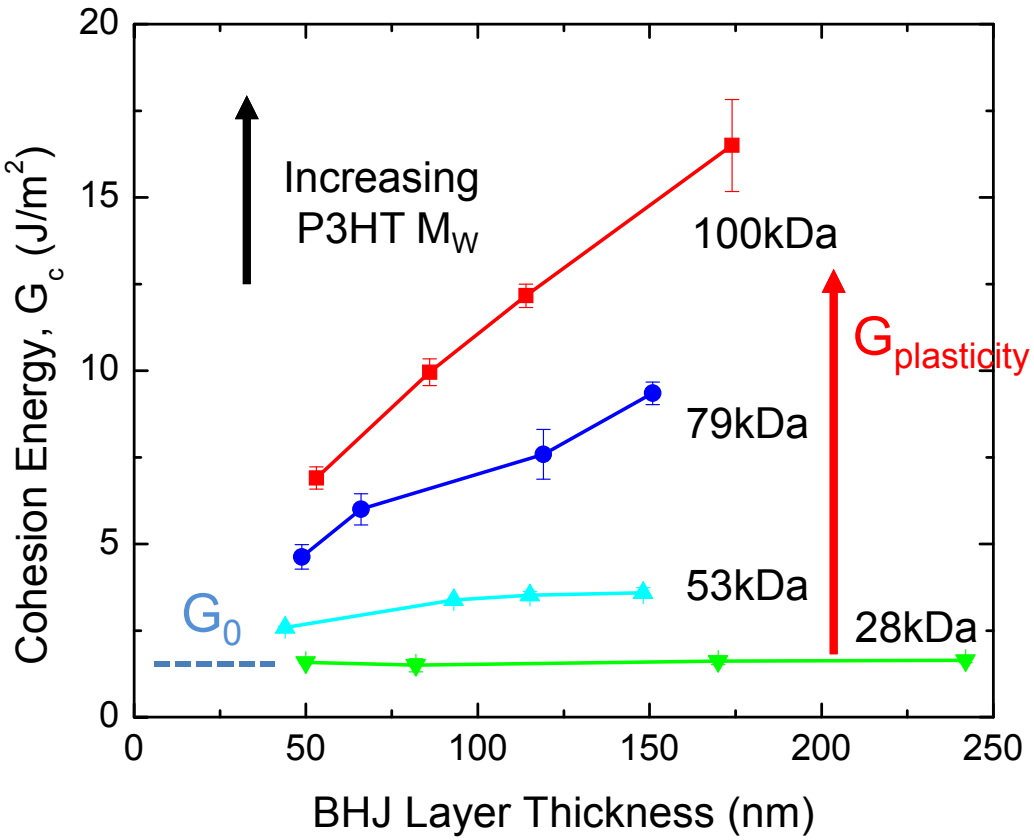
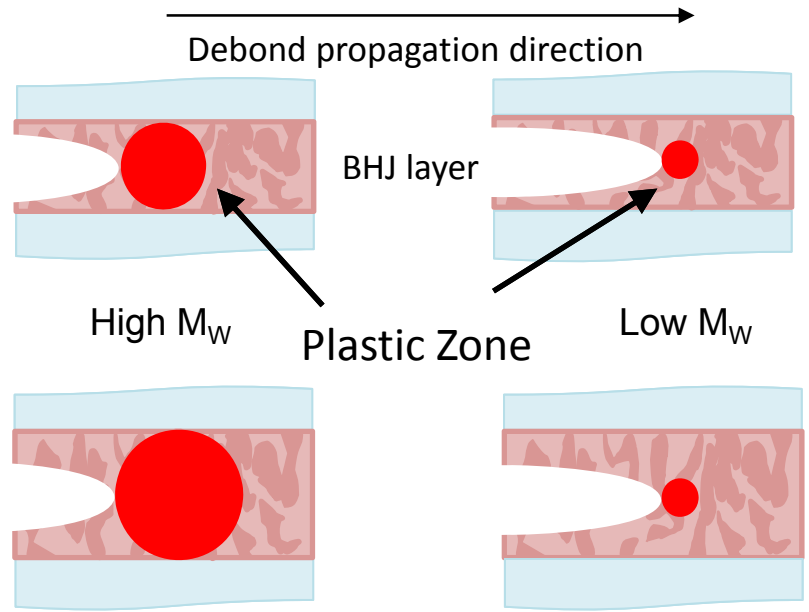
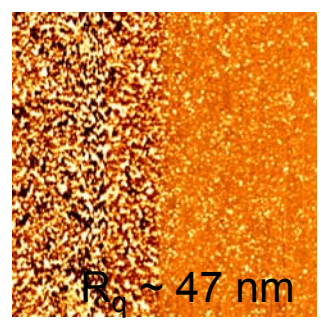
BHJ Layer cohesion w/ P3HT M_W



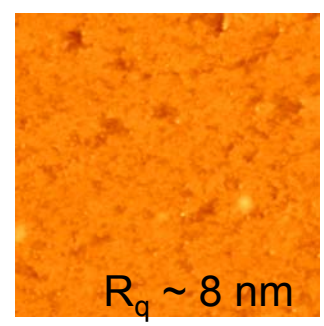
$$G_C = G_0 + G_{plasticity}$$



100 kDa P3HT



28 kDa P3HT

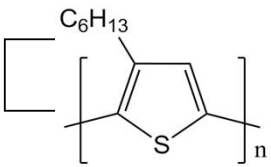


M_W increases cohesion energy significantly

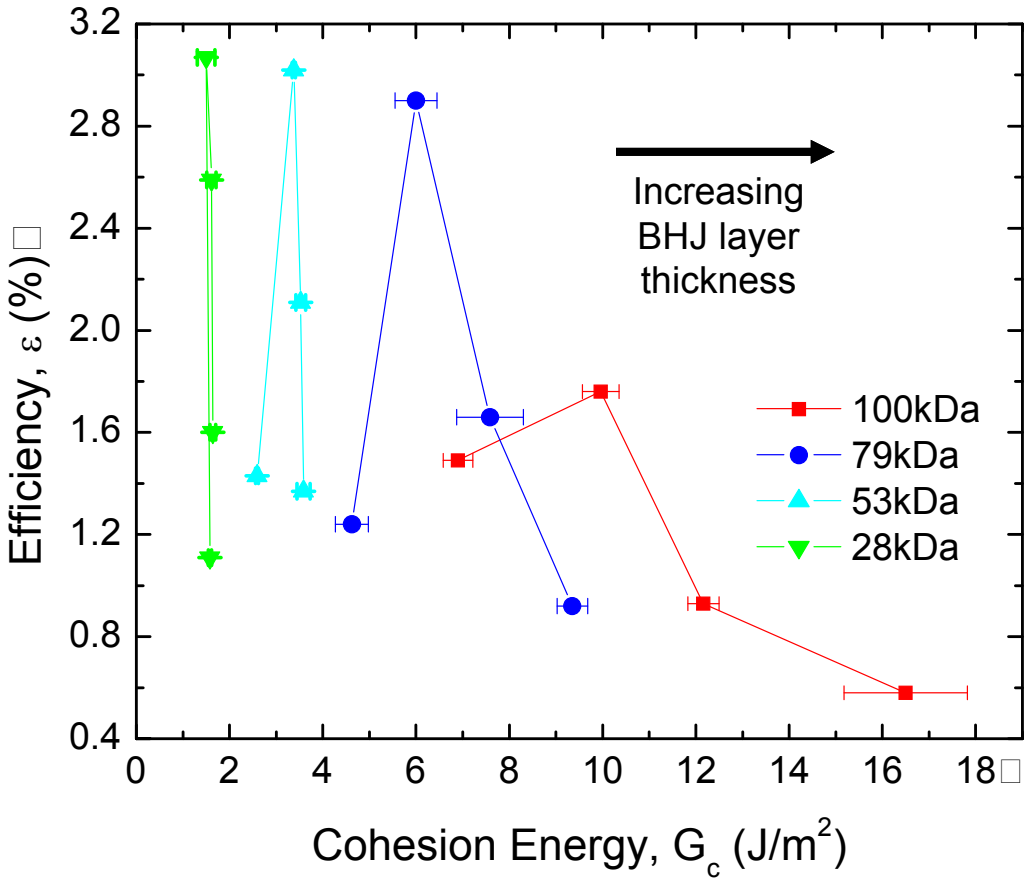
- increased inter-chain entanglement/bridging
- larger polymer domains as polymers fold

Rising slope with thickness due to plasticity

Efficiency vs. Cohesion



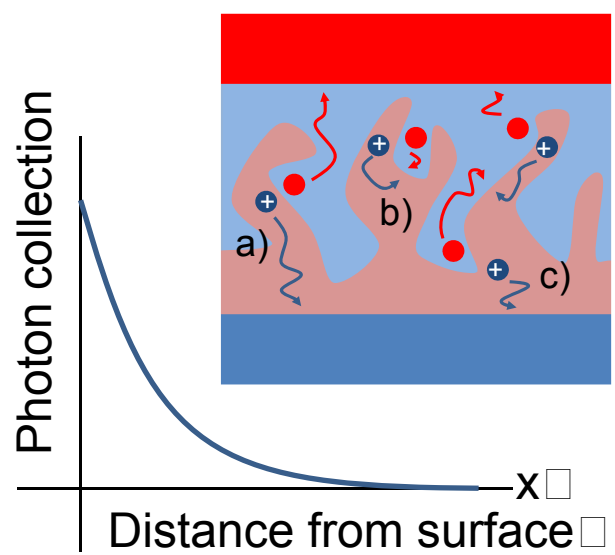
P3HT



$$\varepsilon = \frac{V_{oc} J_{sc} FF}{P_{in}}$$

Thin BHJ layer - low efficiency due to lower photon harvesting

Thicker BHJ layer - greater degree of charge carrier recombination

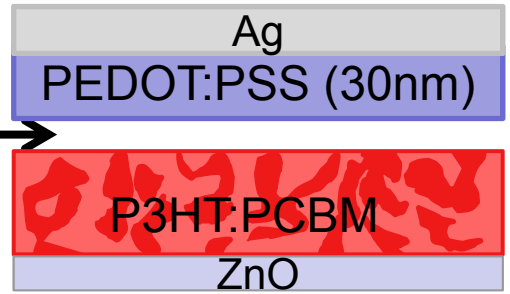


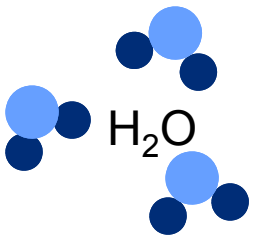
Synergistic Effects on Decohesion Kinetics

Inert Environment

$G \geq G_c$

adhesive failure

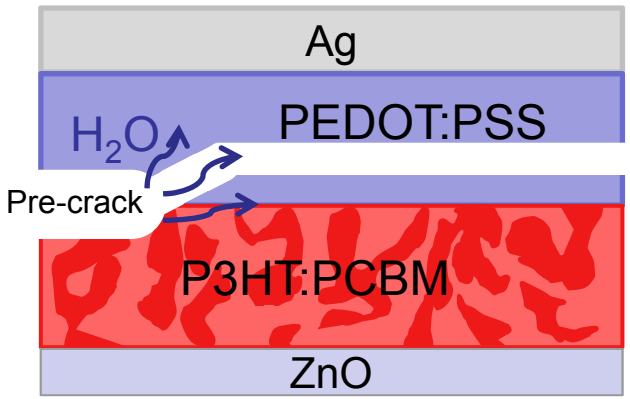


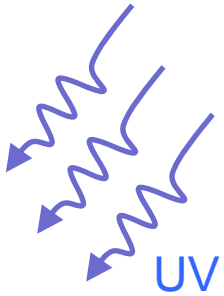


Effect of Moisture

$G < G_{cc}$

cohesive in PEDOT:PSS

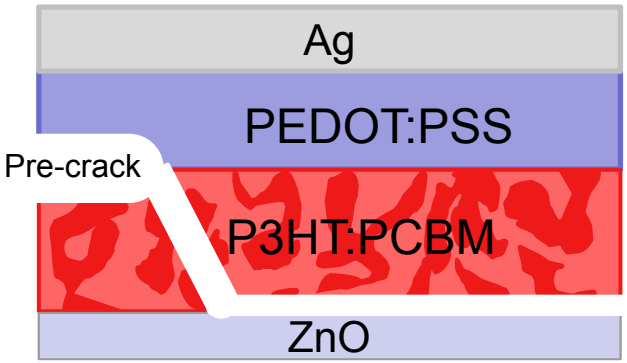




Effect of In-Situ UVB

$G < G_{cc}$

cohesive in P3HT:PCBM
adhesive at the ZnO interface



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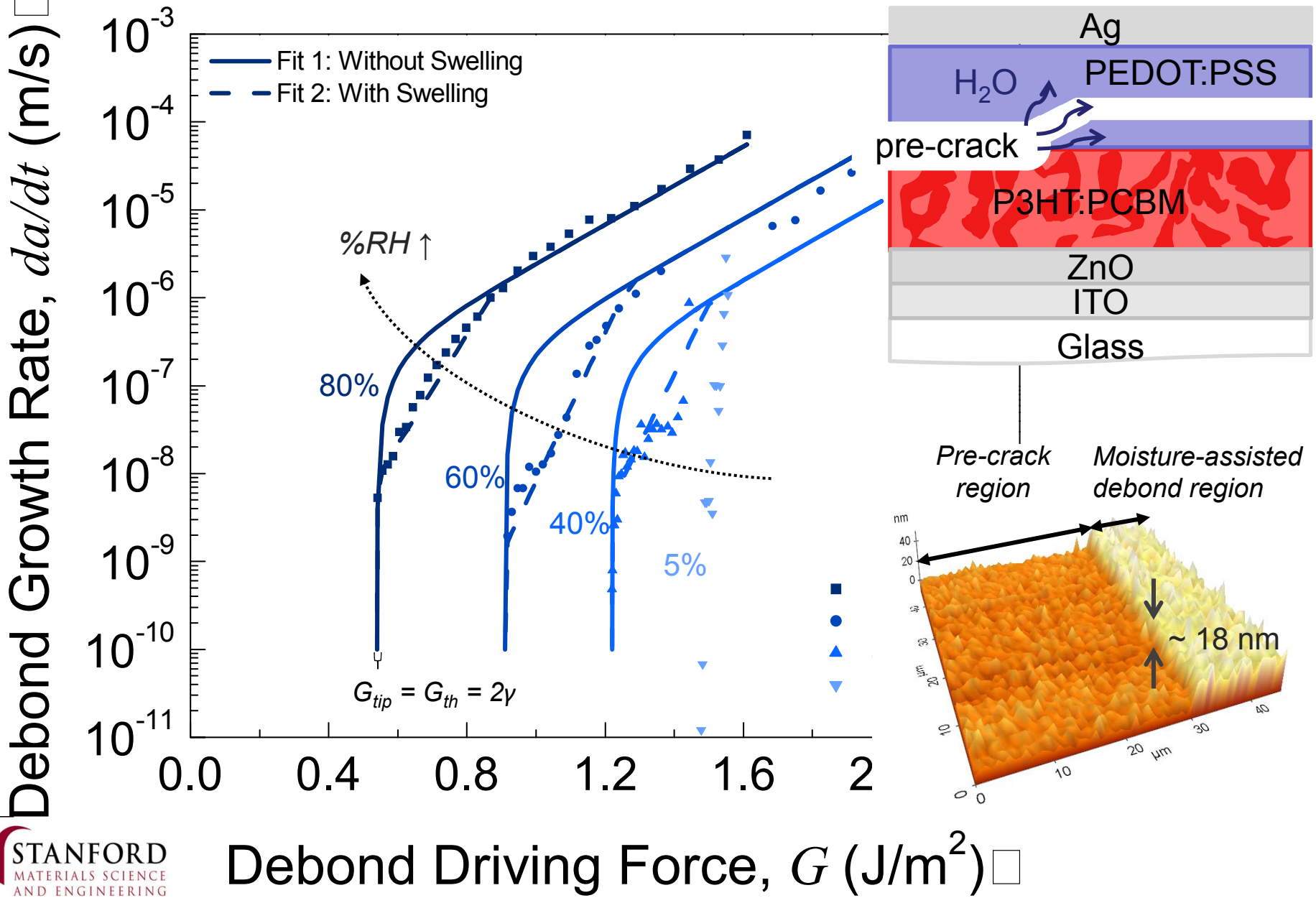
Decohesion of PEDO:PSS Transparent Electrodes



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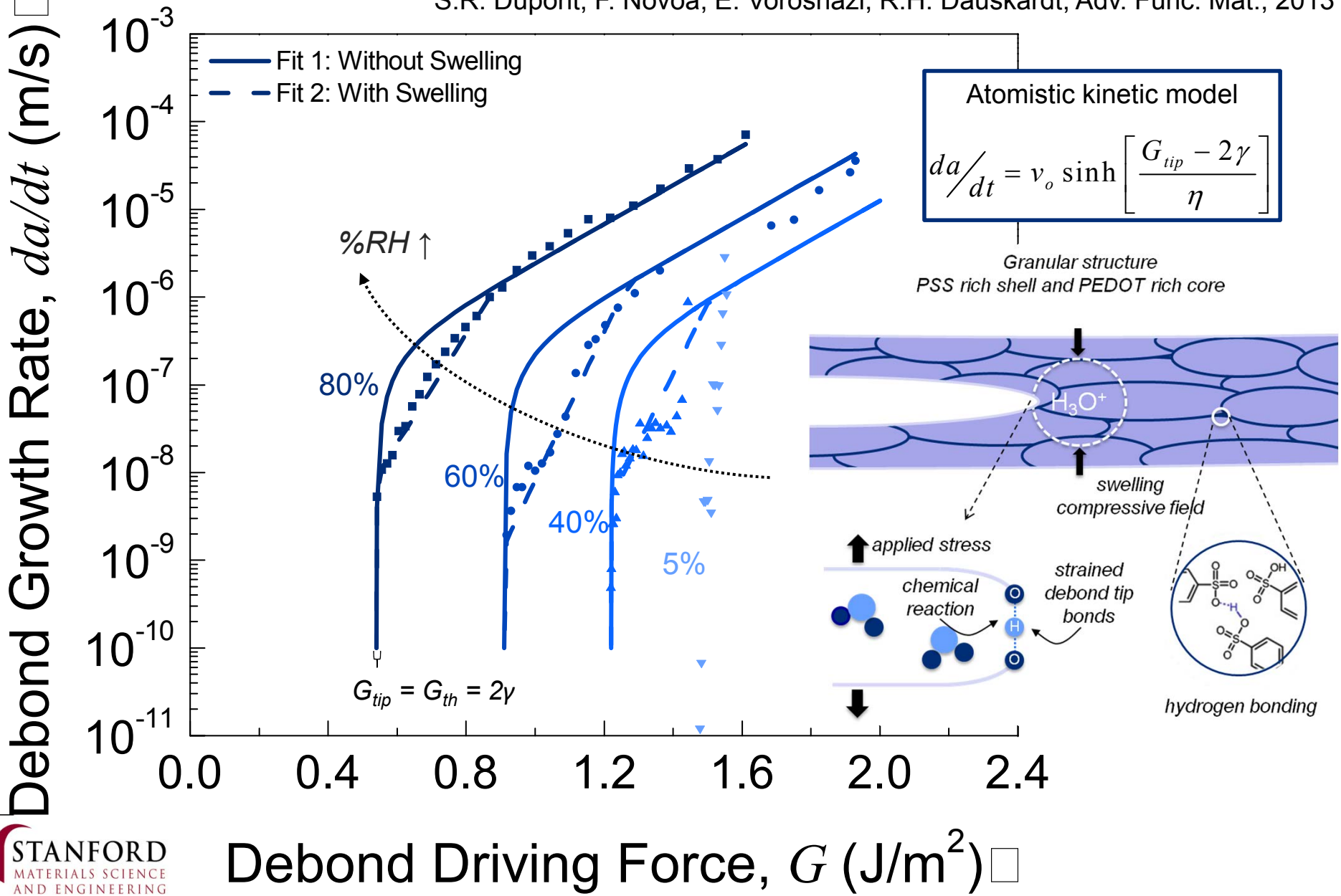
Decohesion of PEDO:PSS Transparent Electrodes

S.R. Dupont, F. Novoa, E. Voroshazi, R.H. Dauskardt, Adv. Func. Mat., 2013



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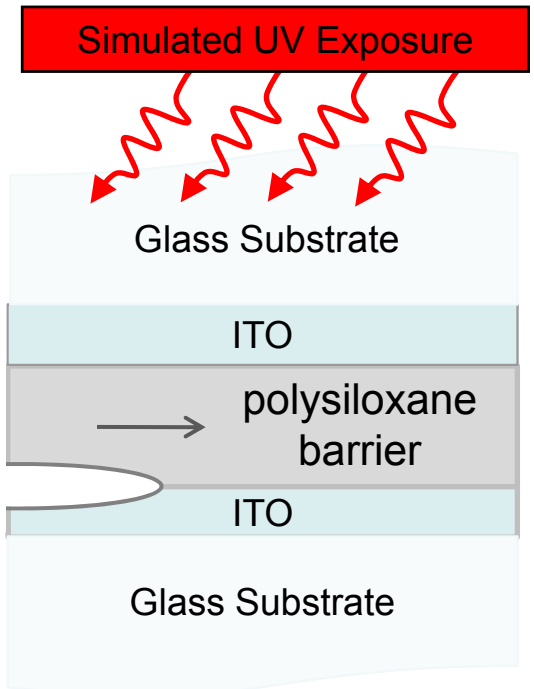
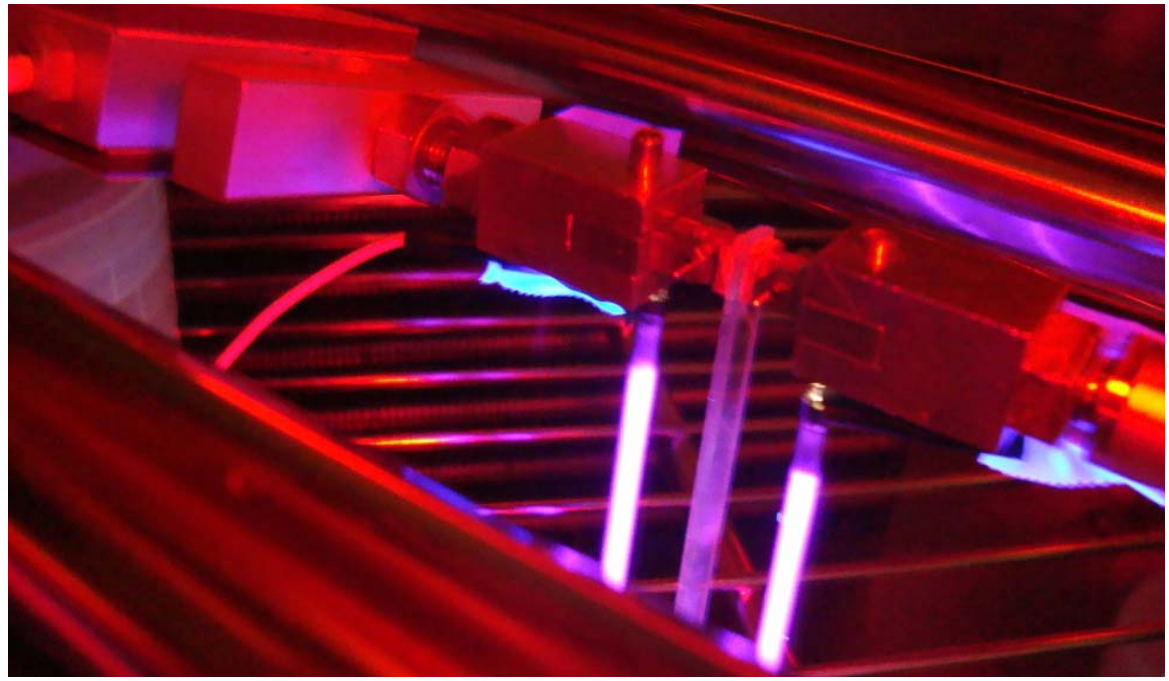
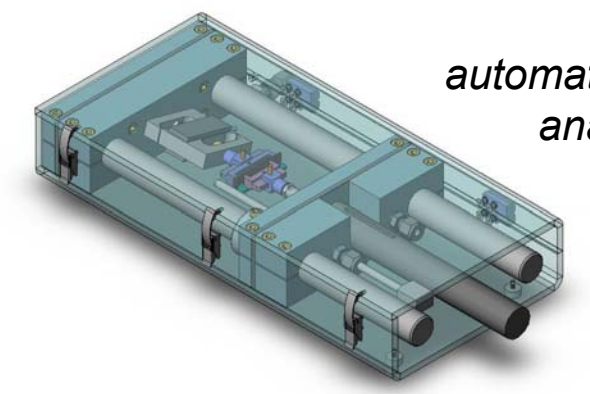
- Encapsulants and Ultra-Barriers in Solar Modules
  - synergistic effects of multiple “stressing parameters”
  - kinetics and lifetimes

Assessing UV and Environment on Debonding Kinetics



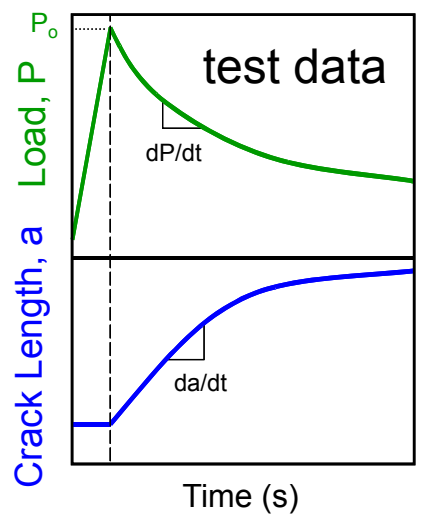


DTS Delaminator v8.2



automated growth analysis

sensitivity to < 10^{-11} m/s



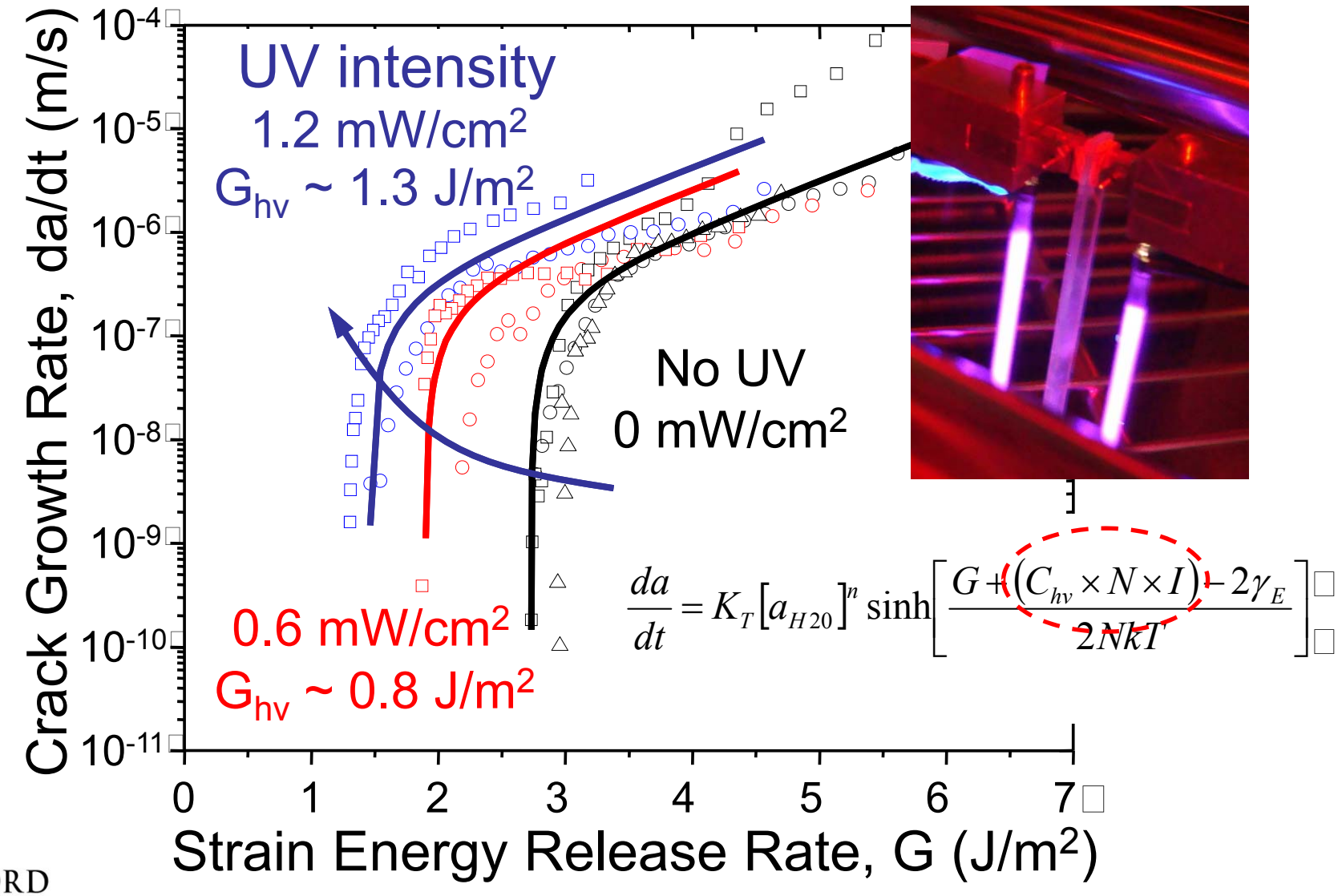
Debonding Kinetics

explore role of:

- UV flux
- humidity, O_2, OH, …
- temperature
- mechanical loading

UV Effects on Molecular Bond Rupture

UV Exposure (3.4 eV)



$$\frac{da}{dt} = K_T \left[a_{H20}\right]^n \sinh\left[\frac{G + \left(C_{hv} \times N \times I\right) - 2\gamma_E}{2NkT}\right]$$

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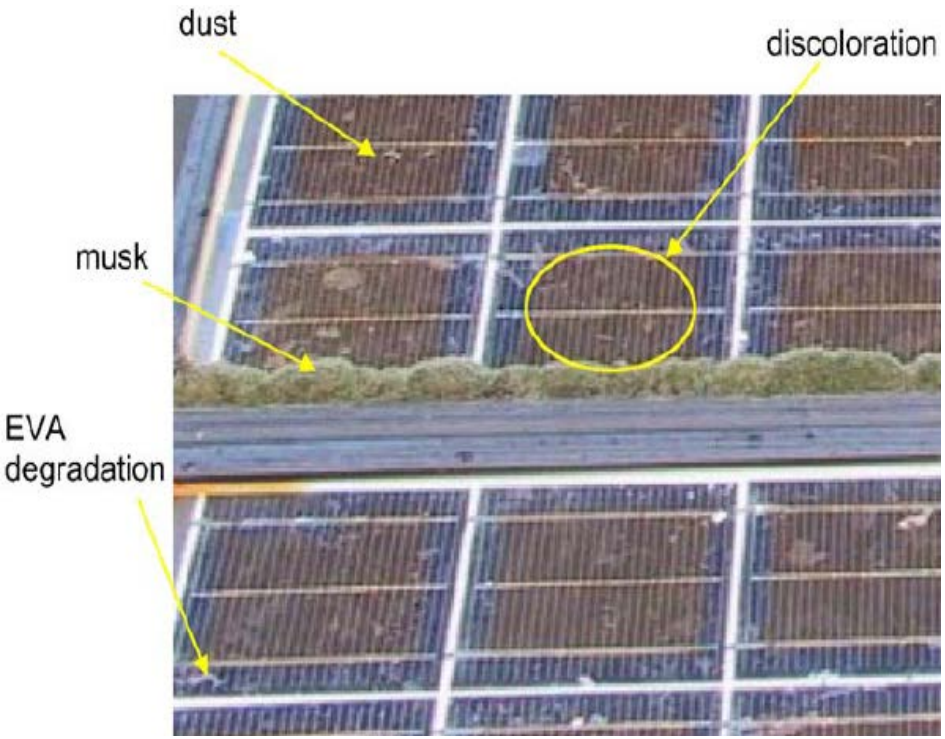
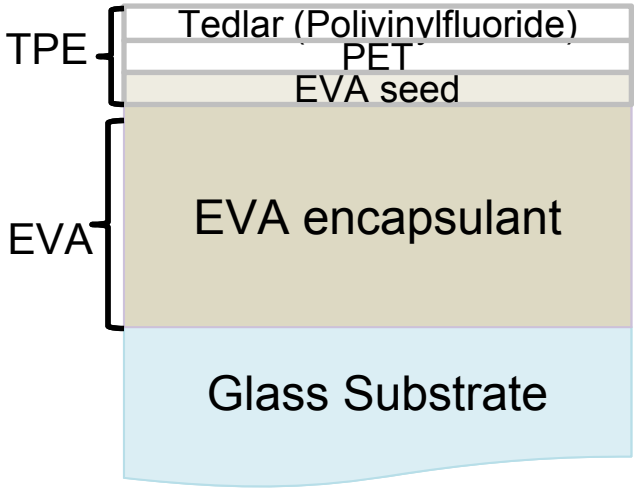
Delamination of EVA-TPE Lamination



Parreta Antonio, et al., Solar Energy Materials & Solar Cells, 2005



- EVA T_g ~ -15°C
- "ductile-to-brittle" transition at lower T
- poor adhesive/cohesive properties at lower T

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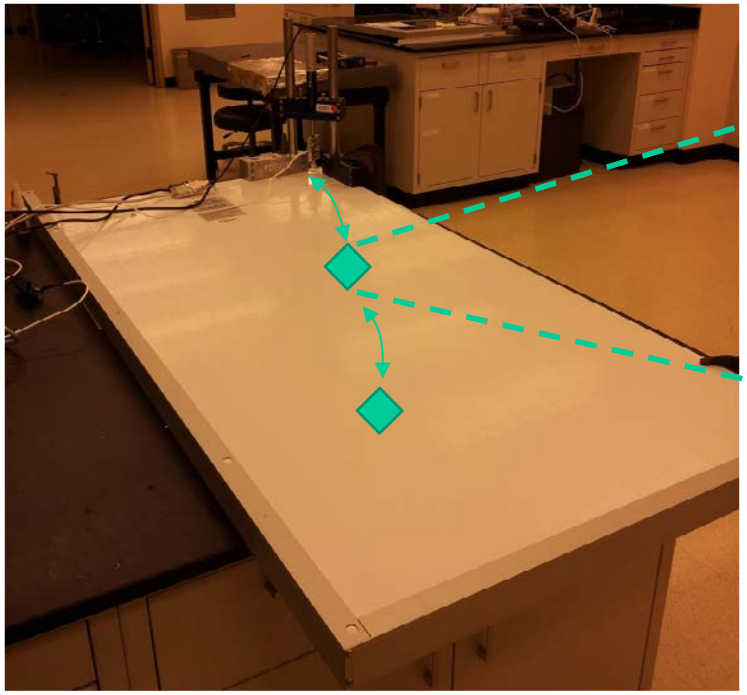
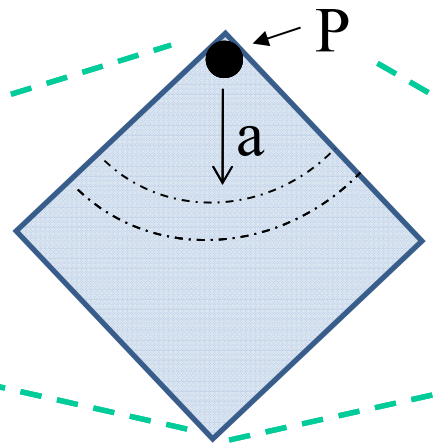
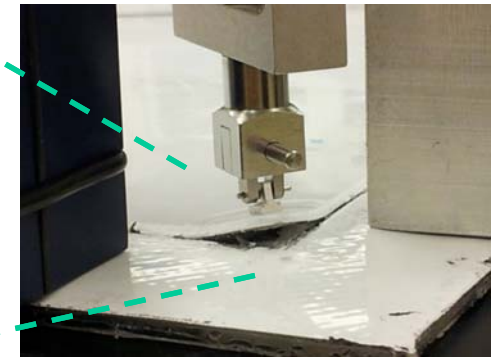
New Portable Full Panel Adhesion

Back Side of Full Panel





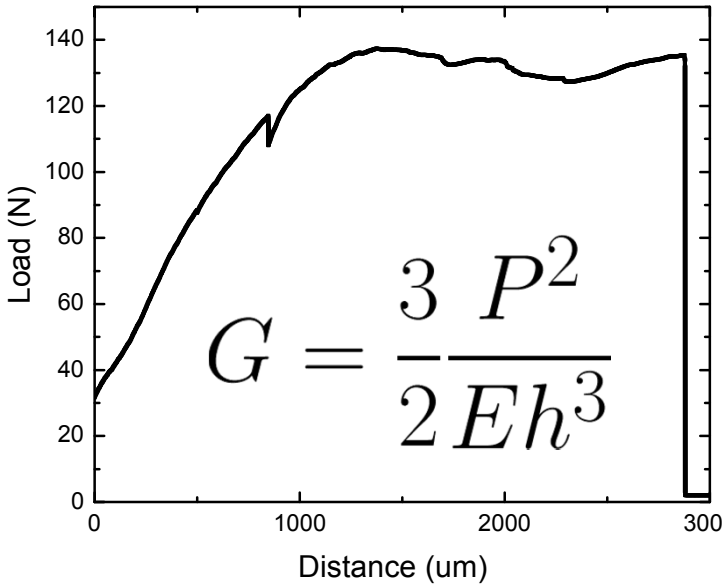


Delaminator (v8.2)
Adhesion Test System

Square Cantilever Beam Adhesion

Adhesion energy, G_c, depends on:

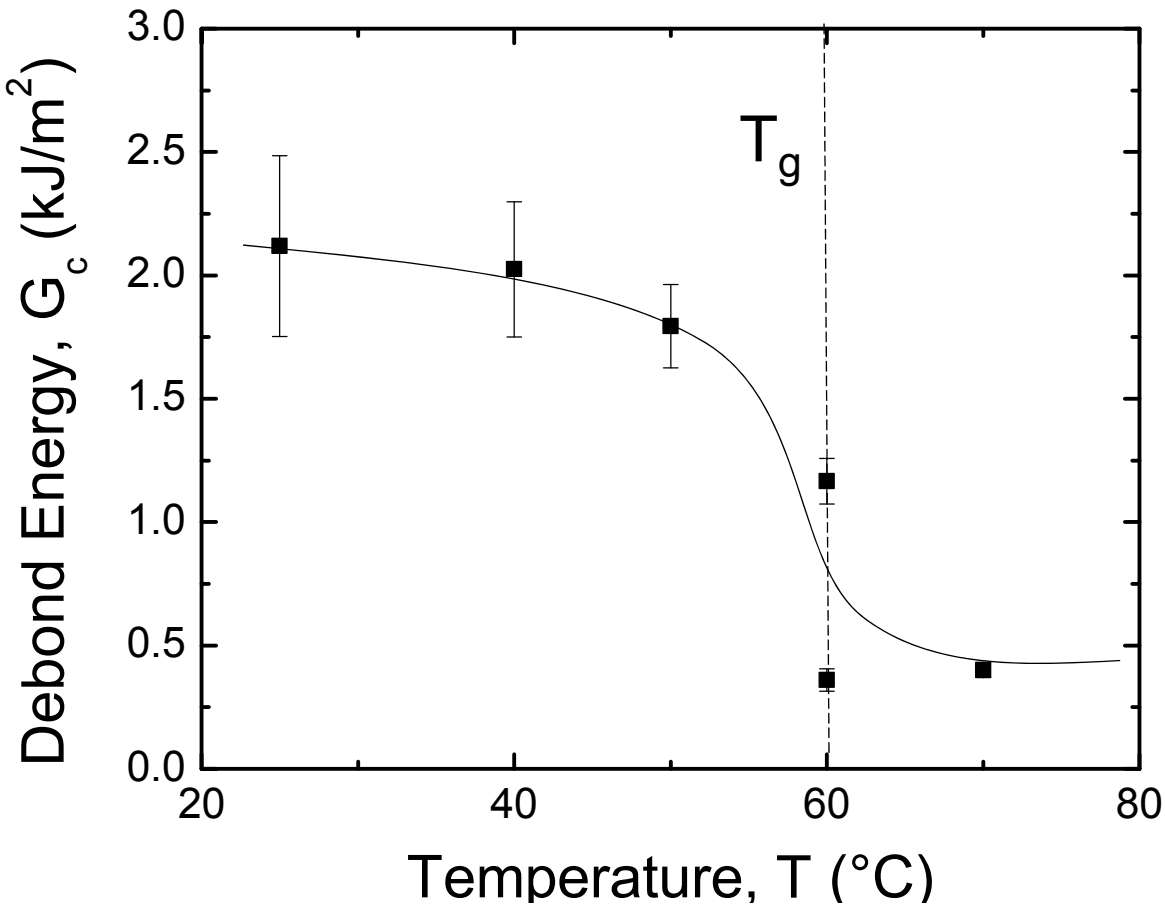
P (delamination force)
E (young modulus of the square)
h (thickness of the square)

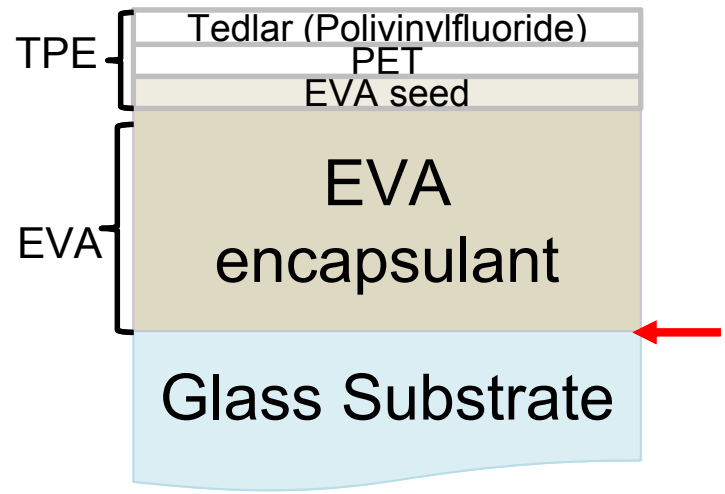


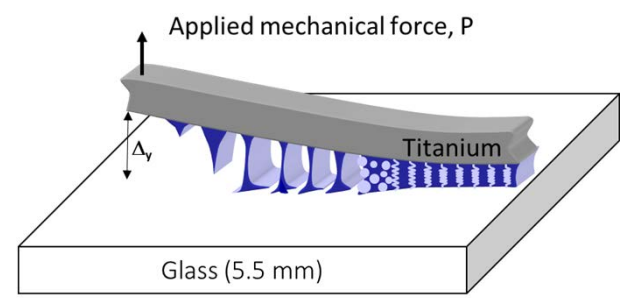
$$G = \frac{3}{2}\frac{P^2}{Eh^3}$$

DTS system and support: dauskardt@stanford.edu

Temperature Dependent EVA Debond Energy







Bridging and cavitation process

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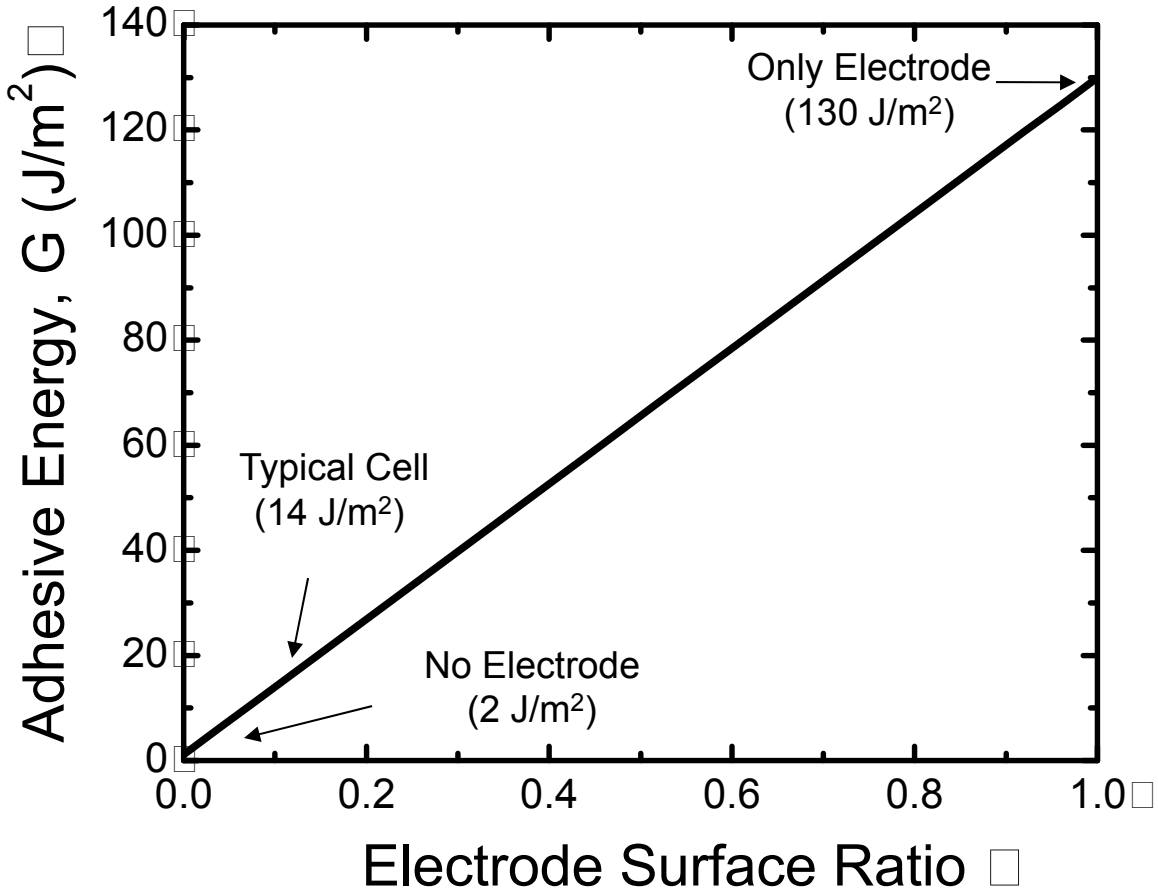
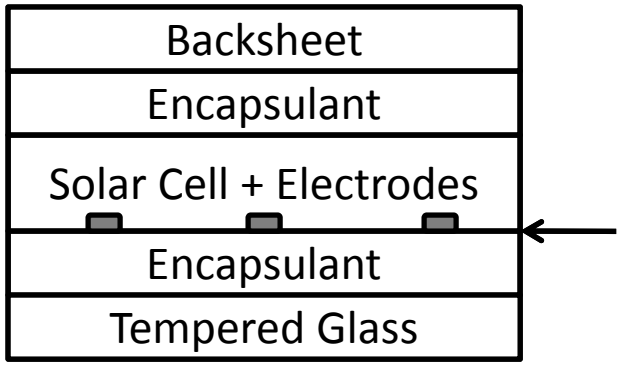
Encapsulant Adhesion is Highest at the Electrodes





Reducing electrode surface decreases adhesive energy and affects module reliability!

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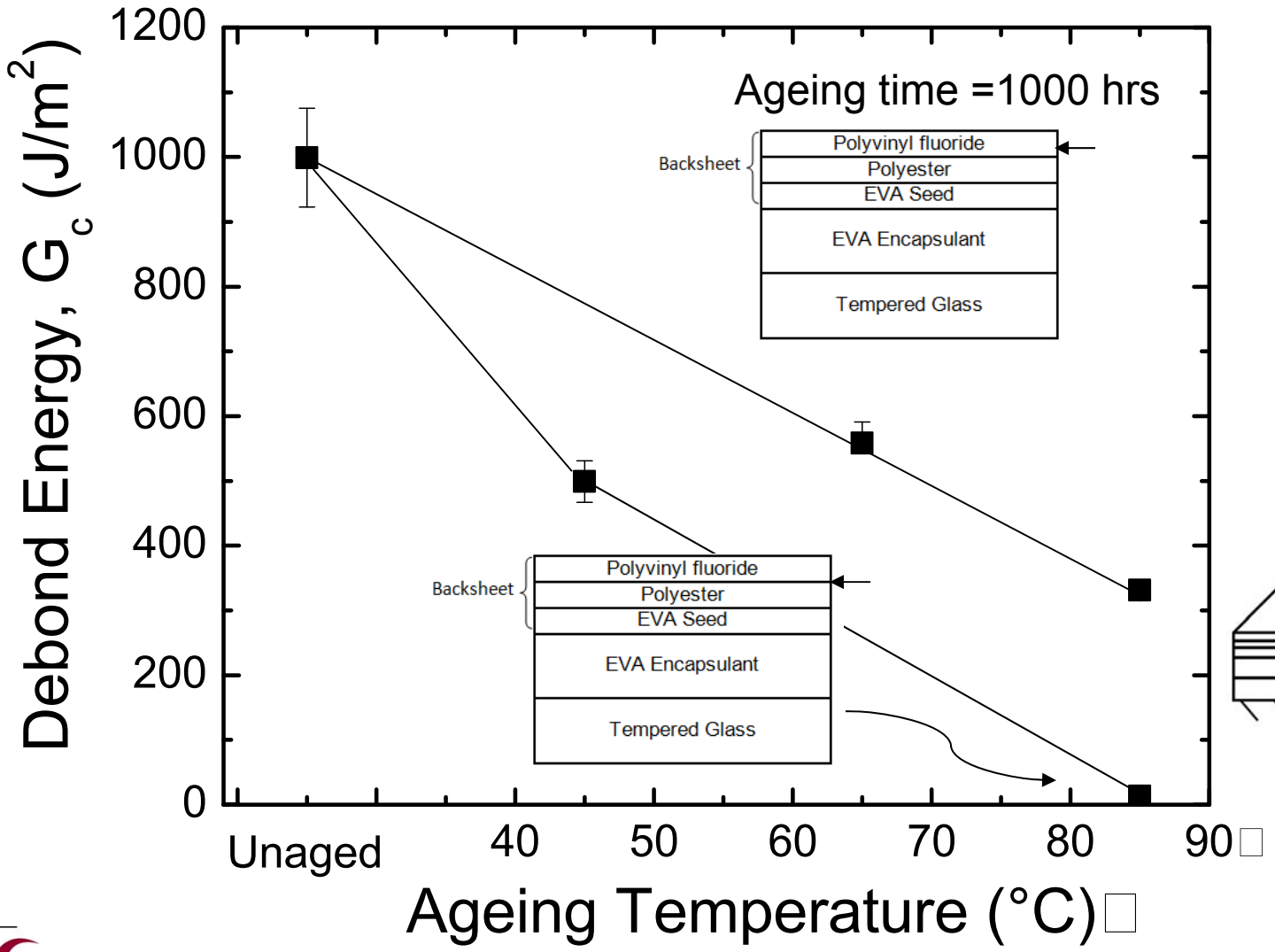
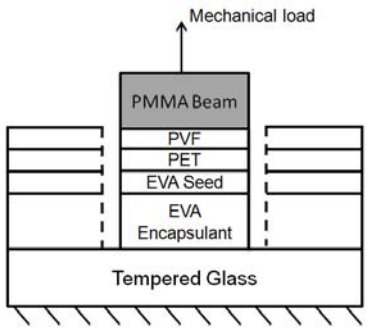
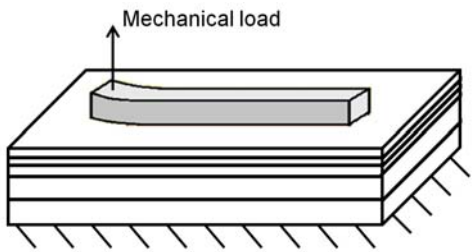
Ageing Temperature Effect on Debond Energy







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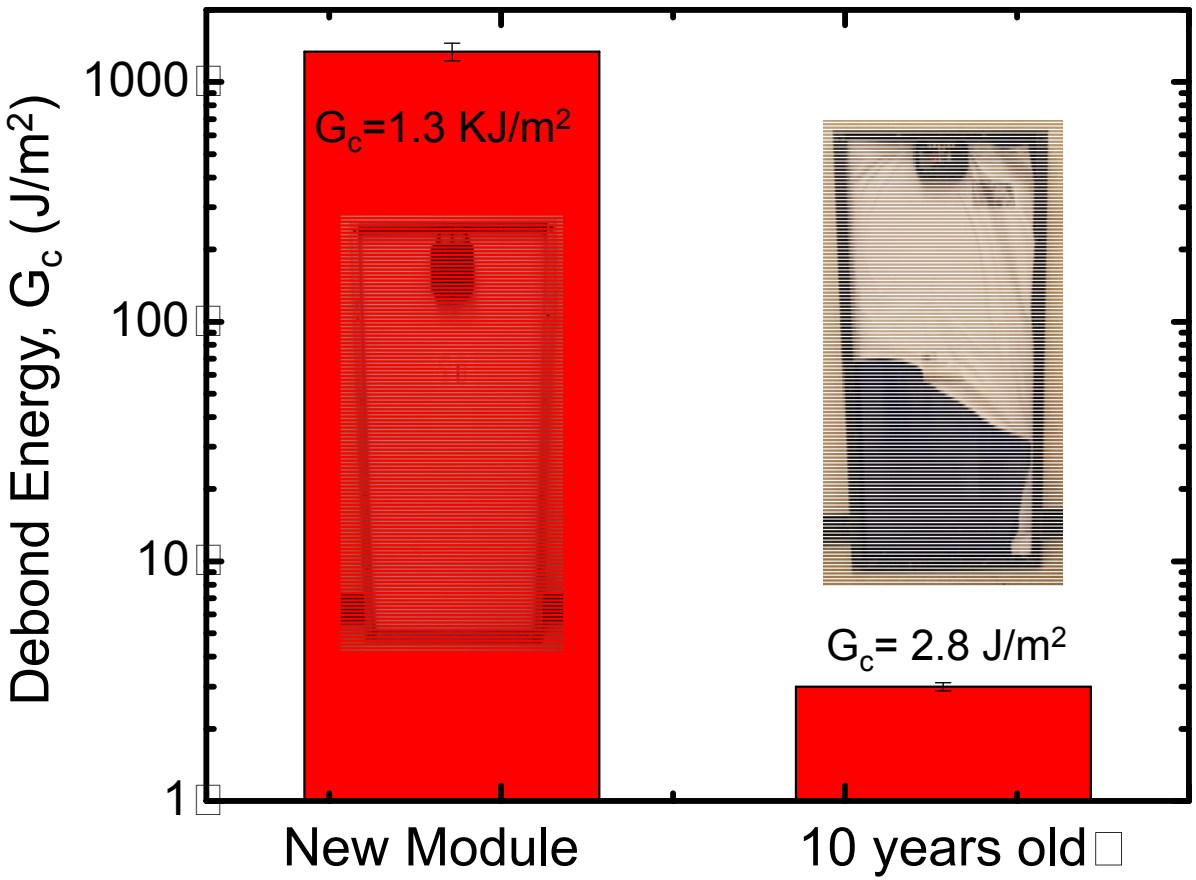
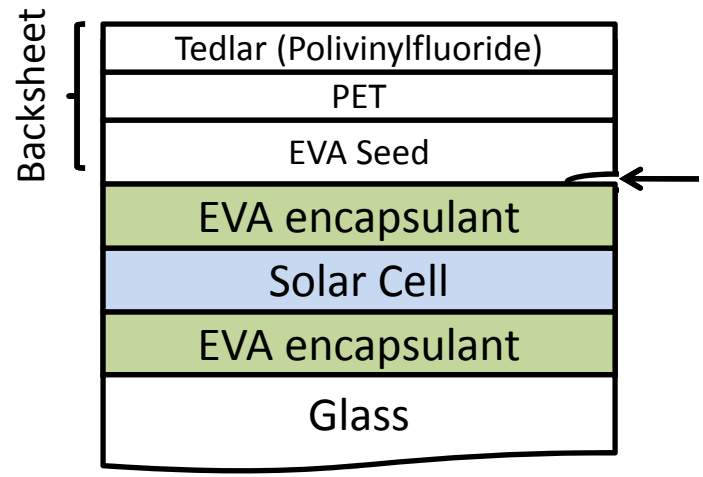
Backsheet Adhesion of Deployed Modules





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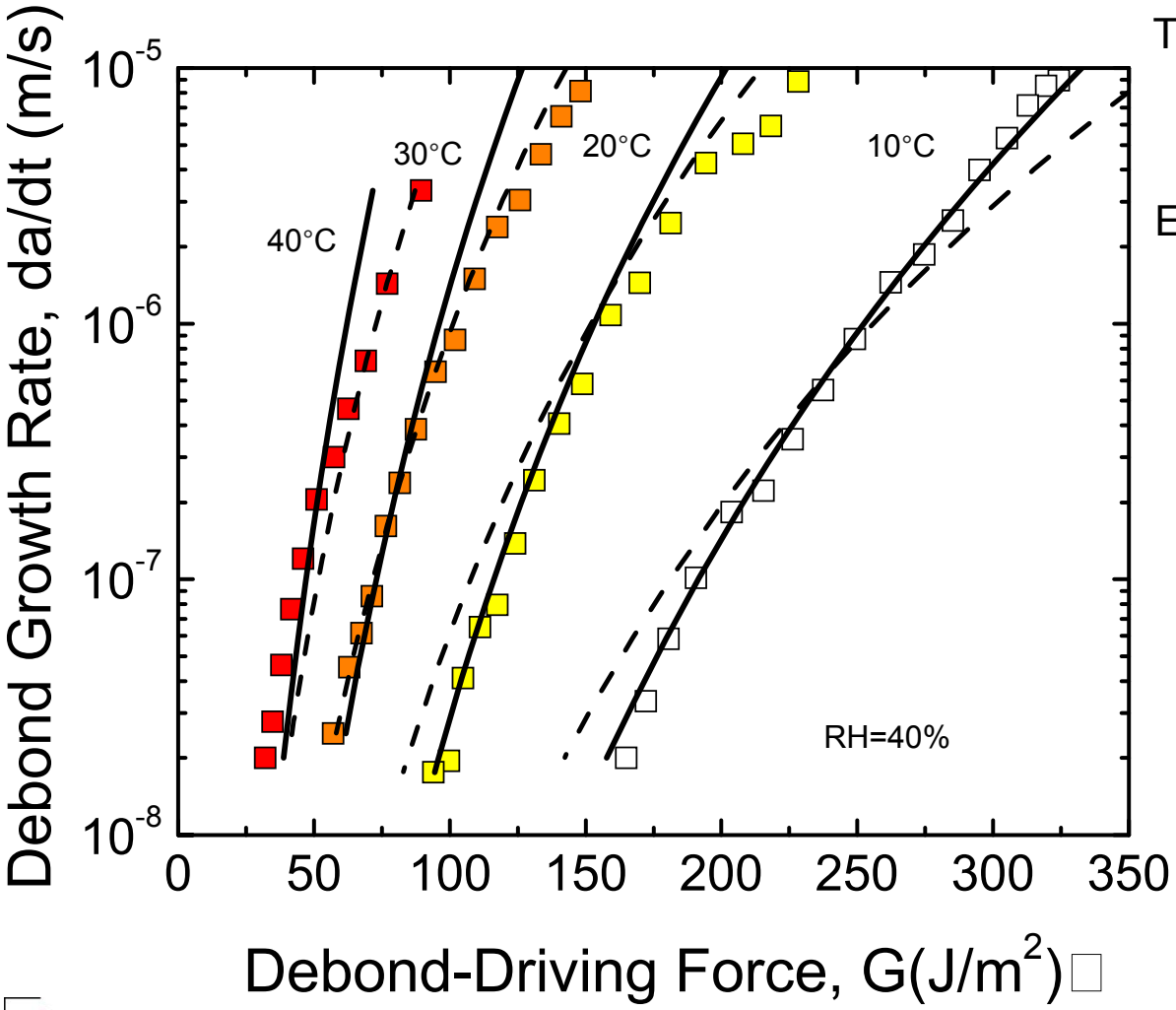
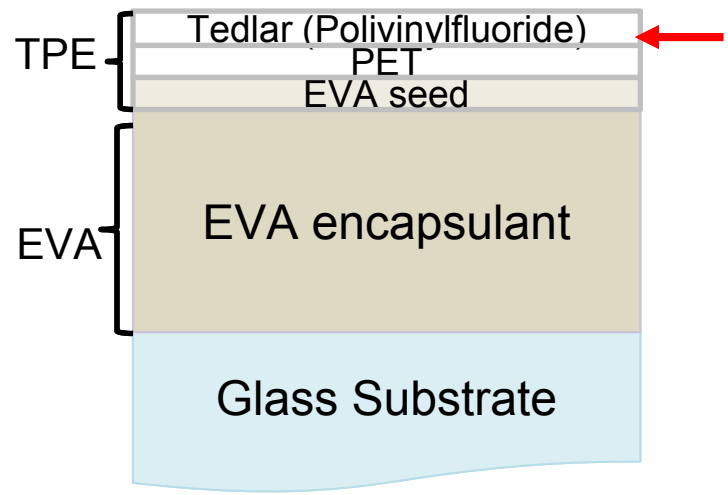
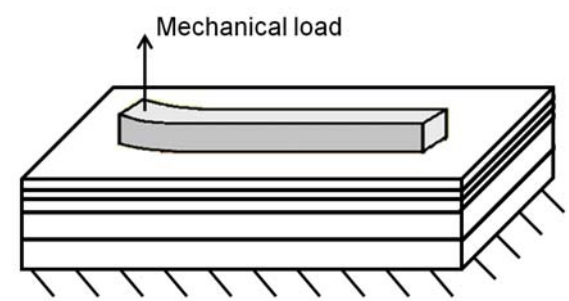
MATERIALS SCIENCE
AND ENGINEERING

Temperature Effect on Debond Kinetics







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Summary

- Inherent Solar Cell Thermo-Mechanical Reliability
  - polymer / PCBM BHJ type devices
  - adhesion and cohesion properties in flexible systems
- Encapsulants and Ultra-Barriers in Solar Modules
  - synergistic effects of multiple “stressing parameters”
  - kinetics and lifetimes

COGENRA SOLAR

Heat. Power. Savings.

Accelerated UV Photothermal Degradation of Polymer Encapsulants used in Low Concentration PV (LCPV)

Feb 25th – NREL 2014 PV Reliability Workshop

Itai Suez, PhD – Cogenra Solar

Design for LCPV Module Reliability

polymeric components

- UV stability of polymers under concentration
  - » Accelerated UV conditioning (close to concentration factor)
  - » UV Spectral matching
  - » Temperature management

- Dielectric stability of polymers
  - » LCPV module designs involve grounded metal for thermal management
    - Accelerated testing requires knowledge of E-field based polymer degradation

- Thermal stability of polymers
  - » LCPV can be required to operate at higher temperatures (~120C) for cogeneration / thermal storage
    - Accelerated testing can be achieved with high temperature ovens and/or running actual system under stagnation conditions
  - » LCPV can be required to cycle between wider temperature ranges and at higher frequency than flat plate solar modules
    - Accelerated via rapid thermal cycling with higher temperature extremes

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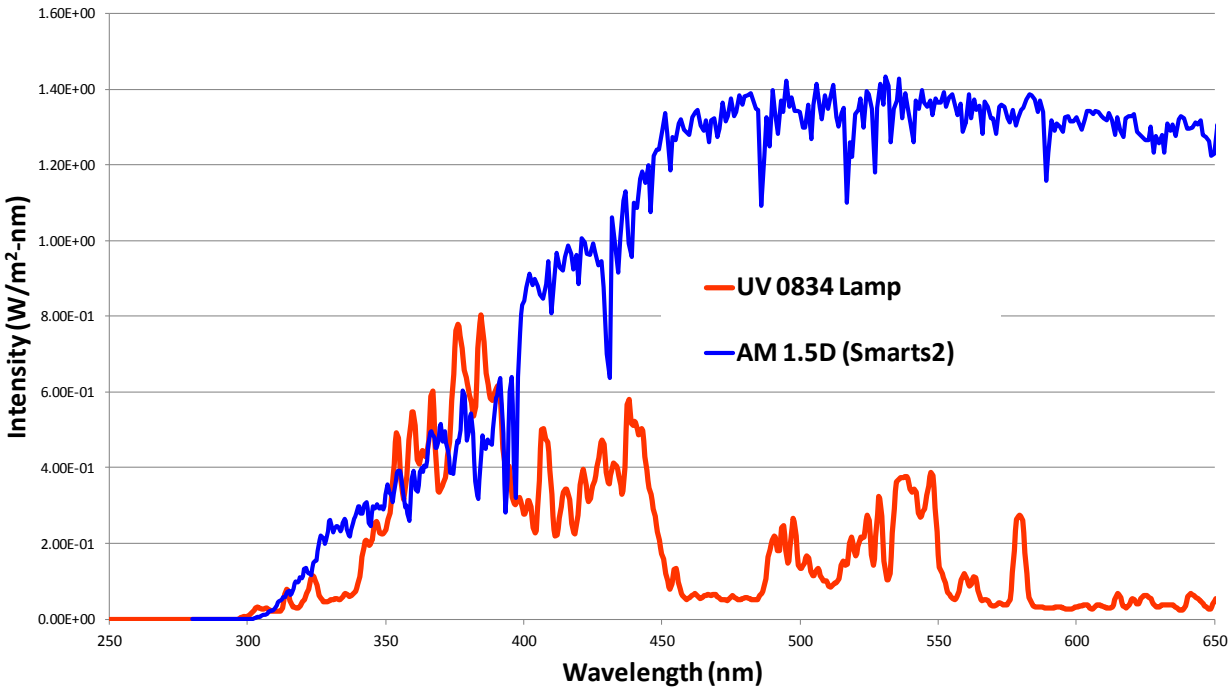
Accelerated UV conditioning



- **UV0834**
  - » UVA Enhanced Metal Halide Lamp 600W medium pressure
  - » Can achieve 150-200mW/cm^2 UV flux (~30-40 suns of UV)
    - Measured between 320nm – 390nm using a UV flux meter
  - » Use of low-Fe glass screen to achieve better spectrum matching

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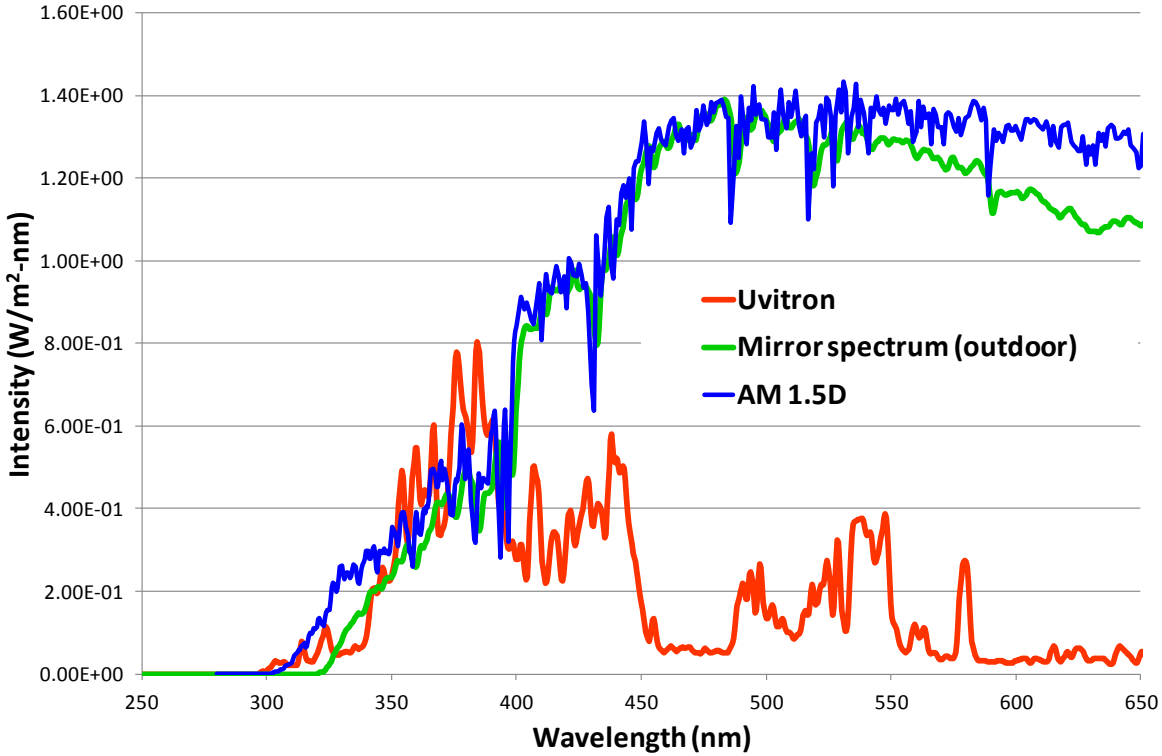
UV Spectral Matching



- Solar spectrum from reflector (silvered mirror) was obtained directly at receiver exposure plane using a calibrated spectrophotometer/fiber optic receptor with a 5% aperture.
  - » Measurements taken at/near solar noon at 37.39° Latitude during peak of summer
- In this accelerated testing, the goal was to match UV spectrum of indoor light source with the light beam from reflected surface (NOT just to AM1.5D)
  - » UVB is considerably attenuated by the mirror and, in effect, has a closer spectral match to the metal halide light source than AM1.5D
  - » Still a bit more UVB (~300nm) in glass filtered metal halide light source than experienced in field conditions…

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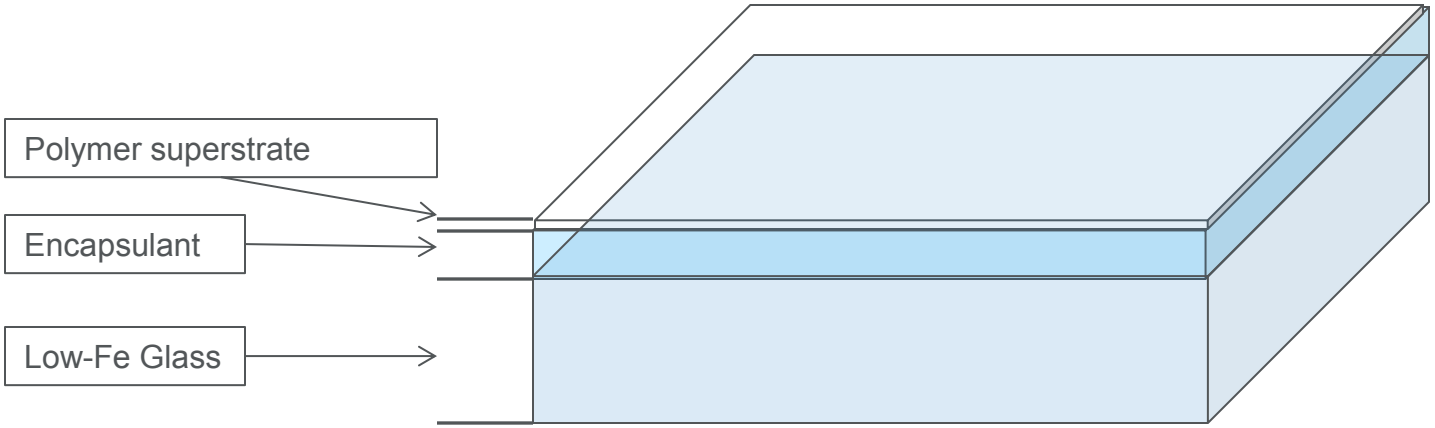
Sample Construction



- Encapsulant and superstrate match product construction
- Backside glass is necessary to quantify optical transmission loss
- Degradation mechanisms will be different than what is typically observed in glass/glass or glass/cell/backsheet type constructions due to front surface breathability

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Experimental Overview

- **Looked at a library of commercially available polymeric encapsulants**
  - » EVA, non-EVA alternatives
- **Placed identical samples on chiller plates vs. no chiller plates at locations under lamp where UV flux was similar**
  - » Provided comparison of degradation rates at two temperature values (55°C vs. 90°C)
- **Carried out exposure for over 4,700hrs approaching many years of simulated UV degradation in the field for LCPV application**
  - » UV flux was measured at each sample location in order to plot degradation as a function of total UV dose
    - As a result, every sample has been accelerated to a slightly different extent

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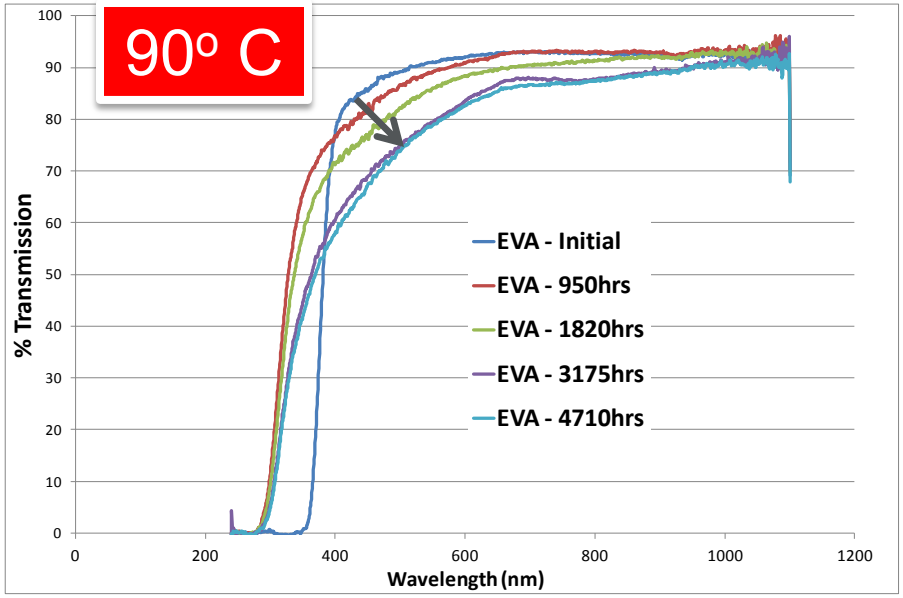
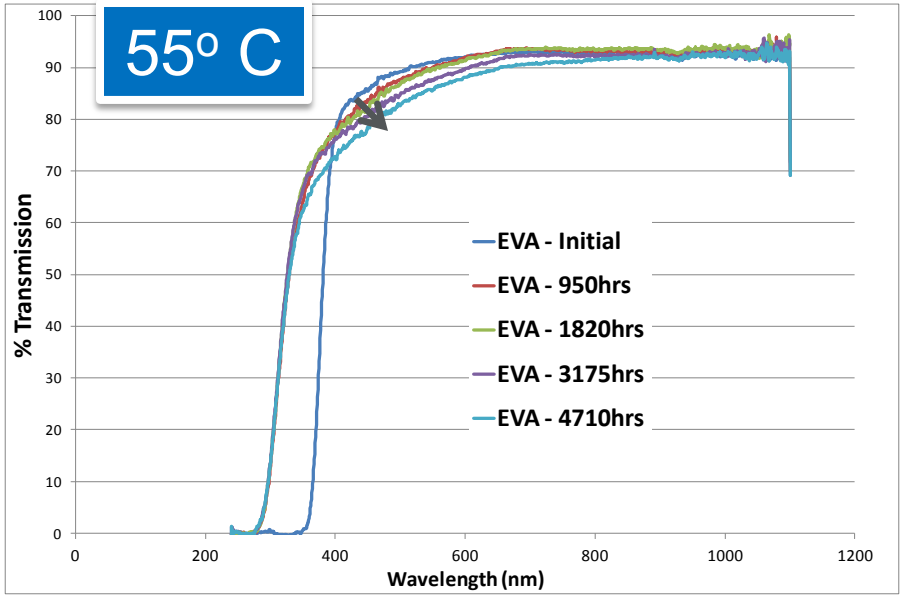
Transmission Loss Curves

EVA "hot" (90C) vs. "cold" (55C)





- Total UV Dose for the EVA samples, specifically, is over 7,500kWh/m^2 (160mW/cm^2 flux)
  - » One year in Arizona on a single-axis tracker ~100kWh/m^2 of UV at 1-sun illumination
- Loss of UV absorbers happens within the 1st 1000hrs of exposure
  - » typical for most samples tested which have UV absorbers/stabilizers
- Rate of transmission loss is severely retarded by effect of photobleaching.
  - » If this were a glass/glass sample, the level of EVA browning would have occurred in less than 1000hrs
- Difference in degradation between two temperature extremes is significant

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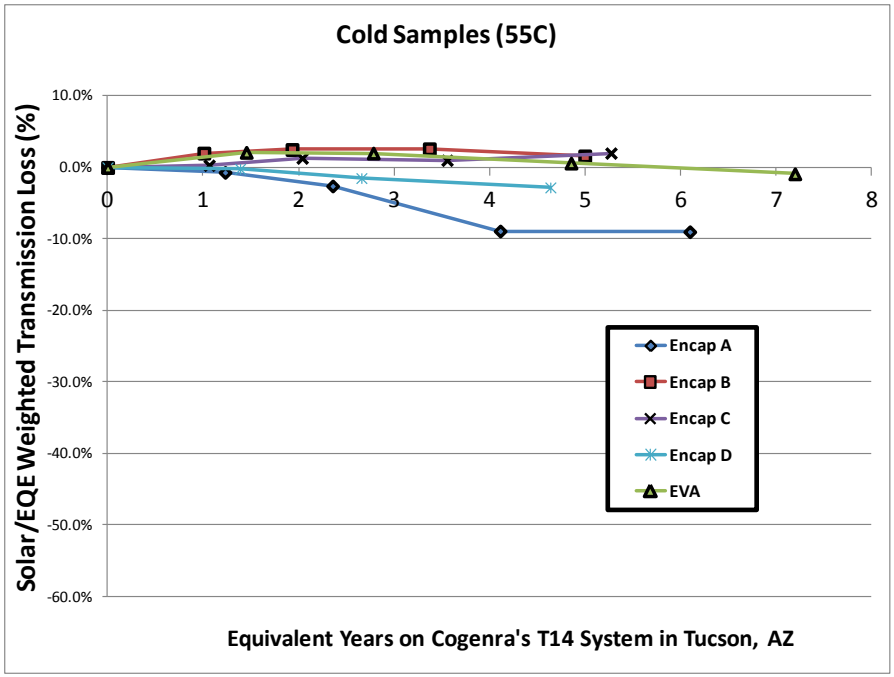
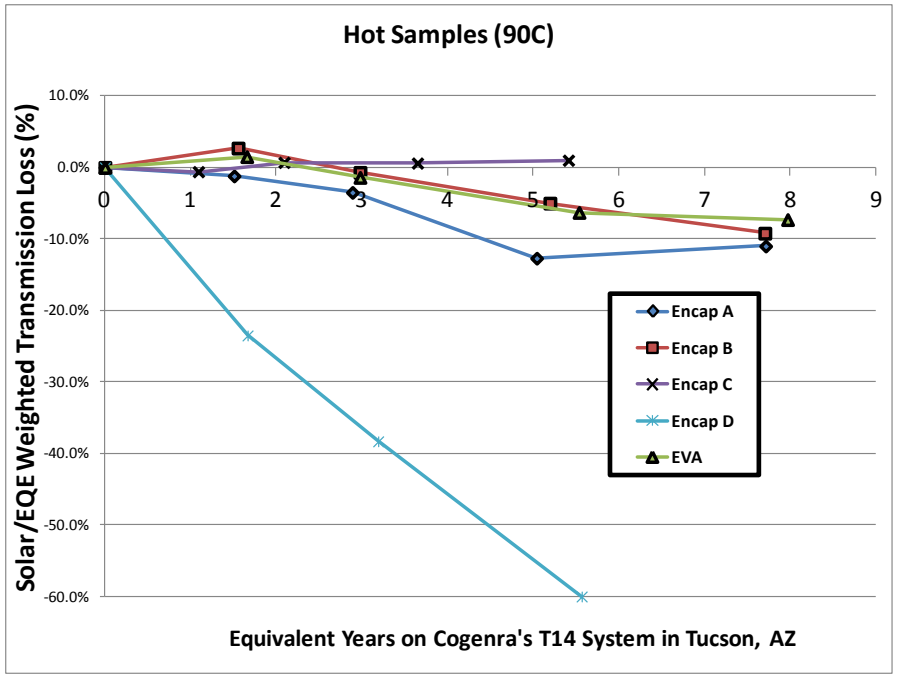
Summary of encapsulant degradation
via solar/EQE weighted optical transmission loss





- Equivalent years is simply a calculation of equivalent UV dose at 14X in Tucson, AZ
  - » If exponential photon energy weighting is used (β=0.07), this would add an acceleration factor of 2 to equivalent years shown
    - Kempe, M.D. IEEE PV Specialists Conference 2008, "Accelerated UV Test Methods for Encapsulants of PV Modules" $E(\lambda) \sim I(\lambda)\lambda e^{-B\lambda}$
- Significant difference in degradation rates between "hot" and "cold" samples for most encapsulants tested

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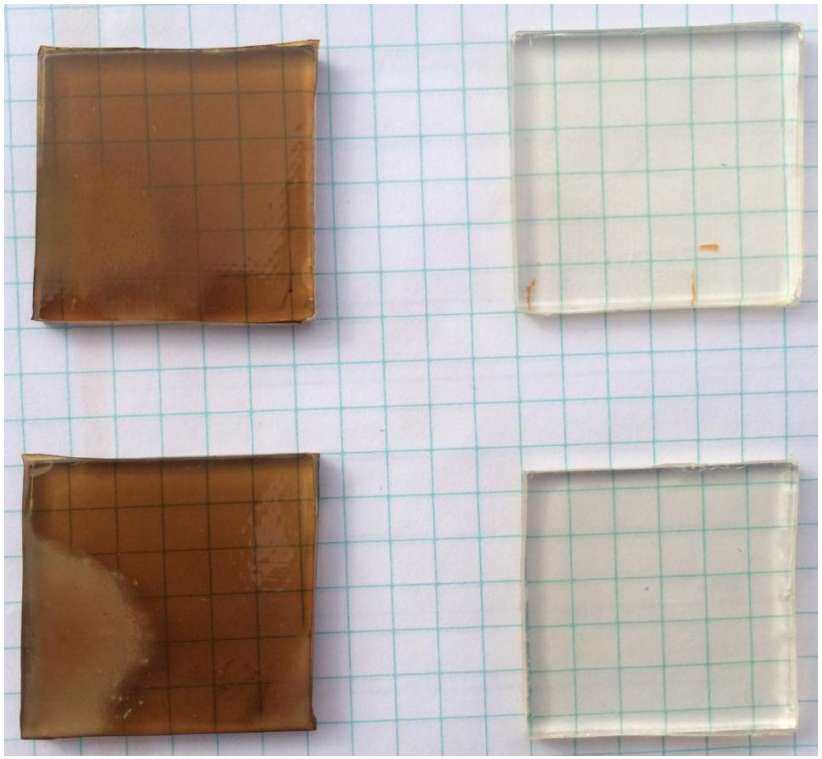
“hot” vs. “cold” UV degradation



	Total UV Dose (kWh/m2)	Eq. Years	"hot" transmission loss	"cold" transmission loss
Encap A	7065	7yrs	-11%	-9%
Encap B	7065	7yrs	-9%	(+)1.6%
Encap C	5652	5.7yrs	(+)1%	(+)2%
Encap D	5080	5yrs	-60%	-3%
EVA	7536	7.5yrs	-7.50%	-1%

- All but two of the polymeric encapsulants tested showed significantly enhanced degradation at higher temperatures
- Most extreme set of samples is shown

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Conclusions

- It is a challenge to accelerate UV stresses for polymers used in LCPV applications
  - » Spectral matching, temperature management, etc.
- If operating for significant periods over 90°C, only one encapsulant tested is viable for >10X concentration
- If temperatures are managed at no greater than 60°C for majority of field operated life, then several other encapsulant options can be chosen

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DaySy
Daylight Luminescence for PV Systems
How to Check 400kW$_{peak}$ Per Day With Electroluminescence

Liviu Stoicescu[a] , Michael Reuter[a], Jürgen H. Werner[a,b]

solarzentrum stuttgart

[a] Solarzentrum Stuttgart, Stuttgart, Germany
[b] Institut für Photovoltaik, Universität Stuttgart, Germany

Solarzentrum Stuttgart

- Research and development in photovoltaics and industrialization thereof
- In close cooperation with Institute for Photovoltaics, University of Stuttgart
- Products/developments
  - Novel surface texture for crystalline silicon
  - PV module optimization
    - White colored cell interconnector +1%$_{rel}$ efficiency
  - Lifetime calibrated photoluminescence imaging system
    - Full QSSPC integration
    - Very high irradiation homogeneity on 20x20cm²
  - Daylight luminescence analysis

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Institute for Photovoltaics, Uni Stuttgart

Solar cell research

- Laser doped selective emitter
- Innovative solar cell concepts
- Fully laser processed IBC solar cells
  - → $\eta \approx 22$ %!

PV system research

- PV system analysis and monitoring since 2004
  - Stuttgart, Cyprus, Egypt

Characterization

- Lifetime calibrated photoluminescence systems
- Daylight luminescence system: DaySy

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Why Electroluminescence?

- Defects are not always obvious!

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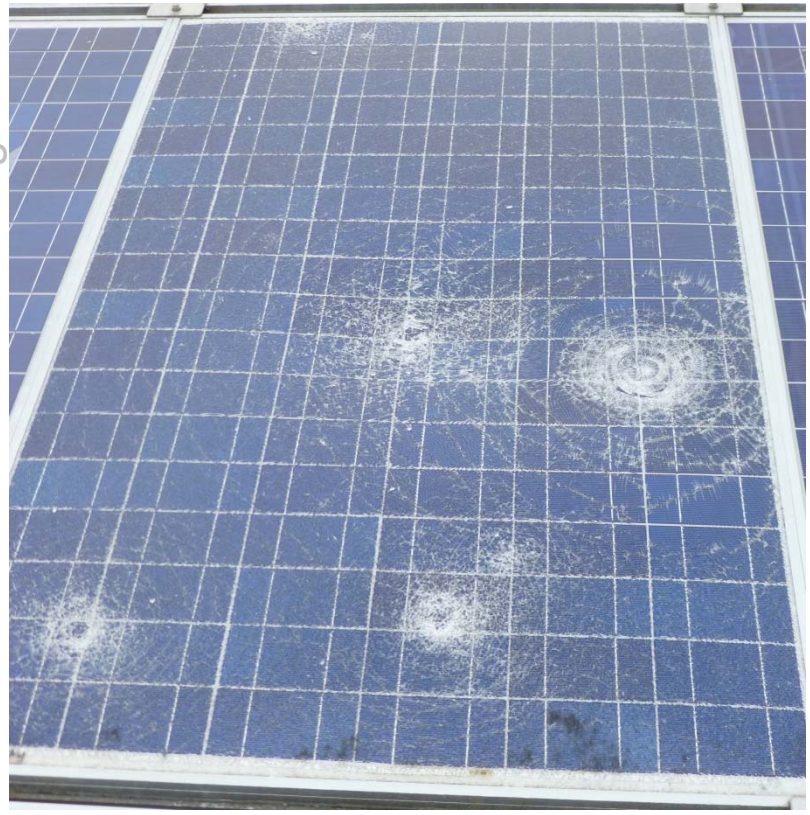
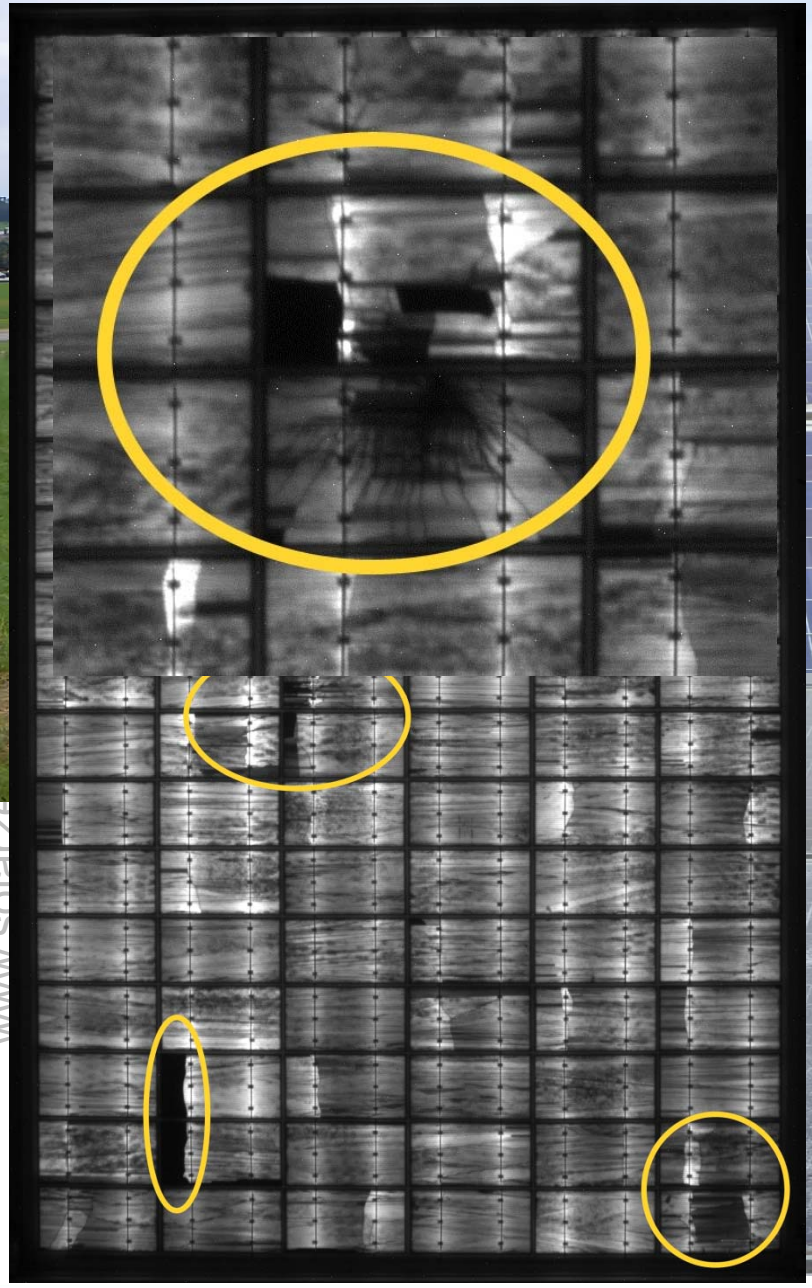




Extreme hail in Germany 2013

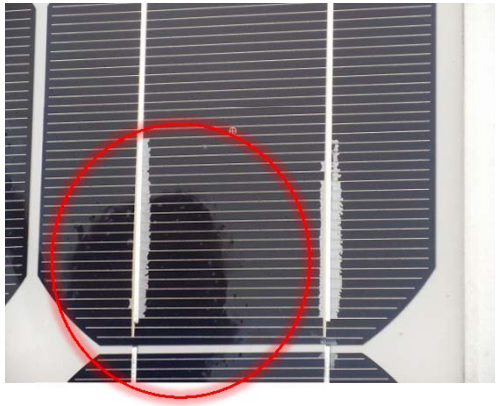
- About 1/3 of modules in this PV plant with obvious glass failure
- All others seemed undamaged

BUT

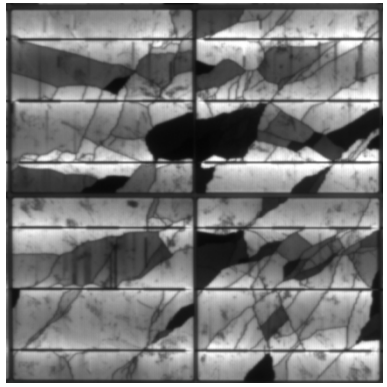
- Dark room EL analysis proves 95 out of 96 modules with hail damage!

Module Failure Modes

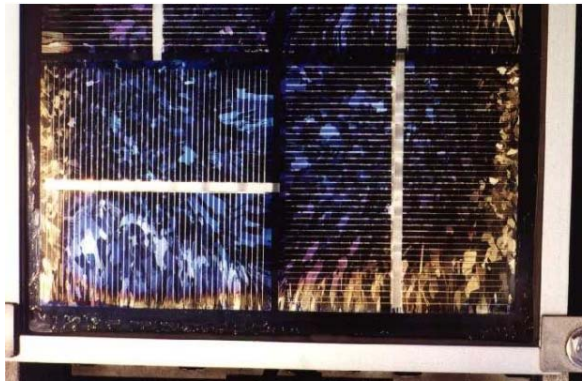
Delamination



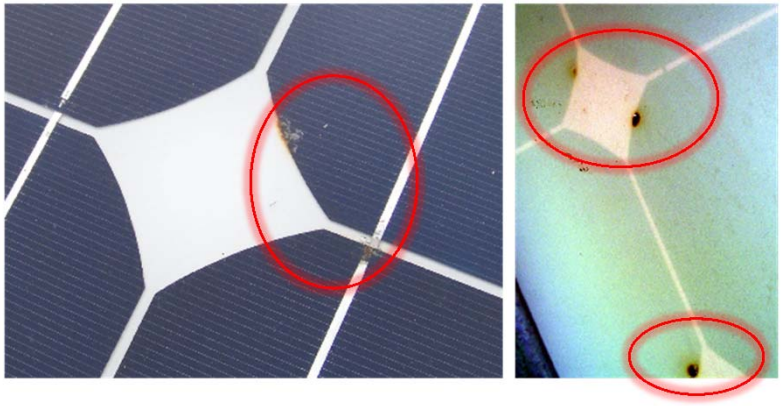
Microcracks, broken cells, finger interruptions



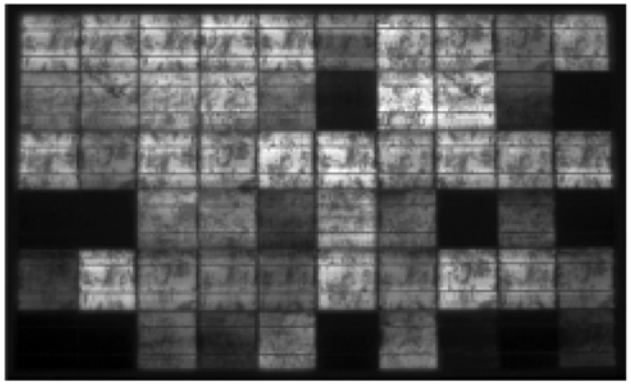
Browning



Hot spots



Potential induced degradation (PID)



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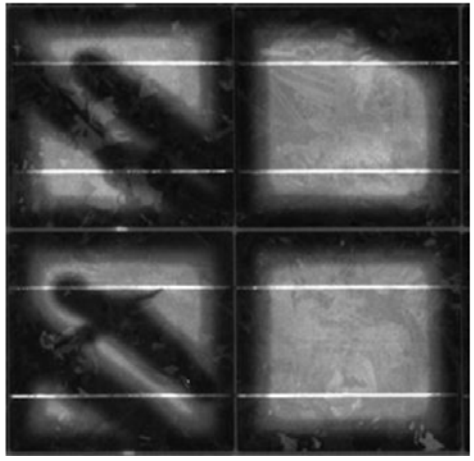
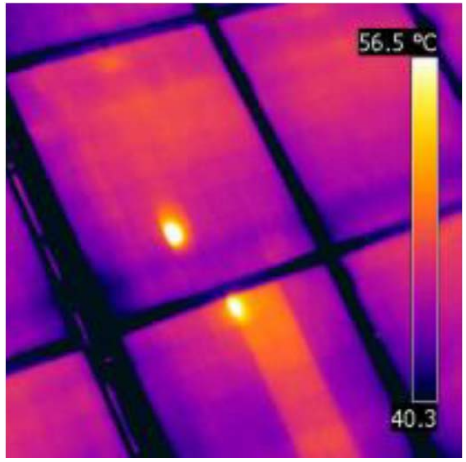
Optical Characterization Methods

UV - Fluorescence

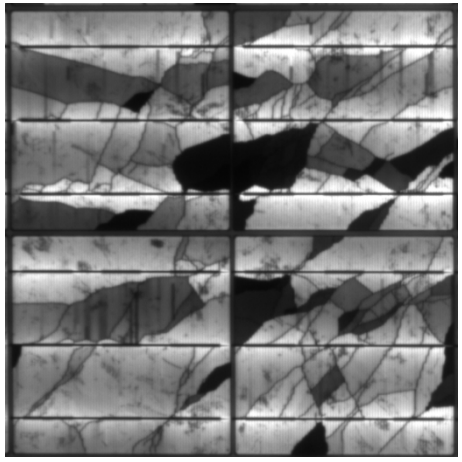


Köntges et. al., 27th EUPVSEC 2012

Thermography



Luminescence



	UV - Fluorescence	Thermography	Luminescence
Pro	Cracks visible	Power loss	All defects
	Cost effective	Cost effective	Identification
Con	**Night**	**Irradiance**	**Night**
			Generator
	Well aged cracks	Identification	Expensive

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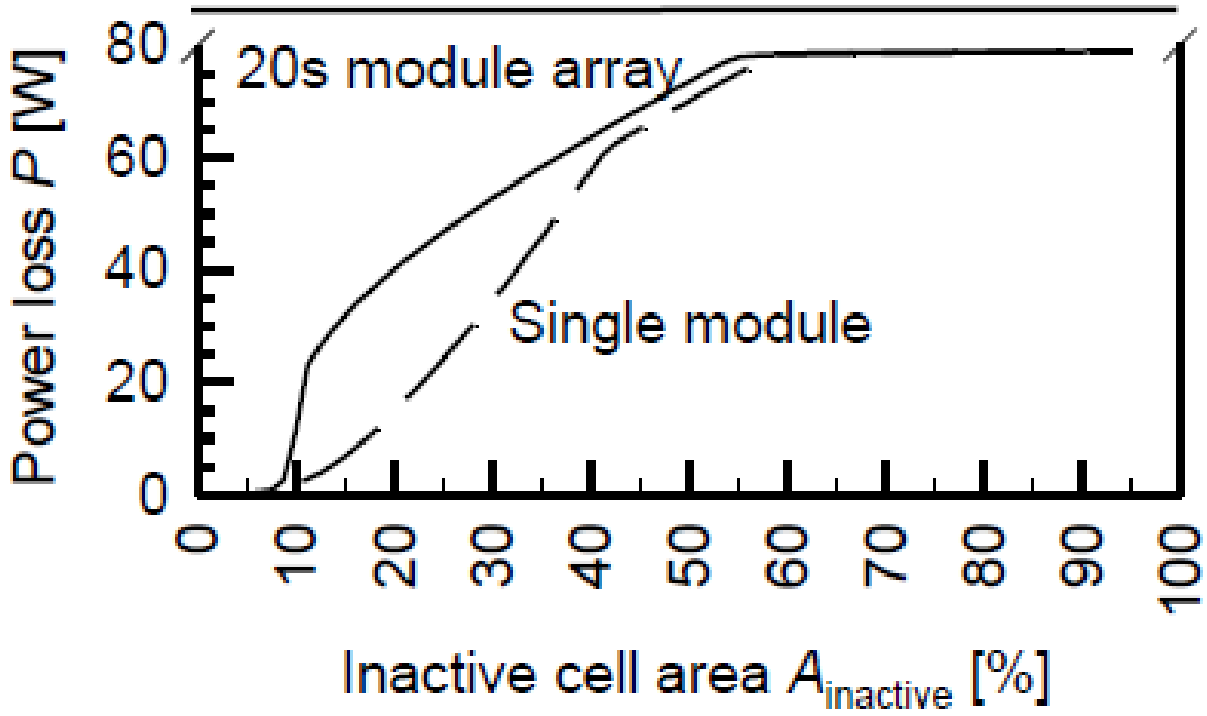
What we do about it?

- Hot spot
  - How hot? Remove, replace or just observe…
- EL cell damage
  - How severe? How to judge?



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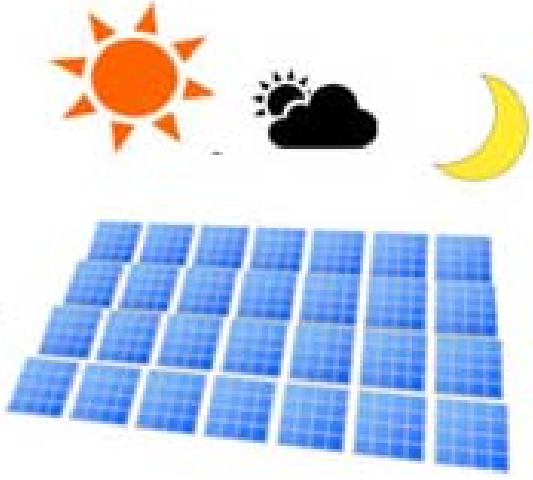
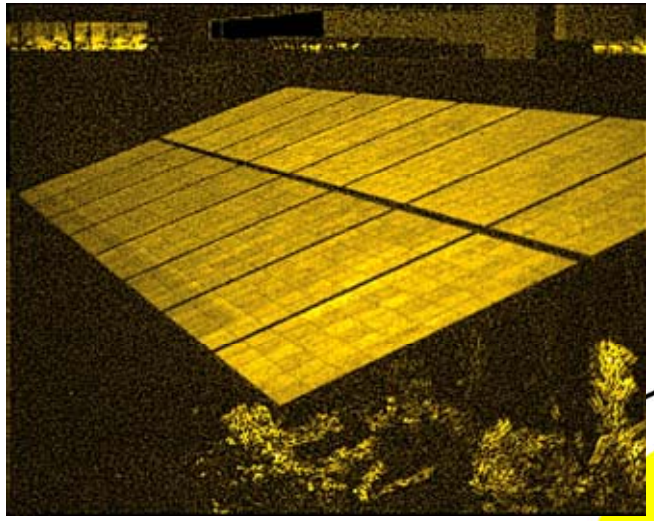
Novel Method: DaySy

- Electro (EL)- and photoluminescence (PL) characterization
  - In full daylight
  - Independent of surrounding light
  - On mounted modules and full strings
  - Using either the PV-plant or a DC source as power supply





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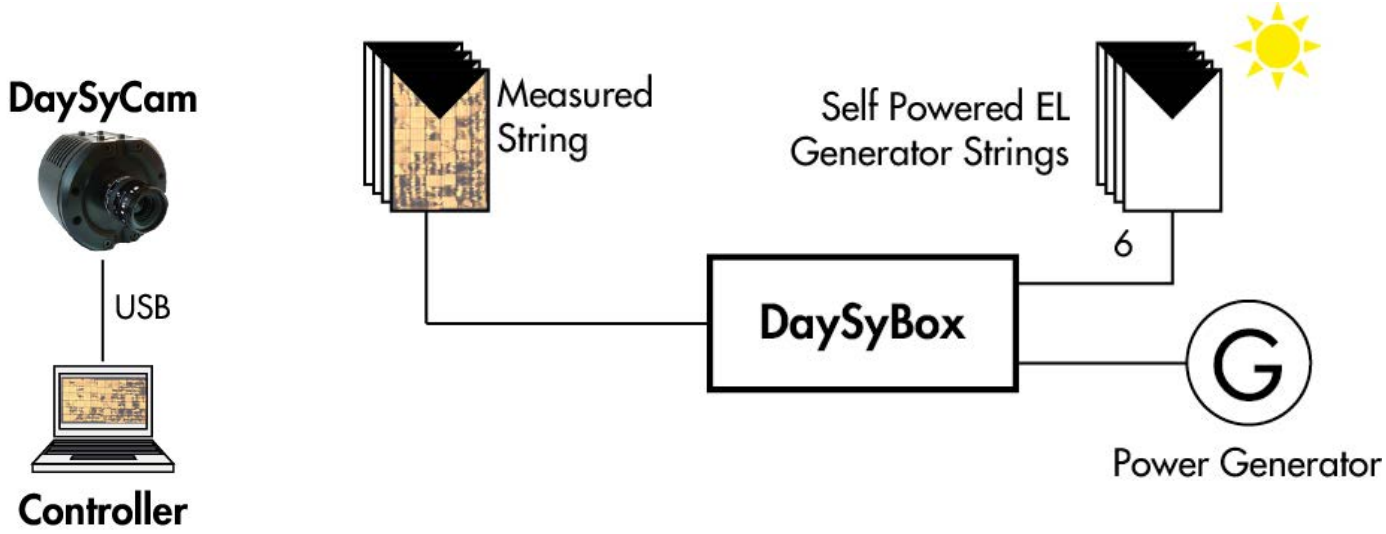
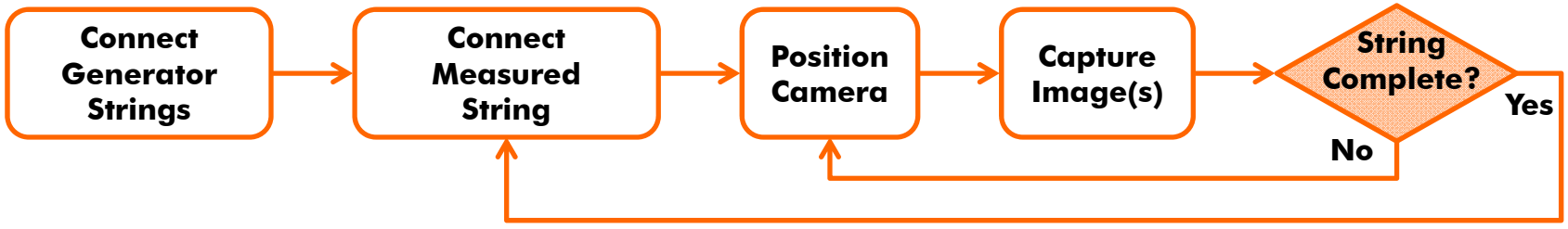
Measurement Procedure





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Service Availability: Sunny Day

Measure when YOU want: 100% availability day and night

DaySy – Self Powered EL

DaySy – EL with Power Generator

Night -EL

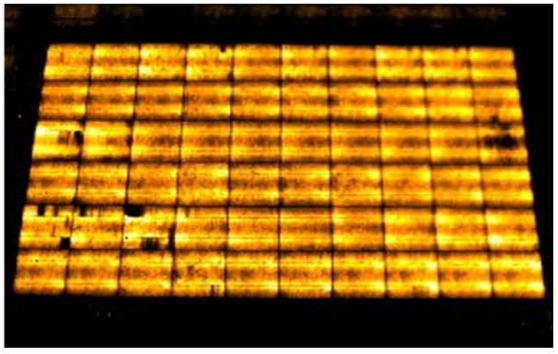
Night -EL

Thermography

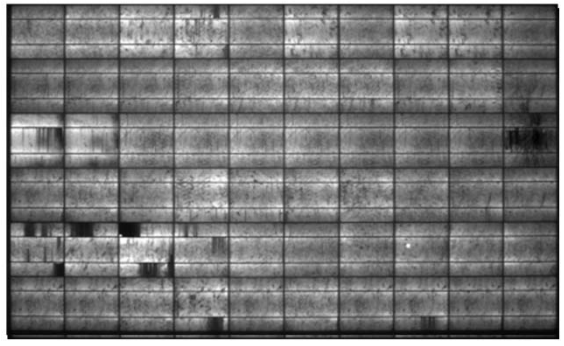
0 100 700 700 100 0

Daytime Irradiance [W/m²]

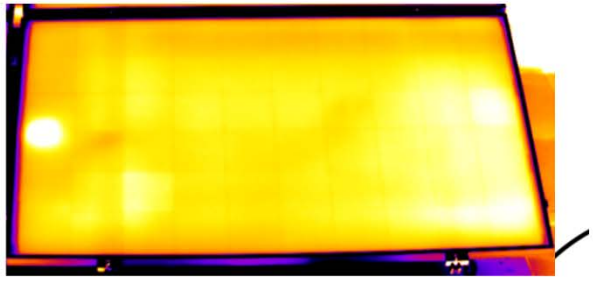
DaySy EL



8 MP Dark-Box EL



MPP Thermography



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Service Availability: Cloudy Day

Measure when YOU want: 100% availability day and night

DaySy – Self Powered EL

DaySy – EL with Power Generator

Night -EL

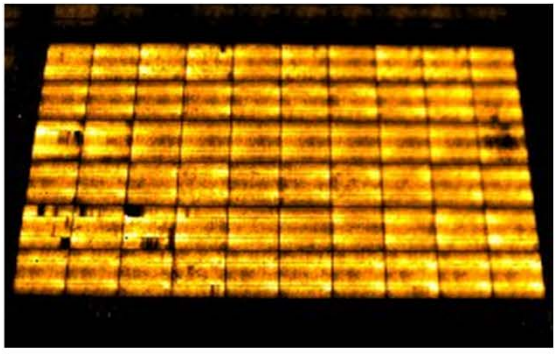
Night -EL

~~Thermography~~

0 30 200 200 30 0

Daytime Irradiance [W/m²]

DaySy EL



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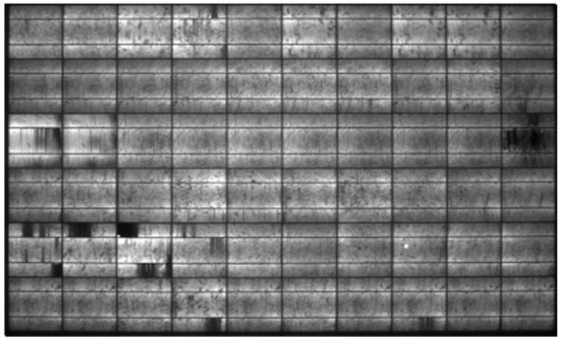
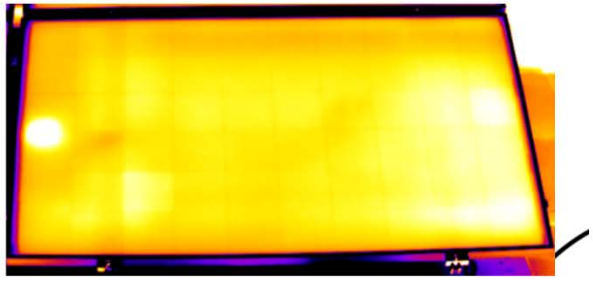


MPP Thermography



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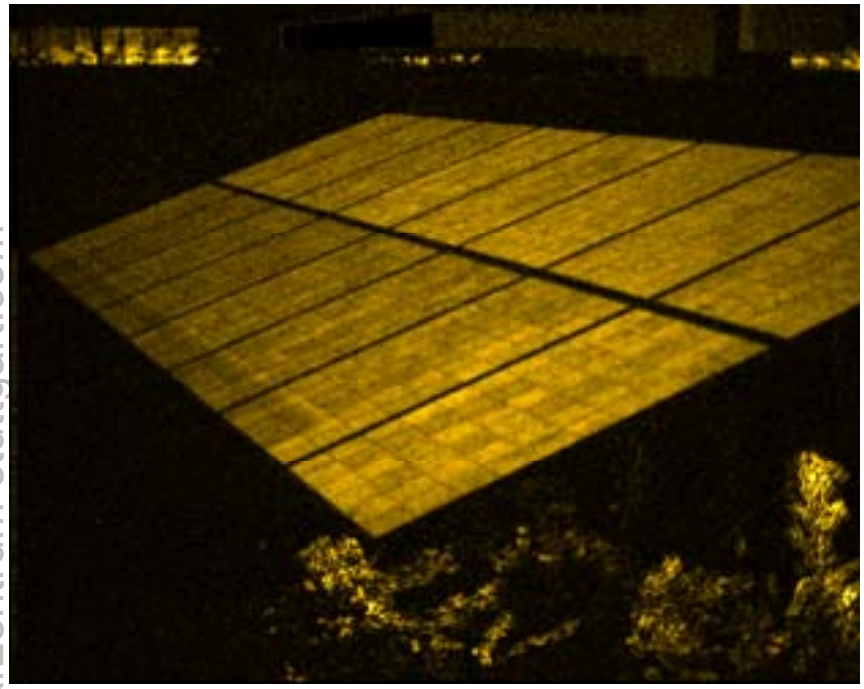
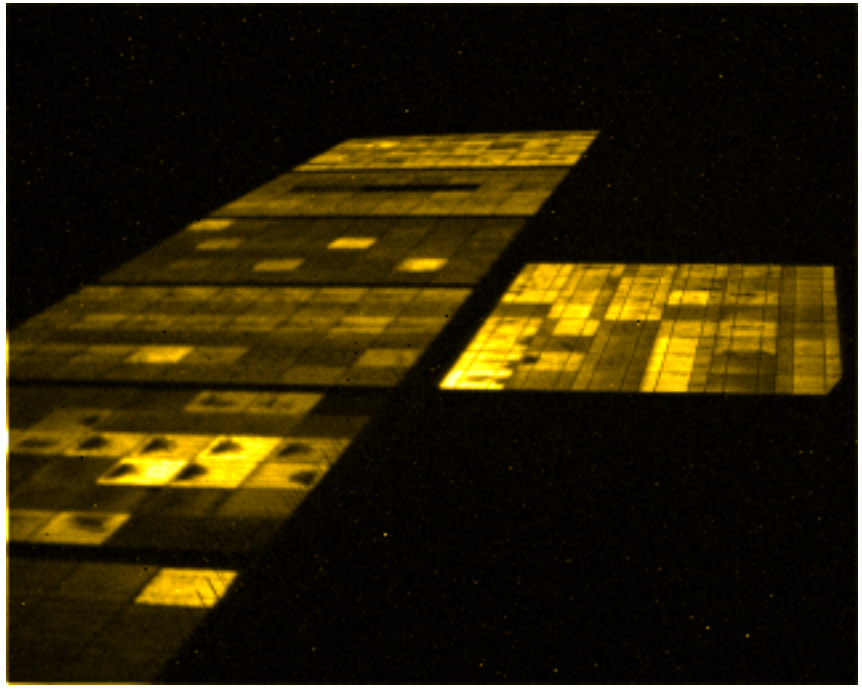
Whole String Imaging





- ✓ Potential induced degradation (PID)
- ✓ poor low light response
- ✓ damaged areas
- ✓ groups of broken fingers
- ✓ Very high throughput possible

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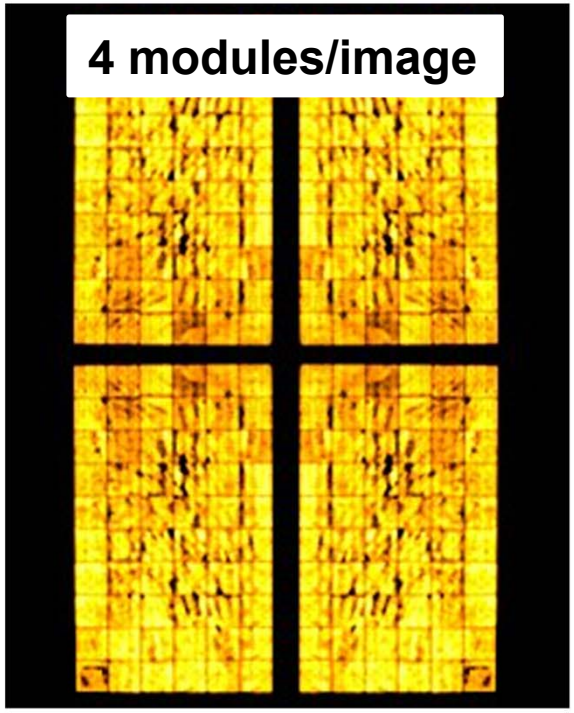
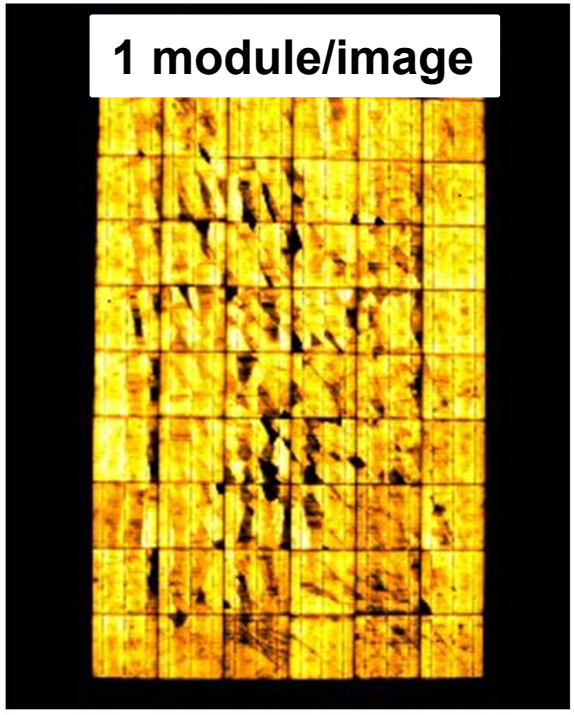
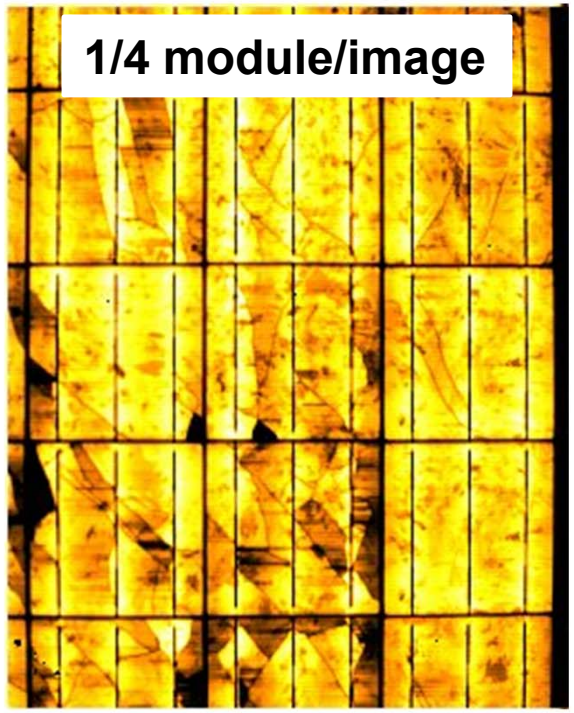
Detection Limit



- ✓ potential induced degra-dation (PID)
- ✓ damaged areas
- ✓ groups of broken fingers
- ✓ poor low light response



- ✓ groups of broken fingers



- ✓ micro-cracks
- ✓ broken fingers

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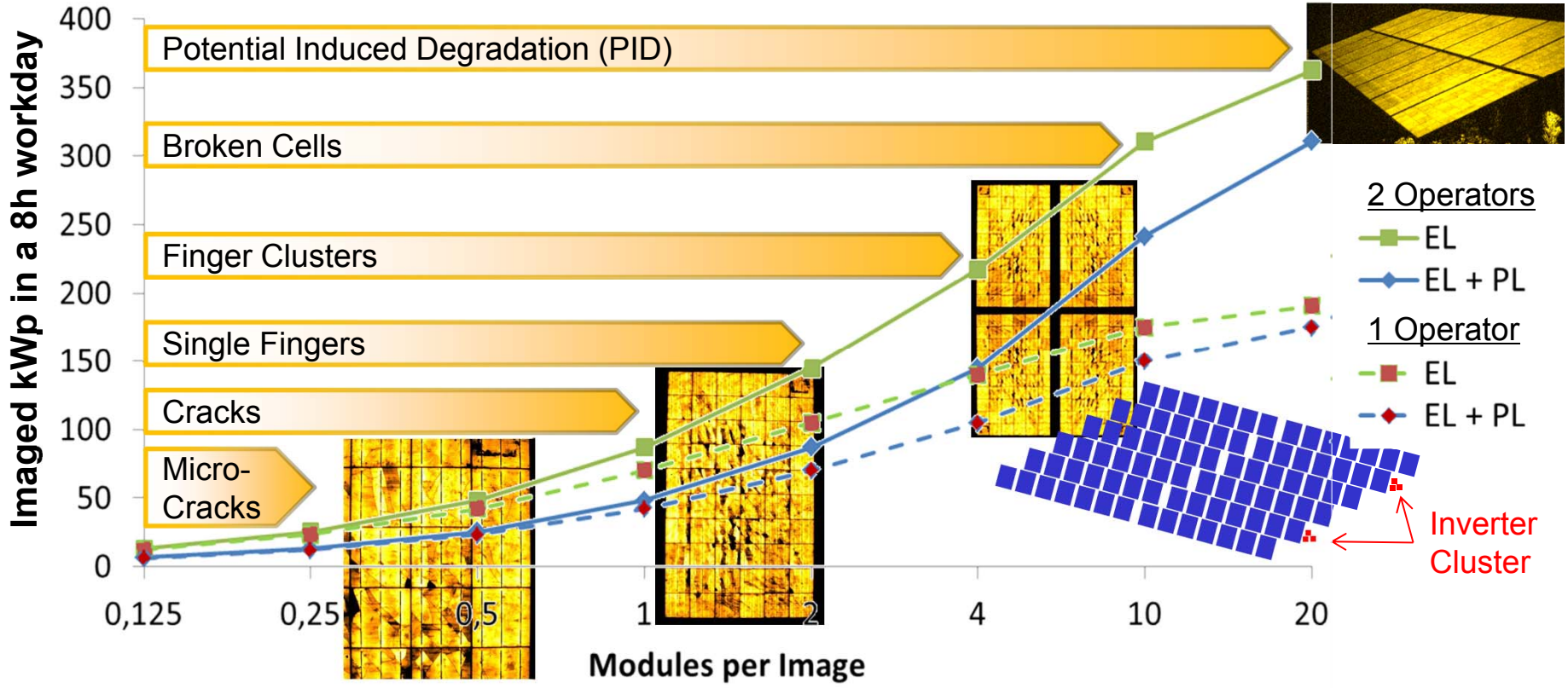
Throughput



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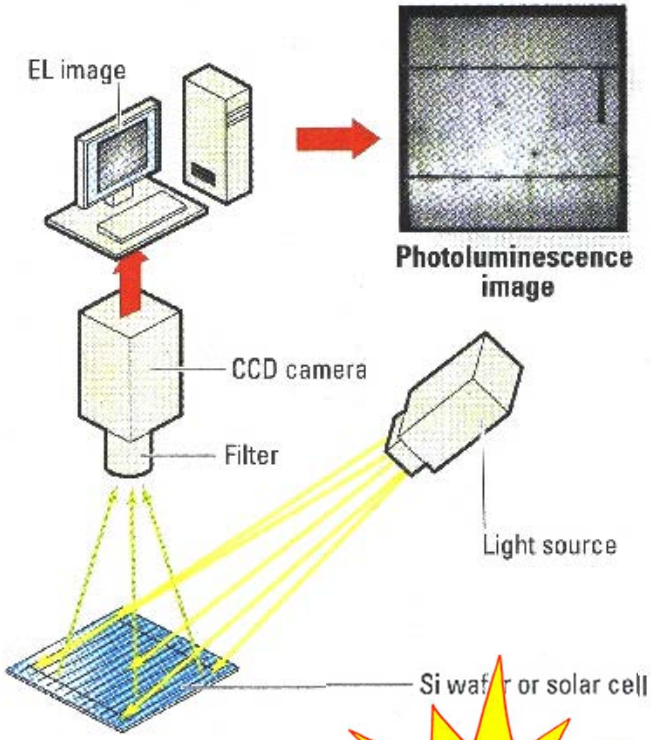
Scenario:

- Field PV installation with clustered string inverters, 250W_p modules, 20 modules/string
- Unpacking & Setup: 30 minutes; Wrap up: 15 minutes / operator
- Location of PV strings is unknown and has to be discovered: 10 min / string / operator
- 1 minute for a EL image; 2 minutes for a EL+PL image

Photoluminescence on module level



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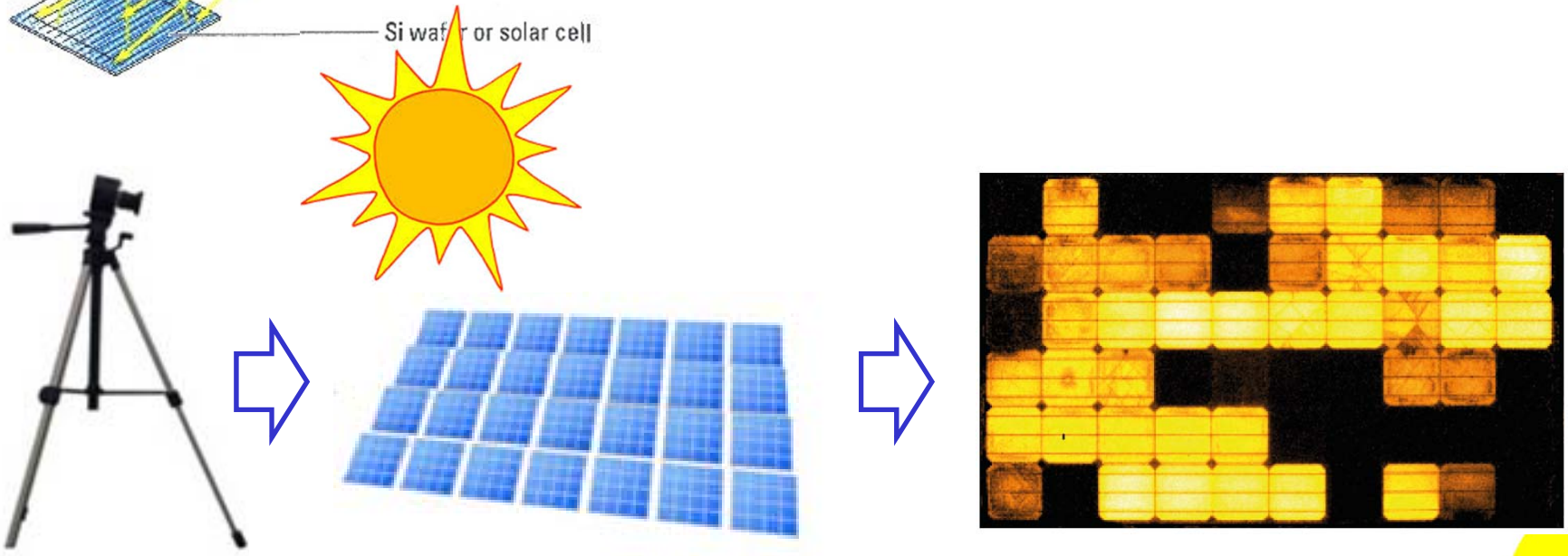
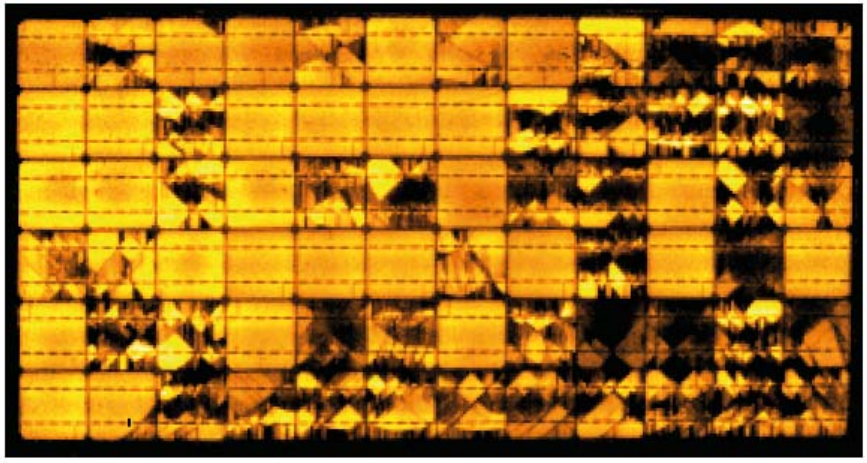
	EL	PL	Example
Ohmic	++	--	Broken fingers
R_P	--	++	PID, low light

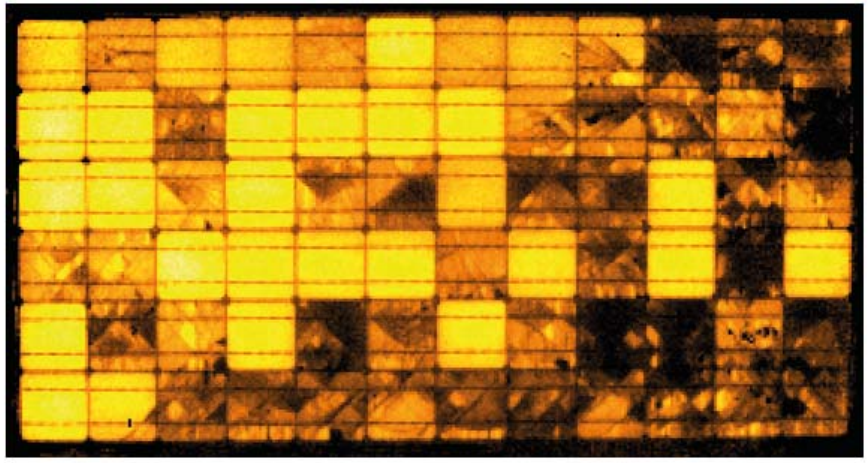


Defective Modules: Broken Cells

Electroluminescence (EL)



Photoluminescence (PL)



Badly damaged module

- Dead areas: Black EL & black PL
- High series resistance: Dark EL & regular PL
- Low parallel resistance: Dark EL

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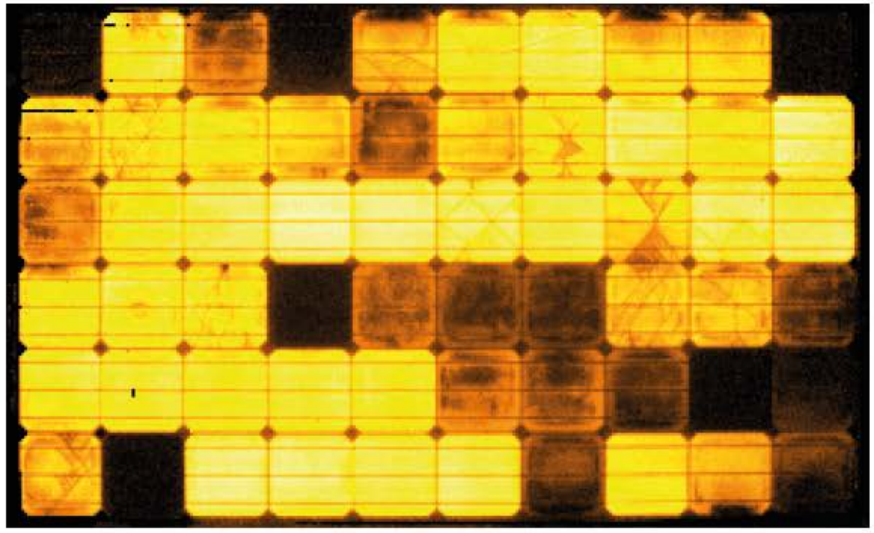
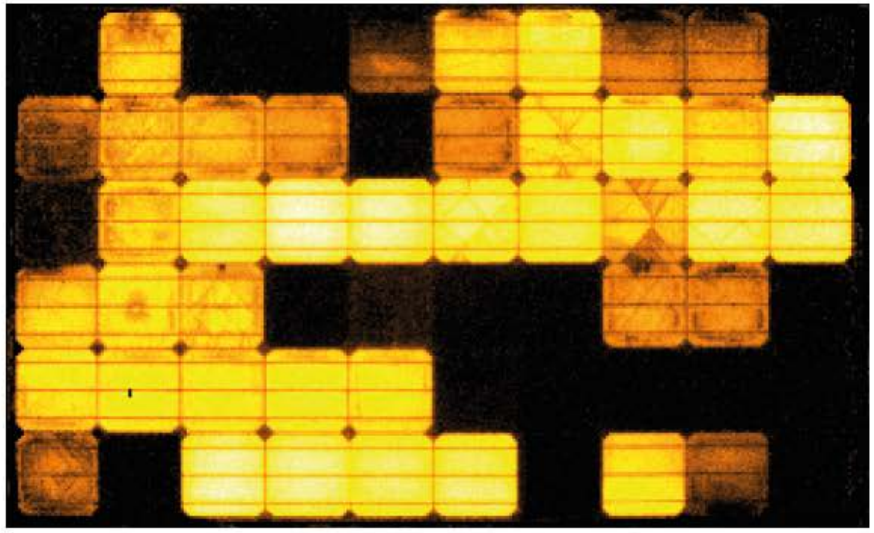
Defective Modules: PID

Electroluminescence (EL)



Photoluminescence (PL)



Potential Induced Degradation (PID)
Chessboard pattern with darker EL and black PL due to low parallel resistance.

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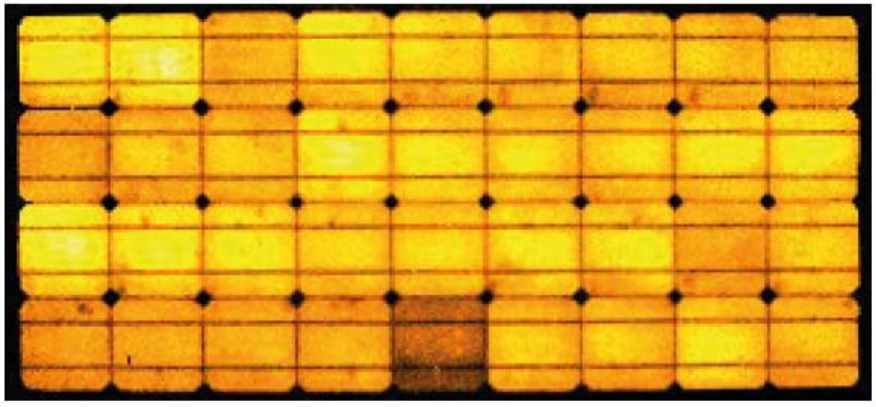
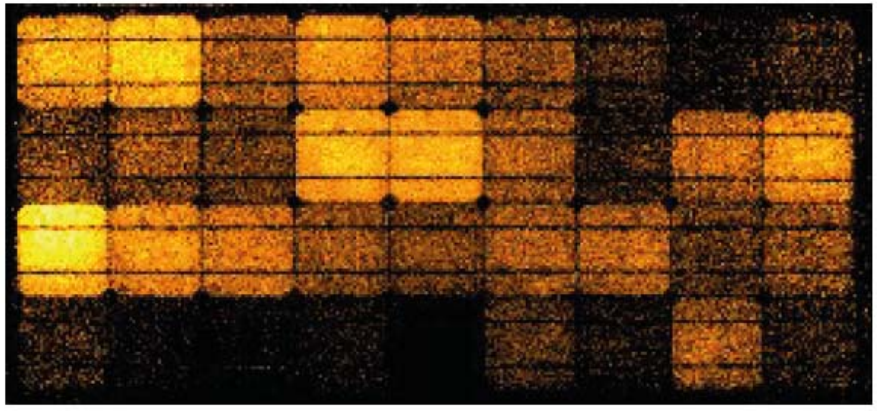
Degraded Low-Light-Response

PL at 800 W/m²



PL at 80 W/m²



Degraded low light response

Low parallel resistance reduces the open circuit voltage at low light intensities

→ Dark cells appear in low light PL image (right).

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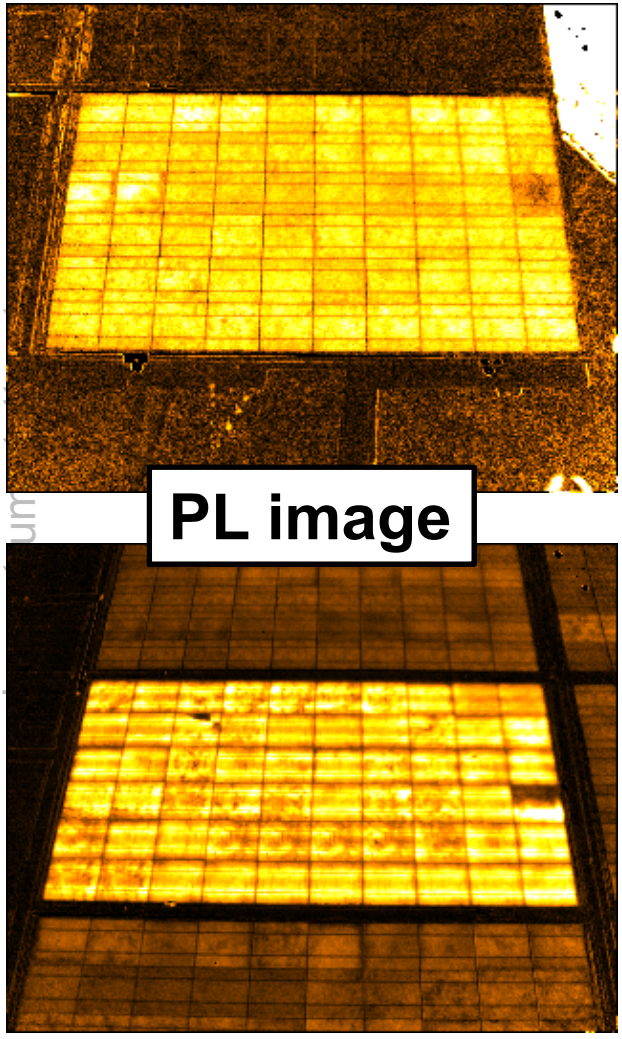
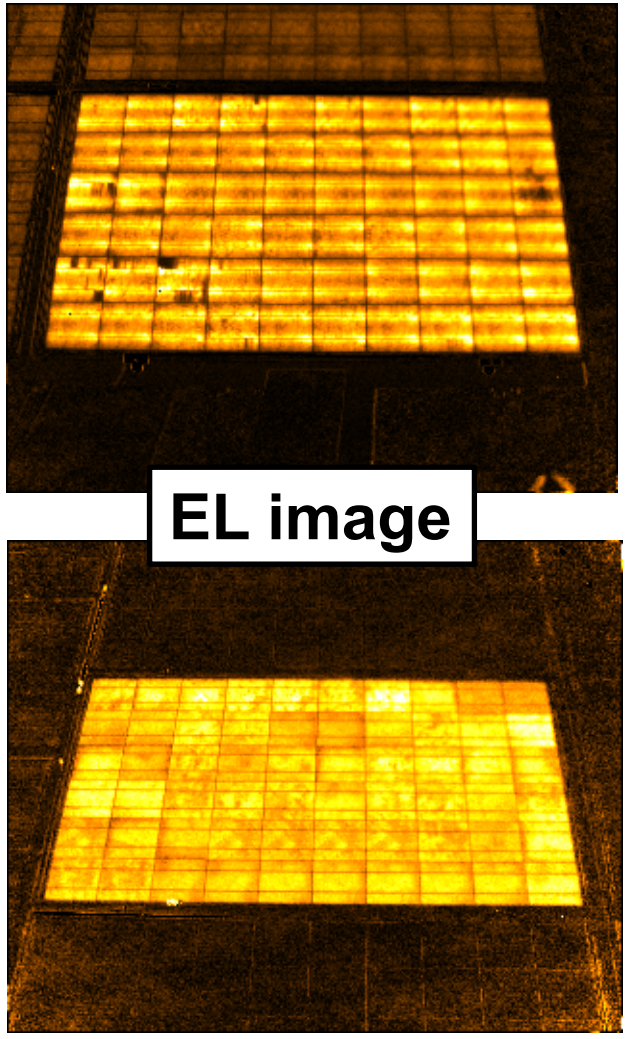
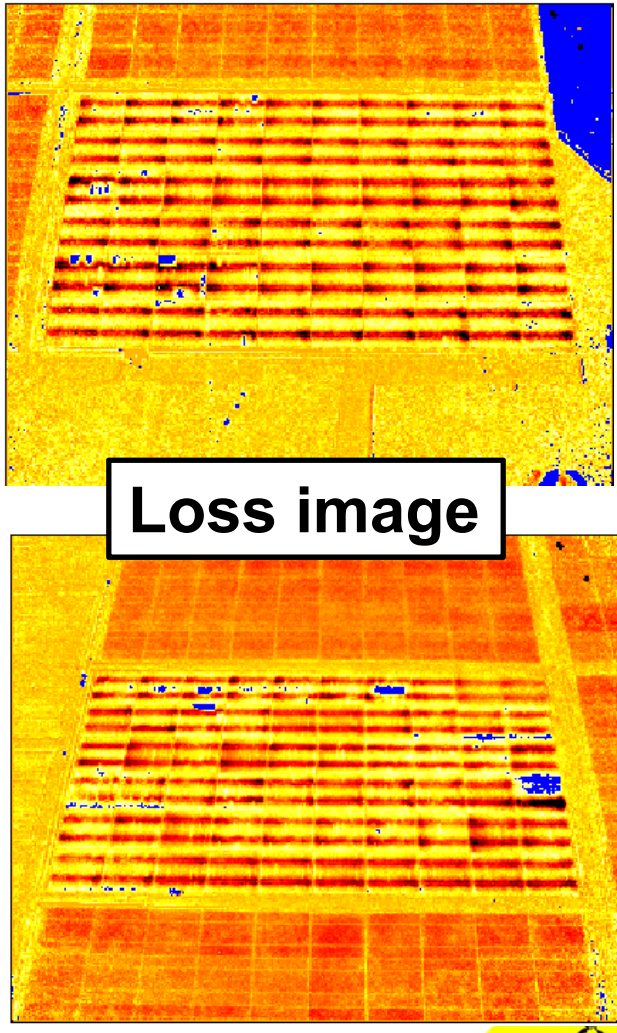
Automated Image Analysis



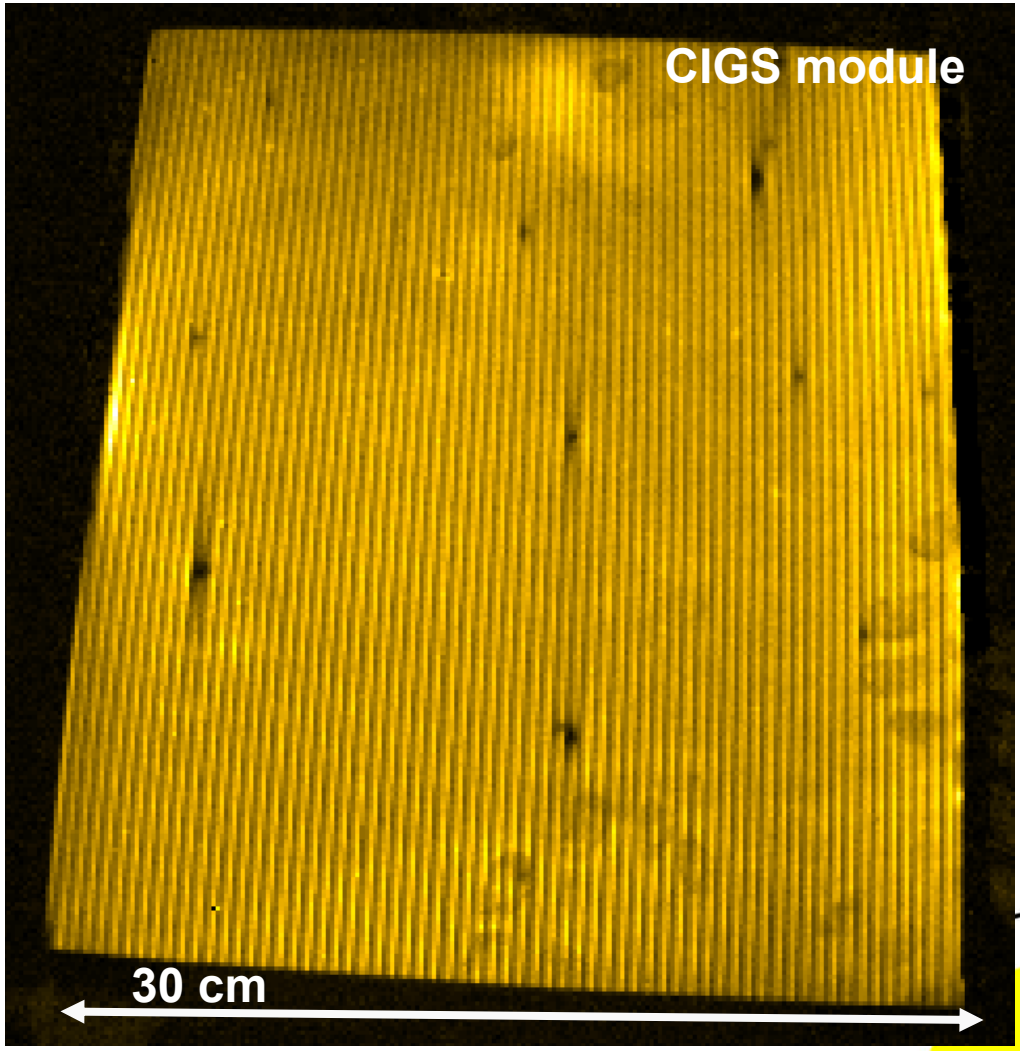




Thin film module

- a-Si
- CIGS

- CdTe coming soon…



Thanks for your attention!

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Reviewing the practicality and utility of electroluminescence and thermography images

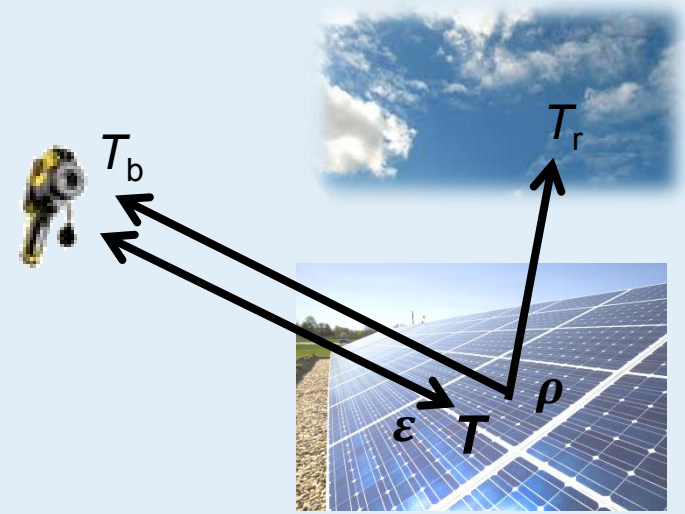
M. Köntges
Institute for Solar Energy Research Hamelin

Extract of TASK13 report
"Review on Failures of Photovoltaic Modules"
Primary authors: M. Köntges, S. Kurtz, C. Packard, U. Jahn, K. A. Berger, K. Kato, Th. Friesen, Haitao Liu, M. Van Iseghem

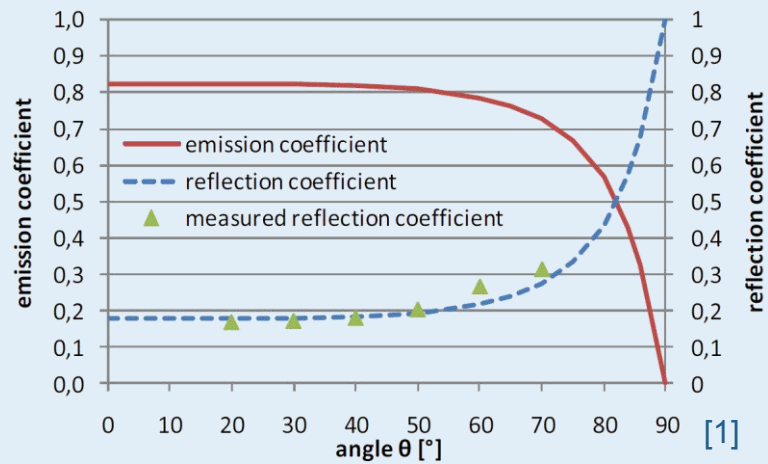
Outline

- Introduction for TG and EL, steady state and lock in techniques
- What physical quantity do we see ?
- Interpretation of the images EL/TG
- How much do the images allow to assess the reliability ?
- Application example for EL: PV module Installation

Steady state thermography (TG)



- Wavelength 8 µm - 14 µm
- Min. 700 W/m² irradiation at the module array
- Measure $\boldsymbol{T}$ in: $\boldsymbol{\varepsilon(T^4 - T_b^4) + \rho(T_r^4 - T_b^4) = 0}$
- Typical emissivity values are[1]
  0.85 for the glass
  0.95 for the polymer back sheet
- Angle of view relative to surface normal
  0° to 40° glass
  0° to 45° polymer back sheet
- Out of angle module appear too cold



[1]

[1] C. Buerhop, H. Scheuerpflug, R. Weißmann: The Role of Infrared Emissivity Of Glass on IR-Imaging of PV-Plants, Proc. 26th EUPVSEC (WIP, Hamburg, Germany, 2011), pp. 3413 – 3416
[2] C. Buerhop, D. Schlegel, C. Vodermayer, M. Nieß: Quality control of PV-modules in the field using infrared-thermography, 26th EUPVSEC (WIP, Hamburg, Germany, 2011), pp. 3894 – 3897

PVPS

ISFH

Camera position

- Chose camera height h_c so that view angle $\gamma < 40^\circ$ to normal of glass surface
- A too high position cause self reflection
- Be aware of other reflections: clouds, houses, trees
- Often high position necessary
  - ➔ Long stick
  - ➔ Lifting ramp/ladder
  - ➔ Octocopter

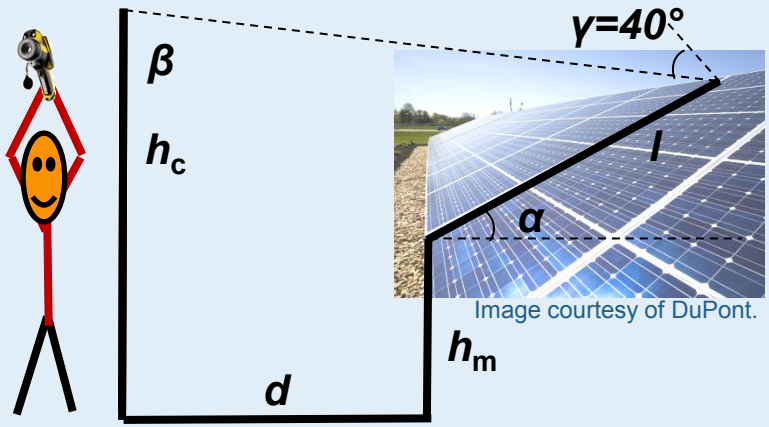
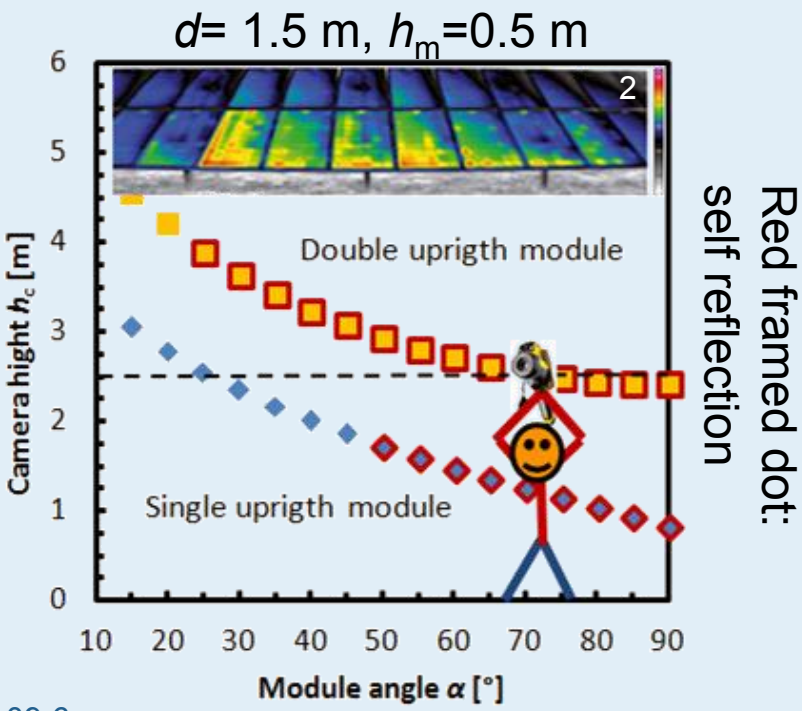
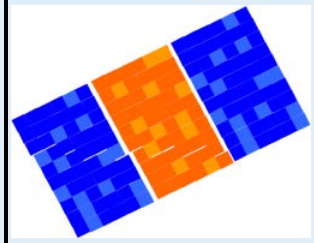
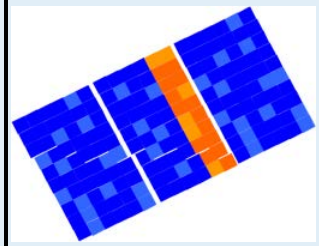
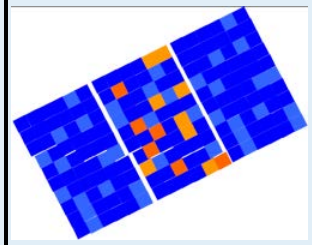
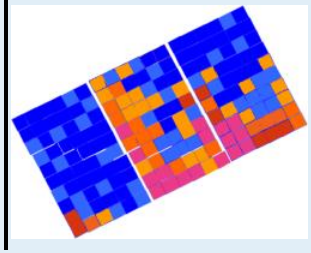


Image courtesy of DuPont.



