NREL
NATIONAL RENEWABLE ENERGY LABORATORY



Technical Report
NREL/TP-5200-60171
November 2013

Photovoltaic Module Reliability Workshop 2010

February 18–19, 2010

Technical Monitor: Sarah Kurtz

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

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

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

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

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

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

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

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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.

In 2010, NREL's PVMRW began a new approach by requiring that all participating companies share at least one presentation (either oral or poster). In most cases, participation from each company was limited to two people. These requirements greatly increase information sharing: If everyone shares a little information, everyone takes home a lot of information. This approach was well received by the community and was adopted as a philosophy for future workshops as well.

In 2010, the PVMRW themes included an overview of PV reliability issues, predicting long-term performance of PV products, and ensuring quality to satisfy the investors. The second day of the workshop had parallel sessions for crystalline silicon, CPV, and moisture sensitivity of thin films in the morning and packaging, CPV, and metastabilites of thin films in the afternoon.

In addition to the oral sessions, the participants presented approximately 50 posters on PV reliability topics. Most of the participants shared their presentations for public posting; this document is a compilation of them. The success of the workshop is a direct result of the participants' willingness to share their results. We gratefully recognize the excellent contributions the community has made and thank all of the participants for the time and information they have shared.

The workshop was chaired by Sarah Kurtz with support from:

John Wohlgemuth
Jim Sites
Ian Aeby
David DeGraaff
Ryan Gaston
Mark George
Jennifer Granata
Geoff Kinsey
Peter Hacke
Steve Horne
Kent Whitfield
Peter Hebert
Mark McDonald
Mike McGoey
Nick Bosco
Terry Jester
Robert Messner
Steve Hegedus
Michael Quintana
Akira Terao
Mike Kempe
David Meakin
Kurt Scott
Govindasamy Tamizhmani
Larry Sherwood

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

TABLE OF CONTENTS

OVERVIEW PRESENTATIONS

Opening Remarks and Overview of DOE Solar Program . . . 1

Welcome and Overview . . . 9

PLENARY SESSION I: OVERVIEW OF PV RELIABILITY ISSUE

Weather Durability of PV Modules; Developing a Common Language for Talking about PV Reliability . . . 13

Overview of Failure Mechanisms and PV Qualification Tests . . . 42

Reliability Modeling for Photovoltaic Modules . . . 67

PV Failure Analysis: Techniques for Microelectronics and Solar . . . 90

Adhesion and Thermomechanical Reliability for PV Devices and Modules . . . 118

Electrical, Mechanical, and Thermal Modeling of Photovoltaic Modules . . . 141

PLENARY SESSION II: PREDICTING LONG-TERM PERFORMANCE OF PV PRODUCTS

Presentation and discussion summary . . . 191

Statistical Lifetime Predictions for PV Modules . . . 194

Beyond Qualification: Testing for Long-Term PV Module Durability . . . 216

Test-to-Failure for Long-Term Performance Assessment . . . 232

Designing for Reliability: Thin-Film Building Integrated Photovoltaic Modules . . . 257

Quantifying the Weather: An Analysis for Thermal Fatigue . . . 272

PLENARY SESSION III: ENSURING QUALITY TO SATISFY THE INVESTORS

What Demonstration of Reliability is Needed Before Investment? . . . 292

Consensus Guidelines for Quality Assurance and Their Role as a Foundation for Lifetime Prediction . . . 298

Case Study: SunPower Manufacturing Quality Methods . . . 309

SILICON ISSUES SESSION

Presentation and discussion summary 328
Failure Modes of Crystalline Si Modules 347
Experience with Qualification and Safety Testing of PV Modules 380
Degradation Rates 396
Decades in the Installed Environment—Do Silicon Modules Really Last More than 20 Years? 429

CONCENTRATING PV ISSUES SESSION I

Presentation and discussion summary 471
Solar Resources for Concentrating PV (CPV) 480
Spectral Effects in CPV Performance - NREL Test and Evaluation 500
Failure Modes of CPV Modules and How to Test for Them 511
Thermal and Current Cycling for CPV Qualification 606

CONCENTRATING PV ISSUES SESSION II

Presentation and discussion summary 625
Durability of Optical Materials 631
Durability of Poly(Methyl Methacrylate) Lenses Used in Concentrated Photovoltaics 646
Questions about IEC 62108 Implementation 666

MOISTURE SENSITIVITY OF THIN FILMS ISSUES SESSION

Presentation and discussion summary 680
Common Failure Modes for Thin-Film Modules and Considerations Toward Hardening CIGS Cells to Moisture 691
Packaging Requirements for ITO-Hardened CIGS 709
Methods for Measuring Moisture Ingress 731
Approaches to Barrier Coatings for the Prevention of Water Vapor Ingress 756

PACKAGING ISSUES SESSION

Presentation and discussion summary 786
Types of Encapsulant Materials and Physical Differences Between Them 795
Safety Concerns with New PV Polymeric Materials 811

Why Glass Sometimes Breaks . . . 832

THIN-FILM METASTABILITIES ISSUES SESSION

Presentation and discussion summary . . . 881
Metastability of Amorphous Silicon – Historical Perspective and Real-Life Performance . . . 886
Metastable Effects in Polycrystalline Thin Film Cells and Correlations with Performance and Durability . . . 923
Comparison of Injection of Carriers Through Light Soaking and Forward Bias in Dark . . . 939

POSTER SESSION

Complete listing of posters . . . 953

CONCENTRATING PHOTOVOLTAICS

Characterization of an Aggregated Total Internal Reflection Optic . . . 957
Solar Radiation Resource Tools and Data Sources . . . 958
Design Verification Testing . . . 959
Durability of Thermally Cycled ELO Solar Cells . . . 970
Ensuring and Predicting the Reliability of CPV: Interconnect Structures . . . 971
Mechanically Induced Microfractures . . . 987
Reliability Considerations for a 7kW Incident CPV Monolithic Concentrator Module . . . 988
Reliability through Field Testing in Real World Conditions . . . 1004
Spectral Dependence of CPV Current Generation in the San Gabriel Valley . . . 1005
Reliability and Qualification of Amonix Solar Power Plants . . . 1017
Thermal Runaway Failures of CPV Solar Cells . . . 1024

PACKAGING

Benefits of a Desiccated Edge Seal in TFPV . . . 1037
Comparative Performance and Reliability of Backsheets for PV Modules . . . 1038
Molecular Bond Rupture Kinetics in Organic PV Transparent Barriers . . . 1039
Lessons Learned Regarding Failure Modes of Glass/Glass Modules in the Field . . . 1040
Relation of Wet Leakage Resistance with Module Front Glass Resistivity . . . 1041
Solar Edge Sealants with a Better Balance of Properties . . . 1055

The Reliability and Durability of Novel Silicone Materials for PV Encapsulation. . . . 1056

TESTED METHODOLOGIES

Accelerated Electro-Chemical Delamination Test for the Durability of Transparent Conductive Oxide (TCO) Glass . . . 1057
Analysis of CPV Optical Components Using an Light Beam Induced Current System . . . 1058
An Approach Towards Light and Heat Management in PV Modules . . . 1059
Characterization and Reliability of Polymeric Components in PV Modules . . . 1060
Comparative Study of the Long-Term Performance of Three PV Systems Installed in Florida . . . 1073
Displacement Test Protocol Considerations . . . 1074
Extended Life Testing of Multi-Crystalline Silicon PV Modules . . . 1086
Faster and Adaptable Accelerated Solar PV/Thermal Durability Testing Solution . . . 1095
High Volume Light Soaking and UV Testing of Photovoltaic Modules . . . 1096
Impedance Measurement as a Diagnostic Tool for Device Degradation . . . 1097
OPV Lifetime Testing. . . . 1117
Pulsed Valve Mass Spectrometry Film Permeation Tool . . . 1127
PV Module Reliability and Durability Studies at the FSEC PV Materials Lab . . . 1128
Comprehensive PV Durability Testing. . . . 1129
PV Standards. What Does the IEC Have for You? . . . 1138
Recommended Protocol for Accelerated Aging Testing: A Literature Review for Protocol Development . . . 1148
Sandia's PV Reliability Program . . . 1149
Short- and Long-Term Spectral Stability over the Life of Tool . . . 1150
Solar Logistics Testing . . . 1151
Split-Plot Design: Characterizing 10 Factors in "12" Runs . . . 1152
Thermalreflectance Imaging for High Resolution Defect Inspection Through Glass . . . 1153

THIN-FILM PV

A Single Layer Thin-Film Moisture Barrier for CIGS Solar Cells . . . 1154
CIGS Cell-Level Reliability Task and Studies at NREL. . . . 1155
Cohesion and Phase Separation in Organic PV Heterojunction Layers . . . 1156

Effects of Various Module Preconditioning Procedures on CdTe Pmax Measurements 1157
Electrically Conductive Adhesive Reliability in Thin Film Photovoltaic Modules..... 1167
Frozen Light Soak Test: Simulating the Dawn Effect..... 1168
Reliability of CIGS Modules 1169
Thin Specialty Glass for Reliable Thin Film PV Modules..... 1177



Solar Energy Technologies Program

PV Module Reliability Workshop

Golden, CO | February 18, 2010

Kevin Lynn
Acting Team Lead for Systems Integration
Solar Energy Technologies Program
U.S. Department of Energy

Solar Program Sub Elements



Photovoltaics (PV)

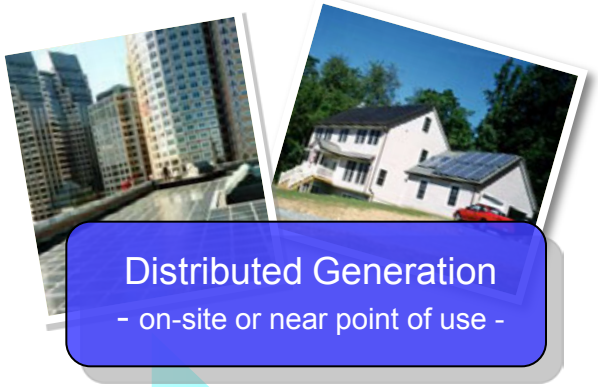
DOE SETP



Concentrating Solar Power (CSP)



Market Transformation System Integration



Distributed Generation
- on-site or near point of use -



Centralized Generation
- large users or utilities -

SETP Sub-Program Focus

Photovoltaics

R&D across a broad range of technologies to increase efficiency and reduce system cost

- Wafer Silicon
- CIGS
- CdTe
- III-V/CPV
- OPV/DSSC
- Intermediate Band-Gap
- Nano PV
- Multi-Exciton

Concentrated Solar Power

R&D across major CSP system technologies to reduce system cost and support of key demonstration activities

- Troughs
- Power Tower
- Stirling Dish
- Thermal Storage

Cost Reduction → *Goal: Grid Parity*

Remove System and Market Barriers → *Goal: High Penetration*

System Integration

Address grid and other barriers required for large scale penetration

- Inverter Development
- High Penetration Demonstration
- System Modeling and Analysis
- Codes and Standards
- **Test and Evaluation**
- Measurement and Characterization

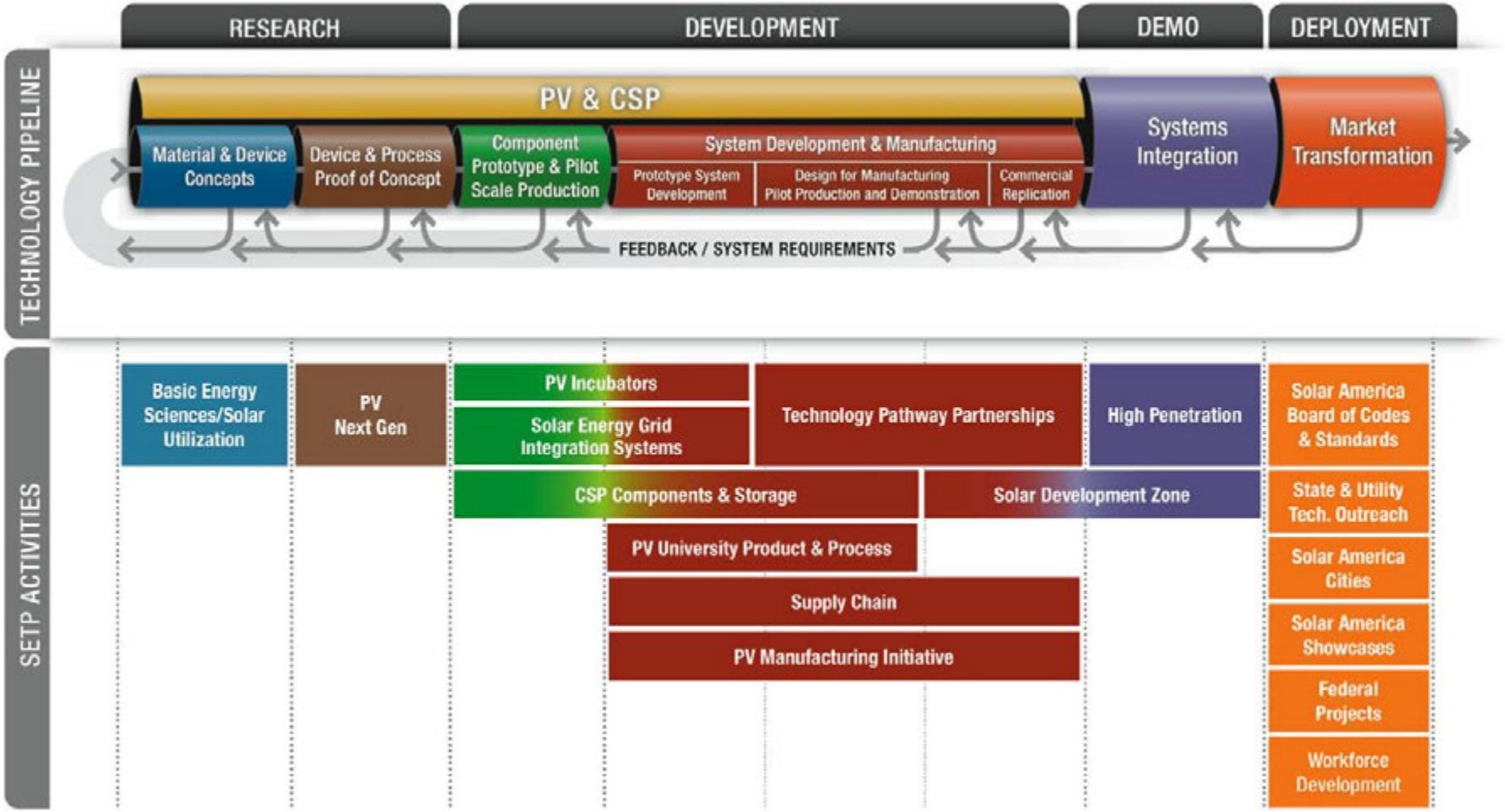
Market Transformation

Address key industry issues through dedicated initiatives, outreach and stakeholders

- Utilities
- State Government
- Solar America Cities
- High profile demonstrations
- Workforce Development

SETP Programs Cover All Parts of the RDD&D Pipeline

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Commercial PV: LCOE Targets

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

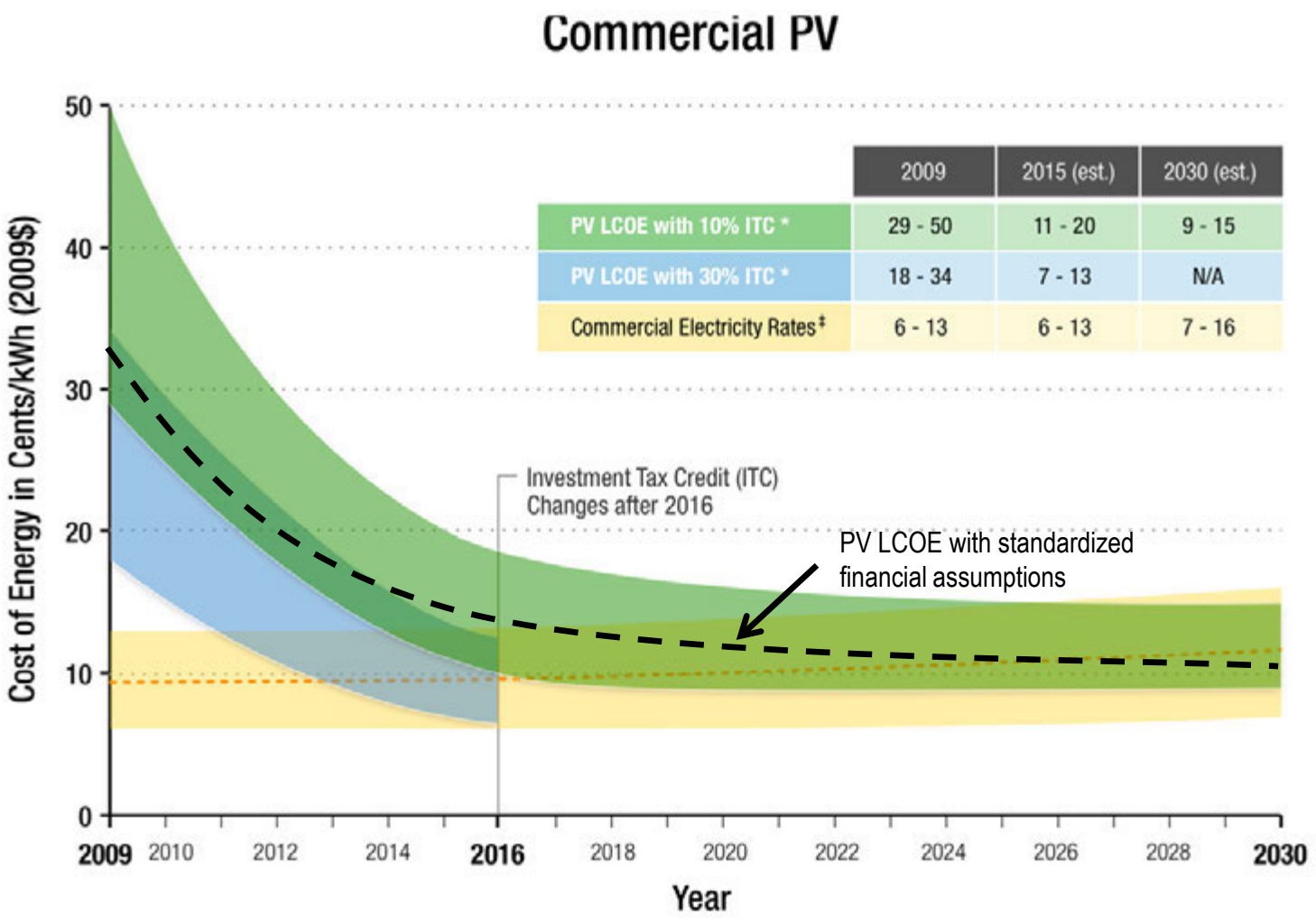
2015

- With the 30% ITC, PV is broadly competitive with commercial electricity rates.
- With the 10% ITC, PV is competitive with high electricity rates under the best insolation and financing conditions

2030

- With the 10% ITC, PV is broadly competitive under all financing, insolation and orientation conditions.

- **Standard financial assumptions yield LCOE estimates that are within the program's range of estimates due to similar cost of capital and mix of tax and financing period effects.**

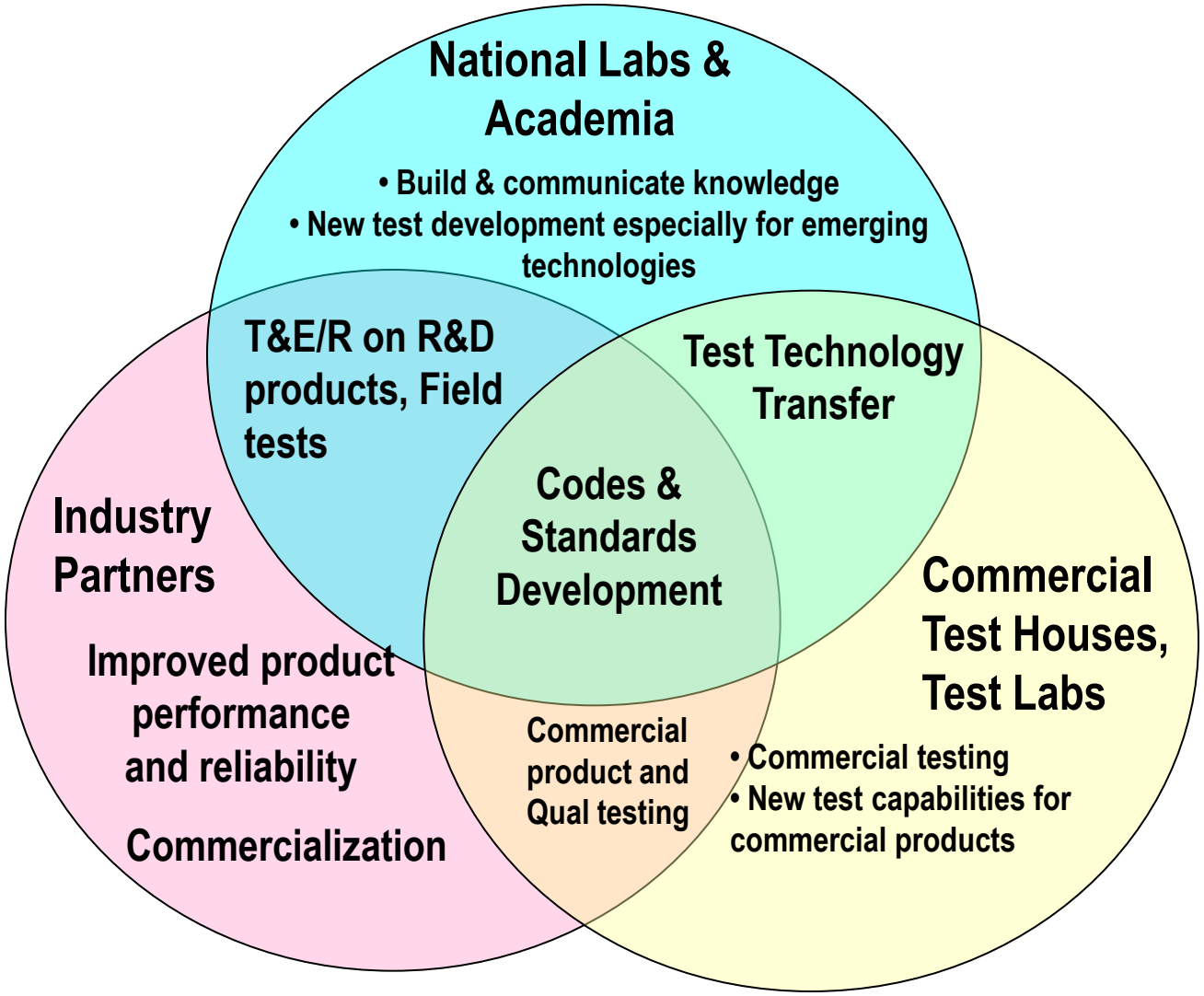


	2009	2015 (est.)	2030 (est.)
PV LCOE with 10% ITC *	29 - 50	11 - 20	9 - 15
PV LCOE with 30% ITC *	18 - 34	7 - 13	N/A
Commercial Electricity Rates‡	6 - 13	6 - 13	7 - 16

* Assumes third-party ownership of PV, and thus the LCOE includes the taxes paid on electricity generated. Includes 5-year MACRS but not state, local or utility incentives. The range in commercial PV LCOE is due to different insolation, financing and orientation conditions. For a complete list of assumptions, see DOE Solar Cost Targets (2009 – 2030), in process.

‡ The electricity rate range represents one standard deviation below and above the mean U.S. commercial electricity prices.

Testing, Evaluation and Reliability



Thank You

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

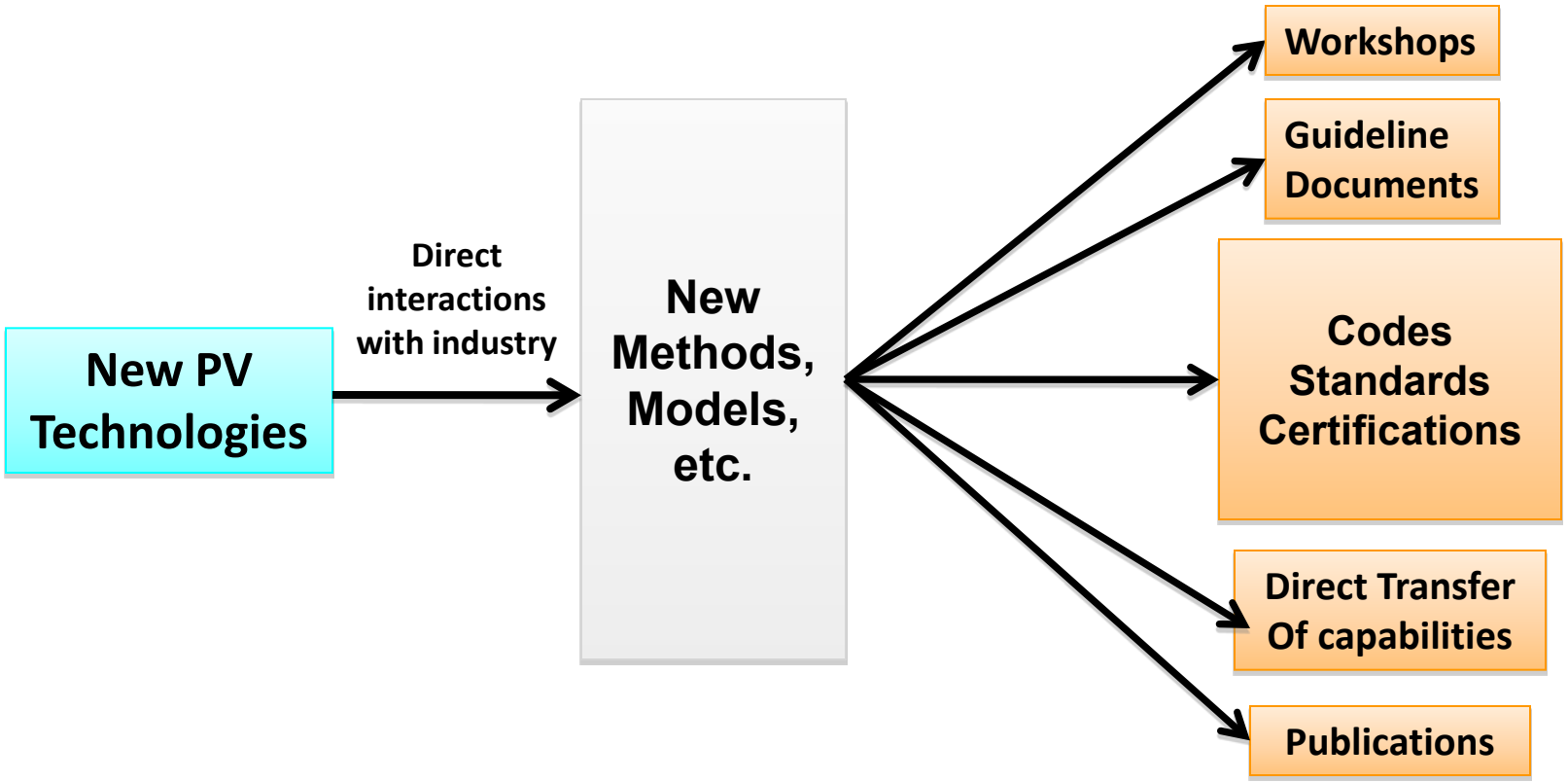


Kevin Lynn
Acting Lead for Systems Integration
Solar Energy Technologies Program
U.S. Department of Energy

Kevin.Lynn@ee.doe.gov

www.solar.energy.gov

Test, Evaluation, and Reliability





PV Module Reliability Workshop

Feb. 18-19, 2010

Welcome!

Why have this workshop?

- Value of reliability:
  - Confidence from investors
  - Lower electricity cost
- Predicting the future is dangerous, unless you have good information
- Sharing information can get us there faster
  - Confidentiality issues pertain more to how to pass the test than to how to design the test
  - If ALL companies share, then everyone benefits
  - Nuclear and fossil fuels are the primary competition

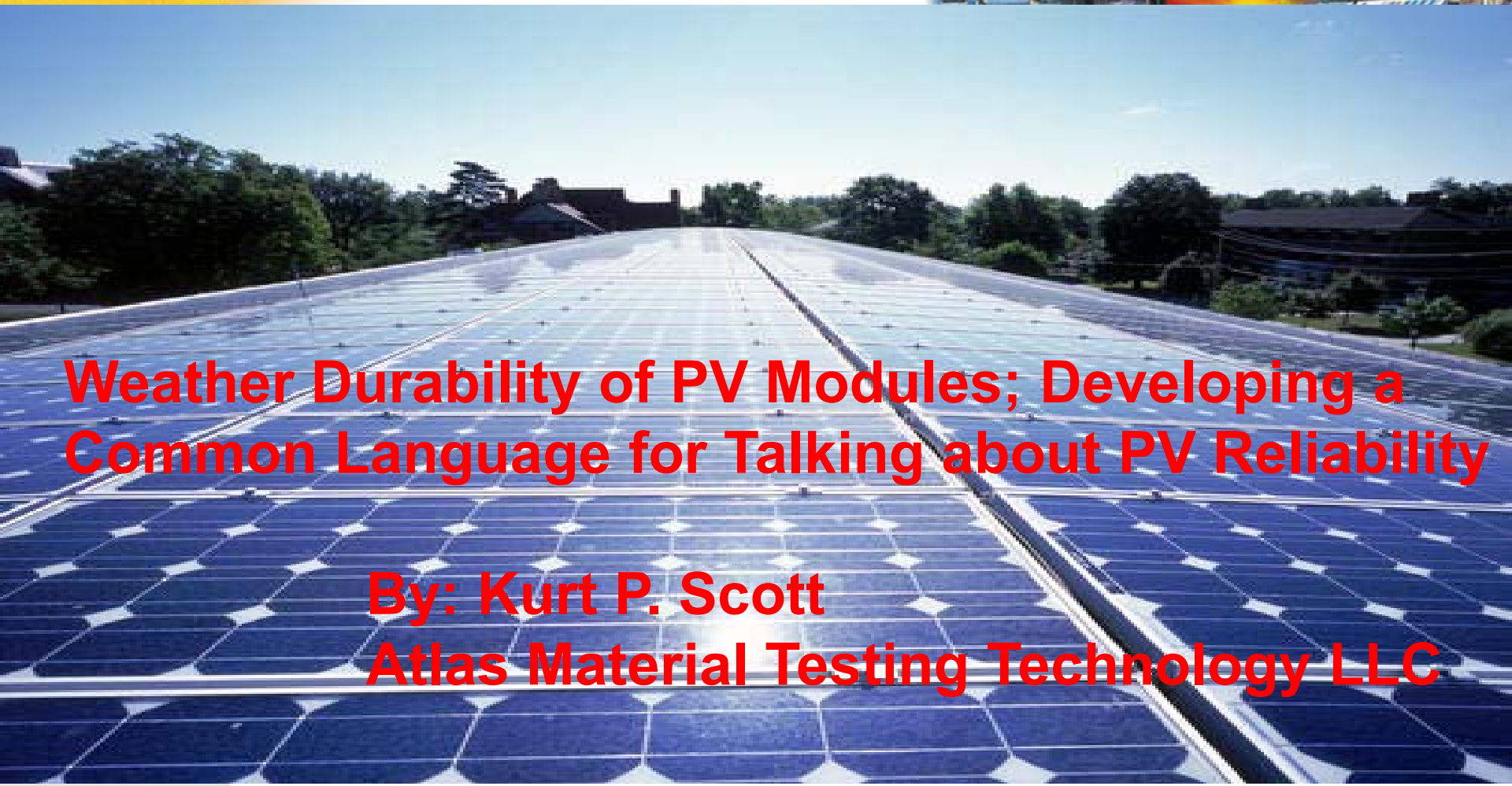
What's different about this workshop?

- Sponsored by the Department of Energy; organized by NREL/SNL
- Only invited talks – designed to give overview and focus on latest results
- Contributed posters
- Every company expected to contribute something

Please join me in thanking many

- Presenters, both oral and poster
- Planning:
  - J. Wohlgemuth, J. Sites, I. Aeby, R. Gaston, G. Kinsey, M. George, Mani, K. Scott, P. Hacke, S. Horne, K. Whitfield, D. DeGraaff, P. Hebert, A. Terao, M. Kempe, D. Meakin, J. Granata, M. Quintana, M. McDonald, M. McGoey, N. Bosco, T. Jester, R. Messner, S. Hegedus, L. Sherwood
- Logistics:
  - D. Glickson, I. Thornton, S. Moon, S. Padilla
  - A. Stokes, S. Glick, R. Sundaramoorthy, K. Emery, D. Jordan, B. Marion, J. Pankow, R. Smith, J. Pern, R. Noufi, D. Levi, D. Miller, D. Albin, H. Ullal, M. Steiner, M. Al-Jassim, C. Deline, K. VanSant, T. James

PV Durability and Reliability



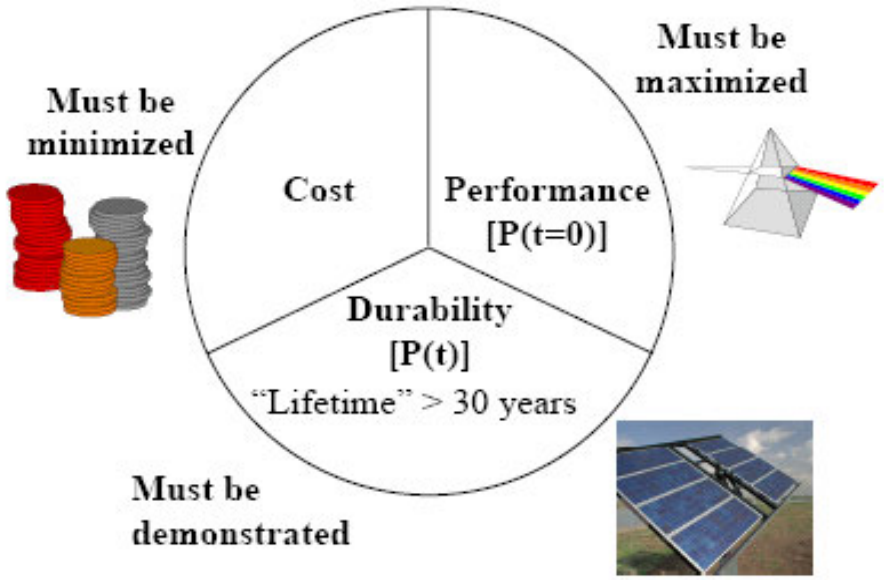
Weather Durability of PV Modules; Developing a Common Language for Talking about PV Reliability

By: Kurt P. Scott
Atlas Material Testing Technology LLC

ATLAS
MATERIAL TESTING SOLUTIONS

PV Today ……

Competing imperatives



(25) Accelerated Life Testing and Service Lifetime Prediction for PV Technologies in the Twenty-First Century. NREL, A.W. Czanderna and G.J. Jorgensen

Summary points:

- The major problem in solar energy technologies is **not** discovering how to collect the radiant flux, but how to collect it in a **cost competitive** way with conventional power generation.
- Service Lifetime Prediction (**SLP**) estimates of the photovoltaic devices **will determine** the life-cycle **costs**.
- The **cost-effective deployment** of any PV device is limited by the **durability** and life-cycle cost of the materials used.

Bankability - Durability Impact



PV bankability - a function of durability

- Common calculation of PV costs = (upfront $ – incentives)
  - Durability often overlooked
  - Factoring in.5%/yr degradation may not be adequate – does not include catastrophic failure
- Internal rate of return (IRR) is sensitive to module degradation rate
- Because module degradation has a substantial impact on utility IRR – it should be of critical concern to investors.

ATLAS
MATERIAL TESTING SOLUTIONS

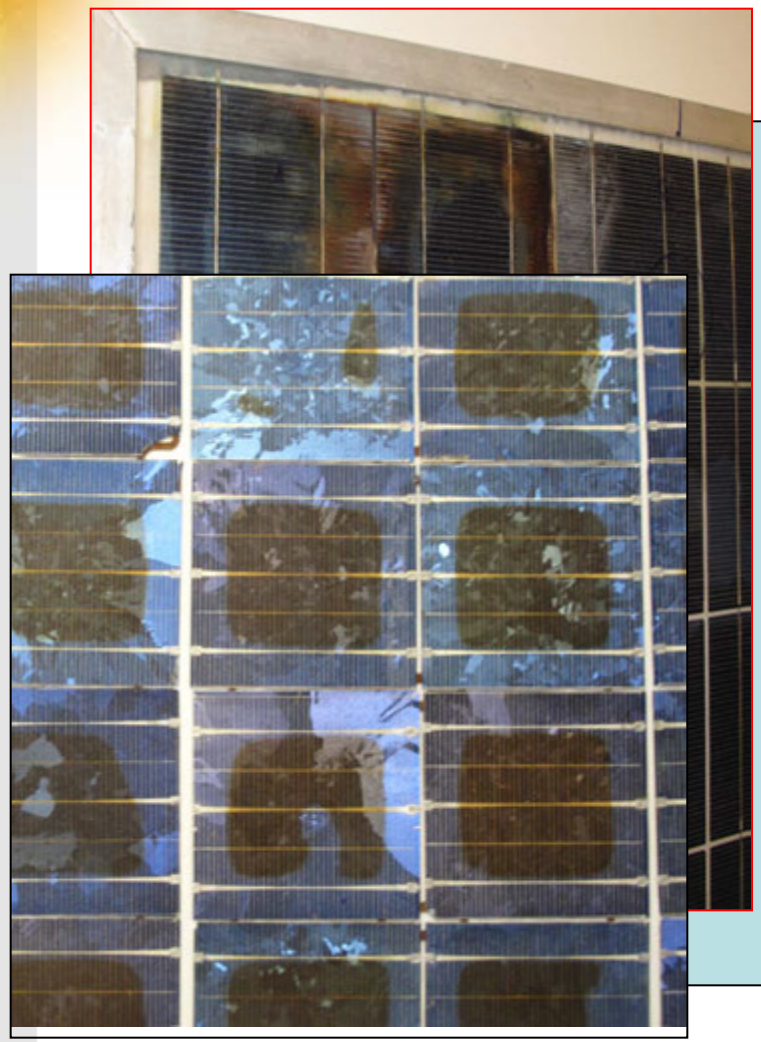
Bankability- Reliability Impact



- PV bankability - a function of reliability
  - Cost of reliability significant to module suppliers
  - Module manufacturers need to set aside a portion of revenue to service warrantees
    - Based on expected failure rates - but in today's world – varies tremendously
    - In these early days of commercialism – manufacturers buying market, liberally replace sub-par modules
  - True warranty costs are not being tracked
  - Threatens profitability

ATLAS
MATERIAL TESTING SOLUTIONS

Significance of Durability & Reliability



The PV “triumvirate”

- Safety
- Performance
- Reliability

Durability impacts all

ATLAS
MATERIAL TESTING SOLUTIONS

Reliability



- **Reliability -** many definitions, but in a broad sense it is the measure of unanticipated interruptions during intended use of a product (or service)
- Reliability & Quality not synonymous
- Reliability is an engineering discipline that should be applied throughout all stages of development and maintenance of the product in its service life

http://www.wired.com/science/planetearth/multimedia/2005/11/69528?slide=3&slideView=3

ATLAS MATERIAL TESTING SOLUTIONS

Reliability



- **MIL-STD-721C and MIL-HDBK-338 have two definitions of for reliability:**
- **The duration or probability of failure-free performance under stated conditions**
- **The probability that an item can perform its intended function for a specified interval under stated conditions**
- ***Notes:*** *For non-redundant items both definitions are equivalent*



when there is redundancy *the second definition is equivalent to definition of mission reliability*

Special case: *Reliability (the absence of failures which defines the probability of the failure-free interval) is often confused with availability (% up time). In redundant systems availability ≠ reliability*

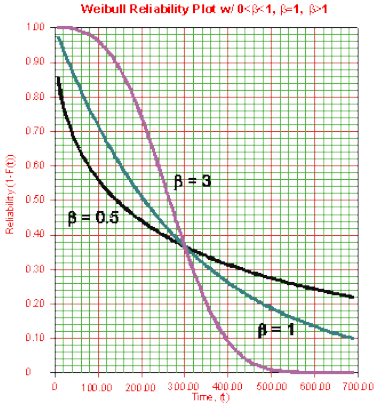
ATLAS
MATERIAL TESTING SOLUTIONS

Reliability



- **Reliability Measurement**
  - Failure rates
  - Cumulative failures
  - Component lifetimes (time until failure or between failures)
  - Estimates of product lifetimes
- Techniques drawn mainly from probability statistics, and the theory of stochastic processes.
- Typically, production units are used and large sample populations are required for statistical purposes.



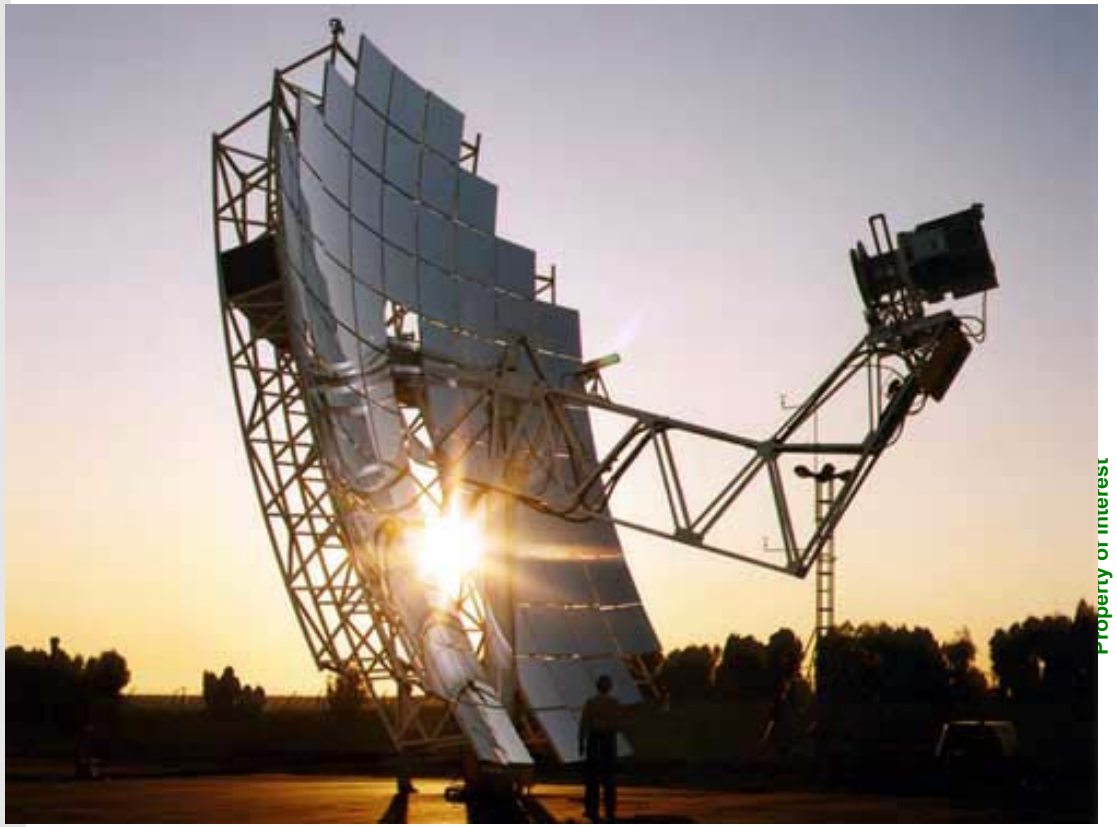


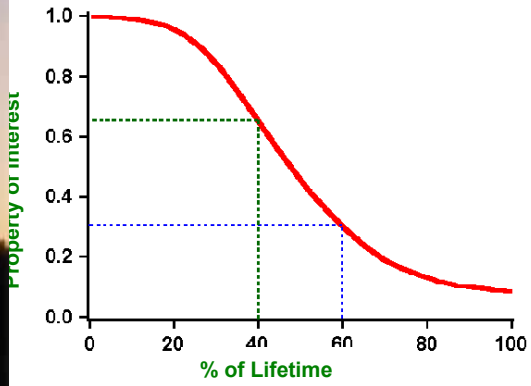
ATLAS
MATERIAL TESTING SOLUTIONS

Durability



- **Durability -**
  Loss of requisite or desirable properties……





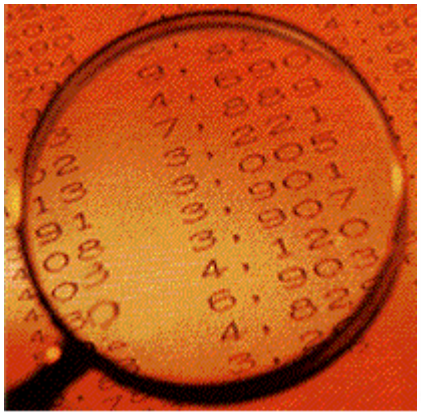
http://www.wired.com/science/planetearth/multimedia/2005/11/69528?slide=3&slideView=3

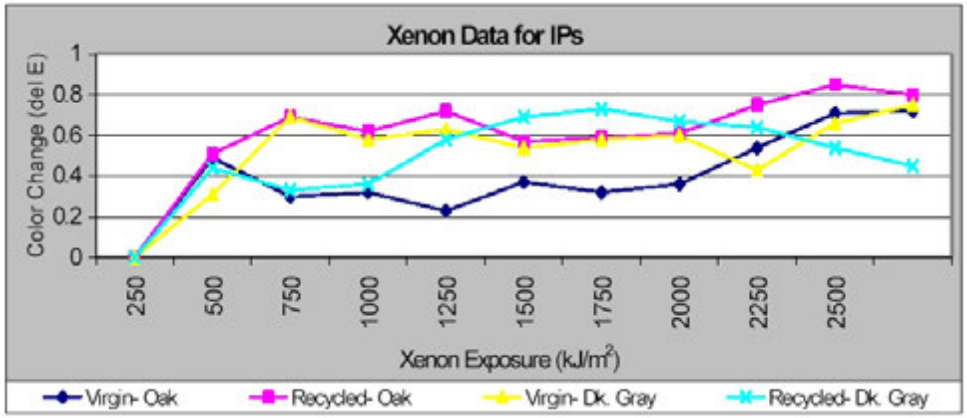
ATLAS
MATERIAL TESTING SOLUTIONS

Durability



- **Durability Measurements**
  - include changes to - chemical, physical or appearance properties,
  - loss of performance
  - Rate of property change with time or stress,
  - Time to unacceptable change, etc.
  - (Note - *the PV industry tends to define these as reliability attributes, when in fact, they are durability issues that may, or may not, actually affect reliability*)





ATLAS
MATERIAL TESTING SOLUTIONS

PV Durability





PV Module Durability = Primarily Weather-durability (weatherability)

ASTM G113 durability, *n*—in weathering, a measure of the retention of original condition and function of a material after exposure to a specified set of (weather) conditions.

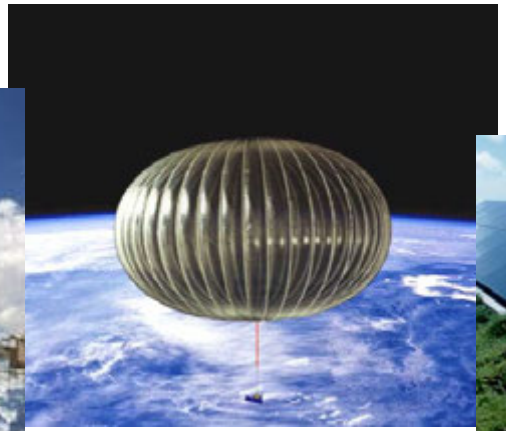
Not: UV test, UV conditioning, Conditioning, or any of those other terms typically used in PV testing community

ATLAS
MATERIAL TESTING SOLUTIONS

Environmental Durability

- **Environmental Durability** – (***Weatherability***, or the resistance to ***weather stresses) special discipline within the larger context of durability***
  - The specific ability of a material, component or product to resist degradation caused by stresses of the service environment(s).
- For PV, “environment” may include extra-terrestrial or terrestrial outdoor exposure







ATLAS
MATERIAL TESTING SOLUTIONS

Durability Tests - examples



- Temperature cycling
- Thermal shock testing
- Freeze/Thaw cycling
  Altitude testing
- Humidity testing
- Temperature/Humidity cycling
- Solar radiation testing
- Rain testing
- Immersion testing
- Icing/Freezing rain testing
- Fungus testing
- Salt fog testing
- Sand and Dust testing
- Vibration”

  - Many others – standard, or as appropriate for application







ATLAS
MATERIAL TESTING SOLUTIONS

Durability Test Categories



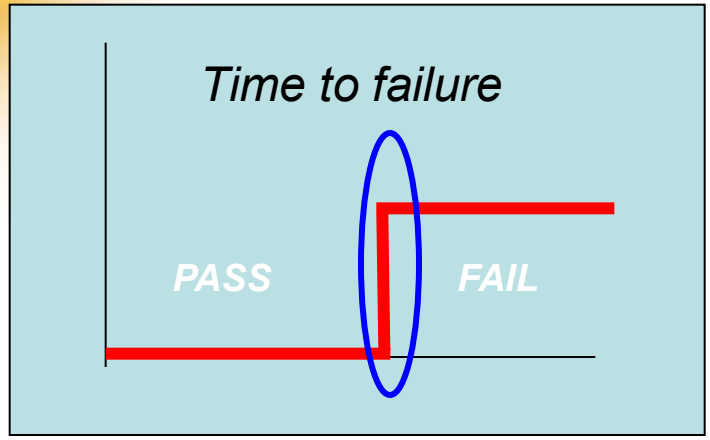
- **Qualitative Accelerated Life Tests -** used primarily to reveal probable failure modes - some examples include:
  - ALT – Accelerated Life Tests
  - HALT – Highly Accelerated Life Tests (product robustness)
  - ESS – Environmental Stress Screening
  - HASS – Highly Accelerated Stress Screening (infant mortality)
  - HAST – Highly Accelerated Stress Test
  - CALT – Calibrated Accelerated Life Tests (General Motors method)

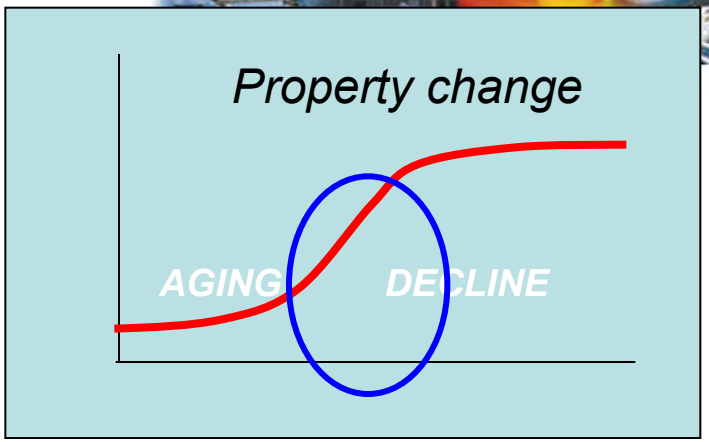
The exact definition and implementation of these tests may vary with specific industry practices



ATLAS
MATERIAL TESTING SOLUTIONS

Reliability vs. Durability



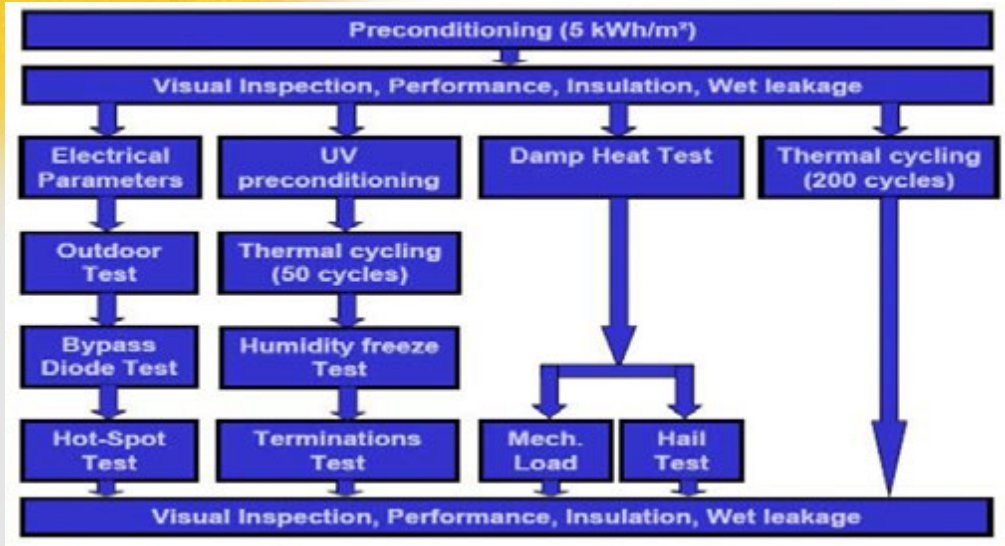


Reliability ***Durability***

- In very general terms, **reliability** analysis is concerned with measuring discrete, **absolute failures**
- **Durability** involves the **route to failures** (mechanisms), the property **rate of change** (kinetics), degree of **robustness,** etc. *These may not cause failure but result in declining performance and shortened service lifetimes.*

ATLAS
MATERIAL TESTING SOLUTIONS

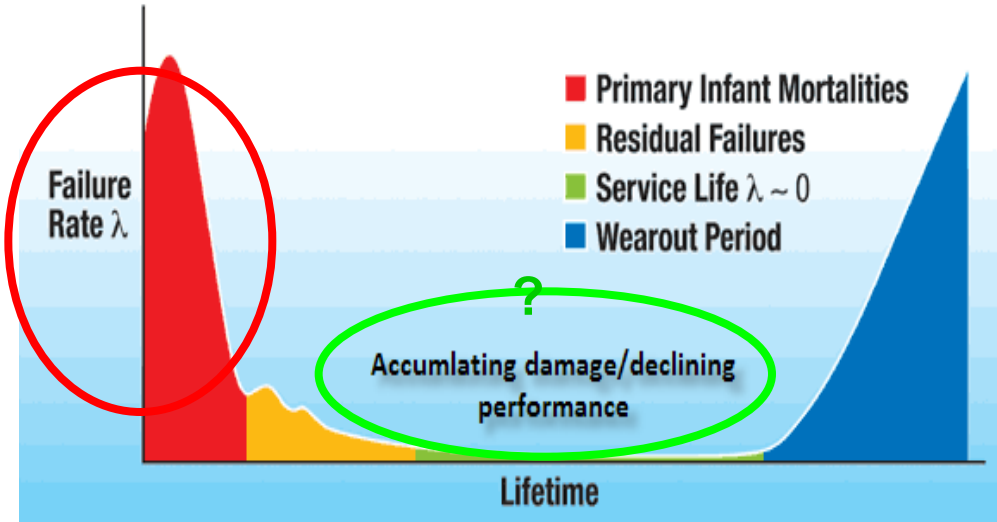
Reliability & Durability Testing



IEC design type qualification tests

IEC 61215 environmental tests

IEC 61646 environmental tests are similar



Qualification Test Objective



- To rapidly detect presence of failure or degradation modes -
  - "That may adversely affect ability of the tested item to serve its intended function in the intended environment"
- Most common use
  - "To verify durability of the final product before mass production is initiated" Serve valuable need in design, development and process control phase of product generation"
- "In the development testing phase,
  - required to provide rapid feedback of the relative strengths and suitability of design alternatives"
- "In process control applications
  - used to in indicate out of tolerance materials or processes"

Qualification Test Issues



- Therefore, “Qual” tests intended to:
  - To identify design and material flaws
  - Rank relative performance – materials, designs & processes
- But - difficult to equate qualification test results and field experience
- Not adequate to predict life-time of modules
- SLP tests –
  - More elaborate & extensive
  - Require expertise in testing and reliability analysis
  - Provide quantitative information

ATLAS
MATERIAL TESTING SOLUTIONS

Solar ABCS



- Accelerated test standard proposal.
  - Objective - Recommend protocol for accelerated aging test
  - Will be offered to one of the standards writing bodies for adoption.
  - Three approaches anticipated
    - Accelerated Qualification – minimum requirement for module to be introduced into market
    - Comparative testing – compare performance of different designs – your own, or competition.
    - Accelerated lifetime testing – Goal to predict life time with high level of confidence
      - **requires more time – more expensive needs good understanding of failure modes and of models.**

ATLAS
MATERIAL TESTING SOLUTIONS

IEC TC 82 Update



• New work item proposed for PV module back-sheet qualification and specification testing

- Based on work done by 15-company European consortium
- Premise\philosophy based on testing and qualification of individual materials, rather than complete cells and modules
-Perceived advantage of this approach – “Won’t need to do 18 months of RTI, but will still require re-test option”

- “Materials” group established

- Big motivation - Complement\ Alternative to RTI

ATLAS
MATERIAL TESTING SOLUTIONS

IEC Update Cont.



- Materials to be tested:-
  - **Backs-sheet, Encapsulant (transparent/opaque), Front-sheets**
  - Edge sealants, Junction box, adhesives, polymeric frames.
  - (Given the enormous effort that this would entail, only those in bold will be tackled in first round)

- Accelerated tests to be performed:-
  -UV (weather- durability & preconditioning), Damp-Heat, Thermal, Chemical, Electrical stress, Flammability, Mechanical Stress

- Properties to be used as pass\fail Criteria:-
  - Flammability – spread of flame, glow wire, ignition temp
  - Mechanical - Tensile, Impact, modulus
  - Electrical – Dielectric CTI, Partial discharge resistivity
  - Optical - transmission, reflection, color change
  - water vapor permeability.

ATLAS
MATERIAL TESTING SOLUTIONS

ASTM E 44 Update – *November, 09*



- New std for durability and reliability of modules
  - Specifically, answering Solar ABCS
  - ASTM work item WK25362
- Approved scope -
- 1.1. This practice describes recommended procedures for conducting accelerated life testing of photovoltaic (PV) modules.
- 1.2. This practice applies to PV modules intended for residential and commercial and utility scale solar power generation.
- 1.3. This practice describes procedures for accelerating the failure mechanisms of PV modules caused by mechanical, electric, and environmental stresses.
- 1.4. The procedures for evaluating the effects of applied stresses on the performance of PV modules in order to predict their reliability under in-use conditions.

ATLAS
MATERIAL TESTING SOLUTIONS

ASTM E 44 – Cont.



- New subcommittee E44.20 on glass for solar Applications - organized 09/29/09
  - Developed standards will address the characteristics that affect performance, durability and reliability
- Initial task - E 1596
  - Old, dormant PV module weathering standard
  - Updated by Atlas – balloted
  - Considered interim and something for other stds to reference until new standards complete
    - For example, ballot of the new Standard Practice for the Installation of Building Applied PV (WK 21327)

ATLAS
MATERIAL TESTING SOLUTIONS

Testing for Durability & reliability



- Development of consensus standards
  - Long process
  - Inclusive of lowest common denominator
    - Compromised value?
- Good reliability testing requires a significant long-term investment
- Expertise is required for test design and proper interpretation of test results

ATLAS
MATERIAL TESTING SOLUTIONS

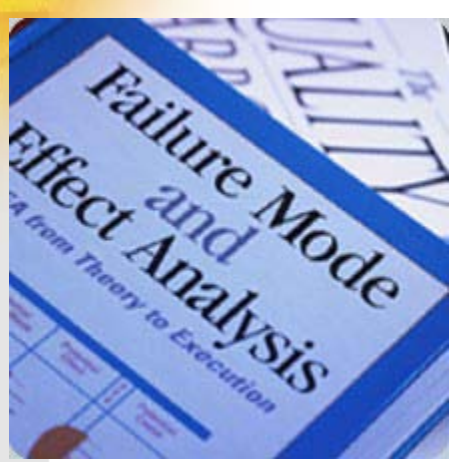
Testing for Durability & Reliability

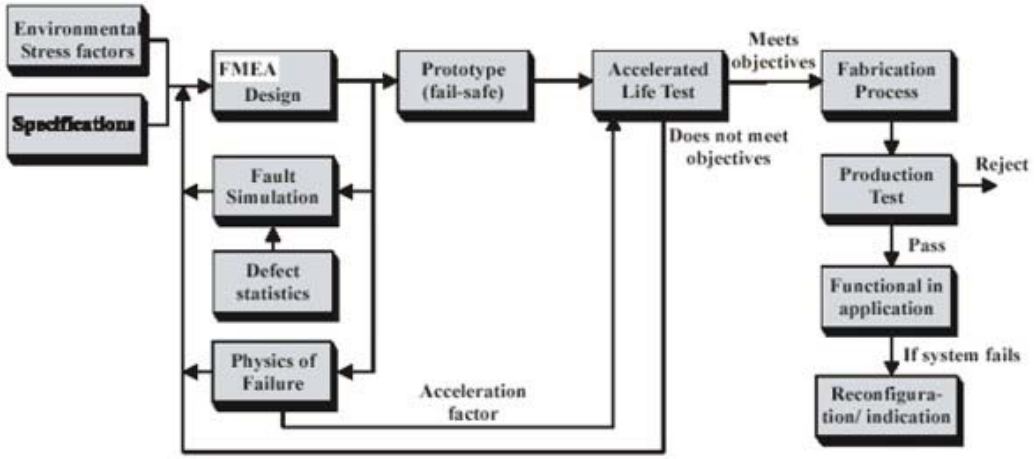


- Alternate methods
  - Utilize:
    - FMEA, Experience, Knowledge
    - Cumulative damage models
    - Results may never have better than “good estimates” (defensible)

ATLAS
MATERIAL TESTING SOLUTIONS

FMEA / FMECA

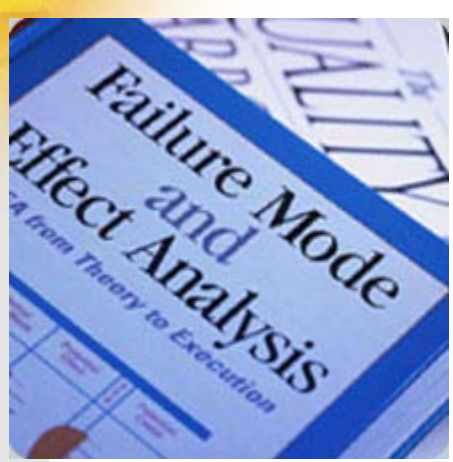


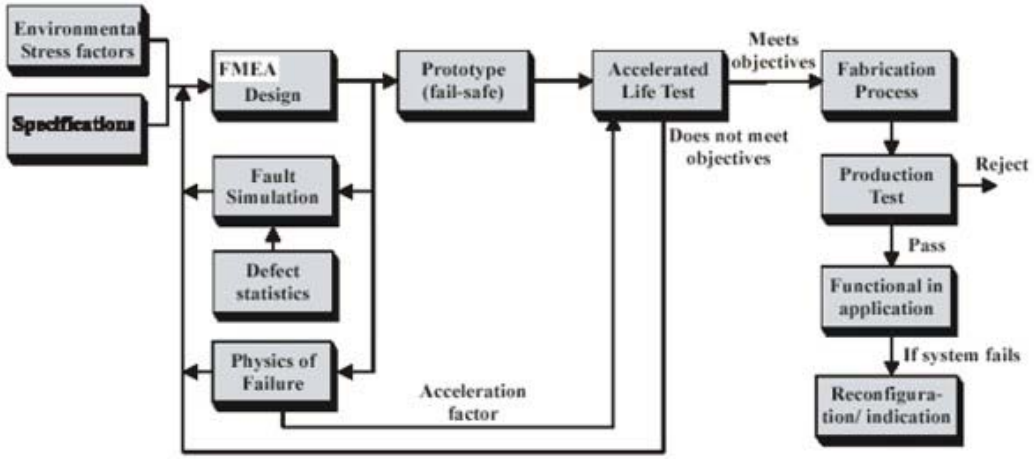


- The *d*FMEA is useful as a basis for establishing a bottom-up "materials" *m*FMEA which focuses on the role specific material chemistries play.
- Useful for planning environmental durability tests
- Determining the suitability of test methods for specific material chemistries
- interpreting the test results.