[2] B. Weinreich, *Feldstudie zur Modul- und Generatorqualität auf Basis thermografischer Messungen über 100 MW*, Proc. 28th Symposium Photovoltaische Solarenergie (OTTI, Bad Staffelstein, Germany, 2013), ISBN 978-3-943891-09-6

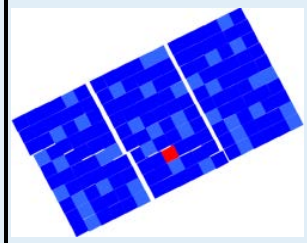
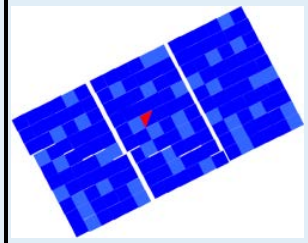
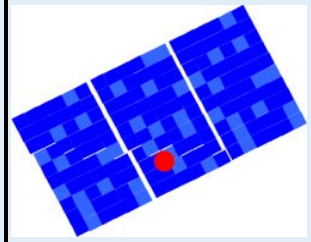
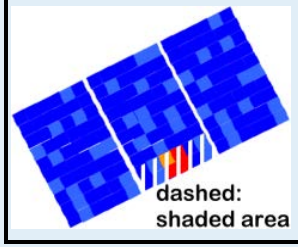
Steady state thermography and their interpretation

Pattern	Description	Possible failure reason	Electrical measurements	Remarks, Chapter
	One module warmer than others	Module is open circuited - not connected to the system	Module normally fully functional	Check wiring
	One row (sub-string) is warmer than other rows in the module	Short circuited (SC) sub-string - Bypass diode SC, or - Internal SC	Sub-strings power lost, reduction of V_{oc}	Probably burned spot at the module 6.2.7 One diode shunted
	Single cells are warmer, not any pattern (patchwork pattern) is recognized	Whole module is short circuited - All bypass diodes SC or - Wrong connection	Module power drastically reduced, (almost zero) strong reduction of V_{oc}	Check wiring 6.2.7 all diodes shunted
	Single cells are warmer, lower parts and close to frame hotter than upper and middle parts.	Massive shunts caused by potential induced degradation (PID) and/or polarization	Module power and *FF* redu-ced. Low light performance more affected than at STC	- Change array grounding conditions - recovery by reverse voltage 6.2.5 (PID)

TG outdoor

PVPS

Steady state thermography and their interpretation

Pattern	Description	Possible failure reason	Electrical measurements	Remarks, Chapter
	One cell clearly warmer than the others	- Shadowing effects - Defect cell - Delaminated cell	Power decrease not necessarily permanent, e.g. shadowing leaf or lichen	Visual inspection needed, cleaning (cell mismatch) or shunted cell 6.1.1 (delam.)
	Part of a cell is warmer	- Broken cell - Disconnected cell interconnect ribbon	Drastic power reduction, *FF* reduction	6.2.2 (cell cracks) 6.2.4 (burn marks) 6.2.6 (interconnects)
	Pointed heating	- Artifact - Partly shadowed, e.g. bird dropping, lightning protection rod	Power reduction, dependent on form and size of the cracked part	Crack detection after detailed visual inspection of the cell possible 6.2.2 (cell cracks)
	Sub-string part remarkably hotter than others when equally shaded	Sub-string with missing or open circuit bypass diode	Massive Isc and power reduction when part of this sub-string is shaded	May cause severe fire hazard when hot spot is in this sub-string

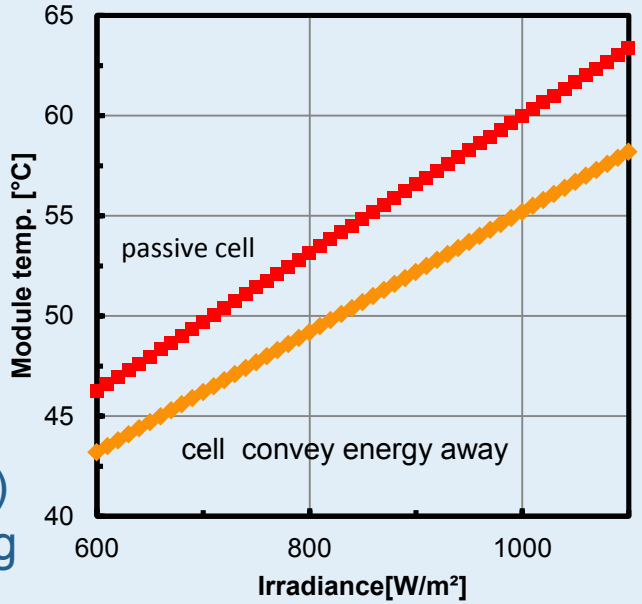
TG outdoor

PVPS

ISFH

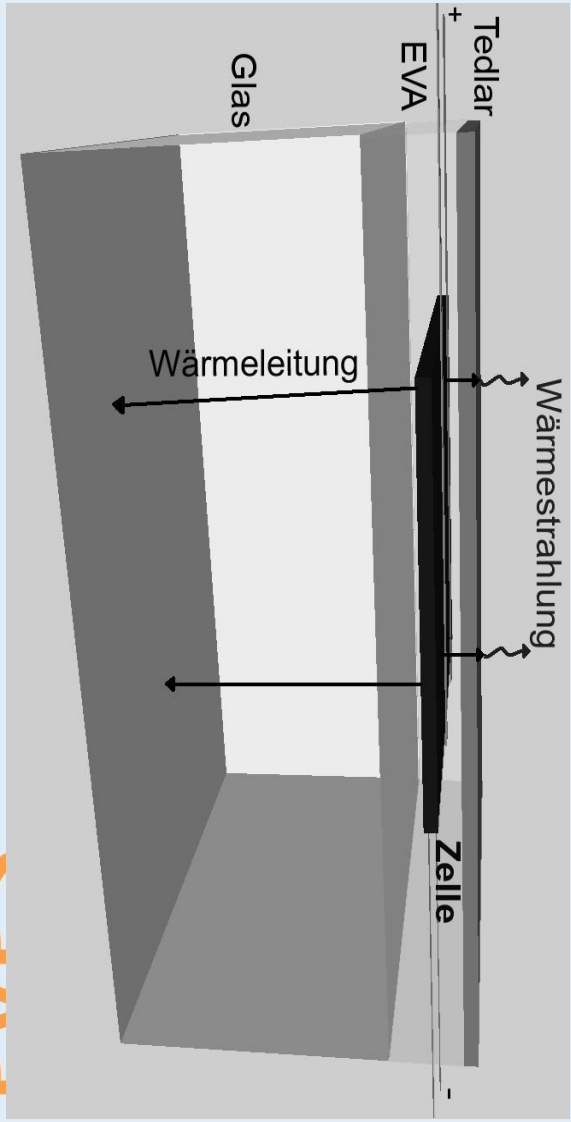
Steady state thermography (TG)

- 2.5 to 10 K temperature increase for:
  shunted by pass diode
  open circuit PV-module
  PID-cells
- Temperature difference increase with irradiation and module efficiency
- Local defects lead to great range of temperatures
- no rejection criterion defined yet (85ºC - 150ºC?)
- Steady state thermography is good for identifying relevant defects, done under working conditions



- Measurement conditions are limiting the technique
- Cheap imaging technique
- High view position necessary (increase costs)

Log-in thermography (LIT)



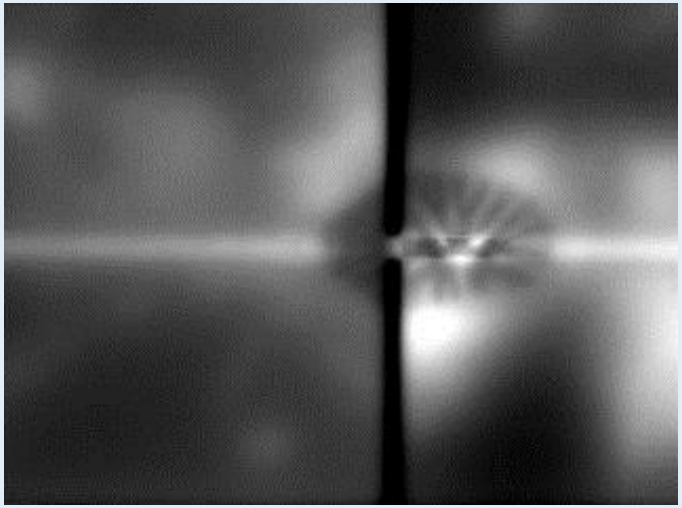
- Wavelength 8 µm up to 14 µm
- AC source to stimulate radiation
- On/off subtraction
- @ Isc ➔ overview
  @ 10% Isc ➔ test for linear shunting
- Visualize power dissipation
- Log-in frequency must be adapted to thermal diffusion length of laminate

$$f_{Lock-In} = \frac{\lambda}{2\pi \cdot \Lambda^2 \rho \, c_P}$$

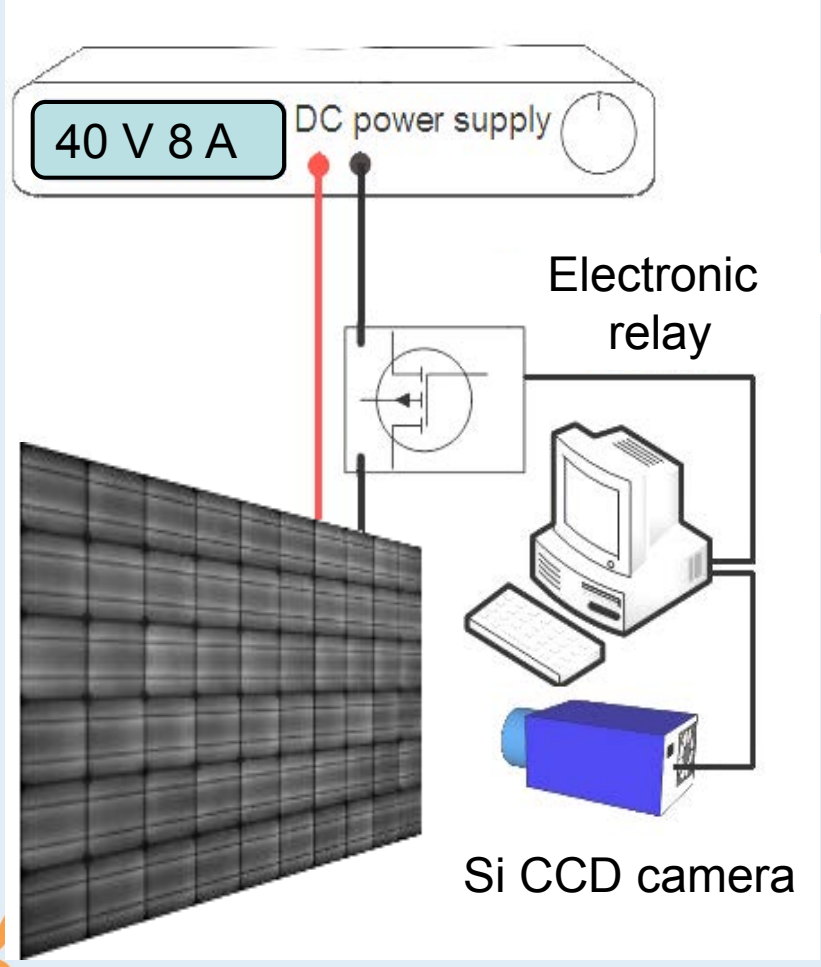
- Lock in frequency for view from backsheet: 0.1 Hz, glass: 0.01 Hz
- Reflections are unimportand

Log in thermography (LIT)

- Medium resolution
- Expensive IR camera
- Slower than EL
- Only lab tool, yet
- Can detect most failures being detectable with EL
- Good for detecting power generating defects (shunts) and invisible laminate defects



Log-in elektroluminescence (EL)

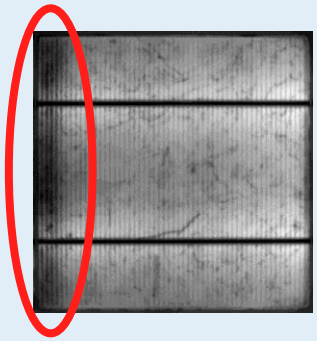


- Wavelength 1150 nm
- Current source to stimulate electroluminescence
- Optional on/off subtraction and 850 nm long pass filter to eliminate extraneous light
- @ Isc ➔ overview
  @ 10% Isc ➔ inactive cell parts, PID
- EL intensity is proportional to logarithmic voltage difference

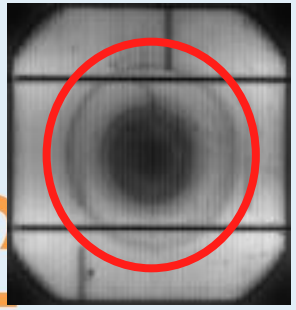
$$\Delta V = V_T \cdot \ln\left(\frac{\Phi_1}{\Phi_2}\right)$$

Features from the wafer

Crystall defects from multicrystallin wafer (multi)
Cell efficiency is higher with smaler defect area



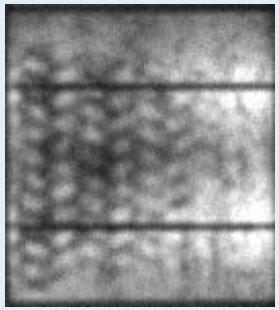
Edge Wafer (multi)
Slightly reduced cell efficiency



Striation rings (mono)
Slightly reduced cell efficiency

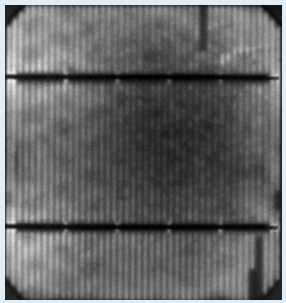
No follow up failure

Metal paste



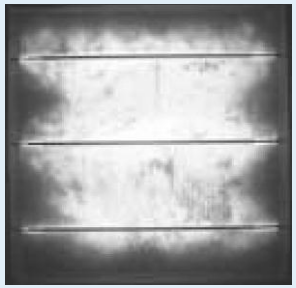
Contact formation – feature A

Temperature distribution during firing of metal paste is inhomogeneous, chain pattern of conveyor belt



Contact formation - feature B

Temperature gradient during firing of metal past from middle to edge



Humidity corrosion

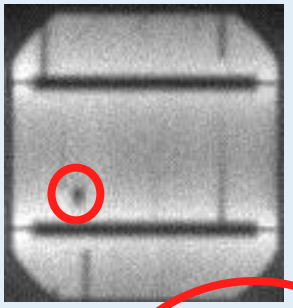
Corrosion of front finger contacts, probably due to acidic acid of laminate, rapidly reduce *FF*

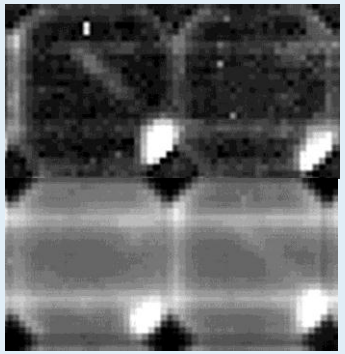
(only reported in DH test, yet)

EL

LIT

Further failure

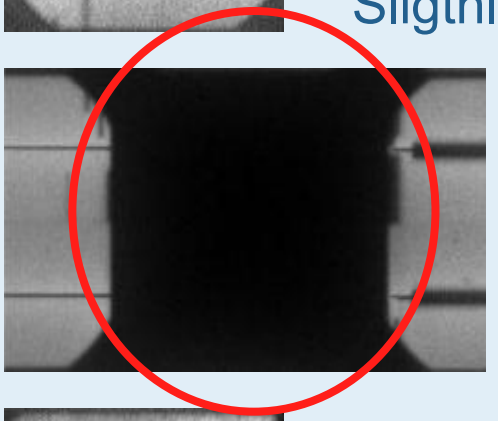


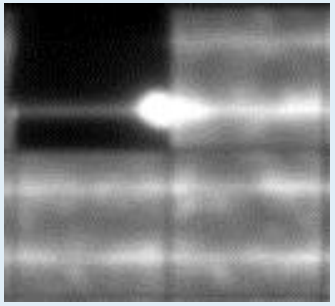


Local shunt on solar cell (validate with TG)

- Edge isolation fault
- Emitter localy defect

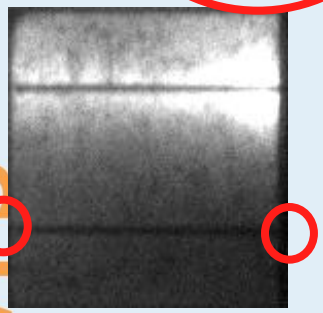
Sligthly reduce V_{oc} and *FF*, possilby hot spot

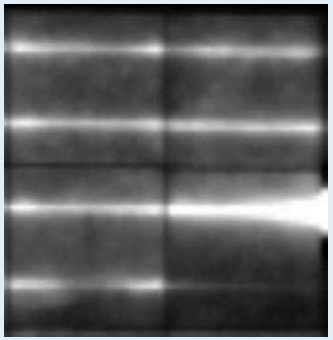




Shunt by cell interconnect ribbon

Reduction of V_{oc}





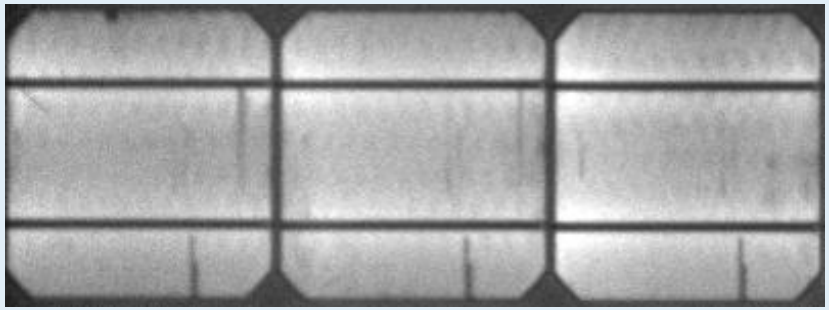
Broken cell interconnect ribbon

Smal reduction of *FF* und I_{mpp},
may generate arcing,
1/3 power loss when last ribbon breaks

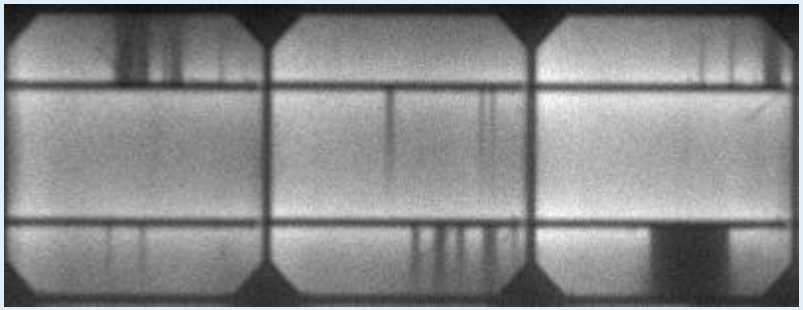
PVPS

Three classes of finger failure

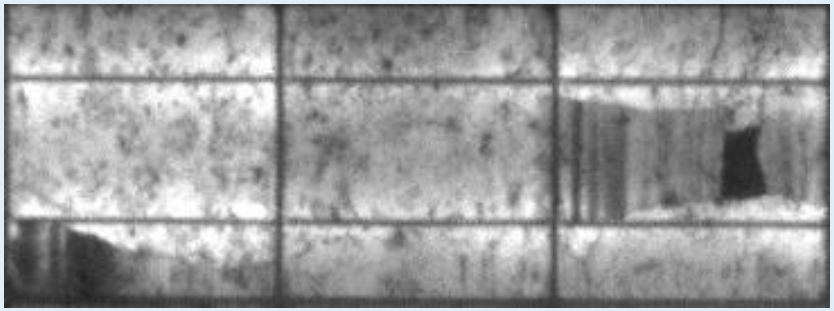
Failure by screen printing
Repeating finger interruption, typically not at cell interconnect ribbon



Failure by stringing
Irregular finger interruption at cell interconnect ribbon



Failure by cell crack
Finger interruption at cell crack, cell part isolation in progress

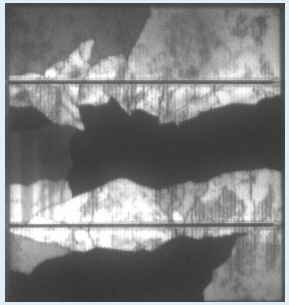


Follow up failure possible

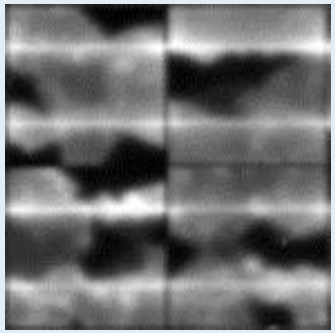
EL

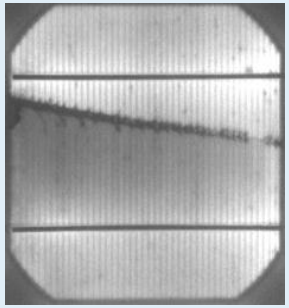
Cracks in solar cells

LIT

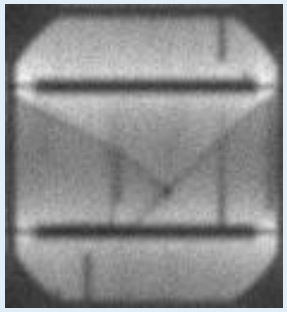


Inactive cell parts
Need to measure image @ 10% I_{sc}
decrease of *FF* and I_{mpp}

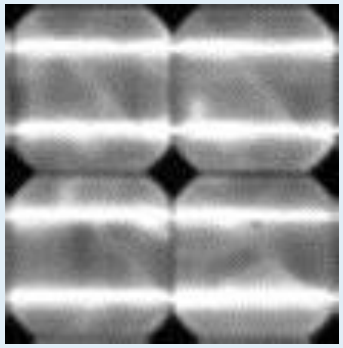




Cross crack line along multiple neighbor cells
E.g. scratching a module corner on back sheet of a PV module
May result in isolation fault, visual inspection needed



Cell cracks in solar cells
How much is the power loss ?



Köntges et al., ep
Photovoltaik aktuell 7/8 2008, S. 36

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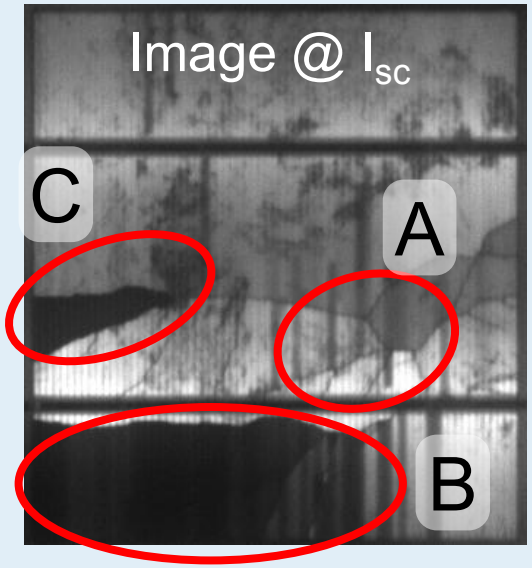
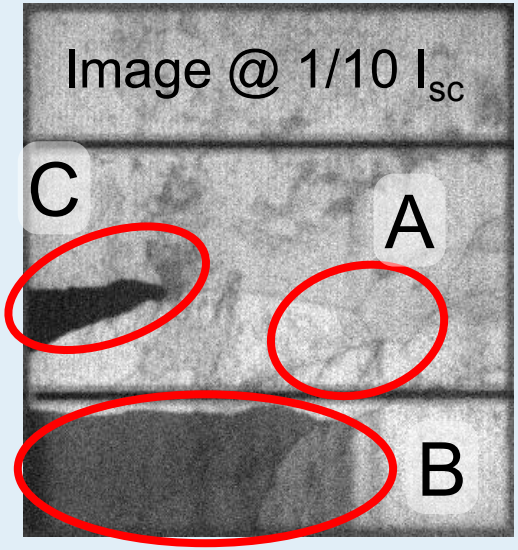
Lock-in electroluminescence (EL)



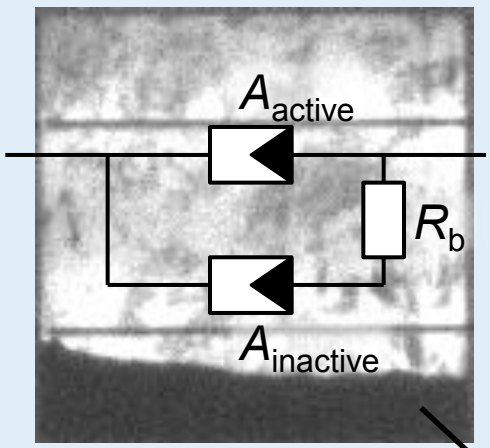


- With cooled 12 bit CCD camera detectable voltage difference: < 150 mV

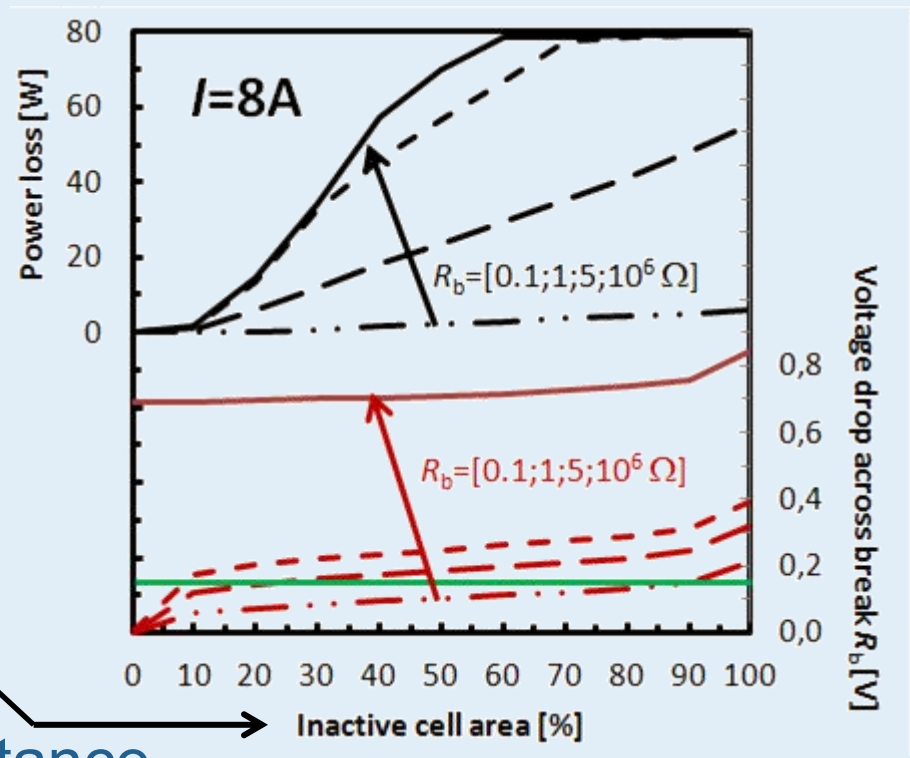
$$\Delta V = V_T \cdot \ln\left(\frac{3500}{10}\right) = 150mV$$

- Voltage drop at break resistance is less at lower current
- Therefore low current image is more sensitive to isolated parts

Spice simulation[1] of voltage drop over break resistance R_b



60 cells 228 W PV module



- At I=8 A one **can not** detect if the break resistance is high enough to generate power loss

[1] M. Köntges, I. Kunze, S. Kajari-Schröder, X. Breitenmoser, B. Bjørneklett, Solar Energy Materials & Solar Cells **95** (2011), pp. 1131–1137

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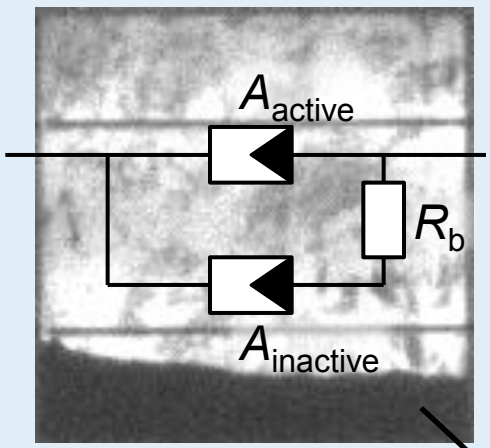
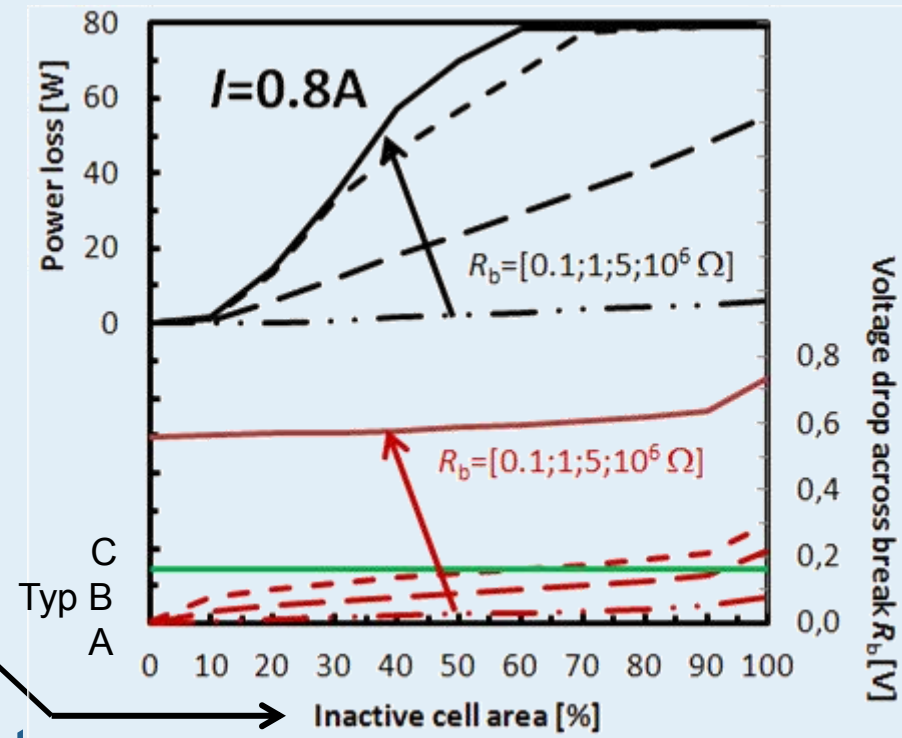
Spice simulation[1] of voltage drop over break resistance R_b



60 cells 228 W PV module



- At I=0.8 A one **can** detect if the break resistance is high enough to generate power loss

[1] M. Köntges, I. Kunze, S. Kajari-Schröder, X. Breitenmoser, B. Bjørneklett, Solar Energy Materials & Solar Cells **95** (2011), pp. 1131–1137

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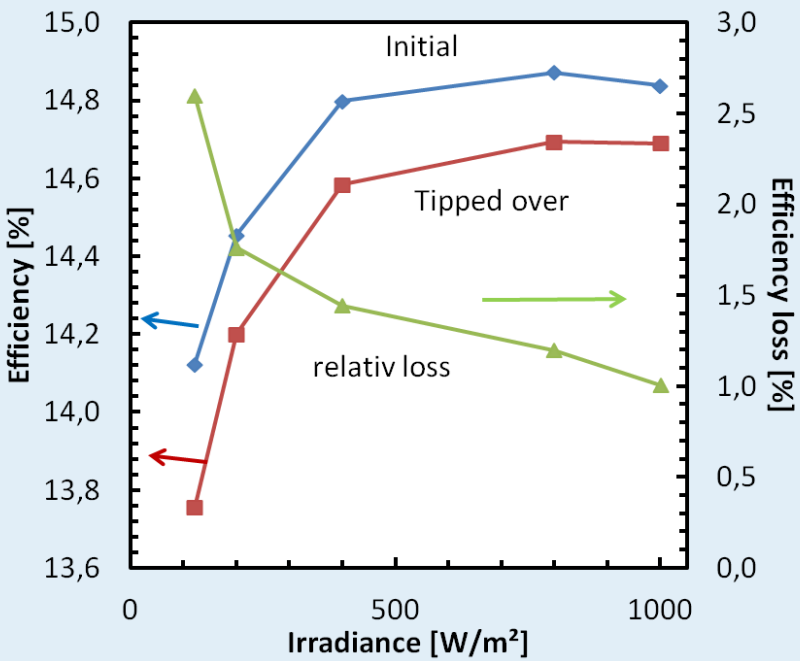
Power loss of PV module with lots of typ A cracked cells at low light conditions



- Typ A cell cracks behave like shunts
- Low intensity efficiency is more influenced (2.6%) than high intensity efficiency (1.0%)
- Weighted assessment with European efficiency definition for inverters
- $\eta_{Euro} = 0{,}03 \times \eta_{05\%Pn} + 0{,}06 \times \eta_{10\%Pn} + 0{,}13 \times \eta_{20\%Pn} + 0{,}10 \times \eta_{30\%Pn} + 0{,}48 \times \eta_{50\%Pn} + 0{,}20 \times \eta_{100\%Pn}$
- Production for this PV module reduced by approx. 1.7%

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Electroluminescence (EL)

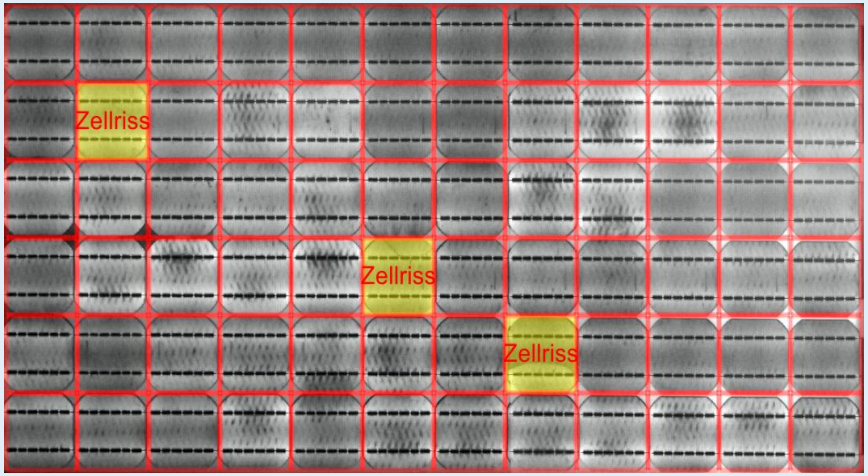
- High resolution
- Cost efficient Si CCD camera for dark environment
- Very expensive camera for daylight imaging
- Fast image recoding
- Often difficult to differentiate between feature and failure
- Automation of failure detection only for production possible
- “Failure cells” are detectable by deviation from mean intensity, but a human has to classify further

- For much more detectable failure and more explanations ➔read TASK13 report

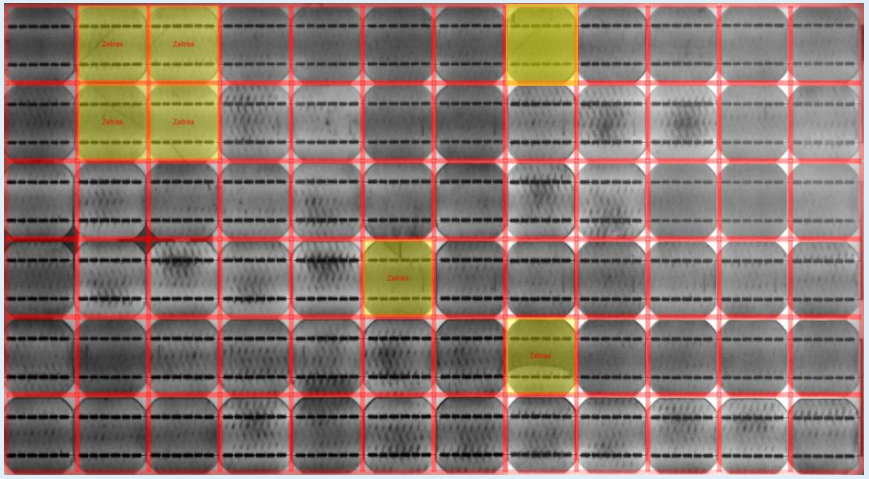
Application example: checking typical handling faults

PV module falls back to stack 20 cm while de-stacking

EL before:



EL after:



Power before:

169,4 Wp

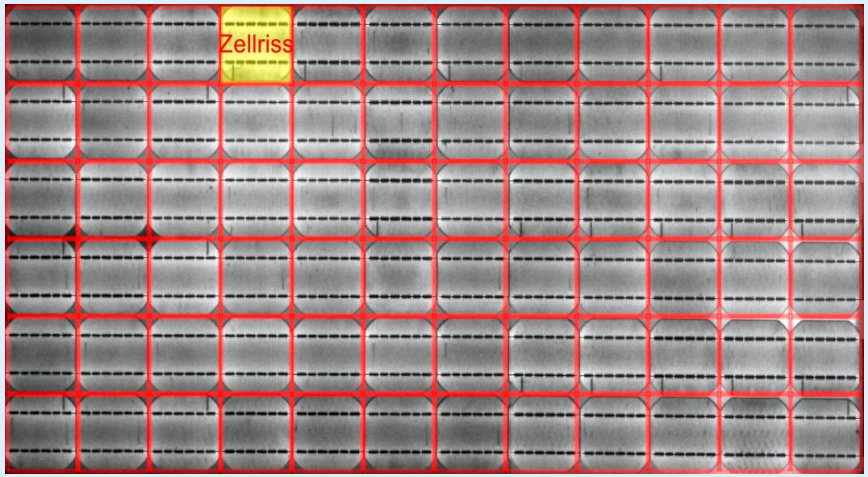
Power after:

169,5 Wp

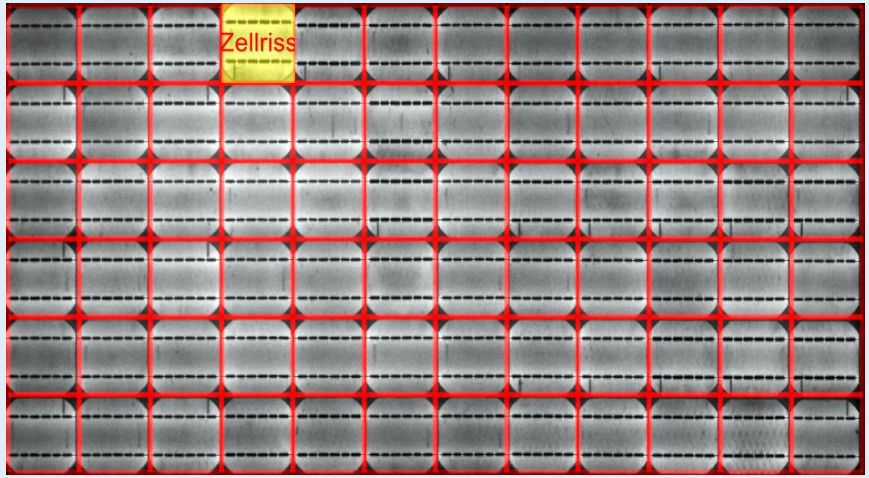
- 4 cell cracks typ A, no power loss

PV module fall down on long side edge 20 cm

EL before:



EL after:



Power before:

171,0 Wp

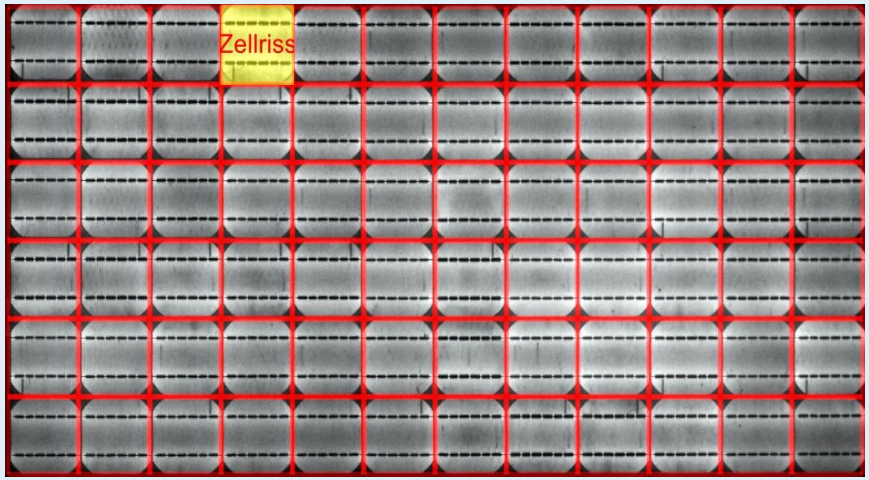
Power after:

171,2 Wp

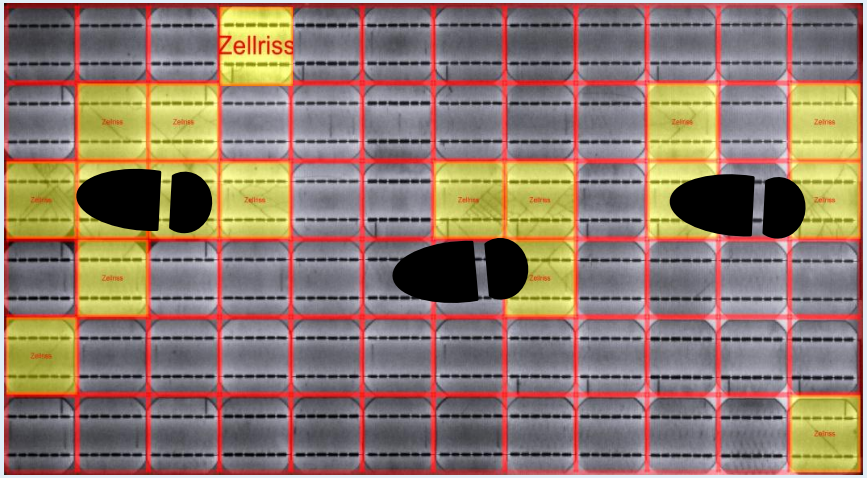
- No cell cracks, no power loss

Walk on sunny side of PV module

EL before:



EL after:



Power before:

171,2 Wp

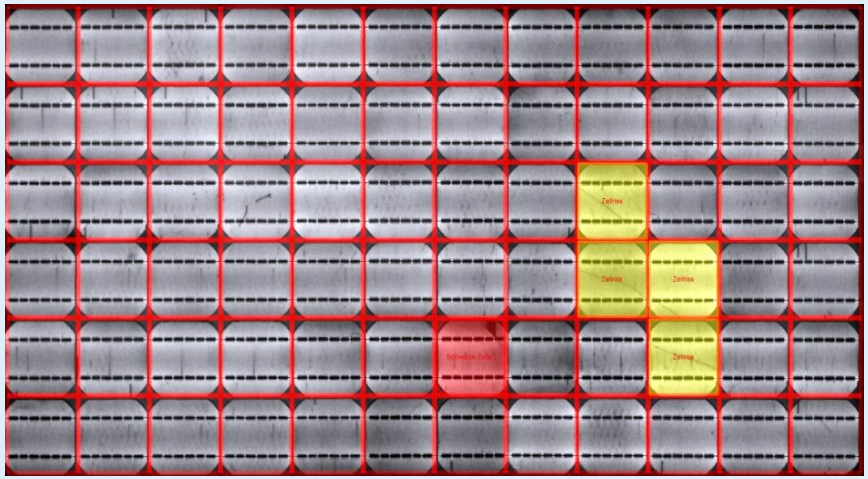
Power after:

170,3 Wp

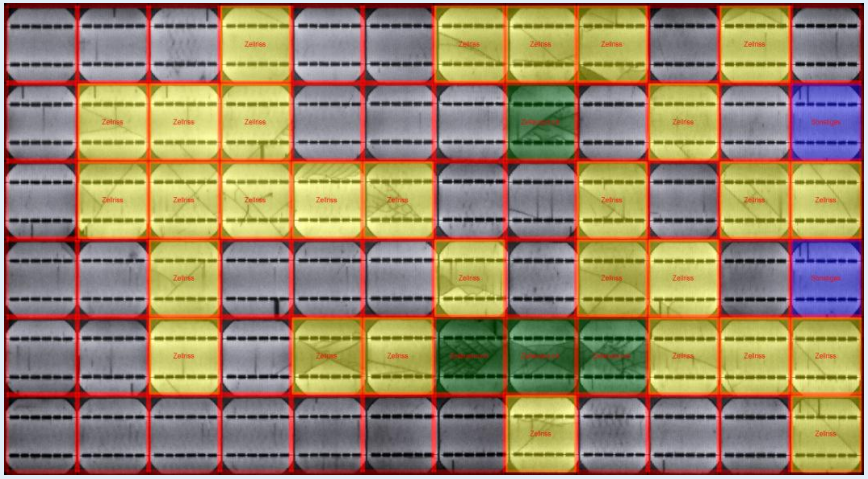
- 16 cell cracks typ A, 1 W power loss

Tiped over module from vertical position on rear side

EL before:



EL after:



Power before:

172,2 Wp

Power after:

170,3 Wp

- 30 cell cracks typ A incl. 4 dendritic cell cracks + 1 typ B, 2 W power loss

Summary:

- Steady state TG is a cheap technique for failure detection in the field, but is strongly restricted by weather conditions
- LIT shows similar defects like EL, but is more expensive and has lower resolution. Strong in stunt detection and hidden laminate bubbles
- EL can detect most defects, often difficult to differentiate between failures and effects, inexpensive technique
- EL for outdoor same advantages like indoor, but quite expensive technique

- TASK13 report “Review on Failures of Photovoltaic Modules” will be available in April 2014

PVPS

Supported by:

Federal Ministry
for the Environment, Nature Conservation,
Building and Nuclear Safety

based on a decision of the German Bundestag

Thanks for financial support:

State of Lower Sachsony and BMUB under contract number FKZ 0325194C.

ISFH

Ongoing standardization:

- Udo Siegfriedt und Eva Schubert, Deutschen Gesellschaft für Sonnenenergie (DGS) e.V. is working on a German standard on “Thermographic tests of PV-modules and plants“
- Bengt Jäckel, Renewable Energies UL International: Suggestion to put together characterization methods for PV modules under one IEC number in two general parts: Non destructive (e.g. VIS, EL, TG, PL, …) and destructive methods (EVA cross linking …)
- Peter Hacke, NREL: preparing IEC initial drafts for EL and TG until June 14
  - goal: support other standards and tests
  - scope: provide some metrics for the interpretation of images

Thank you for your attention

PV Inverter Performance and Component-Level Reliability

Jack Flicker, PhD
Sandia National Laboratories
Postdoctoral Appointee

Thursday, February 27, 2014

"Exceptional Service in the National Interest…"

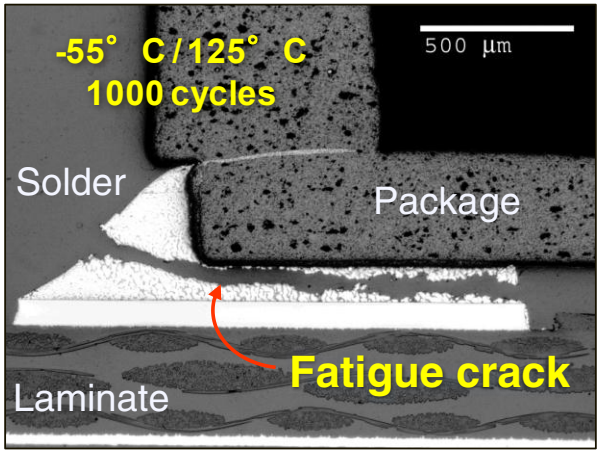
Outline

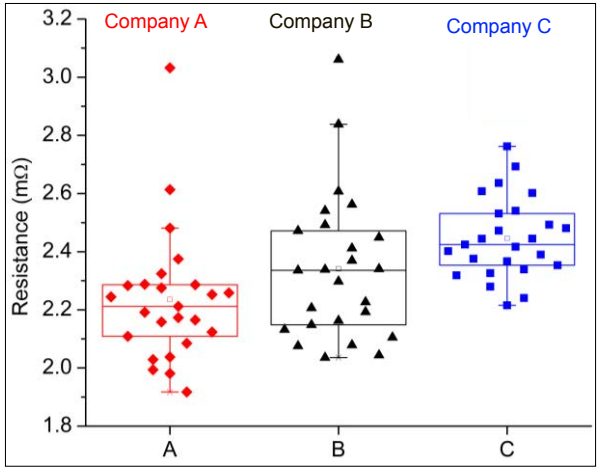
- Inverter Introduction and operation
- PV Inverter Component-Level Reliability
  - Bus Capacitors
  - IGBTs/MOSFET switches
- Future of Inverter Reliability
  - High DC/AC Ratios
  - VAR support
  - Widebandgap devices
  - Microinverter/converter reliability

Sandia PV Reliability Program

PV reliability program spans the spectrum from materials to systems

Focus on Balance of Systems (BOS)





Solder Joint Degradation

Connector Reliability

Inverter Thermal Performance

Advanced Inverter Function

Ground Fault

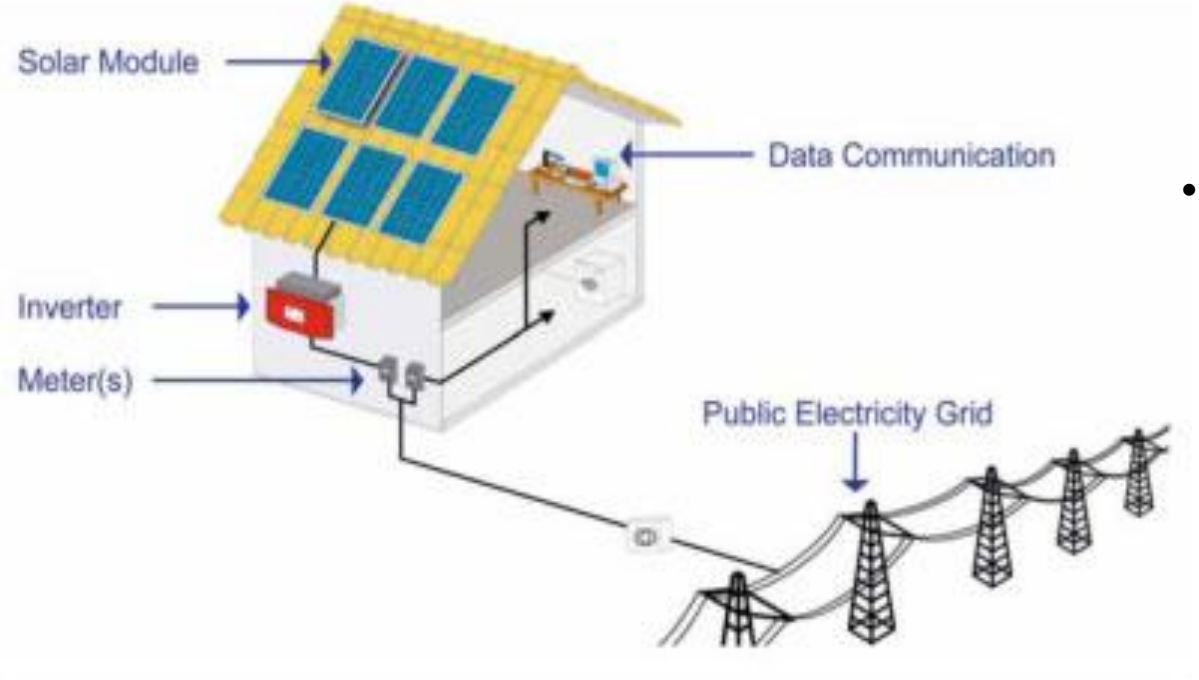
Arc Fault

O & M

Materials | Components | Sub-system | System

Capacitor, IGBT, WBG

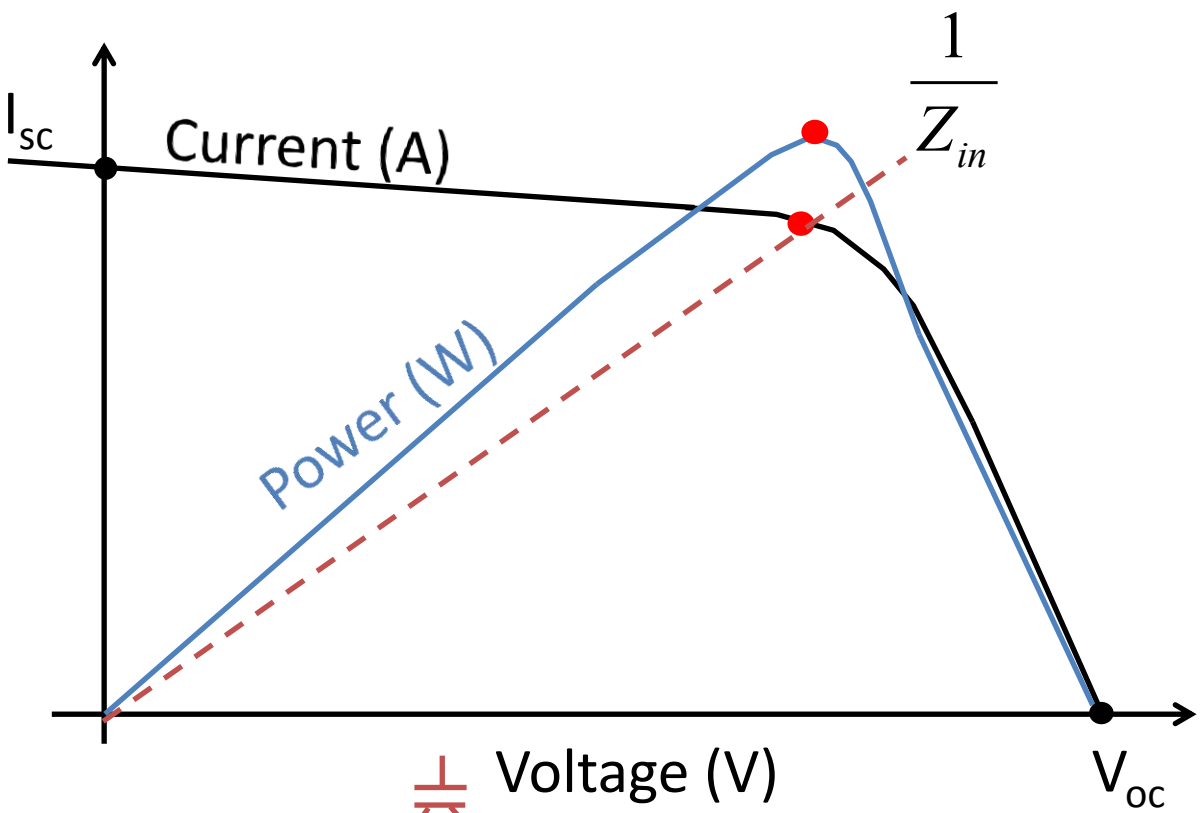
PV Inverter Introduction

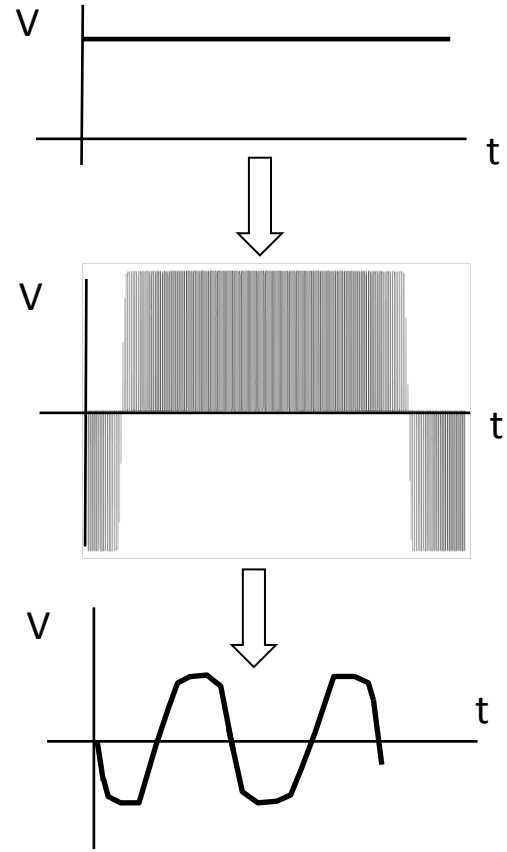


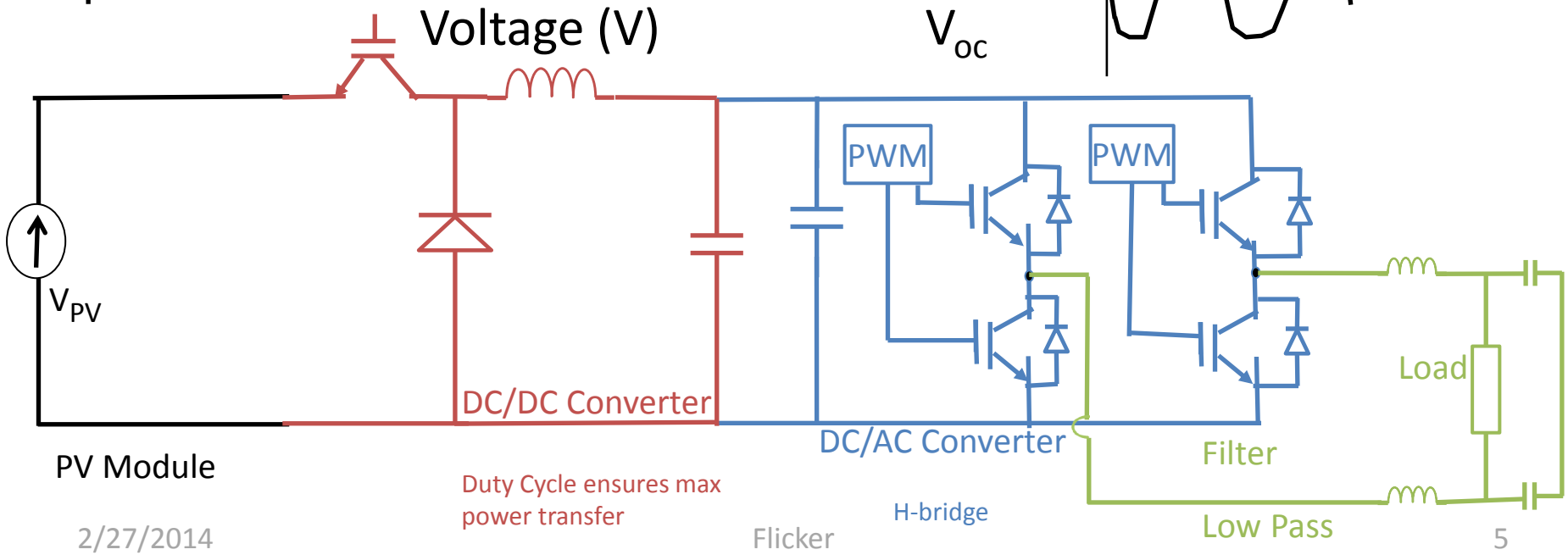
- DC/AC Conversion
  - Maximum power transfer
  - Power quality

- 3 major classes (3 orders of magnitude):
  - 500 kW (utility scale)
  - 5 kW (residential scale)
  - 250 W (microinverter)

- Many various topologies
  - Single/multi-stage
  - Isolated/non-isolated
  - single-/three-phase

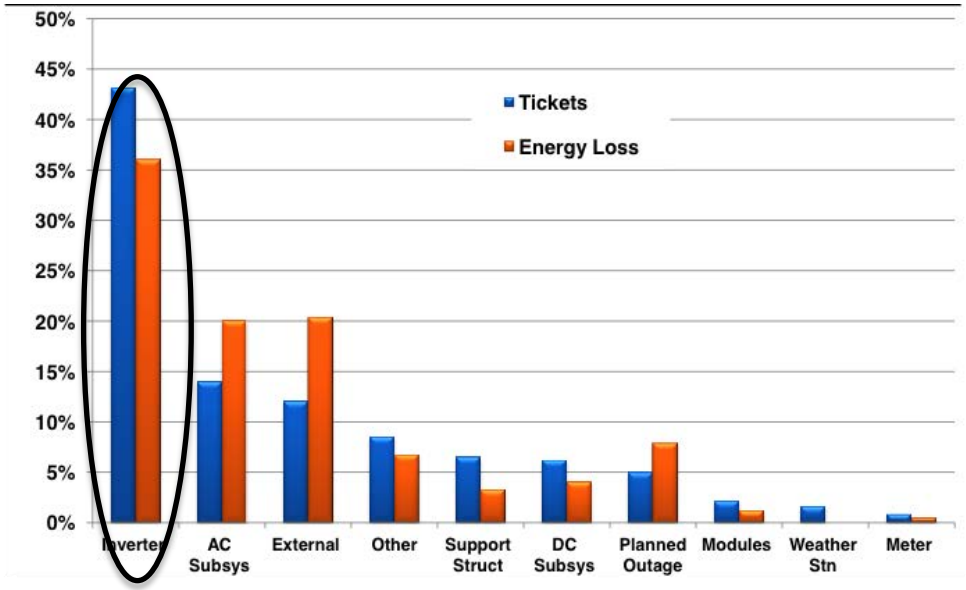

I_{sc}
Current (A)
$\frac{1}{Z_{in}}$
Power (W)
Voltage (V)
V_{oc}


V
t
V
t
V
t


V_{PV}
PV Module
DC/DC Converter
Duty Cycle ensures max power transfer
PWM
PWM
DC/AC Converter
H-bridge
Filter
Low Pass
Load

Current Inverter Reliability Capacitor

- Most research focuses on cost reductions in modules
  - Power electronics now 8-12% of lifetime PV cost ($0.25/W)
  - Well above DOE goal of $0.10/W by 2017



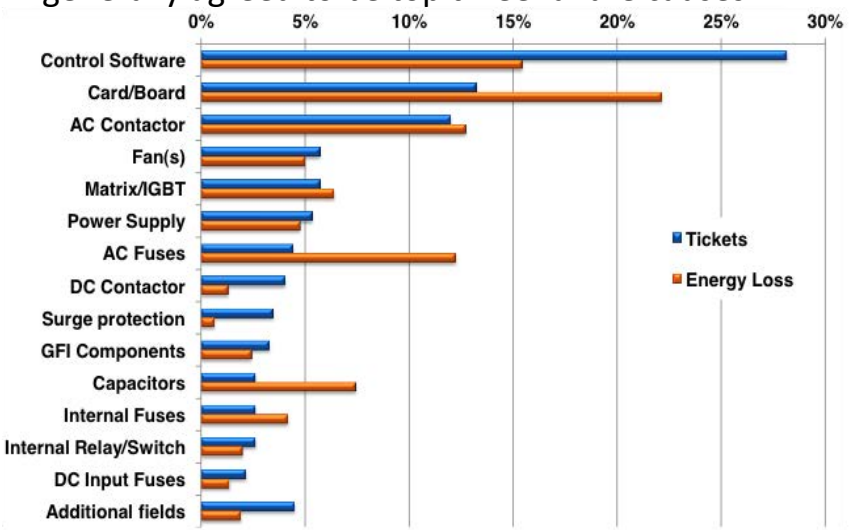
- One reason Reliability
  - Repair/replace multiple times over system lifetime
  - SunEdison says inverter 36% of energy losses from inverter

A. Golnas, "PV System Reliability: An Operator's Perspective," in 38th Photovoltaic Specialists Conference, Austin, TX, Jun. 2012, pp. 1–32.

- Inverters are complicated machines
  - Variable Irradiance/Temperature
  - Power Conditioning
  - Grid Monitoring
  - Array reporting/monitoring
  - VAR management
  - Islanding protection, etc.

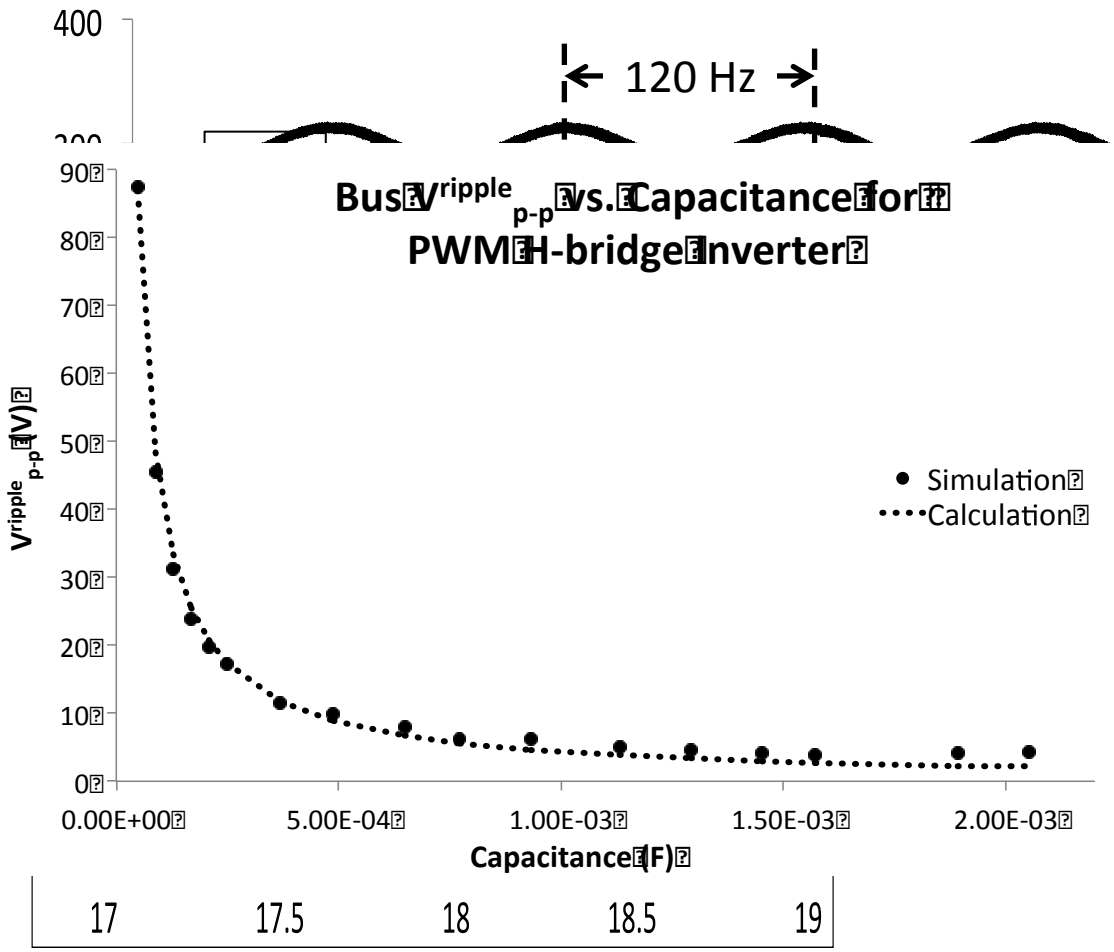
- Must endure harsh environments (humidity, corrosive) with large temperature cycles (ambient and power handling)

- Much disagreement about specific failure mechanisms, but capacitors, PCB, and semiconductor switches generally agreed to be top three failure causes



U.S.Dept. of Defense, *Reliability Prediction of Electronic Equipment Military Handbook 217F, Feb. 28, 1995.*

Current Inverter Reliability Capacitor



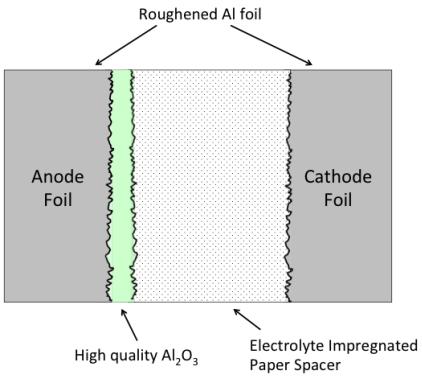
- Bus and load voltage of a simulation shows ripple on DC bus for 250μF capacitor
- AC ripple with frequencies 120Hz and 10kHz due to IGBT switching
  - Much easier to filter
- Ripple as a function of C_{bus} shows 1/C dependence

$$V_{p-p}^{ripple} = \frac{V_{PV}}{32 \times C_{bus} \times L \times f_{PWM}^2}$$

- Diminishing returns for C_{bus}>500μF
- Typically tens of volts (peak to peak) in inverter circuit

Current Inverter Reliability Capacitor

Electrolytic Capacitors



Advantages
- Well characterized behaviors and lifetimes
- Relatively inexpensive ($0.0045/µF, linear)
- Large capacitance per volume (Compact)

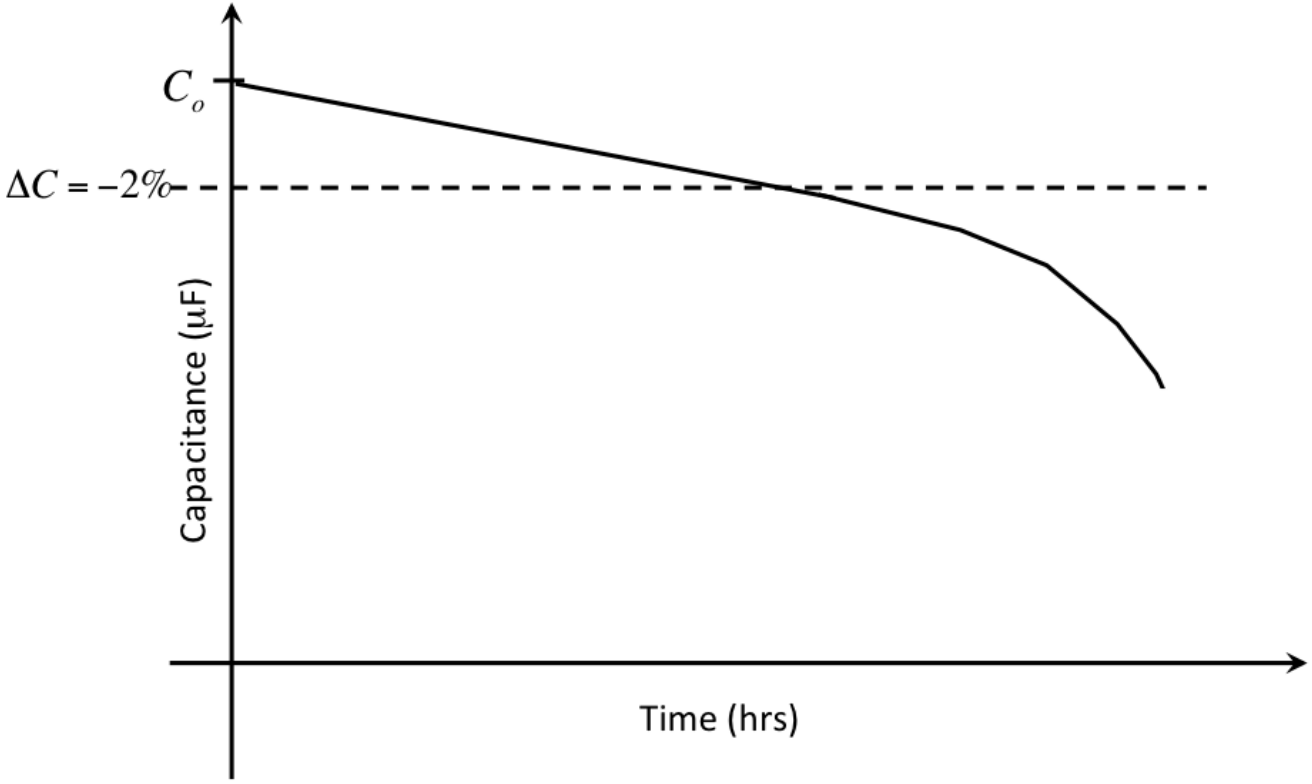
Disadvantages
- Often fail catastrophically
- Polar
- Release H_2 gas
- Must be oversized to handle ripple
- High leakage currents
- Main degradation mechanism is ESR increase

Thin-Film Capacitors

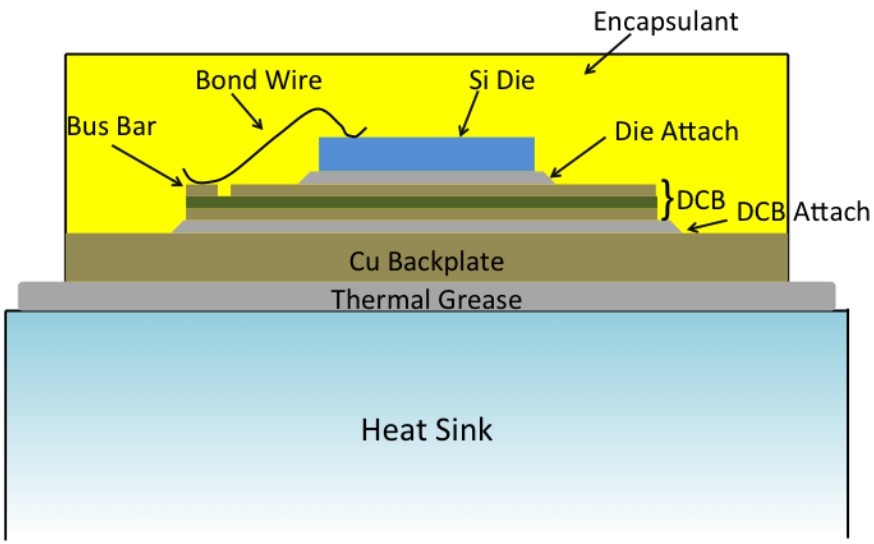
Advantages
- "Safer" with longer lifetimes
- Small ESR
- Degradation failure
- Non-polar

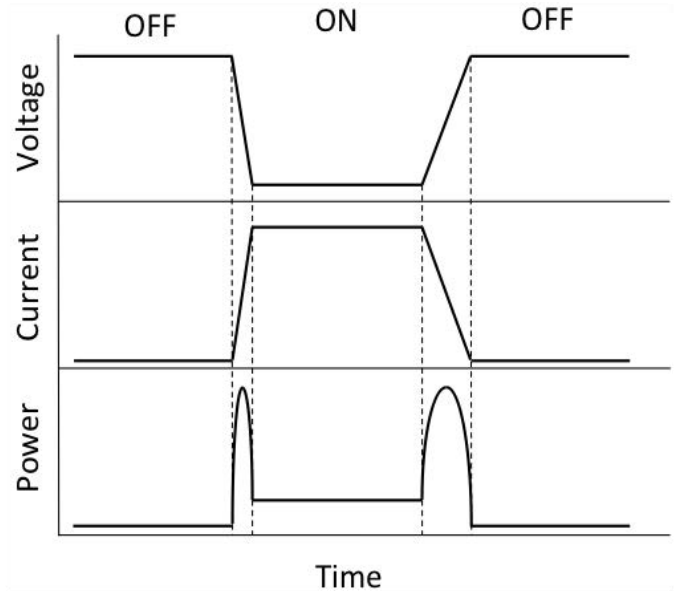
Disadvantages
- Not very well characterized
- Relatively expensive ($/µF is exponential)
- Thin metal limits peak current and energy density
- Low operation temperatures (faster degradation and polymer phase transitions)
- Low capacitance per volume (Bulky)

Current Inverter Reliability Capacitor



Current Inverter Reliability IGBT



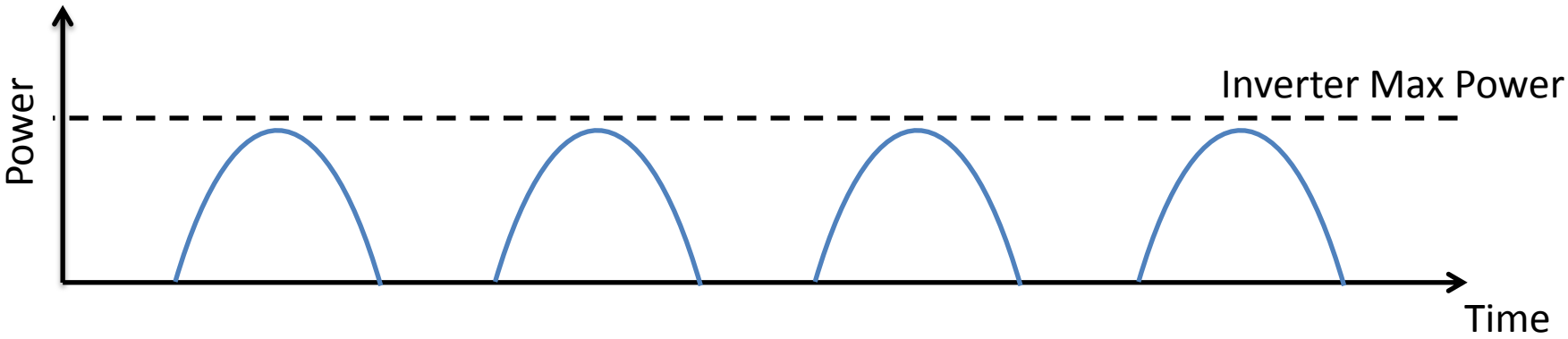


CTE mismatch between metal and Si die

- 4% of controlled power dissipated as heat
- two temperature cycles
  1. short term power cycling
  2. long term ambient temperature

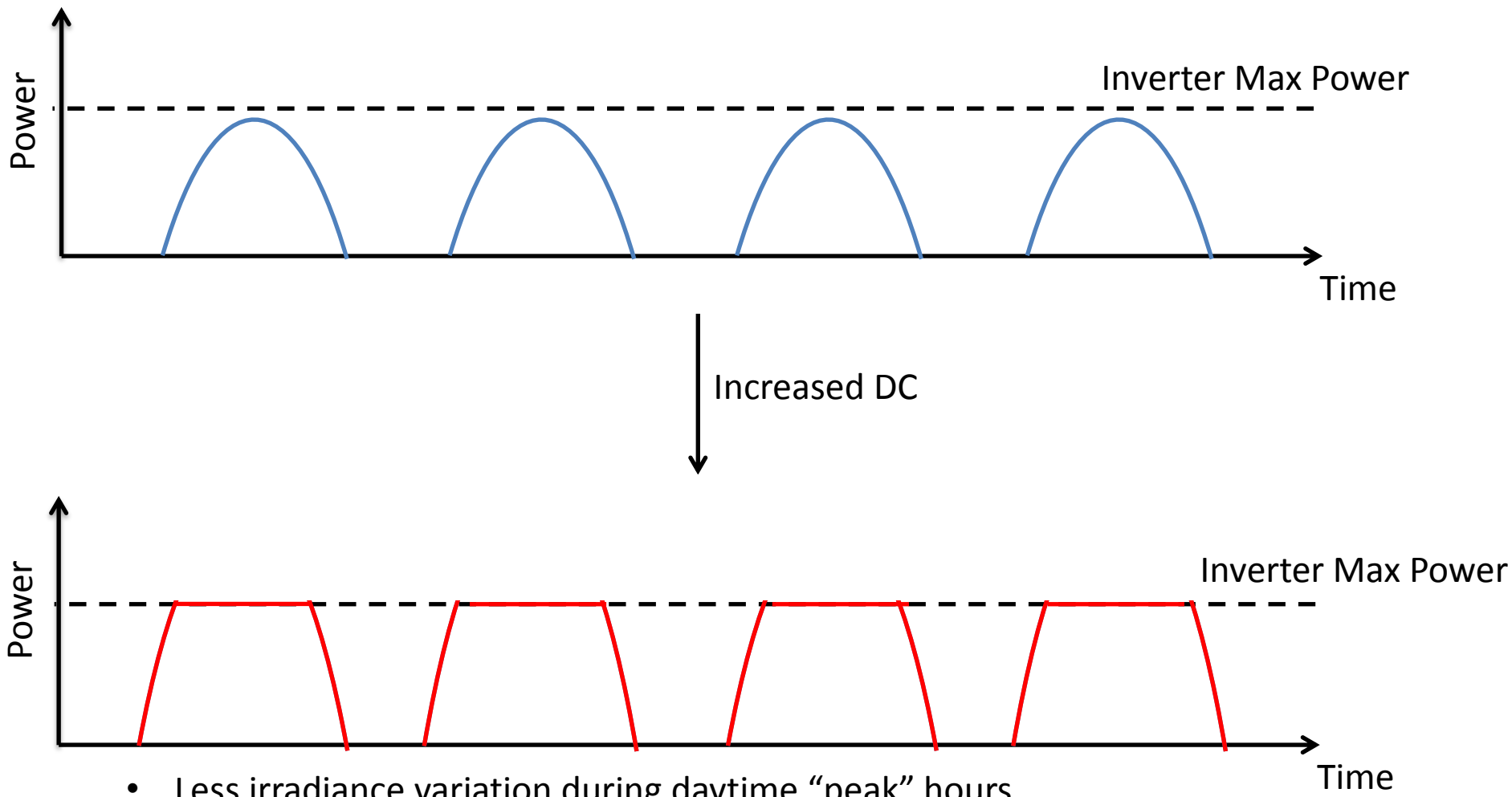
- Companies moving to metal loaded epoxies for cost/environmental reasons, but have much poorer performance
- Die attach degradation leads to voiding
  - Decreased heat transfer away from die
  - Increase in turn-off time, increase power dissipation in junction

Future of Inverter Reliability
High DC/AC Ratios



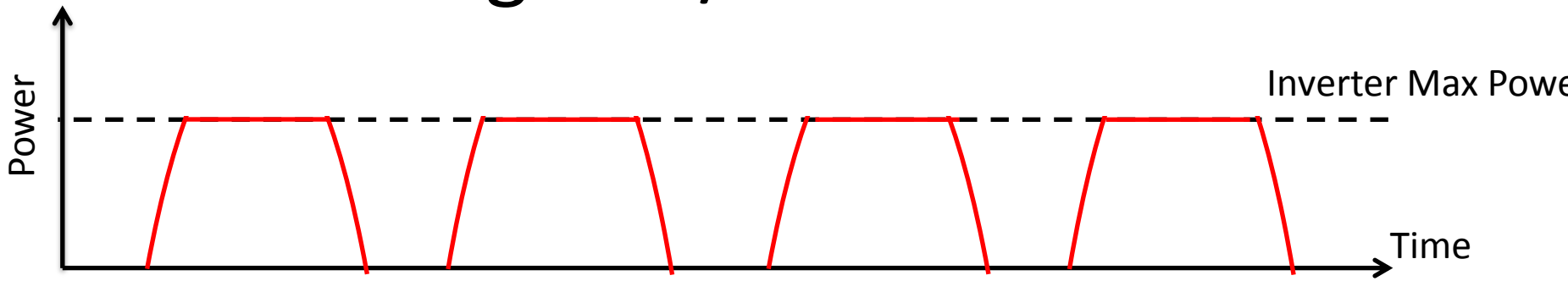
- PV plants can/do experience high variability during peak daytime hours
  - →High power demand(air conditioning)
  - →Difficult to predict supply, so cannot match demand
- Utilities value consistency as much as power generation capability
- As panel prices decrease, wasted power less important
- Can make PV more consistent by increasing DC:AC ratio

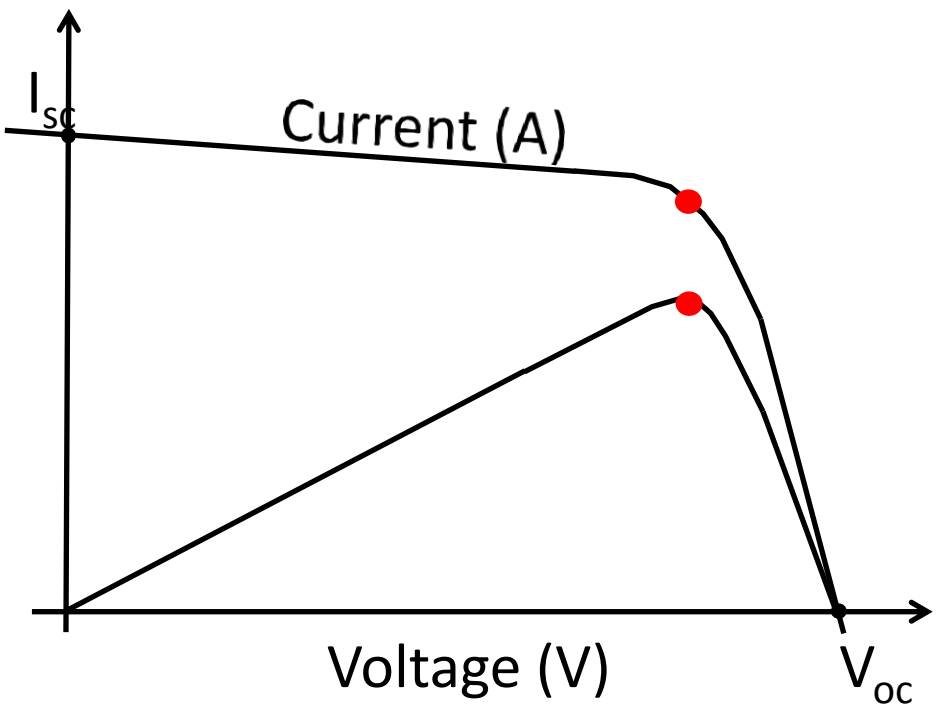
Future of Inverter Reliability
High DC/AC Ratios



- Less irradiance variation during daytime “peak” hours
- Power output profile looks more like base generation

Future of Inverter Reliability
High DC/AC Ratios





- DC/AC Ratios have been climbing in new PV installations
- High DC/AC Ratios can be very challenging inverter reliability environments
- Inverter at maximum power for many hours during the day
- Lifetimes will become shorter due to high power/high voltage environments

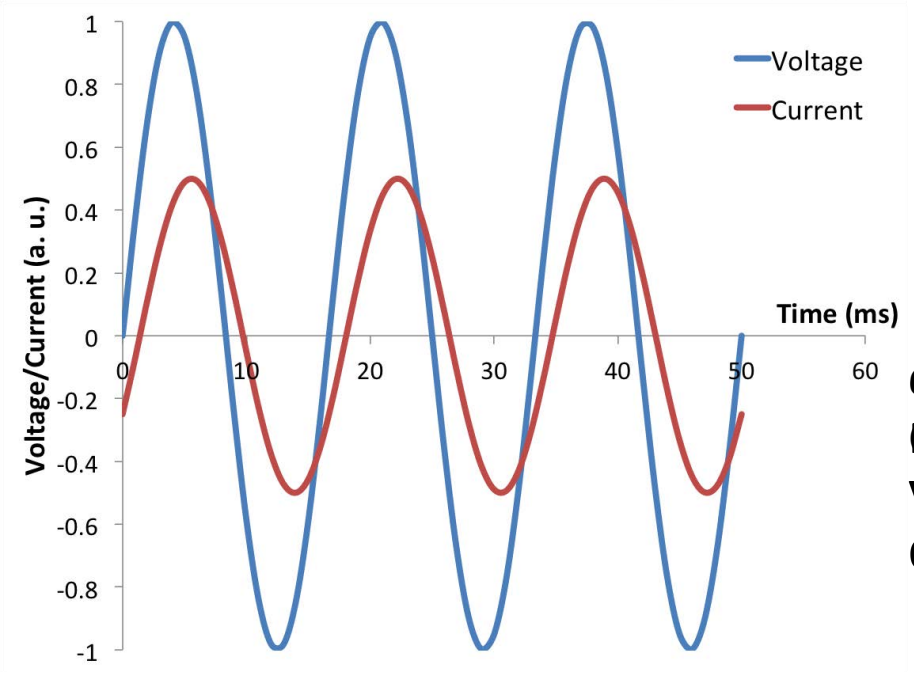
Future of Inverter Reliability
VAR Support

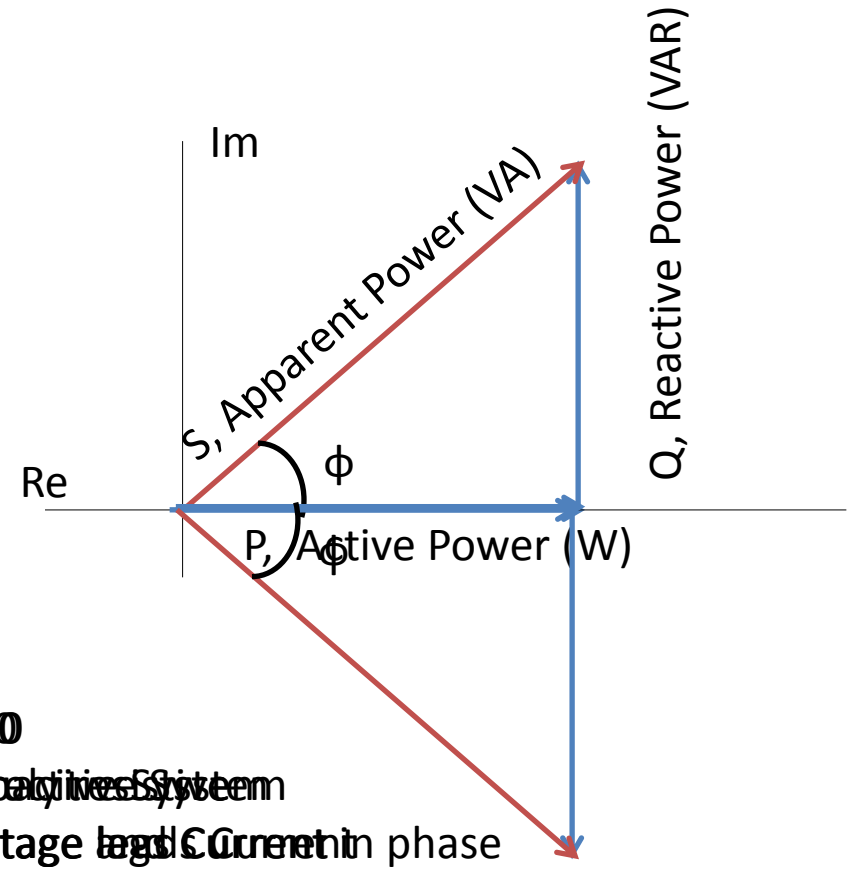
Alternating current described by a sine wave:

$$V(t) = V_p \times \sin(\omega t)$$

$$I(t) = I_p \times \sin(\omega t + \phi)$$

$$S(t) = I \times V \square \quad P\cos(\omega t) + iQ\sin(\omega t)$$





ϕ=0
Capacitive System
Voltage lags Current
Q=0, Sink VARs

ϕ=0
Inductive System
Voltage and Current in phase
Q=0, Source VARs

Future of Inverter Reliability
VAR Support

Used to stabilize grid voltage (voltage droop or rise) and change grid power factor

- Utilities want PF≈1 because maximize active power efficiency

Many blackout events caused by **unexpected** hot days

- Larger usage of air conditioning units than expected
- Large inductive loads coming online causes current inrush

  → Grid voltage decreases

  → Grid PF moves away from 1
- Lower voltage causes higher current draw (at lower efficiencies)

  → further decrease line voltage
- Higher current flow heats overhead line

  → sags and shorts on a tree

  → overloading other lines in blackout

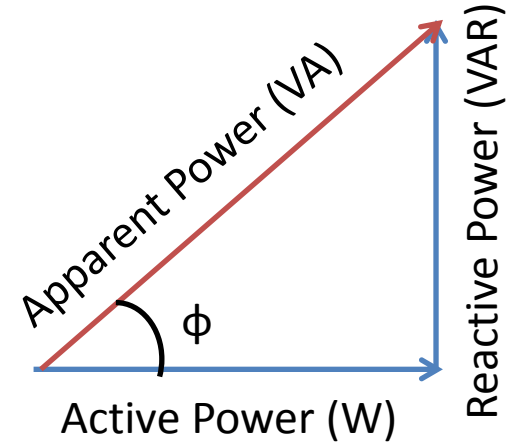
Two solutions to this problem:

1. Increase generating capacity via peaker (Natural Gas or Diesel) plants

   Slow to come online (~10 min), Expensive to operate
2. Increase grid capacitance to cancel out inductive loads (bring PF to 1, resist V droop)

   Fast, capacitor banks are expensive with reliability issues

Future of Inverter Reliability
VAR Support



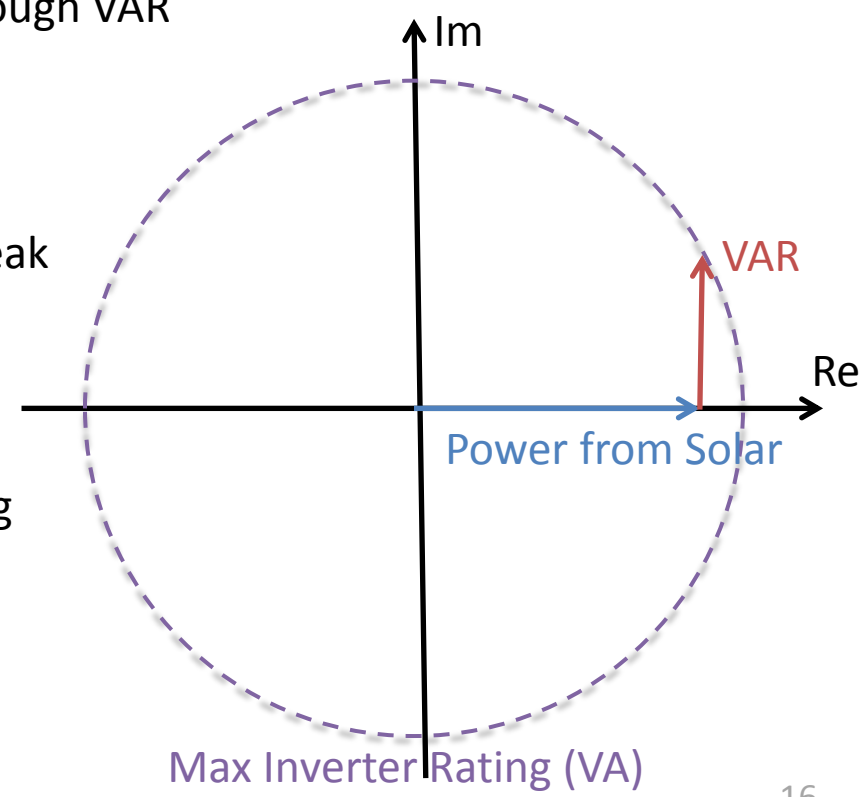
Historically, utilities have asked inverters to disconnect from grid

- Inverters can alter ϕ easily through switching schemes
- Easily and quickly become capacitive/inductive (source/sink VARs)
- Now, utilities asking to stabilize the grid through VAR support

In the future, VARs may become monetized

- Incentive for operators to control VARs at non-peak active power hours
- Inverters can source/sink VARs at full power handling of inverter during all inverter operation
- Lower inverter efficiencies when sourcing/sinking VARS

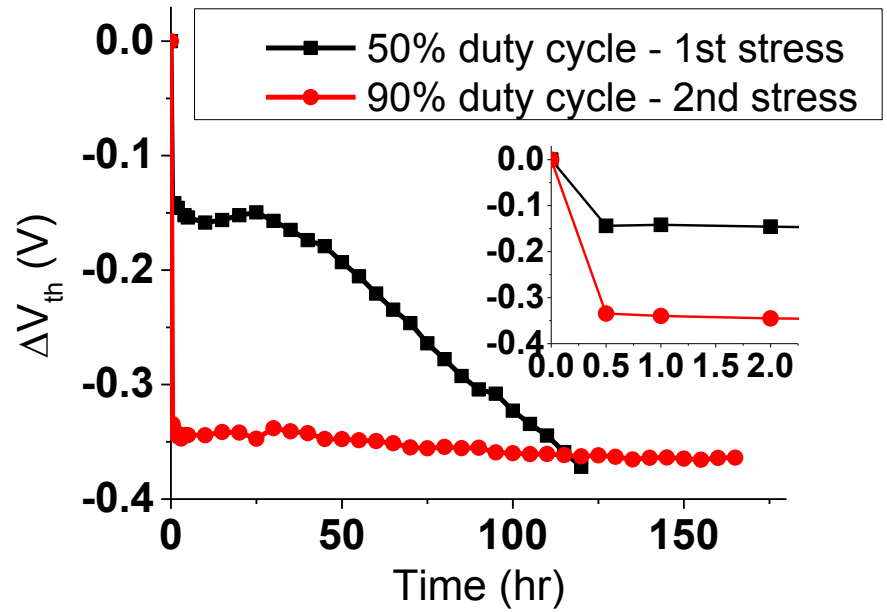
→Increased aging rates, more internal heating →shorter lifetimes



Future of Inverter Reliability
Widebandgap Devices (SiC, GaN)

- Larger bandgap
  →Fewer devices, greater Voltages
- Smaller resistive losses
  →Higher switch frequencies
  →Smaller inductors/capacitors
- Better thermal conductivity

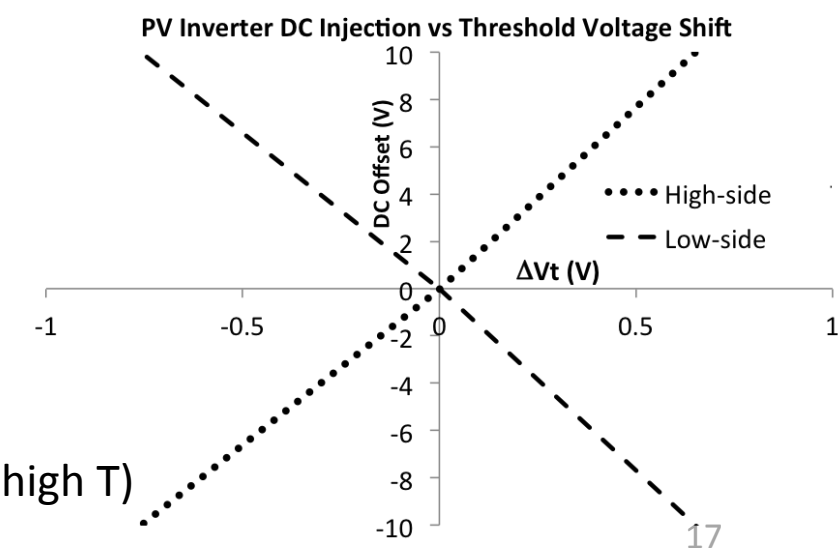
  10% of weight and 12% of volume



SiC MOSFETS suffer from V_T instability

V_T shift due to charge trapping at gate oxide
- SiO_2 bulk traps
- SiC/SiO_2 interface traps

Worse in SiC than Si
- SiC/SiO_2 interface quality is much poorer
- WBG means less conduction band offset with SiO_2
- Thermal activation of carriers over barrier (esp. at high T)



Future of Inverter Reliability Microinverter/Microconverters

- Mounted on module
- More extreme diurnal temperature cycling
  - Increased stress on componentry
  - More difficult thermal management
  - Customers require the inverter lifetime = module lifetime (~20 years)
    - Centralized inverters have warranties ~10 years

- One MLPE unit for every module
  - 5,000 units per MW of PV
  - Tens of thousands to millions of MLPE in installation
  - Difficult to impossible to track and repair/replace units as they fail
    - Unique challenge of PV installations operations and maintenance (O&M)

Statistical Reliability and lifetime extension is critical to successful implementation of O&M schemes for large solar installations

Number of safety, qualification, and reliability standards being developed

IEC62093 (Paul Parker)

62109-3

PREDICTS (Jack Flicker)-Currently seeking members for working group

Acknowledgements

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Application of "Surge and Ring" Test in Qualifying Solar PV Inverters

February 25, 2014

Alan Boyd
Bob Chancy
Derek Phillips
Joe Powell
Dutch Uselton

Lennox Industries, Inc.

A Recent Event…

In early December (2013) North Texas experienced an ice storm with many electrical service interruptions due to "lines down".

One of our solar PV field trial sites experienced a "surge" event…

…and inspired me to speak about Surge Testing at this workshop!

http://2.bp.blogspot.com/-VTuwwSJLBPo/UqCBqeYwvKI/AAAAAAAAXQM/iN1nfbJ-QZk/s1600/Ice+Storm.jpg

The Phenomenon of Surge

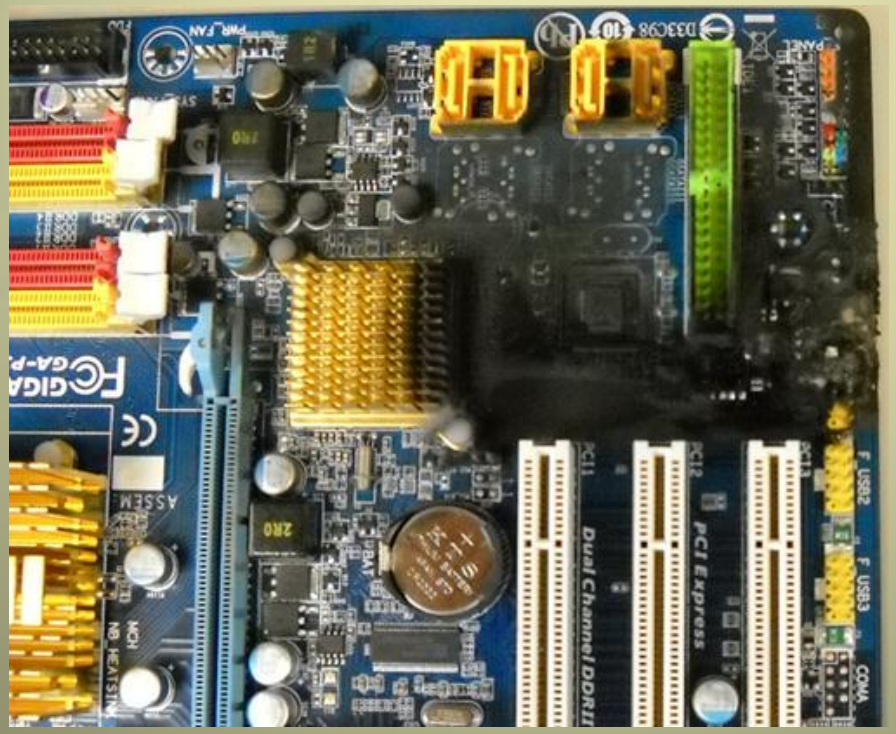
Surge is a word used to describe a sudden rise in voltage, beyond the normal system voltage, that lasts less than one cycle. There are two main causes for surge:

- A high voltage is induced in a conductor because of a nearby, extreme electrical current (to ground) related to a lightning strike
- A high voltage occurs due to switching within the electrical utility network. Inductive energy can be left in a circuit and, when the field collapses, a high voltage is produced.

The Phenomenon of Surge (cont.)

The consequence of a Surge can be a loss of functionality in an electrical device:

- **Permanently, due to arcing damage within circuits**
- **Temporarily, due to microcontroller "crash"**



Increased Interest in "Surge Withstand Capability" of Products

Quote from forward to IEEE C62.41-1991
(Standard Entitled: IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits)

"These problems have received increased attention in recent years because of the widespread application of complex semiconductor devices that are more sensitive to voltage surges than vacuum tubes, relays and earlier generations of semiconductor devices."

See also International Standard: IEC/EN 61000-4-5, Surge Immunity Test

IEEE C62.41 Recommended Practice on Surge Voltages…

The IEEE C62.41 organizes range of situations according to:
1) Location (within the electrical network), and
2) Exposure (both for frequency/intensity of lightning activity and also load-switching activity.)

Each has three levels:

Location

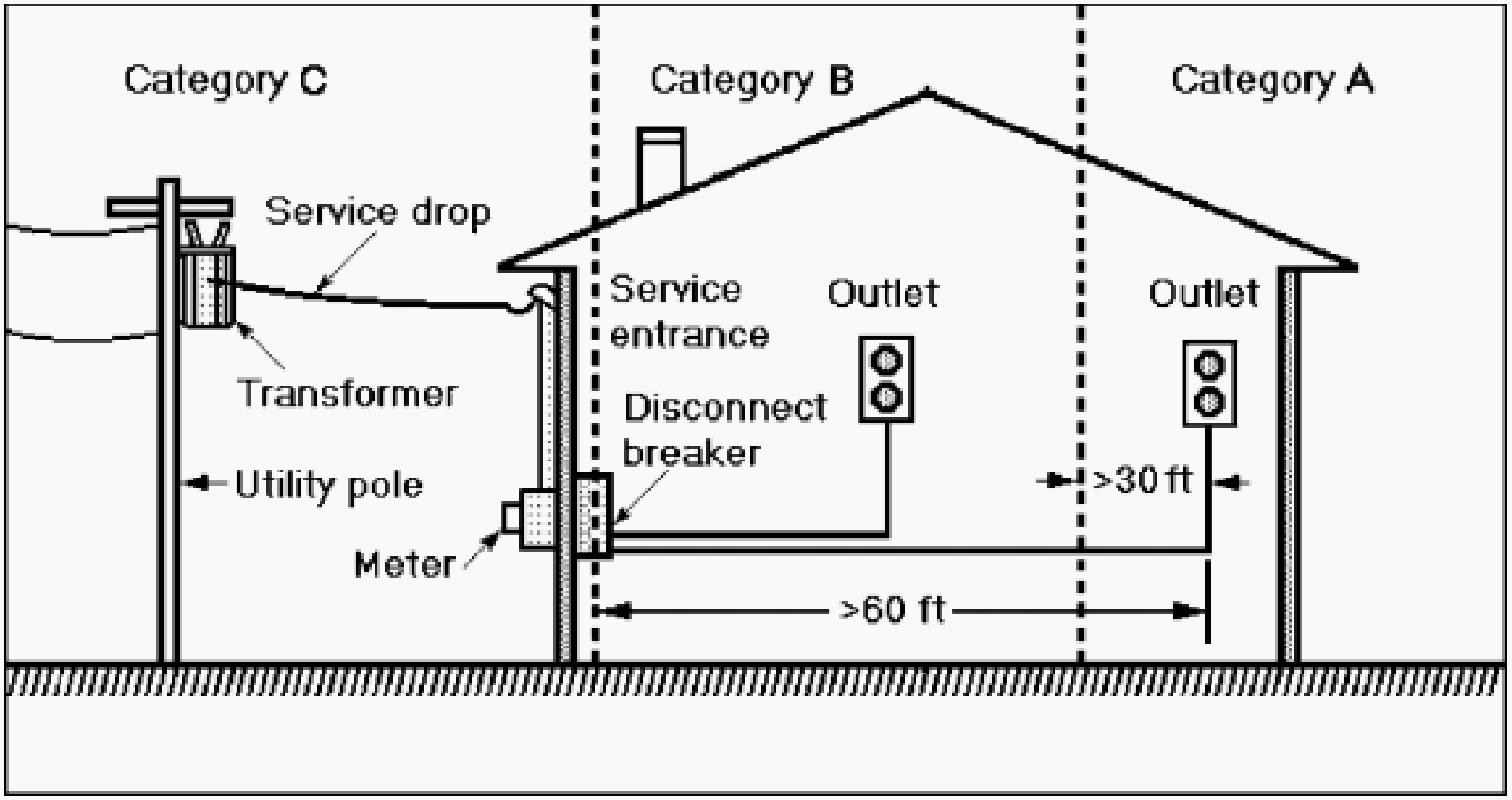
Category A: Long branch circuits, receptacles (indoor)
Category B: Major feeders, short branch circuits, service panel (indoor)
Category C: Outdoor overhead lines, service entrance

Exposure

Low Exposure: areas with low lightning activity & little load-switching activity.
Medium Exposure: medium to high lightning activity, or with significant switching transients, or both.
High Exposure: rare installations that have greater surge exposure

IEEE C62.41 Recommended Practice on Surge Voltages…

Location Categories



IEEE C62.41 Recommended Practice on Surge Voltages…

The Exposure Category is related to annual incidence of thunderstorms and nearby electric utility sources of surge. (Medium Exposure is for systems and geographical areas known for medium to high lightning activity or with significant switching transients or both.)

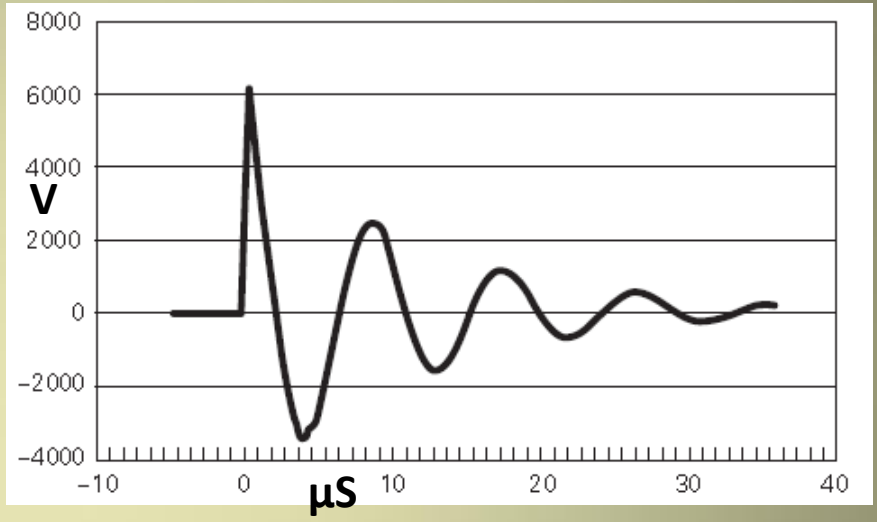
For a microinverter that is designed to be used throughout North America, it is best to choose:

Location Category: B (or C)
Exposure Category: Medium

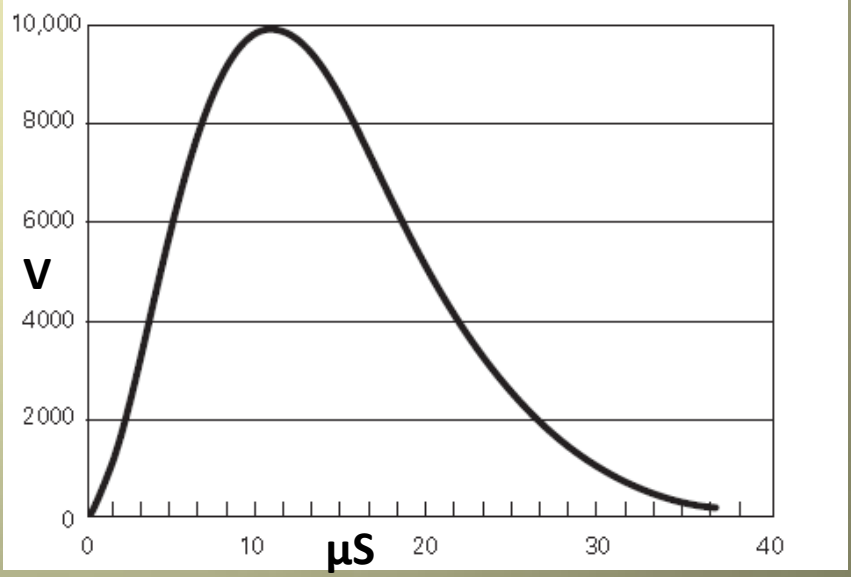
IEEE C62.41 Recommended Practice

Test Waveforms:

- **Ring Waves**



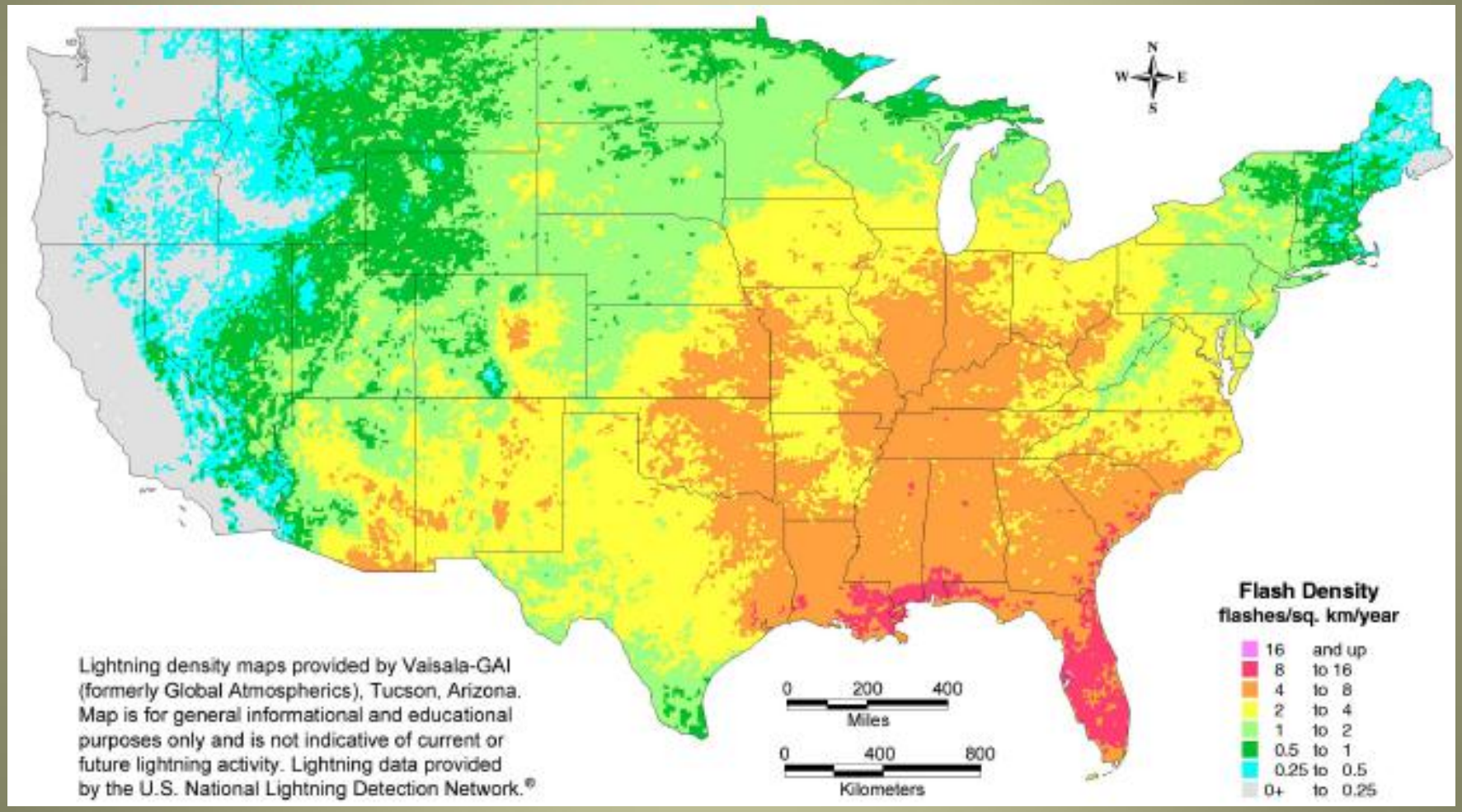
- **High Energy (Combination) Waves**



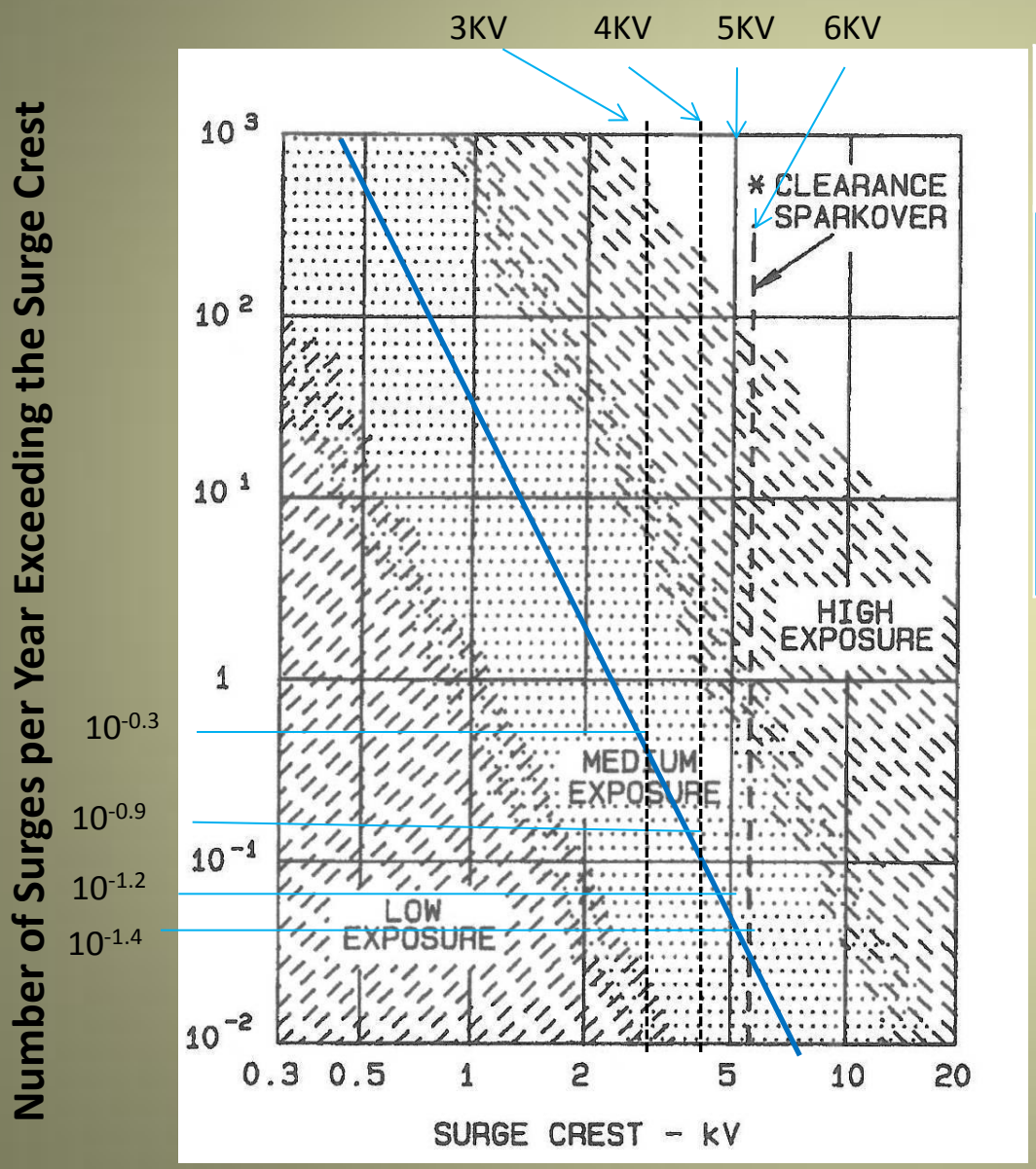
- **Other Specialized Waveforms**

Lightning Flash Map

Flash Density (per square kilometer per year)



Probabilities…



	Surge Level (KV)				
	3	4	5	6	
Number of Surges /year per 100 Sites	**50**	**12.6**	**6.3**	**4**	

Remember: <u>Medium</u> Exposure is for geographical areas known for medium to <u>high</u> lightning activity.

Establishing a Design Surge Resistance Level

% Failure associated with the arbitrary mid line of previous chart							
Design Surge Resistance	Years in Field at Medium Exposure Sites						
	5	10	15	20	25	30	40
3KV	22.1	39.3	52.8	63.2	71.3	77.7	86.5
4KV	6.1	11.8	17.2	22.3	27.0	31.5	39.6
5KV	3.1	6.1	9.0	11.8	14.6	17.2	22.3
6KV	2.0	3.9	5.8	7.7	9.5	11.3	14.8
10KV	0.002	0.004	0.006	0.008	0.010	0.012	0.016
Note: assuming 10 surges required to accumulate sufficient damage for failure							

Testing

The IEEE standard provides different parameters according to the Location and Exposure categories. We use 6 KV as the amplitude limit for surges due to the flash-over clearance in building wiring systems.

Ring Wave:	6000V, 12 ohm	0.5 μs, 100 kHz
Combination Wave:	6000V, 2 ohm	1.2x50 μs - 8x20 μs

Must check all line-to-line and line-to-ground possibilities in forward and reverse polarity.

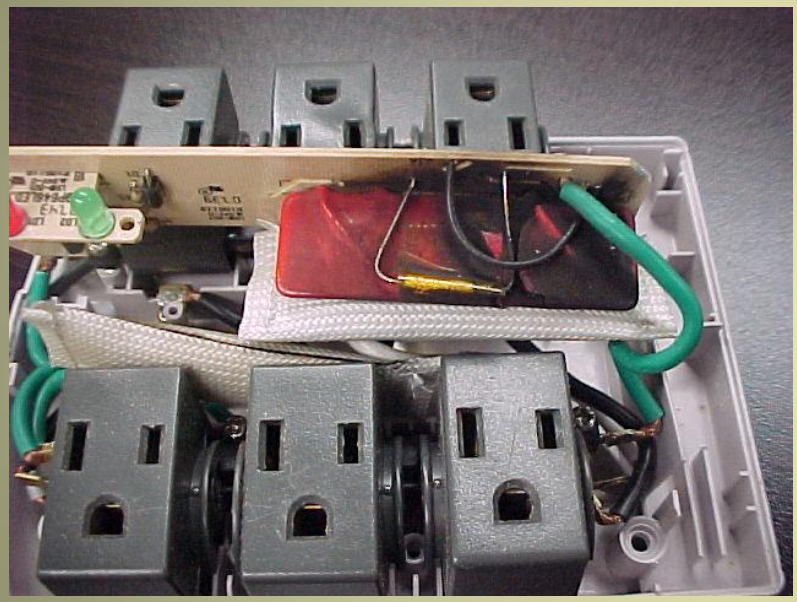
The surge is introduced at different phase-angles of the AC power since it has been found that it can make a difference. (24 pulses of the Combination Wave are applied and 48 Ring Waves are applied for a 240V split-phase product.)

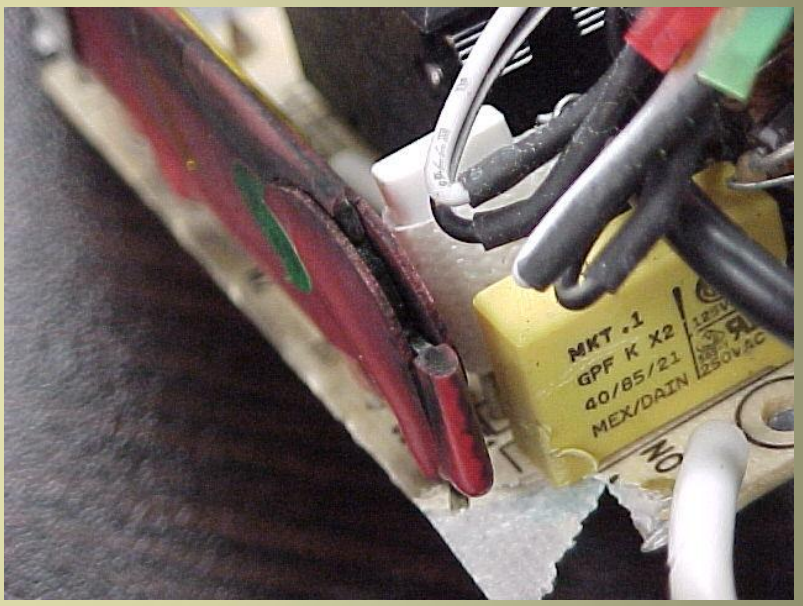
The device must function* throughout this testing and show no signs of damage at the end.

* A “pass” is sometimes a matter of judgment.

That Recent Event…

Solar PV field trial site in Red Oak, Texas had surge event, due to "power anomalies", during ice storm on Dec. 5-6, 2013.





Items ruined:

- electric blanket control
- power strips
- microwave oven
- computer (power supply)
- thermostat

Some items that survived:

- All solar PV microinverters
- 2 heat pump outdoor units
- 2 heat pump indoor units

Conclusions

- **9 out of 10 components that had been qualified according to Surge and Ring Test (Lennox Procedure E99-5) survived this event…while many consumer products within the home did not!**

- **There will always be a surge that can defeat any protection scheme, but, by design, we can assure that most surges will not.**

Un-Concluded

- Could there be a lightning-induced surge failure mode on the dc side of the inverter?

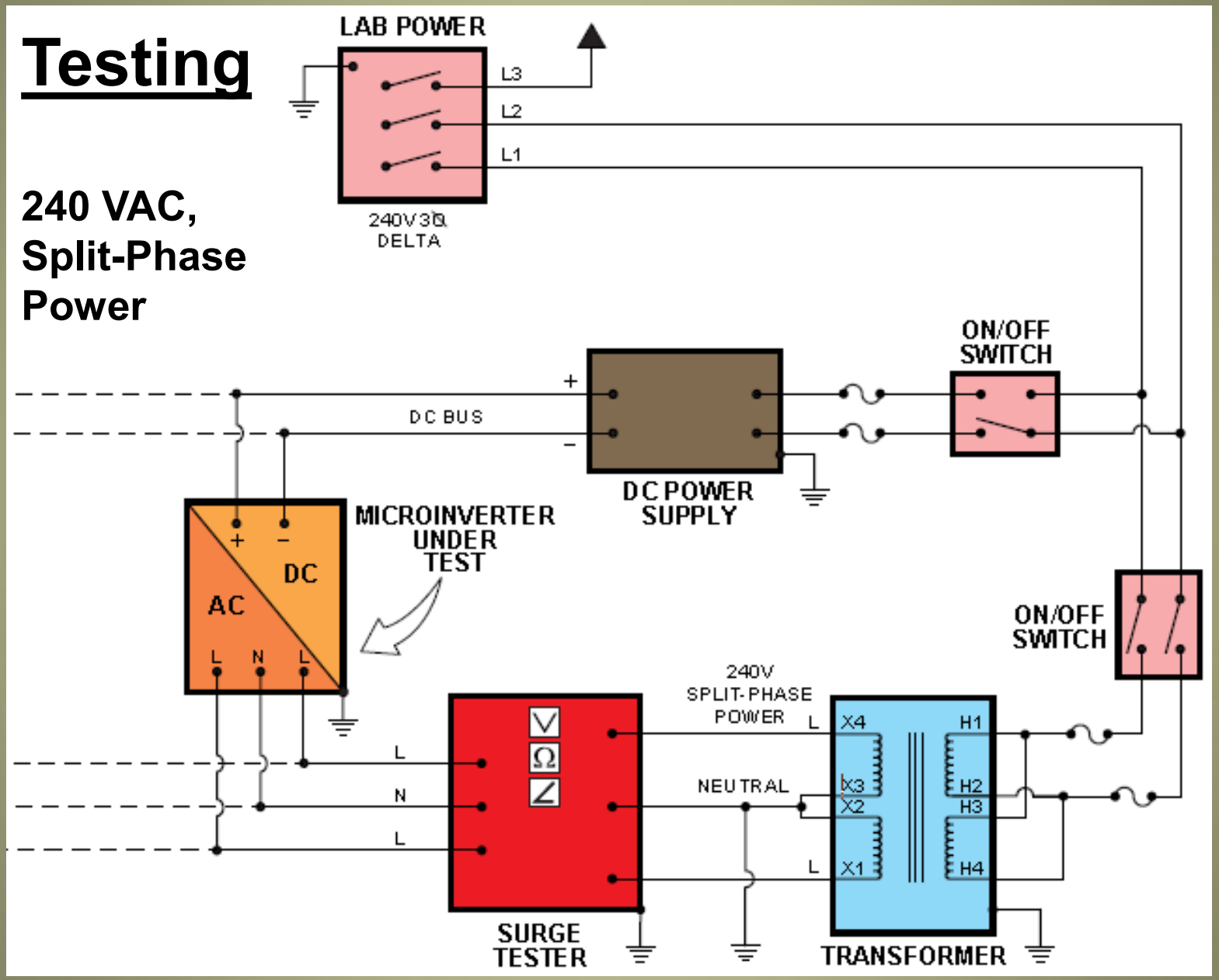
- Damage to MOVs is cumulative and this equipment is expected to last a long time. Should solar PV inverters be evaluated according to Location C rather than B?

Supplemental Information

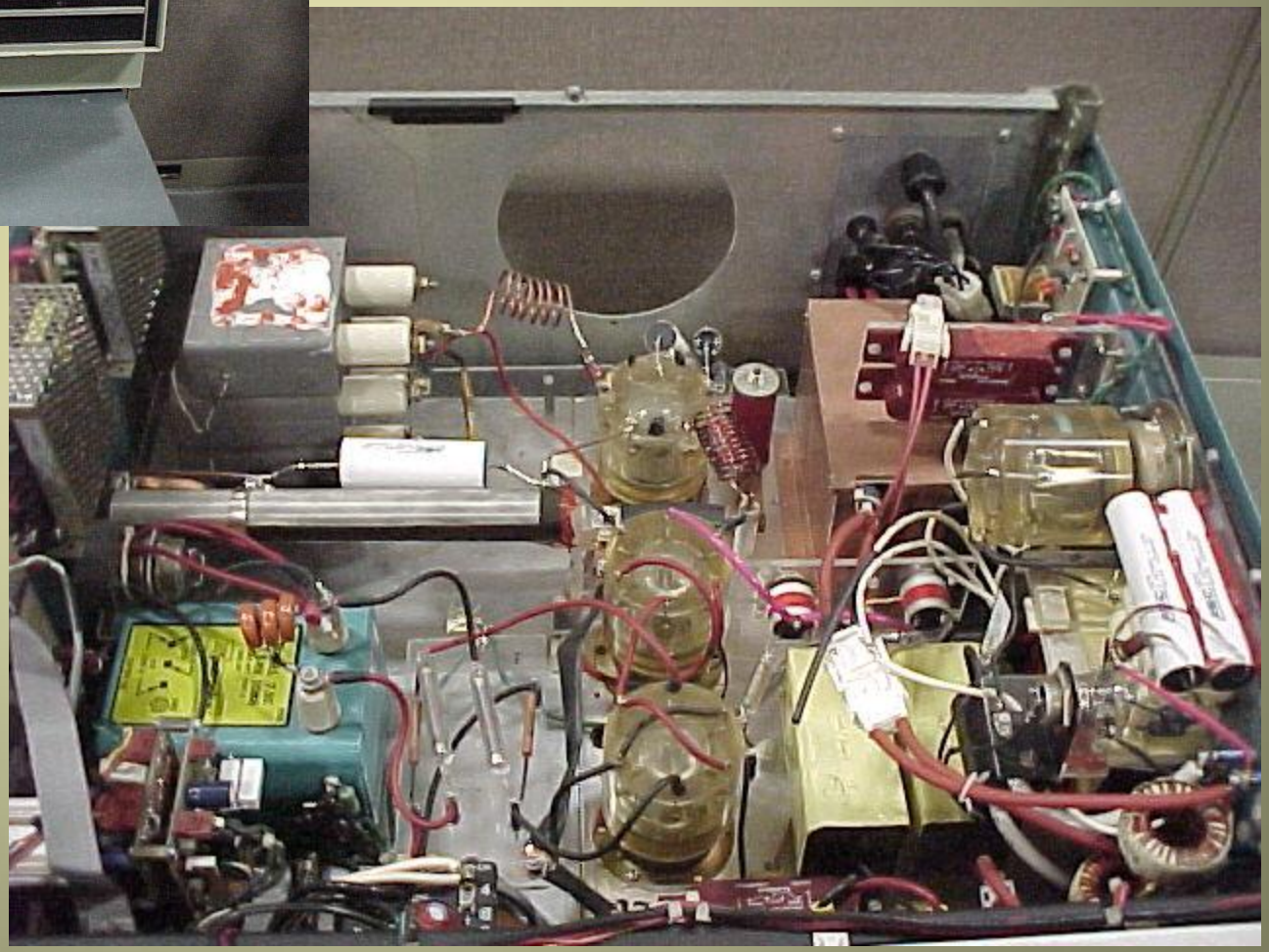
- Schematic of surge test laboratory arrangement
- Photos of original Lennox Surge Tester (built in 1988 – 1989)
- Ring Wave and Combination Wave Circuit Schematics from UL Standard 991
- Its not just electronic components…
- Information on some technologies used to protect electronic circuits from surge

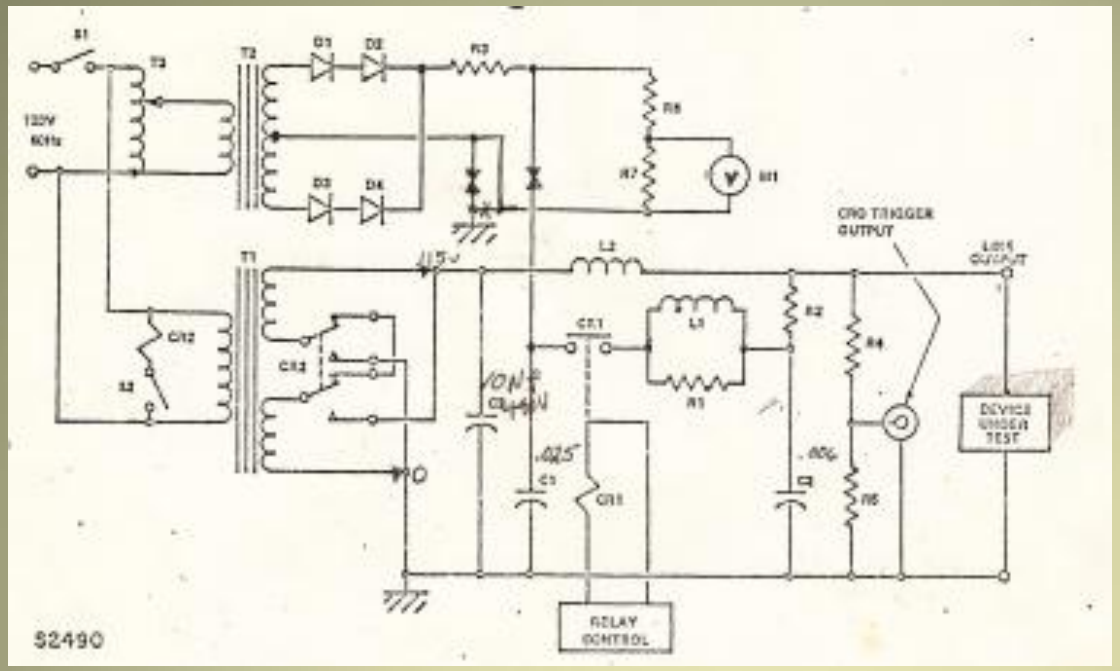
Testing

240 VAC, Split-Phase Power

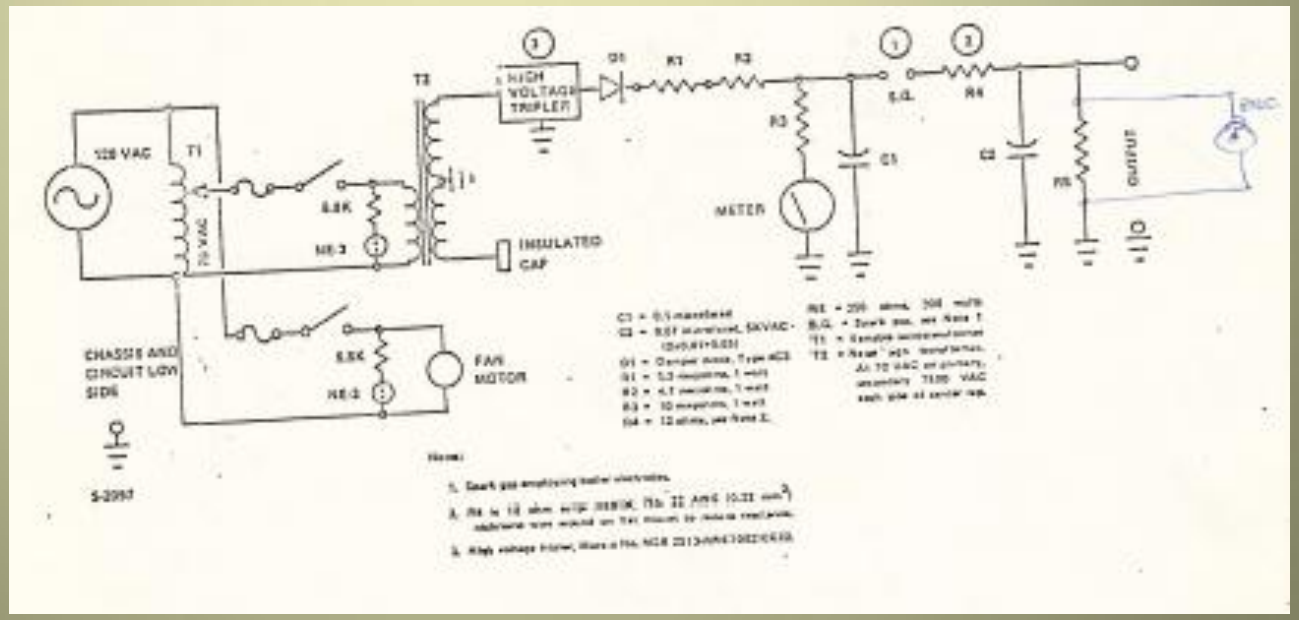


Lennox' Original Surge Tester – Now Retired!



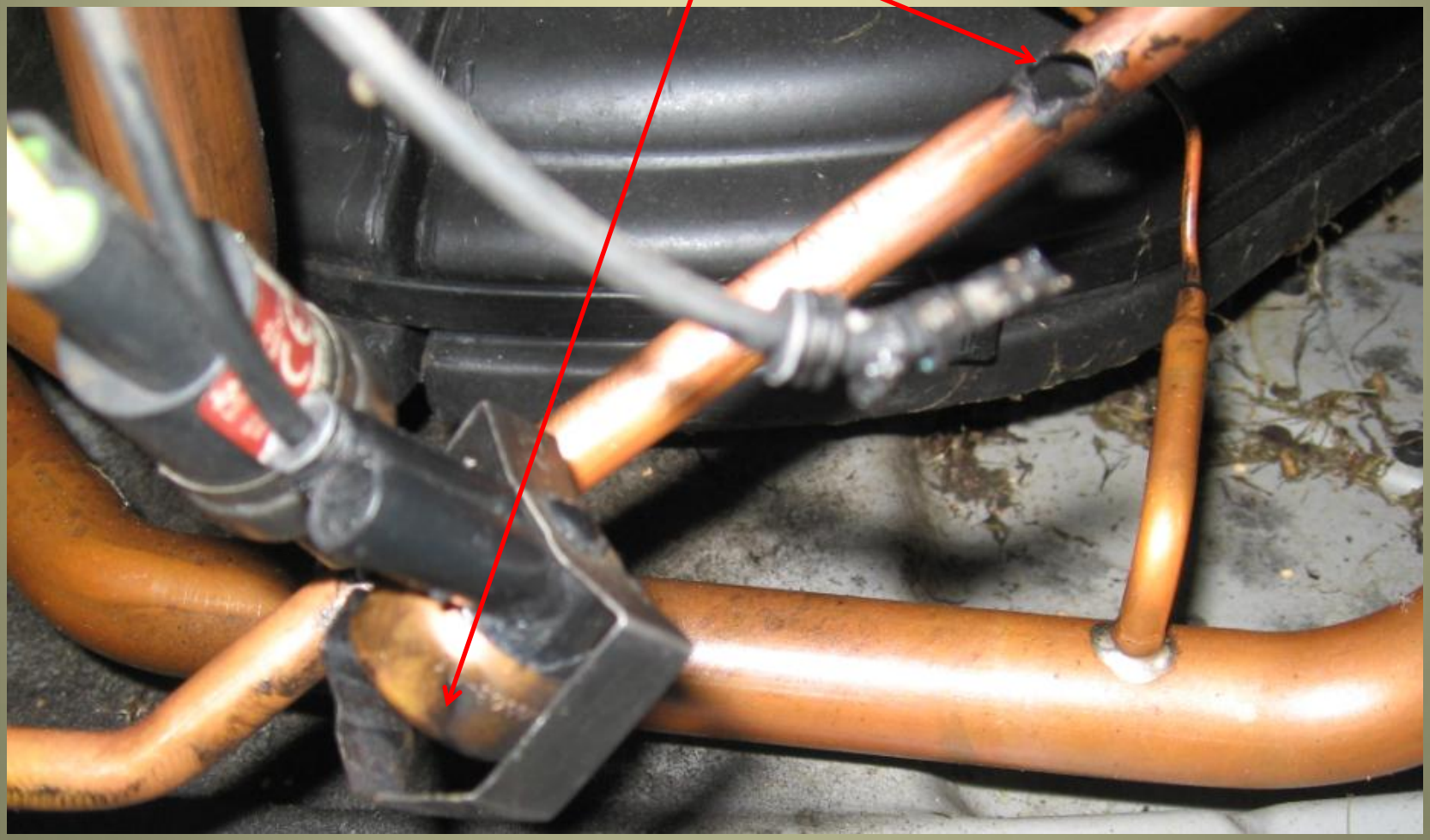


Ring Wave Circuit



Combination Wave Circuit

Its not just electronic components that fail due to surge!
This clamp-on bimetal thermostat arced and ruptured a refrigerant line. This occurred in Washington in winter and is most likely due to power line switching.



Technologies Used to Provide Protection from Surges

Protection: Shorting High Voltage to Ground <u>or</u> Blocking High Voltages from reaching sensitive components. There are several commonly used surge protecting devices of the “shorting high voltage to ground” type. They are developed to have a nominal “clamping voltage”; that is, a voltage above which they conduct electricity to ground. When a surge voltage arrives and the clamping voltage is exceeded, the device provides a short-circuit from a power conductor to the ground conductor. Clearly there would be a limit to the amount of energy that can be handled this way. Fortunately, most surges are short-duration so the actual amount of energy to be handled is small. Most common devices are degraded with each incident. They have a limited life.

Technologies Used to Provide Protection from Surges (continued)

The most common variety is called an MOV (Metal-Oxide Varistor, typically made from sintered zinc oxide). It is relatively low-cost and so has found wide application. As the device experiences many small surges or fewer large ones its clamping voltage begins to drop and it will eventually act as a short circuit even at normal voltages. Because this presents a “thermal runaway” risk, they are usually protected by a thermal fuse. Of course, when the thermal fuse opens, the device no longer acts to protect the circuit from surges. (This is why it is recommended to replace the common electrical power strip/surge protector when your home has experienced a voltage surge.)

Technologies Used to Provide Protection from Surges (continued)

Another technology that is sometimes used is the GDT (Gas Discharge Tube). The GDT has electrodes in a sealed tube filled with a gas mixture. The device is designed to have the gas ionize and begin conducting when an overvoltage condition is reached. The GDT is slower to respond than a MOV. It is able to shunt more current for a given device size. GDTs continue to conduct until the arc extinguishes and this may characteristic may require additional circuit components to assure the GDT stops conducting after the surge event.

ADVANCED ENERGY®

System Reliability for Utility PV Inverters

Ron Vidano

February 26, 2014

AESOLARENERGY

Abstract

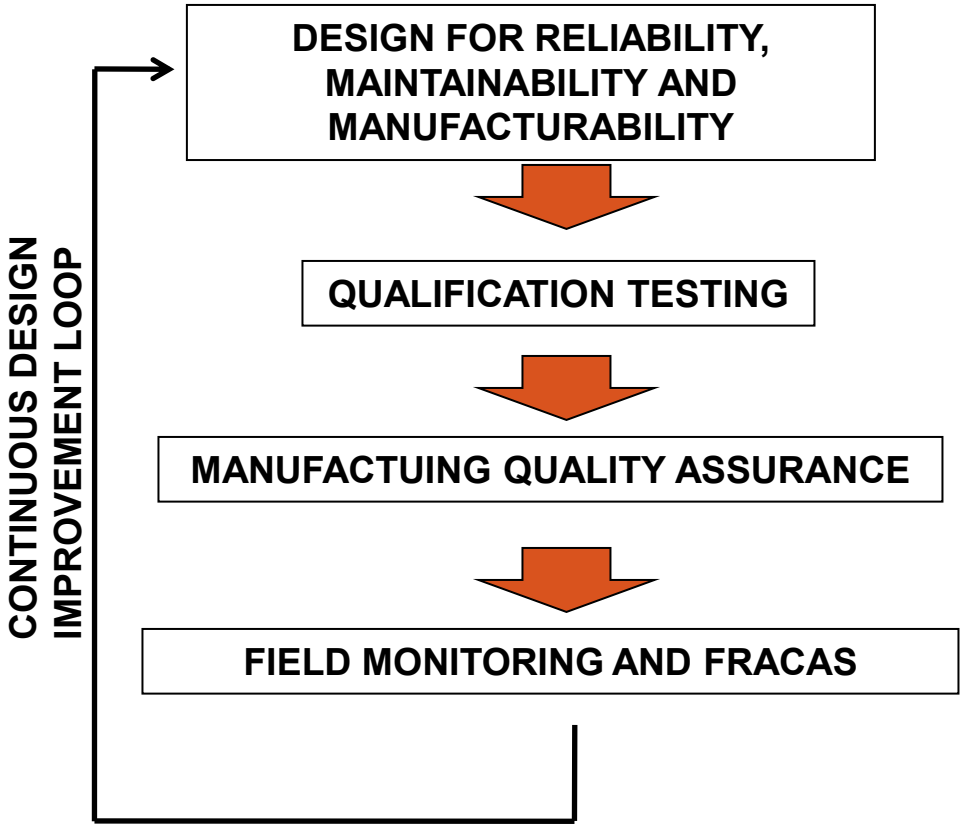
The availability of a PV plant is highly dependent upon the system reliability of the inverter. Systems engineering for PV inverters is accomplished by first performing top down design-for-reliability (DfR) principles including fault tree analysis & reliability prediction methods which result in subsystem reliability allocations. A critical aspect for the design of PV inverters is the ability to simulate both performance as well as environment thereby gaining an understanding for the subsystem and component stress state. Physical testing of the simulation results are accomplished by usage of advanced power supply equipment with the capability to provide both DC and AC performance conditions which represent large scale PV arrays and grid interactions.
Systems reliability analysis provides a basis for subsystem and component technology choices and development. One example of the linkage between simulation and test is applied to the critical inverter subsystem consisting of the IGBT switching subsystem. Simulations and testing to the required performance envelop and environment of operation results in component choices, subsystem design, derating strategies and required cooling methods.

Qualification of inverter reliability is attained by envelope performance testing at environmental extremes to provide for manufacturing burn-in profiles. Durability tests such as system level accelerated life testing (ALT) and component & subsystem highly accelerated life testing (HALT) are key tools to qualify the reliability of new designs. Environmental testing of inverter equipment is performed to ensure that the system availability is maintained over a long lifetime at temperature and humidity variations.

A key aspect for understanding inverter fault modes and the design of efficient maintenance & repair methods is the ability to data mine fielded inverter operation at the component, subsystem, and system level. For that reason, the attainment of high availability is tied to real-time site data acquisition for inverter operational conditions and subsystem states. Actual field performance is fed back into lifetime models used during qualification testing as well as prediction and simulation criteria. Reliability growth is attained by improvements found during prediction, simulation, qualification testing, and field experience.

Methodology - Reliability Assurance Milestones During Inverter Product Lifecycle

- AE uses a closed loop reliability process
- Design for Reliability
  - MTBF, DFMEA, Fault Tree
- Reliability Test
  - ALT, HALT, Thermal, Environmental
- Qualification Test
  - Power profile, efficiency, harmonics, waveform, modulation, control loop, compliance, WCSA, limits, control & communication, burn-in development

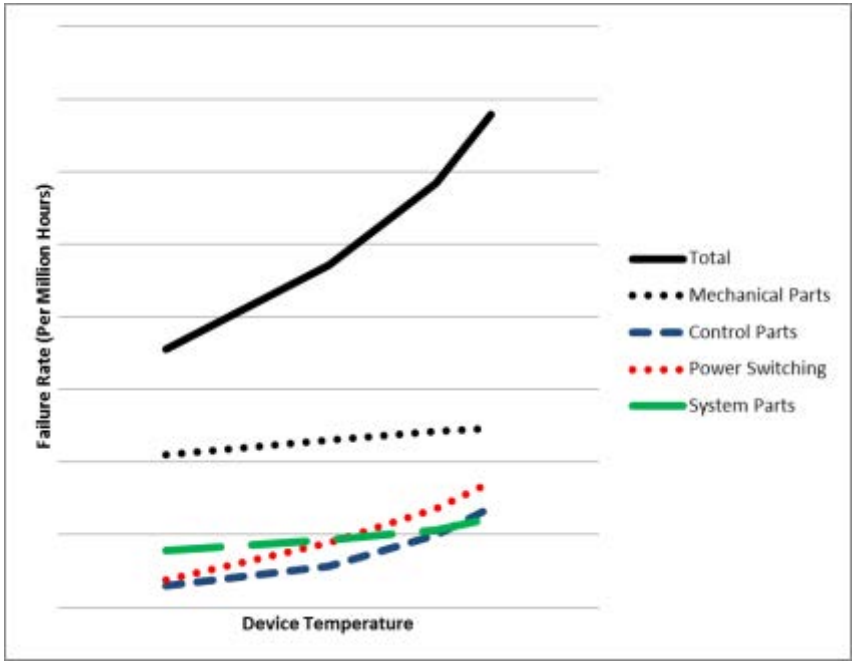


Inverter Reliability Assurance Program

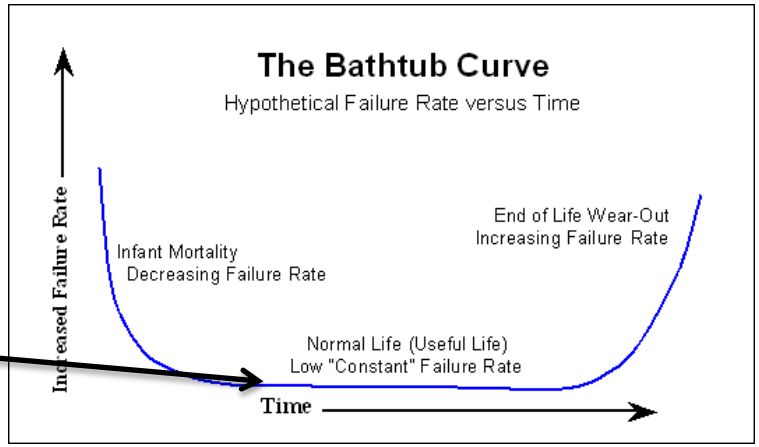
- Design for Reliability (DfR) Focus Areas
  - Modularity; Improves reliability, repair, test, and manufacturing
  - Derating; Component and subassembly derating to reduce operating stress
  - Temperature Management; Achievement of reduced operating temperatures
  - Predictive Methods – MTBF, DFMEA, 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

Design-for-Reliability; Reliability Calculation

- MTBF calculation with software (Such a Windchill) using failure rate libraries (MIL-HDBK-217, Telecordia)
- Provides an understanding for the comparative reliability of different configurations
- Also useful for observing how the reliability is related to cooling efficiency and component stress
- Should not be used as a primary method to predict the actual failure rate



Reliability calculation assesses performance during constant failure rate region



Design-for-Reliability; DFMEA Example

- Team Oriented
- Structured Method, Early Evaluation of Design, Controls to Reduce Risk
- Design FMEA; Detailed, Functional, Interfaces
- RPN Scoring; Severity x Occurrence x Detection

Design Failure Mode Effects Analysis

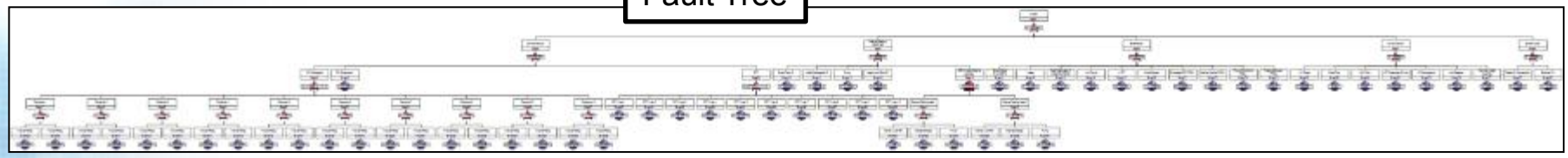
Severity Table Occurrence Table Detection Table

	Design Failure Mode and Effect and Analysis			FMEA Number: INVERTER 1	
System:	INVERTER				
Item:		Design Responsibility: System Engineer		Prepared by	Reliability Engineer
P/N:		Updated Date:		DFMEA Date (Orig.) 2/25/14	(Rev 1
Core Team:	System Eng, Firmware Eng, Power Eng, Mechanical Eng, Quality Eng, Reliability Eng, Manufacturing Eng, Test Eng, Project Mgr				

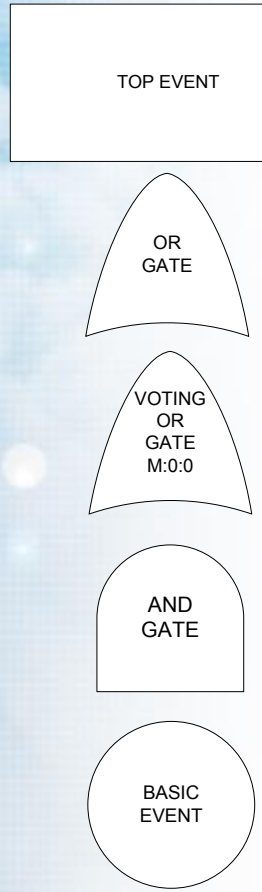
Item No.	Item Function [Item]	Potential Failure Mode	Potential Effect(s) of Failure	Potential Cause(s)/ Mechanism(s) of Failure	Current Design Controls Prevention	Severity	Occurrence	Detection	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results				
												Action(s) Taken	Severity	Occurrence	Detection	RPN
1	Subsystem 1	Overheating	Loss of Power	Thermal, Current Derating	DFMEA, Derating. Fault Tree	8	8	2	128	ALT; Fault Tree Analysis	Pwr Eng, Rel Eng, Test Eng	Subsys ALT complete Derating Met	2	2	2	8

Design-for-Reliability; Fault Tree Analysis Applied to Utility Inverters

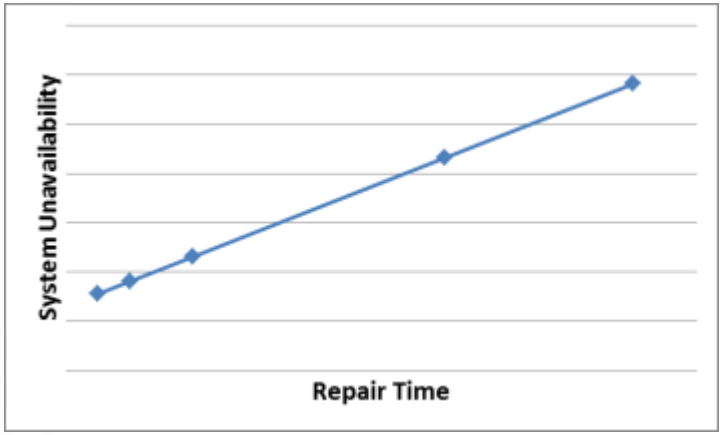
Fault Tree



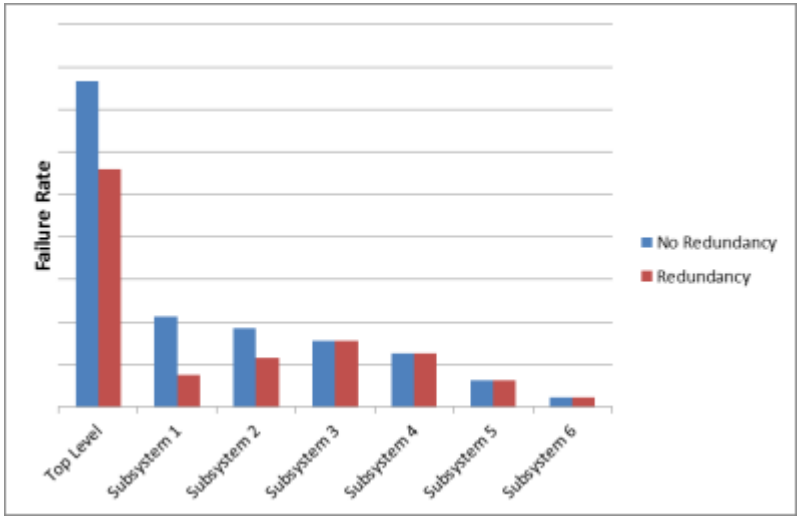
Logic Symbols



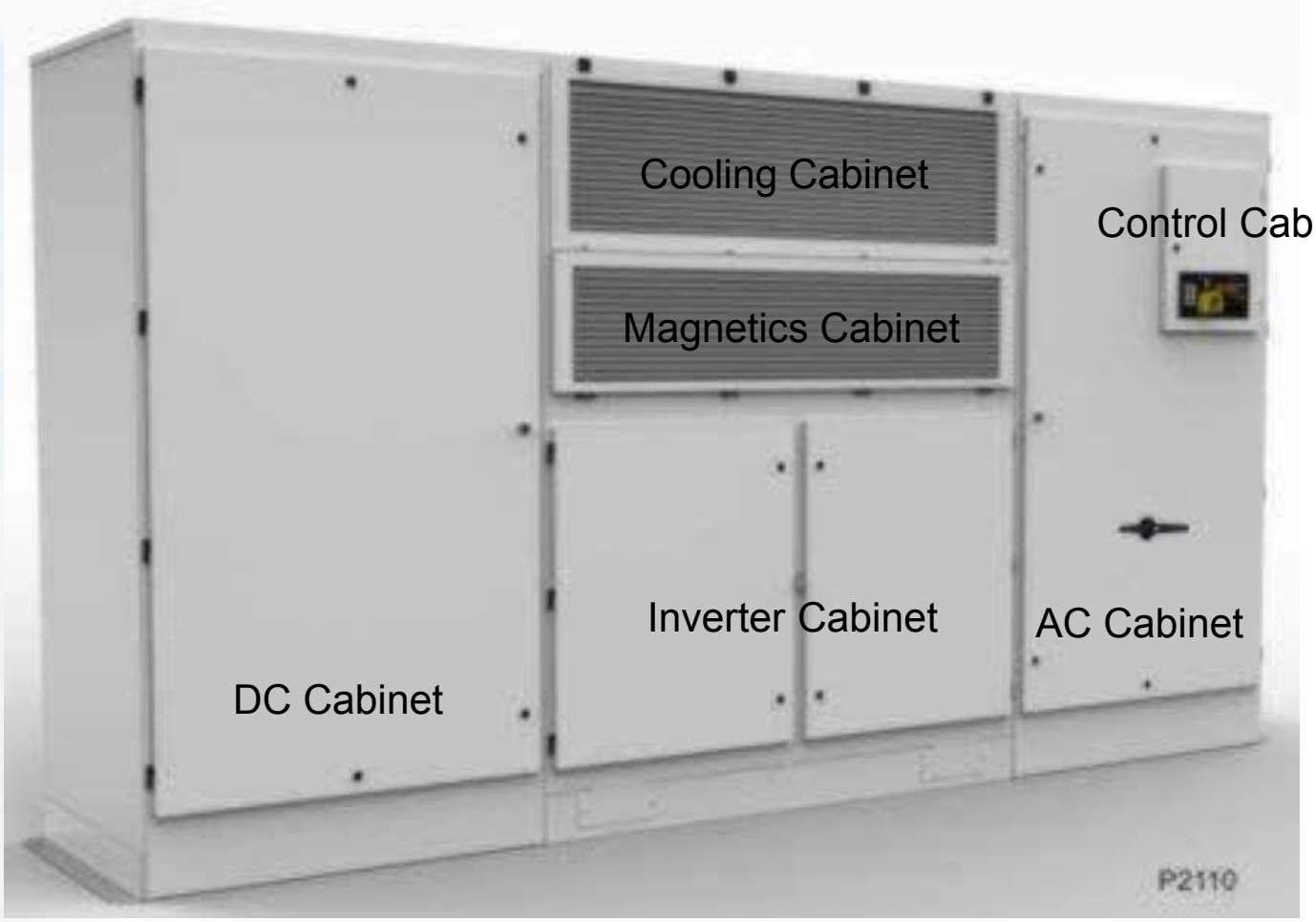
Example of Maintainability Importance with Modularity Improvement



Failure Rate of Subassemblies; Effects of Fault Tolerance

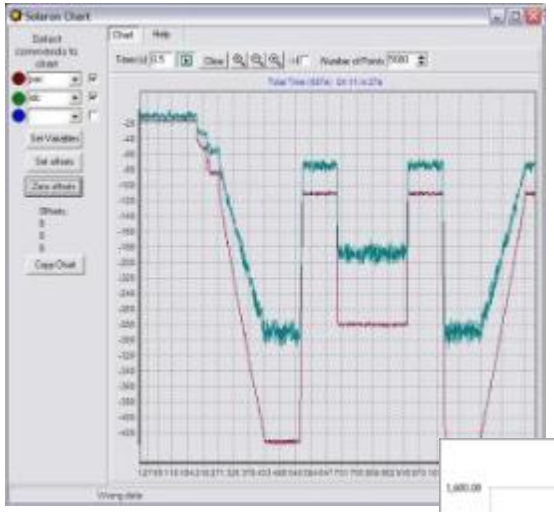


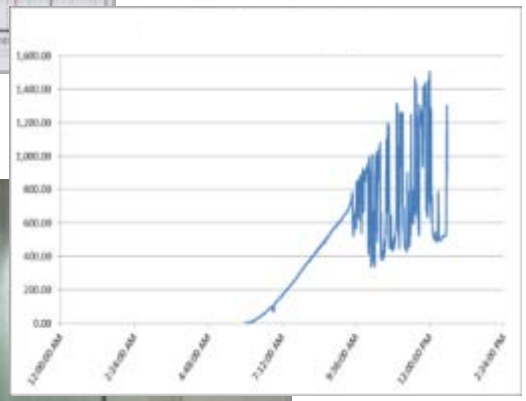
1000NX Modular Design

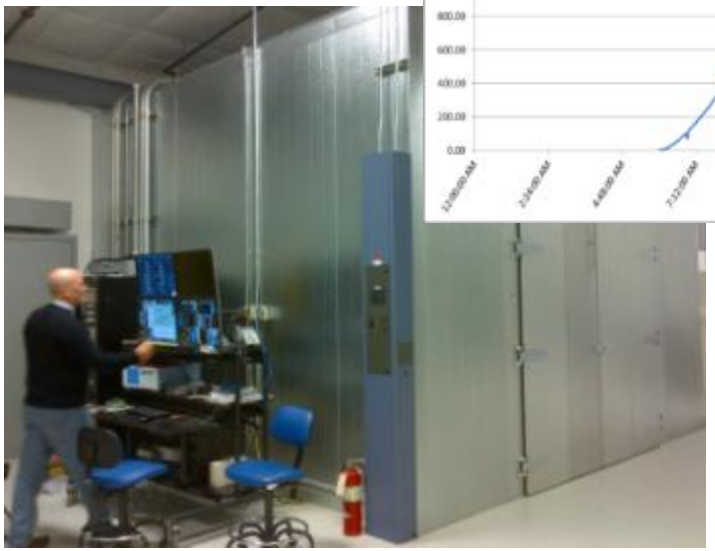


Performance Testing – Solar Simulation

- AE has installed programmable supplies to perform solar simulation testing
- Example of NREL test profile demonstrated with 1000NX
- Example of actual site irradiance data programmed for test



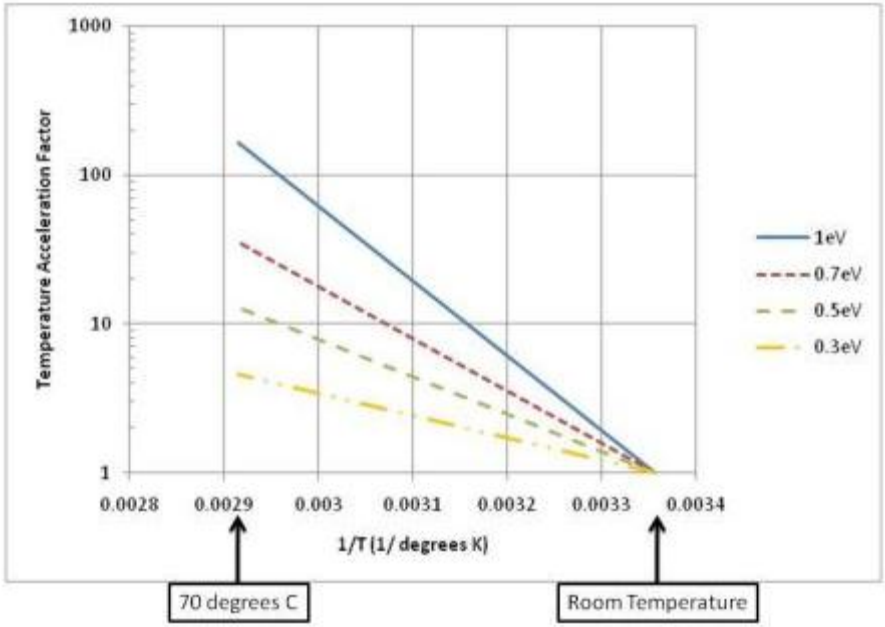




Accelerated Life Test (ALT) – Temperature Acceleration

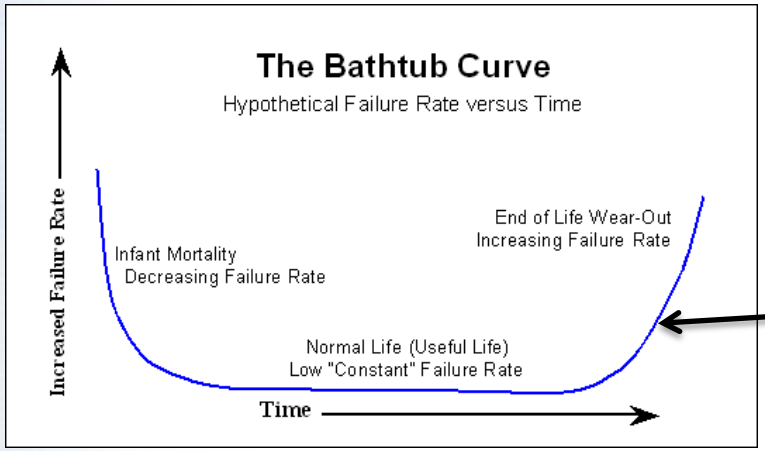
- Durability tests such as system level accelerated life testing (ALT) and component & subsystem highly accelerated life testing (HALT) are key tools to qualify the reliability of new designs
- The most common temperature acceleration factor AF(T) is based upon the Arrhenius model
  - K_b is the Boltzmann's 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.



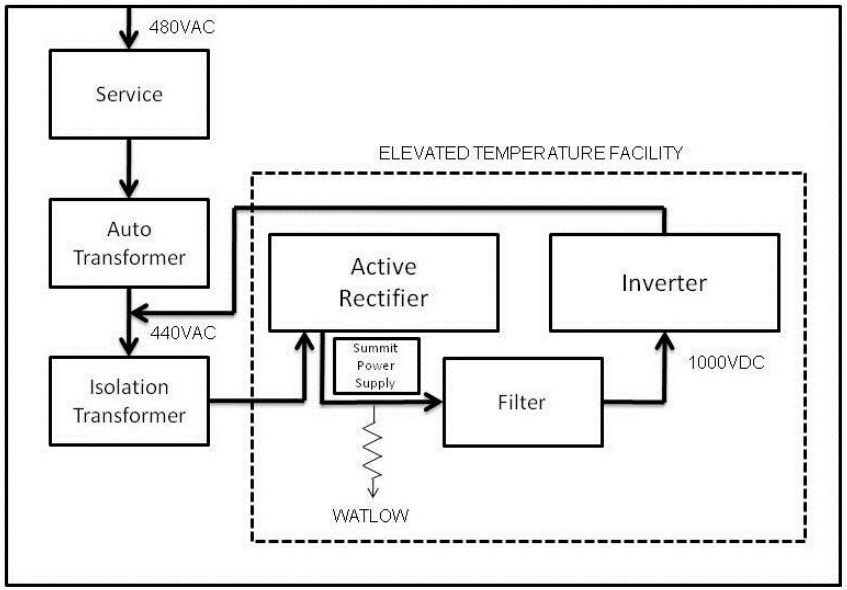
$$\lambda \propto \text{Failures}/(\text{Total Device Hours} \times AF(T))$$

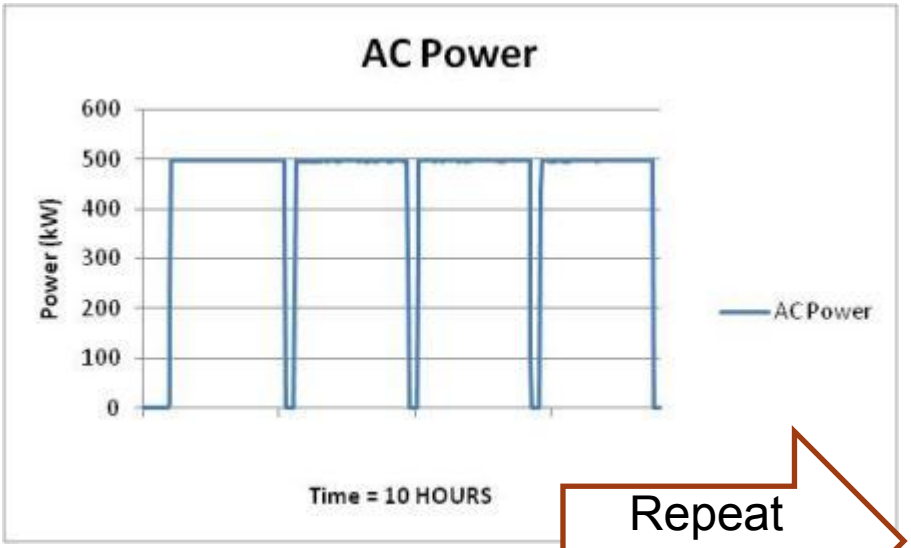
$$AF(T) = \exp[(E_a/K_b)(1/T_o - 1/T)]$$



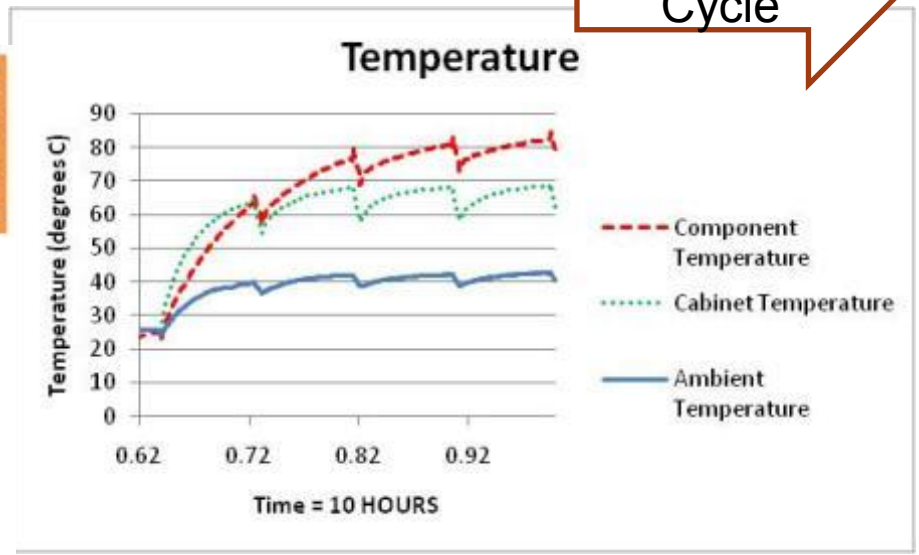
ALT is a gage of the inverter durability to reach end-of-life failure rate region

Life Test Profile Example; System Level ALT





Repeat Cycle



Thermal Qualification – Efficient Cooling Design

- Meet thermal challenges in desert solar site environments
- Thermal characterization has exhibited thermal margins for long lifetime
  - Reliability Rule of Thumb: For every 10degC decrease in temperature, the equipment lifetime is doubled
- Detailed thermal mapping is completed at all operation envelopes

1000NX Installed in Desert

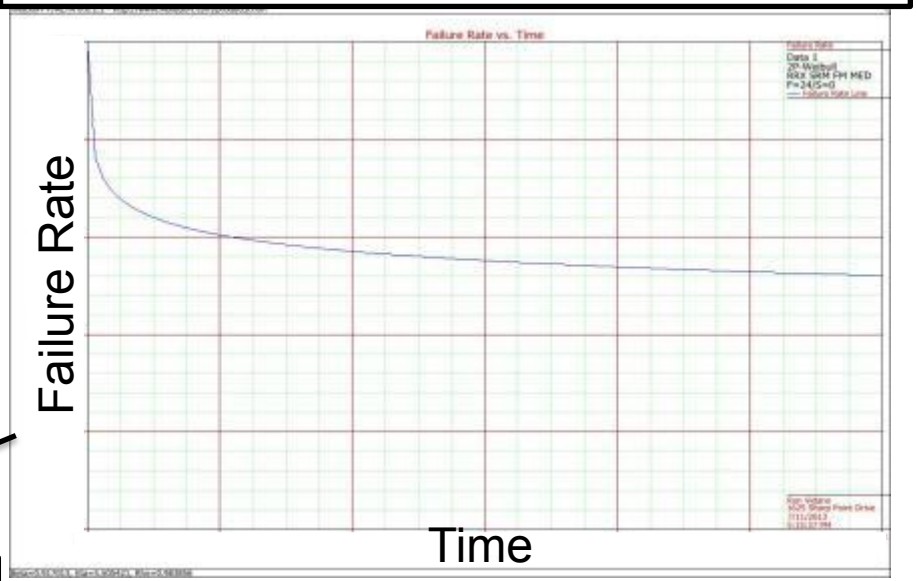
1000NX Tested in Thermal Chamber

Utility Inverter Qualification for a Wide Range of Environments

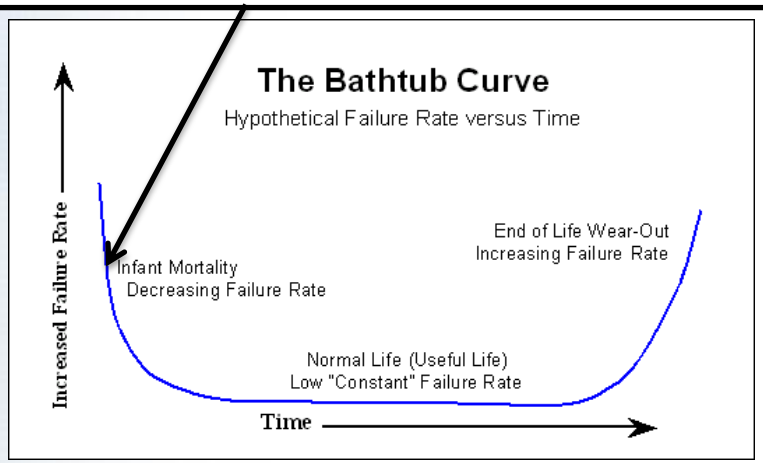
System Level Burn-In for Utility Inverters

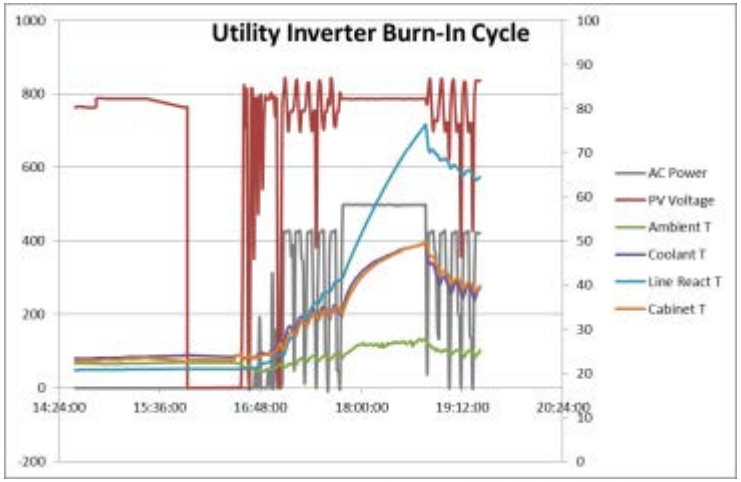
- Burn-in testing takes place at the unit level to stress the components for a designated period time to precipitate component early lifetime mortality - Temperature and Voltage Acceleration Factors
- The burn-in cycle contains voltage and power cycling which is done to ensure that power connections 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



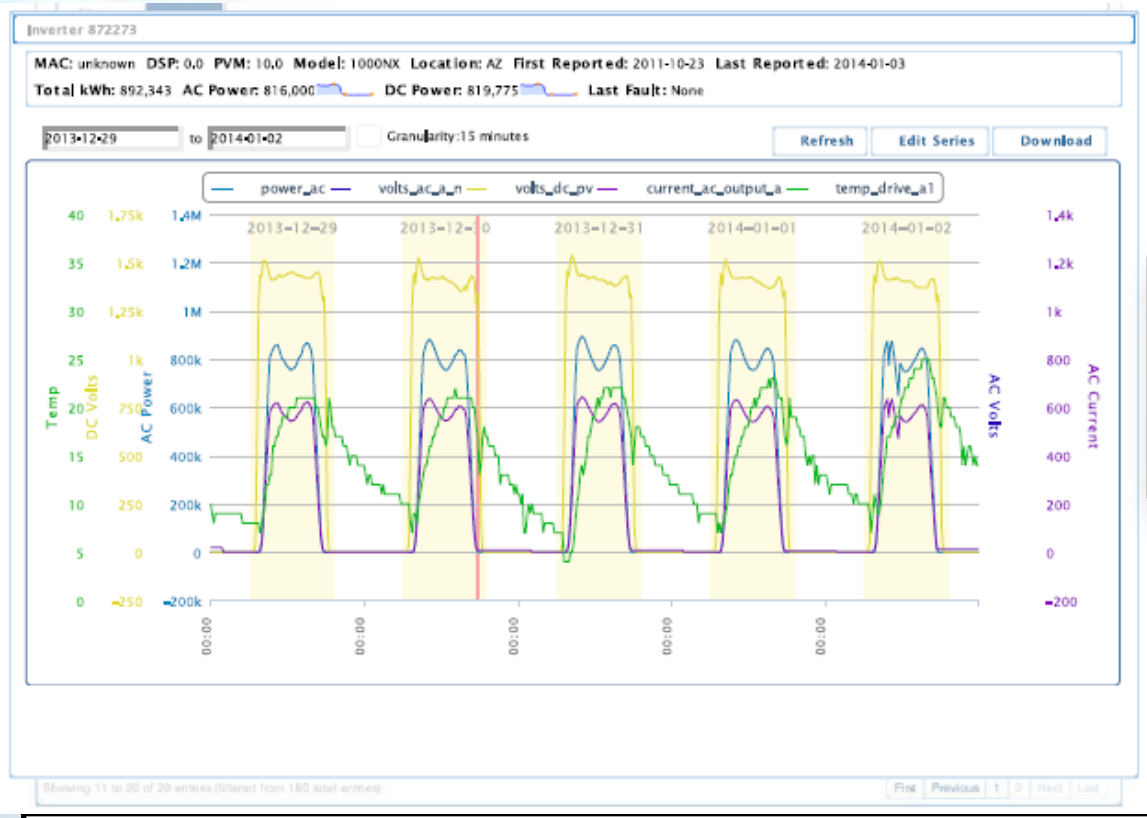
Production Burn-In reduces the number of failures in the early (decreasing failure rate) lifetime region





Inverter Data Monitoring

Example of 1000NX data monitoring – There are 50 performance variables that are constantly monitored



- The attainment of high availability is tied to real-time site data acquisition for inverter operational conditions and subsystem states. Actual field performance is fed back into lifetime models used during qualification testing as well as prediction and simulation criteria.

Conclusion; High Inverter Availability

- Availability is the most important attribute for utility inverters
- High availability is achieved by
  - Design-for-Reliability
  - Design-for-Maintenance
  - Reliability Growth
    - Assurance testing and design improvements
    - Field experience with design improvements

$$\text{Availability} = \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}}$$

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115 Nicholson Lane

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AESOLARENERGY

APPLICATION OF ACCELERATED TESTING AND MODELING TO RELIABILITY ANALYSIS OF MICROINVERTERS

T. Paul Parker – SolarBridge Technologies

NREL PV Module Reliability Workshop

February, 2014

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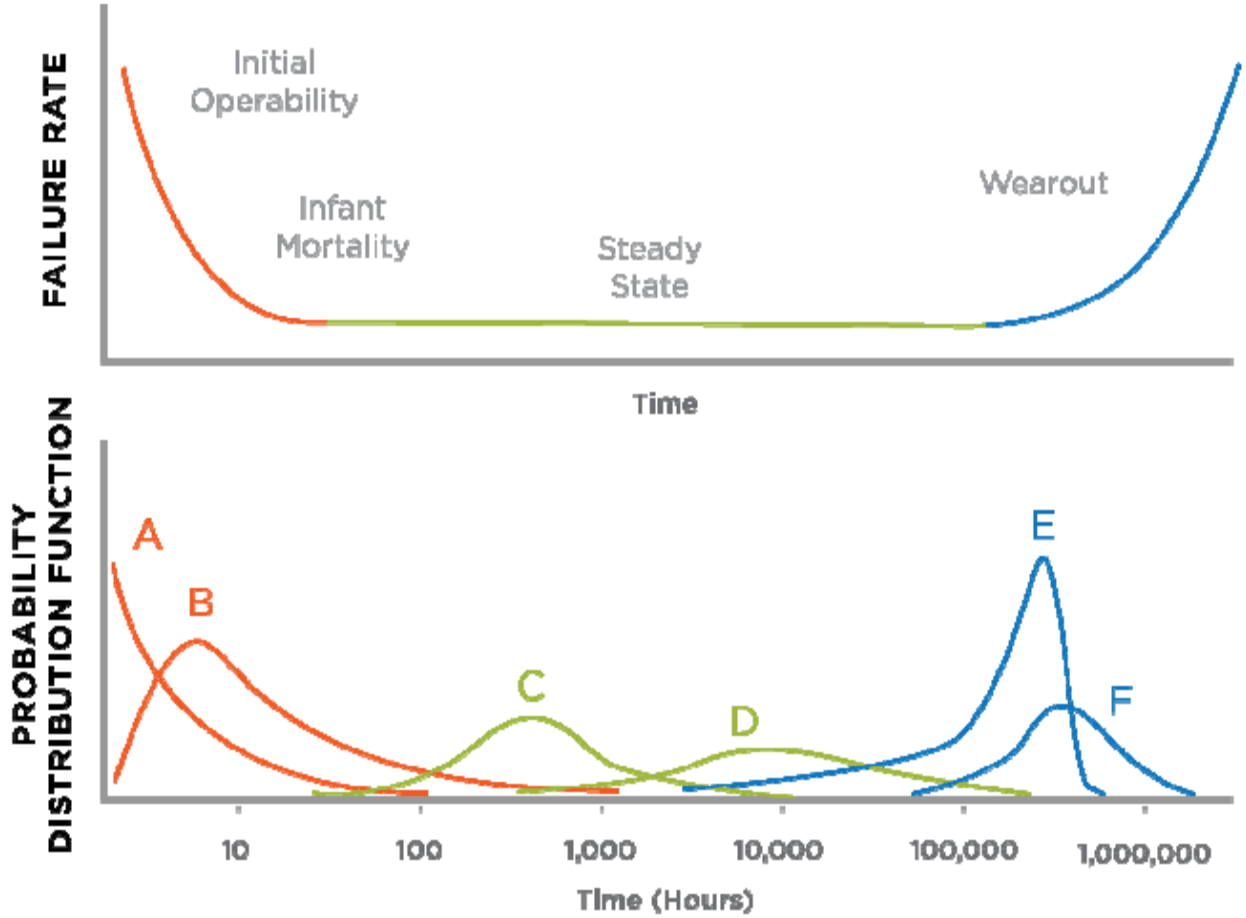
OUTLINE

- Predicting Microinverter Lifetime
- Design Parameters / Field Use Conditions
- Phoenix AZ Case Study
- Reliability Modeling
- Validation using Accelerated Testing

Predicting Microinverter Lifetime

BATHTUB CURVE AND TYPICAL FAILURE MECHANISMS FOR POWER PRODUCTS



Infant Mortality:

A. Weak Solder Joints
B. Cracked Ceramic Capacitor

Steady State:

C. FET Single Event Burnout
D. Corrosion

Wearout:

E. Electrolytic Capacitor Degradation
F. Non Compliant Solder Joints (BGA,etc.)

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PREDICTING PV MICROINVERTER (MI) LIFETIME

- No generic reliability models for Power Electronics Reliability
- Traditional MTBF models (MIL-217, Telcordia SR332, etc)
  - Not applicable to predicting useful life
  - Marginal effectiveness predicting steady state failure mechanisms
- Each MI component has a unique set of failure mechanisms
  - Intrinsic mechanisms limit the lifetime of an inverter
    - 100% of units produced are at risk
    - Cumulative failure of >1% for a given wearout mechanism considered end of life
  - Extrinsic mechanisms are often due to quality excursions of component suppliers or contract manufacturer
    - Small populations at risk, (typically <0.1%)
    - Typical Annualized Failure Rate (AFR) <0.2% for all failure mechanisms

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LIFETIME PREDICTION AND TEST VALIDATION

- Step 1: Review all known intrinsic wearout mechanisms
  - Solder joint fatigue, Film / Electrolytic capacitance reduction, PCB via fatigue, Time Dependent Dielectric Breakdown, etc,
- Step 2: Define failure
  - Solder Joint – hard failure or measurable loss of energy harvest
- Step 3: Measure field stresses associated with failure mechanism
  - Solder joint
    - Minimum and maximum temperature
    - Diurnal Δ temperature
    - Ramp rate and dwell times
- Step 4: Identify appropriate solder joint reliability model
- Step 5: Perform accelerated test to validate model

Design Parameters / Field Use Conditions

DESIGN PARAMETERS / FIELD USE CONDITIONS

- Inverter Electrical Parameters
  - Power dissipation = f(insolation, efficiency, module power)
  - Component Temperature (min, max, ΔT) =

    f(power, ambient temperature, wind velocity, module rooftop gap)
- Material parameters (PCB, solder, components, chassis, potting, etc.)
  - CTE, hardness, Young's modulus, Tg, etc.
- Environmental conditions
  - Ambient Temperature
  - Wind velocity (affects internal component temperature)
  - Relative Humidity
  - Insolation

SOURCES OF DATA

- Inverter reported parameters
  - Voltage, current, power, component voltage / temperature

Date / Time	dc_volts	dc_amps	dc_watts	ac_volts	ac_watts	vbus max	vbus min	vbus avg	FET temp	lte
6/15/2013 6:50	27.99	0.22	6.1	233.17	3.9	376	368	373	10	3354
6/15/2013 6:55	27.69	0.26	7.2	232.72	5	376	368	372	12	3354
6/15/2013 7:05	27.95	0.26	7.5	232.72	5.3	377	369	372	12	3355
6/15/2013 7:10	27.45	0.29	8	232.72	5.7	377	369	373	13	3355
				.						
				.						
				.						
6/15/2013 13:30	26.54	7.81	209.7	248.76	200.5	459	362	400	49	3977
6/15/2013 13:35	25.86	7.82	204.8	246.27	195.8	438	375	416	50	3993
6/15/2013 13:40	25.66	7.92	205.9	249.21	196.9	439	380	422	50	4009
6/15/2013 13:50	26.1	1.77	46.8	234.98	43.3	442	367	389	49	4020
6/15/2013 13:50	26.68	8.68	234.6	249.66	224.5	443	367	405	48	4032
6/15/2013 13:55	18.11	5.7	105.8	241.75	100.2	444	369	386	49	4041
6/15/2013 14:00	26.92	8.9	242.2	251.24	231.9	451	366	429	48	4049
6/15/2013 14:10	26.54	7.92	212.9	249.21	203.5	444	368	408	48	4071
6/15/2013 14:15	26.04	8.54	225.1	249.66	215.3	441	367	420	48	4085
6/15/2013 14:20	21.27	6.82	147.3	245.59	140.3	445	367	386	46	4093
6/15/2013 14:25	26.7	2.02	54.6	235.65	50.8	448	370	386	46	4104
6/15/2013 14:30	26.82	8.15	221.2	249.89	211.6	447	369	405	46	4117

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REGIONAL ENVIRONMENTAL DATA

- NREL Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors, Report NREL/TP--463-5607, 1994

Average Climatic Conditions

Element	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Temperature (°C)	12.0	14.3	16.8	21.1	26.0	31.2	34.2	33.1	29.8	23.6	16.6	12.3	22.6
Daily Minimum Temp	5.1	7.1	9.3	12.9	17.7	22.7	27.2	26.2	22.7	16.0	9.4	5.4	15.2
Daily Maximum Temp	18.8	21.5	24.2	29.2	34.2	39.7	41.1	39.8	36.8	31.2	23.8	19.0	29.9
Record Minimum Temp	-8.3	-5.6	-3.9	0.0	4.4	10.0	16.1	15.6	8.3	1.1	-3.9	-5.6	-8.3
Record Maximum Temp	31.1	33.3	37.8	40.6	45.0	50.0	47.8	46.7	47.8	41.7	33.9	31.1	50.0
HDD, Base 18.3°C	201	126	101	42	4	0	0	0	0	9	74	192	750
CDD, Base 18.3°C	4	12	53	123	242	387	491	457	343	173	23	4	2312
Relative Humidity (%)	51	44	39	28	22	19	32	36	36	37	44	52	37
Wind Speed (m/s)	2.5	2.8	3.2	3.4	3.4	3.2	3.4	3.2	3.0	2.8	2.6	2.5	3.0

- Atlas Material Testing Technology LLC

Date	Time	Ambient	%RH	Wind Speed M/sec	Wind Direction	Rainfall CM	5° TTL Solar W/m²	5° UV Solar W/m²	34° Total Solar W/m²	34° UV Solar W/m²
6/12/2013	16:44	42	9	4.37	206	0	502	24	406	18
6/12/2013	16:45	41	9	4.86	202	0	497	24	401	18
6/12/2013	16:46	41	10	3.87	225	0	496	24	399	18
6/12/2013	16:47	42	9	2.75	224	0	492	24	395	18
6/12/2013	16:48	41	9	4.51	264	0	488	23	391	18
6/12/2013	16:49	41	9	3.70	244	0	484	23	387	18
6/12/2013	16:50	42	10	2.89	238	0	481	23	384	17

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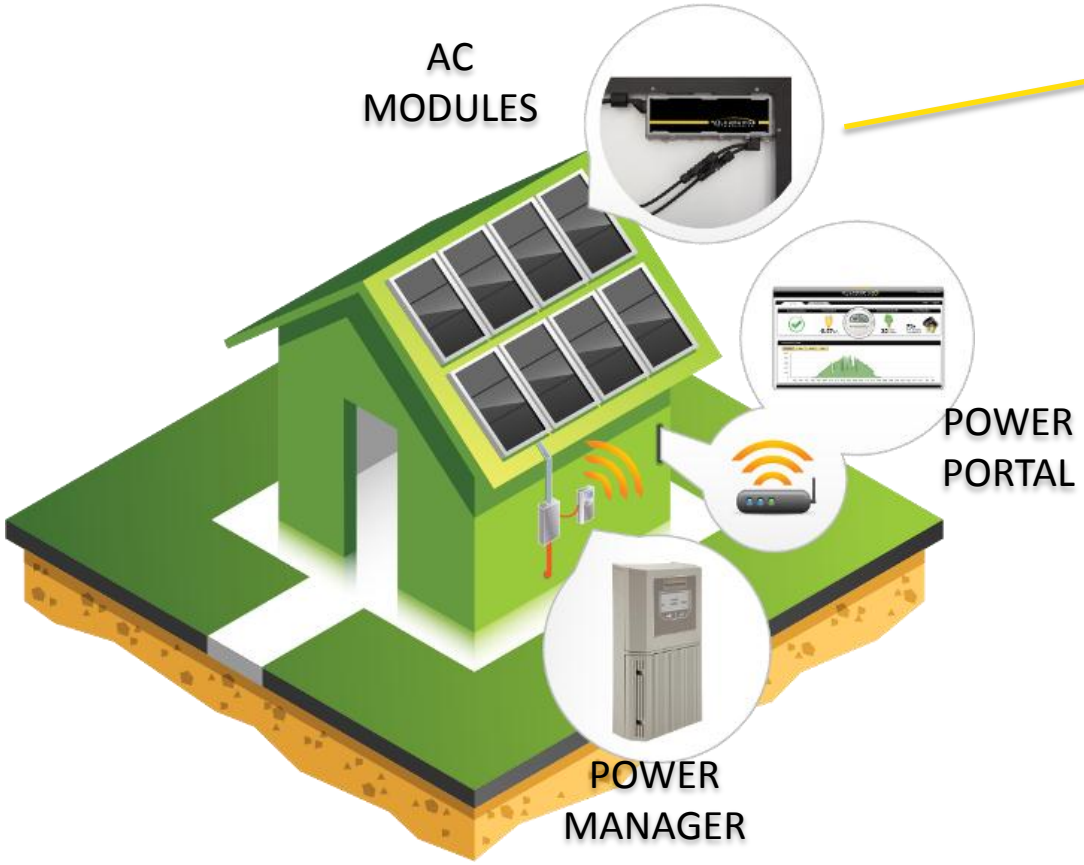
Phoenix AZ Case Study - SolarBridge Microinverter

SOLARBRIDGE AC MODULE



PHOENIX AZ
42 MODULE ACPV INSTALLATION

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SOLARBRIDGE POWER PORTAL VIEW

SolarBridge Technologies Power Portal - Mozilla Firefox

File Edit View History Bookmarks Tools Help

SolarBridge Technologies Power Portal

portal.theenergybridge.com/spp/v4/SiteOwner/layout.cfm?sid=511

MAGE SOLAR

82.1 °F Logout | Back to Site View | Help | My Account

LAST UPDATE ON TUESDAY 2014.02.18 AT 5:51 PM

SUMMARY

2014.02.18 12:20 PM

POWER OUTPUT

TODAY 7 DAYS 30 DAYS

5 kW

0 W

2:00 am 4:00 am 6:00 am 8:00 am 10:00 am 12:00 pm 2:00 pm 4:00 pm

Tue 4 am 8 am 12 pm 4 pm

Site Details

Modules Installed	42	
Power	2.7	kW
Energy		
Today	44.1	kWh
Past 7 Days	273.7	kWh
This Month	584.7	kWh
Lifetime	20.12	MWh

start 19 Micro... 2 Microso... 3 Windo... 2 Interne... SolarBridg... Microsoft E... Book1.pdf ... 6:17 PM

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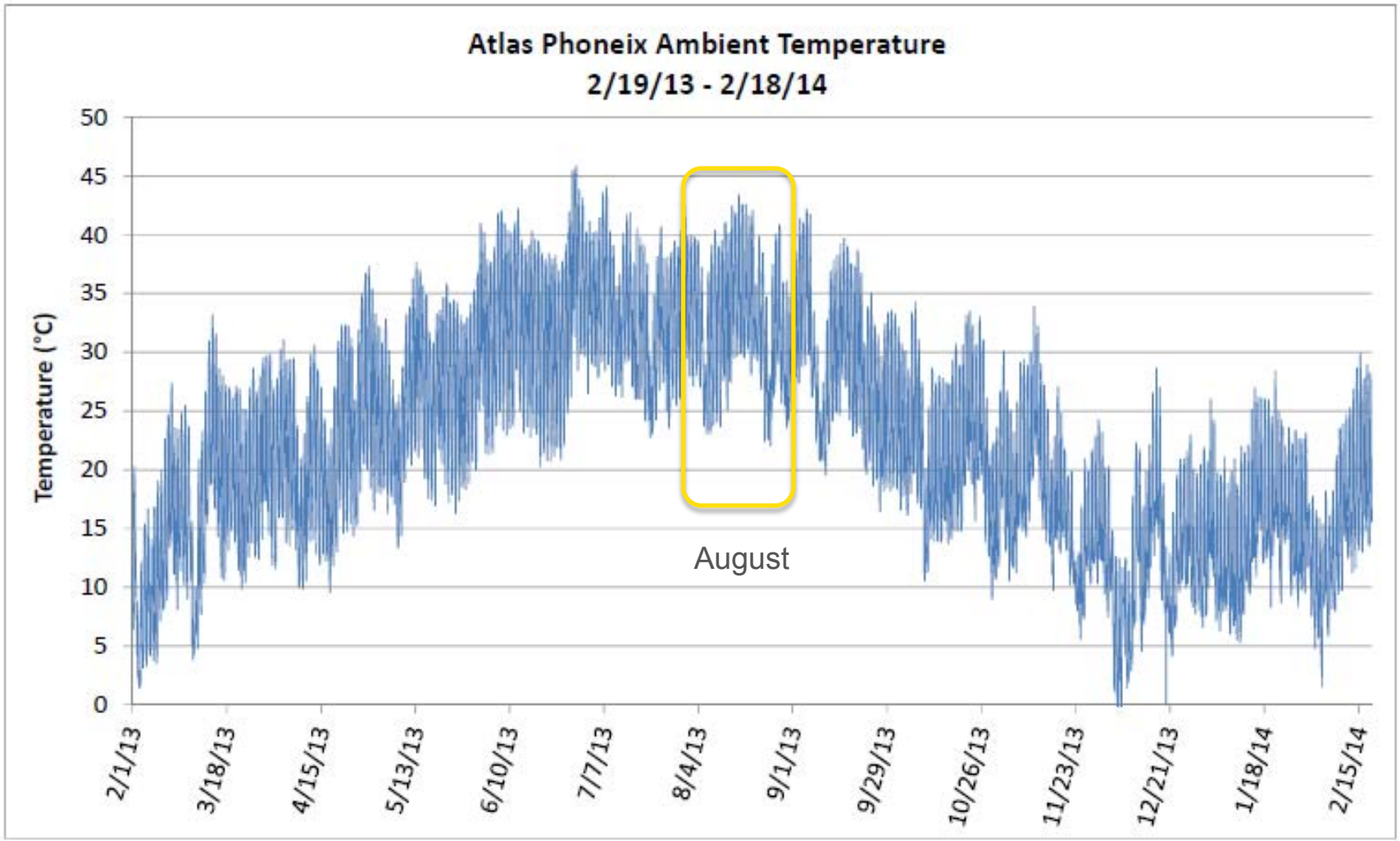
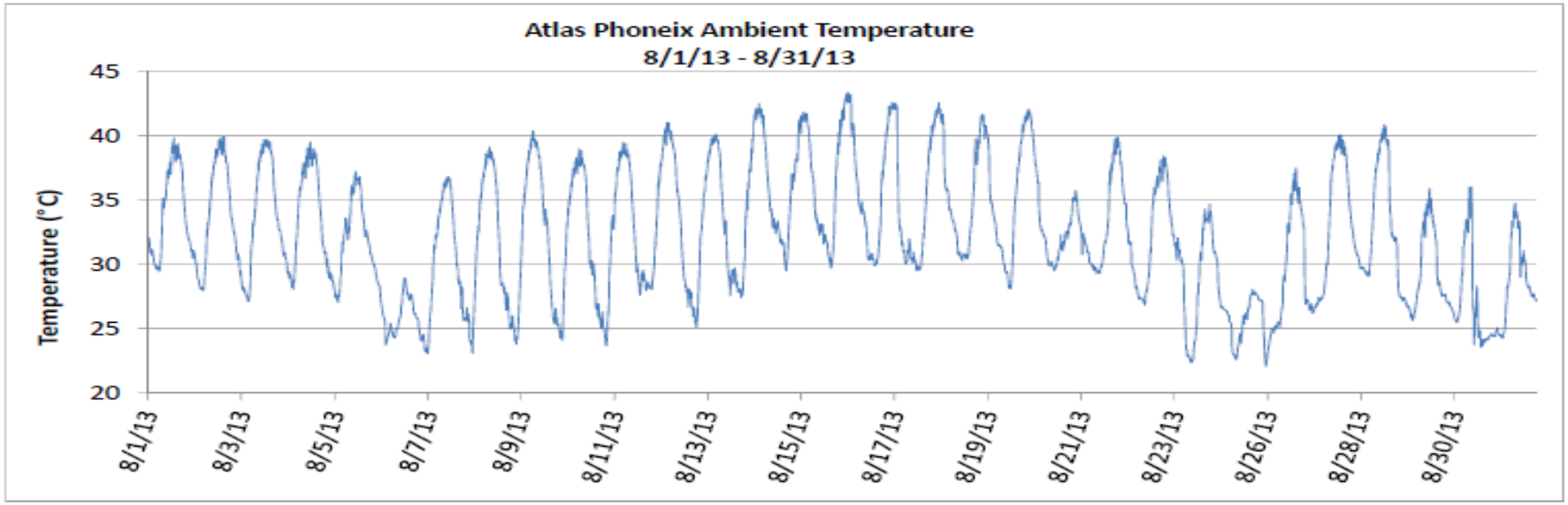
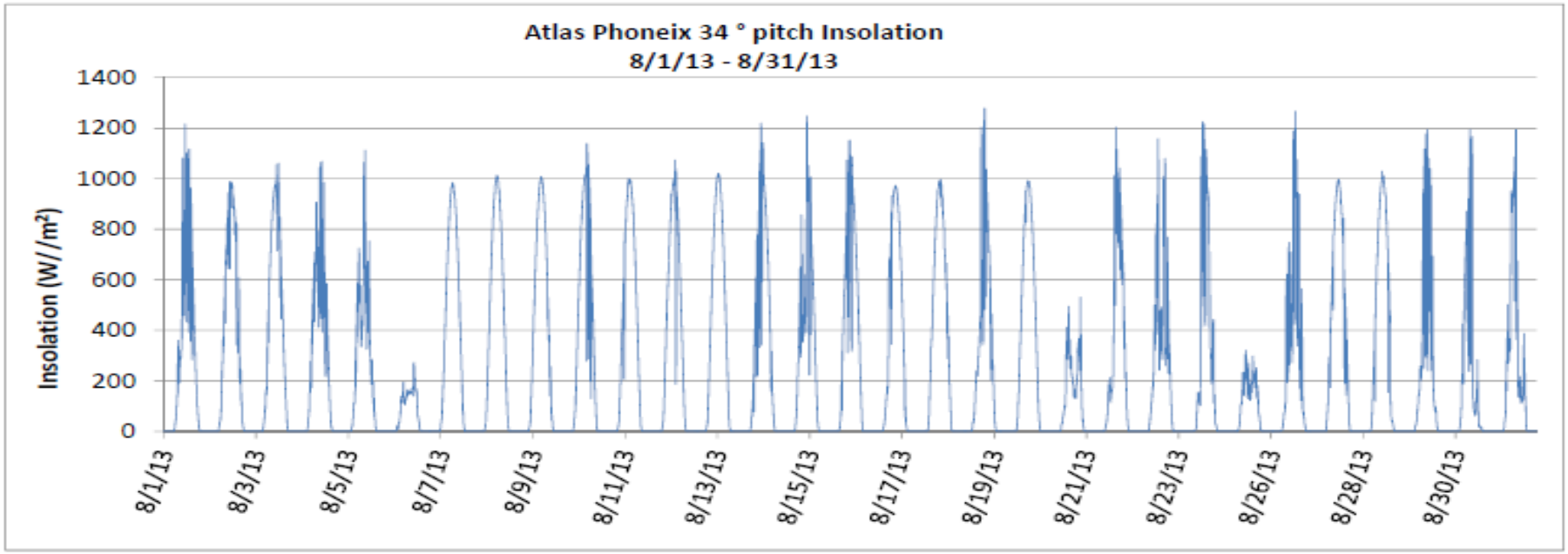
FULL YEAR PHOENIX AZ AMBIENT TEMPERATURE
5 MINUTE SAMPLE INTERVAL (SOURCE – ATLAS)

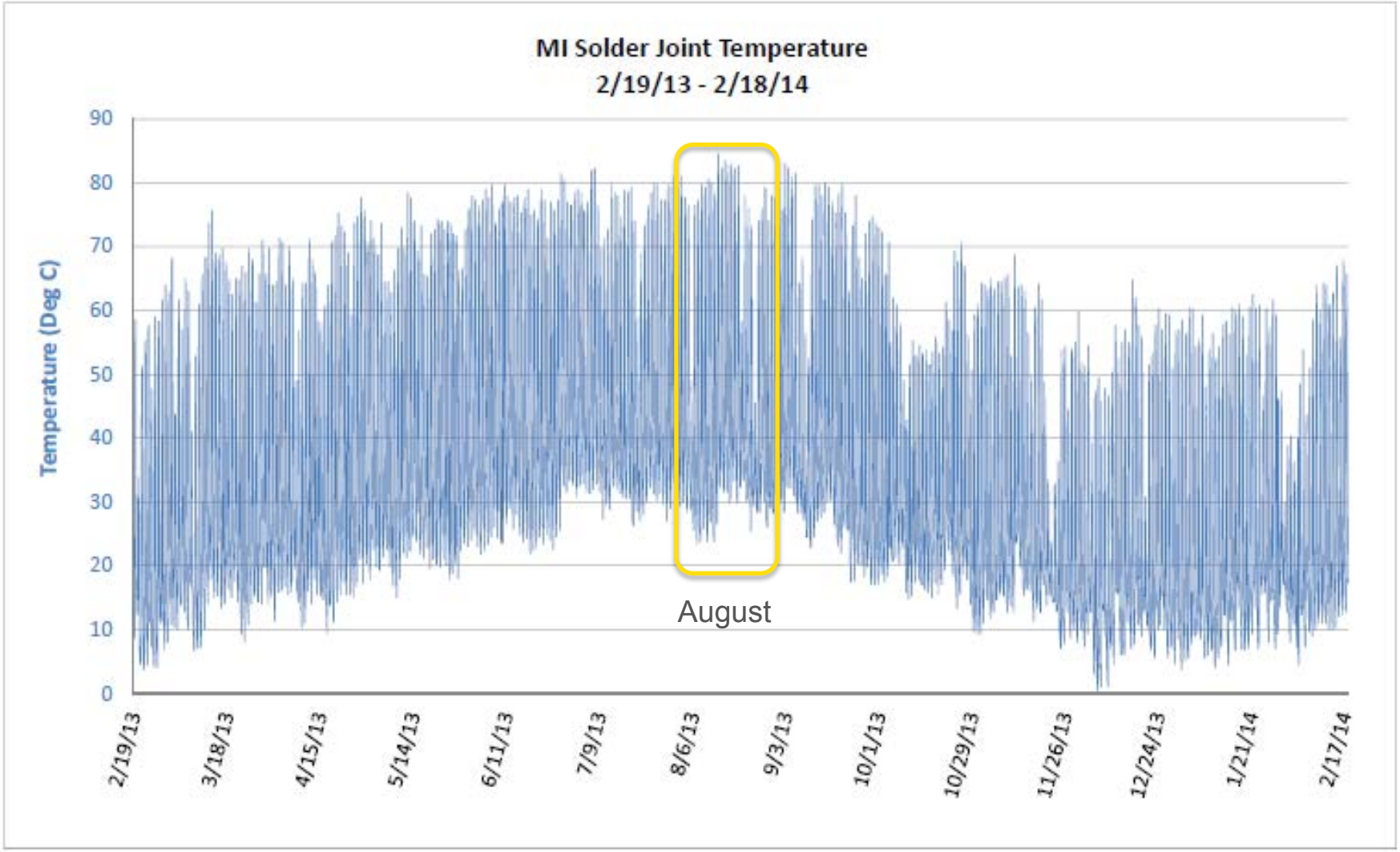


AUGUST '13 AMBIENT TEMP / INSOLATION





FULL YEAR SOLDER JOINT TEMPERATURE
5 MINUTE SAMPLE INTERVAL



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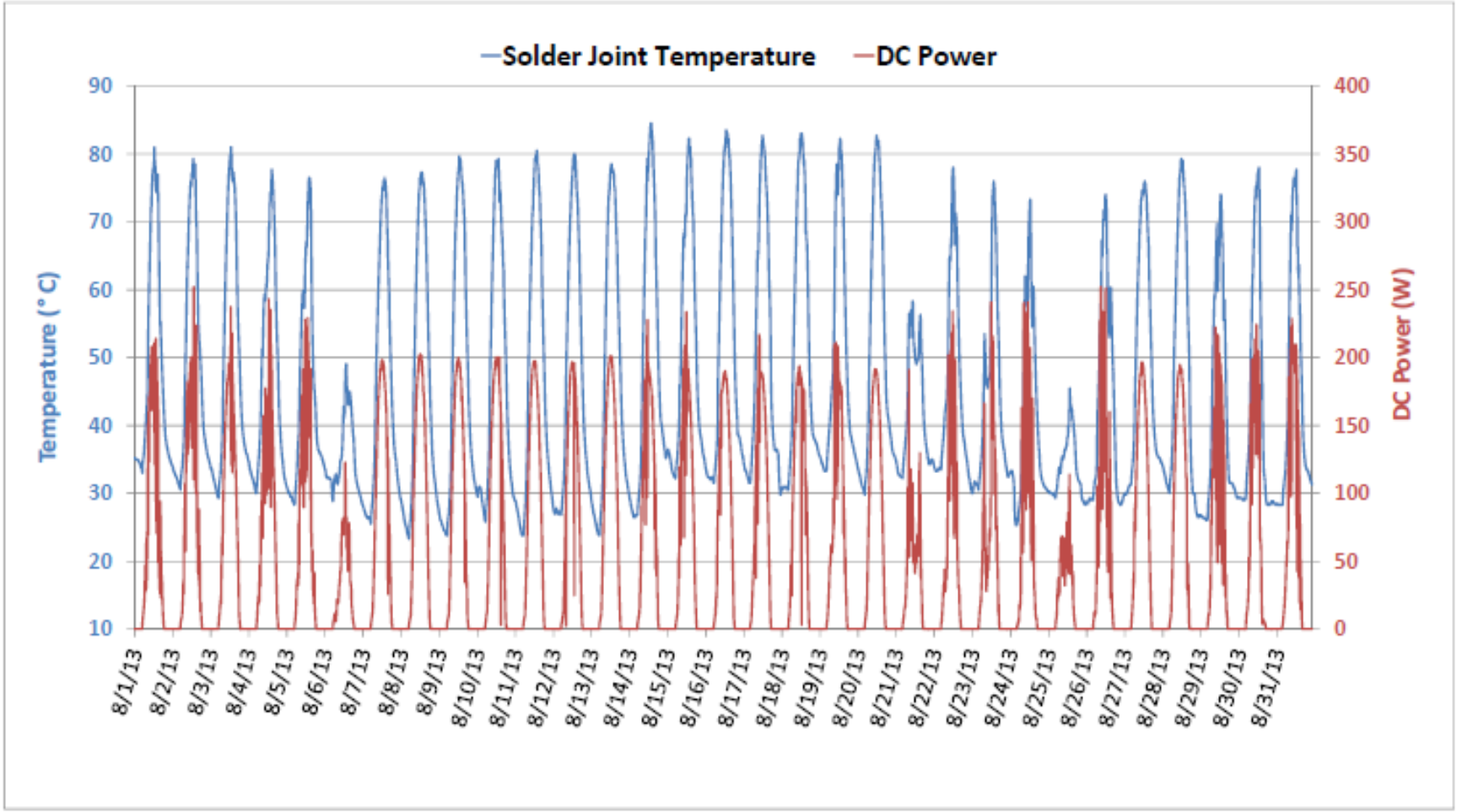
AUGUST '13 MI DC POWER / COMPONENT TEMPERATURE



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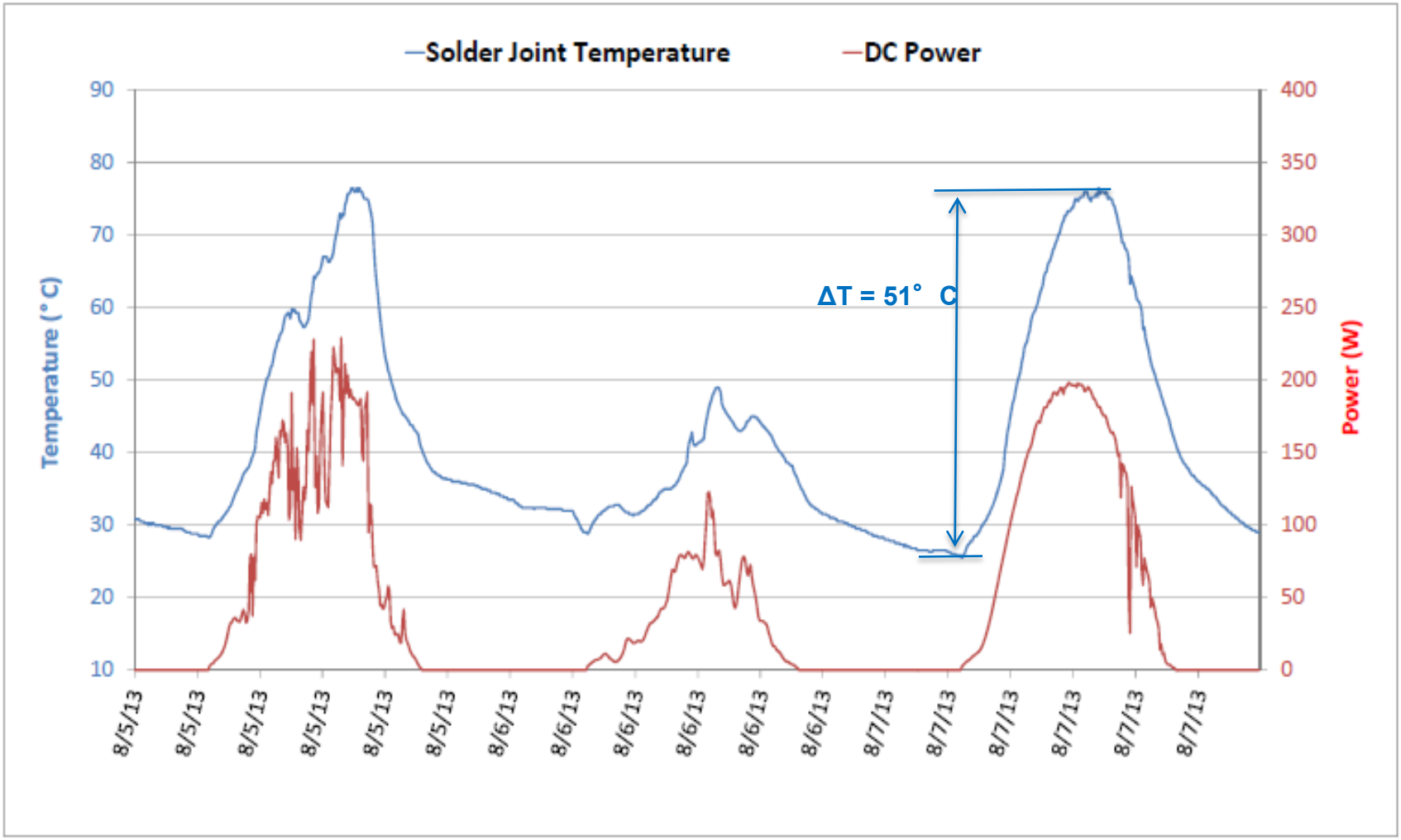
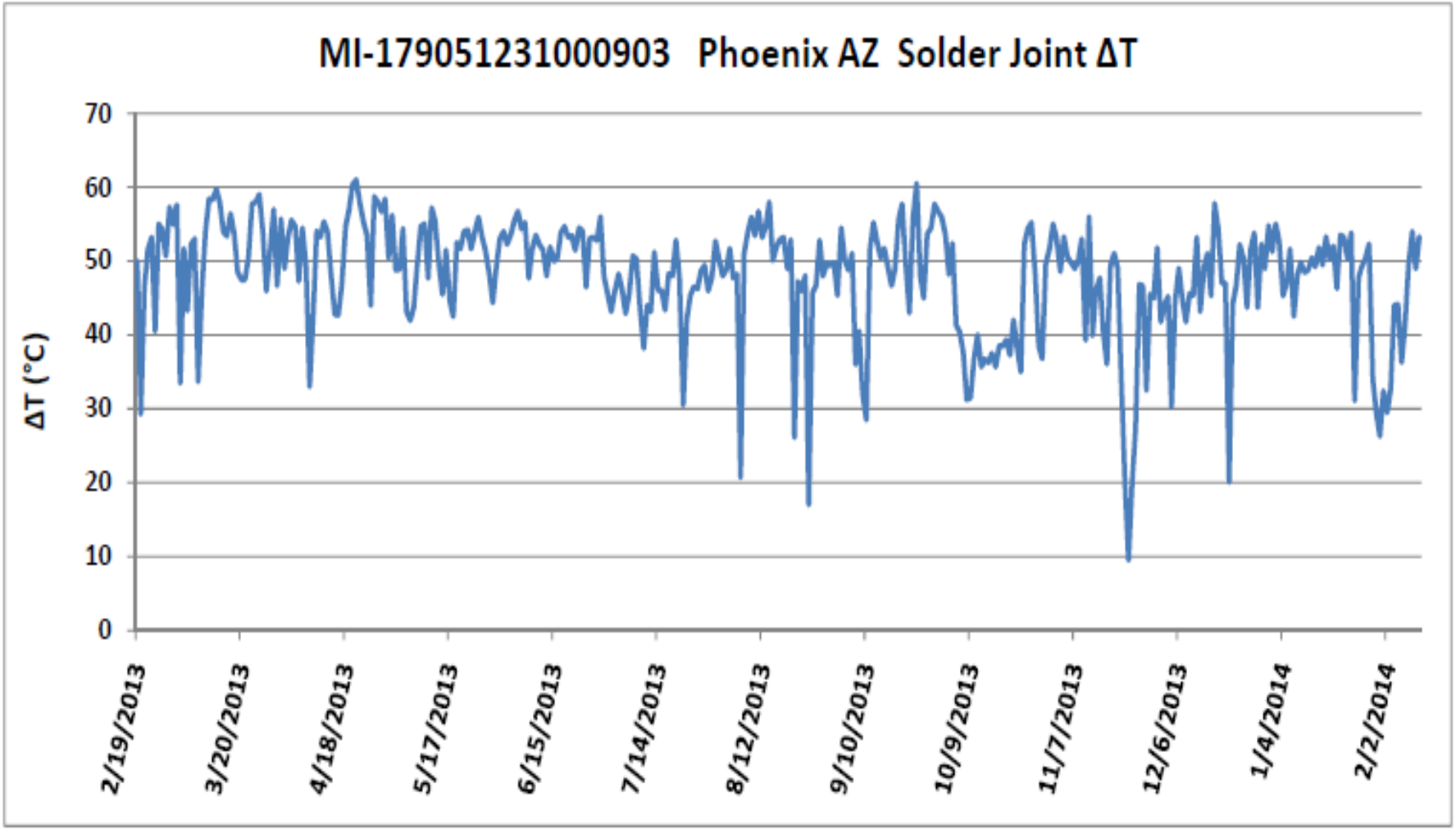
DAILY POWER / TEMPERATURE FLUCTUATION



DAILY SOLDER JOINT ΔT
2/19/13 – 2/18/14



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MONTHLY AVERAGE SOLDER JOINT ΔT

Month	Average MIN	Average MAX	Average Delta
Feb '13	5.9	54.7	48.8
Mar '13	12.4	64.4	52.0
Apr '13	15.1	67.2	52.1
May '13	20.5	71.0	50.5
Jun '13	24.9	77.2	52.3
Jul '13	30.3	76.5	46.2
Aug '13	28.3	76.4	48.0
Sep '13	24.8	74.1	49.4
Oct '13	17.1	59.3	42.2
Nov '13	12.9	56.1	43.2
Dec '13	6.9	53.4	46.5
Jan '14	8.5	56.1	47.6
Feb '14	8.9	51.3	42.4
Average	**16.7**	**64.4**	**47.8**

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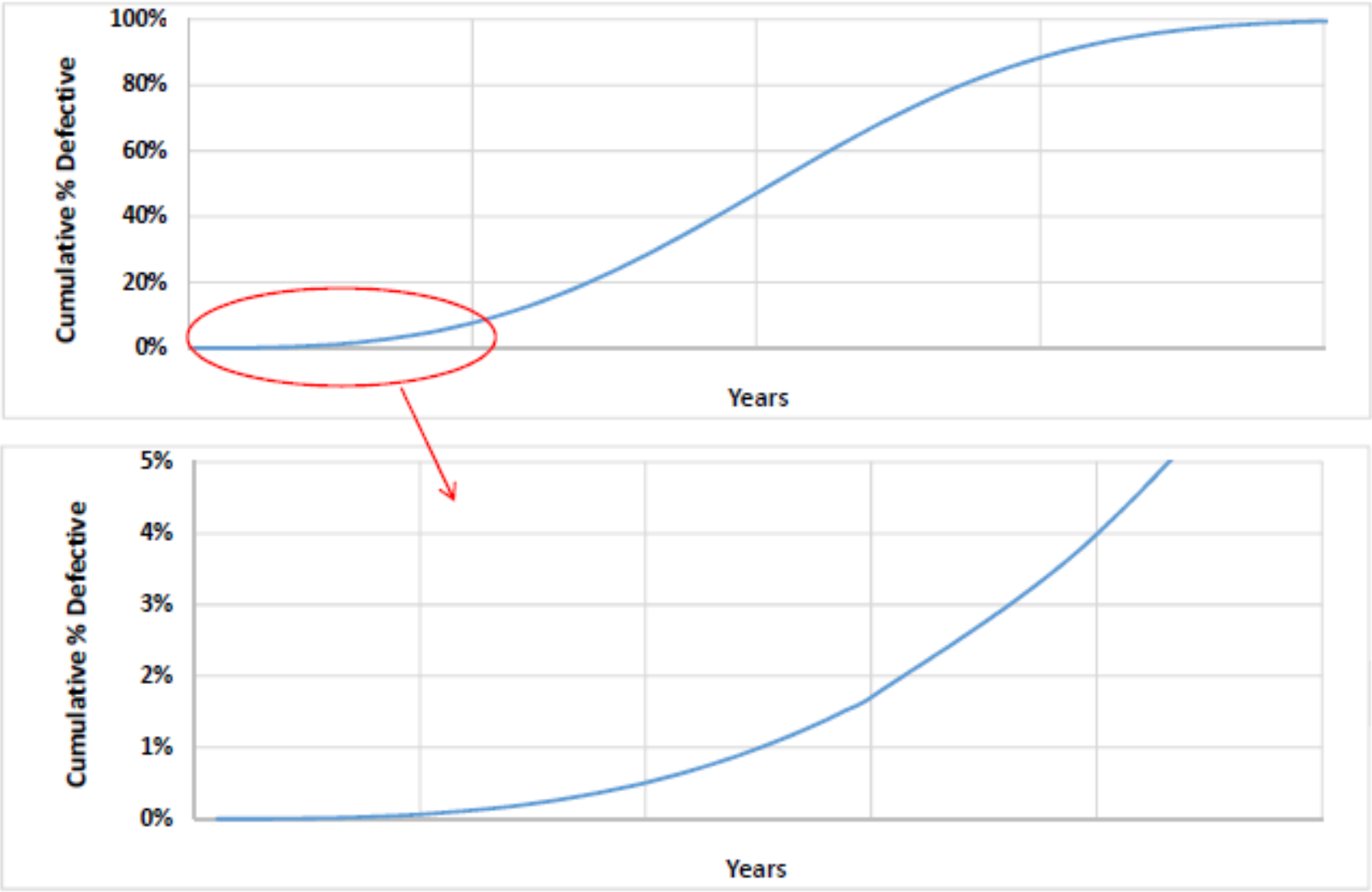
Solder Joint Reliability Modeling

LIFETIME PREDICTION AND TEST VALIDATION

- Step 4: Identify appropriate solder joint reliability model
  - Norris Landzberg
    - N Pan, et.al, “An Acceleration Model for Sn-Ag-Cu Solder Joint Reliability Under Various Thermal Cycle Conditions”, SMTA International, 2005.
  - ANSYS Finite Element Analysis
    - B. Zahn, “Impact of Ball Via Configurations on Solder Joint Reliability in Tape-Based CSP”, ECTC, 2002
  - Cumulative Strain Energy Damage
    - N. Blattau, C. Hillman, “An Engelmaier Model for Leadless Ceramic Chip Devices with Pb-free Solder”, IPC/JEDEC Lead Free Conference, 2006.
  - DfR Solutions Sherlock
    - R. Schueller, C. Tulkoff, “Automated Design Analysis: Comprehensive Modeling of Circuit Card Assemblies, APEX, 2011

SOLDER JOINT FAILURE DISTRIBUTION



Validation Using Accelerated Testing

ACCELERATED TESTING

- Necessary for detection of intrinsic failure mechanisms in a short amount of time
- Requirements:
  - Powering and monitoring to detect intermittents
  - Multiple test environments
    - Thermal cycle
    - High temperature
    - Temperature Humidity
    - Salt Fog
    - Random Vibration
- Requires testing beyond specification
  - Risk of false failures

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IEC 62093* PV INVERTER BOS / ENVIRONMENTAL TEST STANDARD

- Thermal Cycle (TC)
  - -40° C to 85° C
  - Purpose: identifies mechanisms related to thermal mechanical cyclic fatigue such as solder joints and PCB vias
  - Acceleration factor 10x – 30x typical
- Highly Accelerated Life Test (HALT)
- High Temperature Operating Bias (HTOB)
- Damp Heat (DH)
- Humidity Freeze (HF)
- Salt Mist
- UV

Notes:
-UL 1741 / IEC 62109 do not have accelerated test requirement, they address safety only
-Acceleration factors **must** be developed for each failure mechanism;
-Recommend Weibull analysis using multiple stress conditions

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SUMMARY

- Confirmation of useful life requires an understanding of all potential intrinsic wearout mechanisms
- Each failure mechanism requires
  - An understanding of physics of failure
  - Appropriate model capable of predicting time to failure
  - Field use conditions
  - Accelerated test method to speed time to detect failure
  - Acceleration factors to predict time to failure
  - Actual field reliability data to validate model and test

Thin Film PID Field Failures and Root Cause Determination

N.A. Olsson, M. Propst. C Richardson, J. Hevelone*

Pearllaboratories
2649 E. Mulberry St, Unit 15
Fort Collins, CO 80512

*CopperMuse Artisan Distillery
244 N. College Ave
Fort Collins, CO 80524

pearllaboratories

Outline

- Field Data
- Laboratory measurements on return modules
- Degradation model
- Verification
- Acceleration factors
- Manufacturing excursions
- Fixing the problem

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Field

- Location: Germany
- Size: 3 MW
- Inverter: Transformer less
- Voltage: 1000 V
- Grounding: Ungrounded
- Modules: Thin Film (CdTe)

- Issue: Substantial under performance after 1 year of operation

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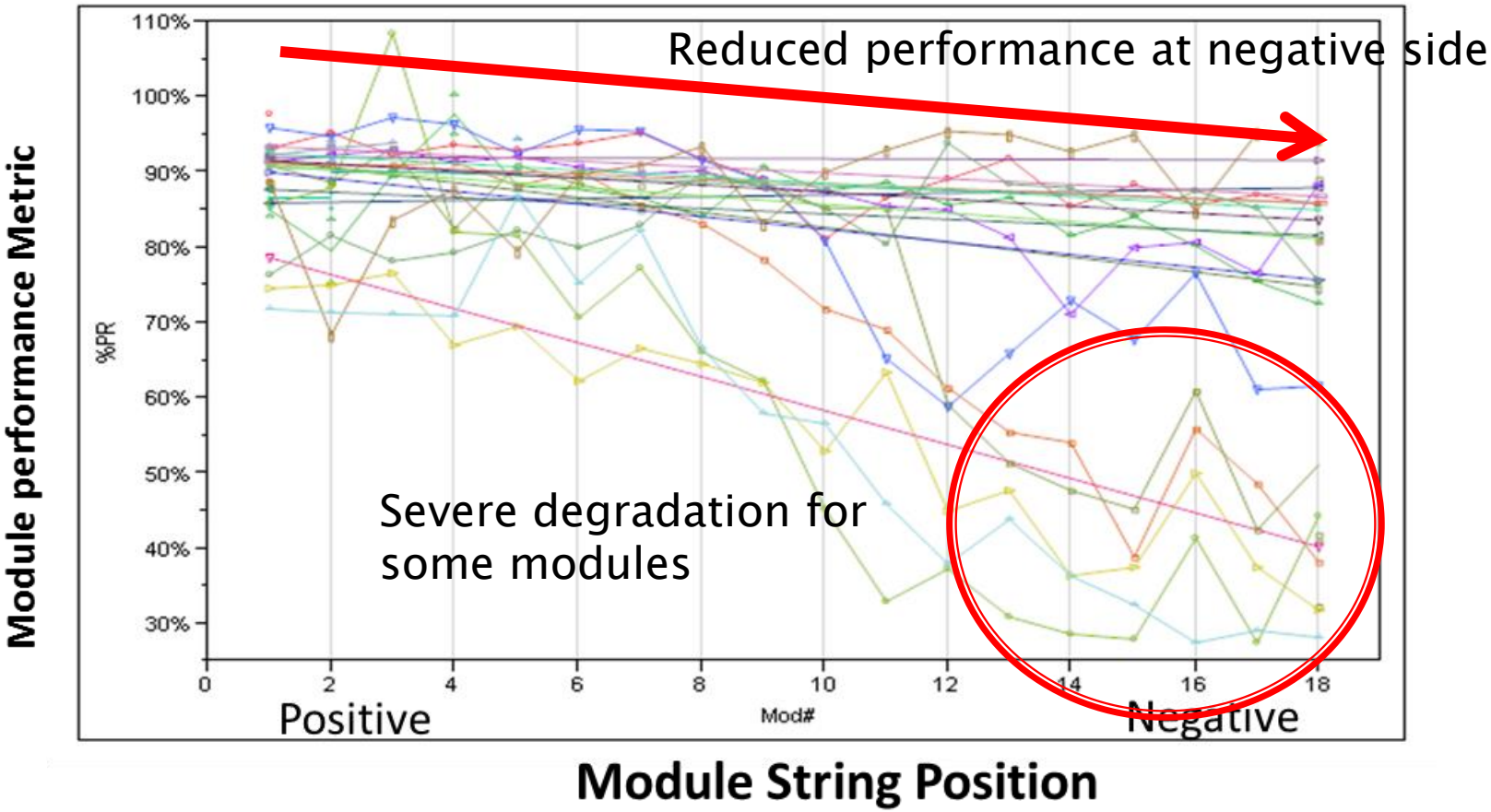
Field Measurements



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Return Module I–V

Severe degradation in Rsh is the issue

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Additional tests on return modules

- HiPot: pass
- H_2O ingress: none
- Delam inspection: none

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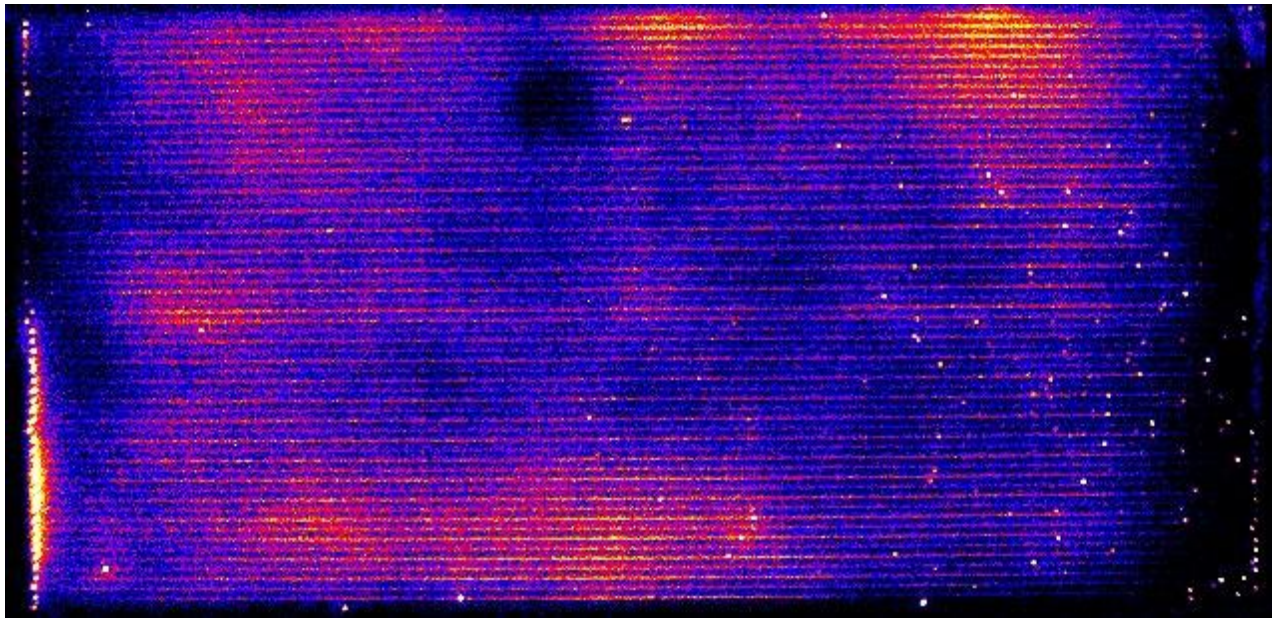
Lock-In thermography

Pinpointing the location of shunts



Severe scribe shunts in degraded module

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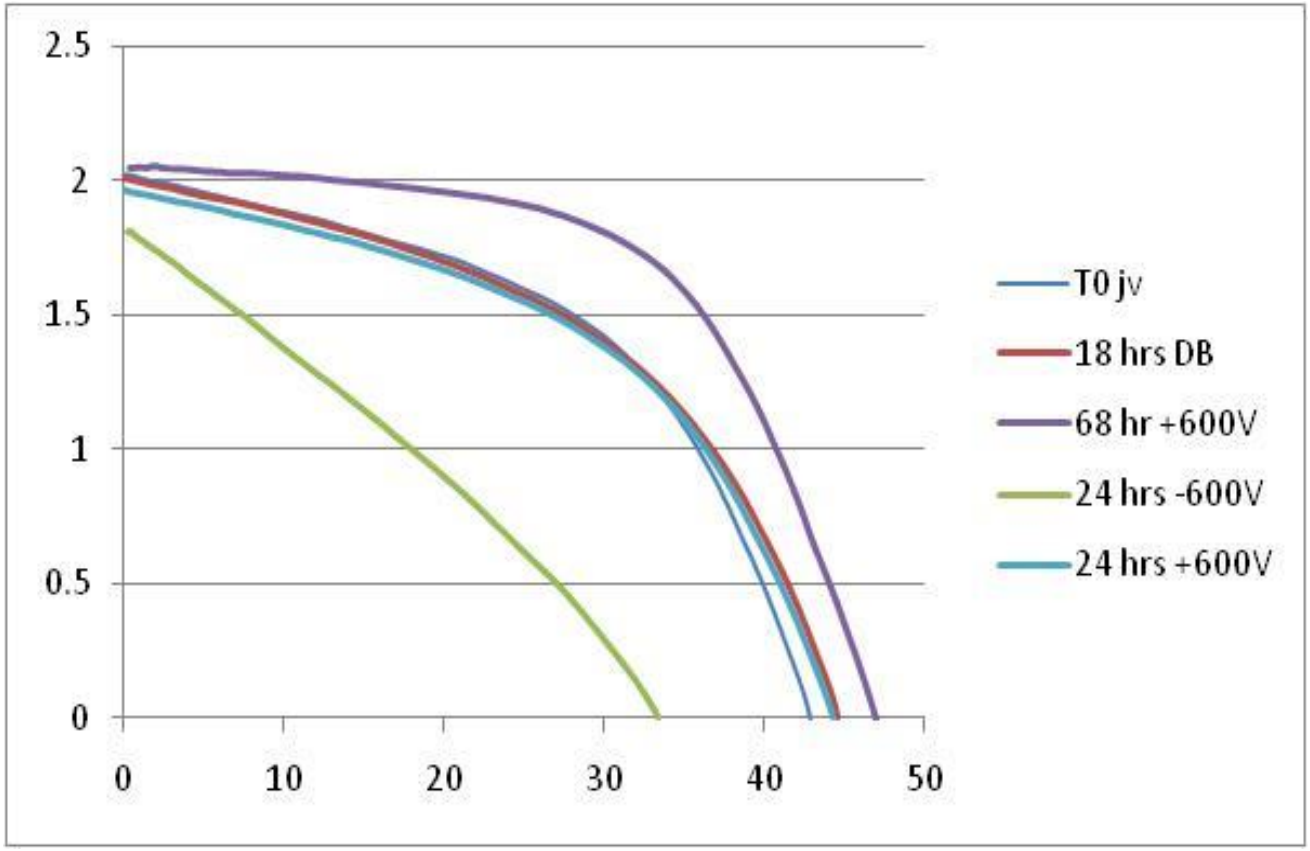
Reversibility of damage



Main degradation is in Rsh and it is a reversible PID type

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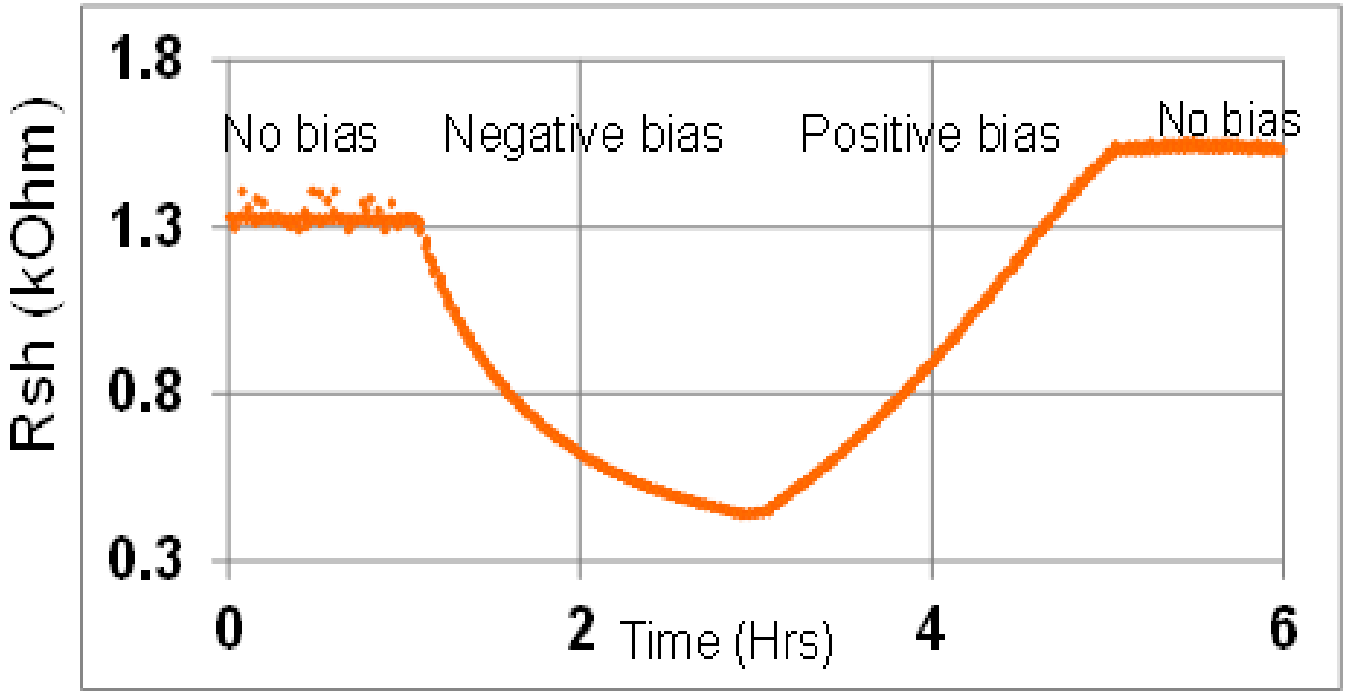
Laboratory PID test on “virgin” modules



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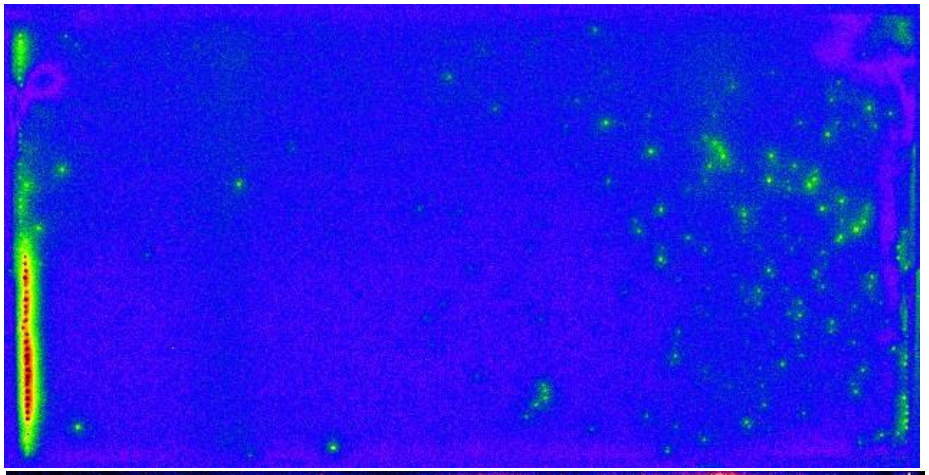
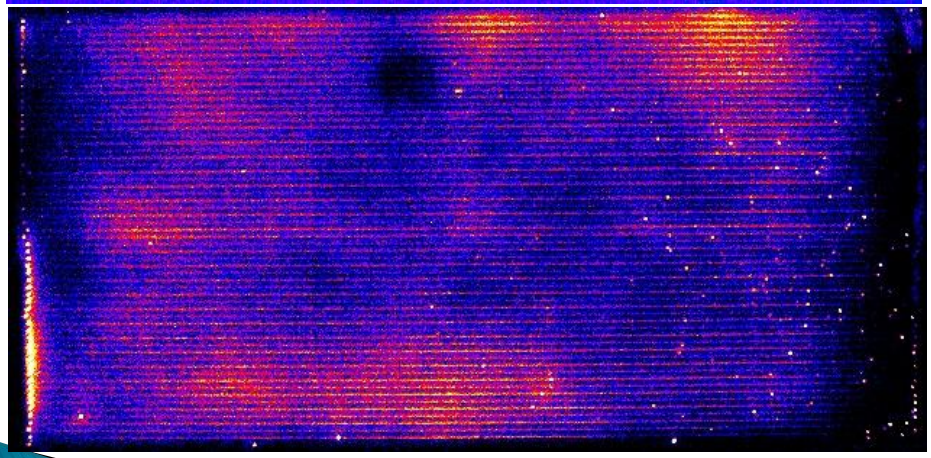
Lock-in thermography of healed module



After positive bias healing



Before

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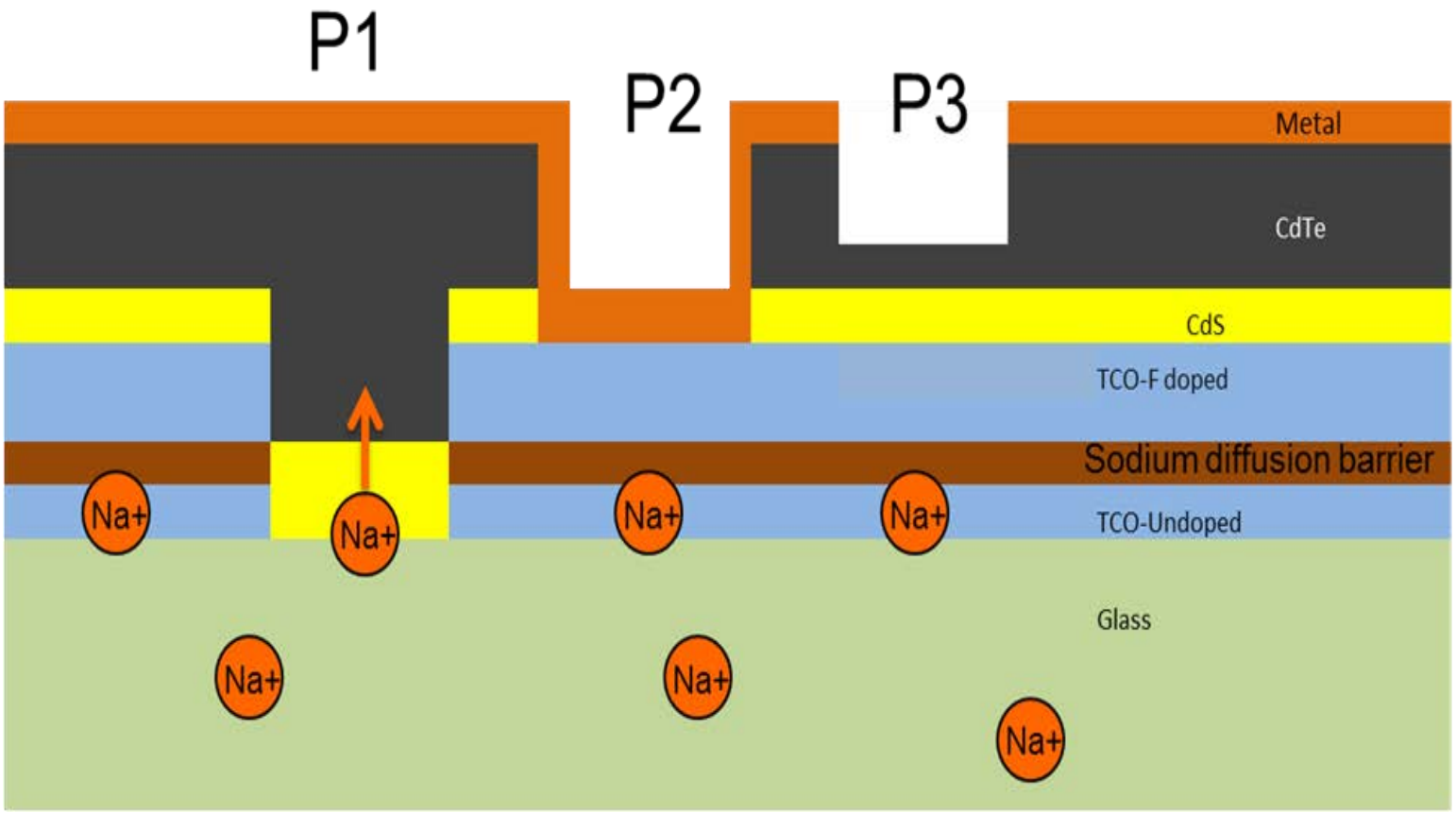
Degradation Model



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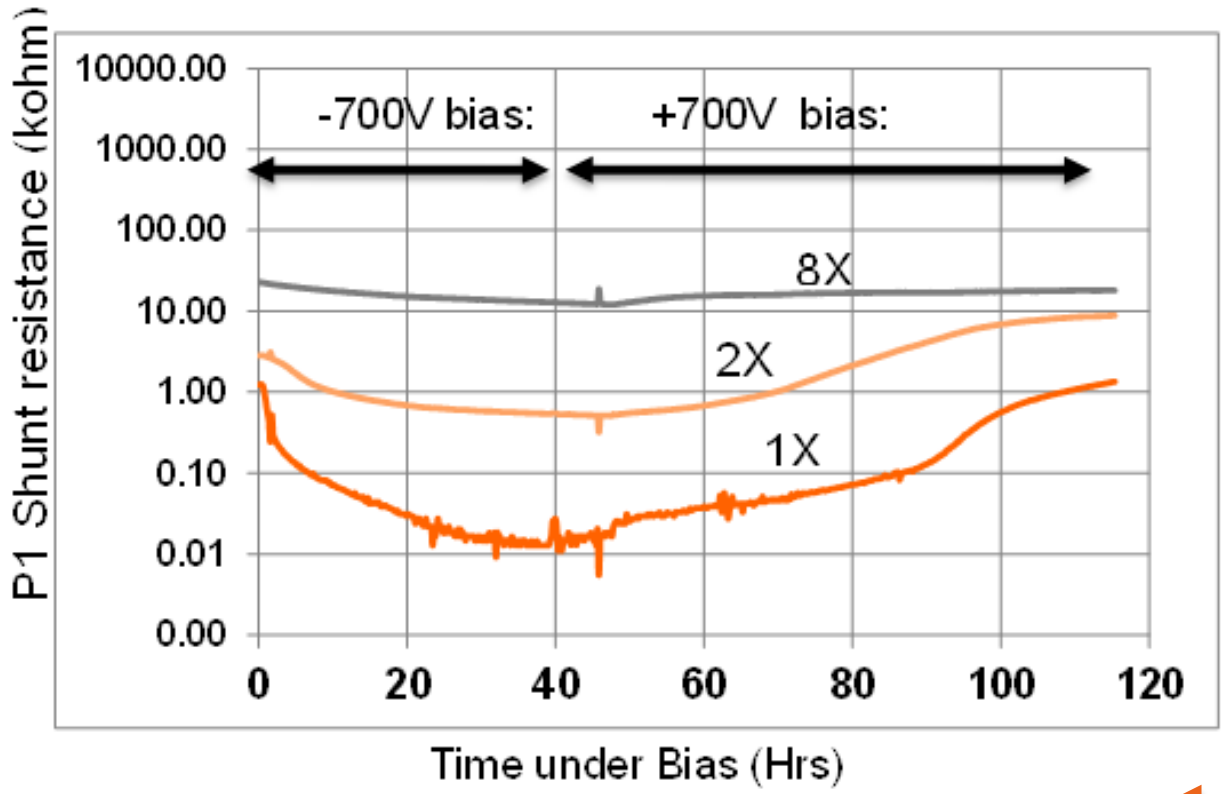
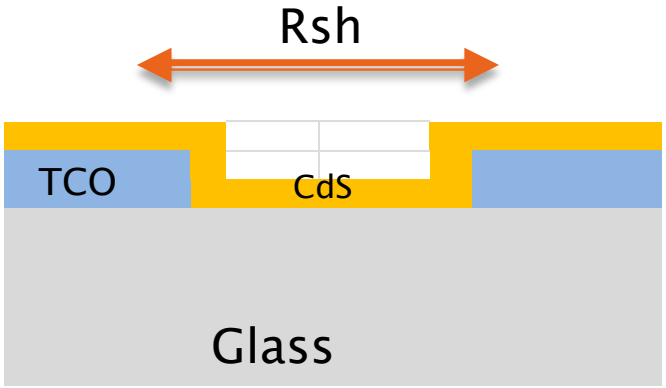
Verification experiments





Acceleration Factors

Time for P1 shunt resistance to drop 50%

	No Bias	-750V
41C	?	~20 hrs
57C	40 hrs	3.5 hrs
77C	8 hrs	0.5 hrs

Both temperature and voltage are strong drivers

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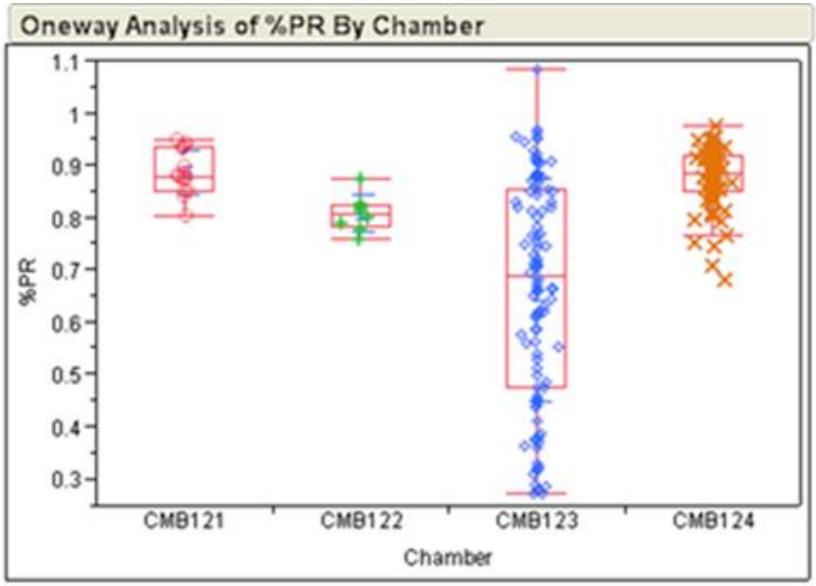
Severely Degraded Modules:
manufacturing excursions

All the severely degraded modules came from only one of 4 production chambers and only from a specific time period.

Root cause:
Broken glass on top of heater coils in the deposition chamber: Excellent source of sodium.



Missing Rows 31

Excluded Rows 59

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
CMB121	14	0.887643	0.043081	0.01151	0.86277	0.91252
CMB122	8	0.810250	0.034997	0.01237	0.78099	0.83951
CMB123	105	0.662857	0.212916	0.02078	0.62165	0.70406
CMB124	79	0.876544	0.056592	0.00637	0.86387	0.88922

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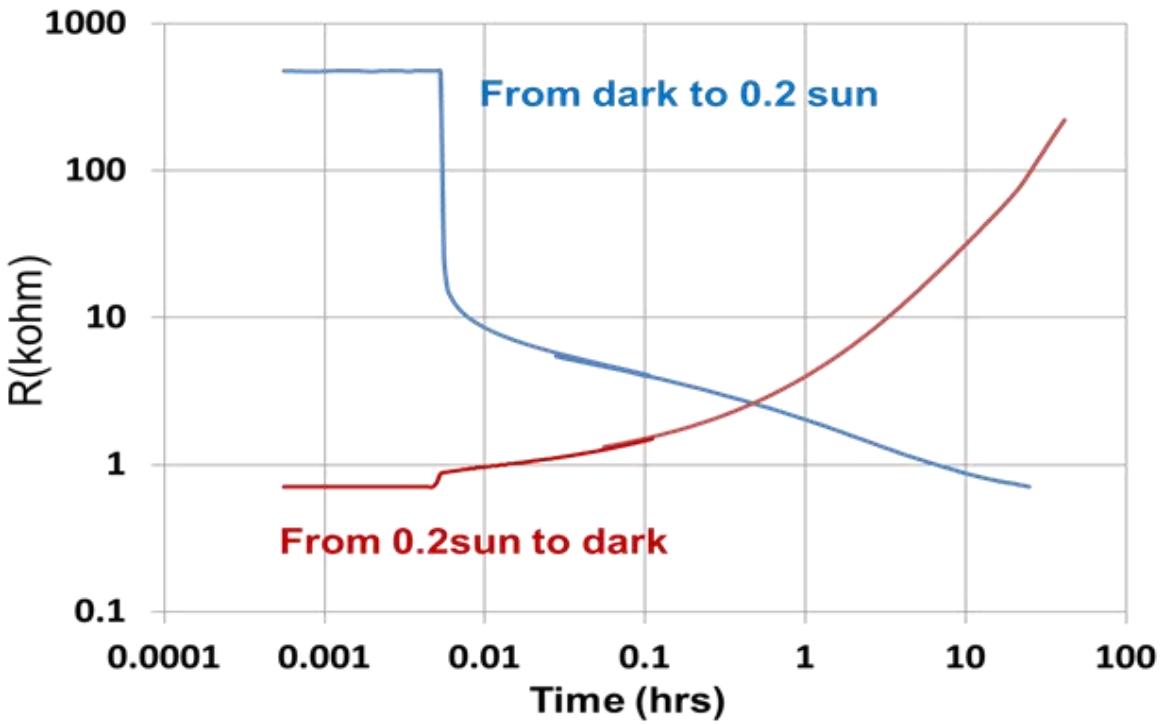
Photoconductivity in CdS



CdS photoconductivity is very dynamic and may take many Hrs to fully develop

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Conclusions

- We have characterized a new type of reversible PID caused by field assisted diffusion of mobile ions into the P1 scribe lines in thin film modules.

It is a bad idea to leave semiconductor material in the P1 scribe.

- Corrective Action
  - Switch P1 scribe and semi deposition process order
  - Backfill P1 with inert material

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Thank You

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Mitglied der Helmholtz-Gemeinschaft

JÜLICH FORSCHUNGSZENTRUM

Direct analysis of *JV*-curves applied to an outdoor-degrading CdTe module

February 26, 2014 | C. Ulbrich[1], S. Kurtz[2], D. Jordan[2], A. Gerber[1], U. Rau[1]

[1] IEK5-Photovoltaik, Forschungszentrum Jülich, Jülich, Germany

[2] National Renewable Energy Laboratory, Golden, CO, USA

Motivation

Measured *JV* curves of outdoor exposed modules hold accessible information on module efficiency and its degradation.

Yet, the dependence on irradiance, temperature and the resistances complicates the analysis. Note that these dependencies might change with outdoor exposure.

We take a critical look at the information in *JV* curves and extract a minimum parameter set that we test for its physical meaning.

Approach – Applying the KH formalism[1]

3 step process:

1) Individual *JV*-curves (raw data) are **determine**d by 4 independent **parameters**.

2) **Analyze** the **dependence** of the parameters on T_{meas}, ϕ_{meas}.

3) **Reconstruct** *JV*-curves **at** chosen **reference conditions**, analyze parameters and degradation.

1) Determine 4 parameters

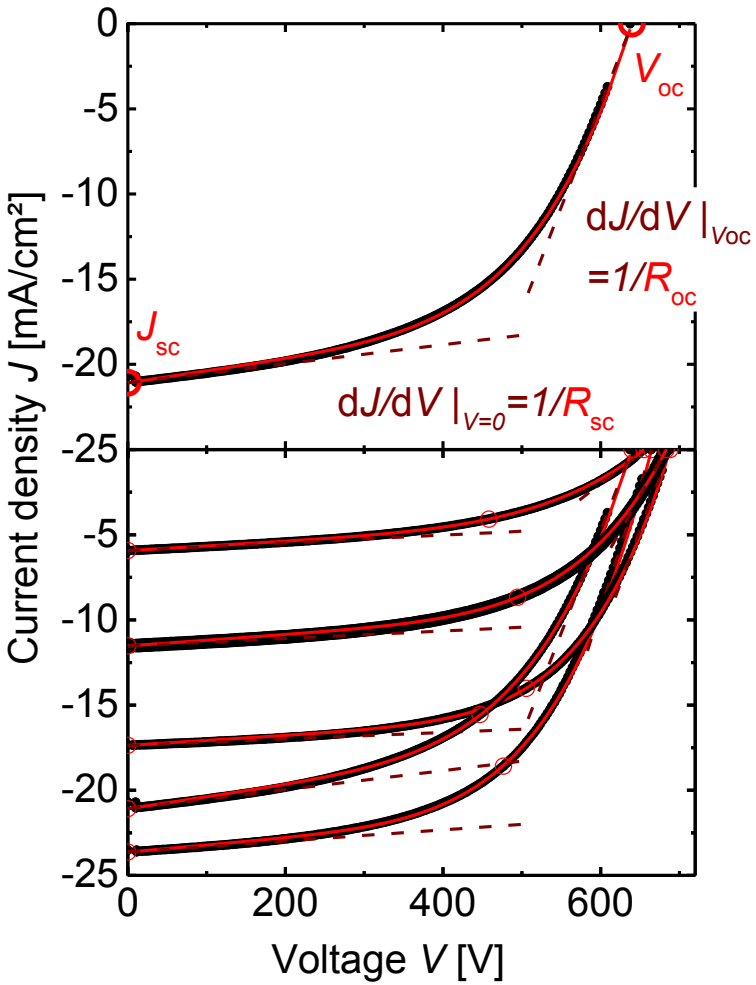
Phenomenological equation[1] is fitted to the measured data

$$J(V) = J_{sc}\left[(1-\gamma)\frac{V}{V_{oc}} + \gamma\left(\frac{V}{V_{oc}}\right)^{m} - 1\right]$$

where

$$\gamma = 1 - 1/R_{sc}\frac{V_{oc}}{J_{sc}}$$

$$m = \frac{V_{oc}\left(1/R_{oc} - 1/R_{sc}\right)}{J_{sc} - V_{oc}/R_{sc}} \quad .$$

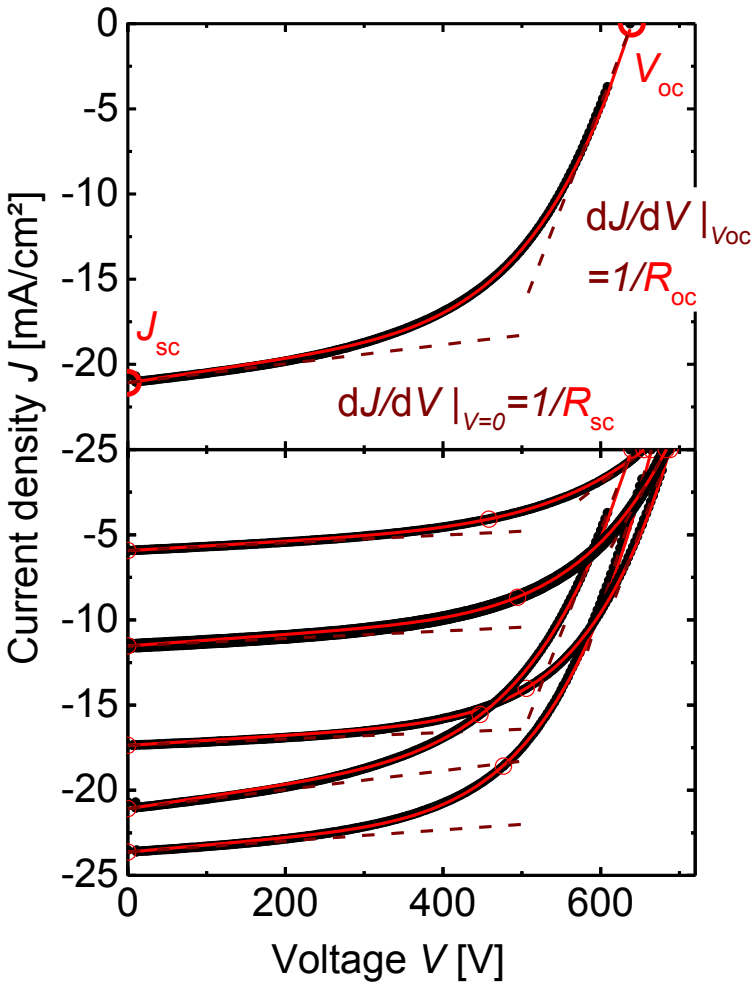


1) Determine 4 parameters

Phenomenological equation is fitted to the measured data

$$J(V) = J_{sc}\left[(1-\gamma)\frac{V}{V_{oc}} + \gamma\left(\frac{V}{V_{oc}}\right)^{m} - 1\right].$$

The equation by itself has no physical meaning but various, more complex, physically motivated solar cell models are compatible with it[2].

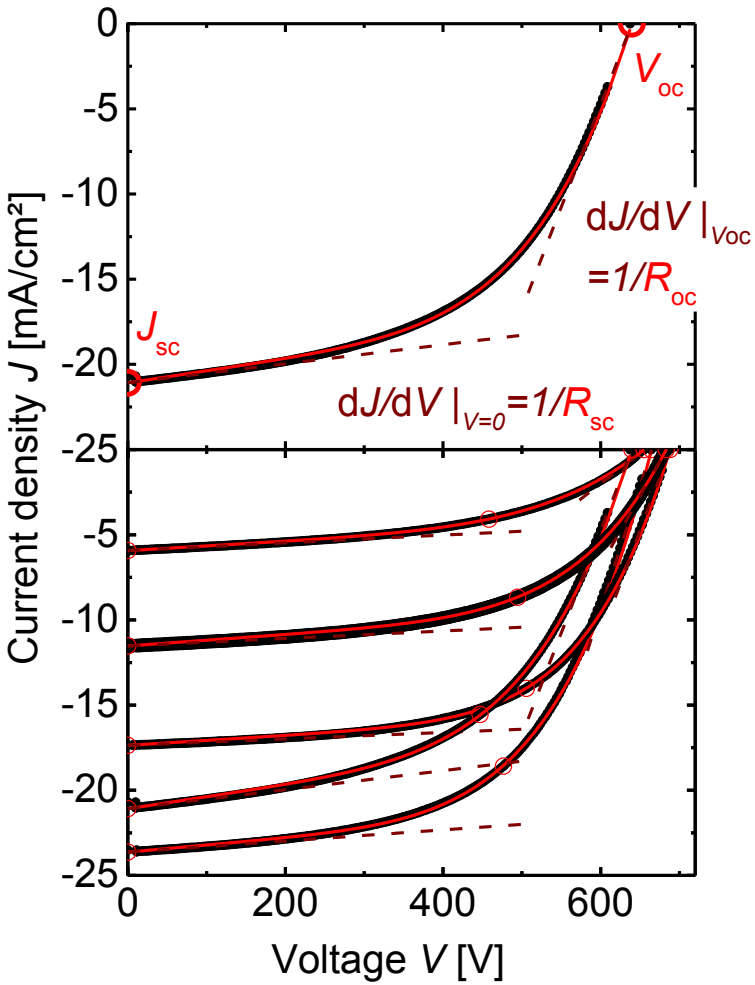


1) Determine 4 parameters

The four parameters

- short circuit current J_{sc}
- open circuit voltage V_{oc}
- differential resistance R_{sc}
- differential resistance R_{oc}

are physically meaningful.



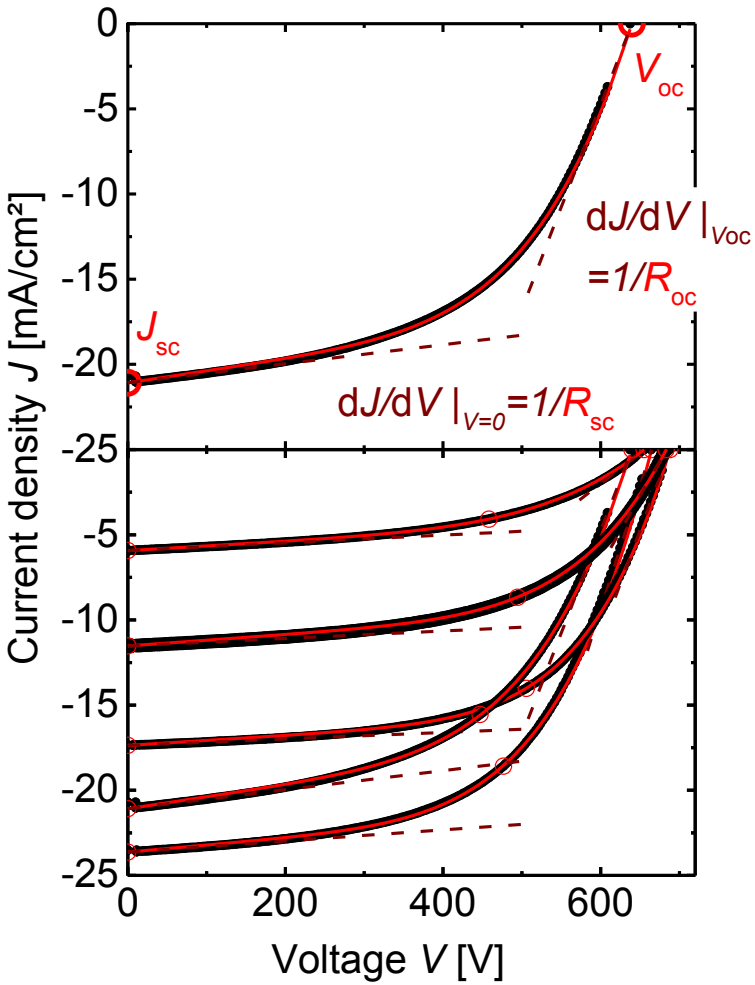
1) Determine 4 parameters

The four parameters

- short circuit current J_{sc}
- open circuit voltage V_{oc}
- differential resistance R_{sc}
- differential resistance R_{oc}

are physically meaningful.

The equation fits the *JV* curves reliably in all irradiance ranges and at all stages of degradation.



2) Analyze T_{meas}, ϕ_{meas} dependence

Parameter: J_{sc}

Assumed dependence: $J_{sc}(\phi_{meas}, T_{meas}) = \{\alpha_{Jsc} T_{meas} + \kappa_{Jsc}\}\phi_{meas}$

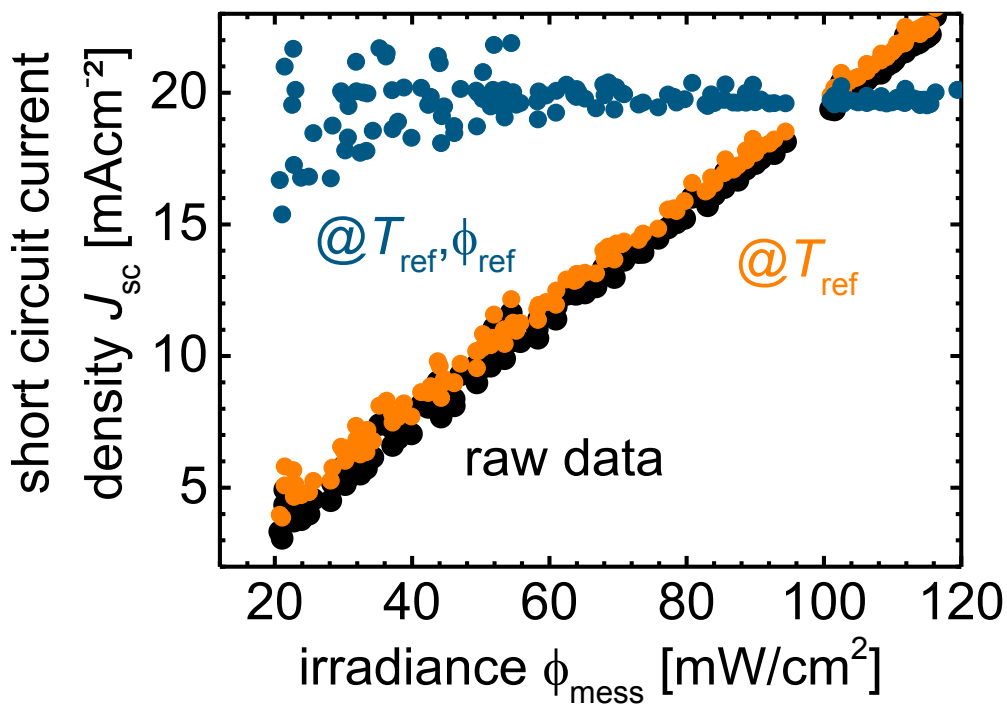
Value at reference conditions: $J_{sc@ref} = J_{sc}(\phi_{ref}, T_{ref}) = \{\alpha_{Jsc} T_{ref} + \kappa_{Jsc}\}\phi_{ref}$

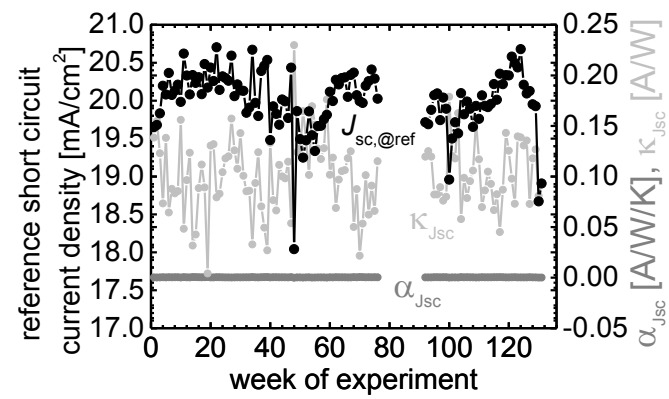
Translation of raw data: $J_{sc,meas@ref} = \{\alpha_{Jsc}(T_{ref} - T_{meas})\}\phi_{ref} + J_{sc}(\phi_{ref} / \phi_{meas})$

2) Analyse T_{meas}, ϕ_{meas} dependence

Exemplary parameter: J_{sc}

Assumed dependence: $J_{sc}(\phi_{meas}, T_{meas}) = \{\alpha_{Jsc} T_{meas} + \kappa_{Jsc}\}\phi_{meas}$



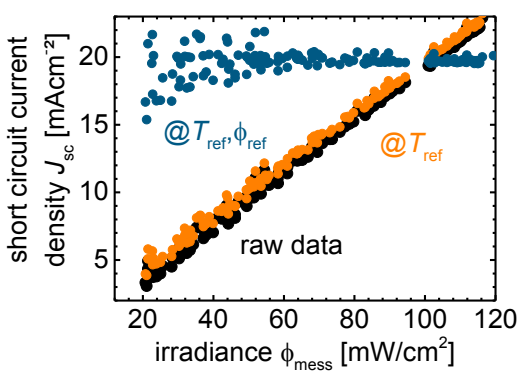


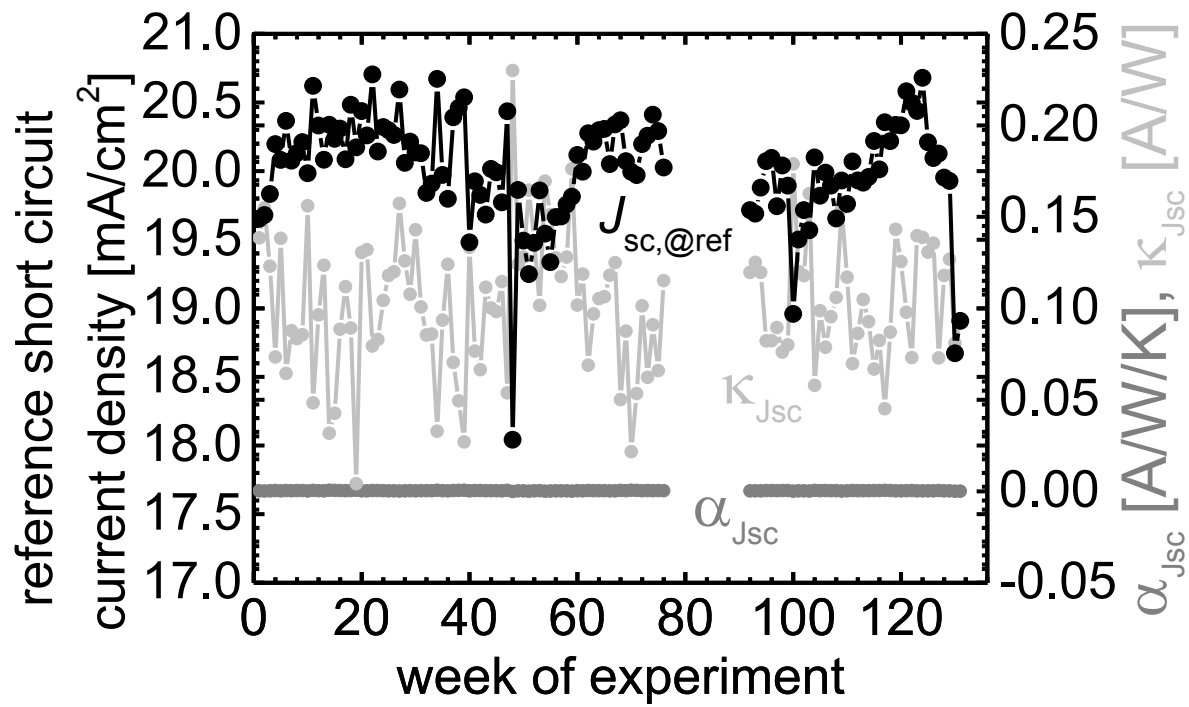
data from 1 week

2) Analyse T_{meas}, ϕ_{meas} dependence

Exemplary parameter: J_{sc}

Assumed dependence: $J_{sc}(\phi_{meas}, T_{meas}) = \{\alpha_{Jsc} T_{meas} + \kappa_{Jsc}\}\phi_{meas}$





data from 2.5 years

Approach – Applying the KH formalism

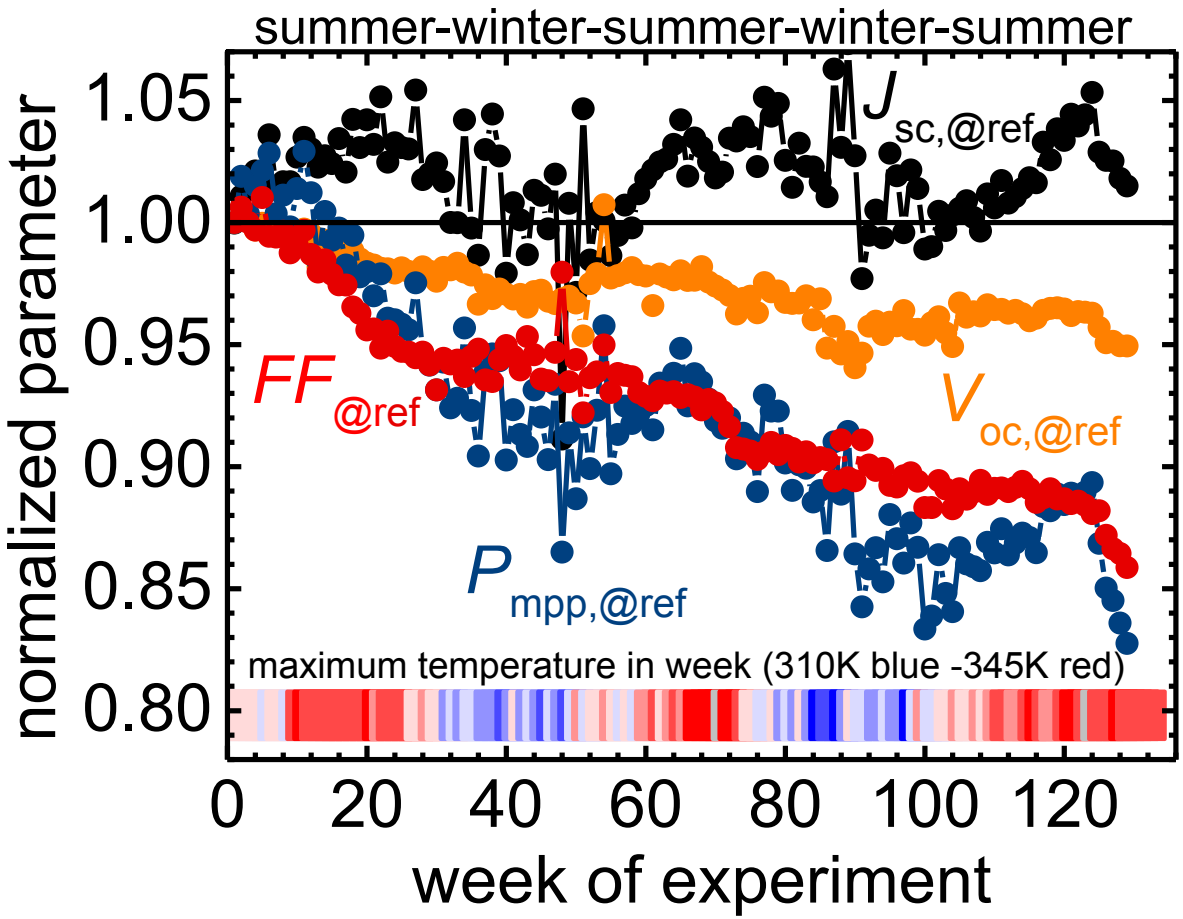
3 step process:

1) Determined individual *JV*-curve parameters.

2) Analyzed T_{meas}, ϕ_{meas} dependence
(Analysis of V_{oc}, R_{sc}, R_{oc} follows)

3) Reconstruct *JV*-curves at chosen reference conditions

3) Reconstruct at reference conditions



Findings

Analyses of V_{oc}, R_{sc}, and, R_{oc} hint at voltage dependent charge carrier collection in CdTe (has been observed before [3])

→ Let‘s go back to step 2)

2) Analyze T_{meas}, ϕ_{meas} dependence

Parameter: V_{oc}

Assumed dependence:

$$V_{oc}(J_{sc,meas}, T_{meas}) = V_{oc}^{0} - \{\alpha_{Voc} - \varepsilon_{Voc} \log(J_{sc,meas})\} T_{meas}$$

standard diode equation of an illuminated solar cell [4]:

$$V_{OC} = E_a / q - \{nk / q \log(J_{00}) + nk / q \log(J_{SC})\} T$$

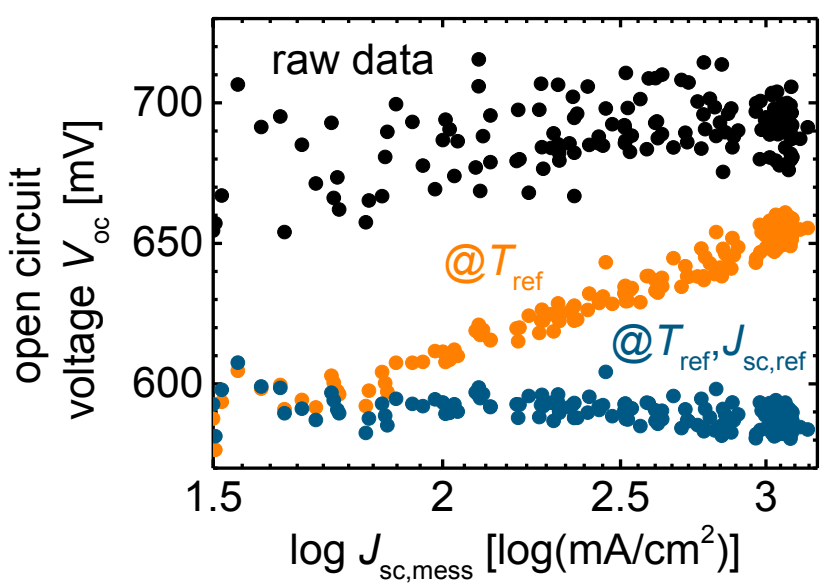
ε_{Voc} ➔ n

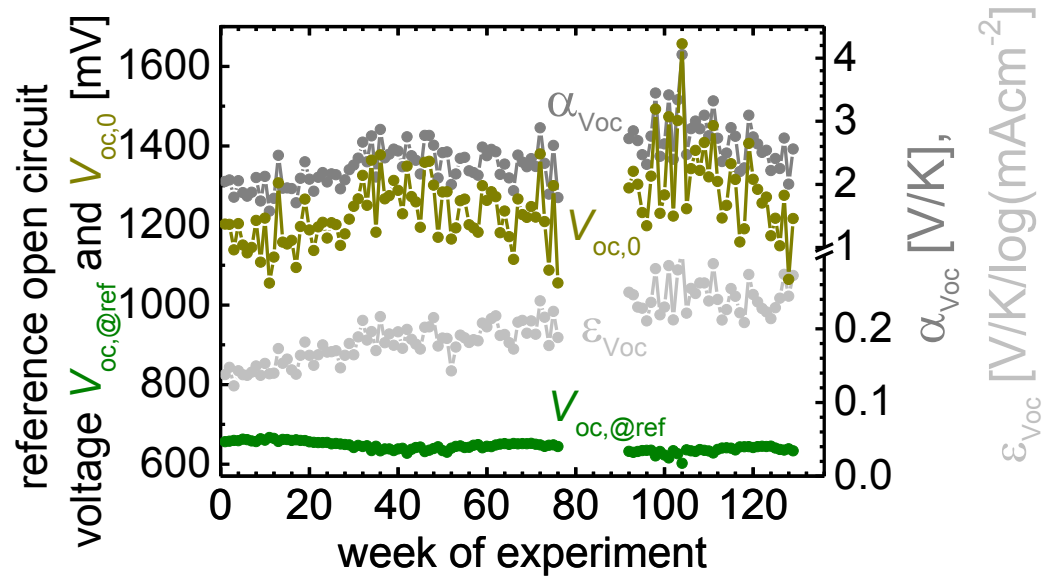
2) Analyze T_{meas}, ϕ_{meas} dependence

Parameter: V_{oc}

Assumed dependence:

$$V_{oc}(J_{sc,meas}, T_{meas}) = V_{oc}^{0} - \{\alpha_{Voc} - \varepsilon_{Voc} \log(J_{sc,meas})\} T_{meas}$$





data from 1 week

data from 2.5 years

2) Analyze T_{meas}, ϕ_{meas} dependence

Parameter: R_{oc}

Assumed dependence:

$$R_{oc}(J_{sc,meas}, T_{meas}) = R_s + \beta_{Roc} T_{meas} / J_{sc,meas}$$

Werner plot[5] equation

$$R_{oc} = R_S + \frac{nkT}{q} \frac{1}{J_{sc,meas}}$$

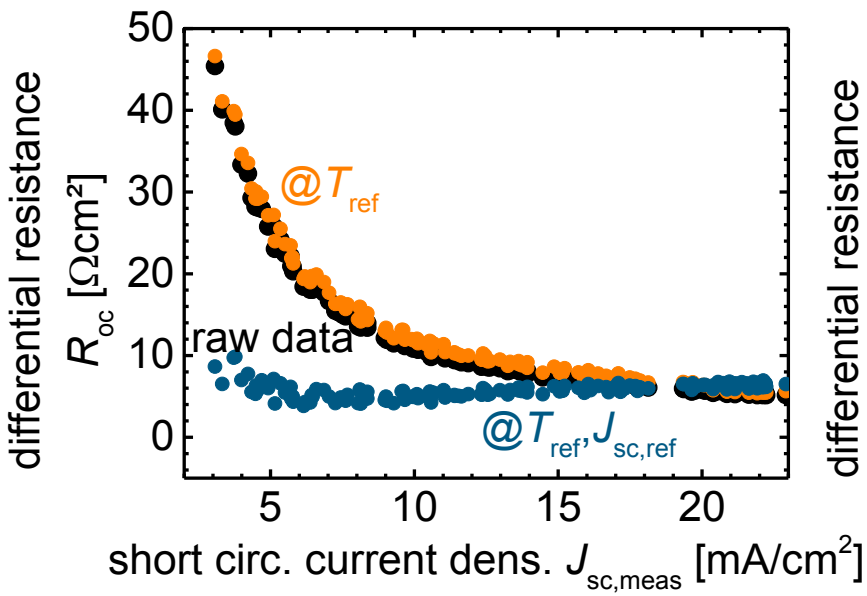
β_{Voc} ➔ n

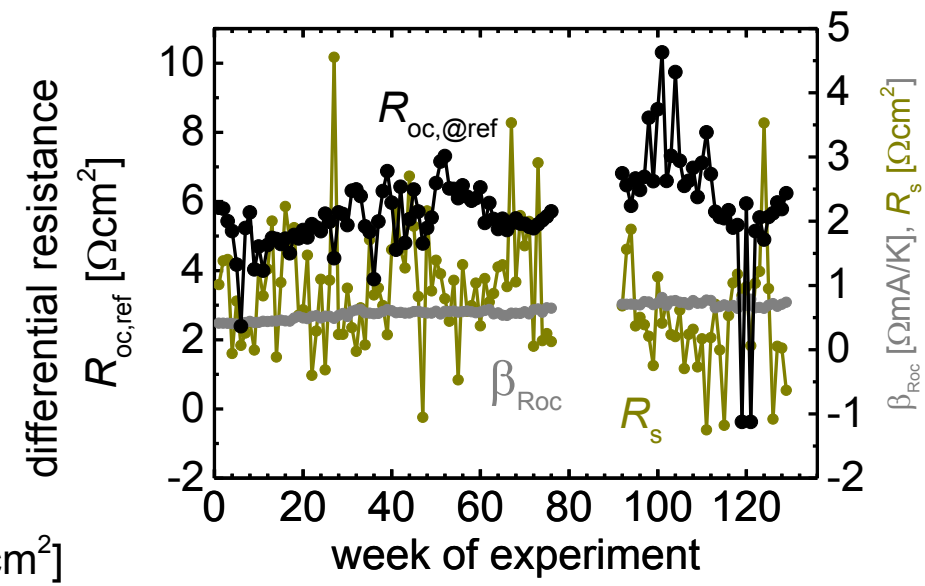
2) Analyze T_{meas}, ϕ_{meas} dependence

Parameter: R_{oc}

Assumed dependence:

$$R_{oc}(J_{sc,meas}, T_{meas}) = R_s + \beta_{Roc} T_{meas} / J_{sc,meas}$$





data from 1 week

data from 2.5 years

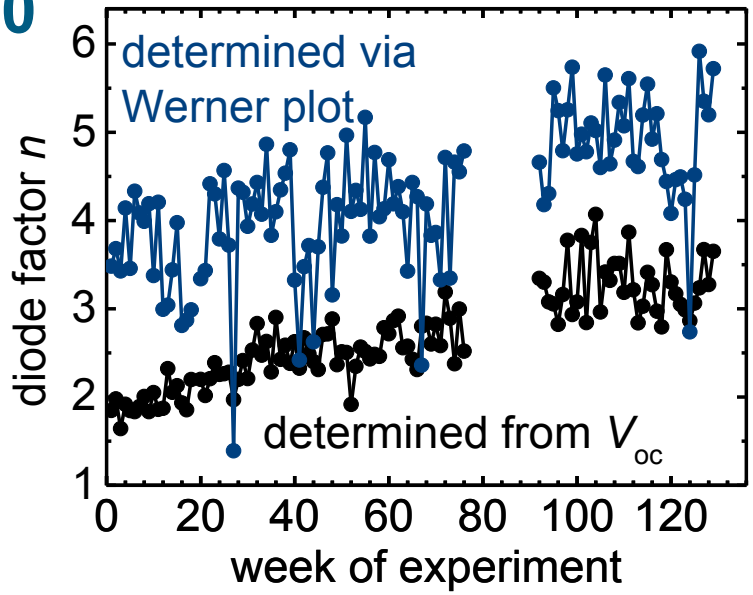
Findings

Diode factor *n* determined from Werner plot[5] **assuming dJ_{sc}/dV=0**

$$R_{oc} = \frac{nkT}{q}\frac{1}{J_{sc,meas}} + R_S$$

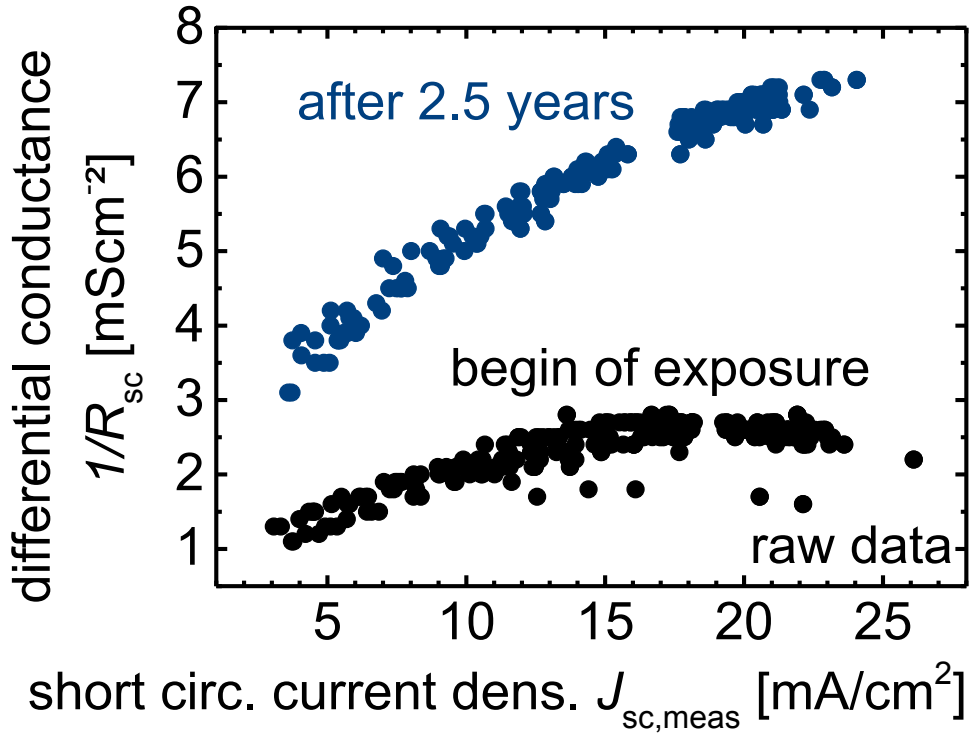
differs from value determined from V_{oc}

$$V_{OC} = E_a / q - nkT / q \log(J_{00}) + nkT / q \log(J_{SC})$$



Findings

R_{sc} raw data hint at a change in voltage dependent charge carrier collection in CdTe over time



Summary and Outlook

Advantages of the Karmalkar-Haneefa formalism

- Only 4 parameters
- Physically meaningful
- Comparison across technologies, interpretation for specific technology and module
- Especially significant in analysis of solar modules with non-negligible resistances
- Easy calculation of effect of losses in energy yield

Thanks

- To the colleagues in Juelich and at the NREL
- To you

Questions and suggestions are very welcome

References:

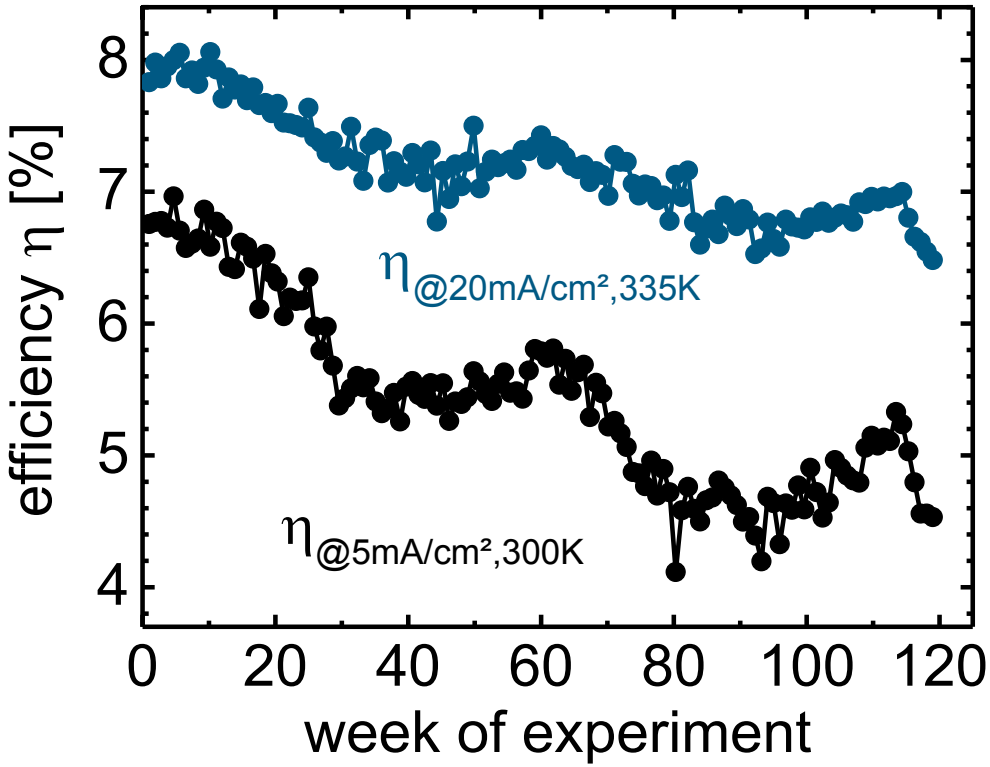
[1] S. Karmalkar, S. Haneefa, “A physically based explicit J–V model of a solar cell for simple design calculations,” *IEEE Electron Device Letters*, vol. 29, pp. 449-451, 2008.

[2] A. K. Das, S. Karmalkar, “Analytical derivation of the closed-form power law J–V model of an illuminated solar cell from the physics based implicit model,” *IEEE Transactions on Electron Devices*, vol. 58, pp. 1176-1181, 2011.

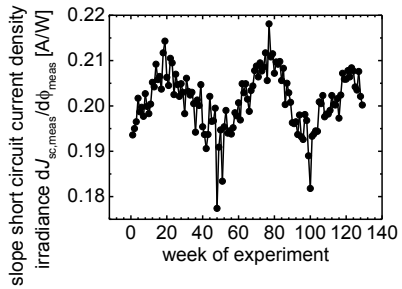
[3] S. Hegedus, D. Desai, C. Thompson, “Voltage dependent photocurrent collection in CdTe/CdS solar cells,” *Prog. Photovolt.: Res. Applic.* 15, 587–602, 2007.

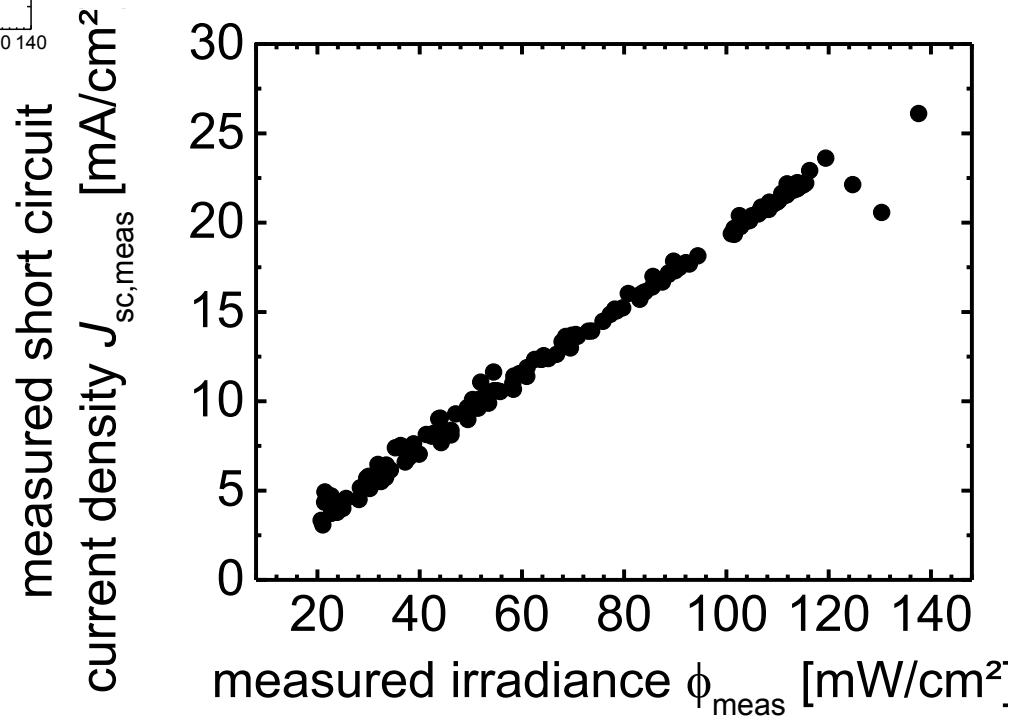
[4] J. Nelson, *The physics of solar cells*, London, Imperial College Press, 2003.

[5] J. H. Werner,. ”Schottky barrier and pn-junction I/V plots- small signal evaluation,” *Applied Physics A*, vol. 47, pp. 291-300, 1988.



Taking into account the differential resistances, we find a stronger degradation of the efficiency $\eta_{@ref}$ for low irradiance intensity/short circuit current density conditions.



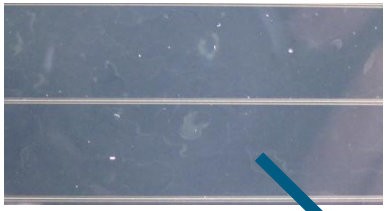


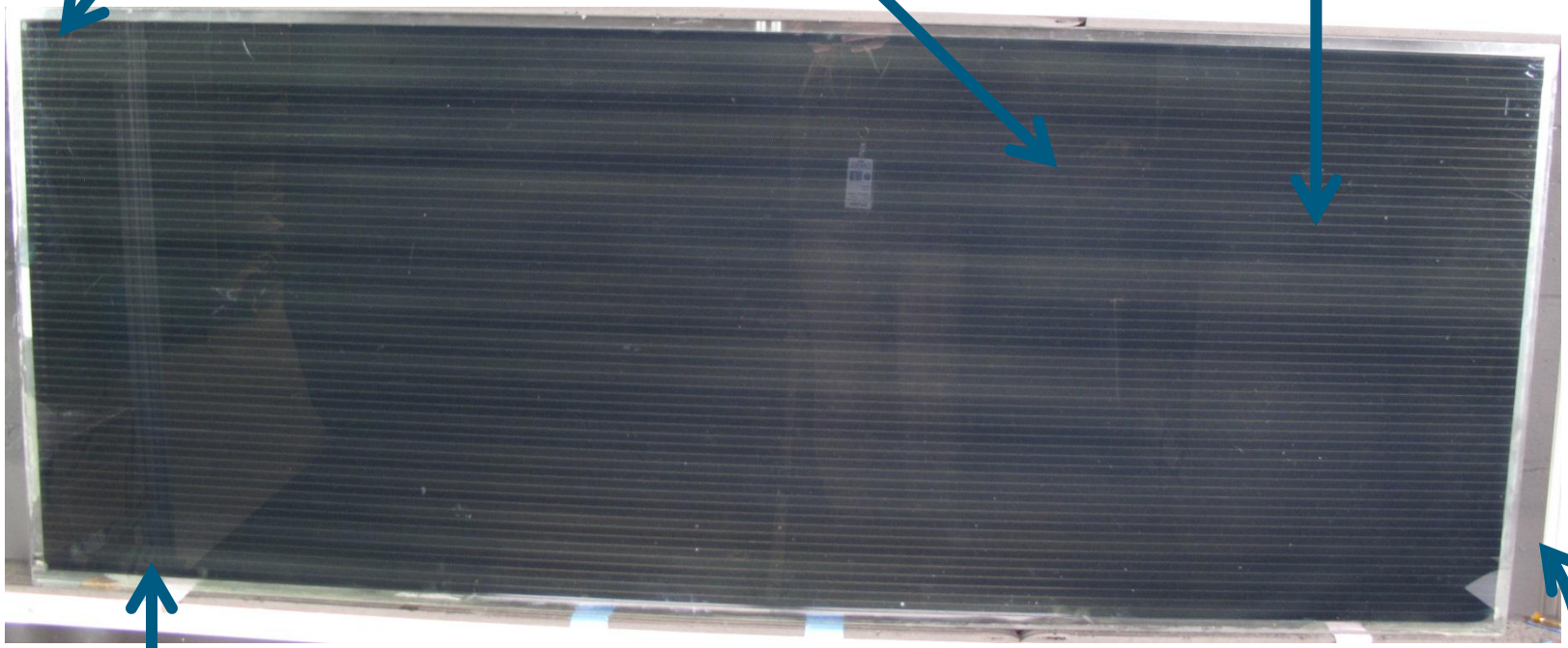
The substitution of irradiance ϕ_{meas} by $J_{sc,meas}$ when calculating the irradiance dependence of the three parameters V_{oc}, R_{sc} and R_{oc} is justified by the linear relation between $J_{sc,meas}$ and ϕ_{meas}.

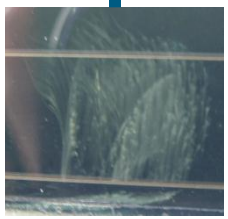
Possible origin of degradation

- Corrosion at junction box (at hot and humid days)
- Ion movement (temperature)
- Applied bias – not temperature
- Bias and temperature combined

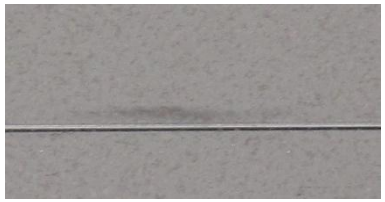
Visual inspection of module



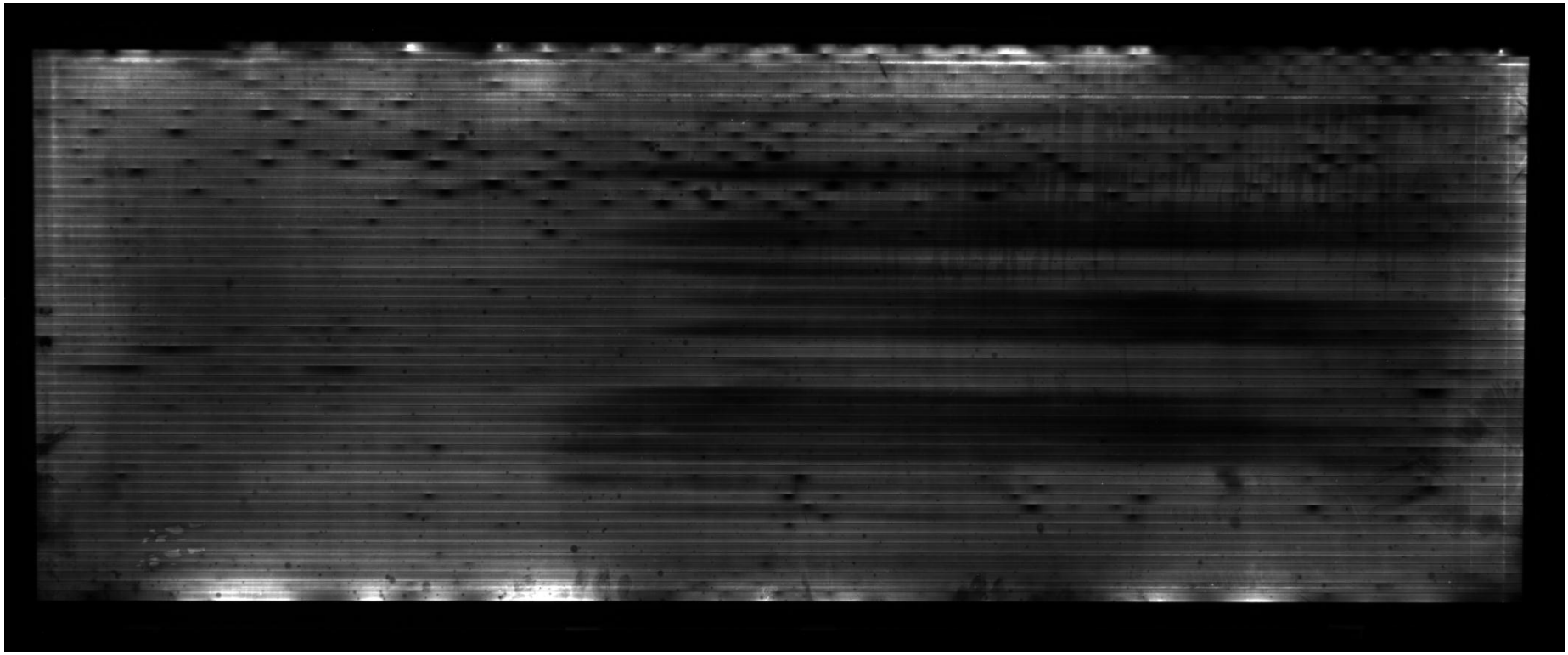




Corrosion of junction box?