ATLAS
MATERIAL TESTING SOLUTIONS

FMEA / FMECA



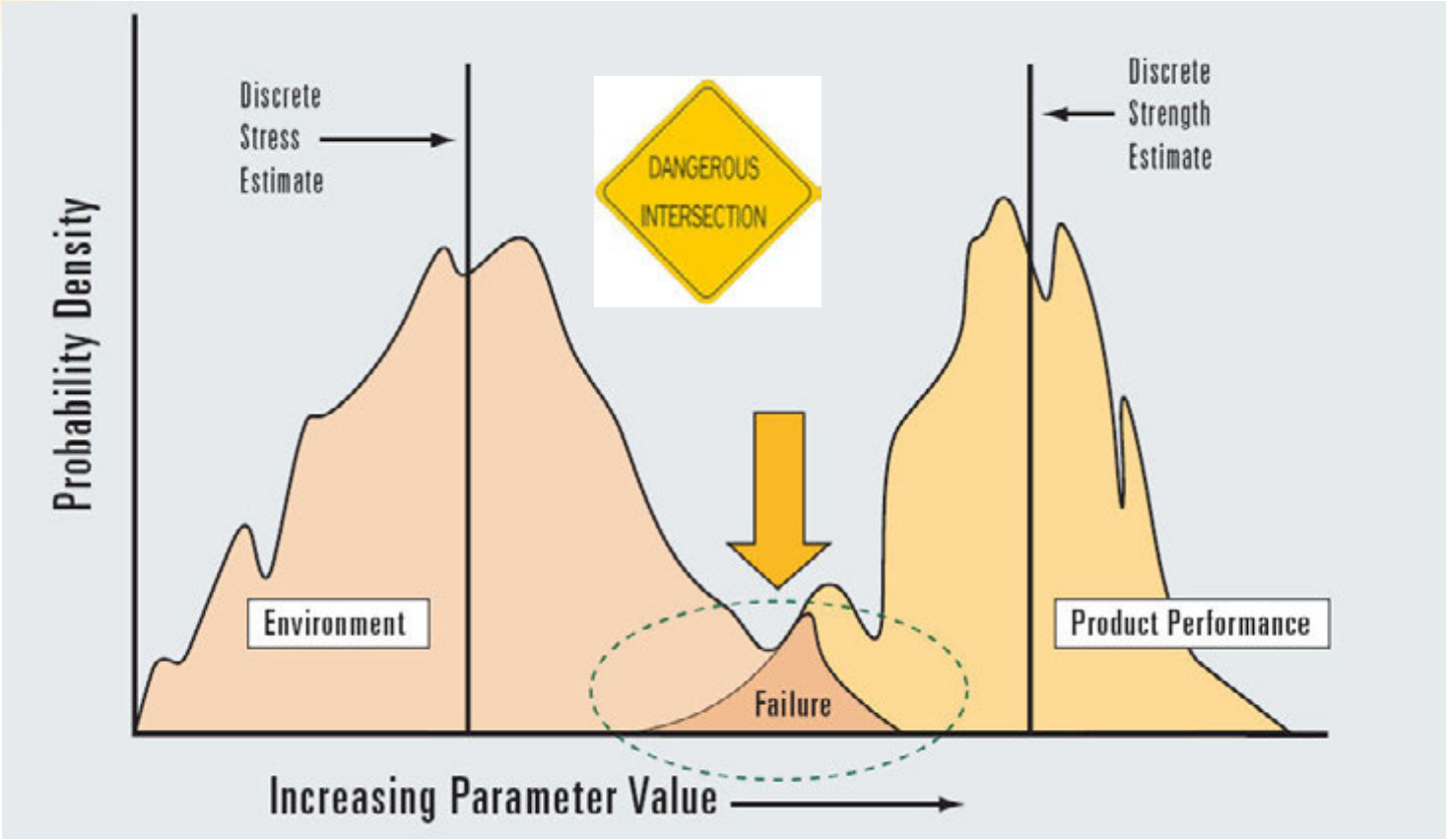


- The *d*FMEA can be a useful tool for deciding which durability test types and specific test conditions are appropriate.

ATLAS
MATERIAL TESTING SOLUTIONS

Design for Reliability/Durability





ATLAS
MATERIAL TESTING SOLUTIONS

Durability & Reliability – wrap up



- Especially as we become more involved in the current flurry of activity to develop PV standards….
- Mind your D's, R's & W's – let's make sure we can understand one another across technologies, disciplines & industries

Thank you!

ATLAS
MATERIAL TESTING SOLUTIONS



bp solar

Overview of Failure Mechanisms and PV Qualification Tests

John Wohlgemuth

Introduction

- Development of a reliable PV module requires an understanding of potential failure mechanisms.
- The most straightforward way to determine these failure mechanisms is to observe them in the field.
- We can't wait 20 or 25 years to see what failure mechanisms a module type might suffer from nor to get an estimate of lifetime or degradation rate.
- Therefore we try to develop stress tests that accelerate the same failure mechanisms.
- So I am going to take you on a short review of history of PV module failure mechanisms and how this information was utilized to develop accelerated stress tests and ultimately the qualification tests that we have all come to love and hate.

History of Field Failures
(Remember all of the early modules were crystalline Si)

- Broken interconnects
- Broken cells
- Corrosion
- Delamination and/or loss of elastomeric properties
- Encapsulant discoloration
- Solder bond failures
- Broken glass
- Hot Spots
- Ground faults
- Junction box and module connection failures
- Structural failures

Accelerated Stress Tests

- So now that we have a list of failures, we can think about developing tests that duplicate the failures in a fairly short time frame (at least compared to outdoor exposure).
- Our goals should be:
  - To use the results of the tests to improve the module's ability to withstand this specific stress.
  - To use the results of the accelerated tests to predict module lifetime
- In using accelerated stress tests we must cause degradation in order to verify that our accelerated test is duplicating the failure mechanism we saw outdoors.

Accelerated tests for PV

- Thermal cycling
  - Broken interconnects
  - Broken Cells
  - Solder bond failures
  - Junction box and module connection failures
- Damp Heat Exposure & Humidity Freeze
  - Corrosion
  - Delamination
  - Junction box and module connection failures
- UV Test
  - Delamination
  - Encapsulant discoloration

Accelerated tests for PV

- Mechanical Load
  - Broken interconnects
  - Broken cells
  - Broken glass
  - Structural failures
- Dry and Wet Insulation Resistance
  - Delamination
  - Ground faults
  - Electro-Corrosion
- Hot Spots
- Hail test
  - Broken cells
  - Broken glass

Qualification testing or Certification

- Qualification testing is often confused with Reliability testing
- Qualification tests are a set of well defined accelerated stress tests developed out of a reliability program.
- They incorporate strict pass/fail criteria.
- The stress levels and durations are limited so the tests can be completed within a reasonable amount of time and cost.
- The goal for Qualification testing is that a significant number of commercial modules will pass and that all subsequent production modules will be built the same way as the test modules were built.
- So passing the Qualification test says the product meets the specific set of tests, but doesn't predict product lifetime nor indicate which product will last longer or degrade in operation.

History of Qualification Testing

- JPL Blocks I-V (1975-1981) – all crystalline Si
- European Union Specifications 501 to 503 (1981-1991)
- SERI IQT (1990) – modifications for thin films (a-Si)
- IEEE 1262 (1995-2000) – all technologies
- IEC 61215 (Ed 1 - 1993, Ed 2- 2005) – Crystalline Si
- IEC 61646 (Ed 1 - 1996, Ed 2- 2007) – Thin Films

History of JPL Block Buys

- JPL Block buys incorporated a set of tests in each procurement document.
- Modules had to pass test sequence before manufacturer could deliver production quantities of modules.
- So where did tests come from?
- Block I tests were based on NASA tests utilized on space arrays.
  - Thermal cycles extremes selected as -40 and +90C based on guesses for worst case conditions in terrestrial environment.
  - Humidity test short as space experience limited to time exposed before launch.

JPL Block Qualification Tests

bp solar

Test	I	II	III	IV	V
Thermal Cycles	100 -40 to +90	50 -40 to +90	50 -40 to +90	50 -40 to +90	200 -40 to + 90
Humidity	70C,90% 68 hrs	5 cycles 40 to 23C 90%	5 cycles 40 to 23C 90%	5 cycles 54 to 23C 90%	10 cycles 85 to -40C 85%
HOT SPOT					3 cells 100 hrs
Mechanical Load		100 cycles 2400 Pa	100 cycles 2400 Pa	10000 2400 Pa	10000 2400 Pa
Hail				9 impacts ¾" –45 mph	10 impacts 1" – 52 mph
High Pot		<15 µA 1500 V	< 50 µA 1500 V	< 50 µA 1500 V	< 50 µA 2*Vs+1000

Block Field Experience

- The earliest Block modules were typically utilized in small remote site systems.
- I remember a JPL report that stated "the major cause of module failure to date was by gun shot".
  - Black or blue CZ cells on white background are good targets
  - Squares cells or non-white back sheets reduced problem
- Many early failures were due to cracked cells:
  - Because of module design one cracked cell resulted in total loss of power.
- Non glass superstrate modules suffered from significant soiling and delaminations usually due to UV.

Testing Development

- Future procurements utilized modified qualification test specifications.
- Block II
  - Added 100 mechanical load cycles – once again probably from space experience based on launch damage,
  - Added a High Pot Test,
  - Changed the humidity test from a constant to 5 cycles between 23 and 40C.
  - Reduced the number of thermal cycles from 100 to 50.

    I don't know why
- Block III
  - Changed the High Pot failure level from > 15 µA to > 50 µA
- Block II and III modules were utilized in some larger systems and started to experience new failure modes.

Lessons from Blocks II and III

- Many Block II and III modules were used in desert environments
  - Pagago Indian Reservation in AZ
  - Tanguze, Upper Volta
  - Natural Bridges, Utah
- Modules that survived 50 thermal cycles began failing in the desert after ~ 5 years due to broken interconnects and/or broken cells that resulted in total loss of module power.
  - Module manufacturers started building in redundant interconnects and stress relief loops.
  - In Block V Thermal Cycles increased to 200 to better evaluate module performance.
  - JPL began recommending paralleling of cells, but modules built this way suffered from shunt related power loss and hot spot problems.

Lessons Learned from Blocks II and III

bp solar

- Hail did significant damage to modules built without tempered glass superstrates:
  - Broken cells
  - Broken annealed glass
- Hail test added in Block IV.

- Large (60 kW), high voltage system at Mt. Laguna, CA
  - Part of array built with Solar Power modules (40 – 4" diameter CZ in series) with no by-pass diodes.
  - Modules began suffering from hot spot failures.
- Hot Spot Test Added in Block V

Encapsulants in Block Buys

- All Block I and most Block II and III modules were manufactured with silicone encapsulants often without glass superstrate.
- Some Block II and III modules and many Block IV modules were manufactured using PVB encapsulant with glass superstrate.
- The corrosion of screen print metallization in the PVB package led to
  - Major power loss of these modules.
  - Modification of humidity cycling test to the humidity freeze test we utilize today 10 cycles from -40 to +85 C at 85% RH.
- All Block V modules used EVA encapsulant.

Block VI

- JPL was in the process of finalizing a Block VI Specification when the program fell victim to Reagan budget cuts.
- Additions they were planning in 1985:
  - Test for bypass diodes
  - UV exposure test
  - Damp heat (85C/85% RH)

European PV Community

- Through ESTI the European Community worked on a PV Qualification Standard at the same time that JPL was working on Blocks.
- European Standards 501 and 502 had some similarities to the Block V document with:
  - Addition of UV Exposure Test
  - Addition of Outdoor Exposure Test
  - Reduction of thermal cycling maximum from 90 to 85
- EU 503 was a draft of IEC 61215, utilized to begin testing to the new standard before it had completed voting by National Committees.

IEC 61215

- International Standard incorporating the best ideas from around the world.
- Blocks VI was the basis for 61215.
- EU 502 provided UV Test, Outdoor Exposure Test and lower maximum temperature in thermal cycle.
- Several tests from Block VI were not included in IEC 61215 – most notably:
  - Dynamic Mechanical Load Test, because the test defined in Block V was unsuitable for large sized modules.
  - Bypass Diode Thermal Test, because international community didn't think the test was adequately developed.
- IEC 61215 rapidly became the qualification test to pass in order to participate in the PV marketplace, especially in Europe.

SERI IQT

- SERI work on thin film modules (mostly a-Si) lead to new "interim standard" for these modules
- Biggest new issue was the high leakage current resulting from inadequate isolation of the TCO on the glass.
- IQT added a Wet Insulation Resistance Test to test for this problem.
- IQT also added:
  - Ground continuity from UL 1703
  - Cut Susceptibility Test from UL 1703
  - Bypass diode Test from Block VI

Thin Film PV

- IQT lead to IEEE 1262 and then to IEC 61646.
- IEEE 1262 was somewhat of a hybrid having components from IQT and IEC 61215. It used the 61215 backbone of tests but incorporated the additions from IQT and introduced annealing steps to address light induced degradation in a-Si.
- IEEE 1262 served its purpose as an the first accepted qualification test for thin film modules.
- Once IEC 61646 was approved there was no reason to have 2 standards so IEEE 1262 was withdrawn after 5 years.

IEC - 61646

- Written for the thin film modules available in 1996 – mostly a-Si.
- Combined ideas of IEC 61215 and IEEE 1262.
- IEC 61646 added new concept of using thermal annealing and light soak in an attempt to characterize the power loss caused by the different accelerated tests.
- Changes from IEC 61215
  - Added wet leakage current test.
  - Added light soak and anneal cycles.
  - Added maximum output power at STC after final light soak as a pass/fail criteria

IEC 61215 Edition 2

- Twist test was eliminated
- Wet leakage current test was added from IEC 61646
- Bypass diode thermal test was added from IEEE 1262
- Pass criteria for dielectric withstand and wet leakage current tests were made dependant on the test module area.
- UV test was clearly labeled a preconditioning test
- Added the requirement to run peak power current through the module during the 200 thermal cycles to evaluate a failure of solder bonds observed in the field.

IEC 61646 Edition 2

- An attempt to adapt IEC 61646 to different types of thin film modules.
- Modified the pass/fail criteria
  - It no longer relies on meeting a plus/minus criterion before and after each test
  - It now requires meeting the rated power after all of the tests have been completed and the modules have been stabilized
- Twist test was eliminated
- Pass criteria for dielectric withstand and wet leakage current tests were made dependant on the test module area.
- Rewrote the Hot Spot Test.
- Added by-pass diode thermal test
- UV test was clearly labeled a preconditioning test

IEC 61215 Edition 3 – In Preparation

- Initial Maximum power at STC made a pass/fail criteria.
- Added retest guidelines.
- Completely changed the hot spot test.
- Updating the other tests to be consistent with changes in IEC 61646 and changes requested by test labs to simplify or clarify the procedures.

Summary

- Qualification Tests are living documents.
- They are continually being updated based on feedback from:
  - Test laboratories in terms of test procedures and interpretation of test results.
  - Field results in terms of failure mechanisms, failure rates and degradation rates.
  - Reliability testing looking to duplicate observed field failures via combinations of stresses, longer durations of accelerated stress tests and new accelerated stress tests.
  - Use of new tools for evaluating changes in performance (for example IR and NIR cameras).
- New PV technologies (for example organic PV) will require field data to identify failure mechanisms that can be duplicated using accelerated stress tests before a new qualification sequence can be developed.

Reliability Modeling for Photovoltaic Modules

F. Patrick McCluskey, Ph.D.
CALCE/Dept.of Mechanical Engineering
University of Maryland, College Park, MD 20742
mcclupa@umd.edu
301-405-0279

Copyright © 2009 CALCE

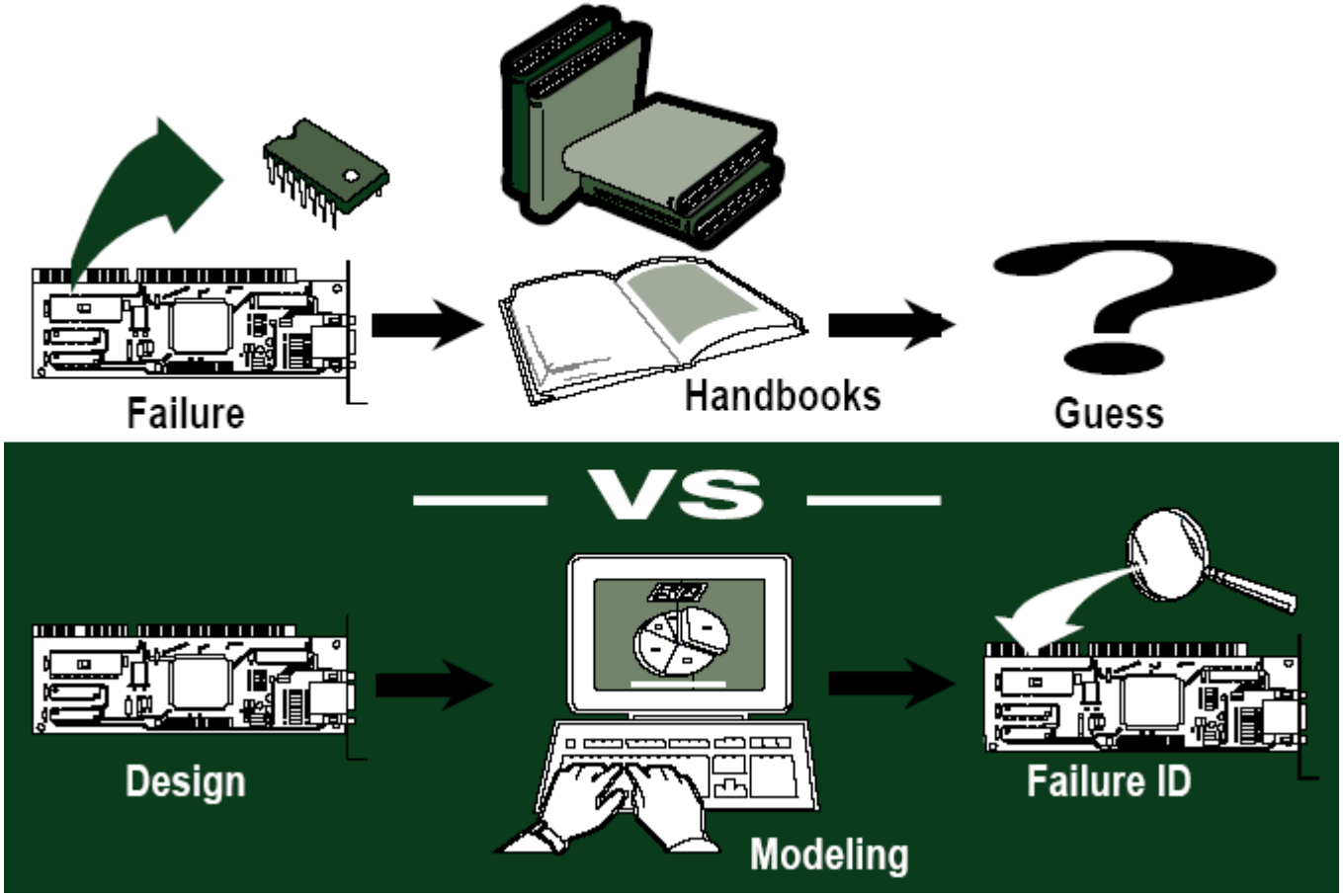
Elements of Reliability Estimation

- To produce an understandable and credible estimate, a reliability assessment must contain the following elements:
  - The specific purposes of the reliability estimate results (i.e. How the reliability assessment is intended to be used).
  - How the reliability assessment shall not be used
  - Where precautions are necessary
  - Definition of failures and failure criteria
    - Failure modes
    - Failure mechanisms
    - Physical parameter values that constitute a failure (voltage level, crack delamination area, etc.)
  - Description of the process to develop the estimation
    - Assumptions
    - Methods and models
    - Source of data
  - Required assessment format
    - Metrics
    - Confidence level

IEEE 1413

Copyright © 2009 CALCE

Empirical methods vs. Physics of Failure



Copyright © 2009 CALCE

Reliability Assessment Uses and Timing

When selecting a reliability assessment method it is important to consider

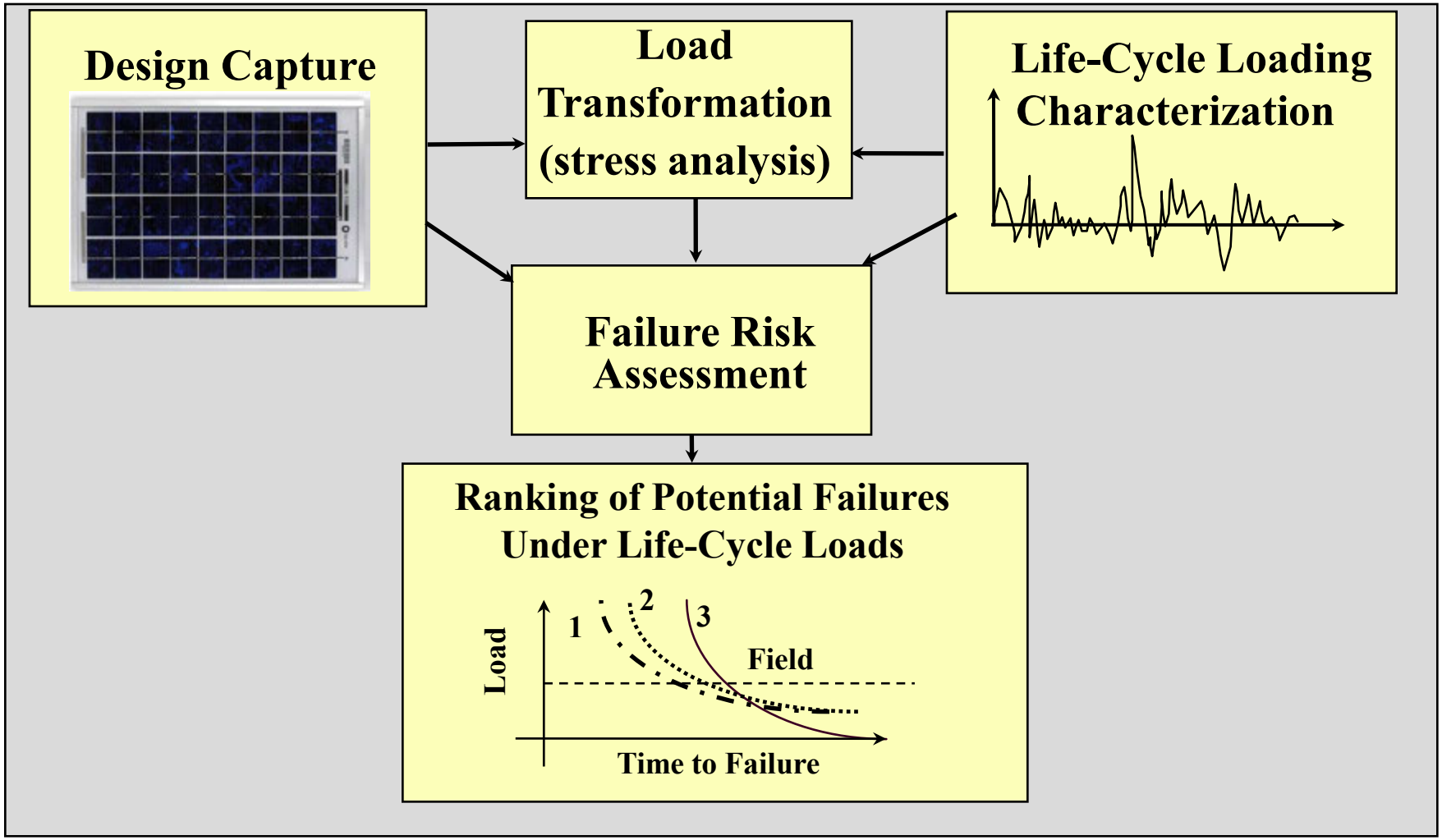
- Why the assessment is conducted
- When in the system life cycle the assessment is conducted
- Which parts of the system are being assessed

In the reliability assessment, the following steps must therefore be taken:

1. Identification and description of the item for which an estimate is made
   - Definition of realistic product reliability requirements
   - Definition of the usage profile.
     - Defines the specific thermal, mechanical, electrical, and chemical loads over time.
   - The specific characteristics of the product design and the manufacturing/assembly process.
2. Results of a virtual qualification assessment
   - Identification of potential failure sites and mechanisms
   - Estimates of time to failure under field and test conditions
3. An accelerated test plan
   - Test vehicle characterization for individual failure mechanisms (STIM not SIM)
   - Conditions for an accelerated life test, and determination of overstress and destruct limits
4. Results of the complete reliability assessment
   - Confidence in estimate, sources of uncertainty, limitations, and repeatability

Copyright © 2009 CALCE

PoF Reliability Assessment Methodology



Copyright © 2009 CALCE

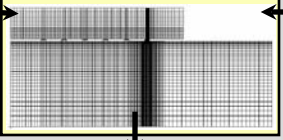
Accelerated Product Qualification

1 Virtual Qualification

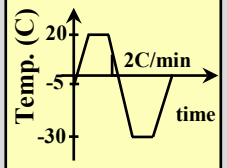
Hardware configuration



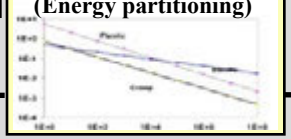
Stress analysis



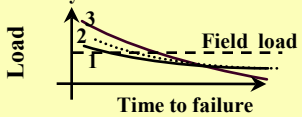
Life-Cycle loads



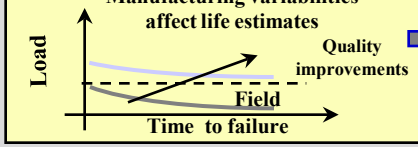
Durability assessment (Energy partitioning)



Potential failures under life-cycle loads are ranked

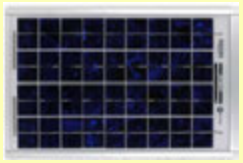


Manufacturing variabilities affect life estimates



2 Accelerated Test Planning and Development

Test configuration
- Test matrix
- Specimen design
- Fixture design
- Test platforms



Sensors (Thermocouples)

Load controller

Data collection & post-processing
- Thermal maps
- Time-to-failure data

Design of expts

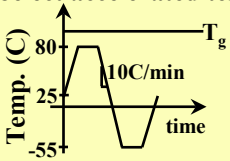
Failure detection scheme
Non-functional : Event detectors

3 Test Vehicle Characterization

- Assess overstress limits (glass transition temp. = 85° C)
- verify failure modes

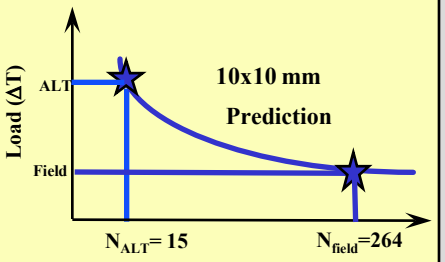


- Select accelerated test loads

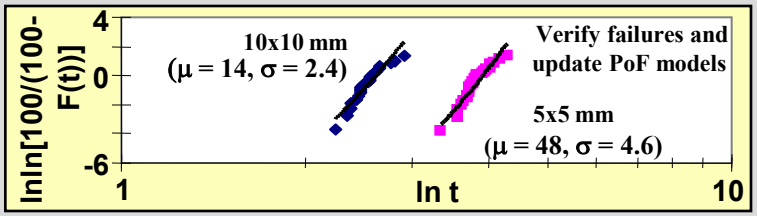


- Calibrate specimen for accelerated test loads

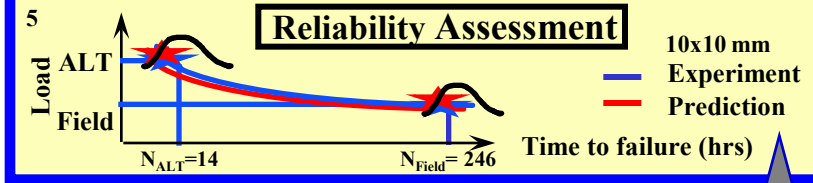
- Repeat PoF analysis for expected failures under ALT loads to obtain acceleration factor



4 Accelerated Life Testing



5 Reliability Assessment

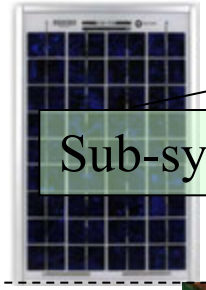


Copyright © 2009 CALCE

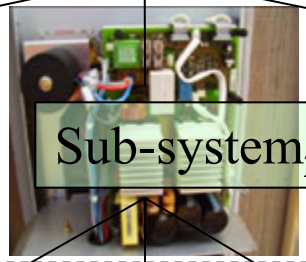
Comprehensive System Reliability Assessment



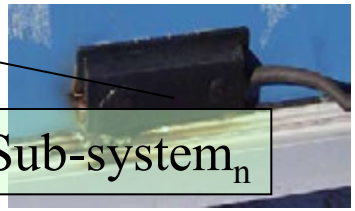
Overall system



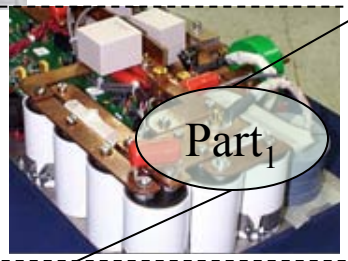
Sub-system1



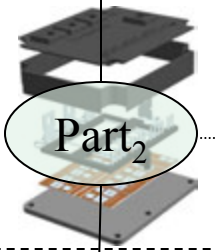
Sub-system$_2$



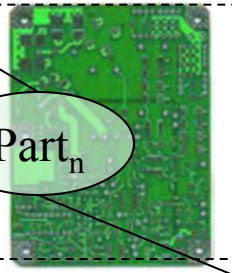
Sub-system$_n$



Part$_1$



Part$_2$



Part$_n$

Parts arranged in different configurations e.g., series, parallel

Failure mechanism$_1$

Failure mechanism$_2$

Failure mechanism$_n$

PoF mechanism identification

FFOP estimation of the overall system

$$L = L_r\left(\frac{V_r}{V_0}\right) \times 2^{\left(\frac{T_r - T_A}{10}\right)}$$

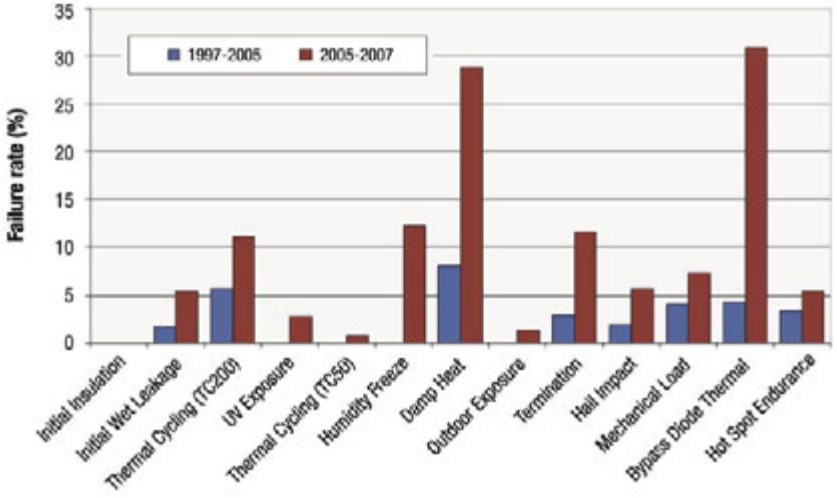
$$\varepsilon = \frac{(R - \rho_f)d\psi}{\rho_i \psi_i} \approx \frac{(\bar{r} - \rho_f)d\psi}{\rho_i \psi_i} = \frac{r(\psi_i - \psi_f)}{\rho_i \psi_i}$$

$$Nf = 0.5\ (\Delta\gamma/2\varepsilon_f)^c$$

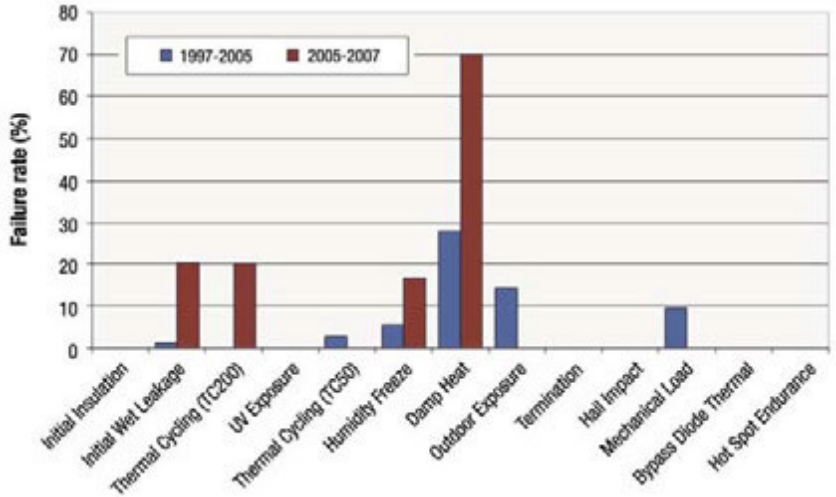
Copyright © 2009 CALCE

Quality issues are occurring in the PV Module

- IEC 61215 Qualification and safety certifications are not a replacement for reliability testing and can only highlight initial design quality issues.
- Failure rates by Arizona State University Photovoltaic Testing Laboratory have shown historically that as an industry failure rates of minimum certification testing has increased.
  - Expansion of the market by new manufactures is largely responsible.
- An increase in certification failures highlights the potential for other reliability issues to increase in the field as new manufacturers enter the market.



Crystalline Silicon PV



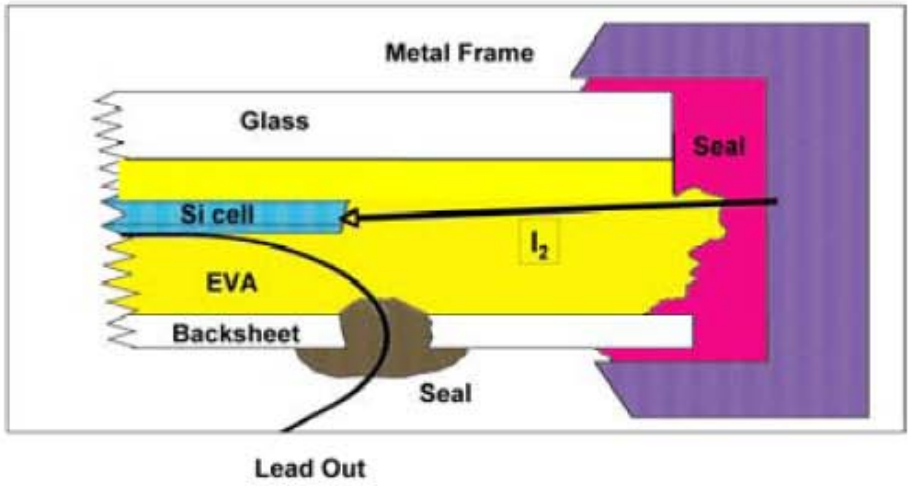
Thin Film PV

G. Tamizhmani, B. Li, T. Arends, J. Kuitche, B. Raghuraman, W. Shisler, K. Farnsworth, J. Gonzales, A. Voropayev, Failure analysis of design qualification testing: 2007 vs. 2005, Photovoltaics International, August 2008.

Copyright © 2009 CALCE

Design Capture
Wafer Type Module





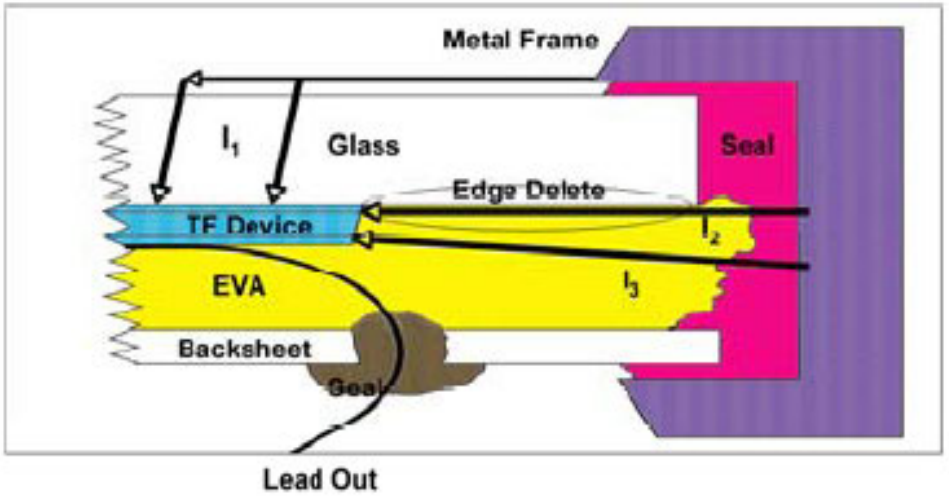


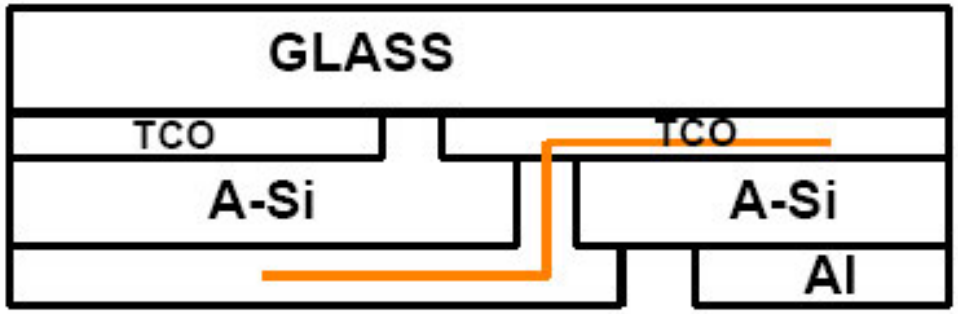
T. McMahon and C. Osterwald, NREL

Copyright © 2009 CALCE

Design Capture
Thin-Film Type Module







Cell Interconnect

T. McMahon and C. Osterwald, NREL

Copyright © 2009 CALCE

Mission Profile Collection

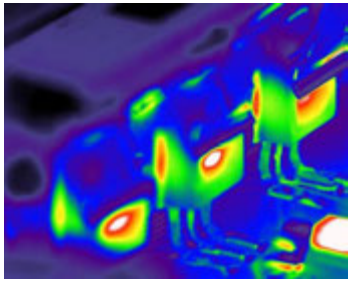
The physical environment describes the operating conditions and loads under which the system operates. It includes temperature, humidity, shock and vibration, voltage, UV radiation, power, contaminants, and so forth. It also includes loads applied in packaging, handling, storage, and transportation.

Temperature: Boundary conditions on temperature can be measured via a diverse array of sensors. Temperature profiles at each component can then be determined by thermal modeling.

Vibration: Vibration can be sensed by as displacement, velocity, or acceleration at specific locations in the system. This can then be translated to vibration at components of interest using vibration modeling.

Corrosion: Characterizing this environment for later qualification testing can be performed through methods that include measuring moisture and temperature.







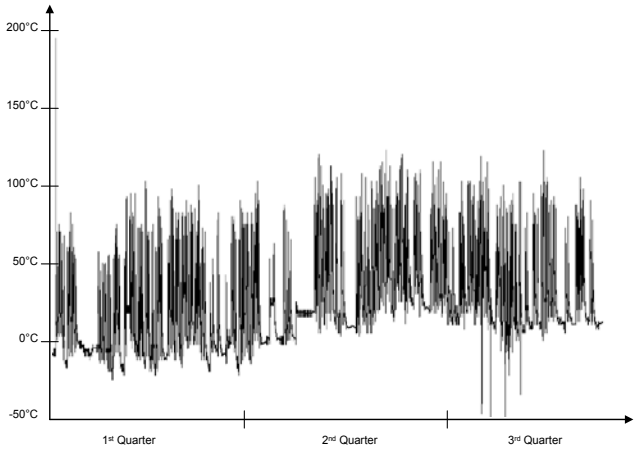




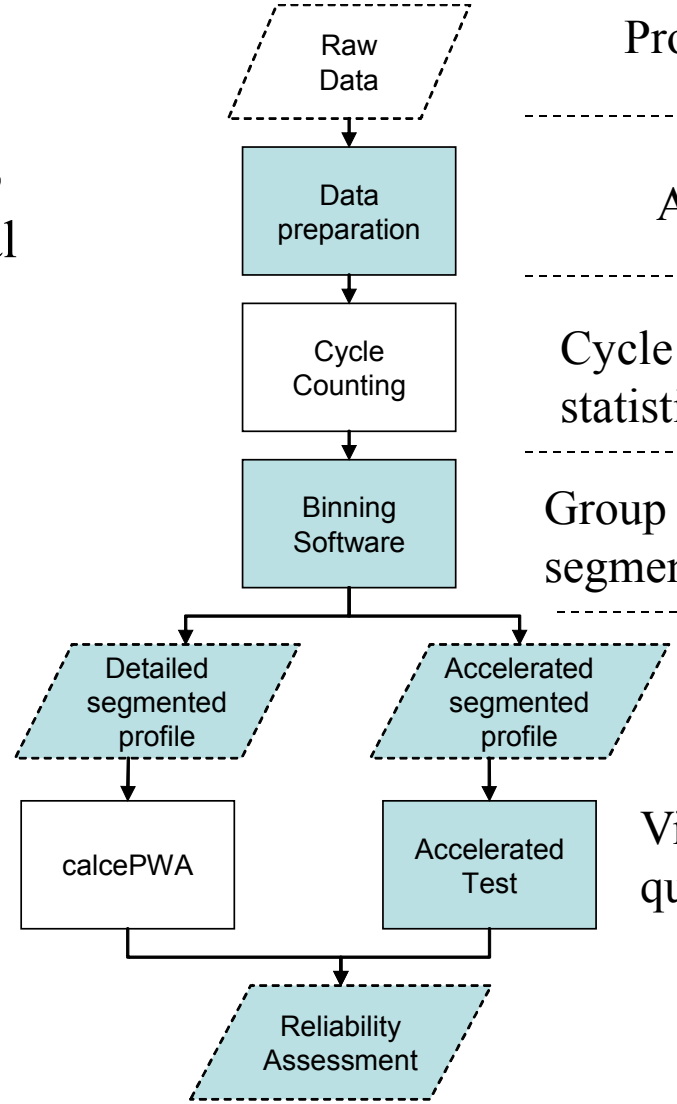
Copyright © 2009 CALCE

Mission Profile Creation

- A methodology is needed to create a segmented life cycle profile from raw field data to be used as an input for virtual qualification and reliability assessment.



Raw Data



Provided by user

Add time stamps

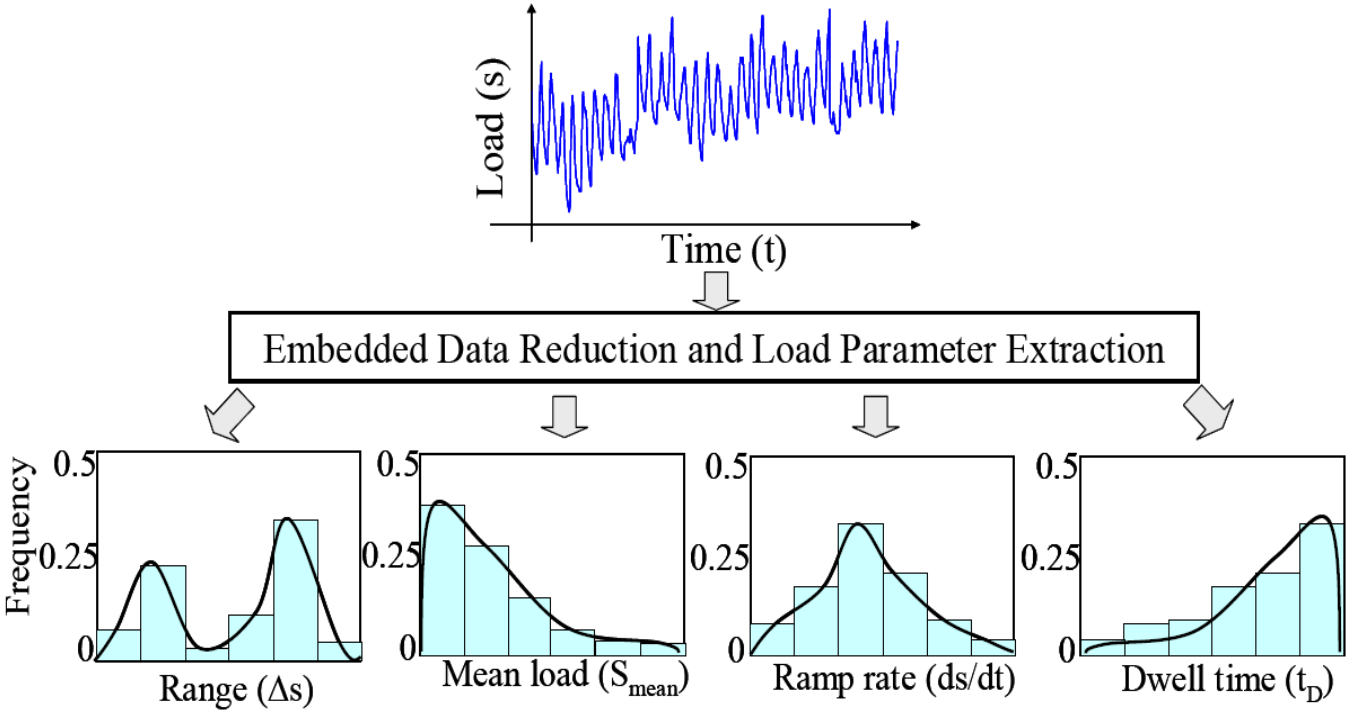
Cycle counting, descriptive statistics and distributions

Group individual cycles into segments based on parameters

Virtual and experimental qualification

Copyright © 2009 CALCE

Load Parameter Extraction



- CALCE software was used to derive cycle characteristics and statistics.
- The software uses a moving average filter to reduce noise above 1 Hz

Copyright © 2009 CALCE

Binning Tool

- Accesses the output file of the cycle counting software containing the cycles with their respective ranges, means and ramp rates.
- Groups cycles in segments according to their range, mean and ramp values.
- Sorts the segments according to the amount of damage they inflict
  - Damage estimate based on the solder fatigue model
- Reduces the profile to contain only its most damaging segments
- User sets
  - Bin width - influences number and resolution of the segments
  - Accuracy - determines how many of the less damaging segments will be discarded
- Output
  - All segments in a plain textfile
  - A calcePWA compatible CSV file with the most damaging segments

Copyright © 2009 CALCE

Failure Mechanisms

- Failures can be described by their relation to failure precipitation.
  - **Overstress failure:** A failure that arises as a result of a single load (stress) condition. Examples of load conditions that can cause overstress failures are shock, temperature extremes, and electrical overstress.
  - **Wearout failure:** A failure that arises as a result of cumulative load (stress) conditions. Examples of load conditions that cause cumulative damage are temperature cycling, abrasion and material aging.
  - **System functional failure:** A failure that arises as a result of an anomalous condition of the system output. Examples of anomalous conditions that cause system functional failure are under-voltage input signals, mismatched switching speeds, and sneak paths.

Copyright © 2009 CALCE

Photovoltaic Failure Mechanisms

- Degradation of Semiconductor Device
- Degradation of Packaging Material
  - Material Aging
    - Encapsulant Discoloration – reduced light efficiency
  - Loss of Adhesion
    - Front Surface – Electrical open
    - Back Surface – Poor Heat Transfer, Hot Spots
  - Moisture Intrusion – increased corrosion and leakage currents
    - Backsheet Cracking and Lamination Disintegration
    - Edge Sealing
- Degradation of Cell/Module Interconnects
  - Solder joint fatigue
    - Metal segregation
    - Grain boundary coarsening/cracking
    - Increase series resistance and heating

Copyright © 2009 CALCE

Field Failures Observed in PV Modules

- From 1994 to 2002, BP Solar Collected Return Data on 2,000,000 modules. Returns were 0.13% or one module per 4200 module years of operation. No increase in failure rate at end of 10 year warranty period. [1]
- NREL did study indicating 0.7%/yr degradation in performance over time.
- Tests prescribed by IEC 61215

Types of Failure	%	Stressors	Accelerated Test
Corrosion	45.3	Moisture Penetration	85°C-85% RH Damp Heat (with UV) for greater than 1000 hrs.
Cell or Interconnect Break	40.7	Thermal expansion or contraction	-40°C to +85°C Thermal cycling (at peak power)
Delamination of Encapsulant	3.4	Moisture Penetration	Humidity Freeze

Other failures were related to leads, wires, junction box, and bypass diodes

[1] J. H. Wohlgemuth, "Long Term Photovoltaic Module Reliability, NCPV and Solar Program Review Meeting 2003 NREL/CD-520-33586, p/179

Copyright © 2009 CALCE

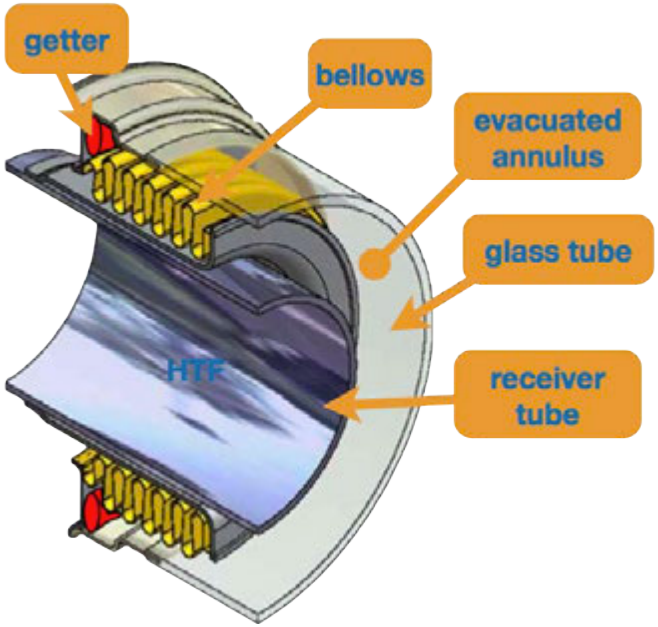
Failure Mechanism Models – PV Module

Failure Mechanism	Failure Site	Failure Mode	Relevant Stresses	Environment Test	Model
UV Reaction Discoloration	EVA Encapsulation	Lower light efficiency	T, Intensity. Frequency	UV Exposure at Temp	Arrhenius $\text{Exp}(-Ea/kT)$
Deadhesion	Front Surface	Electrical Open	ΔT, H, ΔH	Damp heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Deadhesion	Back Surface	Poor Heat Transfer	ΔT, H, ΔH	Damp heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Corrosion	Front Surface Interconnects	Open Circuit Incr. Resist.	M, ΔV, T, impurities	Powered damp heat at Temp	Eyring $(V)^n(RH)^n e^{-Ea/kT}$
Fatigue Disintegration	Backsheet Lamination	Cracking	ΔT, ΔH	Damp Heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Fracture	Glass	Cracking	Mech Load	Mech Load	Paris Law $N=C(\Delta K)^n$
Fatigue	Edge Sealing	Cracking Voiding	ΔT,ΔH	Damp Heat Temp cycle	Coffin-Manson $N = C(\gamma)^n$
Metal Segregation	Solder Connection	Voiding Intermetallic	T, J	Powered Temp Aging	Eyring (Black) $J^n e^{-Ea/kT}$
Fatigue	Solder or Cell Connection	Loss of connection	ΔT, ΔV	Powered Temp cycle	Coffin-Manson $N = C(\gamma)^n$

Copyright © 2009 CALCE

CPV - Trough Collectors – Receivers

- Key parameters:
  - High solar absorbance
    - Efficient absorber coating, high transmittance of glass
  - Low thermal losses
    - Low absorber emissivity, vacuum
  - Minimal shading
    - Short bellows
  - Long operating life
    - Durability of glass to metal seal (low break rate)
    - Sustainment of vacuum (low hydrogen permeation, correctly sized getter)
    - Durability of absorber coating
    - Abrasion resistance of anti-reflective glass coating

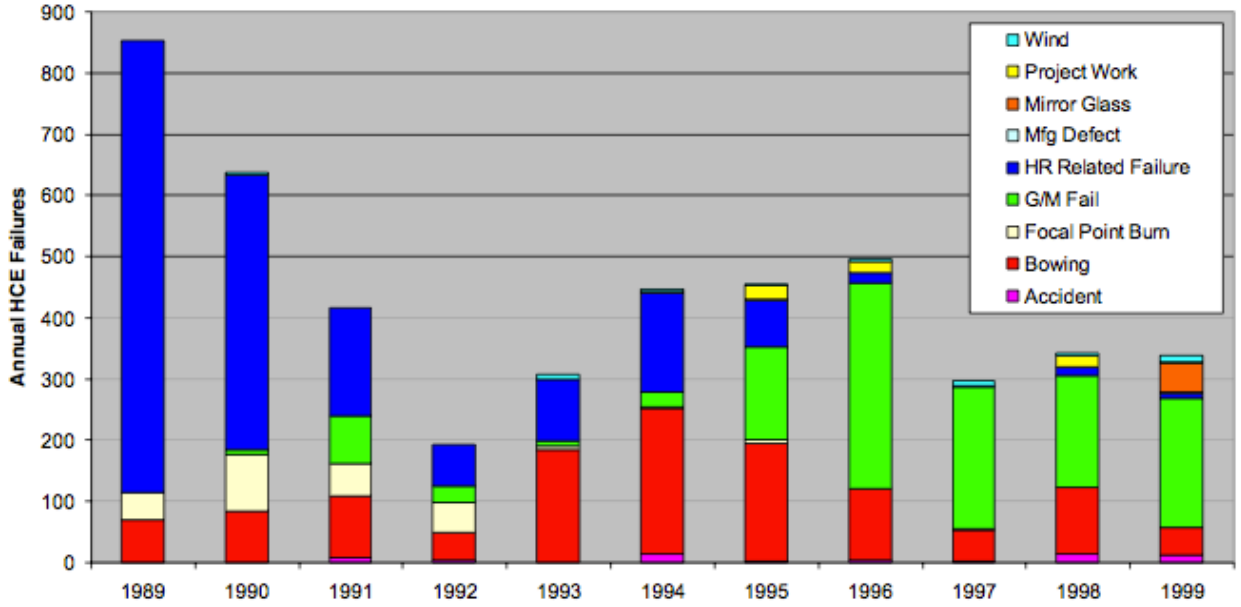


http://www.lehigh.edu/imi/docs_pitt/pdf_Pitt/T1f_Marker.pdf

Copyright © 2009 CALCE

CPV - Trough Collectors – Receivers

- **Receiver failure and degradation is the largest cost factor in plants**
  - **30-40% failure at SEGS VI-IX in first 9-11 years of operation**
  - **Cases include inability to remove hydrogen from vacuum, glass/metal seal failure, coating degradation, and broken glass**
  - **Receiver replacement is approximately $1,000 each, accounting for 0.5 cents/kWh in O&M**



http://www.nrel.gov/csp/troughnet/pdfs/mahoney_receiver_devel.pdf

Copyright © 2009 CALCE

Failure Mechanism Models - CPV

Failure Mechanism	Failure Site	Failure Mode	Relevant Stresses	Environment Test	Model	Ref
Abrasion of Optics	Glass, Coating Encapsulant	Loss of Optical output	Scratching UV	UV Exposure Abrasion	Wear Models	1
Delamination	Cell to Heat Sink	Thermal Overload	ΔT, J	Powered Temp cycle	Coffin-Manson $N = C(\gamma)^n$	1
Fracture	Glass	Cracking	Mech Load	Mech Load	Paris Law $N = C(\Delta K)^n$	2
Delamination	Glass to Metal Seal	Moisture, H Ingress	ΔT	Temp cycle	Coffin-Manson $N = C(\gamma)^n$	2
UV Degradation	Reflectors	Loss of Reflectance	UV	UV Exposure	Arrhenius Exp (-Ea/kT)	3

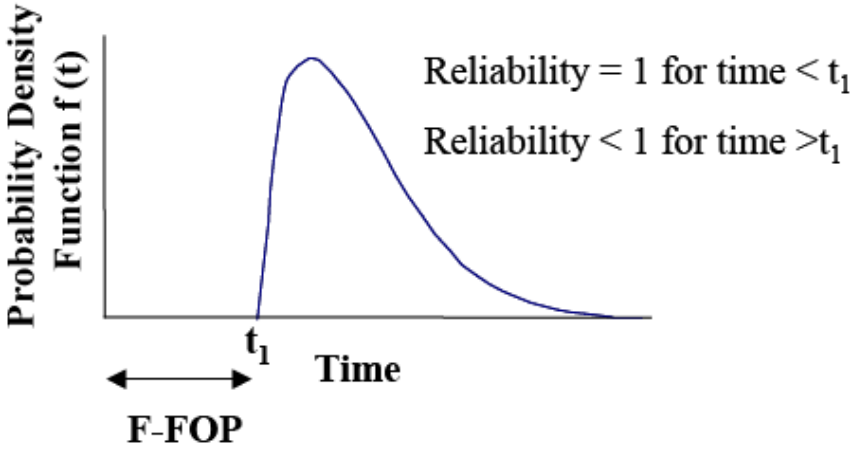
(1) S. Kurtz, J. Granata, M. Quintana, "Photovoltaic Reliability R&D toward a Solar Powered World, Proc. SPIE 7412, 74120Z-2
(2) http://www.nrel.gov/csp/troughnet/pdfs/mahoney_receiver_devel.pdf
(3) T. Fend, B. Hoffschmidt, G. Jorgensen, et al., Comparative Assessment of Solar Concentrator Materials, 2003

Copyright © 2009 CALCE

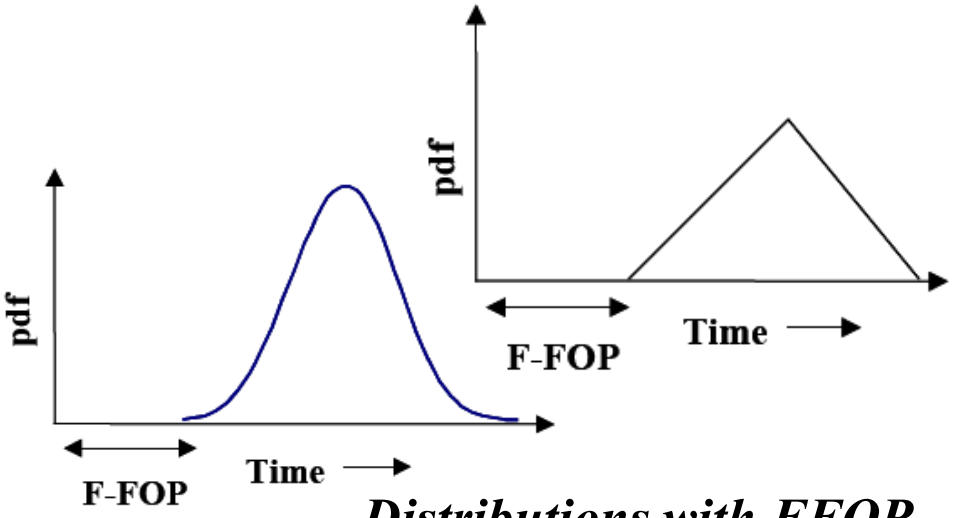
Measuring Reliability

- The preferred metric is Failure Free Operating Period.
- Failure free operating period (FFOP) of a system is defined as:

  "a period of time (or appropriate units) during which the system, operating within specific environmental conditions, is functional without encountering failures."
- There are many distributions that can be used to represent the failures. Exponential, normal, log normal, gamma, Weibull etc. are examples of such distributions. Failure free operating period is a period of time when the probability density function is zero.