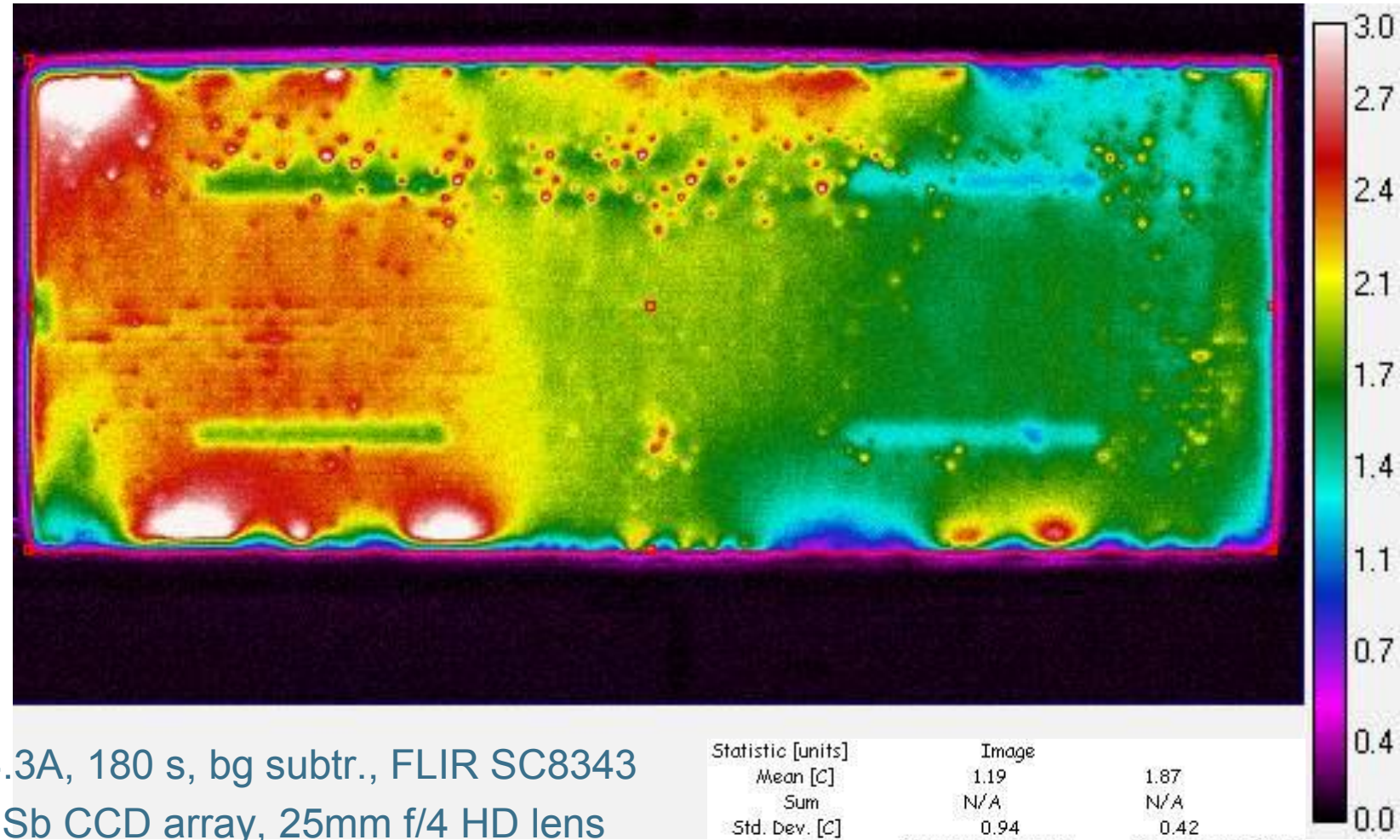
Electroluminescence



54615mV, 2997 mA applied, 1.28min

Si-CCD 16Mpixel (4095x4095) with Zeiss 72mm IR lens, 1.4/85 zoom, no filter

IR image



Statistic [units]	Image	
Mean [C]	1.19	1.87
Sum	N/A	N/A
Std. Dev. [C]	0.94	0.42
Center [C]	(639.5, 359.5) 1.85	(645.0, 333.0) 1.88
Maximum [C]	(93, 126) 3.91	(93, 126) 3.91
Minimum [C]	(958, 697) -0.35	(44, 97) -0.02
Number of Pixels	921600	575225

55V, 4.3A, 180 s, bg subtr., FLIR SC8343 with InSb CCD array, 25mm f/4 HD lens

FLIR 23898-000-0033 cold filter 3-5um

Stability of CdTe Cells with Different Device Structures

Jim Sites, Colorado State University
NREL Photovoltaic Module Reliability Workshop
February 26, 2014

with former students: Jason Hiltner, Alex Pudov, Sam Demtsu, and Caroline Corwine

and current students John Raguse and Russell Geisthardt, and research associates Jennifer Drayton and Tyler McGoffin

Funding from DOE F-PACE program

Cell-Level Stability Testing

Motivation for cell-level CdTe stability testing:

- Possible intrinsic issues with CdTe cells
- Additional issues can arise with different device structures
- Device analysis generally assumes good stability; flawed otherwise

Multiple stress parameters important:

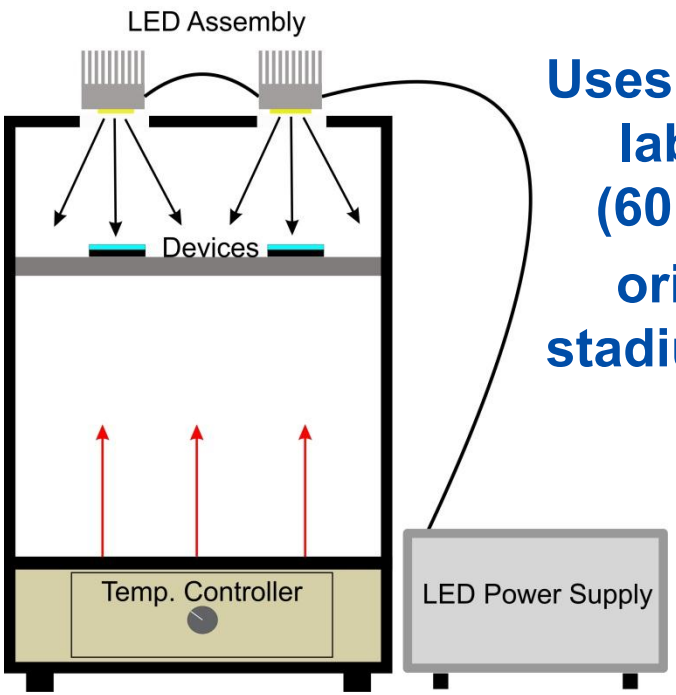
- Temperature
- Voltage bias
- Illumination level
- (Humidity)

Multiple tracking measurements important:

- Average cell properties: J-V, C-V, (QE, J-V-T)
- Cell uniformity: LBIC, EL

Focus on plausible physical mechanisms

Accelerated Life Testing

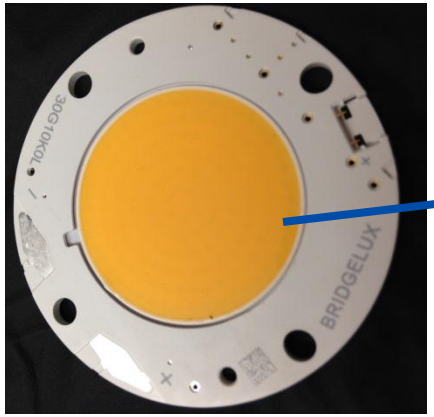


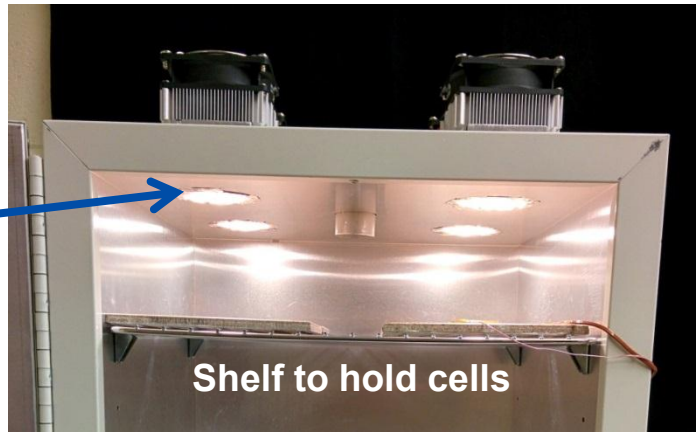
John Raguse, Jennifer Drayton, and Russell Geisthardt

Uses compact lab oven (60-100°C)

originally stadium lights

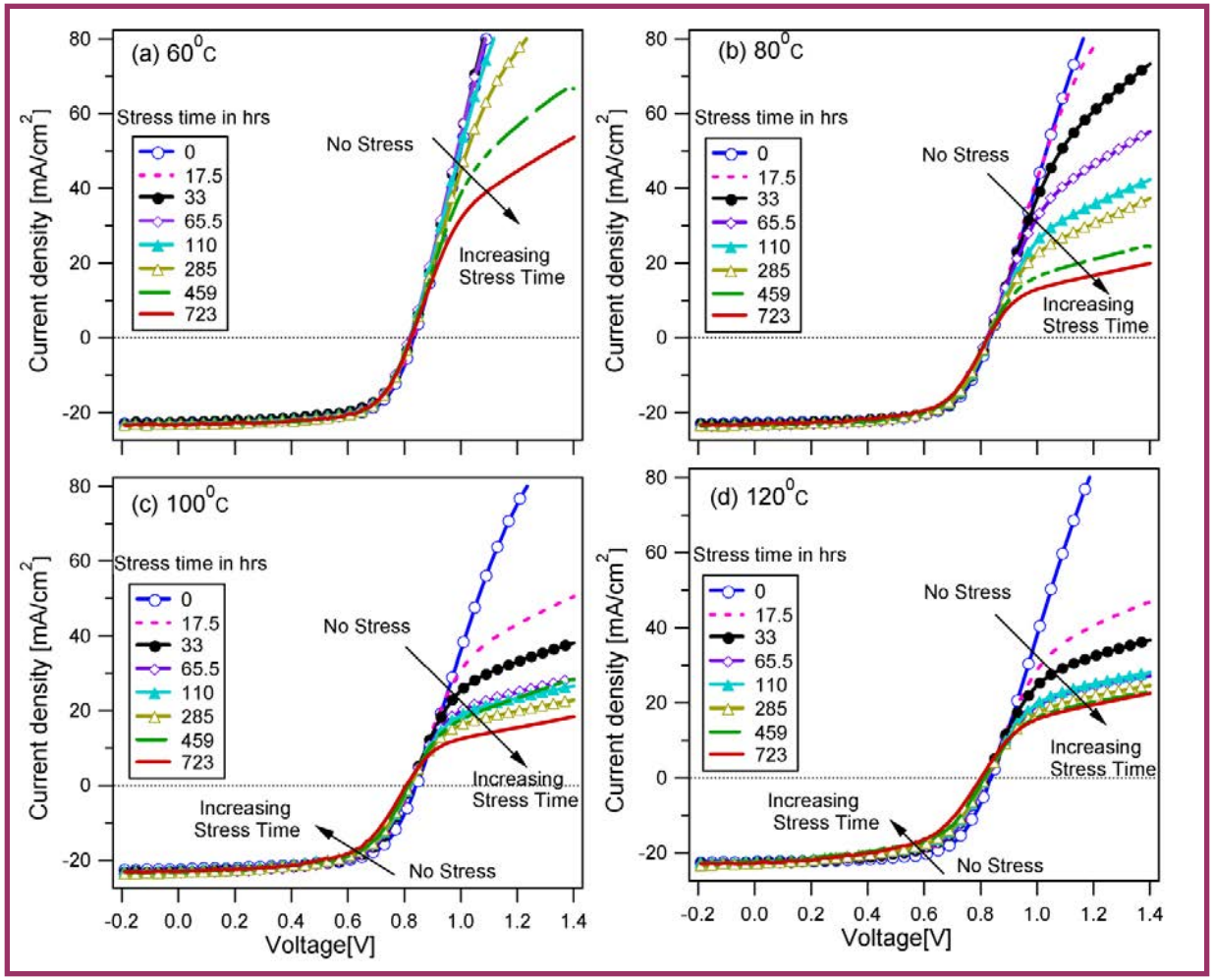
LED arrays for illumination (3 cm diam; 0-2 suns)





Changes in CdTe Current-Voltage

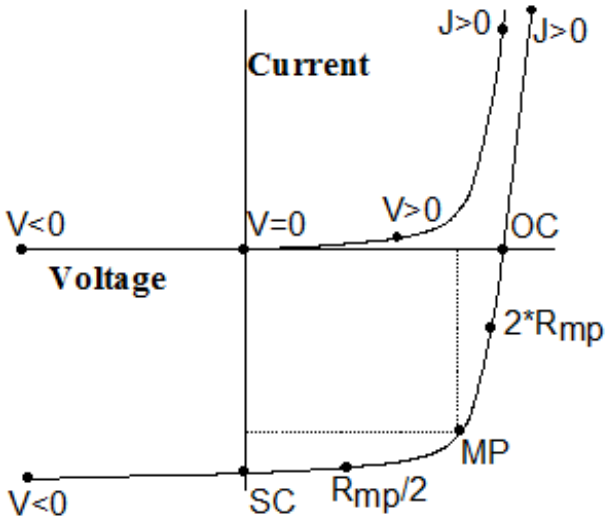
Change seen earlier in first quadrant, later in power quadrant. Increasingly greater at higher temperatures.



From Samuel Demtsu

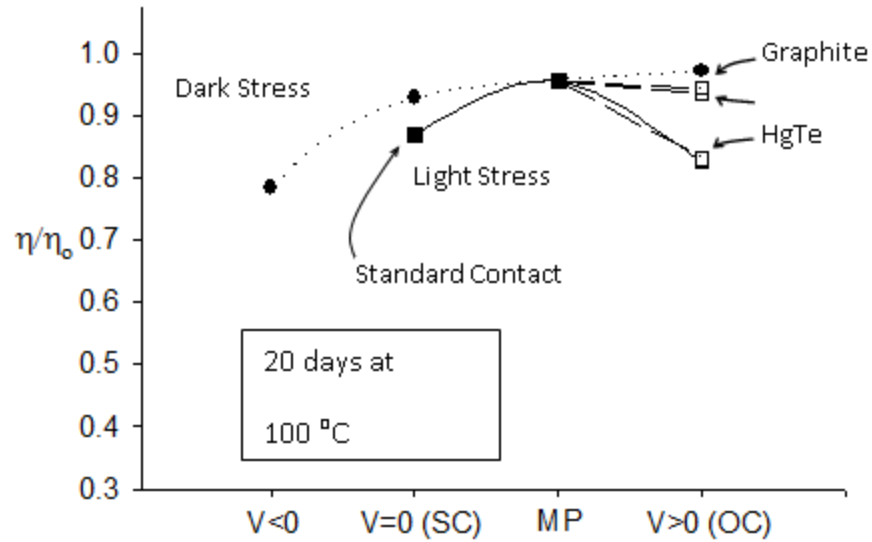
Voltage and Illumination Dependence

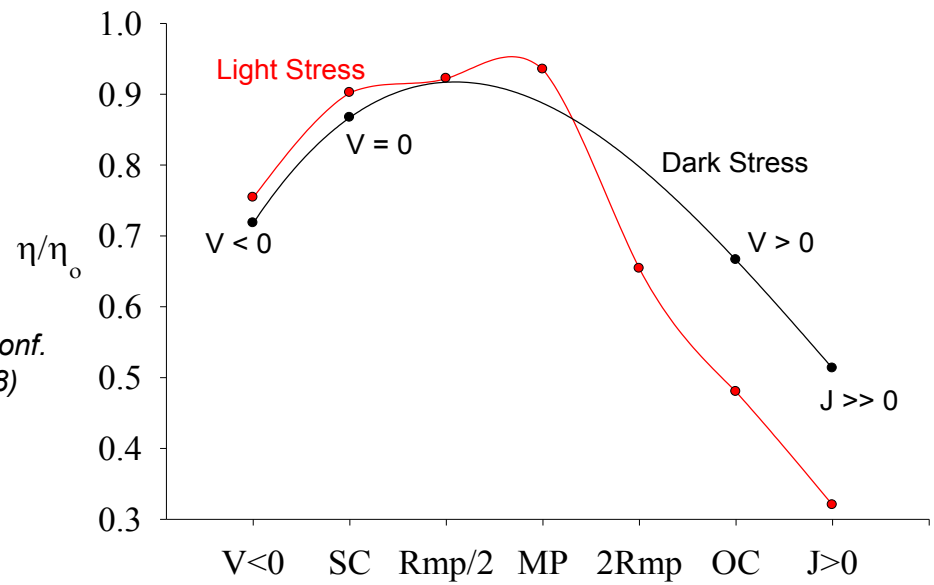
Bias voltage during stress seemed to be the larger factor, but contacting also played a role



*Hiltner and Sites, AIP Conf. Series **462**, 170 (1998)*

Cells from NREL and Solar Cells, Inc

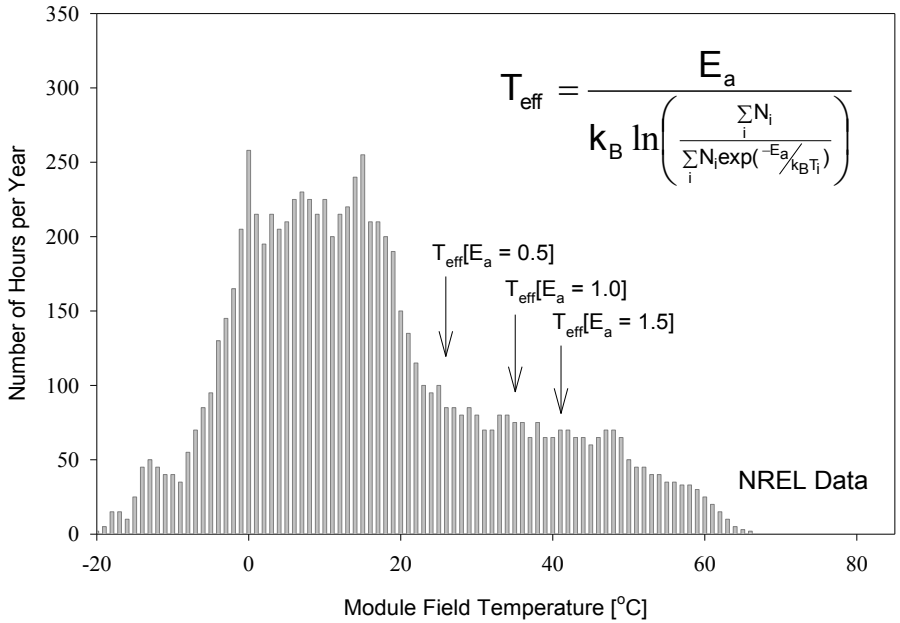




Long-Term Expectations

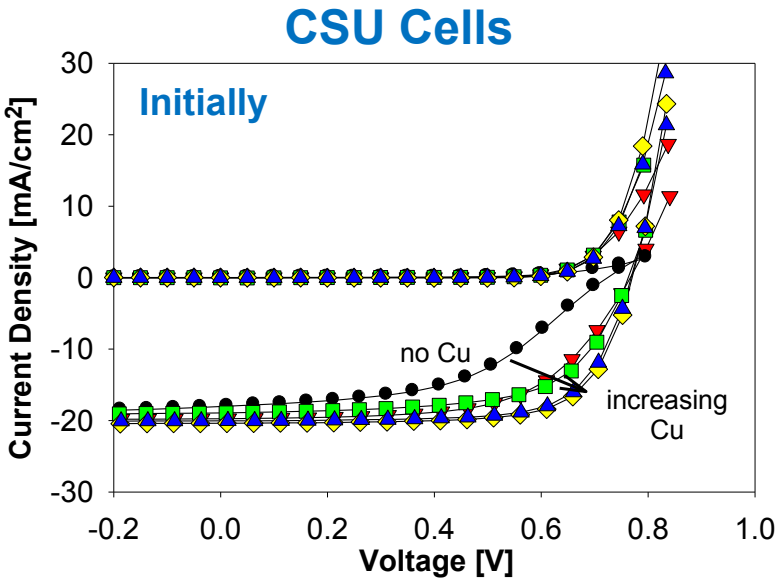
,

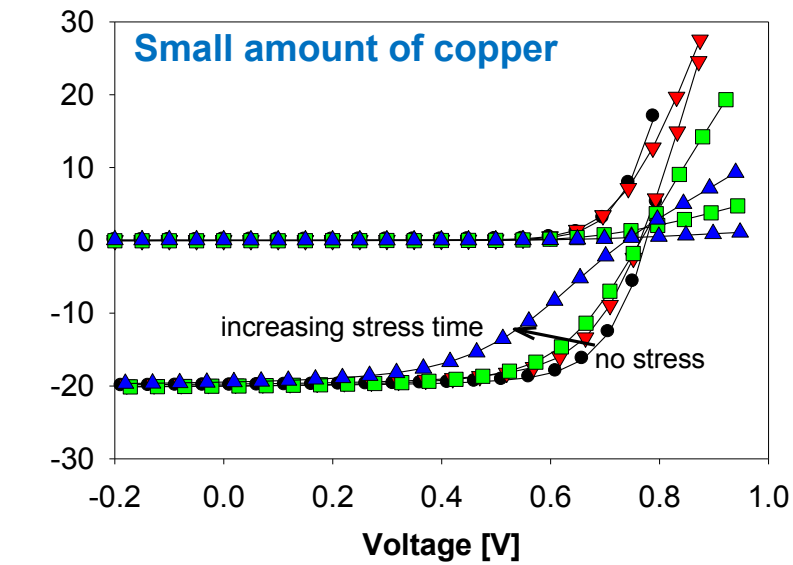
Define Acceleration Factor $a = \exp(E_a/kT_{eff} - E_a/kT_{cell})$ where an activation energy E_a (typically ~1 eV) can be deduced from rate of change at different temperatures and T_{eff} from a histogram of daylight module temperatures (and an estimate of E_a)



For CdTe with T_{cell} = 85°C and typical field temperatures, a appears to be in the range of 100-1000

Copper Model

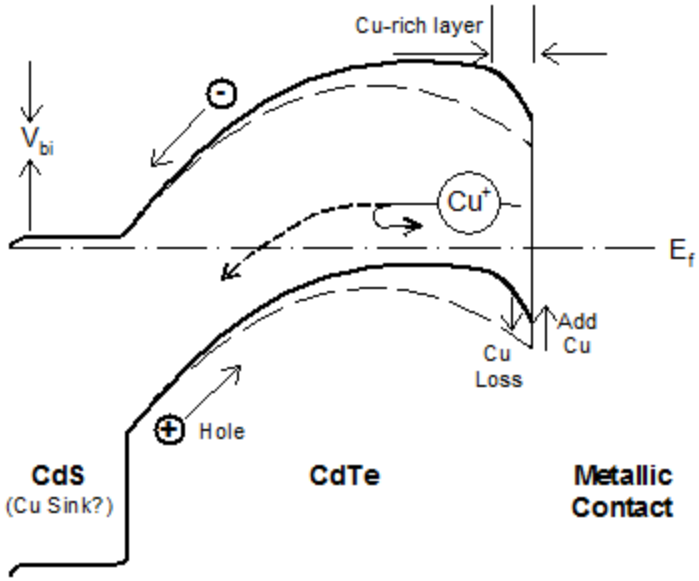




Copper reduces the CdTe back-contact barrier, but can diffuse away.

Positive ions diffuse faster when field is reduced at V_{OC} and above.

Small amount of copper may not be sufficient, and may diffuse from back.

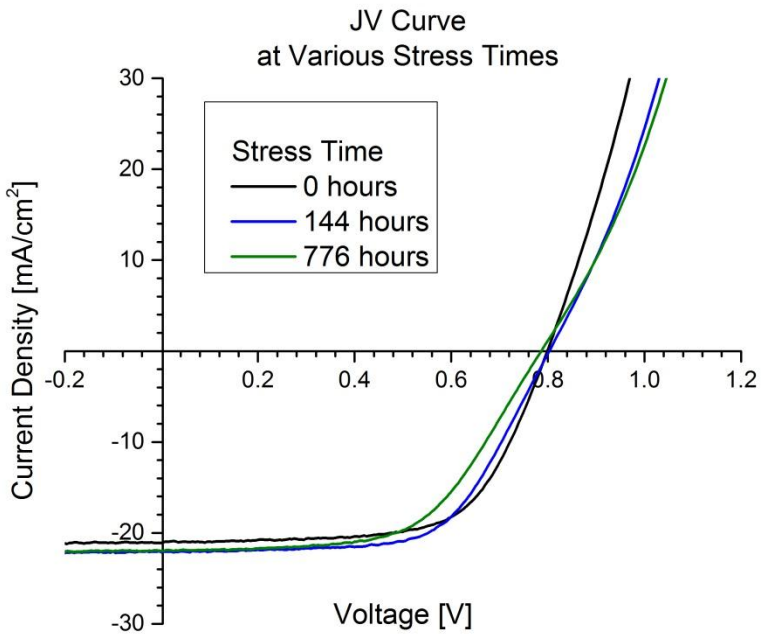


*Caroline Corwine et al, SOLMAT **82**, 481 (2004)*

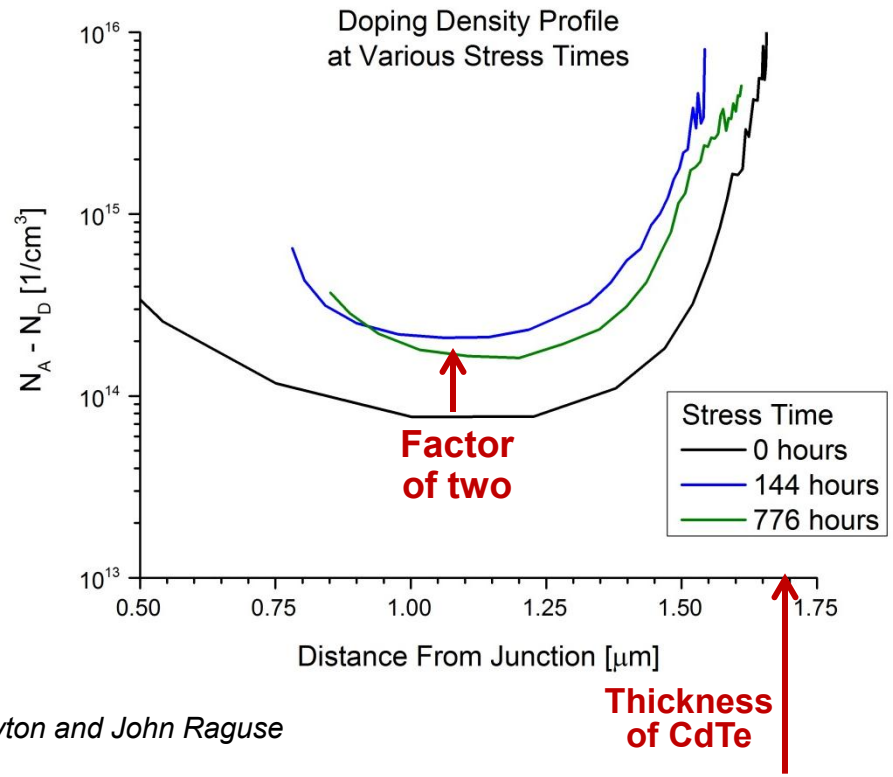
Effect on Capacitance

Copper diffusion appears to also increase carrier density

CSU CdTe cells



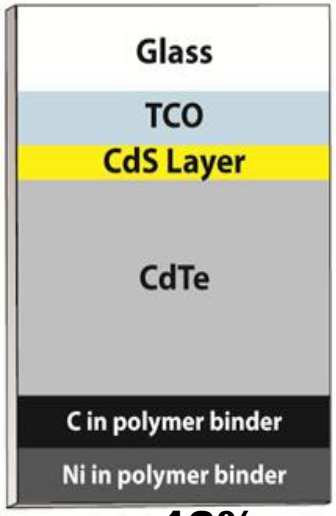
Hole density is derived from C-V



Jennifer Drayton and John Raguse

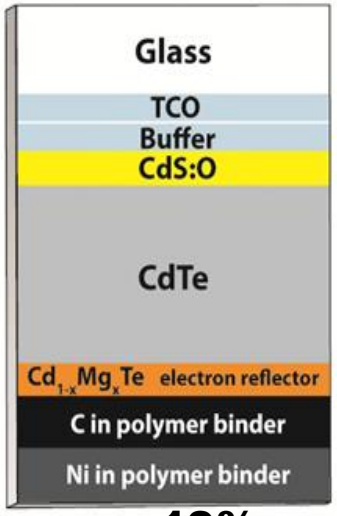
Alternative CdTe Structures

Standard Baseline



η = 13%

Transparent Window and Electron Reflector



$\eta \approx$ 19%

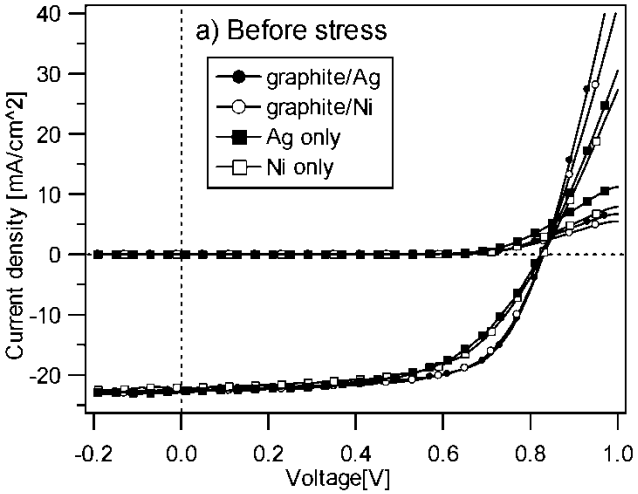
Target

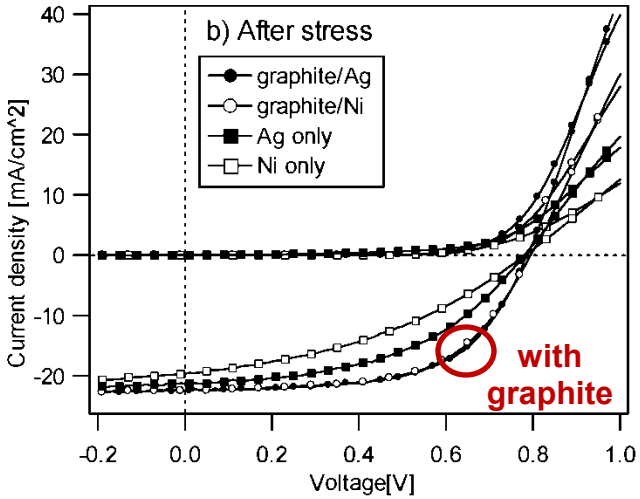
16.2% achieved

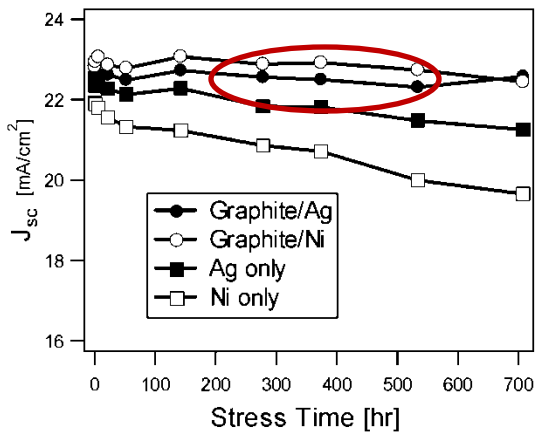
Transparent Back Contact

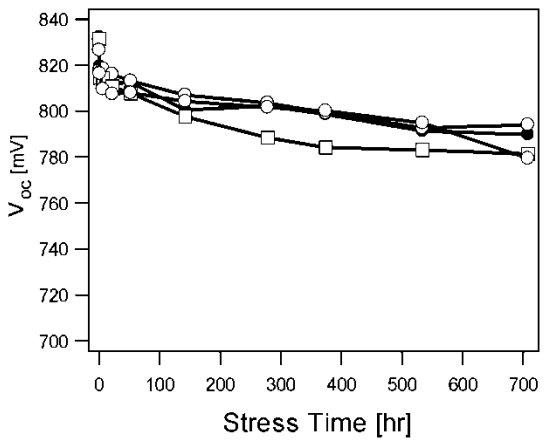
Studies in progress

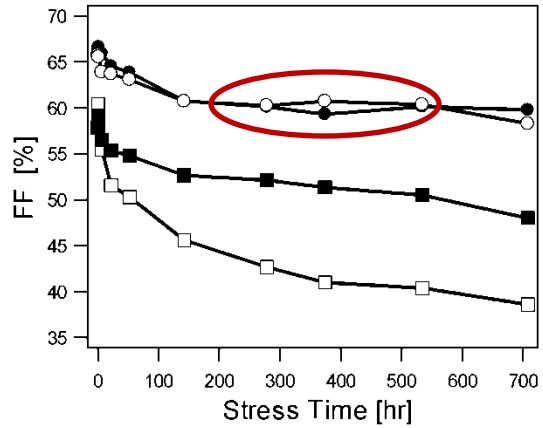
Varying the Back Contact

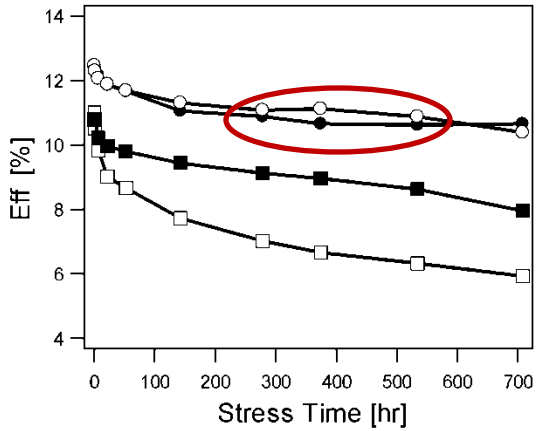








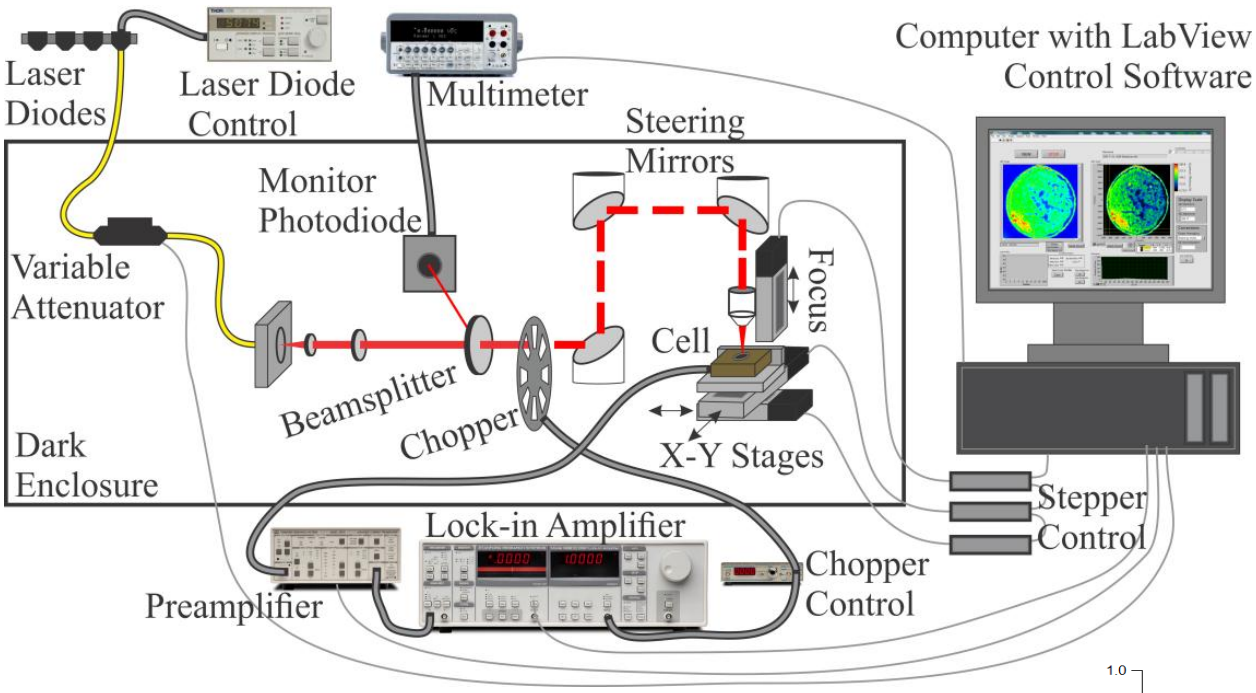




*Demtsu, Albin, Pankov, and Davies, SOLMAT **90**, 2934 (2006)*

Light-Beam-Induced Current

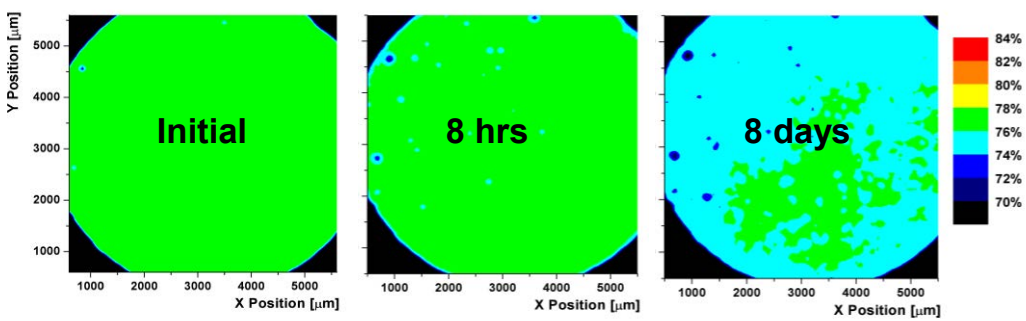
Steps through 10,000 points in 10 min

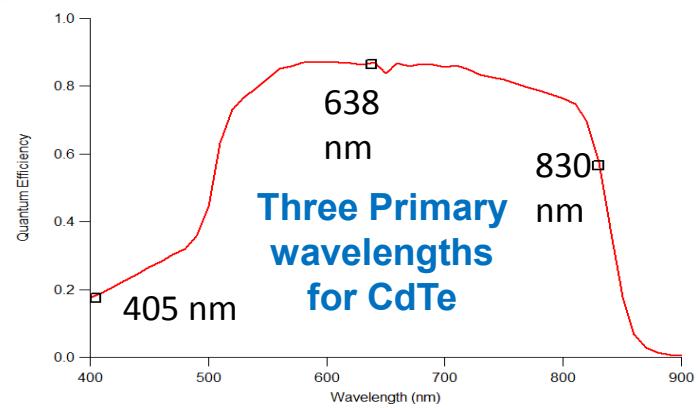


Resolution down to 1 µm at 1 sun intensity

Built by Jason Hiltner

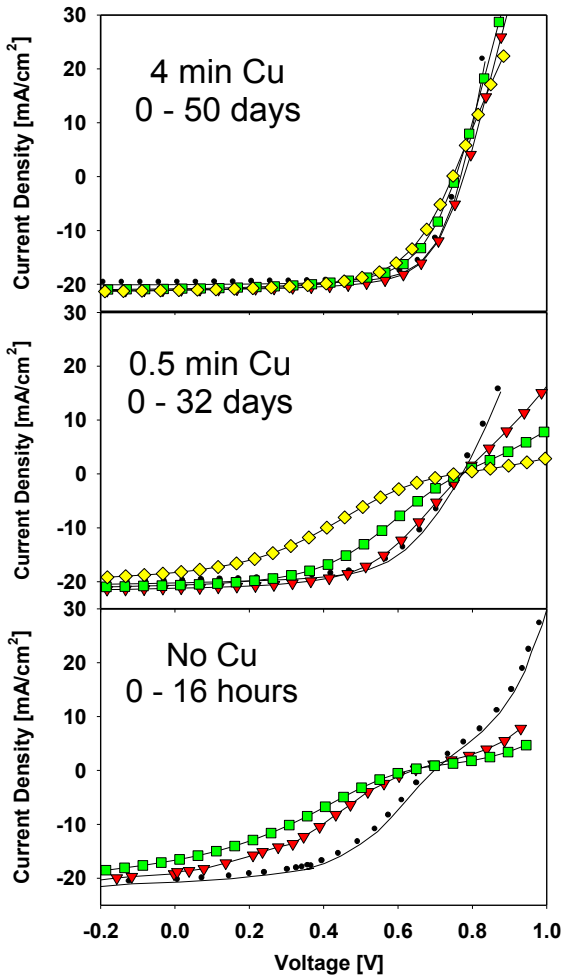
Updated by Tim Nagle and Russell Geisthardt



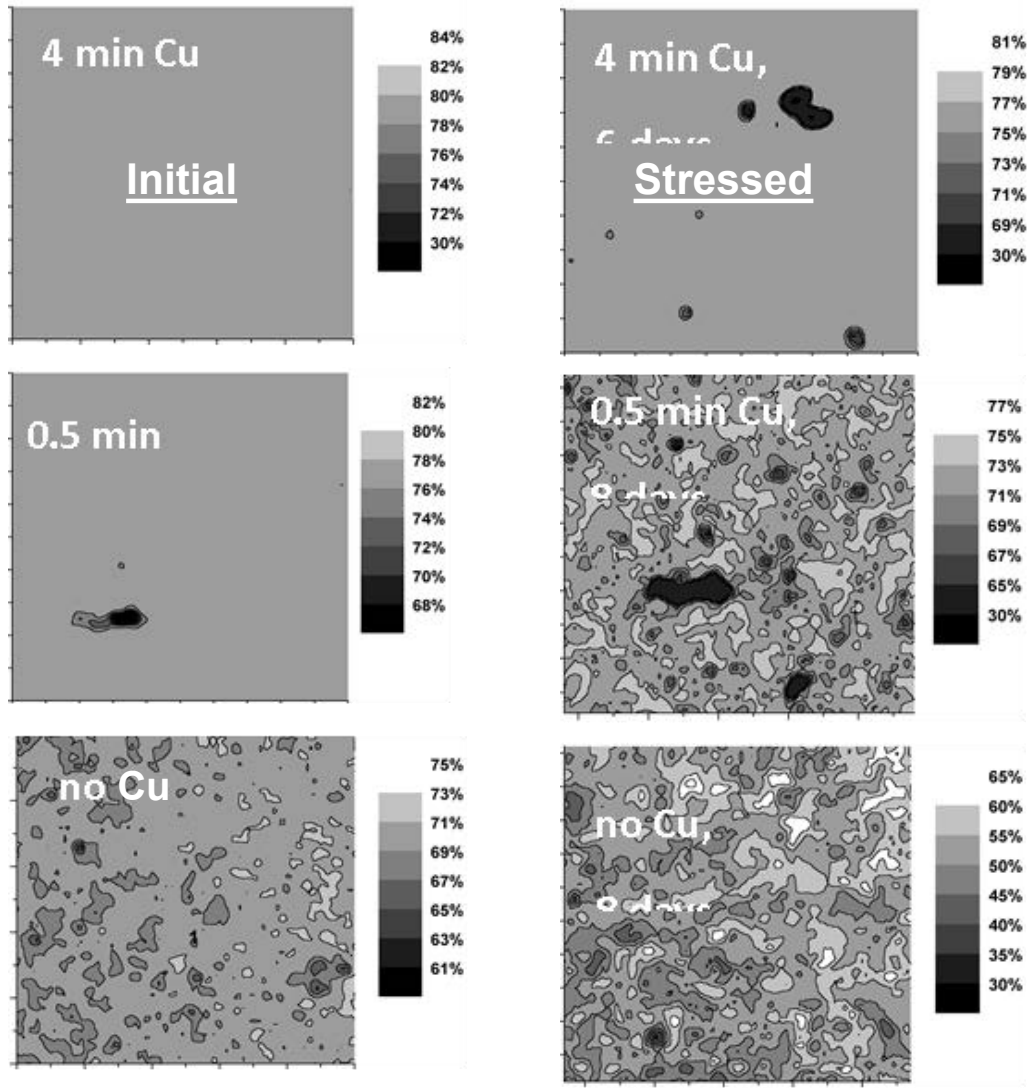


Different Amounts of Copper

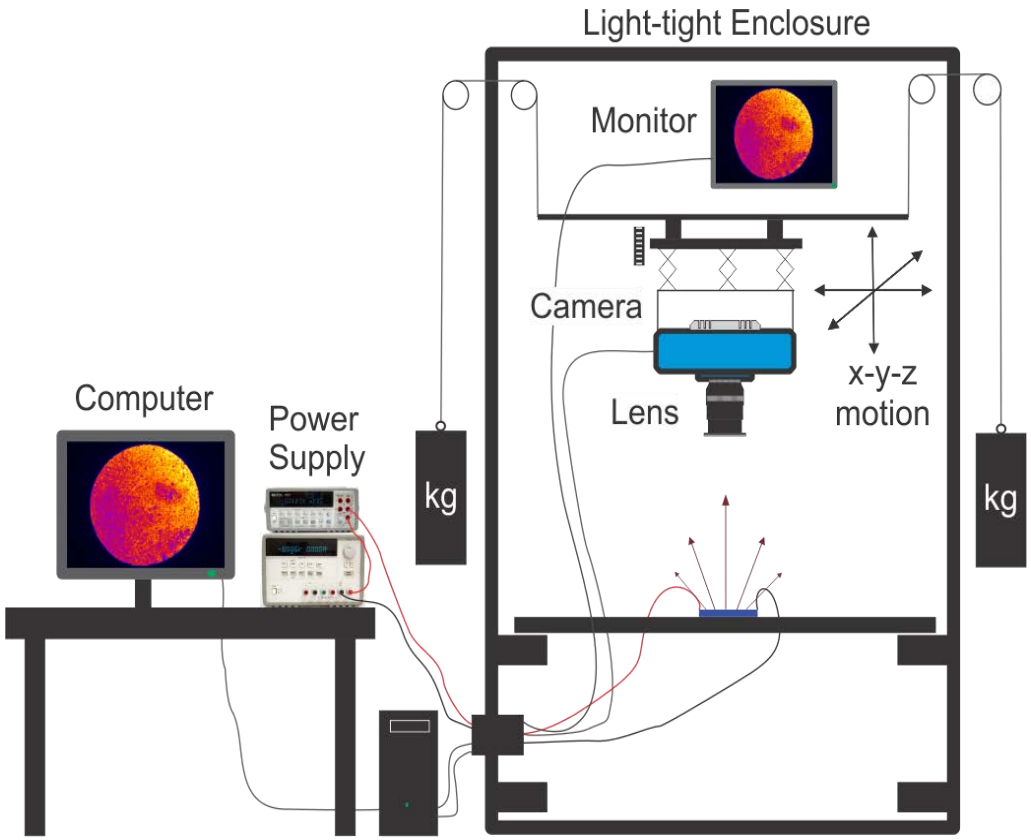
100°C, illuminated, short circuit (CSU cells)



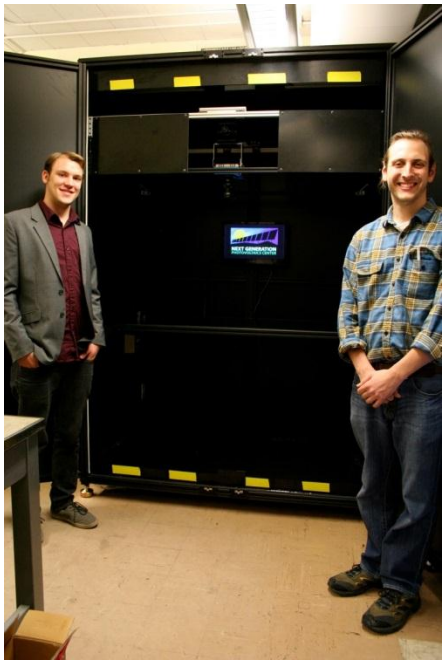
A. Pudov et al, PVSC-29 (2002)

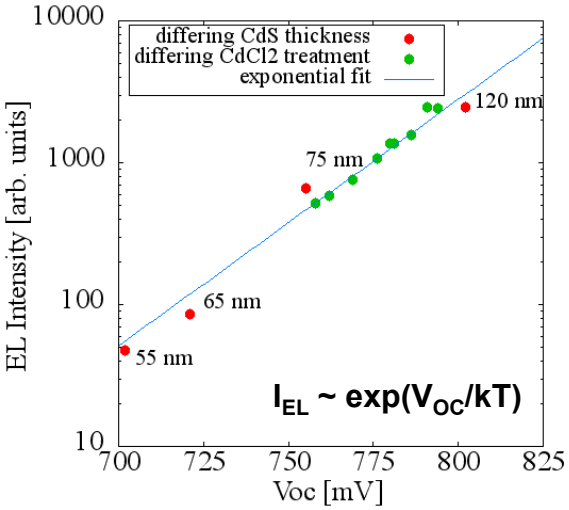


Electroluminescence (EL)



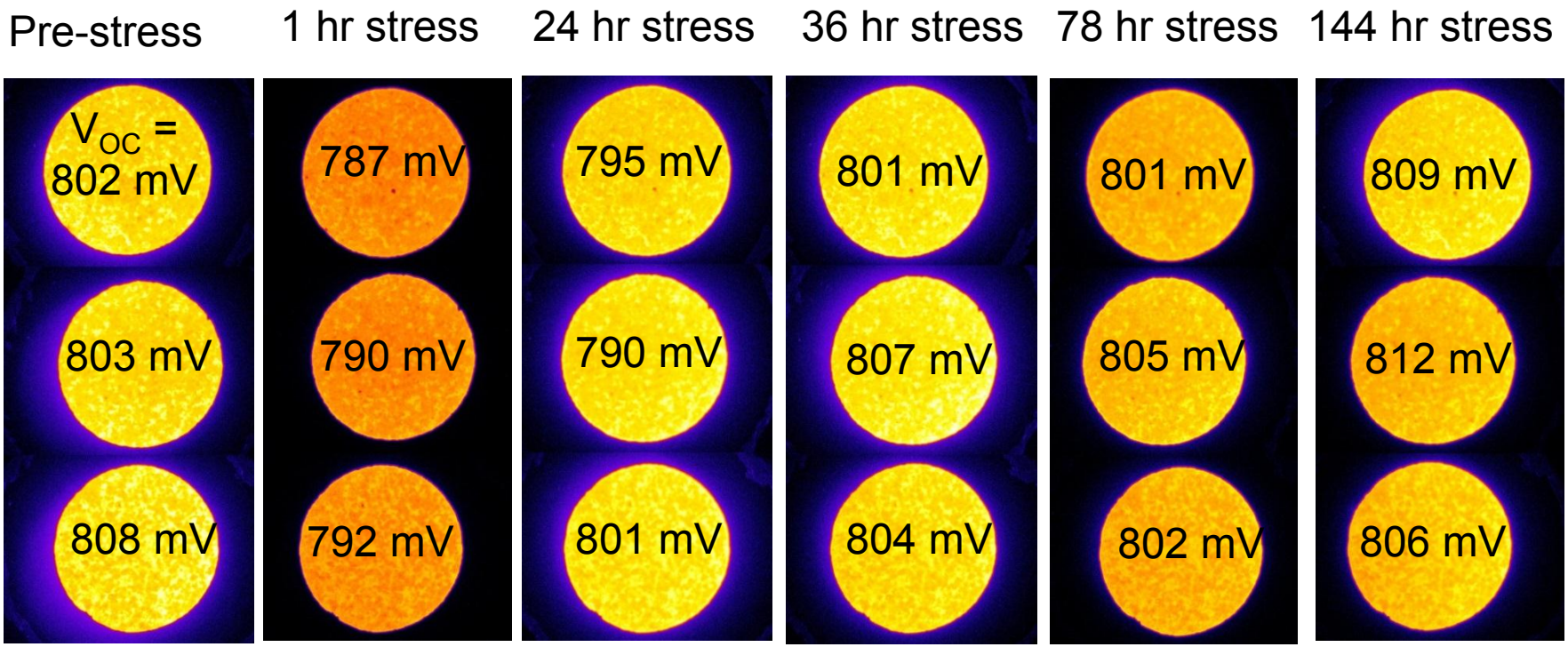
John Raguse and Tyler McGoffin





EL and Voltage of Stressed CdTe Cells

EL tracks voltage; gives confidence to both



John Raguse and Jennifer Drayton

- Devices are standard CSU cell recipe
- Devices stressed at 65°C, at V_{OC} under nominal 1 sun illumination
- Decline and recovery appears real. Two effects from copper diffusion?

Summary

(1) Cell-level CdTe stability is generally good, but needs to be tested with new device structures.

(2) Copper used with back contact is responsible for at least some of the change.

(3) A mix of tracking measurements, including uniformity, is highly desirable.

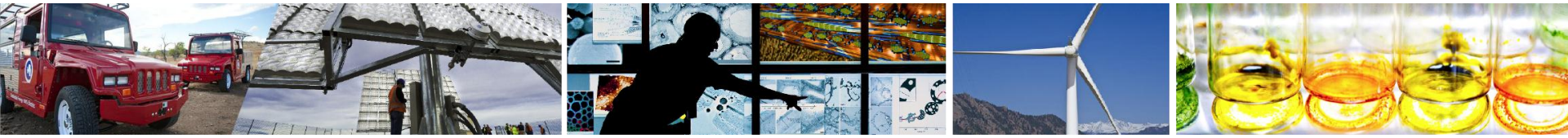
(4) There can be small stability issues that have little effect on performance, but can compromise analysis and could be precursor to later trouble.

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Stabilizing Thin-Film Modules for Indoor Measurements

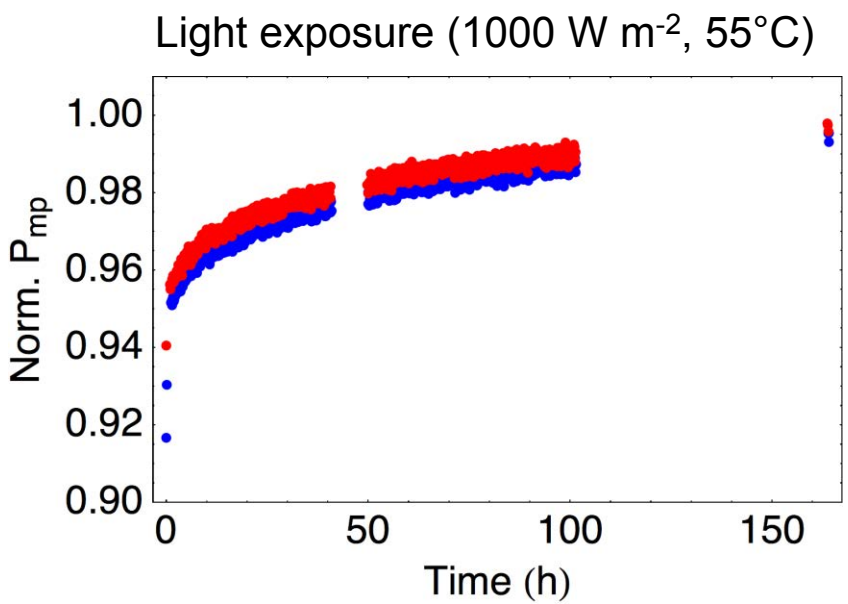
Michael G. Deceglie, Timothy J Silverman,
Bill Marion, Sarah R. Kurtz

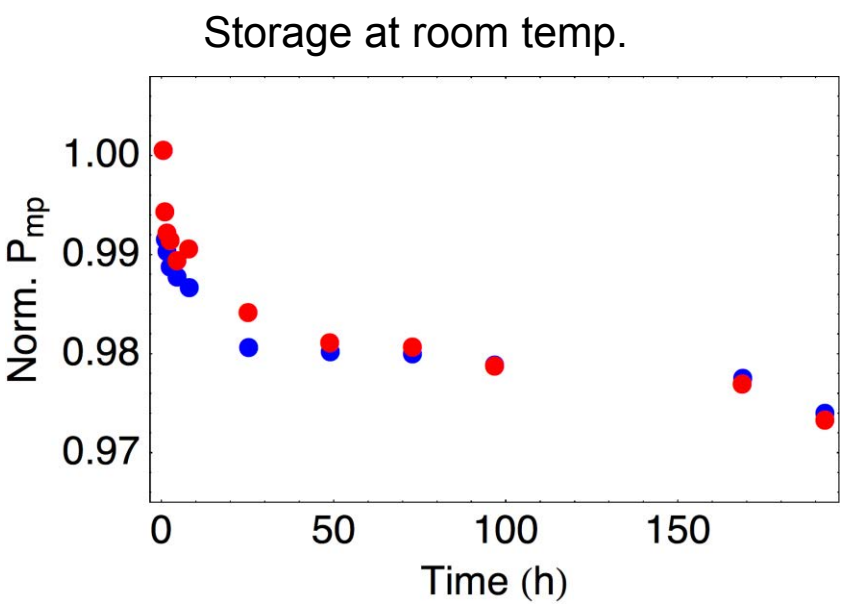
NREL PV Module Reliability Workshop
February 26, 2014



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.

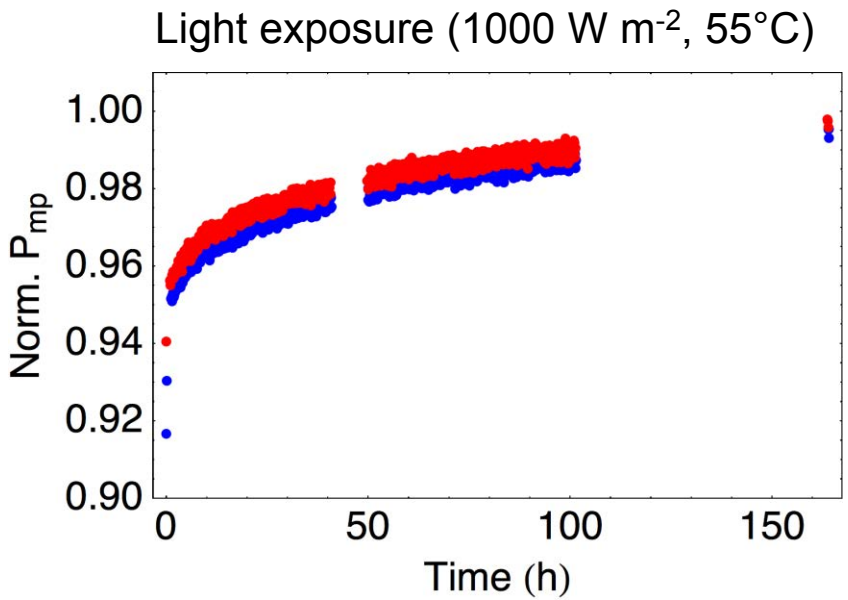
Metastable performance in thin-films

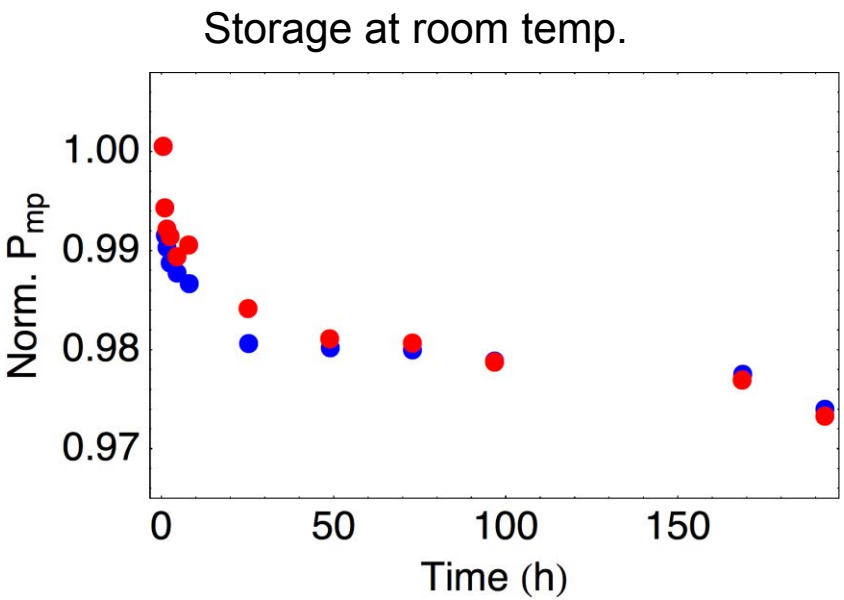




Thin-film modules change performance upon exposure to light and storage in the dark

Metastabilities vs. permanent changes

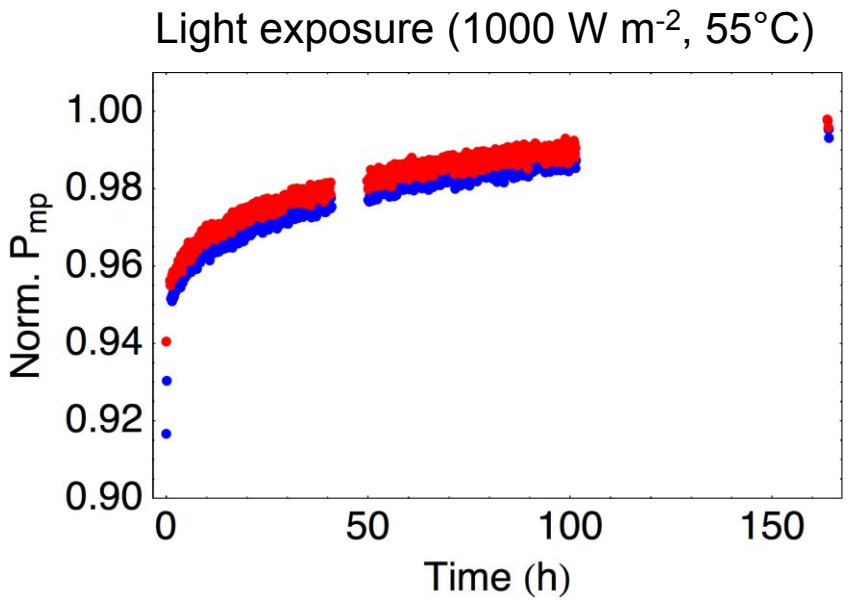


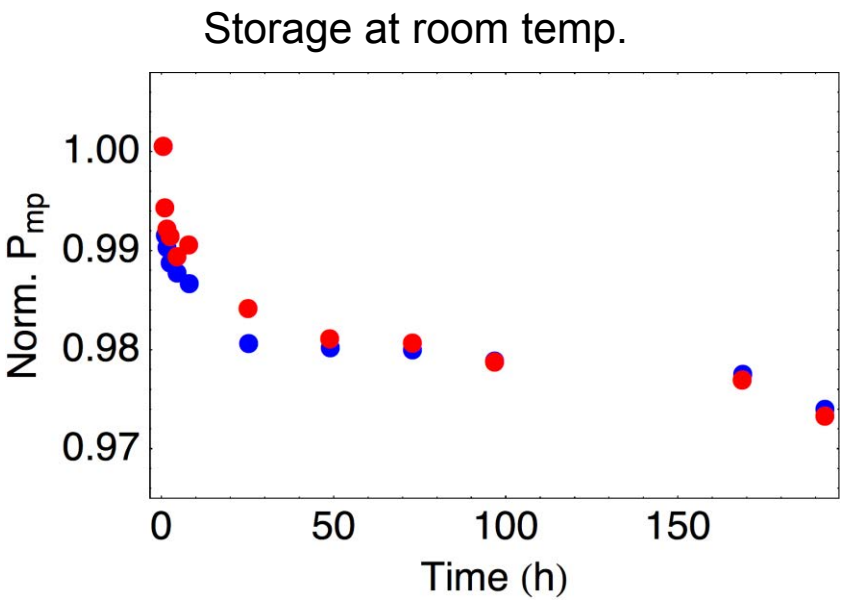


Changes are at often at least partially reversible, especially upon exposure to elevated temperatures

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

Metastabilities vs. permanent changes





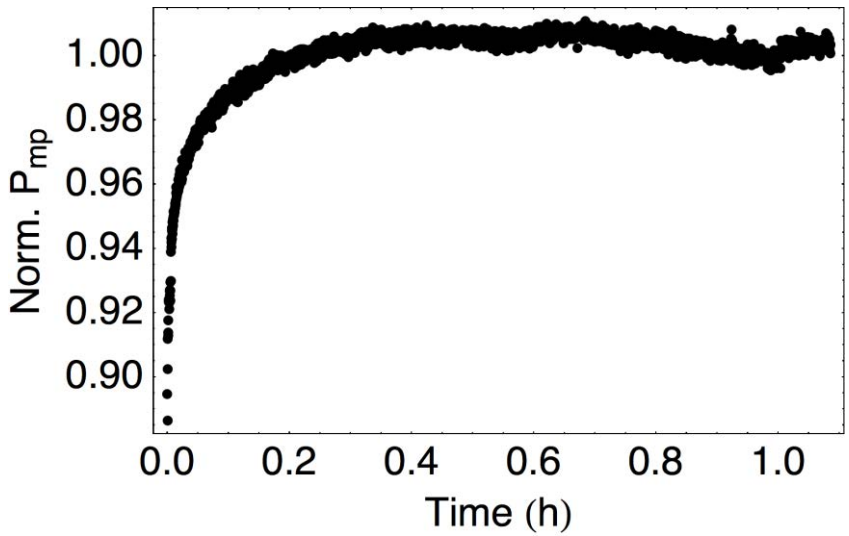
Changes are at often at least partially reversible, especially upon exposure to elevated temperatures

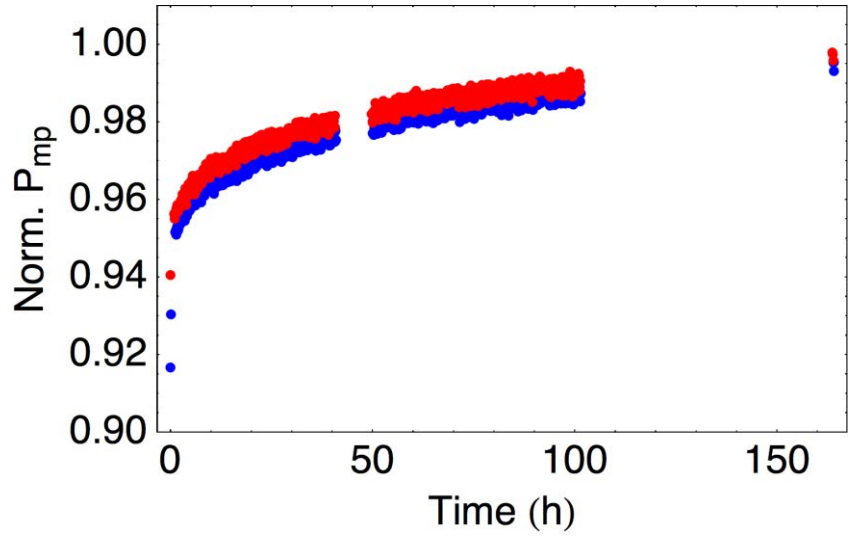
- Initial Norm. P_{mp}: 0.88
- After 165 hours at 55°C: 0.91

Metastabilities: reversible changes
Stabilization: Repeatedly achieving metastable state

Time scales of change

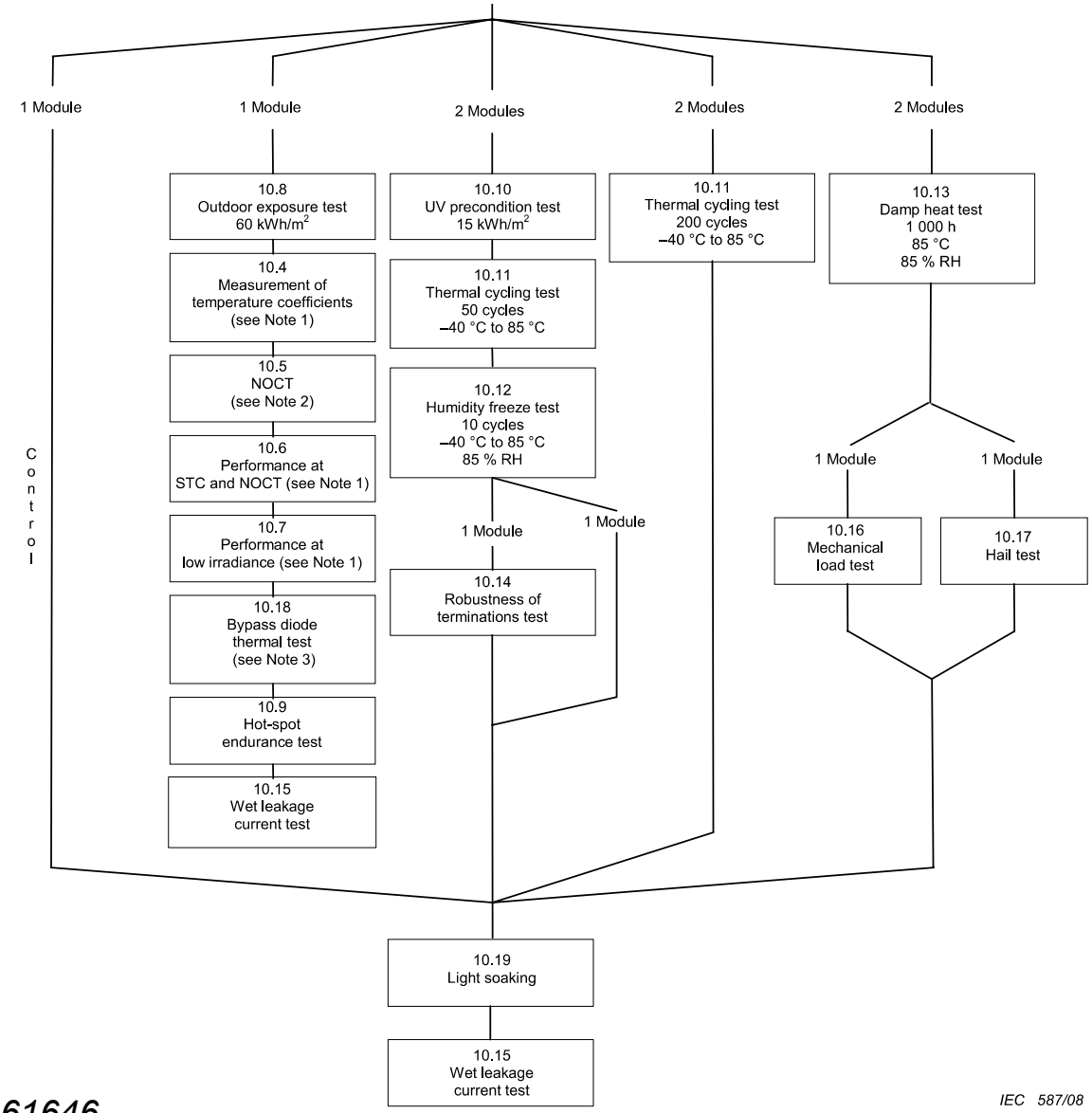
Transient changes in performance of two different types of CIGS modules





Changes can occur at different timescales for different modules

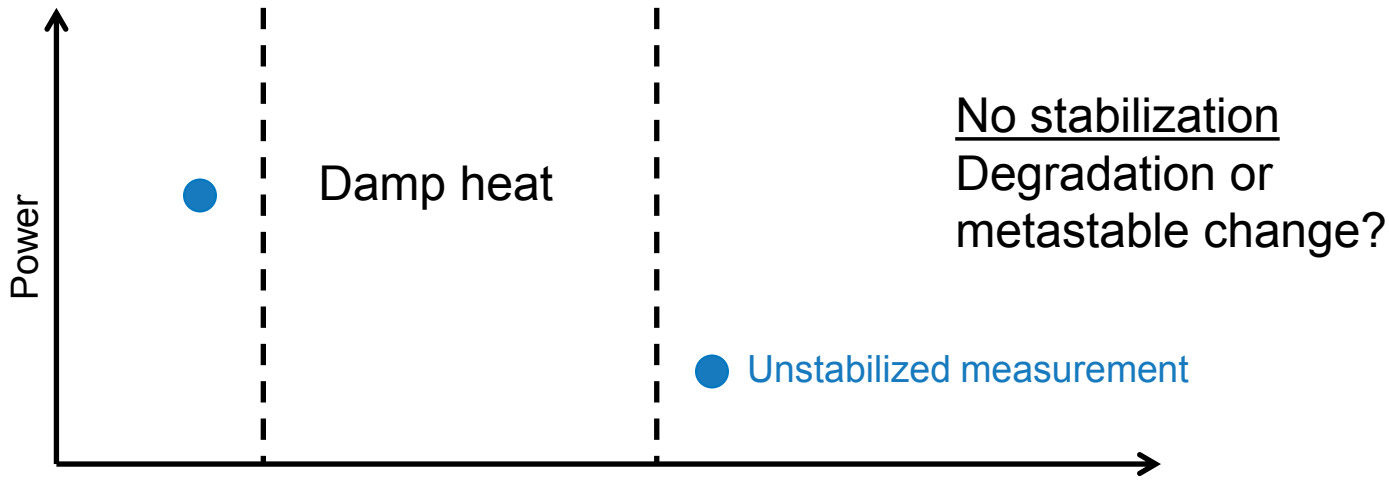
Importance to reliability



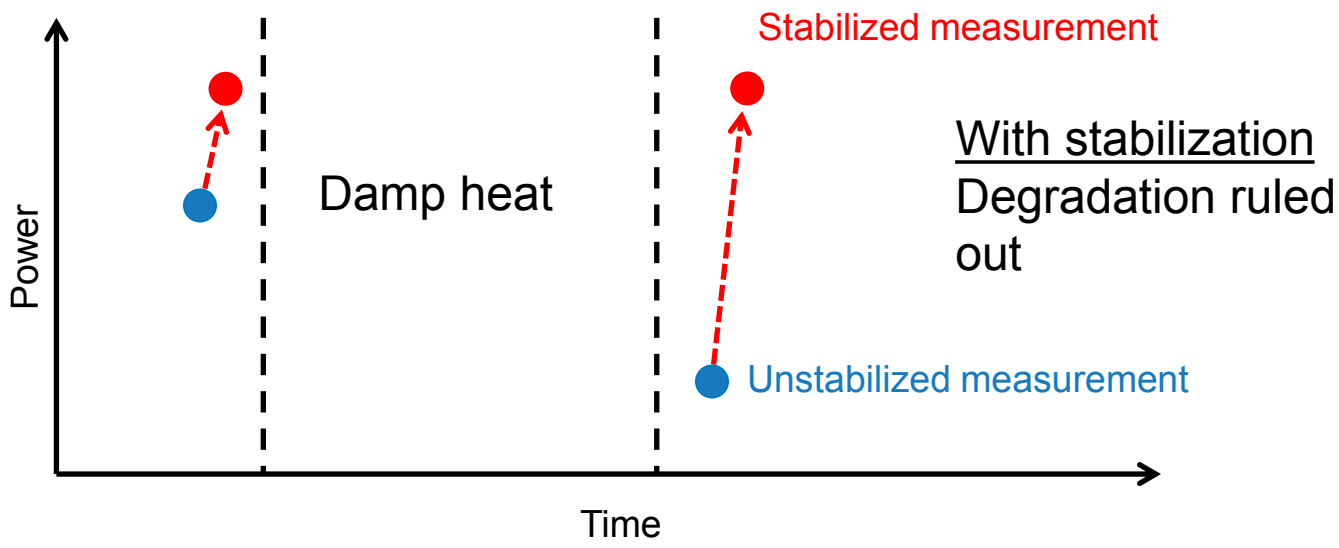
Important to differentiate between permanent degradation and reversible change

IEC 61646

Differentiating degradation



Differentiating degradation



Repeatable stabilization procedure needed before and after reliability test

NREL efforts

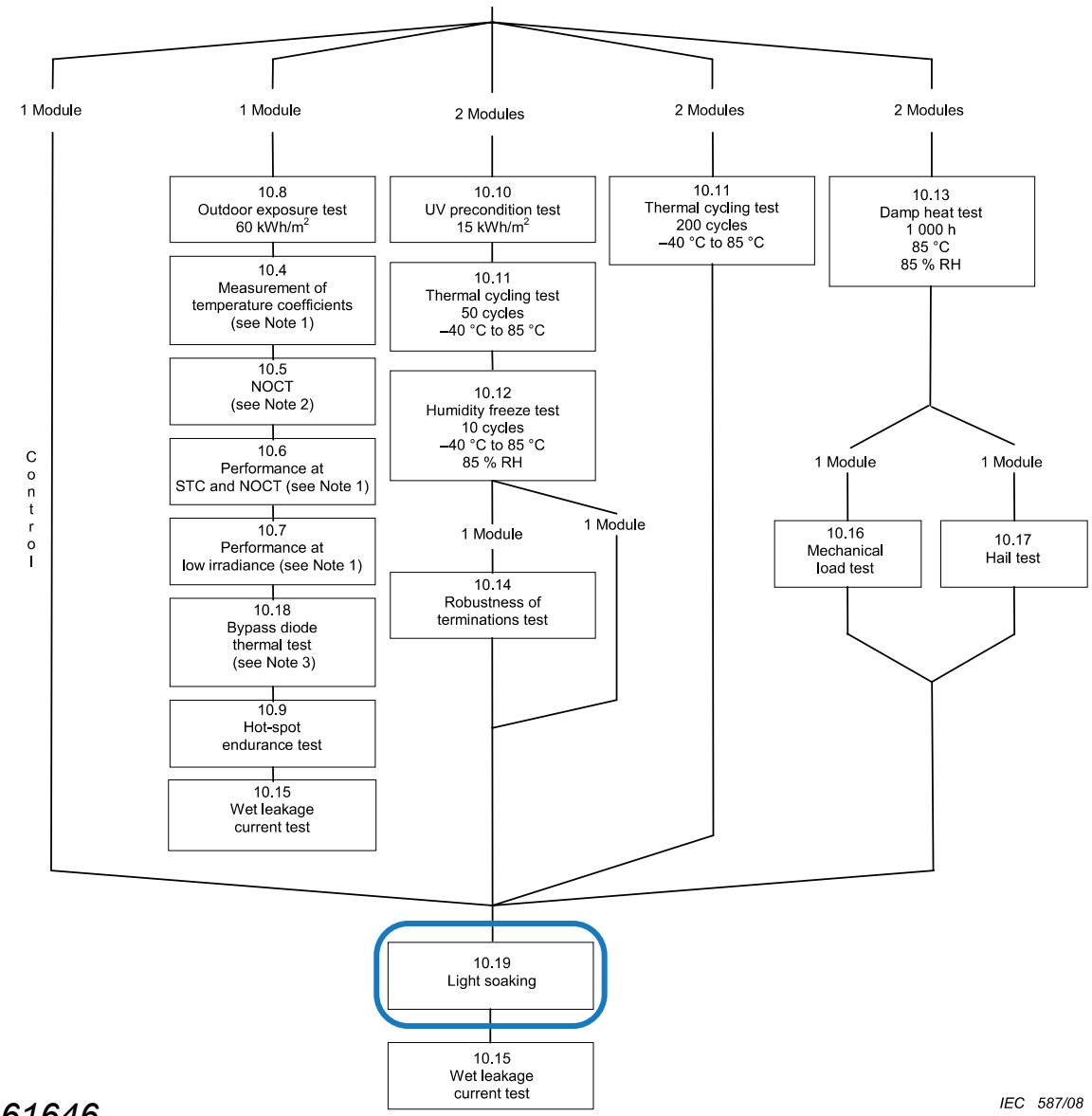
- CIGS: Round robin test of new light-soaking procedure - underway
- CdTe: Currently developing a stabilization procedure for upcoming round robin

NREL efforts

- CIGS: Round robin test of new light-soaking procedure - underway

- CdTe: Currently developing a stabilization procedure for upcoming round robin

Current light soaking standard



Successive doses of 43 kWh m^{-2} until intermediate measurements are stable

Final power is compared to nameplate

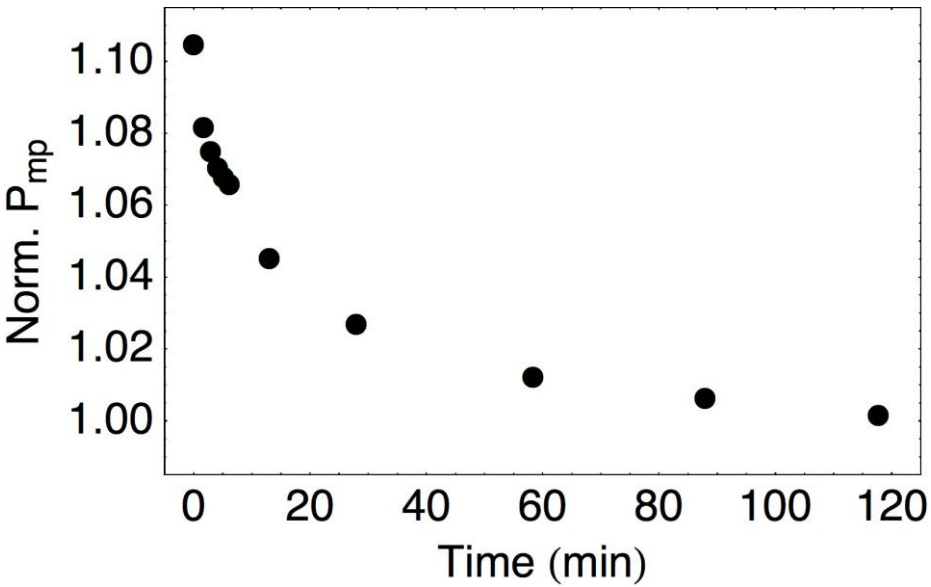
No prescribed time limit between end of light-soak segment and measurement

Note: Currently an effort underway to replace 61646 with new version of 61215 covering all technologies

IEC 61646

Improvements to current standard

Power measurements after CIGS module is brought indoors after light exposure (temperature corrected)



Current standard:

Successive doses of 43 kWh m^{-2} until intermediate measurements are stable

Final power is compared to nameplate

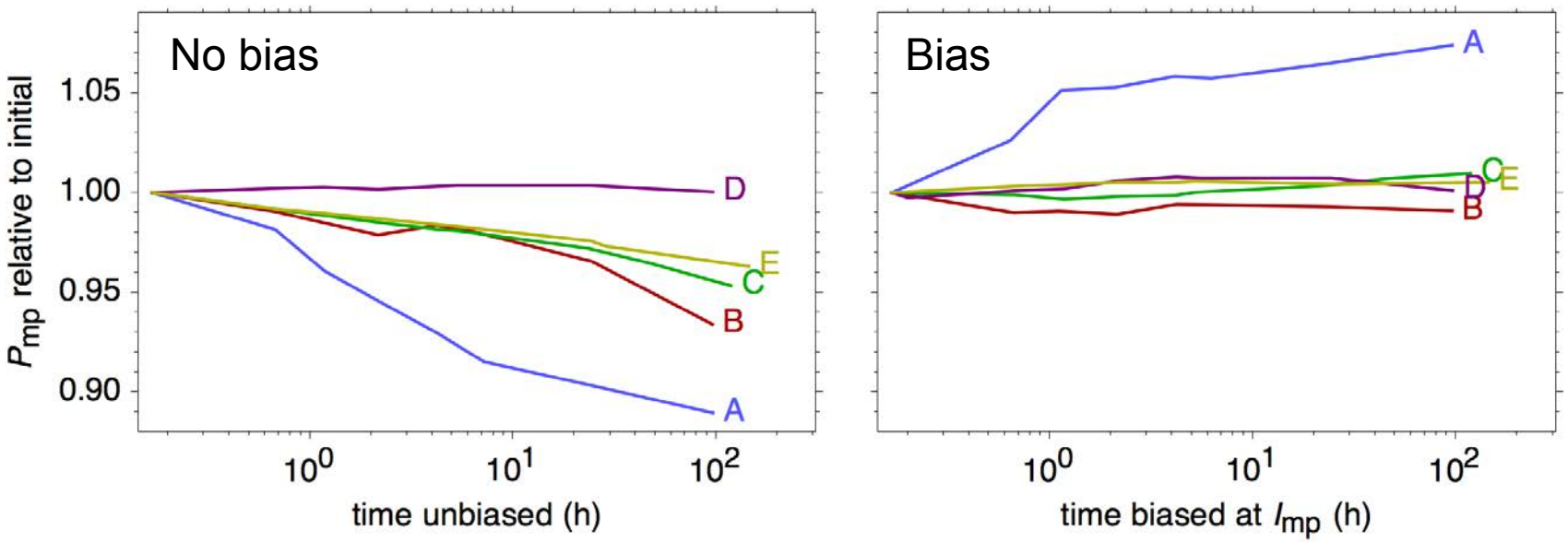
No prescribed time-limit between end of light-soak segment and measurement

- Important to measure promptly after light exposure

Deline, et al, Proc. SPIE 8472, 84720G (2012)

Improvements to current standard

Five different CIGS modules measured after outdoor light exposure, once with forward bias applied once without



- Important to measure promptly after light exposure
- Forward bias can help stabilize power after light exposure

Deline, et al, Proc. SPIE 8472, 84720G (2012)

Procedure for CIGS round robin

Purpose:

- Eliminate variations in measured power from metastable changes occurring in a day or less
- Yield STC performance of a module operating outdoors

Procedure

- Expose to light for 5-5.25 hours
- Measure IV curve within 1 minute, for diagnostic purposes
  - If > 1 min delay, forward bias the module until IV measurement
- Forward bias module as it cools to 25°C
- Measure second IV curve

NREL efforts

- CIGS: Round robin test of new light-soaking procedure - underway

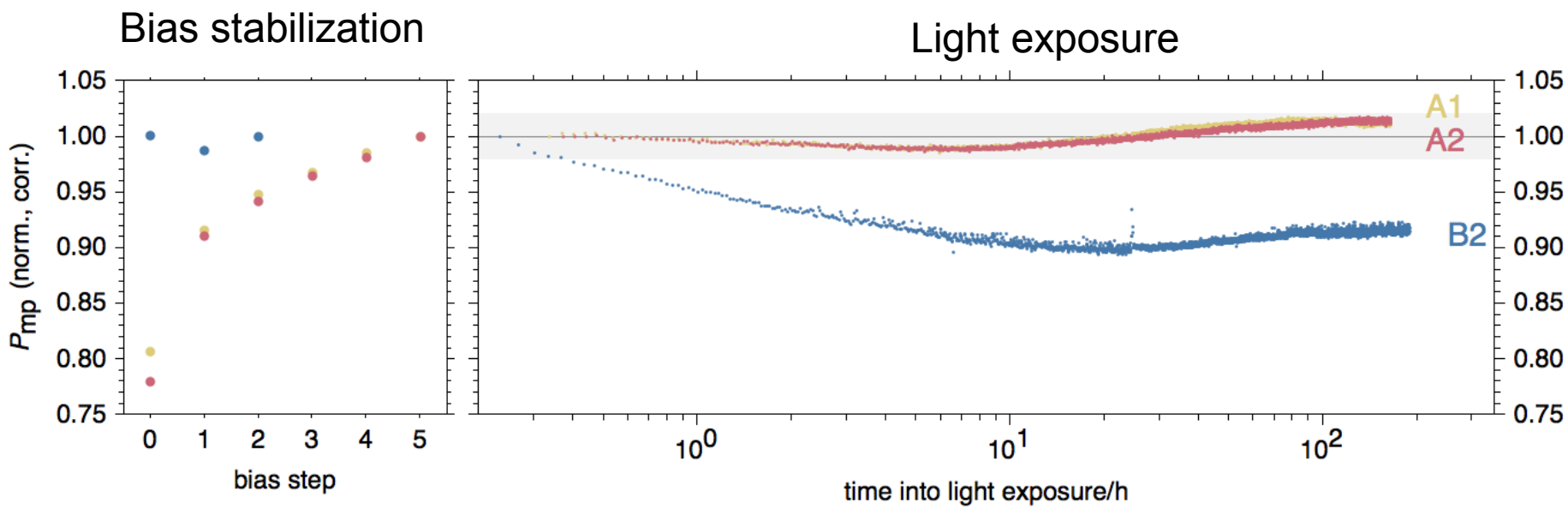
- CdTe: Currently developing a stabilization procedure for upcoming round robin
  - Possibility of stabilizing with forward bias instead of light

CdTe dark bias procedure

- Heat module to 85°C and bias at 90-100% of V_{oc} for 1.5 hours
- Repeat until three successive room temperature power measurements are stable
- Room temperature measurements made within 30 to 60 minutes of cooling down

Repeatable vs. outdoor stabilized

Two types of CdTe module were stabilized with the dark forward bias procedure, then placed in light-soak chamber

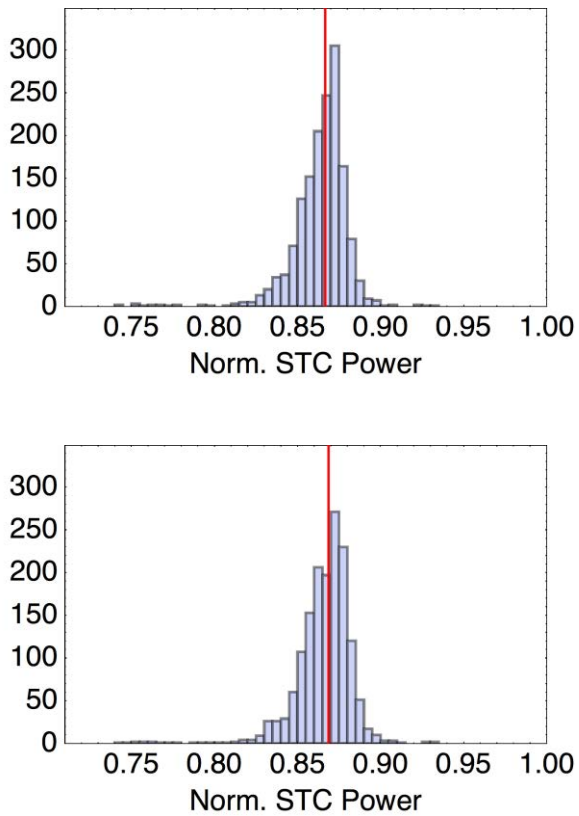


Are we interested in a repeatable measurement, or outdoor performance?

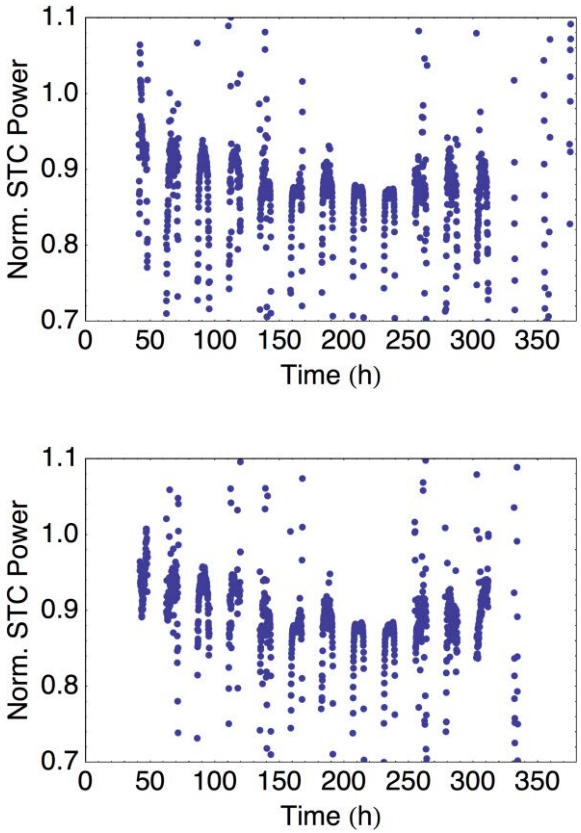
CdTe bias stabilization: outdoor results

Two CdTe modules were bias stabilized and then deployed outdoors

Capacity analysis



Power time series



Outdoor data shows evidence that bias stabilization results in different module state

Conclusion

- Thin-film modules undergo reversible changes in light and dark
- Controlling these changes is important for reliability testing and diagnostics
- Important questions:
  - Time-scale of any standardized procedure?
  - Repeatability vs. outdoor performance?

Acknowledgments

Thank you: Steve Rummel, Allan Anderberg, and Keith Emery (NREL)

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

Cross-Sectional Chemical and Mechanical Characterization of a Multilayer Polymeric Backsheet During UV Exposure

Peter J. Krommenhoek, Chiao-Chi Lin, and Xiaohong Gu

Polymeric Materials Group, National Institute of Standards and Technology, Gaithersburg, MD, USA

Introduction

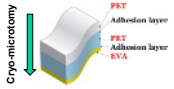
In the field, degradation of the polymeric multilayer backsheet can be detrimental to the efficiency of the photovoltaic (PV) module, causing catastrophic failure and safety concerns. This is a costly problem for industry due to the lack of comprehensive knowledge of multilayer system during weathering.

In this study, cross-sectional characterization techniques were used to provide structural and property changes of a multilayered backsheet before and after exposure to accelerated environmental conditions. New insight into the failure of PV polymeric materials during accelerated aging is presented.

Materials and Measurements

PET/PET/EVA (PPE)

- Section of backsheet was embedded in epoxy
- Sample was faced with diamond knife using cryo-microtomy



Simulated Exposure

- Sample shape/size: Free standing PET/PET/EVA backsheet, 19 mm in diameter
- UV exposure: PET outer layer side face to light
- Exposure conditions: *Simultaneous* UV irradiation, temperature, and humidity.
- T = 85 ℃
- R.H. = 5% (dry) or 60% (wet)

NIST-Patented 2-meter SPHERE*

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

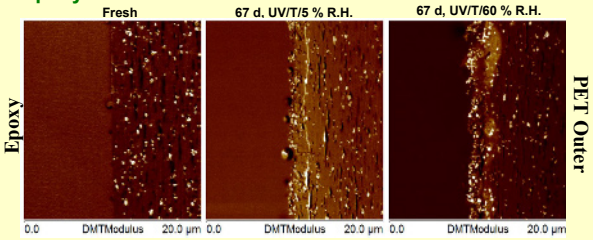
Characterization

- Nanoindentation with continuous stiffness measurement technique
- Atomic force microscopy with quantitative nanomechanical mapping
- Laser scanning confocal microscopy
- Raman spectroscopy with laser λ = 785 nm

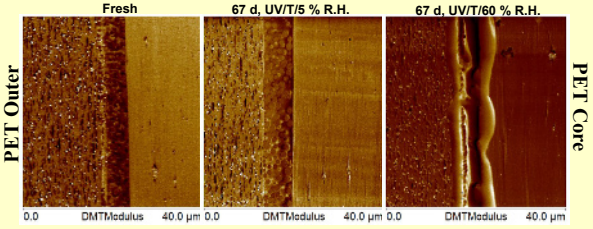
Results and Discussion

Effects of UV Degradation on Interfaces of PPE Multilayers: Modulus Mapping by AFM QNM

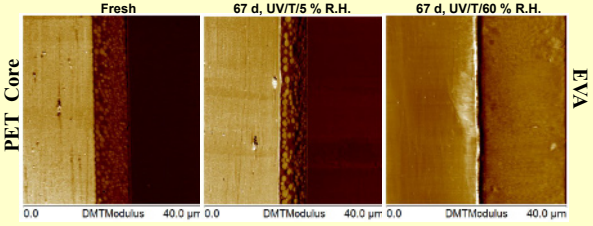
Epoxy/PET Outer Interface



PET Outer/Core Interface



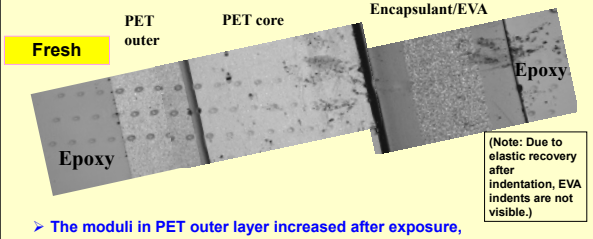
PET Core/EVA Inner Interface



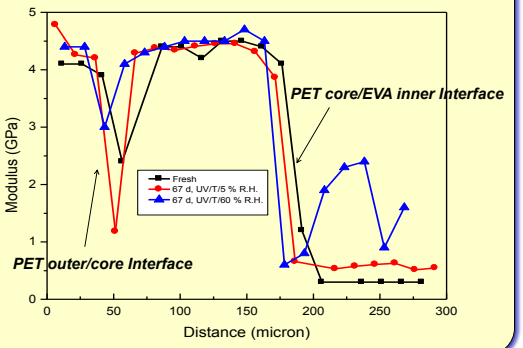
- After exposure, PET outer surface is seen degraded with increased presence of pigment closer to air/PET interface.
- High humidity is detrimental to the structure of the interfacial layers between PET outer/PET core and PET core/EVA inner.

Nanoindentation Depth Profiling of Modulus Change in PPE During UV Exposure

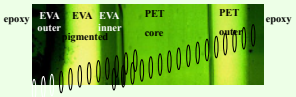
Confocal image of residual indents



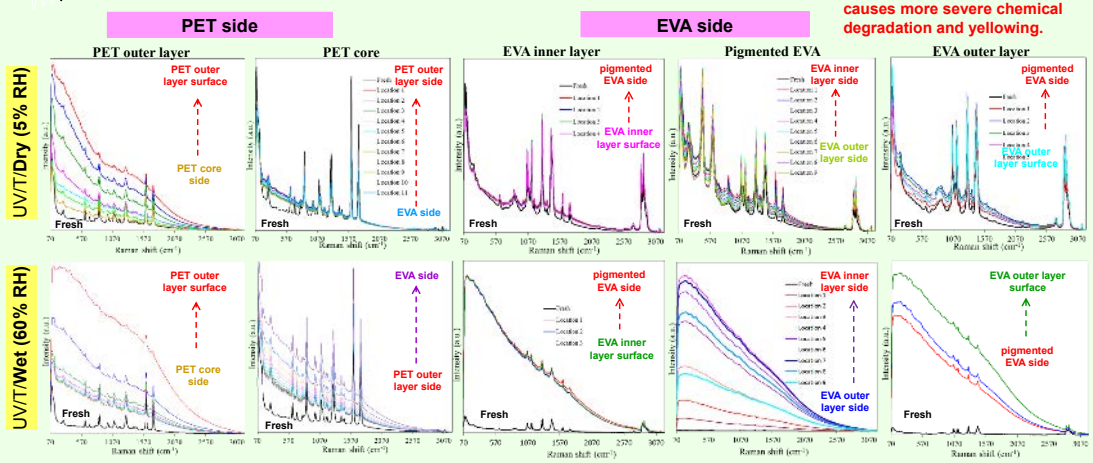
- The moduli in PET outer layer increased after exposure, but no obvious changes observed in PET core.
- EVA moduli substantially increased after exposure in high R.H. due to moisture effect.



Cross-Sectional Raman Spectroscopy of UV-Exposed PPE



- Gradient chemical degradation has been observed on both PET layer and EVA layer
- The wet condition exposure causes more severe chemical degradation and yellowing.



Conclusions

- Both nanoindentation and Raman spectroscopy suggest that high humidity accelerates the photodegradation of backsheet materials in the presence of UV radiation.
- Cross-sectional chemical and mechanical profiling using nanoindentation, Raman spectroscopy, and AFM QNM is an effective tool to understand the interfacial property changes of multilayer backsheet films during UV degradation.

Silicone Encapsulation Enhances Durability, Efficiency, and Enables New PV Cell and Modules Technologies

Jeff Thompson, Markus Putzer, Nina Gonsior, Clarissa Miller

Momentive Performance Materials Inc. is a global leader in silicones and advanced materials, with a 70 year heritage of being first to market with performance applications for major industries that support and improve everyday life. The company delivers science-based solutions by linking custom technology platforms to opportunities for customers.

Momentive's Energy portfolio includes silicone materials for photovoltaic applications such as frame sealing, rail bonding, junction box attach, junction box potting, optical coupling, thermal management and PV encapsulation. The durability and efficiency of photovoltaic (PV) modules can be enhanced significantly when the incumbent PV-cell encapsulation material (Ethylene-Vinyl Acetate, EVA) is replaced with silicone polymer. The physical and chemical property benefits of the SilTRUST* E110 silicone polymer encapsulant ranging from thermal, chemical, and radiation durability to corrosion protection and consistent mechanical properties have all been substantiated with experimental lab and field results.

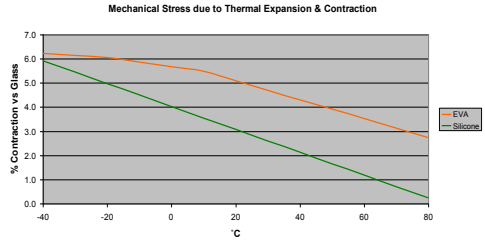
Physical Chemical Properties	EVA	MPM Silicone	Silicone Gel
Tensile strength [N/mm²]	18.9	1.92	-
Modulus 100% [N/mm²]	2.22	0.37	±0.1
Elongation [%]	566	414	-
Density [g/cm³]	0.96	1.036	0.98
Hardness [Shore A]	64	20	12 (Shore 00)
Dielectrical strength [kV/mm]	6.4	19	18
Moisture absorption	0.3%	0.03%	0.03%
Adhesion – Durability	+/-	++	+/-

Key Attributes of SilTRUST* E110 Silicone Encapsulant

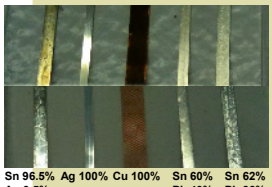
- Enhanced durability vs EVA
- Low thermal module stress
- Corrosion protection
- No yellowing
- Excellent heat resistance
- Prolonged damp heat
- PID mitigation

Induced Mechanical Stress after Cure

Due to the low temperature cure and low modulus of silicone encapsulant the induced thermal stress is less in the glass PV module.



Adhesion & Corrosion Protection



Sn 96.5% Ag 3.5% | Ag 100% | Cu 100% | Sn 60% Pb 40% | Sn 62% Pb 36% Ag 2%

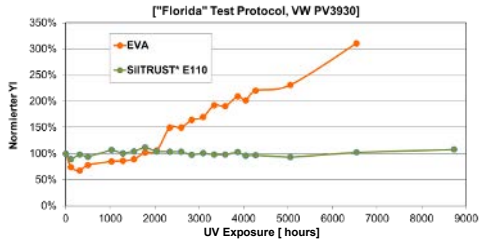
Encapsulated Metals after 500 hours 85°C / 85% RH

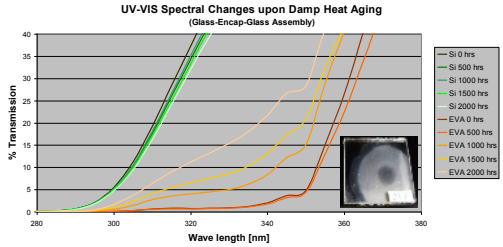
Organic pottants allow significant corrosion in DH.

Momentive Silicone shows good protection against corrosion.

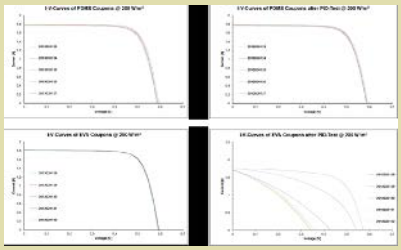
Hours damp heat exposure until adhesive failure		
Back sheet type ▸ / Glass type ▾	Polyamide	Tedlar
Float glass	2000 1)	2000 2)
Solar glass + ARC	2000 1)	>5000

Retention of Optical Properties after Aging

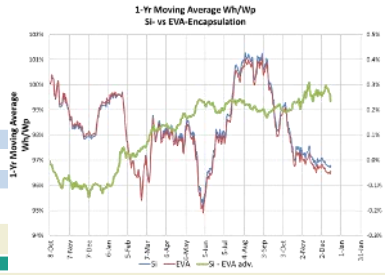


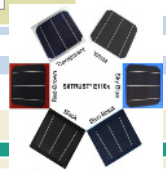


PID Mitigation



Outdoor Data Shows Increased Performance





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Role of Encapsulants in Improved Reliability of Photovoltaic Modules

Kumar Nanjundiah, John Naumovitz, Michael Biscoglio, Tom Burns

The Dow Chemical Company
1605 Joseph Drive, Midland, MI 48642, USA

Abstract

Recent efforts in crystalline silicon module technology have been focused on increasing life and reliability of PV modules to go along with improvements in cell efficiency. The reliability aspect has led to interest in polymeric materials used in module construction as well as BOS components. In this regard, polymer encapsulants play a key role in improving reliability by providing better environmental protection as well as electrical insulation.

In recent years, new materials have been introduced to replace EVA to overcome drawbacks of yellowing, acid generation and moderate electrical insulation. In this report, reliability analysis based on accelerated testing results will be provided comparing different encapsulant materials used in PV modules. Data showing the need for improved electrical insulation and better barrier performance to prevent phenomena like PID will also be presented.

Motivation and test methodology

1. Can encapsulants help increase life time of efficient power generation in PV modules?
2. Does choice of encapsulant and polymeric material properties matter ?

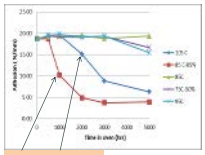
Ideal test: Field testing, Draw back – Long time period, can't be used to develop today's systems

Accelerated testing: Consider stressors as experienced in the field and watch out for unrealistic failure modes.

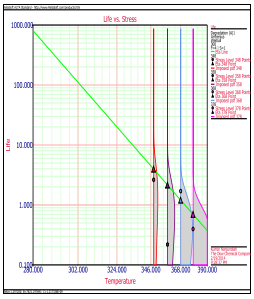
- Temperature
- Humidity
- Voltage
- Harmful radiation

} Combinations are closer to reality

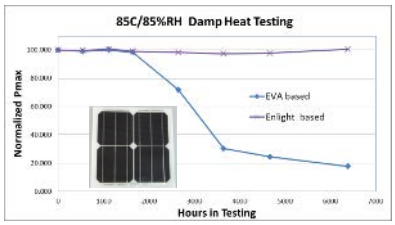
Adhesion data and model



Critical degradation – 10 N/mm
Use temp – 45C
Mean Life = 28.8 Year
Acceleration Factor = 44.9



Degradation of power in DH

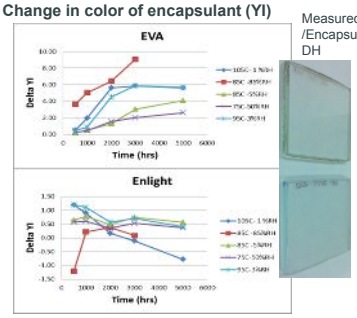


Data average of 3 four cell crystalline silicon modules

Testing at conditions of 75C/50%, 85C/5%, 95C/3%, 85C/85%, 105C/1% temperature and humidity respectively to develop a model for Enlight™ remains unfinished since all modules have retained power close to initial values with 5000hrs of testing

Change in color of encapsulant (YI)

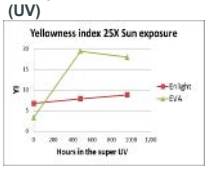
Measured on Glass /Encapsulant / Glass in DH

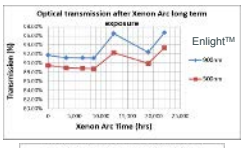


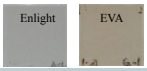
change in color with ageing

NO change in color with ageing

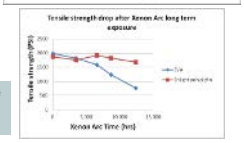
Encapsulant film tensile and degradation (UV)



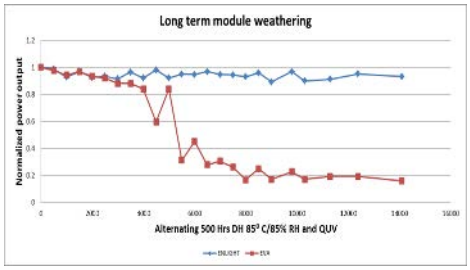




Super accelerated UV exposure shows yellowness increase for EVA compared to Enlight™



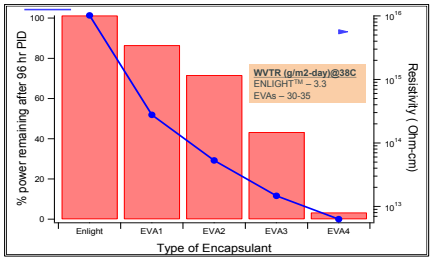
Long term power with alternating QUV and DH



Images of backsheet after DH

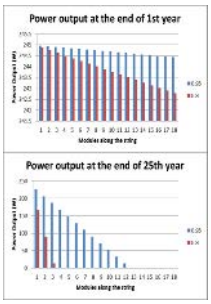
- The power after 14,000 hrs of DH is still above 90%
- The backsheet seems to be completely destroyed.
- With new encapsulants having electrical performance and WVTR comparable to backsheets - calls to question function of backsheets in PV modules

Improved PID by using Enlight™



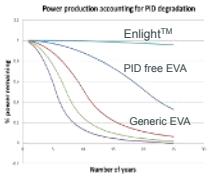
Power remaining after 96hrs at 85°C, 85% RH, -1000V bias

Analysis based on NREL field study

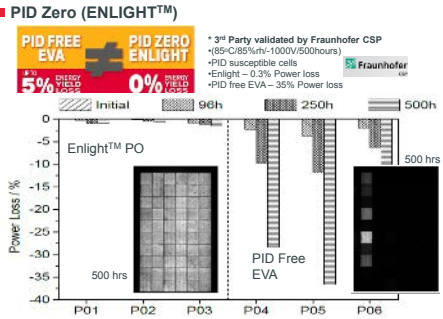


- 245 W module –string model based on module test data (considering linear power drop with voltage bias)
- NREL lab to field correlation based on single modules tested @ 60C/85% RH, 96hrs, in lab ~ 4.7yr in field
- Power retention over time measured, shows a 1-(b*t²) dependence

Peter Hacke et.al, IEEE conference 2012



PID Zero (ENLIGHT™)



Summary

- Accelerated testing studies were conducted with individual stressors and combination of stressors to evaluate the role of encapsulants in durability of crystalline silicon PV modules. Results suggest new encapsulant materials can increase the durability of modules and provide longer life times
- New encapsulant formulations show excellent UV stability
- Modules with polyolefin encapsulant performs with > 90% efficiency under combination of UV and DH after 14,000hrs of ageing
- Analysis based on NREL field studies suggest <0.5% degradation due to PID in accelerated testing necessary to achieve >90% efficiency at the end of 25 years
- It is shown that with proper choice of encapsulant a PID zero solution is possible

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UV Degradation Study of Encapsulate Backsheet System for PV Modules Using Metal Halide Lamp

Shuying Yang, Kent Whitfield, Eugene Rhee, SunEdison Belmont, CA

Alelie Funcell, Cherif Kedir RETC, Fremont, CA

Feb 25~ Feb 26, 2014, NREL PVMRW

Shuying Yang: syang3@sunedison.com
Kent Whitfield: kwhitfield@sunedison.com
Eugene Rhee: erhee@sunedison.com
Alelie Funcell: alelief@retc-ca.com
Cherif Kedir: cherif@retc-ca.com

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Abstract

- The majority of PV module manufacturer's offer a 25 year warranty for their products and some of them are even in the stage of extending their warranty for longer terms. The reliability and durability of the solar modules are highly dependent on the UV stability of the encapsulation system and the protecting backsheet system. Among the environmental factors of temperature, humidity and UV irradiation, it is UV irradiation that is arguably the most difficult stress to accelerate. The commonly used fluorescent UV lamp and Xenon Arc light source typically provide up to about three times natural sunlight irradiance (with irradiation acceleration higher depending on lamp duty cycle). This study considered UV acceleration up to ~ 30X natural sun exposure via a metal halide lamp.
- Activation energy was calculated for different EVA encapsulations (UV transparent version and the traditional fast cure UV stable version) in combination with commercial PET type solar backsheets, using yellowness index as a characterization for UV degradation. The activation energies were found to be about 0.12 to 0.15 ev.
- This low level of activation energy means that the system is easily degraded by UV stress and increasing temperature does not provide significant acceleration. The potential error caused by this large value of irradiance acceleration is discussed as it bears on the finding of low activation energy.
- Validation based upon similarly constructed EVA/Backsheet samples subjected to one-year EMMAQUA exposure (~ 4 to 5X Natural sun concentration in Arizona) is underway and results will be discussed at a future time.

Summary

- Commercial UV transparent and normal Fast Cure EVAs and PET-only backsheet systems were evaluated

- UV aging was performed using Metal Halide Super-UV (SUV) Tester
  - ~30X UV
  - Capable of achieving various yellowness-index values for EVA/backsheet systems in a relatively short time period (~2 weeks)
  - High acceleration may introduce artificial results:
    - The actual degradation effect to be verified by ~5X natural sun testing result (underway)

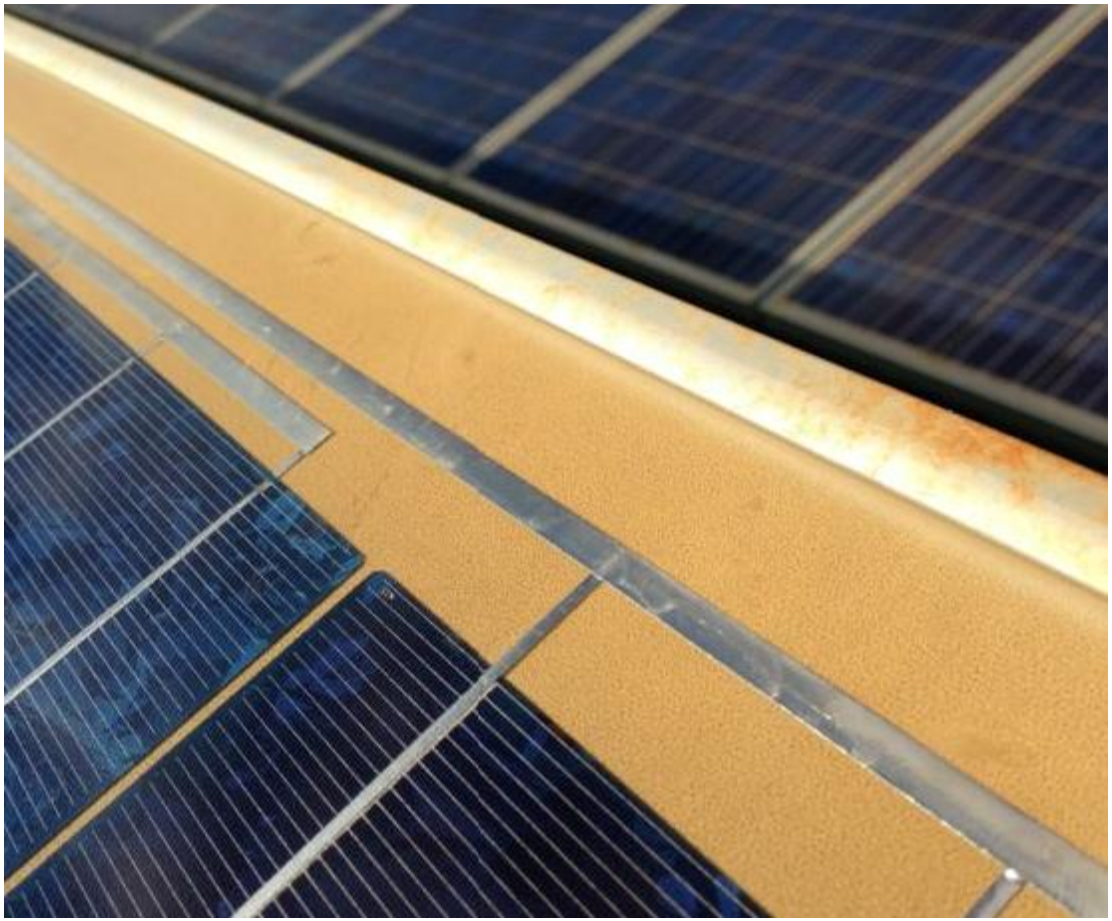
- Activation energies of the three EVA/PET backsheets systems were obtained
  - 0.12 to 0.15ev
  - For this low level of activation energy, the acceleration factor by increasing testing temperature from 45°C to 90°C is only **1.9X**

Background/Objective

- Typical Location Annual UV Dosage
  - Florida: 78 KWH/m^2 (280 MJ/m^2)
  - Arizona: 93 KWH/m^2 (334 MJ/m^2)
- 25 Year Typical Location Total UV Dosage
  - Florida: 1944 KWH/m^2 (7000 MJ/m^2)
  - Arizona: 2319 KWH/m^2 (8350 MJ/m^2)
- IEC61215 UV Precon Dosage
  - Precon: 15 KWH/m^2
- UL746C UV Testing Condition
  - 0.35 w/m^2 @ 340nm for 1000 hours
  - Equivalent to ~ 34 KWH/m^2
- IEC **82/747/NP:** Polymeric materials for photovoltaic (PV) modules – Part 2: Frontsheets and backsheets
  - 0.35 w/m^2 @ 340nm for 1000 hours
- In Summary, compared to 25 years UV total dosage, all typical UV tests are low-dose
  - Need to develop an efficient accelerated UV simulation. How much can we accelerate?
- Objective of this Study: Run UV aging at 3 different temperatures (50, 70 and 90°C), and calculate the activation energy for UV aging, using Yellowness Index as the parameter for aging result.

Sample Field Failure Due to UV Exposure

- ~1.5 Years US Installation Backsheet/EVA Yellowing Picture



Sample Preparation

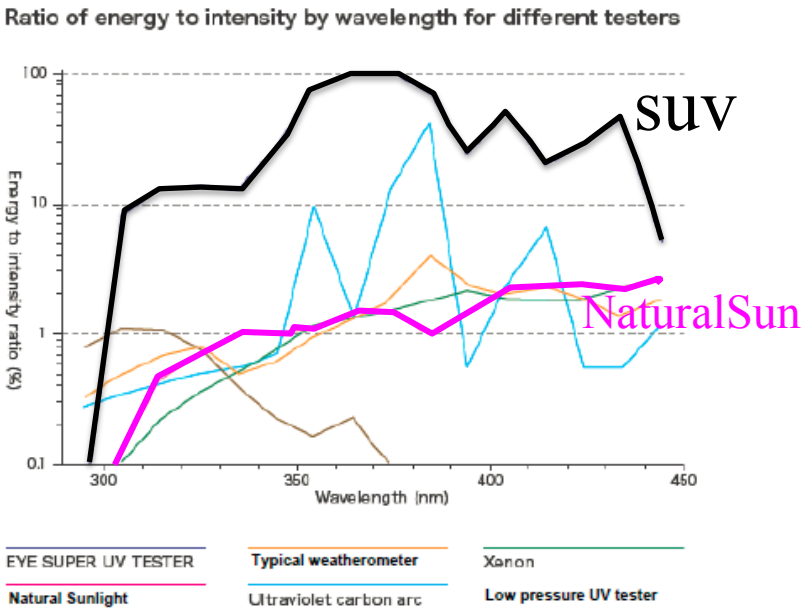
- Raw Materials
  - Glass: 180mm*180mm*3.2mm, AGC Solite solar glass
  - EVAs: Commercial UV Transparent EVA (UVT EVA) and Normal Fast Cure EVA (FC EVA): 0.5mm thick
  - Backsheet: Commercial single layer PET type
  - Stackup:
    - Sample 1: Glass/FC EVA/FC EVA/PET backsheet
    - Sample 2: Glass/UVT EVA/UVT EVA/PET backsheet
    - Sample 3: Glass/UVT EVA/FC EVA/Backsheet

- Lamination Condition
  - 140°C/4min Vacuum/5min Press/90KPa
  - Gel Content: >80%

UV Source: EYE Super UV Tester SUV-W161

- UV Tester @ RETC
  - Iwasaki Electric Corp., Ltd.
    - Lamp: Metal Halide Type
    - ~30X natural sun UV intensity when set to 1500 W/m^2

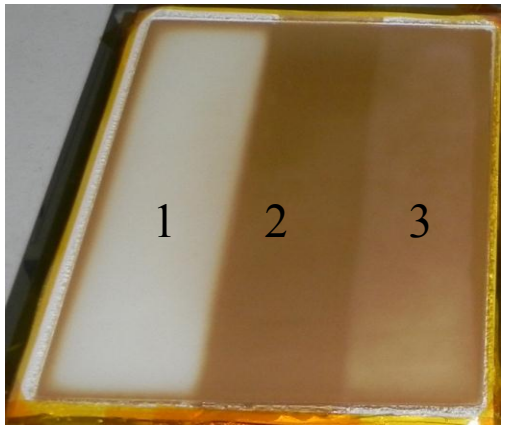
- UV Aging Setting
  - T: 50°, 70°, 90 °C
  - RH: 50%
  - Intensity: 1500 W/m^2
  - Water spray: 8 minutes every 112 minutes
  - Total Duration:
    - Samples were aged @ 70°C/5 day to reach the target Yellowness Index
    - Then new groups of samples were exposed to 50°C and 90°C for varying duration to reach the same yellowness index for activation energy calculation



Pictures of Aged Samples

- Fresh Sample

70°C for 120hrs (180kWh/m^2)



- 90°C for 96hrs (144kWh/m^2)

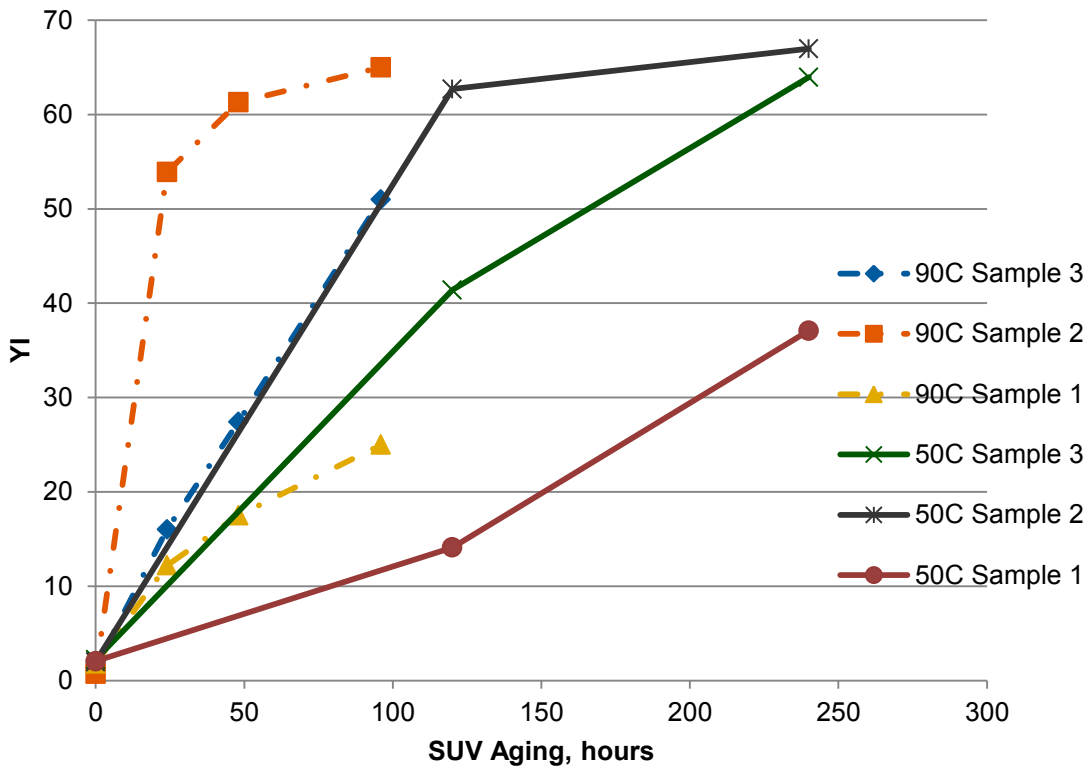
50°C for 240hrs (360kWh/m^2)

Yellowness Index of the Samples

- 70°C/120hrs YI Result: Used to set YI target for subsequent 50°C and 90°C aging

Testing T	YI
Sample 3	56.4
Sample 2	64.8
Sample 1	25.2

- 50°C, 90°C, See right plot



Activation Energy Calculation

- Time to Failure, assume Arrhenius Relationship

$$TTF = A\exp\left(\frac{Ea}{RT}\right)$$

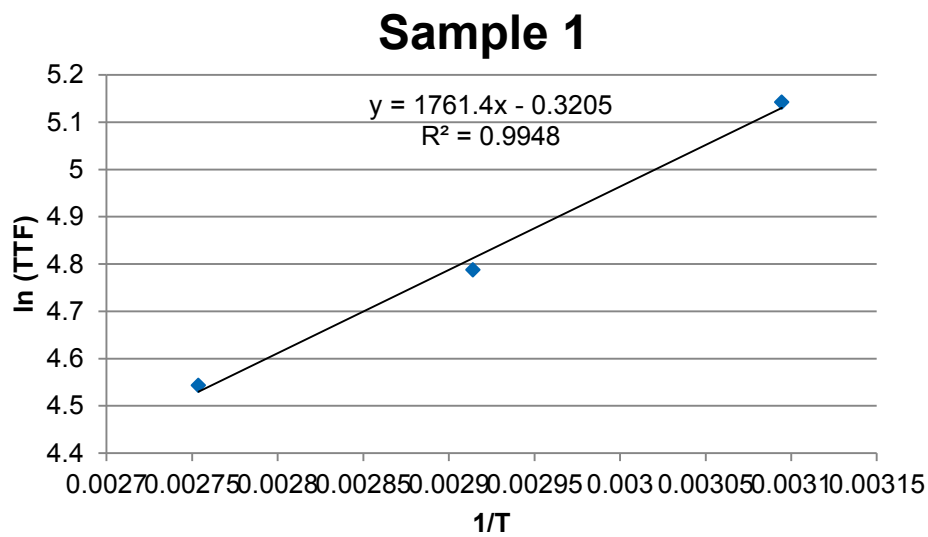
  - Take log on both side:
  - $$\ln(TTF) = \ln(A) + \frac{Ea}{RT}$$
  - Then by plotting ln(TTF) vs 1/T (Kelvin), we are going to get the slope as Ea/R, where R is the gas constant (8.314 J/mol).
    - Ea= Slope*8.314 J/mol

Activation Energy for System 1

- Time to Failure (TTF):

T, C	Time to failure, hrs
50	171
70	120
90	94

- Plotting ln(TTF) vs 1/T:
  - Slope=1761.4
  - Ea=14644 J/mol=0.15eV

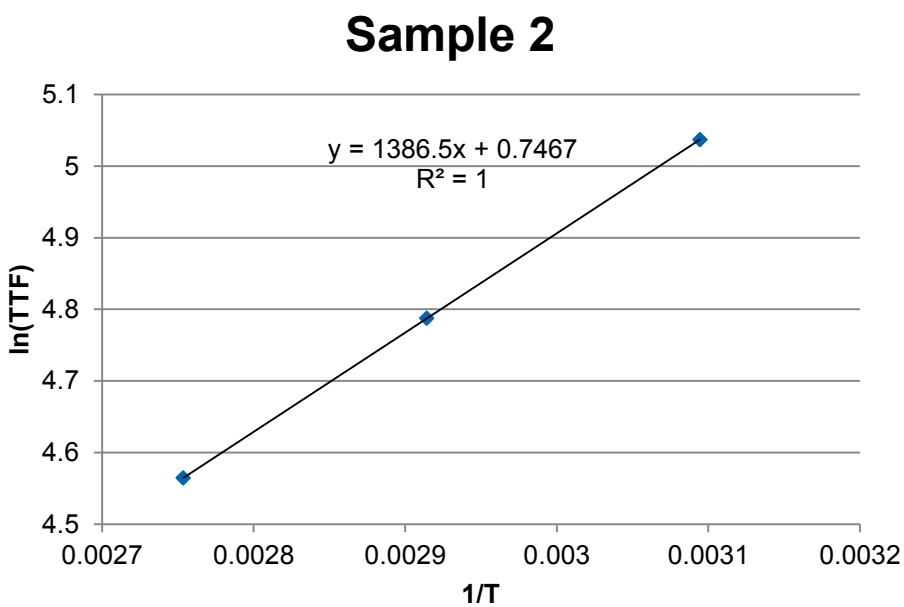


Activation Energy for System 2

- Time to Failure (TTF):

T, C	Time to failure, hrs
50	154
70	120
90	96

- Plotting ln)TTF) vs 1/T:
  - Slope: 1386.5
  - Ea=11527 J/mol=0.12eV

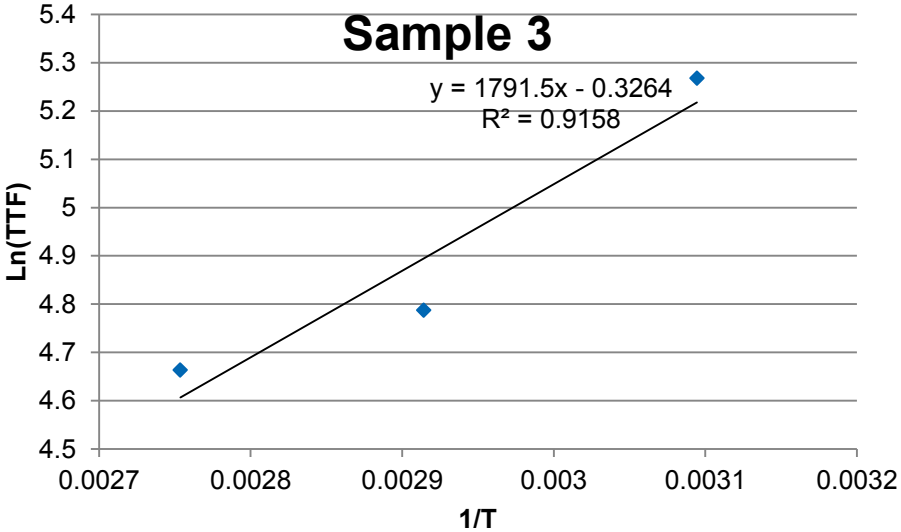


Activation Energy for System 3

- Time to Failure (TTF):

T, C	Time to failure, hrs
50	194
70	120
90	106

- Plotting ln (TTF) vs 1/T:
  - Slope: 1791.5
  - Ea=14895 J/mol=0.15eV



Acceleration Factor at Elevated Testing Temp

- Assume 45°C is the normal module operating temperature
- The degradation rate is proportional to exp(-Ea/RT)
- Then we can calculate the acceleration factor at elevated T:
  - Acceleration Factor=exp(-Ea/RT)/exp(-Ea/R*(45+273.15))
  - Plugging in 11527 J/mol for Ea from the Sample 2 system, the calculated acceleration factors are tabulated below:

T, C	T, K	exp(-Ea/RT)	Acceleration Factor
45	318.15	0.012803877	
60	333.15	0.015579661	1.2
80	353.15	0.019720556	1.5
100	373.15	0.024339276	1.9

Conclusion

- The activation energy of the different EVA/backsheet system were obtained
  - Glass/UV Transparent EVA/UV Transparent EVA/PET backsheet: 0.12eV;
  - Glass/UV Transparent EVA/FastCureEVA/PET: 0.15eV;
  - Glass/FastCureEVA/FastCureEVA/PET: 0.15eV.

- This extremely low level of activation energy means:
  - These EVA/PET backsheet systems may be easily degraded by UV
  - These EVA/PET backsheet systems' aging are difficult to accelerate by elevating temperature:
    - **Testing at 100°C only gets 1.9X acceleration factor**
    - **This implies that you can not just simply do UV aging at elevated temperature to achieve the acceleration effect, you have to run UV testing at increased duration to achieve aging effect.**

RETC California

SunEdison®

Conclusion Cont'd

- Former activation study showed that one has to increase UV dosage to achieve UV aging effect
  - Option 1: by increase testing duration with low UV intensity setting
  - Option 2: by increase UV intensity setting with shorter duration
  - Option 3: by slightly increase both UV intensity and duration

- Super UV technology here takes option 2
  - 1500W/m^2 setting for UV range

- Equivalent to ~30X Sun UV. One can easily get relative UV resistance result on the encapsulant/backsheet system choice within one to two weeks.

Exploring the Behavior of PV Edge Seals on Glass in a Boeing Wedge Test (BWT)

Lori Postak, Quanex IG Systems, Inc.

Can the Boeing Wedge Test be used with rubbery Edge Seals and analyzed using Griffith's Criterion?

Introduction

Three widely commercialized butyl edge seals with good field performance were used to explore how sealants behave using a series of wedge sizes. Monitored adhesive delamination and thickness changes vs time. This exploratory work is being used to support development of a wedge test for PV Edge Seal Durability. The goal was to be able to calculate Griffith's Criterion (G_c), described as Adhesive Fracture Toughness.

Samples

1" x 8" low iron glass 3.25 mm thick

4" glass/4" adhesive ~0.6 mm thick (used 0.5 mm spacer)

4 wedge sizes 1.0 mm 1.25 mm 1.50 mm 1.75 mm

Wedge placed 3.75" from adhesive junction

Conditions & Measurements

85°C DRY QUV UVA lamps 1.18 irradiance ~1.74 Suns - constant on, no dark

Sealant Temperature: Black=93°C Gray=88°C

UV through glass measurements (@ adhesive interface)

@254 nm = 25.5 μW/cm^2 @308 nm = 117 μW/cm^2 @365 nm = 19.7 mW/cm^2

QUV @ 64 days exposure = 99 KWh/m^2 ≈ 1.2 yrs Florida Sun total UV

Facture is any crack growth or branching noted by adhesive delamination or cavitation). Observed as bubble formation which propagates.

Equation & Calculations

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

Griffith's Criterion G_c "Fracture Toughness"

E= 72 GPa low-iron glass

t= 3.25 mm beam thickness

h= wedge size - initial adhesive thickness (varies 0.55-0.60 mm)

a= distance from wedge to longest delaminated point

If no failure, then the G_c Fracture Toughness energy is higher than the value shown. G_c in J/m^2

Conclusions

⇒ Reproduce some failure modes seen in Damp Heat modules

⇒ "Crack tip" is not distinctive: bubbles following cavitation eventually combine and grow

⇒ Too large a wedge increases the strain rate beyond the time domain of creep

⇒ Oversized wedge creates rapid failure

⇒ Oversized wedge creates a failure mode not seen in the field

⇒ In order to study the effect of long UV exposure, the strain rate should not induce rapid failure

⇒ BWT with rubbery materials is not straightforward. There is a complex interaction of modulus, stress relaxation, applied strain and the work of adhesion

⇒ How to analyze the data and interpret the results needs discussion

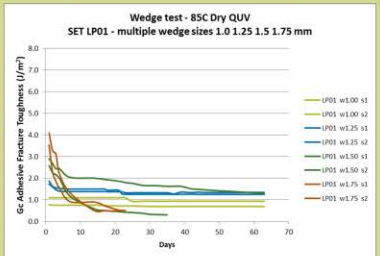
⇒ Failure location can transfer between sides (front/back) resulting in shorter measurable delamination

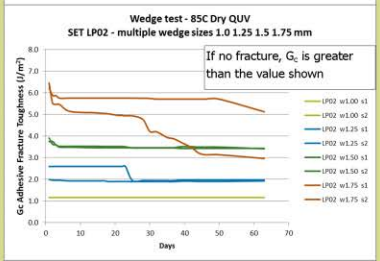
⇒ A more complex model may be needed to account for plastic deformation, a cohesive zone in front of the crack tip, dissipative energy (such as stress relaxation), etc.

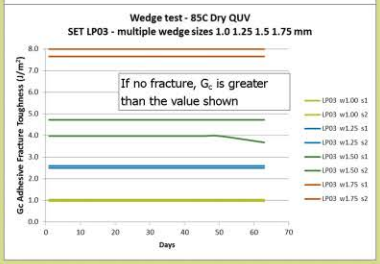
⇒ Griffith's Criterion may be an oversimplification with rubbery materials

⇒ New sealants may be overengineered. Excessive strain yields no failure.

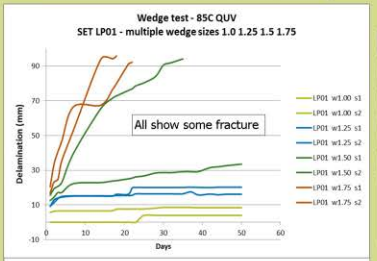
Fracture Toughness vs Time

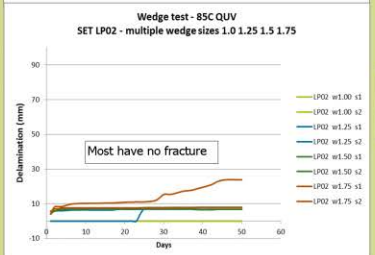


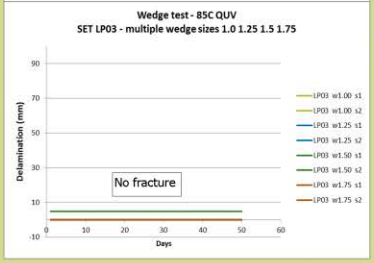




Adhesive Delamination vs Time







LP01 wire 1.75 mm UV side

Adhesive failure pictured one side.
Some fail both sides / less distance.
Failure too rapid

LP02 wire 1.75 mm UV side

Some adhesive failure

LP03 wire 1.75 mm UV side

No adhesive failure even after 64 days

Thickness Change

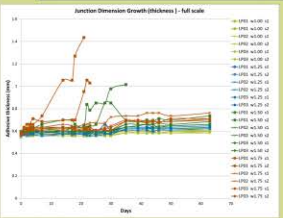
⇒ Thickness measurements were taken at the Junction between glass and adhesive

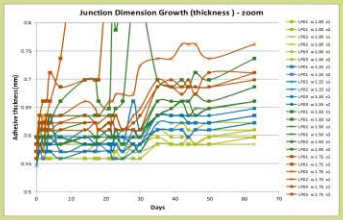
⇒ Wedge size increased the thickness at the junction point within one day after wedge insertion

⇒ Initial growth (Day 1) is proportional to wedge size

⇒ Other variations due to measurement error and equipment used (changed at day 32)

⇒ No cohesive failure or cavitation noted in the adhesives (via back lighting)





Improvements Needed

⇒ Induce a sharp crack tip on the exposed side of the sample

⇒ Compare performance in multiple environments to see impact of the weathering

⇒ Since SET LP01, a functional edge seal in the field, shows some fracture at even the smallest wedge, a smaller wedge at 1.25 mm may be sufficient to induce failure for study of environmental effects of UV and humidity without overstraining the adhesive.

Acknowledgements

The author would like to acknowledge the contributions by Harry Buchroeder and Vlad Bodnev

The information contained here does not include confidential information and is suitable for public release.

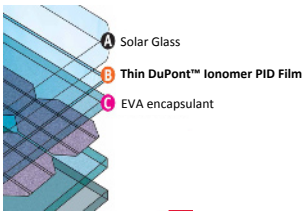
Prevention of Potential Induced Degradation with Ionomer Film

Jane Kapur[1], Jennifer Norwood[1], Alison Bennett[1], Babak Hamzavytehrany[1], Katherine Stika, Craig Westphal[1], Ingo Kueppenbender[2]

[1] E. I. DuPont de Nemours & Co., Inc., Wilmington, DE 19880 U.S.A.
[2] DuPont de Nemours (Deutschland) GmbH, Germany

1. Objective and Performance Goals

Ionomer encapsulants have been shown to prevent potential induced degradation of PV modules. To be more cost effective, thin films of ionomer were used in conjunction with EVA and tested under PID conditions. Both film thickness and ionomer type were optimized to obtain a robust solution.



- Prevent PID under stringent test conditions
- Minimal change to module materials
- Minimal change to module manufacture
- Low added cost

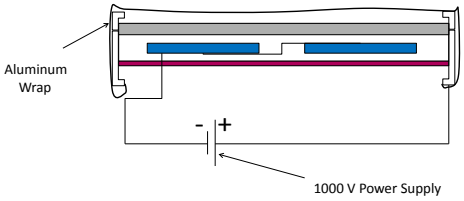
Product Concept:

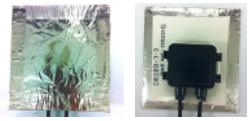
A thin ionomer film between glass and cells, adjacent to front EVA encapsulant

2. PID Method & Criteria

PID:	> 95% Power Retention
Voltage:	- 1000V
Temp/RH:	60 °C / 85%RH
Time:	96h - 500h
Glass Surface:	no treatment, Al **foil**
Solar Cell:	Mono c-Si, not optimized for PID resistance

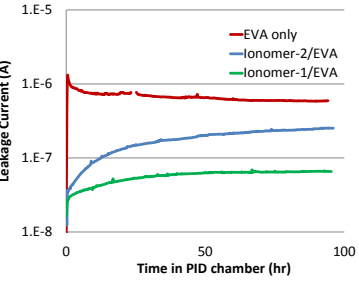
- Foil accelerates PID
- Provides reproducible results





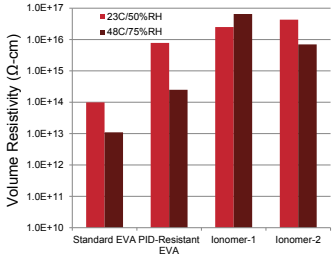
3. Why Use Ionomer?

Low Current Leakage



Higher Leakage Current contributes to PID. The leakage current of EVA is approx. 10x higher than that of Ionomer-1 combined with EVA.

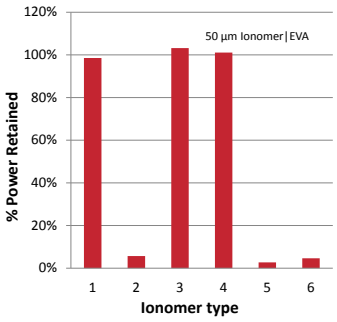
High Volume Resistivity

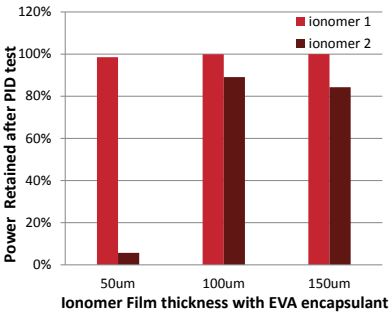


The volume resistivity of ionomer remains high while that of EVA drops 1-2 orders of magnitude with a temperature increase of 25° C.

4. Experimental Results

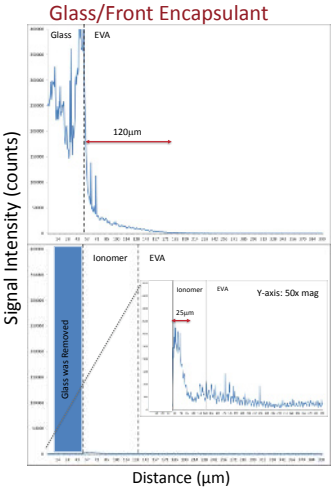
Ionomer selection and **film thickness** have a significant impact on PID and power retention. Optimization of these parameters is needed to provide a low cost solution.





Na Ion Migration Profile Measured Using LA-ICP-MS in Module

Glass/Front Encapsulant



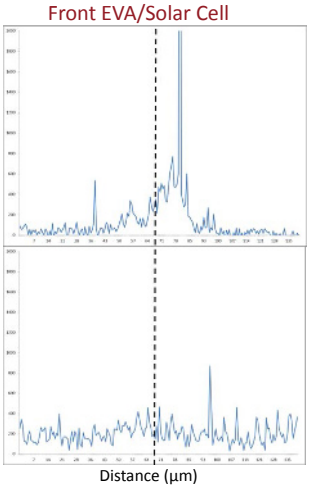
PID 96h test
G/Std EVA/cell

Sodium migration is much faster through the Standard EVA

PID 96h test
G/Ionomer/StdEVA/cell

Sodium migration is much slower through the 50µm ionomer

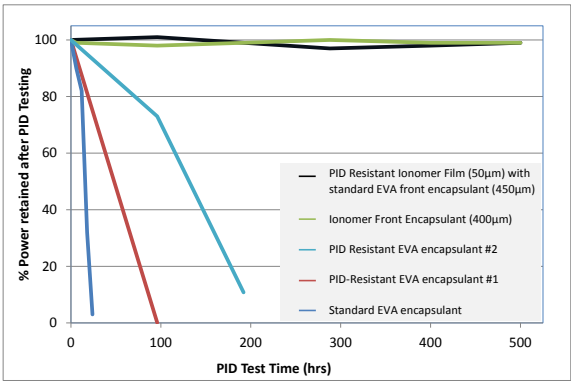
Front EVA/Solar Cell



Elemental mapping of the encapsulant following a simulated PID exposure was determined using Laser Ablation – Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). In this experiment, a laser beam is focused and scanned across the sample surface, generating fine solid particles from the top 5-20 µm of the sample surface. The particles are continuously introduced into a high temperature Argon plasma, which serves as a hard ionization source. The resulting singly charged elemental ions are analyzed by a mass spectrometer

5. Conclusions

50 µm Ionomer|450 µm EVA is **as effective as** single 400 µm Ionomer Encapsulant over 500h of testing.



Acknowledgements: Special thanks to John Jensen, John Kalinowski, Kurt Raughley, and Gail Raty for their contribution to this work.

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The Effect of Florida and Accelerated Weathering Exposures on Photovoltaic Backsheets

A. Lefebvre, G. O'Brien, L. Fang, G. Moeller

2014 NREL Module Reliability Workshop

February 25-26, 2014

ARKEMA
INNOVATIVE CHEMISTRY

This presentation contains no confidential information

Introduction

- **PV module's return on investment is directly related to the module's lifetime and performance.**

- **Photovoltaic power can only truly be considered "green" when modules can produce safe and reliable electricity for very long periods of time.**

- **Module makers should be able to select component materials of construction that have proven, long lasting performance.**

- **Current certification standards (UL and IEC) are focused on safety and short term output performance.**
  - IEC 61215 UV preconditioning test: Preconditions modules – but does not measure durability. Total UV exposure (15 kWh/m2 280-385 nm) is less than 3 months direct exposure in Miami, FL.
  - A weathering durability test is needed for UL and IEC standards

- **Long PV module lifetimes are supported by incorporating materials with proven, long term weatherability into the module.**

KYNAR® BY ARKEMA

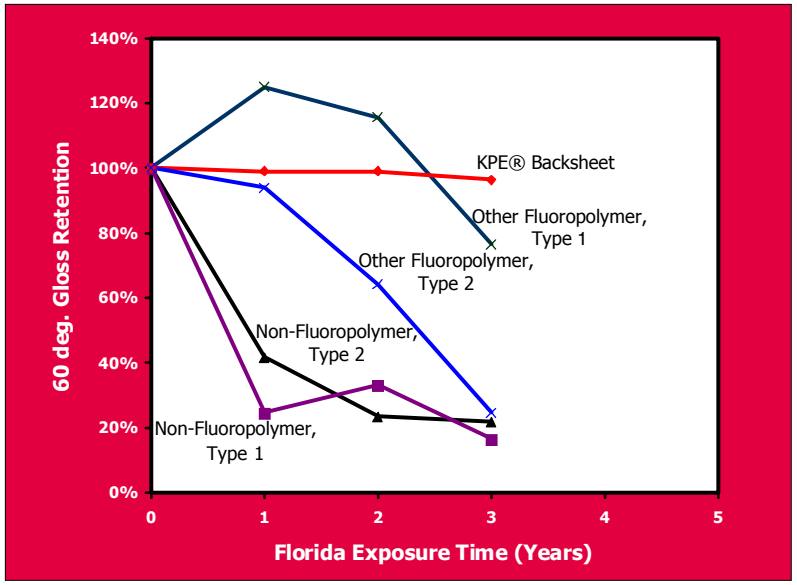
Weathering Study Details

- **Arkema initiated a study to examine effects of FL outdoor exposure on backsheets.**
  - Photo-degradation monitored by gloss retention, optical and SEM microscopy, chalking evaluation, and FTIR spectroscopy.
  - Compare results with accelerated weathering using QUV A.
- **Florida Outdoor Testing Conditions:**
  - Samples located in Miami, FL.
  - Samples oriented south facing at 45 degree angle facing the sun.
- **QUV A - Accelerated Testing Conditions:**
  - Irradiance of 1.55 at 340 nm, 8 hrs light at 60°C and 4 hrs dark at 50°C with condensation
    - (ASTM G154 Cycle 6).
  - UV irradiance 295 – 385 nm = 85 W/m2 or 4.91 MJ/m2 in 24 hrs.
  - Backsheets are facing the lamp.
  - 1300 hrs exposure has equivalent UV radiation to 12 months direct exposure in Florida.
  - In the Field - Backsheet exposure is a percentage of direct exposure (25% - 10%) .
- **Backsheet Materials Tested:**
  - KPE® Backsheet – Kynar® Film/ PET /EVA backsheet
  - Other fluoropolymer film based backsheet
  - Non-fluoropolymer based backsheets

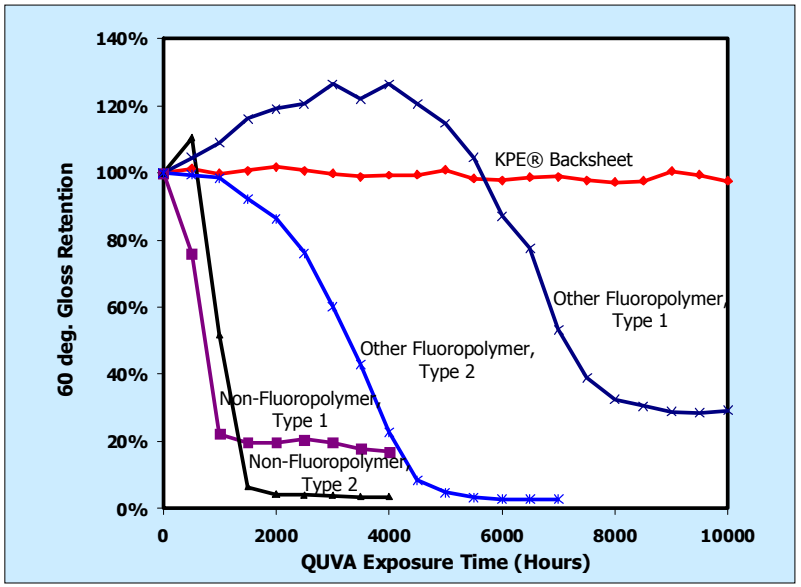
KYNAR® BY ARKEMA

Surface Degradation of Backsheets

Florida Exposure



QUV A Exposure

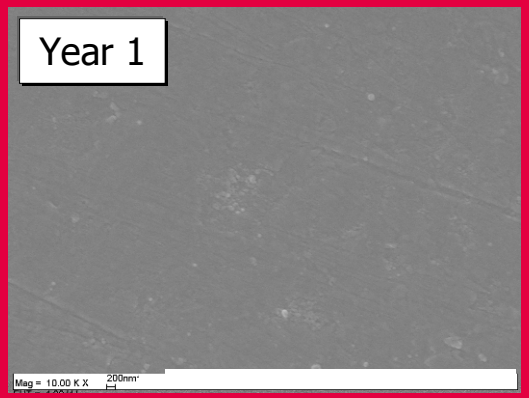


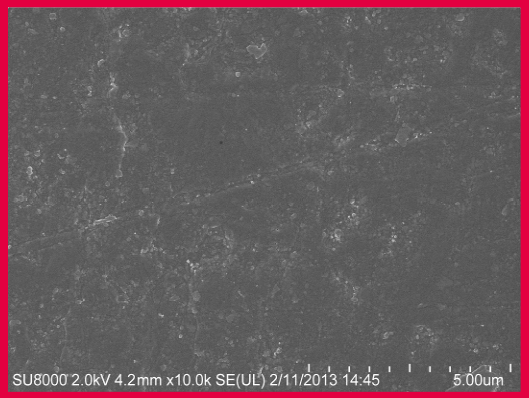
- 1300 hrs. QUV A exposure has equivalent UV radiation to 1 year direct exposure in FL.
- The decreasing gloss retention trends observed in realtime Florida exposure are the same as observed after QUV A accelerated weathering exposure just at slower rates due to the decreased amount of UV radiation.
- We expect Florida exposure results to continue following the trend seen in accelerated QUV A results.

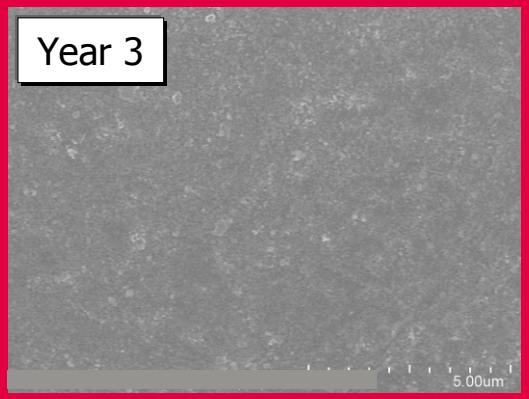
KYNAR® BY ARKEMA

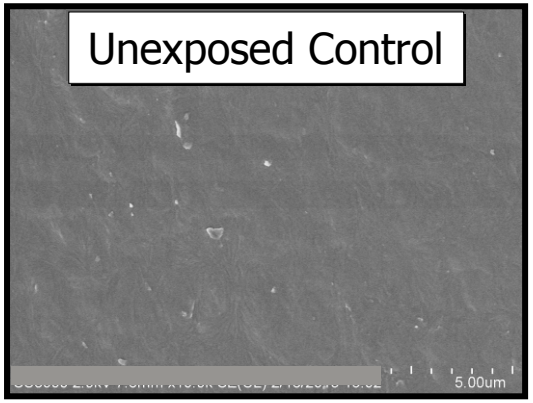
SEM Images of KPE® Backsheet

Florida Exposure









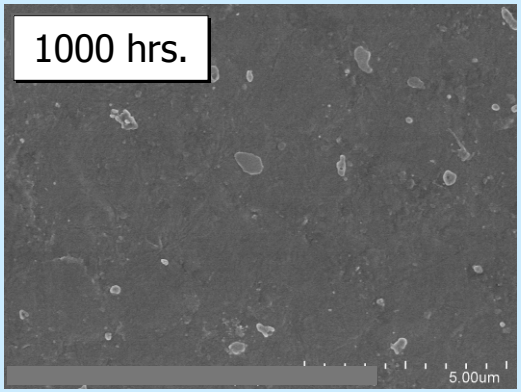
Florida Exposure:

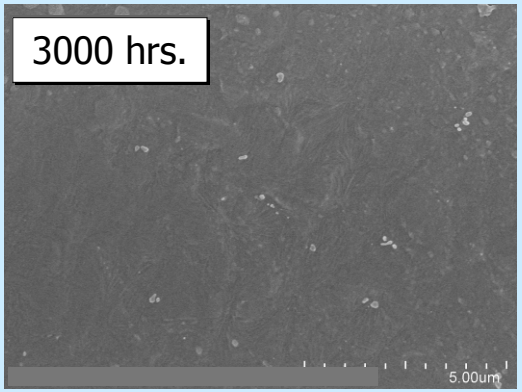
- Year 1, no degradation or cracking of backsheet occurring.
- Year 2, no degradation or cracking of backsheet occurring.
- Year 3, still no degradation or cracking of backsheet occurring.

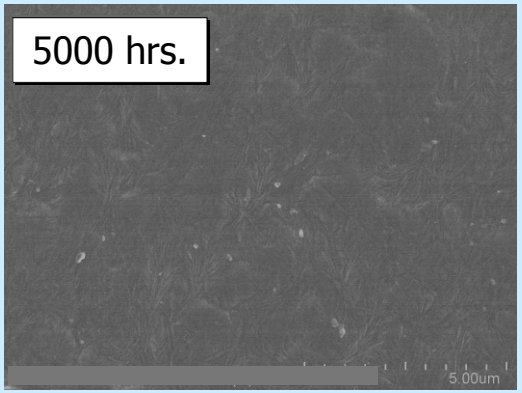
QUV A Exposure:

- 1000 hrs, no degradation or cracking of backsheet occurring.
- 3000 hrs, no degradation or cracking of backsheet occurring.
- 5000 hrs, still no degradation or cracking of backsheet occurring.

QUV A Exposure

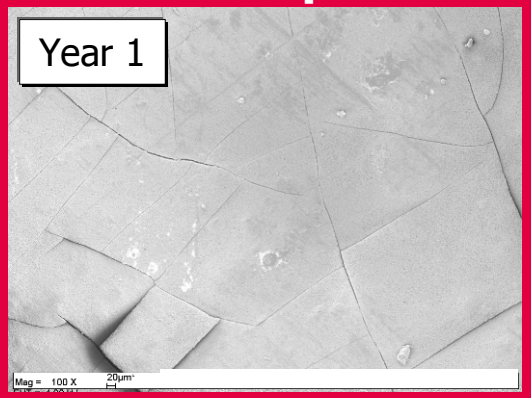


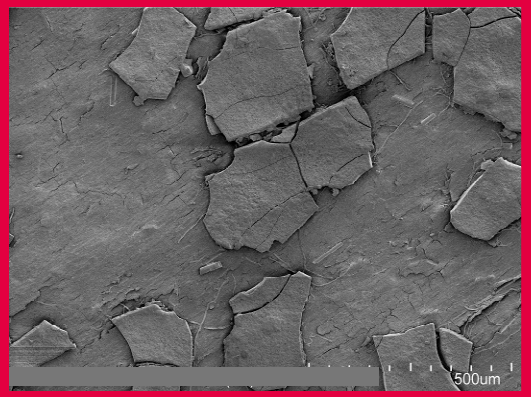


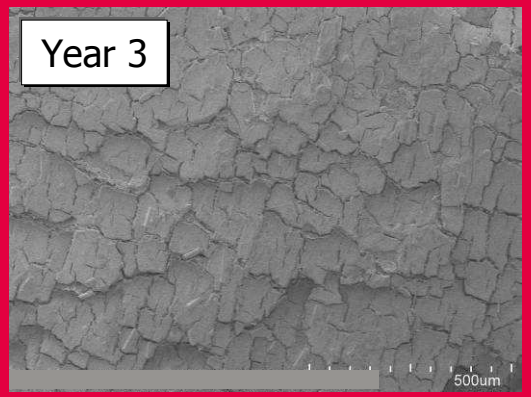


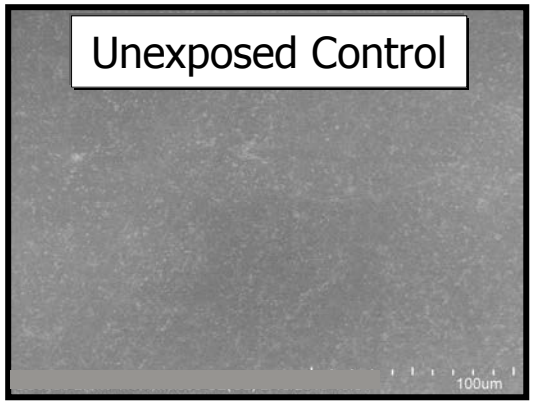
SEM Images of Non-Fluoropolymer Backsheet, Type 1

Florida Exposure









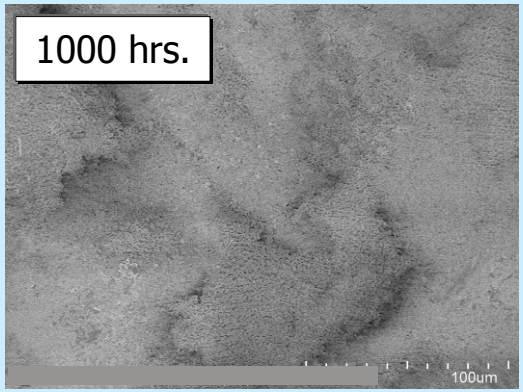
Florida Exposure:

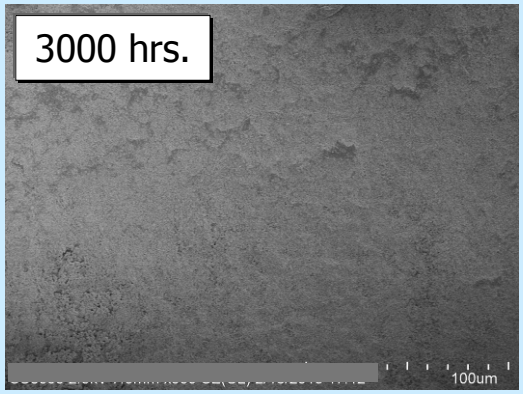
- Year 1, top layer of backsheet is cracking.
- Year 2, outer layer of backsheet is falling off and middle layer is beginning to crack.
- Year 3, middle layer is cracking.

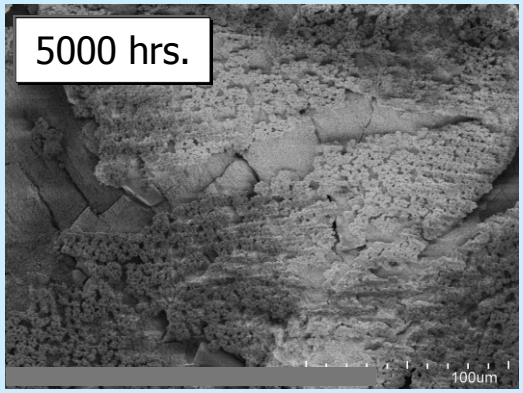
QUV A Exposure:

- 1000 hrs, polymer matrix is degrading leaving pigment particles on the surface.
- 3000 hrs, pigment particles cover the surface.
- 5000 hrs, some of the pigment particles have fallen off the surface revealing that the backsheet is cracking.