Probability Density Function for FFOP



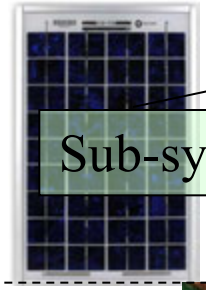
Distributions with FFOP

Copyright © 2009 CALCE

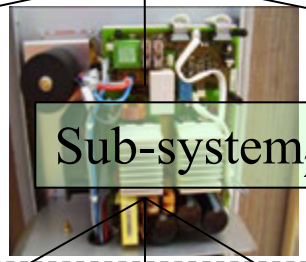
Comprehensive System Reliability Assessment



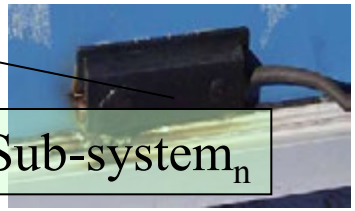
Overall system



Sub-system1

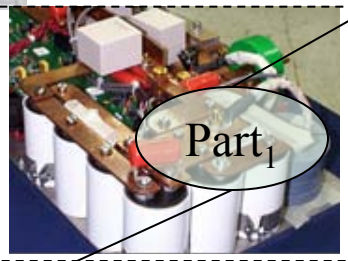


Sub-system$_2$

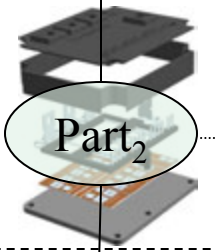


Sub-system$_n$

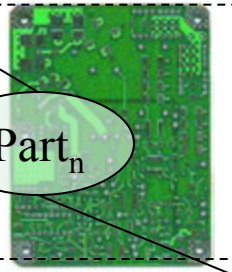
Parts arranged in different configurations e.g., series, parallel



Part$_1$



Part$_2$



Part$_n$

Failure mechanism$_1$

Failure mechanism$_2$

Failure mechanism$_n$

PoF mechanism identification

FFOP estimation of the overall system

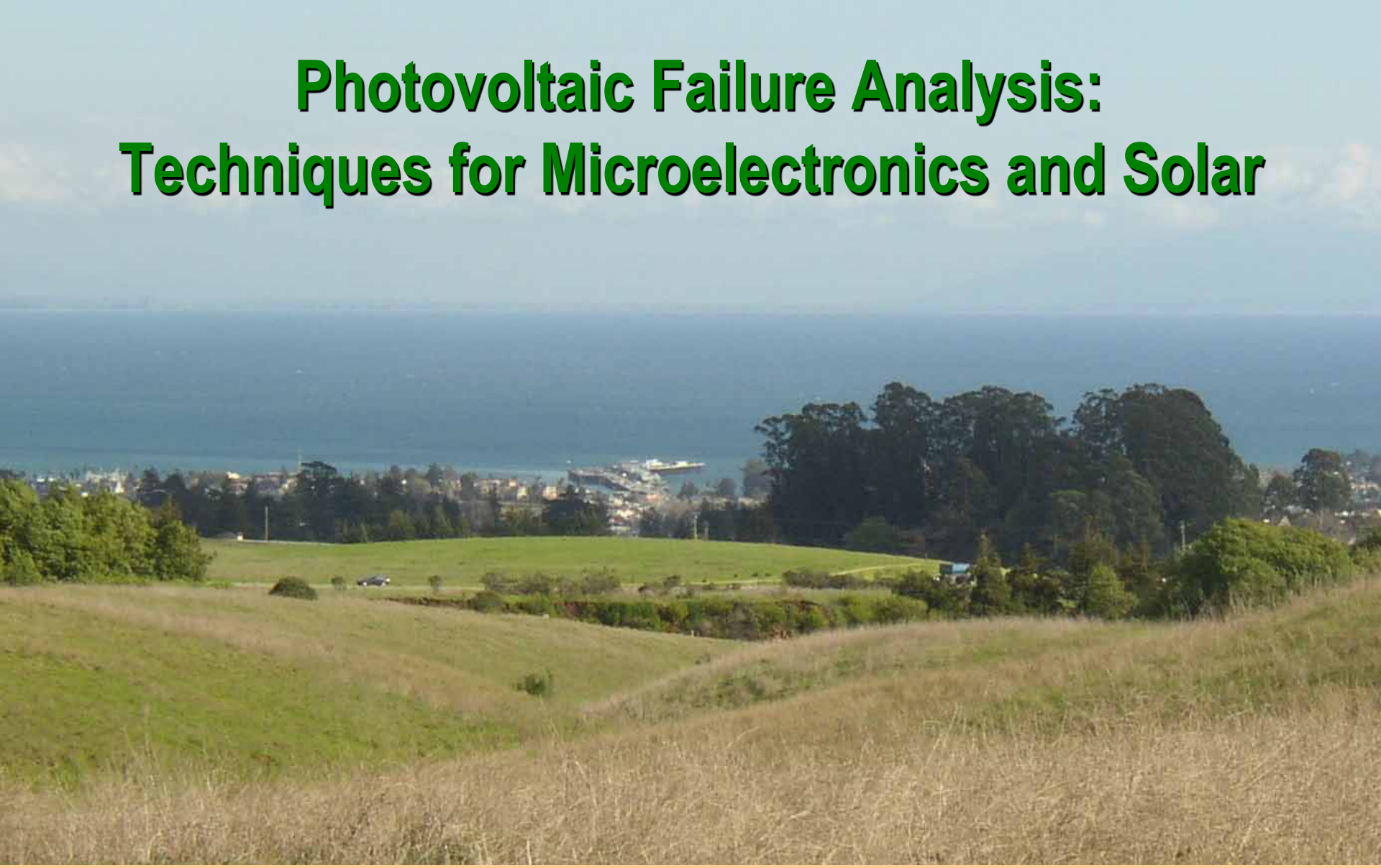
$$L = L_r\left(\frac{V_r}{V_0}\right)\times 2^{\left(\frac{T_r - T_A}{10}\right)}$$

$$\varepsilon = \frac{(R-\rho_f)d\psi}{\rho_i\psi_i} \approx \frac{(\bar{r}-\rho_f)d\psi}{\rho_i\psi_i} = \frac{r(\psi_i-\psi_f)}{\rho_i\psi_i}$$

$$Nf = 0.5\ (\Delta\gamma/2\varepsilon_f)^c$$

Copyright © 2009 CALCE

Photovoltaic Failure Analysis: Techniques for Microelectronics and Solar



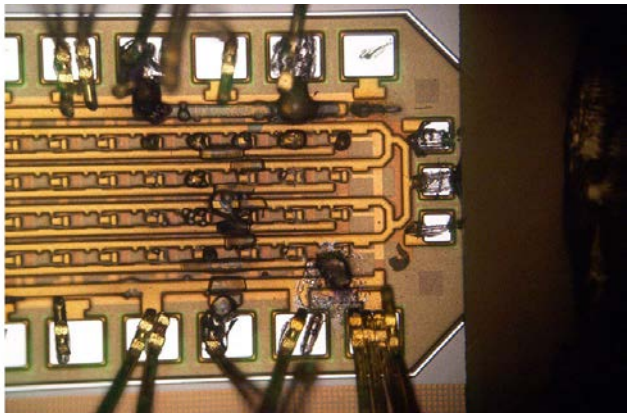
Glenn B. Alers

Department of Physics, University of California, Santa Cruz

galers@ucsc.edu

Review of Failure Analysis Techniques

- **Review failure analysis techniques from microelectronics**
  - **Non-destructive probes for:**
    - Electrical defects (EMMI, voltage contrast)
    - Physical defects (x-ray, acoustic, adhesion)
  - **Most FA tools built for 200mm wafers**

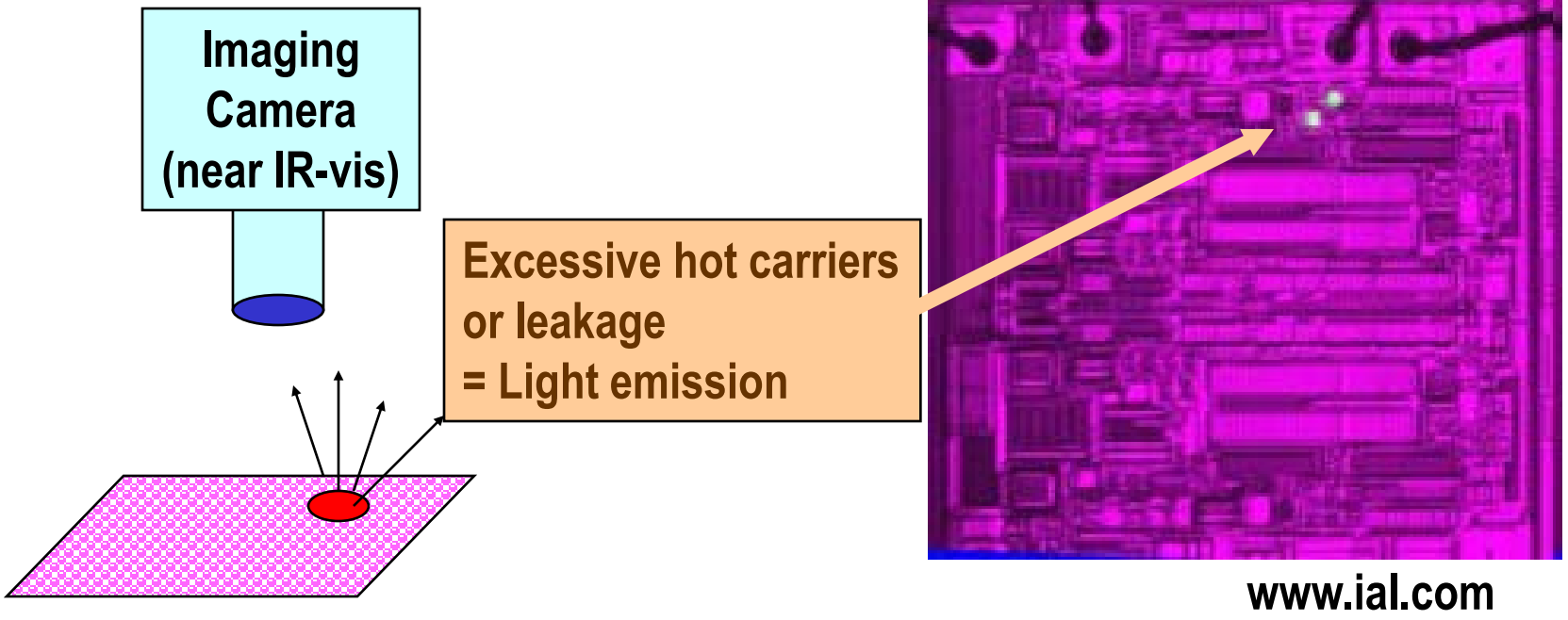


- **Comparison to common techniques for PV industry**
  - **Light beam induced current**
  - **Electroluminesence imaging**
  - **Photoluminesence imaging**
  - **Thermal imaging**
- **Review of companies that provide FA services**

Techniques are the same: Only the acronyms have changed
Focus for electronics is resolution

Electrical Defect Inspection: Light Emission

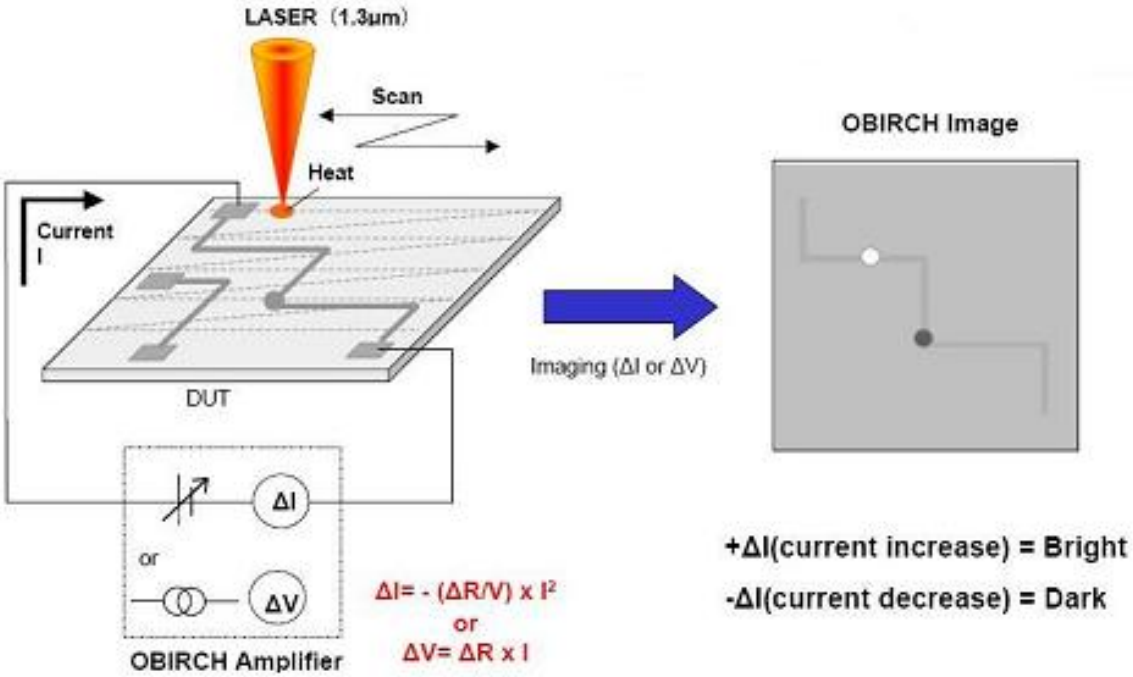
- **Light emission imaging**
  - PEM (photoelectron microscopy)
  - EMMI (emission microscopy)
  - LEM (Light emission microscopy)
  - For photovooltaics: EL/PL imaging
- **Hot carrier generation or leakage**
  - CMOS: low static power consumption
  - Electrons injected above conduction band
  - Broad light emission
  - Imaged during different vectors / operation



www.ial.com

Scanning Optical Probes

- **OBIRCH (Optical Beam Induced Resistance Change)**
  - Scan line with pulsed laser beam = local heating
  - Voltage (resistance) change from local heating ~ current in line



Probe beam = local heating
$\Delta V = I\,(\delta R/\delta T) * \Delta T$

AC voltage signal ~ current

Probe of local current
$I = \Delta V * (\text{constant})$

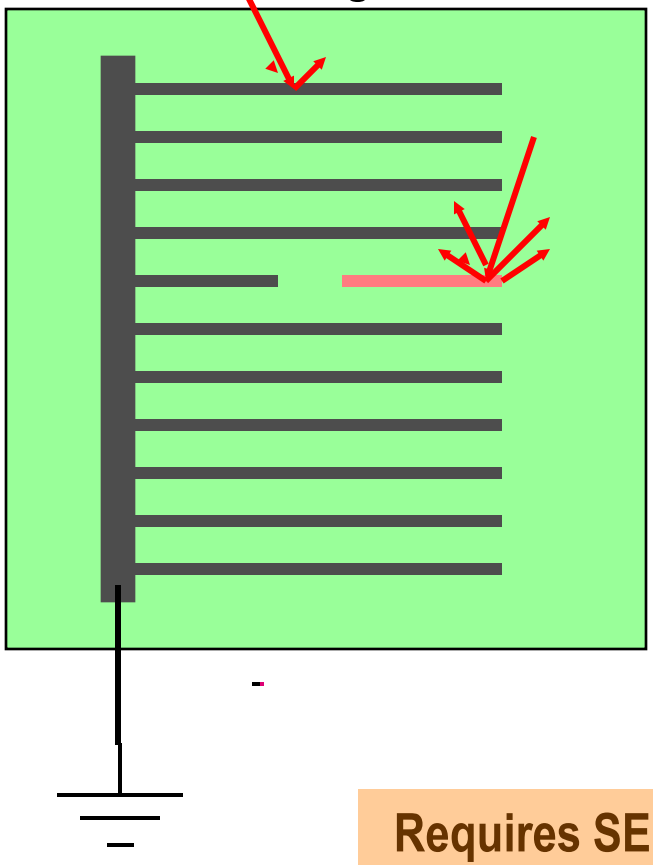
Probe of resistance along line

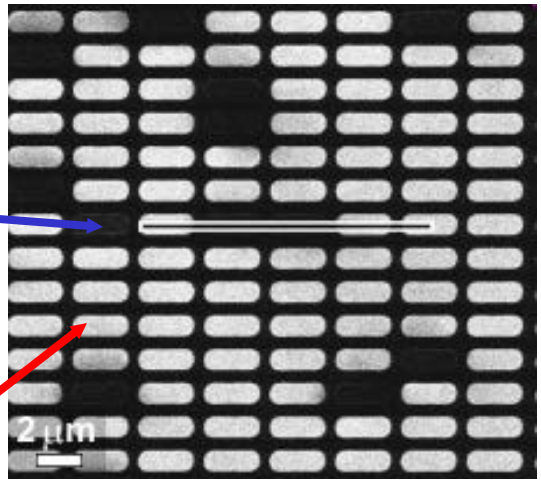
OBRICH gives local quantitative probe of current in interconnect
Analogous to LBIC for photovoltaics

Scanning e-beam: Voltage Contrast Images

- Voltage contrast microscopy (SEM)

Electron Beam
>> ground = few secondary e-

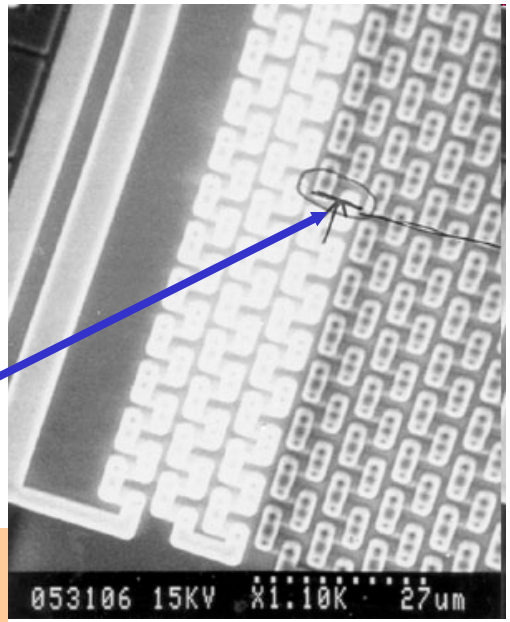




Good bits (dark)

Bad bits (bright)

Line with poor ground Connection:
Charge buildup
Bright in SEM



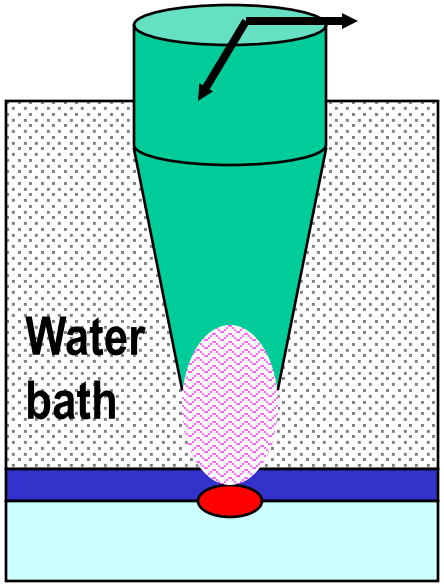
Break in line

Requires SEM (up to 300mm samples)
Very fast with high or low magnification

Physical Defects: Acoustic Microscopy

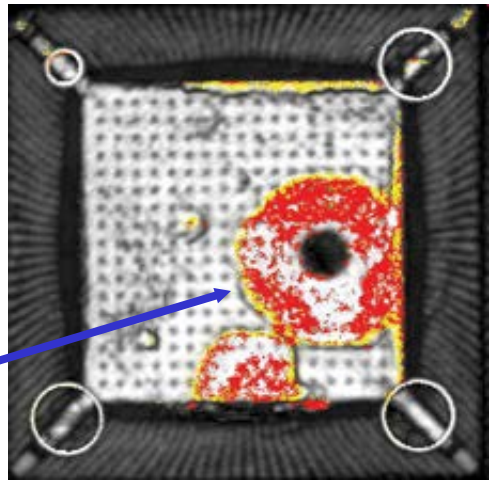
- SAM = Scanning Acoustic Microscopy

Ultrasonic Transducer

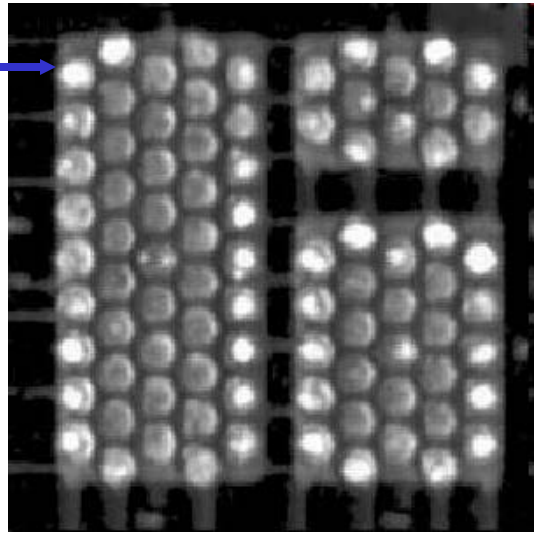


~10μm resolution
Water bath required

Sensitive to delamination
(Failed encapsulant)

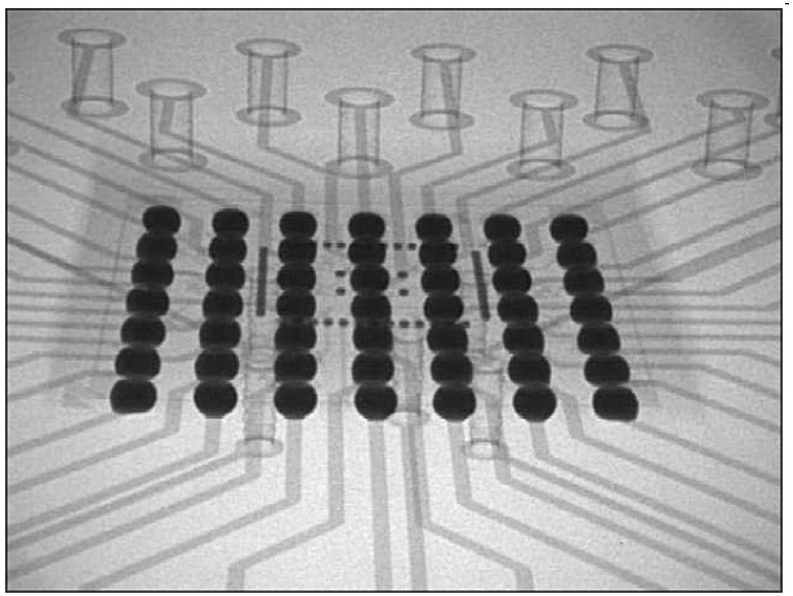


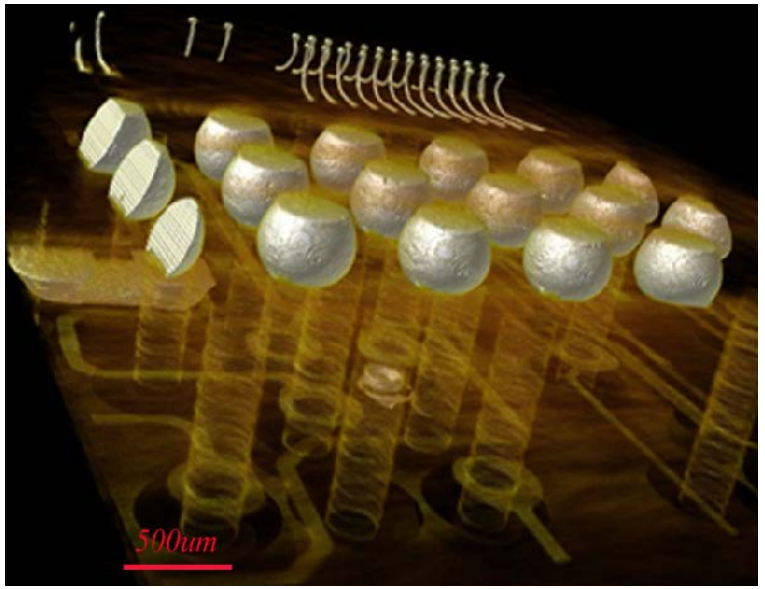
Poor contacts
(solder bumps)



Physical Defects: X-ray tomography

- X-ray tomography
  - 2-dimensional and 3-dimensional imaging
  - Best for embedded metals in dielectric
  - Composition information also available
  - Sample sizes up to 200mm

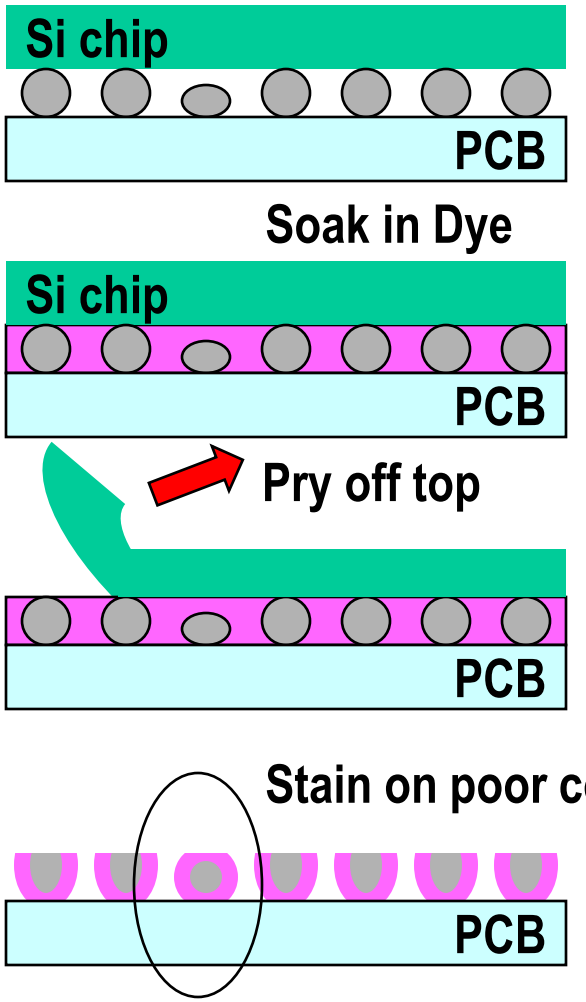


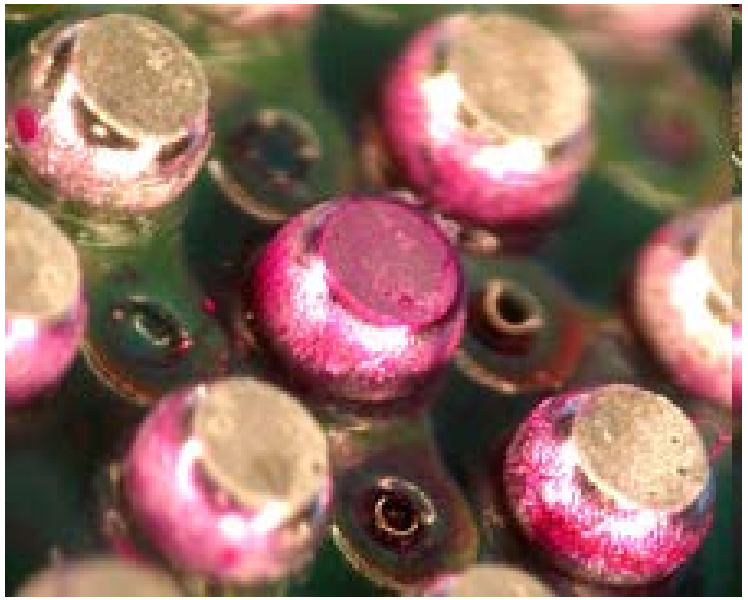


Time intensive, not sensitive to contact resistance / microcracks

Physical Defects: Dye and Pry

- Destructive Test for cracks and poor contacts
  - Applied after thermal cycling or HTOB test

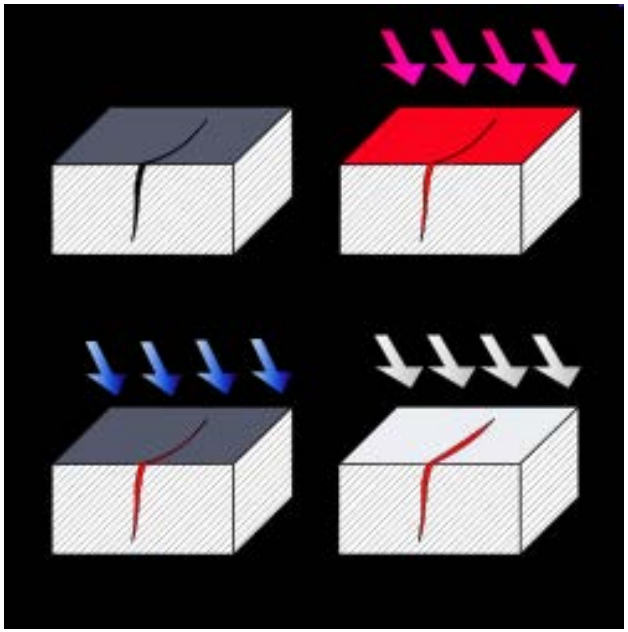


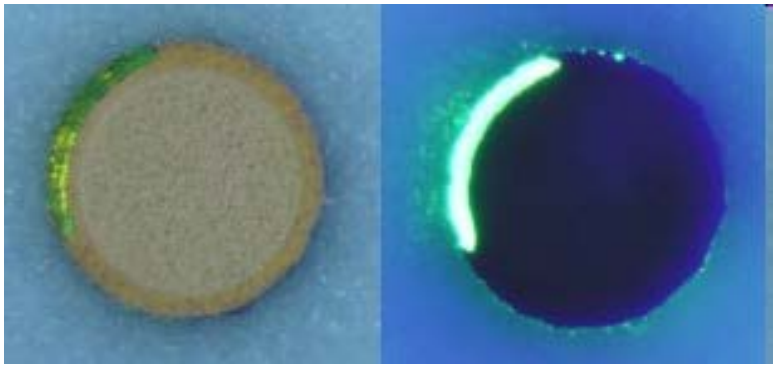


Destructive test
Sensitive to partial failures

Florescence Dye Staining

- **Florescence Dye Imaging**
  - Paint part with florescent dye
  - Remove dye (apply developer)
  - Image with UV





Example: metal feedthrough in glass



Commonly applied to mechanical parts / boilers / etc..
Applicable to field testing

Electrical defects: Thermal Imaging

- **Thermal hot spots in chips: Electronics focus on RESOLUTION**

Table 1 Summary of popular high-resolution thermal measurement techniques in micrometer-nanometer range

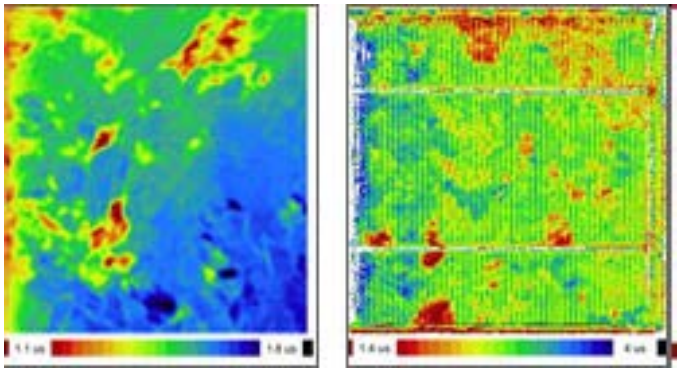
Method	Principle	Resolution			Imaging?
		Spatial (μm)	Temperature (K)	Response time (s)	
Microthermocouple	Seebeck effect	50	0.01	5 m	No
Infrared thermography	Planck blackbody emission	3–10	0.02 (if blackbody) -1 K	10 μm (single point) -0.5 m (image)	Yes
Liquid crystal thermography	Crystal phase transitions (change color)	2–5	0.5 (near phase transition)	3 m	Yes
Thermoreflectance	Temperature dependence of reflection	0.3–0.5	0.01	0.006–0.1 μm	Yes
Scanning thermal microscopy (SThM)	Atomic force microscope with thermocouple or Pt thermistor tip	0.05 (surface morphology)	0.1	10–100 μm	Scan
Fluorescence thermography	Temperature dependence of quantum efficiency	0.3	0.01	200 μm	Scan
Optical interferometry	Thermal expansion, Michelson type	0.5	0.0001 (1 fm)	0.006–0.1 μm	Scan
Micro-Raman	Shift in Raman frequency or ratio of Stokes/anti-Stokes amplitudes	0.5	1	1 μm	Scan
Near field probe (NSOM)	Use near field to improve optical resolution	0.05	0.1–1 (S/N dependent)	0.1–10 μm	Scan
Built-in temperature sensors	Fabricate a thermal sensor integrated into the device	100s	0.0002–0.01	1 μm	No

Proof

Thermal imaging well developed for photovoltaics

Common Photovoltaic Failure Analysis

- **Current induced probes**
  - **LBIC / EBIC / XBIC (light / electron / x-ray beam induced current)**
  - **Spatial mapping of quantum efficiency**
  - **Local mapping of carrier lifetime**
  - **Shunt / series resistance mapping**

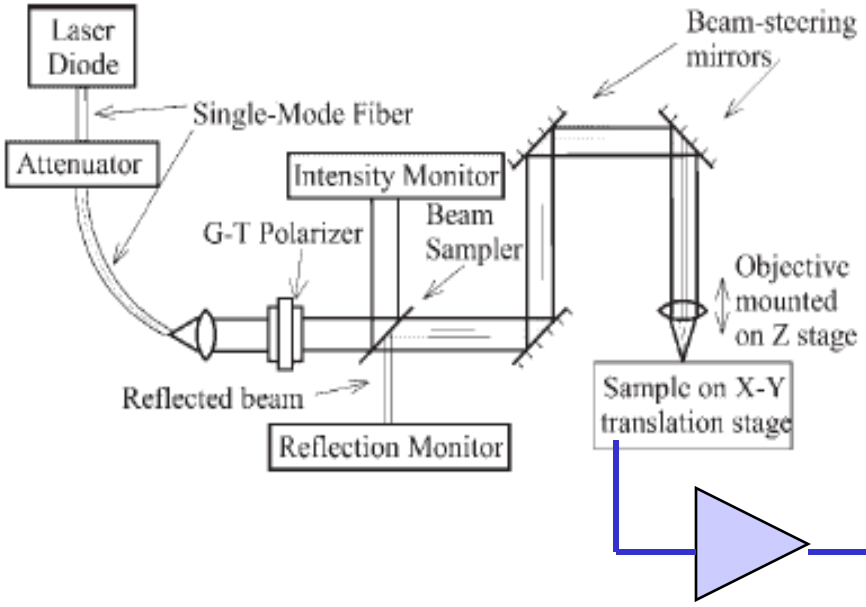


- **Emission Spectroscopy**
  - **Information depends on emission energy**
    - Elecroluminescence (visible – near infrared)
    - Photoluminesence (near infrared)
    - Thermal imaging (far infrared)
  - **Local mapping of current density**
  - **Local mapping of carrier lifetime**
  - **Shunt / series resistance mapping**

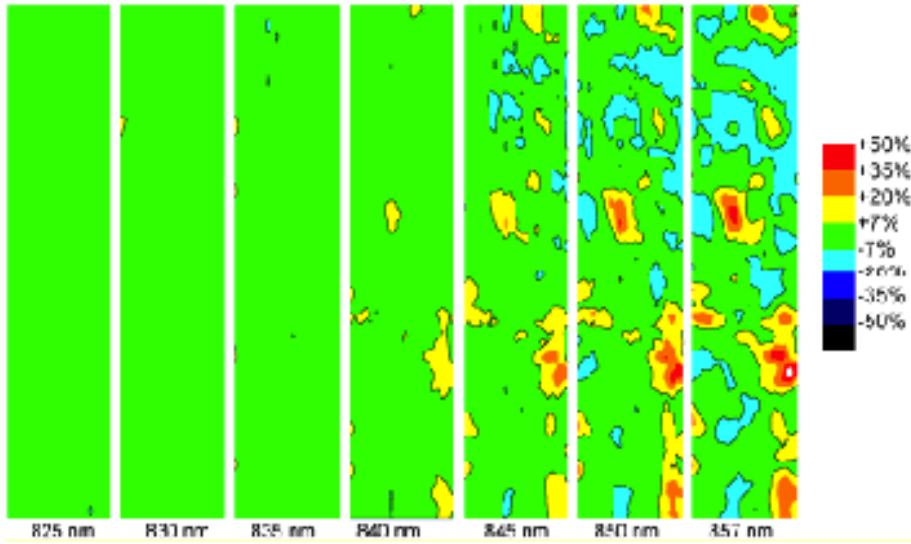
Laser Beam Induced Current (LBIC)
OBRICH for microelectronics

- **Spatial resolution of current across solar cell**
  - Maps quantum efficiency and carrier diffusion length across solar cell
  - Most sensitive near band edge -- choose wavelength carefully (unlike OBRICH)

Scanning local illumination of solar cell



Current output across solar cell



Commercial tools available (Semilabs)
Services available (analogous to OBRICH)

J. Sites et al., (www.physics.colostate.edu/groups/photovoltaic/PDFs/SitesLBIC.pdf)

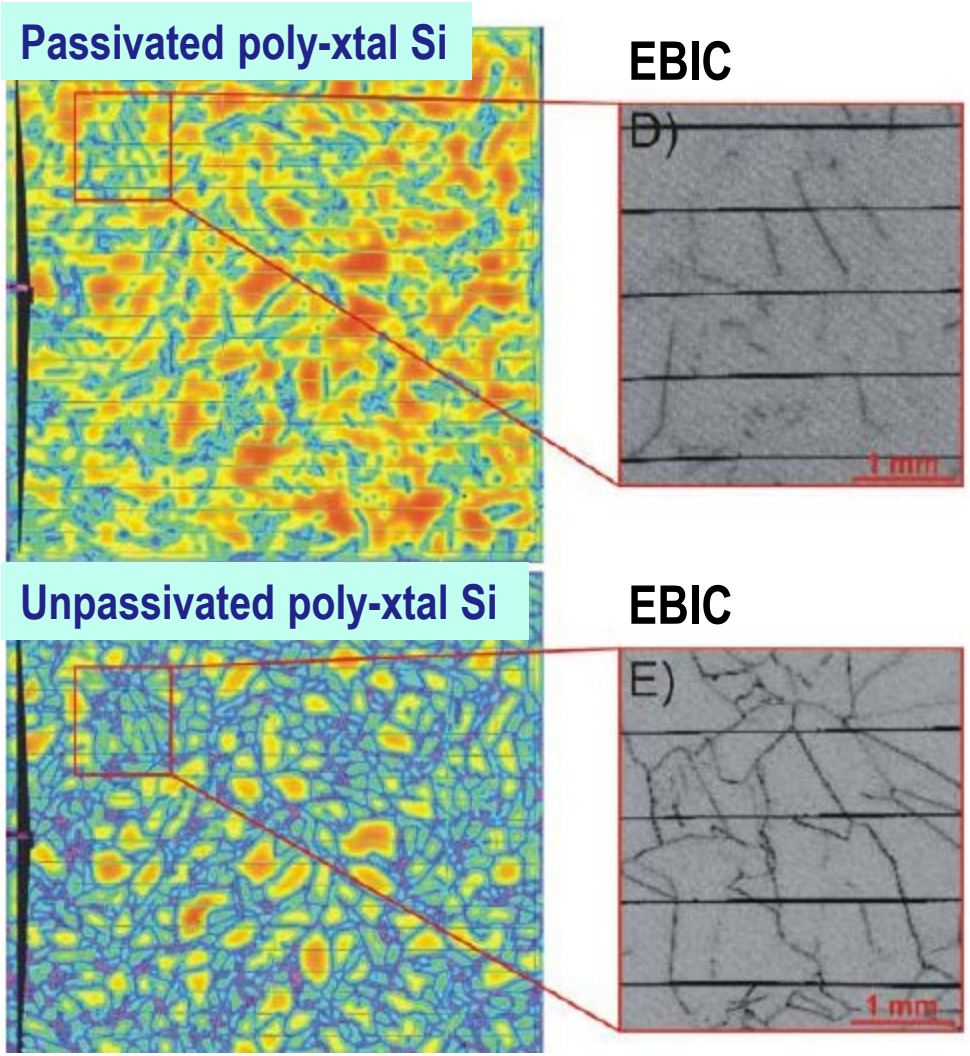
Electron Beam Induced Current
Performed in SEM

- Spatial resolution of LBIC limited by spot size and carrier diffusion

Internal quantum Efficiency maps

Greater carrier lifetime = greater efficiency

Positive impact of passivation



Inject electrons directly into Si (>10keV)

Shorter lifetime = dark at grain boundaries

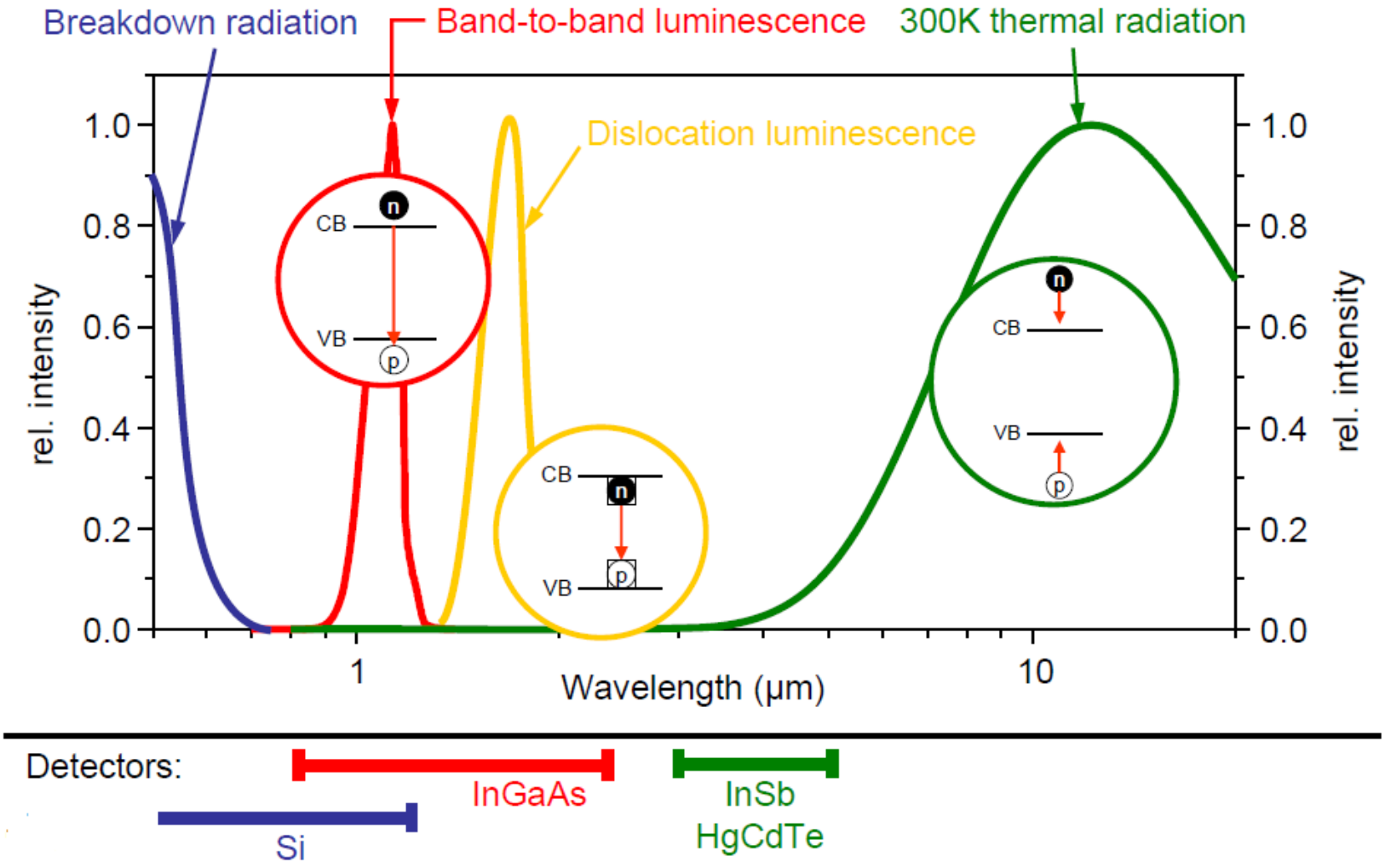
Higher resolution (<10nm spot size)
Grain boundaries
Dislocations

Low temperatures required for best resolution

A. Zuschlag et al., EU PV Energy Conf. (2008)

Optical Emission from Si (EL and PL)
For microelectronics (EMMI, PEM, etc.)

- **Different energy emission = different mechanism**



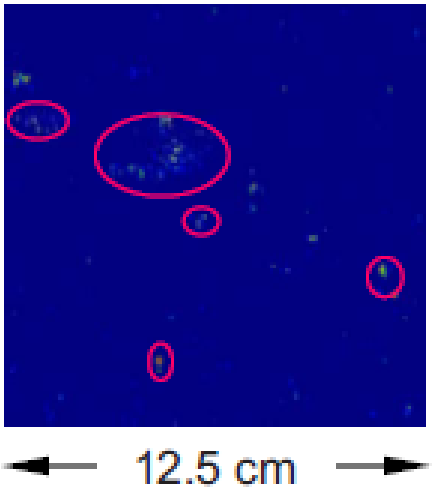
M. Kasemann et al., EU PV Sol. Energy Conf. (2008)

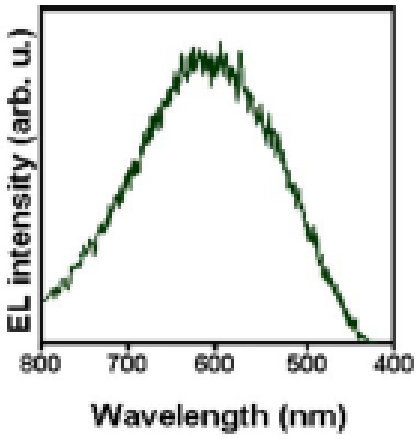
Visible Electroluminescence: Pre-breakdown

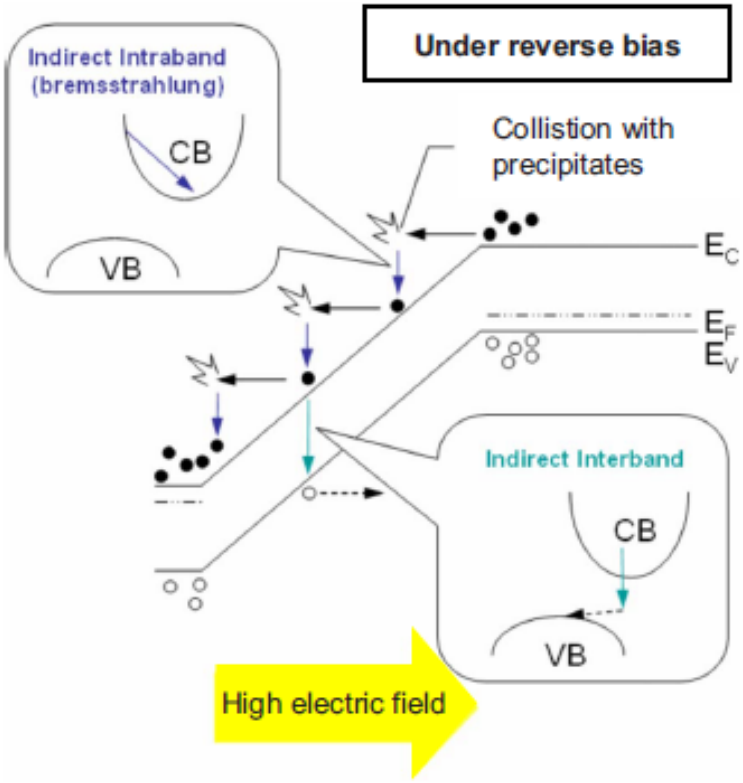
Hot carriers for electronics

Visible Emission Under Reverse Bias:

- localized EL spots visible (5-10V)
- Spectrum in visible







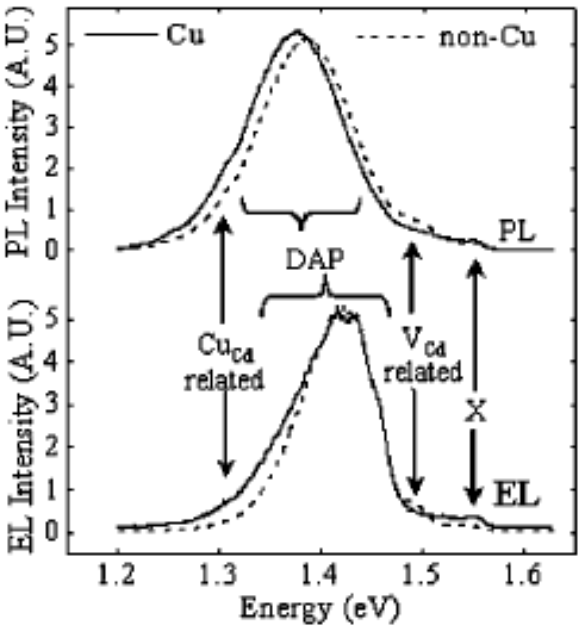
Energenic electrons with large reverse bias:

- "Avalanche" breakdown or "Zener" breakdown = broadband emission
- Correlation to metallic impurities
- Correlated to local heating

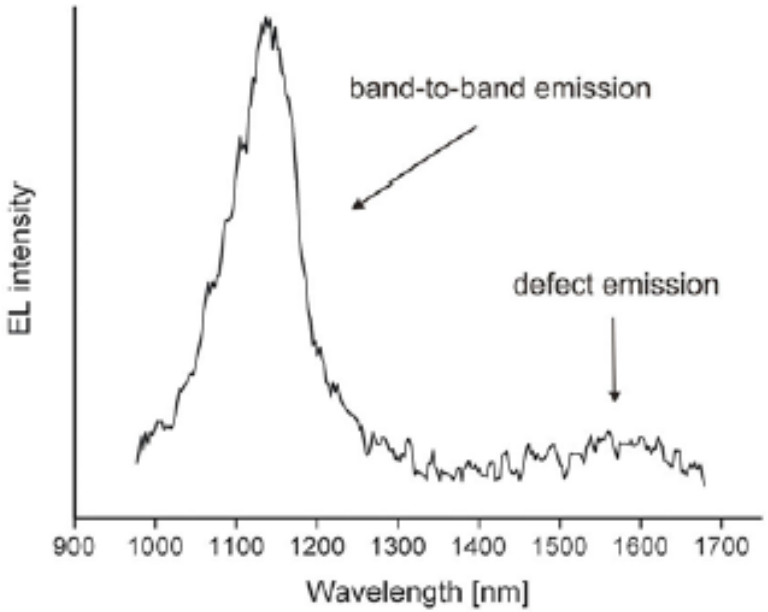
Kitiyanan et al, J. Appl. Phys 106, 043717 (2009)

Near-IR : Band-Band Emission

- Strongest EL and PL emission from band-band
  - CdTe = direct bandgap(strong), Si = indirect (weak)
- Weaker emission from impurity states (band-tail)



EL and PL emission from Cu-CdTe
DAP = Donar acceptor pair
Feldman et al, Appl. Phys. Lett. 85, 1530 (2004)



PL emission from poly Si
Band to band and defect (band edge)
Dreckschmidt et al, EU PV energy Conf (2007)

Carrier Lifetime mapping with Photoluminescence

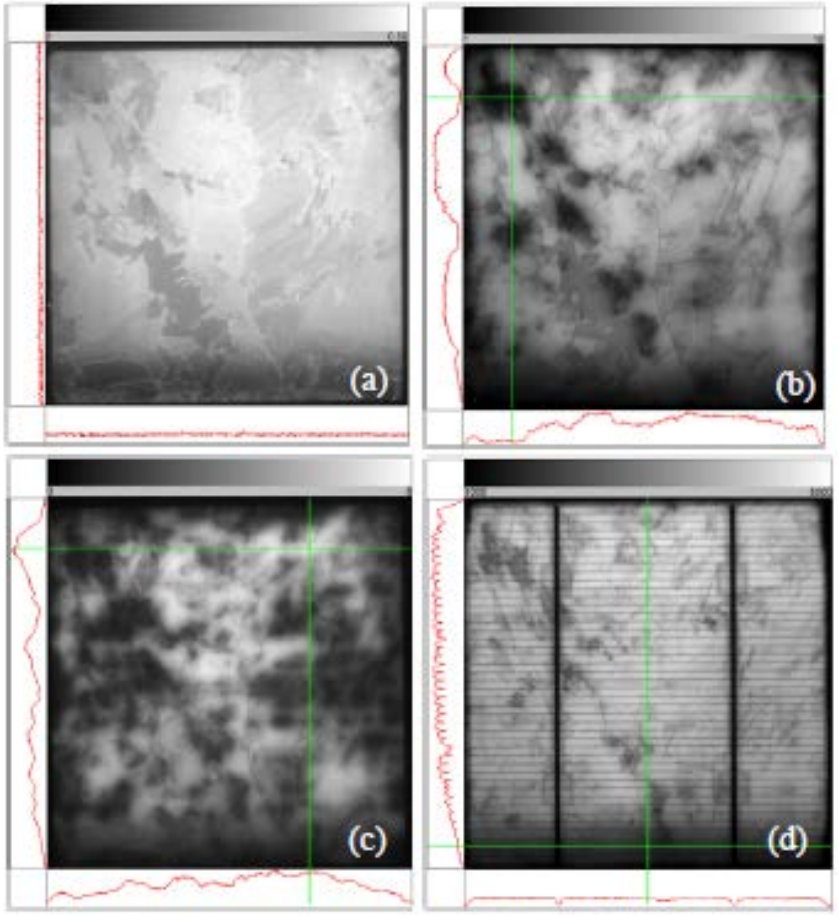


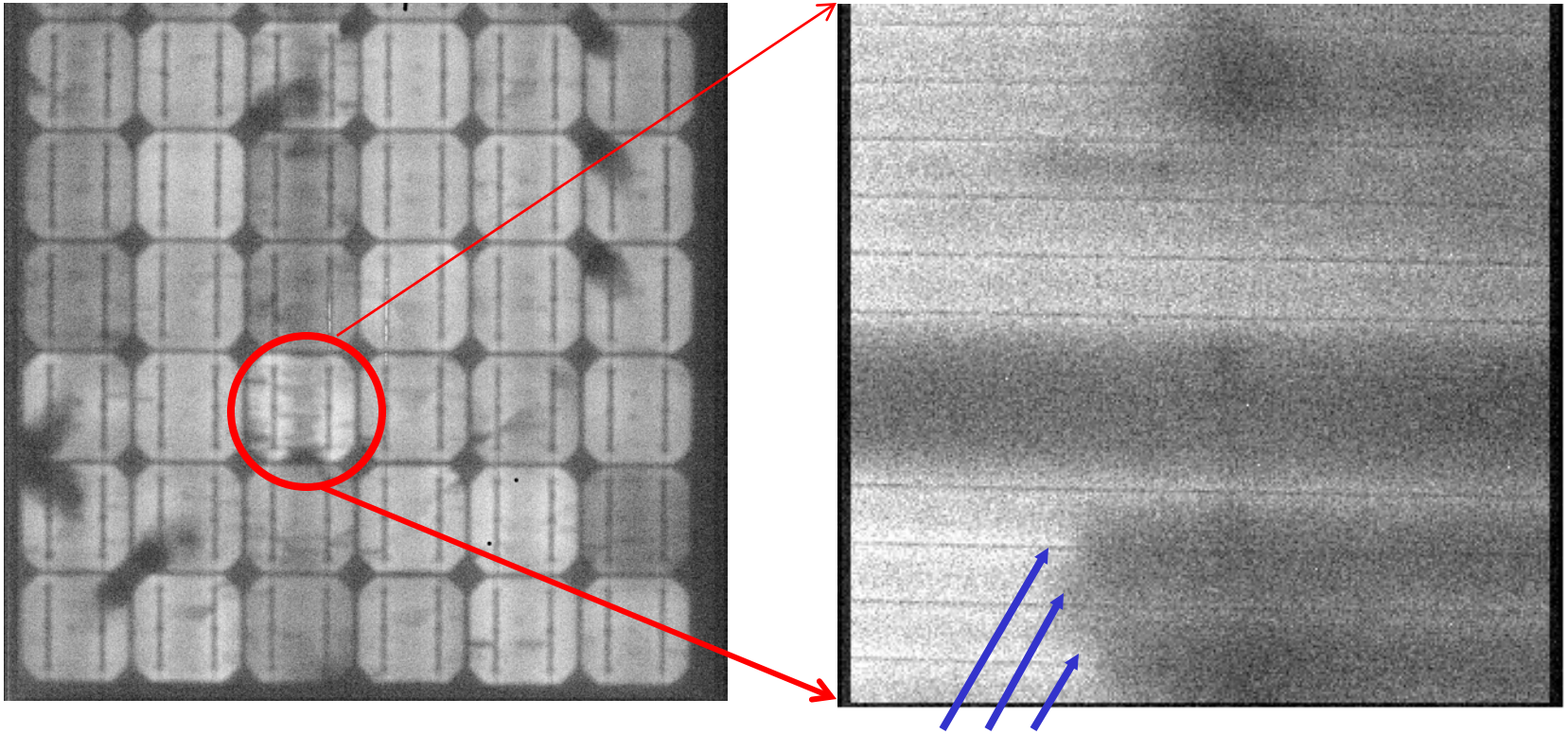
Figure 3: *Effective Minority carrier lifetime in μs from PL images measured on 5-inch mc-Si sister wafers after (a) surface damage etch, (b) emitter diffusion, (c) SiN deposition (not fired), (d) fully processed cell [color scale in counts per pixel and second for (d)].*

- **Photoluminescence: no bias required**
  - **Applicable to unpatterned cells**
- **Emission Intensity ~ lifetime**
  - **Intensity = G * τ**
    (Generation rate * Carrier lifetime)
  - **Fixed generation rate**
    - Intensity ~ lifetime
- **Quantitative lifetime**
  - **Not an absolute measurement**
  - **Calibration with know sample required**
  - **Transient method for calibration**
- **High illumination required**

Trupke et al., PVSC (2008)

Mapping Module Current with EL

- EL emission proportional to local current
  - Forward bias, image in NIR



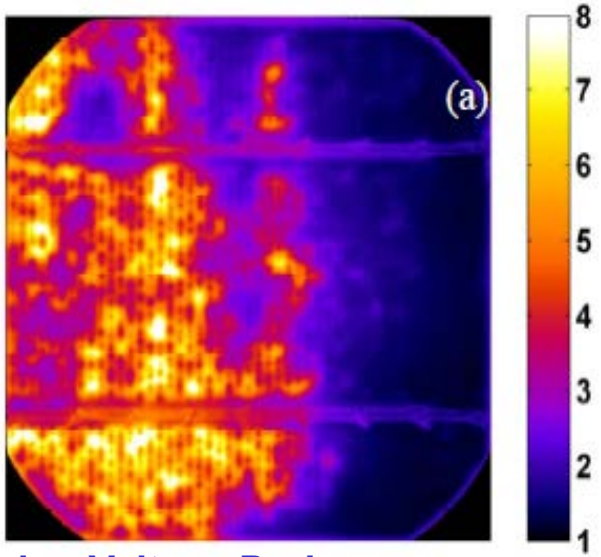
Non-uniform EL emission of cell

Broken contact lines on cell

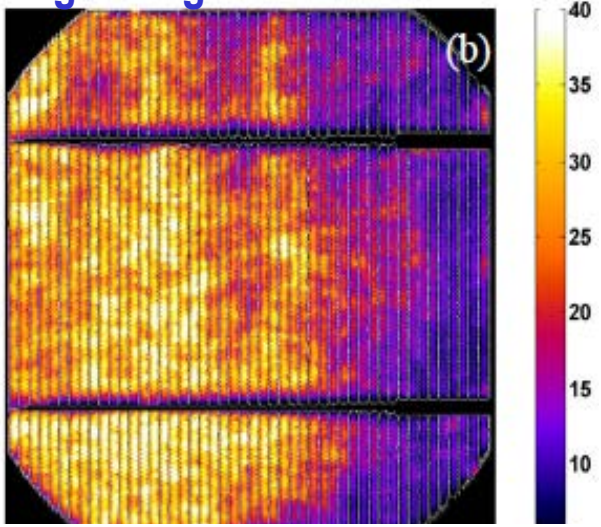
Electroluminescence intensity ~ current → Detect local breaks / cracks

Near IR EL: Series/shunt Resistance Mapping

Series resistance from EL



Scanning Voltage Probe



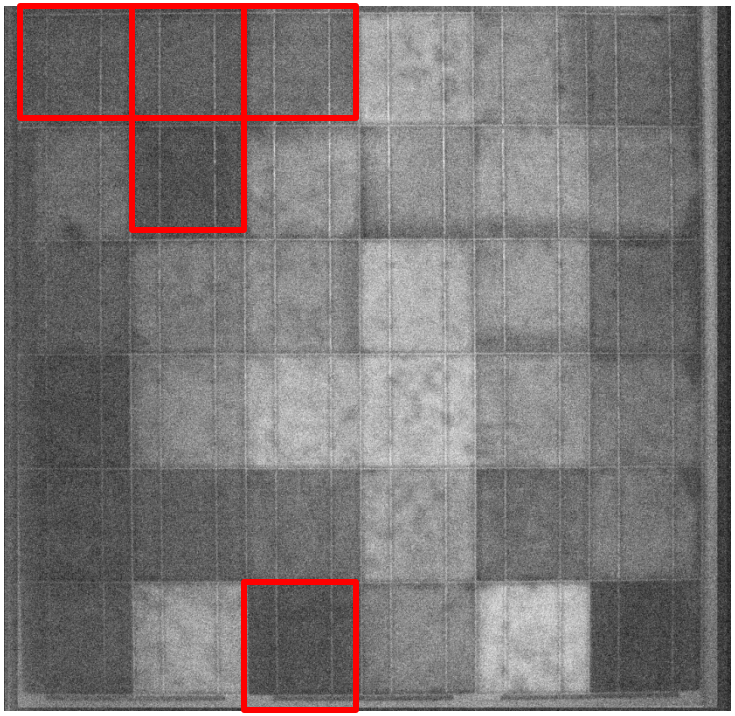
- **EL sensitive to local current and voltage**
  - Carrier diffusion length extraction
  - Diffusion depends on potential
- **Quantitative series and shunt resistance**
  - Difficult to determine why region is dark
  - Possible to extract voltage
  - Non-linear IV dependence → modeling
- **Qualitative: Bias dependence**
  - Current has turn-on voltage
  - Region always dark = High series R
  - Region dark at low current = Low shunt R

Trupke et al., Appl. Phys. Lett 90, 093506 (2007)

Electroluminescence Applied to Modules

- EL emission has turn on voltage near Voc
  - Shunted cells = lower Voltage at given current relative to good cells
  - Cell-cell contrast will depend on bias current

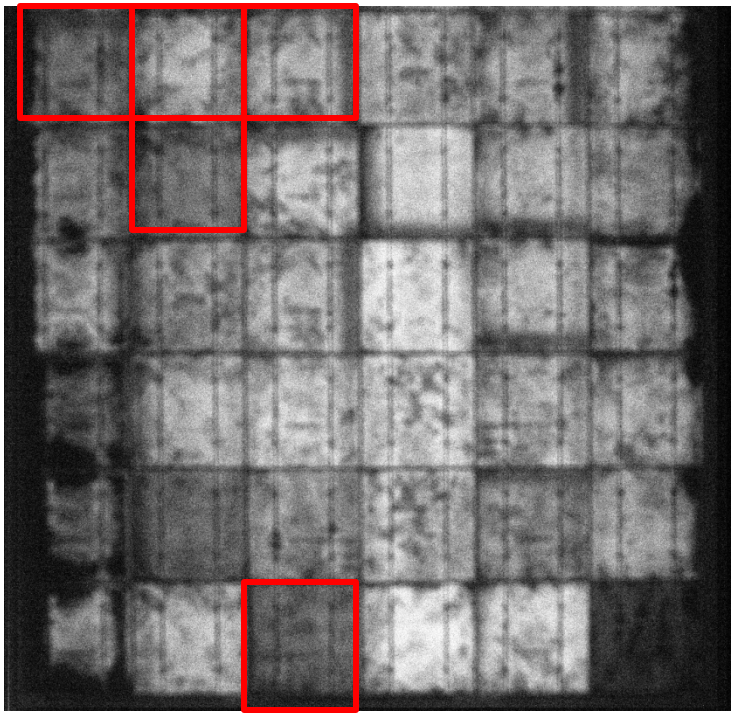
0.75 A / 35V Bias



Bad cells at low bias

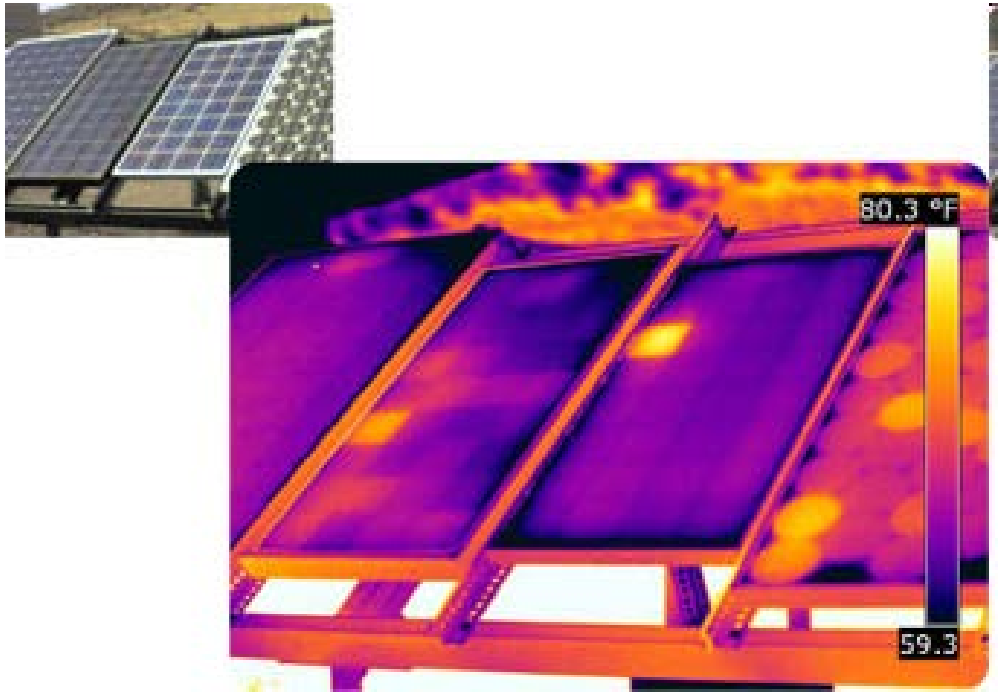
Cells "OK" at high bias

3 A / 45V Bias



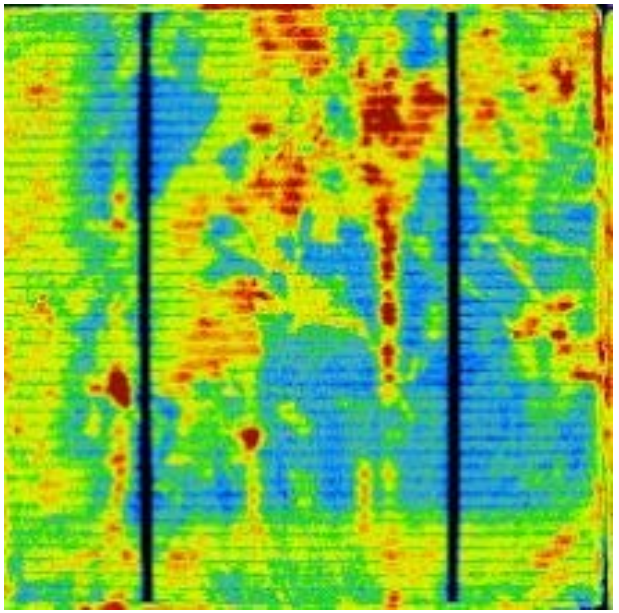
Far-IR: Thermal Emission Imaging

Infrared imaging of modules:
Shunted cells



www.movitherm.com

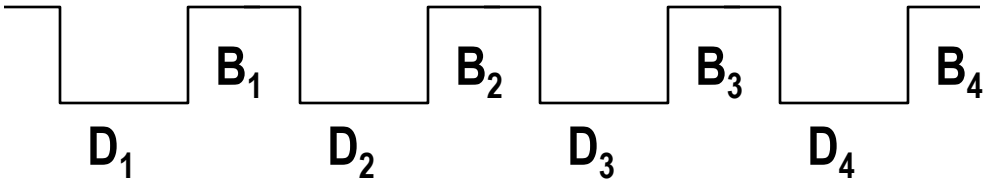
Infrared imaging of cells:
Local shunts / weak diodes



Infrared Imaging: industry standard for PV analysis

Lock-in Thermography

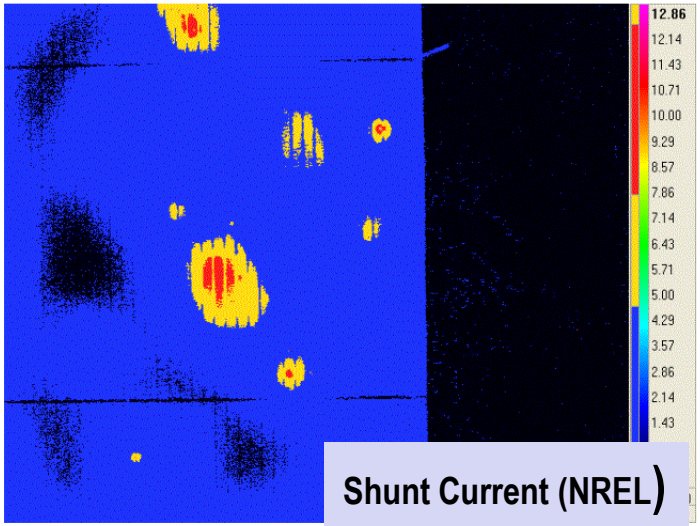
- **Static IR images: Thermal Spreading**
  - Temperature wants to be uniform = low resolution
- **Lock-in thermography: pulses**



Series of Dark images (D)
Series of Bright images (B)
Image = Σ_i [Bi – Di]

  - Uses high speed infrared CCD cameras
  - <1mK thermal resolution
  - Spatial resolution =
    - Thermal Diffusion / frequency ~ 3mm
- **Very quantitative (variables scale out)**
  - Shunt current, shunt IV

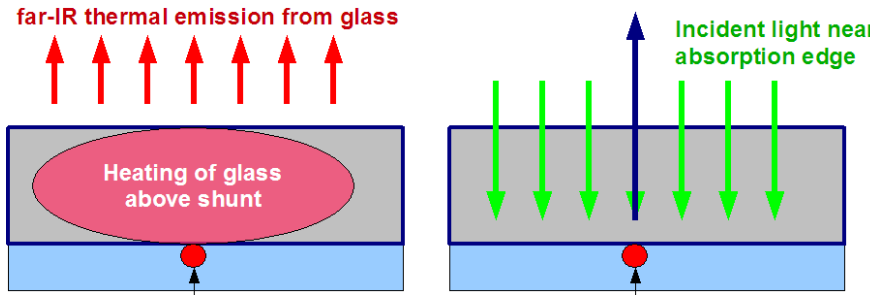
$$I_{\text{shunt}} = \frac{I_{\text{cell}}\left(\overline{T}^{-90^{\circ}}_{\text{shunt}} - \overline{T}^{-90^{\circ}}_{\text{hom}}\right)}{\overline{T}^{-90^{\circ}}_{\text{cell}}} \frac{A_{\text{shunt}}}{A_{\text{cell}}}$$



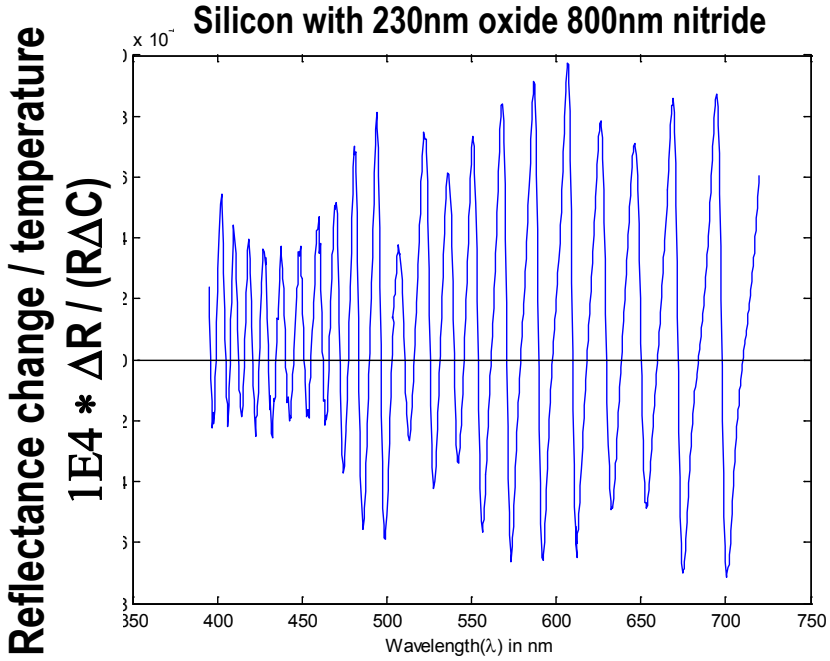
Shunt Current (NREL)

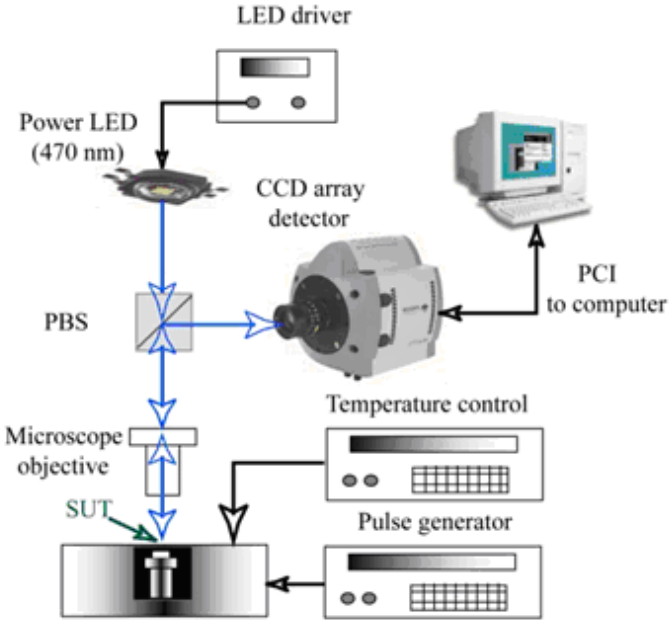
Infrared Limitations

- **Most PV glass is not transparent in IR**
  - Imaging glass, not defects
  - Limits resolution to thickness of glass
- **Imaging is in infrared = lost physics**



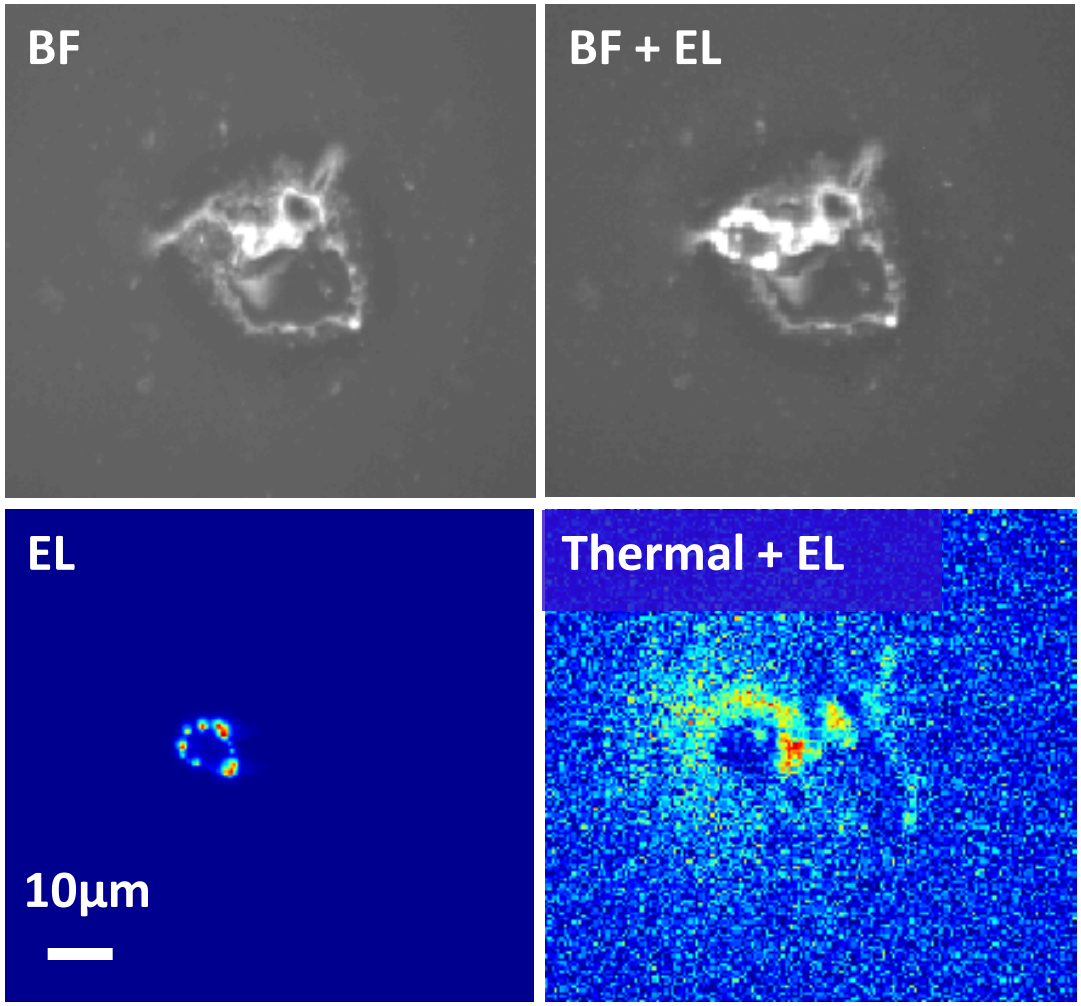
Thermalreflectance imaging in visible





Thermalreflectance imaging (see poster)

- **Thermal imaging in visible**
  - **Glass is transparent**
  - **Combined images**
    - brightfield
    - electroluminescence
    - thermal
  - **Silicon camera**
    - high pixel count
    - inexpensive
- **Example for poly-Si**
- **Available as tool or service**



PARTIAL list of Failure Analysis Service Companies

- **NOT an endorsement by UCSC or NREL**
  - North American companies that service electronics and photonics
  - Incomplete list (I am sorry for those that I left off)

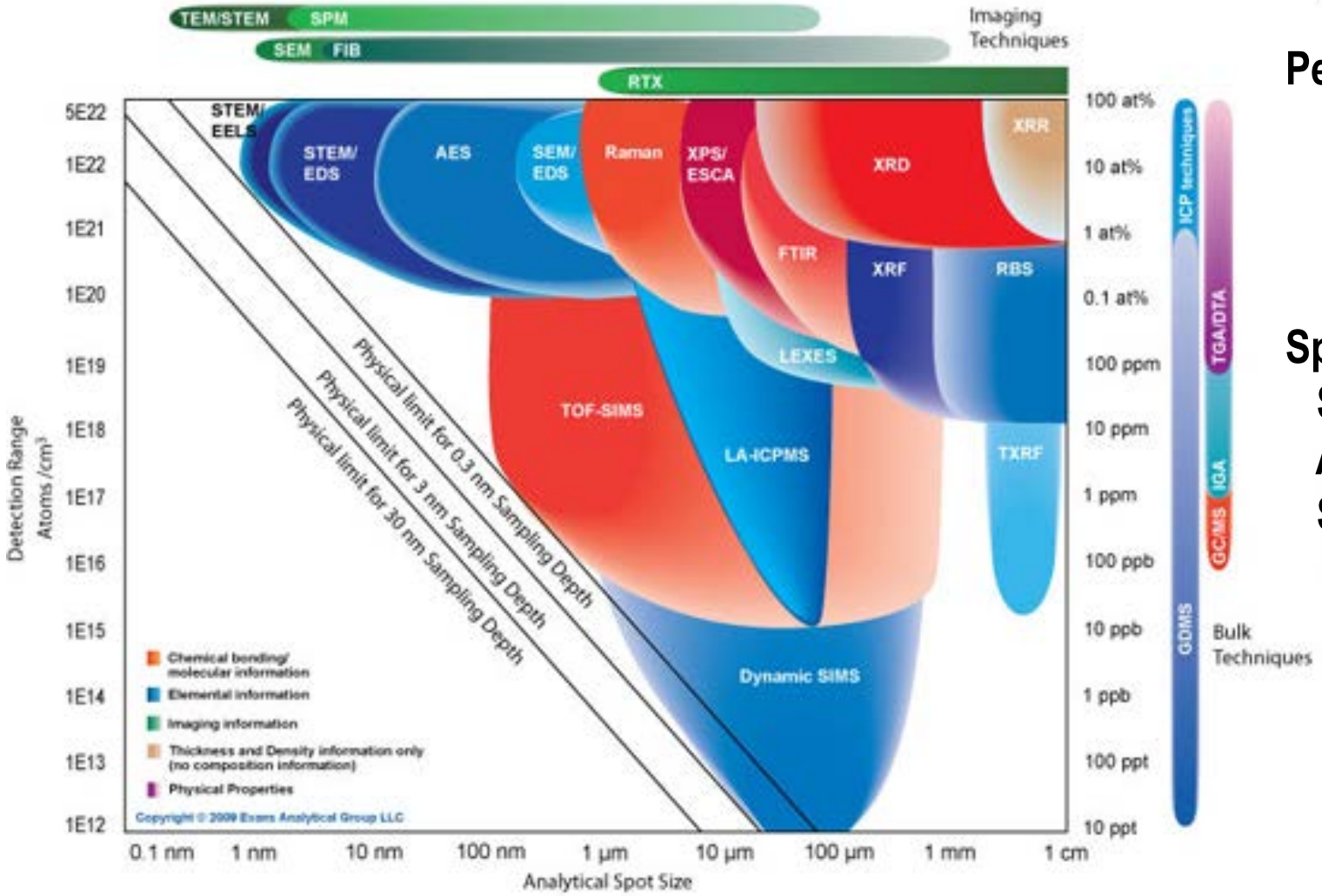
Company Site (Alphabetical order)	State	Scanning Acoustic Imageing	Florescence Dye or Dye and Pry	Emission Microscopy (EL)	Scanning Optical (LBIC/OBRICH)	Photoluminescence	Thermal – Infrared or Liquid Crystal	Thermal – Thermalreflectance	Voltage Contrast SEM	X-ray imaging, 2-D and 3-D
www.alenasimaging.com	MA							■		
www.apvresearch.com	CA			■		■		■		
www.chiptargets.com	TX	■	■	■			■			
www.ial-fa.com	CO	■		■					■	■
www.icchippackaging.com	TX	■	■							■
www.icfailureanalysis.com	CA	■		■	■					■
www.martintesting.com	CA	■					■			■
www.mefas.com	CA	■		■			■		■	■
www.movitherm.com	CA						■			
www.muanalysis.com	ON			■	■	■	■			
www.ors-labs.com	NY	■					■			■
www.reltron.com	CA			■			■			
www.rigalab.com	CA		■		■				■	■
www.svtc.com	CA								■	

Microelectronics and PV failure Analysis

- Most microelectronics techniques applicable to PV industry
  - Only acronym is different
- Different requirements for each industry
  - Focus for microelectronics is resolution
  - Focus of photovoltaics is throughput and wide area
- Future: two industries will converge
  - Transition to thin film technology from crystalline Si
  - Focus on yield improvement
  - Focus on reliability improvement

Physical Microanalysis

- Wide range of surface / composition analysis



Penetrating probes
- XRF/XRD/XRR
- RBS
- FTIR

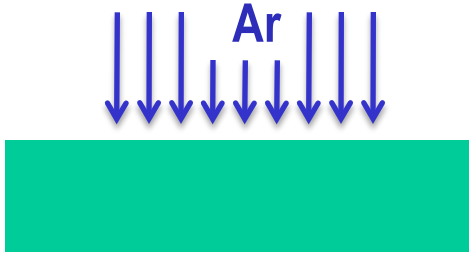
Sputtered / surface
- SIMS
- AES
- SEM/EDS

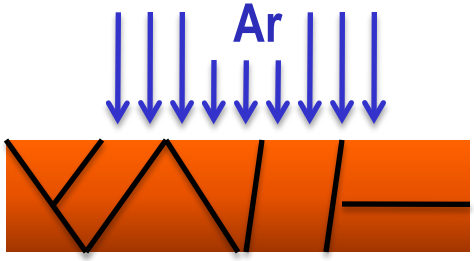
From EAG Inc. (www.cea.com)

Warning with sputtered microanalysis probes

Sputtering profile for single vs. poly crystalline samples

Sputter profile single crystal material





Sputter profile poly-crystal material

Sputter profile Uniform





Sputter rate varies with orientation (channeling)

Sputter profile broadened by redeposition (minor)





VERY broad sputter profile

US DOE, Office of Basic Energy Sciences

CAMP
Center for Advanced Molecular Photovoltaics
STANFORD UNIVERSITY

Adhesion and Thermomechanical Reliability for PV Devices and Modules

Vitali Brand, Chris Bruner, Fernando Novoa, Jeff Yang *(PhD students)*
Monika Kummel *(Post Doc)*
Reinhold H. Dauskardt (dauskardt@stanford.edu)

Collaborators:

Craig Peters, Roman Gysel and Mike McGehee (Stanford)

Uraib Aboudi and Peter Peumans (Stanford)

David Miller, Michael Kempe and Sarah Kurtz (NREL)

William Hou and Yang Yang (UCLA)

Industry collaborators include Colin Reese, Shawn Scully and Juanita Kurtin (SpectraWatt), Steve Lin (Vitex), Matthew Robinson (Nanosolar), Christine McGuiness and Darin Laird (Plextronics).

Solar Outlook

Then…

1. Efficiency
2. Reliability
3. Cost

To make a difference…

1. Cost
2. Reliability
3. Efficiency

- Engineer durable solar technologies with robust and predictable lifetimes. Start early in development – avoid roadblocks.
- Leverage from reliability physics in microelectronics – thin-film metrologies, kinetic models, accelerated tests, life prediction.
- Are degradation processes coupled and how?
- Kinetic models for damage evolution - basis for life prediction and accelerated testing (T, environment, stress, solar flux, etc.)
- Effective defensive strategies – e.g. transparent barriers with anti-reflective properties.

Degradation and Reliability of PV Devices and Modules

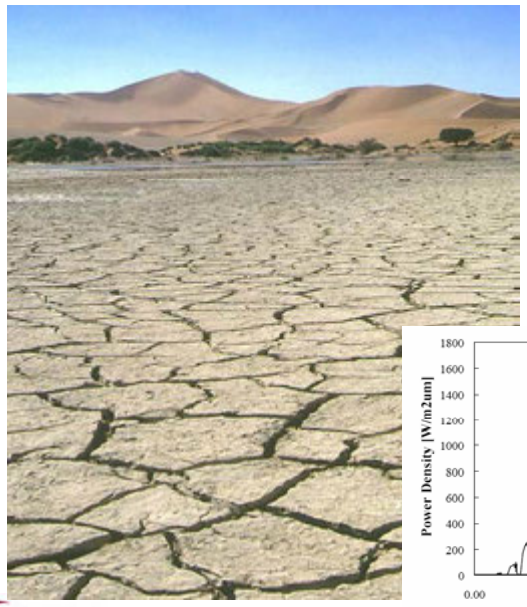
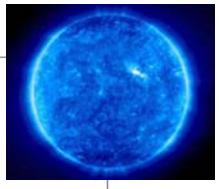


photo from Keele University

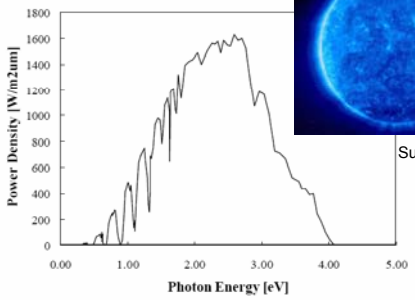
Severe operating environments.

Exposure to thermal cycling, stress, moisture, chemically active environmental species, and UV.

Uncertain degradation kinetics and reliability models.

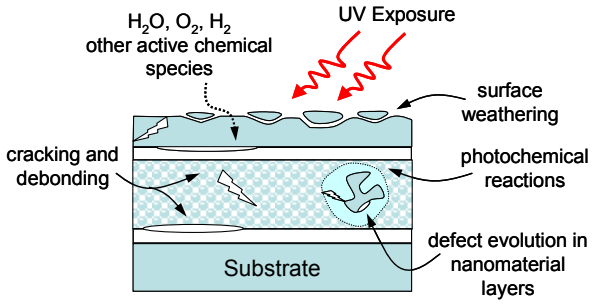


Sun in UV



Solar spectrum from B. Van Zeghbroeck, U. Colorado

Degradation and Reliability of PV Devices and Modules



Severe operating environments.

Exposure to thermal cycling, stress, moisture, chemically active environmental species, and UV.

Uncertain degradation kinetics and reliability models.

Activation Energies for Bond Rupture:

VDW ~ 0.001 - .4 eV/bond

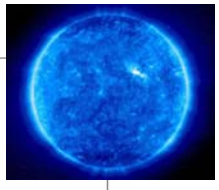
H-bonds ~ .1 - .4 eV/bond

Ester Hydrolysis (100% RH)

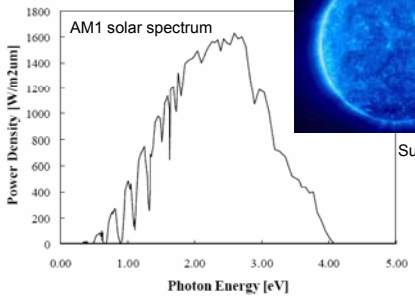
E* ~ .81 eV/bond

SiO_2 cracking in water

E* ~ 1.39 eV/bond

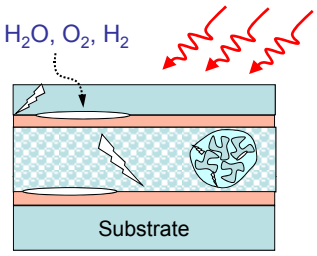


Sun in UV



Solar spectrum from B. Van Zeghbroeck, U. Colorado

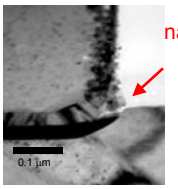
Mechanics of Damage Evolution



Damage occurs when…

$$\underbrace{G}_{\text{crack driving "force"}} \geq \underbrace{G_c\left[J/m^2\right]}_{\text{cracking "resistance"}}$$

- Lower thin-film stresses – driving force for cracking $G = \dfrac{Z\sigma_f^2 h_f}{\overline{E}_f}$
  - nano-scale defect
  - geometry/structure effects Z
  - low modulus organic films
  - multiple films, packaging, flexing



- Optimize fracture resistance G_c – cohesion of layers
  - adhesion of interfaces

Evolution of Defects and Device Reliability

absence of chemically active environmental species, damage propagates if

$$G \geq G_c\left[J/m^2\right]$$

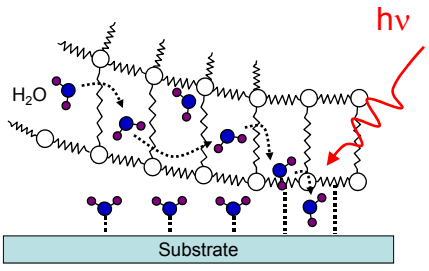
presence of chemical species and photons, damage propagates even if

$$G < G_c\left[J/m^2\right]$$

environment and stress accelerates defect evolution

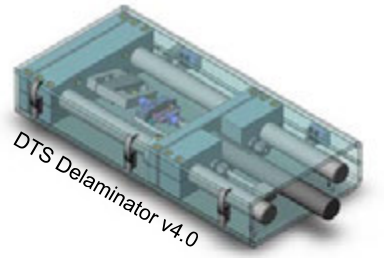
Role of coupled kinetic parameters:

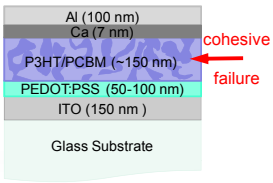
- *mechanical stress*
- *temperature*
- *environmental species*
- *photons (photochemical reactions)*

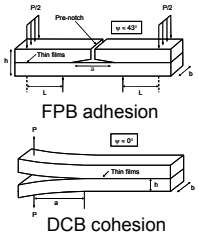


STANFORD MATERIALS SCIENCE AND ENGINEERING

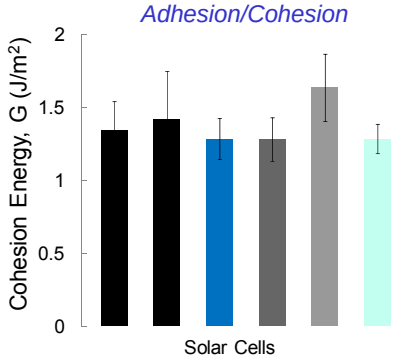
Quantitative Adhesion/Cohesion and Debond Kinetics



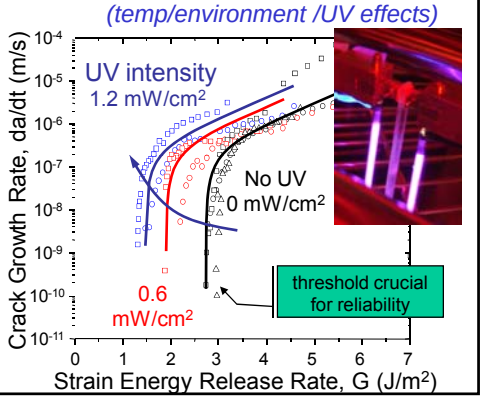




Adhesion/Cohesion



Degradation Kinetics (temp/environment /UV effects)



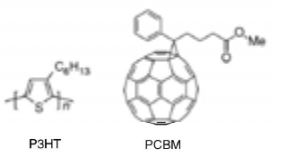
System and support dauskardt@stanford.edu

Inherent Solar Cell Thermomechanical Reliability, G_c

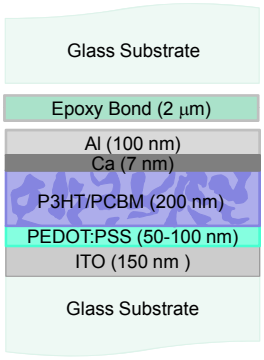
Grad students: Vitali Brand, Jeff Yang and Chris Bruner

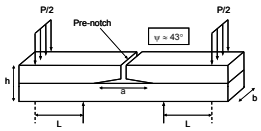
Adhesion/Cohesion Sample Preparation

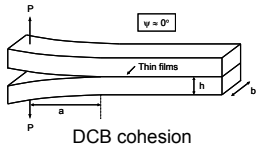
Thin films sandwiched between elastic substrates



Gunes, et. Al. *Chem. Rev.* 2007.



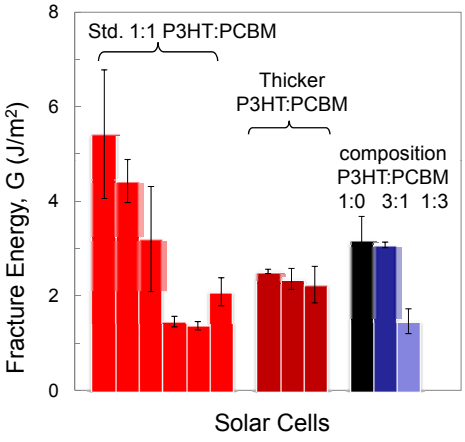


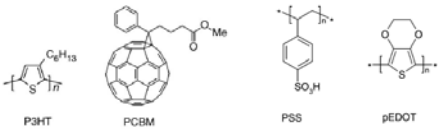


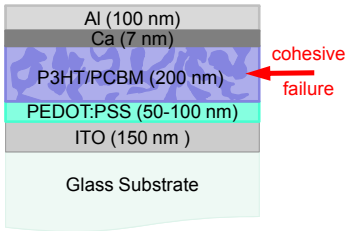
Fabricated 4-point bend adhesion and DCB cohesion test structures using standard epoxy bonding techniques.

Similar transparent glass substrates on each side.

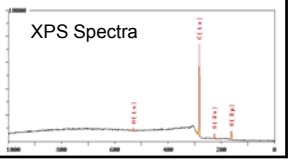
Adhesion/Cohesion of P3HT/PCBM Structures



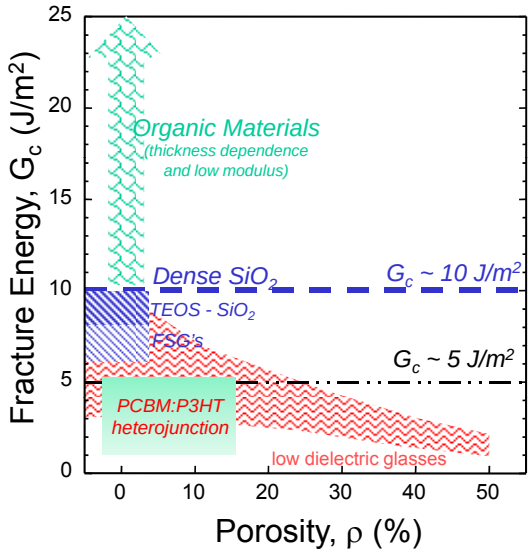


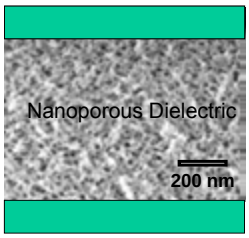


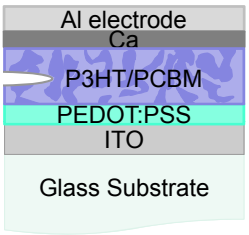
- XPS reveals similar debond path for DCB and 4-pt bend samples
- C ~ 92%, S ~ 6%, O ~ 2%
- Suggests cohesive failure in PCBM:P3HT layer



Cohesive Fracture Properties of Dielectrics

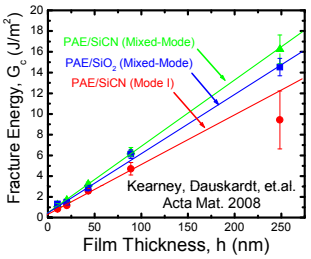




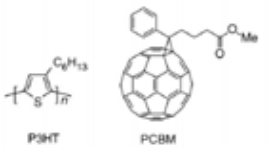


Factors Effecting Cohesion of P3HT/PCBM Layers

- Heterojunction layer thickness
  - cohesion in polymer layers is sensitive to layer thickness
  - plastic energy dissipation in organic layers

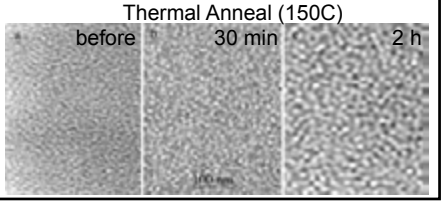


- Composition of the heterojunction layer
  - limited bonding to fullerene – expect low cohesion
  - preliminary measurements indicate higher ratios of P3HT to PCBM make stronger active layer



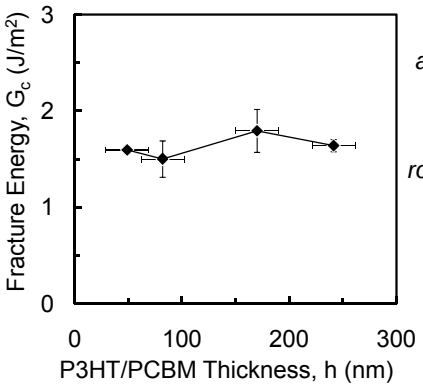
- Annealing
  - morphology of the P3HT:PCBM film changes with annealing, expect effect morphology on cohesion

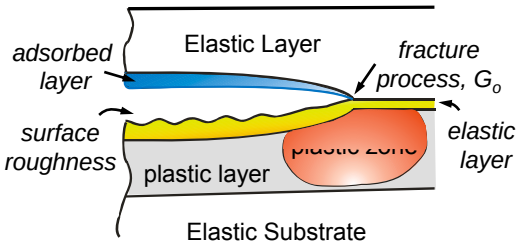
Thermal Anneal (150C)

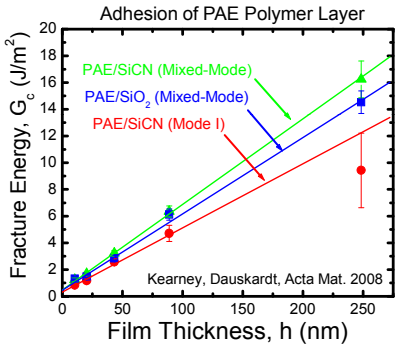


TEM of P3HT:PCBM film
Heeger, et. Al. Adv. Func. Mat. 2005.

Effect of Thickness of BHJ on Cohesion







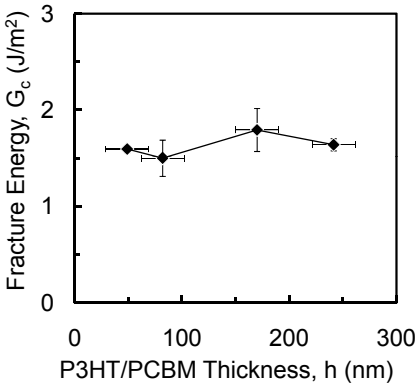
interface chemistry

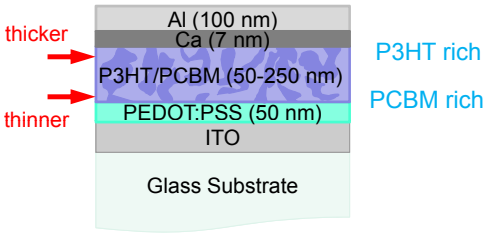
$$G_{total} = G_o + G_{zone}$$

frictional contact
ductile adjacent layer

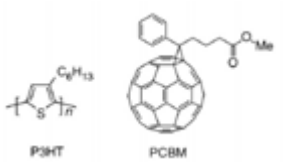
STANFORD MATERIALS SCIENCE AND ENGINEERING

Effect of Thickness of BHJ on Cohesion





Segregation of PCBM towards bottom PEDOT due to more polar nature of PCBM compared to P3HT

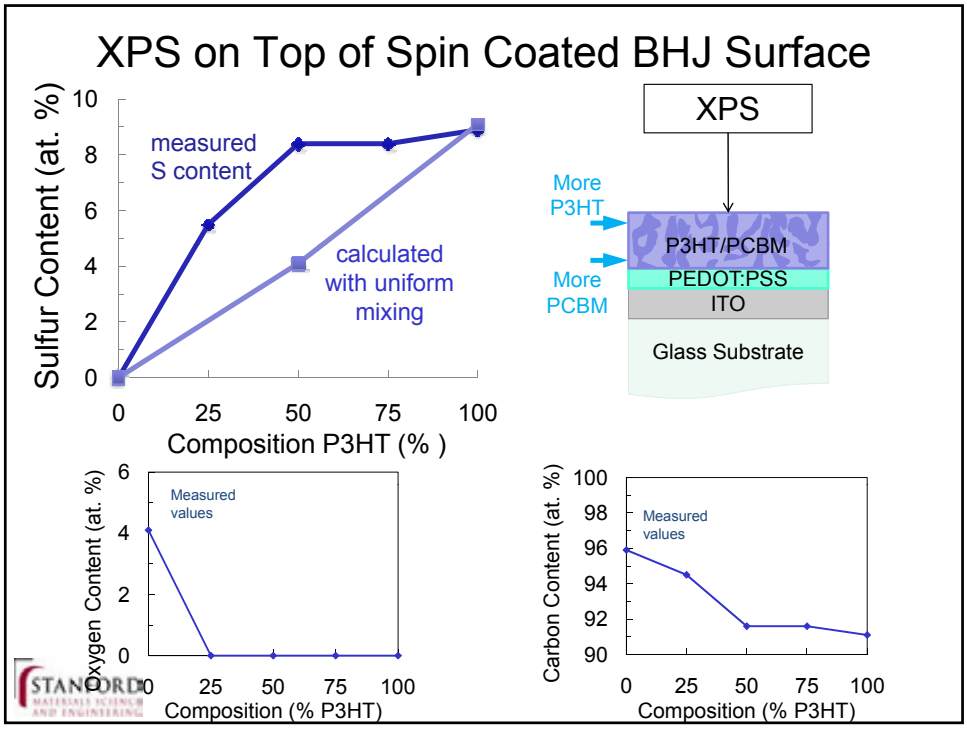


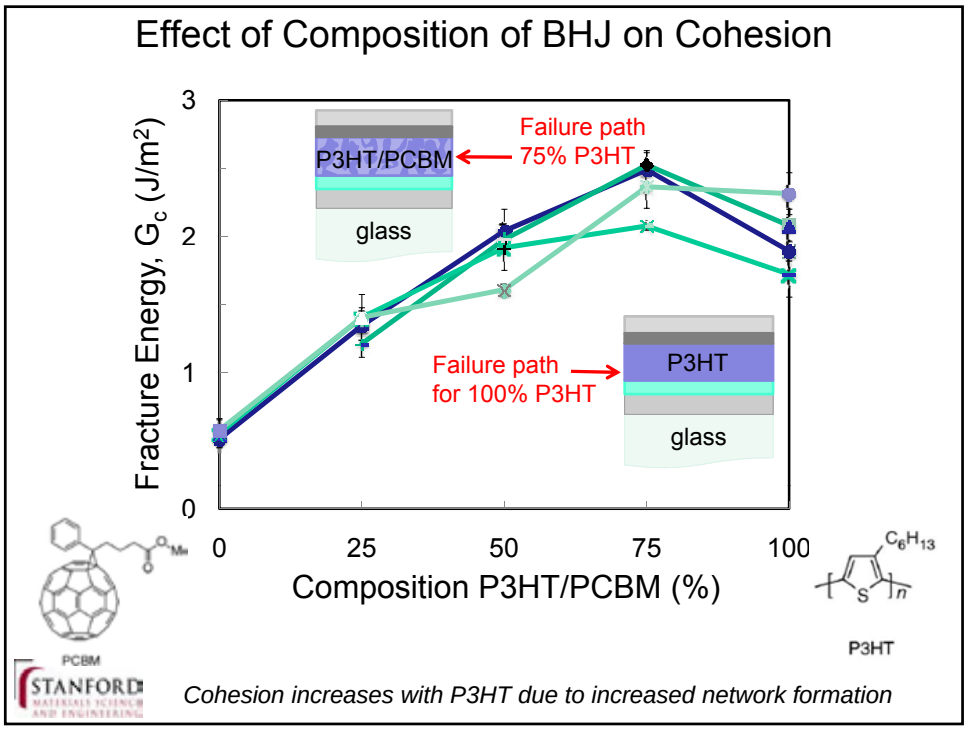
interface chemistry

$$G_{total} = G_o + G_{zone}$$

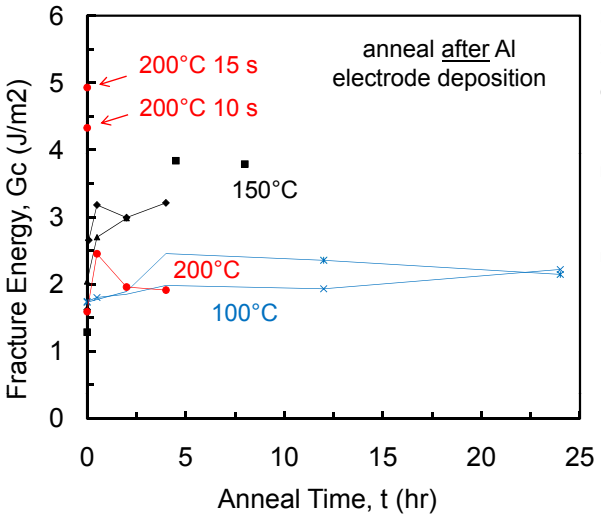
frictional contact
ductile adjacent layer

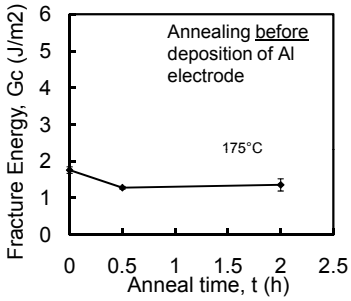
STANFORD MATERIALS SCIENCE AND ENGINEERING


XPS on Top of Spin Coated BHJ Surface
Sulfur Content (at. %)
measured
S content
calculated
with uniform
mixing
Composition P3HT (%)
XPS
More
P3HT
More
PCBM
P3HT/PCBM
PEDOT:PSS
ITO
Glass Substrate
Oxygen Content (at. %)
Measured
values
Composition (% P3HT)
Carbon Content (at. %)
Measured
values
Composition (% P3HT)
STANFORD


Effect of Composition of BHJ on Cohesion
Fracture Energy, G_c (J/m^2)
P3HT/PCBM
glass
Failure path
75% P3HT
Failure path
for 100% P3HT
P3HT
glass
Composition P3HT/PCBM (%)
PCBM
P3HT
STANFORD
Cohesion increases with P3HT due to increased network formation

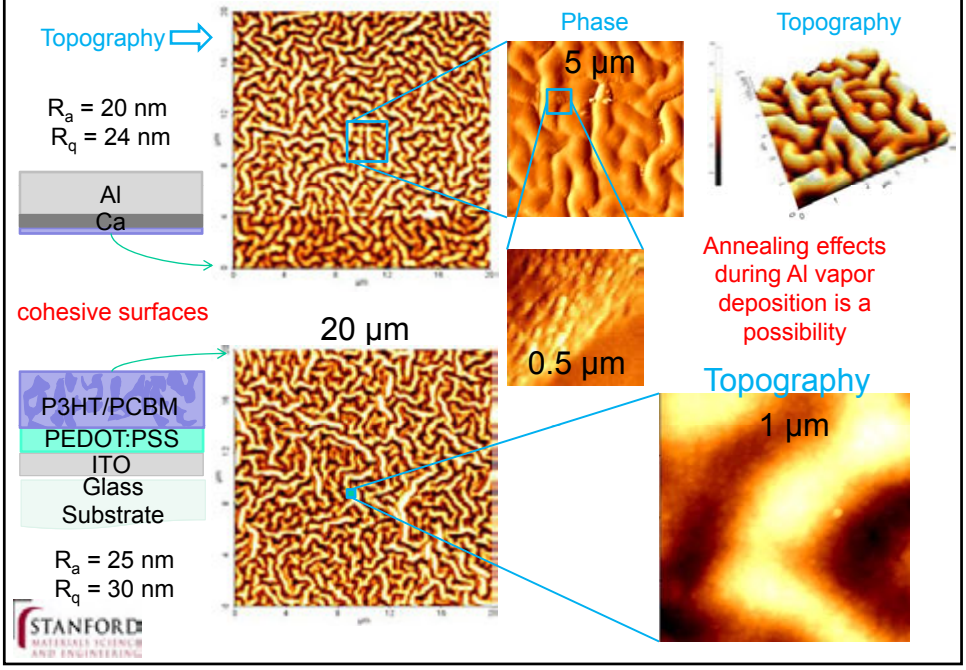
Effect of BHJ Annealing





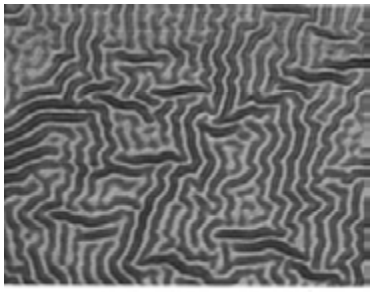
- 150°C anneal increases cohesion significantly
- 200°C anneal degrades the cell
- Anneal before Al deposition does not increase cohesion

AFM of Failure Path Near Ca Interface

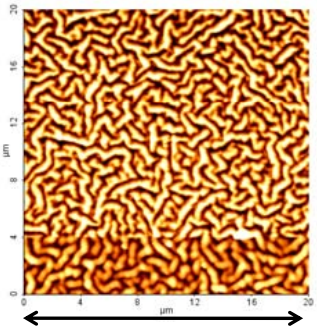


Buckling and Wrinkling in Stressed Films

Lacour et al. Appl. Phys. Lett., Vol. 82, No. 15, 14 April 2003

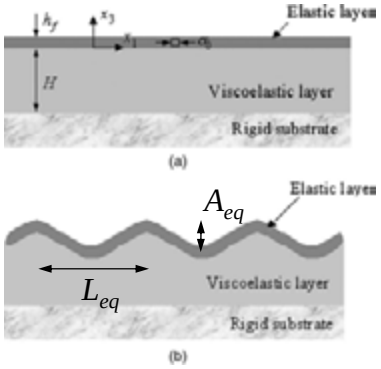


Optical image of the wave pattern formed in a 100-nm-thick gold film evaporated on a 1-mm-thick PDMS membrane



Buckling/wrinkling instability at the BHJ/Ca interface resulting from the vapor deposition of Al

Wrinkling of Stressed Elastic Film on Viscoelastic Layer



Equilibrium amplitude of sinusoidal wrinkle:

$$A_{eq} = \frac{2\sqrt{1-\nu_f^2}}{k}\left[-\frac{\sigma_0}{E_f} - \frac{(kh_f)^2}{12(1-\nu_f^2)} - \frac{2(1-\nu)}{1-2\nu}\frac{\mu_\infty}{E_f}\frac{1}{k^2 H h_f}\right]^{1/2}$$

Equilibrium wrinkle wavelength: $k=2/L_{eq}$

$$L_{eq} = \pi h_f\left[\frac{2(1-2\nu)}{3(1-\nu)(1-\nu_f^2)}\frac{E_f}{\mu_\infty}\frac{H}{h_f}\right]^{1/4}$$

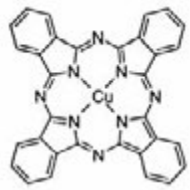
- *Layers initially flat - elastic layer with* in-plane biaxial compressive stress σ_0.
- Wrinkling to relax stress in elastic layer – viscoelastic layer deforms to maintain conformality.
- μ_∞/E_f is ratio of rubbery modulus of the viscoelastic layer and the elastic modulus of the elastic layer.
- k is the wavevector: $k = 2/L_{eq}$

Huang et al. Journal of App. Mech. Nov. 2005, Vol. 72

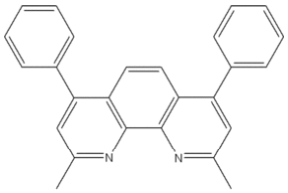
Small Molecule Solar Cell Thin Films



C60

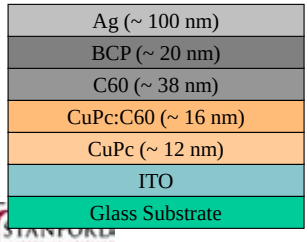


CuPc

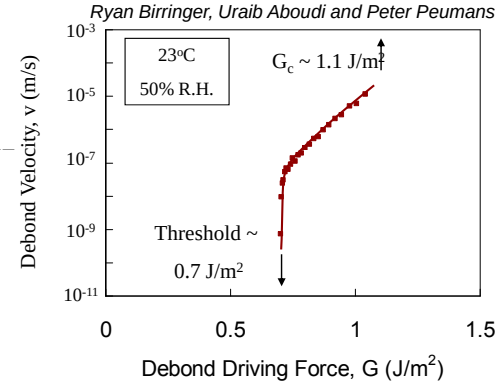


BCP

$$G_c = 1.1 \pm 0.4 \ J/m^2$$



Ryan Birringer, Uraib Aboudi and Peter Peumans



Molecular Bond Rupture Kinetics (Barrier Films)

Grad student: Fernando Novoa and Monika Kummel

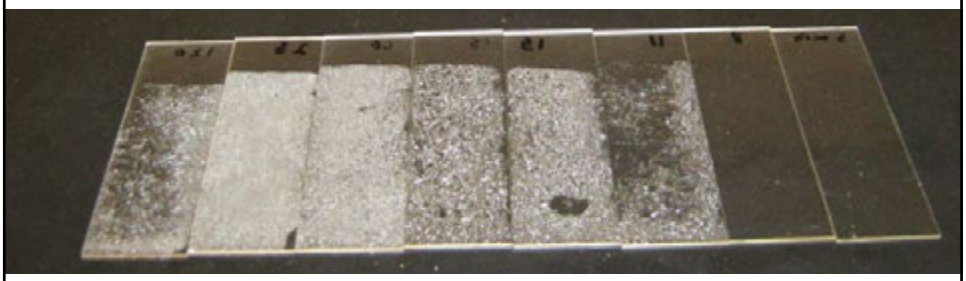
$$G < G_c \left[J/m^2 \right]$$

environment and stress accelerates defect evolution

Weathering Test of Polysiloxane Barrier

UV exposure: 28 mW/cm^2 at 6 mm UV-257nm

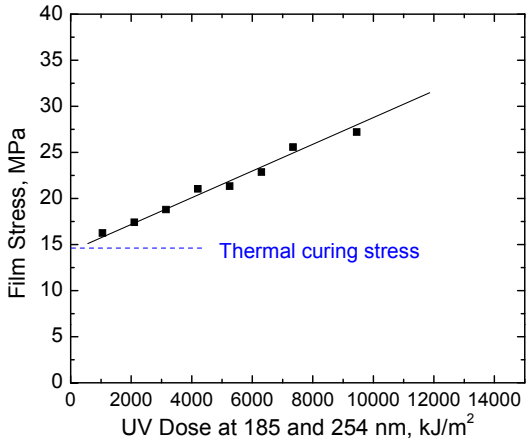
120 min……15 min……5 min



STANFORD MATERIALS SCIENCE AND ENGINEERING

Weathering Test of Polysiloxane Barrier

Film Stress Accumulation with UV Exposure



Driving force for damage:

$$G = \frac{Z\sigma_f^2 h_f}{\overline{E}_f}$$



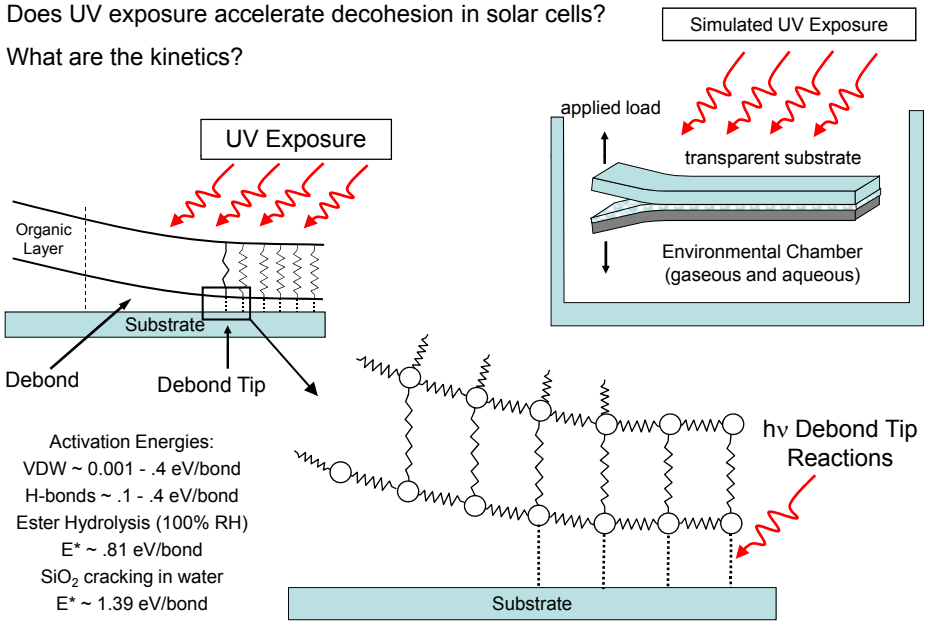
STANFORD MATERIALS SCIENCE AND ENGINEERING

Kamer and Dauskardt - 2009

Environment and Stress Accelerates Damage

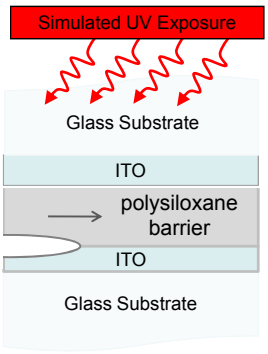
Does UV exposure accelerate decohesion in solar cells?

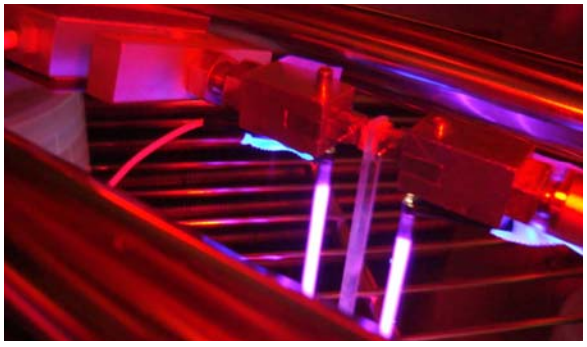
What are the kinetics?

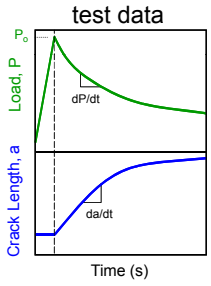


Activation Energies:
VDW ~ 0.001 - .4 eV/bond
H-bonds ~ .1 - .4 eV/bond
Ester Hydrolysis (100% RH)
E* ~ .81 eV/bond
SiO_2 cracking in water
E* ~ 1.39 eV/bond

Assessing UV and Environment on Debonding Kinetics







DTS Delaminator v4.0
automated load relaxation debond growth analysis

compliance analysis

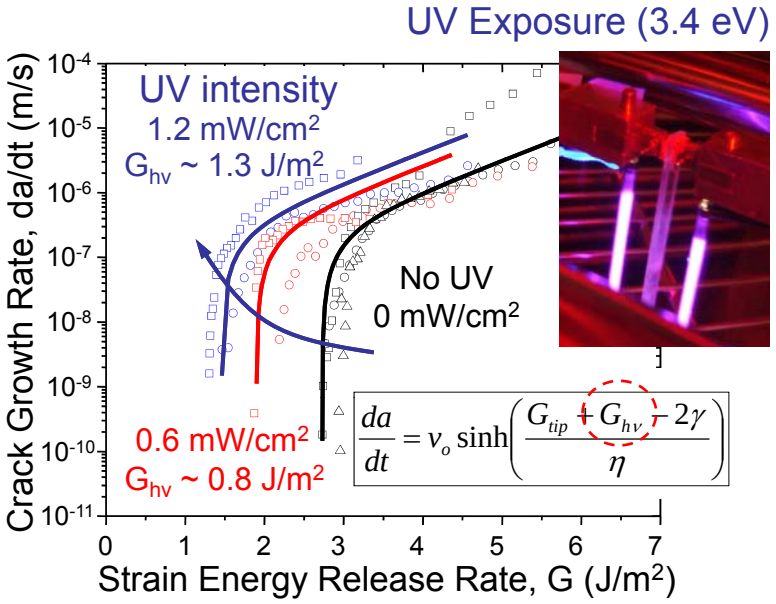
sensitivity to < 10^{-10} m/s

Debonding Kinetics

explore role of:

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

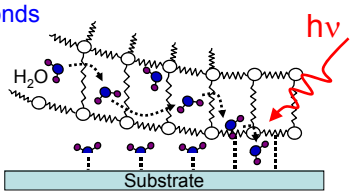
UV Effects on Molecular Bond Rupture



Modeling Bond Rupture Kinetics

- Interaction of moisture with strained debond tip bonds

$$nH_2O + B(\text{debond tip}) \xrightarrow{h\nu} B^*(\text{activated complex})$$



- Atomistic bond rupture models:

$$rate = f_o\left[\exp\left(\frac{-U_+^*}{kT}\right) - \exp\left(\frac{-U_-^*}{kT}\right)\right]$$

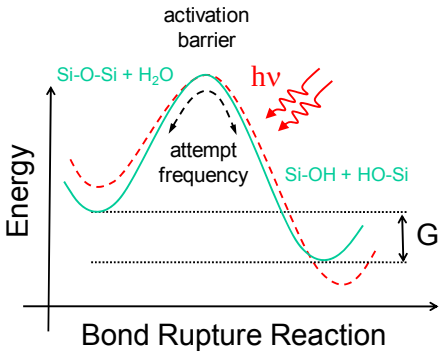
- Damage growth rate:

$$\frac{da}{dt} = v_o \sinh\left(\frac{G_{tip} + G_{h\nu} - 2\gamma}{\eta}\right)$$

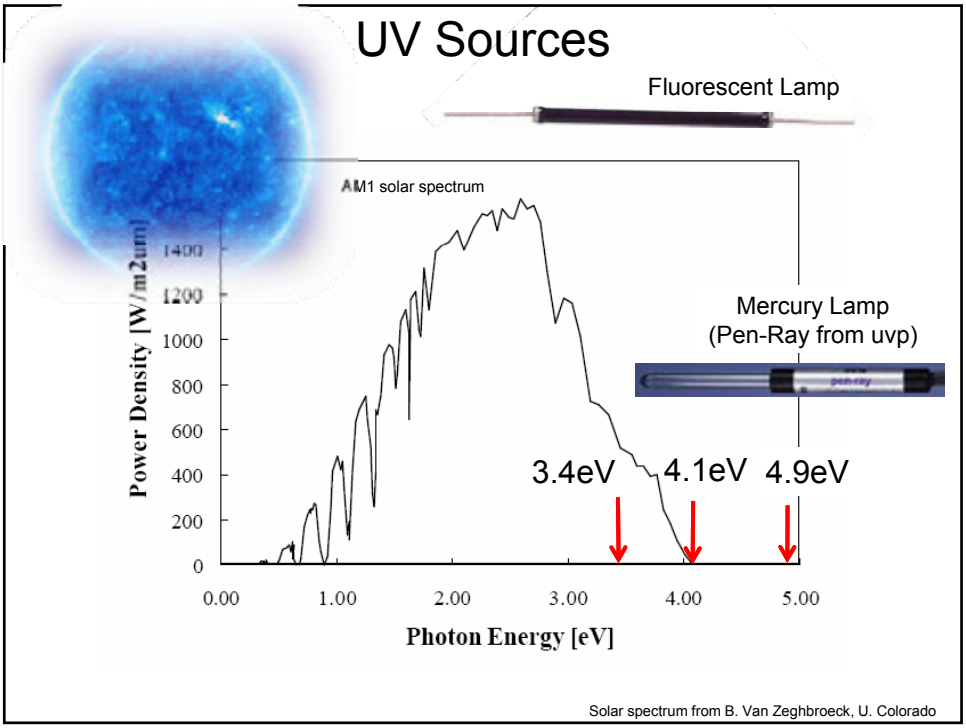
$$v_o = \frac{2 f_o}{Nw} \exp\left(\frac{-u_1}{kT}\right)$$

Bond Rupture Parameters

N - bonds per unit area
u_o - work of rupture
2γ - N u_o
w - crack width
f_o - attempt frequency
u_1 - energy barrier
η - 2NkT

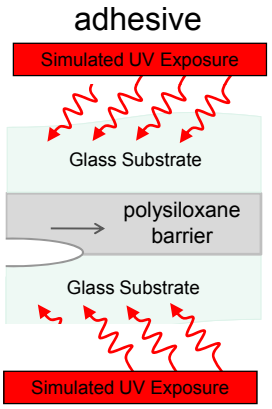


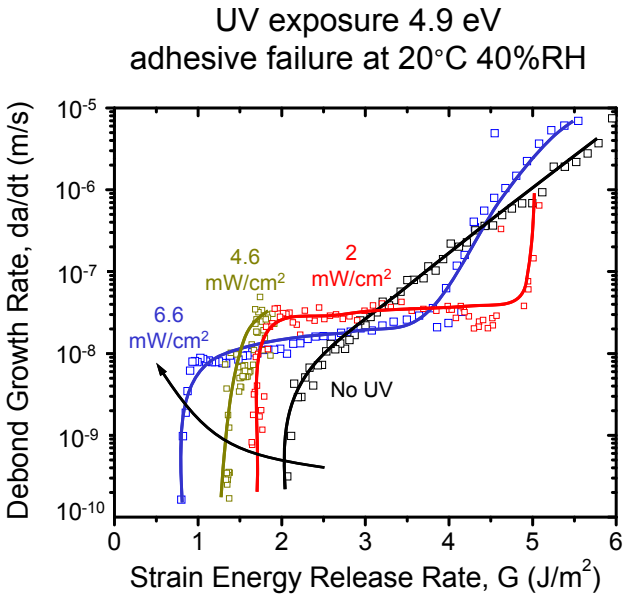
UV Sources



Solar spectrum from B. Van Zeghbroeck, U. Colorado

UV Effects on Molecular Bond Rupture



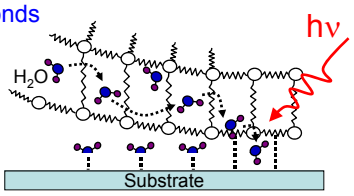


STANFORD MATERIALS SCIENCE AND ENGINEERING

Modeling Bond Rupture Kinetics

- Interaction of moisture with strained debond tip bonds

$$nH_2O + B(\text{debond tip}) \xrightarrow{h\nu} B^*(\text{activated complex})$$



- Atomistic bond rupture models:

$$rate = f_o\left[\exp\left(\frac{-U_+^*}{kT}\right) - \exp\left(\frac{-U_-^*}{kT}\right)\right]$$

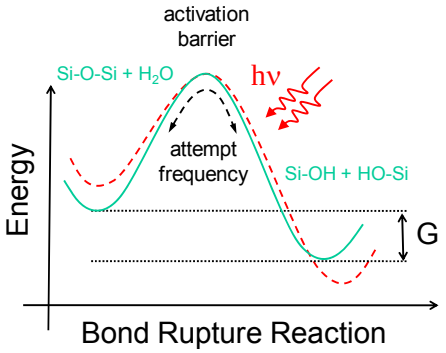
- Damage growth rate:

$$\frac{da}{dt} = v_o \sinh\left(\frac{G_{tip} + G_{h\nu} + 2\gamma}{\eta}\right)$$

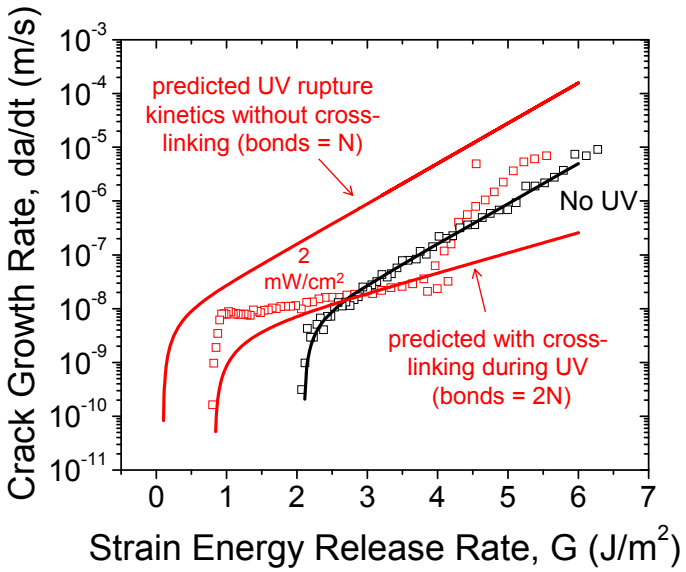
$$v_o = \frac{2 f_o}{Nw} \exp\left(\frac{-u_1}{kT}\right)$$

Bond Rupture Parameters

N - bonds per unit area
u_o - work of rupture
2γ - N u_o
w - crack width
f_o - attempt frequency
u_1 - energy barrier
η - 2NkT

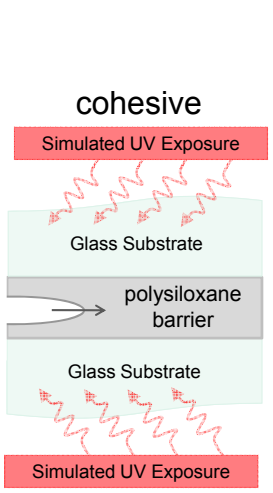


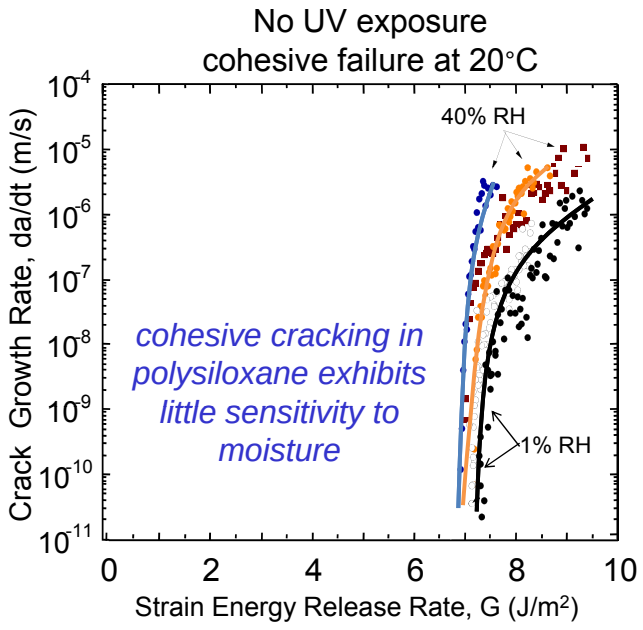
Modeling Bond Rupture Kinetics



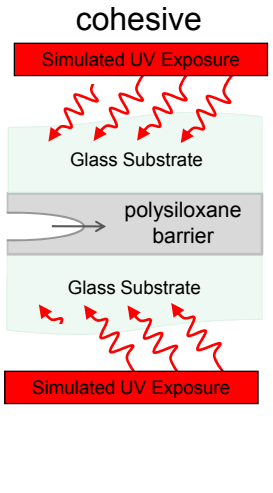
STANFORD MATERIALS SCIENCE AND ENGINEERING

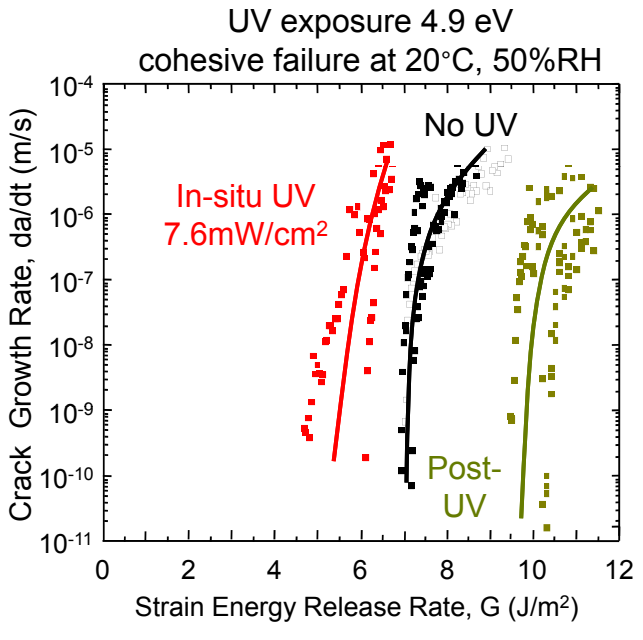
UV Effects on Molecular Bond Rupture





UV Effects on Molecular Bond Rupture

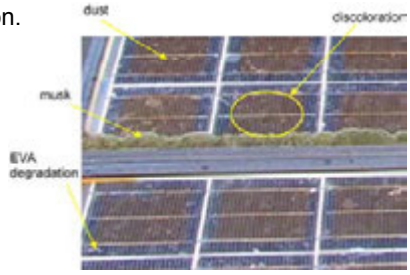




Delamination of EVA-TPE Lamination

- Poly-ethylene vinyl acetate (EVA) copolymer extensively used by solar module manufacturers, particularly for laminating c-Si photovoltaic modules.
- Good optical properties and high adhesive contact with glass cover and Si cells.
- Inexpensive and relatively easy fabrication.

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

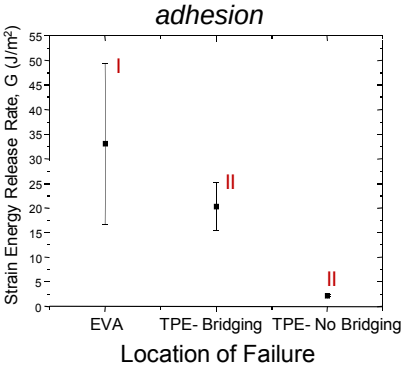


- Delamination can occur between EVA and the front surface of the solar cells.
- More frequent and in hot and humid climates.
- Exposure to atmospheric water and/or ultraviolet radiation leads to EVA decomposition to produce acetic acid, lowering the pH and increasing corrosion.
- EVA Tg ~ -15°C so lower temperatures may result in “ductile-to-brittle” transition in adhesive/cohesive properties.

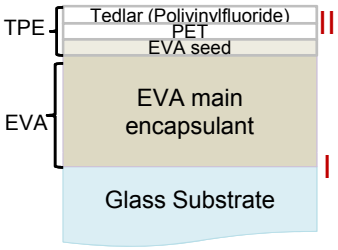
STANFORD MATERIALS SCIENCE AND ENGINEERING

Delamination of EVA-TPE Lamination

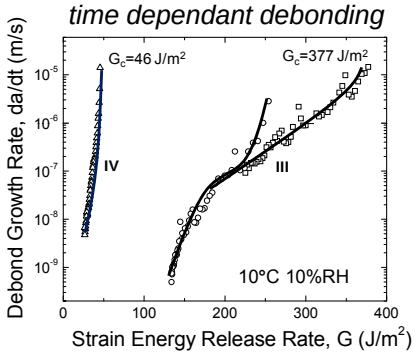
adhesion



Interface “I” located between EVA and Glass
Interface “II” inside the TPE multilayer



time dependant debonding

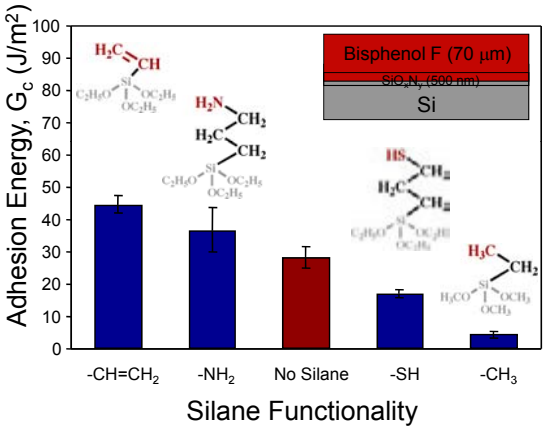


STANFORD MATERIALS SCIENCE AND ENGINEERING

Examples from Microelectronics

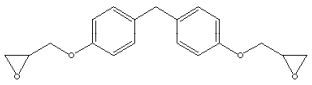
Adhesion of Interfaces in Packages:

Role of Functional Group and Surface Coverage

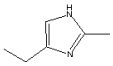


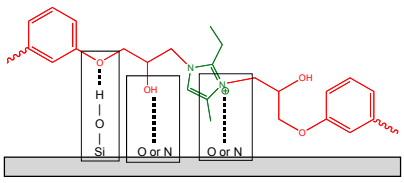
Adhesion energy corrected for surface coverage.