QUV A Exposure

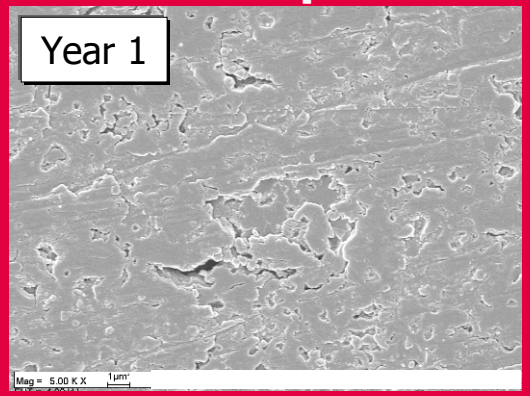


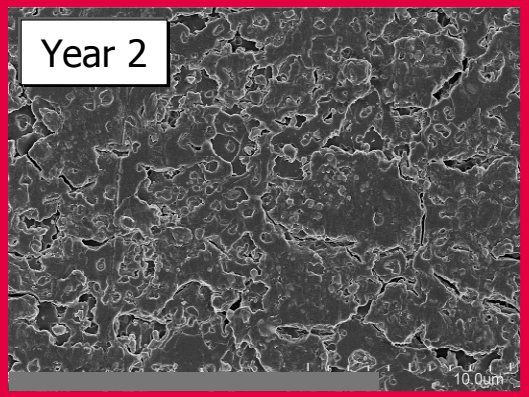


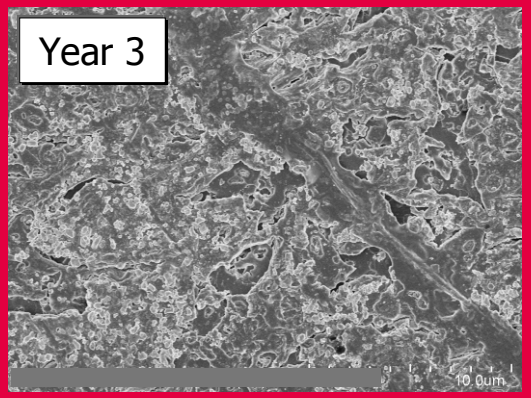


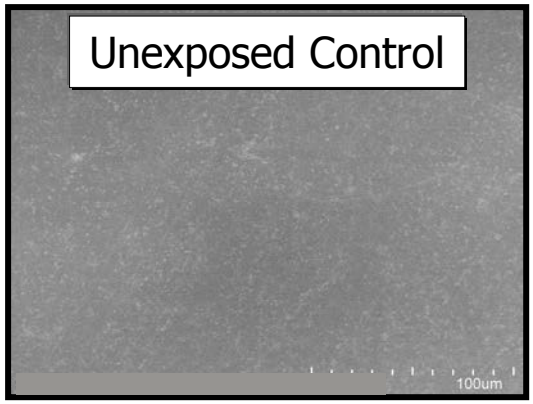
SEM Images of Non-Fluoropolymer Backsheet, Type 2

Florida Exposure









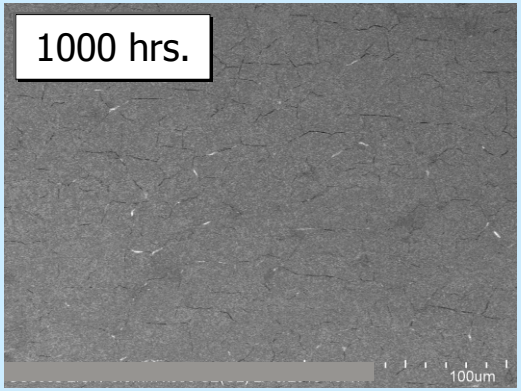
Florida Exposure:

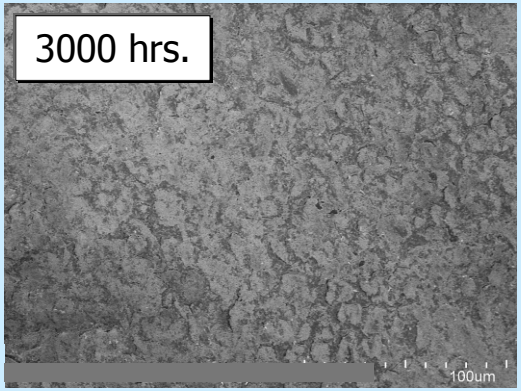
- Year 1, small cracks are appearing and polymer matrix is degrading.
- Year 2, more cracks are forming as the backsheet continues to degrade.
- Year 3, degradation of the polymer matrix is continuing.

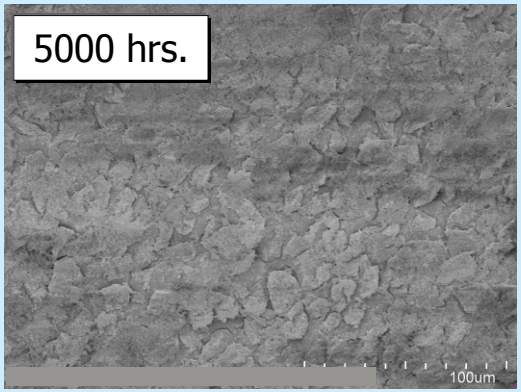
QUV A Exposure:

- 1000 hrs, backsheet is beginning to crack; polymer matrix is degrading.
- 3000 hrs, polymer degradation has progressed - pigment particles cover the surface.
- 5000 hrs, pigment particles have fallen off the surface revealing that the backsheet is cracking.

QUV A Exposure

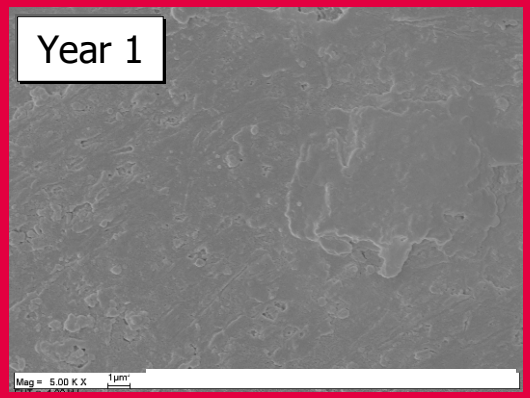


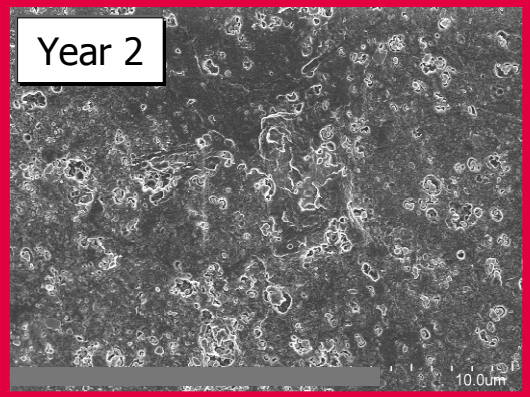


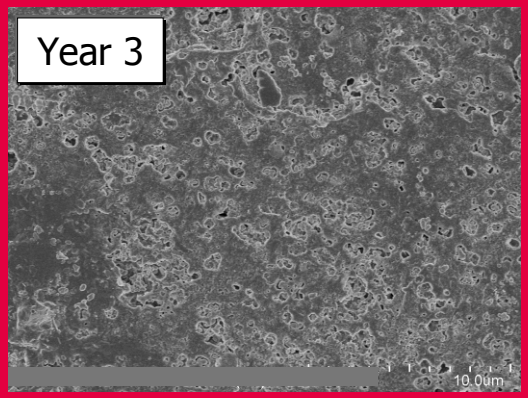


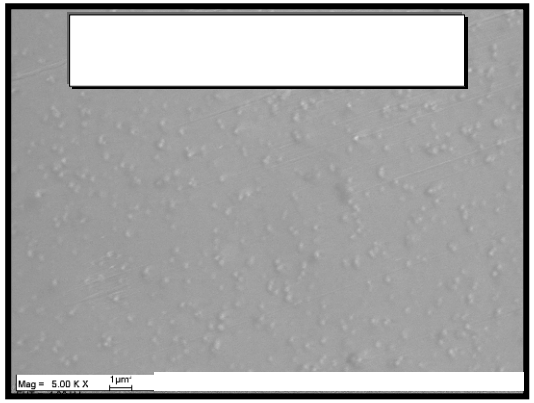
SEM Images of Other Fluoropolymer Film Backsheet, Type 1

Florida Exposure





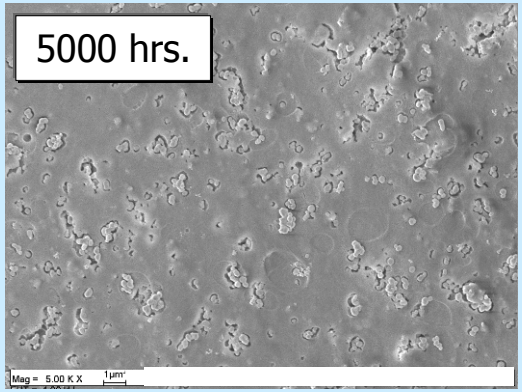




Florida Exposure:

- Year 1, little to no degradation is occurring.
- Year 2, degradation of the polymer matrix is starting around the pigment particles.
- Year 3, degradation is continuing.

QUV A Exposure



QUV A Exposure:

- 5000 hrs, polymer matrix is beginning to degrade around the pigment particles.

Conclusions

- **Gloss retention in Florida exposure correlates well with gloss retention in accelerated QUV A testing.**
- **Similar backsheet degradation mechanisms (cracking and polymer degradation) are observed in Florida and QUV A exposures.**
- **Kynar® film protected backsheets show no signs of polymer degradation or cracking after 3 years of Florida exposure.**
- **Short term Florida and QUVA exposures show significant degradation of Non-Fluoropolymer based backsheets.**
  - Non-Fluoropolymer, Type 1 backsheet shows cracking after only 1 year FL exposure. After 3 years, cracking has progressed into the middle layer.
  - Accelerated QUV A testing of Non-Fluoropolymer, Type 1 shows cracks only after long exposure, but maybe masked by pigment accumulation.
  - Non-Fluoropolymer, Type 2 backsheet shows microcracks and surface erosion in only 1 year of FL exposure. After 3 years, surface erosion is becoming more significant.
  - Accelerated QUVA testing of Non-Fluoropolymer, Type 2 shows larger cracks vs. Florida exposure after 1000 hrs.
  - Both Non-Fluoropolymer backsheets show rapid gloss loss.
- **Other Fluoropolymer Film based backsheets lose gloss with Florida and QUV A exposure.**
  - After 2 years of Florida exposure, the polymer matrix of Other Fluoropolymer, Type 1 backsheet is starting to degrade.

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Accelerated Weathering Test Improvements

- **Better UV Exposure test (than IEC) is needed to test products for durability over 25+ year product lifetime**
  - 5000 hrs QUV A at 1.55 Irrad. approximately equals 25 years in FL at 15% of direct irradiance.
- **Differences between weathering study exposures and use in PV modules**
  - In PV modules, backsheets have more thermal cycle/shock and mechanical stress because of laminated structure and heat build.
  - QUV has no thermal cycle/shock.
  - Florida backsheet exposure lacks applied stress.
- **Concern:**
  - Current backsheet study shows crack development in both Florida and QUV A exposures.
  - Lack of thermal cycle and mechanical stress limits the ability to test propensity for crack propagation.
- **Proposal for Improvement in Accelerated Testing**
  - Add thermal shock/cycle to testing protocol by using multiple water spray – light cycles.
    - Goal is to add many thermal cycles and stress to accelerate this phenomena.

A framework for characterization and prediction of the edge seal performance in PV module. - Kedar H., Dan V. , Ajay S., Todd K.

Introduction

- Degradation in performance of PV modules due to moisture ingress is a concern.
- Typical testing/prediction hinges on convolution of moisture barrier performance of edge seal and device degradation for a particular architecture.
- Testing method for edge seal performance independent of particular solar cell architecture is desired.
- Relatively cheap test method is developed
- Theoretical framework is developed to analyze data from accelerated tests.
- Theoretical framework enables prediction of edge seal performance in the field from analysis of test data.

Theory: Proposing Appropriate Functional Forms

- Objective: Obtain functional form for breakthrough time using rigorous analysis.
- Analytical solution of 1-D diffusion equation can be used in absence of desiccants.
- Presence of desiccants delays moisture penetration further

Analytical solution to 1D diffusion equation (No desiccant)

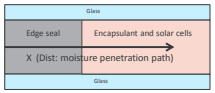
$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \Rightarrow C(x,t) = C_0\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right]$$

$$t_f = Ax^2;\ A \propto \frac{1}{D\left[erf^{-1}\left(1-\frac{C^*}{C_0}\right)\right]^2} \approx \frac{1}{D}\left(\alpha_i + \beta_i \frac{C^*}{C_0}\right)$$

C*: Detection threshold
C_0 – Edge concentration

Functional form in presence of desiccants

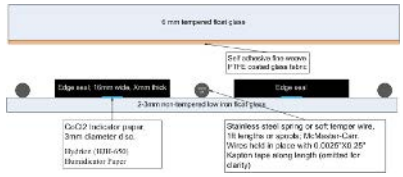
$$t_f = Ax^2 + Bx;$$
$$A = \left(\alpha + \frac{\beta}{C_0}\right)\exp\left(\frac{\gamma}{T}\right);\quad B = \frac{q}{C_0}$$



Schematic: Edge of Glass-Glass PV Module

Designing Sample for Fast Data Acquisition

- Objective is to develop a test method to characterize performance of edge seal in its end product form
- Sample type-I provides a short path for moisture penetration reducing test time for initial data by an order of magnitude

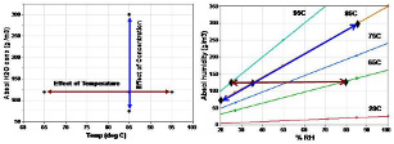


Simulated Module Construction

- Sample type II is representative of module construction

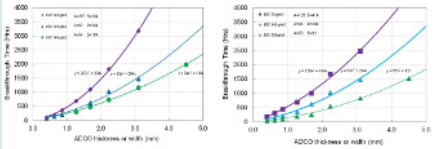
Testing in Environmental Chambers

- Tests carried out in standard temperature-humidity controlled chambers
- Color change of indicator paper was monitored
- Data taken every 24 hrs initially and frequency adjusted later based on estimated breakthrough time (Resolution +/- 12hrs)



Results - I

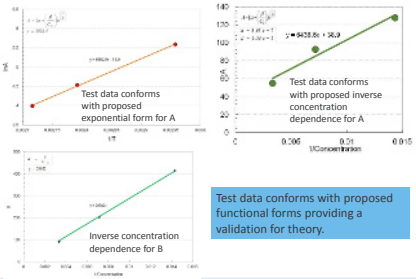
- Test results fit the proposed functional form thereby validating the theoretical framework.
- Extract parameters 'A' and 'B' for different test conditions



Varying temperature at fixed concentration

Varying concentration at fixed temperature

Results- II



Test data conforms with proposed functional forms providing a validation for theory.

Theoretical Framework for Prediction

- Variation in ambient conditions amounts to
  - Variation in edge concentration $C_0(t)$
  - Variation in diffusivity D(T)~ D(t)
- Use effective diffusivity
- External variations decay within ~1mm

Addressing Variation of Diffusivity

$$\frac{\partial C}{\partial t} = D(t)\frac{\partial^2 C}{\partial x^2} \Rightarrow$$

$$C(x,t) = C_0\left[1 - erf\left(\frac{x}{2\sqrt{D_{eff}t}}\right)\right]$$

$$D_{eff} = \frac{1}{t}\int_0^t D(t)dt$$

Addressing varying edge concentration

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2};\ C(0,t) = C_0 \sin \omega t;\ C(x \to \infty, t) = 0 \Rightarrow$$

$$C(x,t) = C_0 \exp\left(-x\sqrt{\frac{\omega}{2D}}\right)\sin\left[\omega t - x\sqrt{\frac{\omega}{2D}}\right] \Rightarrow l_{decay} \propto \sqrt{\frac{2D}{\omega}}$$

Use of effective diffusivity and averaging enables mapping test results to field conditions

Method for predicting field performance

- Obtain breakthrough time for various conditions using test technique developed
- Determine fit parameters using functional forms suggested by theory.
- Determine average absolute humidity for a given location using TMY data.
- Determine equivalent temperature T_{eq} using TMY data

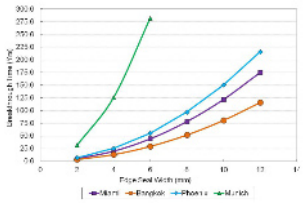
$$\exp\left(-\frac{\gamma}{T_{eq}}\right) = \frac{1}{t_{1yr}}\int_0^{t_{1yr}} \exp\left(-\frac{\gamma}{T(t)}\right)dt$$

- Calculate constants 'A' and 'B' for field conditions at T_{eq}.
- Substitute and obtain time for moisture breakthrough

$$t_f = Ax^2 + Bx$$

Estimated moisture ingress time in the field

- Analysis suggests that in the particular case of the edge seal tested on certain MiaSole glass-glass modules, moisture ingress can be prevented well beyond the intended service life



Conclusions

- A relatively cheap test technique was developed to test moisture barrier performance of the edge seal in a manner decoupled from other components of PV module.
- A theoretical framework was developed to analyze test data from accelerated tests and predict field performance of the edge seal.
- Theoretical model was validated by experimental results.
- In particular case of the edge seal tested on certain MiaSole glass-glass modules it is predicted that moisture ingress can be prevented well beyond the intended service life.

Corresponding Author
Kedar Hardikar, Ph.D.
E-mail: khardikar@miasole.com
Tel: 408-919-5702

Polymeric Materials Group

Evaluation of oxygen and wavelength effects on photo-degradation of Ethyl Vinyl Acetate encapsulant

Stéphane OGIER, Chiao-Chi LIN, Kar Tean TAN, and Xiaohong GU
National Institute of Standards and Technology, Gaithersburg, MD 20878, USA

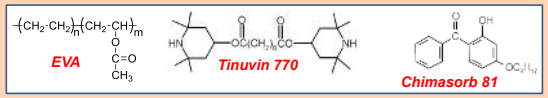
Introduction

One main challenge for solar cells and all components in a photovoltaic (PV) module is their durability and reliability to weathering. Prior efforts to understand the degradation of ethylene vinyl acetate (EVA) due to ultraviolet (UV) radiation, temperature and moisture have made significant progress. However, a comprehensive framework to describe the effect of oxygen on EVA degradation mechanisms has remained vague. This information is particularly important because in real life applications, due to the laminated structure of the modules, the oxygen diffusion to encapsulant layers in the central part of the panels tends to be more restricted compared to the diffusion to those near the edge. At the early stage of the field exposure, from the center to the edge, the environment of EVA layers changes from "anaerobic-like" to "aerobic-like". The objective of this study is to unravel the underlying degradation mechanisms of EVA in both air and argon conditions in the presence of UV radiation. Furthermore, the effect of wavelength on the EVA degradation in both conditions was studied.

Experimental

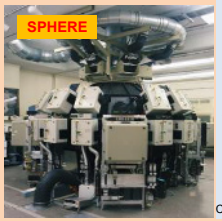
Sample preparation

Materials:
EVA: Evatane®(~32% of VA by mass)
Crosslinker(peroxide): **Luperox TBEC®**
UV absorber/Hindered Amine: Chimasorb 81/Tinuvin 770



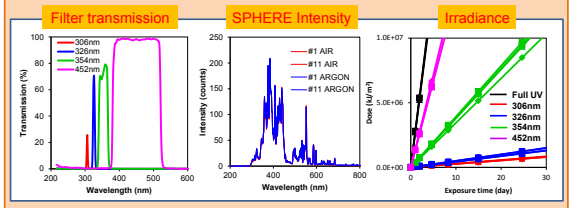
The specimens were prepared by spin casting the EVA solution in CaF_2 substrates and then cured in a vacuum oven at 160°C for 10 min.

Exposure conditions



Temperature : 55°C
Relative Humidity (RH) : 0%
Atmosphere : aerobic (with air)
anaerobic (with argon)
Accelerated UV exposure:
NIST SPHERE *(Simulated Photodegradation via High Energy Radiant Exposure)*
→ 4 ranges of wavelengths (band-pass filters) 306nm, 326nm, 354nm and 452nm

Chin et al., *Rev. Sci. Instrum. (2004)*, 75, 4951



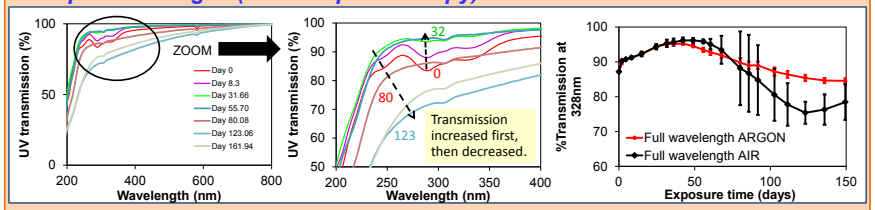
Measurements

Ultraviolet/Visible (UV-vis) spectroscopy: optical degradation
Fourier transform infrared (FTIR) spectroscopy: chemical degradation
Atomic Force Microscopy (AFM): morphological changes

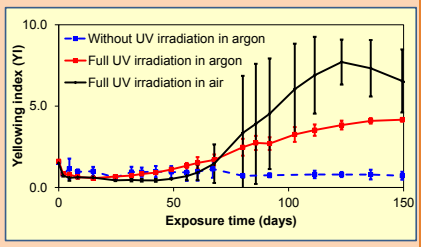
Results and Discussion

Effect of Oxygen on EVA Degradation

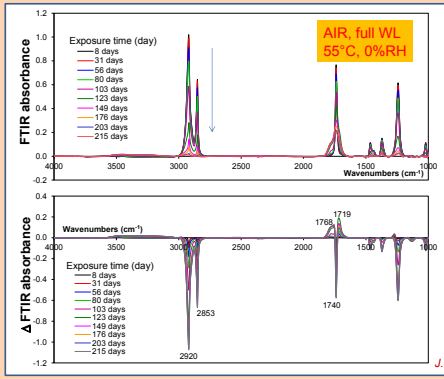
Optical Changes (UV-vis Spectroscopy)



- The transmittance of EVA specimens increased first then decreased with longer exposure. This change is due to the competition between the loss of UV-absorbers and the formation of chromophoric degradation products.
- Initially, the change in transmittance was similar in argon and air. In later stages of exposure, the loss of transmission in argon was much slower than that in air.
- Photodegradation of EVA in oxygen environment caused more yellowing than that in argon, which was consistent with the chemical changes by FTIR (below).
- Specimens exposed in the same condition without UV radiation showed little yellowing, indicating UV is a key factor for yellowing.

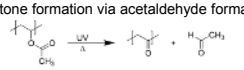


Chemical Changes (FTIR Spectroscopy)

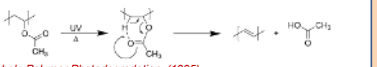


Wavenumber (cm⁻¹)	Group	Assigned vibrational mode
1240	-CO-O-C-	-C-O- stretching
1741	-CO-O-C-	-C=O stretching
1365	$-CH_3$	-C-H symmetric bending
1471	$-CH_2-$	-C-H scissoring
2853	$-CH_2-$ or $-CH_3$	-C-H symmetric stretching
2920	$-CH_2-$	-C-H asymmetric stretching
1719	ketone	-C=O stretching
1768	lactone	-C=O stretching
3465	-OH	-OH stretching

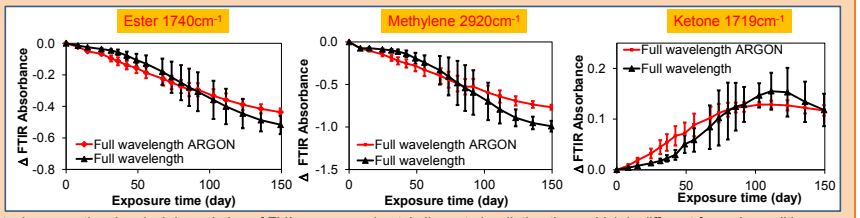
Ketone formation via acetaldehyde formation (Norrish I):



Deacetylation of EVA (Norrish II):



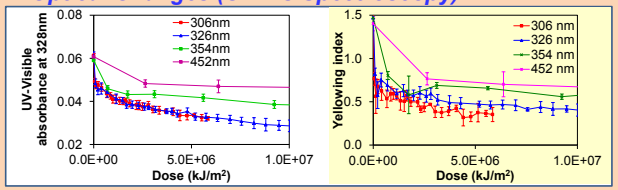
J.F. Rabek, Polymer Photodegradation, (1995)



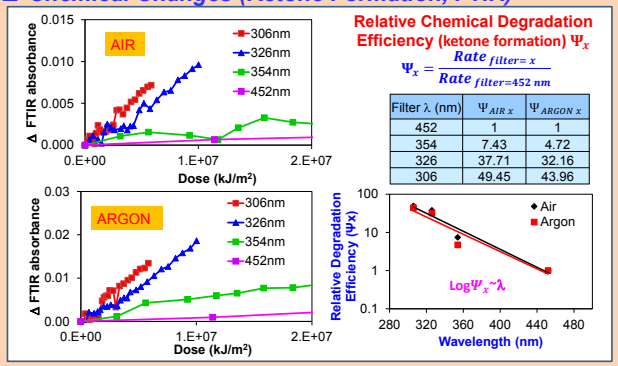
- In argon, the chemical degradation of EVA was approximately linear to irradiation time, which is different from air condition .
- The chemical degradation was inhibited at the early stage in air, then markedly increased and surpassed that in argon. The effect of oxygen on the chemical change of EVA showed similar trend as that on the yellowing.

Effect of Wavelengths on EVA Degradation

Optical Changes (UV-vis Spectroscopy)



Chemical Changes (Ketone Formation, FTIR)



Relative Chemical Degradation Efficiency (ketone formation) Ψ_x

$$\Psi_x = \frac{Rate_{filter=x}}{Rate_{filter=452\,nm}}$$

Filter λ (nm)	$\Psi_{AIR\,x}$	$\Psi_{ARGON\,x}$
452	1	1
354	7.43	4.72
326	37.71	32.16
306	49.45	43.96

Microstructural Changes (AFM Phase Imaging)

Phase imaging of EVA before and after UV exposure

Conditions:
UV, 55°C, 0%RH

- The semi-crystalline structures of EVA became amorphous after 215 days of UV exposure at full wavelength, but smaller changes were observed with a 452nm filter.

Summary

- Effect of oxygen on chemical and optical changes of EVA was observed during UV exposure. The degradation of EVA at early stages appeared to be inhibited in comparison to those in the argon. However, after prolonged exposure, the rates of EVA degradation in oxygen substantially increased and surpassed those under the anaerobic counterpart..
- The depletion of UV absorber/hindered amine was observed during UV exposure of EVA. Dramatical degradation of EVA took place after substantial loss of UVA, especially in the oxygen environment.
- The shorter the UV wavelength, the faster is the degradation for EVA in both aerobic and anaerobic conditions.

The impacts of the encapsulation quality of Photovoltaic modules on their long-term reliability

Heng-Yu Li[1], Yun Luo[2#], Christophe Ballif[1], Laure-Emmanuelle Perret-Aebi[3]

[1] École Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), Photovoltaics and Thin Film Electronics Laboratory, Rue de la Maladière 71b, 2000 Neuchâtel, Switzerland

[2] MEYER BURGER AG, Schorenstrasse 39,CH-3645 Gwatt (Thun), Switzerland

[3] CSEM, PV-center, Jaquet-Droz 1, 2000 Neuchâtel, Switzerland

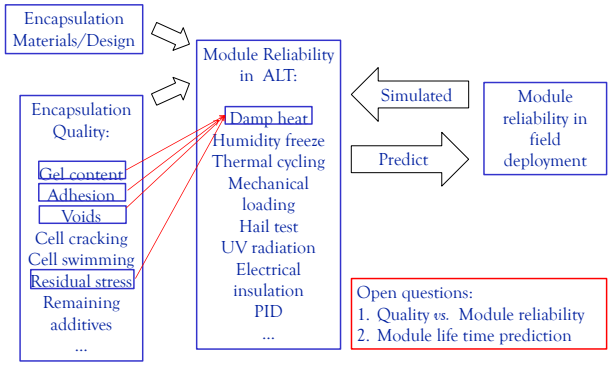
[#]Now: with PlusMat AG, Höheweg 55, 3054 Schüpfen, Switzerland.

Email: Hengyu.Li@epfl.ch

Motivations and goals

- **Currently, there exists a missing link between the encapsulation quality and the reliability of PV modules.**
- **This work aims at studying the effects of several encapsulation quality factors on the reliability of PV modules in DH test.**

Target of the work

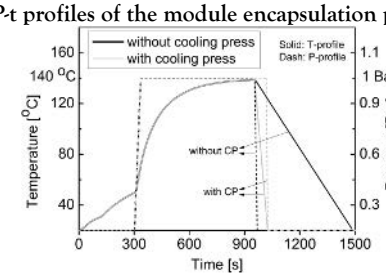


Li, H.-Y., et al. Submitted (2014)

- Focusing on the missing link between EVA gel content/Voids/ Adhesion/Residual stress and the module reliability in DH.

Experimental setup

T-P-t profiles of the module encapsulation process

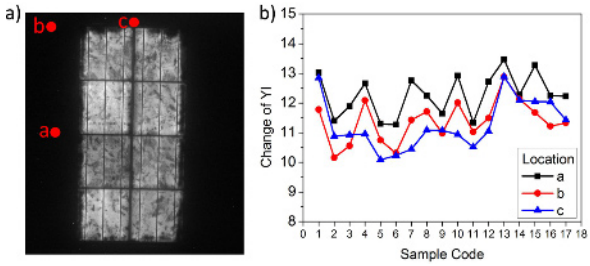


Li, H.-Y., et al. Prog. Photovolt: Res. Appl.. doi: 10.1002/pip.2409

- All g-bs modules were exposed to 3000h of 85/85 DH testing.
- Modules with and without Type-II voids.
- Modules with different EVA gel content.
- Modules with different glass/EVA adhesion and residual stress as a result of the cooling press.

General observation

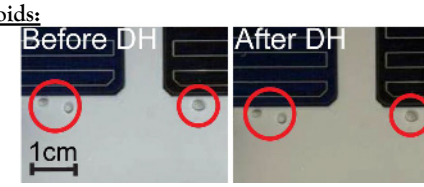
Typical hydrothermal degradation:



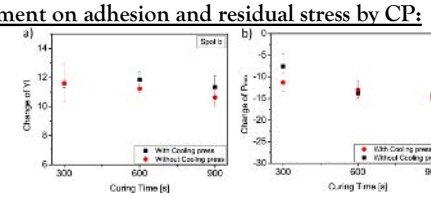
- Acetic acid production+moisture => corrosion;
- Discoloration competing with oxygen bleaching;
- Degradation of IV performance, with dropping I_{sc} and rising R_s.

Effects of Type-II voids and cooling press (CP)

Type-II voids:



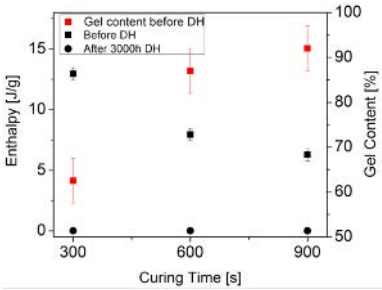
Improvement on adhesion and residual stress by CP:



- No effect of Type-II voids on module reliability in 3000h of DH;
- No effect of improvements by CP on module reliability in 3000h of DH.

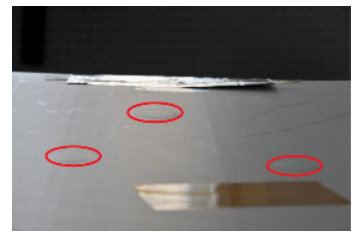
Effect of EVA gel content

On the gel content after DH:



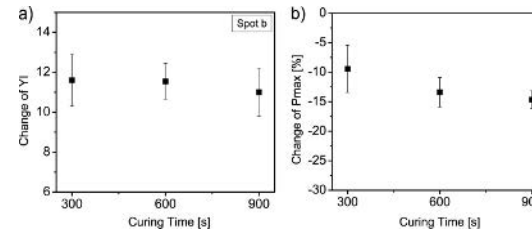
- Post curing due to degradation in EVA

On the Type-I voids:



- Type-I voids and EVA creeping appear only on module with low initial gel content.

On the EVA hydrothermal degradation:



- Too long curing time results in higher degradation rate of EVA and modules.

Summary

- This work studies the missing link between the module encapsulation quality and the module reliability in 3000h of DH test.
- The Type-II voids did not evolve and showed no impacts on the module reliability in 3000h of DH.
- Enhancements on adhesion and residual stress by cooling press showed no impacts on the module reliability in 3000h of DH.
- EVA gel content after encapsulation affects the module reliability in DH, mainly on the aspects of Type-I voids formation, EVA creeping, EVA hydrothemal degradation and degradation of the IV performance of modules.

Void Evolution during the Encapsulation Process of PV modules

Heng-Yu Li[1], Yun Luo[2#], Christophe Ballif[1], Laure-Emmanuelle Perret-Aebi[3]

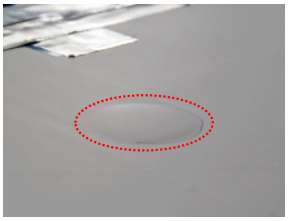
[1] École Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT),
Photovoltaics and Thin Film Electronics Laboratory, Rue de la Maladière 71b, 2000 Neuchâtel, Switzerland
[2] MEYER BURGER AG, Schorenstrasse 39,CH-3645 Gwatt (Thun), Switzerland
[3] CSEM, PV-center, Jaquet-Droz 1, 2000 Neuchâtel, Switzerland
[#]Now: with PlusMat AG, Höheweg 55, 3054 Schüpfen, Switzerland.
Email: Hengyu.Li@epfl.ch

Motivations and goals

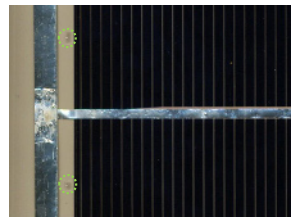
- **Voids formation is an important criteria for judging the encapsulation quality of PV modules.**
- **Deep understanding on the voids evolution is key to the development of voids-free encapsulation process of PV modules.**

Types of voids

Type-I voids



Type-II voids



H.-Y. Li et al., Void Evolution during the Encapsulation Process of Photovoltaic modules. Submitted (2014)

Characteristics
- Flat packet
- Mostly at module back

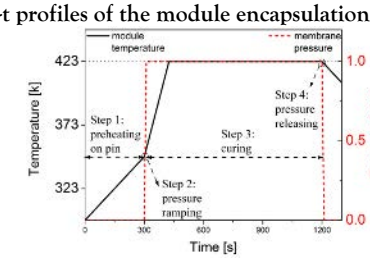
Possible origins
- Mechanically entrapped air due to insufficient evacuation
- Delamination
- Great amount of volatiles during encapsulation (e.g., from Al paste at cell back)

Characteristics
- Quasi-spherical
- Mostly embedded in encapuslant

Possible origins
- Residual solvent in EVA film;
- Volatile from soldering flux;
- Dehydration between silane primer and glass surface;
- Surface contaminations;
- EVA volumetric shrinking;
- **Pre-dissolved wet air**

Modeling approach

T-P-t profiles of the module encapsulation process



Diffusion-controlled voids evolution model

$$\beta = \frac{C_{resin} - C_{vs}}{\rho} \quad (1)^{[1]}$$

$$C_{vs} = 8.651 \times 10^{-14} e^{9784/T} \cdot P_{water}{}^{2} \quad (2)$$

$$\rho = (1 - X_{air}) \cdot \left(\frac{M_{water} \cdot P}{R \cdot T}\right) + X_{air} \cdot \left(\frac{M_{air} \cdot P}{R \cdot T}\right) \quad (3)$$

$$P_{water} = (1 - X_{air}) \cdot P \quad (4)$$

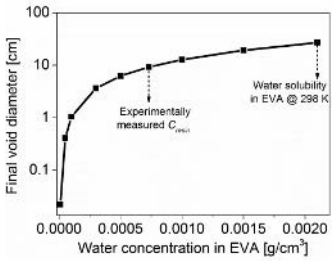
$$X_{air} = \left(\frac{P_0 \cdot T}{P \cdot T_0}\right) \cdot \left(\frac{a_0}{a}\right)^3 \quad (5)$$

$$a = 4\beta \cdot \sqrt{D \cdot t} \quad (6)$$

$$D = D_0 \cdot e^{\frac{-Ea}{R \cdot T}} \quad (7)^{[2]}$$

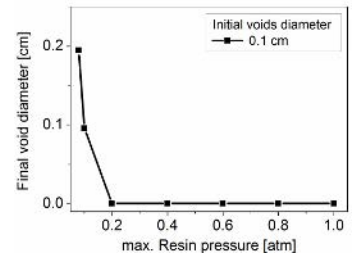
- When β<0, voids will shrink; when β>0, voids will grow;
- Parameters for modeling the voids growth are taken from the typical EVA encapsulation process in flat-bag vacuum-bag laminator.

Selected results: Step 1



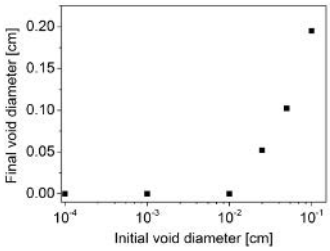
Parameters governing voids evolution
- Duration: moderately long is favored;
- Lower-chamber pressure: lower is favored;
- Water concentration in EVA: minor effect.

Selected results: Step 2



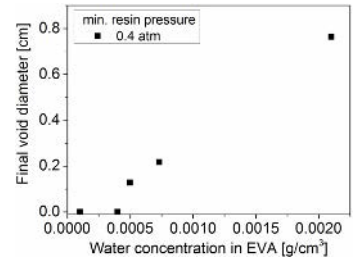
Parameters governing voids evolution
- Upper-chamber pressure: higher is favored;
- Water concentration in EVA: lower is favored.

Selected results: Step 3



Parameters governing voids evolution
- Initial voids size at start: smaller is favored;
- Water concentration in EVA: lower is favored.

Selected results: Step 4



Parameters governing voids evolution
- EVA gel content: higher is favored;
- Water concentration in EVA: lower is favored.
- EVA resin pressure: higher is favored

Summary

- Voids appearing in the PV modules after encapsulation are grouped into 2 types. Possible origins are analyzed.
- A diffusion-controlled model has been adapted to simulate the evolution of voids consisting of wet air in EVA.
- Governing parameters over voids evolution in EVA encapsulation process are analyzed and listed in the 'Results' section.
- Effect of Type-II voids on the PV module reliability in DH testing was studied and presented elsewhere.

[1] Kardos JL, et al. Adv Polym Sci 80 (1986): 102–123. [2] Kempe. MD. Energy Materials & Solar Cells 90 (2006): 2720–2738.

2014 NREL PVMRW

Encapsulant dependence of Ag-ion migration phenomenon during damp heat test with voltage bias

[1]Masaaki Odoi, Hirofumi Zenkoh

[2]Tsuyoshi Shioda

[1]Mitsui Chemicals Tohcello, Inc.
[2]Mitsui Chemicals, Inc.

Motivation &Conclusion

Mitsui Chemicals Group

Motivation

- ✓ Silver used as Photovoltaic cell paste is known as the metal most susceptible to migration and PV modules are often operated under high humidity conditions
- ✓ Encapsulant formulation effect on Silver ion electrochemical migration are investigated using comb-type printed circuit boards
- ✓ PID test was also done for these encapsulant

Conclusions

- ✓ Ion migration and dendrite was observed for some encapsulant formulation and strongly depend on included additives
- ✓ There were NO correlation between migration and PID test

Test encapsulant samples

Encapsulant			Volume Resistivity (Ω・cm)	PID	Ion migration
EVA	EVA – 1	Traditional EVA formulation	5×10^{14}	Poor	Good
	EVA – 2	Changing one additive from EVA-1	2×10^{15}	Good	Poor
	EVA - 3	Changing one additive from EVA-1	2×10^{15}	Good	Good

✓ **There were NO correlation between migration and PID test**

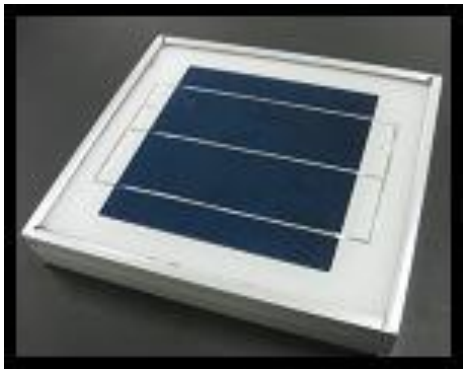
PID durability test

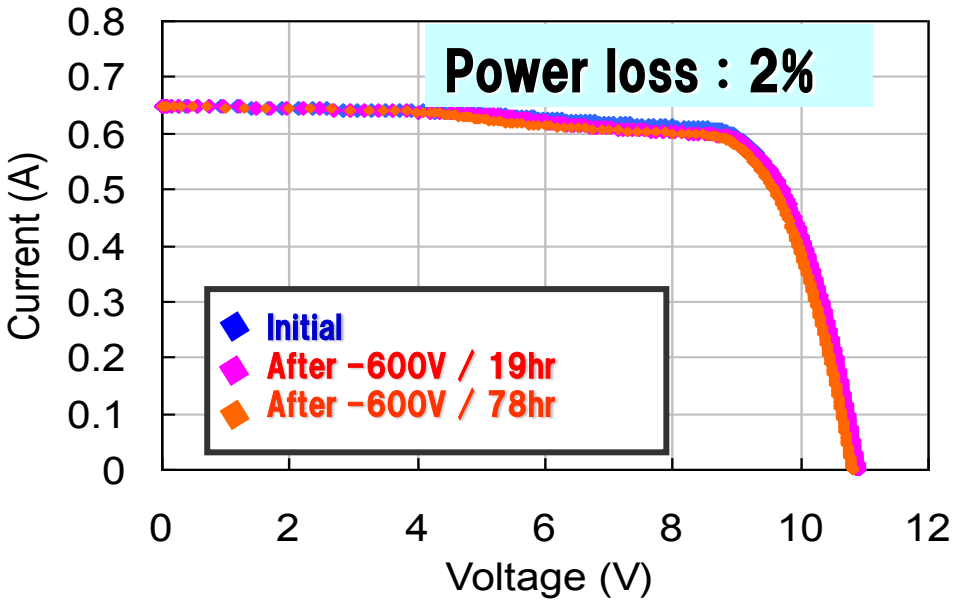
PID test condition

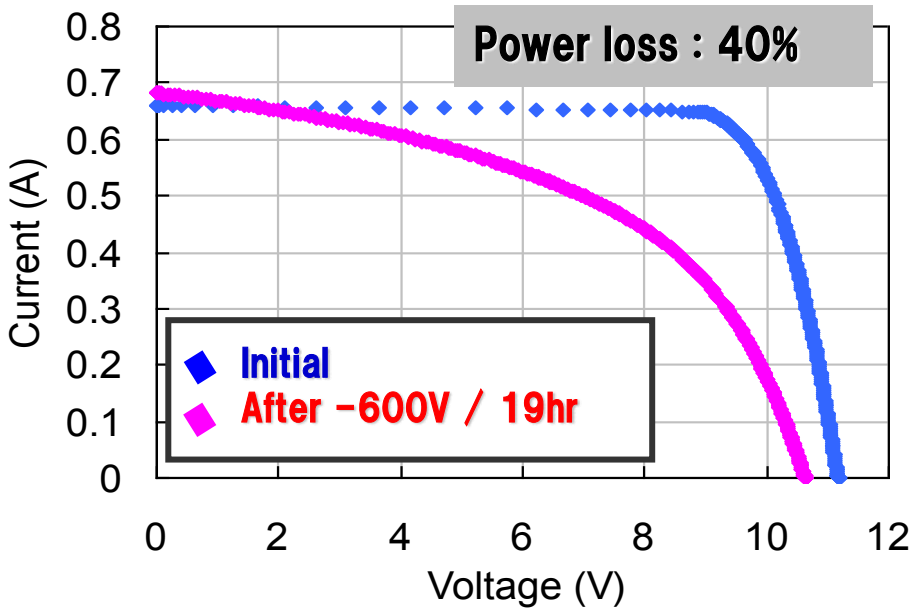
- 85°C85% -1000V
- Cell: 6inch multi-crystalline
- Module : 1 cell

Measurement of Pmax

- Irradiance : 1000W/m2



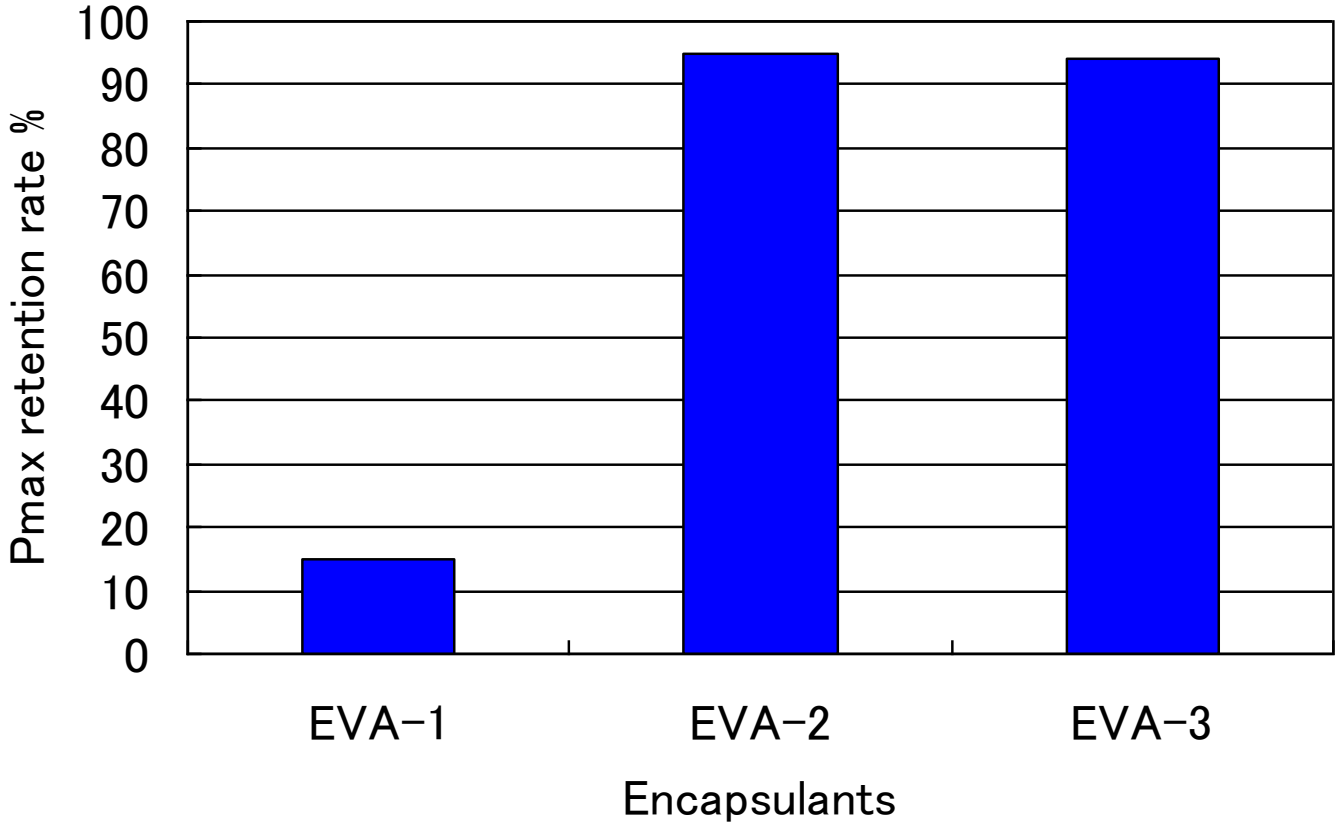




PID prone cell has been selected with EVA-1 encapsulant

PID test results

6inch 1cell mini module
85℃/85%RH, -1kV, 24hr



EVA-2 and EVA-3 shows better PID durability than EVA-1

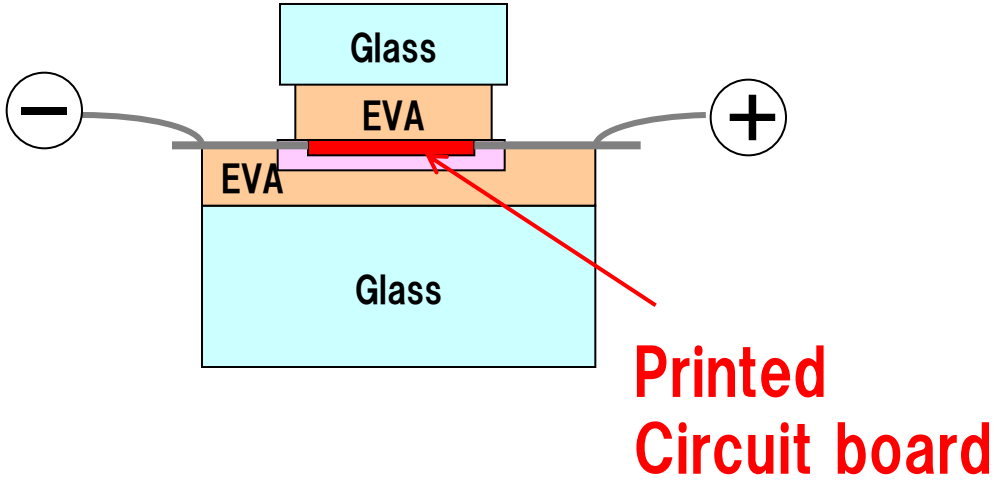
Ion migration test method

Mitsui Chemicals Group

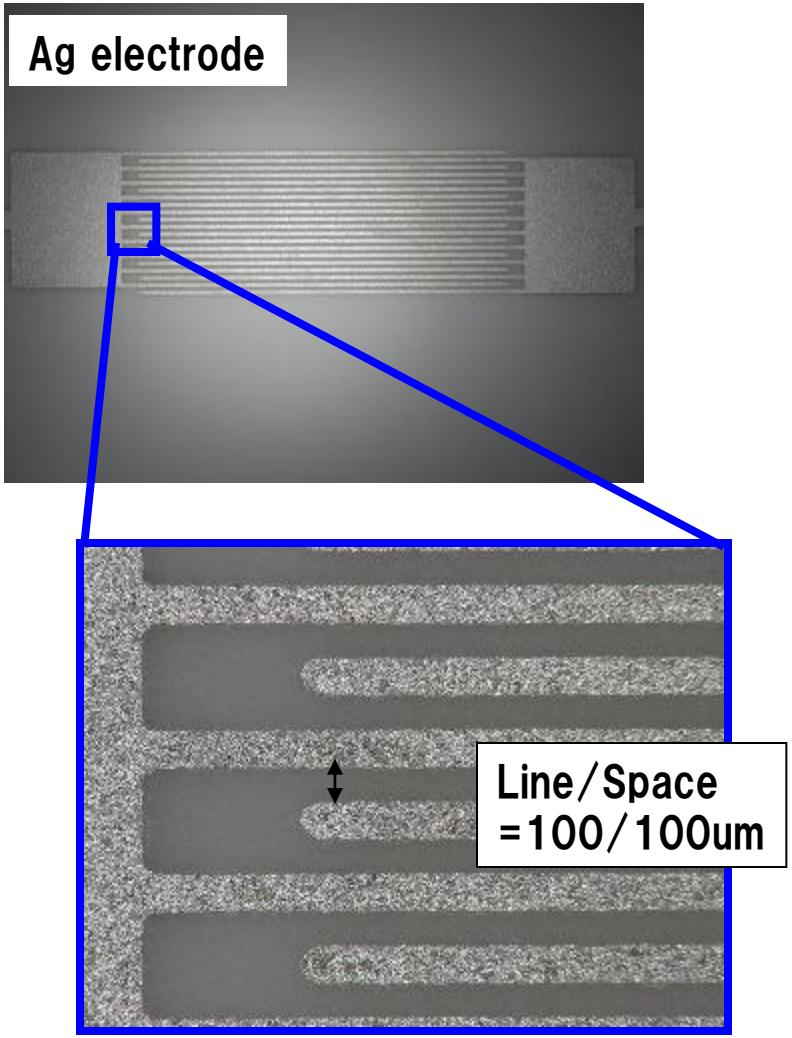
Test method

Electrode : Ag printed circuit board
Line/Space : 100um/100um
Bias: DC100V
Conditions: 85°C/85%RH

Sample structure



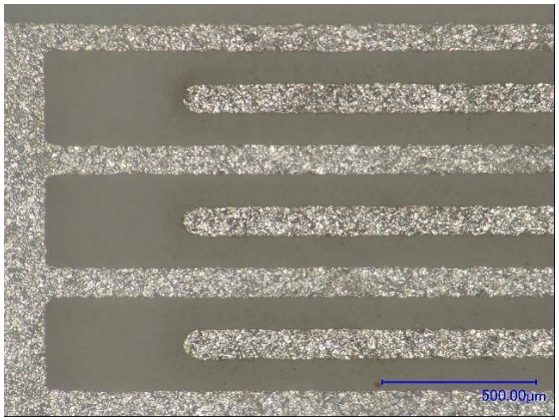
printed circuit board



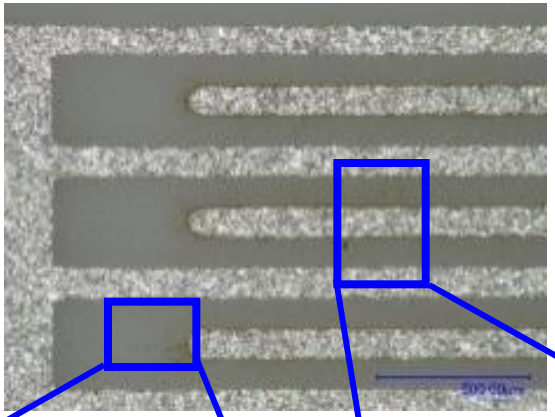
Ion migration test results (1)

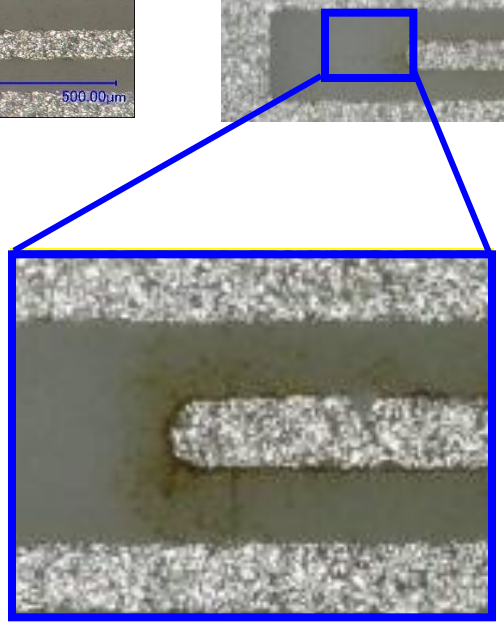
Mitsui Chemicals Group

EVA-1

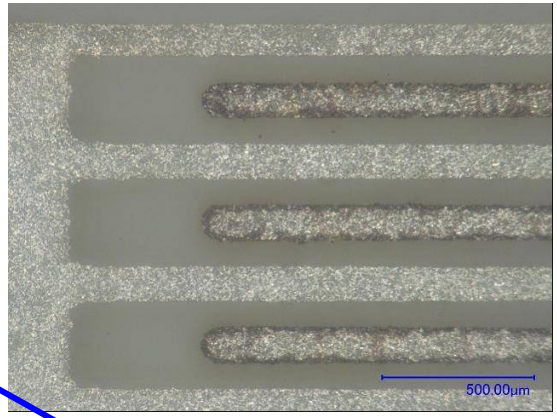


EVA-2





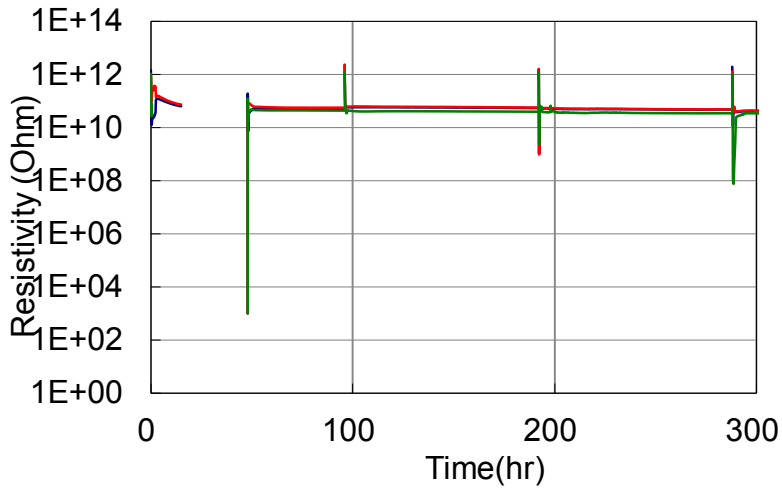
EVA-3



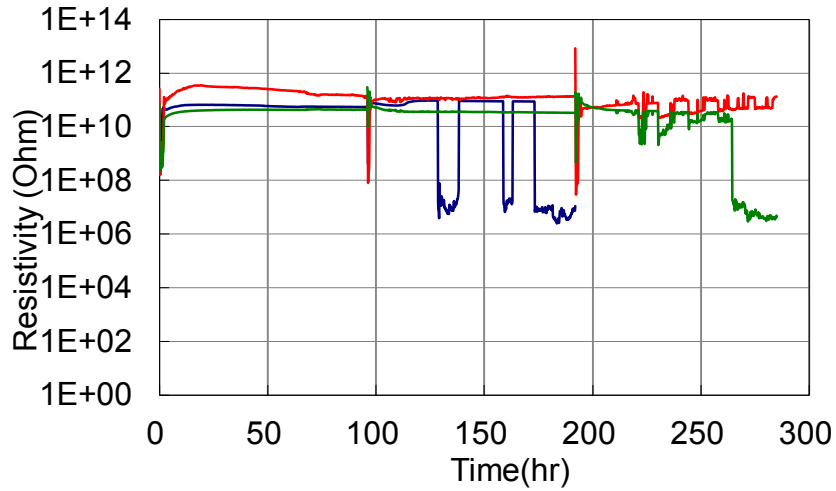
EVA-2 shows silver dendrite formation between electrodes

Ion migration test results (2)

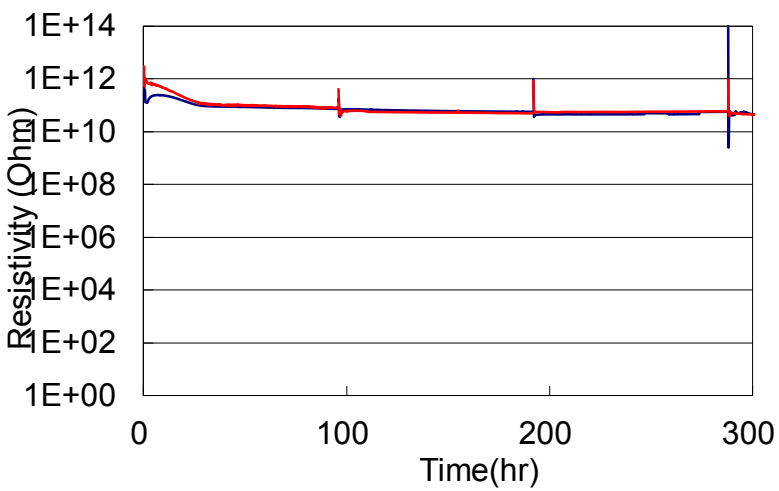
EVA-1



EVA-2



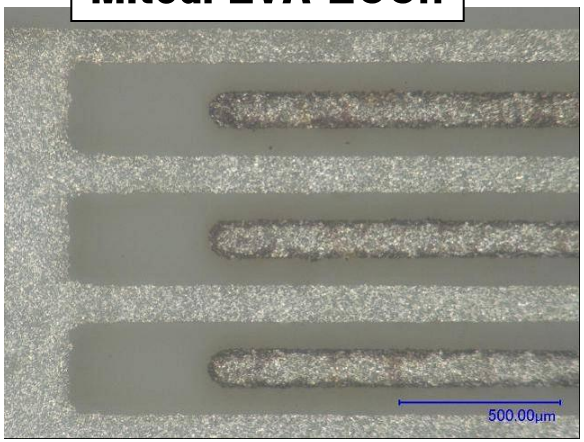
EVA-3



EVA-2 shows resistivity break down caused by silver dendrite

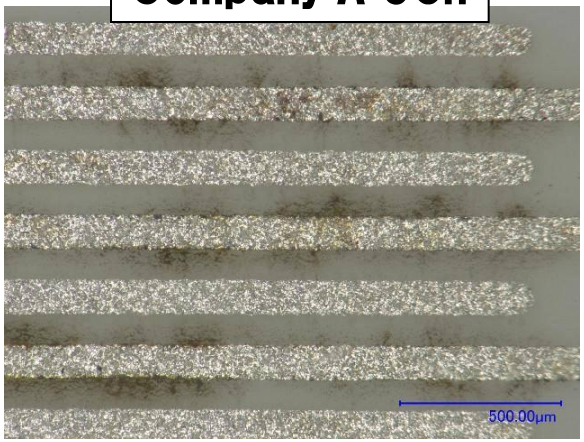
Ion migration test of various commercial ECP for 300hrs

Mitsui EVA 288h



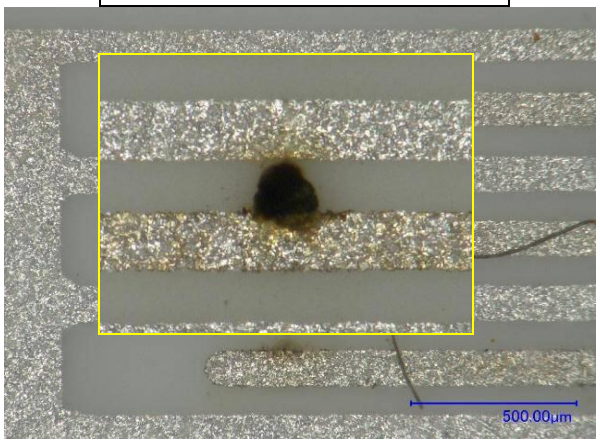
kept initial resistivity

Company A 96h



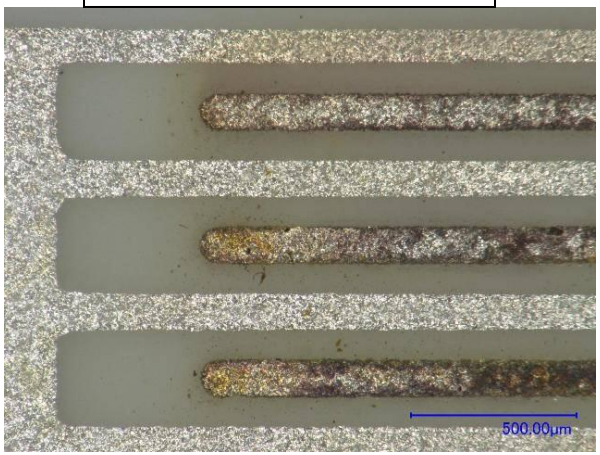
Short-circuited within 100hrs

Company B 192h



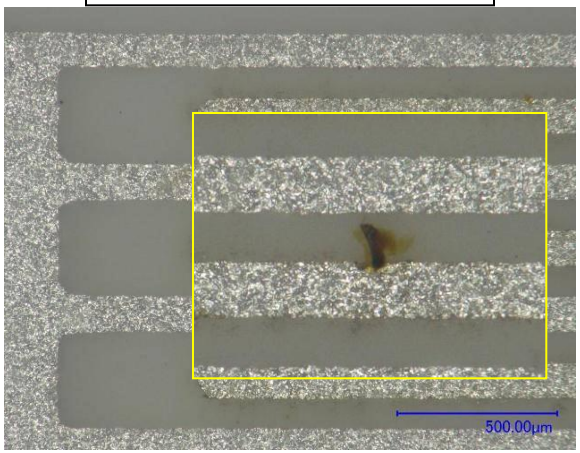
Short-circuited within 300hrs

Company C 288h



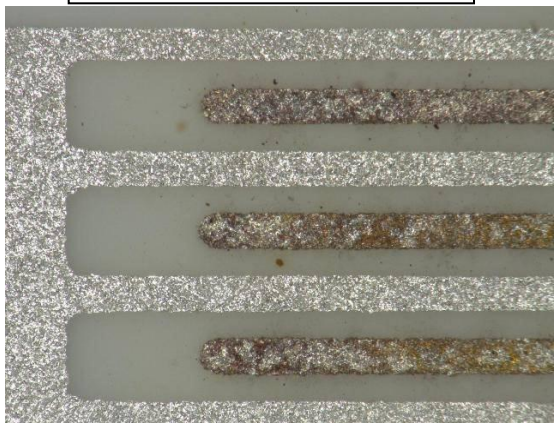
kept initial resistivity

Company D 288h



Short-circuited within 100hrs

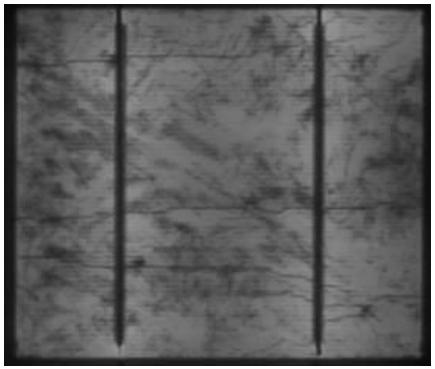
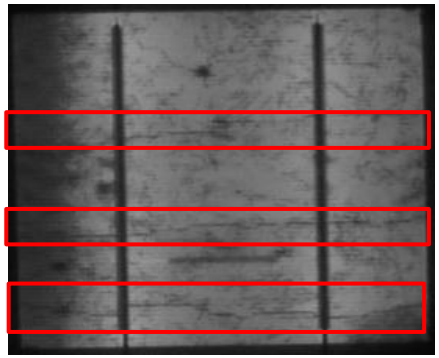
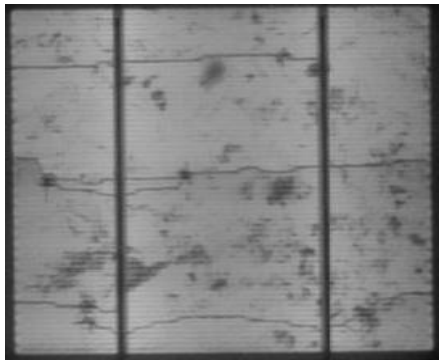
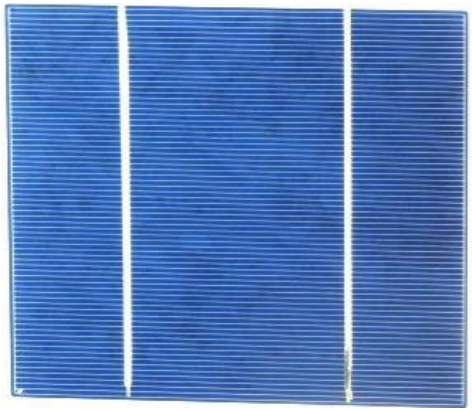
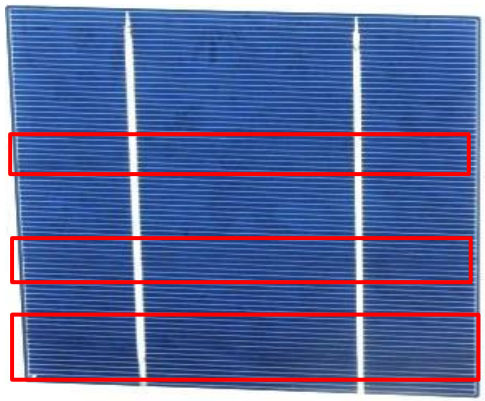
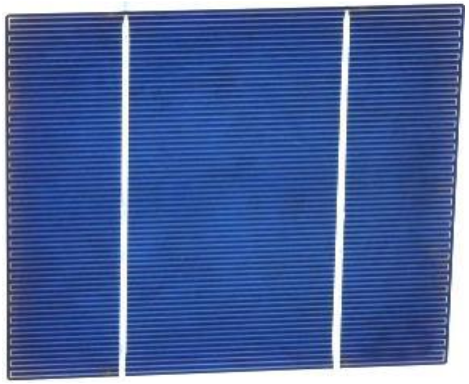
Company E 288h



kept initial resistivity

Snail track test results*)

*) These tests have been done by PI-Berlin

	EVA-1	EVA-2	EVA-3
EL images			
Appearance			

Snail Tracks are observed on the EVA-2 module

Moisture ingress rate and route into c-Si PV modules

Hideyuki Morita [1,2], Masanori Miyashita [2], Atsushi Masuda [3]
1. Photovoltaic Power Generation Technology Research Association, 3-5-8, Shiba-Koen, Minato-ku, Tokyo 105-0011, JAPAN
2. Toray Industries, Inc., Seta Plant, 1-1-1, Oe, Otsu, Shiga 520-2141, JAPAN
3. National Institute of Advanced Industrial Science and Technology, 807-1, Shuku-machi, Tosu, Saga 841-0052, JAPAN

1. Introduction

Background

- The reliability of photovoltaic (PV) module is related to the moisture ingress in some cases.
- However, the moisture ingress rate and the route into PV modules have not been clarified.
- It is necessary to understand an accurate ingress rate and route to obtain guiding principle of appropriate material.

Objective

To develop measuring method of moisture ingress into PV modules

2. Methods

- In order to detect the moisture ingress rate and route into the module, we used Ca as a sensor.

$$Ca + 2H_2O \rightarrow Ca(OH)_2 + H_2$$

(metal color) (transparent)

- Ca was evaporated on the material surface of the single cell module using multi-crystalline Si cells.
- To examine influence of permeability of back material, we prepared test modules using the back material of different water vapor transmission rates (WVTRs).

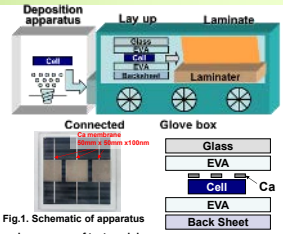


Fig.1. Schematic of apparatus and appearnce of test module.

Cross section of test module

Back materials: PET / Al / PET (PAP) | SiOx BS | Tedlar / PET / Tedlar (TPT) | 50μm ETFE

Low ← WVTRs → High

ETFE : ethylene tetrafluoroethylene

3. Results and Discussion

Damp Heat Test (DHT)

- **Ca is an effective material to detect moisture ingress.**
- **Major moisture ingress route is back material.**

Backsheet	WVTR (g/m²/day)	Initial	DH40h	DH81h	DH145h	DH191h
PAP	Extremely low					
SiOx BS	0.2					
TPT	2.0					
#50ETFE	14					

Fig.2. Change of appearance under DHT.

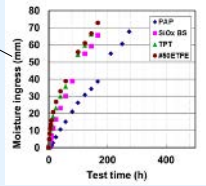


Fig.4. Moisture ingress under DHT.

Backsheet	Edge seal	Initial	DH108h
PAP	Silicone sealant		
PAP	Butyl rubber		
TPT	Butyl rubber		

Fig.3. Change of appearance under DHT.

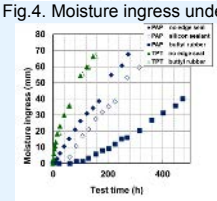


Fig.5. Moisture ingress under DHT.

- Moisture ingress rate into test module with higher WVTRs is larger.
- Edge seal does not affect moisture ingress rate for test module with TPT.

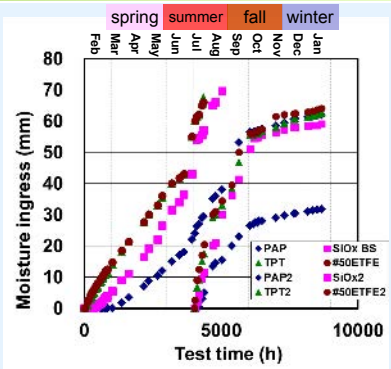
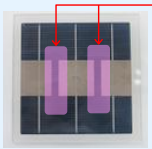


Fig.6. Moisture ingress under field exposure test.

- Samples with four kinds of backsheets were exposed outside from Feb 7th.
- Ca membrane of test module with SiOx BS, TPT, ETFE completely reacts with water in the mid of the test.
- Second samples with the same composition were exposed from Jul 25th.



- Ca membrane is evaporated in the discrete pattern. Moisture may quickly pass in the area without Ca. Therefore, we calculate accelerating effect including error bar.

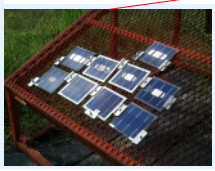
Accelerating effect is defined as
moisture ingress rate under DH / moisture ingress rate under field exposure
Moisture ingress rate is defined as
moisture ingress distance / test time
Considering effect of area without Ca, we used two kinds of moisture ingress:
measured value and measured value minus 10mm (area without Ca)

Table 1. Accelerating effect for each test module

Backsheet	PAP	SiOx BS	TPT	ETFE
Accelerating effect	28.1 - 33.5	21.1 - 23.4	18.8 - 23.5	18.5 - 20.2
Time equivalent to DH1000h (year)	3.2 - 3.8	2.4 - 2.7	2.1 - 2.4	2.1 - 2.3

Field exposure test

- **Moisture ingress rate is larger by 28-34 times under DHT than field exposure test. (ingress from edge)**
- **Moisture ingress rate is larger by 18-24 times under DHT than field exposure test. (ingress from back material)**

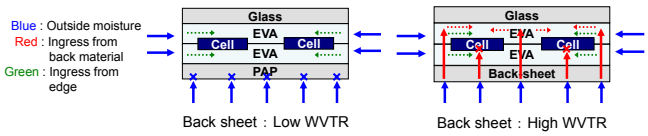


Field exposure test has been done at Kyushu Center, National Institute of Advanced Industrial Science and Technology. Climate division of Kyushu is the Temperate Zone. Test started on Feb. 7th. 2013, in winter.
One year has past since test started.

4.Conclusions

1. **Major moisture ingress route is backsheet and moisture ingress rate depends on WVTR of backsheet.**
2. **Moisture ingress rate from edge under DHT is 28 – 34 times larger than that under field exposure test.**
3. **Moisture ingress rate from backsheet under DHT is 18 – 24 times larger than that under field exposure test.**

Estimated moisture ingress route



Acknowledgements: This work was in part supported by New Energy and Industrial Technology Development Organization (NEDO) under the Ministry of Economy, Trade and Industry.

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Panasonic

Stability of encapsulants using Cu electrode

Naoto Imada, Keisuke Ogawa, Hiroshi Kanno, Hiroshi Inoue, Eiji Maruyama, and Shingo Okamoto
Solar Business Unit, Eco Solutions Division, SANYO Electric Co., Ltd. Eco Solutions Company of Panasonic Group
Phone: +81-72-438-9634, e-mail: imada.naoto@jp.panasonic.com

Motivation

Replacing Ag on a photovoltaic cell with a Cu electrode has attracted increased attention as a way to meet the market need for lowering cost.
However, Cu acts as a catalyst for the 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, …)

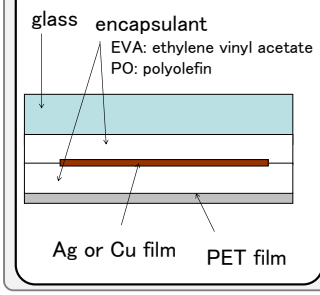
Therefore, we have compared the various impacts of Cu-catalyzed degradation by testing the discoloration and tensile strength of encapsulants.

Conclusions

1. **Cu acts as a catalyst for the thermal-oxidative degradation of encapsulants.**
2. **There is a great difference between the lifetimes of Cu-contacting encapsulants.**
3. **Correlation between discoloration and lifetime is confirmed.**

Discoloration testing of Cu-contacting encapsulants

Sample structure



(1) High temperature testing

Condition
- 120 ºC
- 1000 hours
- Ambient air

(2) Evaluation method

- Reflectivity measurement
- Appearance inspection

Sample	A	B	C	D	E	F
Polymer	EVA	EVA	EVA	PO	PO	PO
Discoloration with Ag※3	◎	◎	◎	◎	◎	◎
Discoloration with Cu※3	○	△	△	◎	○	○

※3 ◎ :no discoloration ○ : yellow discoloration △ : brown discoloration

- All **Ag**-contacting encapsulants do **not discolor.**
- Most **Cu**-contacting encapsulants **discolor.**

◆ Cu acts as a catalyst for the thermal-oxidative degradation of encapsulants.

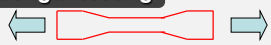
Tensile strength of Cu-contacting encapsulants and analysis of lifetime by using Arrhenius model

(1) High temperature testing

Condition
- 120 ~ 140 ºC
- 1000 hours
- Ambient air

(2) Tensile strength testing

Condition
- Dumbbell shape(JIS K7113-2)
- Room temperature (25 ºC)
- 1.4 mm/sec

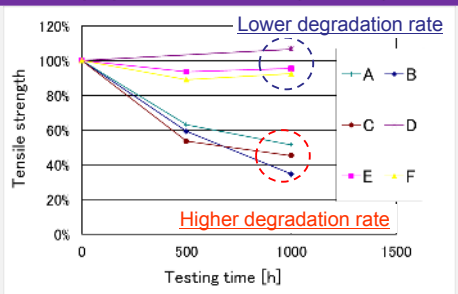


(3) Arrhenius analysis

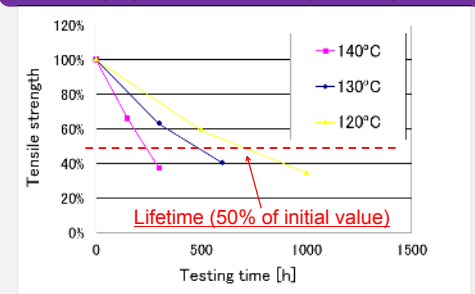
$$L = A \cdot \exp\left(\frac{Ea}{kT}\right)$$

L: Lifetime(the time when the tensile strength decreases to 50% of initial value)
A: Pre-exponential factor
Ea: Activation energy
K: Boltzmann constant
T: Temperature

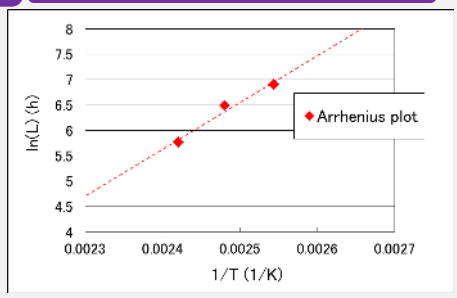
Results of tensile strength testing at 120 ºC (dependence on encapsulants)



Results of tensile strength testing for sample B (dependence on temperature)



Results of Arrhenius plot for sample B



- The tensile strength decreases as testing time increases.
- The decrease in tensile strength is different between encapsulants.
- The degradation rate increases as temperature increases.
- Linear correlation is shown between ln(L) and 1/T.

Sample	A	B	C	D	E	F
Polymer	EVA	EVA	EVA	PO	PO	PO
Discoloration	○	△	△	◎	○	○
Lifetime※4	○	○	△	◎	◎	◎

※4 ◎:Stable ○:over 50 years △:under 50 years

◆ There is a great difference between lifetimes of the encapsulants.
◆ Correlation between discoloration and lifetime is confirmed.

Why does this difference occur?
1. **Different polymer structures (EVA, PO, etc.)**
2. **Different additives : concentrations, types (antioxidant agent, HALS, crosslinking agent, etc.)**

Future plans

1. **Compare high temperature testing and outdoor testing (some papers show a non-linear Arrhenius plot for PO degradation).**
2. **Develop novel method to quantify Cu-catalyzed degradation (yellow Index, transmittance, etc.).**
3. **Develop high durability encapsulants.**

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Improvements on PID for c-Si based solar cells

Yi-Cin Chen , Chen-Chan Wang, Sheng-Hsiung Yang, Yao-Hsuan Wang, Ching-Tang Tsai, Kang-Cheng Lin, Gen-Fong Chen and Walt K.W. Huang

Gintech Energy Corporation, Jhunan, Taiwan, R.O.C.

Abstract

Potential induced degradation (PID) of silicon solar cells has been discussed extensively in the past couple years and PID-resistant cells is becoming a standard in the PV industry. Here we try to identify different ways to further avoid the PID for c-Si based solar cells.

In this work, it is demonstrated that PID resistance of c-Si based solar cells can be improved by several approaches, including the Refraction Index (RI) adjustment of SiNx film, the additional oxidation process, and the modification of wafer surface morphology etc… The oxide film deposited before SiNx deposition can act as a barrier layer between the antireflection coating (ARC) film and the p-n junction. In addition, different oxidation processes made by thermal, plasma, and chemical show different PID resistances. The most promising condition shows a power degradation of less than 1% after PID test, which is stressed under -1000V (PID prone EVA, 60℃, 96hrs, and module covered with aluminum foil). Besides, some potential problems while transferring these technologies into mass production are also discussed.

Introduction

Recently, the studies and solutions for PID issue on silicon solar cells are become more important[1][2]. In the previous study, we have demonstrated the relations between the PID performance and the cross-linking rate of encapsulation material[3]. In this work, we focus on cell level using the standard c-Si solar cell process to improve it and discuss the advantage and disadvantage.

Experiments

PID stress tests of the modules were carried out under -1000V, 60℃ environment during 96 hours. IV test of the modules were measured before and after stress testing at standard test conditions according to IEC60904-1(25℃, 1000 W/m², AM1.5G). The standard processes are including wafer surface texturing; emitter formation by $POCl_3$ diffusion; PSG remove; edge isolation; anti-reflection coating (SiN_x, refraction index=2.06~2.08) and the metallization of font and back contacts by screen printing and co-firing processes.

Results

I. SiNx refraction index adjustment

The following two graphs show the power degradation ongoing PID with refraction index(RI) adjustment and the electrical performance loss. Exp.1 to Exp.6 are SiNx RI modification from 2.08 to 2.20. Exp.6 has the best PID resistant, but the cell efficiency is less 35% than Ref.. Therefore, RI modification is a easy way to enhance PID resistance, but it's definitely not a final solution.

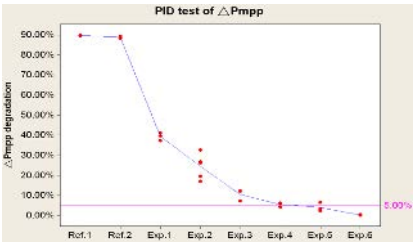


Fig.1 Normalized power degradation of PID test

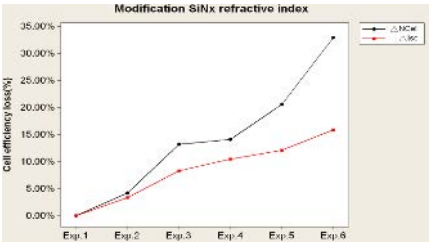


Fig.2 Normalized cell efficiency loss of modification SiNx refractive index

II. Surface treatment

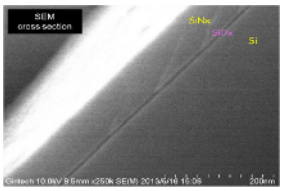


Fig.3 SEM cross-section image

Surface oxidation treatment appears efficient PID improvement and also has good cell performance. The different oxidation ways show results as Table.1. According to our assessment, those ways shows the different mass production possibility.

Comment	oxidation condition	cell performance	process flow	mass production realizable
mono Ref.	none	–	–	–
thermal oxide A	furnace w/Gas A	↑0.25%	another process	difficult
thermal oxide B	furnace w/Gas B	↑0.25%	another process	difficult
plasma oxide	PECVD	↑0.1%	–	realizable
organic oxide	chemical post-treatment	↑0.1%	–	realizable

Table.1 The comparison of different surface treatment

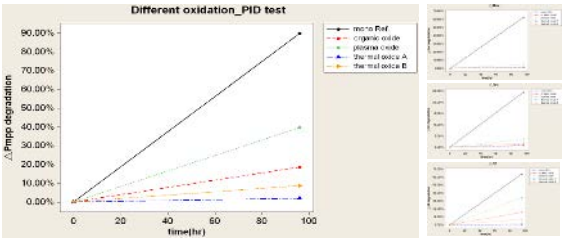


Fig.4 Normalized change of the electrical performance parameters caused by PID

III. Surface morphology effect

When the groove of mono texture become rounding, PID resistant can be improved but not be enough to reach the goal of PID free.

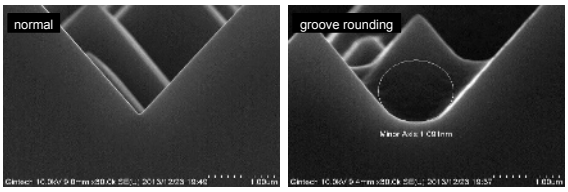


Fig.5 SEM cross-section image by different texture grooving (left:normal ; right:groove rounding)

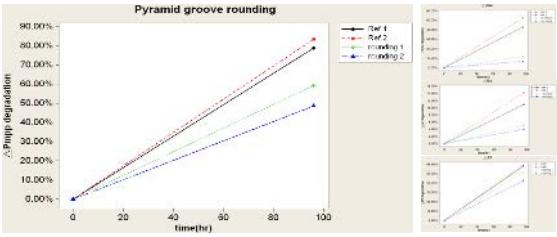


Fig.6 Normalized change of the electrical performance parameters caused by PID

Conclusion

In this article, we have demonstrated that how to improve PID performance for c-Si based solar cells manufacturing by Refraction Index (RI) adjustment of SiNx film, the additional oxidation process, and the modification of wafer surface morphology. The surface treatment is one way to get PID resistant cells without cell performance loss. We continuously improve the PID issue in cell level to reach the goal of PID free. Besides, the selection of module encapsulation material is also a good solution instead of process modification on cell level to resolve PID issue.

Reference

1. P. Hacke, K. Terwilliger, R. Smith, S. Glick, J. Pankow, M. Kempe and S. Kurtz, "System Voltage Potential-Induced Degradation Mechanisms in PV Modules and Methods for Test," 37th IEEE Photovoltaic Specialists Conference, 2011.
2. H. Nagel, A. Metz and K. Wabgemann, "Crystalline Si Solar Cells and Modules Featuring Excellent Stability Against Potential-Induced Degradation," 26th European Photovoltaic Solar Energy Conference, p.3107,2011.
3. C.C. Wang, S.H. Yang etc., "The impact of encapsulation material on PID test"

Towards Service Lifetime Prediction of Photovoltaic Modules

a joint effort within the Photovoltaic European Research Infrastructure (SOPHIA) project

Jiang Zhu[1], Ralph Gottschalg[1], Michael Koehl[2], Stephan Hoffmann[2], Karl A. Berger[3], Shokufeh Zamini[3], Ian Bennett[4], Eric Gerritsen[5], Philippe Malbranche[5], Lionel Sicot[5], Paolamaria Pugliatti[6], Agnese Di Stefano[6], Francesco Aleo[6], Fabrizio Paletta[7], Francesco Roca[8], Giorgio Graditi[8], Michele Pellegrino[8], Oihana Zubillaga[9], Paco Cano[9], Stathis Tselepis[10], Alberto Pozza[11], Tony Sample[11]

1 CREST, UK; 2 Fraunhofer ISE, Germany; 3 AIT, Austria; 4 ECN, Netherlands; 5 CEA, France; 6 ENEL, Italy; 7 RSE, Italy; 8 ENEA, Italy; 9 Tecnalia, Spain; 10 CRES, Greece; 11 JRC, Italy.

Abstract:

The energy yield during PV module lifetime is crucial for PV manufacturers, developers and end-users. The well-known IEC 61215 and 61646 qualification do an excellent job of identifying design, materials and process flaws that could lead to premature field failures, but do not yield sufficient information which can be used to model realistic outdoor performance. A service life-time prediction requires an understanding of wear-out mechanisms and how they are progressing in the presence of different environmental stresses. A series of durability experiments were designed to explore progression of different ageing mechanisms in relation to different severity and combination of environmental stresses. This work is carried out by a number of research teams under the framework of the Photovoltaic European Research Infrastructure (SOPHIA) project.

The experiments were carried out on a number of crystalline silicon commercial modules with different types of encapsulants and backsheets. Different stresses were imposed well in excess of normal certification timescales. The progression of ageing was monitored by several characterisation methods.

This poster reports the degradation in the power. All devices would pass certification, though very different ageing behaviour were observed, which depends strongly on the module type, possibly due to the backsheet. The most differentiation of power degradation showed in damp-heat, but other tests also showed deteriorations in power.

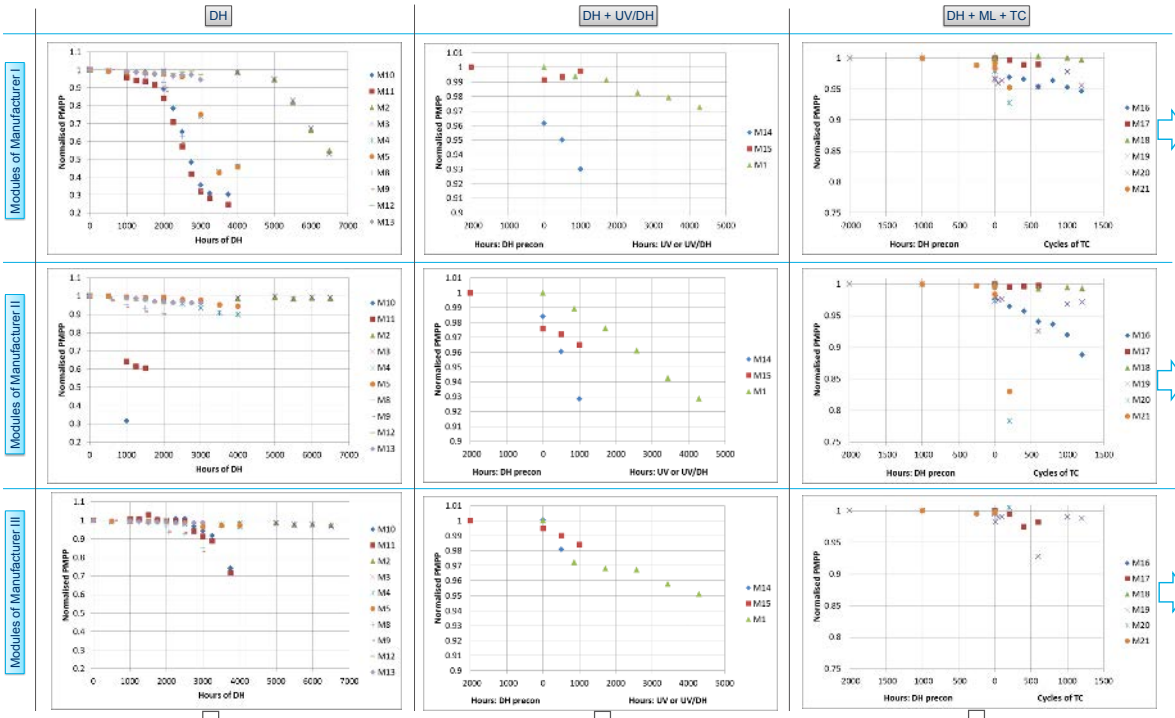
Summary of tests within SOPHIA project

Module No.	Test lab	Test type	T [ºC]	R.H. [%]	UV	Test time intervals [hours] and number of cycles
1	FhG-ISE	Dry UV exposure	~60	<5	140 W/m²	UV 120, 240, 360, 480, 600 kWh/m²
2,3	FhG-ISE	Damp-heat (DH)	75	85		DH 2000, 4000, 5000, 5500, 6000, 6500, 7000, 7500, 8000
4,5	AIT	Damp-heat (DH)	85	85		DH 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000
6,7	ECN	Damp-heat (DH)	95	95		
8,9	INES	Damp-heat (DH)	95	85		DH 600, 1000, 1500, 2000, 2500, 3000
10,11	CREST	Damp-heat (DH)	95	70		DH 1000, 1250, 1500, 1750, 2000, 2250, 2500, 2750, 3000, 3250, 3750
12,13	ENEL	Damp-heat (DH)	90	50		DH 1000, 1250, 1500, 1750, 2000, 2250, 2500, 2750, 3000
14	FhG-ISE	Damp-heat followed by UV exposure (DH + UV/DH)	85 (T_{mod})	55	180 W/m²	DH 2000, UV/DH 500, 1000, 1500, 2000
15	FhG-ISE	Damp-heat followed by UV exposure (DH + UV/DH)	65 (T_{mod})	55	180 W/m²	DH 2000, UV/DH 500, 1000, 1500, 2000
16	AIT	Thermal cycling (TC)	-40/+85			TC 200, 400, 600, 800, 1000, 1200
17	RES	Thermal cycling (TC)	-20/+40			TC 200, 400, 600
18	FhG-ISE	Thermal cycling (TC)	-40/+40			TC 600, 1000, 1200, 1400, 1600
19	FhG-ISE	Damp-heat followed by thermal cycling (DH + TC)	-40/+40			DH 2000, TC 10, 50, 100, 600, 1000, 1200, 1400, 1600
20	AIT	Mechanical loading (ML) 5400Pa	25			DH [85ºC/85%r.h.] 750,1000, ML 1hr, TC 200
21	AIT	Mechanical loading (ML) 5400Pa	-40			DH [85ºC/85%r.h.] 750,1000, ML 1hr, TC 200

Modules used for testing are commercial modules from three manufacturers

Manufacturers	I	II	III
Type of cells	P-type homojunction	P-type homojunction	N-type heterojunction
Type of encapsulant	EVA	Thermoplastic	EVA
Type of backsheet	Without aluminium moisture barrier	Without aluminium moisture barrier	With aluminium moisture barrier

Results: P_{mpp} degradation of the three types of modules under different tests



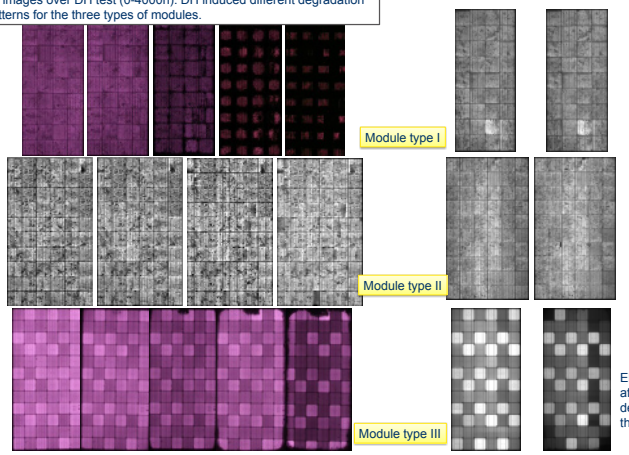
Summary of degradation behaviour of three types of modules

- DH caused P_{mpp} degradation after 1000 – 4000hrs depending on the levels of T and RH. Losses were mainly due to decreasing I_{sc} and FF (potentially recombination losses, shunting, grid corrosion, increase in series resistance); V_{oc} was not affected by DH. Typical DH ageing.
- UV or DH + UV/DH caused minor degradation in P_{mpp}, which was due to I_{sc} losses. No apparent corrosion or transmission losses due to discoloration.
- TC caused minor P_{mpp} degradation, which was due to the FF losses.

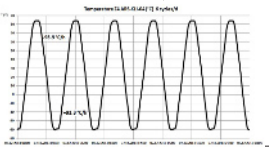
- DH temperature above 90ºC, encapsulant lost structural integrity. This was observed for modules M8, M9, M10, M11, M12, M13 at three institutes. However, not much degradation at lower T.
- UV or DH+UV/DH caused minor degradation in P_{mpp}, which was due to I_{sc} losses. No corrosion, transmission losses due to discoloration.
- TC after DH+ML caused more severe P_{mpp} degradation than DH+TC or TC only. This was due to crack creation and propagation.

- DH caused P_{mpp} degradation at 95ºC after 2000 – 3000hrs.
- The back-sheet was a better moisture barrier and significantly reduced the rate of water ingress. Water ingress was observed starting from the areas around junction box and module corners and edges.
- UV also caused minor P_{mpp} degradation due to discoloration.
- Very stable to stresses of TC and ML. Result of M19 at 600 cycles was due to problems with STC measurement, not due to the ageing test.

EL images over DH test (0-4000h). DH induced different degradation patterns for the three types of modules.

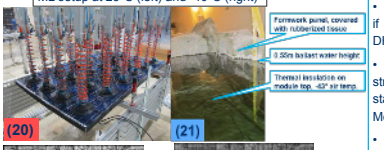


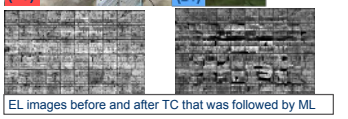
EL images before and after DH+UV. Similar degradation pattern for the three modules



Temperature ramp rate is believed to be crucial for TC, max 100ºC/hour

ML setup at 25ºC (left) and -40ºC (right)





EL images before and after TC that was followed by ML

Conclusions and future work:

- Module type I degraded severely during extended DH stresses. Module type II were stable to DH provided that the temperature was kept below 85ºC. Higher temperature would cause early failure. Module type III might have similar power degradation pattern as Module type I. However, it has a slower rate of moisture ingress due to an aluminium barrier in the backsheet.
- The degradation pattern (as identified in EL) of Module type I due to cumulative build up of acetic acid has not been seen under outdoor operation.
- DH + UV accelerated the decomposition rate of EVA if comparing Module types I and III results of DH+UV/DH to their results of DH only, respectively.
- Module type II degraded the most by mechanical stresses, whereas Module type III were relatively stable. ML followed by TC caused faster degradation to Modules I and II due to crack creation and propagation.
- Further sequential tests of UV followed by DH and ML will be carried out in order to evaluate the combined effects of tests.
- To model module performance under various realistic outdoor environments, using combination of tests with careful design of testing sequence may be possible.

MODEL FOR PREDICTING THERMAL RUNAWAY IN BYPASS DIODES

Narendra Shiradkar[1], Eric Schneller[1], Neelkanth G. Dhere[1] and Vivek Gade[2]

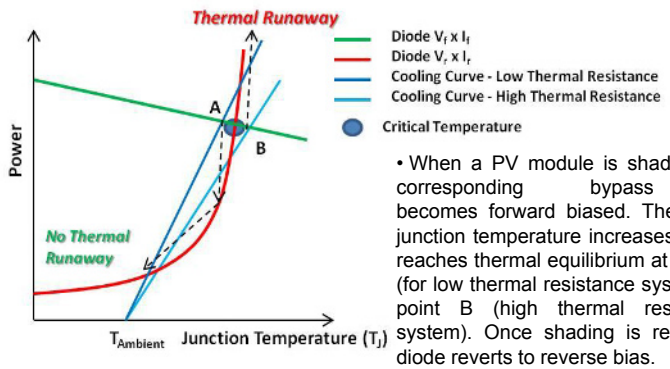
[1]Florida Solar Energy Center, University of Central Florida, 1679 Clearlake Road, Cocoa, FL 32922-5703, USA

[2]Jabil Circuit Inc., 2007 Gandy Blvd, Suite 100, St. Petersburg, FL 33702, USA

INTRODUCTION

- Bypass diodes are used in Photovoltaic (PV) modules to prevent the application of reverse voltage across the cells in the event of shading or current mismatch. Failure of bypass diodes often causes significant degradation in PV modules due to formation of hot spots.
- When shading on PV modules is suddenly removed, bypass diodes can undergo thermal runaway while transitioning from forward bias condition to reverse bias.
- Current bypass diode test in IEC 61215 test standard does not address this failure mode. Recently, a new "thermal runaway test" has been proposed.
- Theoretical framework to understand the dynamics of thermal runaway in any bypass diode-junction box system, and predict the vulnerability of the bypass diode for thermal runaway is presented.
- Predictions from the model are verified using a specially designed setup for thermal runaway testing of bypass diodes.

THERMAL RUNAWAY CRITICAL TEMPERATURE



- When a PV module is shaded, the corresponding bypass diode becomes forward biased. The diode junction temperature increases until it reaches thermal equilibrium at point A (for low thermal resistance system) or point B (high thermal resistance system). Once shading is removed, diode reverts to reverse bias.
- If the power dissipation in reverse bias is greater than the power dissipation in forward bias (point B), temperature of diode begins to increase. Increased temperature results in increased conductivity of diode and this leads to increase in current. The increased current further heats up the diode and this cyclic process results in diode failure by thermal runaway.
- The temperature at which power dissipation in diode in forward bias is equal to the power dissipation in reverse bias, for given forward current and reverse voltage, is termed as the **Critical Temperature** for thermal runaway.

- **The diode undergoes thermal runaway during forward to reverse transition only when:**

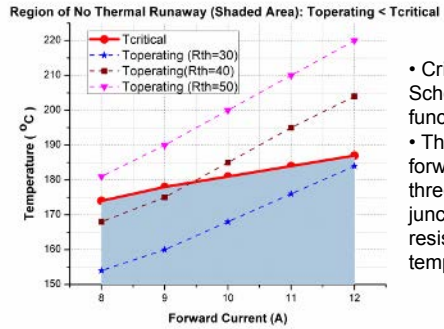
Operating Junction Temperature > Critical Temperature

- The operating temperature is determined by various factors such as thermal resistance of junction box, ambient temperature and forward current.
- However the critical temperature is only dependent on the diode parameters, for a given forward current and reverse voltage. Therefore, the critical temperature can be used as a tool to predict vulnerability of bypass diodes for thermal runaway.
- Critical temperature data can be obtained using the following two methods

1. Application of Schottky diode model to diode manufacturer's datasheets
2. Experimental measurement of forward and reverse power dissipation in diode at various temperatures.

- Both methods were found to give similar results.

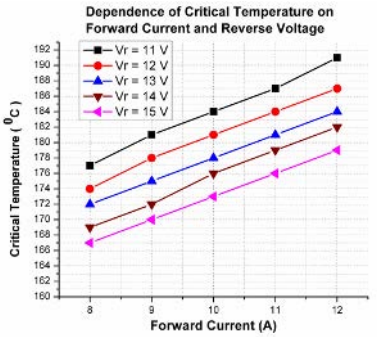
AVOIDING THERMAL RUNAWAY



- Critical temperature of an axial Schottky diode was measured as a function of forward current.
- The operating temperature in forward bias was estimated using three representative values of junction to ambient thermal resistances (Rth) at an ambient temperature of 90 °C.

- This analysis can be used to choose the appropriate value of forward current (Isc or 1.25 x Isc) during thermal runaway test.
- In order to avoid thermal runaway, the diode-junction box system must be chosen in such a way that the diode operating temperature is always less than the corresponding critical temperature (shaded area).
- Using such an analysis, it is possible to obtain quantitative information about how close the diode is operating to the thermal runaway point.
- Additionally, comparative risk analysis can be carried for various bypass diodes and junction boxes in order to asses the vulnerability for thermal runaway.

DESIGN GUIDELINES



- The critical temperature is experimentally measured at various values of forward current and reverse voltage.
- Critical temperature is seen to increase when the forward current is increased and reverse voltage is reduced.

- The information about variation of critical temperature with forward current and reverse voltage can act as a design guideline for PV module manufacturers to choose appropriate bypass diodes for specific module types, depending on the short circuit current of the module and open circuit voltage of individual strings.

RECOMMENDATIONS

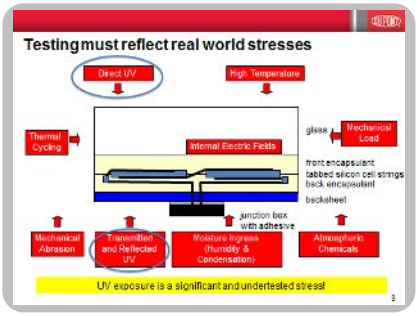
- The operating temperature of the diode at 1.25 x Isc during the bypass diode test in IEC 61215 can be used as an estimate for worst-case operating temperature.
- This information, along with the critical temperature data obtained by either of the described methods can be used to understand the vulnerability of bypass diode towards thermal runaway.
- Whenever necessary, the "thermal runaway test" can be carried out as an additional test.
- In order to avoid potential for thermal runaway, the diode should be operated several degrees below critical temperature as the region near critical temperature is experimentally found to be unstable.

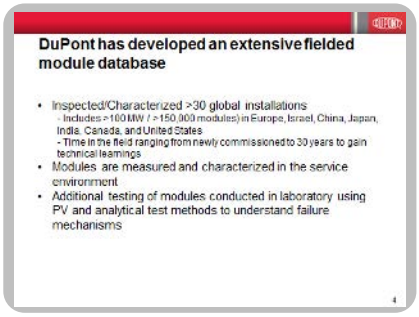
Durability of Photovoltaic Modules to UV and Weathering in Accelerated and Outdoor Exposure

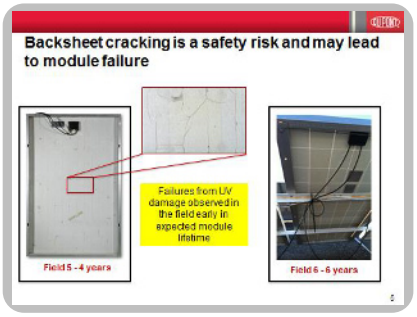
W. Gambogi[1], O. Fu[2], Y. Heta[3], J. Kopchick[1], T. Felder[1], S. MacMaster[1], A. Bradley[1], B. Hamzavytehrany[1] and T. J. Trout[1]

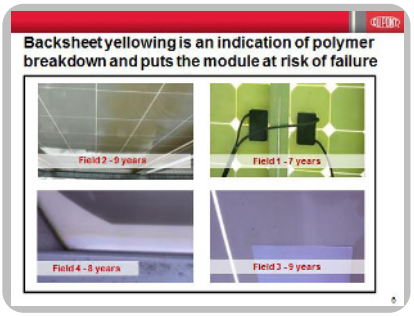
(1) (1) DuPont Photovoltaic Solutions , Wilmington, Delaware, (2) DuPont Photovoltaic Solutions, Shanghai, China, (3) DuPont K.K., Utsunomiya, Japan

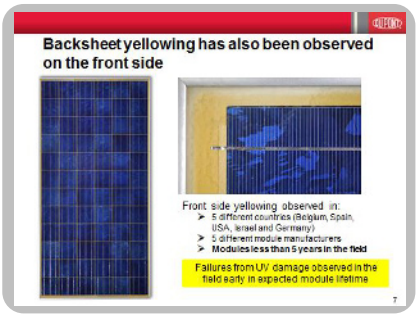
2014 NREL PV Module Reliability Workshop, Golden, CO

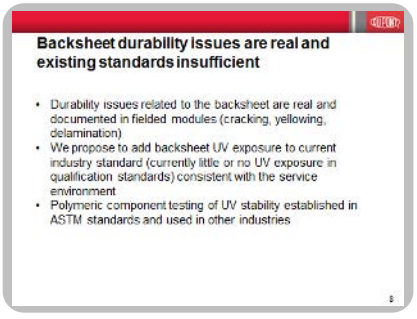


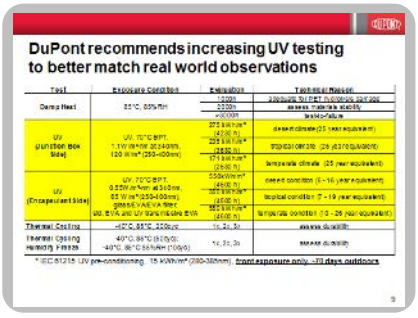


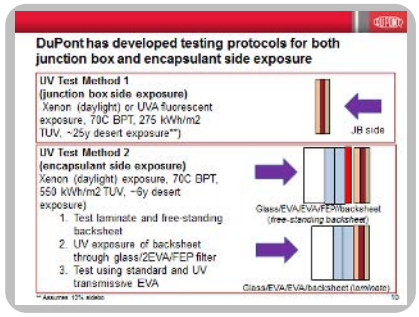


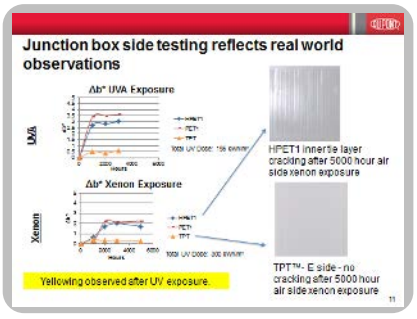


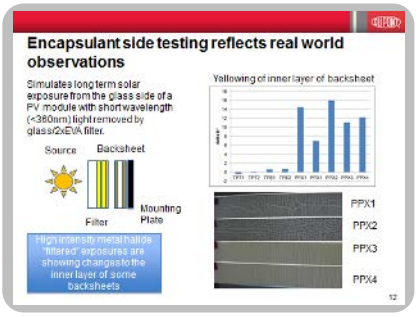


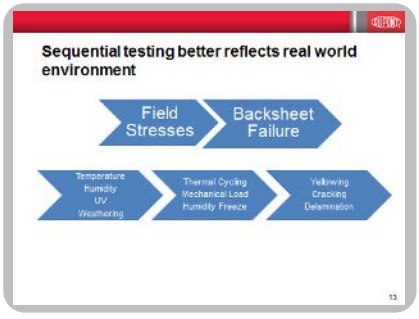


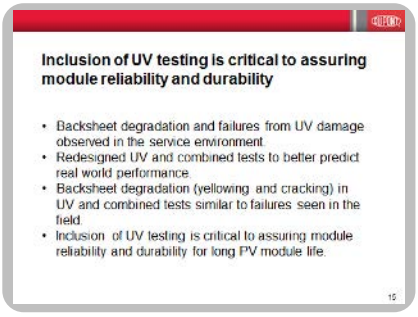












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Special thanks to JRC (European Commission Joint Research Centre) and AIST (The National Institute of Advanced Industrial Science and Technology) for use of their fielded modules.

Evaluation of Mechanical Stress Beyond IEC 61215

R. Desharnais, K. Borden
Yingli Green Energy Americas, Photovoltaic Testing Laboratory
472 Eccles Ave South San Francisco, CA 94080
Tel.: +1 650.615.9328 E-mail: Ryan@yingliamericas.com

Introduction & Motivations

- A robust and comprehensive mechanical load test protocol for evaluating new frame design and alternative mounting methods is critical to ascertaining the impact to long-term product performance and reliability.
- Developed at Yingli's state-of-the-art Photovoltaic Testing Laboratory, the Yingli Mechanical Loading Sequence is a mechanical evaluation procedure focused on systematically quantifying the performance implications from stress induced defects, such as micro-cracks, through sequential mechanical, thermal, and humidity stresses.
- Module characterization is expanded both quantitatively and qualitatively with multi-irradiance power measurement and electroluminescence (EL) imaging throughout the test process.

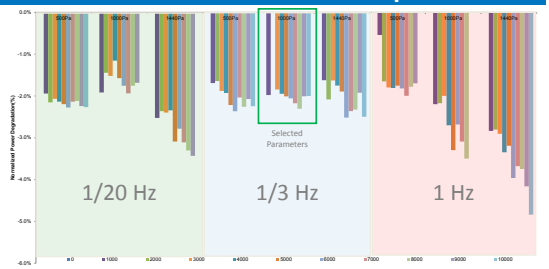
Existing Standard Review

IEC 61215 10.16[1]	YGE Mechanical Loading Sequence	Benefits of YGE MLS
STC Power Measurement	Multi-Irradiance Testing 200-1000W/m^2 in 100W/m^2 Increments	Full evaluation of how the stress affects module performance at irradiances other than 1000W/m^2
Single Mounting Method	Multiple Mounting Methods	Provides module manufacturer with understanding of risk associated with different mounting methods & provides end user with more flexibility with system design
No EL Imaging	Electroluminescence Imaging at I_{sc} and 1/10th I_{sc}	Better qualitative assessment into the type of micro-cracks being formed, with a focus on high-energy versus low-energy cracks. [2]
Static Mechanical Loading	Sequential Static and Dynamic Load Testing	Stresses both the interconnect ribbons and mechanically separates the micro-cracks.
No Post Mechanical Loading Atmospheric Chamber Stress	Thermal Cycling and Humidity Stresses	Thermal and humidity induced stress allow the potential power loss from a micro-crack to be fully realized.

Dynamic Mechanical Load Protocol Development

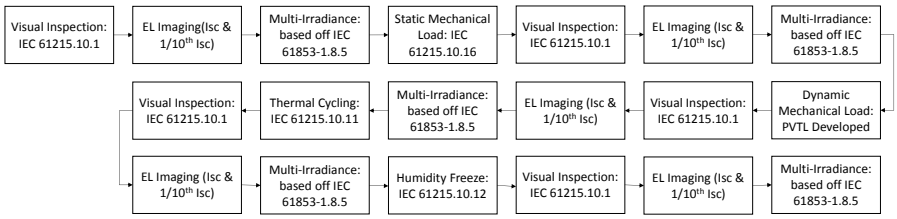
- A 3x3 factorial experiment was performed on modules for dynamic mechanical stress after static mechanical stress based off existing literature review and communication with industry experts.[3]

	500 Pa	1000 Pa	1440 Pa
1/20 Hz	10,000 Cycles, with power & EL characterization every 1,000 Cycles		
1/3 Hz			
1 Hz			

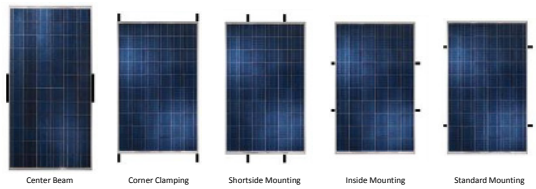


Yingli Solar Mechanical Load Testing Sequence

Test Process Flow

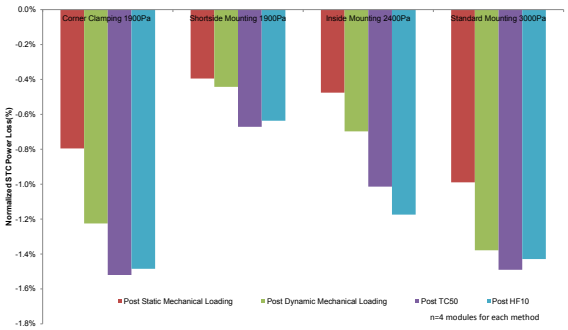


Different Mounting Methods

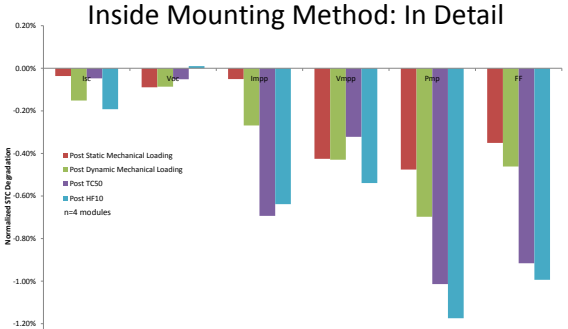


Example of Test Results

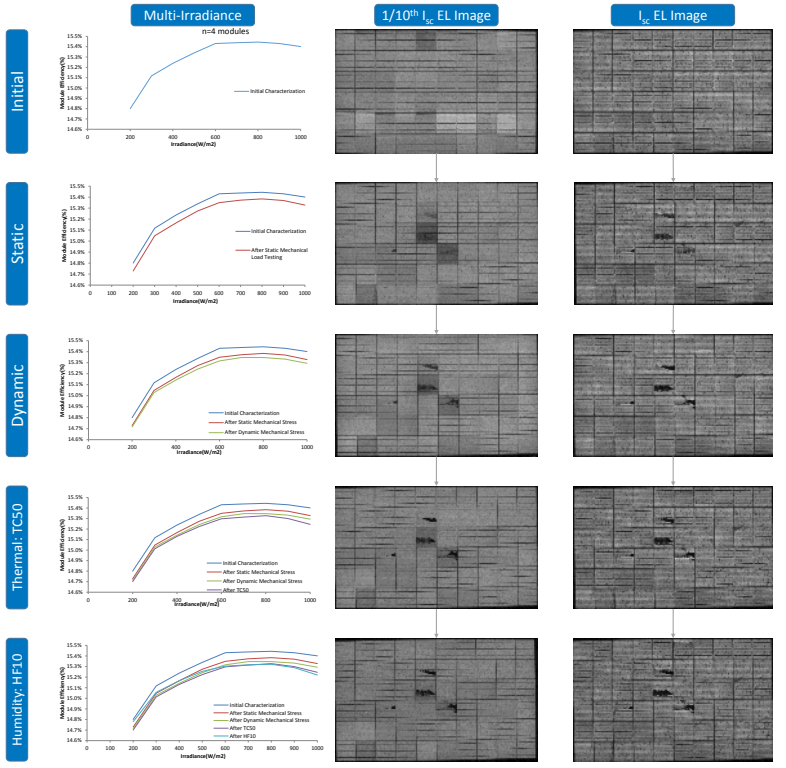
Comparison of Mounting Methods



Inside Mounting Method: In Detail



Inside Mounting Method: Progression of Micro-cracks



[1]IEC 61215, "Crystalline Silicon Terrestrial Photovoltaic Modules- Design Qualifications and Type Approval" edition 2, 2005
[2]Köntges et al., "Origins and Consequences of (Micro)-Cracks in Crystalline Silicone Solar modules", NREL PV Module Reliability Workshop(2011)
[3] Wohlgemuth, J. "Dynamic Mechanical Load Test Protocols" Email to the author. 30 July 2012. E-mail

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Photovoltaic BOS Connector Accelerated Test for Reliability Model Development and Arc-Fault Risk Assessment

Benjamin B. Yang, Jay Johnson, Kenneth M. Armijo, Jason M. Taylor, N. Robert Sorensen

Introduction

Adverse effects of BOS connector degradation include:

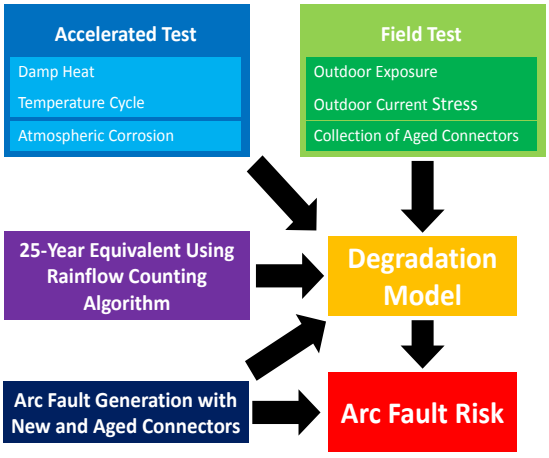
- Ohmic loss
- Increased series arc fault risk

This project aims to:

- Develop a model of resistance degradation using accelerated test and field data
- Study the effects of connector resistance on arc fault risks

Example of connector arc fault event [1].

Methods

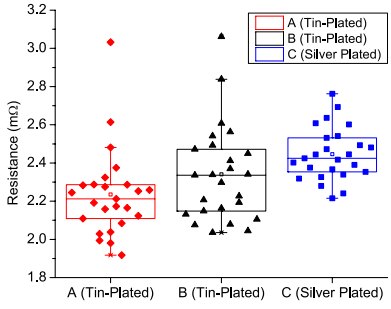


The research approach is outlined in the above figure. Key features include:

- A degradation model based on accelerated test and field data
- Arc fault risk assessment by subjecting new and aged connectors to an arc fault generator

The arc fault generation experiments establish a suitable failure criterion while the degradation model translates the results into BOS connector lifetime.

Current Results



A study of unstressed contact resistance variation by brand shows a manufacturer dependence on statistical variations [2].

Silver-plated connector had the tightest distribution.

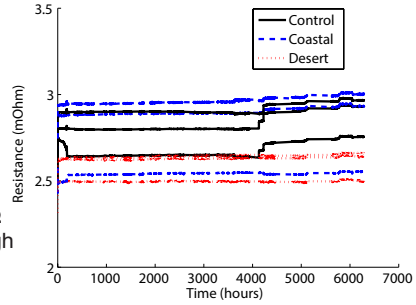
Current results suggest that system designers should expect contact resistance of 2.3 mΩ with a standard deviation of 0.2 mΩ.

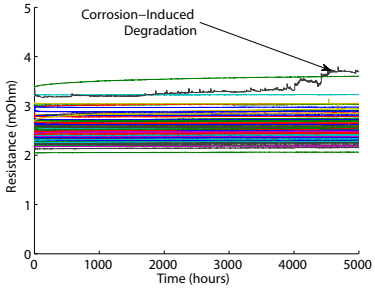
Over 6000 hours of damp heat test results are shown in the figure on the right.

A subset of the samples included contamination of coastal- and desert-simulating grime for comparison with a control group [3].

Resistance remained below 5 mΩ during time period shown, although variations begin to develop after 4000 hours.

Presence of grime has been a non-factor in this data set.





Contact resistance of 99 connectors as a function of exposure in a Class II corrosion chamber are shown in the left figure.

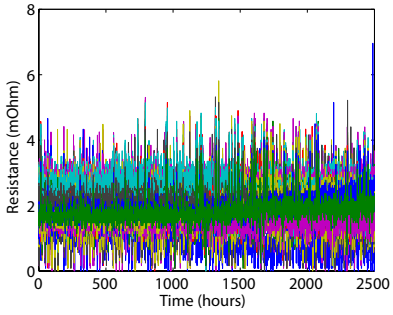
Corrosion-induced degradation is observable in one connector.

Continued monitoring as well as implementation of a Class III corrosion environment will provide additional information on the effects of corrosion-induced degradation.

Contact resistance of connectors exposured to an outdoor high-desert environment for over 2500 hours is shown in the figure to the right. The effects of daily temperature variation are visible.

Long-term exposure is likely necessary to achieve resistance change.

Outdoor exposure experiments coupled with field stress and analysis of aged connectors will provide more information.



Conclusions

A degradation model is being developed to assess arc fault risk and predict connector lifetime using accelerated tests and field data.

Current accelerated test results suggest that BOS connectors are robust to the stress factors studied, though degradation and resistance variation in some samples are observed.

Additional accelerated and field tests as well as arc fault experiments are in progress to generate the additional data needed.

Analysis of aged connectors is another crucial source of information. If you would like to assist with this effort by supplying connectors of known age and history for analysis, please contact the authors (Benjamin Yang <bbyang@sandia.gov>).

[1] J. Kalejs, J. Gadomski, and Z. Nobel, "Connector issues on reliability," presented at the NREL PV Module Reliability Workshop, 2013.

[2] Benjamin B. Yang, N. Robert Sorensen, et. al., "Reliability Model Development for Photovoltaic Connector Lifetime Prediction Capabilities", PVSC, 2013

[3] P. D. Burton and B. H. King, "Application and Characterization of an Artificial Grime for Photovoltaic Soiling Studies," IEEE Journal of Photovoltaics, vol. 4, no. 1, pp. 299–303, Jan. 2014.

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GIGASOLAR

STRESS TESTING AND MATERIAL SELECTION FOR A NON-GLASS CRYSTALLINE SILICON MODULE

5th Annual NREL PV Module Reliability Workshop
Golden, CO
February 25 -26, 2014

Thomas G. Hood and Dr. Sicco Westra
Giga Solar FPC, Inc. – Portola Valley, CA

Special Thanks to Dr. Duncan Harwood and the D2 Solar Team/San Jose, CA

Abstract

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There are benefits from reducing the weight of today's crystalline silicon module. Lighter weight modules can help to reduce costs associated with transportation, installation, and balance of systems (BOS). Reduction in module weight also provides opportunity for practical use of larger modules with lower BOS costs. Thin film flexible PV has historically been the technology of choice for lightweight applications. Unfortunately, thin film flexible PV has become increasingly uncompetitive in price and performance, and thus, scarcely available. The glass and aluminum frame constitute 85-90% of a traditional module's weight, and therefore, any significant weight reduction requires their replacement. However, glass and aluminum are inexpensive and durable, which makes finding a replacement difficult. The combination of high-efficiency, low-cost crystalline silicon cells with a lightweight, rigid, and low-cost substrate structure is a meaningful next step in the evolution of solar PV module construction. Two main challenges in accomplishing this design are cost and durability. This poster summarizes the results of durability testing of a 5-layer composite core sandwich that could provide a high stiffness, high strength, and low-cost substrate for crystalline silicon cells. The generic design of this lightweight substrate composite is shown in Figure 1. Three 170Wp Giga Solar modules built for rooftop exposure testing are shown in Figure 2.

Module Design

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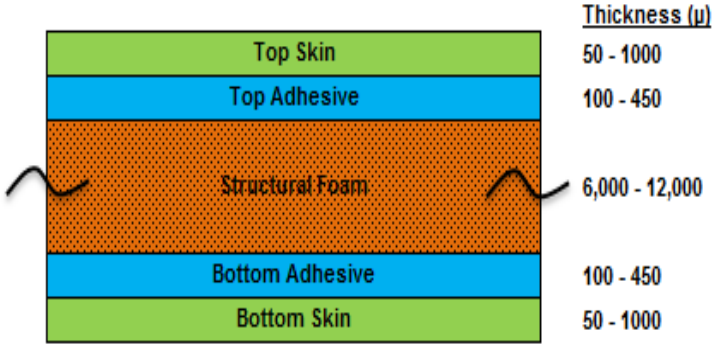

Figure 1 - Composite Cross-Section

Figure 2 – Three 170Wp Roof Panels
5 kg (11lbs) each

Composite Layer Contributions:

1. Skins – Carry both tensile and compressive stresses when the composite is under load
2. Adhesives – Bond the skins to the foam core, transferring stress across the interface; requires high shear strength
3. Foam – Supports the skins and maintains a constant distance between them, prevents buckling and requires high shear strength

Materials Evaluated:

1. Skins - PET, Aluminum, and glass fiber/thermoplastic
2. Adhesives – EVA and Silicone
3. Foam - PET, PES, and proprietary High Performance (HP)

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Testing

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Giga Solar chose two tests from the IEC 61215 standard that are highly challenging for a non-glass/frame module: thermal cycling and damp heat. A third test was performed to investigate the effects of cycling load and deformation on the electrical integrity of this composite module.

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Thermal Cycling (Shock)

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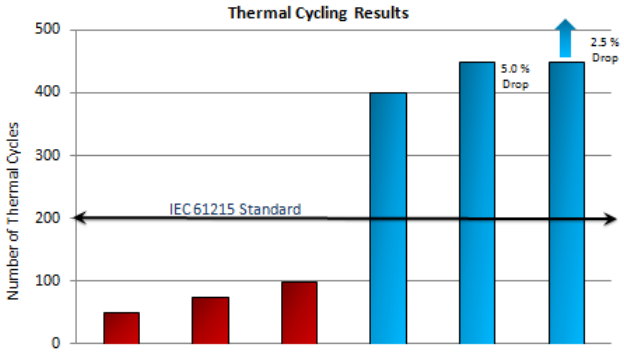
Thermal Cycling – IEC 61215 requires the module to be thermally cycled between -40°C and +85°C for 200 cycles with less than a 5% power drop. The challenge for a non-glass module is to find a material set that can perform over this temperature range and has a low coefficient of thermal expansion (CTE) to avoid interconnect fatigue and failure. The test was performed on a 1 x 2 cell sample at the rate of 50 cycles per day. Results are shown in Figure 3 to the right.



Foam	PET	PET	PET	HP	HP	HP
Skins	PET	Aluminum	PET/Al/PET	CFRTP-1	CFRTP-2	CFRTP-3
Adhesive	EVA	Silicone	EVA	EVA	EVA	EVA

Observations from Thermal Shock (TS)

1. Skins with a low CTE and good mechanical properties improve TS performance.
2. Softer, low temperature encapsulant did not improve TS performance.
3. Secondary effects may result from the foam selection – material, density and thickness.
4. It is possible for a non-glass, rigid module to exceed 400 thermal cycles with less than 5% drop in Pmax.

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Damp Heat Test

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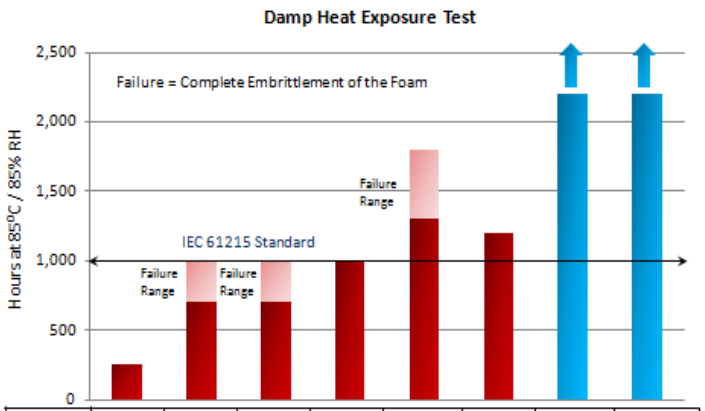
Damp Heat – This IEC test exposes the module to 85°C and 85% RH for 1000 hours, continuously. Testing was done on the composite structure only. The retention of mechanical properties and adhesion were evaluated. Because PET is known to exhibit hydrolysis under these conditions, protecting the PET foam was a major focus in this test. A number of low permeability skins combined with edge sealing were investigated along with different structural foam chemistries. Results are shown in Figure 4 to the right.



Foam	PET	PET	PET	PET	PET	PES	HP	HP
Skins	PET	PET/Al/PET	PET/Al/PET	Al	PVF/Al/PET	PET	CFRTP-1	PET
Edge	None	Al - Acrylic	Al - Butyl	Al - Butyl	Al - Butyl	None	None	None
Adhesion	Poor - 100% Cohesive	Poor - 100% Cohesive	Poor - 100% Cohesive	Poor - 100% Cohesive	Poor - 100% Cohesive	Poor - 100% Adhesive	Very Good - 50% Cohesive	Excellent – PET Skin Fails

Observations from Damp Heat

1. Unprotected PET foam deteriorates rapidly at 85/85 conditions ~ 250 hours.
2. Low MVTR skins and edge tape combined assist greatly to extend PET foam composites to 1,000 hours, and more, but poor adhesion becomes a problem.
3. PES is a hydrolytically-stable polymer foam that performs well, but adhesion is poor with EVA.
4. HP is the only hydrolytically-stable foam that was shown to withstand several thousand hours of 85/85 without foam embrittlement or adhesion loss of the EVA and skins.

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Dynamic Load

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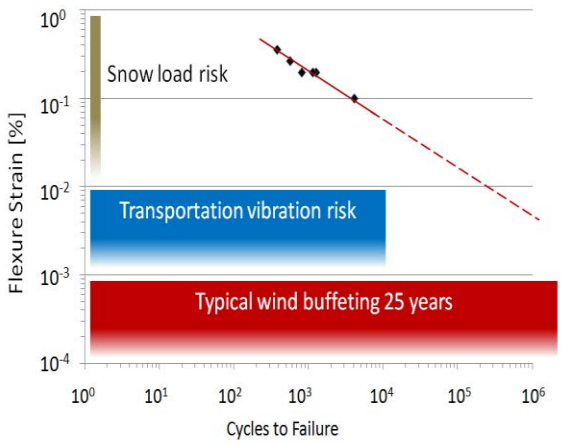
Dynamic Load – This test was done to simulate the mechanical stress on cell connecting ribbons caused by vibrations created during transportation and wind exposure, along with dead loads created by snow. Samples were mounted in an Instron Dynamic Fatigue tester and fixed at the short ends. A cyclic mechanical pressure was applied to the center of the sample to create a predetermined displacement. The number of cycles to reach electrical failure was recorded for different levels of displacement (i.e. strain). This experiment was done at room temperature.

Figure 5 – Dynamic Load Test



Observations from Dynamic Load

1. The composite material maintained its mechanical integrity over a wide range of dynamic loads
2. Cycles to failure were many times higher than what would be typically expected for stresses caused by transportation, wind buffeting or snow load.
3. It is possible to design a crystalline-silicon, non-glass module with sufficient mechanical strength to avoid mechanically-induced ribbon fatigue.

No Confidential Information Contained in this Presentation

Conclusions

GIGASOLAR

The IEC 61215 test standard for flat plate PV modules presents a number of very difficult requirements for a non-glass/frame module. Thermo-mechanical stability over a wide range of temperature and at high humidity demand careful selection of the materials. The data reported here suggest that potential does exist for an all-polymer rigid PV module design that can meet the more demanding industry tests used to validate module reliability. Large sample evaluation over the full IEC 61215 regimen is now required to establish the next level of confidence that this concept is commercially feasible.

No Confidential Information Contained in this Presentation

CFV solar test laboratory

Temperature Coefficients Measured pre-post Thermal Stress Testing and Comparison of Four Measurement Procedures

Nicholas Riedel*, Larry Pratt*, Erica Moss and Michael Yamasaki
CFV Solar Test Laboratory, Inc., Albuquerque, NM

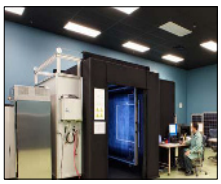
Introduction

The IEC 61215 standard requires that module performance be measured post stress testing to observe any degradation in power output. However, the standard does not require that temperature coefficients be measured post stress testing. Here we present the temperature coefficients of four different mono-crystalline silicon module types measured before and after IEC 61215 stress testing. Modules are selected to undergo either Damp Heat (DH), Thermal Cycling (TC200), or Humid Freeze (HF10) testing.

Additionally, the temperature coefficients of a non-stressed mono-Si module are measured using four separate procedures. Three procedures are done in a solar simulator wherein three different heating and cooling profiles are used. The fourth set of temperature coefficients are measured outdoors per a procedure developed by Sandia National Laboratories. Temperature profiles are varied in the solar simulator to observe if results differ when the cell and back sheet temperatures are uniform. We compare these four procedures to see if any significant differences in temperature coefficient values arise due to the measurement method used.

Procedures

Temperature coefficients of ten mono-Si modules (four types from three manufacturers) were measured for the pre-post thermal stress analysis. Four of these modules (one from each type) were chosen as controls and two to three modules from each type underwent a specific IEC 61215 stress test. The temperature coefficients were measured per IEC 61215 § 10.4 with a class AAA+ h.a.l.m. solar simulator. An Espec climate chamber was used for the thermal stress tests.



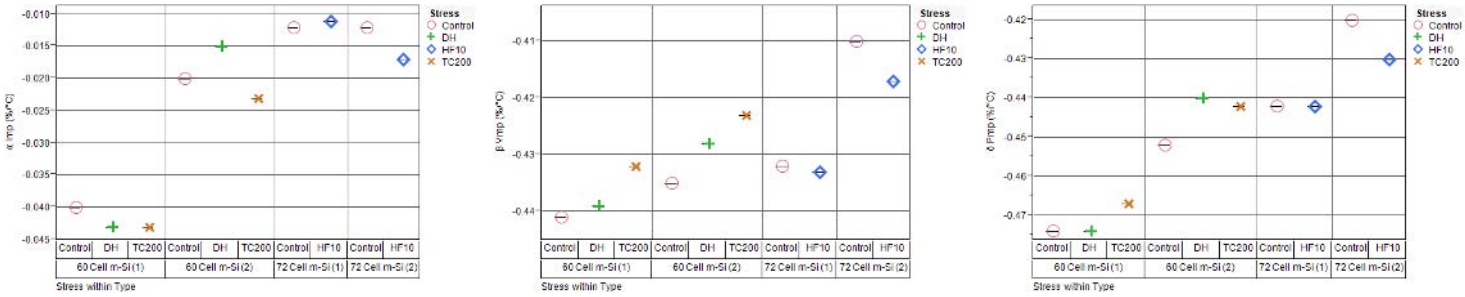
Espec Climate Chamber (left) and h.a.l.m Class AAA+ Solar Simulator (right)

For the second part of this study, we measured the temperature coefficients on a non-stressed mono-Si module using four different procedures:

1. **Indoor Flasher Linear Heat up** - Heat the test bed from 25-65 °C, with I-V measurements every 2 °C.
2. **Indoor Flasher Temperature Stabilization** – Same as Procedure 1, but allow the back sheet temperature to remain constant for 5 minutes before measurement.
3. **Indoor Flasher Cool Down** – Cool the test bed from 65-35 °C, with I-V measurements every 1 °C.
4. **Outdoor per Sandia Labs** – Module is heated naturally by the sun from a shaded state to a minimum temperature increase of 25 °C.

Results

Pre and Post Thermal Stress Testing



Variability plots showing temperature coefficients for Imp (left), Vmp (center), and Pmp (right) in absolute units. The stress received is indicated within the module type.

Four Temperature Coefficient Measurement Procedures

Tester and Procedure	Imp (%/C)	Isc (%/C)	Vmp (%/C)	Voc (%/C)	Pmp (%/C)
Indoor Flasher - Linear Heat up	-0.03	0.03	-0.41	-0.31	-0.43
Indoor Flasher - Temperature Stabilization	-0.03	0.03	-0.42	-0.31	-0.44
Indoor Flasher - Cool Down	-0.04	0.02	-0.41	-0.31	-0.45
Outdoor Curve Trace - Sandia Labs	-0.05	0.04	-0.50	-0.38	-0.56

Summary table showing the temperature coefficients of a 250W mono-Si module measured with four different procedures.

- No significant differences are seen between the control and stressed modules.
- The largest shifts are seen in the Pmp temperature coefficients (< 0.01%/ °C), which are primarily driven by changes in Vmp.
- No differences are seen pre and post stress, likely because a module's temperature sensitivity arises from the intrinsic properties of the semiconductor's band gap, which likely remain intact after the stress test.
- All three methods done within the class AAA+ solar simulator show good agreement.

Conclusions

- Module temperature coefficients did not change after DH, TC200 and HF10 tests.
- The Outdoor Sandia Labs procedure was the only measurement method significantly different than the others. This delta is being studied in order to improve the outdoor method and results will be presented at PVSC 40.
- There was good agreement between the Indoor Linear Heat up and Temperature Stabilization methods, which reduces some concerns over the delta between cell and back sheet temperature during testing.

References

- D. King, B King "Measurement of PV Module Temperature Coefficients" Sandia National Laboratories, Albuquerque, NM, 2013.
- IEC 61215, Edition 2.0, 2005
- IEC 60904, Photovoltaic Devices, Parts 1-10
- K. Emery, et al., "Temperature Dependence of Photovoltaic Cells, Modules, and Systems" in *25th IEEE PVSC,* 1996

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

Sean Fowler
Q-Lab Corporation
sfowler@q-lab.com
(216)870-0932

Purpose

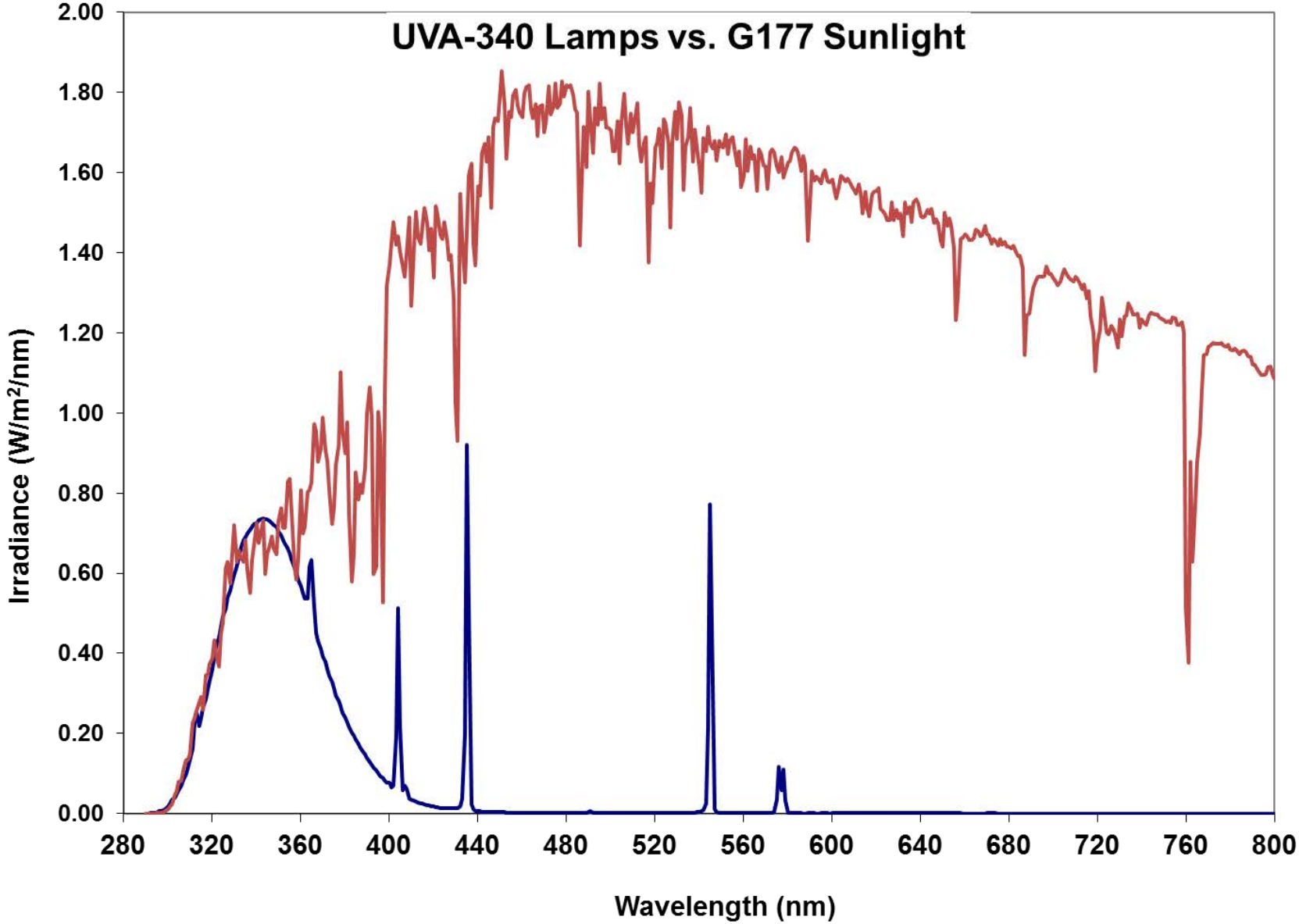
Fluorescent UV test chambers are commonly used for weathering tests of durable polymeric materials.

UVA-340 type lamps are a good match to the noon summer sunlight spectrum from the cut-on (295 nm) to approximately 350-360 nm

What are the best test conditions for achieving the same dosage of UV radiation as a backsheet would see in 1 year?

For a 6 month test, how many years of energy dosage could be achieved at various irradiance set points in the weathering chamber?

Caution: This exercise is done to provide an estimate of the approximate exposure time in a test chamber. It is useful for time budgeting purposes only. It does not account for the effects of temperature and moisture on the long term durability of any material. Also, reciprocity of UV exposure should never be assumed. Assuming that a laboratory exposure of equivalent energy dosage to a given outdoor exposure will result in equivalent degradation normally leads to gross errors.

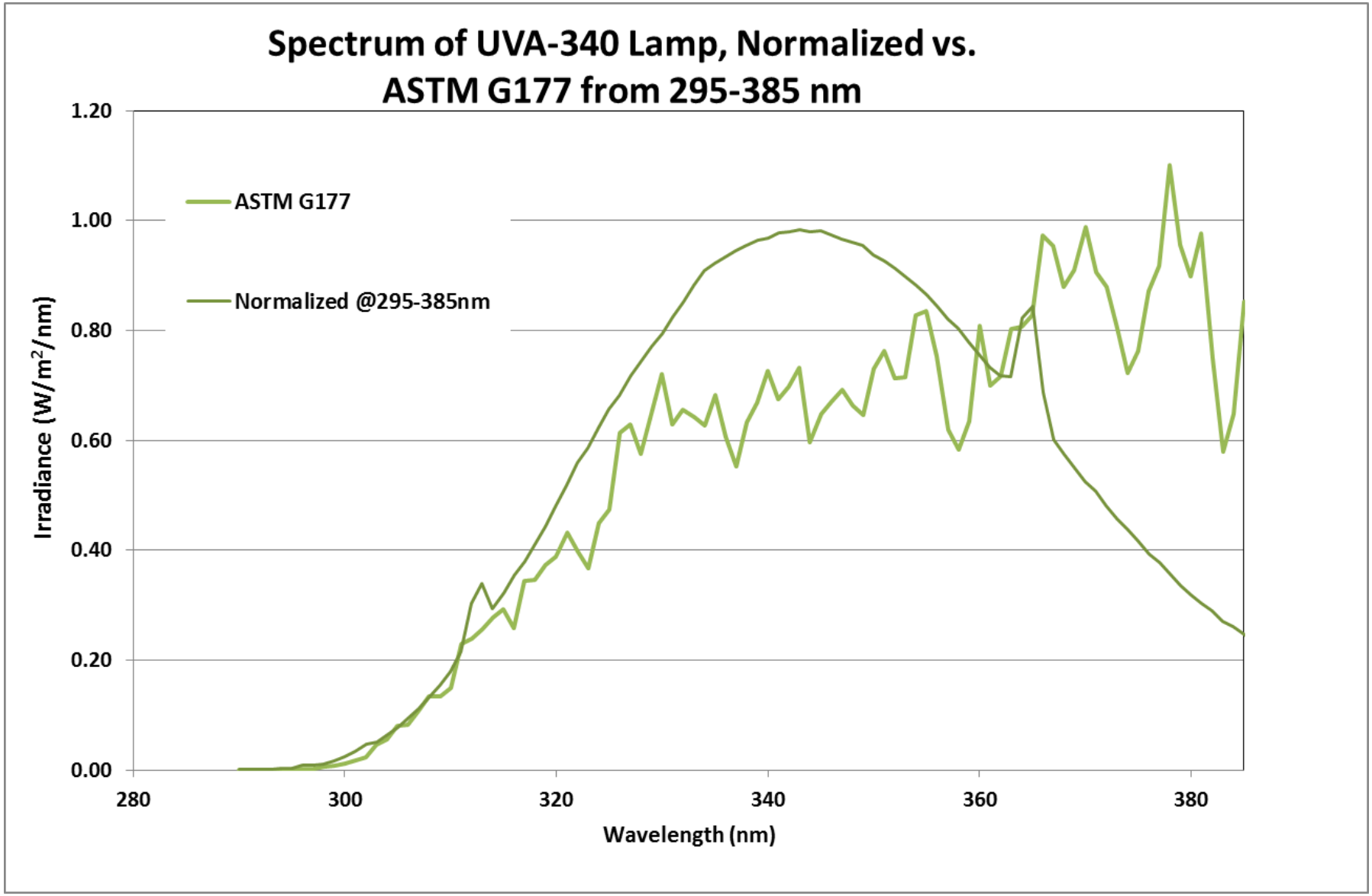

UVA-340 Lamps vs. G177 Sunlight
Irradiance (W/m2/nm)
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
280
320
360
400
440
480
520
560
600
640
680
720
760
800
Wavelength (nm)

The Challenges

- Outdoor weathering site data measures energy dosage in range from 295-385 nm
- UVA-340 lamps only have a good match to sunlight through approximately 340 or 360 nm, making direct dosage comparisons difficult
- Matching the dosage in the entire UV range causes a spectral mismatch error

Questions

- What wavelength range should be used to compare the chosen sunlight spectrum (G177) to the UVA-340 lamp?
- Over this wavelength range, what multiplier is used to convert outdoor sunlight data into data for UVA-340 dosage calculations?
- Putting this all together, calculate exposure times using fluorescent UV weathering chambers to achieve dosages very similar to the outdoor sites



Integrated irradiance is the same for both curves.

How well does the UVA-340 lamp match sunlight?

- Designed to match the UV portion of noon summer sunlight
- ASTM G177 is a reference noon summer sunlight standard, based on SMARTS2
- Method
  - Normalize UVA-340 spectrum to match ASTM G177 integrated irradiance
    - 295-385 nm
    - 295-360 nm
    - 295-350 nm
    - 295-340 nm
  - Compare the resulting normalized spectrum to the reference
    - Calculate a correlation coefficient
      - Standard deviation using a Pearson Chi-square statistic
      - 1.0 means perfect correlation
  - Use the longest wavelength that results in > 0.90 coefficient

Correlation Coefficient: 1 Minus the Standard Deviation Using a Pearson Chi-square Statistic

$$1-\sqrt{\frac{\sum_{\lambda=295}^{\lambda=x}\frac{\left(I_{G177}-I_{UVA340}\right)^2}{I_{G177}}}{x-295}}$$

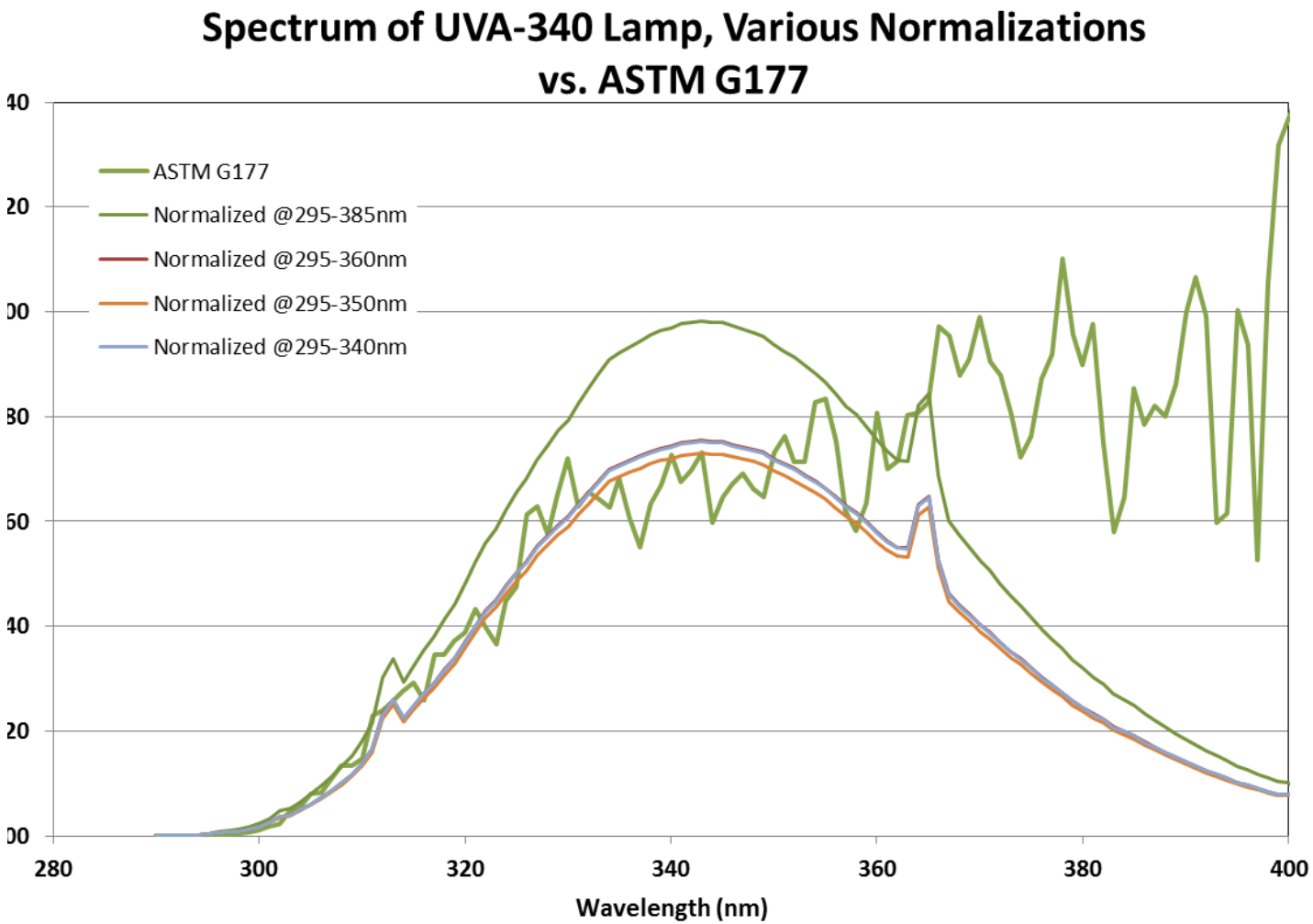
Where

I_{G177}	= Spectral irradiance according to ASTM G177
I_{UVA340}	= Spectral irradiance of UVA-340 Lamp
x	= integration upper limit
λ	= wavelength in nanometers

Results

Range	UVA-340 to G177 (W/m2) correlation
295-385	0.59
295-370	0.83
295-360	0.91
295-350	0.92
295-340	0.92

Use the integral 295-360 nm to compare UVA-340 to ASTM G177



Areas under the curve for UVA-340 equal G177 for the given wavelength range: for example, the curve for 295-360 nm has an equal integrated irradiance versus G177, also from 295-360 nm.

Results

- Outdoor UV dosages include energy from 295 nm to 385 nm
  - Using ASTM G177 as the reference, calculate a multiplier to convert dosage from 295-385nm into the dosage from 295-360nm
  - G177 Irradiance from 295-385 nm = 50.8 W/m^2
  - G177 Irradiance from 295-360 nm = 29.6 W/m^2

$$29.6 \div 50.8 = 0.583$$

Integrating UVA-340 Irradiance

UVA-340 Spectral Irradiance							
Wavelength	Irradiance		Wavelength	Irradiance		Wavelength	Irradiance
295	0.0029		331	0.6334		366	0.5278
296	0.0060		332	0.6538		367	0.4619
297	0.0072		333	0.6763		368	0.4405
298	0.0088		334	0.6982		369	0.4218
299	0.0123		335	0.7073		370	0.4029
300	0.0179		336	0.7164		371	0.3888
301	0.0254		337	0.7254		372	0.3696
302	0.0361		338	0.7327		373	0.3520
303	0.0394		339	0.7401		374	0.3369
304	0.0496		340	0.7435		375	0.3199
305	0.0600		341	0.7505		376	0.3019
306	0.0726		342	0.7516		377	0.2892
307	0.0865		343	0.7546		378	0.2742
308	0.1014		344	0.7521		379	0.2574
309	0.1181		345	0.7529		380	0.2448
310	0.1375		346	0.7467		381	0.2326
311	0.1657		347	0.7420		382	0.2218
312	0.2321		348	0.7373		383	0.2075
313	0.2600		349	0.7322		384	0.1997
314	0.2248		350	0.7196		385	0.1905
315	0.2466		351	0.7102		386	0.1789
316	0.2717		352	0.7001		387	0.1688
317	0.2911		353	0.6882		388	0.1600
318	0.3168		354	0.6767		389	0.1505
319	0.3405		355	0.6644		390	0.1415
320	0.3710		356	0.6472		391	0.1329
321	0.3989		357	0.6295		392	0.1237
322	0.4287		358	0.6166		393	0.1169
323	0.4495		359	0.5981		394	0.1097
324	0.4775		360	0.5804		395	0.1022
325	0.5037		361	0.5633		396	0.0965
326	0.5225		362	0.5506		397	0.0901
327	0.5508		363	0.5491		398	0.0841
328	0.5714		364	0.6312		399	0.0791
329	0.5922		365	0.6476		400	0.0785
330	0.6090						

From 295-360 nm

Irradiance = 29.58 W/m^2

At 340 nm

Irradiance = 0.7435 W/m^2

29.58 ÷ 0.7435 = 39.79

Use this multiplier to convert UVA-340 machine set point to integrated irradiance from 295-360 nm

Results

- Fluorescent UV test chambers typically control irradiance at 340 nm
  - To convert a 340 nm set point into irradiance from 295-360 nm, multiply by 39.79

Now, divide outdoor dosage by irradiance to calculated time in the test chamber

Example: 202 MJ ÷ (1.55 W/m^2 @340 x 39.79) ÷ 3600 seconds/hour

= 910 hours

UVA-340 Dosage vs. Outdoor Data

	Annual UV (295-385 nm)	Annual UV (295-360 nm)	time to 1 year at 340 nm set point			years @ 4200 hours		
Location	(MJ/m^2)	(MJ/m^2)	0.55	0.80	1.55	0.55	0.80	1.55
Phoenix--34° Rack	360	210	2663	1831	945	1.6	2.3	4.4
Sanary (from Atlas)	226	132	1672	1149	593	2.5	3.7	7.1
Miami--5° Rack	344	200	2544	1749	903	1.7	2.4	4.7

The ground facing side of a backsheet is subject to reflected radiation. The values above can be scaled to accommodate any albedo assumptions, such as 10%, 12% or 20%.