Diglycidyl ether of bisphenol F



2,4-ethyl methyl imidazole

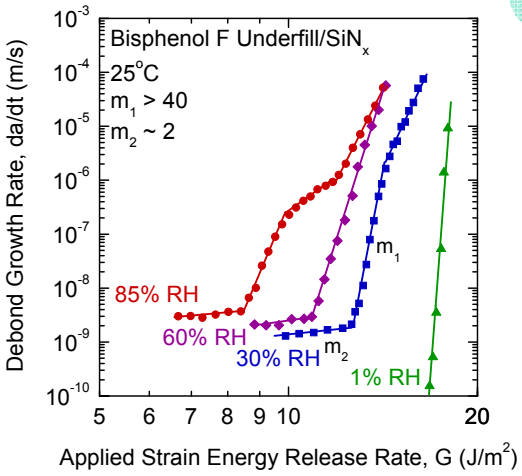


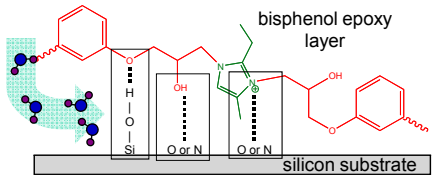


Jenkins, Dauskardt Bravman, J. Adhesion Sci. Tech., 2004.

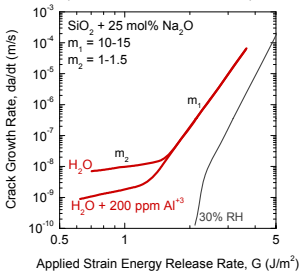
Adhesion and Debonding in Device Packaging

Anomalous Threshold Behavior





Bulk Na_2O Containing Glasses
(Simmons, Freiman, 1981)



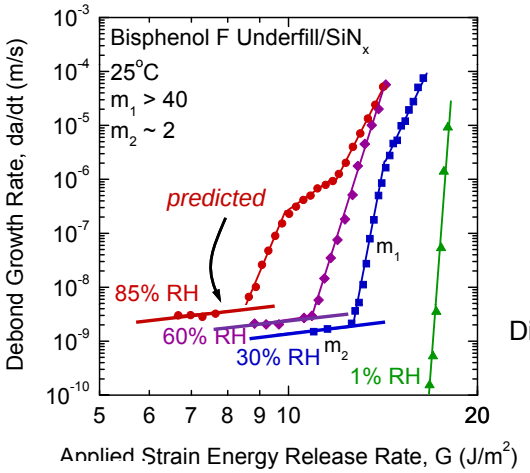
Wang, Sharratt and Dauskardt, Acta Materialia – 2007.

Stress-Dependent Moisture Transport Model

$$D = D_0 \exp(k_2 C + k_3 \sigma) \quad \Leftrightarrow \quad D = D_0 \exp\left(\frac{-E^* + \alpha\sqrt{G}}{RT}\right)$$

Petropolous & Roussis (1978)

$$\frac{da}{dt} = \frac{cux_{H_2O}}{\delta n \Sigma} D_0 \exp\left(\frac{-E^* + \alpha\sqrt{G}}{RT}\right)$$



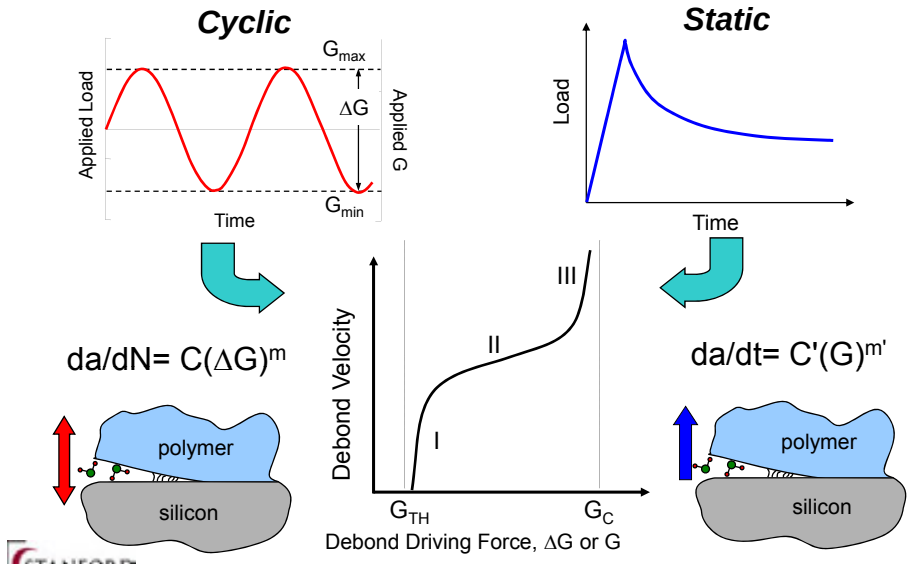
$E^* \sim 25$ kJ/mol

Diffusion in similar epoxy systems:

DGEBA/1,3-BAC (Barral et al, 1996)	31.2 kJ/mol
TGDDM/DDS (Musto et al, 2002)	34 kJ/mol

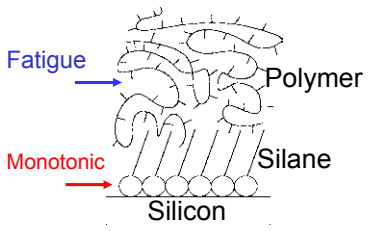
Wang, Sharratt and Dauskardt, Acta Materialia – 2007.

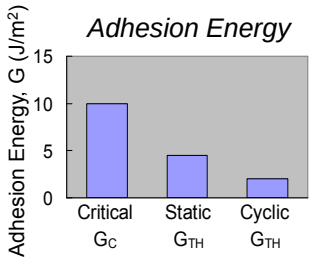
Time Dependent Debonding:
Cyclic and Static Loading

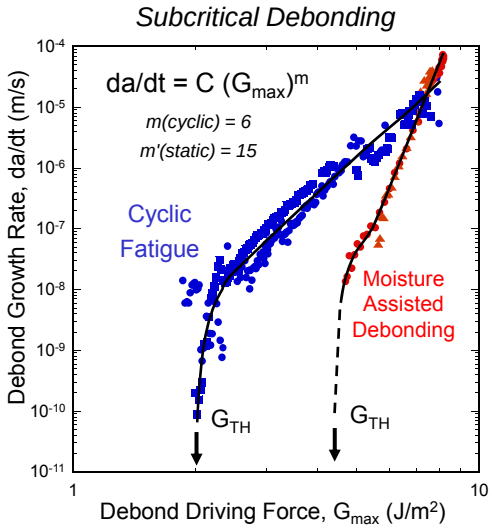


STANFORD MATERIALS SCIENCE AND ENGINEERING

Polymer(BCB)/Silica Subcritical Debonding



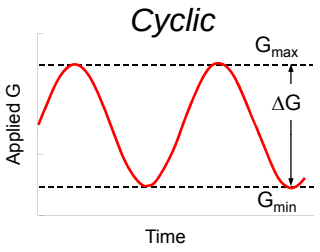




STANFORD MATERIALS SCIENCE AND ENGINEERING

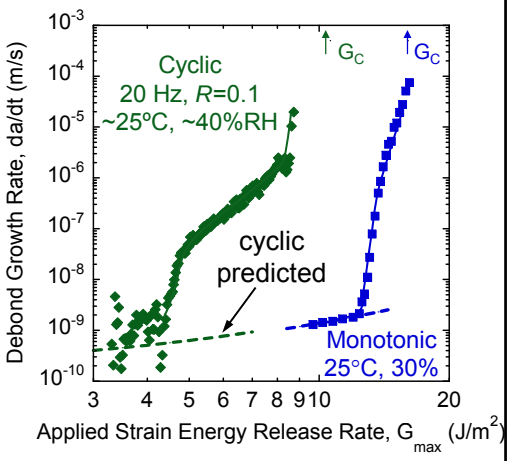
Snodgrass, Pantelidis, Jenkins, Bravman, Dauskardt - Acta Materialia, 2002.

Cyclic Stress-Dependent Transport Model



monotonic

$$\frac{da}{dt} = \frac{cua_{H_2O}}{\delta n \Sigma} D_0 \exp\left(\frac{-E_d + \alpha\sqrt{G}}{RT}\right)$$



cyclic (integrate stress-dependent diffusion over fatigue loading cycle)

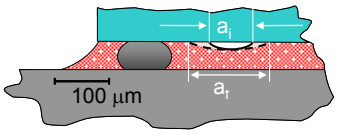
$$\frac{da}{dt} = \frac{cua_{H_2O}}{\delta n \Sigma} D_0 \exp\left(\frac{-E_d}{RT}\right) g(f,t) \qquad g(f,t) = f\int_0^{1/f} \exp\left[\frac{\alpha}{RT}\sqrt{(G_{ave} + \Delta G \sin(2\pi ft))}\right] dt$$

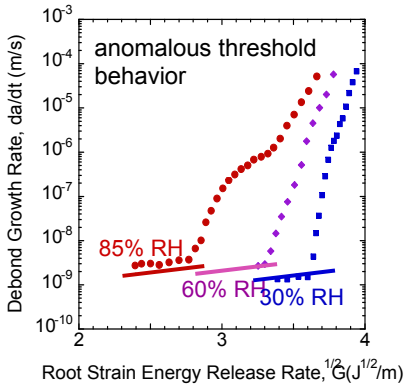
STANFORD MATERIALS SCIENCE AND ENGINEERING

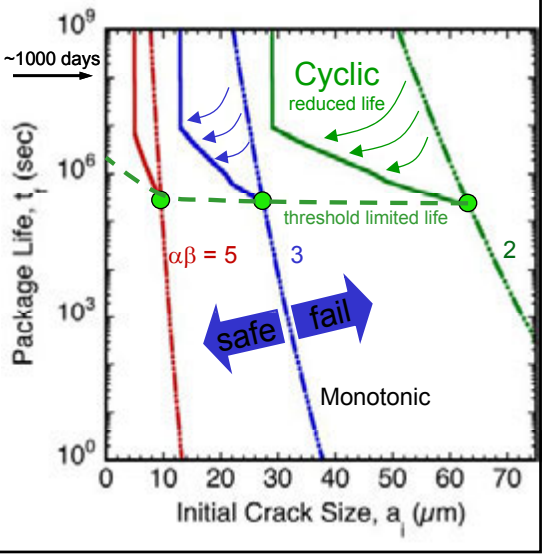
Wang, Sharratt and Dauskardt, Acta Materialia – 2007.

Effect of Fatigue and Thresholds on Package Life

- Significant reduction in life under cyclic loading indicated by arrows.
- Further limits on package life result from anomalous thresholds







Our Goals for Reliability of PV Technologies

We want to engineer reliable PV devices and modules with robust and predictable lifetimes.

- Leverage from reliability physics in microelectronics – mechanisms, kinetic models, accelerated tests and life prediction
- Develop metrologies to quantitatively characterize thermo-mechanical properties (e.g. adhesion, cohesion), photochemical and environmental degradation processes
- Are degradation processes coupled and how?
- Kinetic models of damage evolution - basis for life prediction and accelerated testing (effect of operating temperature, environment, mechanical stress, solar flux, etc.)
- Effective transparent barriers with anti-reflective properties and low cost.

Electrical, Mechanical, and Thermal Modeling of Photovoltaic Modules

An Overview

Max Davis
Steel & Silicon Engineering

Note: This is the first version of this presentation, and an updated version will be available in the future. If you are reading this after March 2010, please check http://steelandsilicon.com/pubs/ for an updated version.

This presentation does not contain any proprietary or confidential information.

Overview

The presentation surveys a broad range of topics relevant to modeling of PV modules, based on experience doing modeling for a number of PV companies and technologies (conventional front-contact, rear-contact, CPV).

The hope is that this will be useful not only to people who do modeling, but also to people who work on teams with modeling experts, or make decisions about which areas to explore through modeling or testing.

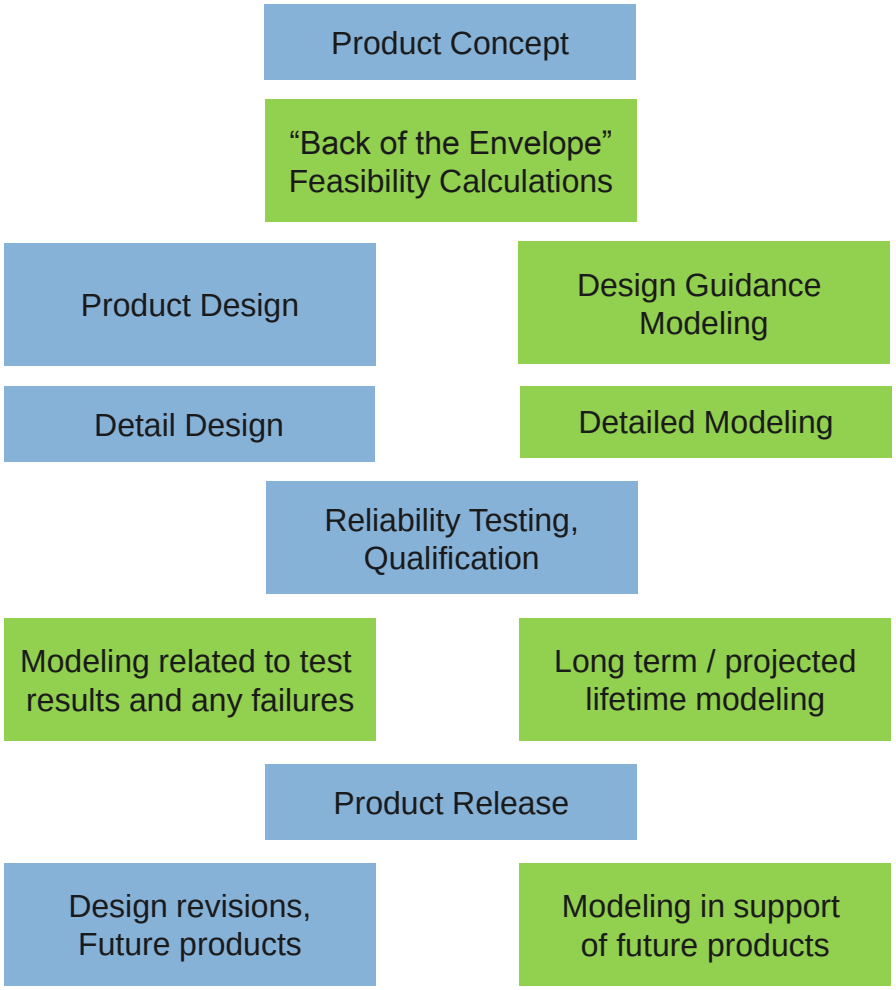
Outline

- Modeling Overview
- Material Properties and Testing
- Electrical Modeling
- Mechanical-Thermal Modeling

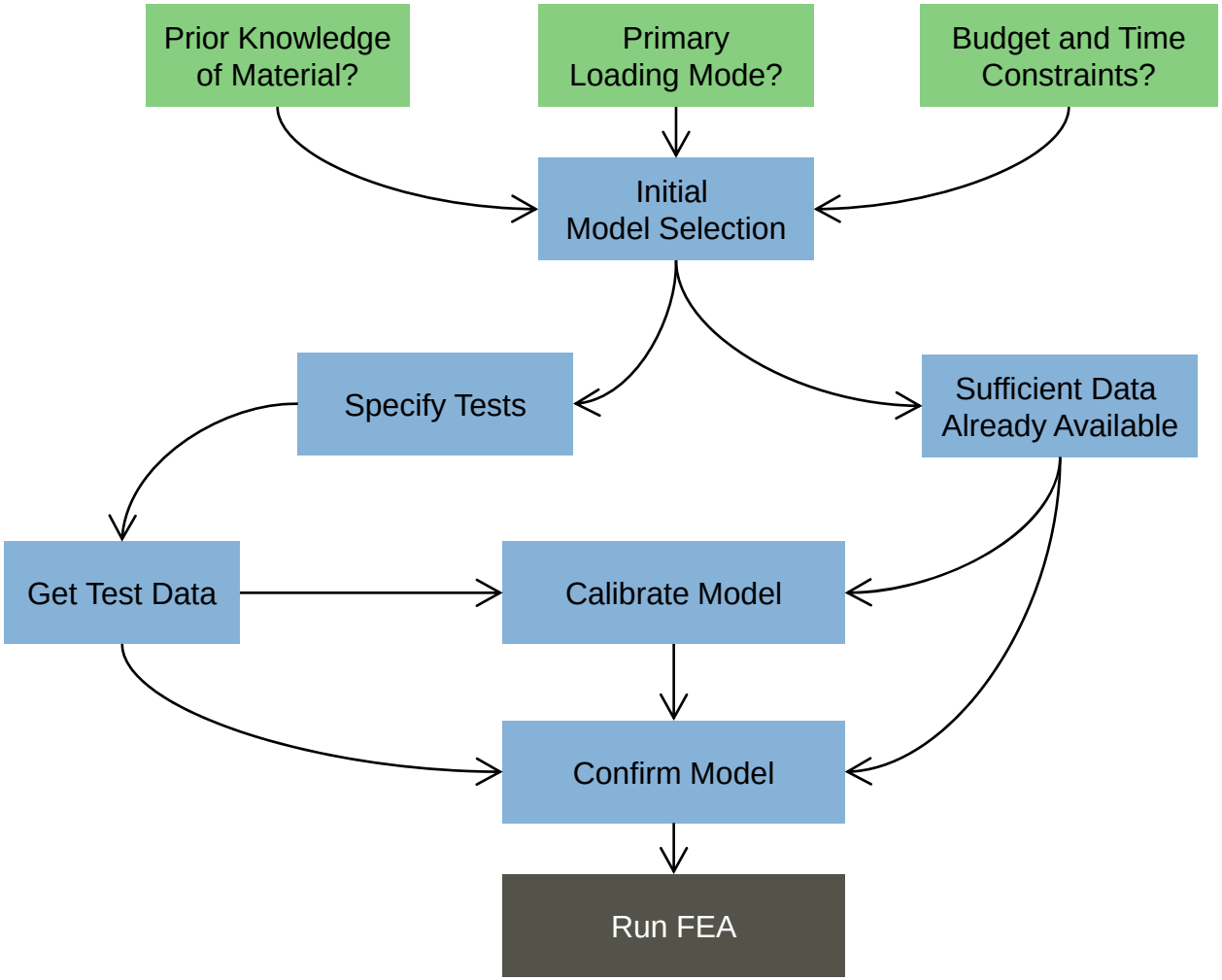
Note that there are a number of other important reliability-related areas (moisture, UV, acceleration factors, statistics, and so on) that are not covered here.

Modeling Process

Modeling in the Development Process

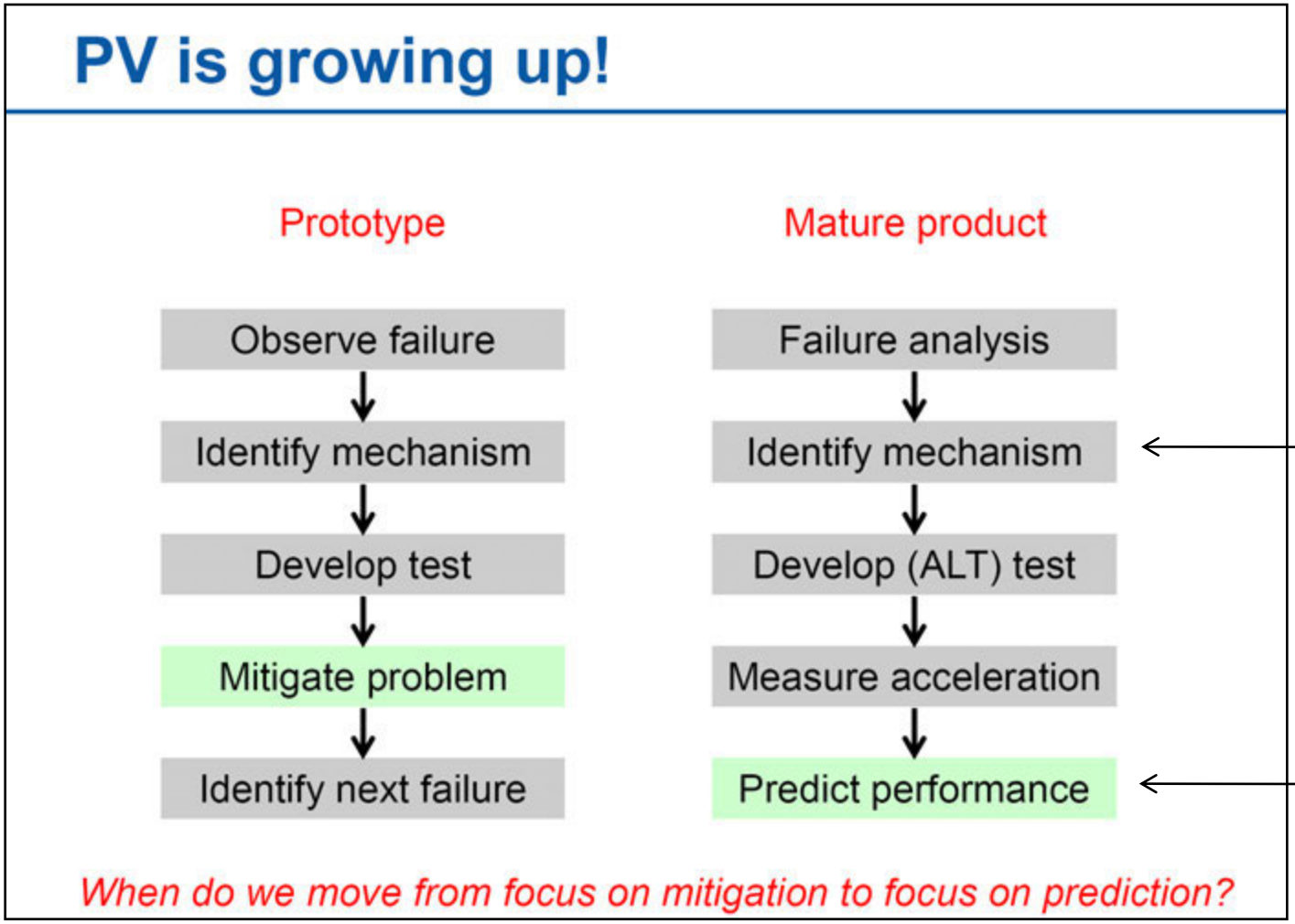


Material Testing/FEA Flow Diagram



Credit: John Lawler, GreenMountain Engineering

When to Model?



Slide Source: Sarah Kurtz, NREL

Limits of Modeling

"All models are wrong; some models are useful."

--attributed to George Box, 1979

To model every aspect of a complex material's behavior, in detail, can be a PhD-thesis-level effort.

However, many aspects of a material's behavior may have only modest impact on the overall model conclusions.

Benchmarking against test data, sensitivity analysis, and relative modeling all help.

Despite the fact that this is a modeling presentation, I will say: modeling is not a substitute for testing.

Material Properties & Testing

St&Si

Material Models

Hand calculations and basic models typically assume linear elastic material properties.

More complex models can give better accuracy but take more effort to develop and benchmark.

Material	Typical Models
Glass	Elastic
Silicon	Elastic
Encapsulant	Viscoelastic, or hyperelastic(?), or temperature-dependent elastic
Backsheet	Elastic or temperature-dependent elastic
Copper	Elastic-Plastic
Solder or Adhesive	Elastic-Plastic or viscoelastic

Material Properties

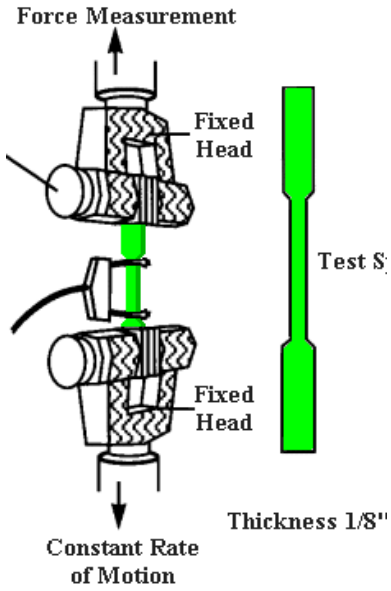
Some key material properties for modeling (not including failure criteria):

Property	Symbols	Typ. Units
Modulus (stiffness)	E, G	Pa
Poisson's ratio	v	None
Plastic Deformation	σ_y, E_t	Pa
Viscoelasticity	T_g, E_s, E_l, $E_{1..n,}$ $\tau_{1..n}$	Pa, s
Thermal expansion	c_{te}, α	ppm/ºK
Thermal conductivity	K	W/m-ºK
Electrical resistivity	ρ	Ω-cm

Material Testing

There are numerous labs that can test materials to extract model parameters, at a moderate cost ($500 - $5k).

Description	Sample ASTM test standards
Modulus	E8, D638 (full stress-strain curves) D5026 (polymer modulus as a function of temperature)
Poisson's ratio	see above
Plasticity	see above
Viscoelasticity	D2990/2991 for creep D5279, D5026 for DMA
Thermal expansion	E228, E831, D696 (polymers)
Thermal conductivity	E1225, D5930 (polymers)
Electrical resistivity	B193 (w/ four-point probe)

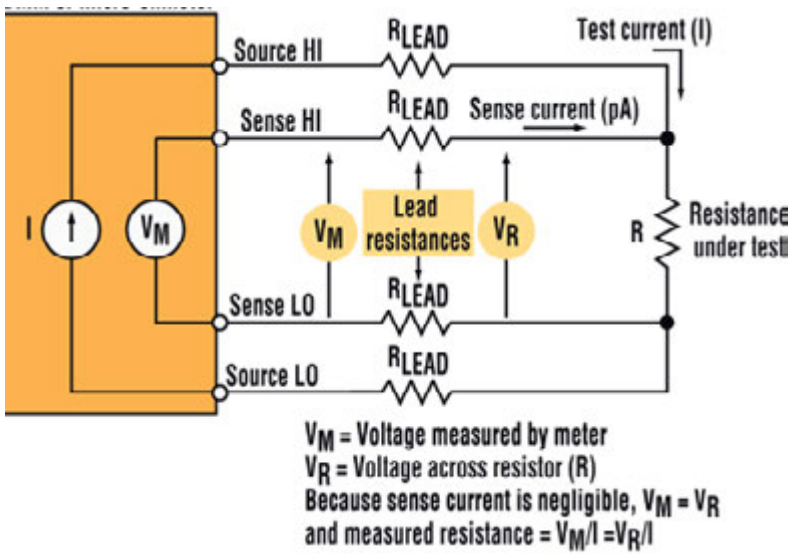


Source: Matweb

Example: Resistance Testing

Measuring the electrical resistance of conductors is not trivial, as the resistance of the measurement system can introduce errors.

Various four-point measurement methods are useful.



Semiconductor industry Kelvin structure for measuring contact resistance

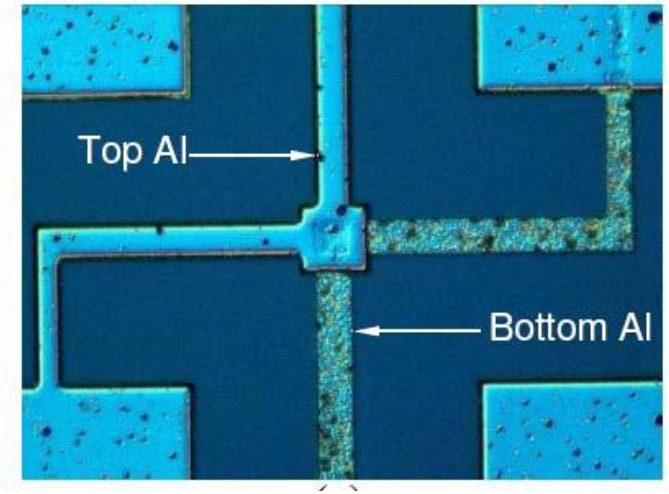


Image Source: H.Lin, An Evaluation of Test Structures for Measuring the Contact Resistance of 3-D Bonded Interconnects

Custom Test Example: Fatigue

With sufficient cyclic fatigue, solders and electrically conductive adhesives can exhibit some resistance degradation (at stresses and strains below what would cause cohesive mechanical failure or delamination).

Some publications detail custom methods for testing this resistance degradation over time.

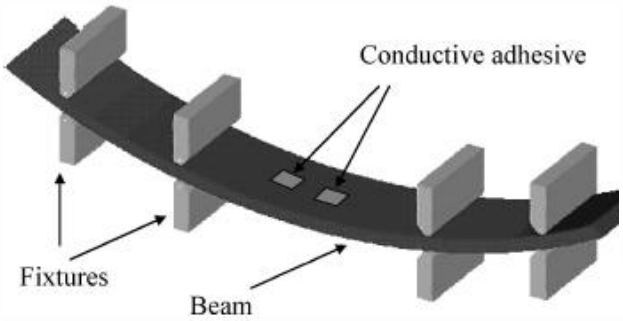


Figure 1. Schematic illustration of the four-point beam bending test.

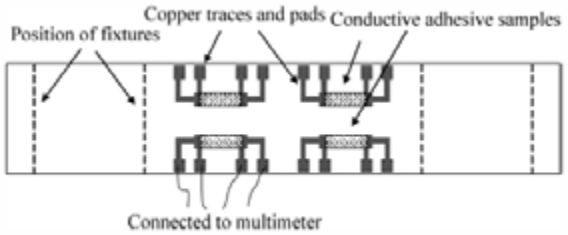


Figure 6. The layout of the upper surface of the PCB beam.

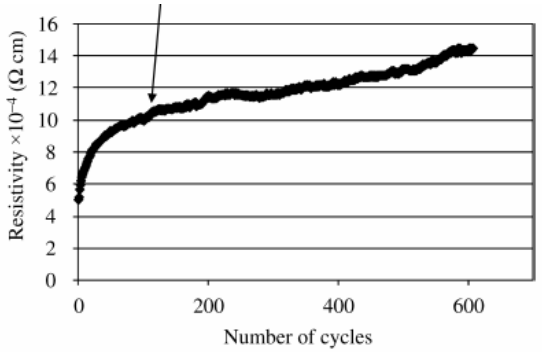


Figure 10. Resistivity of a conductive adhesive sample in fatigue test.

Source: PhD Thesis, Bin Su
[more detailed citation to be added]

Electrical Modeling

Applications

- Cell effective series resistance
  - Metallization, emitter, contacts, current distribution
- Metallization pattern optimization
- Bypass diodes
- Power losses in series strings
  - Cell-to-cell variation, binning
  - Shading
  - Irradiance variation (especially in CPV)
  - Interconnect and cell failures
- Contact fatigue and resistance degradation
- Semiconductor cell models (not covered here)

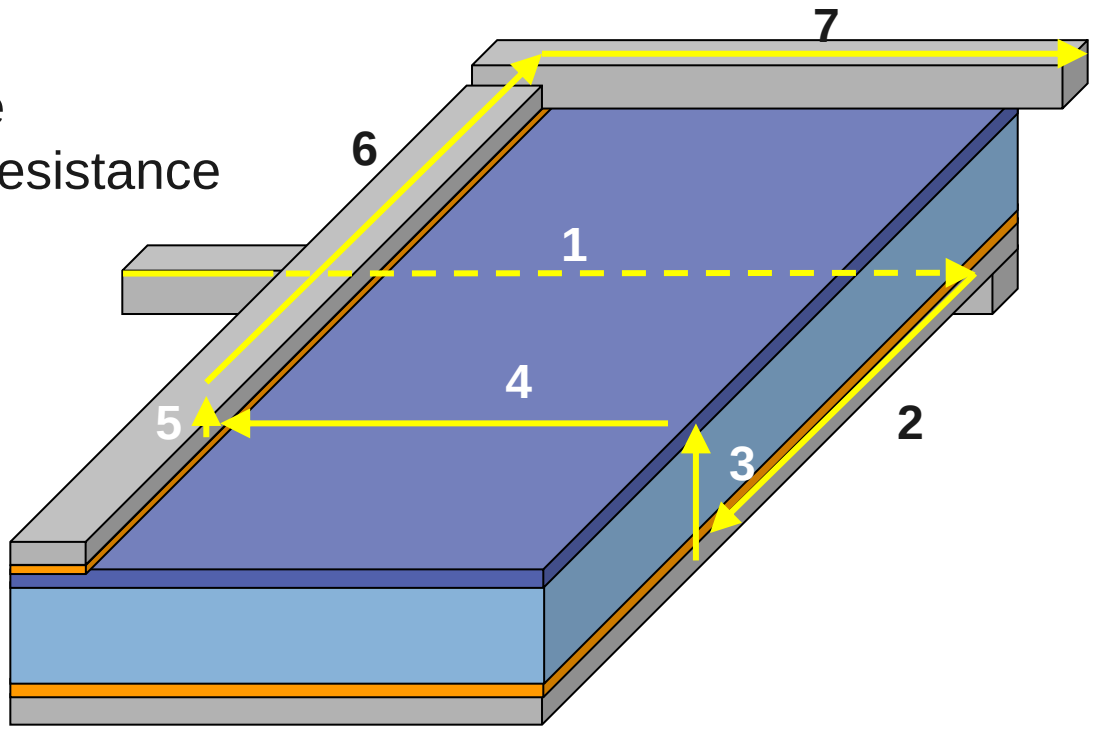
Physics and Tools

- Basic series resistance and power calculations can often be done “by hand” (or using spreadsheets, MATLAB, or similar software) without need for FEA
- SPICE is useful for circuit models
- Semiconductor models using PC1D, Sentaurus, etc.
- For 2D and 3D current distribution calculations, FEA tools are useful (especially in rear-contact or point-contact cells with significant 2D transport)

Series Resistance Components

In conventional front-contact cells, most current flow can be considered to be linear within each layer, to allow simpler, non-FEA modeling of series resistance losses.

1. Bottom bus resistance
2. Rear metallization resistance
3a. Rear metallization contact resistance
3b. Bulk resistance
4. Emitter sheet resistance
5. Finger contact resistance
6. Finger resistance
7. Top bus resistance



Electrical: Scaling Laws, Rules of Thumb

Resistance of a conductor scales linearly with geometric parameters (cross-section, length): $R=\rho*L/A$

Voltage drop is also linear with resistance and current: $I*R$

Power loss in a resistance scales with current squared: I^2R

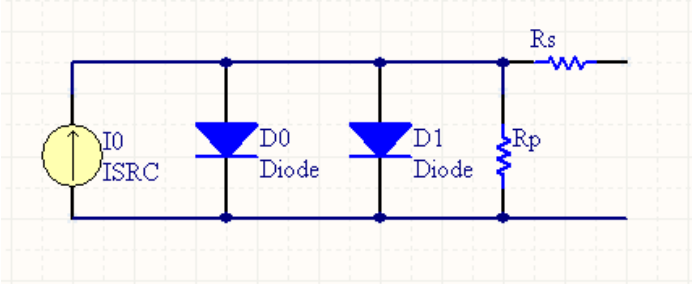
Therefore, if you reduce the current in a conductor by 2x, power loss goes down by 4x (or the conductor can be made 4x smaller with the same power loss).

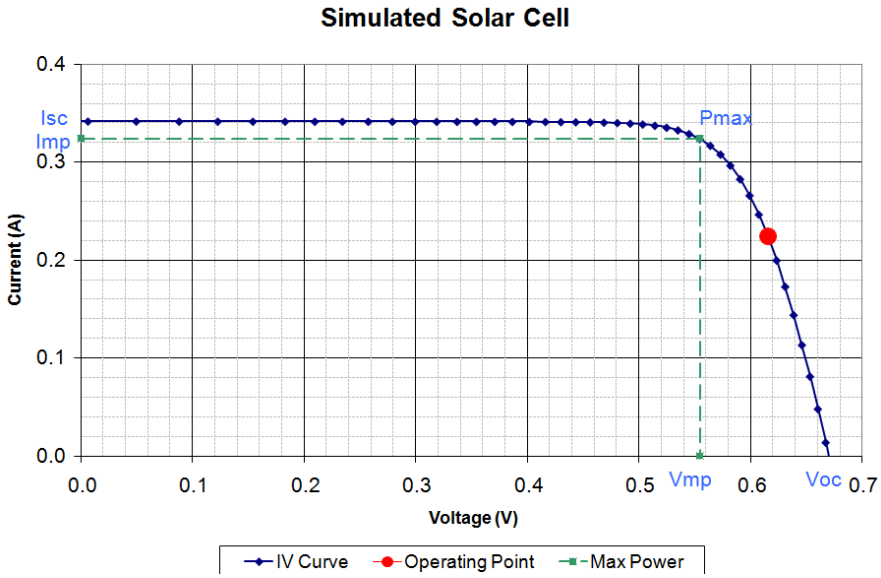
This is relevant in metallization optimization, and is also part of what drives various electrical system designs towards higher voltage and lower current.

Solar Cell Circuit Model

A circuit model* combining a current source, one or two diodes, and two resistances can simulate the I-V curve of a solar cell fairly accurately.

Using SPICE-based modeling tools, this model can then be parameterized and used to study the behavior of strings and modules, cell-to-cell variation, and other factors.

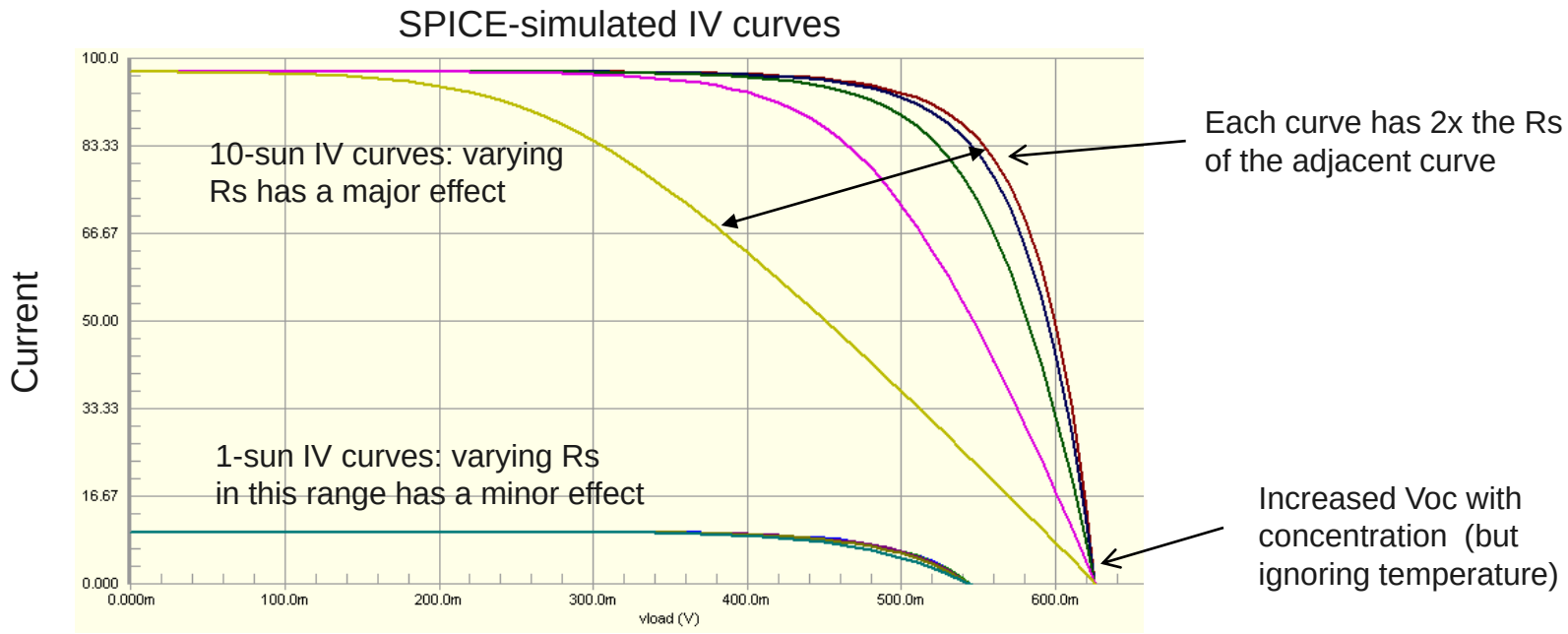




* I've implemented and benchmarked a simple, parametric SPICE subcircuit model for solar cell modeling: contact me if you want a copy of it.

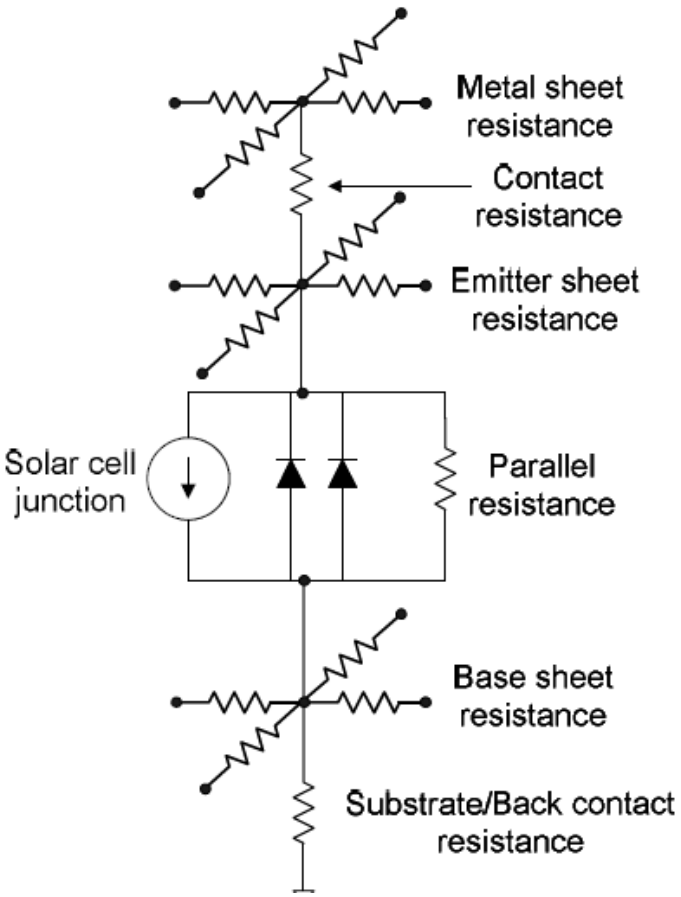
Series Resistance and CPV

Unless cell series resistance is low, it can be a significant source of efficiency loss for concentrating photovoltaics.



Note that Voc,efficiency increase under concentration, but efficiency decreases w/ heating or nonuniform illumination.

Distributed Resistance

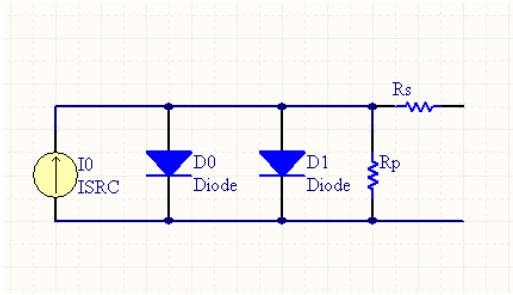


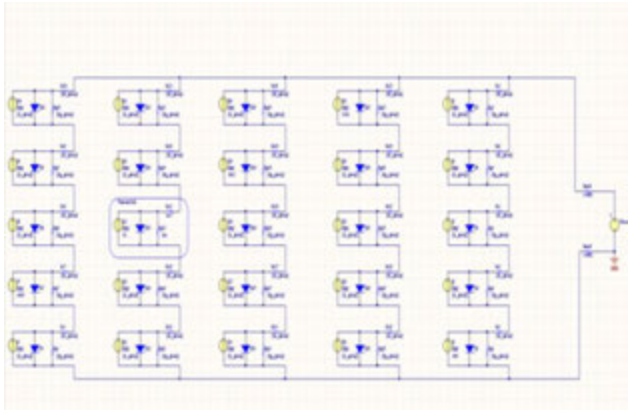
A solar cell can more accurately be modeled as a distributed network of unit cells and resistances (especially important if non-uniform illumination will be modeled).

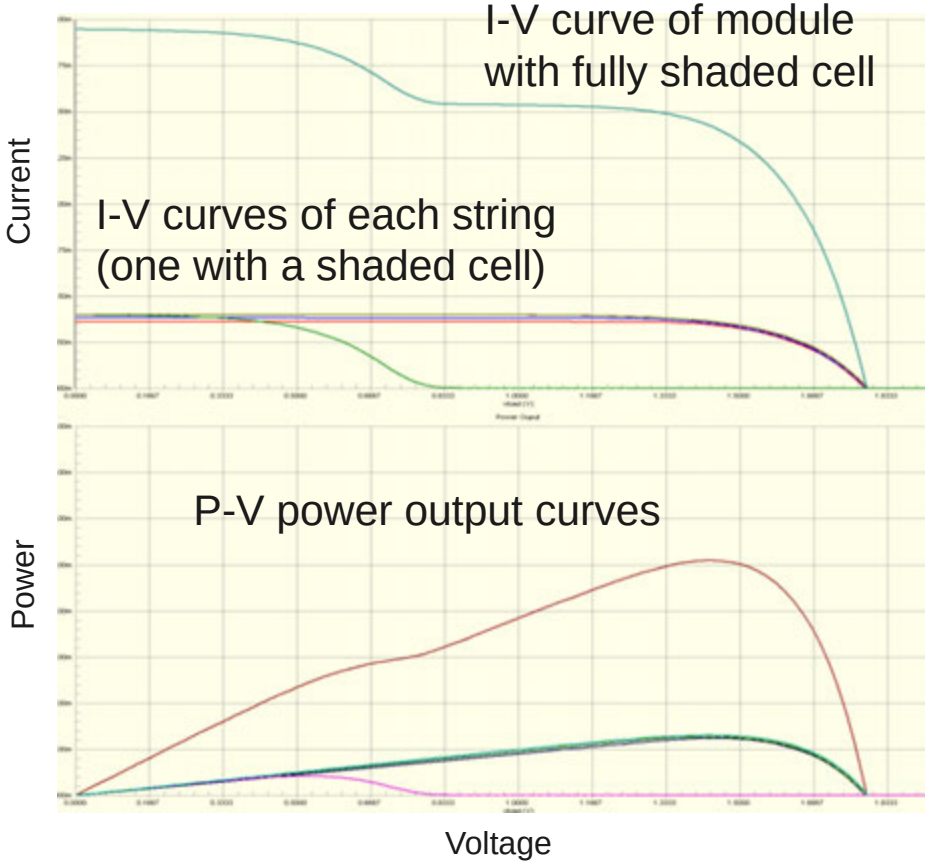
SPICE can be used to simulate this network, though a separate script may be used to generate the circuit.

Series / Parallel Array Modeling

SPICE models can also be used to examine shading, bypass diodes, and changes in cell operating points.







Electrical: Advanced issues

- Metal-semiconductor contacts can be non-ohmic (nonlinear resistance) if doping is low.
- Current crowding: higher effective resistance.
- Each diode in the circuit model represents a combination of several different physical phenomena / types of recombination.
- Under high concentration, a three-diode model (with N=2/3 for the third diode) may be helpful to model Auger recombination.
- Some conductors may show resistance degradation prior to mechanical failure.

Mechanical & Thermal Modeling

St&Si

Outline

- Modeling applications
- Core physics
  - Stress and strain
  - Thermal expansion
  - Fatigue
  - Creep and viscoelasticity
- Scaling Factors
- Examples

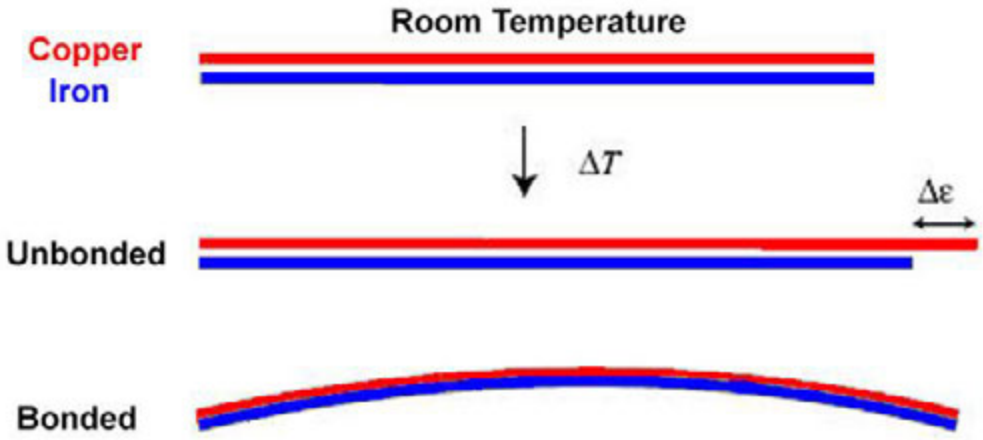
PV Applications

- Stress in glass and cells in physical loading (wind, snow)
- Stress in cells and interconnects due to thermal expansion (both during the initial cool-down from lamination, and thermal cycling)
- Stress in cells from local heating (soldering during manufacturing, irradiance variation in CPV)
- Crack propagation in cells (damage initiated during handling in manufacturing, stresses applied later)
- Failure / delamination of solder joints, encapsulant
- Low-cycle fatigue of copper, solder, adhesives

Thermal Expansion

In PV modules, the most relevant causes are:

- Cooling from lamination to room temperature
- Thermal cycling (in testing, in the field)
- Temperature gradients (especially in CPV)



[image source: electrical-forensics.com]

Note that thermal expansion does not cause stress in a simple, unconstrained material.

Stiffness: higher is not always better

People sometimes confuse a material's 'strength' (yield stress, for example) with its stiffness (modulus).

- High stiffness: low deflection for a given force
- Low stiffness: low stress for a given deflection



Source: Wikimedia Commons, Rich Niewiroski Jr.

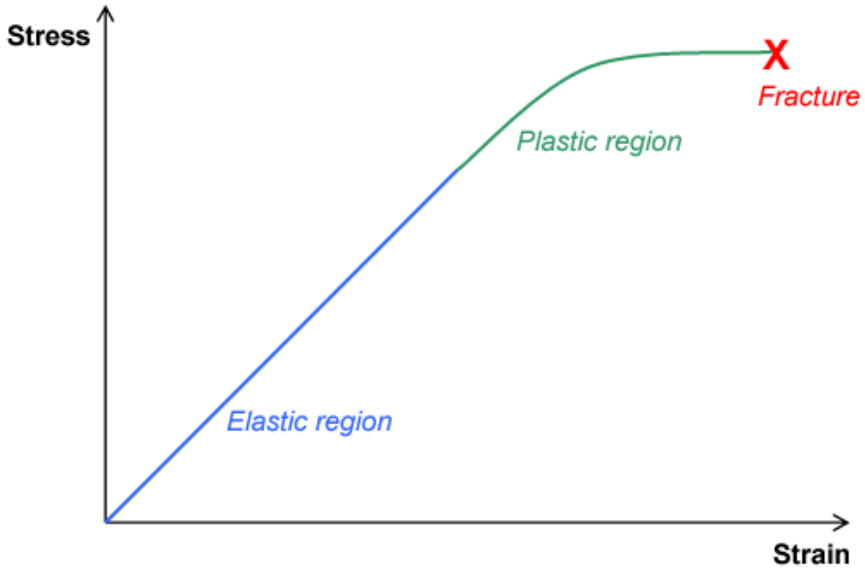


Source: Wikimedia Commons

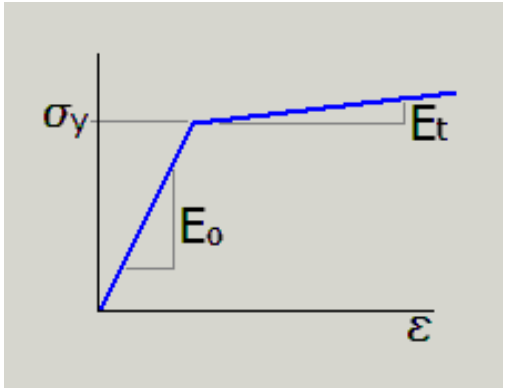
For example, processes like tempering affect a metal's strength but not its stiffness.

Plastic Deformation

Plastic deformation is irreversible strain in a material that is loaded beyond its yield stress (think of bending a paper clip). In PV modules, it can be important in modeling copper and solder joints under cycling loading.



A typical elasto-plastic modeling approximation:



Source: Beaufort Analysis

Fatigue

High-Cycle Fatigue: low stress over many cycles (but... PV modules only see 13k day-night thermal cycles in 20 years)

Low-Cycle Fatigue: cyclic plastic deformation to failure (think bending a paper clip). Relevant to solder, adhesives, and copper in solar modules, and can be modeled.

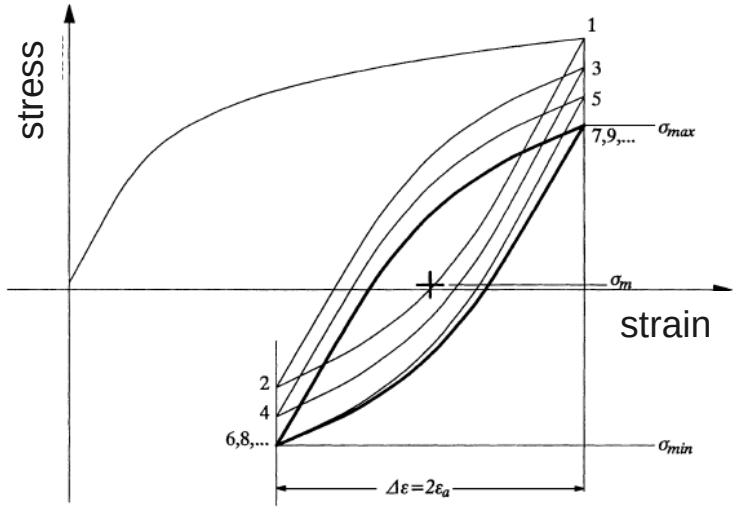


FIG. 5.45 Stress relaxation during a mean strain axial fatigue test.

[Source: Rothbart, *Mechanical Design Handbook 2nd Edition*]

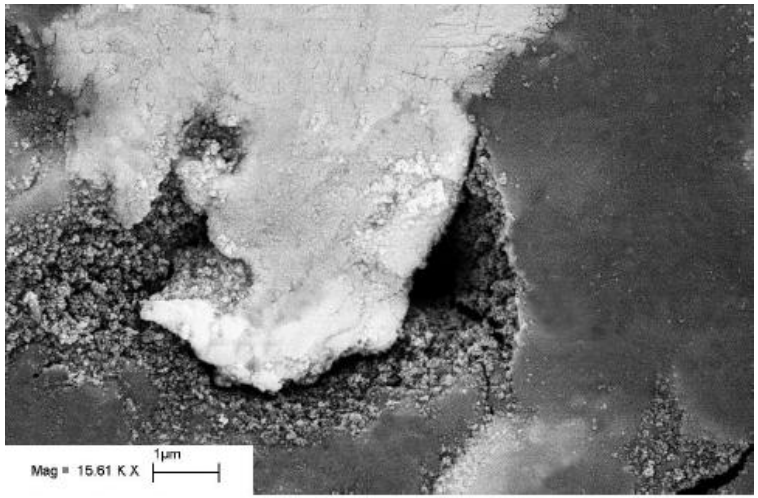


Figure 64. A silver flake in a conductive adhesive sample after fatigue test

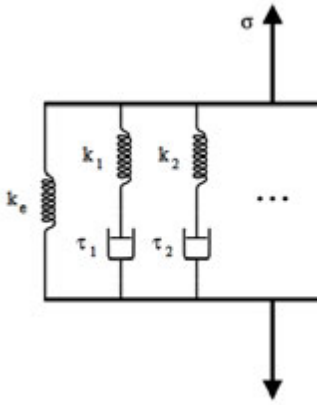
[Source: Bin Su J. Adh Science, citation details to be added]

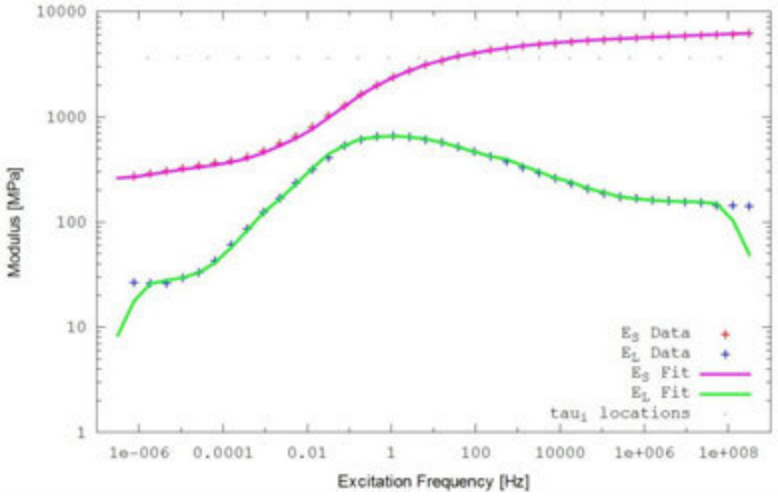
Viscoelasticity

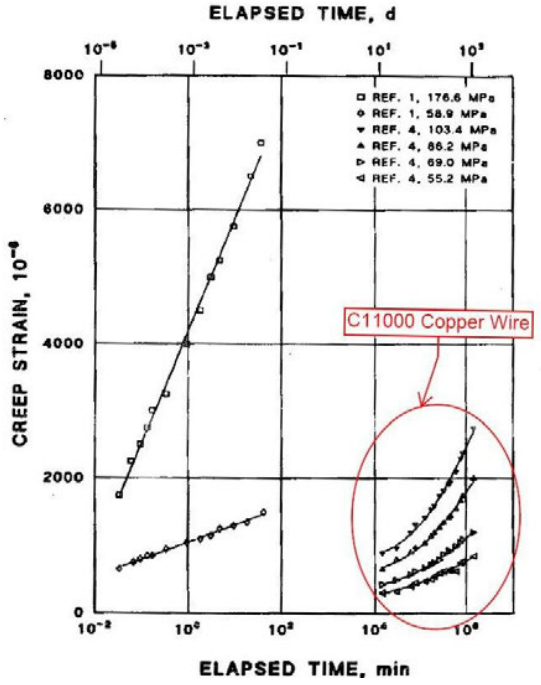
Encapsulants, adhesives, and solders can exhibit creep and viscoelasticity (e.g. stress relaxation over time).

These effects can change by many orders of magnitude over reasonable temperature ranges.

Material models can take this into account, with enough characterization (see Appendix).

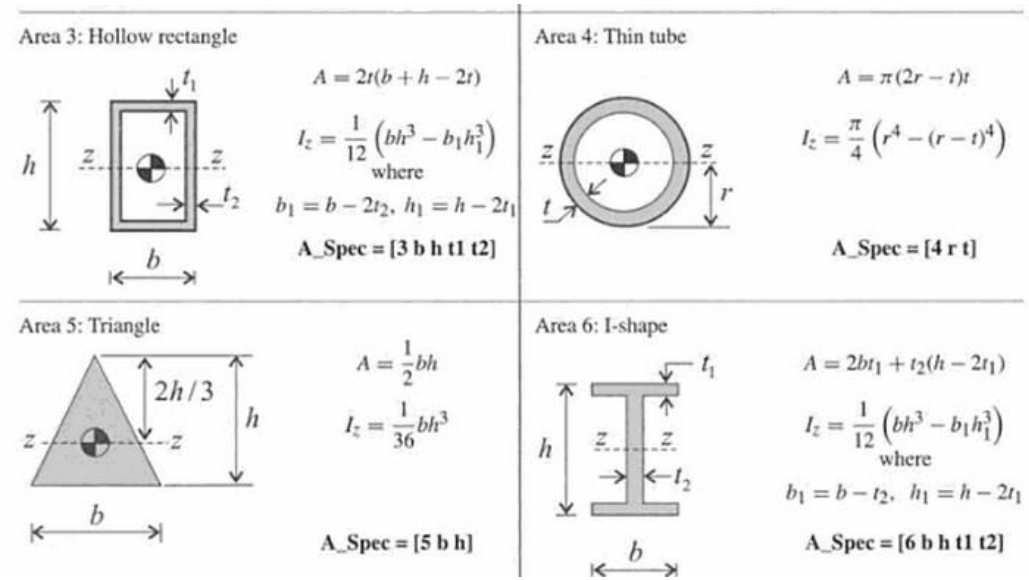






Scaling Laws, Rules of Thumb

- Beam bending stiffness scales with thickness^3, while tensile stiffness and many other properties scale linearly with thickness.



Source: B. Yang, Stress, Strain, and Structural Dynamics

- Optimizing the aspect ratios of components such as cell interconnects can significantly reduce stresses.

Scaling Laws, Rules of Thumb

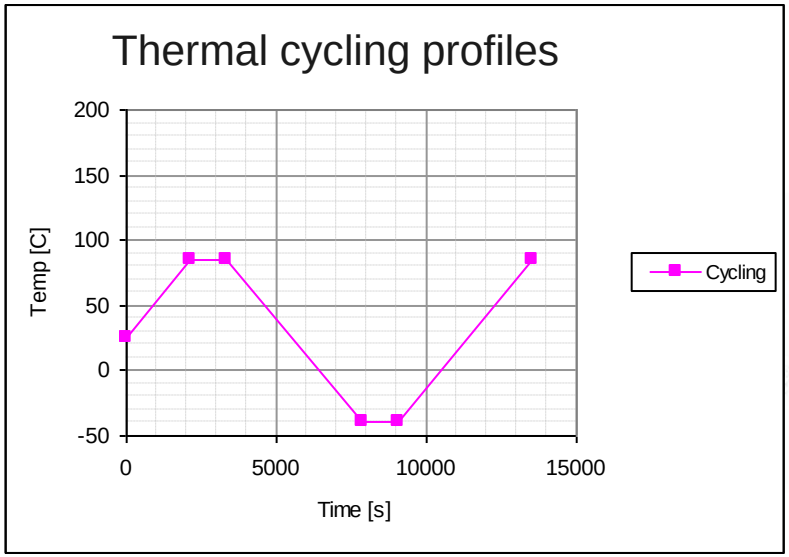
- The product of E * t * c_{te} of various layers in a module can be compared to get a general feeling for which layers will dominate thermal expansion effects.

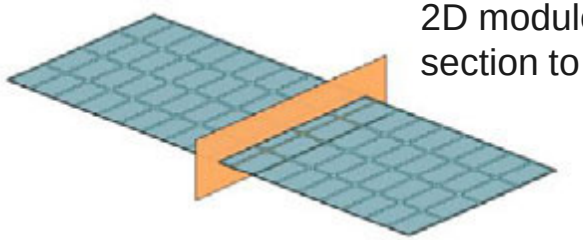
Material	E (GPa)	t (mm)	C_{te} (ppm)	E * t * c_{te}
Glass	73	4.0	9	~2600
EVA	0.006	0.4	400	1
Backsheet	2.7	0.35	100	~100

- This is especially useful for non-standard module or CPV designs.

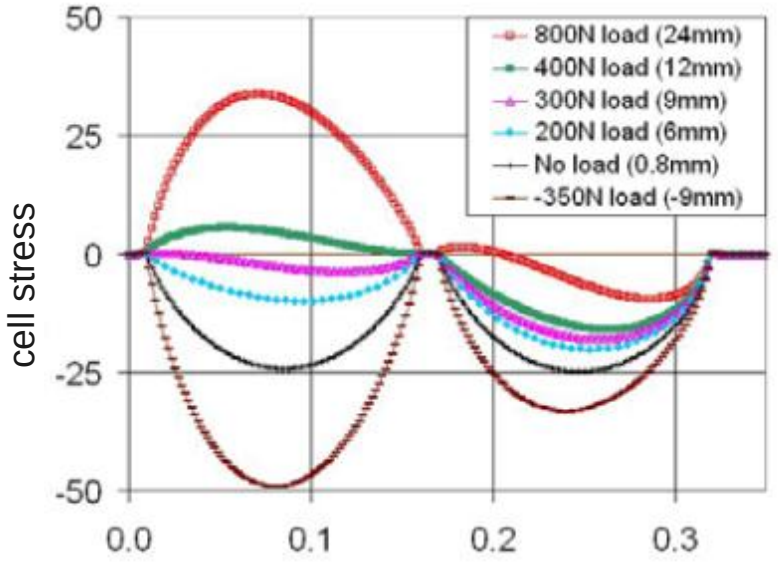
Cell Stress Modeling

A common useful model examines stress in cells and interconnects in a PV module due to either thermal expansion or weight/wind loading.





2D module cross-section to plot



Source: Evergreen Solar / GreenMountain Engineering, EUPVSEC 2007, and other sources

Global-Local Modeling

- FEA is still limited by computational power: Analyzing full-module, complex 3D models with accurate results at every small feature is not practical.
- Model the global system coarsely, use those results to determine constraints and assumptions for detailed 2D/3D models of certain regions.

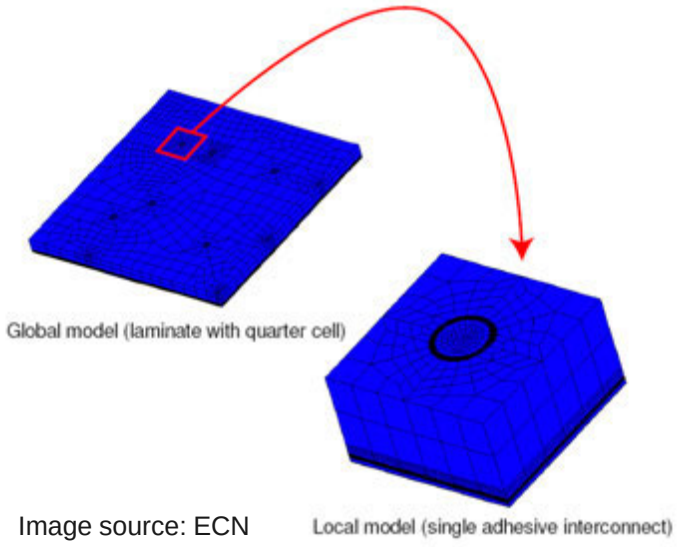
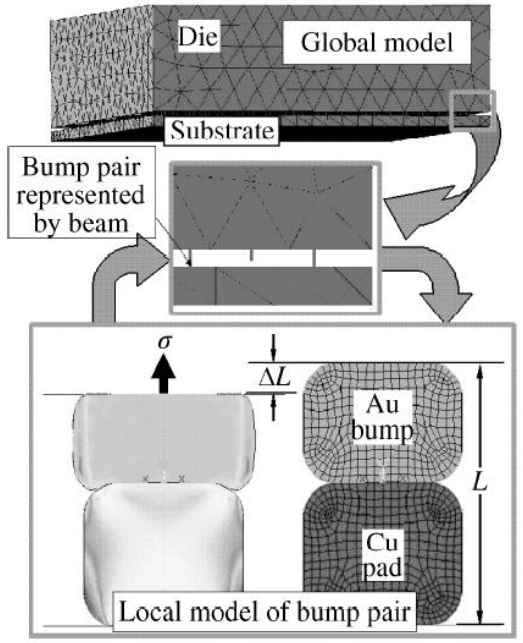


Image source: ECN

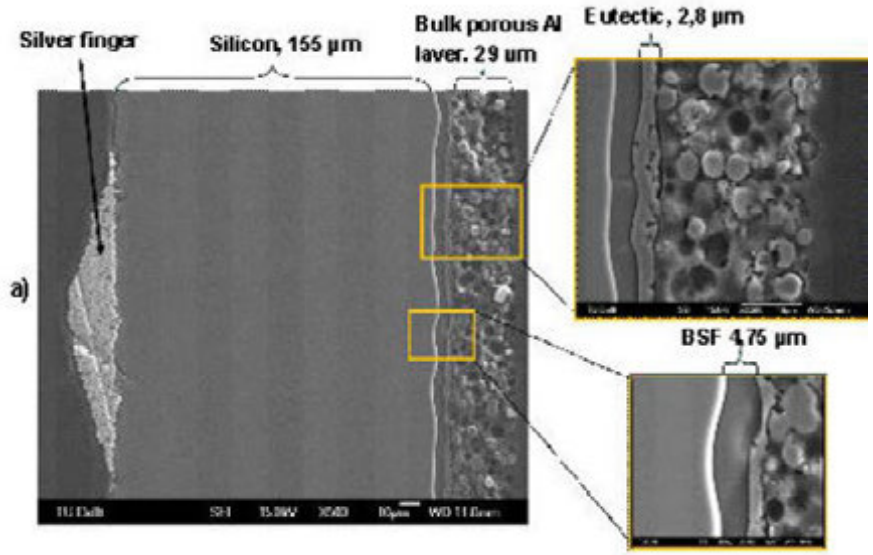


IC modeling, source: D. Farley et al. / J. Adh Sci

Advanced Issues

Some common mechanical modeling non-idealities:

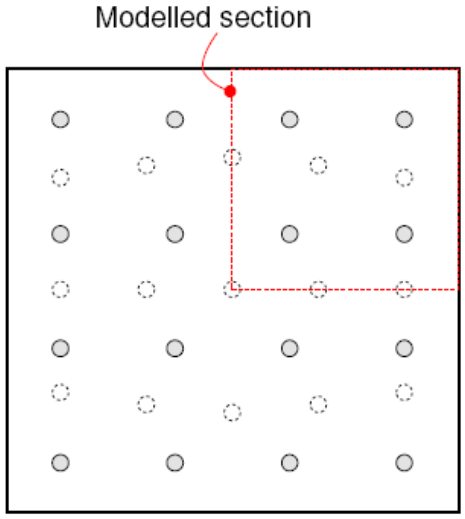
- Traditional furnace-fired cell metallization can have very different mechanical properties from the bulk properties of aluminum or silver.
  - See, for example 2.CV.2.13 from EUPVSEC 2009, suggesting a modulus only about 50% of ideal, for porous rear metallization.



Paste type	Porosity, %	Bismuth glass, %	Bowing over 150mm, mm	Young's Modulus, GPa
A	10.9	1.8	1.4	41
B	14	3.9	2.6	44
C	16	4.2	1.8	46

Advanced Issues, FEA Tips

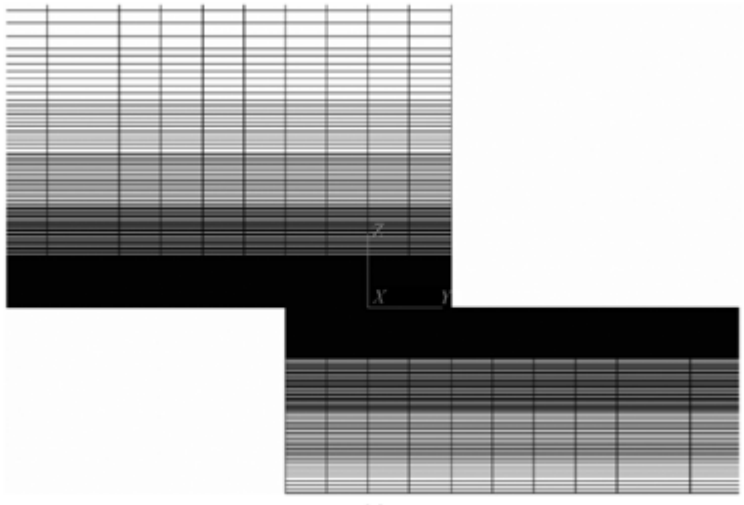
- Consider 2D simplifications, but understand differences in “plane stress” vs. “plane strain” assumptions.
- Use symmetry to reduce model size
  - Most 2D module models can be modeled as a half module, and 3D cell modules may be reducible to a quarter-cell model via symmetry in two planes.

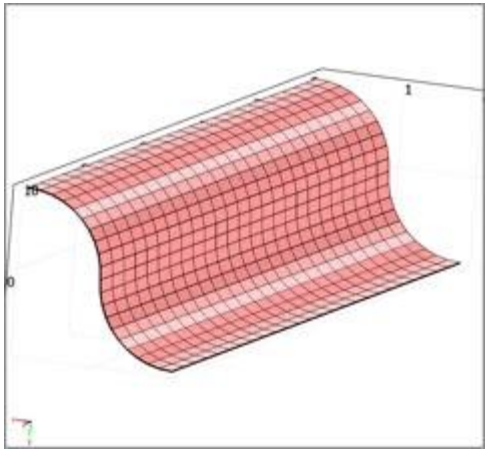


Source: ECN paper

Advanced Issues, FEA Tips

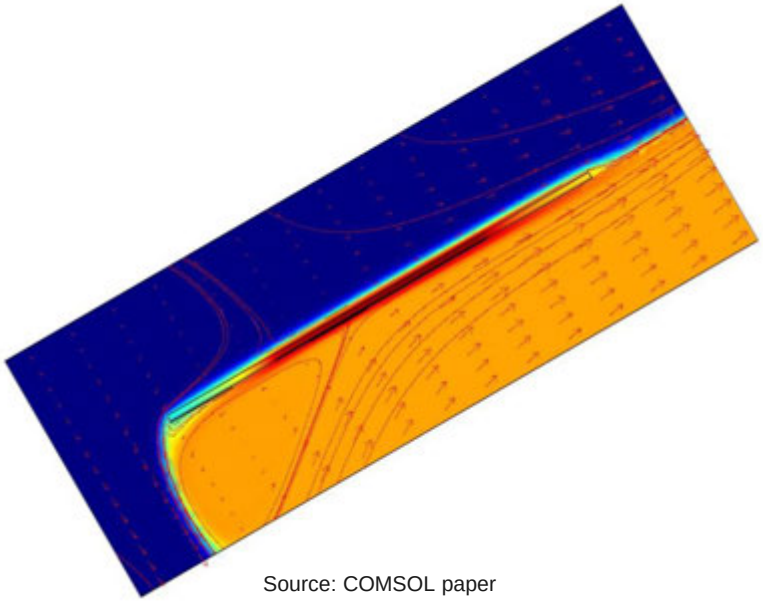
- Typically in FEA packages, meshing high-aspect-ratio models (like solar modules, which consist of many thin, stacked, large-area layers) can be a challenge.
  - Using triangular or tetrahedral elements leads to huge mesh density, or poor element quality.
  - Using rectangular or “brick” elements to mesh in 2D and then extruding or sweeping this mesh into 3D can give you much more control over mesh density in the areas you care about (interfaces and so on).





Thermal Modeling

- In addition to thermal-stress modeling, pure thermal modeling can examine areas such as:
  - Module temperature due to material stack-up, convection, stagnation, mounting structures
  - Temperature distribution in CPV and heat sinks



Source: COMSOL paper

Conclusions

Conclusions

- Useful and feasible electrical models include:
  - Series resistance losses in cells, metallization, interconnects
  - Losses due to shading, bypass, string layout, and cell variation
  - Performance of cells under concentration
- Useful and feasible mechanical models include:
  - Stresses due to thermal expansion, wind, weight
  - Fatigue of adhesives, bonds, and interconnects
  - Creep and viscoelasticity of encapsulants
- Material testing can help determine model parameters and benchmark and validate models.
- Complex models can be time-consuming: rules of thumb, hand calculations, engineering intuition, and testing can help prequalify designs before detailed modeling.

Bibliography & Acknowledgments

This presentation was based on a number of modeling projects done at GreenMountain Engineering, as well as excellent publications by a number of authors at research institutes and companies.

I'm in the process of assembling a detailed bibliography related to modeling of PV modules: contact me if you want a copy when it is ready.

Thanks to John Lawler and Tyler Williams for feedback and certain images, and to Sarah Kurtz and NREL for the invitation to speak.

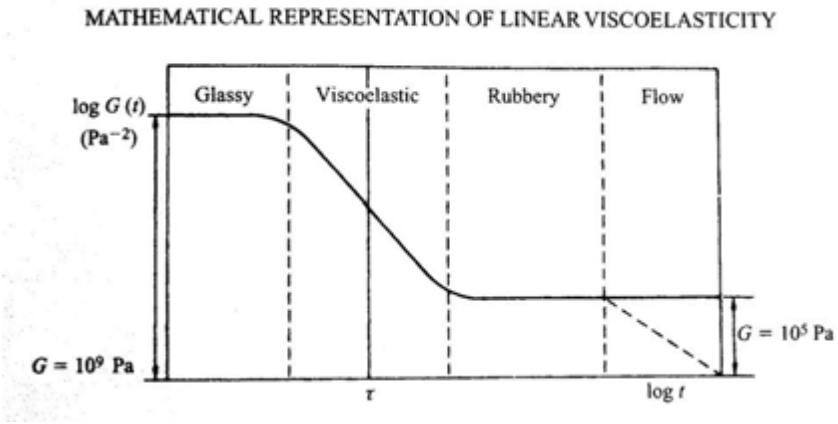
Appendix A: Viscoelasticity

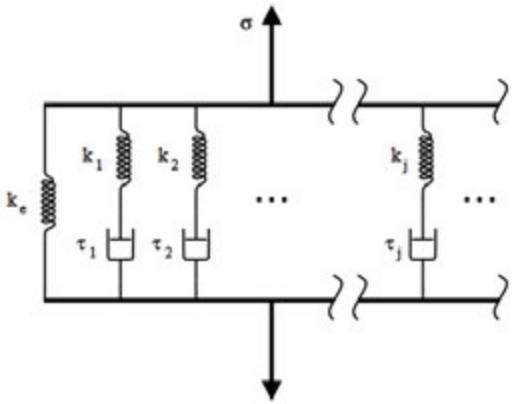
Viscoelasticity

Some materials (notably encapsulants, but to some extent solders and copper) exhibit viscoelasticity or creep.

This can be a strain that gradually increases over time under a certain load, or a stress that relaxes over time.

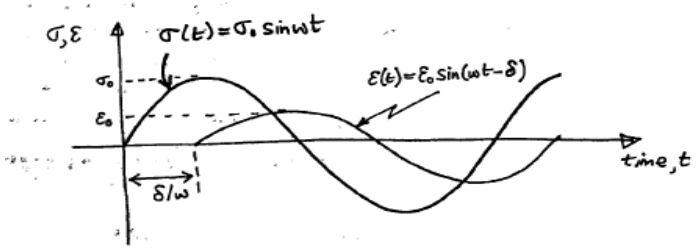
One typical way to model this is the “Generalized Maxwell Model”, representing the material as a parallel combination of springs and dampers (each branch models behavior on a certain time constant)





Viscoelasticity: Storage & Loss Moduli

- For a sinusoidal stress profile, the strain in a viscoelastic material will be out of phase by some angle *δ.*



- Qualitatively, a high value of the *loss tangent*, tan*δ,* suggests greater material stiffness at high-frequency loading.
- This behavior is specifically described by decomposing the elastic modulus into real and imaginary components:

$$E^*(i\omega) = E_S + iE_L$$

Storage & Loss Moduli

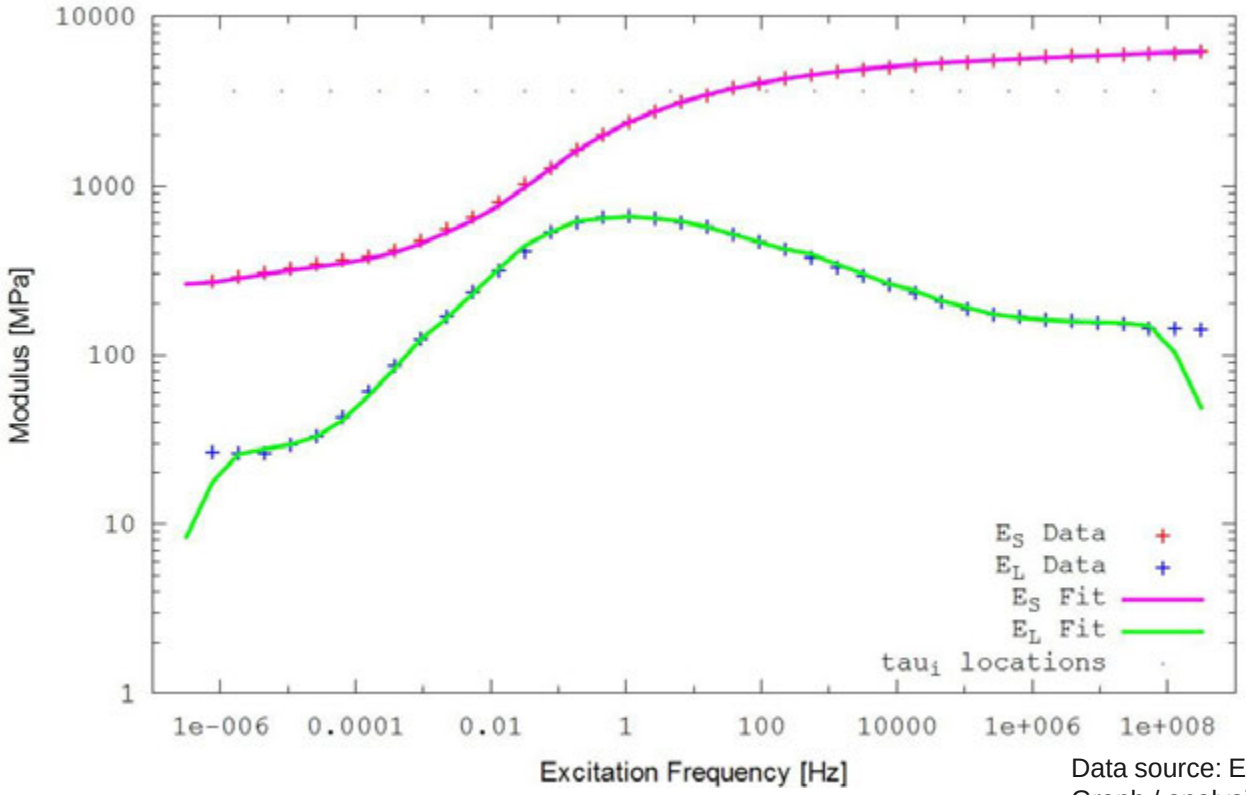
- E_S (also called E'), the *storage modulus,* and E_L (also called E''), the *loss modulus,* can also be expressed as

$$E_S = \frac{\sigma_0 \cos\delta}{\varepsilon_0} \qquad E_L = \frac{\sigma_0 \sin\delta}{\varepsilon_0}$$

- Qualitatively, a high loss modulus suggests that viscous effects are having an effect on material behavior.

Data Reduction

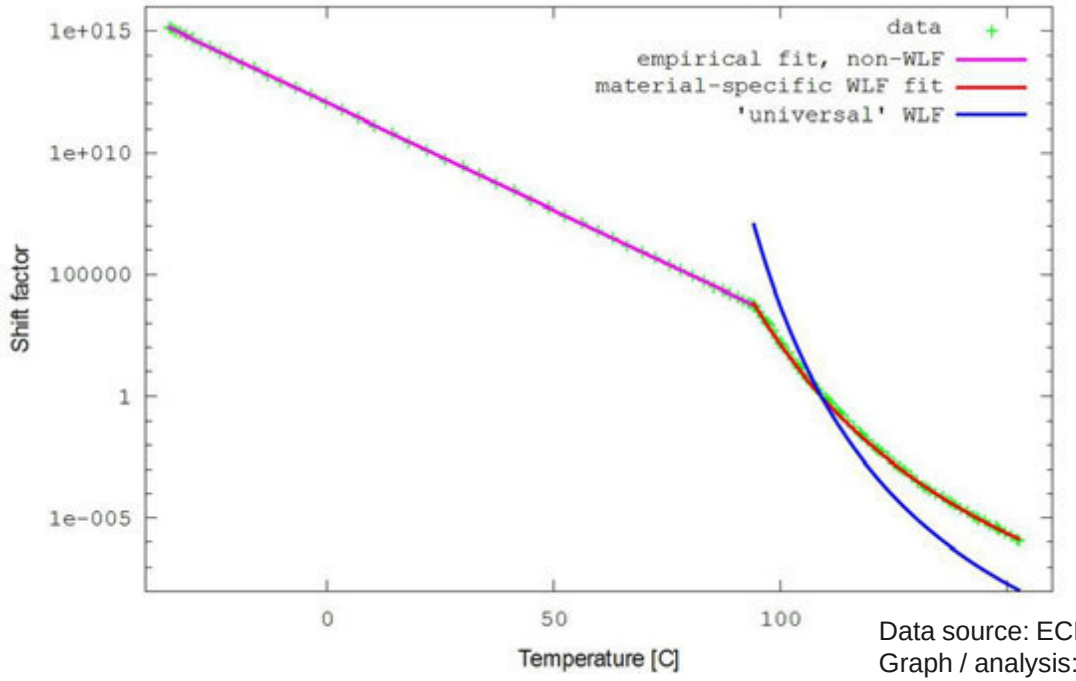
Once material data under a number of different conditions has been measured, algorithms can fit a frequency-dependent viscoelastic model to the data.



Data source: ECN publication
Graph / analysis: GreenMountain Engineering

Viscoelasticity and Temperature

The viscoelasticity of polymers can change by many orders of magnitude over a temperature range. While a challenge to model, “time-temperature curves” and “WLF shifts” can use this phenomenon to help predict long-time viscoelastic behavior from shorter tests done at higher temperatures.

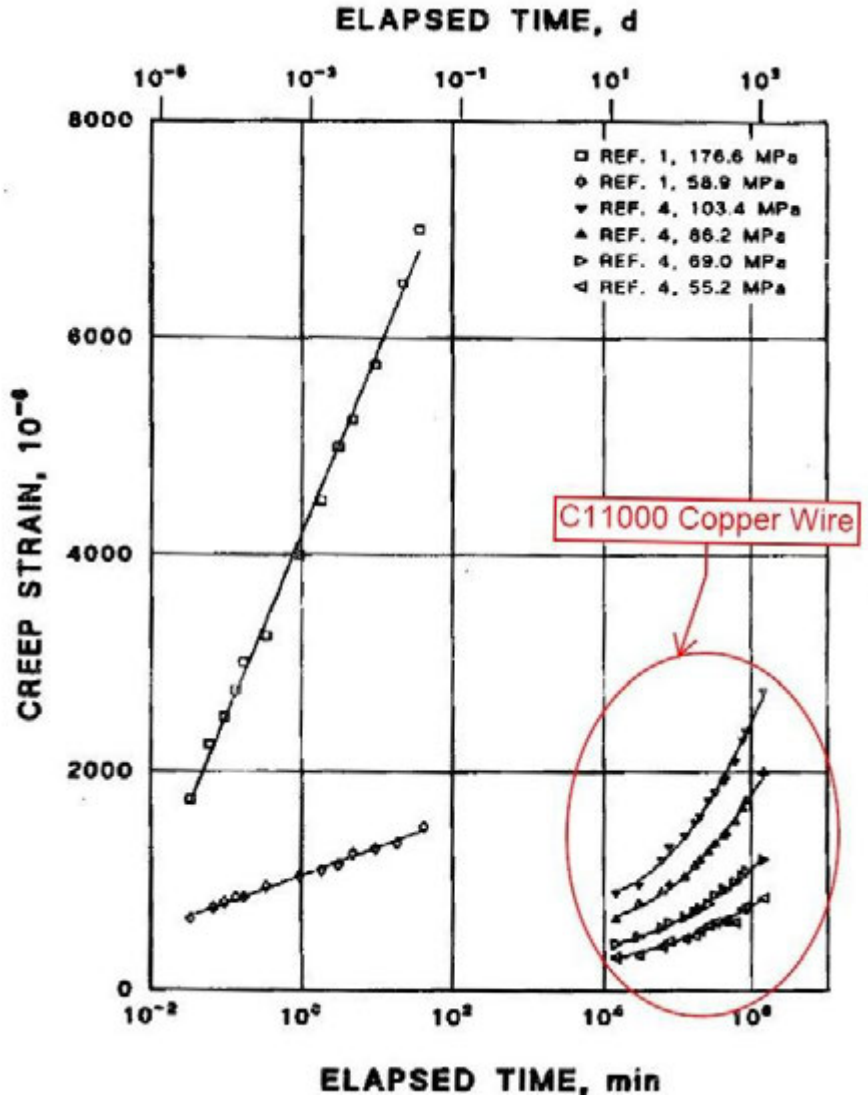


Data source: ECN publication
Graph / analysis: GreenMountain Engineering

Creep in Copper

As an example of slower creep, room-temperature strain data for C11000 copper is shown here.

On a time scale of hours, the strain is below 0.05%. Over several years, this increases to 0.2% or more.



Discussion notes

Thursday afternoon

– Predicting Long-Term Performance for PV Products

– Ensuring Quality to Satisfy the Investors

Can we predict 20-30 years for products that have been around for one year?

- Some said “yes”, some said “no”
- Reasons for “no”
  - There are many failure mechanisms
  - Effects may be interrelated, so testing for each stress separately can give the wrong answer
  - The weather is variable, so lifetime depends on location; sequence of applying stresses may depend on location
  - Need many samples to provide adequate statistics
- Reasons for “yes”
  - More detailed understanding of fundamental mechanisms of failure can lead to improved projections
  - It’s difficult, but careful work can help

Is our quality assurance adequate?

- In 2007-2008, people would buy whatever you could deliver; now, the bar is higher
- Qualification tests are a “cost of entry”, not an “assurance of quality”
- Solar ABCs has recently issued a recommendation that products pass a qualification test. Although many US organizations do not require a qualification test, SunEdison requires it for all of their purchases and will not decrease quality standards for a lower price product. Passing a qualification test is not helpful if you do not have a quality plan, but Solar ABCs did not mention this.
- It’s not clear whether requiring an ISO 9000 standard is useful. ISO 9000 standards assure quality processes, not necessarily quality products.
- A product with higher efficiency could have lower efficiency after field exposure
- The panel was asked whether they would embrace third-party factory inspections to measure quality; the panel response was negative both about the value and acceptability of the concept
- 25 year warranties were begun without a rigorous evaluation; then, most companies followed for marketing reasons rather than because the reliability engineers recommended it.
- A 3-sample testing size is adequate for some failures, but not for others

TÜV Rheinland PTL

STATISTICAL LIFETIME PREDICTION FOR PHOTOVOLTAIC MODULES

Joseph M. Kuitche

Arizona State University &
TUV Rheinland PTL
Arizona, United States

ASU ARIZONA STATE UNIVERSITY

OUTLINE

- Introduction & Scope
- Conventional Approach: Time-To-Failure Analysis
- Degradation Analysis with non-constant model parameters

TÜV Rheinland PTL

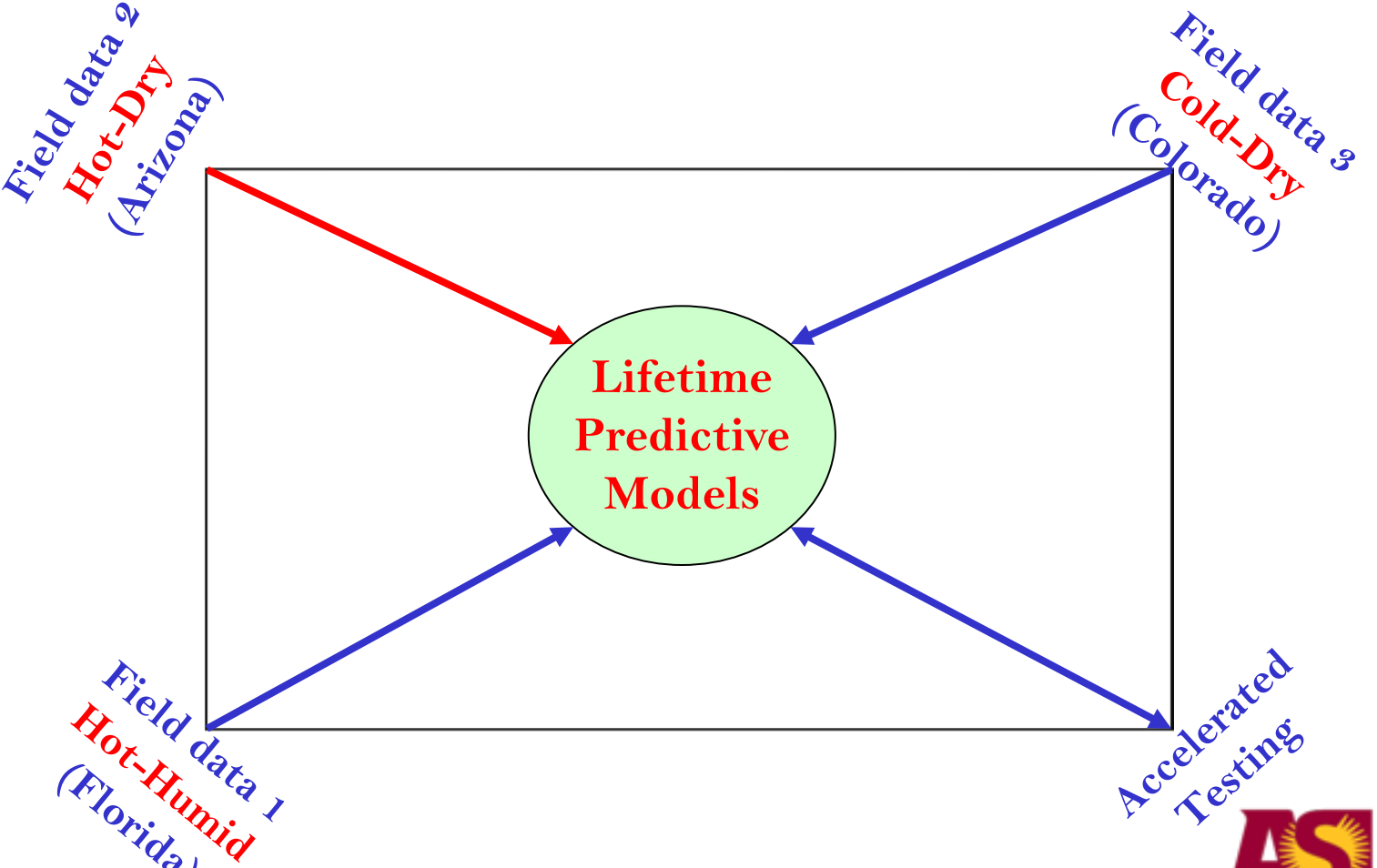
INTRODUCTION & SCOPE

ASU ARIZONA STATE UNIVERSITY

TÜV Rheinland PTL

Our approach to lifetime prediction

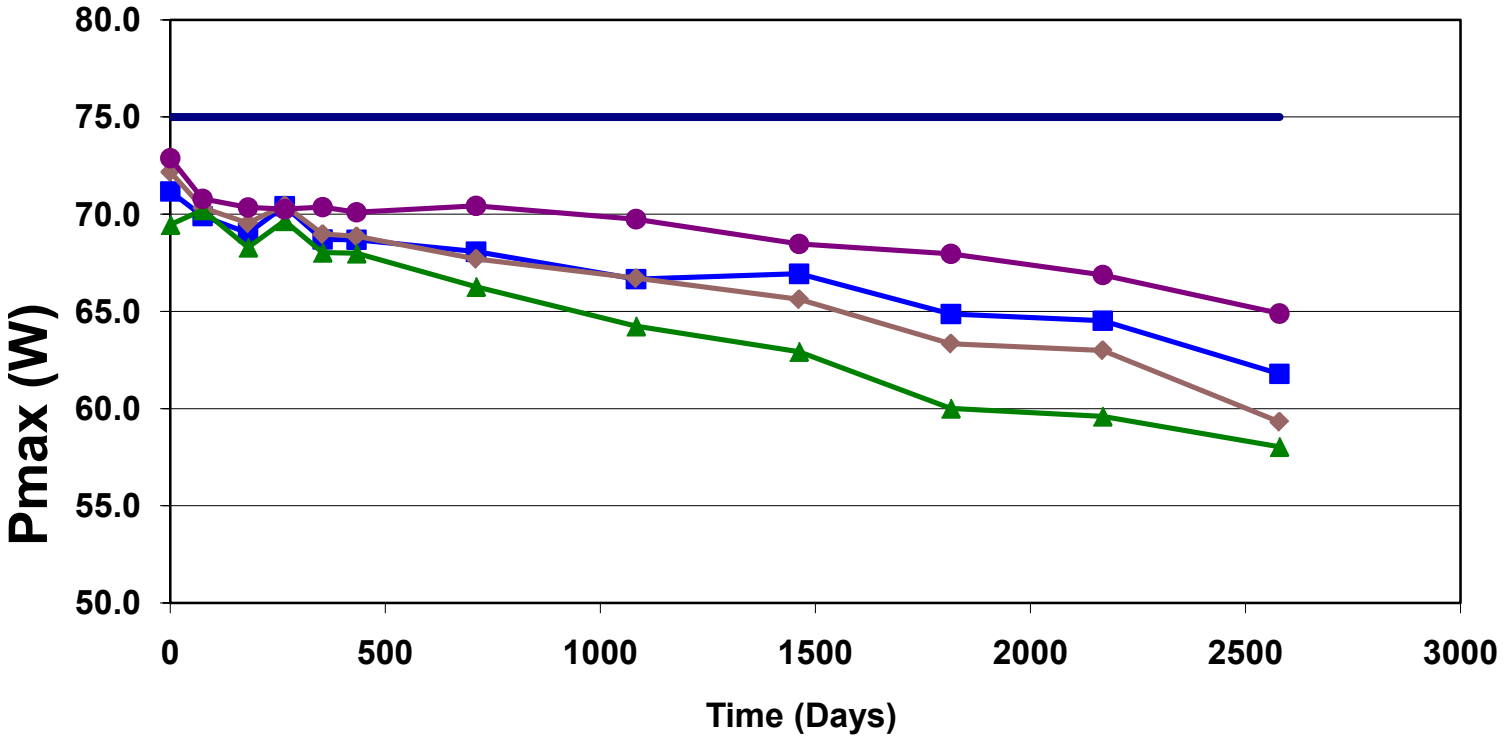
- Field data analysis from different climates
- Accelerated test data analysis
- Correlation between field and accelerated data



ASU Arizona State University

TÜV Rheinland PTL

- The purpose of this presentation is to provide our statistical approach to predicting lifetime of of PV modules undergoing long-term outdoor exposure at TUV Rheinland PTL, located in Tempe, Arizona.
- Two groups of c-Si modules are used: One installed at latitude tilt and the other on a two-axis tracker.
- Both groups have been installed for at least 8 years
- The plot below is an example of the max power output over time as reported.



ASU Arizona State University

TÜV Rheinland PTL

TIME-TO-FAILURE ANALYSIS

ASU ARIZONA STATE UNIVERSITY

TÜV Rheinland PTL

- Sample Power output data for modules installed on a two-axis tracker
- Data are shown as fraction of measured initial power output

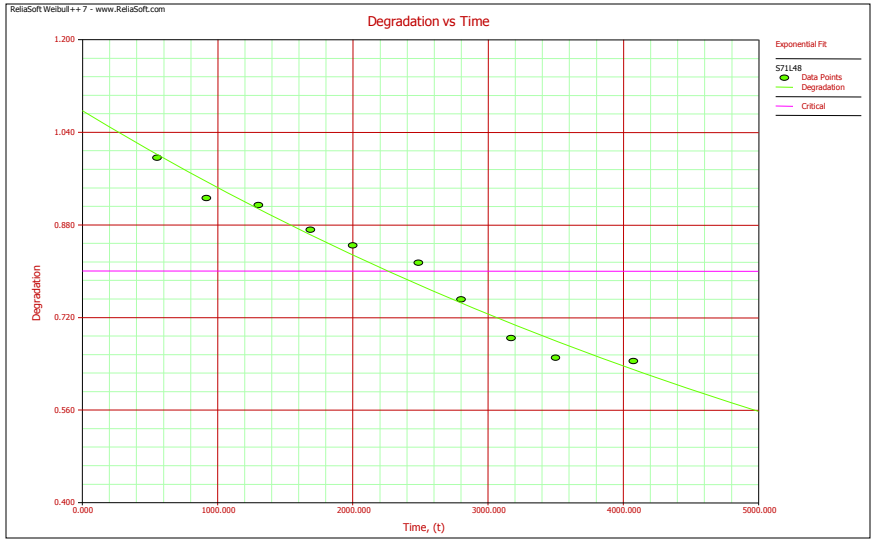
Test Date	S70L45	S72L46	S73L47	S71L48
9/24/1998	100	100	100	100
3/23/1999	98.13371	97.99541	98.08094	99.05143
3/29/2000	98.56707	98.30695	98.13213	99.64207
3/30/2001	96.17613	95.50743	99.06003	92.65495
4/18/2002	95.99587	93.96017	97.29334	91.41772
5/7/2003	94.70425	91.75761	97.08592	87.15466
3/16/2004	92.98966	88.53482	95.50054	84.47388
7/14/2005	86.65919	88.54046	93.44639	81.48294
5/25/2006	76.14737	77.13774	88.38811	75.11946
5/29/2007	69.60249	71.62216	82.89079	68.44898
4/23/2008	69.07595	72.03201	83.63877	64.46939
11/20/2009	58.31153	63.49378	76.61548	65.06237

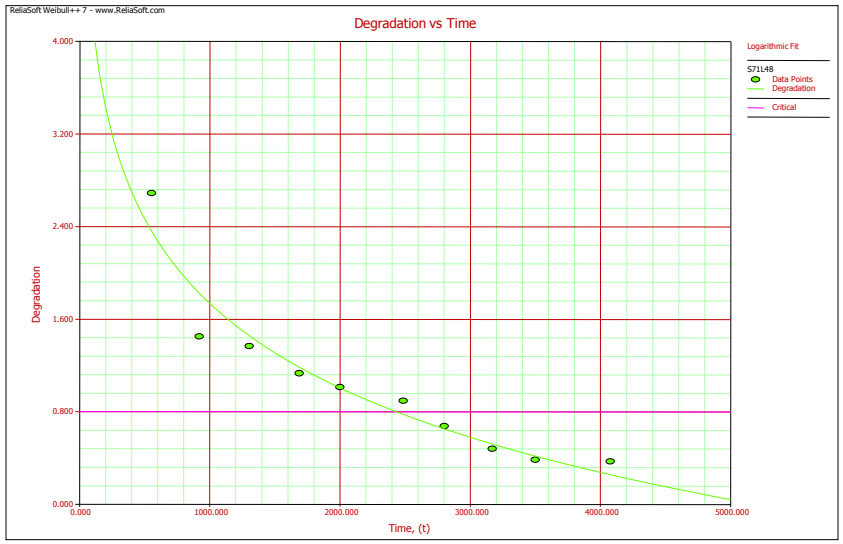
ASU Arizona State University

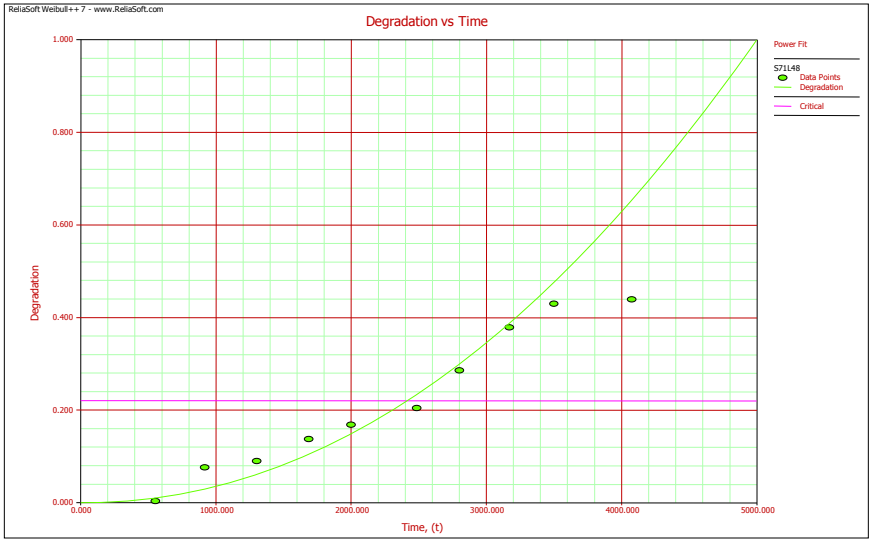
TÜV Rheinland PTL

From Degradation to TTF Data

- Mathematical models (Linear, exponential, power, and logarithmic) were used on each unit of test to extrapolate the degradation measurements to the defined (80%, 50%) failure level
- Time-to-failure (TTF) of each unit was estimated from the best fit.
- These failure times can now be used for reliability estimations







ASU ARIZONA STATE UNIVERSITY

Extrapolated TTF at 80% degradation

Samples at Latitude tilt		Samples on the Tracker	
Unit	Failure time (years)	Unit	Failure time (years)
3801	33.41386	S64L38	8.270246
4821	26.93645	S66L40	48.78274
DG22	25.60665	S67L39	9.783445
DG822	20.84669	S68L37	9.667831
RA240	32.01457	S70L41	8.06494
		S70L45	7.041274
		S71L44	11.47928
		S71L48	6.419939
		S72L42	8.141393
		S72L46	7.273979
		S73L43	7.866981
		S73L47	10.91259

Fitting the TTFs to a distribution

Three types of statistical failure (distribution) models are generally appropriate for PV reliability analysis:

- Exponential distribution

$$f(t) = \lambda e^{-\lambda t}$$

- Weibull distribution

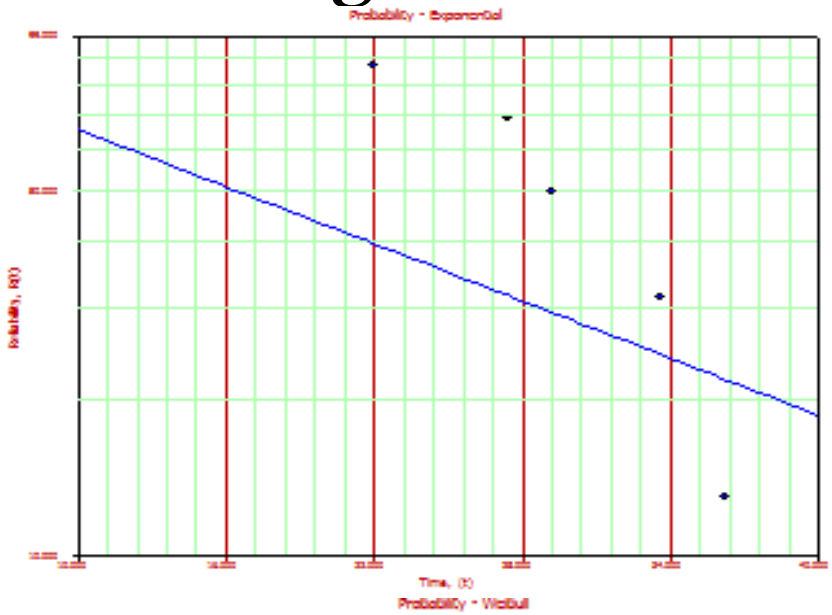
$$f(t) = \frac{m}{c}\left(\frac{t}{c}\right)^{m-1} e^{-\left(\frac{t}{c}\right)^{m}}$$

- Lognormal distribution

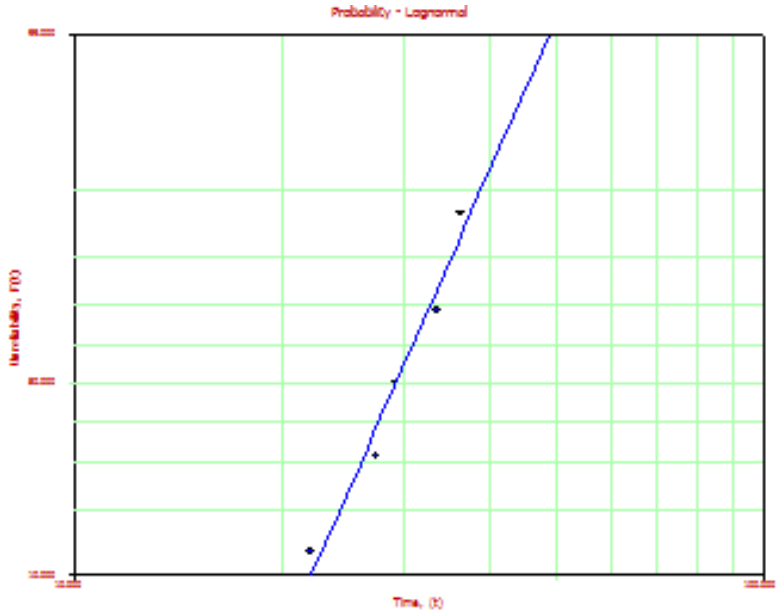
$$f(t) = \frac{1}{\sigma t\sqrt{2\pi}} e^{-(\ln t - \ln T_{50})^2/2\sigma^2}$$

To determine what distribution will adequately represent the data, we used graphical methods. This consists of linearizing the above functions and plot the relevant quantities.

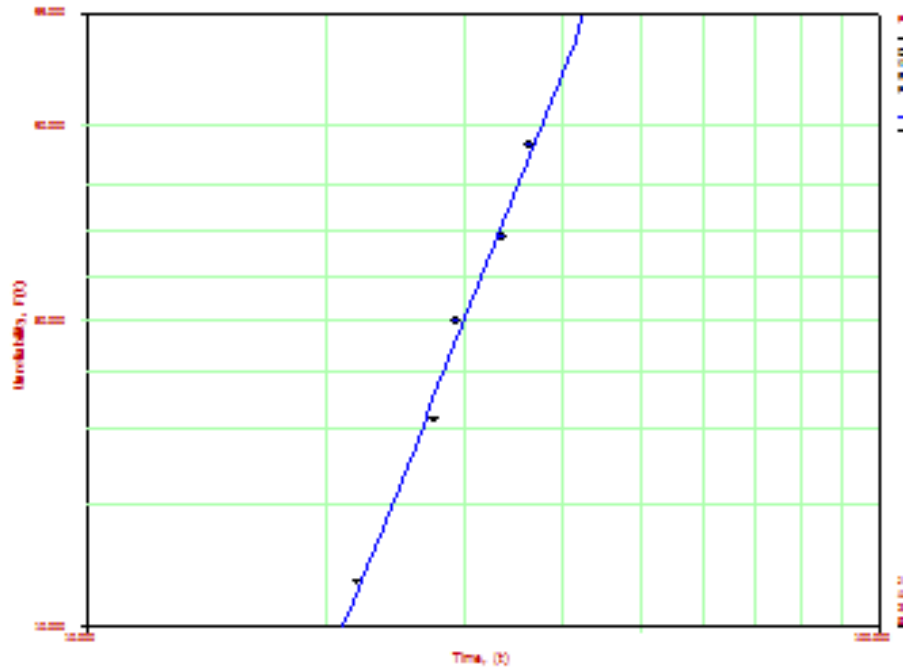
Fitting the TTFs of the fixed latitude data



Exponential distribution

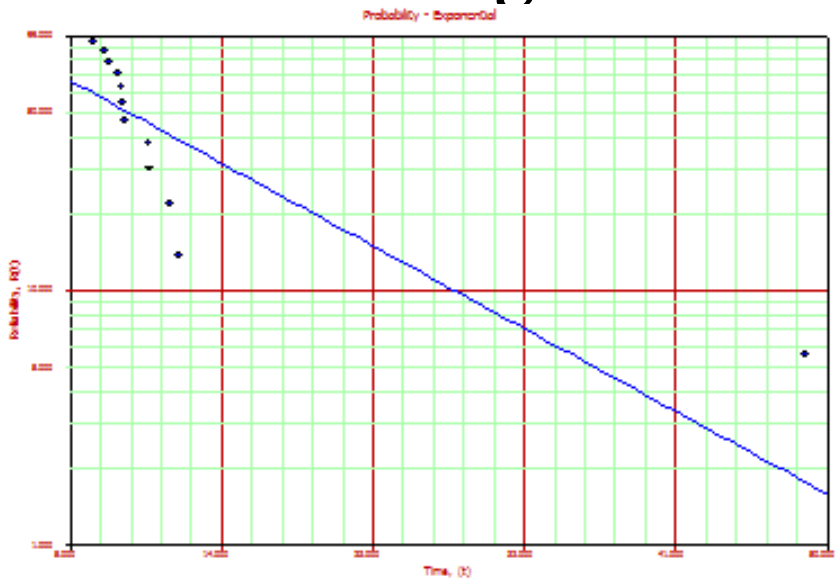


Lognormal distribution

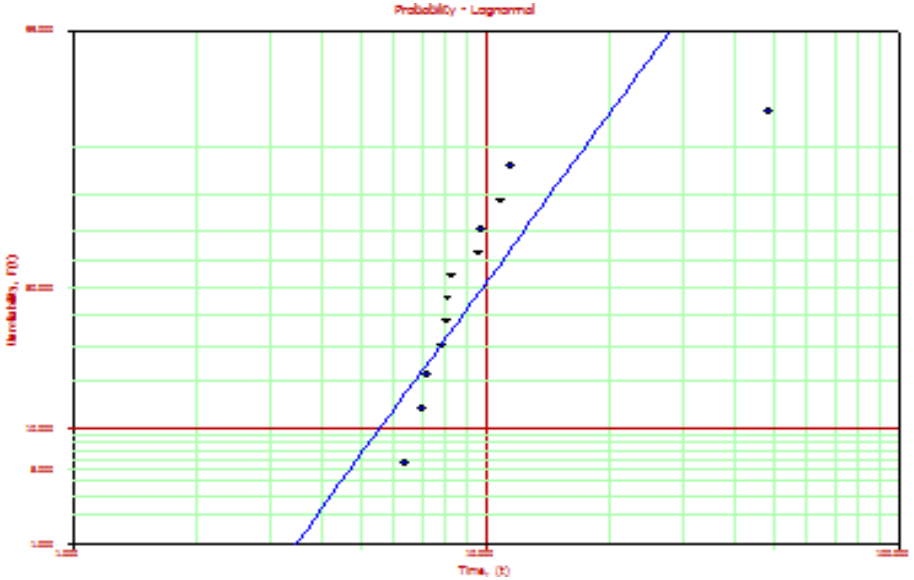


Weibull distribution

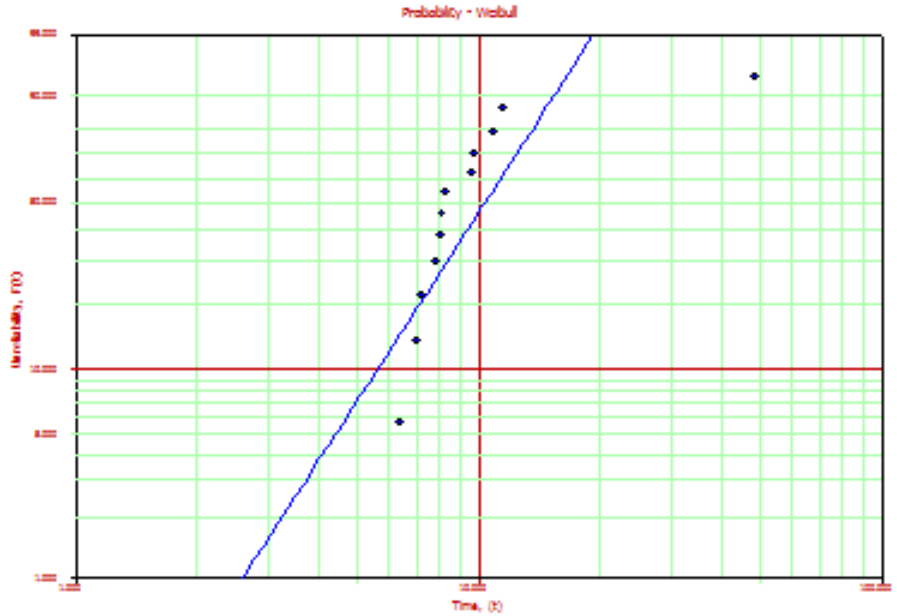
Fitting the TTFs of the tracker data



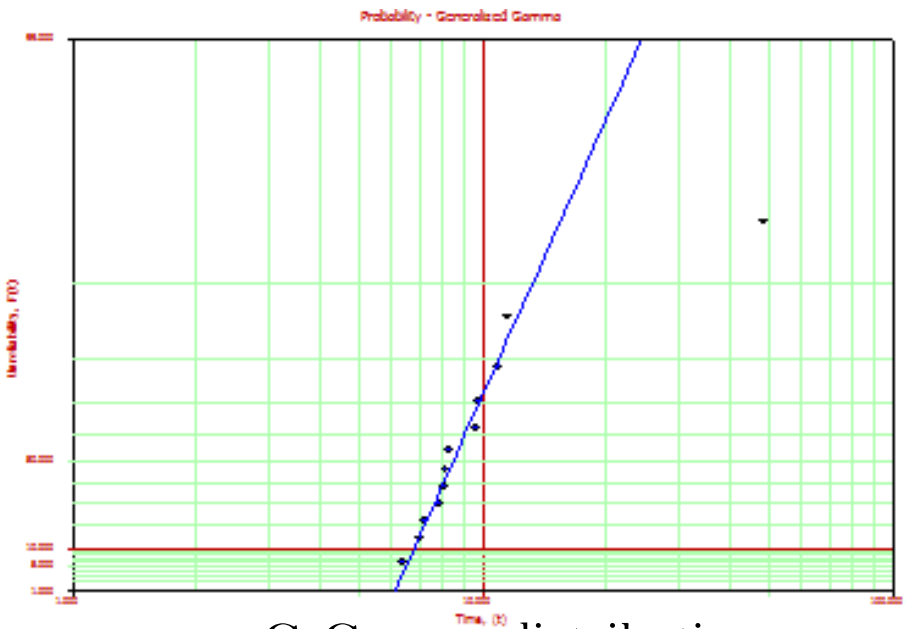
Exponential distribution



Lognormal distribution

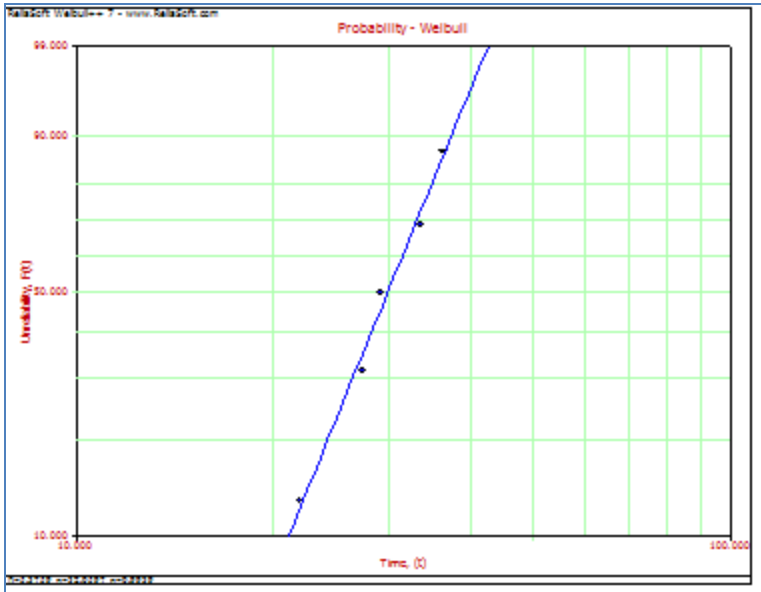


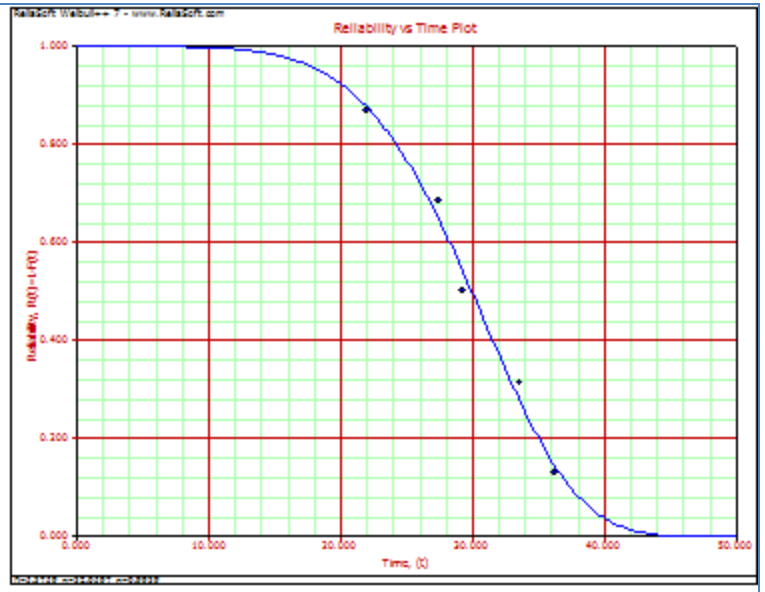
Weibull distribution

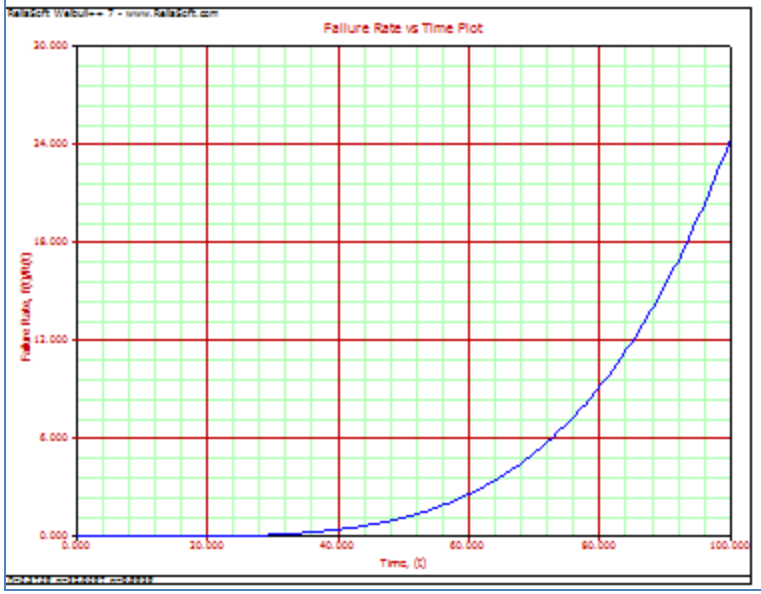


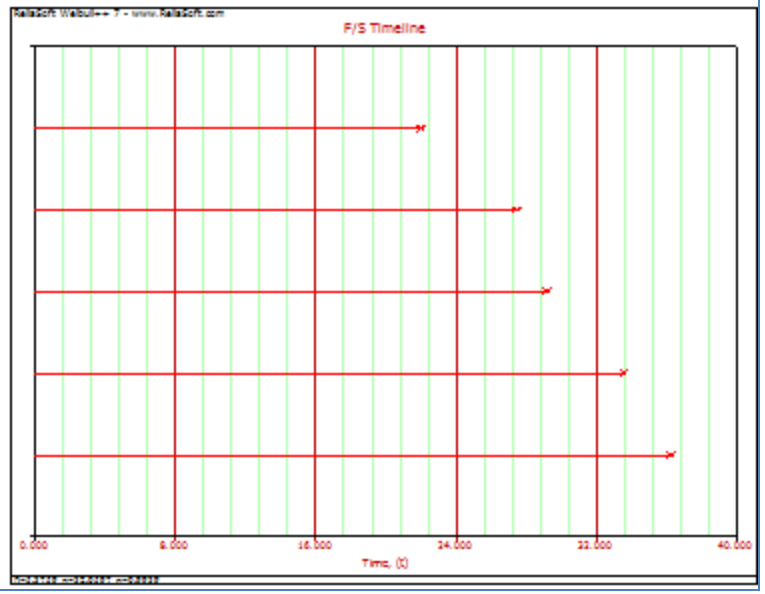
G-Gamma distribution

Analysis of fixed latitude data









Analysis of fixed latitude data

- The 2-parameter Weibull distribution was selected
- The output below was obtained from Weibull++7 software

	Value	Lower Bound	Upper Bound
Beta (m)	5.3759	3.3	8.7484
Eta (c)	32.0597	28.5706	35.975
Mean Life	29.5591	25.2656	34.5821
Failure Rate	24.3424	0.2683	2208.7097

- A module from that batch would need an average of 29 years before seeing its power output drop below 80%
- An average of 24 of those samples are expected to fail per year

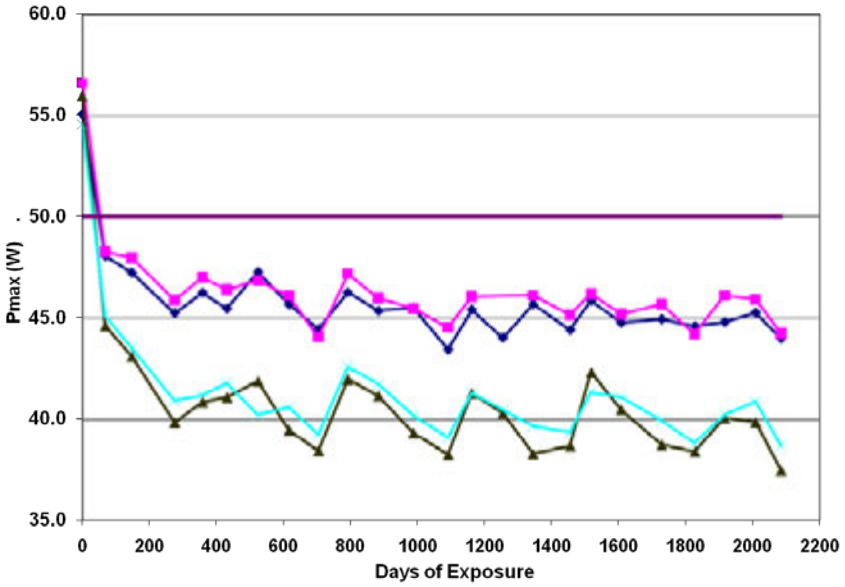
TÜV Rheinland PTL

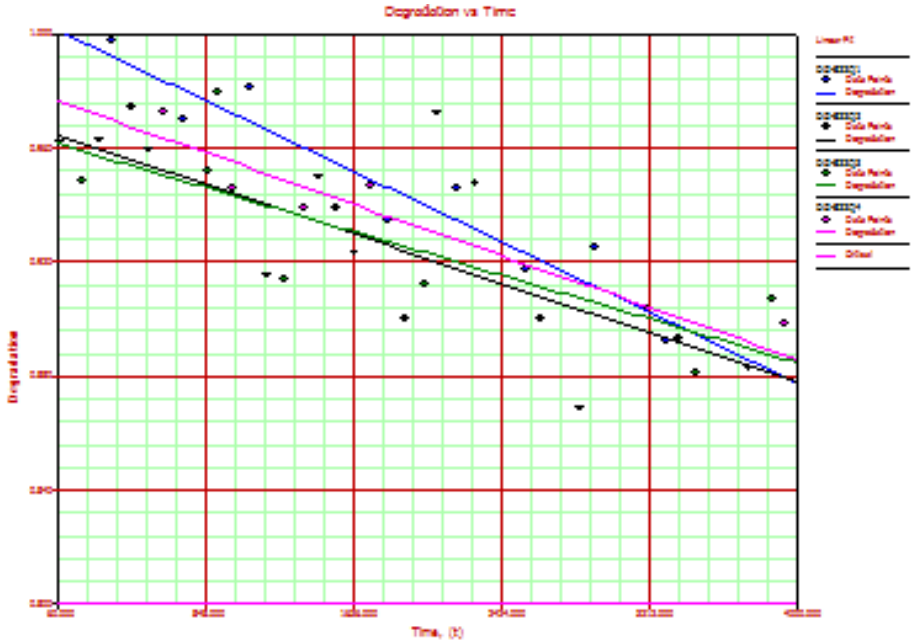
DEGRADATION ANALYSIS WITH NON-CONSTANT MODEL PARAMETERS

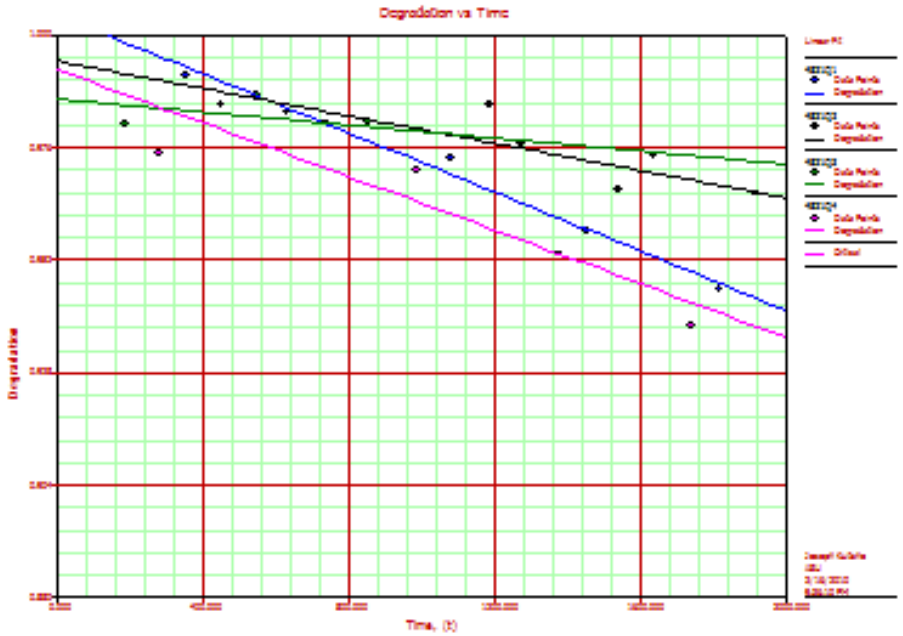
ASU ARIZONA STATE UNIVERSITY

Non-linear degradation of PV Modules

- PV modules degradation is not really linear
- Such behavior makes it difficult to use the approach just described to adequately model module degradation
- The two figures below show how modules behave by quarters.







Accounting for Environmental Variables

- PV degradation analysis must account for environmental effects
- Assuming an end-of-life criterion of 50%
- Let R be the likelihood that an item is still functioning at time t;

  i.e. degradation of power output $< 50\%$

  $R = Pr$ [fraction of initial $P_{max} > 0.5$]
- We make the following assumptions:

R = fraction of initial power if > 0.5;

= 0 otherwise

Non-Constant parameters approach

- Fit the data to a mathematical model → choose a distribution.
- The fraction of power output can be written as a function of that model, with non-constant parameters; say, a & b
- The parameters of the model above are function of environmental parameters

  a, b = f(Insolation, Tambient, RH, WS, etc.);

  $(\text{insolation, Tambient, RH, WS, etc.})_i$ = environmental cell i
- From the weather data, define a “typical day” of a month as a series of x hours period.