Analysis of commercial PV modules after PID test

Takuya DOI*1, Kohji MASUDA*2, Hiroshi KATO*2, Yasunori UCHIDA*2, Katsuaki SHIBATA*2*4, Shinji KAWAI*3, Yutaka FUKUMOTO*3, Fujio TAMAI*3, Atsushi MASUDA*1 and Michio KONDO*1

*1 National Institute of Advanced Industrial Science and Technology (AIST); *2 Japan Electrical Safety & Environment Technology Laboratories (JET); *3 Industrial Technology Center of SAGA; *4 current affiliation is Chubu Electrical Safety Services Foundation.

Introduction and Procedures

Motivation:
To obtain the basic data about the PID test
→ Understanding Mechanism of PID
→ Find knowledge for PID prevention

PID Test [1] : Water film method, 25 °C, 168 hours, V_{SYS}
Samples: PV module purchased from markets

Test modules

module type	cell type	module type	cell type
A	mc−Si	E	mc−Si
B	mc−Si	F	sc−Si
C	mc−Si	G	mc−Si

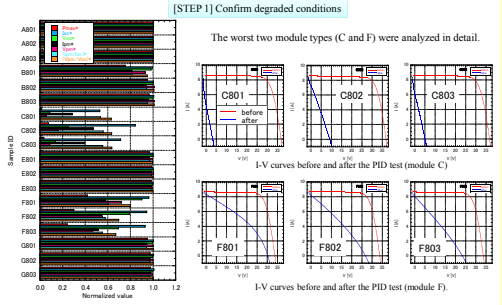
[1] Koch S *et al.*, "Polarization effects and tests for crystalline silicon cells", 26th EUPVSEC (2011–9).

Analysis Procedure:

Largely degraded modules → R_{sh} is decreased significantly.
→ Analysis was conducted in the following procedures:

[STEP 1] Confirm degraded conditions
[STEP 2] Check bypass diode health
[STEP 3] Evaluate dark I-V for check of R_{sh}
[STEP 4] EL images comparison, Reverse potential application
[STEP 5] Chemical analysis for understanding degradation factor

[STEP 1] Confirm degraded conditions



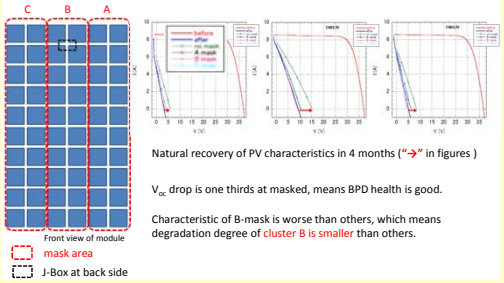
Results of PID test, PV characteristics normalized by initial.

Results

Module C: 6x 10 = 60cells
"cluster" separated by BPD

[STEP 2] Check bypass diode health

Compare I-V curves, mask each cluster and no mask;



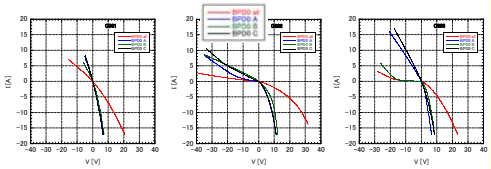
Natural recovery of PV characteristics in 4 months ("→" in figures)

V_{oc} drop is one thirds at masked, means BPD health is good.

Characteristic of B-mask is worse than others, which means degradation degree of cluster B is smaller than others.

[STEP 3] Evaluate dark I-V for check of R_{sh}

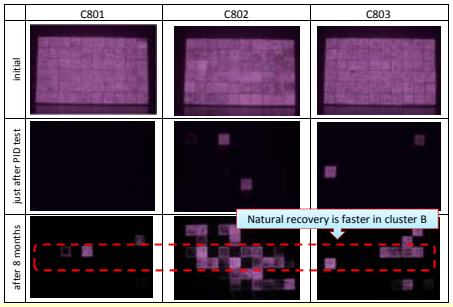
Module C — Remove BPD, compare dark I-V of each cluster and connected all;



Connected all: Shunt characteristics are different each other. C803 has good shunt properties in the second quadrant.

Each cluster: Cluster B in all modules shows good properties in the fourth quadrant.
→ This is a result to support a result shown in [STEP 2]. Correspond to brighter area of EL images indicated in [STEP 3]

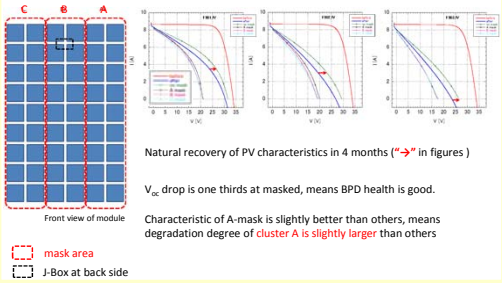
[STEP 4] EL images comparison — Module C



Module F: 6x 9 = 54cells
"cluster" separated by BPD

[STEP 2] Check bypass diode health

Compare I-V curves, mask each cluster and no mask;



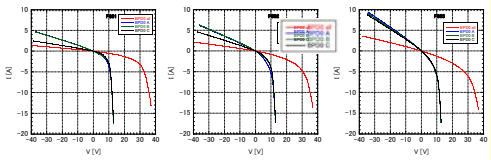
Natural recovery of PV characteristics in 4 months ("→" in figures)

V_{oc} drop is one thirds at masked, means BPD health is good.

Characteristic of A-mask is slightly better than others, means degradation degree of cluster A is slightly larger than others

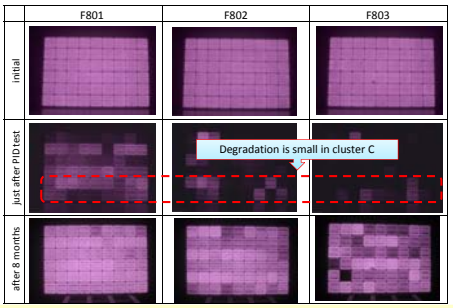
[STEP 3] Evaluate dark I-V for check of R_{sh}

Module F — Remove BPD, compare dark I-V of each cluster and connected all;



Each cluster: Cluster C in F801 and F802 shows good properties.
→ Correspond to brighter area of EL images indicated in [STEP 3]

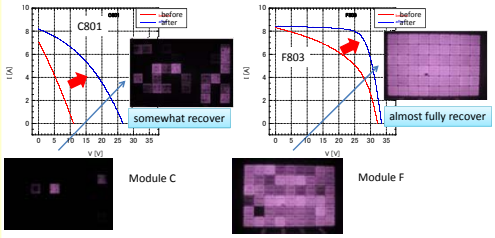
[STEP 4] EL images comparison — Module F



[STEP 4] Reverse potential application, EL images comparison

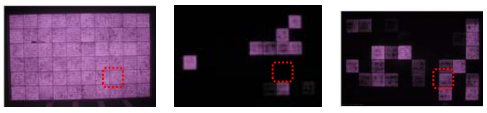
Reverse potential application to the most degraded PV module → Confirm recovery effect

Reverse potential test: Just changing the polarity of applied voltage to PV modules, other conditions are the same as PID test procedure.



[STEP 5] Chemical analysis for understanding degradation factor

Presence of Na ions in the vicinity of ARC [2]
→ To confirm the relation between PID degree and the presence of Na ion
→ SIMS analysis for different cell conditions of the same module type

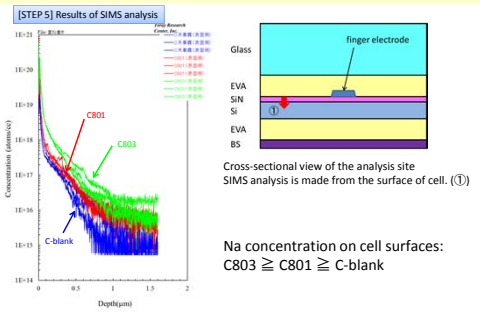


(a) C-blank (no exposure) (b) C803 (w/o reverse pot. test) (c) C801 (w/ reverse pot. test)

(a) blank cell from the module "C-blank" (no exposure to any test)
(b) cell from the module "C803" experienced only PID test and has dark EL image.
(c) cell from the module "C801" experienced reverse potential test after PID test and has some recovery in EL image.

[2] Bauer J. et al., Phys. Status Solid RRL 6, No. 8, 331-333 (2012).

[STEP 5] Results of SIMS analysis



Cross-sectional view of the analysis site
SIMS analysis is made from the surface of cell. (①)

Na concentration on cell surfaces:
C803 ≧ C801 ≧ C-blank

SIMS depth profile of Na

Conclusions

It was considered that:

(1) PID degradation is a combination of reversible process and irreversible process because the recovery of PV characteristics by the applied reverse potential was depending on the module type.

(2) Degraded cells indicated higher Na concentration than no exposure one from SIMS analysis; it was suggested that diffusion of Na is due to PID phenomenon. Furthermore, a possibility that Na collected by PID test was dispersed from the cell surface by reverse potential application was shown.

Acknowledgments

This work was supported by the joint project of PVTEC, AIST, SAGA-ITC and JET under "Asia-Pacific Industrial Science & Technology and International Standardization Cooperation Program" conducted by METI. We appreciate to all the persons who supported this project.

Contact Person: Takuya DOI (t.doi@aist.go.jp)
This presentation contains no confidential information.

Acceleration of Potential-Induced Degradation (PID) by Salt-Mist Preconditioning in c-Si PV Modules

Soh Suzuki [1], Naoki Nishiyama [2], Seiji Yoshino [3], Takumi Ujiro [2], Shin Watanabe [3], Takuya Doi [4], Atsushi Masuda [4], and Tadanori Tanahashi [1] ([1] ESPEC, [2] JFE-Techno Research, [3] NPC, [4] AIST)

Introduction & Procedures

Motivation: To Propose the Long-Term Reliability Testing

Salt-Mist Stress: - decrease the insulation level.
- not induce the drastic power loss.

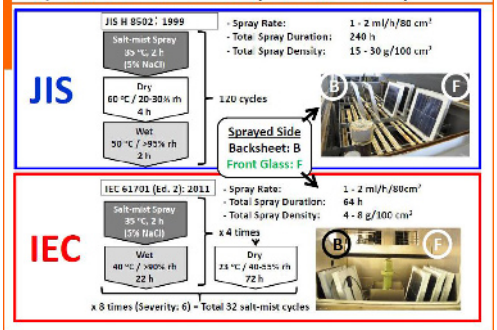
High System-Voltage Stress :
- induce the drastic power loss within relatively short-term (1 ~ 2 years).

It is assumed that the degradation by salt-mist stress will be relatively slowly compared to the PID from their characteristics.

Thus, the combined effects of these stresses may manifested themselves only after long-term exposure, not in the early "infant mortality" period.

-> Salt-Mist Stress Followed by High System-Voltage Stress

Experimental Procedures (Salt-Mist Stress)



Experimental Procedures (PID Testing)

ESPEC PID Evaluation System for Mini-PV Module

AMI-020-PID

Applying Voltage: +/- 10 ~ +/- 2,000 V

Measurable Leakage Current: +/- 0.1 pA ~ +/- 1 mA

Exp. Conditions in Present Work
60 °C / 85% rh
-1,000 V
based on IEC 62804 draft

PID Evaluation System for the Full-Size PV Module, Please Contact to https://www.espec.co.jp/english/inquiry/inquiry_customer.html

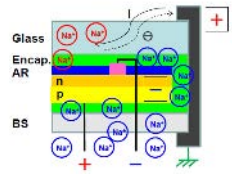
Summary

- We demonstrated that the drastic degradation of PV modules was caused by the salt-mist stress followed by the high system-voltage stress **[Panel 3]**.
- It is concluded that PID is accelerated by the salt-mist preconditioning, because the degradation profiles obtained by the current-voltage characteristics **[Panel 6 & 7]**, EL image **[Panel 8]**, LBIC image **[Panel 9 & 10]**, LIT image **[Panel 9 & 10]**, and the characteristics of PV parameters (increasing of ideally factor [n] and decreasing of Rsh) **[Panel 12]** are closely similar with those of PID phenomenon.
- PID accelerated by salt-mist stress crucially depended on the wet incubation just after the salt-mist spray **[Experimental Procedures & Panel 13]**, but not the penetration through Edge-Slit **[Panel 13]**.
- Exogenous sodium ions (which passed through the backsheet and then diffused in the encapsulant) also may be a crucial factor to induce PID, as well as the endogenous sodium ions contained in the front glass **[Panel 1]** . If so, the salt-mist penetration into PV modules would be a possible threat to the long-term reliability of PV modules installed near coast.

Conclusion — Panel 1

Endogenous Na Ion Liberated from Front Glass
=> No PID Induction in Our Exp. Conditions

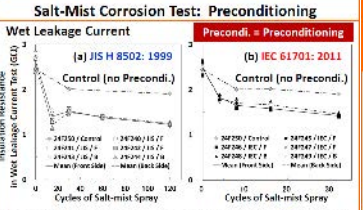
Exogenous Na Ion through Backsheet from Ambient
=> Possibly a Crucial Factor to Induce PID



Experimental Results

Panel 2

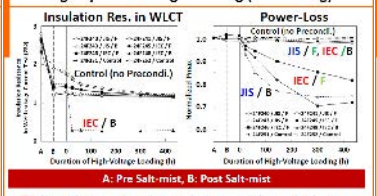
Salt-Mist Corrosion Test: Preconditioning



The insulation resistance was reduced by two-thirds (JIS protocol) and by three-quarters (IEC protocol), relative to controls. However, this resistance remained well above the critical value (250 MΩ in this module) specified in IEC 61215: 2005, clause 10.15.

Panel 3

High System-Voltage Loading (PID Testing)

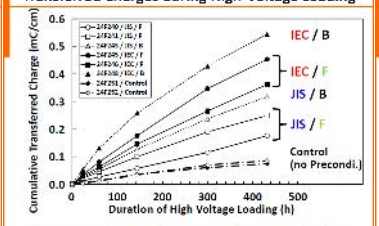


IEC / B module was the only module that came close to having its electrical insulation fail in the initial phase of high-voltage loading.

Two types of salt-mist preconditioning can induce a critical loss of power during high-voltage loading, but "Control" was not degraded.

Panel 4

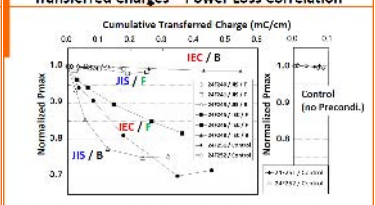
Transferred Charges during High-Voltage Loading



The properties that cause the charge transfer during high-voltage loading are imprinted during the salt-mist preconditioning phase.

Panel 5

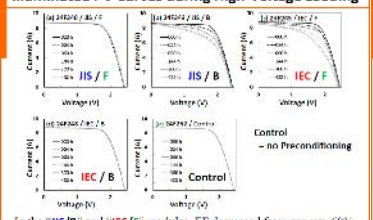
Transferred Charges – Power Loss Correlation



The total amount of transferred charge does not directly correspond to the reduction of output power.

Panel 6

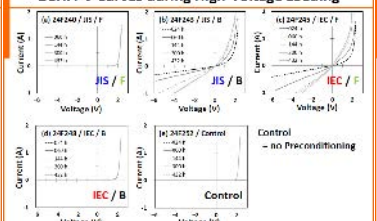
Illuminated I-V Curves during High-Voltage Loading



In the "JIS/B" and "IEC/F" modules, FF decreased from approx. 69% to 52-54%, depending on the duration of loading, however FF remained at 69% in other modules.

Panel 7

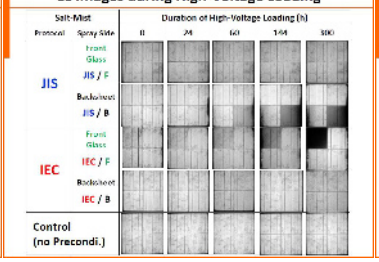
Dark I-V Curves during High-Voltage Loading



The current-voltage curves in "JIS / B" and "IEC / F" modules exhibited ohmic behavior with a reduction of shunt resistance.

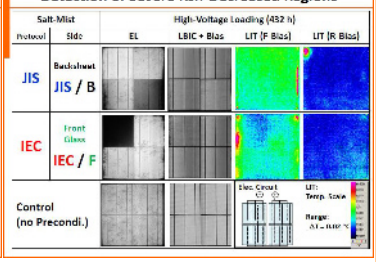
Panel 8

EL Images during High-Voltage Loading



Panel 9

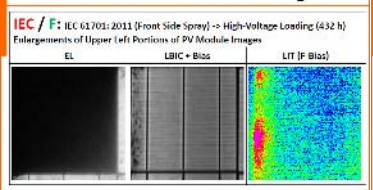
Detection of Severe Rsh-Decreased Regions



Panel 10

Detection of Severe Rsh-Decreased Regions

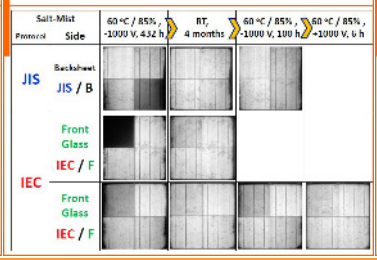
IEC / F: IEC 61701: 2011 (Front Side Spray) -> High-Voltage Loading (432 h)
Enlargements of Upper Left Portions of PV Module Images



The penetrate spots were identified only near the sides of "JIS/B" and "IEC/F" modules that lie in parallel with the bus-bar, and at the corners of the PV module, but not at the sides that are oriented perpendicular to the bus-bar.

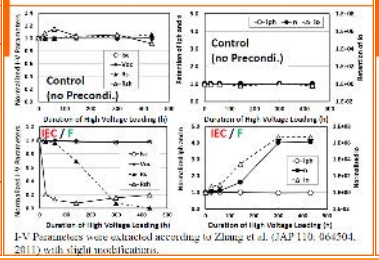
Panel 11

Evolution of PID in Alternation Manner



Panel 12

Extracted I-V Parameters from Illuminated I-V Curves



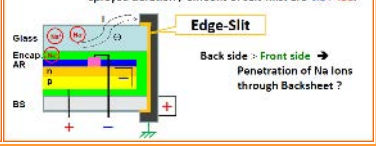
I-V Parameters were extracted according to Zhang et al. (JAP 110, 064504, 2011) with slight modifications.

Panel 13

Degradation Order

IEC / B : Wet Leakage Current Test: nearly NG
> JIS / B >= IEC / F
> JIS / F

IEC > JIS ➔ Na ions penetration: not through Edge-Slit, because sprayed duration / amount of salt-mist are JIS > IEC.



Contact Person: Tadanori Tanahashi (t-tanahashi@espec.co.jp)

This work was supported by the Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability (National Institute of Advanced Industrial Science and Technology, Japan).

This poster does not contain any proprietary or confidential information.

An examination of the acceleration method of thermal cycling test for crystalline silicon PV modules

Soh Suzuki[1,2], Tadanori Tanahashi[2], Takuya Doi[3] and Atsushi Masuda[3]
[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 : Though longer service life time is expected for PV modules, existing standards such as IEC 61215, 61730 do not provide the performance assurance in 20 – 25 years. In addition, tests specified in IEC 61215 are not sufficient to guarantee the long-term reliability. Therefore, extension of the test duration and test combination have been implemented in order to ensure long-term reliability.

Purpose : In this study, we have developed the load cycle bending machine with four points and some tests were conducted in order to consider how to accelerate thermal cycling test (TCT).

Fig. 1. Photographs of load cycle bending machine.

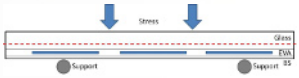


Fig. 2. Images of 4 point stress .

EXPERIMENTS

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 (Fast Cure)	Nondisclosure
Interconnector	A-SPS (Leaded, Ag)	Hitachi Cable
Back sheet	Tedlar / PET / Tedlar	Nondisclosure
Size	540 mm × 200 mm × 4 mm	-

Fig. 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.

Size	540 mm × 200 mm × 4 mm
Young's modulus	73 GPa (7.3 × 10^4 N/mm)
Poisson's ratio	0.21
Specific gravity	2.50 g/cm^3 (2.40 × 10^{-5} N/mm^3)

Fig. 4. Results of 4 point bending test.

In order to estimate the suitable stress condition in the load cycle bending test, simulation was made by assuming the property of glass represents those of PV modules. From the results of simulation as shown in Fig.4, the maximum displacement was calculated to 6.2 mm with the stress of 500N.

RESULTS & DISCUSSION

Table 4. Results of 4 point load cycle bending test.

Tem-perature	Stress direction from	EL Initial	After test	I-V	Break point: Cell crack	Break point: Interconnector break
25℃	Glass side 20,000 times				○	×
	BS side 30,000 times				×	○
-20℃	Glass side 20,000 times				○	×
	BS side 20,000 times				○	×
80℃	Glass side 10,000 times				×	×
	BS side 10,000 times				×	○

Table 5. Results of TCT.

EL Initial	200 cycles	400 cycles	600 cycles	I-V
Enlarged view				

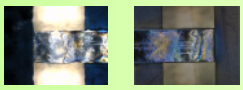


Fig. 5. View from glass side (left) and BS side (right).

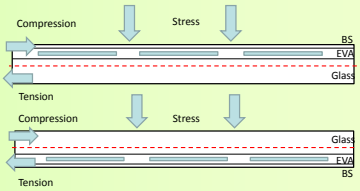


Fig. 6. Image of stress. a) Glass side and b) back side.

1. In case of 25℃, comparison of stress direction → Failure mode was specific, that is, cell crack was observed only in "from glass side" and interconnector break was only in "from BS side". Interconnector break can be confirmed from both side of sample as shown in Fig. 5 by using transparent BS.
2. In case of -20℃ : Only cell crack mode was observed regardless of stress direction. However, the forms were slightly different, that is, cell crack runs vertically to bus bar in "stress from glass side" , on the other hand, it runs diagonally in "stress from BS side". The reason is that EVA's elastic modulus becomes high (stiffer) at -20℃ then the impact from stress transferred strongly to cells, on the other hand, interconnector was subjected lower bending stress.
3. In case of 80℃ : No change was observed in "stress from glass side". The reason is that EVA's elastic modulus becomes low (softer) at 80℃ then the impact from stress was absorbed by EVA. On the other hand, high damage occurs from BS side stress and P_{max} was decreased by 40% since the bending for the interconnector was high.
4. From results of TCT, P_{max} was decreased by about 4% at 200 cycles and decreased slowly thereafter. Cell crack occurred along the bus bar in EL images.
5. The reason for different failure modes between stresses from glass side and BS side is that cell is compressed by BS side stress and receives tension by glass side stress, as shown in Fig. 6.

SUMMARY

In this study, it was found that failure mode is different between TCT and load cycle bending tests. It was possible to accelerate open mode failure in load cycle bending test. Combination of TCT and load cycle bending test seems effective for acceleration.

Contact Person : Soh Suzuki (so-suzuki@espec.co.jp)

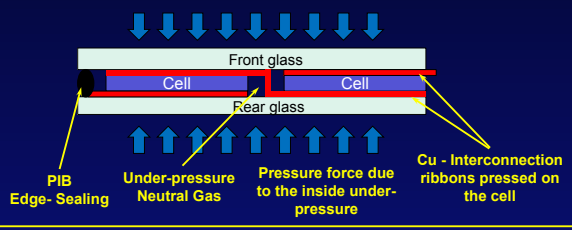
This work was supported by New Energy and Industrial Technology Development Organization under Ministry of Economy, Trade and Industry, Japan.
This presentation contains no confidential information.

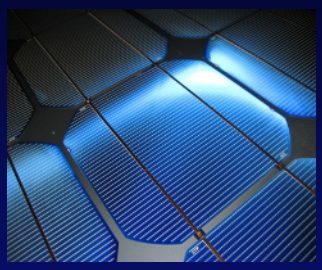
Extended degradation tests of NICE modules to investigate long term reliability

F. Madon, O. Nichiporuk, R. Einhaus
[1]APOLLON SOLAR, 66 cours Charlemagne, F-69002 Lyon, France
Contact email: madon@apollonsolar.com

NICE Module Technology – Overview:

- Reduced module production costs
- Expected increased module lifetime: >30 years
- Compatibility with high efficiency cells





Key benefits :

- No EVA
- No Soldering
- Cost effective
- Ag-busbar free cells
- Short production cycle time
- Full automation
- Low footprint requirement
- Low Module R_s

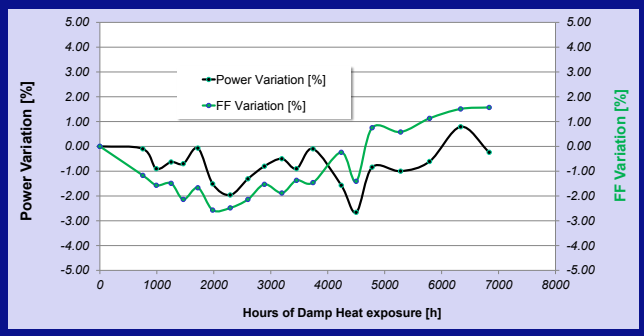
Purpose of this ongoing work:

- Identification and understanding of potential failure modes, particular to NICE modules
- Most suited (combined) degradation tests for NICE modules

Extended Damp Heat Test

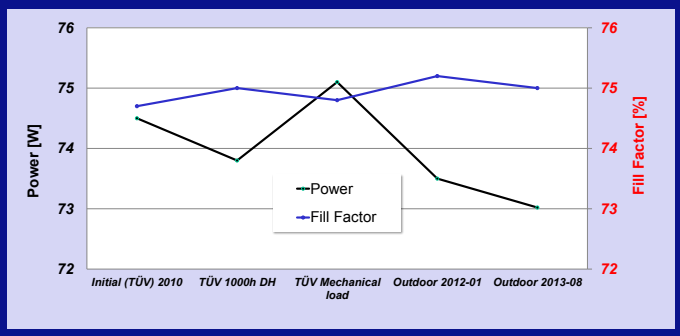
(Collaboration with CEA -INES)

Conditions:
- Standard NICE Module with Heterojunction solar cells
- Damp Heat test + regular monitoring (IV, EL)



Field data – longest serving NICE module

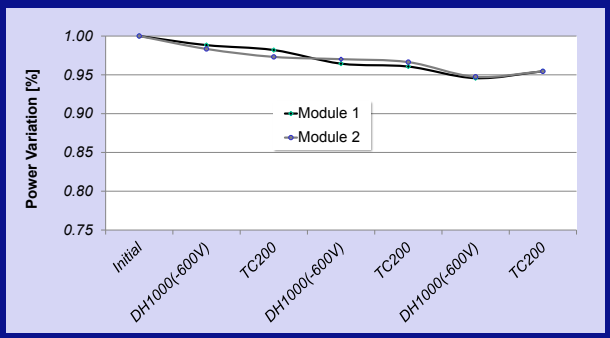
Conditions:
- 36 cells (multi-c) Module from 1st NICE generation
- Damp heat and static mechanical load test during TÜV Certification
- Outdoor exposure for 3 years in France



NREL test-to-failure protocol (PID)

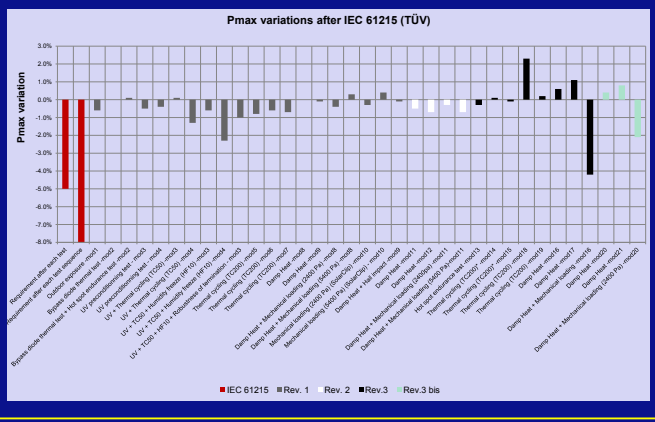
(Collaboration with NREL)

Conditions:
- 2 NICE 60 cells (multi-c) under test
- Alterations between 1000 hours Damp Heat @-600V and 200 Thermo Cycle tests (-40°C -> +85°C)
- Total of 6 rounds during 1 year



Accelerated Ageing Tests/ Certification

Conditions:
- Different Revisions of NICE modules (rev.2 & 3bis frameless)
- Cumulated TÜV Certification results according to IEC 61215 and 61730 parts 1 & 2



Conclusion and outlook

- Moisture ingress and PID excluded as dominating degradation mode on NICE modules
- More and extended field testing under different extreme climatic conditions foreseen
- Different combined tests are planned for further investigation of potential degradation modes
- CEA –INES and NREL are acknowledged for carrying out degradation tests and fruitful discussions

NICE
New Industrial Cells Encapsulation
TECHNOLOGY

Non-Intrusive Cell Quantum Efficiency Measurements of Accelerated Stress Tested Photovoltaic Modules

Brett Knisely[1], Joseph Kuitche[1], Govindasamy TamizhMani[1], Aaron Korostyshevsky[2], Halden Field[2]

[1]Arizona State University Photovoltaic Reliability Laboratory (ASU-PRL), Mesa, Arizona, USA
[2]PV Measurements, Inc., Boulder, Colorado, USA

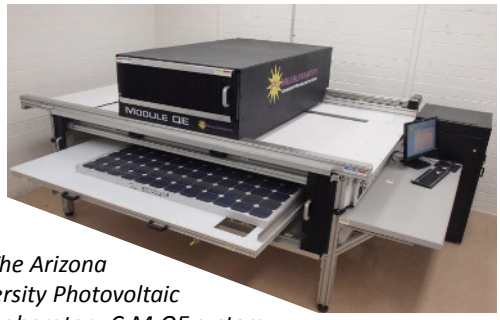


Figure 2. The Arizona State University Photovoltaic Reliability Laboratory C-M-QE system

Cell-Module Quantum Efficiency (C-M-QE) Technique

- Different from Cell QE and Full Module QE
- Measures QE of specific location on individual cell within module
- Avoids backsheet penetration, enabling multiple measurements during multi-step stress tests
- Beneficial for analysis of failures due to stress testing
- Technique involves voltage and light biasing of module, see Figure 1

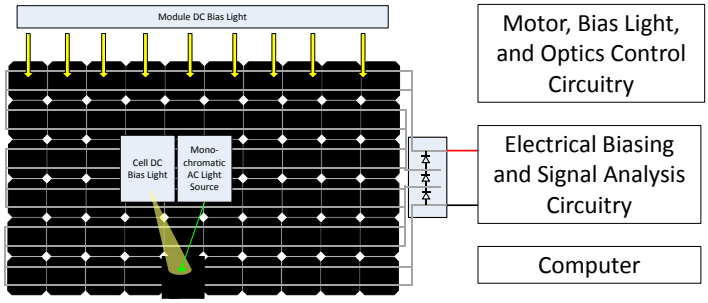


Figure 1. C-M-QE System configuration

Cell QE, Full Module QE, and Cell-Module Quantum Efficiency (C-M-QE) comparison

- **Cell QE** requires electrical connection to the individual cell. In a module, this requires backsheet penetration to access the cell's terminals, preventing subsequent stress tests.
- **Full Module QE** illuminates entire module. Result is current-limiting cell response at each wavelength. Different cells may limit current at different wavelengths. Stress tests may change which cell is limiting.
- **Cell-Module QE** enables one to measure QE at a location of interest, apply stress, and measure the same location again.

References and Acknowledgement

[1] J.-J. Li, S. H. Lim, and Y.-H. Zhang, "A novel method to eliminate the measurement artifacts of external quantum efficiency of multi-junction solar cells caused by the shunt effect," SPIE 8256, page 616, Physics, Simulation, and Photonic Engineering of Photovoltaic Devices, 2012.
[2] J. Oh, S. Bowden, and G. TamizhMani, "Application of reverse bias recovery technique to address PID issue: Incompleteness of shunt resistance and quantum efficiency recovery," Abstract submitted, IEEE PVSC, 2014
[3] J. Oh, G. TamizhMani, and S. Bowden, "Scaling Error of Quantum Efficiency Measurements for Heavily Shunted Cells in Reliability Research," Abstract submitted, IEEE PVSC, 2014

The funding support of Science Foundation Arizona (SFAz) is gratefully acknowledged.

Measurement Validation

- QE scaling affected by extent of stress, see Figure 3
- Scaling artifact understood to be due to stress-induced cell shunting
- Authors are interested in exploring use of pulsed voltage and/or pulsed light bias to counteract signal loss due to cell shunting [1]

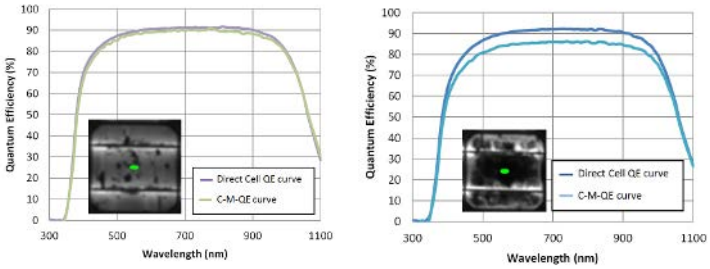


Figure 3. Example QE Measurements showing scaling artifact. Green spot superimposed on EL image indicates tested location

Use case example

- QE of an encapsulated silicon solar cell coupon before and after PID stress, see Figure 4
- Scaling understood to be due to stress-induced cell shunting
- Explanation of permanent loss of blue response explained elsewhere [2]

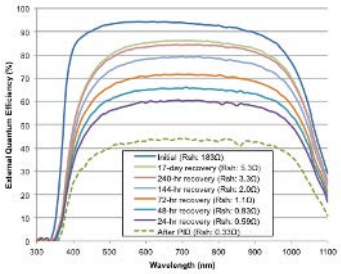


Figure 4. Cell QE Measurements showing wavelength-dependent PID-induced loss [3]

Summary

- Useful Cell-Module QE measurements require module-level light and voltage bias.
- Cell-level light bias not found to have significant influence on QE measurement of crystalline Si module.
- QE of stressed cells reveals information about wavelength-dependent module failure mechanisms.

Govindasamy TamizhMani
manit@asu.edu
www.asu.edu

Halden Field
halden@pvmeasurements.com
www.pvmeasurements.com

PVMRWS – 2014

Utilization of PV module microclimates to establish pathways to accelerated weathering protocols

Presented by:

Nancy Phillips, 3M Company and Kurt Scott, Atlas Material Testing Technology

(Reporting on work being done by weathering group)

Motivation:

"Outdoor testing is a must, but it takes m too long to be of much use as a decisio maker. We clearly can not wait 25 yea even a significant fraction of 25 years t introduce a new product. Therefore we must develop and utilize accelerated te to qualify these new products."

John Wohlgemuth

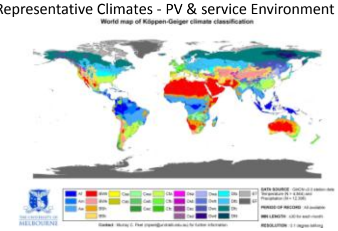
Accelerated Weathering Goals

- Capture the degradation reactions doing the bulk of the damage in the microclimate
- Ignore degradation reactions not occurring in the microclimate
- Compress the test duration to get results comparable to real life.

- All of the above are material specific: what to do to for a test that is aiming to be not material specific?

Considerations:

Representative Climates - PV & service Environment



Considerations:

- Representative Climates:

Hot Arid

(e.g. Phx , AZ)

Northern Temperate

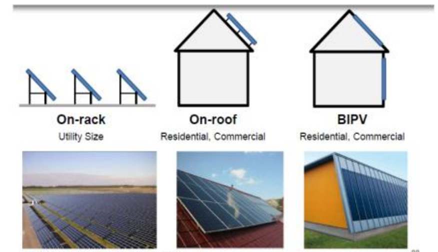
(e.g Sanary, Fr)

Tropical\Subtropical

(e.g. Mia. FL)

Ground Cover Reflection - Albedo

Module Mounting



Climate Data Analysis

Irradiance Data

Goal: establish references for:

- Irradiance set points
- Dosage levels by climate/application

Reviewed Maximum for pre-selected Geographies

Spectral Irradiance at 340 nm (W/m2/nm)

- Data from:
  - Handbook of Material Weathering, 3rd Ed., 2003
  - Atlas Data
- Value depends on:
  - Latitude
  - Humidity/cloud cover/pollution
    - Lauder, New Zealand: → 0.91
  - Time of year
    - AZ, winter solstice → 0.37
    - AZ, summer solstice → 0.70
  - Elevation
    - Boulder, CO, USA; September: → 0.90

date	Season	Location	Solar 339-340 (W\m2\nm)
3/21/2001	Spring\Fall Equinoxes	Phoenix	0.63
6/21/2001	Summer Solstice	Phoenix	0.7
12/21/2001	Winter Solstice	Phoenix	0.37
3/21/2001	Spring\Fall Equinoxes	Miami	0.64
6/21/2001	Summer Solstice	Miami	0.69
12/21/2001	Winter Solstice	Miami	0.52
3/21/2013	Spring Equinox	Sanary	0.58
6/21/2013	Summer Solstice	Sanary	0.7
1/21/2013	Winter Solstice	Sanary	0.34

Typical Max: (at 340 nm) = 0.7 W/m2/nm

Total Irradiance data and analysis – Phoenix

		front side				backside (refl = 10%)
Location	**Appl. Type**	**Total Solar (MJ/m2)**	**TUV (5% of TS) (MJ/m2)**	**%TUV/Total Solar from data**	**TUV (MJ/m2)**	TUV Bkside MJ/m2
Desert (Phoenix)	lat-rack	8612	431	4.03	347	35
Desert (Phoenix)	track	11948	597	4.50	538	54
Desert (Phoenix)	roof	7850	392	4.50	353	0

Total Solar data:

- From Meteonorm 7.0, compares well to Atlas data (all based on TS = 290-3000nm)
- "Roof mounting" defined as = 5 degree, south facing
- %TUV data: Rack and Roof data from AWSG 10 year average 1999-2008

Backside Irradiance Data:

- 3M, May 2011 at DSET:
  - TS on backside as % of TS on front side = ~10%
  - UV on backside as % of TUV on front side = ~7%
- DuPont: 12% (TS data) => %TUV ~10%
- Fraunhofer: %TUV varies between
  - 5% for 23° (south-oriented POA) and
  - 20% (vertical mounting) of the horizontal UV irradiation.

Miami, Phoenix & Sanary - Time to Dose *– 1 yr equivalence in Xe @ 0.7 w/m²/nm @ 340nm*

				front side			backside (refl = 10%)		
Location	**Appl. Type**	**Exp**	**AnnualTotal Solar (mod) (MJ/m2)**	**Annual TUV (MJ/m2)**	**time to 1 year dose @ 0.7**	**tcf**	**Annual TUV Bkside (MJ/m2)**	**time to 1 year dose @ 0.7**	**tcf**
Desert (Phoenix)	lat-rack	34	8612	347	1354	6	35	135	65
Desert (Phoenix)	track	2 axis	11948	538	2097	4	54	210	42
Desert (Phoenix)	roof	5	7850	353	1378	6	0	0	
Temperate (Sarany, FR	lat-rack	45	6848	226	881	10	23	88	99
Temperate (Sarany, FR	track	2-axis	9481	341	1331	7	34	133	66
Temperate (Sarany, FR	roof	5	6116	220	859	10	0	0	
Hot/Wet (Miami)	Rack	26	6750	334	1303	7	33	130	67
Hot/Wet (Miami)	Track	2 axis	8711	415	1617	5	41	162	54
Hot/Wet (Miami)	Roof	5	6475	334	1303	7	0	0	

Temperature Data

- Goal:
  - Establish a target temperature to represent the microclimates
    - Average T
    - Max T
    - "Typical Max T"
    - Effective T (materials specific)

Phoenix Module – Modeled and measured

Temperature of Buildling Applied Photovoltaic BAPV Modules: Air Gap Effects (Tamizhmania et al)

Mani's paper	Roof		
Tmodule (max) obs.	92.73C		
Roof model, no wind	Tm= 0.05(Irrad) + 0.64*Tamb+15.82		
	Ir	Tamb	Wind speed
	993.5	41.9	1.2
Tmodule (max))calc.	89.9		

Highest Tmod

Date	10/17/2009
Time	12:42
Tamb (°C)	41.9
Irradiance (W/m2	993.5
Wind Speed (m/s)	1.2
module T	**92.7**
ΔT	50.8

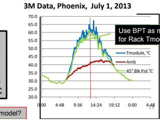
Phoenix
Calc Tmodule (max):

Tmodule, Roof: 90°C
Tmodule, Rack: 70°C
Tmodule, Track: 70°C

Evaluation of High Temperature Exposure of Rack Mounted Photovoltaic Modules (Kurtz et al)

NREL 2009 paper, Max Tmod (location not specified)	Rack	Tmax=75C	
	Roof	Tmax=96C	
Tmodule, using Mani's data:			
Rack Model, Tm=Tamb + Irr*e(-3.473-0.0594*WS)			72.7
Roof Model, Tm=Tamb + Irr*e(-2.98-0.0471*WS)			89.6

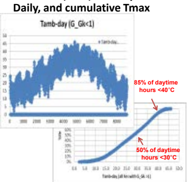
3M Data, Phoenix, July 1, 2013



What temperature to feed the model?

Phoenix Ambient Temperatures

Phoenix T(amb) over 1 year. Daily, and cumulative Tmax



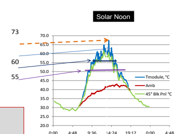
Plan

- Analysis:
  - Define ambient conditions
  - Model module temperatures
  - Where available, compare to module data
- Translation to T during Accelerated Weathering:
  - **Philosophy: run at or near maximum conditions all the time**
- Consider concept of **"Typical Max T"**
  - 85%ile T
  - For Phoenix: **Typical Max T(amb) = 40°C**

Temperature Setting Options

(Rack Mounted)

- Plausible "max Tmod"
  - NREL model, w Tamb (max) °C — 73
  - Actual Tmod (max) 68 °C
  - "Average" Tmod (max) °C — 60
  - "Typical Max" Tmod (85th%) °C — 55



- Goal:
  - A temperature that will
    - Accelerates actual degradation mechanisms
    - Limit mechanisms that do not occur

Estimating Module Temperatures: BPT, and Calculated from "Typical Max T(amb)"

- Rack Mounted:
  - A. Modeled T(amb) = "Typical Max"
  - B. 85th %ile BPT.
- Roof Mounted:
  - Model with Typical Max
- Will be collecting real data
- Key question:
  - What's the "right" or "best Temperature setting?

Rack Mount	Ir	"Typical Max" Tamb	Tmodule (Calc w/ Typ max)	85th %ile BPT
Sanary	967	27	57.0	44
Phoenix	994	42	72.7	
Miami	1050	33	65.6	49

*Rack Model, Tm=Tamb + Irr*e(-3.473-0.0594*WS)*

Roof Mount	Ir	"Typical Max" Tamb	Tmodule (Calc w/ Typ max)
Sanary	943	27	80.3
Phoenix	994	42	92.3
Miami	950	33	84.4

*Roof Model: Tm= 0.05(Irrad) + 0.64*Tamb+15.82*

Humidity Data

Goal: Establish a target humidity to represents each microclimate

- Options
  - Maximum %RH
  - %RH at Maximum T
  - RH (wa)
  - Moisture content

Relative Humidity: Some typical days

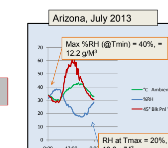
Using Moisture Content to understand microclimate humidity

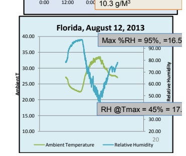
Arizona

T	RH	g/M3	RH (est)
30	40	12.2	
40	20	10.3	
70		11	5.5
90		11	2.6

Miami

T	RH	g/M3	RH (est)
22	95	16.5	
35	45	17.9	
70		17	8.6
90		17	4.1





Summary: Microclimate Descriptors

Indicated RH numbers

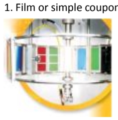
Location	Appl. Type	Exp	side	TUV (annual)	Max Irr	Max T (calc)	Typical Max BPT	RH(wa)
Desert (Phoenix)	lat-rack	34	front	347	0.7	73	55	10
Desert (Phoenix)	track	2 axis	front	538	0.7	73	55	10
Desert (Phoenix)	roof	5	front	353	0.7	92	na	3
Temperate (Sarany, FR	lat-rack	45	front	226	0.63	57	44	25
Temperate (Sarany, FR	track	2-axis	front	341	0.63	57	44	25
Temperate (Sarany, FR	roof	5	front	220	0.63	80	na	10
Hot/Wet (Miami)	lat-rack	26	front	334	0.65	66	49	36
Hot/Wet (Miami)	Track	2 axis	front	415	0.65	66	49	36
Hot/Wet (Miami)	Roof	5	front	334	0.65	84	na	14
Desert (Phoenix)	lat-rack	34	back	35	0.07	73	55	10
Desert (Phoenix)	track	2 axis	back	54	0.07	73	55	10
Desert (Phoenix)	roof	5	back	0	na	92	na	3
Temperate (Sarany, FR	lat-rack	45	back	23	0.07	57	44	25
Temperate (Sarany, FR	track	2-axis	back	34	0.07	57	44	25
Temperate (Sarany, FR	roof	5	back	0	na	80	na	10
Hot/Wet (Miami)	lat-rack	26	back	33	0.07	66	49	36
Hot/Wet (Miami)	Track	2 axis	back	41	0.07	66	49	36
Hot/Wet (Miami)	Roof	5	back	0	na	84	na	14

Summary of Xe (340) Setpoint Options

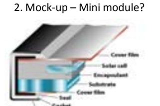
- Xe @ 340 setting (W/m2):
  - 1.4
  - 0.7
  - 1.1
  - 0.5
- Temperature (°C)
  - 70 (WPT)
  - 90 (WPT)
  - 70 (BPT)
- Humidity (%RH)
  - 50% (@ 70°C
  - Uncontrolled at 90°C
  - Uncontrolled at 70°C
  - 15% at 90°C
  - 35% at 70°C

Specimens – what to test?

1. Film or simple coupon?



2. Mock-up – Mini module?



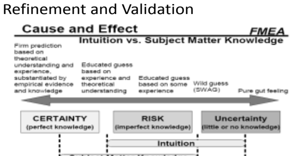
Depends on question being asked –

- opt 1. Materials Screening – A better than B? - **suitable for IEC 62788*?**
- opt 2. Will there be attachment issues over time? – **a must for IEC 61730-2** & 61215**
- opt 2. Will safety be maintained in PV stack ? – a **must for IEC 61730 & 61215*****

* MEASUEMENT PROCEDURES FOR MATERIEALS USED IN PHOTOVOLTAIC MODULES
**PHOTOVOLTAIC (PV) MODULE SAFETY QUALIFICATION – PART 2: REQUIREMENTS FOR TESTING
*** CYSTALINE SILICON TERRESTRIAL PHOTOVOLTAIC (PV) MODULES- DESIGN QUALIFICATION AND TYPE APPROVAL

Future work – Consensus & Validation

- Addressing Open questions
- Developing Interim standards e.g. "Qualification plus"
- Refinement and Validation



Mechanical Load Test Optimization

Dohyun Baek, Ph. D
Samsung SDI

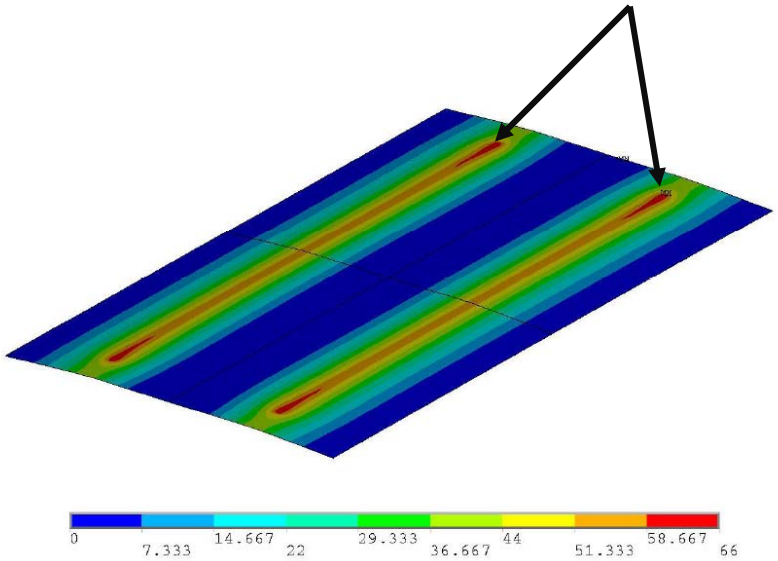
Objective

- Issues
  - How to distribute loads evenly on PV module?

- Mechanical Load System Optimization
  - CAE simulation & optimization
  - Measurement Data(54 pts) + Simulation Correlation
  - Stress Distribution Profile
  - Glass Stress Profile
  - Glass + Cell Stress Distribution Profile
  - Stress Profile at Clamp Location
  - Stress Profile at Cell Thickness

Mechanical Loading Stress Theory

Heavy tensile stress area

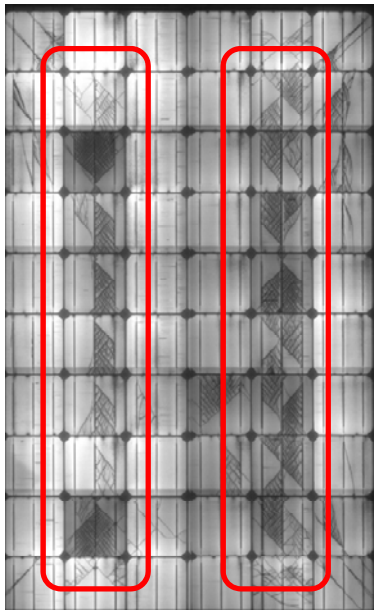


Heavy snow load glass tensile stress

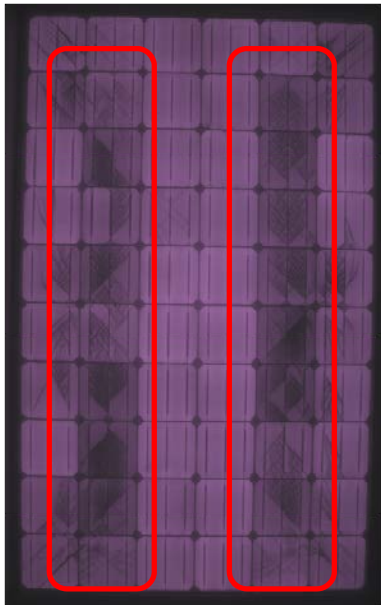
James E. Webb, 24th European Photovoltaic Solar Energy Conference and Exhibition, Hamberg, Germany 2009

Cell Cracks by EL Image

Sand



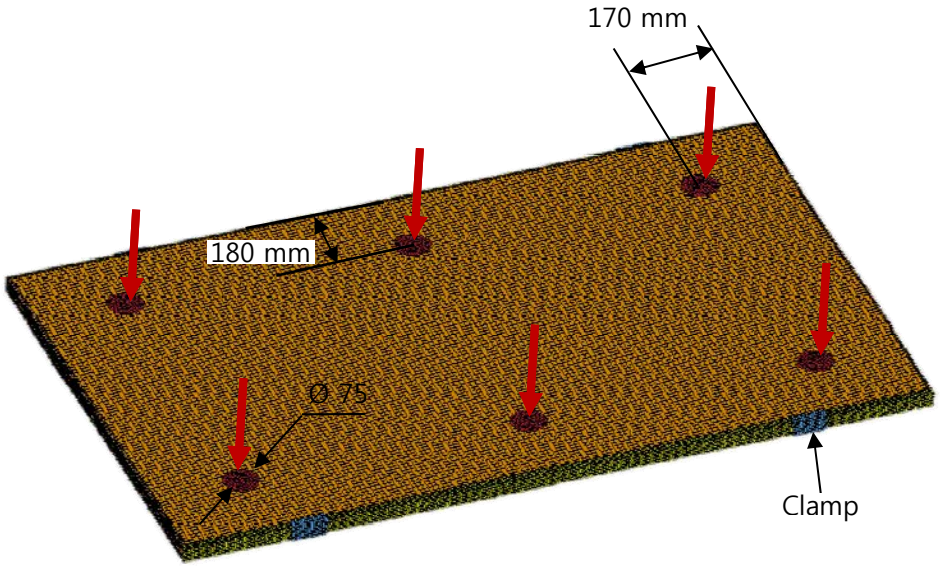
MLT System



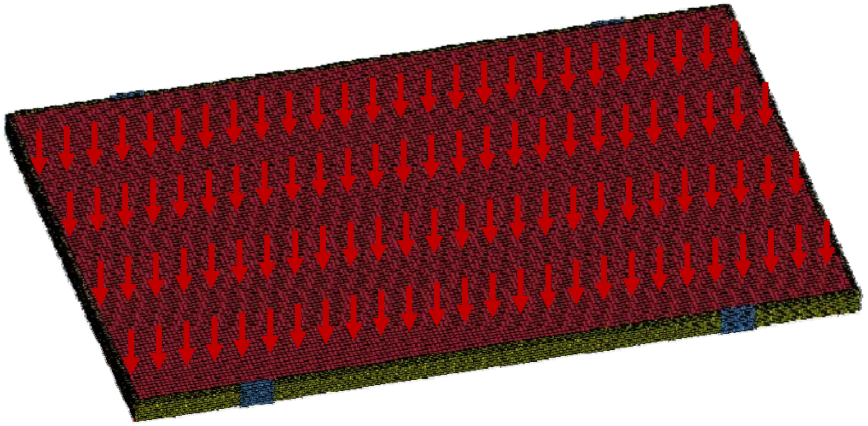
Tensile Stress vs. EL image
Cell crack distribution is similar
⇒ Cell crack by tensile stress

CASE I: CAE Simulation Condition

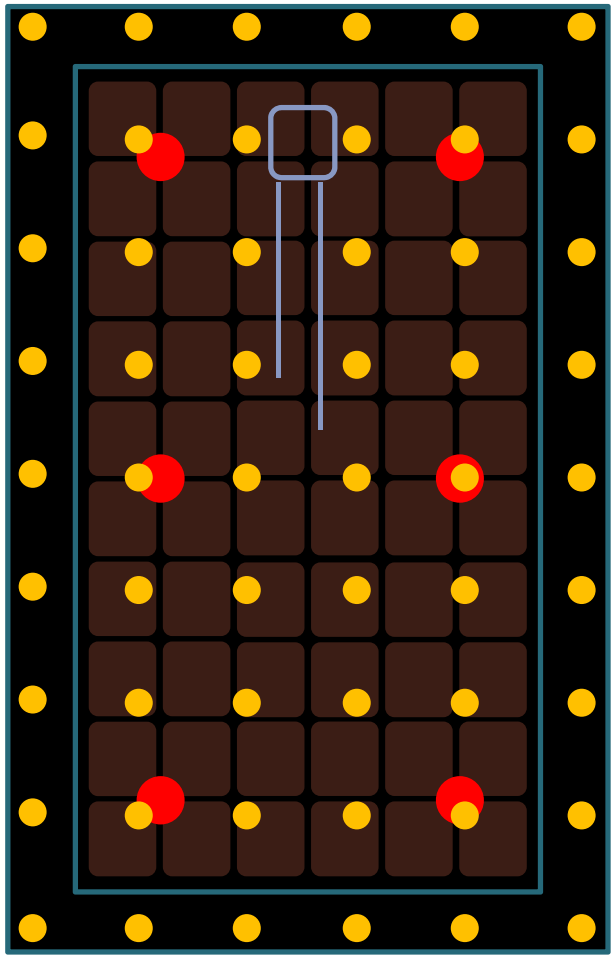
6 Stress Points



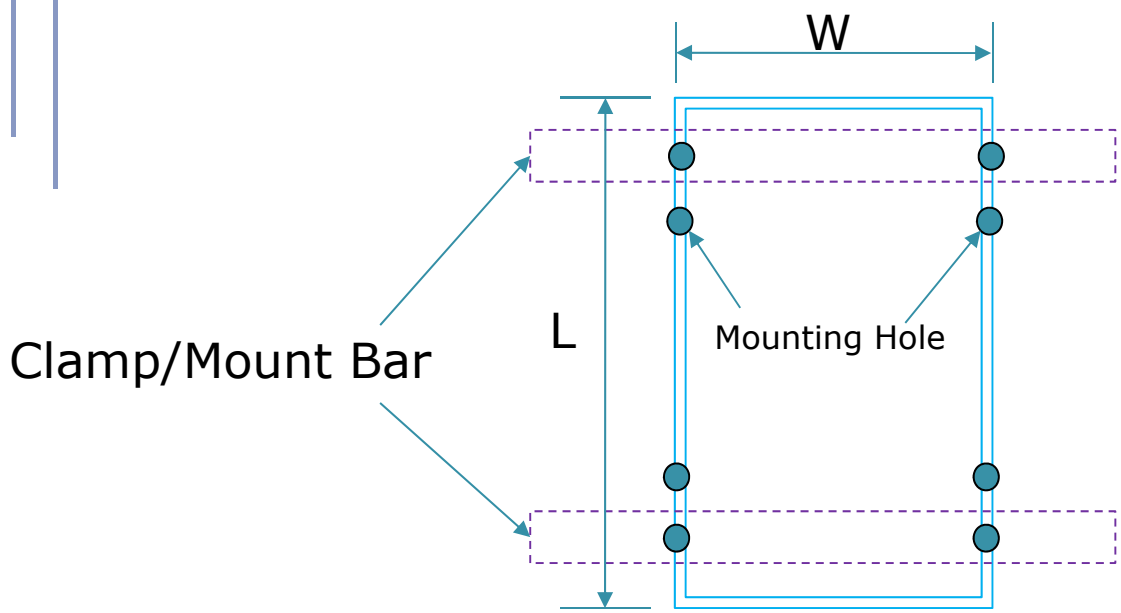
Uniform Stress



CASE I: Measurement Points

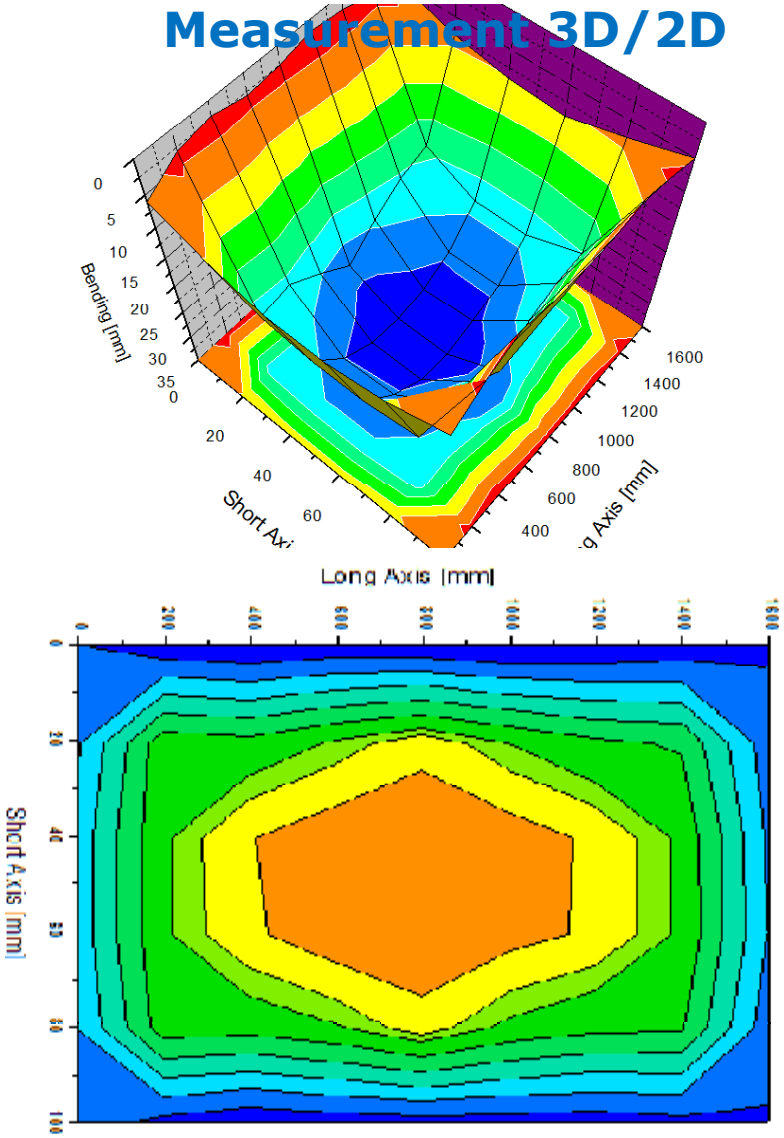


- Measurement Points
- Pressure Points
- Solar Cells
- Junction Box

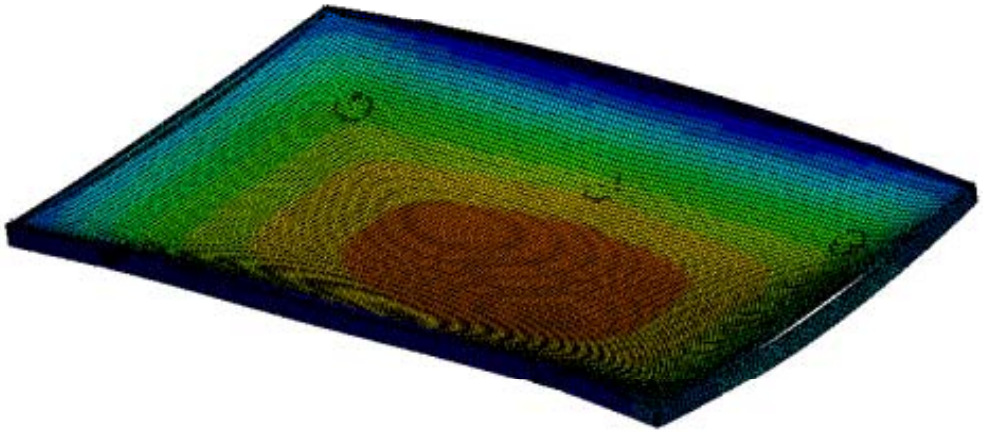


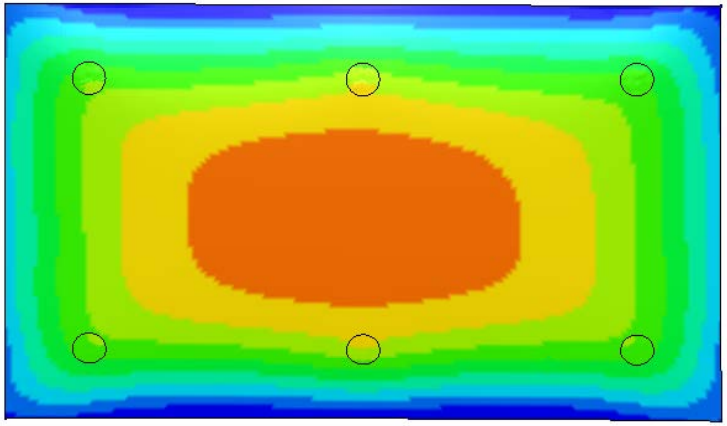
CASE I: Bending Measurement vs. Simulation

Measurement 3D/2D



Simulation 3D/2D

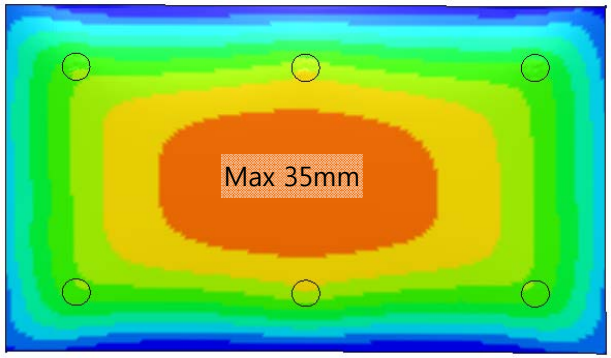




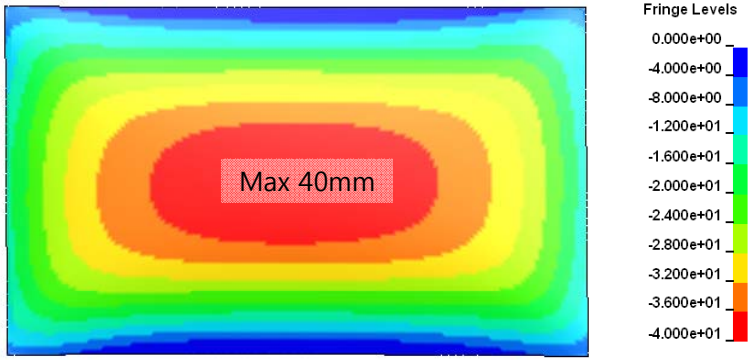
CASE I: Stress Distribution

- Deflection
  - Uniform stress > Measurement
- Glass Stress
  - Stress distribution is similar

Deflection (mm)

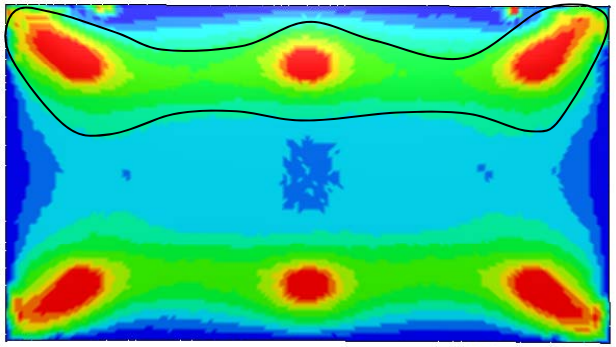


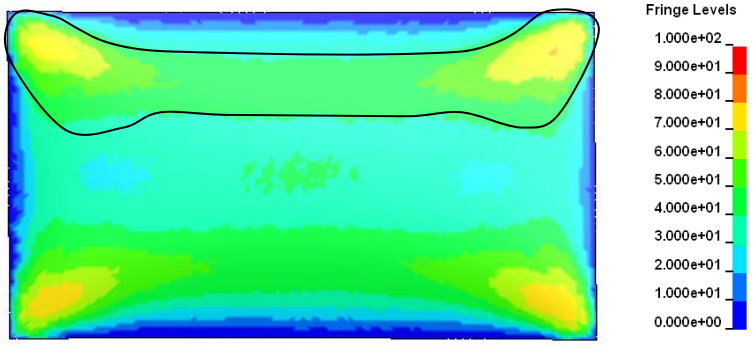
6Point Load



Uniform Load

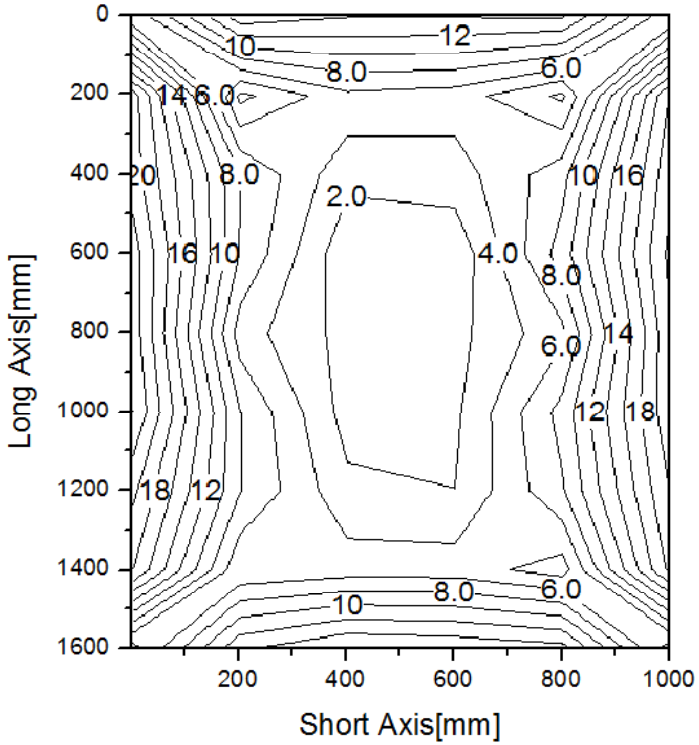
Panel Stress (Mpa)



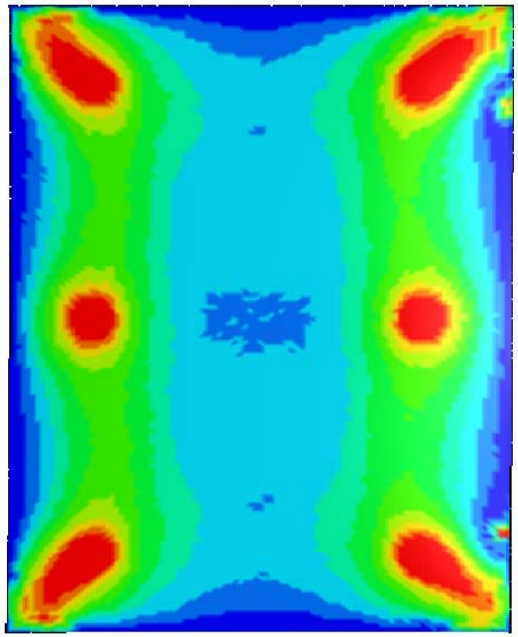


CASE I: Calculation vs. Simulation

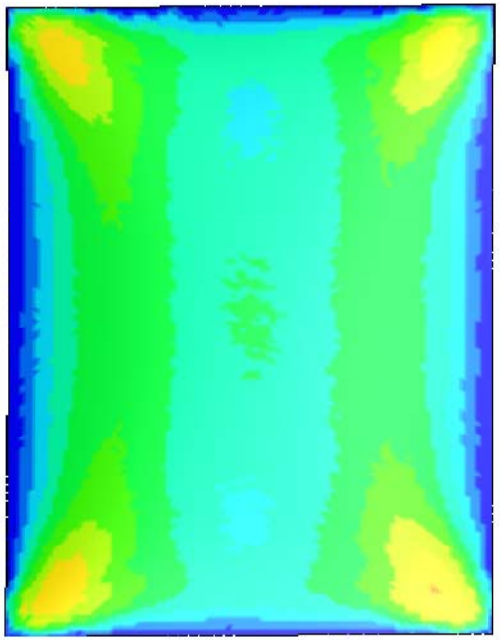
Analytical Calculation



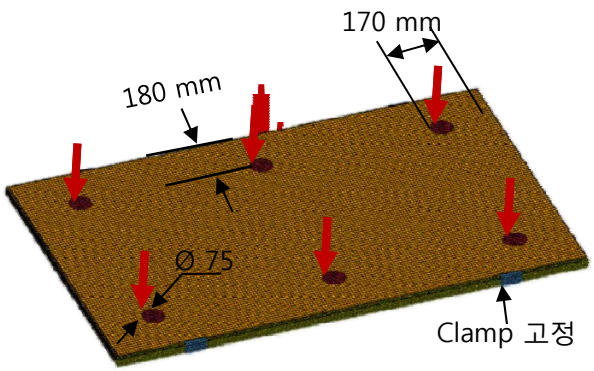
6 Point Simulation

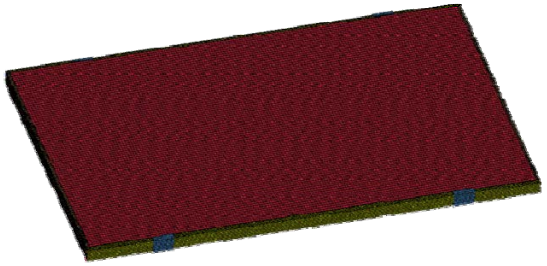


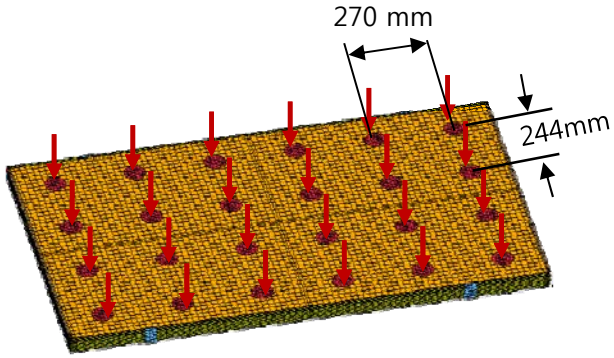
Uniform Simulation



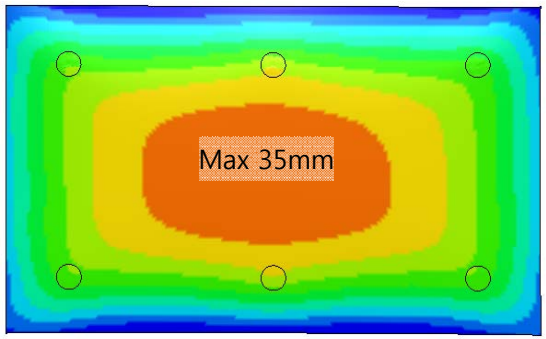
CASE II: 6 PAD vs. 24 PAD Comparison



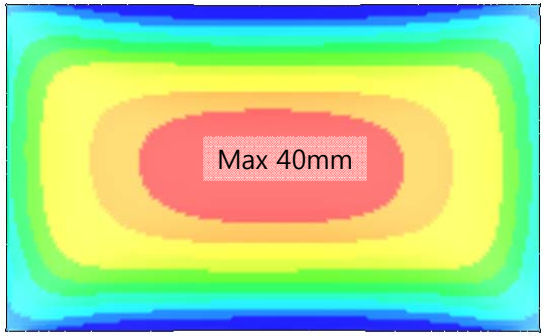




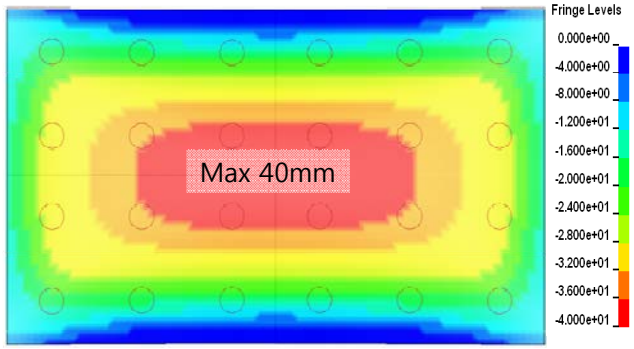
6Point



Uniform

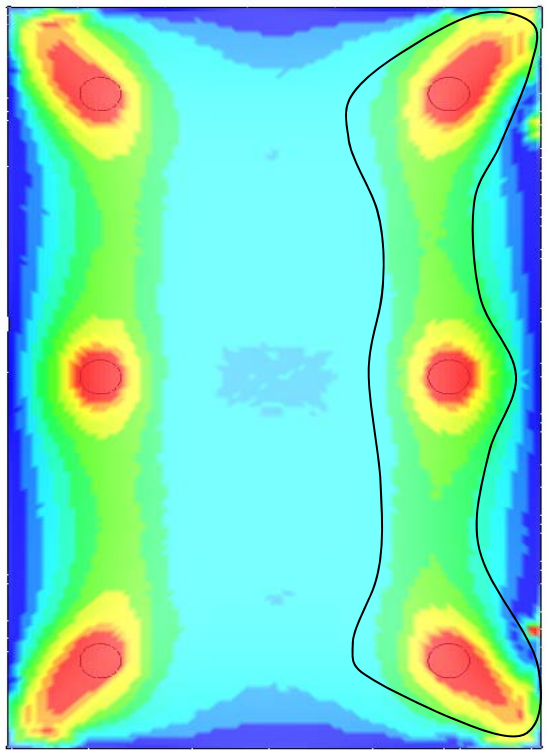


24Point

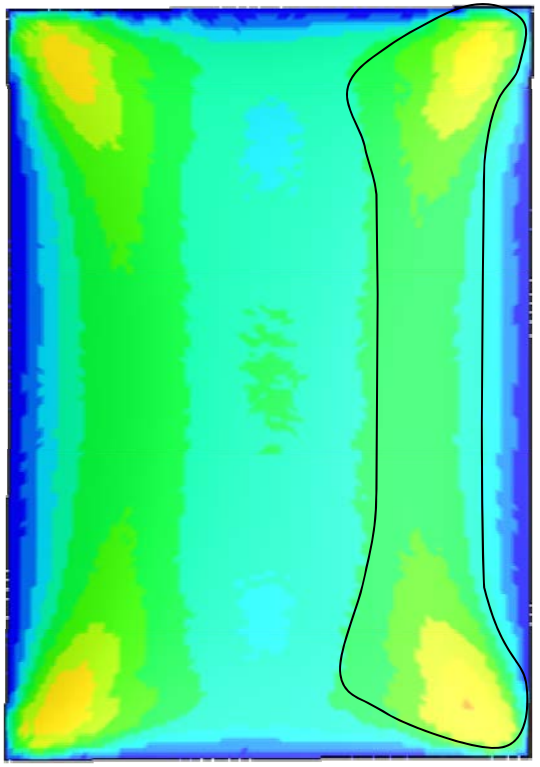


CASE II: 6 PAD vs. 24 PAD Comparison

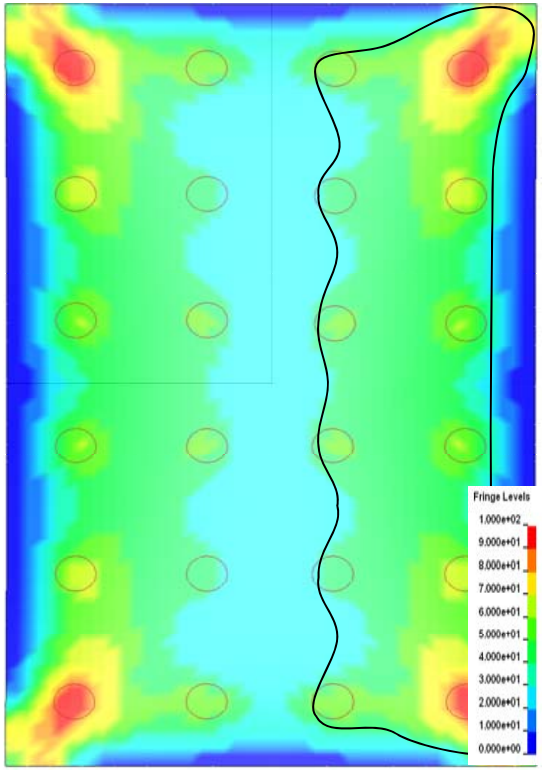
6Point



Uniform

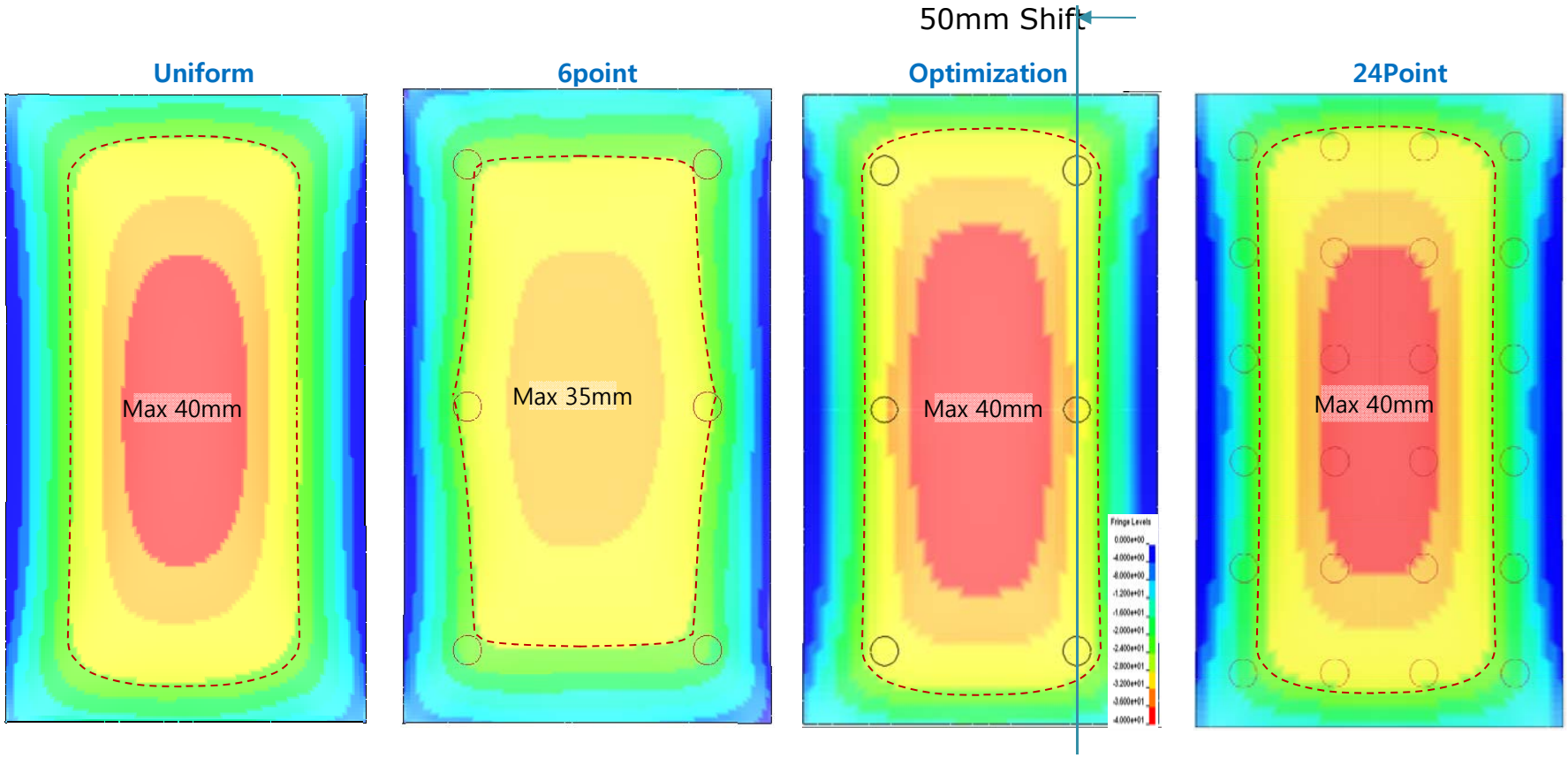


24Point

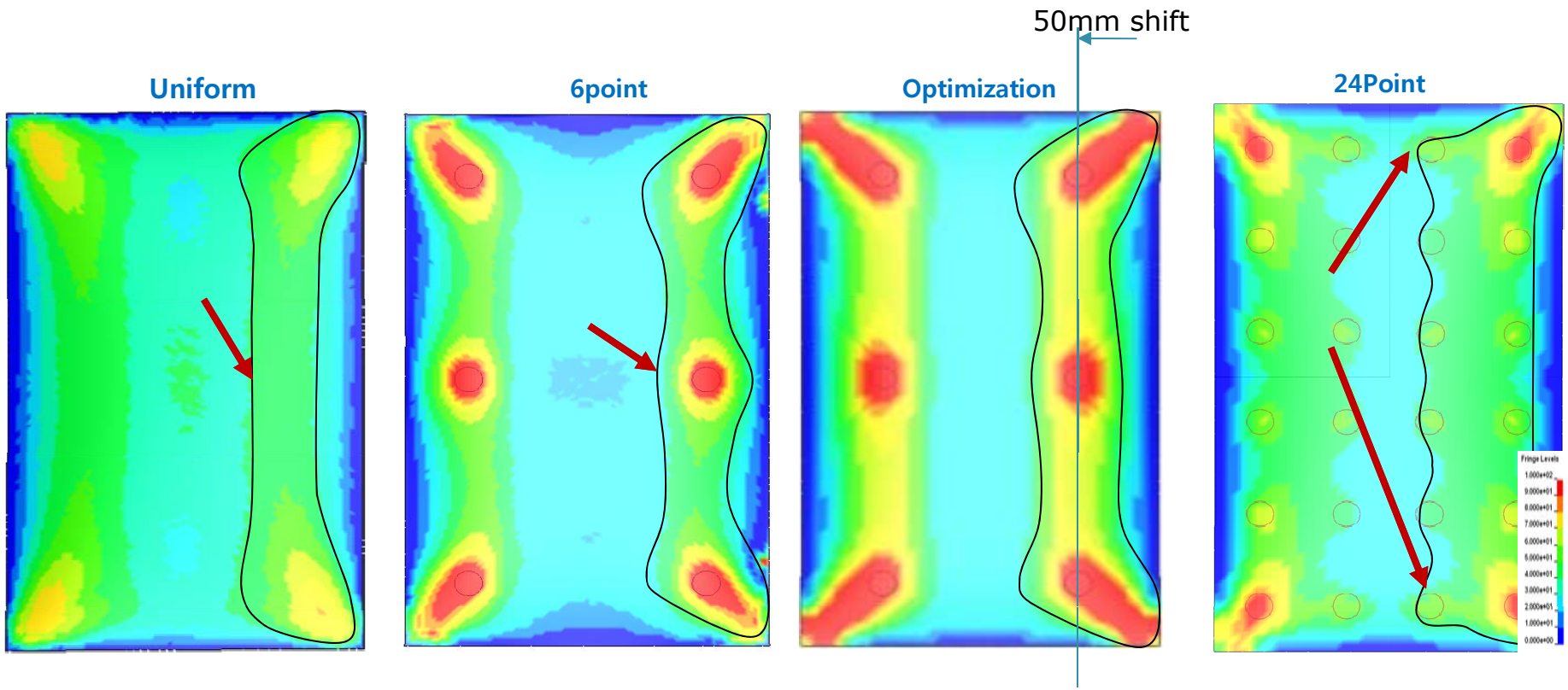


CASE III: Deflection Optimization

- Glass deflection optimization
  - Move points to center by 50mm



CASE III: Stress Optimization



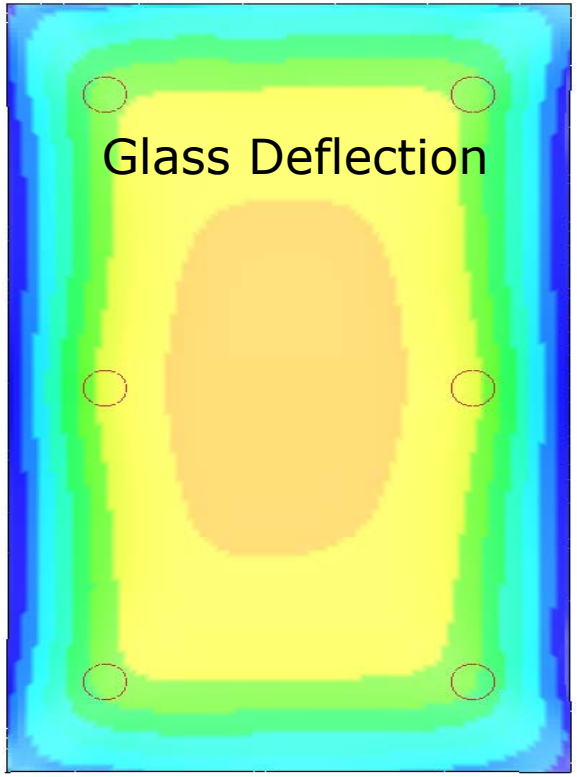
CASE IV: Cell Crack Analysis

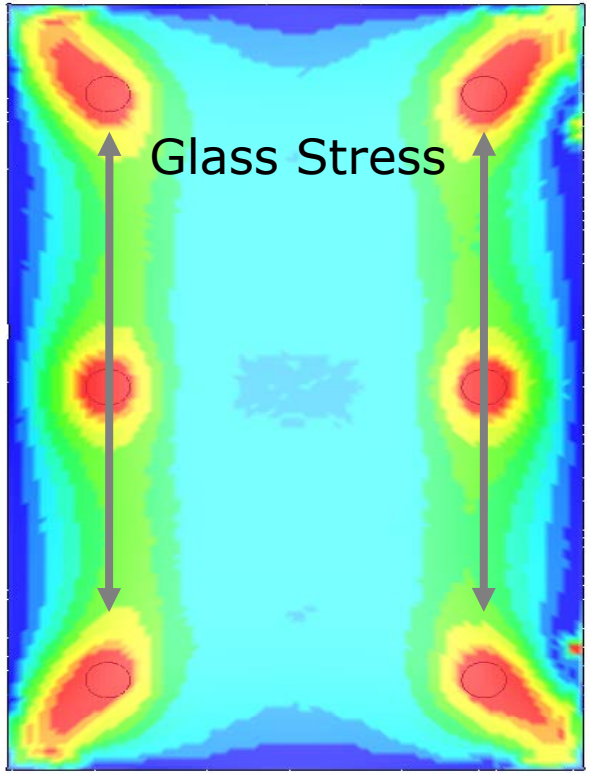
- Objective
  - Cell stress analysis by deflection and stress
  - Cell stress at clamp position
  - Cell stress for wafer thickness

Clamp position & Wafer Thickness

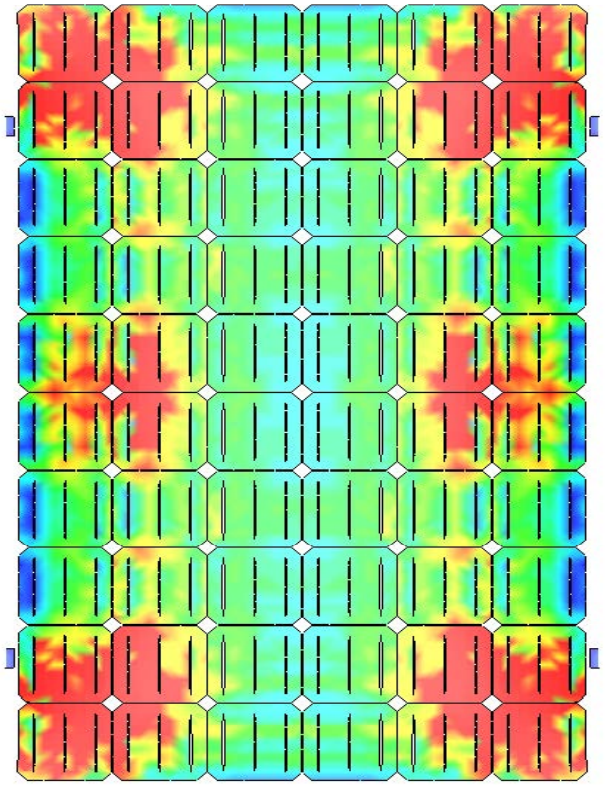
Case	Clamp (mm)	W1 (mm)	Wafer Thickness (um)
Default	260	180	200
1	260	230	200
2	0	180	200
3	130	180	200
4	330	180	200
5	260	180	180

CASE IV: Cell Crack Analysis



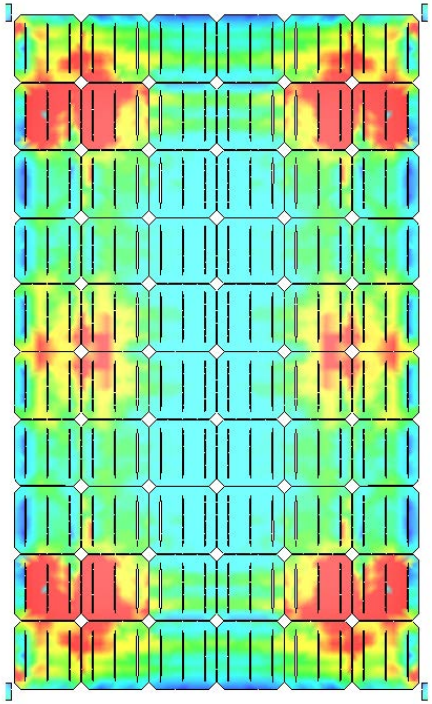


Cell Stress

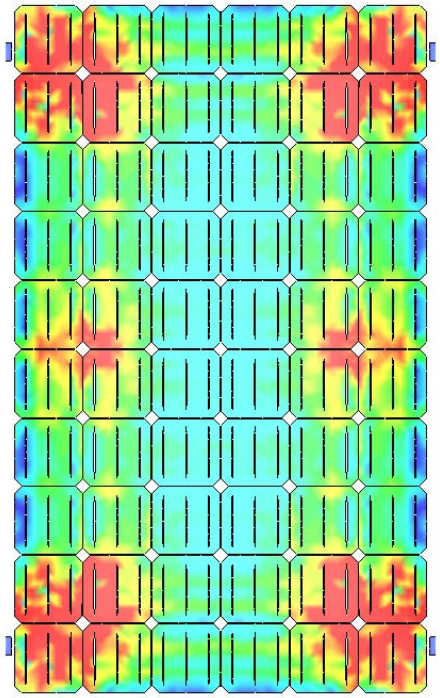


CASE IV: Cell Crack Analysis

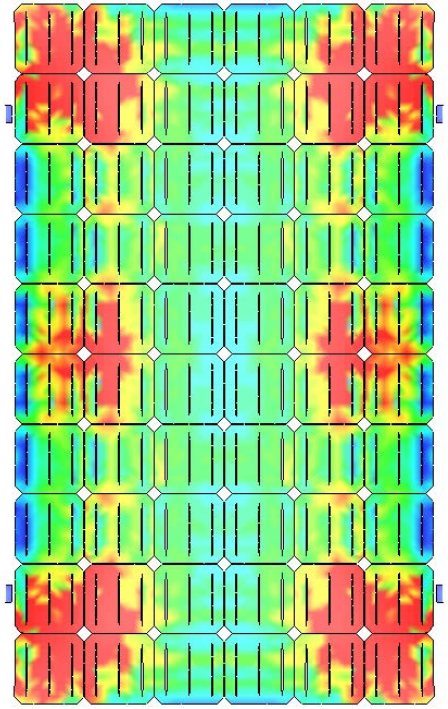
Edge Clamp
0mm



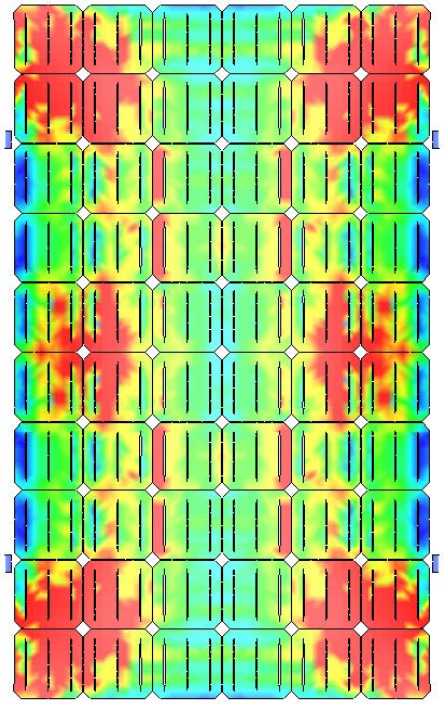
1/12 Clamp
130mm



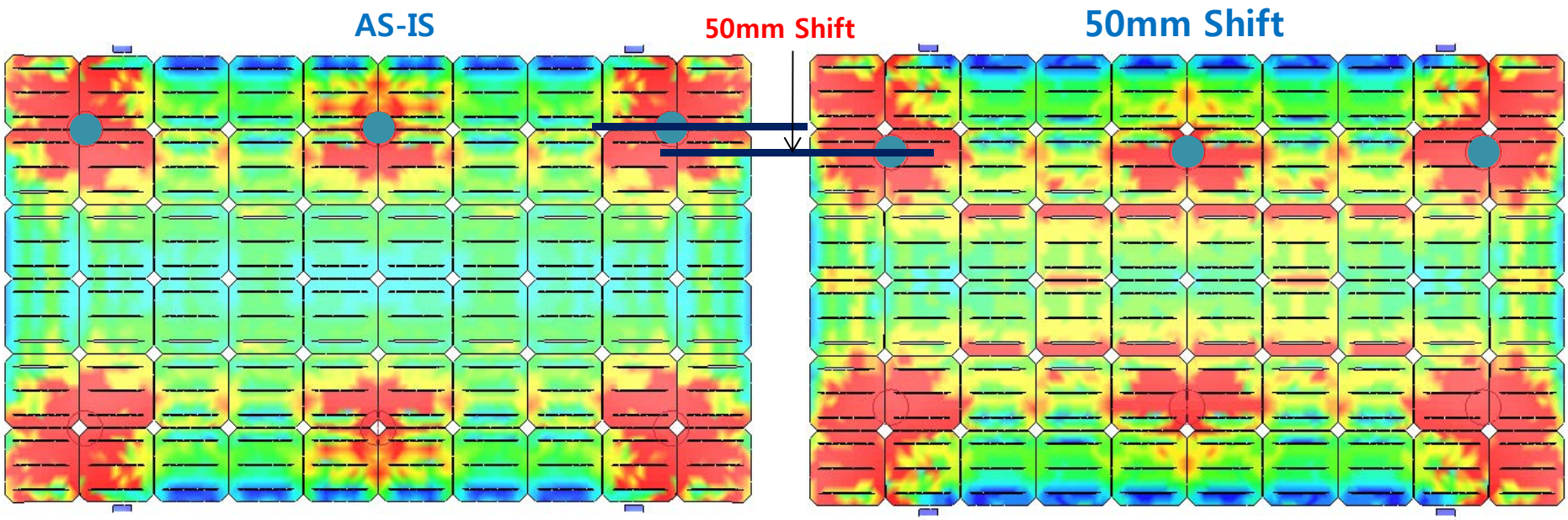
1/6 Clamp
260mm



1/5 Clamp
330mm

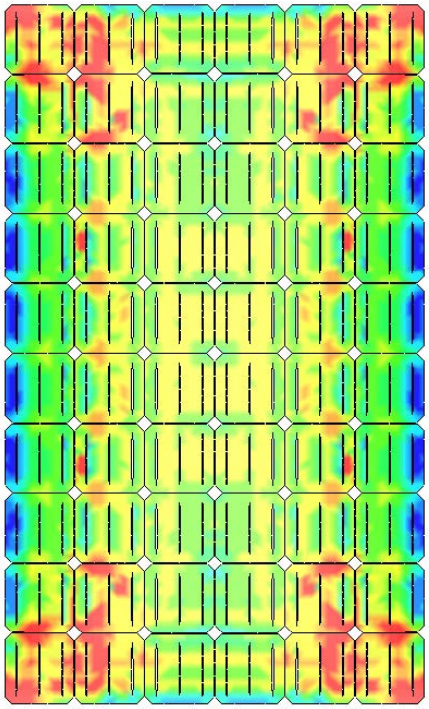


CASE IV: Cell Crack Analysis

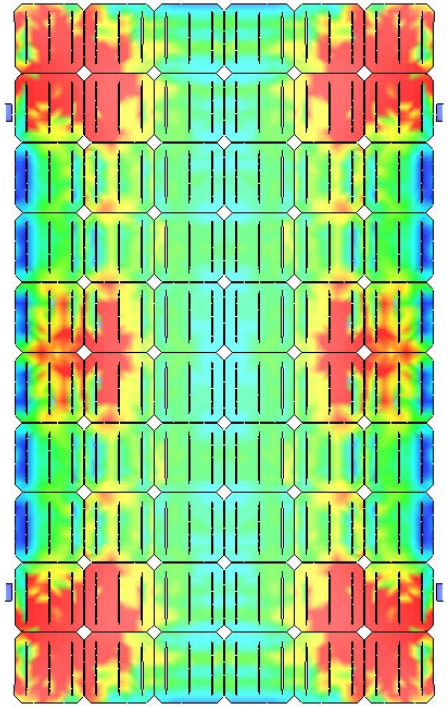


CASE IV: Cell Crack Analysis

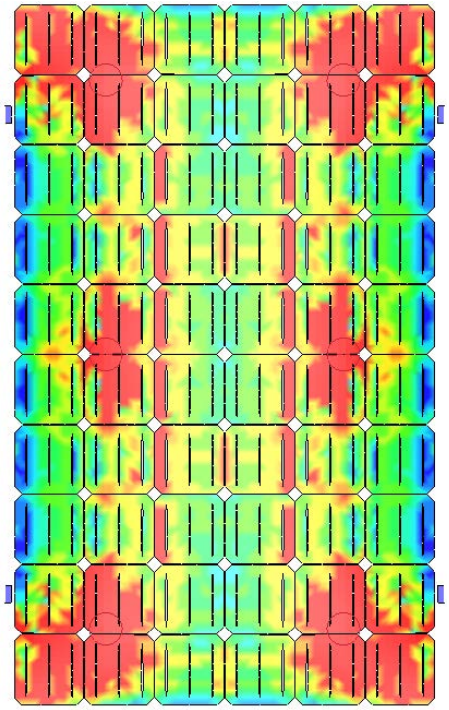
Uniform



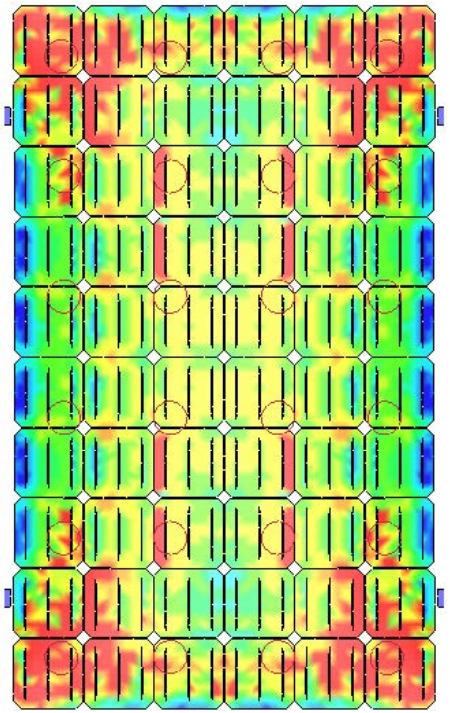
6point



Optimization



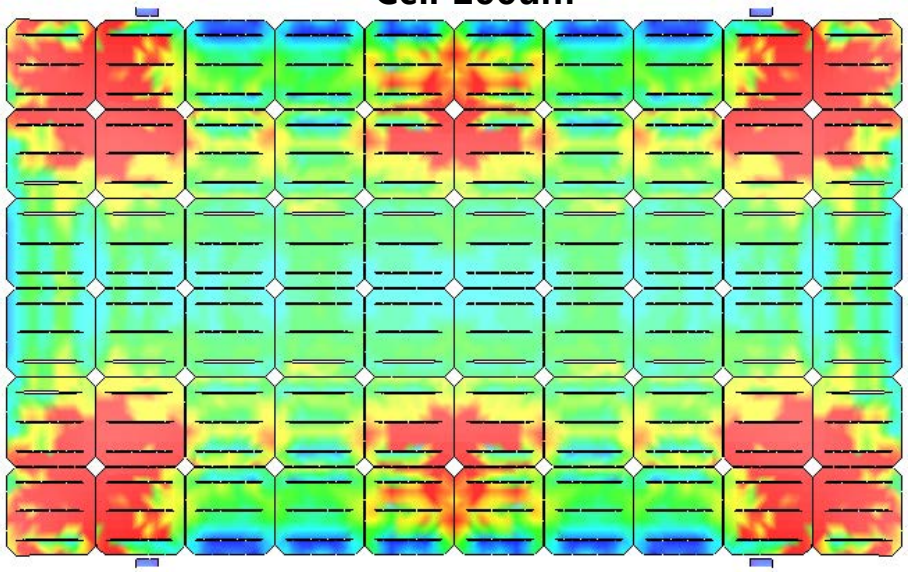
24point



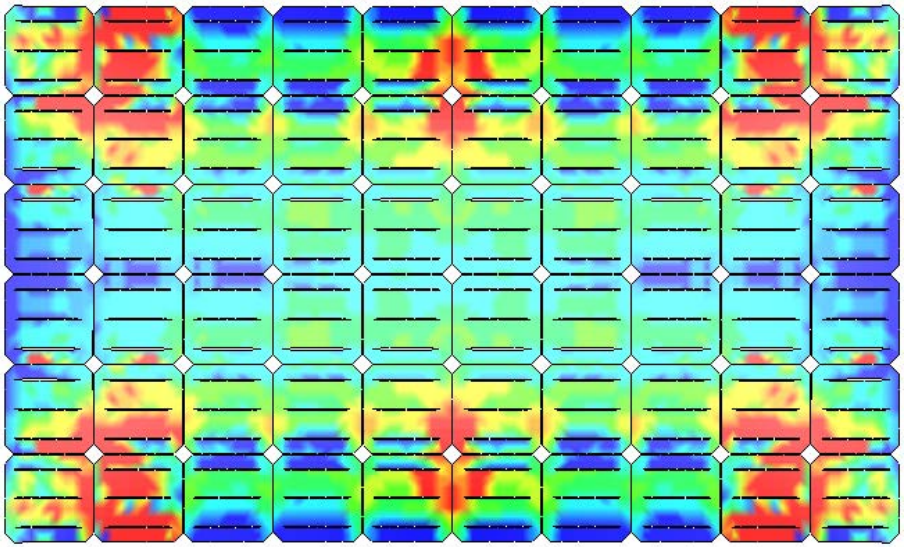
CASE IV: Cell Crack Analysis

6point

Cell 200um



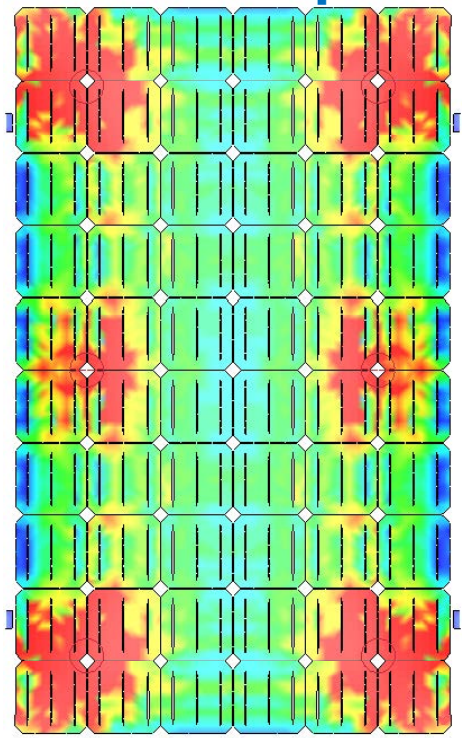
Cell 180um



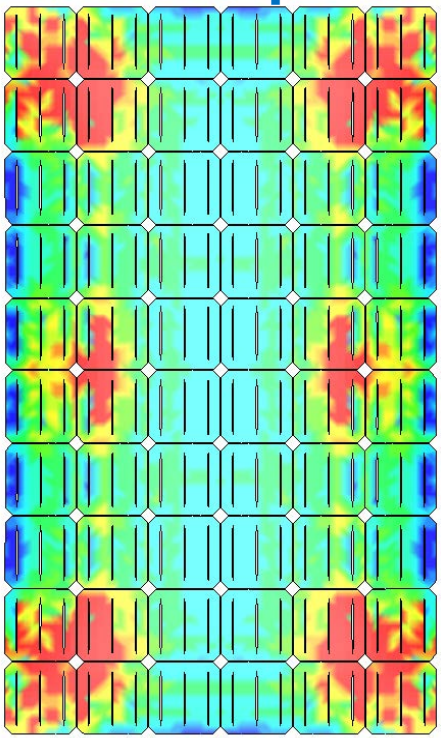
CASE V: Cell Crack vs. Cell Stress Simulation

6point

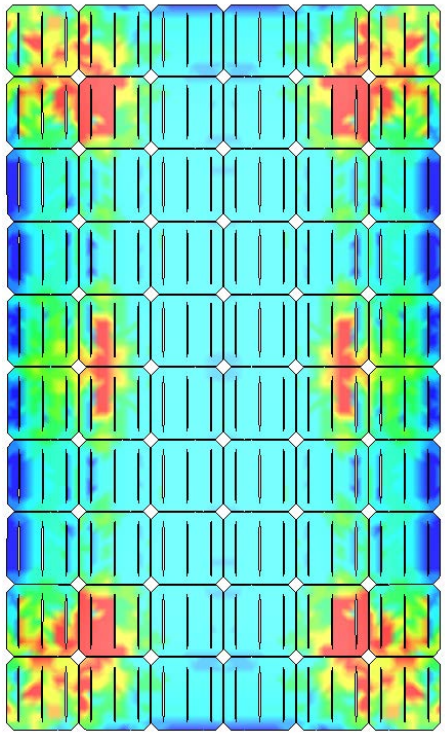
250Mpa



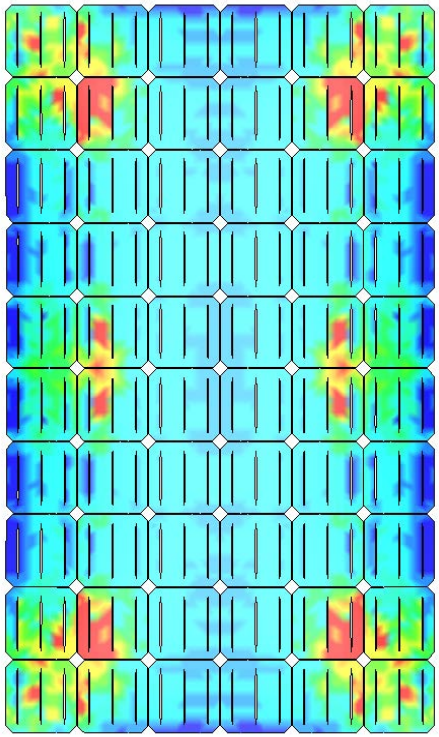
300Mpa



400Mpa



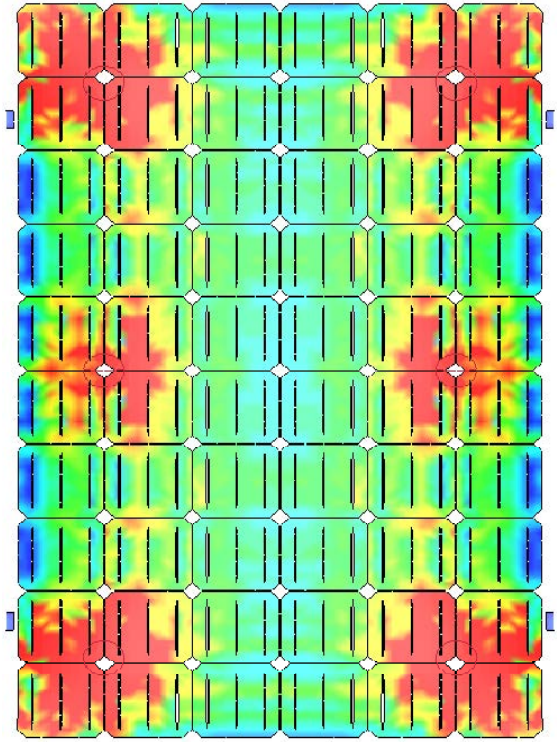
500Mpa



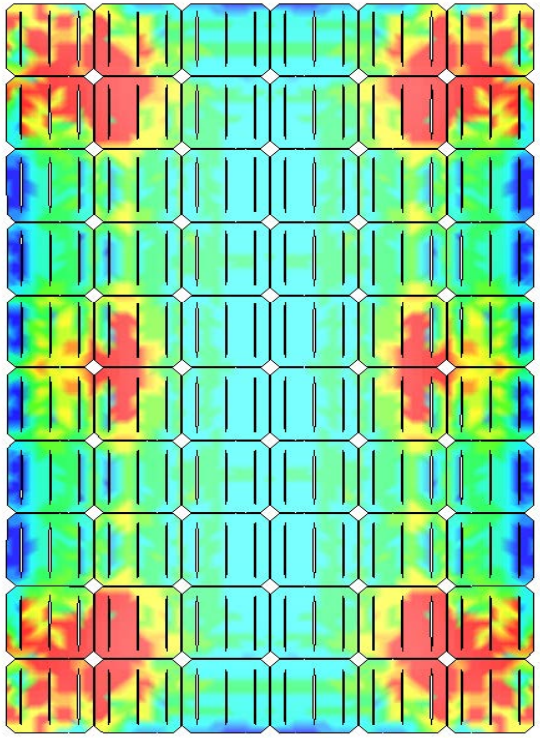
CASE V: Cell Crack vs. Cell Stress Simulation

6point

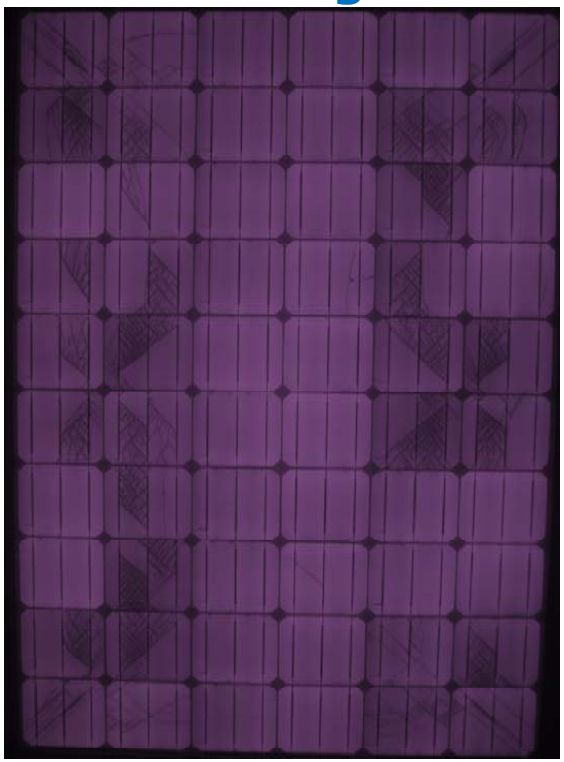
250Mpa



300Mpa



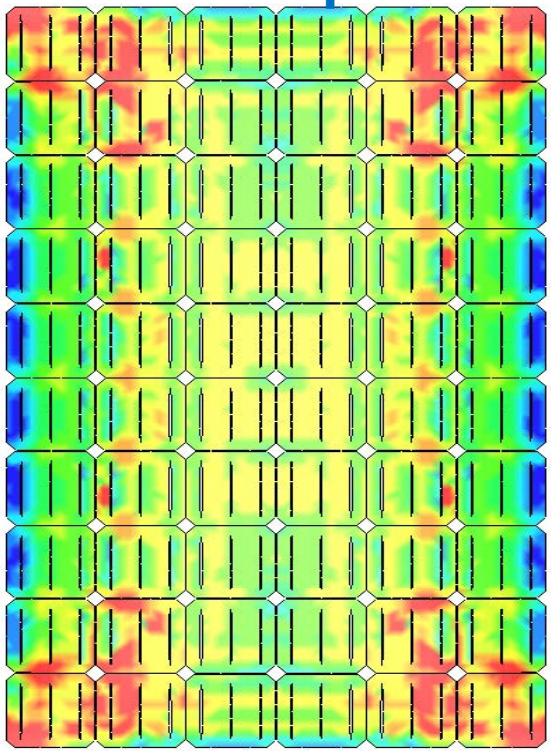
EL Image



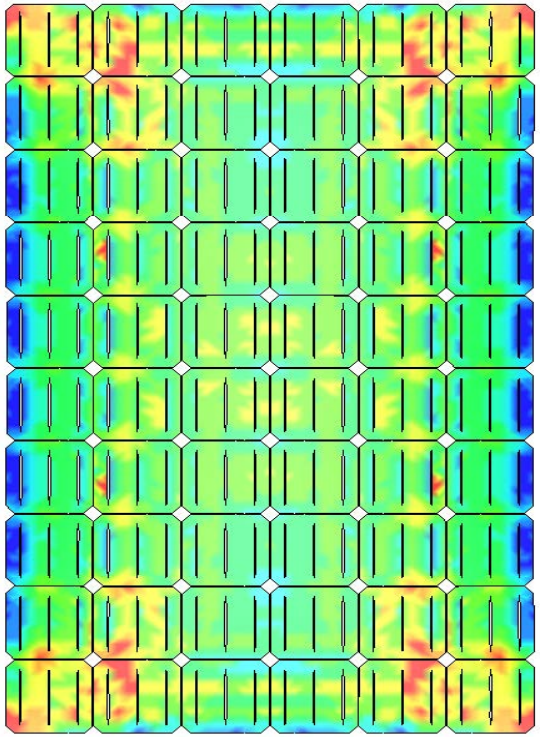
CASE V: Cell Crack vs. Cell Stress Simulation

Uniform

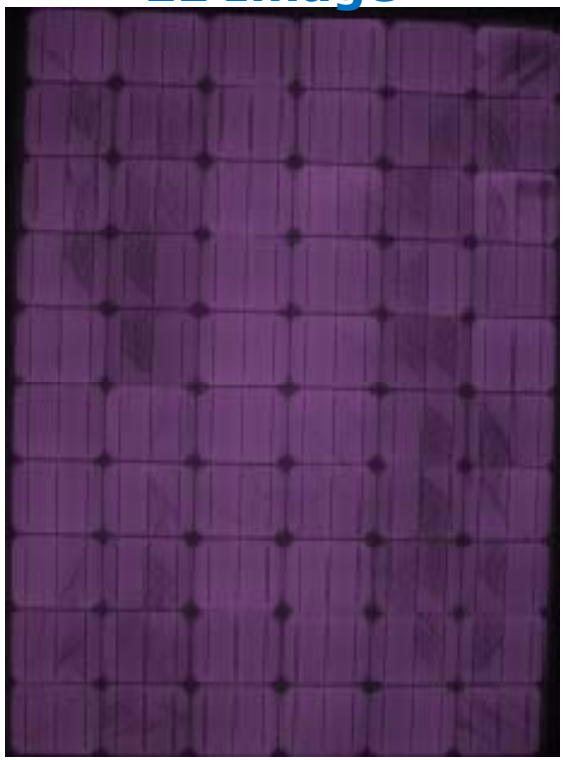
250Mpa



300Mpa

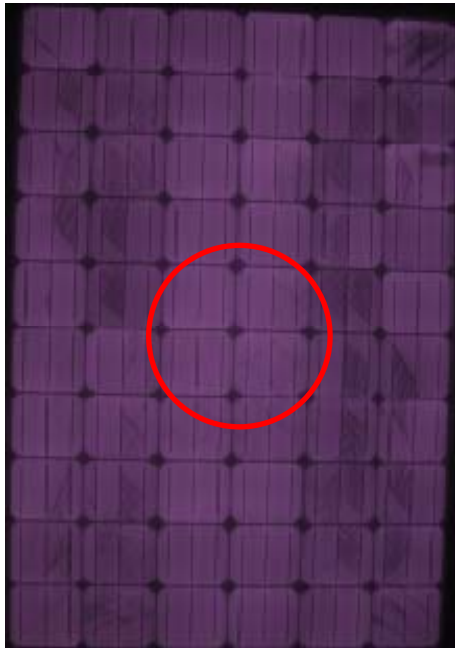


EL Image

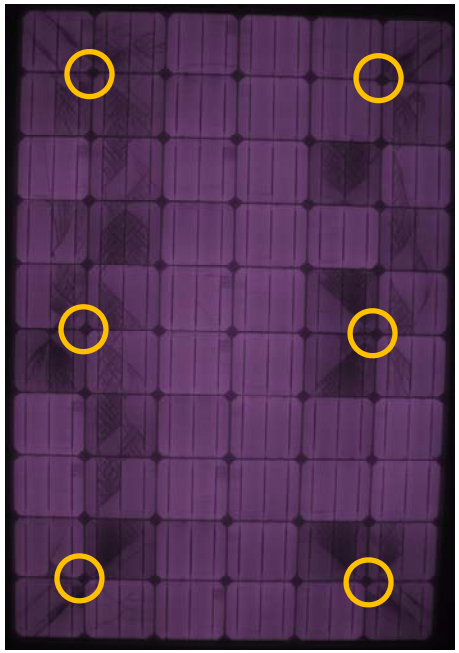


CASE VI: 6 PAD vs. Sand Cell Crack

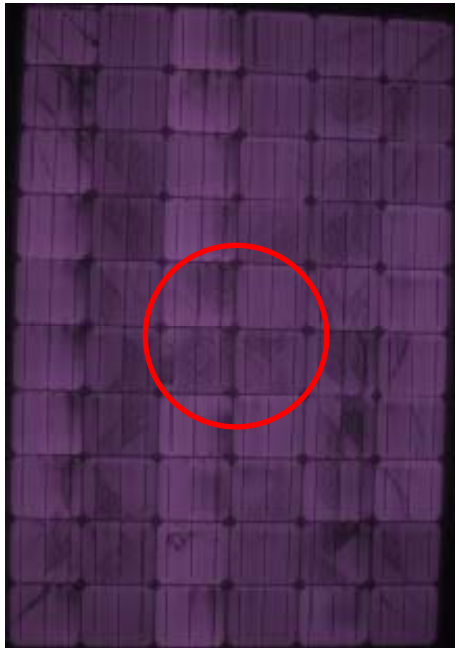
Sand 1/6



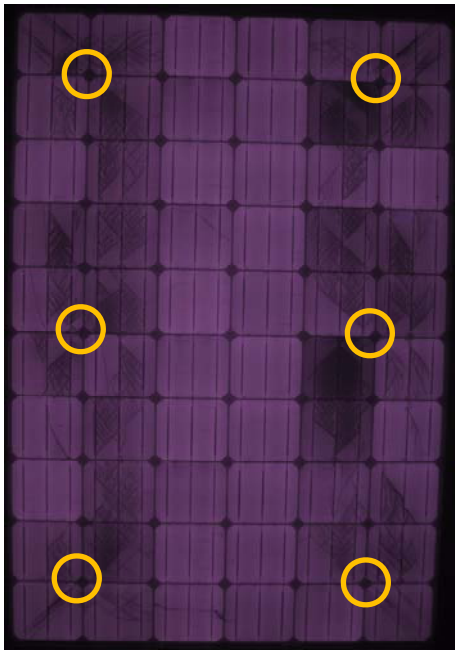
MLT 1/6



Sand 1/5



MLT 1/5



KOREA UNIVERSITY
SOLAR ENERGY RESEARCH CENTER

Analysis of the degradation of multi-crystalline silicon solar cells after damp heat tests

Wonwook Oh[1], Seungtak Kim[1], Soohuyn Bae[1], Byungjun Kang[1], Nochang Park[1,2], Seungeun Park[1], haeseok Lee[1] and Donghwan Kim[1†]

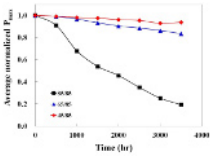
[1] Department of Materials Science and Engineering, Korea University,
[2] Components & Materials Physics Researcg Center, Korera Electronic Technology Institute (KETI)

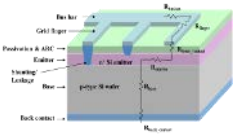
ABSTRACT

Lower performance is usually observed after long-term damp heat test (DH) at 85℃/85% Relative Humidity (RH) condition. It is known that the phenomenon of degradation results from fill factor (FF) loss by high series resistance. However, the cause for the series resistance increase is unclear. We attempted to evaluate the dominant factor on the solar cells. We conducted 3 kinds of damp heat tests using un-packaged multi-crystalline silicon solar cells. Also. We analyzed Light I-V, EL, Suns-Voc, QSSPC, Corescan and SEM after damp heat test. Samples were over-stressed sufficiently under thermal and moisture conditions. Severe degradation by FF loss after damp heat condition (85/85) originated from the contact resistance between Si and Ag finger. Especially, Ag crystallites in the edge of Ag finger were oxidized and could not play a role of current path of photo-generated electrons. We also calculated the contact resistance and transfer length using transfer length method (TLM) after dicing of samples.

MOTIVATION

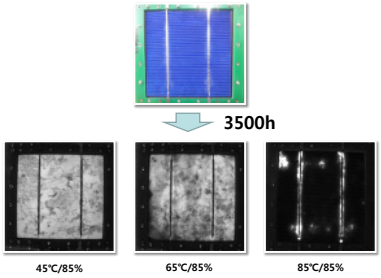
- Low performance after long-term damp heat test at 85℃/85%RH condition is usually observed.
- Many researchers know the phenomenon of degradation resulting from FF loss by high series resistance.
- However, the part which affect series resistance is unclear. Especially, we attempted to evaluate dominant factor in respect of solar cells.
- We focused on contact resistance in Ag/Si interlayer.





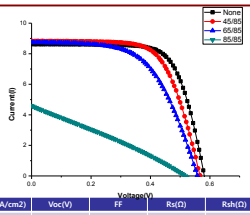
RESULT AND DISCUSSION

1. Sample & Electroluminescence image



- Sample : Multi-crystalline Si solar cell + PV ribbon soldering

2. Light I-V



Samples	Jsc(mA/cm2)	Voc(V)	FF	Rs(Ω)	Rsh(Ω)	P_{max} ratio(%)
None	36.43	0.581	0.706	0.01	28.52	100
45℃/85%	36.30	0.567	0.665	0.013	9.658	94.2
65℃/85%	35.94	0.558	0.579	0.016	4.361	80.0
85℃/85%	18.87	0.517	0.287	0.076	0.124	19.1

- Sample at 85/85 condition is degraded severely.

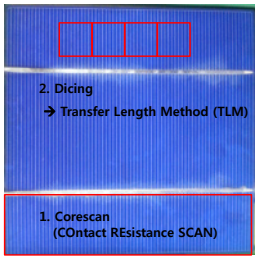
3. Suns-Voc

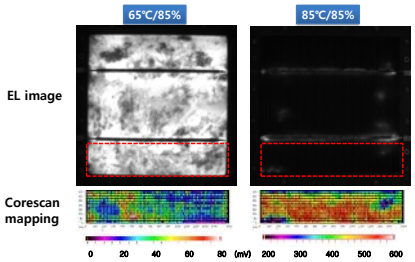
- Suns-Voc can measure pseudo Fill Factor (pFF).

Samples	Jsc (mA/cm2)	pFF	FF	pFF-FF	FF_0	FF_0-pFF	Rs(Ω)	Rsh(Ω)
None	35.43	0.813	0.706	0.107	0.817	0.004	0.01	28.52
45℃/85%	36.30	0.805	0.665	0.140	0.810	0.005	0.013	9.658
65℃/85%	35.94	0.802	0.579	0.223	0.809	0.007	0.016	4.361
85℃/85%	18.87	0.814	0.287	0.527	0.823	0.009	0.076	0.124

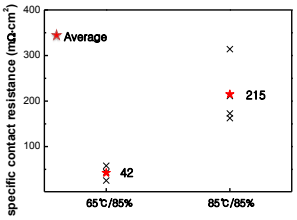
- pFF - FF = FF loss by series resistance (Rs)
- FF0-pFF = FF loss by shunt resistance (Rsh)
- Low performance is due to series resistance, not shunt.

4. Measurement of contact resistance (Corescan, TLM after dicing)





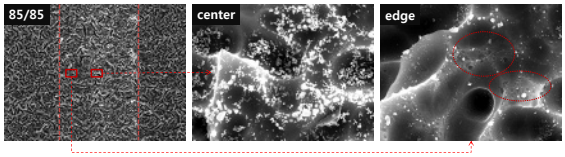
- Low performance in EL mainly depends on contact resistance between Si and Ag finger.



- Specific contact resistance(ρ_c) at 85/85 is 5 times bigger than that at 65/85
- Specific contact resistance measured by TLM is more correct than mapping by Corescan.

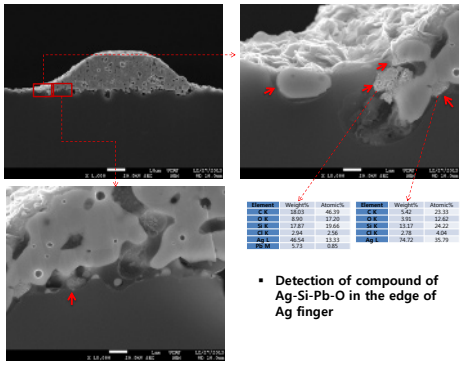
5. SEM image

- Ag crystallites after HNO_3/HF etching (Ag bulk and glass layer etching)



- Density of Ag crystallites after etching : center >> edge

- Cross-sectional image of 85/85

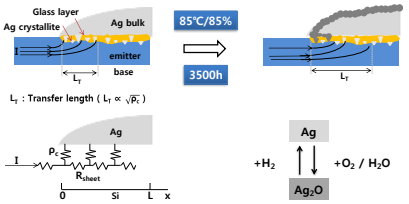


Element	Weight%	Atomic%
C K	18.03	46.39
O K	8.90	17.20
Si K	17.87	19.66
Cl K	2.94	2.56
Ag L	46.54	13.33
Pb M	5.73	0.85

Element	Weight%	Atomic%
C K	5.42	23.33
O K	3.91	12.62
Si K	13.17	24.22
Cl K	2.78	4.04
Ag L	74.72	35.79

- Detection of compound of Ag-Si-Pb-O in the edge of Ag finger

6. Mechanism of low contact resistance



Dieter K. Schroder, Semiconductor Material and Device Characterization, Third Edition 2008

- Degradation factors after DH test are :
  reduction of contact ribbon/Ag
  series resistance of Ag finger
  Ag/Si contact resistance

Summary

- We analyzed the degradation of solar cells after damp heat test. Samples were tested as unpackaged solar cells and over-stressed sufficiently under thermal and moisture conditions.
- Severe degradation by FF loss after damp heat condition (85/85) is due to contact resistance between Si and Ag finger. Especially, Ag bulk and crystallites in the edge of Ag finger were oxidized.

Global KU Frontier Spirit

Solar Cells Laboratory

Adhesion and Debond Kinetics of Encapsulants PV Backsheets

Fernando D. Novoa[1], David C. Miller[2] and Reinhold H. Dauskardt[1]
1. Materials Science and Engineering, Stanford University, Stanford, CA.
2. National Center for Photovoltaics, NREL, Golden, CO.

Objectives

•Develop a quantitative technique to measure adhesion and debond kinetics in EVA Encapsulants and TPE backsheets.

•Characterize the effect of ageing treatment duration, as well as the effects of environmental temperature and relative humidity on backsheet and encapsulant debond energy.

•Investigate the effect of mechanical stress, moisture and temperature on debond growth rate.

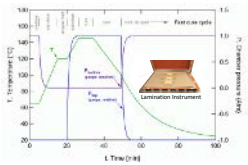
•Develop a predictive model of the effect of mechanical stress, moisture and temperature on debond growth rate.

Encapsulation Specimen Preparation

A Polyvinyl fluoride-polyester backsheet with EVA seed was laminated to a layer of EVA encapsulation and a glass substrate.

Encapsulation System

Lamination Heat Cycle



Lamination was performed at 145°C for 8 minutes at 1 atmosphere pressure.

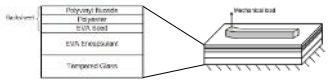
The glass was cleaned prior to lamination, including: buffing with pumice powder; washing and rinsing.

The specimen components were fixed during lamination to improve their thickness uniformity.

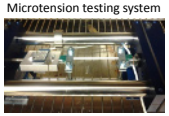
Debond Energy and Debond Growth Experiment

A single cantilever beam (SCB) testing metrology, based on the well-known double cantilever beam method, was developed.

Single cantilever beam (SCB) experiment



Microtension testing system

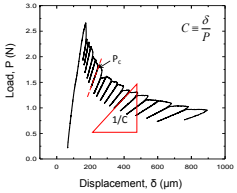


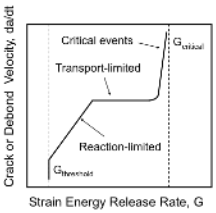
•A PMMA (or Ti) beam was bonded to the backsheet and a loading tab was bonded to one end of the beam. An incision was made through the backsheet and underlying encapsulant

•The glass substrate was rigidly fixed to a testing table and the loading tab was connected to a linear actuator in series with a load cell.

• Load and displacement were measured during the experiment. The debond energy, G_c was calculated using crack length (a), critical load (P_c), thickness of the beam h, width B and plane strain elastic modulus E'.

$$C = \frac{4a^3}{E'Bh^3} \qquad G_c = \frac{P_c^2}{2B}\frac{\partial C}{\partial a}\bigg|_{a_c}$$



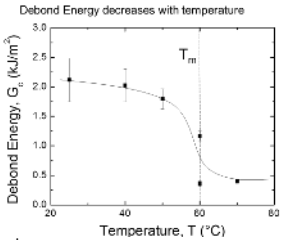


• To measure debond growth, the SCB specimens were loaded below G_c. The displacement was fixed and the load relaxation inherent to debond growth was recorded.

• Analysis of the load relaxation and increasing compliance determined the debond growth rates.

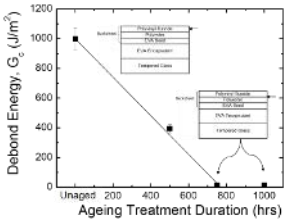
• The experiments were performed at selected values of temperature and relative humidity.

Debond Energy of EVA Encapsulants and TPE Backsheets



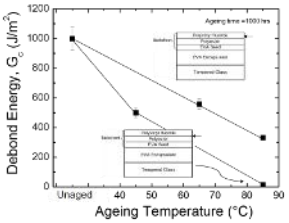
• The debond energy of the EVA–glass structure decreased with testing temperature.

• The debond energy decreased precipitously at T~60°C, which corresponds to one of the transition temperatures of the polymer.



• The debond energy of the backsheets decreased linearly with ageing duration for 800hrs to very low values (~28 J/m²).

• Failure occurred at the PVF-PET interface

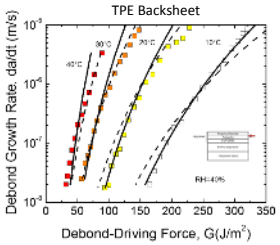


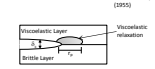
• Higher ageing temperature and relative humidity corresponded to lower debond energies .

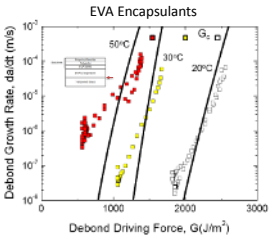
• High values of debond energy corresponded to partially cohesive failure in the PVF.

Debonding Kinetics of EVA Encapsulants and TPE Backsheets in Controlled Environments

Temperature Effect on Debond Growth Rate



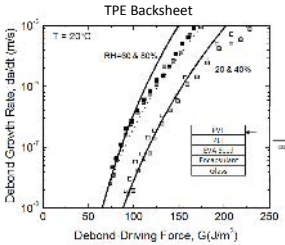


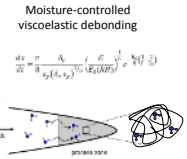


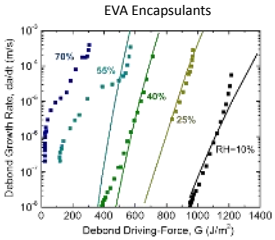
The debond growth curves were shifted to lower values of G at higher temperatures.

Lines are model model predictions using the Arrhenius and the Williams-Landel-Ferry equation.

Moisture Effect on Debond Growth Rate







The debond curves were shifted to lower values of G with increasing RH.

Lines are model predictions using the humidity dependence of the PVF modulus (backsheet), and the plasticizing effect of water (EVA encapsulants.)

Conclusions

• The debond energy of a PV encapsulant and backsheet were measured after several ageing treatments. The debond energy decreased with ageing treatment duration, relative humidity and temperature.

• The effect of mechanical stress, temperature and relative humidity on encapsulant and backsheet debond growth was reported. The debond growth rate increased up to 500-fold with small changes of temperature (10°C) and relative humidity (20%) .

• The effect of temperature on debond growth was modeled with the Arrhenius and the Williams-Landel-Ferry equation. The effect of moisture on the debond growth rate was modeled with the humidity dependence of the PVF modulus and the plasticizing effect of water on EVA.

Acknowledgments

This research was supported by the Bay Area Photovoltaic Consortium.

Cell defect analysis post Dynamic Mechanical Load and thermal cycling Testing at Jabil

Vivek Gade, Jared Opalewski and Philip Capps, Jabil Photovoltaic Certification and Testing Laboratory St. Petersburg, Florida.

Introduction

Jabil's state-of-the-art photovoltaic certification and testing laboratory in St Petersburg, Florida provides wide range of photovoltaic testing services such as prototyping, certification, product validation, extended testing and Failure analysis. Specialized tests such as potential induced degradation, glass soiling, array & individual module monitoring and dynamic mechanical load testing is regularly performed in the Jabil laboratory. Technical Data is presented here involving dynamic mechanical load testing performed using a unique test set up that very closely simulates the field conditions as observed by the mounted module. A group of modules were studied and analyzed as part of new cell validation and qualification process. Modules were taken through the sequential tests involving 1000 cycles of dynamic mechanical loading performed at 1440 Pascals followed by 50 thermal cycles similar to IEC 61215 10.11. Cell area defects particularly cracks were mapped to understand root cause and help further improve yield in manufacturing. Some of the data and analysis is presented in this poster.

Jabil Photovoltaic Certification & Testing Laboratory(JPCTL)

Experiment: Dynamic mechanical load testing

IEC 61215 Static Mechanical load testing for wind and snow load while the actual conditions in the field are not always static. The Dynamic mechanical Load test (DML) is called out in IEEE 1262 PV standard and ASTM e-1830 standard. These standard call for 1440 Pascal's of pressure for 10,000 cycles at least 3 s per cycle.

This test is not yet required by IEC 61215, but is being considered as a potential addition. BP Solar reported power losses up to 20% after combining this test with climate chamber tests on intentionally damaged modules with micro cracks [1]. JPCTL has been using its special test set up to perform DML on customers panels to access long term reliability. The test program has been very effective in assisting to find damaged cells due to latent defects, micro cracks, solder joint stresses and other defects introduced during manufacturing. The cell cracking was classified based on severity. The location was mapped out to understand what process in manufacturing (solder bonding, stringing or lamination) would have more impact and if the issue was inherent to the latent defects in the cells.

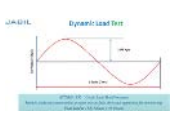


Figure 1: Dynamic mechanical load test profile

Table 1: Test plan

Results

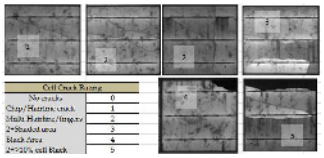


Figure 2: Cell cracks scoring/rating criteria

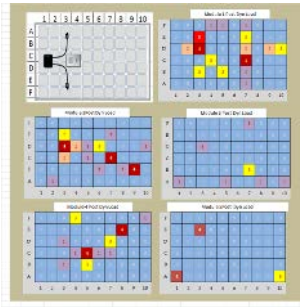


Figure 3: Cracked cell map post dynamic load testing based on severity of cracks

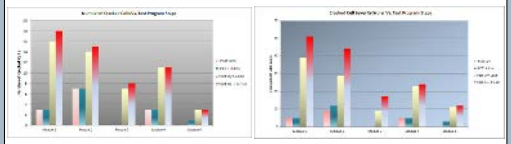


Figure 4: Quantity of cracks and cumulative severity scores at different stages of testing

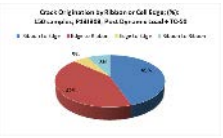


Figure 5: Pie chart for crack origination distribution

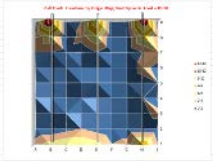


Figure 6: Mapping of crack location/origination on cell

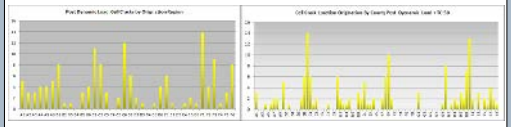


Figure 7: Cumulative crack count based on location on the cell area as mapped in figure 6 above.

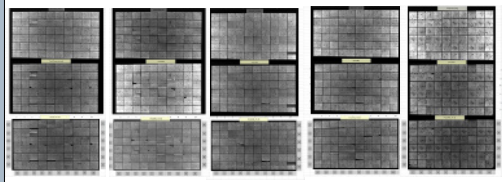


Figure 8: Electroluminescence images of all the modules in test during initial, post DML and post TC50 stages.

Results and discussion

Table 2: Change of Power and I-V Characteristics at the completion of final test stage

% Change from Initial post DML and TC50 JPCTL (ve number indicates decrease)						
Module #	Pmax	FF	Voc	Isc	Vpm	Ipm
Module 1	0.0%	-2.0%	-0.3%	2.4%	-0.8%	0.8%
Module 2	-0.6%	-2.3%	-0.3%	2.1%	-0.4%	-0.2%
Module 3	1.4%	-1.0%	0.0%	2.5%	-0.2%	1.6%
Module 4	0.0%	1.9%	0.3%	2.2%	0.4%	0.3%
Module 5	-0.6%	0.1%	-0.1%	-0.5%	-0.2%	-0.4%

- The overall power did not decline more than 2% in spite of evidence of several cracks post dynamic mechanical load testing. This was still the case even after they completed the thermal cycling segment of the test schedule.
- Post TC-50, the severity score rate increased more compared to the number of cracks formed.
- Cell inter-distance was at least 50% higher for module 5 compared to the rest of the module. Glass, back sheet and encapsulation material properties were assumed to be relatively similar. All modules used softer ribbons with low yield strength.
- There appears to be a direct correlation of cell crack origination location to the overlapping ribbon "connected end" locations. Most of cracks originated from the ribbon end of the cell.
- As seen in Figure 6 crack origination is concentrated around the soldered ribbon area that is overlapping the edge of the cell.
- There were no cell shunts that developed in the tests. Overall the modules pass the reliability test. A power degradation of >5% would have been a cause of concern. This further establishes our confidence in the fact that minimal stresses are introduced in the cells and joints during the manufacturing processes.

Conclusion

- Though the modules tested did not show significant loss/degradation post DML and 50 thermal cycles, the data generated through electroluminescence imaging and power performance testing is of great value to manufacturing.
- Severity rating can be used to provide certain ratings to arrive at a rough estimate for yield estimation/breakage rate using typical material set during the validation and qualification process of new cells.
- Factors that will help explain few of the defects would be characterization of cells and ribbon material for latent defects and physical properties. Other influencing factors would be ribbon soldering pattern on the silver bus. Pattern would be defined as number of soldering points, distance to the edge and inter-distance.
- Defect mapping can help predict weak areas that needs to be analyzed to further improve yield (reduce cell breakage rate) and also potentially help address long term reliability issues that could occur in the field.

References

[1] Wohlgemuth, John H.; Cunningham, Daniel W.; Placer Neil V.; Kelly George J.; Nguyen Andy M. "The effect of cell thickness on module reliability". 33rd IEEE Photovoltaic Specialist Conference, San Diego, 11-16 May 2008, pp. 444-445

Acknowledgements

- Art Rawers, Jabil Global Failure Analysis Manager
- Jean-Marie Siefert, Jabil Business Unit Director
- Nick Bosco, NREL, 2014 PVMRW Chair
- Vivek Gade, Jabil photovoltaic certification and testing Laboratory Lab Manager

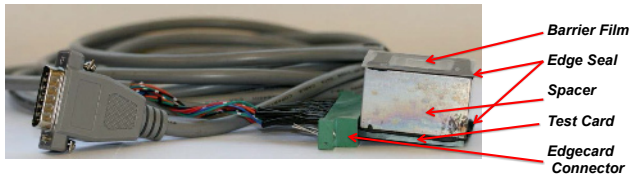
This poster does not contain any proprietary or confidential information

NREL's e-Ca Test: A Scalable, High-Sensitivity Water Permeation Measurement Methodology

Arrelaine A. Dameron, Michael D. Kempe, Matthew O. Reese

Motivation:

Barriers to oxygen and moisture are critical packaging components for a wide variety of industries. The requirements of each application vary significantly, with differing needs for cost, flexibility, transparency, and permeation rates. It is believed that for next generation technologies like OLEDs and organic PV (OPV) modules, extremely low (10^{-6} to 10^{-8} g/m²/day) water vapor transmission rates (WVTR) may be required. To aid in the research and development of such barriers, a quantitative high-throughput technique that can measure many barriers in parallel under a series of conditions is necessary. NREL's e-Ca Test is this technique!



NREL's e-Ca Test Assembly. *Components are fabricated separately and assembled in a module design, so that the test can be scaled to many simultaneous measurements, while retaining high quantitative sensitivity.*

Common Water Vapor Transport Testing Methods

Test Method	Standards and References	Description	Range (g/m²/day)	Advantages	Disadvantages
Cup Test	ASTM E96	Scavenger method using gravimetric evaluation	0.1 - 1000	• ASTM Standard • Commercially available • High throughput • Wide range of environmental control possible • Inexpensive	• Very low sensitivity • Can not monitor transients • Prone to user error
Isostatic (MOCON)	ASTM F1249	Diffusion cell with coulometric moisture sensor	0.05 - 100 (Permatron) 5x10⁻⁴ - 5 (Aquatron)	• ASTM Standard • Commercially available • Can monitor transients • Intermediate sensitivity	• Temperature (5-50C) • Limited throughput • Sensitivity • Intermediate cost
HTO/ Radioactive Tracer	Dameron, Dunkel	Diffusion cell with detection of water doped with tritium either by ionization chamber or indirectly by hygroscopic salt and scintillation method	10^{-9} - 10	• Extremely good sensitivity • Potentially high throughput (indirect)	• Expensive • Radiation • Not commercially available • Multiplexing difficult for ionization chamber method • Limited environmental control
Optical Ca Test	Nisato	Scavenger method monitoring Ca oxide formation optically	10^{-6} - 10	• Good sensitivity • Potentially high throughput • Wide range of environmental control possible • Can monitor transients	• High capital investment • Not commercially available • No standard - potential for inaccurate numbers
Mass Spectroscopy	Zhang, Renade, Obrien; Hulsmann	Diffusion cell with residual gas analyzer, sometimes paired with programmed valving system to increase sensitivity	10^{-7} - >10	• Very good sensitivity • Can monitor other species than moisture	• High capital investment • Not commercially available • Limited throughput • Limited environmental control
Electrical Ca Test	Paetzold; Choi; NREL	Scavenger method monitoring Ca oxide formation electrically	10^{-7} - 10	• Good sensitivity • Potentially high throughput • Low capital investment • Wide range of environmental control possible	• Not commercially available yet • Moderate level of accuracy.

Ca Test Basics:

The generic electrical Ca Test method uses the resistance of a Ca metal trace or pad as a sensor element to detect water permeation [17-19]. The premise of the test is that as water permeates through the barrier on test it will react with the conductive Ca metal to form resistive $Ca(OH)_2$. If the Ca test area and geometry is known, then by measuring the resistance of the Ca as a function of time, the amount Ca consumed by water that has permeated through the barrier can be determined and, thus, the rate of permeation is obtained.

Assumption:

$$Ca + 2H_2O(g) \rightarrow Ca(OH)_2 + H_2 \quad n=2 \qquad \Delta G^0_{rxn} = -441\ (kJ/mol)$$

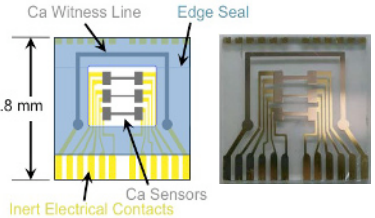
Working Equation:

$$WVTR = n\delta\rho_{Ca}\left(\frac{l_{eff}}{w}\right)\left(\frac{A_{Ca}}{A_B}\right)\left(\frac{M_w}{M_{Ca}}\right)\left[\frac{d\left(1/R\right)}{dt}\right]$$

E-Ca Test Components:

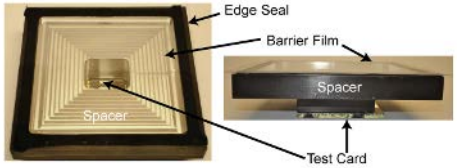
Test Card:

Data traces consist of evaporated Ca traces contacted by evaporated Ti/Au contacts in a 4-pt configuration. Multiple lines allow several measurements of the WVTR to be made and averaged. A "witness line" is integrated into the test structure to examine failure of the edge seal and to provide an estimate of background noise.

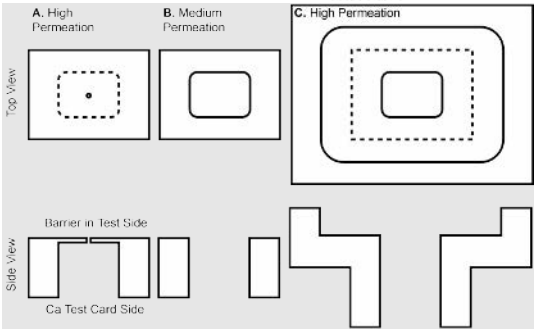


Spacer:

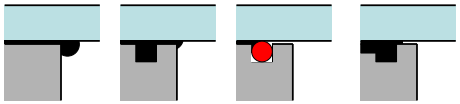
Pinholes and other defects can create localized and/or nonuniform oxidation of Ca, which would give spurious results (see simulation below). In addition to mitigating the effects of pinholes, the spacer serves to regulate the sensitivity of the test and to control the edge seal position and flow.



Spacer Designs. *By adjusting the ratio of barrier area to exposed Ca area the sensitivity of the test can be optimized.*



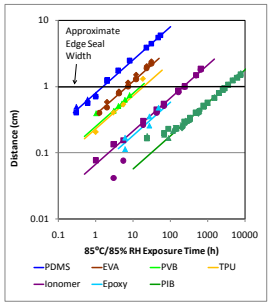
Spacer Surface Design. *The sealing surface of the spacer dictates the edgeseal flow and the exposure of the edgeseal to the inside of the assembly.*



(a) Flat (b) Trench (c) "O" Ring (d) Al Ridge

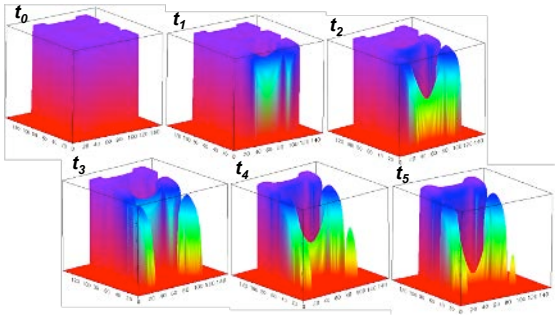
Edgeseal:

Several Commercial edgeseals were tested for moisture ingress and overall durability. A desiccated PIB material was best for both overall performance and ease of use.



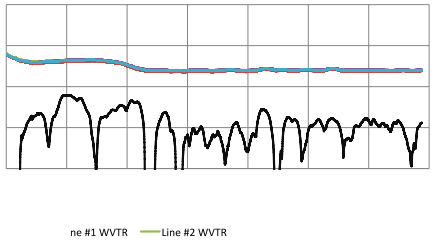
Simulation of Ca Degradation for No Spacer:

In this simulation, we examine the effect of a defect in the barrier near the edge of the aperture. This time-lapse simulation is for the case of ~3 mm separation between the barrier and the test card. This demonstrates the difficulty of introducing redundancy and patterned Ca sensors in traditional Ca test geometries, which place the sensor in contact with the barrier. In NREL's standard spacer designs, such simulations are boring, because each Ca sensor degrades uniformly. This is because of sufficient separation between the barrier and the test card such that diffusion allows us to measure an average WVTR.



Ultimate Sensitivity:

We have demonstrated measurement in the 10^{-5} g/m²/day range and have confidence that 10^{-6} g/m²/day and possibly 10^{-7} g/m²/day can be measured with this technique.