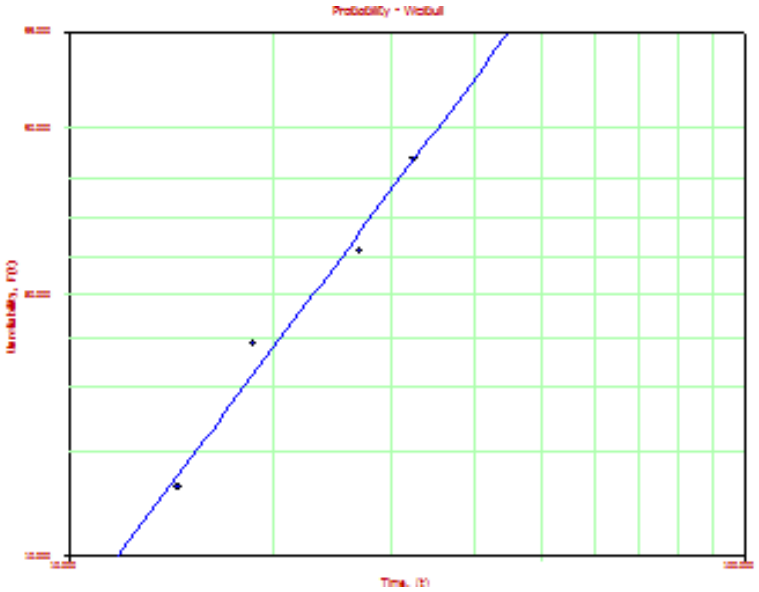
Non-Constant parameters approach

	1006	1012	4425	4510	Days	Average R	ln (1/R)	Month
4/9/2004	0.840257667	0.83049	0.73012	0.75569	359	0.789139	0.23681	A
4/12/2006	0.78911445	0.78723	0.68367	0.71686	1092	0.74422	0.29542	A
4/11/2007	0.806853207	0.79791	0.69166	0.72138	1456	0.754453	0.28176	A
4/17/2008	0.810279984	0.78122	0.68636	0.71219	1828	0.747514	0.291	A
12/23/2004	0.829707377	0.81488	0.70536	0.74428	617	0.773555	0.25676	D
12/29/2005	0.826896293	0.80344	0.70281	0.73692	988	0.767515	0.2646	D
12/21/2006	0.829814596	0.81501	0.68434	0.72719	1345	0.764091	0.26907	D
12/30/2008	0.799022942	0.78191	0.66973	0.7096	2085	0.740065	0.30102	D
6/24/2003	0.873406436	0.85342	0.79745	0.82749	69	0.837942	0.17681	J
6/21/2004	0.825861406	0.82025	0.73449	0.76658	432	0.786798	0.23978	J
6/16/2005	0.840483675	0.83395	0.75017	0.78105	792	0.801412	0.22138	J
6/21/2006	0.824962664	0.8139	0.73793	0.75718	1162	0.783494	0.24399	J
6/13/2007	0.832947475	0.81657	0.75642	0.75829	1519	0.791058	0.23438	J

Non-Constant parameters approach

- The data were found to best fit a Weibull
- Thus, ln(1/R) can be defined by a power function

  $Ln(1/R) = bt^a$
- The fit yields the parameters (a, b) showed in table



Test Month	Parameter a	Parameter b	Avge Max Tamb
A	0.1298	0.112	35.03
D	0.12	0.113	24.95
J	0.095	0.122	43.02
S	0.114	0.113	41.03

- Average Max Tamb obtained from weather data
- For simplicity, we consider only thermal effect; i.e. (a,b)=f(Tamb)
- Assuming a linear relationship with natural temperature:

$(a, b) = C_1 + C_2/T$

Non-Constant parameters approach

- The data were found to best fit a Weibull
- If a is constant, we have for a day:

  $Ln(1/R) = [b_{7\text{-}9}^{(1/a)}(2/24) + b_{9\text{-}11}^{(1/a)}(2/24) + \ldots]^a$
- We can now predict over a given time frame.

Parameter	C2	C1
a	126.94	-0. 295
b	-31.8	0.218

Typical Day	7a - 9a	9a - 11a	11a - 1p	1 - 3 p	3 - 5p
Avge Max Temp	20.87	39.37	50.65	50.12	43.7
b = C1+C2/T	0.109842813	0.11626	0.11981	0.11965	0.11766
$b_i^{(1/a)}$	5.39131E-09	8.8E-09	1.1E-08	1.1E-08	9.7E-09
$Ln(1/R) = [Sum(\ldots)]^a * (kt)^a$					

Thanks for Your Attention!

Beyond Qualification:
Testing for Long Term PV Module Durability



NREL PV Module Reliability Workshop, 18-19 February, 2010

Allen Zielnik
Solar Energy Competence Center
Atlas Material Testing Technology LLC



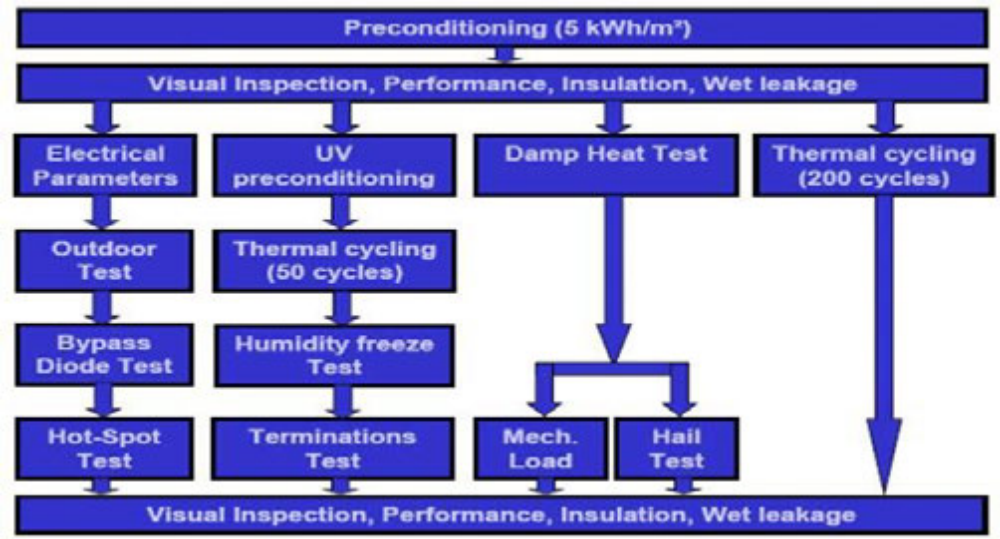






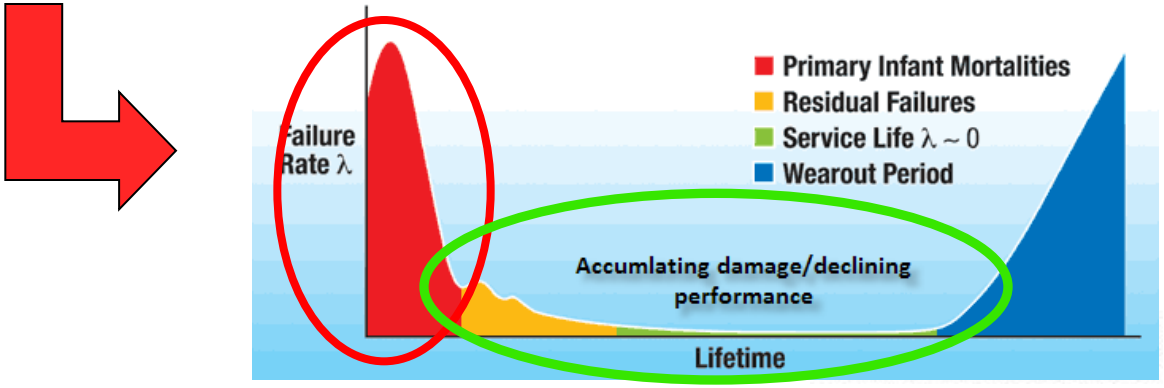
ATLAS
MATERIAL TESTING SOLUTIONS
Experience.
The Atlas Difference.

IEC design type qualification tests

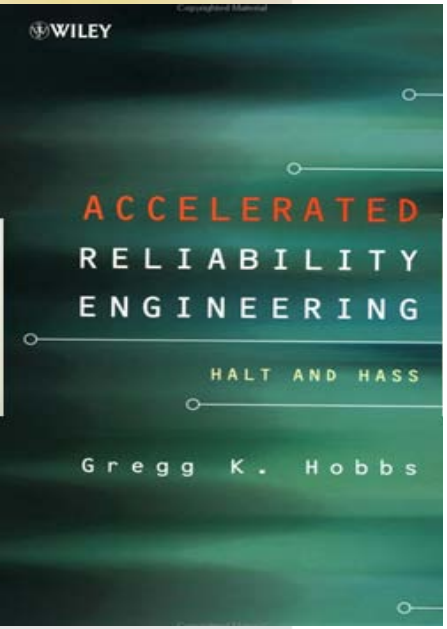


IEC 61215 environmental tests

IEC 61646 environmental tests are similar



Perspectives on HALT testing



- "HALT does not attempt to simulate the field environment-only seeks to find design and process flaws by any means possible.
- Intent is to determine failure modes, NOT demonstrate that a product meets specified requirements.
- Not meant to determine reliability but to improve it.
- Test environments are not directly related to real life and may be controversial.
- Time-dependent failure modes may not be revealed.
- Difficult to do on complex structures because of complex loading – FMVT" (failure mode verification testing

- Gregg Hobbs, *recognized originator of HALT & HASS* testing

ATLAS
MATERIAL TESTING SOLUTIONS

Weathering test tools

Materials → Cells → Modules → Systems















All photos courtesy NREL

ATLAS MATERIAL TESTING SOLUTIONS

An empirical approach . . .



- Based on known PV degradation
- Fundamental weathering testing
- Experience of other industries
- An accelerated weather aging protocol, not a service life predictor
- Takes advantage of technology from weathering and reliability testing
- Independent of PV technology
- Complements IEC-type qualification testing
- Acknowledges basic limitations & constraints
- Not pass/fail but provides early known indicators of failure modes

ATLAS
MATERIAL TESTING SOLUTIONS

IEC and weathering methods

Design Qualification environmental tests	Atlas module weathering tests
Intent: Accelerated tests to screen for major materials design and manufacturing flaws which result in premature (infant mortality) failures.	**Intent:** Accelerated environmental durability tests to reproduce likely field failures and estimate service life. Tests target failures resulting for the accumulated damage of long term outdoor exposure.
Climate Stresses: E.g. Temperature-only cycling; UV-only exposure; Humidity-Freeze cycling; Damp-Heat. Most tests delivered to separate modules.	**Climate Stresses (comprehensive):** Alternating cycles of SolarSim-Temperature-Humidity and SolarSim-Temperature-Humidity-Freeze; additional UV, salt spray, condensing humidity and outdoor solar tracking (AZ,FL). Modules under solar operate at max power point.
Stress levels and delivery not representative of end-use: No module goes through all tests; limited to 1 or 2 stresses, e.g., thermal cycling, damp heat, humidity-freeze.	**Stress levels based on climate-derived conditions:** Multiple simultaneous stresses delivered in short and long term cycles and at levels more representative of nature. **"Global Composite" climate condition standard;** alternative Hot Arid Desert, Tropical/Subtropical or Northern Temperate climate conditions available. **Optional test modifiers:** Coastal/Marine; Alpine/Snow Load; Urban Industrial; Agricultural Chemicals, Dust-Dirt, Acid Rain, Mildew effects.

ATLAS
MATERIAL TESTING SOLUTIONS

IEC and weathering methods

Design Qualification environmental tests	Atlas module weathering tests
Corrosion Testing: Limited to Damp-Heat test	Salt Spray and Condensing Humidity tests and outdoor exposures included.
No long term outdoor exposure. IEC cautions about shortness of test; most tests are chamber-based with limited stresses.	Uses combination of lab accelerated and outdoor solar tracking exposures with additional outdoor reference modules on one-year exposure in Arizona and Florida.
Few cycles but under harsh conditions: Designed to stress for infant mortality failures; may induce failures which will not occur in service	Higher number of cycles (diurnal >1500) under climate derived conditions designed to stress to longer term environmental effects.
Modules exposed non-operational Only short outdoor test is electrically active under load.	Modules exposed during solar load (lab and outdoor) operated under resistive load at maximum power point.
Solar Load: No solar load in chamber tests – modules at chamber temperature	Modules primarily under full spectrum solar load (natural or SolarSim) for differential heating and solar load effects. Max module temperature typically < 90°C

ATLAS
MATERIAL TESTING SOLUTIONS

Atlas 25$^{PLUS™}$ comprehensive weathering program

Atlas *25^{Plus}* "global composite" environmental test cycle
(other climates available)

1 module

- UV conditioning
- Salt spray corrosion
- Condensing humidity
- Solar – Thermal – Humidity Cycle
- Solar – Thermal – Humidity/Freeze Cycle
- Arizona solar tracking including peak summer

1 module FL 1 module AZ

1-year solar tracking South Florida & Arizona



Total test program duration: 12 months

ATLAS
MATERIAL TESTING SOLUTIONS

UV/Corrosion/Moisture stress

	Arid Desert	*Tropical / Subtropical*	*Northern Temperate*	*"Global"*
Corrosion	N/A (optional)	ISO 9227, ASTM B117 200 hours; 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour "Neutral Salt Spray Test"	ISO 9227, ASTM B117 400 hours; 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour "Neutral Salt Spray Test"	ISO 9227, ASTM B117 400 hours; 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour "Neutral Salt Spray Test"
Condensing Humidity	ASTM D2247, 125 hours @38°C or ISO 6270 40 °C	ASTM D2247, 125 hours @38°C or ISO 6270 40 °C	ASTM D2247, 125 hours @38°C or ISO 6270 40 °C	ASTM D2247, 125 hours @38°C or ISO 6270 40 °C
UV preconditioning	IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB	IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB	IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB	IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB



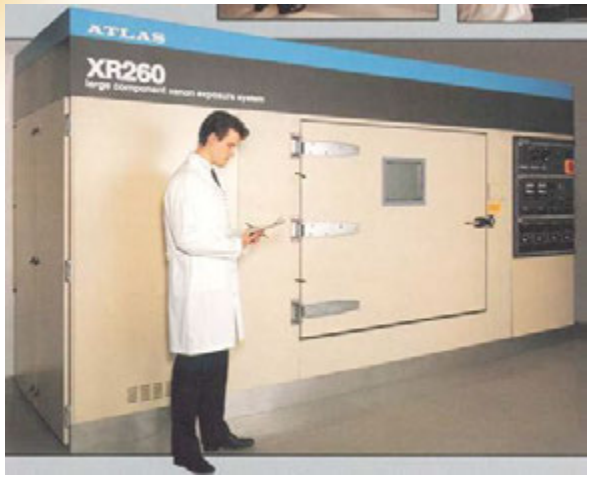
Large Corrosion Chamber

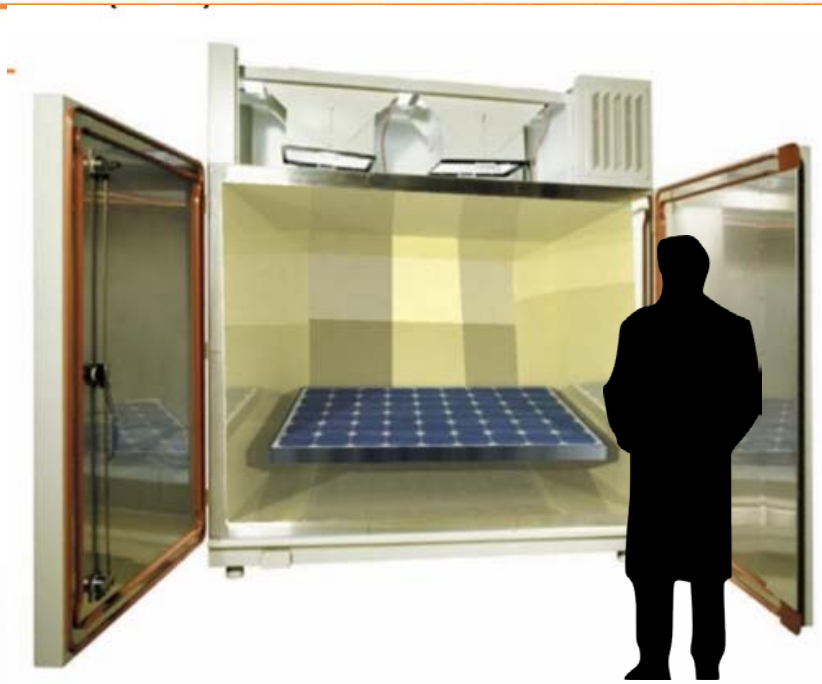


UV Exposure/Preconditioning

ATLAS
MATERIAL TESTING SOLUTIONS

Large scale lab accelerated weathering







Full spectrum solar sim AM1 – 1.5

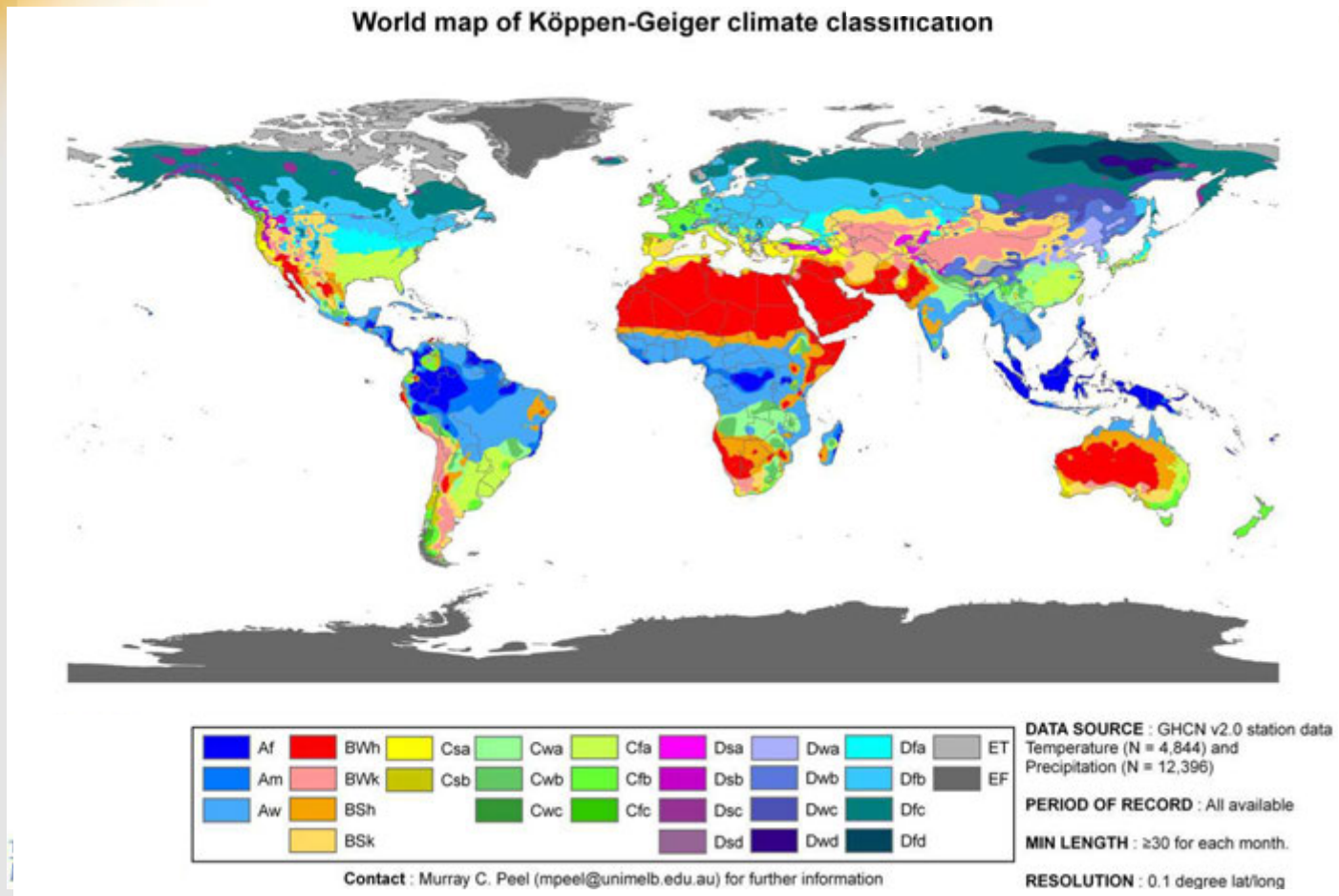
Thermal/Humidity cycling

Freeze/thaw temperature range

Modules under resistive load at MPP

ATLAS
MATERIAL TESTING SOLUTIONS

PV and service environment



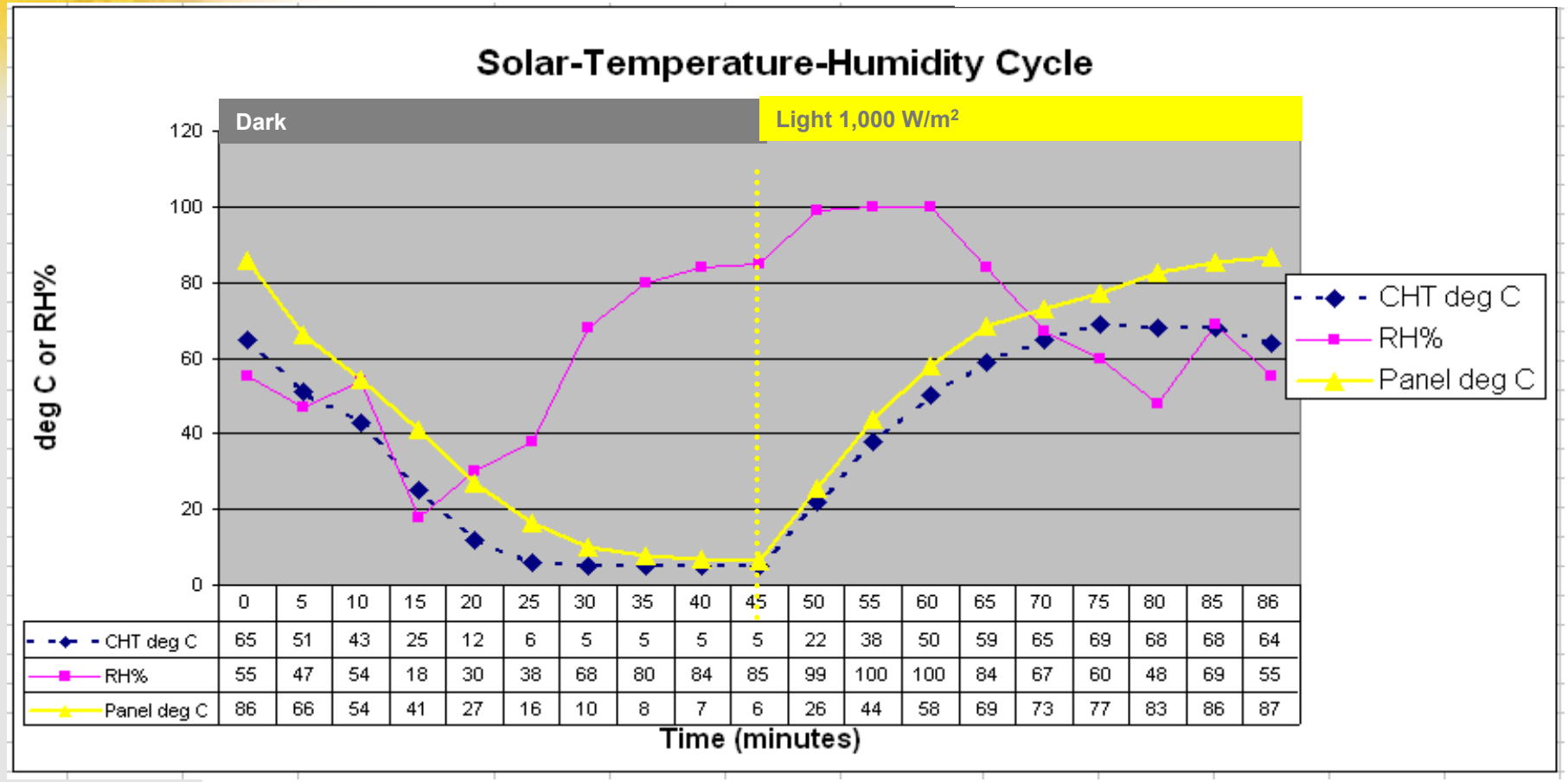
ATLAS
MATERIAL TESTING SOLUTIONS

Solar/Environment chamber

	Arid Desert	Tropical / Subtropical	Northern Temperate	"Global"
Temperature-Humidity Cycle with simultaneous Solar SC 2000 or Enviromental Chamber w/Solar	30% RH (turn RH% control off at 40°C) and 65°C →5 °C (dark) in 25 min, hold 20 min. ramp up (ligh 1000 W/m²) 21 minutes, hold 20 min; repeat Cycle time 86 minutes 16.7cycles per day repeat 9.5 days (158 cycles)	55% RH (turn RH% control off at 40°C) and 65°C →15 °C (dark) in 25 min, hold 20 min. ramp up (ligh 1000 W/m²) 21 minutes, hold 20 min; repeat Cycle time 86 minutes 16.7cycles per day repeat 7 days (117 cycles	55% RH (turn RH% control off at 40°C) and 65°C →5 °C (dark) in 25 min, hold 20 min. ramp up (light 1000 W/m²) 21 minutes, hold 20 min; repeat Cycle time 86 minutes 16.7cycles per day repeat 7 days (117 cycles	55% RH (turn RH% control off at 40°C) and 65°C →5 °C (dark) in 25 min, hold 20 min, ramp up (light 1000 W/m²) 21 minutes, hold 20 min; repeat Cycle time 86 minutes 16.7cycles per day repeat 7 days (117 cycles)
Temperature-Humidity Freeze Cycle with Solar	55% RH (turn RH% control off at 40°C) and 65°C →-10 °C (dark) in 40 min), hold 20 min, ramp up (light 1100 W/m²) 25 minutes, hold 20 min; 105 minute cycle, 13.7 cycles/day, repeat 0.5 day (7 cycles) [4% of total 10 day cycles are freeze]	N/A 55% RH (turn RH% control off at 40°C) and 65°C →-+5 °C (dark) in 40 min), hold 20 min, ramp up (light 1100 W/m²) 25 minutes, hold 20 min; 105 minute cycle, 13.7 cycles/day, repeat 3 days (44 cycles) *No freeze in tropics*	55% RH (turn RH% control off at 40°C) and 65°C →-10 °C (dark) in 40 min), hold 20 min, ramp up (light 1100 W/m²) 25 minutes, hold 20 min; 105 minute cycle, 13.7 cycles/day, repeat 3 days (44 cycles) [27% of total 10 day cycles are freeze]	55% RH (turn RH% control off at 40°C) and 65°C →-10 °C (dark) in 40 min), hold 20 min, ramp up (light 1100 W/m²) 25 minutes, hold 20 min; 105 minute cycle, 13.7 cycles/day, repeat 3 days (44 cycles) [27% of total 10 day cycles are freeze]

ATLAS
MATERIAL TESTING SOLUTIONS

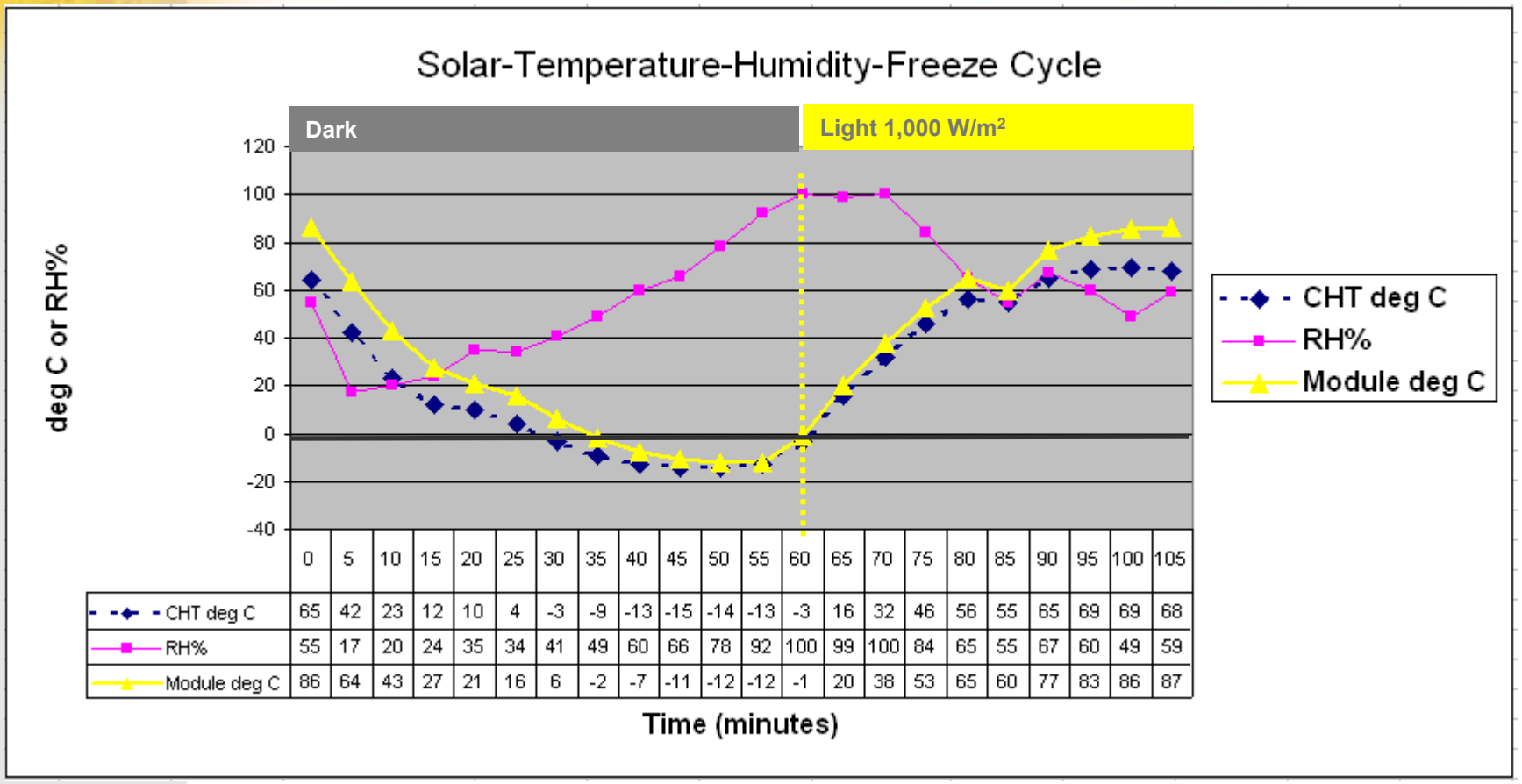
Cyclic Weathering Stresses



	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	86
CHT deg C	65	51	43	25	12	6	5	5	5	5	22	38	50	59	65	69	68	68	64
RH%	55	47	54	18	30	38	68	80	84	85	99	100	100	84	67	60	48	69	55
Panel deg C	86	66	54	41	27	16	10	8	7	6	26	44	58	69	73	77	83	86	87

ATLAS
MATERIAL TESTING SOLUTIONS

Module temperature tracking



	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105
CHT deg C	65	42	23	12	10	4	-3	-9	-13	-15	-14	-13	-3	16	32	46	56	55	65	69	69	68
RH%	55	17	20	24	35	34	41	49	60	66	78	92	100	99	100	84	65	55	67	60	49	59
Module deg C	86	64	43	27	21	16	6	-2	-7	-11	-12	-12	-1	20	38	53	65	60	77	83	86	87

ATLAS MATE MATERIAL TESTING SOLUTIONS

Available or in development options

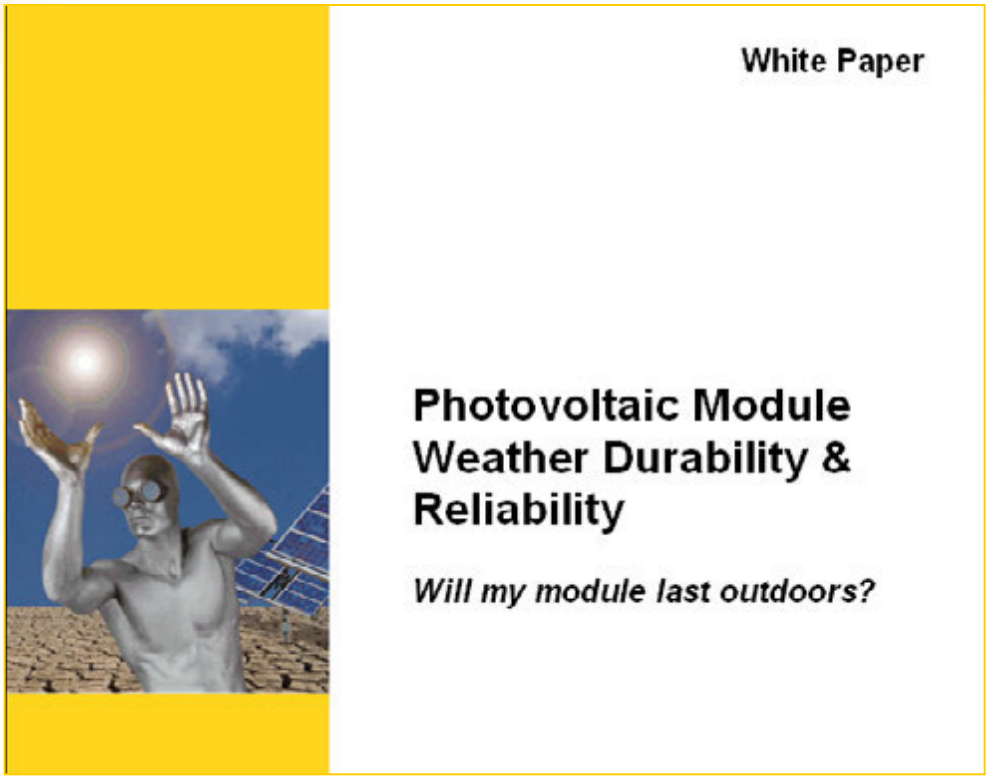


- Marine atmosphere
- Acid rain
- Mold/Mildew growth
- Dust/Dirt pickup & retention
- Urban/industrial fouling
- Agricultural chemical (ammonia)
- Wind blown abrasion

ATLAS
MATERIAL TESTING SOLUTIONS

Questions?

More info . . .



azielnik@atlas-mts.com
+1 773-289-5580
4141 N. Ravenswood Avenue
Chicago, IL 60613 USA
www.solardurability.com

ATLAS MATE MATERIAL TESTING SOLUTIONS

National Renewable Energy Laboratory
Innovation for Our Energy Future

National Center for Photovoltaics

Test-to-Failure for Long-Term Performance Assessment



Peter Hacke

PV Module Reliability Workshop
February 18–19, 2010

This presentation does not contain any proprietary or 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

Acknowledgments

Performance & Reliability Accelerated Lifetime Testing
•Ed Gelak
•Kent Terwilliger
•David Trudell

Performance & Reliability Diagnostics
•Nick Bosco
•Steve Glick
•Cassi Sweet

Performance and Reliability Management
•Sarah Kurtz

UCSC
•Glenn Ilers

Test & Measurement group/ Device Performance
•Allan Anderberg
•Keith Emery
•Steve Rummel
•Andrew Sellstrom

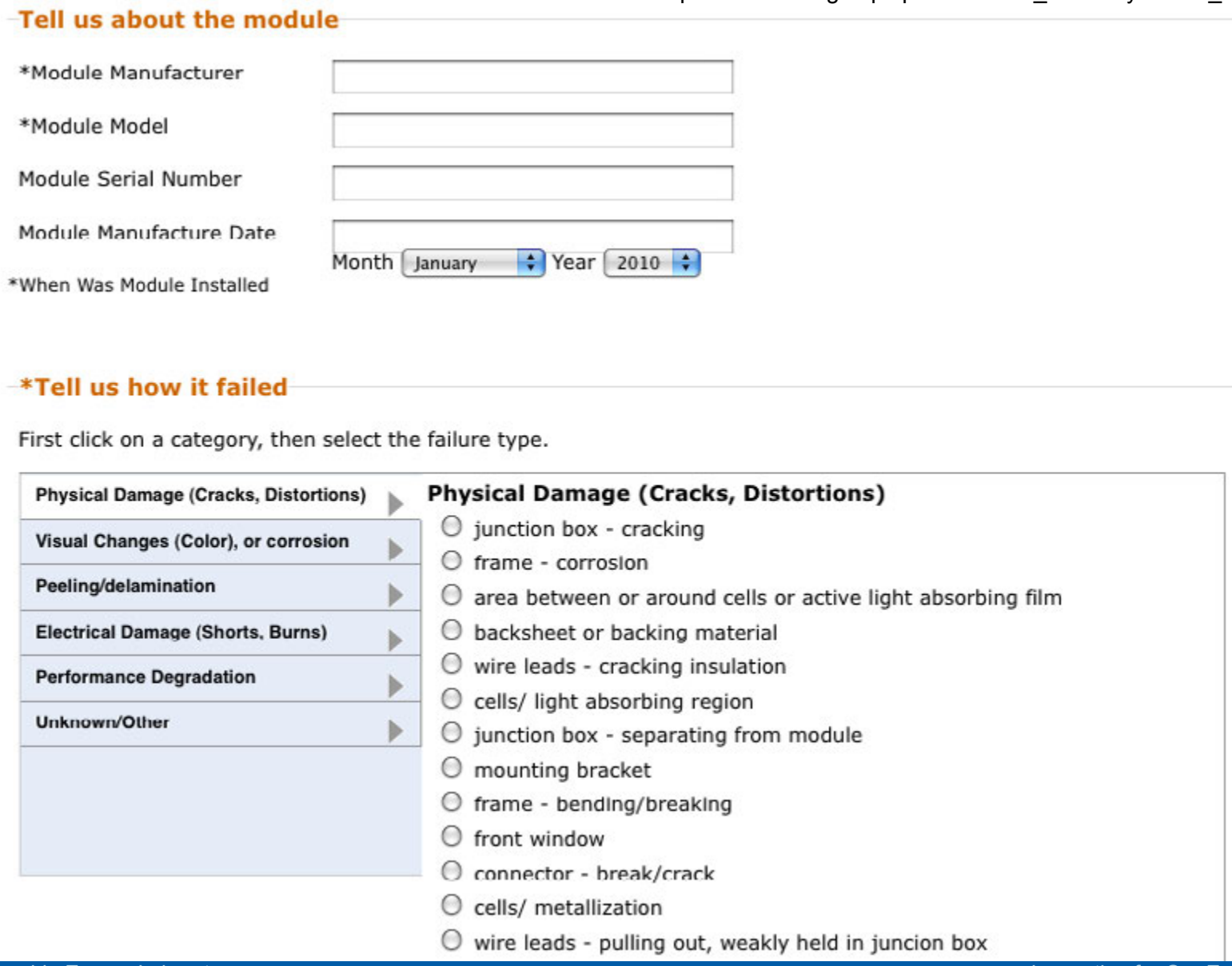
Test & Measurement Group/ Surface Analysis
•Sally Asher
•Joel Pankow

Test & Measurement Group/Analytical Microscopy
•Mowafak Al-Jassim
•Chun-Sheng Jiang

Test & Measurement Group/Electro-Optical Characterization
•Steve Johnston
•Nathan Call

Photovoltaic Module Field Failure Database

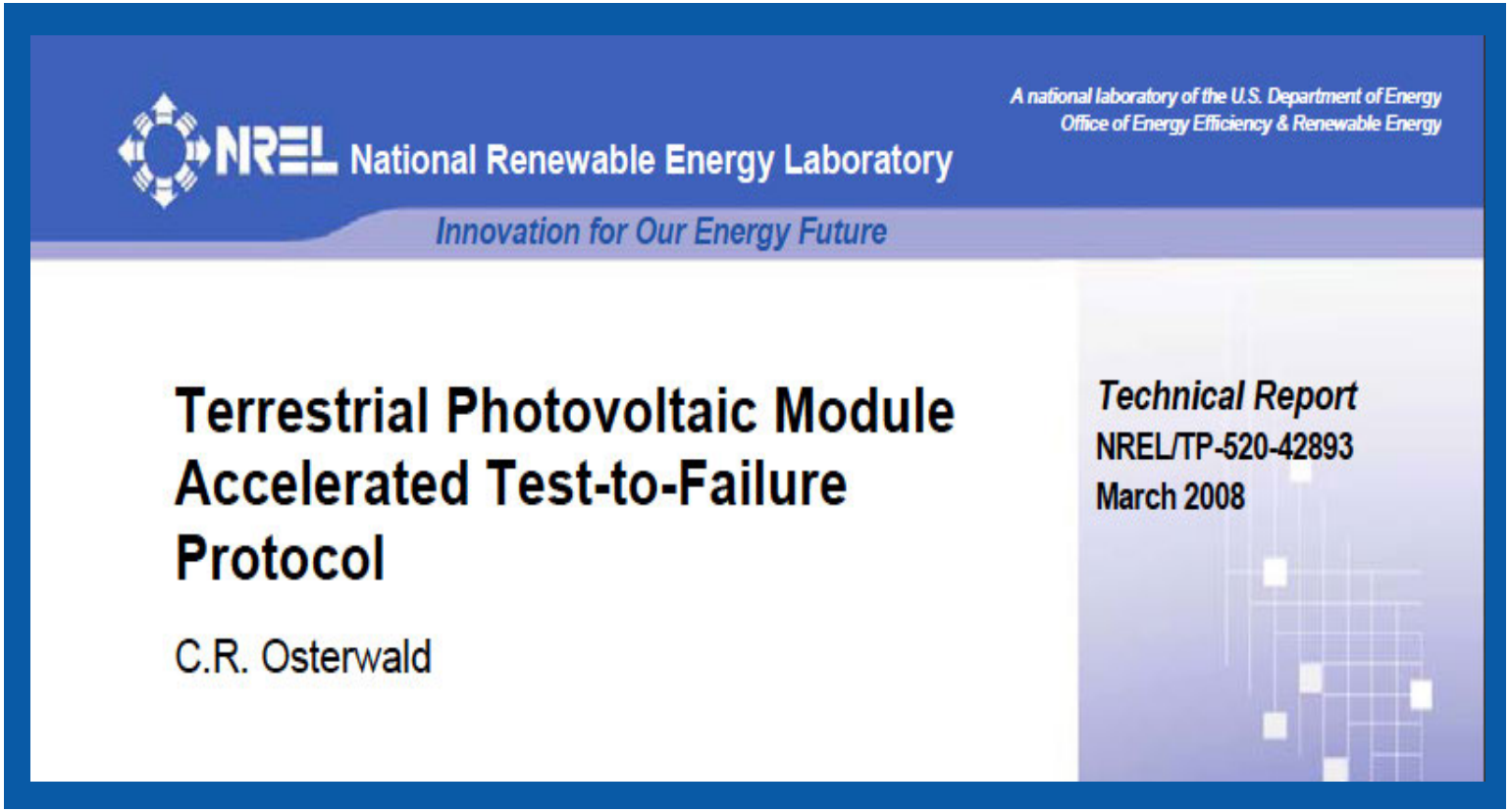
https://www.nrel.gov/pv/performance_reliability/failure_database/



Overview

- Motivation for the Test-to-Failure protocol
- Test description
- Program description
- Results and discussion from application of the protocol
  - Thermal cycling with load
  - Damp heat with bias
  - Failure mechanisms
- Main results

Background


NREL National Renewable Energy Laboratory
A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Innovation for Our Energy Future
Terrestrial Photovoltaic Module Accelerated Test-to-Failure Protocol
C.R. Osterwald
Technical Report
NREL/TP-520-42893
March 2008

Background

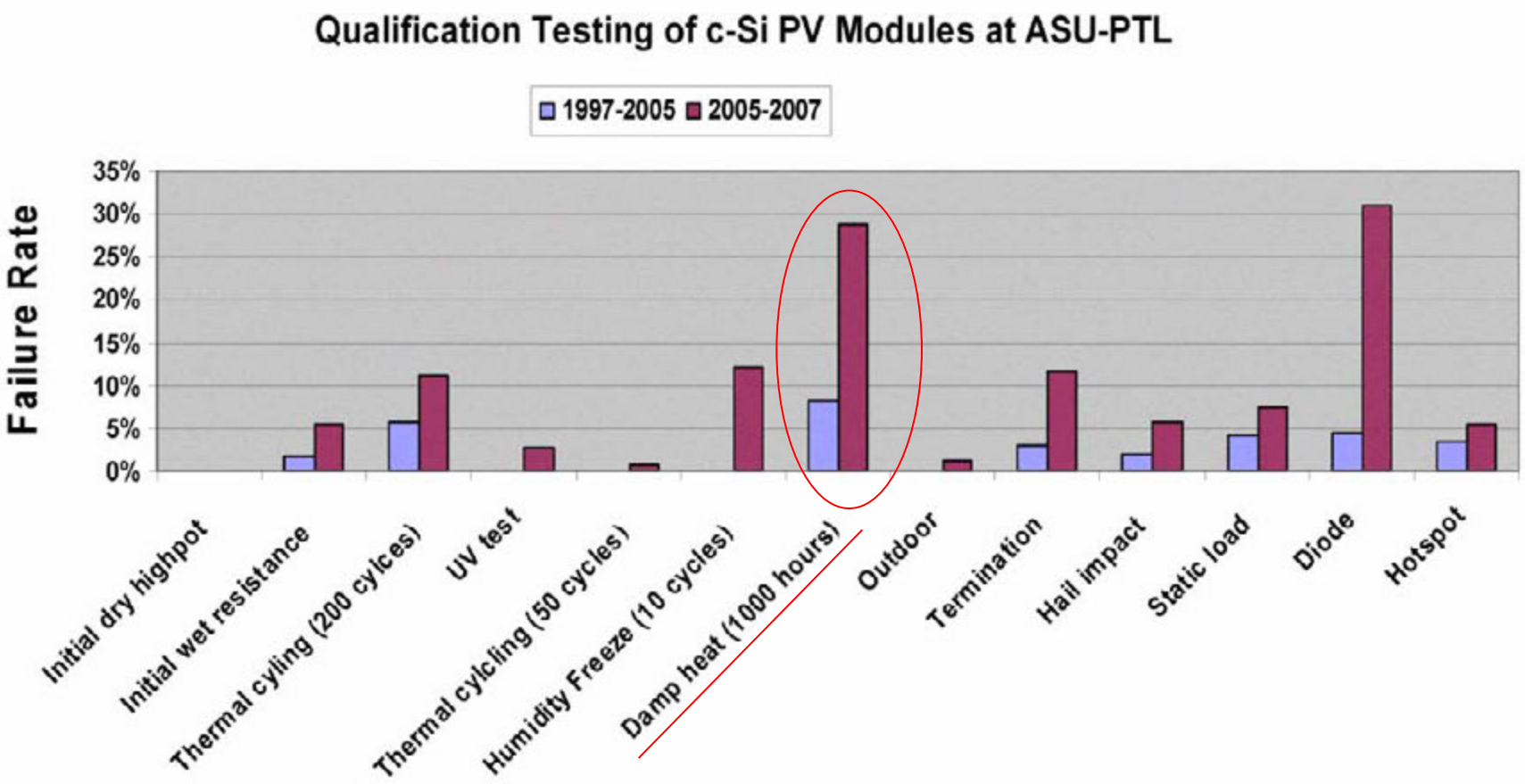

Field Reliability Experience
Qualification Test
Test-to-Failure
Lifetime Prediction

Motivation

- Test new module technologies on a comparative basis in a highly accelerated manner
- Perform due diligence between various module technologies before large capital outlays for PV power plants are committed
- Characterize potential performance and reliability problems for high voltages systems
  - 600 V systems in USA
  - 1000 V, 1500 V systems in EU
- Accelerate the onset of failure so that failure mechanisms can be analyzed, compared to field failures, and then addressed

Failure rate of c-Si modules through IEC 61215 qualification testing at ASU-PTL for 1997-2005 and 2005-2007

Damp heat a key environmental stress challenge



Courtesy G. TamizhMani et. al. TUV-PTL

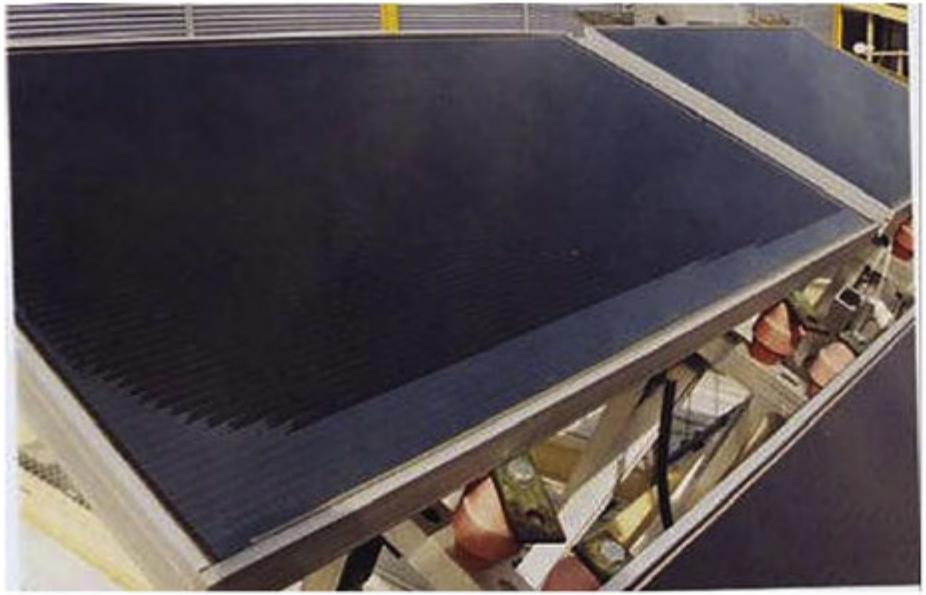
Qualification testing at EU JRC Institute for Energy/ Ispra

Distribution of major defects of commercial modules provoked per Qualification Tests performed between 1990 and 2006

Type of module failure	Tests type								
	OE	HSP	UVE	Total irrad. tests	TC50	HUF	TC200	DAH	Total envir. tests
Modules which failed the IEC 61215									
Visual defect	0	1	1	2	3	3	7	3	16
Power loss	1	0	3	4	2	2	7	3	14
Visual defect and power loss	0	0	0	0	2	0	5	1	8

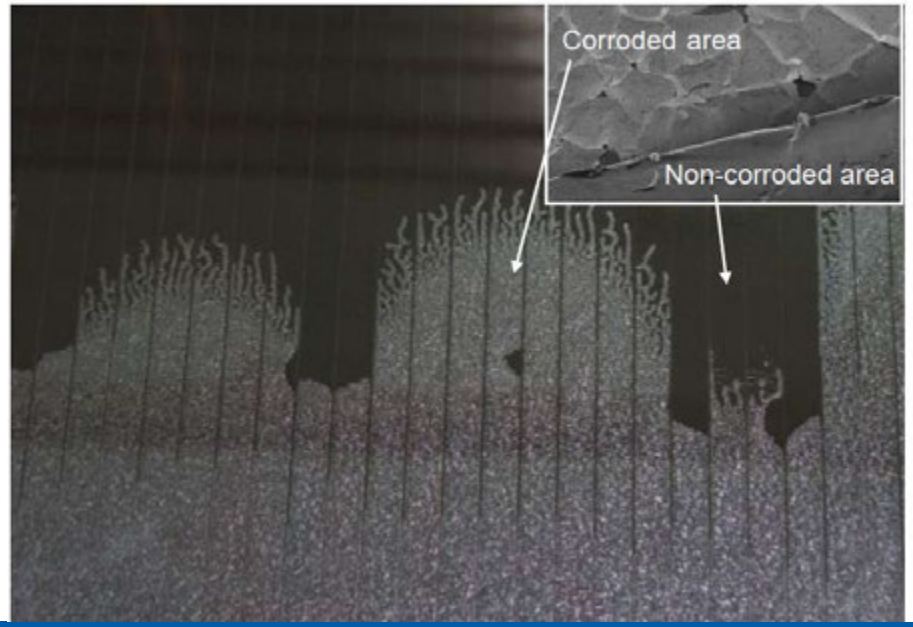
A. Skoczek, JRC IE/Ispra

Effects of Damp Heat *with System Bias*



J. H. Wohlgemuth et al. "LONG TERM RELIABILITY OF PHOTOVOLTAIC MODULES", WPSEC-4 (2006) p. 2050

- a-Si
- - 600 V
- 12 months in the field



Electrochemical corrosion from sodium ions with water at the TCO/glass interface causes de-lamination of the TCO

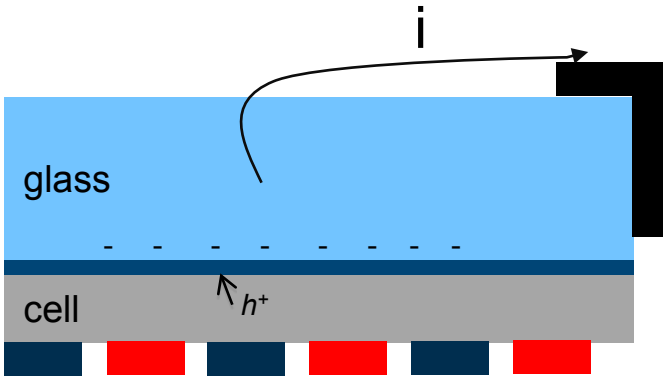
key drivers are:

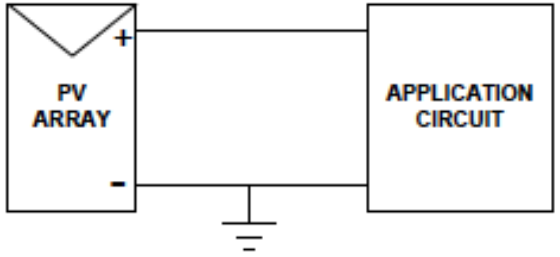
- negative cell polarity vs. ground
- moisture ingression
- temperature
- Na content in glass

Stefan Krauter, Jürgen Arp, Sven Lehmann, Paul Grunow
PI Photovoltaik-Institut Berlin AG

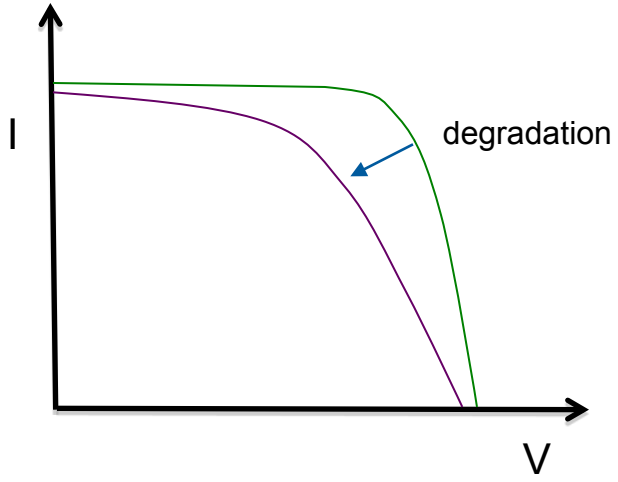
Damp heat - *with system bias*

SunPower 2005 press release, reports 'surface polarization' in solar cells



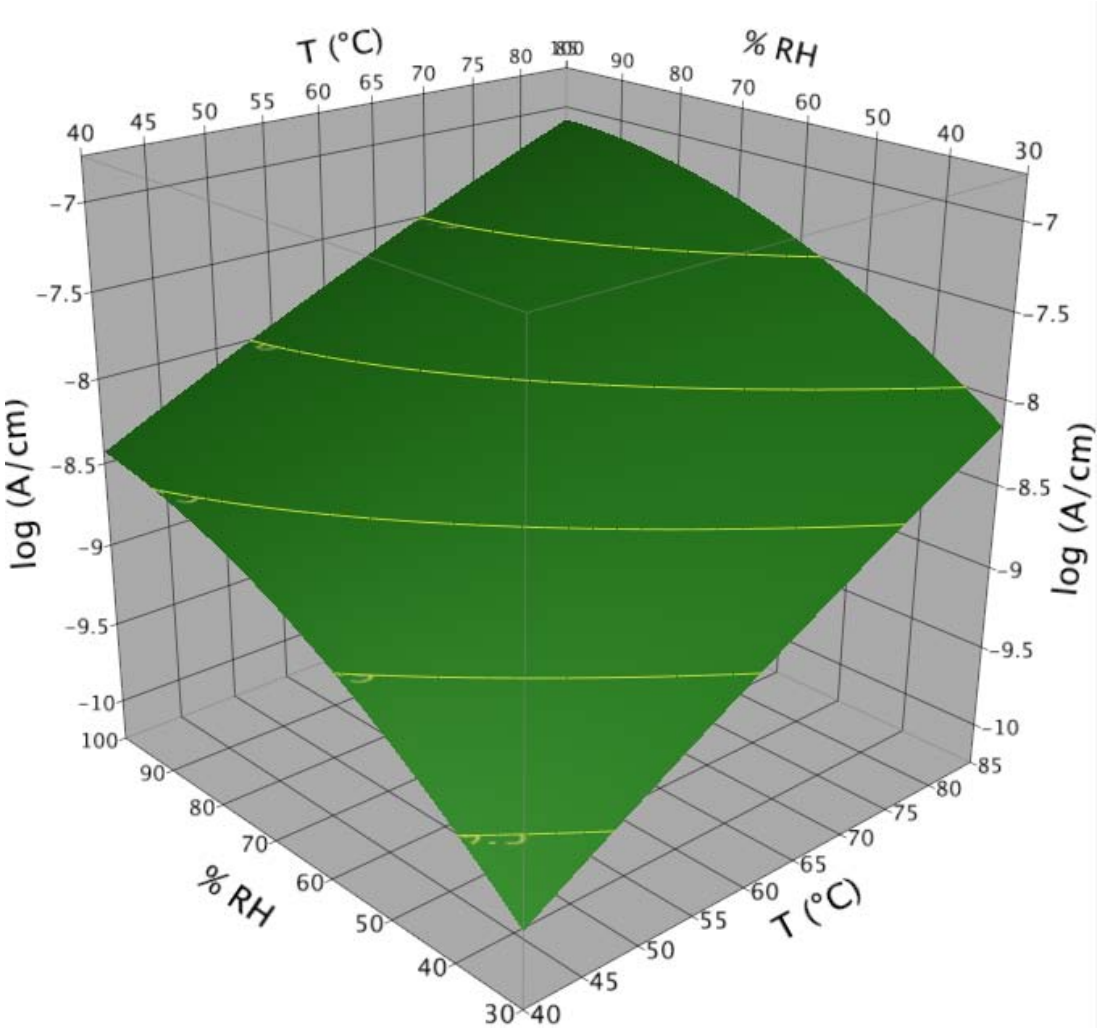


- Positive bias string leads to leakage current through glass to ground, leaving negative charge on cell surface, degrading effectiveness of the n^+ front surface field of the n^+/n structure
- Minority carriers (holes) recombine at front surface, leading to degraded cell performance



Effects of Damp Heat *with System Bias*

Leakage current vs temperature (T) and relative humidity (RH) per unit length of module frame (500 V bias) in a c-Si mini module with EVA-Tedlar construction



- Leakage current vary by orders of magnitude with modest changes in temperature and humidity
- Electrolytic corrosion directly related to the coulombs transferred

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

Test-to-Failure Protocol

- Thermal cycling to accelerate diurnal solar thermal loading of the extreme conditions seen in high desert
- Damp heat with system bias to accelerate hydrolytic and corrosive action of hot humid environments





The organization of the modules within the accelerated lifetime test sequences in the Test-to-Failure protocol.