This presentation contains no confidential information. The e-Ca test is available to license from NREL. For licensing information please contact Ty Ferretti. ty.ferretti@nrel.gov; 303-275-4353

SunShot
U.S. Department of Energy

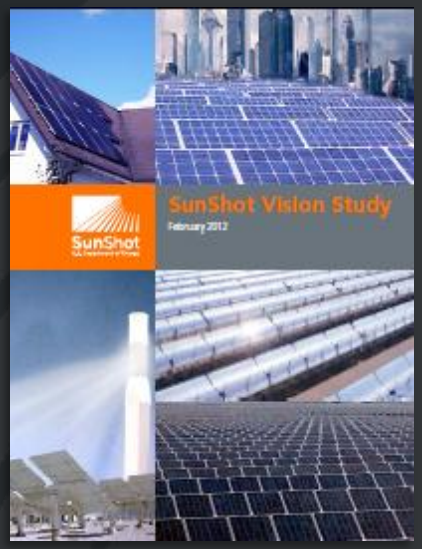
Reliability and the SunShot Initiative

Becca Jones-Albertus, Ph.D
Program Manager for PV R&D
Solar Energy Technologies Office

Outline

- **The SunShot Initiative and the Solar Energy Technologies Office**
- Reliability Projects
- Current Opportunities

SunShot Initiative

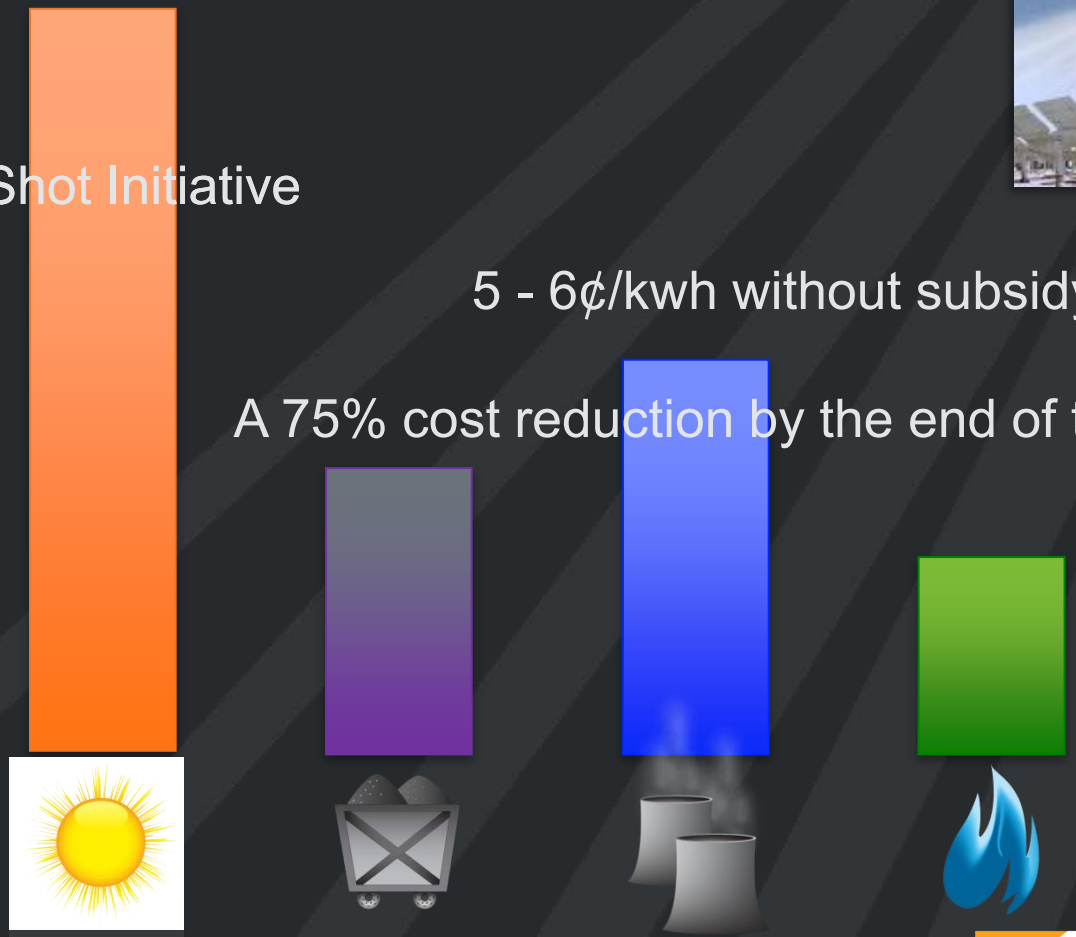


Price

SunShot Initiative

5 - 6¢/kwh without subsidy

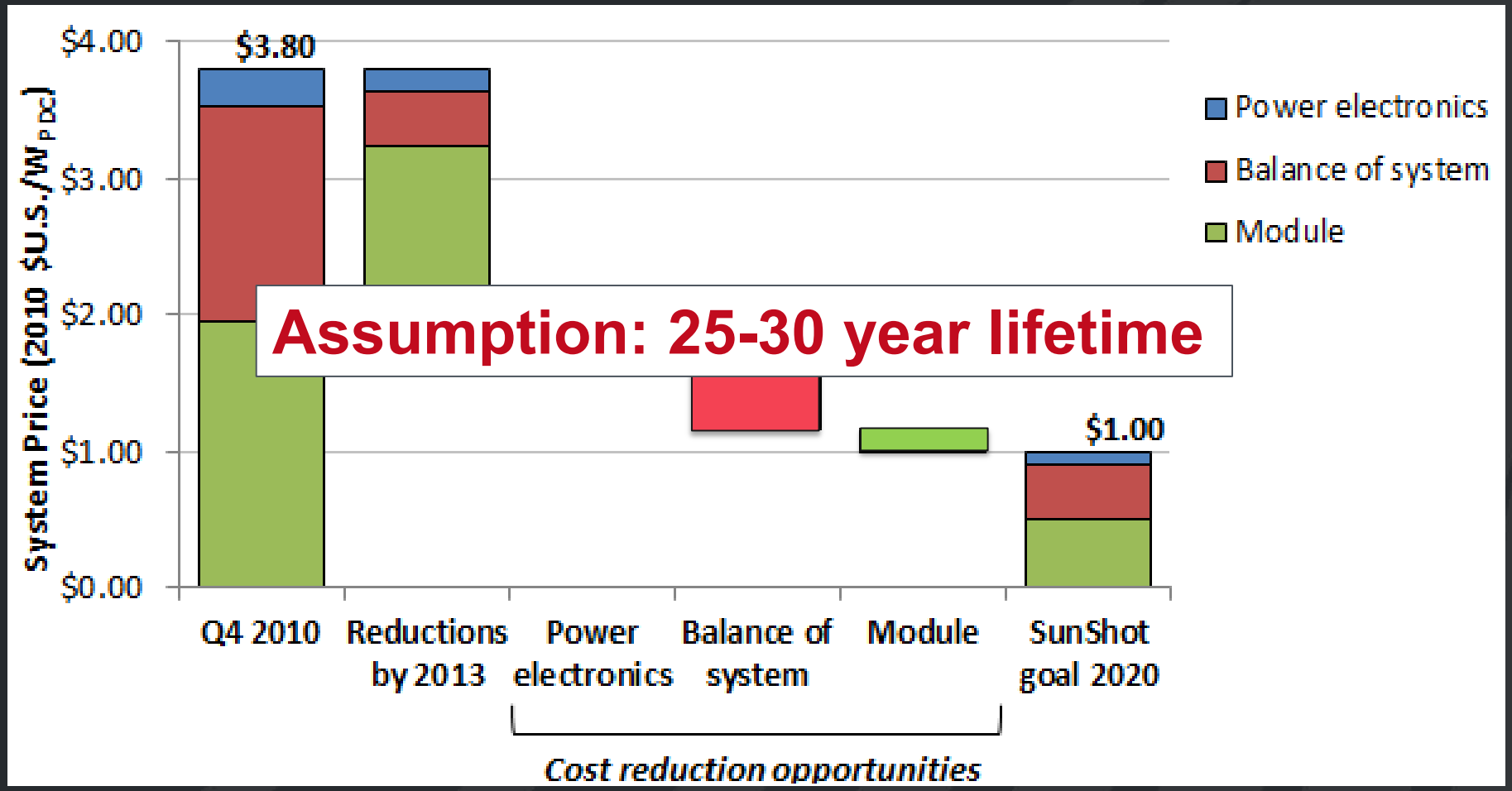
A 75% cost reduction by the end of the decade



energy.gov/sunshot

SunShot
U.S. Department of Energy

SunShot Utility Scale Progress Q4 2013



Sources: Margolis , R., et al. (2012). "*SunShot Vision Study*." DOE/GO-102012-3037. Golden, CO: National Renewable Energy Laboratory, pp. 265. Accessed 2013: http://www1.eere.energy.gov/solar/pdfs/47927_appendices.pdf; Goodrich, A; James, T; and Woodhouse, M. "*Residential, Commercial, and Utility-Scale Photovoltaic System Prices in the United States: Current Drivers and Cost Reduction Opportunities.*" NREL Technical Report No. TP-6A20-53347, Available Online at: www.nrel.gov/docs/fy12osti/53347.pdf . ; NREL internal (PV system cost) analysis (September 2013).

SunShot U.S. Department of Energy

Solar Energy Technologies Office Portfolio

- **Photovoltaics R&D** - Advances R&D that has resulted in US leadership in world records, scientific publications, and patents to provide US industry technology advantages
- **Concentrating Solar Power R&D** - Develops concentrating solar thermal technologies with thermal energy storage to meet SunShot goals
- **Systems/Grid Integration** - Develops technologies to enable integration of solar power with the grid for reliability and resiliency
- **Soft Costs**- Work with state and local governments to reduce red tape which can be ~50% of residential costs
- **Tech to Market** - Increase US market share for manufacturing value add commensurate with domestic market demand through manufacturing process R&D

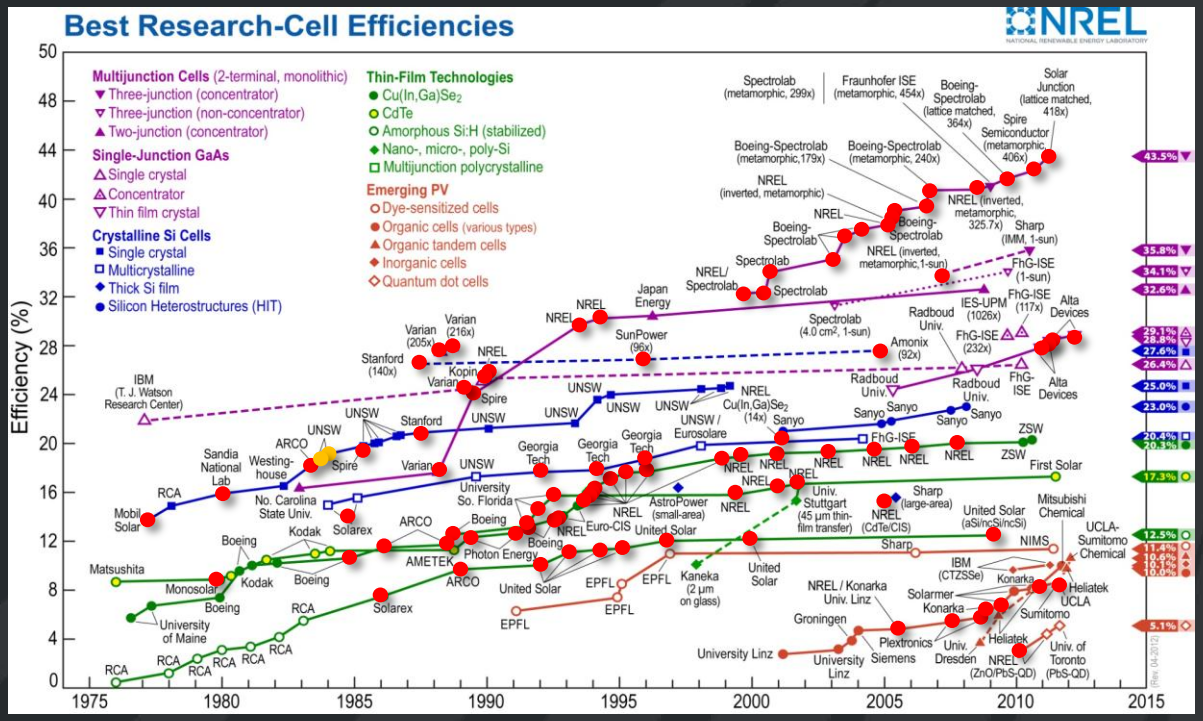
- **SETO FY14 Budget: $257 million**

energy.gov/sunshot

SunShot
U.S. Department of Energy

Photovoltaics R&D

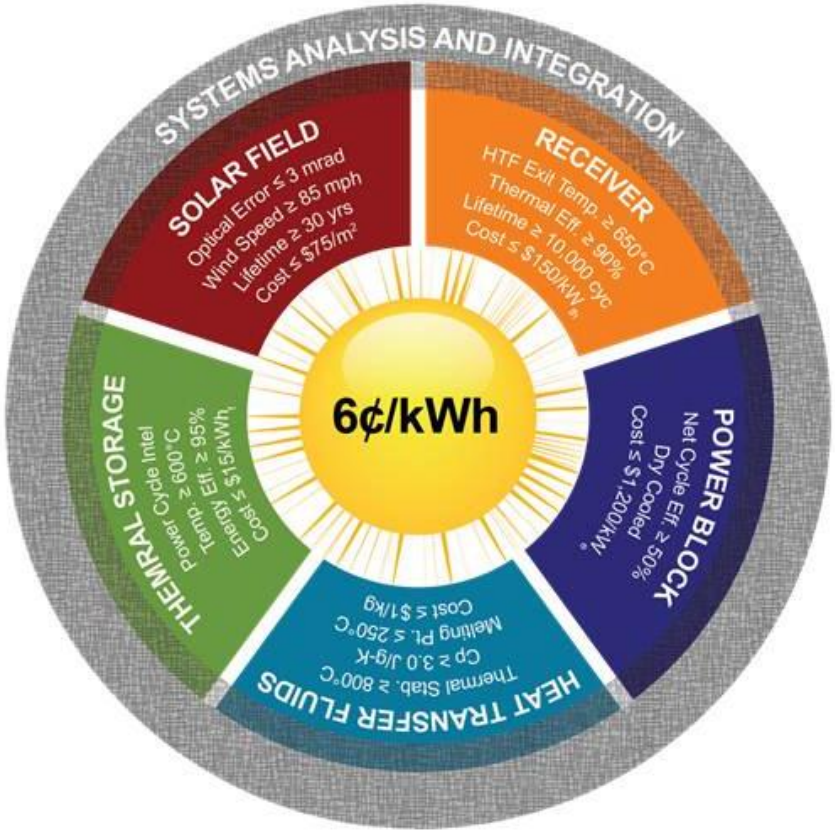
- New materials and device concepts to increase solar cell efficiency and decrease cost



- Addressing the R&D needs of the PV industry
  - **Improving reliability**
  - Training a diverse, technical workforce to support innovation
  - Bridging the gap between basic science and applied PV research

Concentrating Solar Power R&D

Deconstructing 6¢/kWh



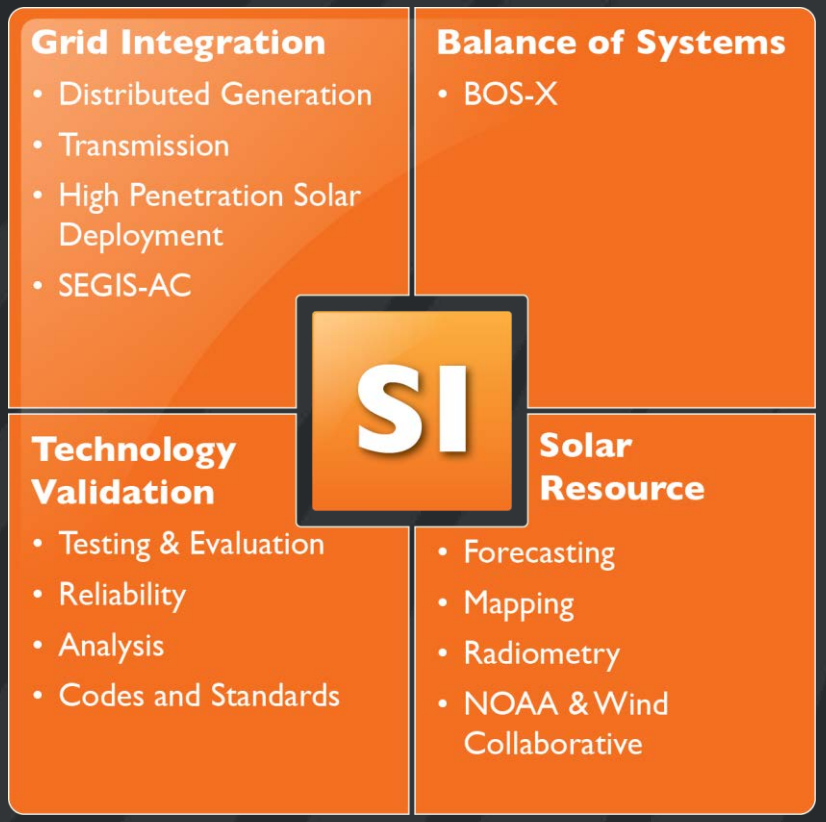
Competitive Programs

- CSP: ELEMENTS (2014)
- CSP-HIBRED (2013)
- PREDICTS (2013)
- SolarMat (2013)
- SunShot MURI (2012)
- National Lab R&D (2012)
- BRIDGE (2012)
- SunShot CSP R&D (2011)
- Incubator (Recurring)
- CSP Baseload (2010)
- ARRA (2009)
- Thermal Storage (2008)

Systems Integration

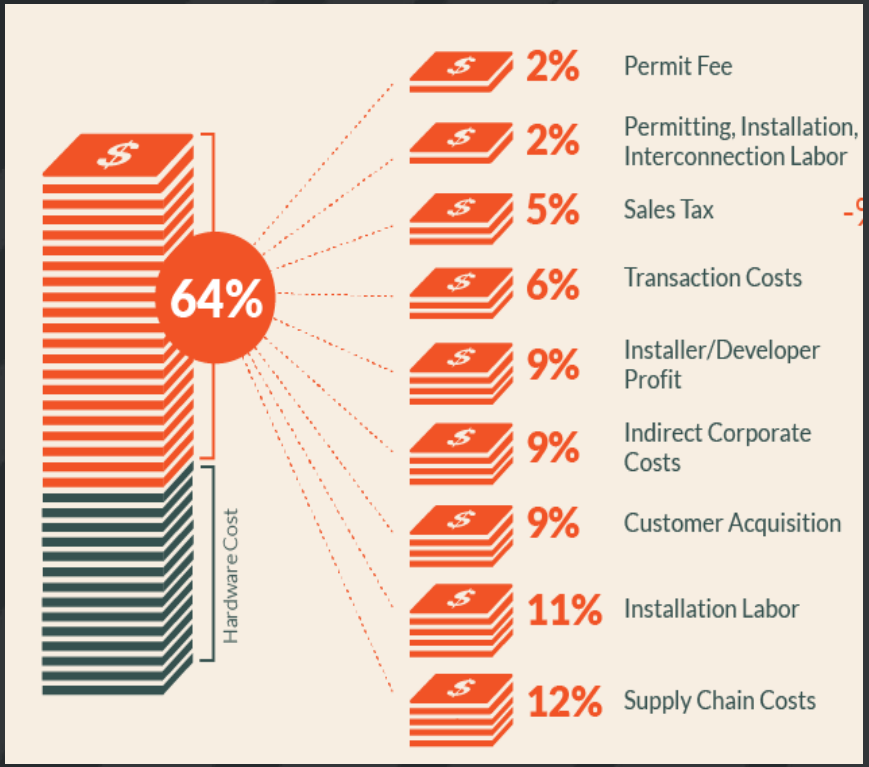
Goals

- **BOS Costs:** Reducing the costs of power electronics and balance of system hardware
- **Bankability:** Reducing the risk associated with the use of new technologies
- **Grid Integration:** Establishing a timely process for integrating high penetrations of solar technologies into the grid in a safe, reliable, and cost-effective manner while providing value to the system owner and the utility grid.



Soft Costs

- Focus areas:
  - State / local support to reduce red tape
  - Innovative small businesses to help accelerate adoption of solar
  - Enabling a solar workforce
- Performed at state and local government, national laboratories, research universities, and industry



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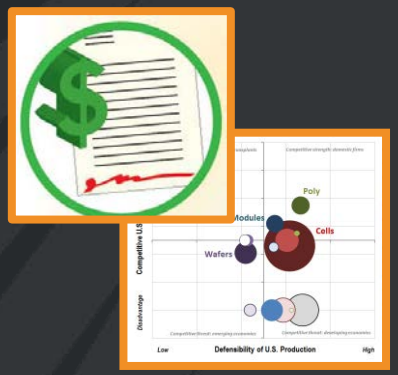
Technology to Market & Strategic Initiatives



Bottom-up cost analysis (PV, CSP, systems-level)
Market analysis

Competitiveness analysis
Uncertainty analysis (finance, policy)

Commercialization
Incubator program, SBIR

Strategic planning
SunShot targets

Innovations in Manufacturing
SolarMat, SUNPATH

QBotix

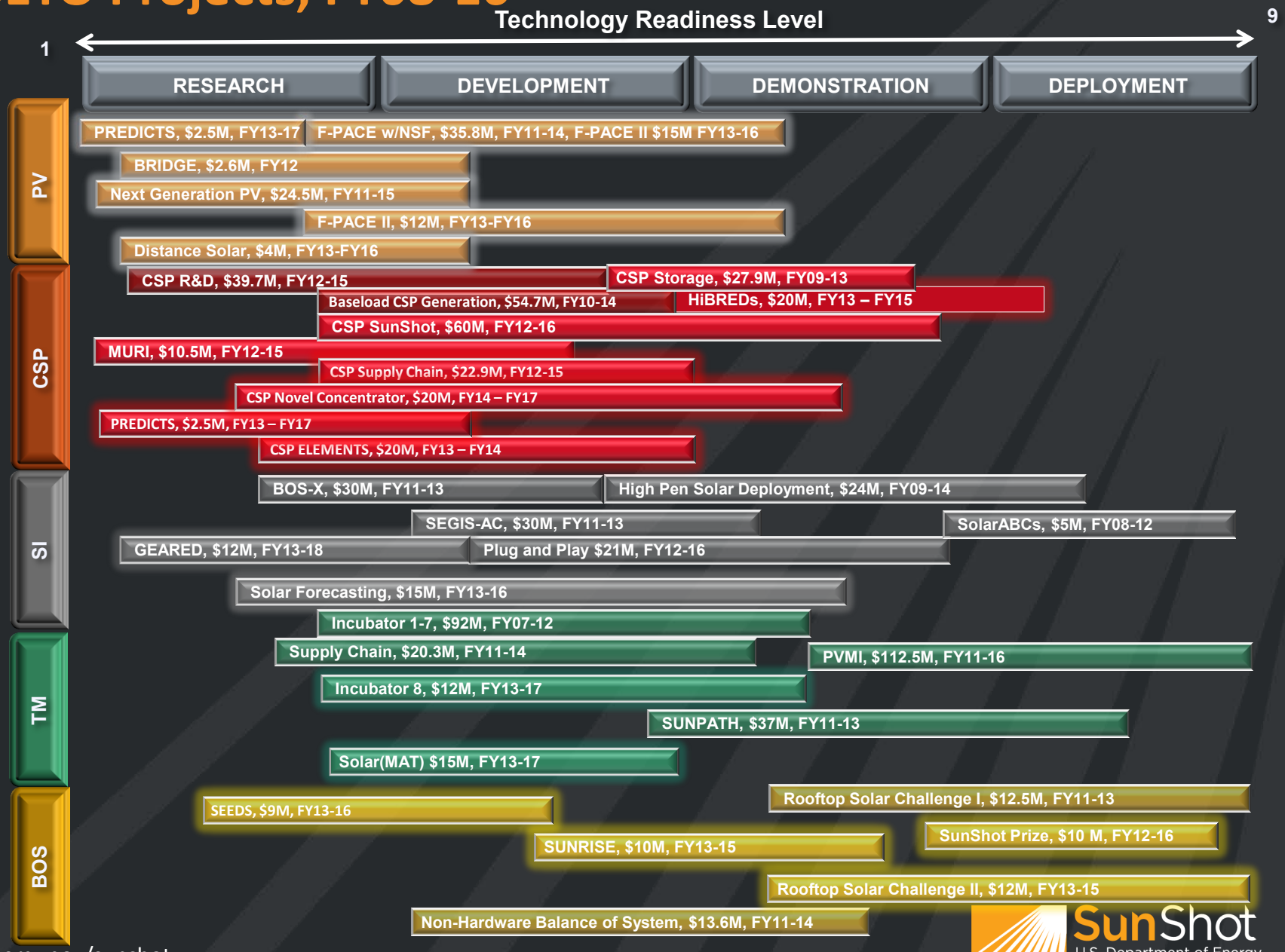
MOSAIC

6 ¢/kWh

Suniva
The Brilliance of Solar Made Sensible

ABENGOA SOLAR

SETO Projects, FY08-16



energy.gov/sunshot

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U.S. Department of Energy

Outline

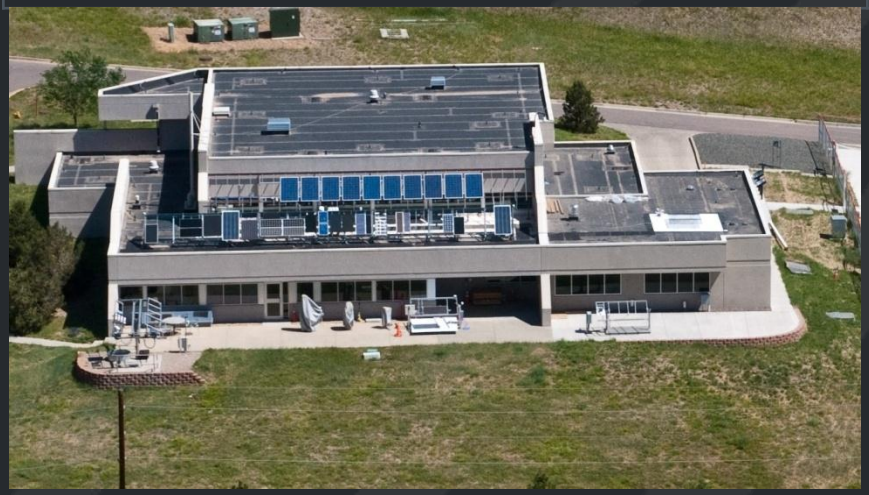
- The SunShot Initiative and the Solar Energy Technologies Office
- **Reliability Projects**
- Current Opportunities

Reliability Overview

- National Laboratories (NREL and Sandia)
- PREDICTS Funding Opportunity Announcement (FOA)
- Reliability tasks incorporated into individual projects

Performance and Reliability: Key Activities at the national labs

NREL NATIONAL RENEWABLE ENERGY LABORATORY	Sandia National Laboratories
FY14 Funding: $11M	FY14 Funding: $8M
• QA Task Force • Qualification Plus • Degradation Rate Calculations • Regional Test Center Support	• Performance Modeling Collaborative • Arc Faults • AC Modules • Regional Test Center Support



Regional Test Centers

- **Background / 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
    - Test in multiple climates, using a comprehensive validation approach to compare performance and initial reliability against prediction
- **Locations:**

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

Topic 1: Development of physics- and chemistry-based models to:

- Quickly and accurately predict degradation modes
- Map active pathways associated with macroscopic failure
- Develop relationship networks for relevant physical and chemical processes
- Determine component lifetimes

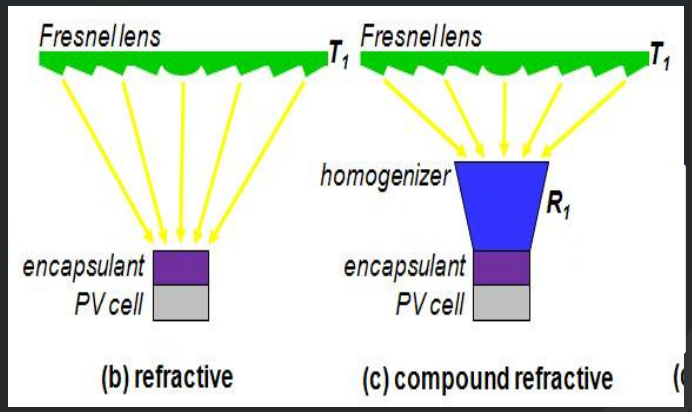
Topic 2:

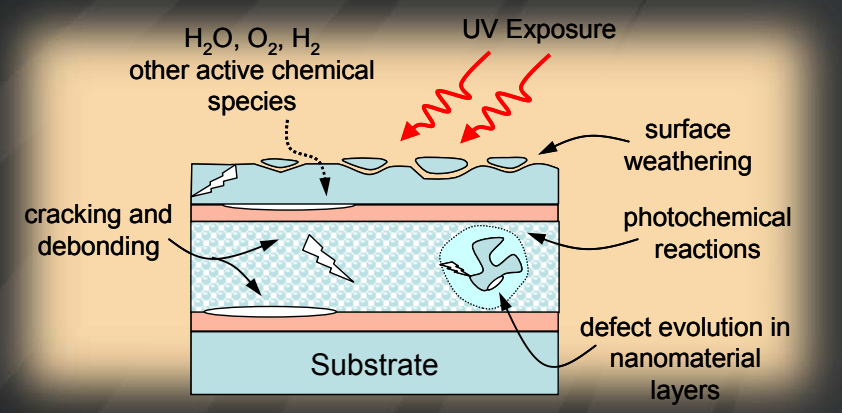
- Collaborative development and initial implementation of industry standard tests for microinverter and microconverter reliability in stand-alone and module-integrated configurations
- Extensive laboratory and field testing to validate tests and test protocols to ensure broad applicability across the industry
- Testing to be vendor- and technology-neutral

Max. award duration
3 years
Max award size
$2.25M
Total cost (DOE + Cost-share)
$9.5M
Total DOE funding
$7.5M
Cost-share minimum
20%

Coupled Thermo-Mechanical and Photo-Chemical Degradation Mechanisms that determine the Reliability and Operational Lifetimes for CPV Technologies

Reinhold H. Dauskardt, Stanford University with BAPVC, Spectrolab and NREL





CPV systems are an ideal PV vehicle with elevated "stress" parameters for reliability studies

Focus: **Identify** and **characterize** the *coupled* intrinsic thermo-mechanical and photo-chemical degradation mechanisms that determine the reliability and operational lifetimes for CPV technologies with *direct implications* for other PV technologies.

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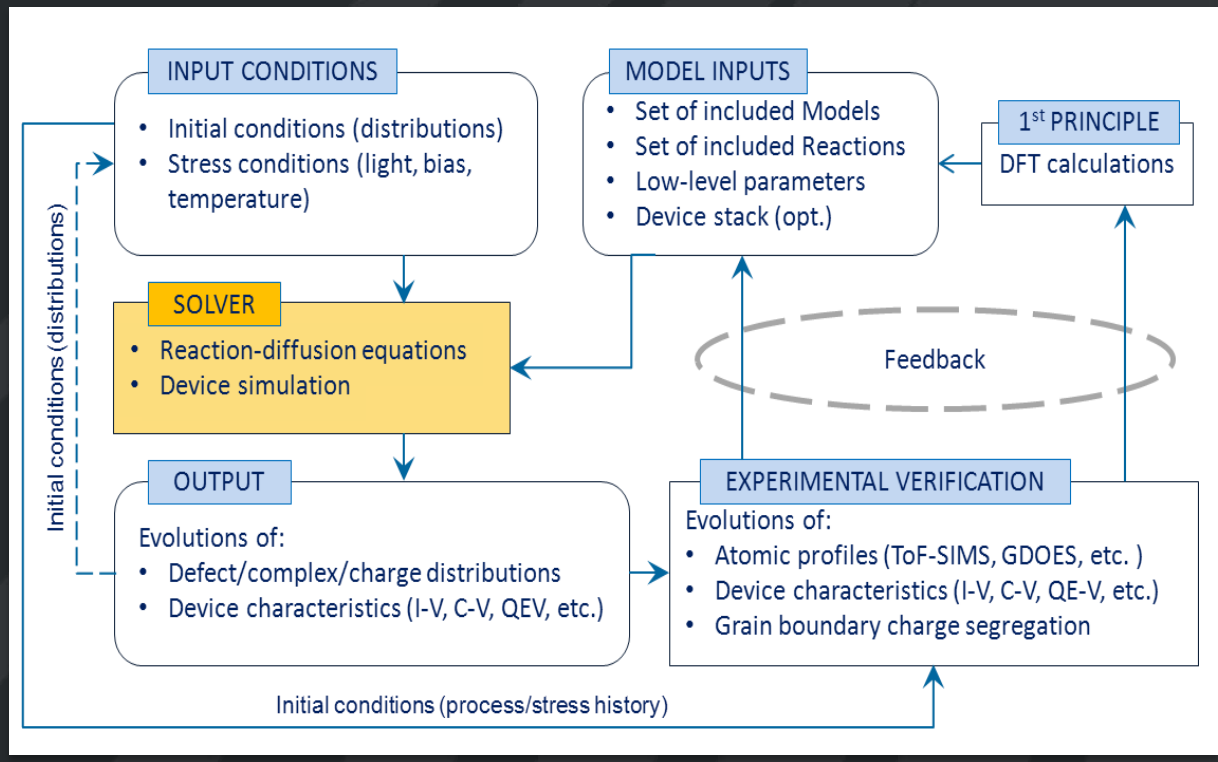
Unified Numerical Solver for Device Metastabilities in CdTe Thin-Film PV

Dragica Vasileska, Arizona State University with First Solar, NREL and CSU

- Integrating 1st principle DFT, kinetics of materials, semiconductor physics and characterization into a unified 2D solver for understanding the performance and metastabilities of CdTe



PREDICTS: CSP and Power Electronics

Physics-Based Reliability Models for Supercritical-CO_2 Turbomachinery Components: Azam Thatte, GE Global Research with Southwest Research Institute

Developing predictive performance and reliability models for key components of supercritical CO_2 expanders and heat exchangers used for lower cost CSP

Predictive Physico-Chemical Modeling of Intrinsic Degradation Mechanisms for Advanced Reflector Materials: Ross Larsen / NREL with Abengoa

Developing predictive models for intrinsic degradation and failure mechanisms of advanced materials and coatings targeted for use in CSP systems

Module Level Power Electronics Reliability and Accelerated Testing Standards Development: Jack Flicker/ Sandia National Laboratories with several partners

Analysis of failure in module level power electronics taking into account field reliability data and usage environments; recommendations for standard reliability test protocol

SERIIUS Solar Energy Research Institute for India and the United States

DOE Basic Research Needs/Priority Areas

- Maximum energy from solar photons at low costs
- Nanostructures for solar energy conversion; low cost and high efficiencies
- Materials and architectures for solar energy; assembling complex structures

Critical Barriers called out by EERE SunShot Vision Study

- Understand materials and structures to improve conversion efficiency
- Optimize molecular, polymeric and nanocrystalline structures to produce systems
- High-throughput and continuous (roll-to-roll) processes that do not require high temperature or vacuum

Critical Barriers–India

- Earth abundant and green materials
- Low capital manufacturing at multiple scales
- Distributed power generation and integration
- **Degradation mechanisms (reliability, dust)**

Bay Area PV Consortium: Encapsulation and Reliability Thrust

- Reinhold Dauskardt (Stanford): *Reliability and Operational Lifetimes for BAPVC Technologies*
- Roger French (Case Western): *PV Module Performance & Lifetime Prediction: Inserting New Technologies Without Lifetime Penalty*
- Rachel Segalman and Jeffery Urban (Berkeley): *Novel Polymer-Nanocrystal Composite Barrier Layers*
- Bernard Kippelen and Samuel Graham (Georgia Tech): *Tailoring Electrostatic Interactions to Produce Hybrid Barrier Films for Photovoltaics*

Outline

- The SunShot Initiative and the Solar Energy Technologies Office
- Reliability and Performance Projects
- **Current Opportunities**

SunShot
U.S. Department of Energy

May 19-22
Anaheim, CA

SAVE THE DATE

SunShot Grand Challenge Summit 2014

Keynote Speakers and Panel Sessions

- From business leaders, academia, and policymaking communities of the U.S. solar energy industry.

Industry Workshops

- Focused discussions to encourage stakeholder feedback.

Peer Review

- SunShot projects will be evaluated by peer reviewers.

Technology Forum

- Experience our interactive technology demonstrations and poster displays from SunShot awardees, interact with solar industry innovators and foster new partnerships.

Open Funding Opportunity: SolarMat 2

- Purpose:
  - Spur photovoltaic (PV) and concentrating solar power (CSP) manufacturing and supply chain companies in the U.S.
  - Assist in the development and demonstration of innovative manufacturing technologies
  - Help create cost advantage for domestic manufacturers
- Details:
  - Total federal funds available: $25M
  - Minimum industry cost-share: 50%
  - Project period: 1 to 4 years
  - Number of expected awards: 6 to 10
  - Concept Paper must be submitted by March 12 5:00 pm EST

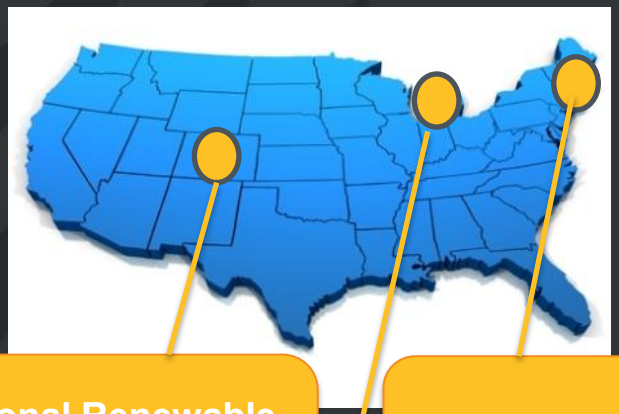
https://eere-exchange.energy.gov
DE-FOA-001018

SunShot Postdoctoral Research Awards

Develop the next generation of solar scientific leaders

- Solar research topic areas include:
  - Fundamental understanding of mechanisms of degradation in PV devices and research developing physics based models for device degradation.
  - Reducing the gap between module and PV cell efficiencies
  - Advanced modeling, visualization and control of photovoltaic systems and grid integration
- U.S. citizen applicant finds research mentor and writes joint proposal
- **20% Innovation Time – A unique fellowship opportunity**
  - Fellows pursue innovative self-directed projects in addition to mentored research project

Current Jobs of Alumni



National Renewable Energy Lab: Staff Scientist

Yale University: Staff Scientist

University of Michigan: Assistant Professor

APPLICATIONS DUE APRIL 30, 2014

http://www1.eere.energy.gov/education/postdoctoral/

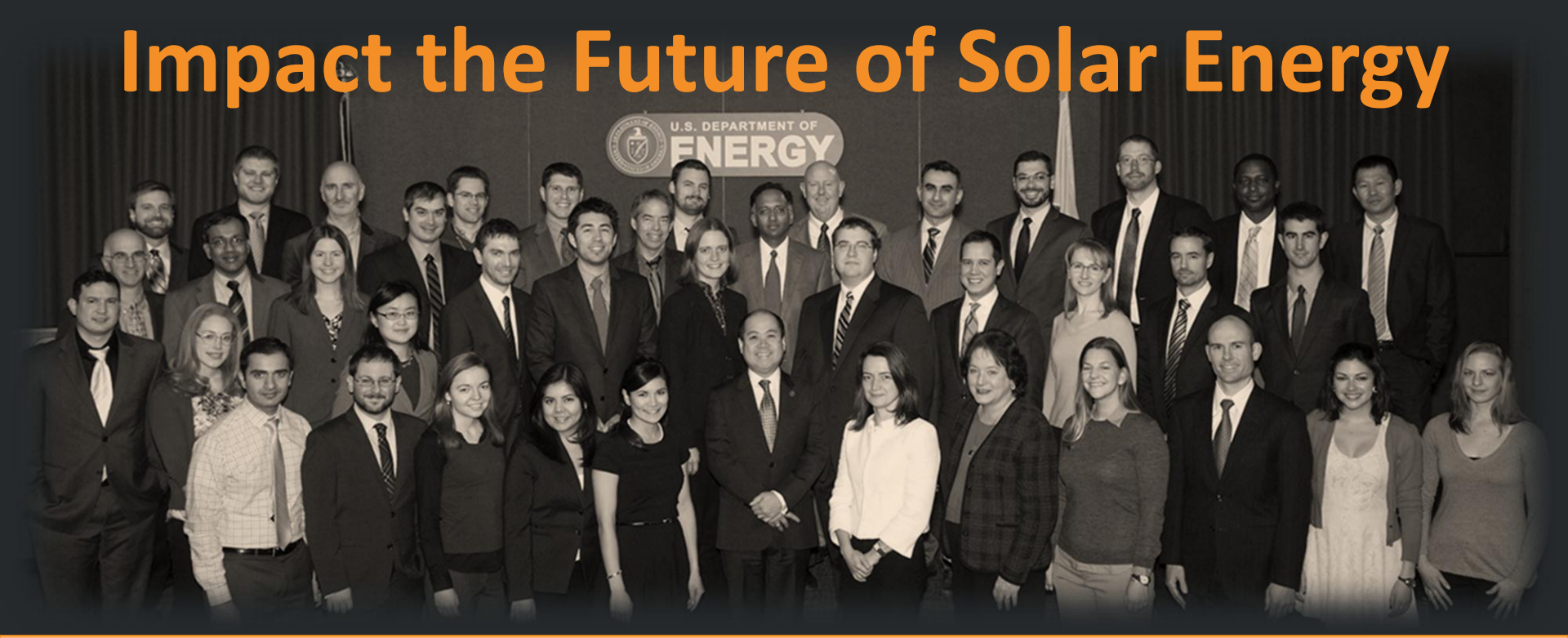
SunShot Science & Technology Policy Fellowships

- Two-year fellowships with DOE in Washington, DC
- Active involvement in current and new R&D programs
- Professional mentorship from DOE leadership
- Open to BS, MS, and PhD graduates
- Competitive stipend, benefits, and travel allowance

Applications due: January 31 | May 30 | September 30

Website: eere.energy.gov/education/stp_fellowships.html

Impact the Future of Solar Energy



Join our team! Take on the SunShot grand challenge to make solar energy cost-competitive with traditional energy sources by 2020.

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

energy.gov/sunshot

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Thank You!

Becca Jones-Albertus
Rebecca.Jones-Albertus@hq.doe.gov

International Electrotechnical Commission
TC 82 on Solar Photovoltaic Energy Systems

Conformity Assessment:
Introducing IECRE

By George Kelly
TC 82 Secretary

February 26, 2014

Background

- Industry Growth
  - Demand increasing 20%+ per year
  - Significant increase in large commercial 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 PV

Roles & Responsibilities

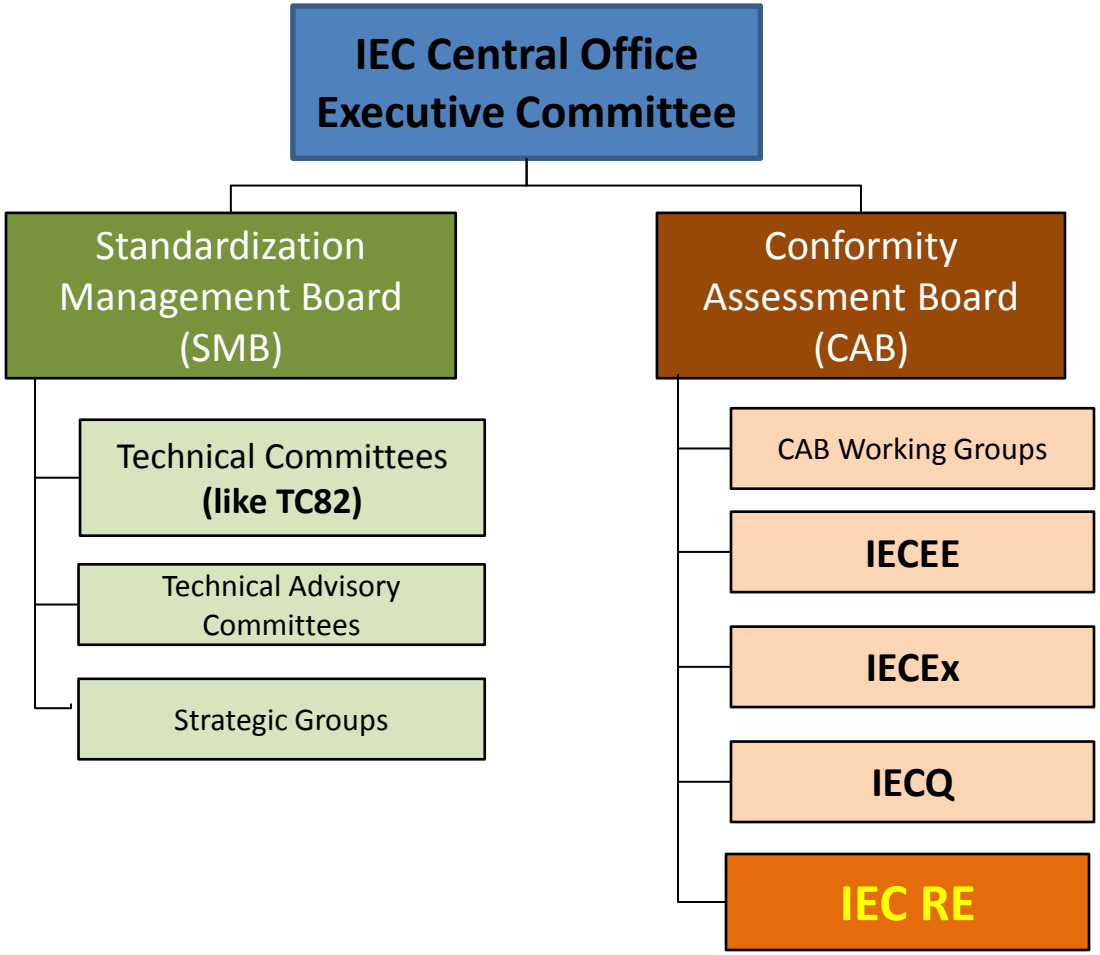
- Standards Management Board (**SMB**)
  - Technical Committees => Write the standards
  - Manage nomination of experts and voting by National Committees

- Conformity Assessment Board (**CAB**)
  - Assessment Schemes => Evaluate implementation of standards in specific situations
  - Manage accreditation of Certifying Bodies

Existing CA Schemes

- **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

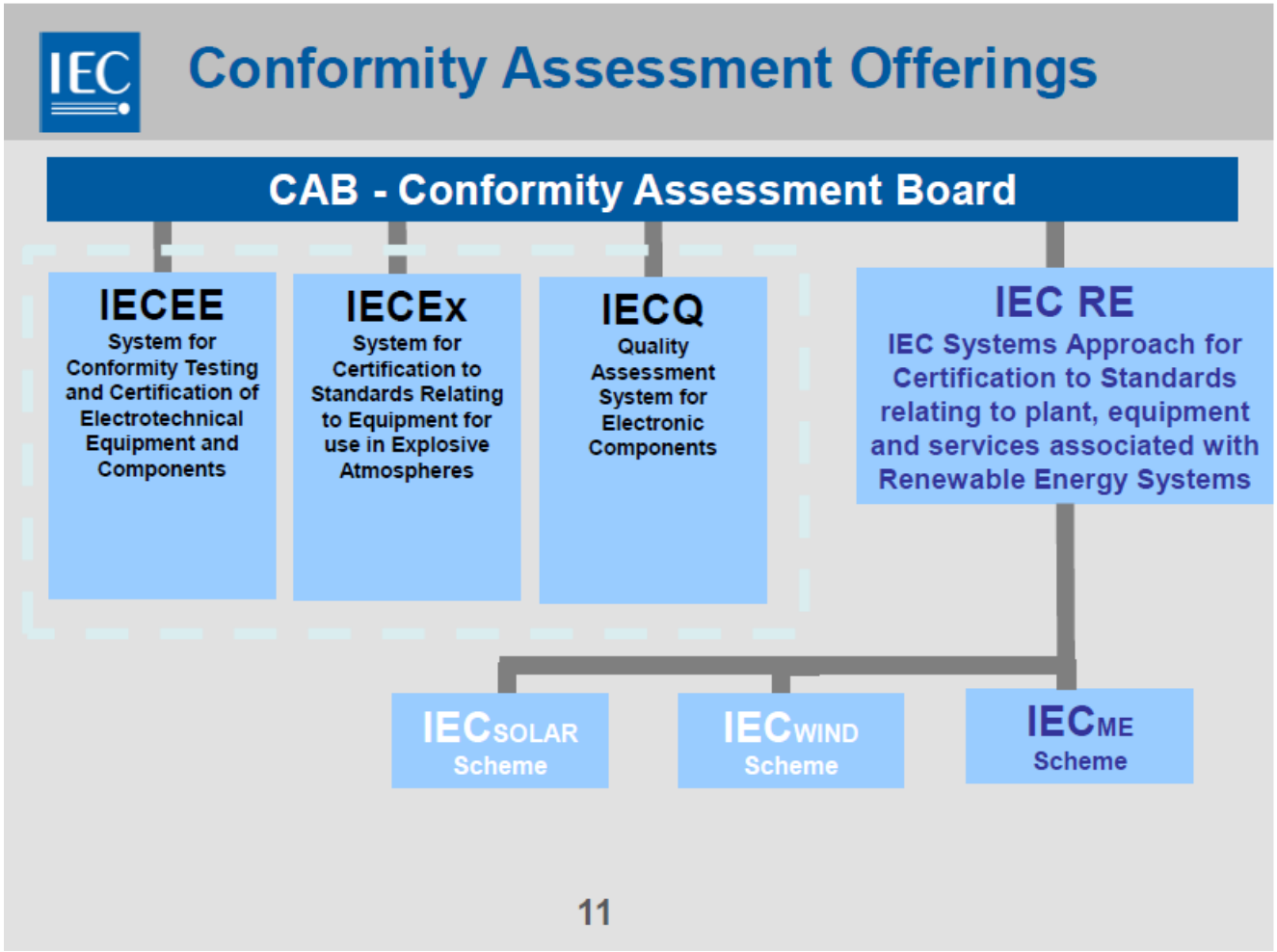
New IEC Organization



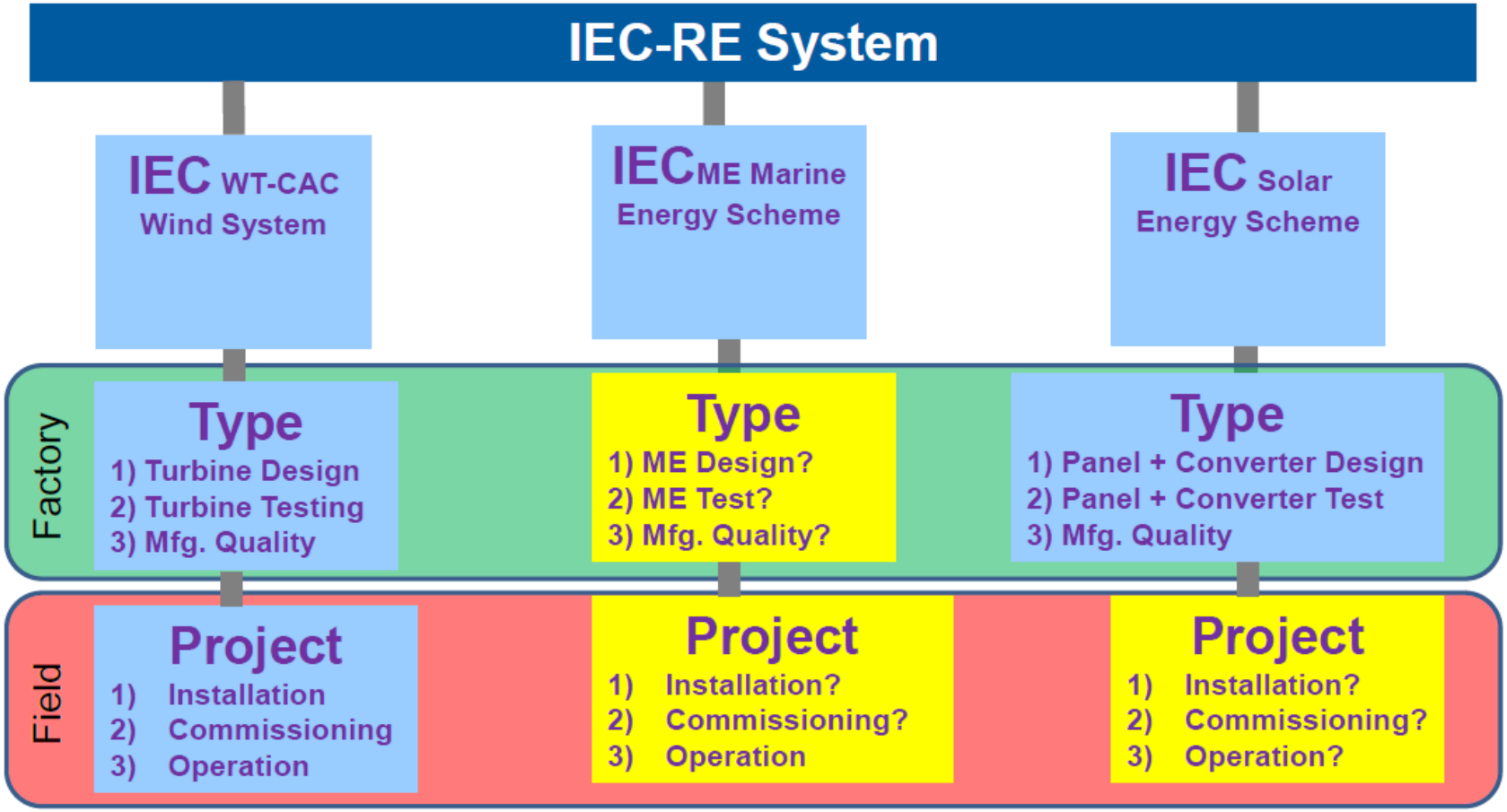
TC 88 - Wind Turbines

- Wind industry identified need to standardize "system aspect" of large complex projects
  - Not addressed by any existing CA scheme
- IEC structure / policy requires separation of standardization and CA activities
  - WT-CAC allowed to exist temporarily due to strong industry support
- Concept developed for new CA scheme (IECRE)
  - Similar requirements exist for Marine Energy projects as well as large PV plants
  - Specific differences in details apply for each industry

IECRE Concept



RE System Common Elements



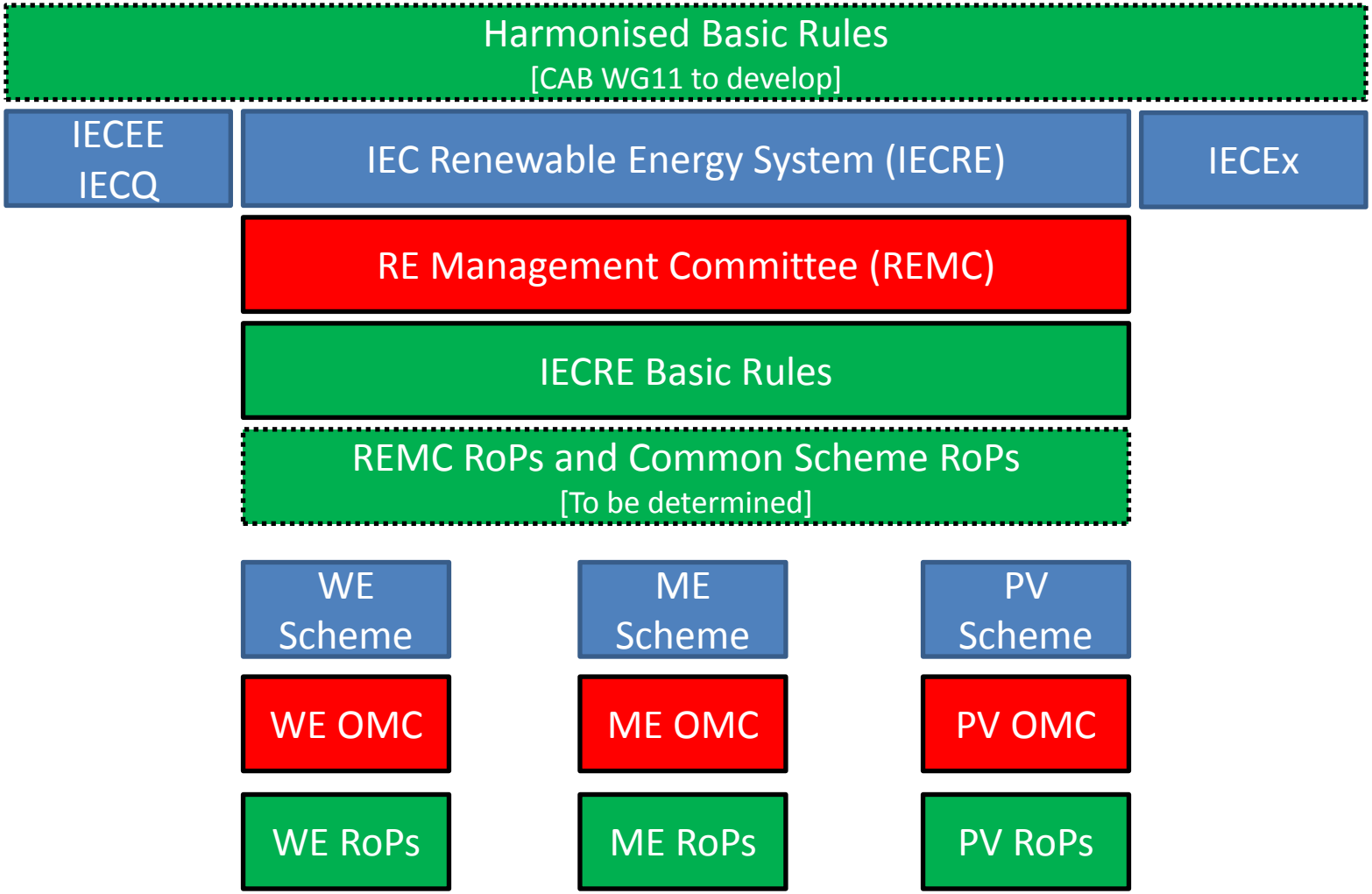
CAB Decisions (June 2013)

- Proposal for a new RE System was endorsed along with the recommended next steps
- Decision 33/20
  - CAB approves the creation of a Renewable Energy Conformity Assessment System once the Basic Rules have been developed
- Decision 33/21
  - Establishes a working group to prepare a draft set of Basic Rules and report back at the next CAB meeting in New Delhi

IECRE kickoff meeting

- Oct-2013 in Aarhus, Denmark
  - Participation by TC82, TC88 (Wind Turbines) and TC114 (Marine Energy)
    - Seeking 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 industry-specific

IECRE Hierarchy



Latest Progress

- IECRE Basic Rules
  - Draft reviewed by all 3 sectors
  - To be finalized at RE Forum meeting
    - Geneva 2-3 April 2014
  - CAB approval expected June 2014
- First Meeting of IECRE MC
  - To be hosted by USNC in Sept 2014
  - Location TBD in Colorado
    - (CSU or CSM)

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

IECRE-PV Documents

- PV Rules of Procedure (RoP)
  - Draft reviewed in Madrid last week
  - Updated draft to be circulated 10-Mar
  - Final draft by Sept 2014
- PV Operational Documents (OD)
  - Based on IECEx system
  - Administrative details for processing requests, record-keeping, etc.

PV Rules of Procedure

- Scope
- Normative references
- Terms and definitions
- Acceptance of certification bodies
- Management of the certification system
- Extent of certification
- Aspects of certification
- Final evaluation
- Plant certificate

Aspects of Certification

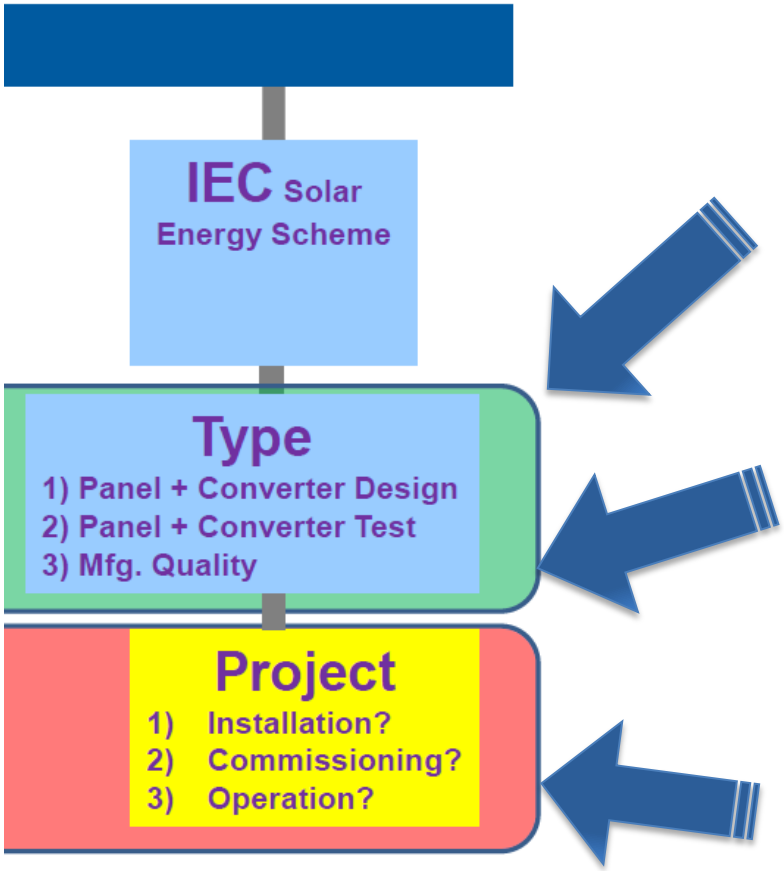
- General
- Site conditions evaluation
- Design evaluation
- Equipment evaluation
- Structural and electrical evaluation

- Installation surveillance
- Output characteristics measurement
- Commissioning surveillance
- Operation and maintenance surveillance

Operational Documents

- OD 001 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

PV Standards for Assessment



Module - 61215 / 61730
Inverter - 62109 / 62891
BOS - 62509 / 62093 + TBD

Manufacturing Quality System
- 82/800/NP

System Design - 62738 / 62548
Installation - TBD
Commissioning - 62446 / 61829
Operation - 61724 + TBD

Gaps to be Closed

- Standards Needed:
  - Installation
  - Operation & Maintenance
  - BOS Components
- RoP Issues:
  - References to specific standards
  - Output measurement details
  - Type certification requirements

International Electrotechnical Commission

TC 82 on Solar Photovoltaic Energy Systems

Thank you for your attention

Questions?

Contact solarexpert13@gmail.com

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NREL 2014- Photovoltaic Module Reliability Workshop Golden, Colorado

Overview of the Proposed PV Quality Management System

Task Group 1- Govind Ramu

SunPower Corporation, San Jose, CA

About the presenter

- Director of Global Quality Management Systems, SunPower Corporation
- Has over 25 years of experience implementing quality management systems in various global locations from various industry sectors
- US TAG TC 176/SC2 participating member for ISO 9001:2015 standards
- Expert on IEC TC 82 WG 2- Solar photovoltaic energy systems- Modules- non concentrating
- A licensed professional engineer in the province of Ontario, Canada, mechanical engineering degree from Bangalore University, India
- An ASQ Fellow, holds six ASQ certifications: quality manager, quality engineer, Six Sigma Black Belt, quality auditor, software quality engineer and reliability engineer
- Registered QMS ISO 9001:2008 principal auditor from IRCA (UK)
- Has coauthored ASQ's Certified Six Sigma Green Belt Handbook, one of the major contributing authors for The Lean Certification Handbook
- Served as an examiner in 2006, 2011, and 2012 for the California Awards for Performance Excellence (CAPE) and as an Examiner for the Malcolm Baldrige National Quality Award in 2010

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Table of contents

- Why Quality Management System (QMS)?
- Introduction to ISO 9001
- ISO 9001 perceptions and fact
- Audits and Certification
- PV QMS Task group
- Why Industry standard?
- Comparison of ISO 9001 Vs PV QMS
- ISO 9001-What next?
- PV QMS- Future possibilities
- Appendix

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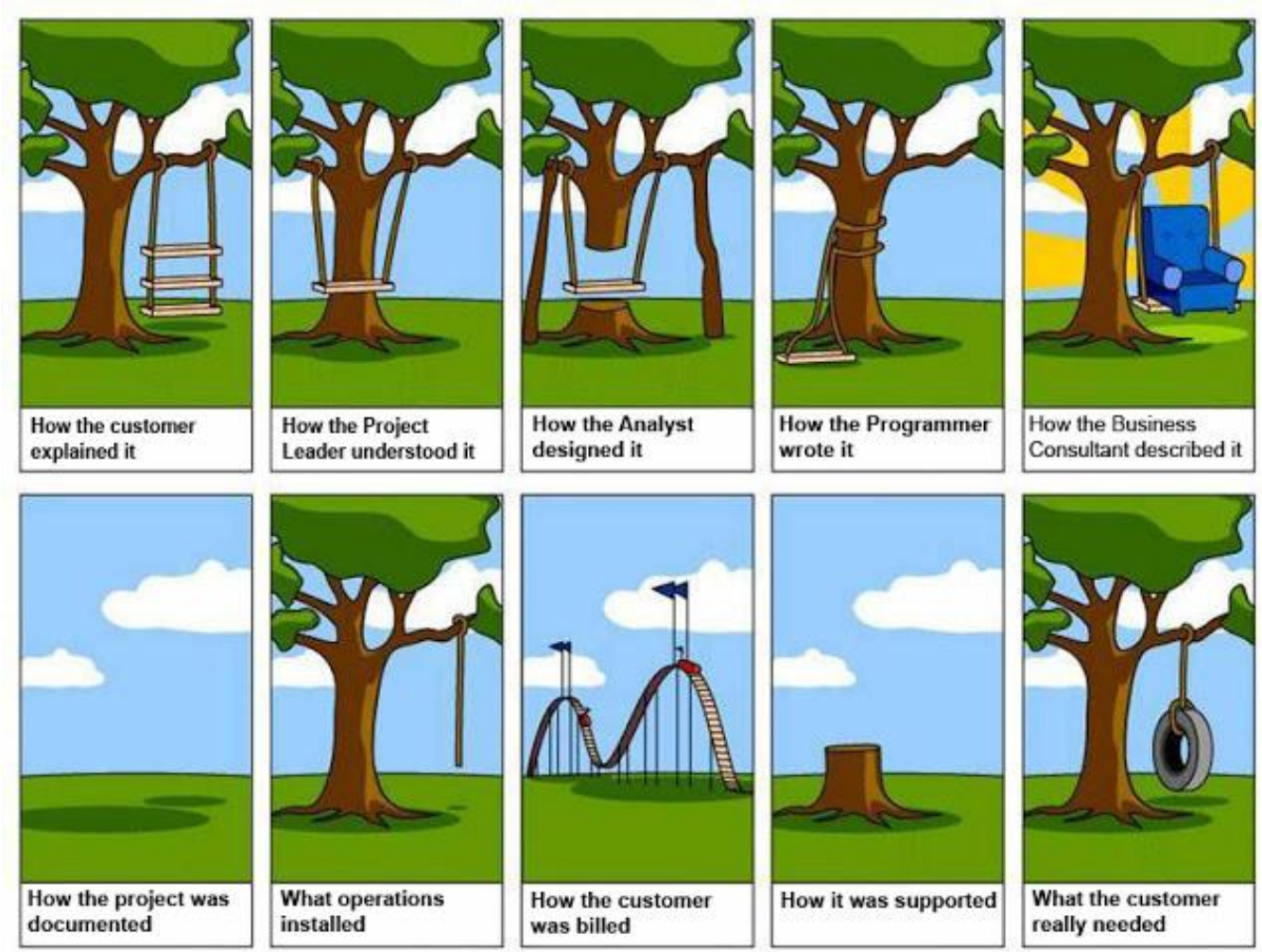
What customer needs?



Quality Management System= Business Management System

Source: Unknown

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ISO 9001 Quality Management System Requirements

- Over 25 years of evolution since its inception in 1987. Subsequently revised in 1994, 2000 and amended in 2008
- Covers general and foundational quality management requirements applicable to any industry or service sectors
- Most widely used standard. Over 1 million organizations worldwide are registered to this standard
- Hundreds of registration bodies worldwide are accredited to issue certification for client organizations
- ISO 9001 is now a contractual requirement for many organizations worldwide, often prerequisite for bidding new tenders

ISO 9001 is implemented in various industries, countries worldwide

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ISO 9001 Myth

Perception: ISO 9001 certification does not help improve quality of products and services. Only helps with consistent product/services.

Fact: There are 16 instances in the ISO 9001: 2008 requirements that call out improvement of product/service, process, effectiveness.

Why this perception?

Back in 1990s consultants and quality practitioners summarized ISO 9001 implementation in a nut shell for simplicity as:

"Say what you do, Do what you say".

In the year 2000, ISO 9001 was significantly updated to change this perception. Customer focus, Improvement and effectiveness became a common theme throughout the standard.

ISO 9001 is more than just consistent product/services.

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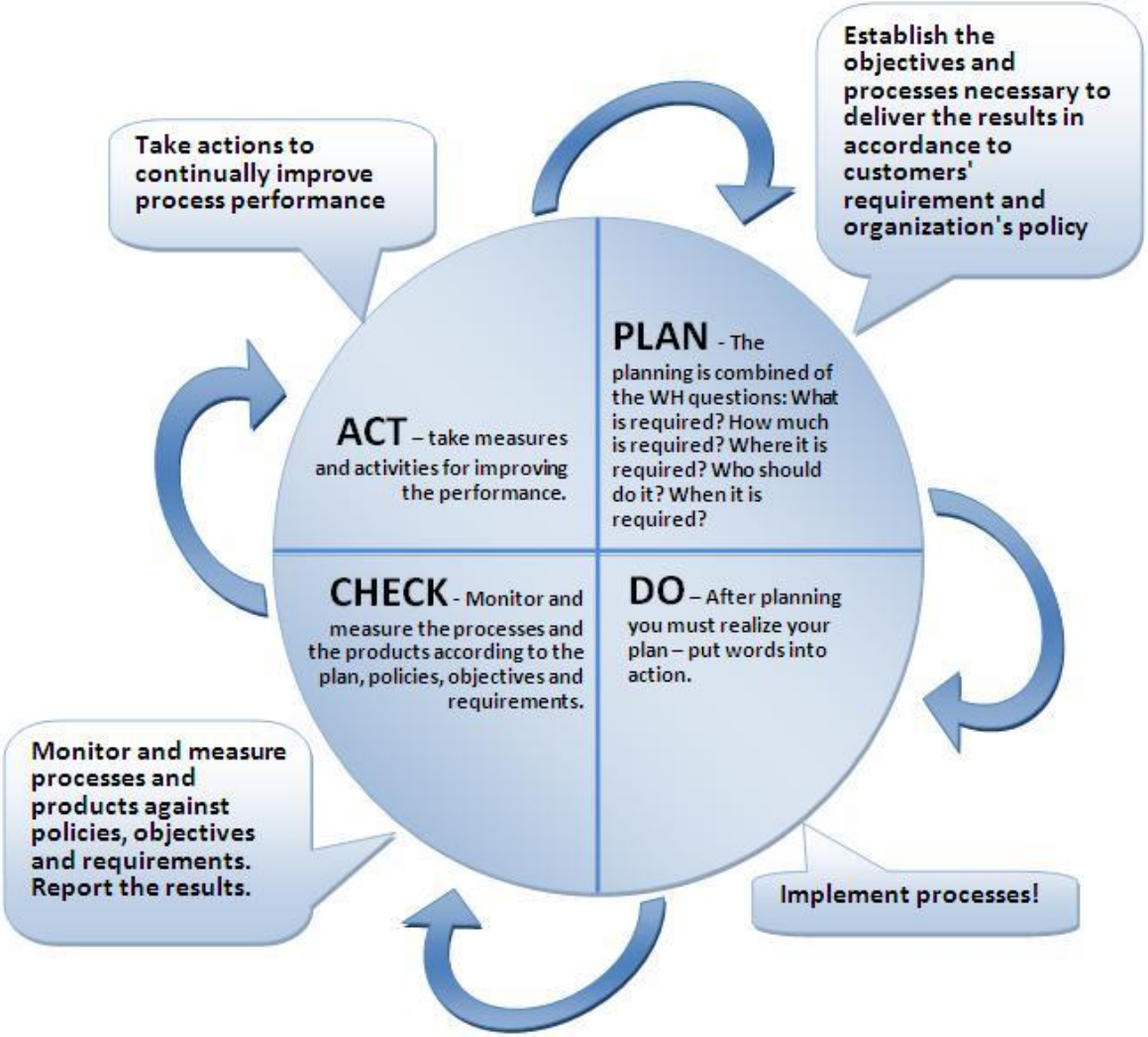
PDCA Cycle*- ISO 9001 framework



ISO 9001 requirements follow PDCA improvement model.

*Also popularly known as Deming Wheel/Cycle

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Types of System audits

- First party audit: Organization use the standard to verify compliance. Also known as Internal quality systems audit
- Second party audit: Organization use the standard to verify compliance of their suppliers
- Third party audit: An independent organization (registrar) verify compliance to the standard to issue ISO 9001 certificate for a client
- An accreditation body audits the registrars to verify their ability to issue ISO 9001 certificates

Audit verify compliance to standard, organization's QMS, and its effectiveness

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Certification Process

- Stage 1 audit- Registrar auditors verify compliance to the standard as a desk audit and review overall QMS framework
- Stage 2 audit- Registrar auditors verify compliance to the standard by auditing processes covered in the scope of registration
- Once certificate is issued, registrars conduct periodic surveillance audit annually, conduct recertification audit every 3 years

Due diligence all the way

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Highlights of QMS requirements for PV Module Manufacturing- Task group 1

Task group1Participants

Govind Ramu
SunPower

Paul Norum
Amonix

Yoshihito Eguchi
Japan Electrical Safety and Environment Technology Laboratories (JET)

Wei Zhou
Trina Solar

Alex Mikonowicz
Powermark

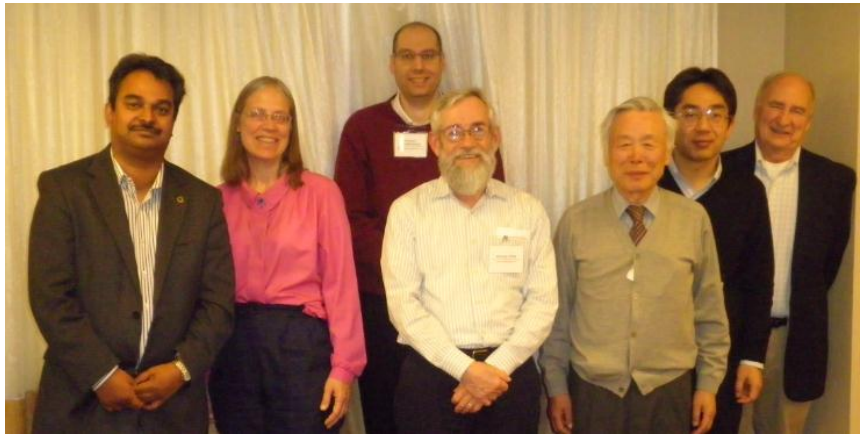
Ivan Sinicco
Tokyo Electron

Sumanth Lokanath
First Solar

Masaaki Yamamichi
National Institute of Advanced Industrial Science and Technology (AIST)

Gunnar Brueggemann
Tokyo Electron

Sarah Kurtz
National Renewable Energy Laboratory



Partial group of Task group 1 participants

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Why Industry specific standard?

- ISO 9001 Guidance notes: The extent of the quality management system documentation can differ from one organization to another due to the size of the organization and type of activities, the complexity of processes and their interactions, and the competence of personnel
- However organizations that are superficially implementing the QMS can unfortunately get certified due to:
  - Generic nature of requirements, inappropriate use of “Exclusion” clause
  - Lack of in-depth review by external auditors, auditor competency
  - Organization’s ability to prepare ahead of audit
  - Impress auditors with pockets of good practices and compliance
- Supplementing Industry requirements on top of the foundational ISO 9001 requirements provides organization specific expectations relevant to the industry

ISO 9001 alone may not be adequate to address industry specific requirements

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Industry specific QMS standards Started from mid 1990s

- TS 16949- Automotive
- AS9100- Aerospace
- ISO 13485- Biomedical
- TL 9000- Telecommunication
- Service sectors are also developing QMS standards to address specific requirements.
- Some interesting standards currently under development:
  - Guidelines for the application of ISO 9001:2008 in local government
  - requirements for the application of ISO 9001:2008 for electoral organizations at all levels of government

Other industry sectors are very successful in development and deployment of standards

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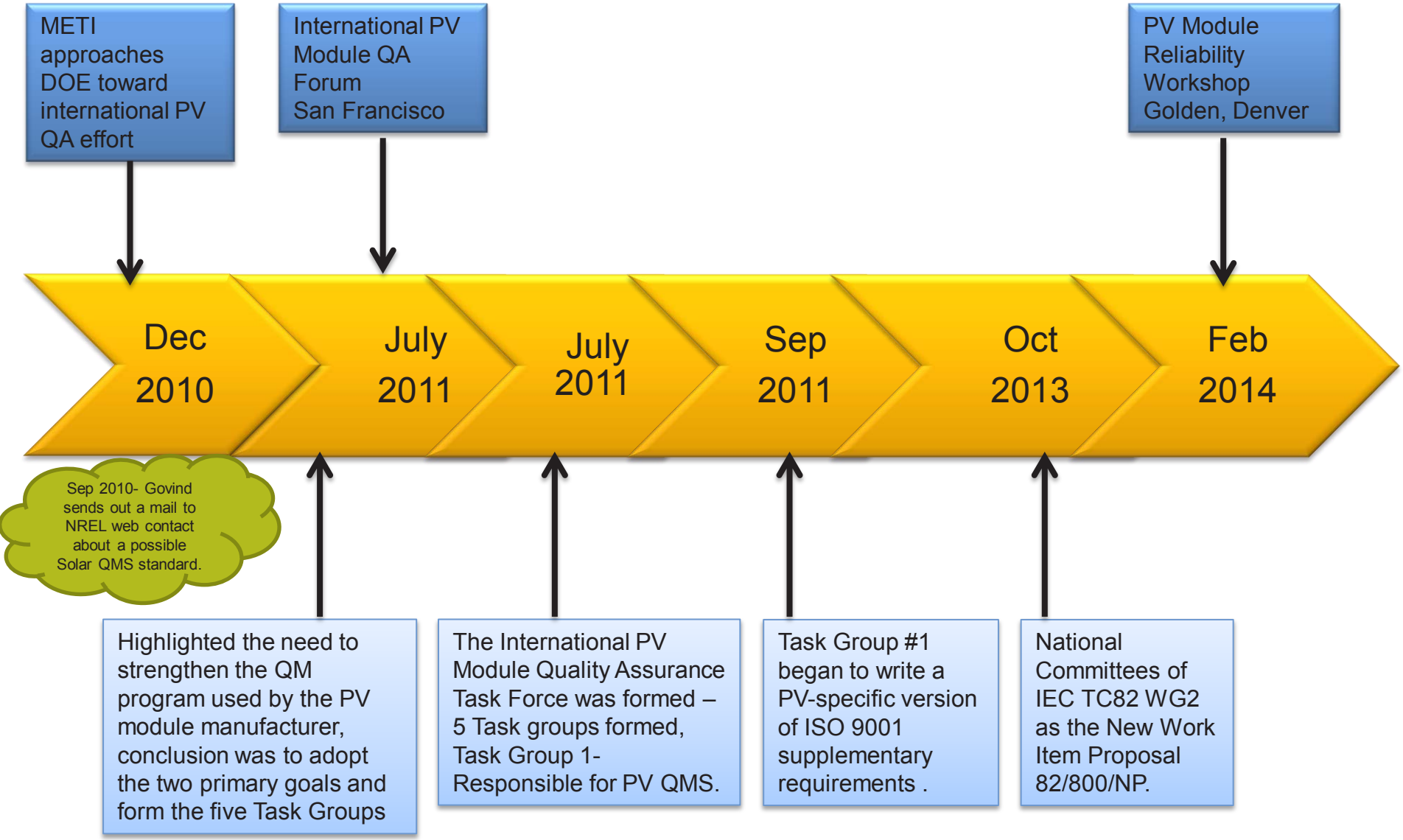
PV QMS Standard Development timeline



9001 Vs PV QMS

ISO 9001 QMS requirement

- Inputs relating to product requirements shall be determined and shall include functional and performance requirements
- The organization shall determine requirements specified by the customer, including the requirements for delivery and post-delivery activities (Warranty)

PV QMS Requirement

- 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 FMEA
  - Reliability testing
  - Lessons learned

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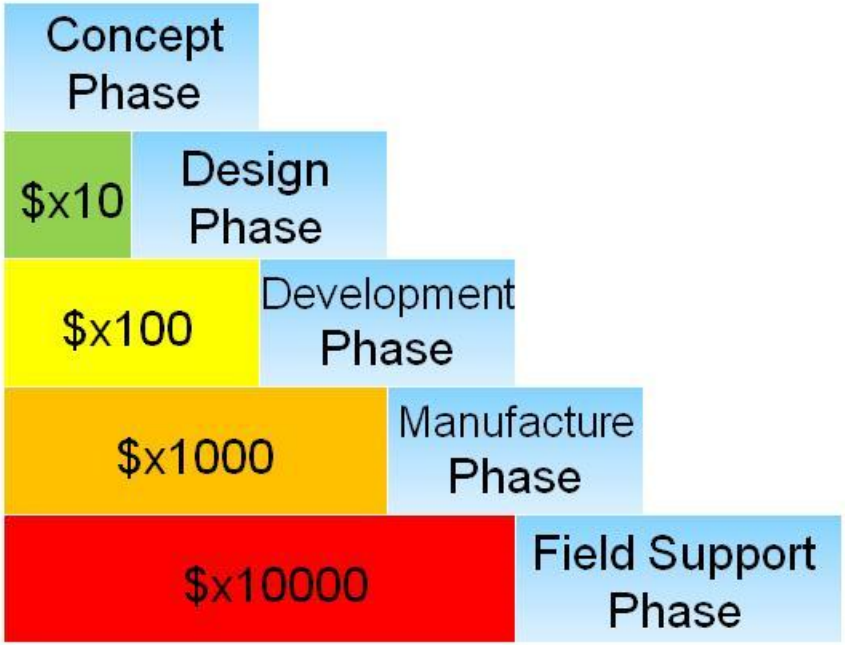
Design at the Source:
Factor of 10 thumb rule

The cost of addressing reliability issues increases tenfold as you move through the development process



"...and we can save 700 lira by not taking soil tests."

9001 Vs PV QMS

ISO 9001 QMS requirement

- Inputs relating to product requirements shall be determined and shall include applicable statutory and regulatory requirements

PV QMS Requirement

- A product realization that includes appropriate certification (e.g. IEC qualification, including both type approval and safety testing), a design lifetime that enables compliance with warranty, and recycling provisions
- Controls:
  - Internal/external qualification
  - Certification
  - Design FMEA/ Risk assessment

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9001 Vs PV QMS

ISO 9001 QMS requirement

- Where traceability is a requirement, the organization shall control the unique identification of the product and maintain records

PV QMS Requirement

- 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:
  - constituent key materials and components
  - lot/batch level
  - Traceable to supplier, date, Mfg. location
  - Traceable to Internal processes
  - Reworked/repaired products

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9001 Vs PV QMS

ISO 9001 QMS requirement

- The organization shall monitor and measure the characteristics of the product to verify that product requirements have been met.
- This shall be carried out at appropriate stages of the product realization process in accordance with the planned arrangements

PV QMS Requirement

- An ongoing, periodic monitoring program to ensure consistency of aspects of manufacturing that may affect safety, performance, and reliability
- Controls:
  - Reliability Monitoring Program (RMP)

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9001 Vs PV QMS

ISO 9001 QMS requirement

- The organization shall validate any processes for production and service provision where the resulting output cannot be verified by subsequent monitoring or measurement
- The analysis of data shall provide information relating to conformity to product requirements

PV QMS Requirement

- Special processes such as control of solder connections
- Control of processes for ESD protection
- Assignment of PV module power rating with allowed tolerance including measurement uncertainty
- Controls:
  - Software validation
  - ESD Program effectiveness
  - determine parameter sets for the acceptance tolerance
  - Determine measurement uncertainty.

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9001 Vs PV QMS

ISO 9001 QMS requirement	PV QMS Requirement
• The organization shall determine and provide the resources needed to enhance customer satisfaction by meeting customer requirements	• Resources needed to maintain the product warranty system, product reliability measurements, provision of after-sales service
• No requirement on Succession planning for key functions	• Succession planning for key functions that affect customer, quality reliability, safety and performance
• The organization shall determine and manage the work environment needed to achieve conformity to product requirements	• ESD- Electrostatic Discharge (ESD) safe environment at the raw material storage, processing, assembly areas, as appropriate

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9001 Vs PV QMS

ISO 9001 QMS requirement

- Inputs relating to product requirements shall be determined. These inputs shall include where applicable, information derived from previous similar designs

PV QMS Requirement

- Previous failure information incorporated into the requirements of the QMS
- Controls:
  - Failure information database management
  - Design Review

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9001 Vs PV QMS

ISO 9001 QMS requirement

- The organization shall evaluate and select suppliers based on their ability to supply product in accordance with the organization's requirements. Criteria for selection, evaluation and re-evaluation shall be established.
- The organization shall establish and implement the inspection or other activities necessary for ensuring that purchased product meets specified purchase requirements.

PV QMS Requirement

- A method for selection of vendors that can provide quality materials or products
- Receiving inspection and/or testing such as statistical sampling based on performance.
- Ensure that the supplier maintains product quality consistently, and will 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.

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9001 Vs PV QMS

ISO 9001 QMS requirement

- The organization shall monitor and measure the characteristics of the product to verify that product requirements have been met. This shall be carried out at appropriate stages of the product realization process
- The organization shall review the requirements related to the organization's ability to meet the defined requirements
- The organization shall plan under controlled conditions shall include the availability and use of monitoring and measuring equipment

PV QMS Requirement

- Routine tests on 100% of product to ensure consistency of initial quality
- Manufacturing feasibility at the necessary scale, including risk analysis
- 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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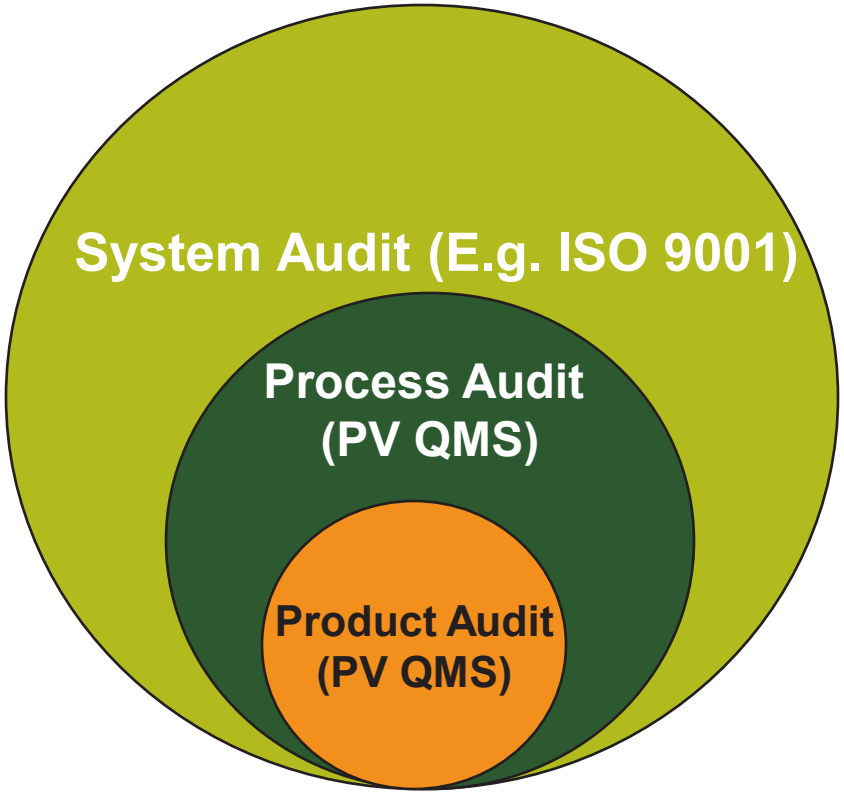
9001 Vs PV QMS- Product- Process- System audits



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Cost of Poor Quality (COPQ)

Warranty

Inspection

Field Service

Yield

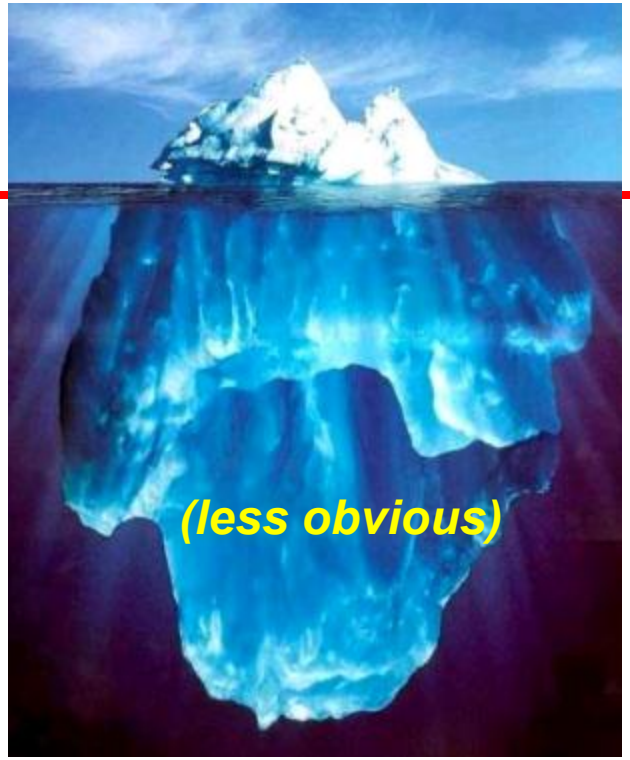
Gross Margin Erosion

RMA

Rework / Re-grade

Rejects / Scrap

Visible Costs



Engineering change orders

Lost sales / opportunities

Late delivery

Time value of money

Expediting costs

More Set-ups

Excess inventory

Long cycle times

Working Capital allocations

Hidden Costs

Lost Customer Loyalty

Degraded Brand Image

Excessive Material Orders/Planning

COPQ ranges 15-20% of total cost! Hidden costs can be up to 4 times the visible costs!

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9001 Vs PV QMS

ISO 9001 QMS requirement

- The organization shall determine, collect and analyze appropriate data to demonstrate the suitability and effectiveness of the quality management system
- The organization shall apply suitable methods for monitoring of processes
- The organization shall continually improve the effectiveness of the quality management system through the use of analysis of data, corrective and preventive actions

PV QMS Requirement

- Use 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 error proofing, Statistical process Control, control plan, Failure mode effects analysis, and 8 Discipline -methodology to build PV modules with consistent quality and reliability
- Controls:
  - Process FMEA
  - Poke Yoke
  - Control Plan
  - SPC
  - 8D methodology

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What is next in ISO 9001 (2015)?

- Standard becoming more generic to cater all industry types including service sector. Mandatory documentation requirements for some process go away (Even more so why we need PV Industry specific QMS!)
- Risk management-leveraged with leadership managing risks when making organizational decisions. (adding good foundation)
- specific requirements for adopting the process approach*. (adding good foundation)

(Standard currently at the Committee draft stage. Draft standard expected by April 2014)

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PV QMS future Possibilities (Brainstorm ideas)

- 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”
- 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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Appendix

References, Bibliography & Acknowledgements

- **References:**
  - ISO 9001:2008 Quality Management System requirements
  - 82/800/NP- Guideline for increased confidence in PV module design qualification and type approval
- **Bibliography:**
  - ISO 19011:2011 Guidelines for auditing management systems
  - Tip of the iceberg- Quality Progress article, May 2001
- **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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BACK UP SLIDES

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Nuggets in the ISO 9001 notes
(Items gets pushed to notes during standards review)

- Ensuring control over outsourced processes does not absolve the organization of the responsibility of conformity to all customer, statutory and regulatory requirements
- The extent of the quality management system documentation can differ from one organization to another due to the size of the organization and type of activities, the complexity of processes and their interactions, and the competence of personnel
- Conformity to product requirements can be affected directly or indirectly by personnel performing any task
- Design and development review, verification and validation have distinct purposes
- Customer property can include intellectual property and personal data
- Confirmation of the ability of computer software to satisfy the intended application would typically include its verification and configuration management to maintain its suitability for use
- In some industry sectors, configuration management is a means by which identification and traceability are maintained

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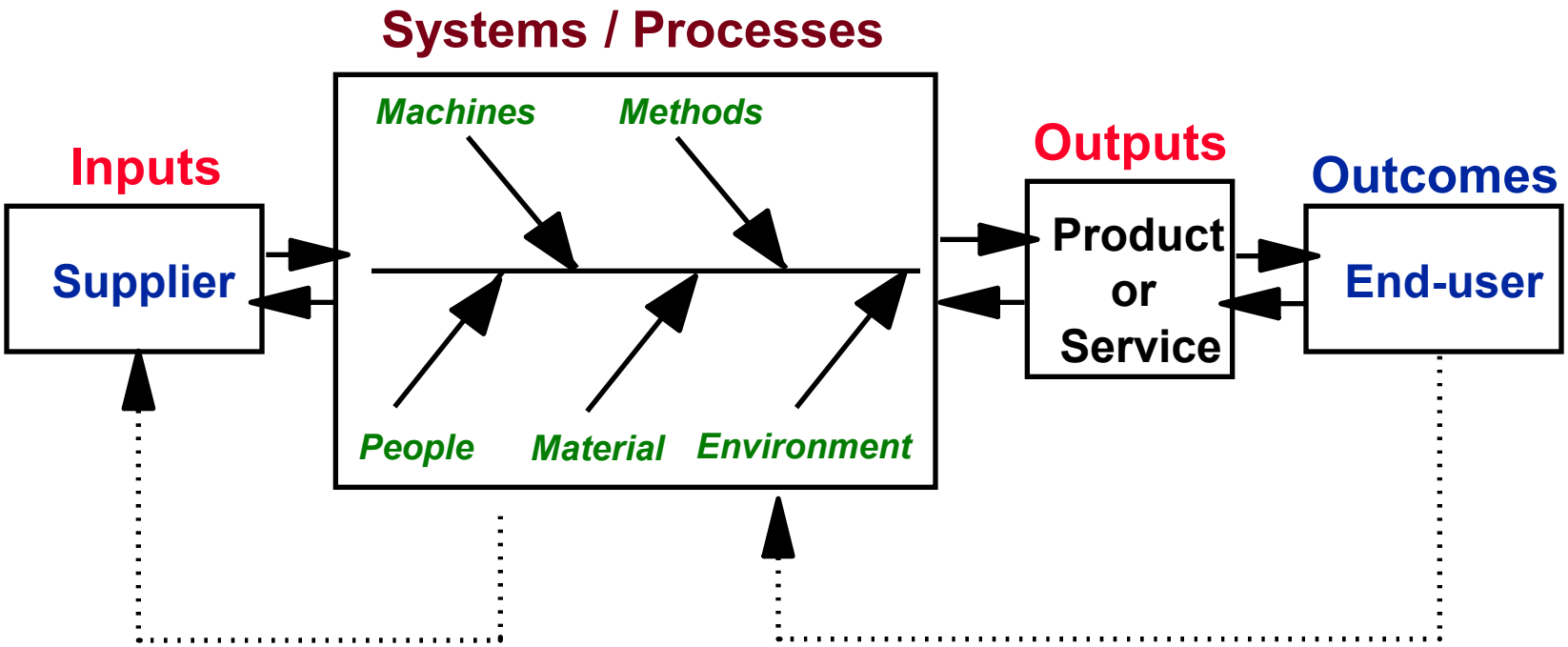
*Process Approach



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BUILDING A WORLD OF DIFFERENCE

26 February 2014

OBSERVATIONS ON PV MODULE QUALITY MANAGEMENT

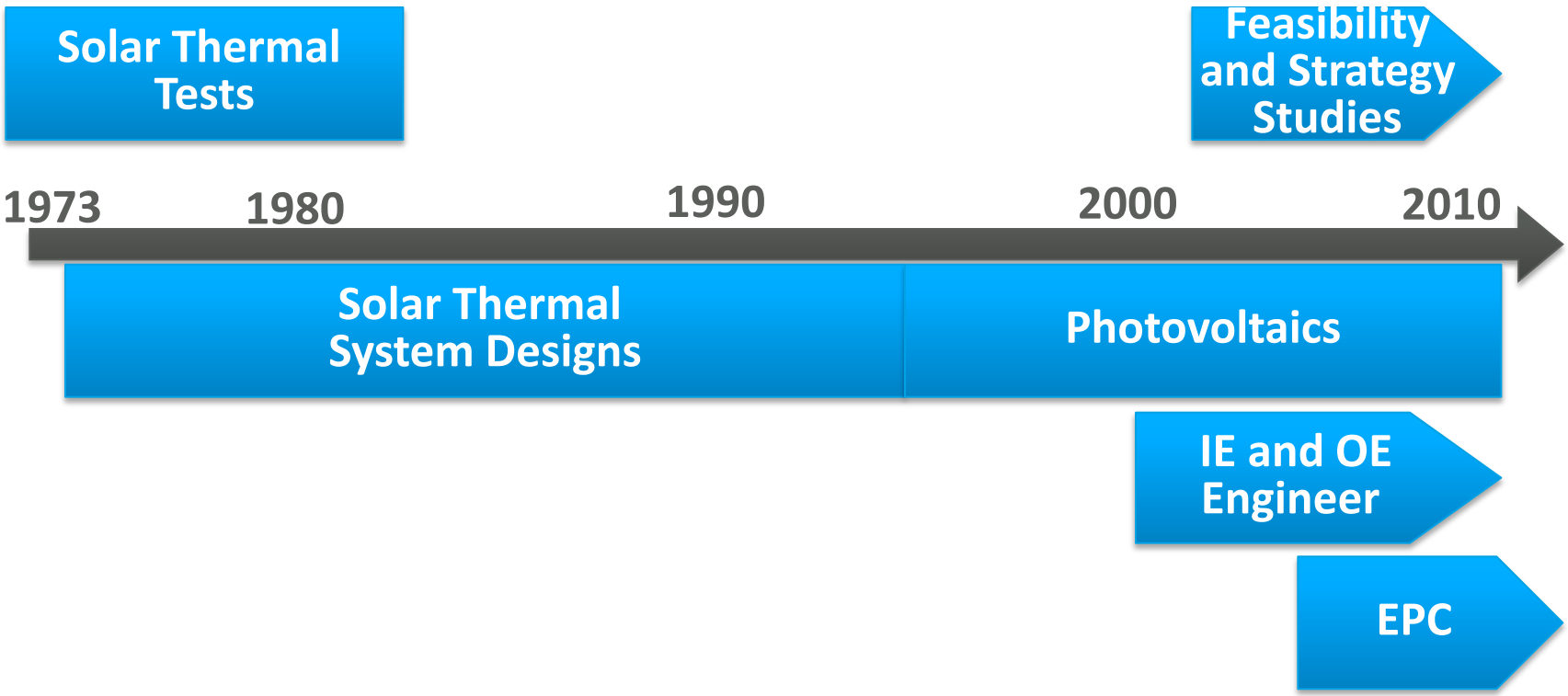
DR. RALPH ROMERO
DIRECTOR
MANAGEMENT CONSULTING DIVISION

BLACK & VEATCH
Building a world of difference.

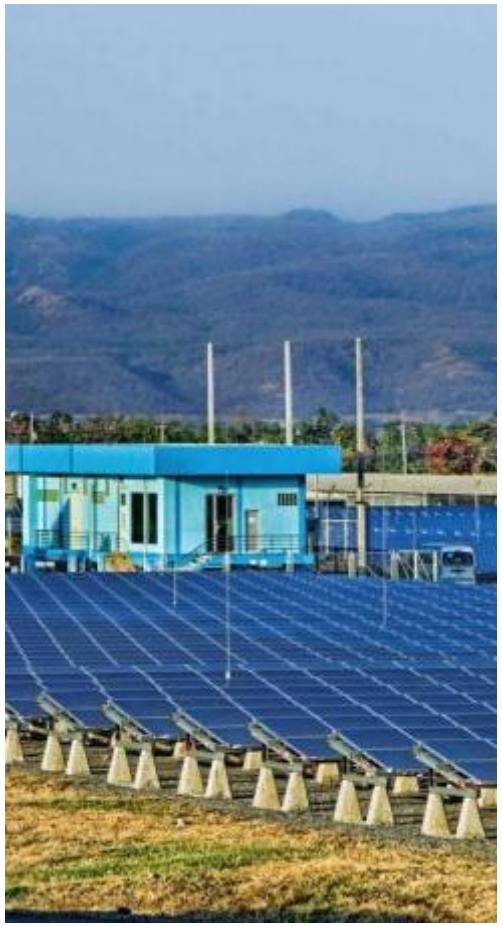
PRESENTATION SUMMARY

- **Comment on:**
  - **Key requirements in proposed guide for Quality Management Systems (QMS) for PV manufacturing and,**
  - **QMS in manufacturing today**
- **Discuss possible actions to narrow the gaps**
- **Conclusions**

BLACK & VEATCH HAS BEEN ACTIVELY ENGAGED IN THE SOLAR INDUSTRY FOR DECADES



Black & Veatch has been actively engaged in the solar industry for decades.



INDEPENDENT ASSESSMENTS PERFORMED

- **Modules**
  - Crystalline silicon - 31
  - Thin film - 10
- **Trackers - 22**
- **Inverters -7**
- **Concentrator PV- 4**

QMS GUIDE KEY REQUIREMENT

"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…"

OBSERVATIONS

- **Proliferation of PV component manufacturers**

Chinese suppliers	More than
Wafers	50
Glass	25
Encapsulant	15
Backsheet	15
Junction box	25
Connectors	25

- **Module manufacturers rely heavily on successful IEC 61215 and UL 1703 test results to include a specific component in a bill of materials.**

Suggestions:

- **Implement tests, such as the Qualification Plus protocol, that reveal failures modes seen in the field, e.g.**
  - Corrosion
  - Delamination
  - Encapsulant discoloration
  - Junction box failures
  - Power degradation
- **Further develop component technical specifications.**

KEY REQUIREMENT IN QMS GUIDE FOR PV MANUFACTURING

"Design of a manufacturing process that will ensure conformance to the design intent for power, lifetime, and warranty."

OBSERVATIONS

- The module manufacturing process contains steps that are common to all manufacturers.

SOME DIFFERENCES:

- Personal safety (personal protective equipment, electrical safety)
- Incoming inspection (equipment, sampling plans)
- Degree of automation (soldering, module assembly)
- Quality control (peel test, electroluminescence, flash test, hipot test)
- Personnel retention and training

SUGGESTIONS:

Implement industry accepted best practices in:

- Personal safety
- Incoming inspection
- Soldering and assembly
- Quality control
- Staffing and training

QMS GUIDE KEY REQUIREMENT

"A product realization that includes appropriate certification (e.g. IEC qualification, including both type approval and safety testing), a design lifetime that enables compliance with warranty, and recycling provisions"

OBSERVATIONS

- Modules that are sold in North America have BOMs that successfully passed IEC 61215 and UL 1703.
- High number of module bills of materials.
- Strict control required of certified BOMs following IEC 61215 and UL1703 retesting guidelines.
- Implement Qualification Plus testing.

KEY REQUIREMENT IN QMS GUIDE FOR PV MANUFACTURING

"Improve product traceability through the entire supply chain to enact positive control of the product for recalls and warranty claims."

OBSERVATIONS

- Most module manufacturers have a means to correlate direct material, component and manufacturing information to module serial numbers.
- Less than half of the manufacturers have this information in electronic databases.
- Upstream product traceability requirements are not widespread.

<u>Suggestions:</u>

- Expand electronic storage of module traceability data.
- Increase upstream supplier traceability.

KEY REQUIREMENT IN QMS GUIDE FOR PV MANUFACTURING

"An ongoing, periodic monitoring program to ensure consistency of aspects of manufacturing that may affect safety, performance, and reliability."

OBSERVATIONS

- Manufacturers have ongoing production monitoring programs.
- Manufacturers receive and react to customer claims.
- Most manufacturers have had modules in the field for less than ten years.

Suggestion:

- Focus production monitoring programs on revealing known failure modes.

KEY REQUIREMENT IN QMS GUIDE FOR PV MANUFACTURING

“Routine tests on 100% of product to ensure consistency of initial quality”.

OBSERVATIONS

- **Most manufacturers utilize electroluminescence (EL) testing before and after lamination.**
- **Over thirty percent of the manufacturers use EL systems where the operator is not able to clearly identify cell defects.**

Suggestion:

- **Utilize EL systems that provide clear images of cell defects.**

CONCLUSIONS

- **Quality should be the leading module differentiator.**
- **Continued increase in stakeholder demands will lead to further quality improvements.**
- **The PV QMS guide can assist in improving module quality.**

THANK YOU!

Dr. Ralph Romero, Director
Black & Veatch
489 Fifth Ave, 14th Floor
New York, N.Y. 10017
+ 1 757-903-7528
RomeroR@BV.com

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PERFORMANCE ANALYSIS OF CIGS THIN-FILM PHOTOVOLTAIC SYSTEM AFTER 10 YEARS IN THE HOT AND HUMID CLIMATE OF FLORIDA

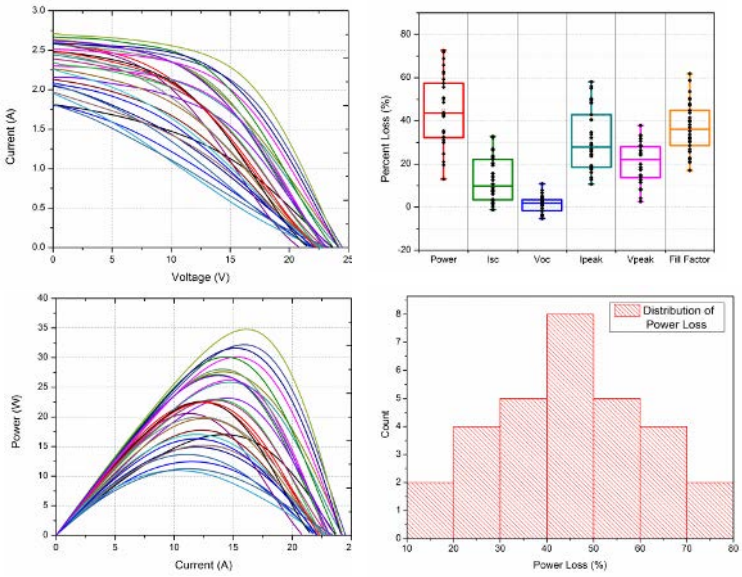
Eric Schneller, Narendra Shiradkar and Neelkanth G. Dhere

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

INTRODUCTION

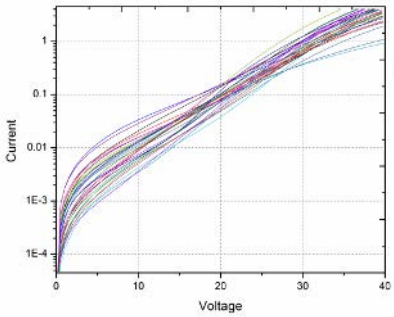
A CIGS thin-film photovoltaic array has been deployed at the Florida Solar Energy Center for almost 12 years. This array consisted of 8 strings in parallel, each with of 4 modules. The open circuit voltage of the system was just under 100 V with an operating voltage of 60 V. Analysis of the array was performed including illuminated and dark I-V measurements, electroluminescence and infrared imaging, and visual inspection.

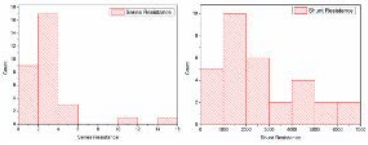
CURRENT-VOLTAGE CHARACTERISTICS



Outdoor I-V measurements were taken with a tolerance of 1000 W/m^2 ± 5 % and 25 °C ± 1 °C. The percentage loss of each parameter was calculated with reference to the nameplate ratings for the modules. The large variation in power loss among the modules exhibited a normal distribution with an average power loss of 44.6 %. This loss was mainly a result of decrease in fill factor and more specifically the operating current.

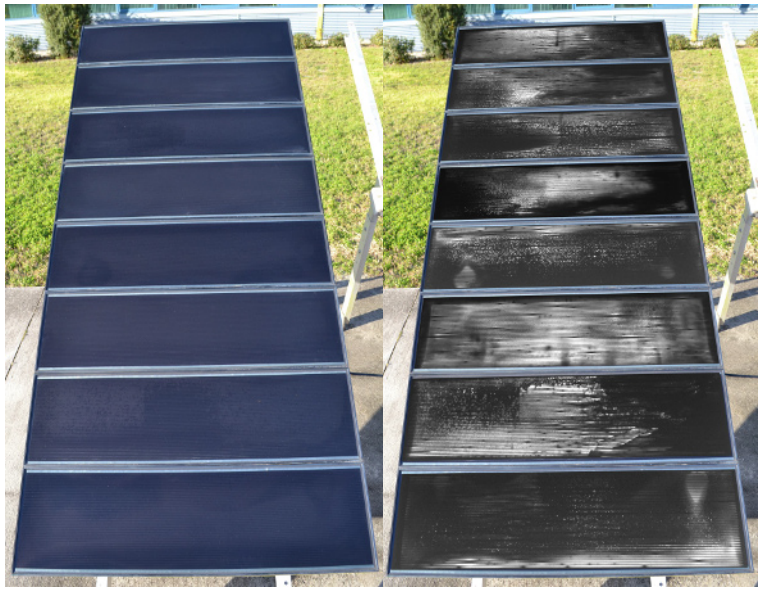
DARK I-V CHARACTERISTICS





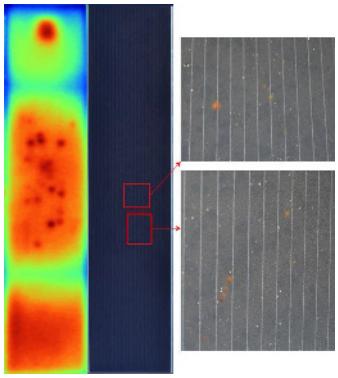
Dark I-V characteristics were measured for all modules at a temperature of and 25 °C ± 1 °C. Values for series and shunt resistance were extracted from these characteristics. The distribution of resistances is shown above. The few modules with very high series resistance corresponded to modules in which severe interconnect corrosion/ delamination had occurred.

VISUAL DISCOLORATION



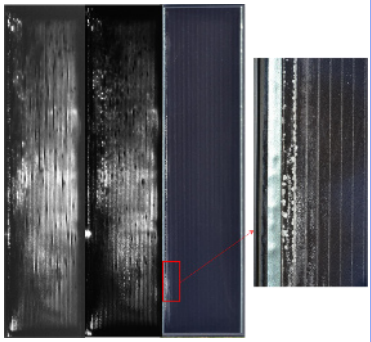
Visual image (left) and imposed electroluminescence images of corresponding modules (right). Distinct features and severe discoloration were observed on several modules. It was found that this directly correlated with underperforming regions of the device as shown in the EL images. This was attributed to issues within the front Transparent Conducting Oxide (TCO).

HOT SPOTS



Outdoor infrared image showing multiple hotspots within the module and corresponding visual image highlighting visible browning of the encapsulant.

DELAMINATION AND INTERCONNECT CORROSION



Electroluminescence images and corresponding visual image highlighting corrosion of the interconnects along the bottom edge of the module.

CONCLUSIONS

Analysis of a CIGS thin-film photovoltaic array has been carried out to quantify the electrical performance and identify the degradation modes. The three main defects included visual discoloration, hot-spots and interconnect corrosion/delamination. Further investigation to correlate the observed defects with the electrical performance as well as destructive testing and materials characterization would lead to a better understanding of specific degradation mechanisms.

The authors would like to acknowledge the Solar Energy Research Institute for India and the United States (SERIIUS) for partial support of this work

Update on Edition 2 of IEC 61724: PV System Performance Monitoring

Michael Gostein, Atonometrics, Inc.

On Behalf of 61724 Project Team of IEC TC82 WG3

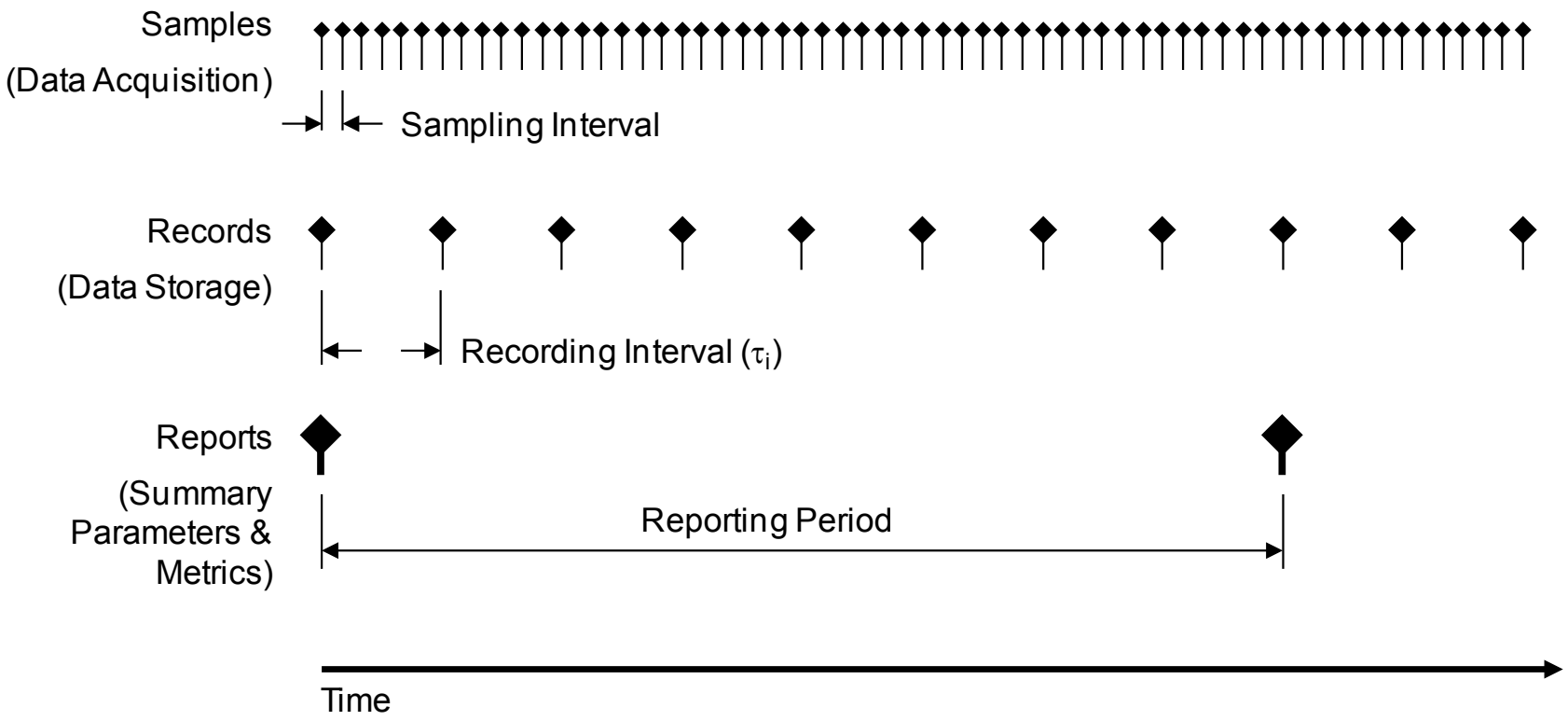
Prepared for NREL PV Module Reliability Workshop, February 2014

This presentation does not contain confidential information.

Overview

- Draft of second revision of IEC 61724 is in progress
- Text completely revised and updated from 1st Rev dated 1998
- Monitoring system classification introduced
  - User may select classification (A, B, or C) according to PV project size or monitoring objectives
  - Measurement parameters and sensor requirements to be specified according to monitoring system class
- New measured parameters include additional irradiance values, soiling, and power quality
- Addressing curtailment & clipping
- New metrics include temperature-corrected performance ratios
- Highlights presented here from current draft – not final

Samples, Records, & Reports



Monitoring System Classifications

	Class A	Class B	Class C
Description	Greatest precision	Medium-level precision	Basic precision
Typically targeted PV system size	Utility-scale	Commercial-scale	Residential and small commercial
Suitable applications			
System performance assessment	X	X	X
Documentation of a performance guarantee	X	X	
Forecasting performance	X	X	
Electricity network interaction assessment	X	X	
Monitoring integration of distributed generation, storage, & loads	X	X	
System losses analysis	X		
PV technology assessment	X		
PV system degradation measurement	X		

Measured Parameters

Category	Parameter	Symbol	Units	Required?		
				Class A	Class B	Class C
Irradiance	In-plane irradiance	G_i	$W \cdot m^{-2}$	√	√	√
	In-plane direct beam irradiance	$G_{i,b}$	$W \cdot m^{-2}$	for concentrator systems	for concentrator systems	for concentrator systems
	In-plane diffuse irradiance	$G_{i,d}$	$W \cdot m^{-2}$	for concentrator systems	for concentrator systems	
	Global horizontal irradiance	G_G	$W \cdot m^{-2}$	√		
	Diffuse horizontal irradiance	G_d	$W \cdot m^{-2}$			
Environmental Factors	Ambient air temperature	T_{amb}	°C	√	√	√
	PV module temperature	T_{mod}	°C	√	√	
	Soiling ratio	SR		√		
	Wind speed	WS	$m \cdot s^{-1}$	√	√	
	Wind direction	WD	degrees	√		

Sensor requirements for each classification will be provided in the Standard.

Measured Parameters, Cont'd

Category	Parameter	Symbol	Units	Required?		
				Class A	Class B	Class C
Tracker system	Tracker tilt angle	ϕ_T	Degrees	for tracked systems		
	Tracker azimuth angle	ϕ_A	Degrees	for tracked systems		
PV array output	PV array output voltage (DC)	V_A	V	√		
	PV array output current (DC)	I_A	A	√		
	PV array output power (DC)	P_A	kW	√	√	
Inverter output	Inverter output voltage (AC)	V_{inv}	V	√		
	Inverter output current (AC)	I_{inv}	A	√		
	Inverter output power (AC)	P_{inv}	kVA	√	√	√
	Inverter output power factor	λ_{inv}		√		
System output	Output voltage (AC)	V_{out}	V	√		
	Output current (AC)	I_{out}	A	√		
	Output power (AC)	P_{out}	kVAr	√	√	√
	System power factor			√		

Soiling Ratio

- Soiling ratio SR = ratio of PV array output power to the power that would be obtained if the PV array were clean and free of soiling.
- Setup: Side-by-side comparison of: 1) Routinely cleaned cell or module and 2) Soiled module.
- Methods
  - 1: Normalization of temperature-corrected Pmax of soiled module when compared to clean reference.
  - 2: Normalization of temperature-corrected Isc of soiled module when compared to clean reference.**
  - Equations given in Standard.
- **Method 2 shortcut is suitable for modules that are unaffected by non-uniform shading.
  - But do not hold c-Si modules continuously at Isc.

Calculated Parameters

Parameter	Symbol	Unit
Irradiation		
In-plane irradiation	H_i	$kWh \cdot m^{-2}$
Electrical energy		
PV array output energy	E_A	kWh
Inverter output energy	E_{inv}	kWh
Energy output from pv system	E_{out}	kWh
Array power rating		
Array power rating (DC)	P_0	kWp
Yields and yield losses		
PV array energy yield	Y_A	$kWh \cdot kWp^{-1}$
Final system yield	Y_f	$kWh \cdot kWp^{-1}$
Reference yield	Y_r	$kWh \cdot kWp^{-1}$
Array capture loss	L_C	$kWh \cdot kWp^{-1}$
Balance of system (BOS) loss	L_{BOS}	$kWh \cdot kWp^{-1}$
Efficiencies		
Array efficiency	η_A	None
System efficiency	η_f	None
BOS efficiency	η_{BOS}	None

Traditional Performance Ratio

- Indicates the overall effect of losses on the system output
- Quotient of the system's final yield Y_f to its reference yield Y_r

$$PR = Y_f / Y_r$$

$$= (E_{out} / P_0) / (H_i / G_{i,ref})$$

$$= \left(\sum_k \frac{P_{out,k} \times \tau_k}{P_0} \right) \Big/ \left(\sum_k \frac{G_{i,k} \times \tau_k}{G_{i,ref}} \right)$$

Units = h / h

- Moving P_0 to the denominator sum expresses both numerator and denominator in units of energy:

$$PR = \left(\sum_k P_{out,k} \times \tau_k \right) \Big/ \left(\sum_k \frac{P_0 \times G_{i,k} \times \tau_k}{G_{i,ref}} \right)$$

Units = kW-h / kW-h

- Traditional *PR* neglects array temperature, resulting in seasonal variation when calculated for time periods less than one year

Temperature-Corrected Performance Ratios

- Seasonal variation of the traditional *PR* is removed by calculating a temperature-corrected performance ratio:

$$PR' = \left(\sum_k P_{\mathrm{out},k} \times \tau_{\mathrm{k}}\right) \Big/ \left(\sum_k \frac{(C_k \times P_0) \times G_{\mathrm{i,k}} \times \tau_{\mathrm{k}}}{G_{\mathrm{i,ref}}}\right)$$

$$C_{\mathrm{k}} = 1 + \gamma \times (T_{\mathrm{mod,k}} - T_{\mathrm{ref}})$$ Temp. correction to power

- Using 25 °C as T_{ref} gives $\boldsymbol{PR'_{\mathrm{STC}}}$.
  - Corrects for difference between actual temperature and STC temperature used for power rating.
  - Values of PR'_{STC} are closer to 1 than for traditional *PR*.
- Using irradiance-weighted annual average module temperature for T_{ref} gives $\boldsymbol{PR'_{\mathrm{annual\text{-}eq}}}$.
  - Approximates the value that would be obtained for traditional *PR* evaluated over one full year, by compensating for seasonal variation.

Clipping and Curtailment

- Clipping
  - Inverter clipping often considered a loss of the system due to design limitations.
  - But many systems now intentionally designed with high DC/AC ratio for more stable output to grid.
  - For these system types, considering additional performance metric based on system AC power rating instead of DC rating.
- Curtailment
  - Periods of reduced grid/load demand or availability should not count against PV system performance.
  - Standard notes that irradiation and yield sums should be calculated with such periods excluded for purposes of performance assessments and performance guarantees (while still documenting complete sums).

Open Issues / Work in Progress

- Treatment of systems with local loads, storage, or hybrid sources
- Precision requirements for each sensor type
- Dealing with missing data
- Systems with high DC/AC ratio
- Additional performance metrics

Current status of TG5 region Japan

Tsuyoshi Shioda
Mitsui Chemicals, Inc.
Tsuyoshi.Shioda@mitsui-chem.co.jp

Present approach and activities

1. Collect field failures in Japan, especially sharing efforts of projects led by AIST
2. Pick up field failures focusing on stresses of UV, temperature, humidity
3. Decide failure mode to be discussed considering features of Japanese industry
   Japan has long-term experiences and experienced module and material manufacturers.
4. Categorize the target failure mode.
5. Find indicator which reflects stress level suffered in a PV module.
   (Example: acetic acid, YI for encapsulant, electric performances, not YI for BS…)
6. Come up with appropriate accelerated test for each category.

We had a face to face meeting once a month from this May, jointly with TG3 JP.

As the third step, we decided that delamination was first target failure, taking account of other region's progresses.
In addition, we attempted to categorize delamination failure in field.

Delamination

Definition of “delamination” :

Delamination is an interface with adhesion strength of completely zero [N]. There is (air-)gap (cavity) at the portion. A void and a cluster of voids are included in delamination failure.

Probable causes :

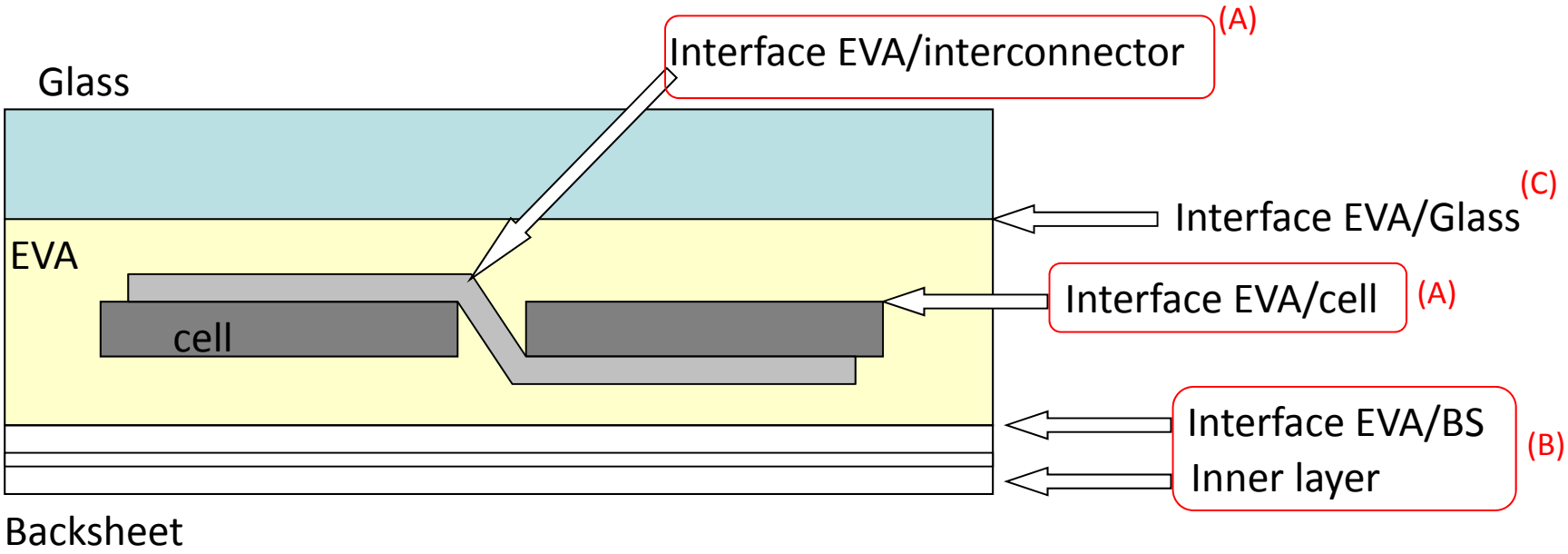
Delamination is due to weaken adhesion strength, mechanical stress, and gases from polymers. Probable causes for each component material are as follow;

Cell : AR coating in front of cell : ex) TiOx
Interconnector : flux (type and amount)
Encapsulant : Missing coupling primer, Degradation of coupling primer due to storage with bad environment and expiration, Large amount of additives
Backsheet : adhesion agent of inner-layer of backsheet / fabrication process?
Lamination process : not enough heat supply to activate coupling primer and soften encapsulant, remaining voids : due to not appropriate lamination condition

Delamination

Which interface did we see delamination failure in field aged PV modules?

We attempt to categorize delamination based on an interface it happened.



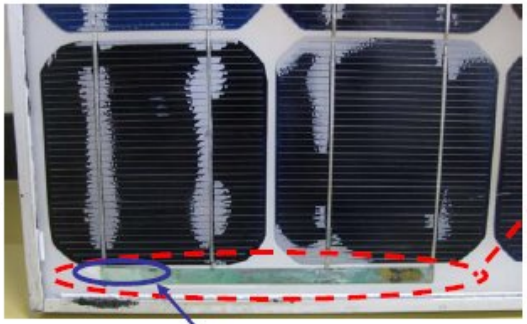
(A)

3.4 Other failures -Corrosion-

2013.02.26

Mitsui Chemicals

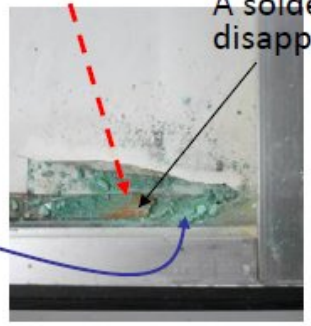
closeup picture



Patina

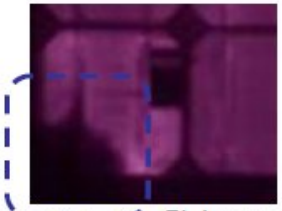
Severe degradation of copper

A solder layer disappeared.



A part of Copper ribbon disappeared.
= No electrical conduction

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



EL image

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

© Mitsui Chemicals, Inc.

T. Shioda, NREL PVMRW 2013, Feb 2013.

(A), (B)

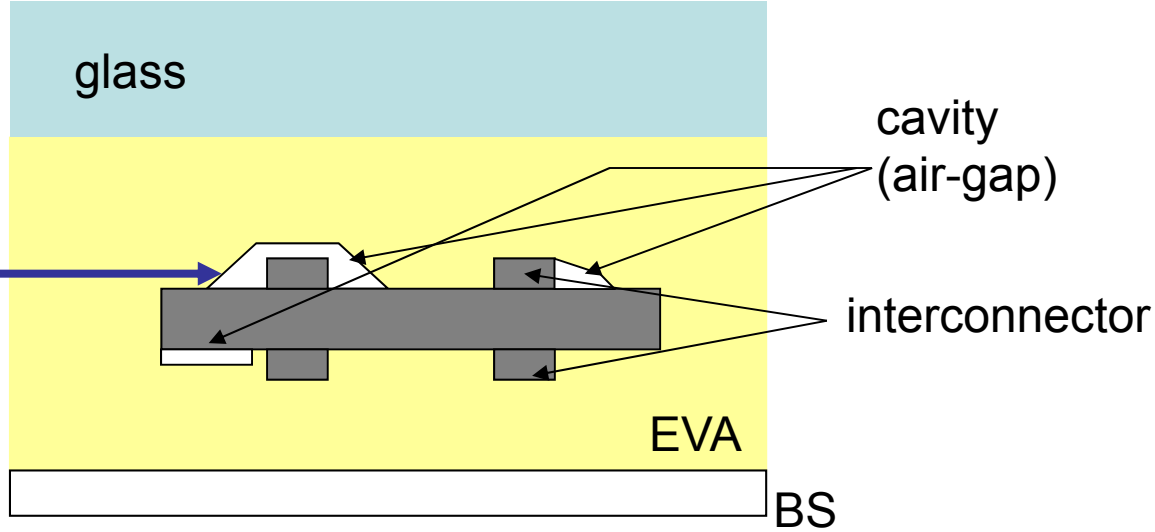
Japan 2013

A 20y-field-aged PV module with delamination failure and induced corrosion

Delamination at inner-layer or inter-layer of backsheet and penetration of water into front side of cell

Category (A) Delamination at interface between EVA and cell / interconnector

Is there a "pass" for liquid water penetration? or isolated?

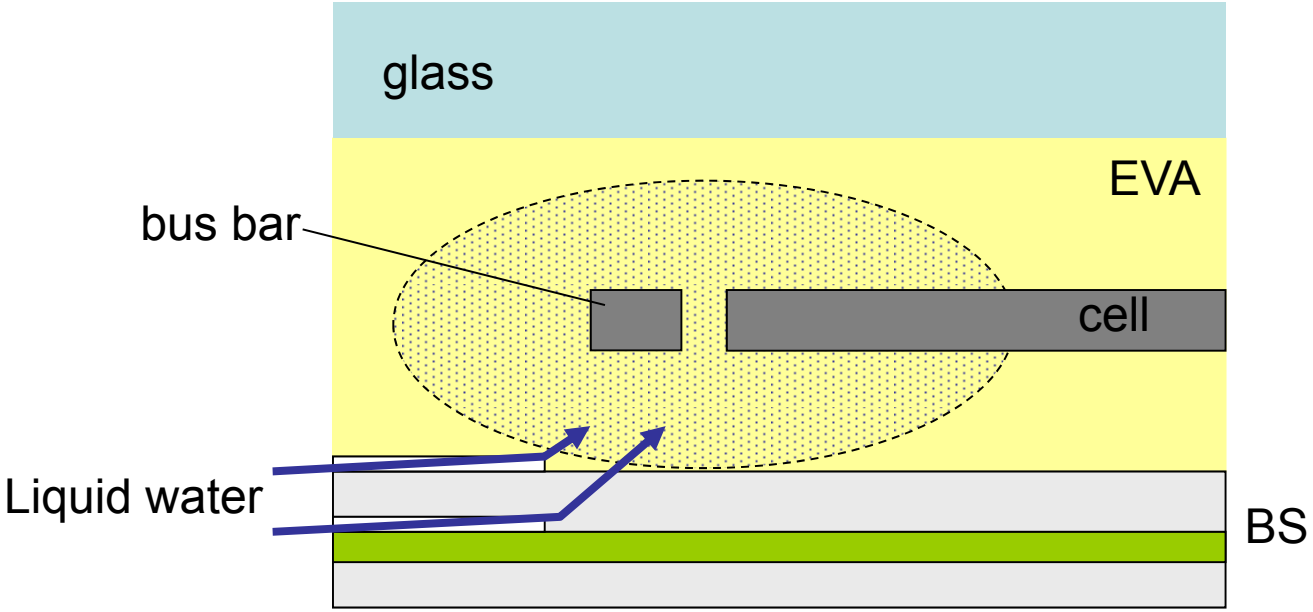


This is considered to be **isolated** from liquid water penetration.

There is a pass for liquid water penetration.

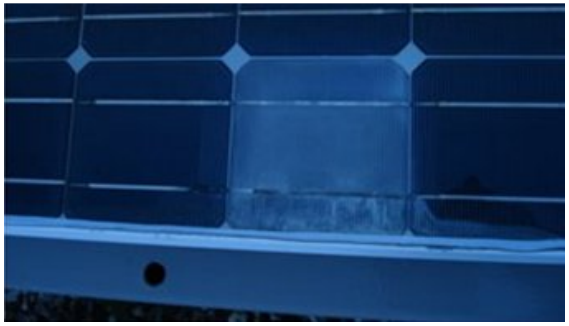
Higher severity
High priority

Category (B) Delamination at interface of inner-layer of BS / BS and EVA



Liquid water induces corrosion and delamination which leads to corrosion.

Thus we will focus on delamination failure which leads to corrosion, in terms of severity.



This failure is typically observed at corners of a PV module and lower side for deployment in field.

Adhesion of the interface between inner layers and BS/EVA would be important.

New test, such as dipping hot water, may be necessary for duplicate this delamination, instead of or after typical chamber tests such as UV, DH, TC and these sequence… We need some ideas and data. Of course, we still collect field failure information concerning delamination.

Tentative Timeframe of TG5 JP

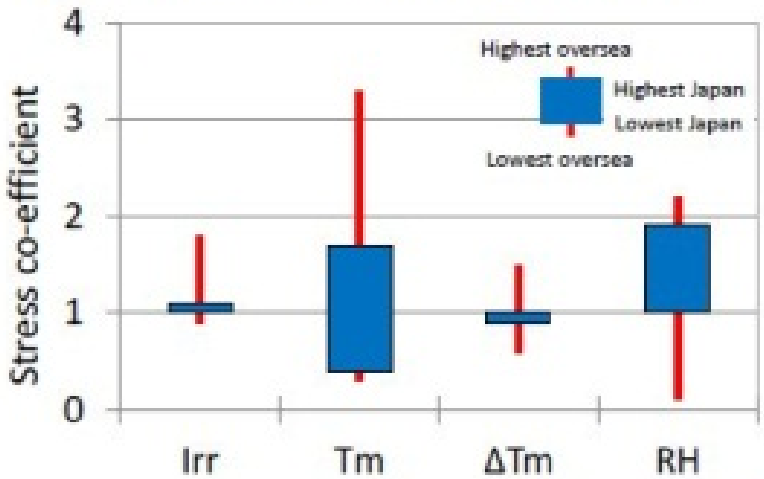
Current status	2014 goal	2015 goal
Confirmation of climate of Japan köppen climate classification Report by Kato of JET	Correct field data in Japan	
Failure modes focused Delamination / Cracks	Analysis of field aged PV modules	
Find Indicators	Insulation ?	Pass/fail criteria
Accelerated test 4 cell mini module combined test (ex) UV+DH+TC)	Accelerated test with a mini module	Determination of test condition and procedures

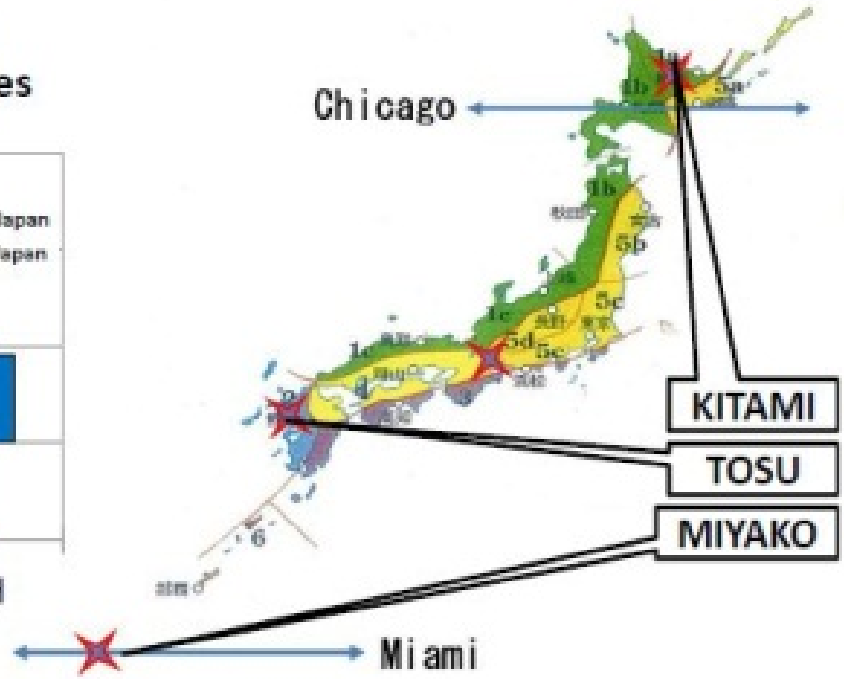
3. OUT-DOOR EXPOSURE TESTS FOR THE DEGRADATION EVENTS (1) PV SITES

Comparison with stress factors at three sites

	UVB	T_m	ΔT_m	Relative Humidity
KITAMI	0.9	0.4	0.9	1.6
TOSU	1.0	1.0	1.0	1.0
MIYAKO	1.2	1.7	1.0	1.9

Comparison of stress factor with overseas cities and three typical sites

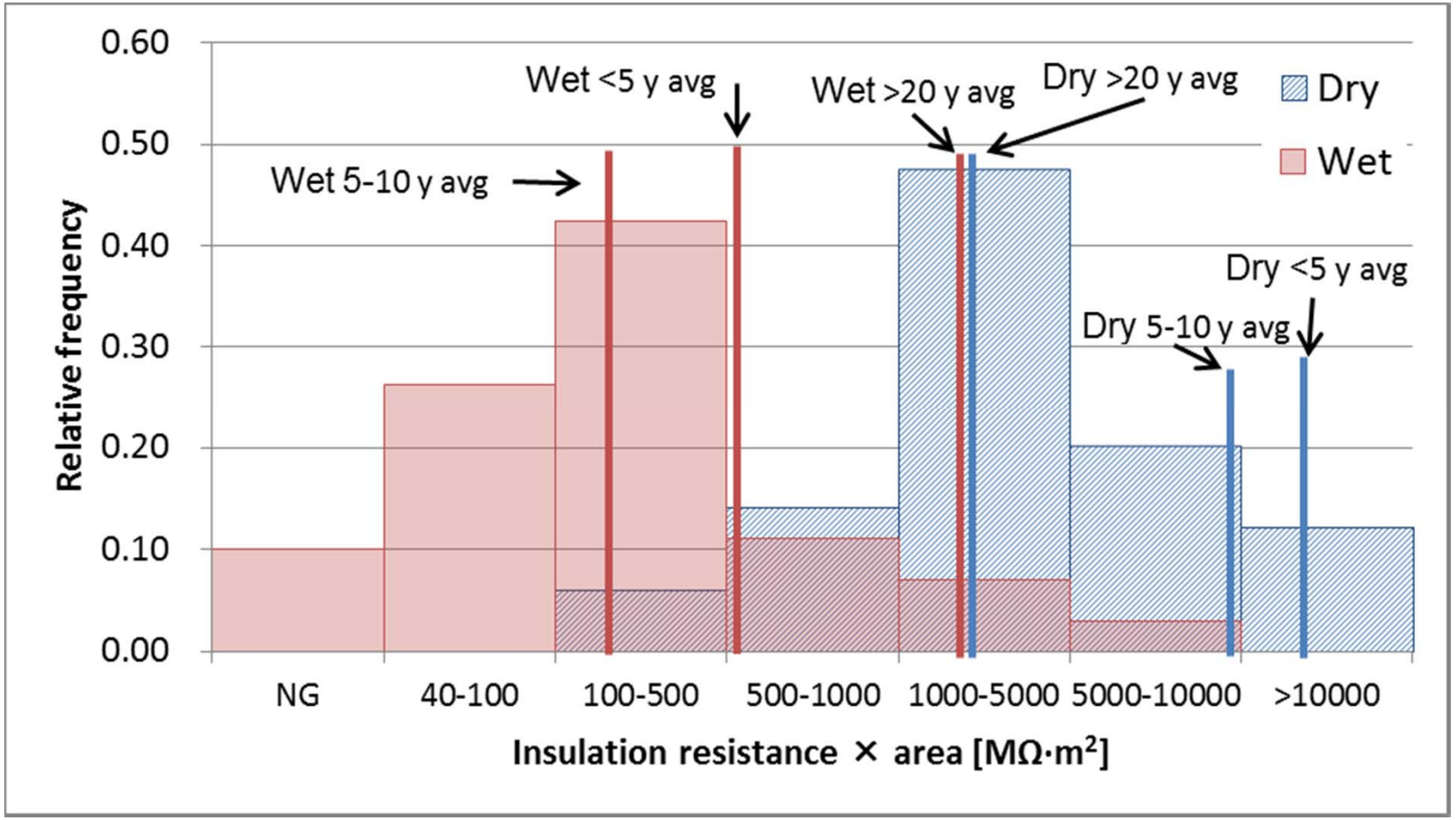




12

H. Kato, 4th International QA forum in Kyoto Oct. 2013

Histogram of insulation performances of field-aged PV modules with no visible failure modes (delamination, cracks) and deployed in Japan



Applied bias voltage was 500V for both measurements.
Total number of evaluated modules are roughly 100.

Combined test of UV, DH, TC for 4 cell mini modules

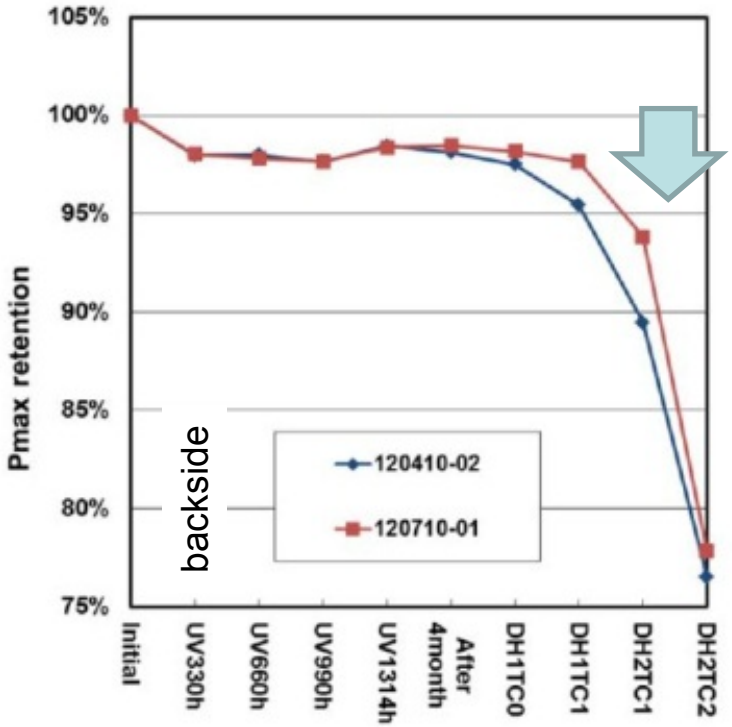
UV irradiation : 90W/m^2 @ 300-400nm
Chamber temperature : 65 ^{O}C
correspond to around 90 ^{O}C of backside module temperature

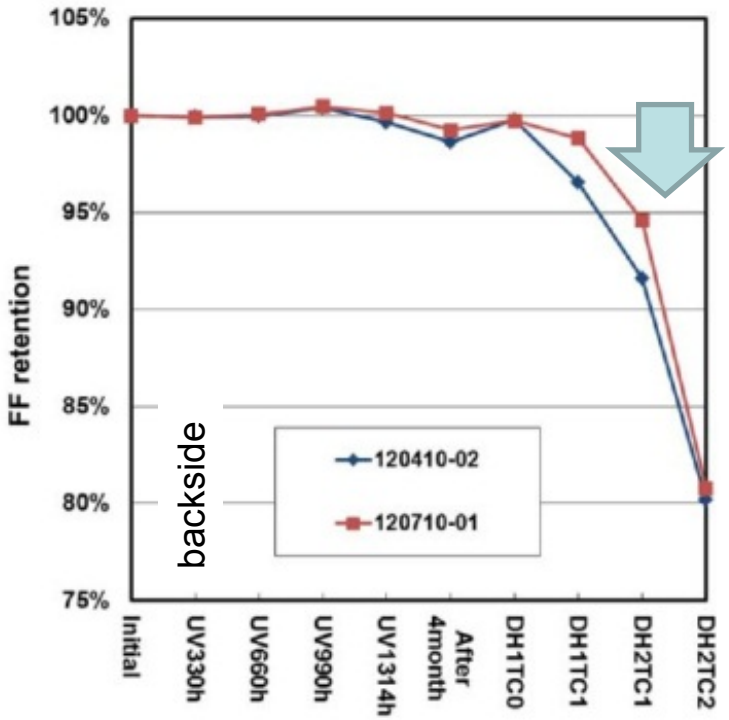
After UV irradiation, 2 cycles of DH500 and then TC100 had been done.

Termination of PV cables of 4 cell mini PV module
During UV irradiation : open
UV irradiation had been done for 984hr for front side and 330hr for backside
During DH test : short
During TC test : short

Monitoring performances of PV modules during these tests
IV curve (Pmax, FF, Isc, Voc)
EL image
Insulation (wet / dry) at bias of 500V
Appearance (Delamination, crack of backsheet, etc)

After 2nd DH500, TC100, Pmax, FF was dramatically reduced.





ID	Initial	UV990h	UV1314h	DH1TC0	DH1TC1	DH2TC1
120410-02						
120710-01						

120410-02 UV+DH+TC

Insulation performances of tested modules were still high.

Insulation test

	dry				wet	
	Leakage current [μA]	Pass	Insulation resistance [GΩ]	Pass	Wet leakage [GΩ]	Pass
Initial	0	○	>99.9	○	4.54	○
UV330h (backside)	0	○	15	○	0.833	○
UV660h	0	○	75	○	1.05	○
UV990h	0	○	>99.9	○	4.29	○
UV1314h	0	○	>99.9	○	5.22	○
DH1TC0	2	○	2.38	○	1.13	○
DH1TC1	0	○	>99.9	○	1.14	○
UV1814h/DH2TC1	0	○	>99.9	○	1.24	○
UV2314h/DH2TC2	0	○	>99.9	○	1.61	○

■The proposal of thermal runaway test for bypass diode
■Tj measurement method for bypass diode

(J-TG 4 activities of QA Forum / QA Task Force 4 ; Diode, Shading & Reverse Bias)

This presentation contains no confidential information.

This work was performed in cooperation with SHARP, Onamba, Nihon Inter Electronics and Sanken Electric.

Feb. 25-26, 2014 ***@ Denver, USA***

Y. Uchida / JET (Japan Electrical & Environment Technology Laboratories)

1. The proposal of thermal runaway test for bypass diode

Current situation ;

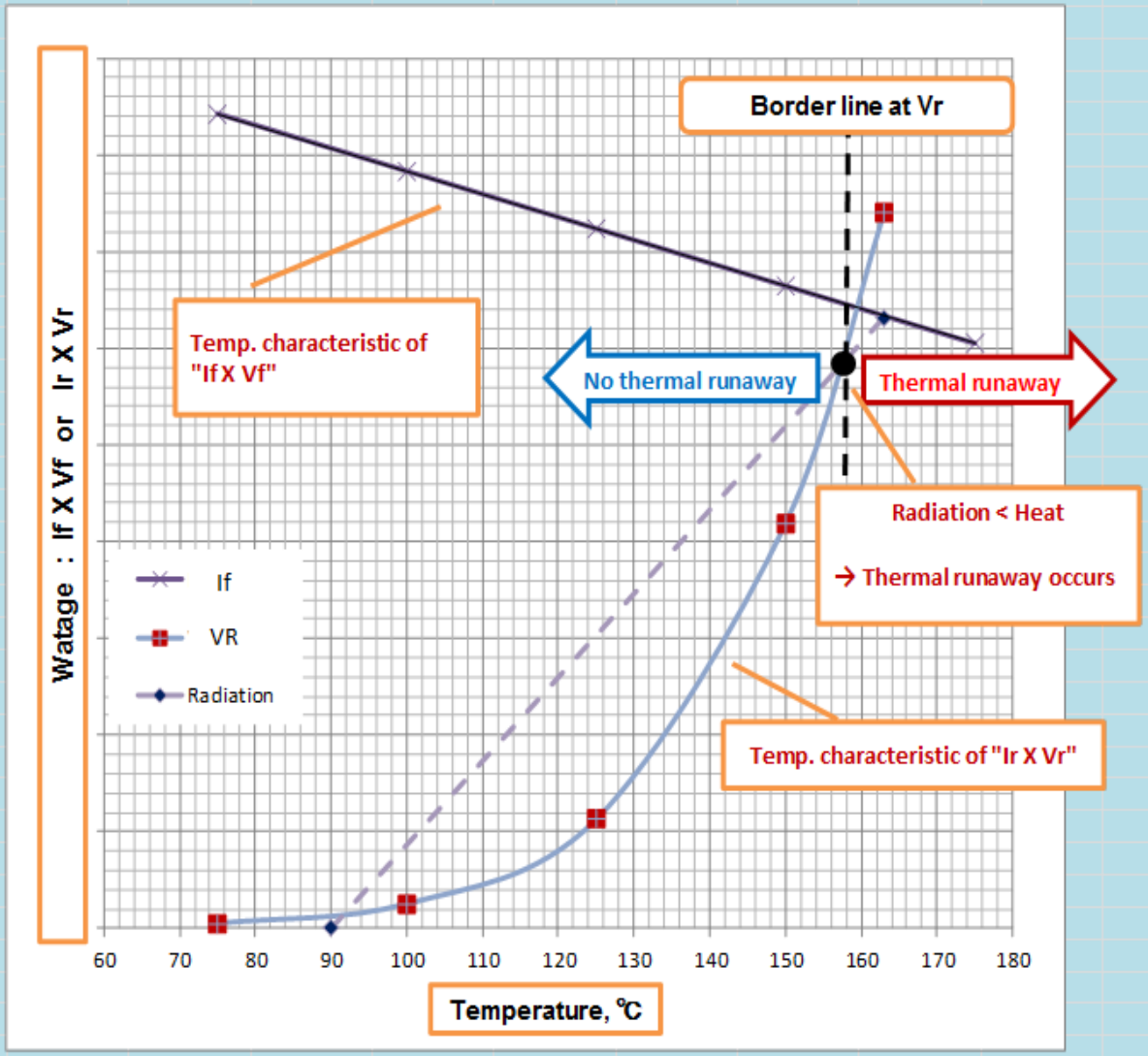
NWIP draft for "Thermal runaway test for bypass diode" was submitted to TC82/WG2 on Jan. 18, 2014 and is expected to be discussed in the next WG2 meeting in June.

Scope and Purpose

This international standard provides a method for evaluating whether a bypass diode as mounted in the module is susceptible to thermal runaway or if there is sufficient cooling for it to survive the transition from forward bias operation to reverse bias operation without overheating.

The concept of thermal runaway occurrence

When the amount of heat generated in the diode is greater than the capability of radiation to extract the heat, thermal runaway occurs.



Test procedure

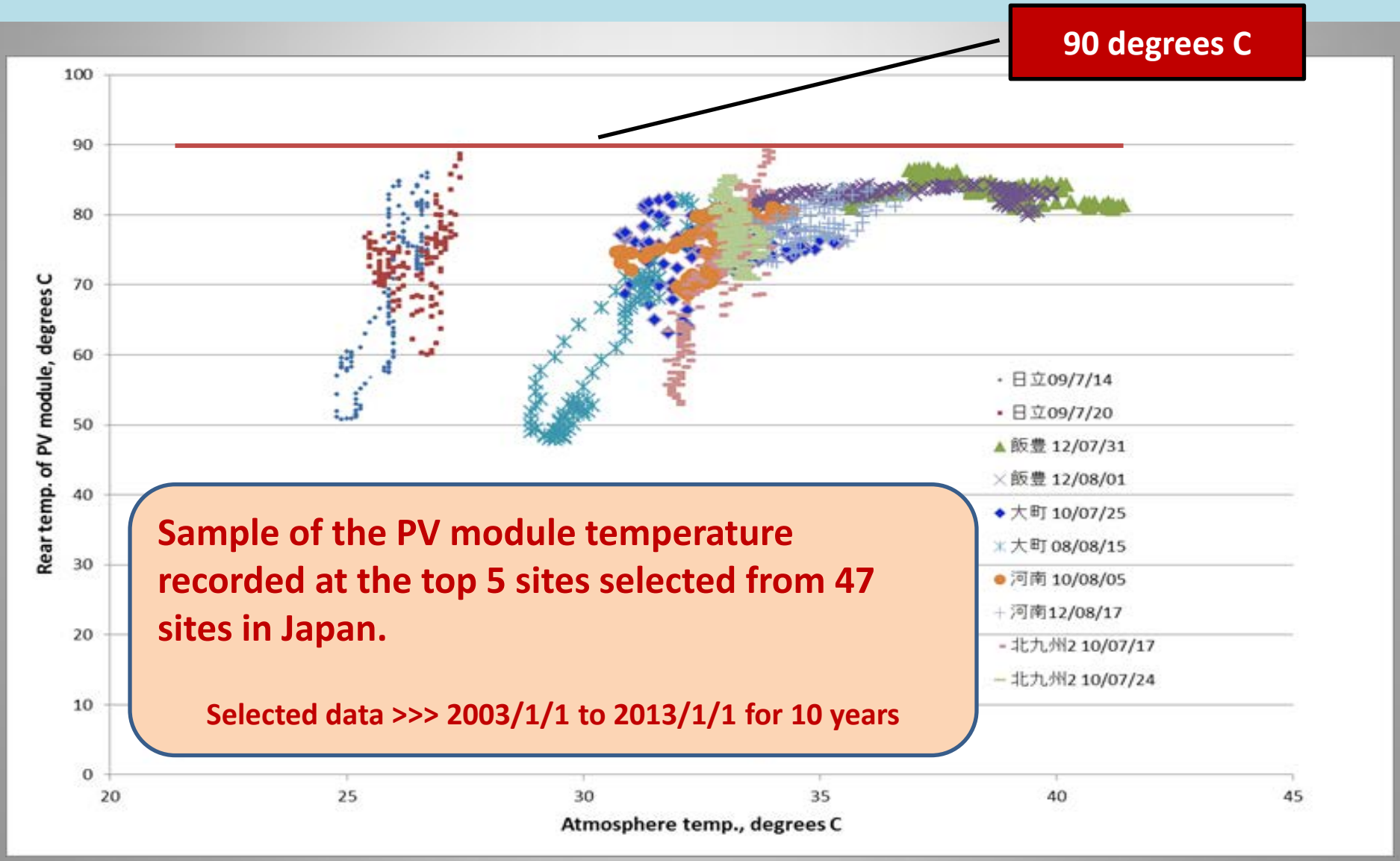
(1) In the preheated climate chamber at 90℃, apply the forward current equal to “the 1.25 X STD short circuit current of the module” until the diode temperature stabilizes

(2) Within 10ms after shutting off the forward current supply, apply the reverse bias voltage (Vr*) to the diode and keep it for one minute unless the temperature of the diode extraordinarily increases.

* Vr = Sum of Voc of the cells protected by one bypass diode

(3) If the temperature stabilizes or begins to decrease during one minute, remove the J-box from the chamber and verify that the diode is still operational.

The test condition "90℃" is proposed assuming the worst case according to the following results.



Sample of the PV module temperature recorded at the top 5 sites selected from 47 sites in Japan.

Selected data >>> 2003/1/1 to 2013/1/1 for 10 years

2. Tj measurement method for Bypass diode (BD)

At NREL workshop last year, we discussed “Vf-Tj method" and "Tcase / lead method“ of Tj measurement of BD.

This time, I will indicate the issues of Tcase/lead method by the specific examples.

\- -

Case 1 ;

#1 ; The temperature of the center diode in the J-box becomes always the highest.

#2 ; Tj by Vf-Tj method is higher than Tj by Tlead method.

【 Chamber temp. ; 75℃】

		Left diode		Center diode		Right diode	
		Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃
If	9A	158.1	160.1	165.0	173.3	143.1	156.7
	11A	175.2	178.7	183.4	192.7	156.9	176.8
	12A	183.5	187.5	192.4	201.5	164.0	184.5
	13A	192.0	195.5	201.2	212.1	170.7	193.7

【 Chamber temp. ; 90℃】

		Left diode		Center diode		Right diode	
		Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃	Tlead, ℃	Vf-Tj, ℃
If	9A	168.8	171.0	175.2	182.6	154.2	169.8
	11A	185.4	189.2	192.8	201.4	168.1	186.4
	12A	193.7	197.2	201.9	211.3	174.7	194.3
	13A	201.7	205.3	210.4	220.1	181.3	203.7

Note 1 Tlead : Tj by "Tlead method"

Tj = Tlead + (Vf X If X Rth) Rth ⇒ 2.5℃/W provided by diode manufacturer

Note 2 Vf-Tj : Tj by "Vf-Tj method" in accordance with "IEC61646 Ed.2

10.18 Bypass diode thermal test / Procedure 2"

Case 2 ;

Measured Rth (Thermal resistance) varies widely, even if the sampled diodes are taken from the same type lot.

For example ;

Sample	Rth (℃/W) at 9A
Diode – A	3.0
Diode – B	5.0
Diode - C	4.8

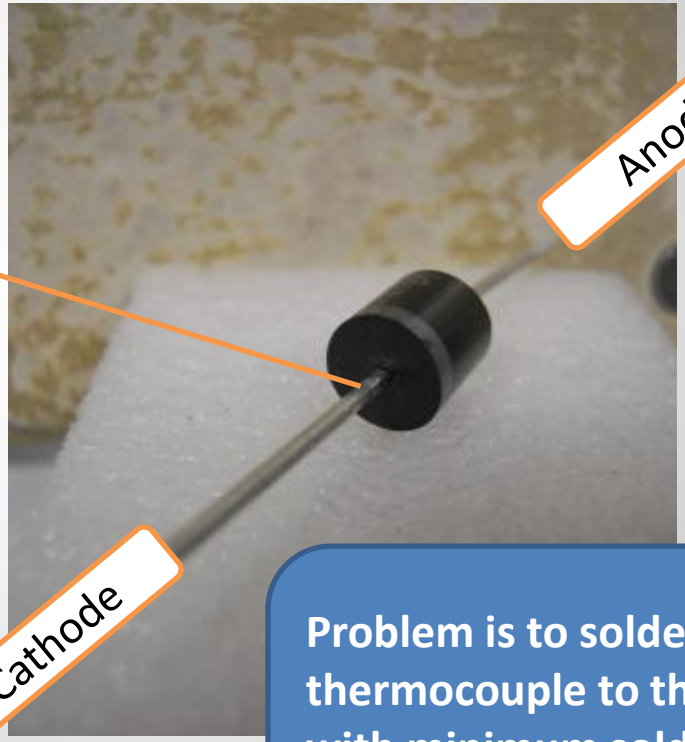
Note 1 ; Rth presented by diode manufacturer is 2.5 ℃/W.

Note 2 ; These Rth were measured by JET.

Case 3 ; Problem of Tlead measurement

■ Axial diode

Theory ;
should be soldered as close as possible to the cathode terminal of diode.

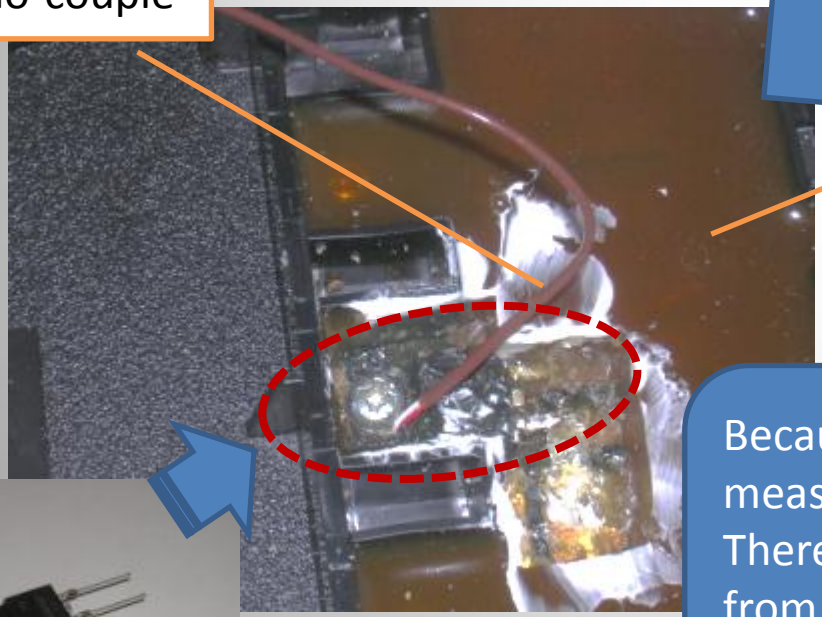


Problem is to solder the thermocouple to the diode lead with minimum solder and as close as possible to the diode body.

Case 4 ; Problem of Tcase measurement

■ TO220 type diode in J-box

Thermo-couple

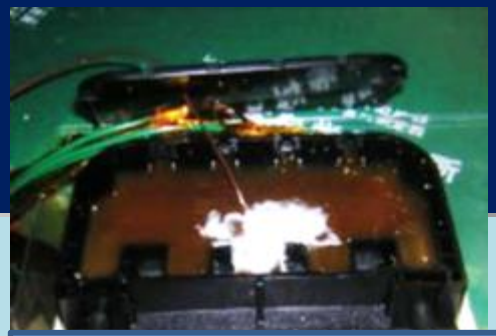


Molded resin

TO220 type diode

Because it is covered by the molded resin, the measurement of Tcase is difficult.
There is no choice but to get the measurement from the part of the screw.

Comparison results
between "Tcase method" and "Vf-Tj method"



Test sample

■ Tcase method

Tj = Tcase + Vf ×If×Rth

Tcase : 95.6℃ (Temp. of diode's case)

Vf : 0.3391V

(Saturated voltage after 1h operating)

If : 9A (Forward current)

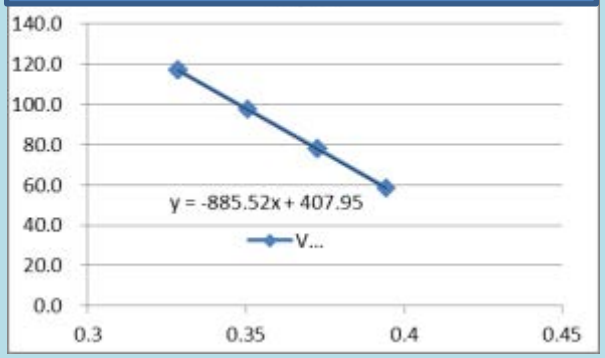
Rth : 1.5℃/W presented by manufacturer

Tj = 95.6(℃) + 0.3391(V) ×9(A)×1.5(℃/W)

= 100.2℃

■ Vf-Tj method

Vf-Tj characteristic



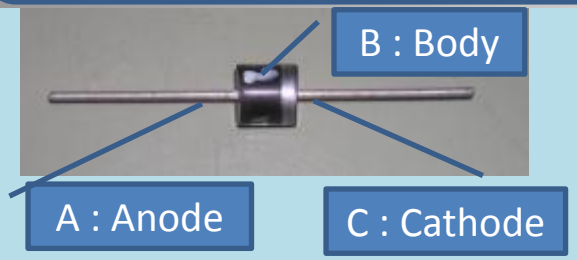
Tj = -885.52 Vf + 407.95

= -885.52×0.3391 + 407.95

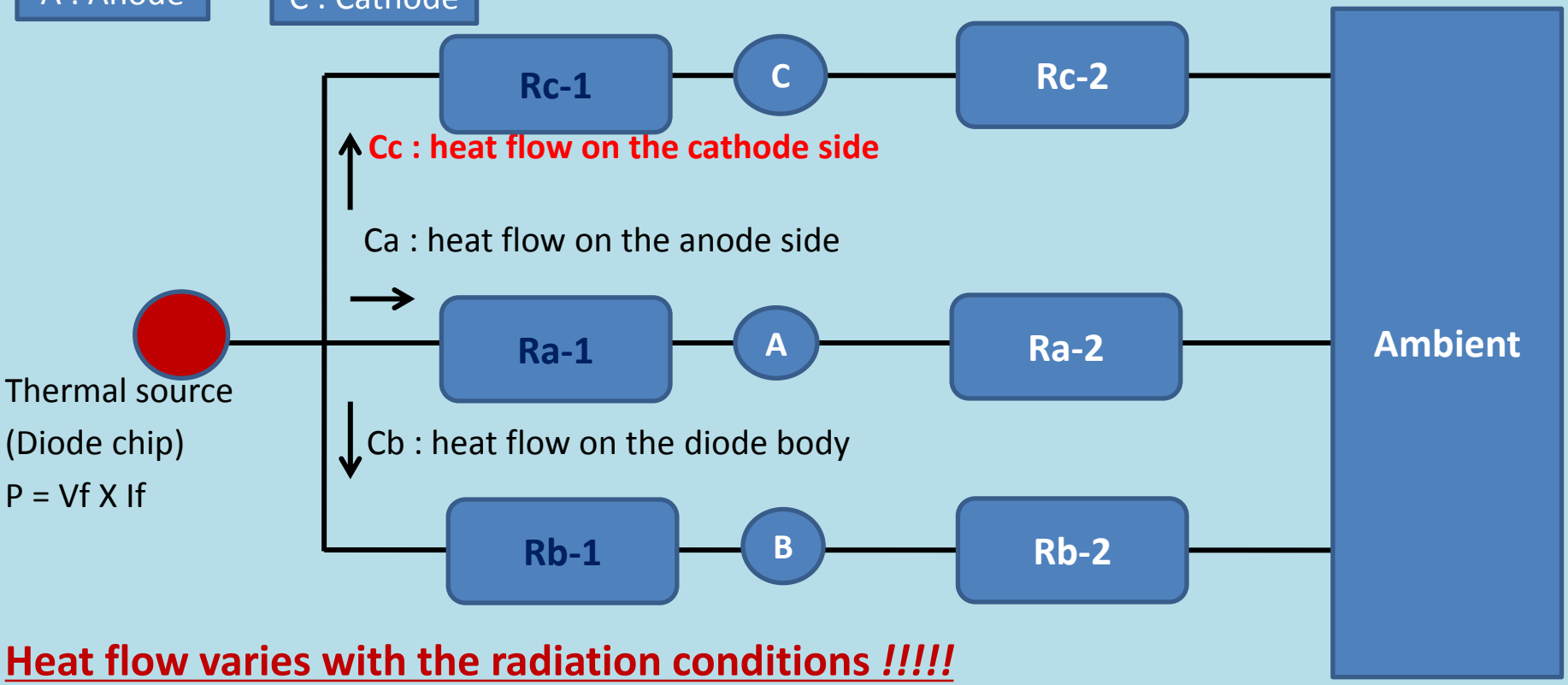
= 107.7 ℃

The Rth changes depending on where the diode is placed in the J-box.

Heat flow from Diode chip



Rc-1 ≒ Ra-1 << Rb-1



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

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

Heat flow from diode chip.

In the case of a Rth measurement for single diode,

- First of all, diode chip will be heat up by the applying current into J-box.
- Then, this heat will flow to C, A and B divergently.
- In this case, the constant Cc would vary depending on the heat radiation conditions.
- When the diode is mounted in the J-box, this constant changes.
- Therefore, the apparent Rth changes.

Tj that is calculated,

$$Tj = \underline{Tcase/lead} + (Vf \times If \times \underline{Rth})$$

The temperature of Tcase/lead is very difficult to measure correctly, because there are the issues of the soldering technique including the soldering place and the amount of solder.

By being incorporated in the J-box, Rth presented by the diode manufacturer changes.

As a result, the error of the calculated value may become large.

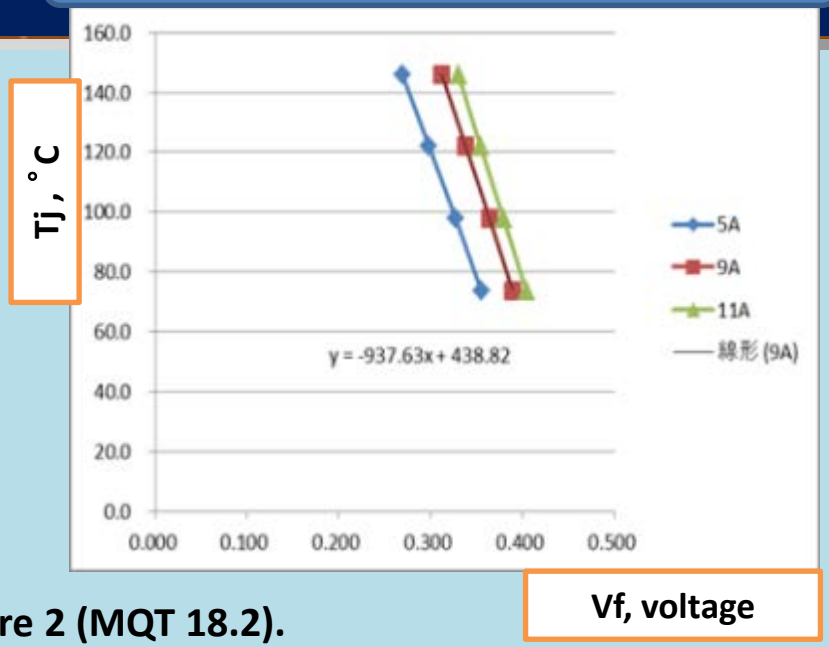
Conclusion of $T_{case/lead}$ method

Due to the Rth change and the Tcase/lead measurement error, the calculated value of the Tj has some error compared to the real Tj.

Therefore, the judgment by using Tj value which is calculated by Tcase/lead method is misleading *!!!!!*

Vf – Tj method

Case of Vf-Tj characteristics



- Once Vf-Tj relation is obtained,
  Tj is easily and accurately decided from the value of Vf.
  Vf-Tj relation can be acquired by measuring the temperature of the lead and the voltage across the diode in thermal equilibrium condition.
- It is specified in IEC61215-2 Ed.1 draft / 4.18.2 Procedure 2 (MQT 18.2).

- To achieve this, the preparation of some special measuring equipment is required.

Therefore, I will continue to explore the practical measuring method.

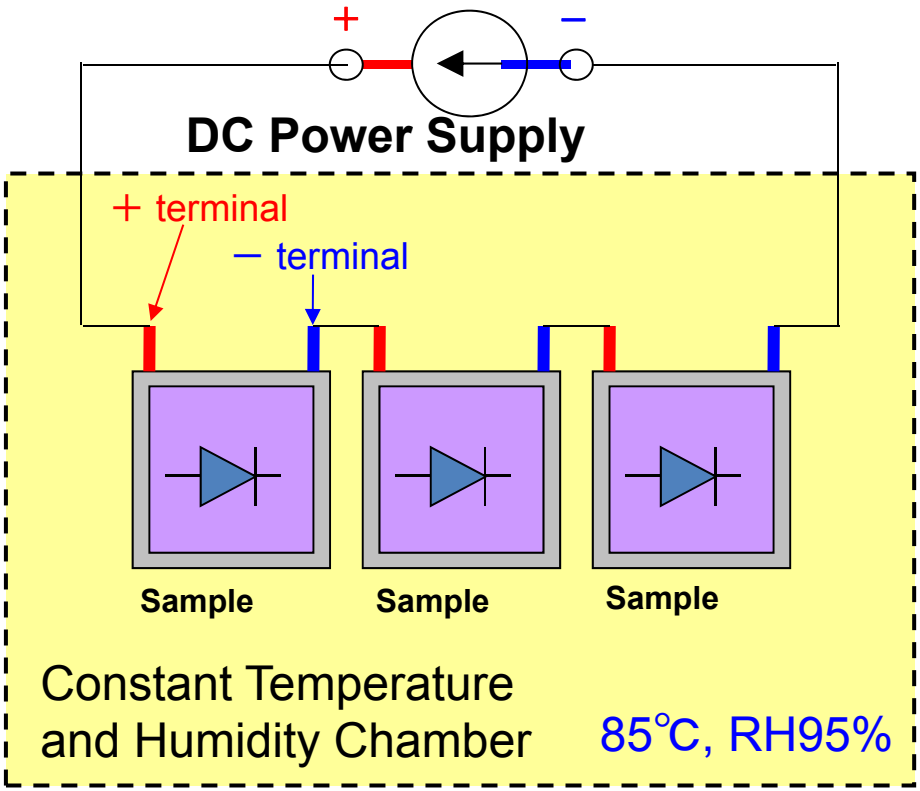
Japanese Task Group 8 Activities in International PV Module Quality Assurance

Akihiro TAKANO, Keiichiro SAKURAI, Masaaki YAMAMICHI, Hiroko SAITO, Masahiko TOMITA, Akira TERAKAWA, Hisanobu YOKOYAMA, Tadashi Obayashi, Keizou ASAOKA, Mika KAMBE, Hideki YOSHIKAWA, Michihiro TAKAYAMA, Yuna KOIZUMI, Shuuji TOKUDA, Masayoshi TAKANI and Michio KONDO

Photovoltaic Power Generation Technology Research Association (PVTEC)
Tokyo, Japan

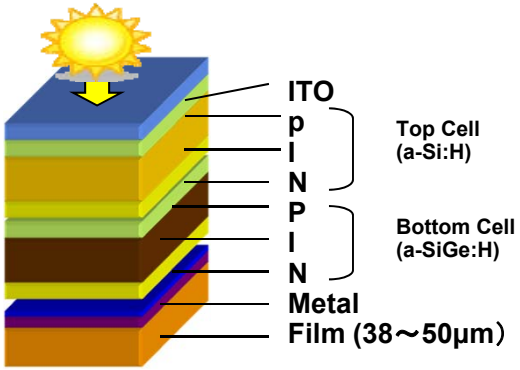
PVMRW 2014, Feb 25-26, 2014, Golden, CO, USA

Current Injection during DH test

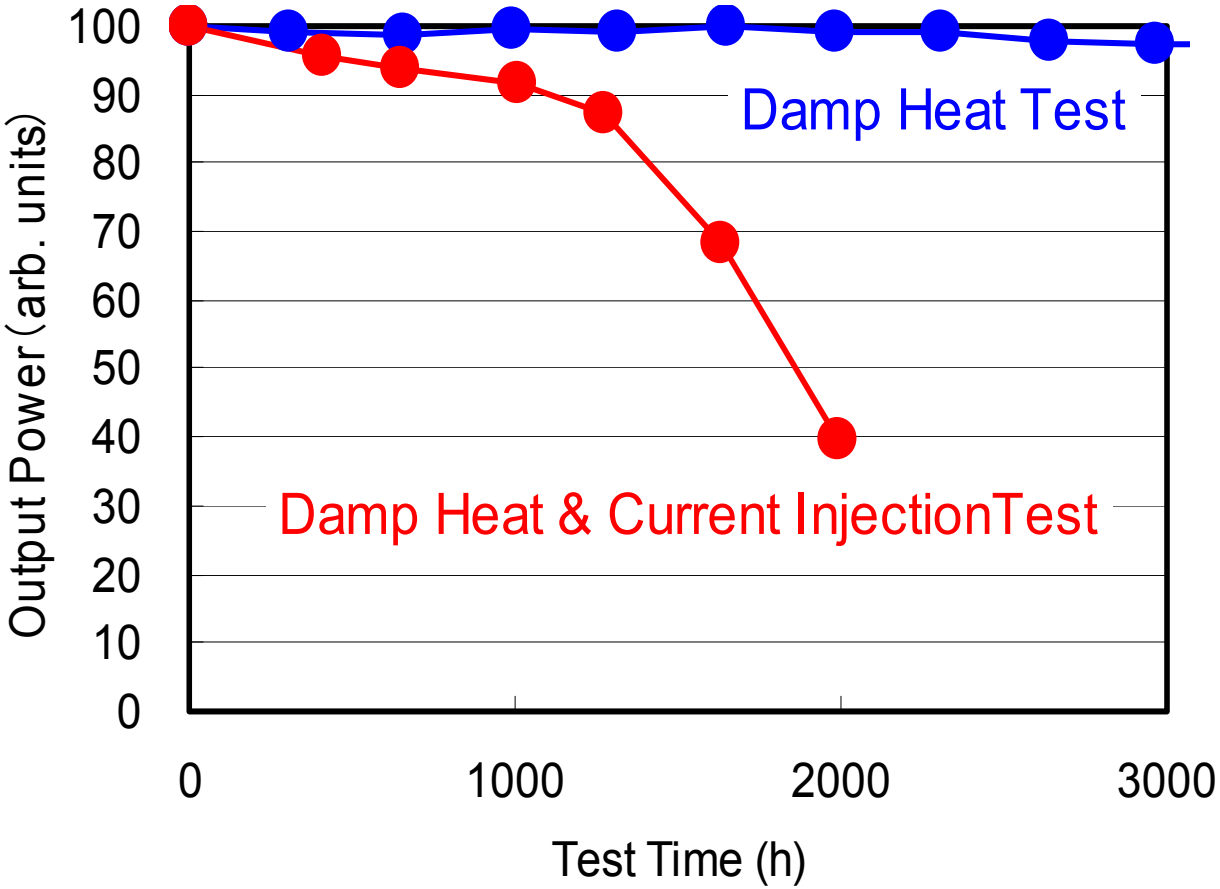


Current Injection during DH test: observation

Test results of prototype thin-Si flexible modules (note: not commercial models)



a-Si/a-SiGe Tandem Cell

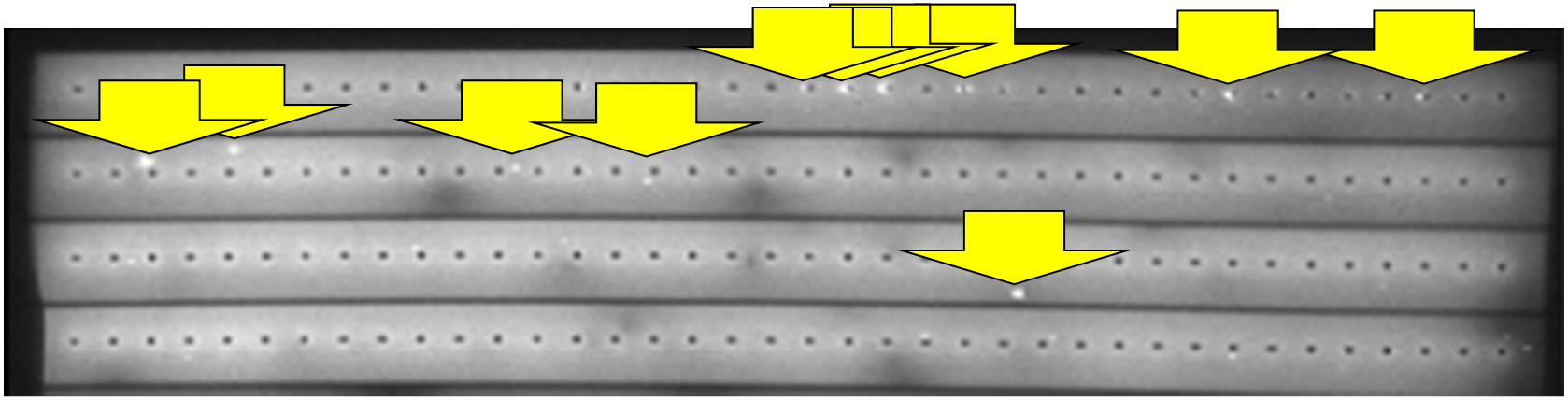


A. Takano et al, *Acceleration Test of Combined Stressess for Flexible Thin Film Si Solar Modules*, 28th EUPVSEC, Paris, 30 Sep 2013 – 4 Oct 2013, 3BO.5.4.

current injection during DH test have accelerated degradation

Leak points in EL image

Electro Luminescence Image of a module after the "Damp Heat + Current Injection Test".

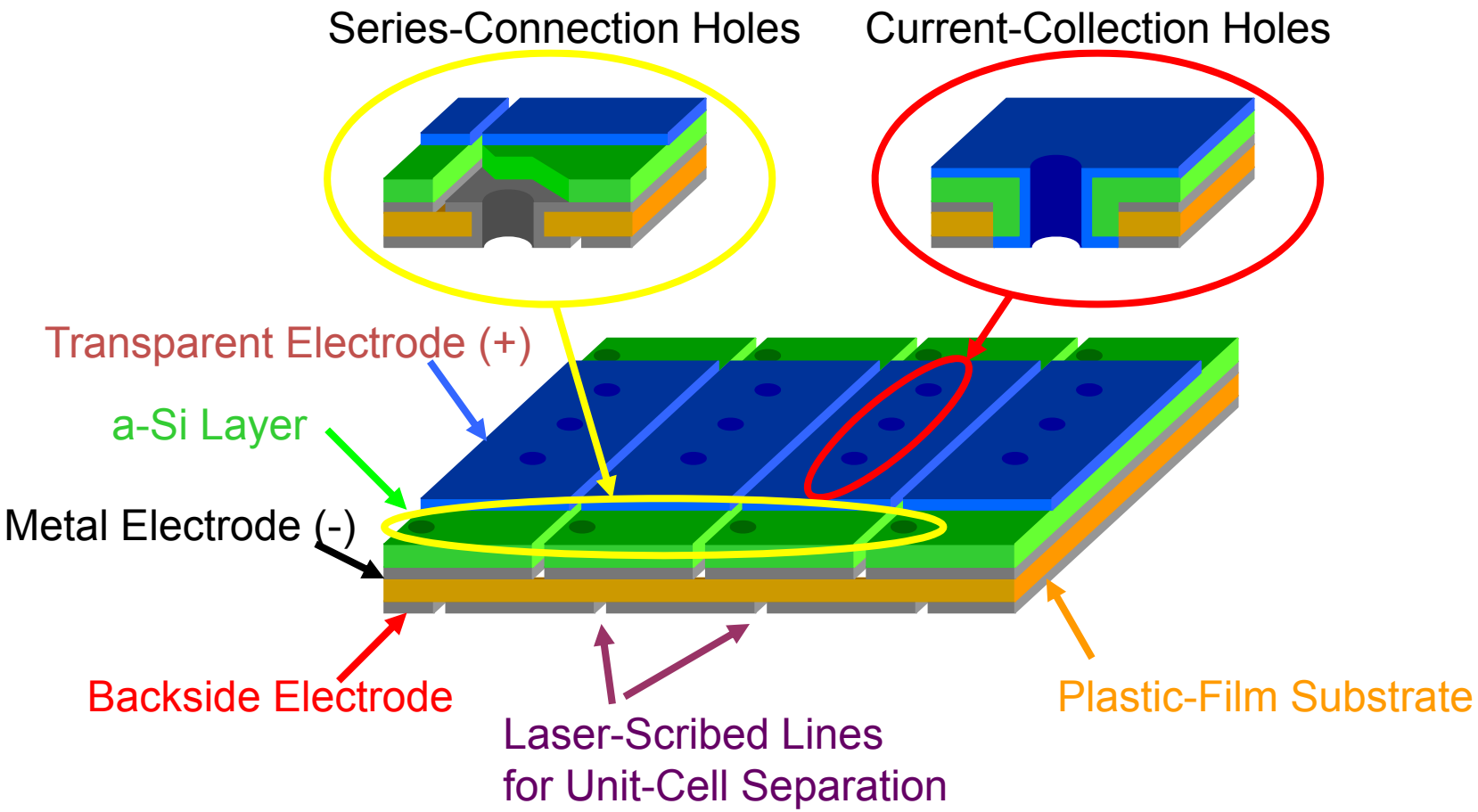


A. Takano et al, *Acceleration Test of Combined Stressess for Flexible Thin Film Si Solar Modules*, 28th EUPVSEC, Paris, 30 Sep 2013 – 4 Oct 2013, 3BO.5.4.

Bright spots = leak points around the interconnection holes (similar to what have been observed in the field)

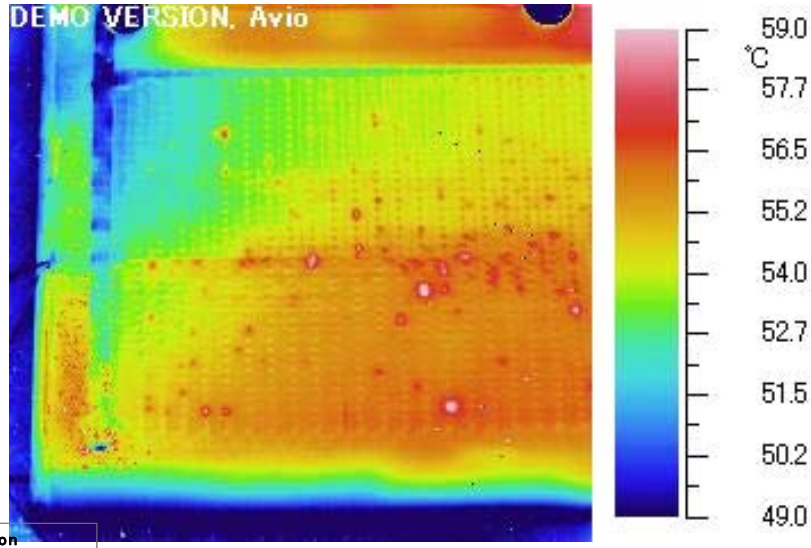
EVA encapsulant may induce an hydrolysis reaction and form acetic acid in the module. Acetic acid may have caused the formation of defects (leak points).

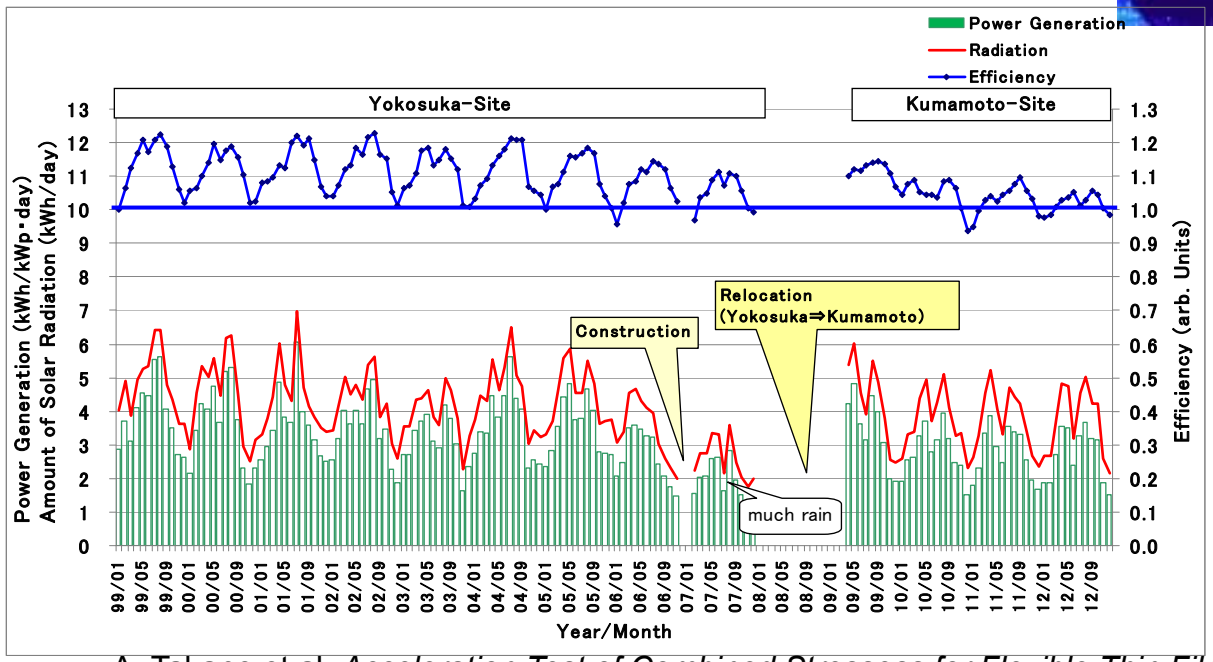
Location of the leak points



- SCAF (Series-Connection through Apertures formed on Film) structure.

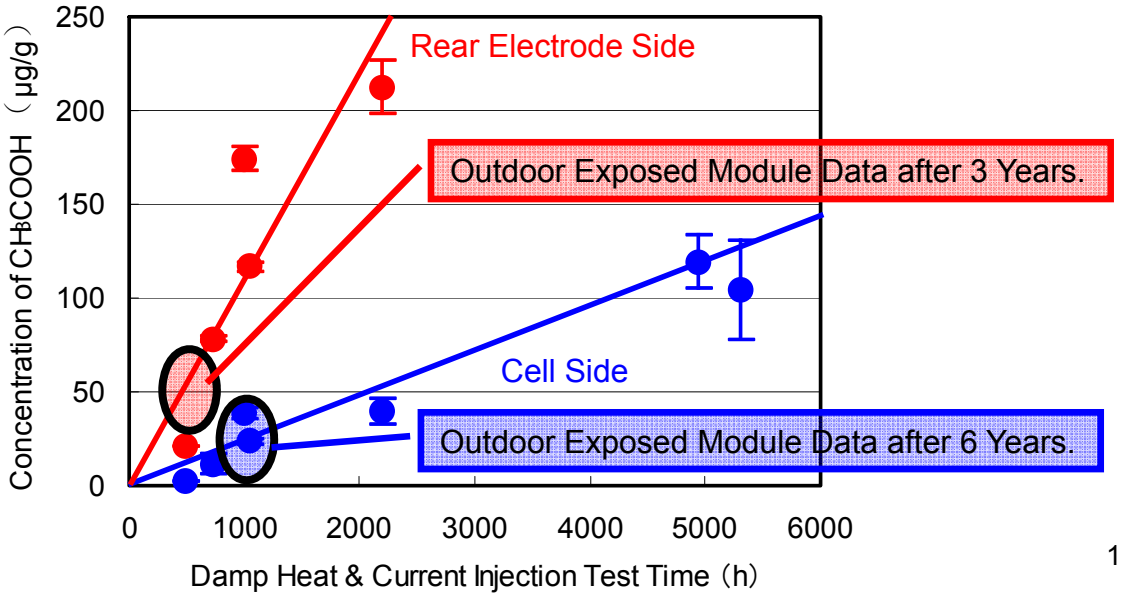
Similar results at outdoors

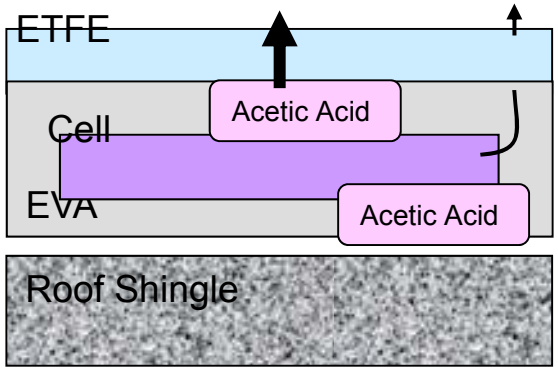




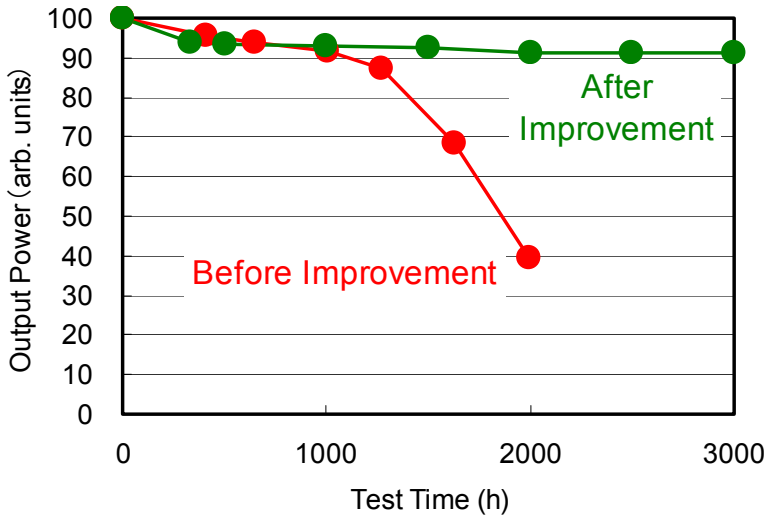
A. Takano et al, *Acceleration Test of Combined Stressess for Flexible Thin Film Si Solar Modules*, 28th EUPVSEC, Paris, 30 Sep 2013 – 4 Oct 2013, 3BO.5.4.

Acetic acid from EVA?





Encapsulant
EVA ⇒ Polyolefin



A. Takano et al, *Acceleration Test of Combined Stressess for Flexible Thin Film Si Solar Modules*, 28th EUPVSEC, Paris, 30 Sep 2013 – 4 Oct 2013, 3BO.5.4.

What we can say now..

At least in one flexible thin film Si case:

- Conventional Damp Heat test could not reproduce one certain type of degradation observed in the field.
- Current injection during the Damp Heat test have reproduced a certain type of degradation.
- The degradation was eliminated by changing the encapsulant from EVA to Acetic-acid-free materials, such as Polyolefin or Ionomer.

Possibly,

- Adding current injection (or light irragiation) +DH tests may be recommended for QA of certain type of thin film Si flexible modules, especially of those using EVA.
- The same may apply on other types of flexible modules ... we need to check if it does or not.

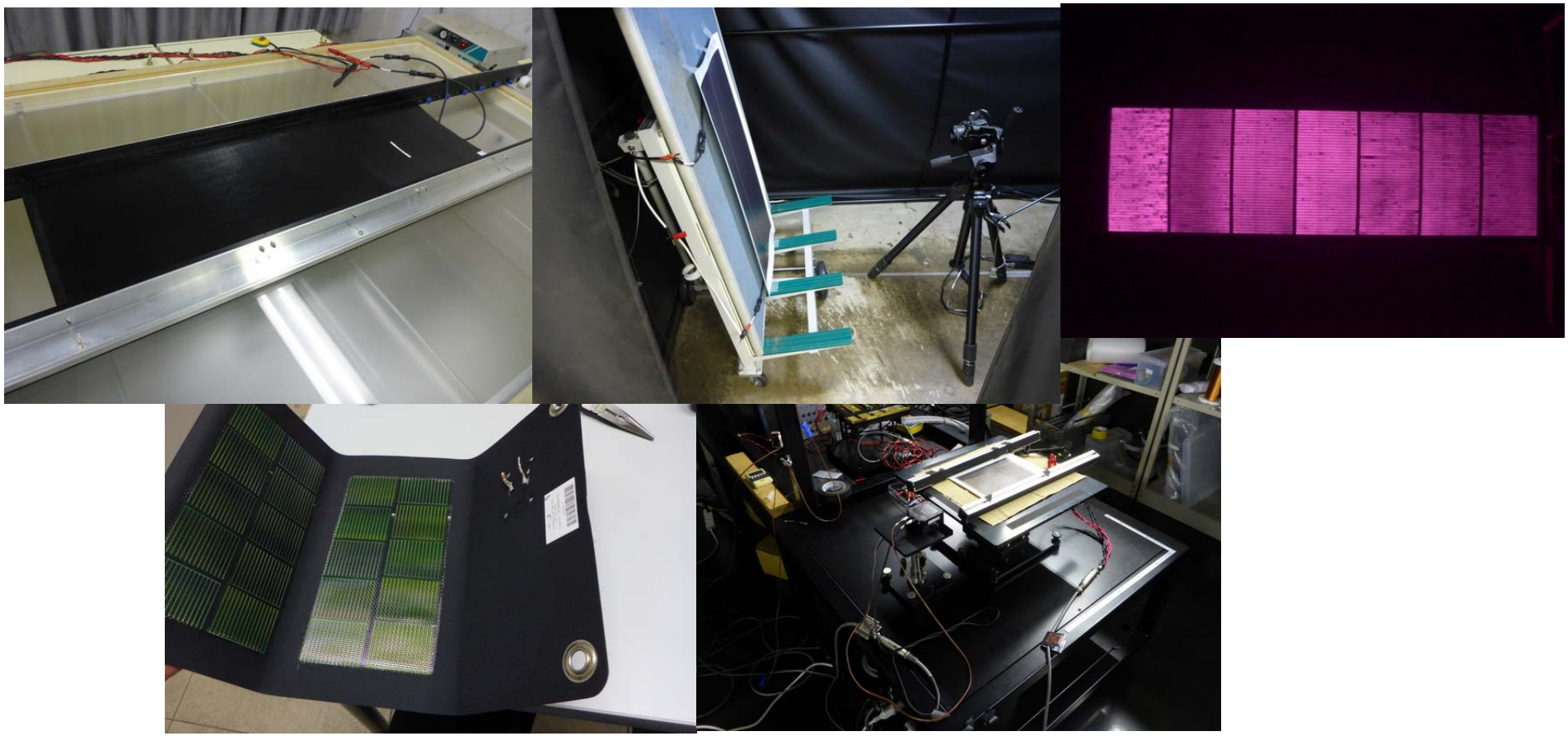
Activities of QA forum TG8 JP team

Compare "DH + Current" vs "DH + Light" vs DH on flexible modules

- Samples:
  - CIGS (Global Solar, Ascent Solar)
  - Thin Film Si (Fuji Electric)
- Test Condition
  - ✓ AIST & SolarFrontier ：DH Chamber with Light
    Light = max 1sun
  - ✓ Fuji Electric ：DH Chamber with Current
    Current = 1.5 / 1.0 / 0.5 times of Ipm.
  - ✓ Send same samples to FSEC&JABIL
- Evaluation
  - ✓ IV, EL, IR

TG8 JP: current status

- Samples have arrived to AIST
- initial measurement in progress



- will be distributed to other institutes soon
- first set of results expected to be available around May

Ressources naturelles Canada | Natural Resources Canada

Standards Contributing to Reliability of Photovoltaic Modules and Systems

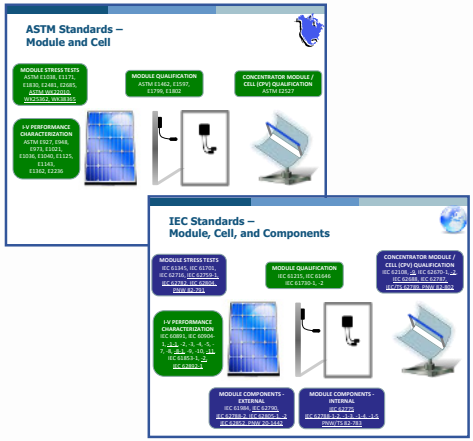
Poster Presentation By: Tanya Dhir, P.Eng., CanmetENERGY

Introduction

- In assessing module reliability, stakeholders utilize a variety of methods, from conceptual failure mode analysis to qualitative and quantitative stress testing. The PV community has pooled its knowledge on the common failure modes to develop standardized test methods to screen for these failure modes. This poster examines, in visual form, the existing standards relating to both module-level and system-level issues, and highlights the areas still in development or without any activity. Participants can examine the areas which need work, including some which the QA Task Groups are addressing. By working with other stakeholders, these gaps can be addressed, thereby increasing module reliability.

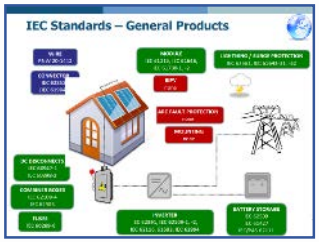
Module Standards

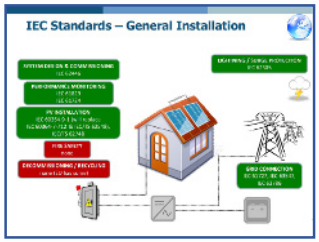
- Module qualification and silicon solar cell characterization standards are well established
- Long-term reliability and durability testing are critical to identifying product design issues that may manifest in the field after several years, however they have been difficult to standardize. This is due to the long time required for field failures to appear and be translated into equivalent test-stresses, and the variety of field failures observed due to different factors, from the product design, components used, and manufacturing quality, to installation techniques and the outdoor environment.
- Module stress tests are in development by IEC Technical Committee TC82, to address specific issues that have been observed in the field. These include farm-environment pollution (ammonia), degradation of module performance in high voltage systems, shading, and component-specific aging.
- Concentrator module qualification and characterization tests are also in IEC development

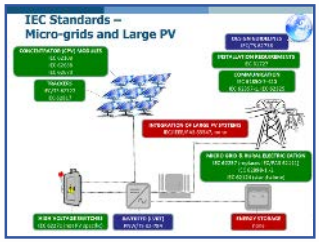


Installation Standards

- Module handling, system design, and Balance-of-System (BoS) components can play a key part in module reliability, either by creating additional stress on the module (for example, accidental impact, shading, and high operating voltages), or ideally reducing the overall stress on the modules (for example, protective fuses and strain relieving).
- General system design, commissioning, and installation standards exist through the IEC and ASTM. Grid interconnection IEC and IEEE standards also exist, including IEC guidance for micro-grids and rural electrification. As well, various committees have developed standards for specific BoS components, leading to an overall increase in PV system reliability, and array protection.
- Based on international experience, particularly in Europe, new inverter standards are being developed to address higher-PV-penetration concerns impacting grid stability. Large-scale PV arrays and energy storage (not limited to batteries) are also being explored.







BIPV Standards

- Many varying standards and specifications are currently used to qualify BIPV components and functions, however there is not a harmonized set of requirements. The exact list depends on location.
- A main factor influencing BIPV reliability and durability is their high operating temperature, due to limited rear ventilation. Key reliability issues are wind resistance, roof water tightness, roof replacement and service loads[1] .
- Similarly for PV-Thermal (PVT), although normal operating temperatures may be lower, stagnation temperatures can exceed the recommended limits of certain components such as the encapsulation material. The PVT Roadmap[2] lists electric hazard protection, capacitive coupling to ground, corrosion from moisture, stagnation resistance, and thermal shock resistance as key issues, and measurement techniques, standards, and certification as a high priority item.

EcoTerra House in Quebec demonstrating BIPV. System design issues such as low 30° tilt, textured PV surface, and roof soffits, led to snow retention in winter. Trees also led to shading in summer – ideal for cooling the house, but not BIPV module reliability.

References & Legend

[1] Pike Research, 2012, "Building Integrated Photovoltaics – BIPV and BAPV: Market Drivers and Challenges, Technology Issues, Competitive Landscape, and Global Market Forecasts", Navigant BIPV report, Boulder.

[2] PV Catapult, 2006, "PVT Roadmap A European Guide for the Development and Market Introduction of PV-Thermal Technology."

ASTM standards are available via: www.astm.org

IEC standards are available via: www.iec.ch

IEEE standards are available via: www.ieee.org

PUBLISHED STANDARD | NO STANDARD | STANDARD UNDER DEVELOPMENT

Acknowledgements:
Véronique Delisle, Lisa Dignard-Bailey, Dave Turcotte, and Yves Poissant

The information contained here does not include confidential information and is suitable for public release.

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Canada

ACTIVITIES OF TASK GROUP 8 ON THIN FILM PV MODULE RELIABILITY

Ramesh G. Dhere[1], Eric Schneller[2], Narendra Shiradkar[2] and Neelkanth G. Dhere[2]

[1]Episolar Inc., 450 N Weber Road, Unit A, Romeoville, IL 60446, USA

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

INTRODUCTION

• Task Group 8 of the International PV Module QA Task Force has been working on thin film module reliability.
• Thin film task group kick-off meeting was held on February 28, 2013.
• In the breakout session 1, field failure modes for thin film modules were identified and prioritized. The important failure modes are listed below:

Delamination: "micro" delamination of TCO / Mo films as well as macroscopic delamination of structural components such as encapsulant, edge seal etc.
Semiconductor Junction Degradation: Diode quality degradation by diffusion of impurities.
Corrosion: Moisture facilitated corrosion around scribe lines, degradation of contact layers (TCO, Mo film)
Interconnect Degradation: Increased shunting at scribe lines, poor edge delete leading to ground faults,
Glass Breakage: Residual stress, use of diurnal temperature cycling and hotspots leading to glass breakage.

• The breakout session #2 consisted of discussion on identifying an appropriate accelerated stress test or test sequence for predicting long term field performance for every failure mode.
• Four subgroups have been formed to focus on specific areas such as micro-delamination, shading, semiconductor junction degradation and monolithic interconnects.

STRATEGY

1. **Field Inspection:** Identifying field failure modes, Using I-V measurements, visual inspection and EL/IR imaging whenever possible.
2. **Failure Mode Analysis:** Statistical analysis of field inspection data to understand impact of each failure mode on module degradation.
3. **Failure Mechanism Determination:** Probing to the materials level to decipher the failure mechanism.
4. **Development of Accelerated Tests:** Based on the failure mechanisms, designing accelerated tests to replicate the observed field failure modes.

PLAN

• It is essential to determine whether the newly defined IEC test sequences in proposed rating system will require modifications to cover thin films specific stressors that would influence the failure modes.
• Therefore, subgroups have been assigned to investigate various failure modes specific to thin-film module.

Label\ Stress	Humidity	High Temperature	Thermal cycling	UV
IEC 61215 or 61646	IEC 61215 or 61646	IEC 61215 or 61646	IEC 61215 or 61646	IEC 61215 or 61646
Temperate	IEC 61215 or 61646	IEC 61215 or 61646	IEC 62XXX -2 Task Group 2	IEC 62XXX -3 Task Group 5
Hot & Dry	IEC 61215 or 61646	IEC 62XXX -4 Task Groups 2, 3 and 5	IEC 62XXX -2 Task Group 2	IEC 62XXX -3 Task Group 5
Hot & Humid	IEC 62XXX -5 Task Group 3	IEC 62XXX -4 Task Groups 2, 3 and 5	IEC 62XXX -2 Task Group 2	IEC 62XXX -3 Task Group 5

MICRO-DELAMINATION

• Delamination is defined as the separation between dissimilar materials in a given system
• Fracture occurs within the same material /cohesive failure.
• Delamination has a variety of different meanings within Thin-Film PV.
• Stressors and micro-delamination caused by them are described below:

General Interface	Specific Interfacial Example	Moisture	Diffusion Temperature	Bias (electrical)	Pure Mechanical	Thermo-mechanical (cycling)	Light
Glass/EVA	Same as c-Si module	X			X		X
Superstrate Glass/TCO	Glass/SnO_2:F (Bar Graphing)	X	X	X			
EVA/TCO(Cell)	Organic/Inorganic	X		X	X	X	X
TCO/Semiconductor	ZnO/CdS	X	X				
Heterojunction (P-N)	CdTe/CdS, CIGs/CdS		X	X			
Back Contact/Semiconductor	(Ni, Mo, Al)/CdTe or Mo/CIGS		X	X			
Back Contact/ Substrate	Mo/Glass		X			X	
Back Contact/EVA	Ni/EVA	X					
Front-Back Contact/Bus Bar	Bus Bar Delamination				X	X	

EFFECT OF SHADING ON THIN FILM MODULES

This group is working closely with the Task Group 4 on Diodes and Shading on the following goals:

1. Identification of field failure modes in thin film modules that can be attributed to shading.
2. Studying the long-term degradation in thin film modules due to hot spots.
3. Designing new /improved tests to reproduce the failure modes observed in field.

Following field failure modes have been identified:

1. Hotspots caused by shading resulting in glass breakage, loss of electrical insulation and long term degradation due to high temperature.
2. Permanent damage caused to the semiconductor junction and shunting due to application of reverse bias during shading.
3. Current crowding through small areas during event of shading leading to degradation of semiconductor material.

- The effect of worst case shading scenario where shaded cell has to withstand the reverse voltage generated by the rest of the module is being investigated further.
- The role of current crowding caused by shading in degradation of cells is also being studied.

Tightening nameplate rating tolerance below 5%: Can it be rationally and objectively required in test standards?

G. TamizhMani[1], S. Radhakrishnan[1,2] and B. Shisler[1]
[1]TUV Rheinland PTL, Tempe, Arizona; [2]Arizona State University, Mesa, Arizona

TÜV Rheinland PTL

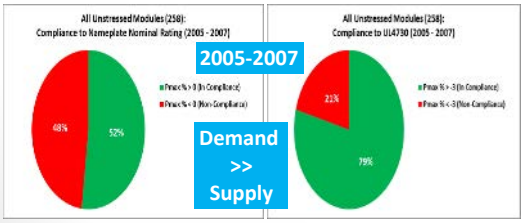
1. PROBLEM

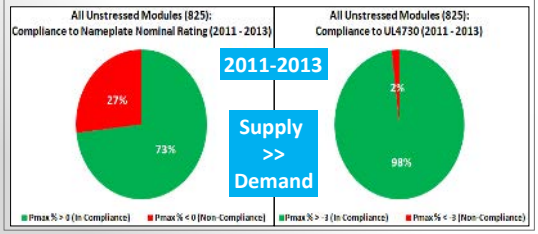
- SITUATION: Nameplate NOMINAL power rating is used for incentive calculations and the energy estimation
- PROBLEM: WIDE TOLERANCE or NO TLERNACE LIMIT in power rating (IEC 61215 or EN 50380) unduly allows over incentive compensation, over energy estimation and higher module mismatch issues in the arrays
- POTENTIAL SOLUTION: Tighten the nameplate rating tolerance below 5%
- QUESTION: Can it be practically tightened below 5%?
- ANSWER: A data-driven objective evidence is needed

2. DATA ANALYSIS APPROACH

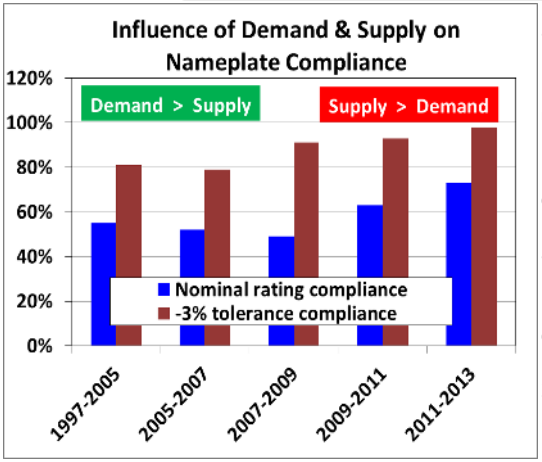
- TUV Rheinland PTL (formerly Arizona State University PTL) is an independent, accredited testing laboratory. TUV-PTL has statistically and chronologically compared the measured Pmax with the nameplate Pmax data of about 2000 modules for the past 17 years.
- Statistical comparison was done using Minitab based on the Access Database
- Chronological comparison was done in five periods (1997-2005; 2005-2007; 2007-2009; 2009-2011; 2011-2013) to observe the influence of demand & supply on the "$/watt" and hence on the "nameplate tolerance limits"

3. COMPLIANCE TO NOMINAL RATING & -3% TOLERANCE LIMIT





4. DEMAND/SUPPLY vs. NAMEPLATE COMPLIANCE



- If lower tolerance limit is NOT set by the standards, then the consequences are….

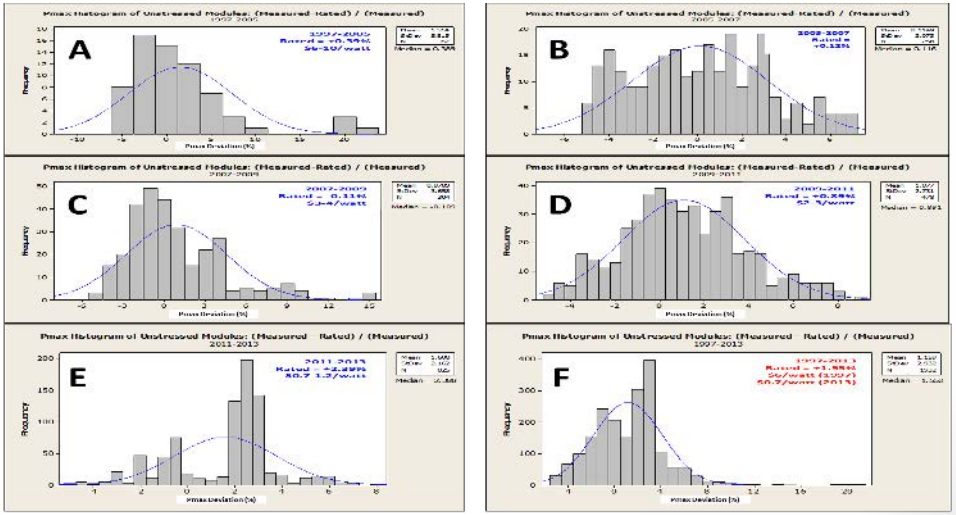
Uninformed consumers (e.g. homeowners) may pay for the nominal power which is over rated (**Blue column**; 25% of them are overrated in 2013)

&

Informed consumers (e.g. large project) may demand for the minimum power which is not practically over rated (**Maroon column**; only 2% of them are overrated in 2013)

➢ **Not good for the industry reputation!**

5. "$/watt" Pressure on "Median Deviation"



6. CONCLUSIONS

- If no lower tolerance limit set by the test standards, the demand/supply ratio will certainly dictate the marketplace nameplate tolerance limit which is not good for the reputation of the industry and the consumers.
- Based on the positive nameplate tolerance maintained by the manufacturers since 2011, it is recommended that the nameplate tolerance in the test standards can easily be tightened below 5%.

Contact (Mani): gtamizhmani@tuvptl.com

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.

International Electrotechnical Commission
Technical Committee 82 on
Solar Photovoltaic Energy Systems

PV Standards: What's new from TC 82?

By George Kelly, TC82 Secretary
solarexpert13@gmail.com

February 26, 2014

"this presentation contains no confidential information"

TC 82 Working Groups

WG 1: Glossary

WG 2: Modules, non-concentrating

WG 3: Systems

WG 6: Balance-of-system components

WG 7: Concentrator modules

WG 8: Solar cells

JWG 1: (TC 88/21/21A) Decentralized rural electrification

JWG 82: (TC 21) Batteries

TC 82 Standards

Standards published by TC 82 can be found on on the IEC website. This is public information and does not require a special login or password.

Go to www.iec.ch and search for "TC 82 dashboard".

The TC 82 dashboard also contains the Work Program (active projects), stability dates, membership, and other useful information

The following pages list Work Items that are presently active. Figures in red indicate expected completion dates, or other status of the project.

Recently Published Standards

Document	Edition	Title	Date
IEC/TS 62257-1	2.0	Recommendations for small renewable energy and hybrid systems for rural electrification - Part 1: General introduction to IEC 62257 series and rural electrification	2013-10-14
IEC 62670-1	1.0	Photovoltaic concentrators (CPV) - Performance testing - Part 1: Standard conditions	2013-09-25
IEC/TS 62548	1.0	Photovoltaic (PV) arrays - Design requirements	2013-07-26
IEC 62716	1.0	Photovoltaic (PV) modules - Ammonia corrosion testing	2013-06-27
IEC/TS 62257-9-5	2.0	Recommendations for small renewable energy and hybrid systems for rural electrification - Part 9-5: Integrated system - Selection of stand-alone lighting kits for rural electrification	2013-04-03

WG2 Projects

Project Reference	Title	Stage	Forecast Publication Date
IEC 60904-1-1 Ed. 1.0	Photovoltaic devices - Part 1-1: Measurement of current-voltage characteristics of multi-junction photovoltaic devices	ANW	2015-07
IEC 60904-2 Ed. 3.0	Photovoltaic devices - Part 2: Requirements for reference solar devices	CCDV	2015-02
IEC 60904-8 Ed. 3.0	Photovoltaic devices - Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device	CDIS	2014-05
IEC 60904-8-1 Ed. 1.0	Photovoltaic devices - Part 8-1: Measurement of spectral response of multi-junction photovoltaic (PV) devices	ANW	2015-07
IEC 61215 Ed. 3.0	Terrestrial photovoltaic (PV) modules – Design qualification and type approval Part 1: Requirements for testing Part 1-1: Special requirements for crystalline silicon Part 2: Test procedures	CDV	2014-12
IEC 61215 Ed. 3.0	Terrestrial photovoltaic (PV) modules – Design qualification and type approval Part 1-2: Special requirements for CdTe Part 1-3: Special requirements for a-Si and u-Si Part 1-4: Special requirements for CIGS and CIS	1CD	2015-06

WG2 Projects

Project Reference	Title	Stage	Forecast Publication Date
IEC 61730 Ed. 2.0	Photovoltaic (PV) module safety qualification Part 1: Requirements for construction Part 2: Requirements for testing	2CD	2014-05
IEC 61853-2 Ed. 1.0	Photovoltaic (PV) modules performance testing and energy rating - Part 2: Spectral response, incidence angle and module operating temperature measurements	ADIS	2014-05
IEC 62759-1 Ed. 1.0	Transportation testing of photovoltaic (PV) modules - Part 1: Transportation and shipping of PV module stacks	CCDV	2015-02
IEC 62775 Ed. 1.0	Cross-linking degree test method for Ethylene-Vinyl Acetate applied in photovoltaic modules - Differential Scanning Calorimetry (DSC)	ANW	2015-03
IEC 62782 Ed. 1.0	Dynamic mechanical load testing for photovoltaic (PV) modules	ACDV	2015-04
IEC 62788-1-2 Ed. 1.0	Measurement procedures for materials used in photovoltaic modules - Part 1-2: Encapsulants - Measurement of volume resistivity of photovoltaic encapsulation and backsheet materials	1CD	2014-12

WG2 Projects

Project Reference	Title	Stage	Forecast Publication Date
IEC 62788-1-3 Ed. 1.0	Measurement procedures for materials used in photovoltaic modules - Part 1-3: Encapsulants - Measurement of dielectric strength	ANW	2014-10
IEC 62788-1-4 Ed. 1.0	Measurement procedures for materials used in Photovoltaic Modules - Part 1-4: Encapsulants - Measurement of optical transmittance and calculation of the solar-weighted photon transmittance, yellowness index, and UV cut-off frequency	ANW	2014-12
IEC 62788-1-5 Ed. 1.0	Measurement procedures for materials used in photovoltaic modules - Part 1-5: Encapsulants - Measurement of change in linear dimensions of sheet encapsulation material under thermal conditions	ACDV	2016-01
IEC 62788-2 Ed. 1.0	Measurement procedures for materials used in photovoltaic modules - Part 2: Polymeric materials used for frontsheets and backsheets	ANW	2015-12
IEC 62790 Ed. 1.0	Junction boxes for photovoltaic modules - Safety requirements and tests	ADIS	2014-06
IEC 62804 Ed. 1.0	System voltage durability qualification test for crystalline silicon modules	1CD	2014-12

WG2 Projects

Project Reference	Title	Stage	Forecast Publication Date
IEC 62805-1 Ed. 1.0	Test method for total haze and spectral distribution of haze of transparent conductive coated glass for solar cells	ANW	2014-12
IEC 62805-2 Ed. 1.0	Test method for transmittance and reflectance of transparent conductive coated glass for solar cells	ANW	2014-12
IEC 62852 Ed. 1.0	Connectors for DC-application in photovoltaic systems - Safety requirements and tests	ADIS	2014-06
IEC 62892-1 Ed. 1.0	Comparative testing of PV modules to differentiate performance in multiple climates and applications - Part 1: Overall test sequence and method of communication	ANW	2015-12
IEC/TS 62915 Ed. 1.0	Photovoltaic (PV) Modules - Retesting for type approval, design and safety qualification	ANW	2014-12
IEC/TS 62916 Ed. 1.0	Bypass diode electrostatic discharge susceptibility testing	ANW	2015-02
PNW 82-791 Ed. 1.0	Non-uniform snow load testing for photovoltaic (PV) modules	PNW	2015-12
PNW/TS 82-800 Ed. 1.0	Guideline for Increased Confidence in PV Module Design Qualification and Type Approval	PNW	2015-10

WG3/6 Projects

Project Reference	Title	Stage	Forecast Publication Date
IEC 61829 Ed. 2.0	Crystalline silicon photovoltaic (PV) array – On-site measurement of I-V characteristics	CCDV	2014-09
IEC 62109-3 Ed. 1.0	Safety of power converters for use in photovoltaic power systems - Part 3: Particular requirements for PV modules with integrated electronics	ANW	2014-12
IEC 62109-4 Ed. 1.0	Safety of power converters for use in photovoltaic power systems - Part 4: Particular requirements for combiner box	PWI	TBD
IEC 62116 Ed. 2.0	Utility-interconnected photovoltaic inverters – Test procedure of islanding prevention measures	BPUB	2014-03
IEC 62446 Ed. 2.0	Grid connected PV systems - Minimum requirements for system documentation, commissioning tests and inspection	CCDV	2015-04
IEC/TS 62738 Ed. 1.0	Design guidelines and recommendations for utility scale photovoltaic power plants	ANW	2015-12

WG3/6 Projects

Project Reference	Title	Stage	Forecast Publication Date
IEC/TS 62748 Ed. 1.0	PV systems on buildings	ANW	TBD
IEC 62891 Ed. 1.0	Indoor testing, characterization and evaluation of the efficiency of photovoltaic grid-connected inverters	ANW	2015-12
IEC 62894 Ed. 1.0	Data sheet and name plate for photovoltaic inverters	CCDV	2014-12
IEC/TS 62910 Ed. 1.0	Test procedure of Low Voltage Ride-Through (LVRT) measurement for utility-interconnected photovoltaic inverter	1CD	2016-12
PNW 82-797 Ed. 1.0	Future IEC 6xxxxx: EMC requirements and test methods for grid connected power converters applying to photovoltaic power generating systems	PNW	2015-09

WG7 Projects

Project Reference	Title	Stage	Forecast Publication Date
IEC 62670-2 Ed. 1.0	Concentrator photovoltaic (CPV) performance testing - Part 2: Energy measurement	CCDV	2015-03
IEC 62688 Ed. 1.0	Concentrator photovoltaic (CPV) module and assembly safety qualification	ACDV	2015-09
IEC 62787 Ed. 1.0	Concentrator photovoltaic (CPV) solar cells and cell-on-carrier (COC) assemblies - Reliability qualification	ANW	2015-02
IEC 62817 Ed. 1.0	Solar trackers for photovoltaic systems - Design qualification	ADIS	2014-05
IEC/TS 62108-9 Ed. 1.0	Concentrator Photovoltaic (CPV) modules and assemblies - Design qualification and type approval - Part 9: Retest guidelines	CDTS	2014-10
IEC/TS 62789 Ed. 1.0	Specification of concentrator cell description	APUB	2014-07
PNW 82-802 Ed. 1.0	Thermal cycling test for CPV modules to differentiate increased thermal fatigue durability	PNW	2015-10

WG8 Projects

Project Reference	Title	Stage	Forecast Publication Date
IEC 60904-11 Ed. 1.0	Photovoltaic devices - Part 11: Measurement of initial light-induced degradation of crystalline silicon solar cells	ANW	2015-09

A NEW PV MODULE RELIABILITY LABORATORY IN QATAR

معهد قطر لبحوث البيئة والطاقة
Qatar Environment & Energy Research Institute
Member of Qatar Foundation

MARTINEZ-PLAZA, DIEGO[1]; FIGGIS, BEN[2]; MIRZA,TALHA[3]

(1) QEERI, (2) Chevron, (3) GreenGulf

GreenGulf

ABSTRACT

- An R&D effort is necessary to support the expected multi-GW PV deployment in the Gulf region by providing solutions to PV modules reliability in Qatar-like environment.

- A joint effort is being carried out by both **GreenGulf** and **QEERI** in order to:

- **Identify** the key environmental stress factors that can decrease performance and lifetime of PV modules in hot environments like Qatar
- **Design** solutions to mitigate such a problems by introducing improvements in PV modules design, particularly in the materials side.
- **Validate** such new improvements through accelerated testing at both outdoor and indoor labs.

BACKGROUND

- PV module manufacturers offer nowadays a power yield guarantee of 90% for the first 10-15 years and 80% for the rest till a 25-year panel lifetime. (Zielnik, 2013)

- Hot and dusty environmental conditions in Qatar may seriously handicap the power yield and even the life span of PV modules. (Mani, 2010)

- Accelerated aging techniques, both indoor and outdoor, allow to obtain results in reasonably short testing periods for both:

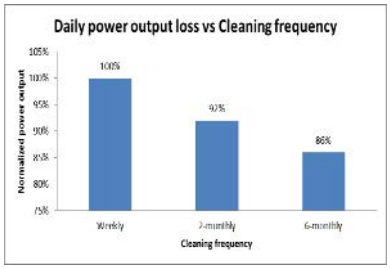
- Validation of new solutions
- Degradation of existing PV panel products

METHODOLOGY

1. **Collect field data** about most relevant environmental factors with an influence on PV module degradation:
   - UV spectrum within solar radiation on ground
   - Dust composition and deposition rate
   - Other chemicals in the atmosphere, aerosols, salinity….
   - Meteorological variables: temperature, relative humidity..
2. **Set-up indoor and outdoor labs** for accelerated aging and performance testing of PV modules, in addition to existing ones from **GreenGulf.**
3. **Design and implement engineering solutions** to prevent PV modules performance and lifespan to be handicapped in hot climates as Qatar's one.
4. **Commercialize solutions** through Qatar Foundation's dedicated mechanisms

CURRENT WORK / FINDINGS

- **Qatar Foundation (QSTP)**, **GreenGulf** and **Chevron** partnered in 2010 to establish the **Solar Test Facility**. Its purpose is to determine which solar technologies are most suited to Qatar, by measuring their energy production and response to heat and dust.
- The 35,000 m² site at QSTP was installed with crystalline silicon, thin film and concentrating PV technologies from multiple manufacturers.
- This site was commissioned in December 2012, and data recorded since February 2013..
- **Preliminary results about the effect of soiling on power output of c-Si modules are presented in this poster.**
- PV modules are mounted at 22° fixed tilt South, as single strings of 1.5 – 2.0 kW.
- Arrays are cleaned manually with a dry cloth under one of three cleaning schedules: weekly, every two months, and every six months. A reference c-Si module and one sample of each thin-film technology are tested simultaneously.
- Three hydrophilic and one resin-based anti-soiling coatings from commercial suppliers are tested, but none of them have so far had a significant effect on soiling.
- DC energy production is measured by dedicated sensors and meteorological data is recorded.



Two identical modules with different cleaning frequencies

The Meteo Station at the STF

Overall view of the STF

CONCLUSIONS/ SUMMARY

- PV is to be massively deployed in the Gulf region, but problems concerning **outdoor degradation of PV modules** need to be addressed.
- **GreenGulf** is already running the **Solar Test Facility** where many different PV module samples are under testing.
- **QEERI** plans include the **set-up of both indoor and outdoor facilities** to characterize the problem and test newly developed solutions.
- Some resources to be deployed are:
  - Weathering chamber, corrosion cabinet, IR imaging system, spectrophotometer, electroluminescence device
  - Exposure solar trackers, test stands, UV spectroradiometer and dust measurement sensor

REFERENCES

- Mani, M. (2010) 'Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations'. Renewable and Sustainable Energy Reviews. Volume 14: pg. 3124-3131

- Zielnik, A. (2013). 'Validating photovoltaic module durability tests'. Solar America Board for Codes and Standards.

ACKNOWLEDGEMENTS

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This presentation contains no confidential information

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Searching Stable Cu_xS Structures for Photovoltaic Application

Qiang Xu

Bing Huang

Yufeng Zhao

Yanfa Yan

Rommel Noufi

Su-Huai Wei

National Renewable Energy Lab

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

Introduction

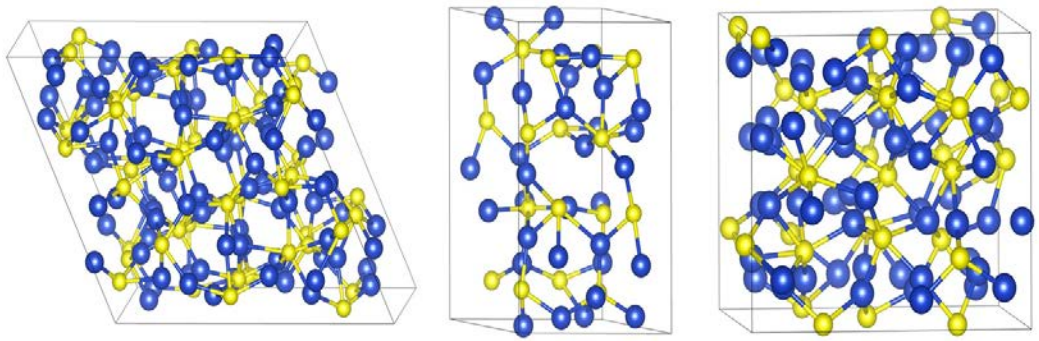
- Cu_xS is one of the promising solar cell absorber materials to replace CIGS.
- Solar cells based on Cu_xS have reached an efficiency as high as 10%.
- To further improve its efficiency and especially the stability, it is important to understand the stability and electronic structure of Cu_xS.

However, due to the complexity of their crystal structures, no systematic studies have been carried out to understand the stability and electronic structure of the Cu_xS systems.

Cu_xS Crystal Structure

The experimentally identified stable compounds of Cu_xS ($1<x\leq2$):

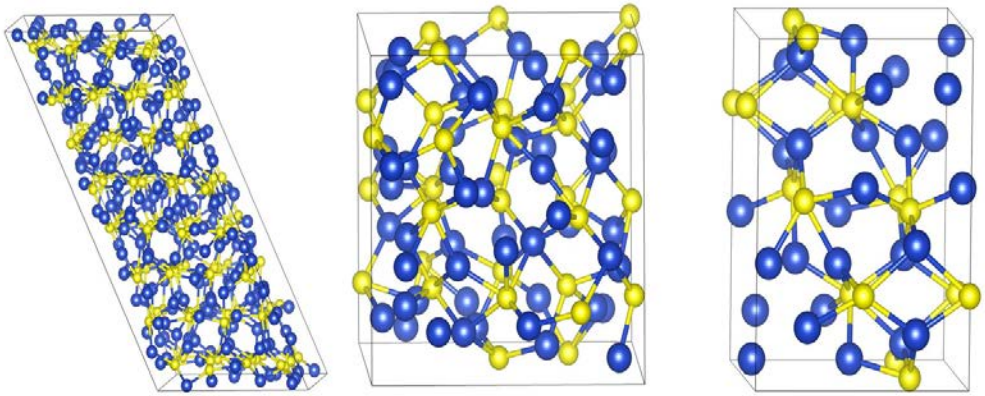
- Chalcocite (Cu_2S)
- Djurleite ($Cu_{1.94}S$)
- Digenite ($Cu_{1.8}S$)
- Anilite ($Cu_{1.75}S$)



(a) Low-Chalcocite Cu_2S (b) High-Chalcocite Cu_2S (c) Cubic-Chalcocite Cu_2S

Three different structures of chalcocite Cu_2S :

- monoclinic phase (low-chalcocite) ($t<104$ °C).
- hexagonal phase (high-chalcocite) (104 °C$<t<$436 °C)
- cubic phase (cubic-chalcocite) ($t>436$ °C).



(d) Djurleite $Cu_{1.94}S$ (e) Digenite $Cu_{1.8}S$ (f) Anilite $Cu_{1.75}S$

Methods of Calculations

- Using Vienna Ab-initio Simulation Package (VASP)
- All-electron-like projector augmented wave (PAW) potential
- The Perdew-Burke-Ernserhof (PBE) exchange correlation potential
- For more accurate calculation of band gaps, we also use hybrid functional (HSE) potentials
- Plane wave expansion up to 500eV
- The calculated cell are fully relaxed, which maximum force converges below 0.01eV/Å

The Optimized Structure Parameters and Band Gaps

The calculated lattice parameters, volume (V), band gap (E_g), and heat of formation per formula unit (ΔH) of Cu_xS.

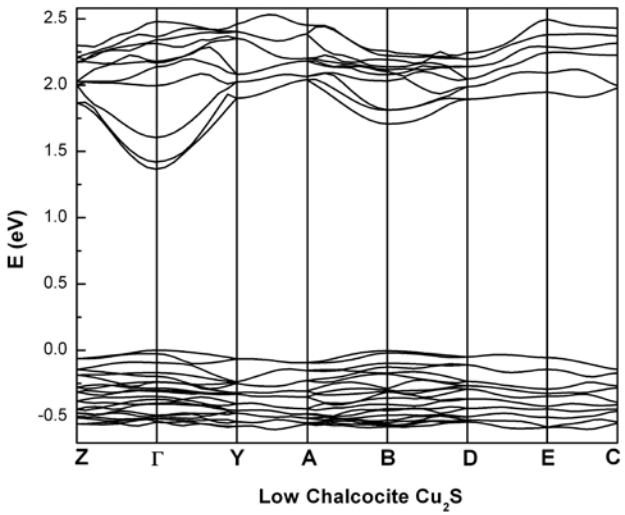
x	Crystal system	a_0 (Å)	b_0(Å)	c_0 (Å)	α	β	γ	V (Å^3)	E_g (eV)	ΔH (eV)
2	Monoclinic	15.27	11.93	13.45	90.0°	115.6°	90.0°	46.04	1.39	−0.40
2	Hexagonal	7.87	8.19	13.36	90.7°	90.0°	118.5°	47.28	1.49	−0.36
2	Cubic	12.04	12.26	10.47	90.3°	90.3°	87.0°	48.20	1.34	−0.34
1.94	Monoclinic	13.53	15.95	29.95	90.0°	116.7°	90.0°	45.13	1.12	−0.41
1.80	Cubic	11.36	11.15	11.27	90.6°	89.1°	91.4°	44.61	1.20	−0.38
1.75	Orthorhombic	7.91	7.98	10.92	90.0°	90.0°	90.0°	43.06	1.39	−0.44

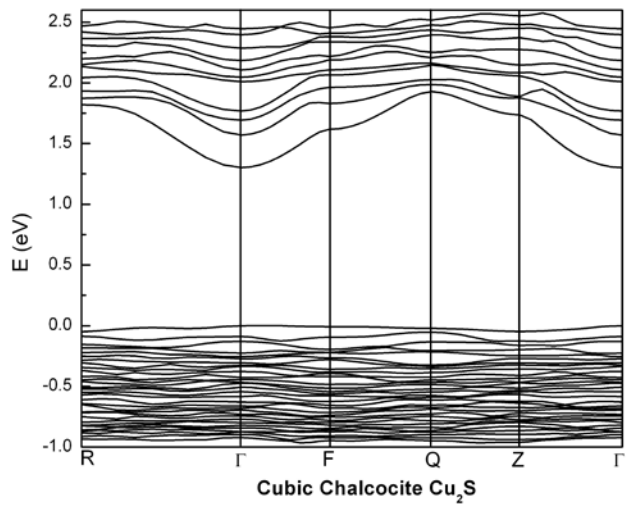
The heat of formation ΔH(x) of Cu_xS

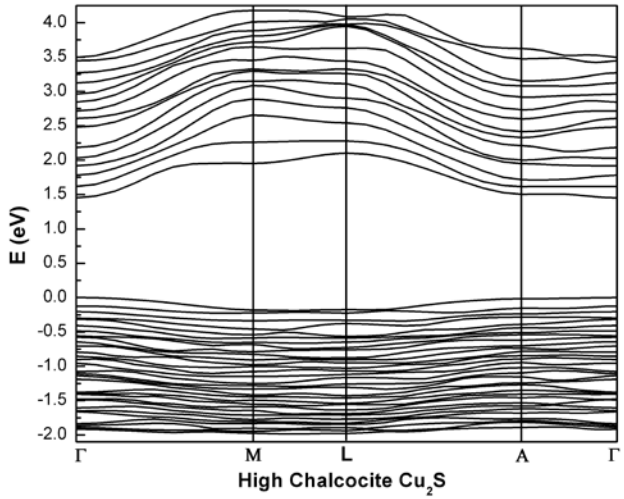
$$\Delta H(x) = E(\mathrm{Cu}_x\mathrm{S}) - xE(\mathrm{Cu}) - E(\mathrm{S})$$

- Monoclinic Cu_2S is the most stable structure at x=2
- Anilite $Cu_{1.75}S$ has lowest formation energy among the calculated Cu_xS compound

The Band Structures of Chalcocite Cu_2S



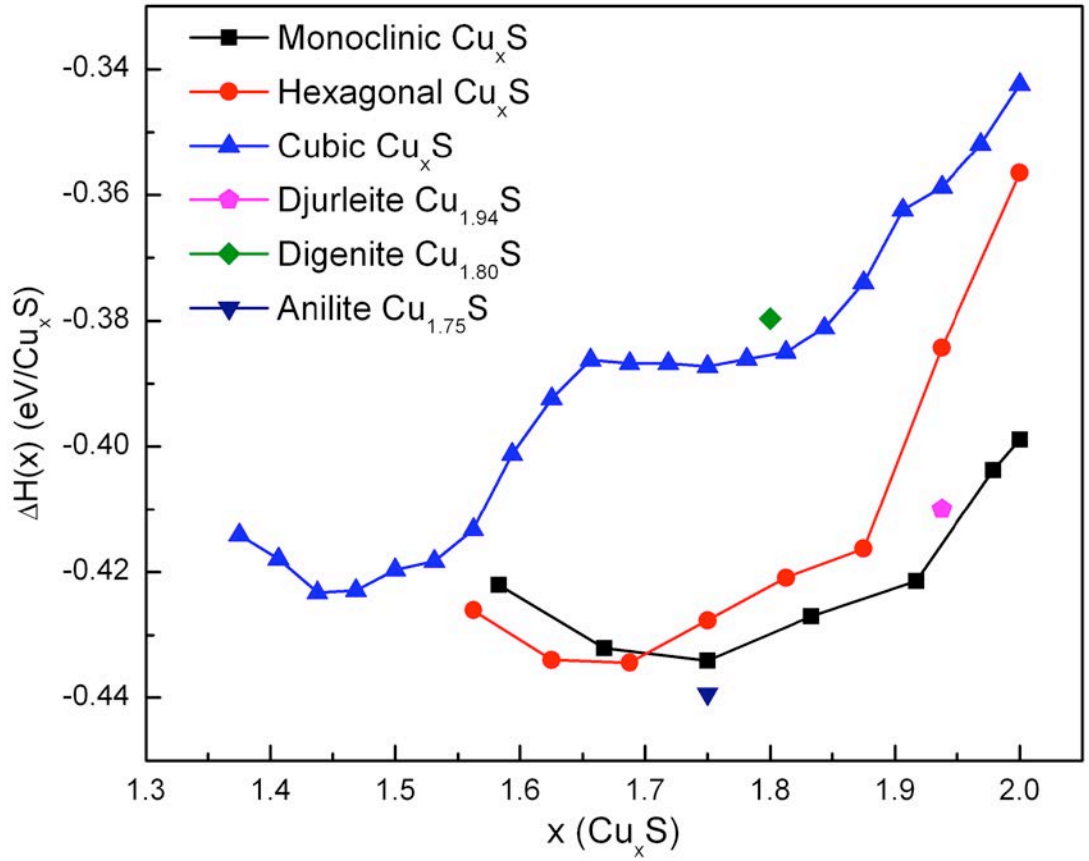




All three chalcocites have direct band gaps at Γ with values around 1.3–1.5 eV (HSE results).

Calculated Heat of Formation of Cu_xS as a Function of x

- The global minimum of the ΔH(x) occurs at about x=1.7 for the hexagonal and the monoclinic phases.
- A phase transition from the monoclinic to the hexagonal phase can occur at $x_c \approx 1.70$.
- However, the heat of formation of the low chalcocite and high chalcocite $Cu_{1.75}S$ is 20meV higher than that of the anilite $Cu_{1.75}S$.

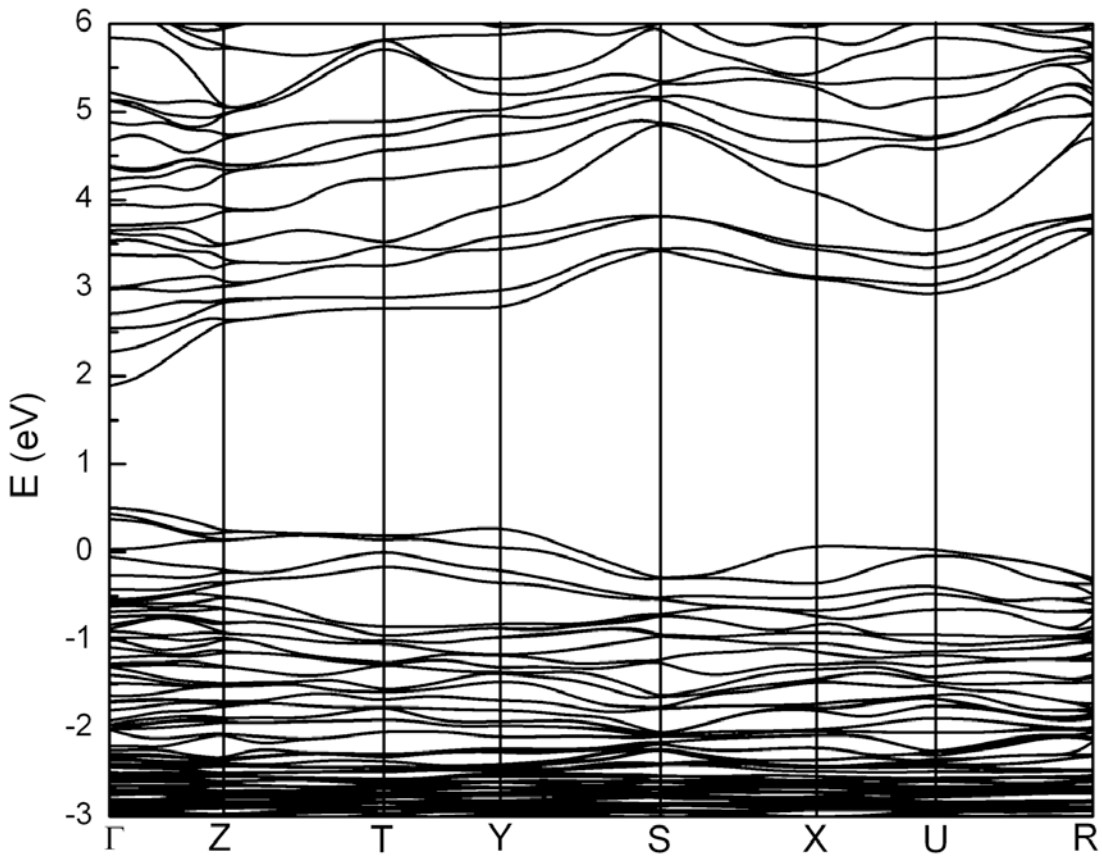


The initial structures, i.e., x=2, are based on the three chalcocite Cu_2S structures.

The anilite structure is indeed the most stable structure among all Cu_xS at the Cu-rich limit.

The HSE Band Structure of Anilite $Cu_{1.75}S$

- It has a band gap of 1.39 eV at the Γ point and is heavily hole-doped
- The hole carrier concentration can be controlled by doping anilite with donors such as Sn.
- The large curvature at the band edge indicates that it should have good electron as well as hole conductivities.



We suggest that anilite based Cu_xS could be promising materials for photovoltaic absorbers.

Conclusion

- Cu_2S is more stable in the low-chalcocite structure, in agreement with experimental observations. However, it is not stable against the formation of Cu vacancies.

- We identified that at the Cu-rich limit, the most stable crystal structure is $Cu_{1.75}S$ in the anilite structure, which has a band gap around 1.39 eV and could be a promising solar cell absorbers.

Thanks for Your Attention !

Developing a Roadmap for the Establishment of PV Weathering Standard

Kurt Scott,
Atlas Material Testing Technology

Nancy Phillips
3M Company

IEC Weathering Roadmap Workshop

February 27, 8AM – 2PM, at NREL. *Must be registered in advance.*

Organizers:
Kurt Scott, Atlas
Nancy Phillips, 3M
John Wohlgemuth, NREL
Crystal Vanderpan, UL
Mike Kempe, NREL

Workshop Goals

For weathering sequences in IEC Standards:

- Review the variety of approaches
- Develop a consistent underlying philosophy
- Provide guidance on how to incorporate weathering testing into Standards
- Draft a road map/timeline showing:
  - Est. completion dates for PVQA expts
  - Target standard draft dates

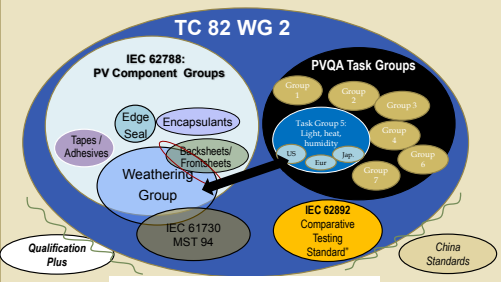
Agenda

- John's vision for TC 82 WG 2 Weathering
- Weathering approaches to TC 82 WG2
- Ongoing weathering studies (PVQA, others)
- Discussion: Guiding Principles

Lunch

- Roadmap Exercise
- Moving Forward…
- Wrap-up

Some TC82 WG 2 groups related to long term wear out



Weathering Standards in Process

Standard	Title	Weathering Portion	Status
IEC 62788-1	Encapsulant Component Standard	Not started yet	Pending
IEC 62788-2	Backsheet Component Standard	Under discussion.	Draft in progress
IEC 62788-?	Tapes/Adhesives Component Standard	Not started yet	Pending
IEC 62788-?	Edge Seal Component Standard	Under discussion.	Draft in progress
	Component Weathering Guidelines	Guidelines for sample preparation, exposures, testing: considerations and approach	Under consideration
IEC 62892	Comparative Testing Standard	Differentiation of module testing for different applications in different climates	Draft in progress
Qualification Plus	Extension of 61730 and 61215, with focus on improved Reliability	See "Qualification Plus" Table	Open comment period
IEC 61730 ed 2	Photovoltaic Module Safety Qualification	Method A, cycle 3 of ISO 4892-2.	CD submitted for comment
IEC 61215Ed 3	Weighted junction box test [36]	Tests robustness of junction box mounting	Draft in progress
Chinese National Standards			Draft circulating in China

•**Abstract:** **Long term wear-out is not addressed well in existing PV standards. Numerous groups are working to address this gap, writing standards using the best available knowledge, and performing experiments to gather data around the issues. A number of different approaches are being considered.**

•**The Weathering Group is hosting the Weathering Roadmap Workshop on Thursday. Take a moment to review a weathering perspective of standards in progress and some of the issues prompting discussion.**

•**This is a <u>Working Poster</u>! Please review the questions and add your comments.**

Standardized Weathering Tests

Standard	Material	Test Coupon	Exposure Side (Sun or J-Box)	Evaluation Tests	Xe (340) setpoint*	ChT	RH	BPT	cycling	hours
Qualification Plus	Encapsulants	*"same configuration in which they will be deployed", e.g.* Glass Encapsulant Film*	Sun	% Transmission	0.55	70°C	50%	90°C	-	4000
	Backsheet Set 1	Glass Encapsulant Encapsulant Backsheet	Sun	Visual	0.8	50°C	50%	70°C	-	4000
	Backsheet Set 2	Glass Encapsulant Encapsulant Backsheet	J-Box	Visual	0.8	50°C	50%	70°C	-	4000
	Backsheet Set 3	Glass Encapsulant Encapsulant Transp. Release Matl Backsheet	Sun	Remove backsheet and test alone: a) Visual b) Elongation at break	0.8	50°C	50%	70°C	-	4000
	Backsheet Set 4	Glass Encapsulant Encapsulant Transp. Release Matl Backsheet	J-Box	Remove backsheet and test alone: a) Visual b) Elongation at break	0.8	50°C	50%	70°C	-	4000
	Alternative exposure for front/backsheets and encapsulants:				*0.8*	*70°C*	*50%*	*90°C*	-	*4000*
	Cables and Connectors	Cables w/ connectors	J-Box	Visual Temperature rise, Mechanical operation Bending (flexing) test, Dielectric strength	0.55	70°C	50%	90°C	-	4000
	Junction Boxes	Junction box w/ cables and diodes, fixed to the substrate	J-Box	Fixing of lid at rewireable junction box Terminations and connection TMs Test of cord anchorage Retention of the mounting surface Wet leakage current test Knock-out inlets (outlets)	0.59	50°C	65%	65°C	18 min spraying, 102 min dry	500
61730 ed 1, Materials (current)	Front/Back Sheet	film	none, if no direct exposure							
61730 ed 2, Materials (draft)	Front/Back Sheet	as used, e.g. glass encapsulant encapsulant backsheet	film toward light source	Impulse voltage Ignitability 90° Peel	UVA, 60 W/m2 ref ISO 4892-2	50°C	nc	50°C	Cont. illum. 5 h UV, 1h water spray	1000
62788-2, film and coupon	Front/Back Sheet	film only, options: A) expose with no filter B) expose with manf. specified filter	tbd	Tensile strength Breakdown voltage Colour Surface gloss Outer appearance	tbd					
		coupon, as used, e.g. glass encapsulant encapsulant backsheet	tbd	harmonize with 61730 ed 2?	tbd					

1. What should be used as a basis for Accelerated Weathering Setpoints (irradiation, temperature)?

•Material Specific: based on activation energies
•Material Agnostic: based on microclimate
•Other

2. Comment on which light source should be used for small (non-module) samples.

•Xe with filter only
• Target Xe, provide guidelines for other light sources
• Combination (Xe for new materials, other for requalification)
•Other

3. Goal of a PV weathering test

•Demonstrate 25 year service life in "average" locations
•Demonstrate 25 year service life in "extreme" locations
•Demonstrate the material doesn't change after a limited accelerated weathering exposure
•Other

4. What philosophy should be used for weathering Pass/Fail Criteria?

•Low Bar: Pass for any sample that survives somewhere
•High Bar: Pass only for samples that survive everywhere
• Variable Bar: Segment by climate and application
•Other

5. How should weathering standards address the very different microclimates found with different applications?

•Same test for roof and rack mounted materials
•Different tests for rack mounted and roof mounted
roof ➔ higher T, no backside UV
• Other

6. How should weathering standards address the very different microclimates found with different applications?

•Same test for roof and rack mounted materials
•Different tests for rack mounted and roof mounted
roof ➔ higher T, no backside UV
• Other

7. Given the need for component materials to work together (e.g. backsheet and encapsulant), how should the weatherability of components be determined?

•Weather each component by itself
•Weather each component in an environment similar
•Different tests for rack mounted and roof mounted
roof ➔ higher T, no backside UV
• Other

8. Different standards address PV safety, PV performance, and characterization of components. Comment on how the weathering testing should be coordinated between the various groups.

•Define a generic weathering cycle to be used for all three
•Leave it to each group to decide their approach
•Start by considering each group separately, then coordinate and improve.
• Other

9. How much real time is reasonable to allow for a weathering test?

•One month
•Six months
•As long as it takes to establish confidence in the targeted service life
•Other

10. Comments on Qualification Plus Weathering Cycles?

•Individual cycles
•The set of cycles

TG2: Thermal and Mechanical Fatigue

Global TG-2 Leader: Nick Bosco (NREL)
TG-2 (JP) Leader:
Tadanori Tanahashi (ESPEC)

in NREL PV Module Reliability Workshop 2014
2014/02/26 (Golden, CO)

TG2: Thermal and mechanical fatigue including vibration

Proposed scope:

Failures of cell interconnects and solder bonds have been identified as a key cause of long-term failure of PV modules.

The primary stresses affecting the failure rates have been shown to be thermal and mechanical.

There is evidence that vibration during transportation and/or caused by wind can contribute.

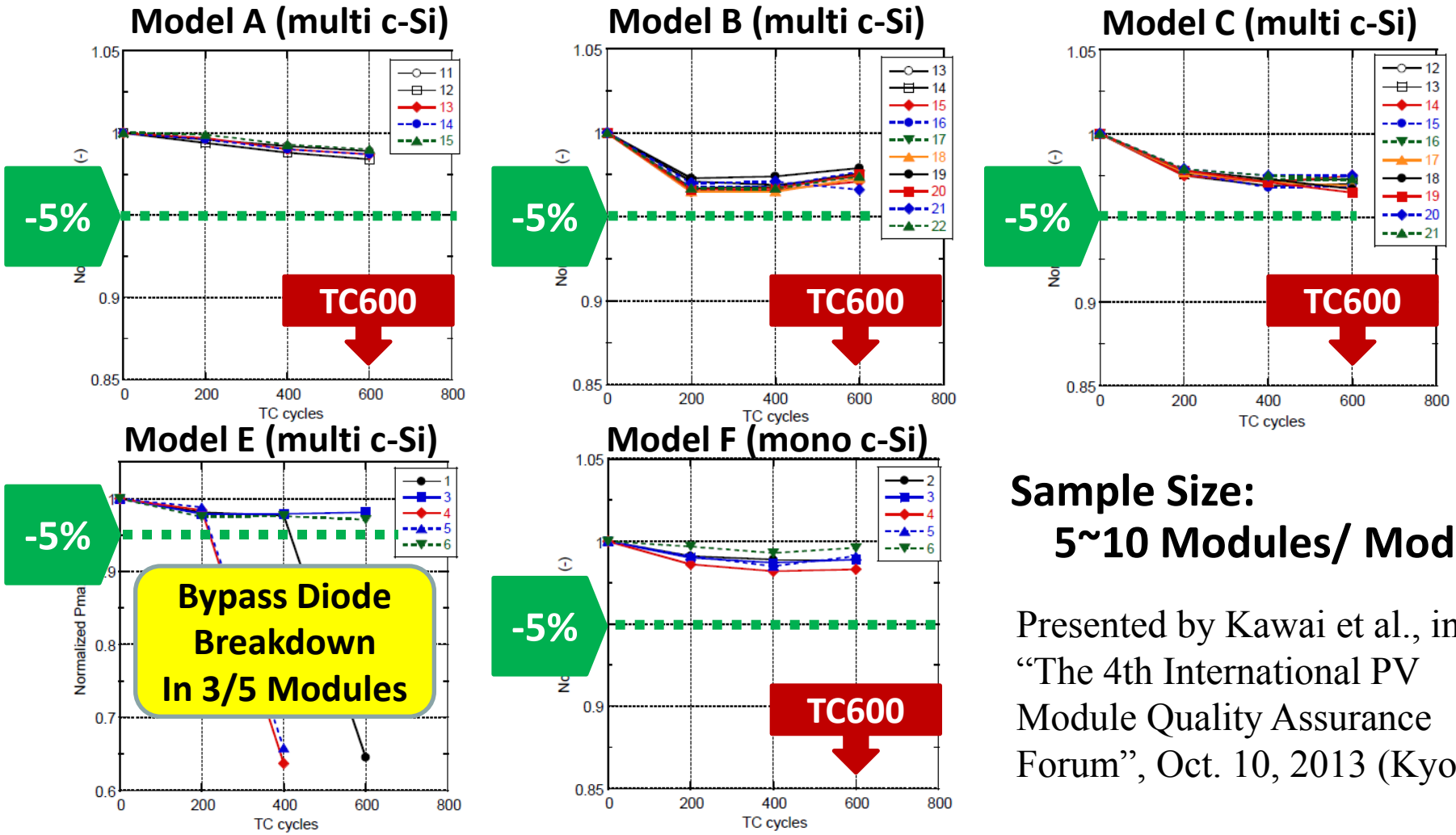
This task group will study how to best induce and quantify these failures.

Current Status

1. Recognition of Current Situation
   - TC 200 is not enough
     (NREL: PV Module Reliability Workshop, 2012).
   - Extended TC (ex. TC 600) may effective, but the long-term period is required.
   - In our experience, the interconnectors- / solder bonds-failures have been observed even in the moderate climate.
   - We need an option for subjecting the module <u>to greater thermal-cycling stress than IEC 61215</u>.

2. Requirements
   - Time Saving
   - Similar Failure Mode with Thermal Cycling
     -> Dynamic Mechanical Loading (DML) w/ or w/o TC

Massive Survey of PV modules Purchased from Market



Sample Size:
5~10 Modules/ Model

Presented by Kawai et al., in "The 4th International PV Module Quality Assurance Forum", Oct. 10, 2013 (Kyoto).

In the recently-designed PV modules, obvious power-loss was not induced even by TC600, except "Bypass Diode Breakdown".

Efforts for the DML Testing w/ or w/o TC

1.NREL

"Evaluation of Dynamic Mechanical Loading as an Accelerated Test Method for Ribbon Fatigue" in IEEE PVSC (June, 2013)

Most of the interconnect ribbons may be strained through module mechanical loading to a level that will result in failure in a few hundred to thousands of cycles……. To evaluate the equivalence of DML to thermal cycling, parallel tests were conducted with thermal cycling.

2. TG-2 (JP)

DML-TC sequential testing may be effective to detect the solder-bond / interconnector failures.

NREL PV Module Reliability Workshop (Feb., 2013)
IEC TC82/WG2 Meeting (May, 2013)

Global TG-2: Discussion (Nov, 2013)

Discussion to follow separated the purpose of the DML/TC sequence and DML alone.

DML/TC:	**Break susceptible cells and realize that effect on module performance.**
DML:	**Quick evaluation of ribbon interconnects fatigue resistance, will not assess cracked cells nor solder bonds.**

Philosophy for DML loading level:

Should be equivalent to manufacturing/ use/ environmental loading. Therefore <u>it may be reasonable to define a single loading level regardless of module size or shape</u>.

Not attempting to produce equivalent deflection or strains:

Since <u>smaller modules are naturally stiffer</u>, they have a higher resistance to these types of failures.

Global TG-2: Timeline (tentative)

	Qualification	QMS	Comparative Rating (TG-2)	Service Life Prediction
Current status	Issued as standards	Revised NWIP submitted	Proposed as concepts	Concepts
2014 goal	Submit Ed 3 61215 Ed 2 61730	Publish new TS	Enumerate tests Establish framework	Develop criteria to evaluate QMS related to service life; NWIP
2015 goal	Publish new editions	Start use of the TS in factory inspection	Complete drafts of set of tests	Complete CD
2016 goal		Revise QMS document to reflect feedback	Revise rating system to reflect tests	Publish
Chamber test times	Modules: ~ 6 weeks	TBD	TBD	3 years ?

Want to Volunteer!

To volunteer for TG-2, individuals may contact to TG-2 Leaders (Nick-san or Tanahashi) directly,

or request access to the website at http://pvqataskforceqarating.pbworks.com/

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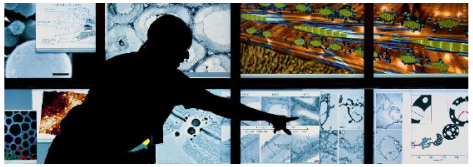
Task Group 3
Humidity, Temperature and Voltage



John Wohlgemuth for Group 3

February 26, 2014

NREL PVMRW

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

Introduction

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

Where we stand today

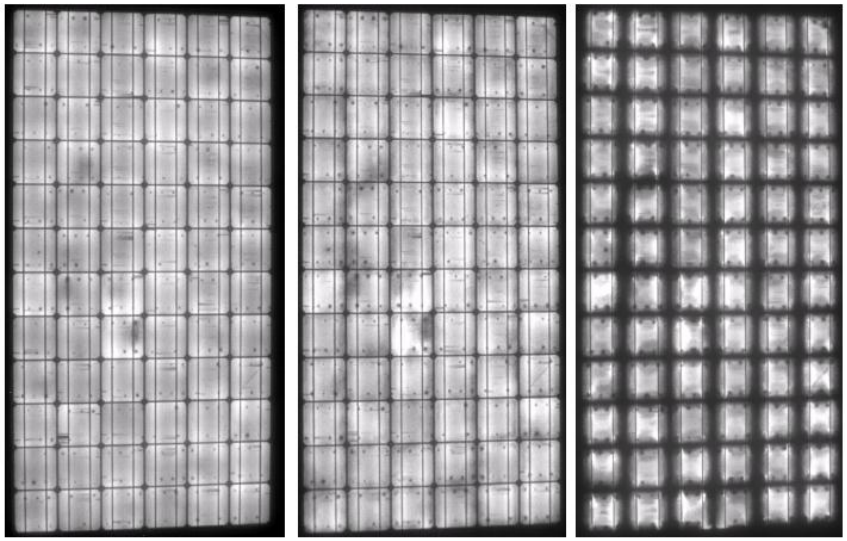
- **The module qualification test sequence IEC 61215 for cry-Si & IEC 61646 for Thin Films contain:**
  - **a 1000 damp heat test (85 °C at 85% RH) and**
  - **a humidity-freeze test (10 cycles from 85 °C at 85% RH to -40 °C) performed after a short UV exposure and 50 Thermal Cycles.**
- **These stress test appear to do an excellent job of screening out module designs and materials that would fail in the field in short time periods.**
- **So TG 3 is looking to find field failures that are not identified in the qualification test sequence, but are limiting the lifetime of PV modules.**
- **TG3 is also using modeling to better understand what the accelerated testing represents.**

Results from Long Term Field Exposure

- **Two failure modes identified**
  - **PID leading to significant power loss.**
    - **We had a whole session on this yesterday so I won't add anything except to remind you that IEC has a draft standard under development**
  - **Corrosion Associated with Delamination**
    - **Lets review what we see in the field and how we might duplicate it in the laboratory**

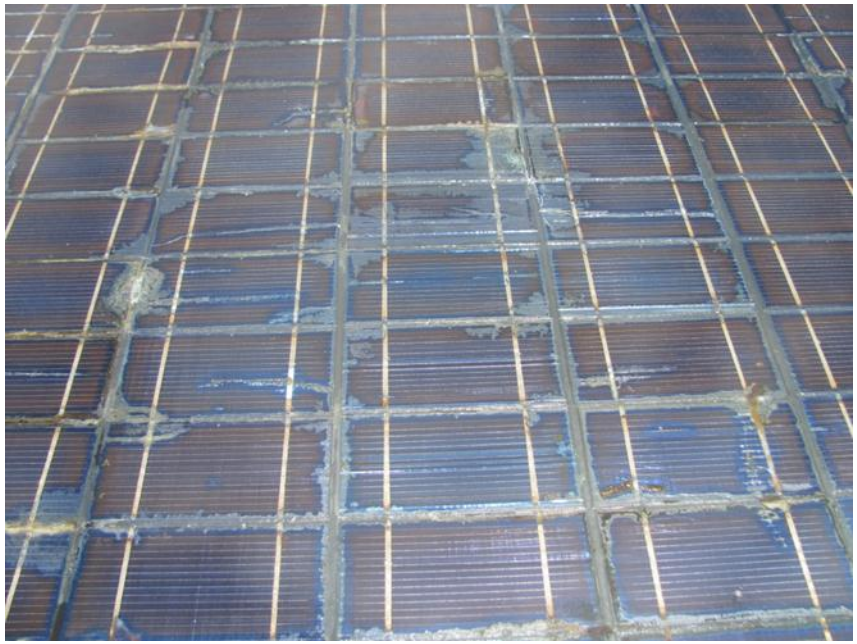
Approaches to Testing for Corrosion

Prolonged damp heat testing causes corrosion and power loss, but no visual evidence of metal corrosion. Not the same corrosion we see in the field



1000 hrs 2000 hrs 3000 hrs

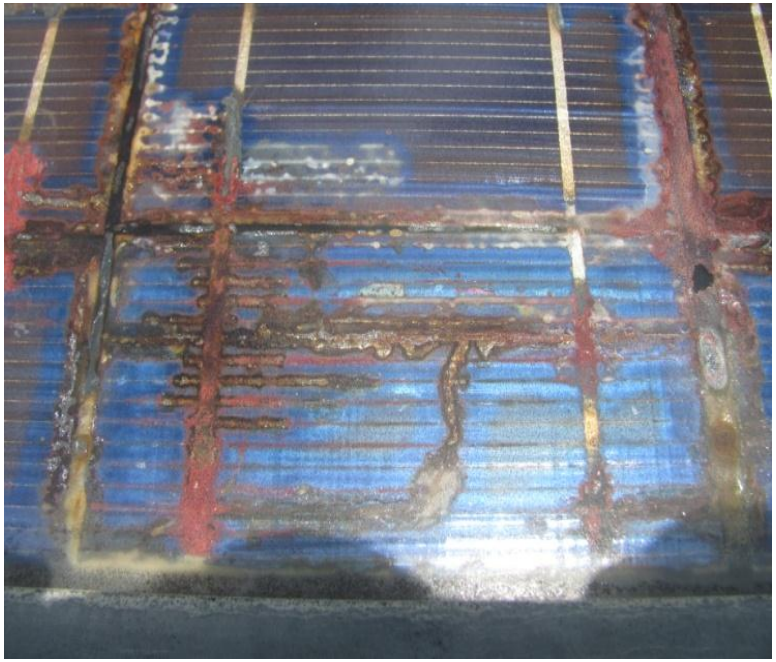
Corrosion seen in the field is associated with delamination.



Conclusion: We should move away from prolonged damp heat testing and move toward test sequences that cause delamination.

Delamination

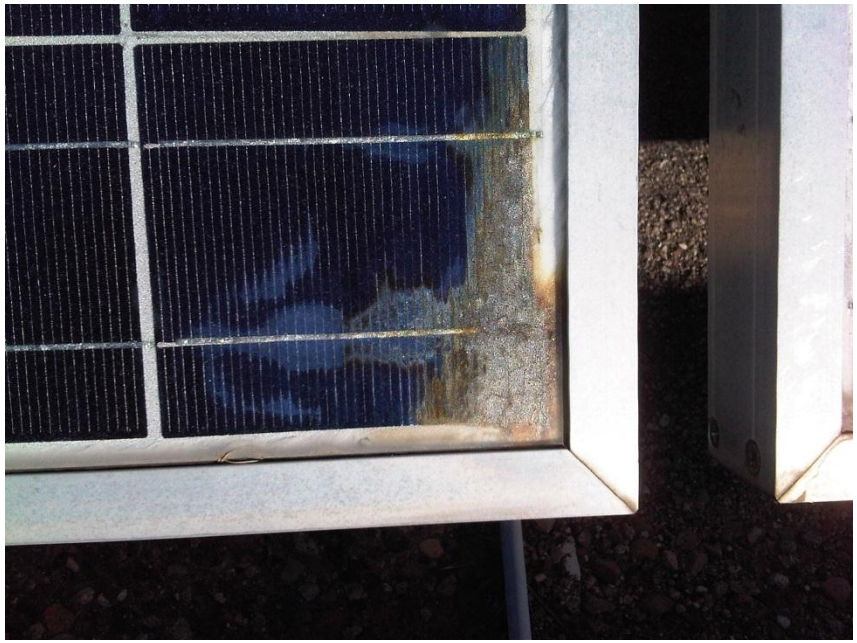
- Delamination of encapsulant from glass or cells is a failure mode seen regularly in the field. See picture.
- Much of the evidence of corrosion comes in conjunction with delamination.
- Any of the metals (grid lines, interconnect ribbons, solder bonds) will likely corrode if exposed to liquid water.
- Delamination is not adequately evaluated in the present qualification test sequence nor is it caused by extending the time for the 85/85 test.



Corrosion of cell metallization occurring with delamination of the encapsulant. No adhesion promoter was used on the cell or in the encapsulant, but the glass was primed. This module was exposed in Florida for 23 years.

Why do Modules Suffer Delamination?

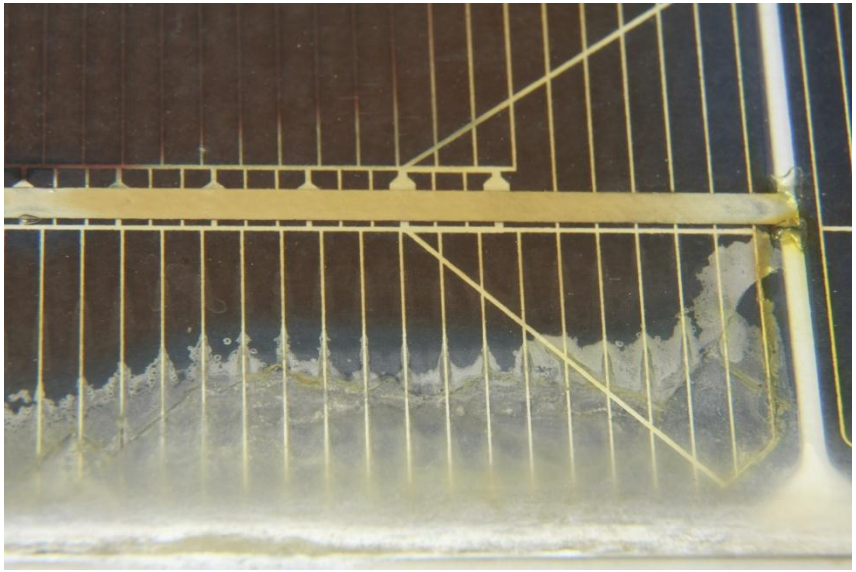
- **Manufacturing issues:**
  - Inadequate priming
  - Inadequate or incorrect glass cleaning
  - Use of wrong glass; too much sodium
  - Selection of wrong encapsulation material
  - Inadequate processing; either lack of cross-linking or primer reaction



Corrosion of cell metallization occurring with delamination of the encapsulant. Glass/glass module after 13 years in Tucson, AZ.

What Stresses Cause Delamination?

- UV Exposure Degrading the Adhesion
- Thermal Cycling
- Humidity Freeze
- Dynamic Mechanical Loading especially for glass/glass.
- Damp Heat especially after adhesive bonds are weakened.



Corrosion of cell metallization occurring with delamination of the encapsulant. Glass/polymer backsheet module after 27 years in California.

Status of Test Development

- **TG5 is running a large experiment to measure the change of adhesion between the encapsulant and the glass as a function of UV exposure, temperature and humidity.**
- **There is a materials task group that is looking at the best method for measuring adhesion.**
- **This may not be simple because of glass breakage. The adhesion value a glass/glass double cantilever beam wedge sample can measure is an order of magnitude less than the pristine adhesion value for EVA to glass.**

Status of Test Development (cont)

- **The qualification test already has a sequence of UV/TC/HF. (Probably why we don't see delamination occurring rapidly in qualified designs.)**
  - **UV irradiation can break the adhesive bonds formed between the encapsulant and glass or encapsulant and cells.**
  - **Thermal cycling puts mechanical stress on the interfaces because of different thermal expansion coefficients.**
  - **Humidity freeze pumps moisture into the package.**
  - **During the cold part of the cycle the moisture in any voids that have formed at the interface will condense as liquid water and then freeze.**
  - **This rips apart any weakened interfaces.**
- **WG2 has a draft standard for Dynamic Mechanical Loading (DML) with a plan to propose a UV/DML/TC/HF sequence. DML will add additional mechanical stress on the interfaces especially for glass/glass constructions.**
- **Hopefully the TG5 experiment will provide data on the appropriate UV exposure to improve the sequence for incorporation into the Comparative Testing Standard.**
- **Both NREL and JRC are planning experiments with sequential tests to validate their ability to duplicate the observed field failures.**

Conclusions

- **TG3 is looking for a combined set of accelerated stresses that can lead to delamination. Likely using the UV/DML/TC/HF sequence (with improved test levels especially for UV) followed by an appropriate damp heat exposure.**
- **TG3 is continuing to investigate field failures and is looking to:**
  - **Inspect older arrays (>10 years), especially those exposed in hot/humid environments.**
  - **Determine the correlation between visual corrosion (with or without delamination) and power loss due to lower fill factor.**
  - **Use failure analysis to identify failure mechanisms and then try to duplicate them using sequences of accelerated stress tests.**
- **The goal of this effort is to develop comparative tests for moisture driven failure modes in PV modules.**

US & Japan TG 4 activities of QA Forum

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

- Vivek Gade(Jabil)/Paul Robusto (Miasole)/Co-Leaders US Team
Uchida San (Leader Japan team)

2014 Photovoltaic Module Reliability Workshop

(PVMRW) Golden, Colorado, February 25–26.

Overview

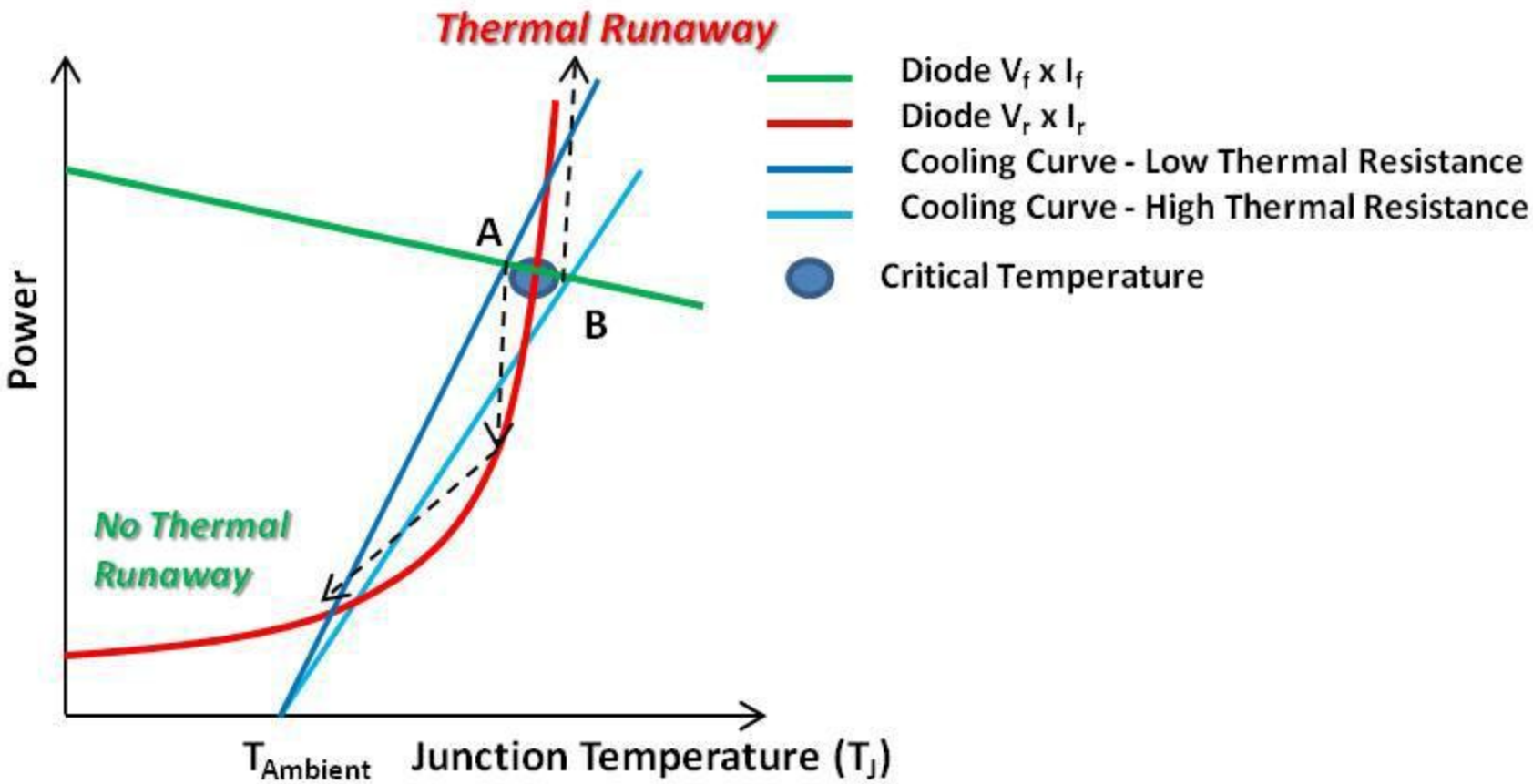
- History and Results
- Poster - Testing by the Japan Team (ESD, Diode, J-box & Module)
  - Y. Uchida (JET) & Y. Konishi (Onamba)
- Posters and papers - Testing at FSEC and Jabil (Thermal runaway model and experiments)
  - - Narendra Shiradkar, Eric Schneller, Neelkanth Dhere
- Next steps

History

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

- 2012: Task Group performed series of experiments
  - ESD testing HBM, MBD, IEC Model
  - Extended bypass diode tests
  - *HTRB and thermal cycling testing*
  - *Statistical and Weibull*

- 2013: Experiments and NWIP's
  - Thermal runaway tests and runaway models
  - IEC 62916 TS(Guideline) Bypass diode electrostatic discharge
  - NWIP for Thermal runaway from team in Japan is out for vote.


Thermal Runaway
Diode V_f x I_f
Diode V_r x I_r
Cooling Curve - Low Thermal Resistance
Cooling Curve - High Thermal Resistance
Critical Temperature
A
B
Power
No Thermal Runaway
$T_{Ambient}$
Junction Temperature (T_J)

International PV Module Quality Assurance Forum
Task-4 J-TG4

The proposal of thermal runaway test for bypass diode
Tj measurement method for bypass diode

(J-TG 4 activities of QA Forum / QA Task Force 4 ; Diode, Shading & Reverse Bias)

This presentation contains no confidential information.

This work was performed in cooperation with SHARP, Onamba, Nihon Inter Electronics and Sanken Electric.

Feb. 25-26, 2014 *@ Denver, USA*

Y. Uchida / JET (Japan Electrical & Environment Technology Laboratories)

1. The proposal of thermal runaway test for bypass diode

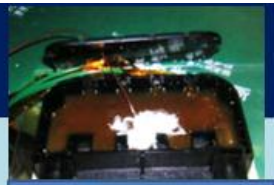
Current situation ;

NWIP draft for "Thermal runaway test for bypass diode" was submitted to TC82/WG2 on Jan. 18, 2014 and is expected to be discussed in the next WG2 meeting in June.

Scope and Purpose

This international standard provides a method for evaluating whether a bypass diode as mounted in the module is susceptible to thermal runaway or if there is sufficient cooling for it to survive the transition from forward bias operation to reverse bias operation without overheating.

Comparison results
between "Tcase method" and "Vf-Tj method"


Test sample

■ Tcase method

Tj = Tcase + Vf × If × Rth

Tcase : 95.6℃ (Temp. of diode's case)

Vf : 0.3391V

(Saturated voltage after 1h operating)

If : 9A (Forward current)

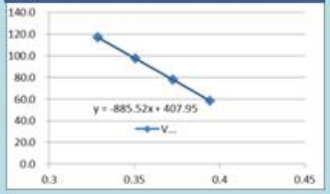
Rth : 1.5℃/W presented by manufacturer

Tj = 95.6(℃) + 0.3391(V) × 9(A) × 1.5(℃/W)

= 100.2℃

■ Vf-Tj method

Vf-Tj characteristic



Tj = -885.52 Vf + 407.95

= -885.52 × 0.3391 + 407.95

= 107.7 ℃

The Rth changes depending on where the diode is placed in the J-box.

Conclusion of Tcase/lead method

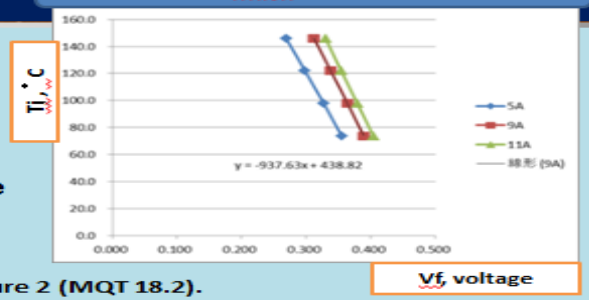
Due to the Rth change and the Tcase/lead measurement error, the calculated value of the Tj has some error compared to the real Tj.

Therefore, the judgment by using Tj value which is calculated by Tcase/lead method is misleading !!!!!

Vf – Tj method

- Once Vf-Tj relation is obtained, Tj is easily and accurately decided from the value of Vf. Vf-Tj relation can be acquired by measuring the temperature of the lead and the voltage across the diode in thermal equilibrium condition.
- It is specified in IEC61215-2 Ed.1 draft / 4.18.2 Procedure 2 (MQT 18.2).
- To achieve this, the preparation of some special measuring equipment is required.

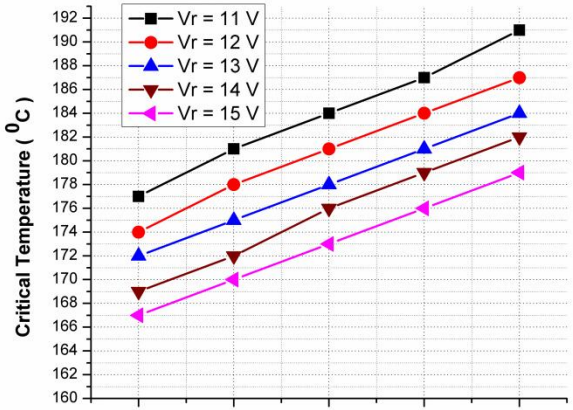
Case of Vf-Tj characteristics



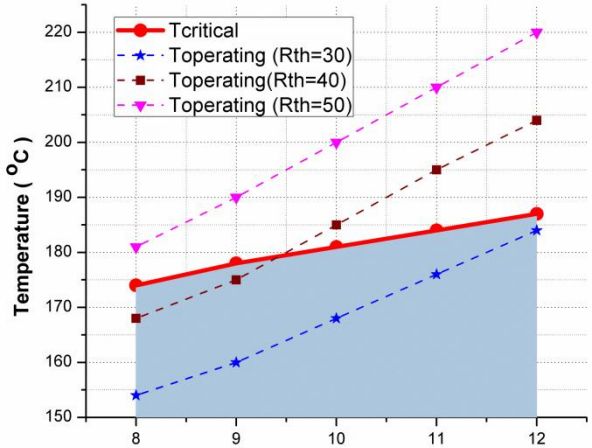
MODEL FOR PREDICTING THERMAL RUNAWAY IN BYPASS DIODES

Narendra Shiradkar[1], Eric Schneller[1], Neelkanth G. Dhere[1] and Vivek Gade[2]
[1]Florida Solar Energy Center, University of Central Florida, 1679 Clearlake Road, Cocoa, FL 32922-5703, USA
[2]Jabil Circuit Inc., 2007 Gandy Blvd, Suite 100, St. Petersburg, FL 33702, USA

Dependence of Critical Temperature on Forward Current and Reverse Voltage



Region of No Thermal Runaway (Shaded Area): Toperating < Tcrit



RECOMMENDATIONS

- The operating temperature of the diode at 1.25 x Isc during the bypass diode test in IEC 61215 can be used as an estimate for worst-case operating temperature.
- This information, along with the critical temperature data obtained by either of the described methods can be used to understand the vulnerability of bypass diode towards thermal runaway.
- Whenever necessary, the "thermal runaway test" can be carried out as an additional test.
- In order to avoid potential for thermal runaway, the diode should be operated several degrees below critical temperature as the region near critical temperature is experimentally found to be unstable.

Next activities

1. Preparation of special measuring equipment for establishing Vf-Tj relation to calculate Tj.
2. More tests to validate theoretical models related to critical temperature using different diode manufacturers. This can potentially result in a NWIP for guidance in diode selection.
3. Extended temperature soak tests. As performance and reliability is known to degrade with exposure to high temperatures for longer periods.
4. Evidence of diode failures in field has been observed by several group and the intent would be to investigate field diode failures to suggest relevant tests that can generate a NWIP within the next 6 months.
5. Make suggestions for qualification test protocols related to diode tests.

Thank you for your attention.

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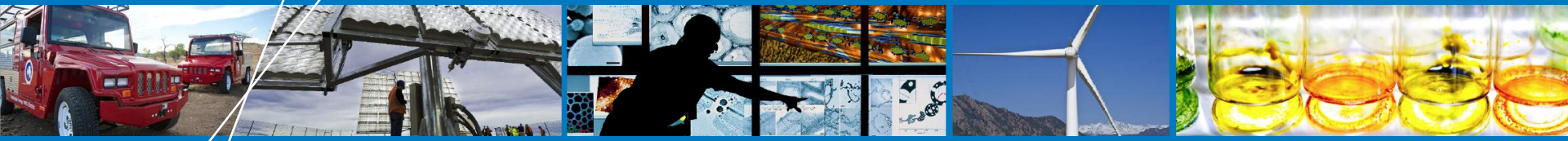
IEC Quality Assurance Task Group 5: UV, Temperature and Humidity



NREL PV Module reliability Workshop

David C. Miller* (*speaker, NREL, USA, David.Miller@nrel.gov),

Jasbir Bath (SEMA, USA, jasbir_bath@yahoo.com),

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

Tsuyoshi Shioda (Mitsui Chemical Co., Japan, Tsuyoshi.Shioda@mitsui-chem.co.jp)

Index #99, Weds 2014/2/26, 4:40-4:50 pm

-this presentation contains no proprietary information-

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.

Topics Covered Today

- Motivation: Goals and activities for QA TG5
- E_a interlaboratory experiment (TG5 US)
  - Motivation
  - Some details of the E_a experiment
- Timeline for TG5
- Mini-module experiment (TG5 Japan)
- SoPhia round-robin (TG5 Europe)

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

<u>Core Activities:</u>

1: Study weathering and climates (*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 observed failure modes.

e.g., the literature, site inspections

4-2 Confirm appropriate models for aging.

5: Verify suitable UV sources.

√summary of *module* capable equipment from David Burns *et. al.*

6: Generate protocol for accelerated service testing.

7: Perform laboratory verification of proposed test standard/failure mode.

mini-module study, SoPhia round-robin, E_a interlaboratory study

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 common UV-related PV degradation modes.

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

The modified Arrhenius equation

Critical unknowns
(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 E_a for different sources, *i.e.*, Xe-arc, UVA 340.
Is visible light required in addition to UV light?

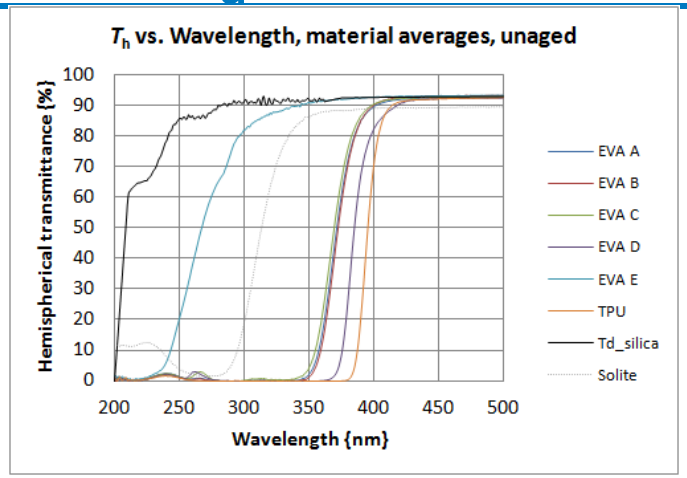
Some Details of the E_a Methods and Experiment

Optical transmittance:

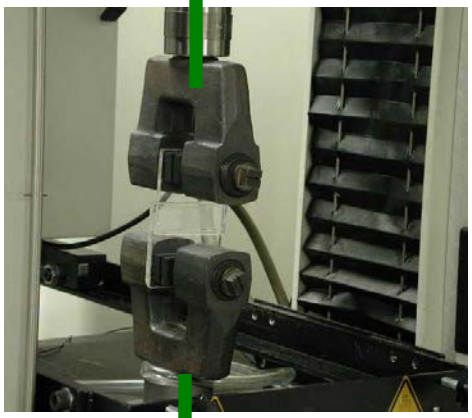
- (5) EVA + (1) TPU in encapsulation transmittance study.
- (10) intermittent measurements will be performed.

Mechanical attachment:

- (1) EVA will be examined using the compressive shear test.
- (2) edge seals will be examined using shear and wedge tests.
- (5) intermittent measurements will be performed.

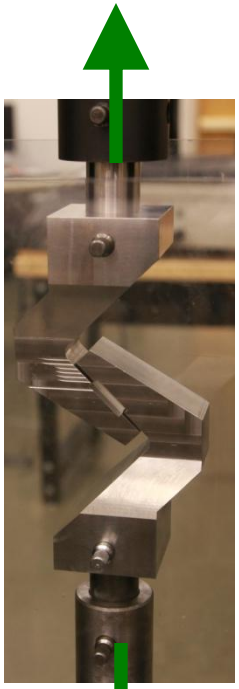


Transmittance will be examined using silica/polymer/silica samples.

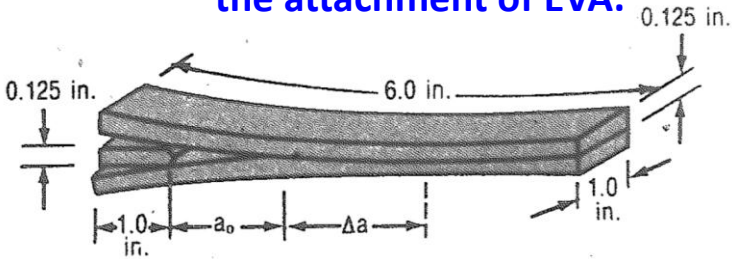


Overlap shear will be used to examine the attachment of edge seals.

Photo courtesy Kempe *et. al.*



The CST will be used to examine the attachment of EVA.



A DCB wedge test will be used to examine the attachment of edge seals.

Marceau *et. al.*, Adhesives Age, 1977, 28-34.

The E_a Interlaboratory Experiment Enables a Wider Range of Study

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

- A standard condition (60°C in chamber) allows a broad variety of other instruments (light sources) to also be compared.

LIGHT SOURCE, FILTER	Xe Arc (right-light/cira filter) or (Suga-Q/#295/Ircut)					UVA 340 fluorescent (no filter)		UVA 340 fluorescent (no filter)	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")			ambient
CHAMBER TEMEPRATURE {°C}	40	60	80	40	60	40	60	60→ 80 → 40	40	60	80	ambient
PARTICIPANT (INSTRUMENT MODEL)	3M (Ci5000)	3M (Ci5000)	3M (Ci5000)	Mitsui (SX120)	NREL (Ci5000)	QLAB (QUV)	QLAB (QUV)	Fraunhofer (custom)	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 (customized)					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)

Summary of participating laboratories and test conditions

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

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

Timeline and Goals for TG5

	Qualification	QMS	Comparative Rating	Service Life Prediction
Current status	Issued as standards	Revised NWIP submitted	Proposed as concepts	Concepts
2014 goal	Submit Ed 3 61215 Ed 2 61730	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 E_a test.	
2016 goal		Revise QMS document to reflect feedback	Publish E_a results. Submit CD UV standard.	
Chamber test times	Modules: ~ 6 weeks	TBD	~6 months	~18 months

The Mini-Module and SoPhia R-R TG5 Experiments

Mini-Module Experiment (TG5 Japan)

- Examines module performance (I/V), encapsulation durability, and backsheet durability after aging (UV, T, %RH).
- UV exposure can affect results of other tests, i.e., DH & TC.
- Will be examining adhesion within PV modules.
- See also PVMRW 2014 poster (index #85) by Shioda *et. al.*

SoPhia R-R (TG5 Europe)

- Samples (7) backsheet vendors at (7) test labs.
- Examines light sources (fluorescent, metal-halide, xenon) using 3 longpass and 2 neutral density filters.
- Examining test temperature (60 °C and 80 °C used in experiment).
- Refer to future work of Köhl *et. al.*

Acknowledgements

- There has been fantastic participation in TG5.

Thank you - to the many participants!

- If interested in TG5 or the experiments, please contact the corresponding regional TG5 leader. (See title slide)
- Let me know if you are interested in any of the related material standards? (encapsulation transmittance, encapsulation adhesion, edge-seal attachment)
- TG5 dinner meeting Weds 2/26, 6:15 pm at Mimi's Café (14265 W Colfax Ave)

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

FLORIDA SOLAR ENERGY CENTER®

Creating Energy Independence

Philosophy, Strategy, Activities and Plans of Task Group #8: Thin Film PV Module Reliability

Neelkanth G. Dhere
Florida Solar Energy Center
University of Central Florida
1679 Clearlake Road, Cocoa, FL 32922-5703, USA
E-mail: dhere@fsec.ucf.edu

Task Group Focus and Activities

- Task Group #8 Thin Film PV Module Reliability focuses on thin film specific issues that are not covered by c-Si related task groups are provided in the next slide.
- The group is trying to develop an appropriate accelerated stress test or test sequence for predicting and assuring long term field performance.

Thin Film Specific Issues

- **Semiconductor Junction:** Diode quality degradation by diffusion of impurities.
- **Microdelamination:** "micro" delamination of TCO / Mo films as well as macroscopic delamination of structural components such as encapsulant, edge seal etc.
- **Monolithic Integration:** Increased shunting at scribe lines, poor edge delete leading to ground faults.
- **Flexible Modules**: Front transparent polymer coversheet, etc.

Strategy

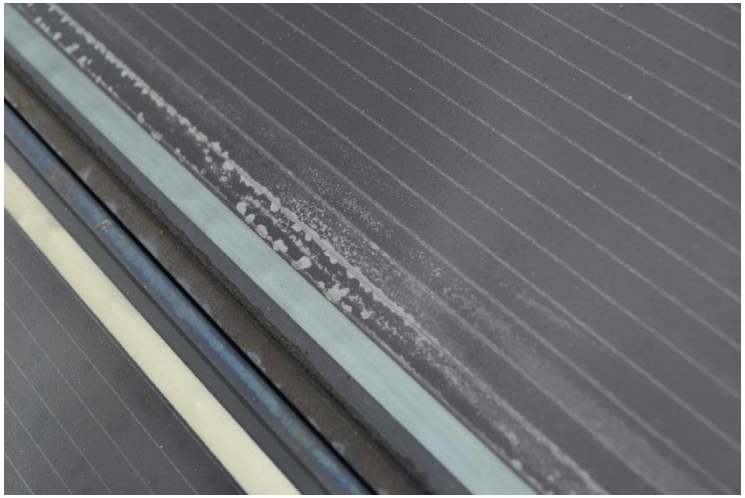
1. **Field Inspection:** Identify field failure modes, Use I-V measurements, visual inspection and EL/IR imaging whenever possible.
2. **Failure Mode Analysis:** Statistical analysis of field inspection data to understand impact of each failure mode on module degradation.
3. **Failure Mechanism Determination:** Probing down to the materials level to decipher the failure mechanism.
4. **Development of Accelerated Tests:** Based on the failure mechanisms, designing accelerated tests to replicate the observed field failure modes.

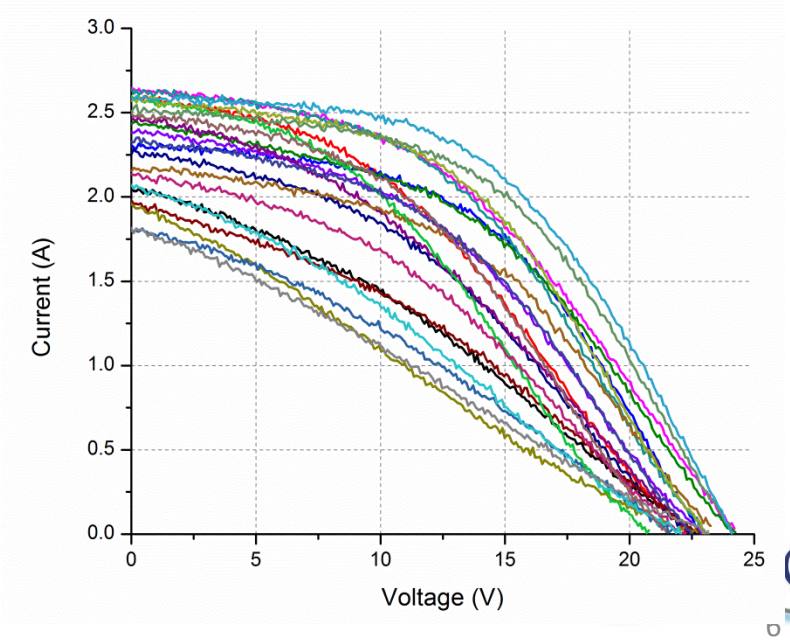
IEC Ratings System Proposal

- It is essential to determine whether the newly defined IEC test sequences will require modifications to cover thin films specific stressors that would influence the failure modes.
- Therefore, subgroups have been assigned to investigate various failure modes specific to thin-film module.

Collection of Field Data

- An effort to collect field data from thin-film PV systems is essential to identify the significance and occurrence of various failure mechanisms.
- Detailed analysis is required to allow for a quantitative analysis. This includes visual inspection, I-V characteristics and if possible electroluminescence and thermal imaging.





IEC Qualification Tests

- The recent proposal to develop replacement of the IEC61636 should not be based initially on cell materials such as CdTe, a-Si:H and CIGS.
- It should be based on thin film specific issues such as Semiconductor Junction, Microdelamination, Monolythic Interconnection, and Flexible Modules.
- Material specific issues would be considered in the second iteration.

Thank You!

- Questions and Comments?

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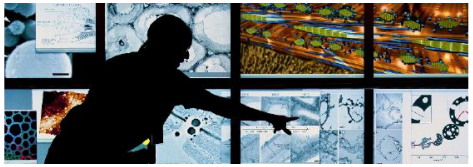
Task Group 9 Update



National Renewable Energy Laboratory
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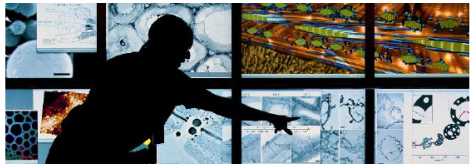
COMPARATIVE THERMAL CYCLING TEST FOR CPV MODULES TO DIFFERENTIATE THERMAL FATIGUE DURABILITY

NWIP submission



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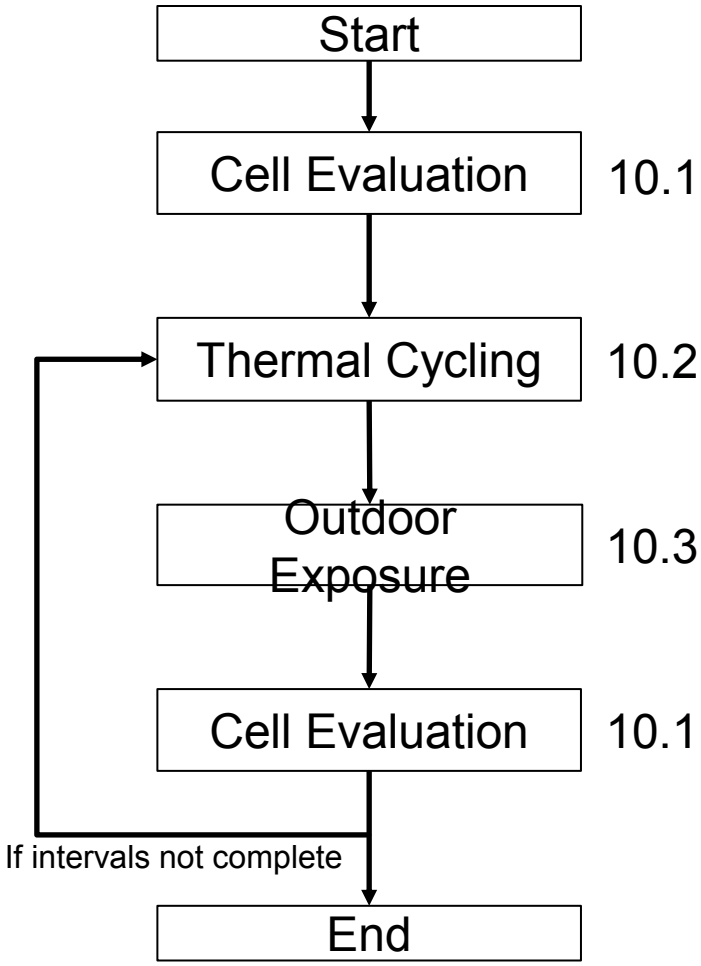
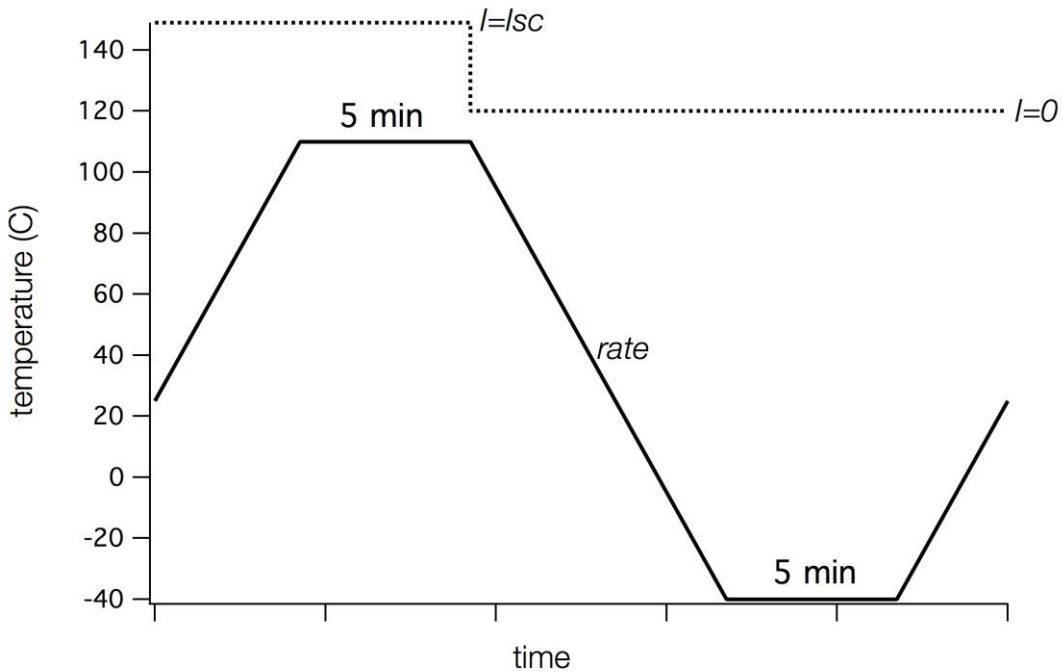
Test Procedure

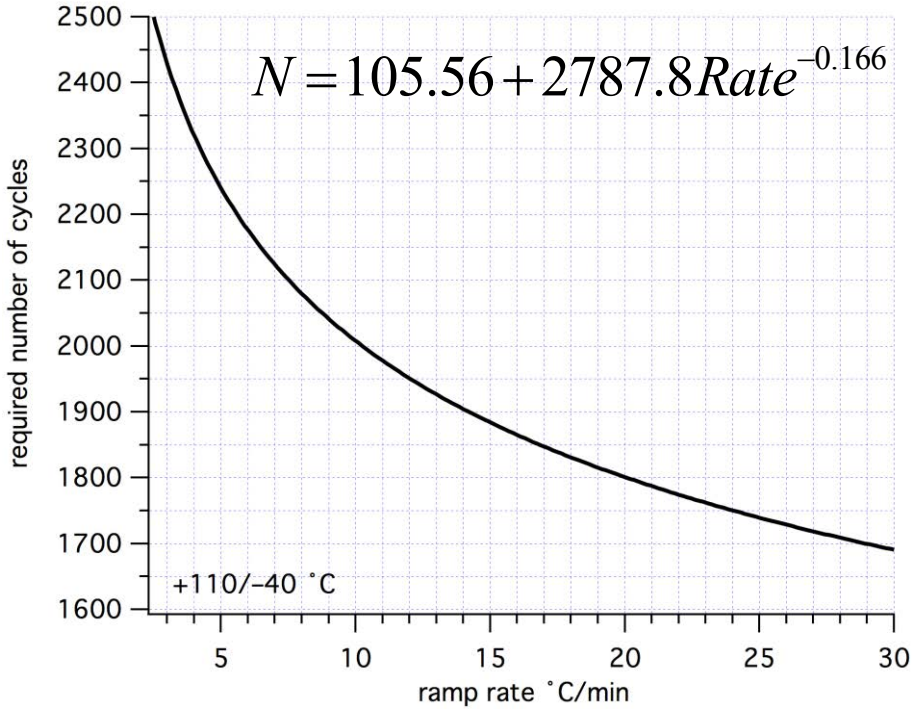


Test Procedure: Thermal Cycling



- 110 to –40 ˚C with 5 minute dwell times
- Isc applied at 25˚C until end of hot dwell
- Maximum average ramp rate of 30 ˚C/min
- Number of cycles required depends on *rate*

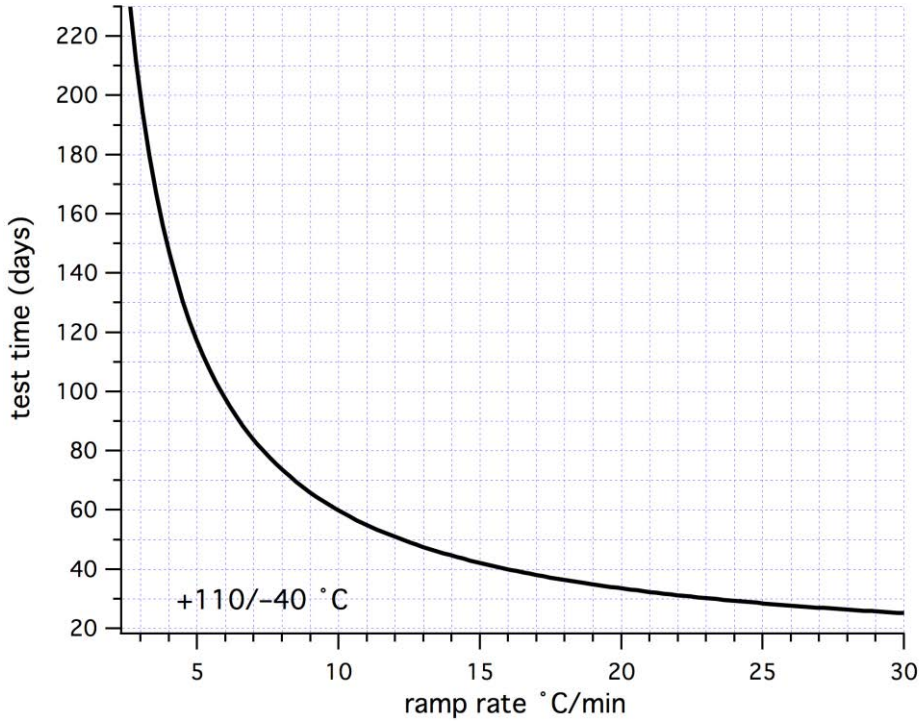
Test Procedure: Thermal Cycling



- Test equivalency is ~5x qualification level
- Number of cycles required depends on *rate*

N. Bosco, T. Silverman, and S. Kurtz, "SIMULATION AND EXPERIMENT OF THERMAL FATIGUE IN THE CPV DIE ATTACH," in International Conference on Concentrating Photovoltaics (CPV-8), Toledo, SP, 2012.

Test Procedure: Thermal Cycling



- Motivation for increasing ramp rate….to a point.

Rating

The rating system is based on the qualification level of testing.

$$rating = N_C \frac{N_R}{5}$$

N_C: number of completed cycles
N_R: number of required cycles, according to Equation (2)

The rating achieved is therefore reported in terms of multiples of the qualification level of thermal cycling.

Report on Activities in QA Task 10: Durability of Junction Box Connectors and Wiring

Juris Kalejs, Task 10 Leader

CTO, American Capital Energy

For more details on Task 10, email jkalejs@americancapitalenergy.com

NREL QA Workshop, February 25-26, 2014, Golden CO

Topics of Presentation

American Capital Energy

- Field experience drivers for durability issues in junction box wiring and connectors
- Survey results from PV community on junction box wiring and connector issues and durability study priorities (about half of approximately 15 participants in Task 10 responded)
- Task 10 future activities

Field Failure Observations at Junction Boxes and Connectors*

Additional connector failures observed after 2-4 years include broken latches and separated connectors

***Reported at NREL PV Module Reliability Workshop February 26-27, 2013, Golden CO**

Results of Survey on Priorities for Junction Box Durability Studies

AMERICAN CAPITAL ENERGY

Task 10. Durability of Junction Box (JB) Connectors and Wiring

Summary of top objectives voted in survey for topic A- manufacturing

Task	Objective	Description	Proposed Action Items
10.1	Junction Box wiring – electrical and mechanical stress testing	Review standards for electrical and mechanical assembly procedures and strategies for junction box manufacturing and propose stress tests to extend them to expose potential failure mechanisms.	1. Review IEC 6252 ed.1.CVD, 60364-7-712, 62548(CD) 2. Review work of Tasks 1-9 for duplication, overlap 3. Define stress parameters for testing 4. Propose experiments to expose critical stress factors causing failures
10.2	Durability parameters for Junction Boxes	Review standards and testing for durability issues for junction boxes and propose durability tests to extend them and expose potential failure mechanisms.	1. Review IEC 62790 ed.1.CVD (JB's), 62852 ed.1.CVD (connectors), IEC 60998, 60999 (terminals). 2. Review work of Tasks 1-9 for duplication, overlap 3. Define durability parameters for testing 4. Propose experiments to expose durability issues
10.3	Junction Box materials	Review durability testing methods for component materials to examine insulation and corrosion properties and propose tests for various JB material constituents.	1. Compile information on available characterization methods or polymer degradation rates, molded material in-process produced stresses, flux corrosiveness, and wiring 2. Define durability parameters for testing 3. Propose experiments to test for durability failures including melt flow rate analysis, chemical stress crack analysis and residual stress.
10.4	Junction Box Wiring terminations	Review manufacturing practices and designs for soldered, resistance welded and pressure contacts and propose tests to uncover end-of-life JB metal corrosion failure modes	1. Develop best practices and designs for soldered, resistance welded and pressure contact formation. 2. Propose tests to uncover JB metal corrosion failure modes induced by pottants, fluxes and humidity. 3. Propose durability tests to reveal end of life failure modes for JB metal joints.
10.5	Junction Box manufacturing	Establish testing protocols and verification methods for manufactured JB component and assembly durability.	Develop testing protocols and verification methods for manufactured JB component and assembly durability.

Example of Task 10 Review Activity for Standards

American Capital Energy

Standards Reference Area (standard development in progress)	Test Area	Current IEC Reliability and UL Scope	Durability Concerns to be Established and Tests to be Developed
Tasks 10.1-10.3 review IEC TC 6252 ed.1.CVD et al - Junction box wiring- electrical and mechanical stress testing	Design, manufacturing strategies	Connector terminations (solder vs pressure vs welding) and wiring	Propose testing to accelerate and extend stressing factors to reveal failures
	Materials	Polymer degradation, molding stresses, flux, corrosion resistance, flammability, dielectric resistance, etc.	Characterization methods, durability factors in material failures in ageing

I would like to acknowledge contributions of Task 10 members from Industry, Universities and National Laboratories

Task 10 Future Activities

- Review of existing standards and application to durability of Junction Box connectors in progress
- Development of tests to extend IEC and UL standards on Junction Boxes to establish durability of wiring and connectors
- Writing of durability testing protocols

I would like to acknowledge contributions of Task 10 members from Industry, Universities and National Laboratories