Sequence	A. Control		B. Damp Heat with Bias 85°C/85%RH		C. Thermal Cycling with load -40°C/85°C		D. Alternating Seq. B/C DH/TC	
	A1	A2	B1	B2	C1	C2	D1	D2
	5 kW hrs/m^2 light soak							
Round 1			DH+	DH-	TC	TC	DH+	DH -
Round 2			DH+	DH-	TC	TC	TC	TC
Round 3			DH+	DH-	TC	TC	DH+	DH -
Round 4			DH+	DH-	TC	TC	TC	TC
…								
Round 15			DH+	DH-	TC	TC	DH+	DH -

- DH refers to 1000 hrs 85°C 85% relative humidity, IEC 61215 Ed. 2 sec. 10.13
- DH+(-) indicates +(-) voltage bias of 600 V or module's rated system voltage (whichever is greater) on shorted module leads with respect to grounded frame
- TC refers to 200 cycles between -40°C and 85°C, IEC 61215 Sec. 10.11 (I_{mp} applied when T> 25°C)
- Alt. DH/TC refers to a sequence of alternating 1000 Hrs. DH and TC 200 stress cycles described above

Test-to-Failure Program Description

I

Group 1 Pilot run with 1 c-Si model, now entering 5th round

Group 2 3 models c-Si, now entering 2nd round

Group 3 3 models c-Si, 1 now entering first round

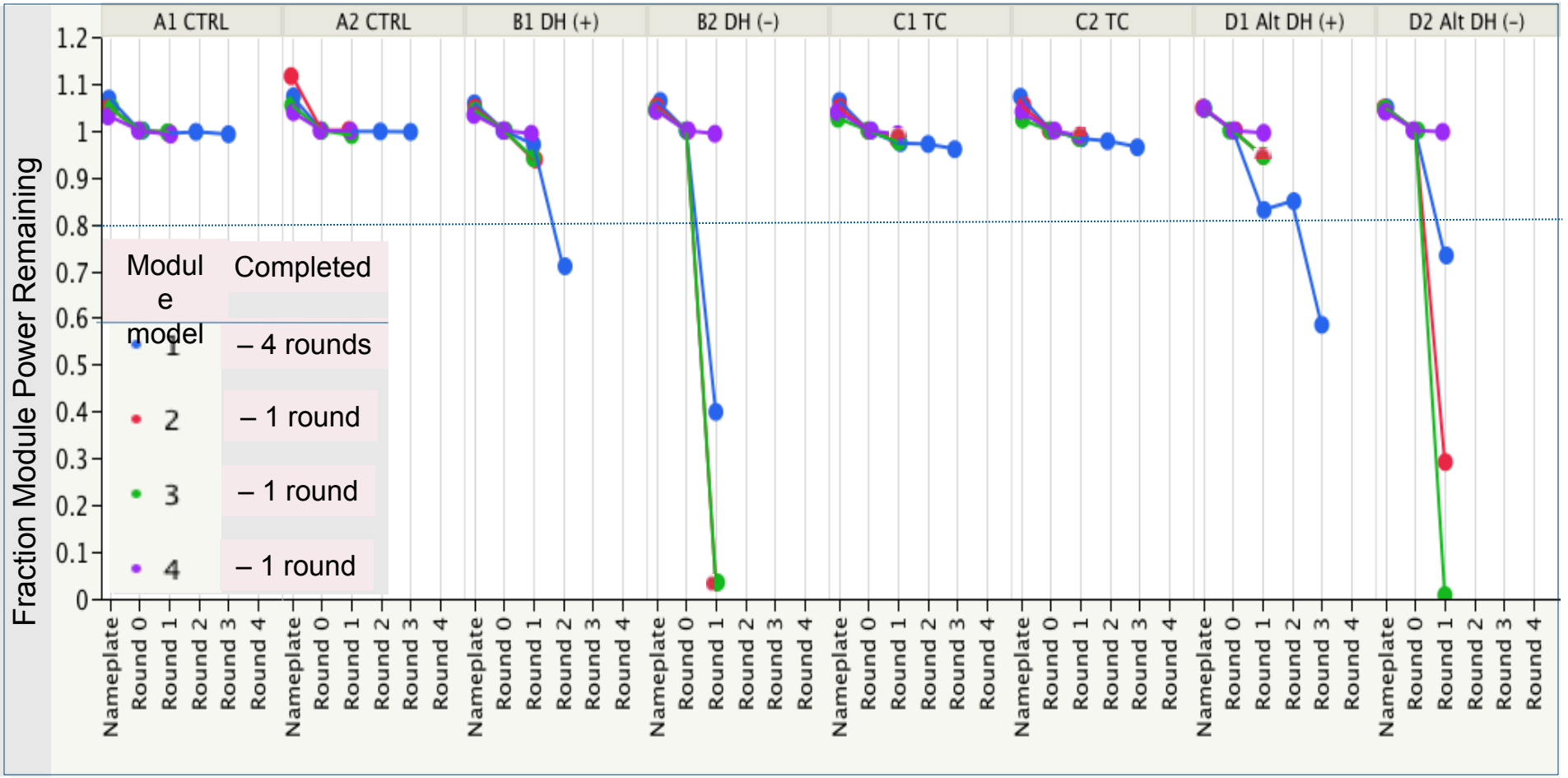
II Outdoor parallel tests

III Experiments varying factors and levels, and consideration of other stress factors to study degradation rates, determine, any necessary modifications to the test to failure program, and develop relationships for service lifetime

IV Thin film tests

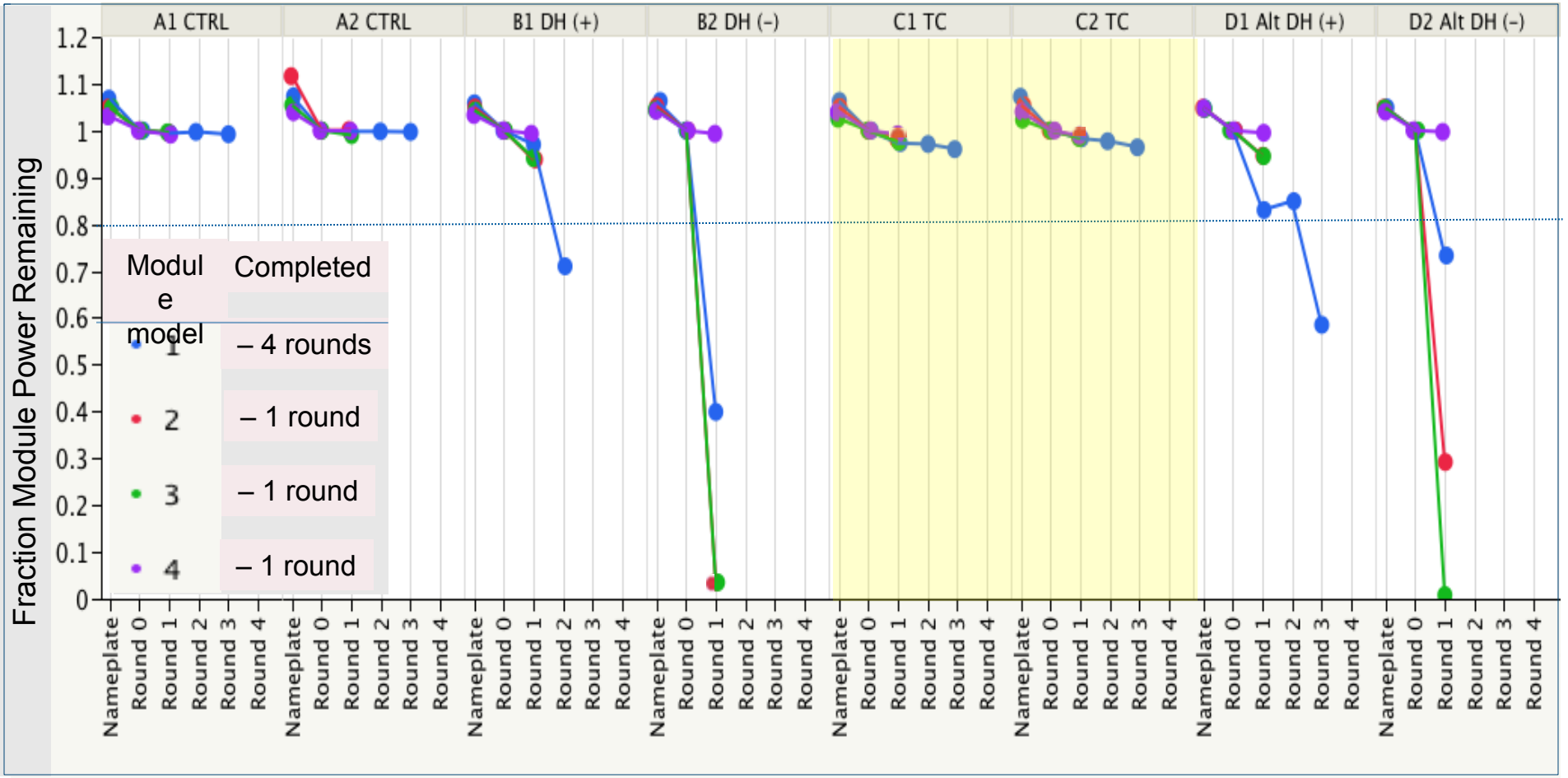
Performance Results

Fraction module power remaining vs. measurement round by test sequence & module model



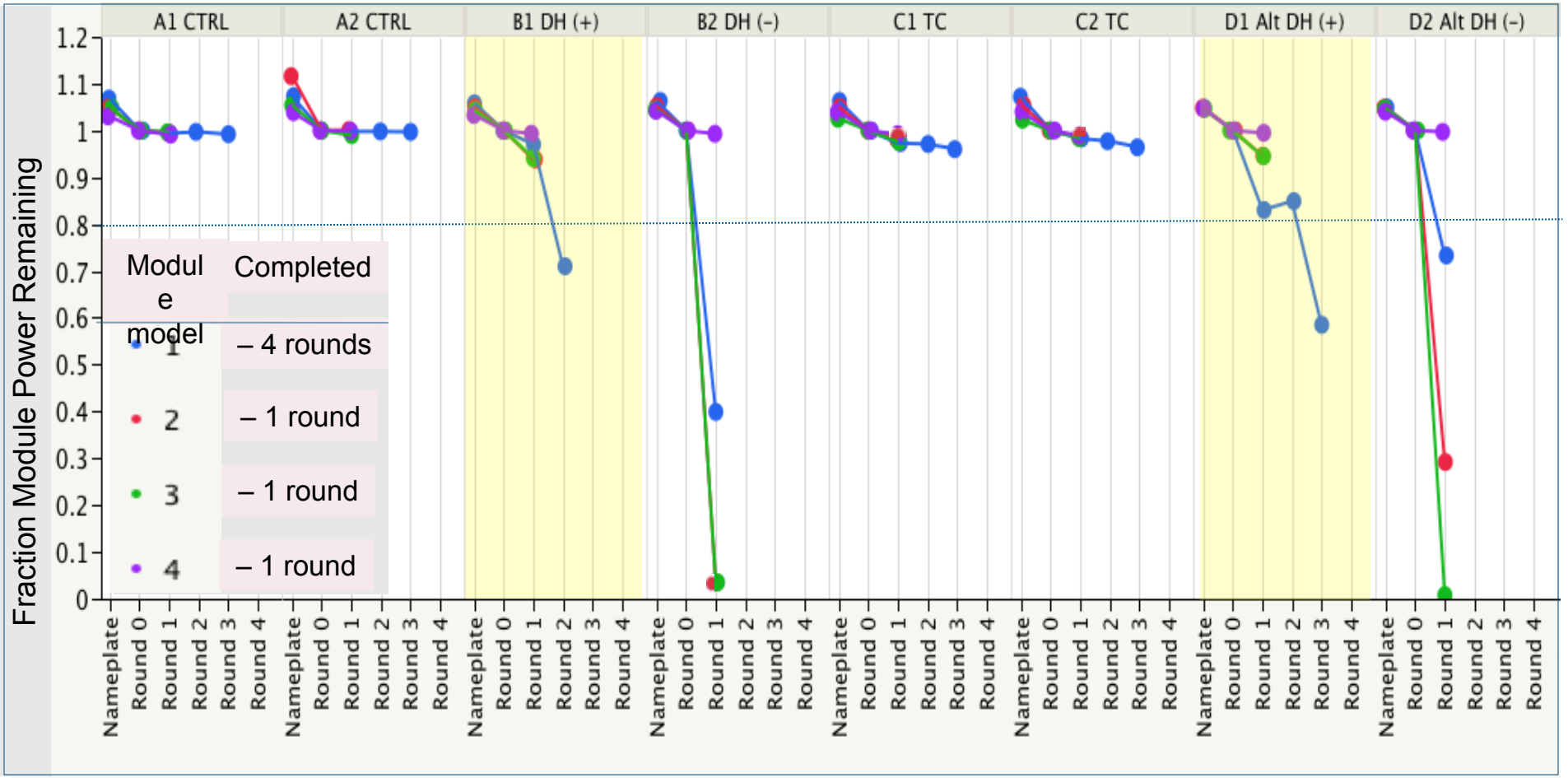
Performance Results

Fraction module power remaining vs. measurement round by test sequence & module model



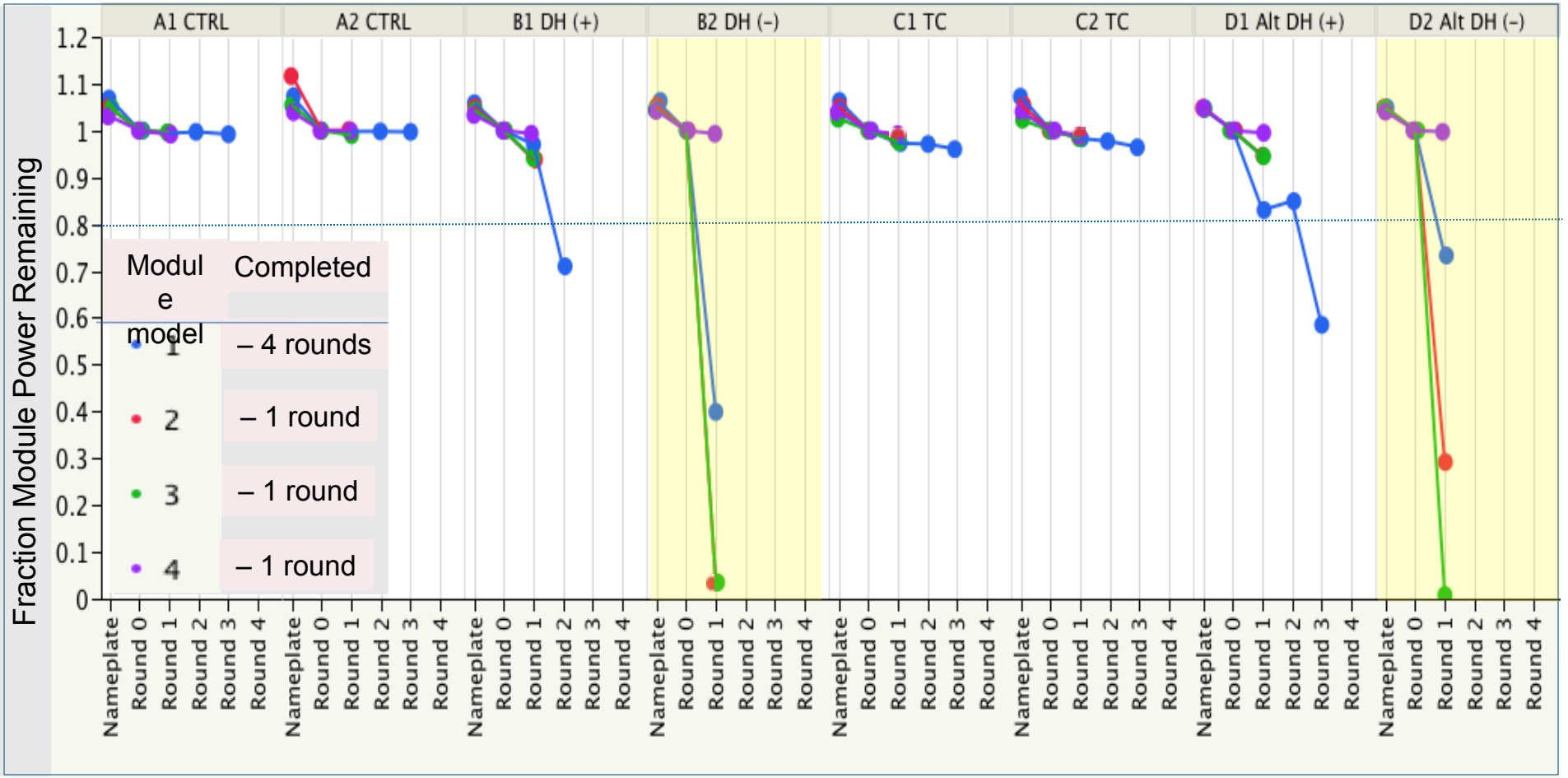
Performance Results

Fraction module power remaining vs. measurement round by test sequence & module model



Performance Results

Fraction module power remaining vs. measurement round by test sequence & module model



Failure analysis, DH (+)

Ag gridline corrosion visible

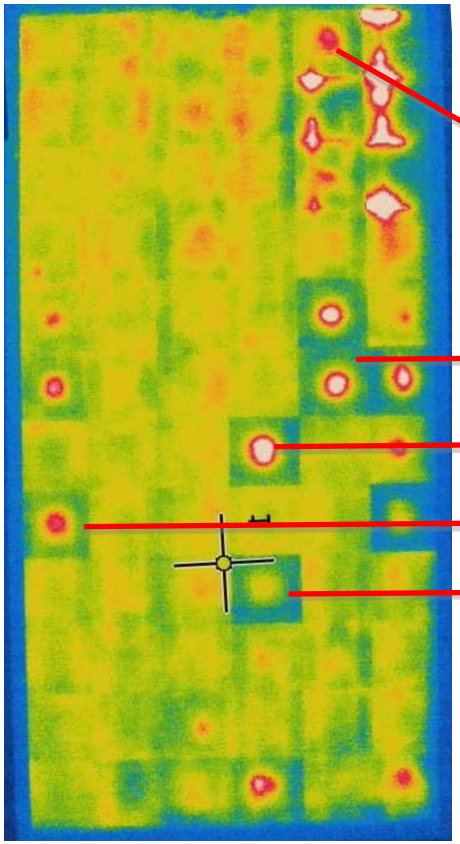
Series resistance increase according to dark I-V curve fitting



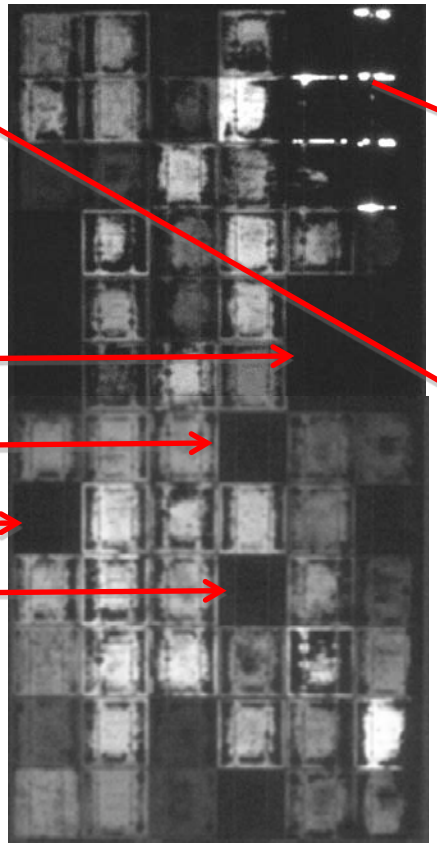


	0 hrs	1000 Hrs	2000 Hrs
r_s (Ω cm^2)	0.83	1.02	1.22

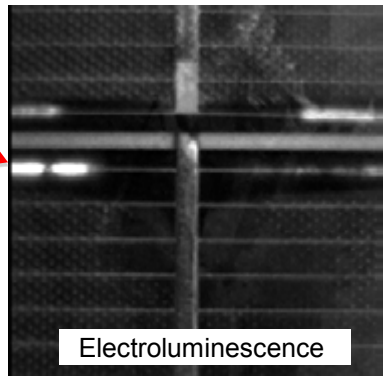
Failure analysis, DH (-)

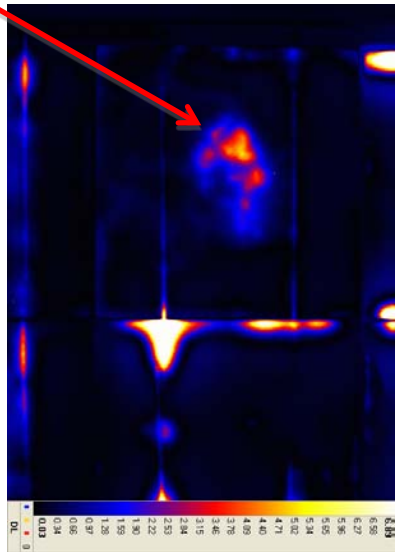


Thermal image

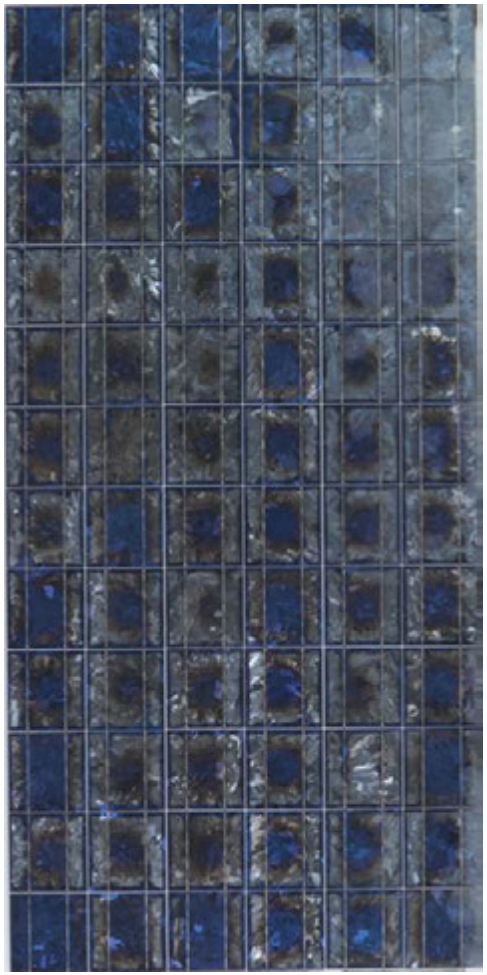


Electroluminescence



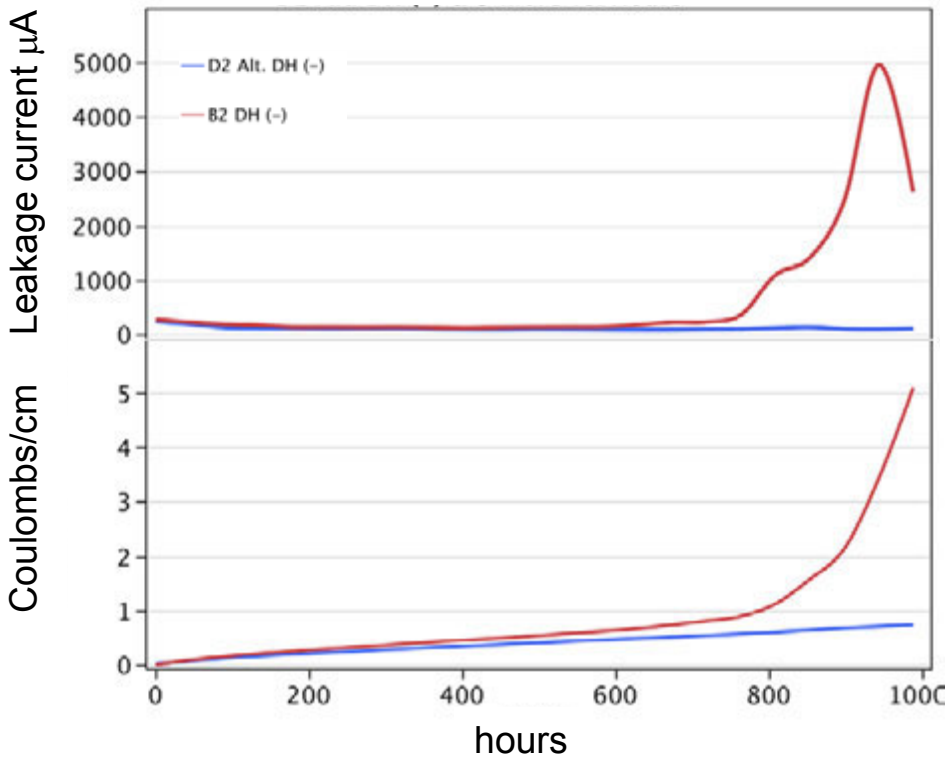


Lock-in thermography



- Shunting, often in the middle of the cells; cell dependent, suggests ionic motion
- Degradation of the Ag-Si interface, series resistance
- Decomposition of silicon nitride with water to ammonia and hydrous silica

Monitoring corrosive damage by counting Coulombs



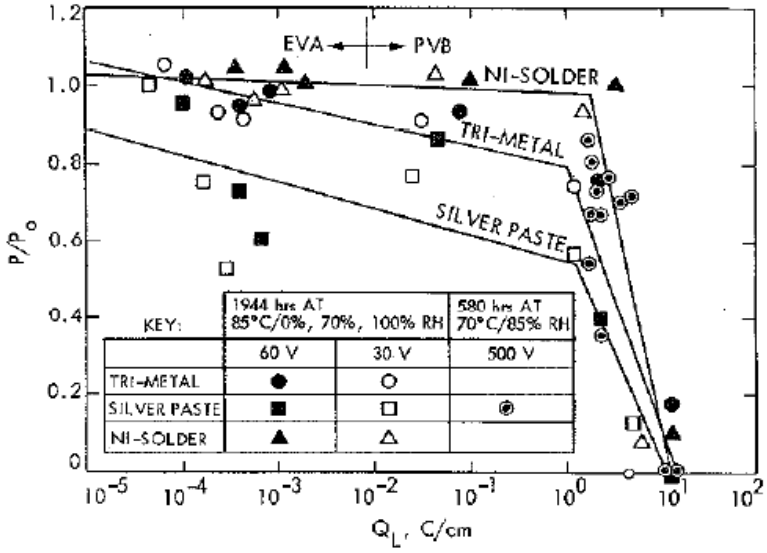


Figure 3. Power Output Reduction Versus Accumulated Unit Charge Transfer for C-Si Cells

G. Mon and R. G. Ross, (JPL), 18th IEEE PVSC (1985)

- > 20% power degradation in less than 1 Coulomb per cm of module edge

Main Results

1) Crystalline silicon modules are holding up well so far in thermal cycling
2) Modules in damp heat with positive bias to active layer show varying degrees of Ag metallization oxidation and hydrolytic degradation of backsheet—the extent is related to leakage current
3) Modules in damp heat with negative bias to active layer show varying degradation rates attributable to cell shunting and Si-Ag interface degradation, the extent appears related to leakage current

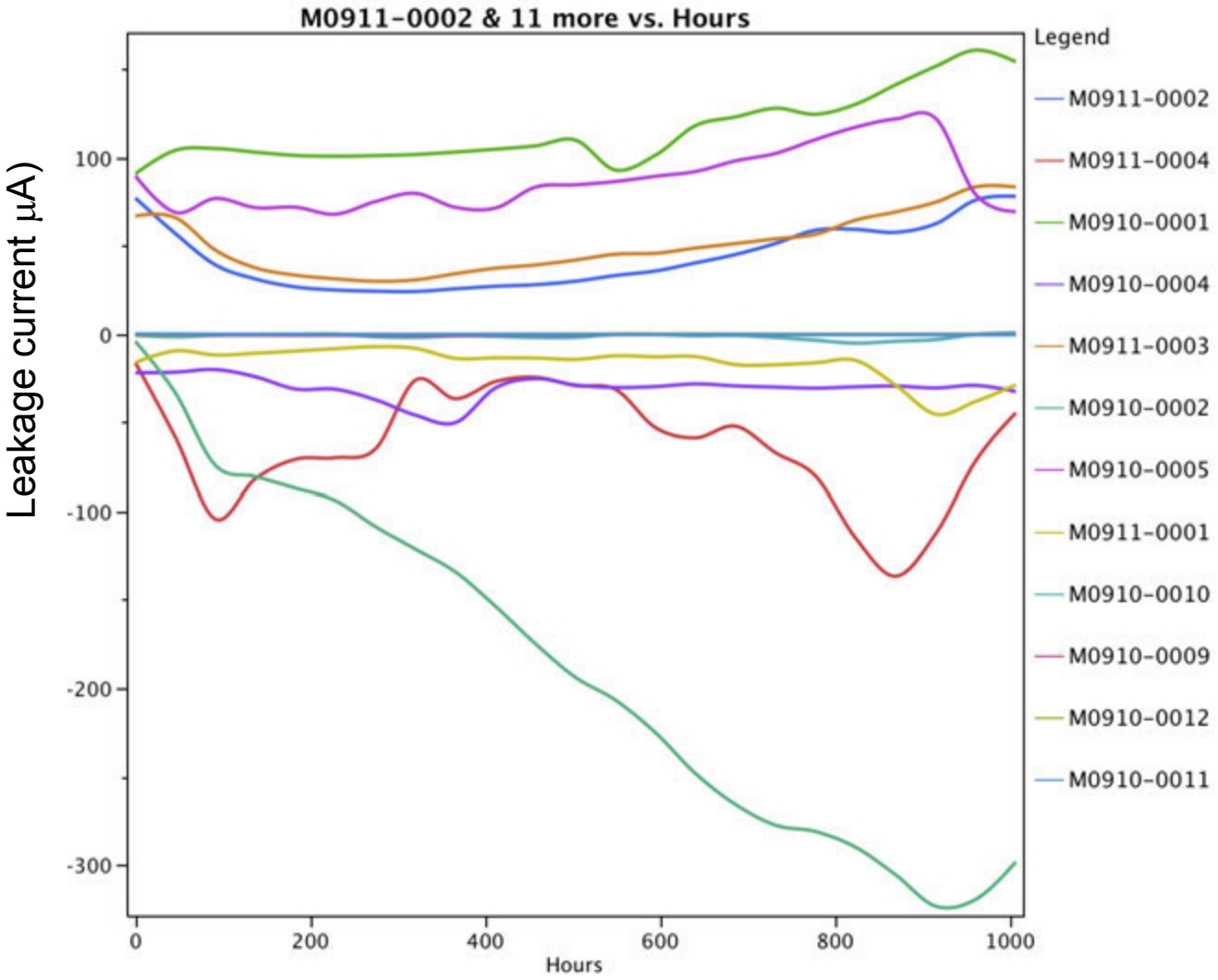
Lessons from the past, from thin films*

1) The degradation depends on the direction of the internal electric fields; modules biased positively relative to a grounded frame show less damage (thin film, p-base Si)
2) Modules that lack a frame and use mounting points bonded to the backsheet glass show no damage.
3) Water vapor enhances the corrosion if it can enter the module through the edges, and by increasing the conductivity of the front glass surface.
4) Damage rates can be slowed if leakage currents that are caused by voltage potentials between the frame and the internal circuitry are reduced.

* Adapted from C.R. Osterwald, T.J. McMahon, and and J.A. del Cueto, **Electrochemical Corrosion of SnO2:F Transparent Conducting Layers in Thin Film Photovoltaic Modules,** Solar Energy Materials and Solar Cells, 2003 Vol.79 (No.1)

Thank you for your attention !

Monitoring of module leakage current, ± 600 V

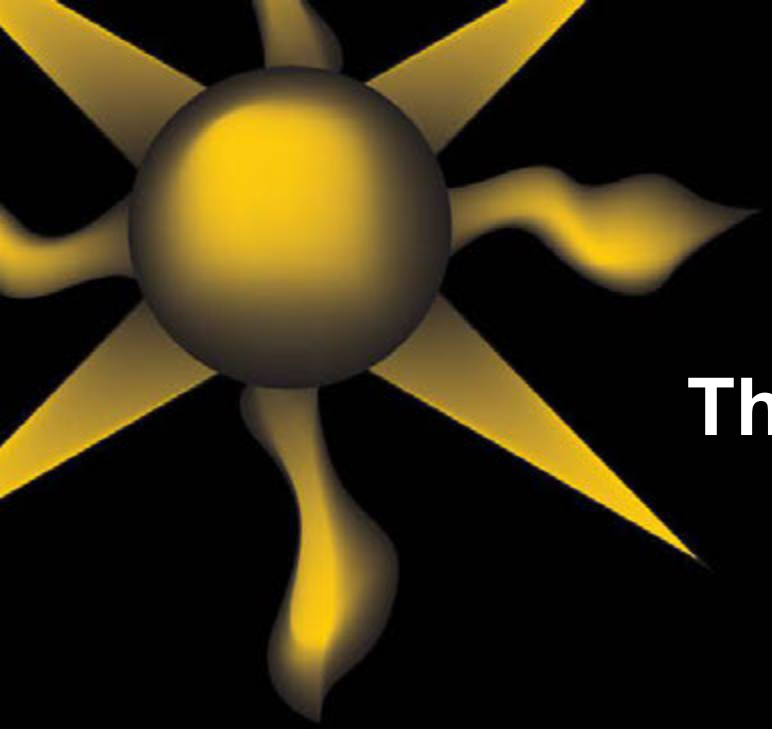


Worst case field monitored leakage current of modules:

NREL, 1 μA

FSEC, 8 μA

85°C DH, 85% RH is yielding generally 10x, up to 100x worst case field leakage currents



Designing for Reliability: Thin-Film Building Integrated Photovoltaic Modules

Ryan Gaston

The Dow Chemical Company
Midland, MI

DOW Solar Solutions

Purpose

- Review Reliability Challenges for PV, Thin Film and BIPV
- Emphasize Importance of Reliability
- Purpose a Reliability Methodology and Process
  - Design for Reliability Process
  - Reliability Best Practices
- Introduce a Staged Approach to Reliability Assurance
- Provide a Quantitative Example – Temp Humidity Test
- Gather Feedback and Consensus

DOW® Solar Solutions

Reliability Challenges for PV

1. Incorporation of reliability methodologies in the product development process
2. Assuming current qualification testing is a reliability prediction
3. Instituting test to failure
4. Failure Modes and Effects Analyses that adequately capture field experience
5. Accelerated test models
6. Increased acceleration factors – without compromising prediction
7. Combined simultaneous stress effects
8. Quantitative reliability analysis tools/techniques

Reliability Challenges for Thin Film and BIPV

- Thin Film Reliability Challenges
  - Potential for New Failure Modes and Mechanisms
  - Acceleration Factors for Accelerated Tests Largely Unknown
  - Limited, Long Term Field Data to Develop Correlations with Accelerated Testing
  - Metastable Effects (e.g. light, thermal, bias induced)
- BIPV Reliability Challenges
  - Multifunctional Design – additional interfaces and requirements
  - Roof Functionality (wind, hail, rain)
  - Retention of Aesthetics

Importance of Reliability

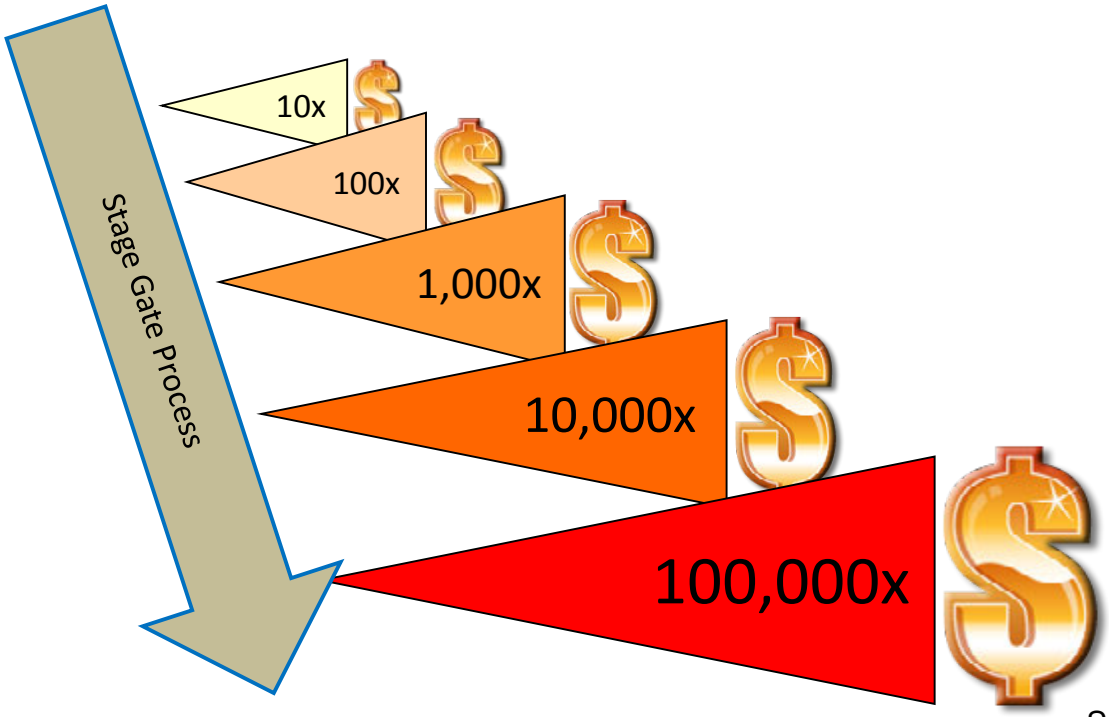
- Customer Expectations
  - Long Operational Life (20+ years)
  - “Trouble-Free” Operation
  - Predictable Financial Return
- Impact of Reliability Failures – Company Level
  - Destruction of Brand Integrity
  - Product Claims
  - Reduced Sales
- Impact of Reliability Failures – Industry Level
  - Negative Perception of PV
  - Reduced Future PV Market Size

Pay Now or Pay Later

Factor of 10 Rule

If you discover a reliability problem in this stage…

…it will cost you this much



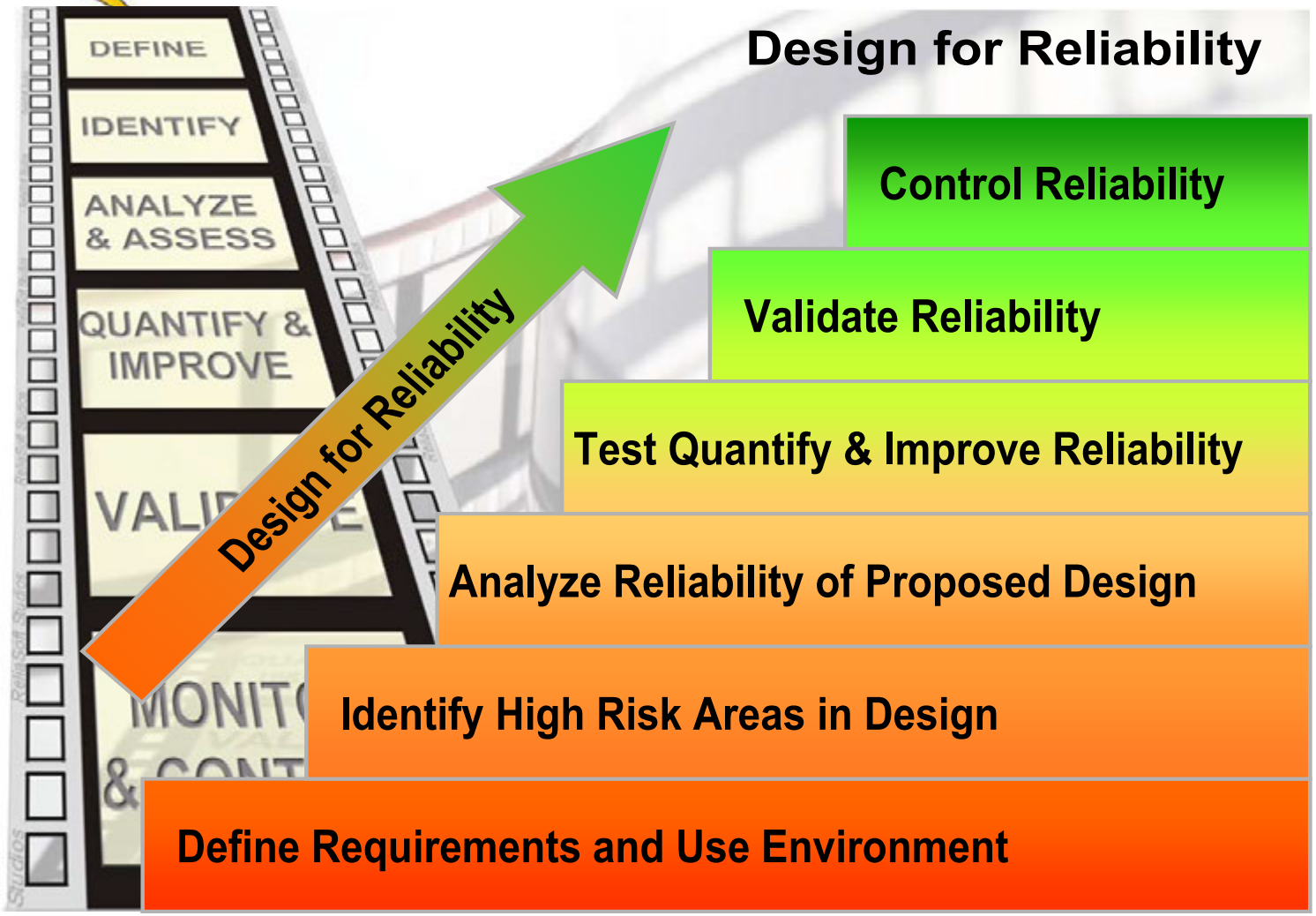
Source: Reliasoft

Product recalls and field repairs can be extremely expensive, for example, it is reported that Xbox field issues have cost Microsoft more than a billion dollars

Solar Solutions

Taub, E., "Microsoft to Spend $1.15 Billion for Xbox Repairs", The New York Times, July 6 (2007).

Design for Reliability Process



Source: Reliasoft

Reliability Best Practices

Concept Stage
- System Operating Conditions
- System Reliability Requirements
- Flow Down of Requirements to Subsystems and Components
- Identify Reliability Critical Components

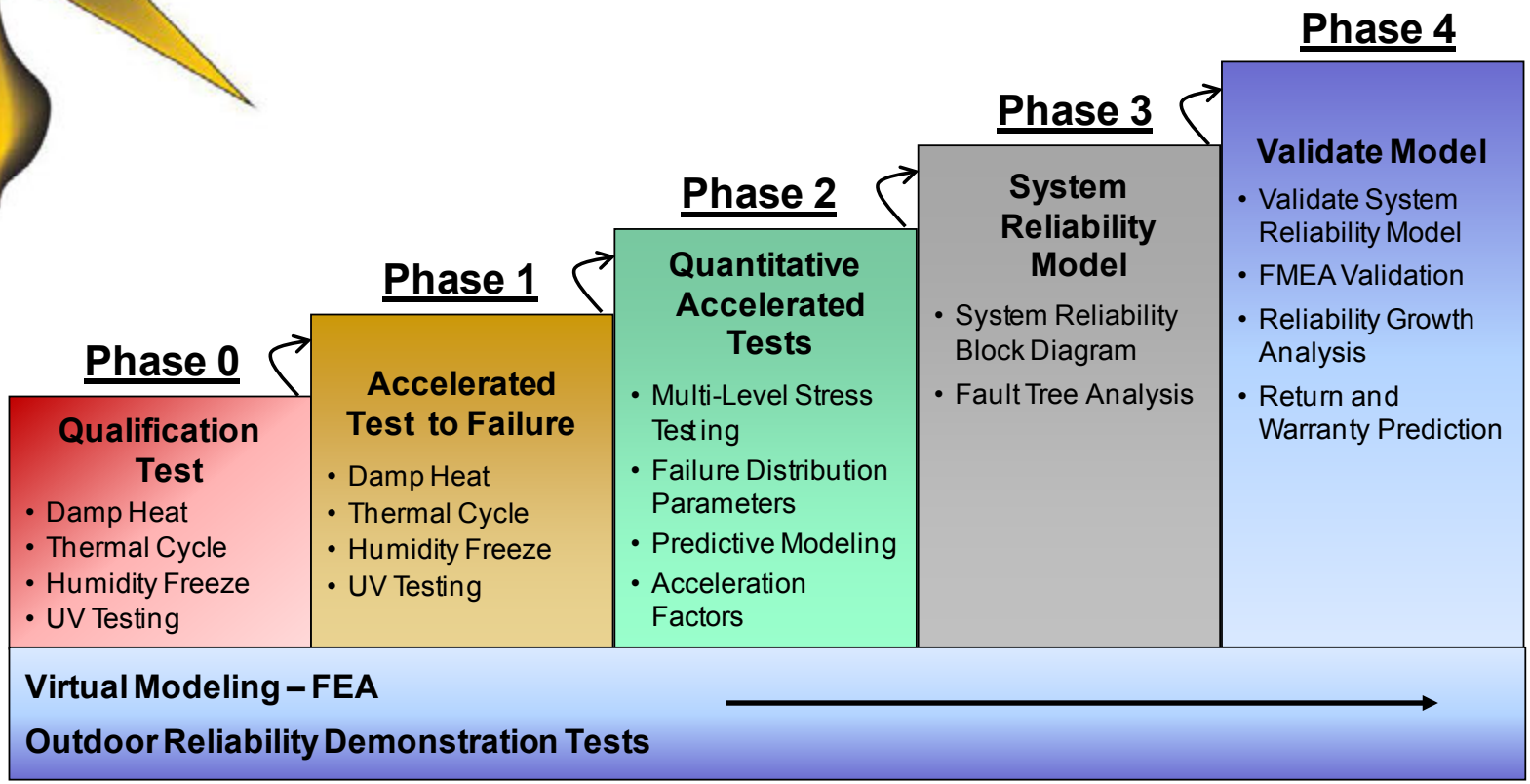
Design Stage
- Design Margin Analysis
- Failure Modes and Effects (FMEA)
- Virtual Modeling (FEA)
- Physics of Failure (POF)
- Highly Accelerated Testing (HALT)

Manufacturing Stage
- Manufacturing Control (SPC, QA/QC)
- Field Test Plans
- Preventative Maintenance
- Verification of Reliability

Assurance Stage
- Accelerated Life Testing Methods
- System Reliability Model
- Supplier Reliability
- Reliability Growth

DOW® Solar Solutions

Dow's Approach to a Staged Reliability Assurance Process



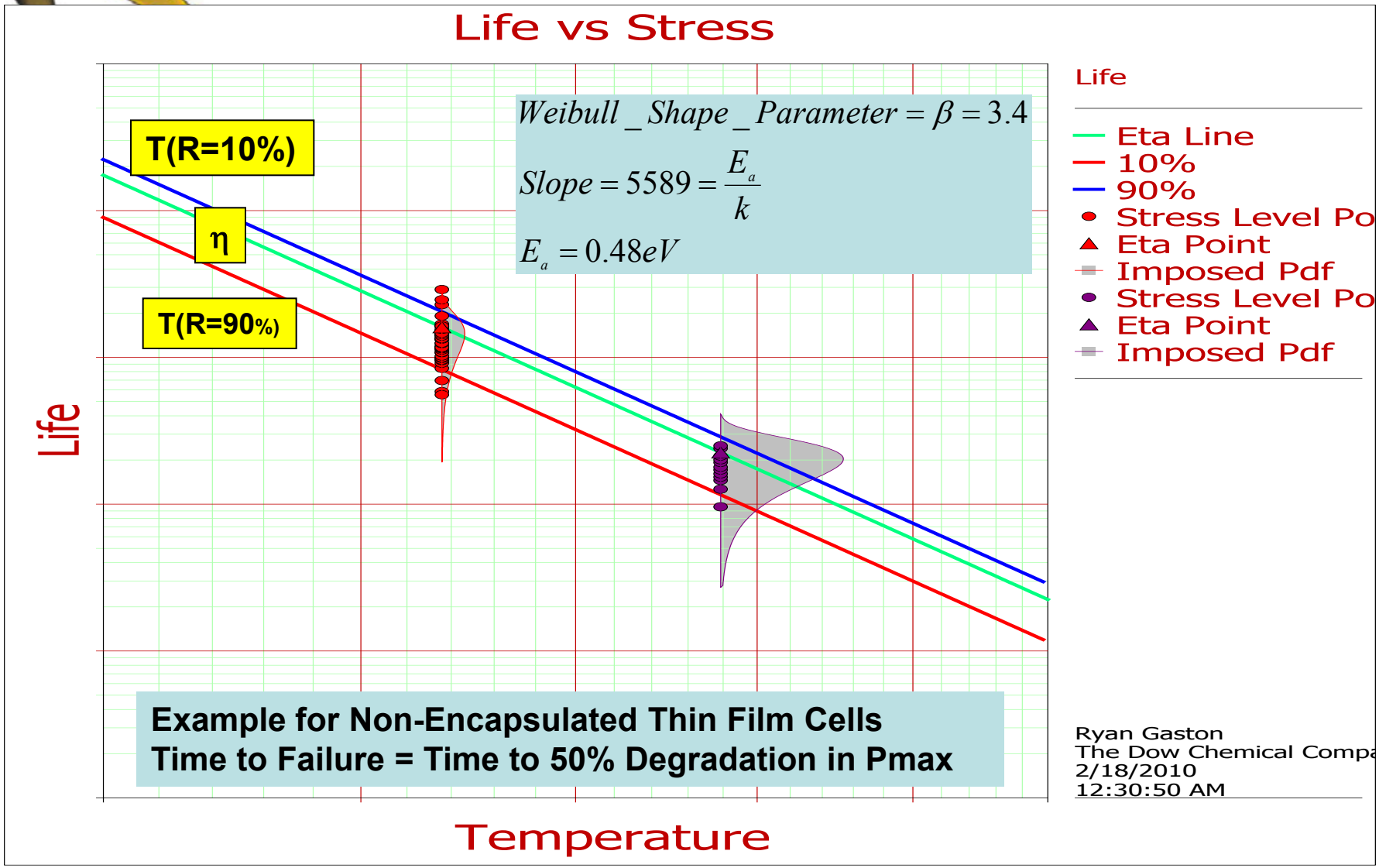
Objectives:

- Maximize results while minimizing resource requirements
- Screening and qualification of new materials, designs, and process changes
- Quantify impact to reliability and assess risk to business

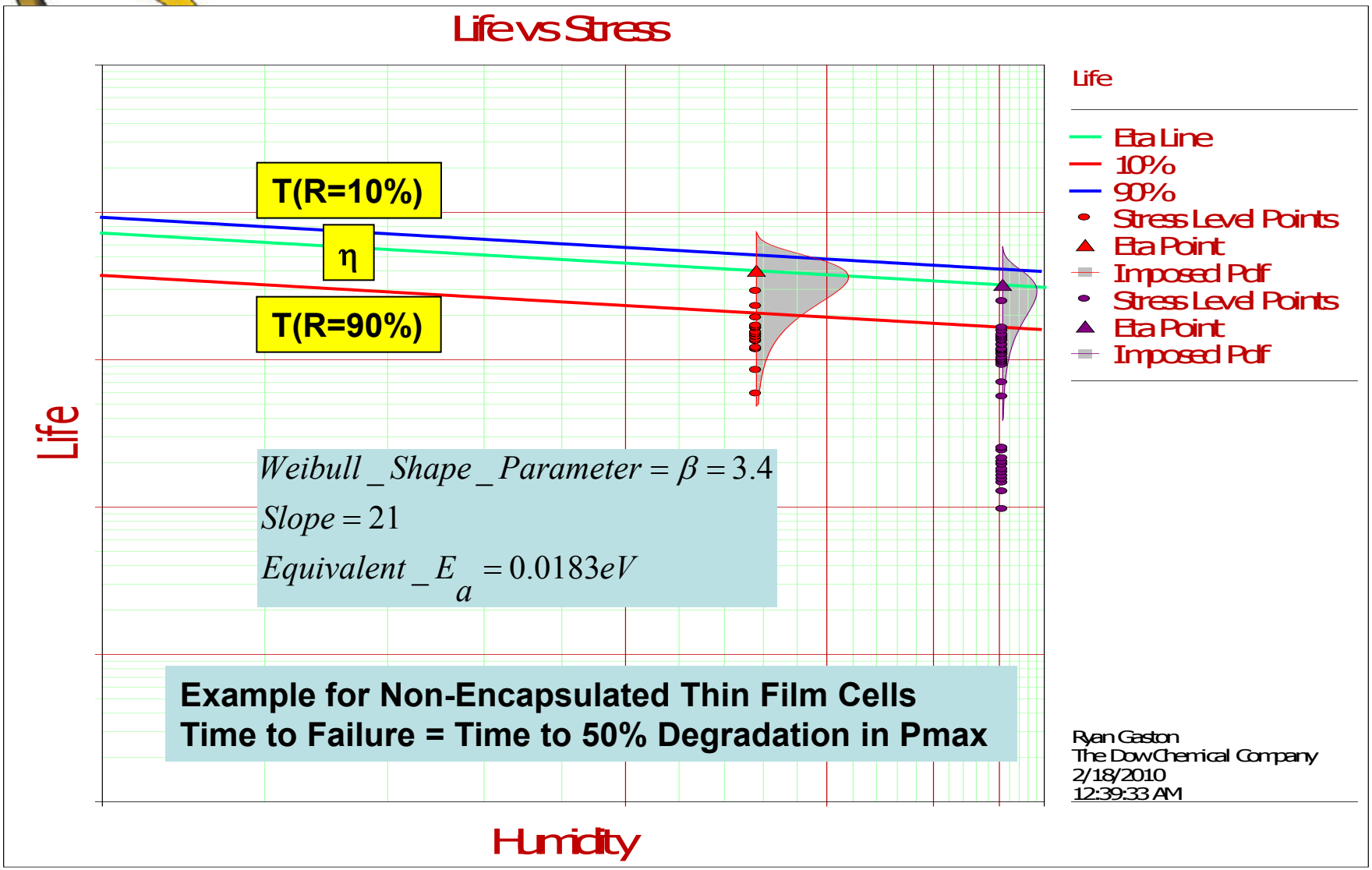
Phase 2 Example: Quantitative Temp-Humidity Test

- Two Stress Test Plan Development (Damp Heat Example)
  - Two Stresses (Temperature and Relative Humidity)
    - Stress Life Relationship Assumed – Modified Eyring Model
    - Highest Stress Level and Use Stress Level Set
    - Failure Distribution Function (Weibull/LogNormal)
    - Probability of Failure Estimate
    - Desired Reliability and Confidence Interval
- Test Plan Output → Test Conditions and # of Samples
- Conduct Tests → Degradation in Performance vs Time Interval
- Critical Degradation Level Set
  - Time to Failure Calculated
- Failure Distributions Estimated from Time to Failure Data
- Acceleration Factors Calculated for Each Stress Type
- Reliability/Unreliabilty at Use Stress Predicted
  - Confidence Bounds Estimated

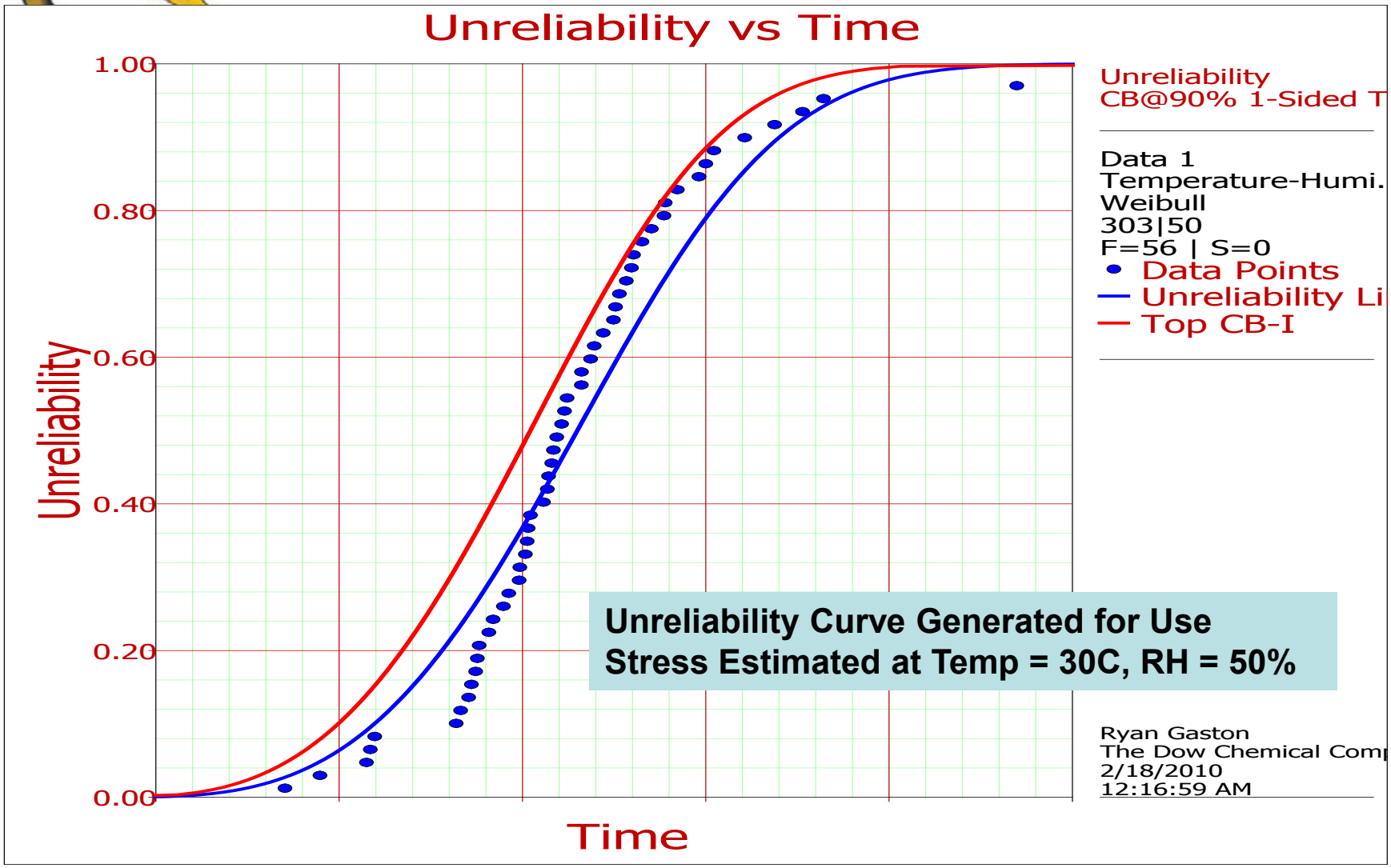
Phase 2 Example: Life vs Temp Profile



Phase 2 Example: Life vs Humidity Profile



Phase 2 Example: Unreliability vs Time



Acknowledgements

This material is based upon work supported by the U.S. Department of Energy under Award Number DE-FC36-07GO17054

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by tradename, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof

Summary

- Incorporating reliability methodologies into PV design and manufacturing is an ongoing opportunity
- Reducing reliability issues early in the product development process saves time and money
- Reliability is more than testing – touching on all aspects of development (Design for Reliability)
- A Staged Reliability Assurance approach can maximize results, while minimizing resource requirements
- Dow has successfully implemented a Reliability program for estimating product lifetimes for Thin Film BIPV Modules and Systems

DOW® Solar Solutions

National Renewable Energy Laboratory
Innovation for Our Energy Future

National Center for Photovoltaics

Quantifying the Weather: an analysis for thermal fatigue



Nick Bosco and Sarah Kurtz

NREL PV Module Reliability Workshop
February 18-19, 2010
Golden, CO

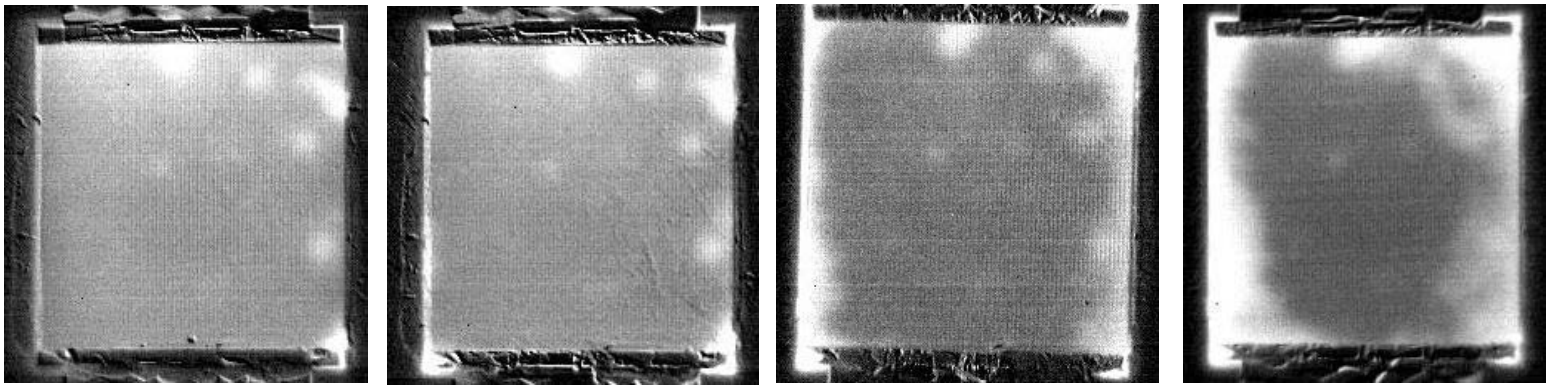
This presentation does not contain any proprietary or confidential information.

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

quantifying the weather

Problem:

- Thermal fatigue will cause die-attach failure.
- How can we predict this failure if it's driving force is weather?



initial 500 cycles 1000 cycles 1500 cycles

- Progression of IR images illustrating die-attach cracking through thermal cycling [1]

quantifying the weather

Questions:

- Can we quantify the amount of thermal cycling damage a deployed module will accumulate?
- If known, can we relate this damage to that incurred during accelerated testing?
- Will a life-time prediction result?

quantifying the weather

Can we quantify the amount of thermal cycling damage a deployed module will accumulate?

- What is the cell/ module temperature when in service?
- As this temperature changes, how do we quantify those changes (cycles)?
- Once known, how can we relate those changes to module damage?

quantifying the weather: temp model

What is the cell/ module temperature while in service?

Given local metrological data, models exist to estimate cell temperature:

Steady State Models

$$T_{cell} = T_{amb} + E\exp\left(a + bW\right) + ER$$

$$T_{cell} = T_{amb} + E\exp\left(a + bW\right) + \frac{E}{E_o}\Delta T$$

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

Non-Steady State Model

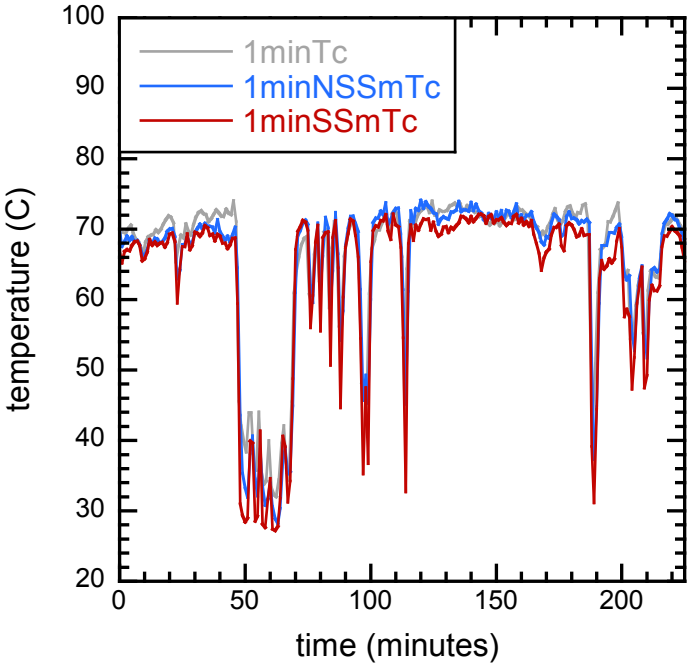
$$T_{cell}\left(t+1\right) = T_{cell}\left(t\right) + \frac{dT_{cell}}{dt}$$

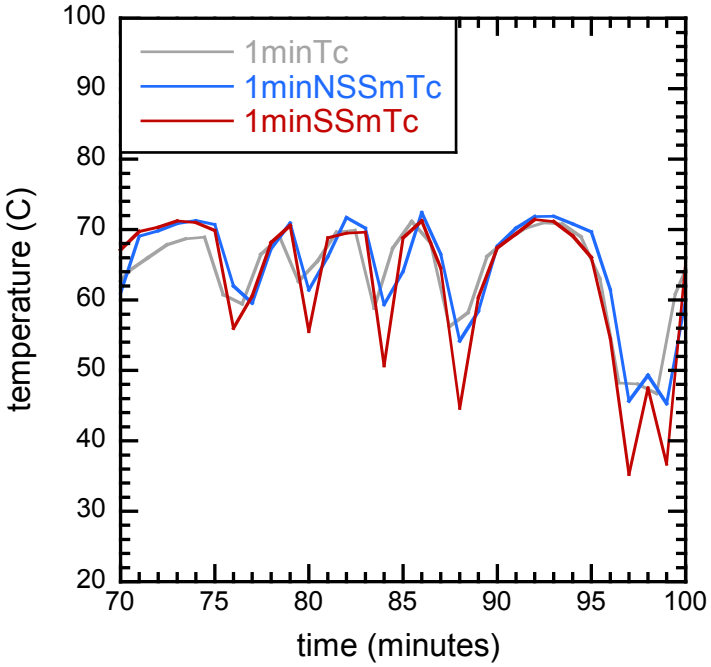
$$\frac{dT_{cell}}{dt} = f\left(E, A, \varepsilon, T_{amb}, T_{cell}, h_c, C_m\right)$$

A. D. Jones and C. P. Underwood, "A thermal model for photovoltaic systems," *Solar Energy,* vol. 70, pp. 349-359, 2001

quantifying the weather: temp model

Comparison of temperature models

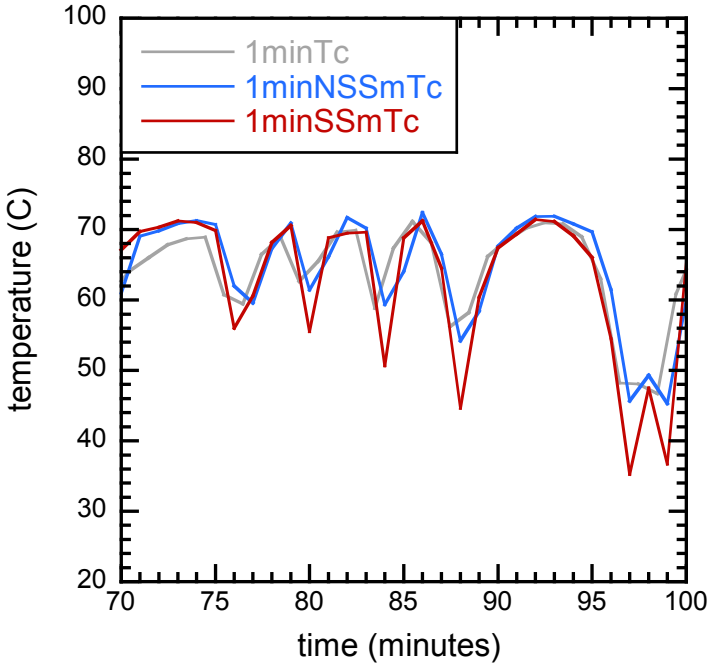


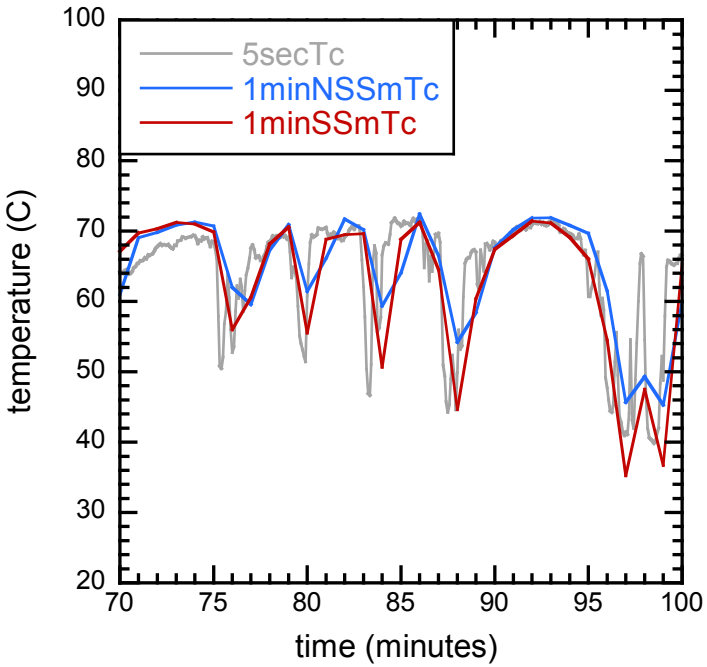


- The non-steady state model estimates the 1 minute average data well.
- The steady state model underestimates temperature “valleys” since it assumes an equilibrium condition has been reached.

quantifying the weather: temp model

Comparison of temperature models



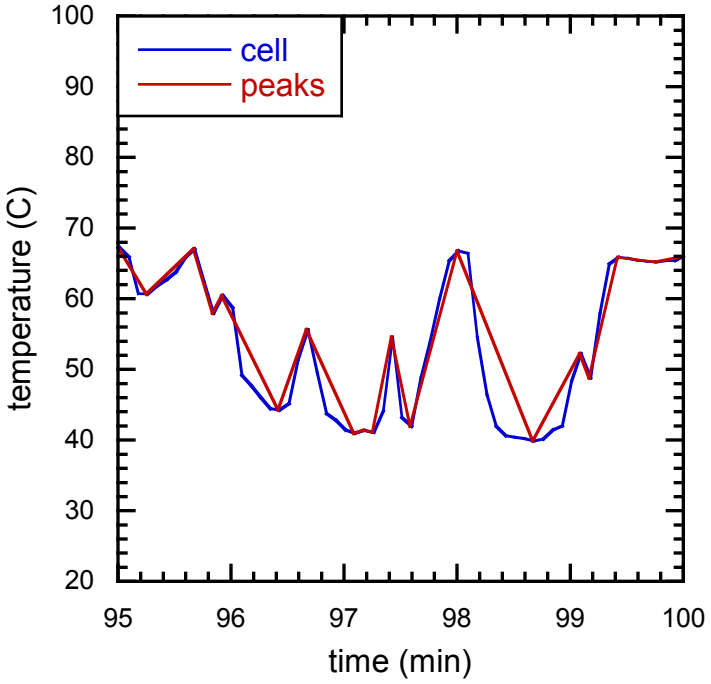


- When considering 5 sec. data, the steady state model fits better (and is used for this study).
- Note 5 sec. data reveals detail not captured with with the less frequent data.

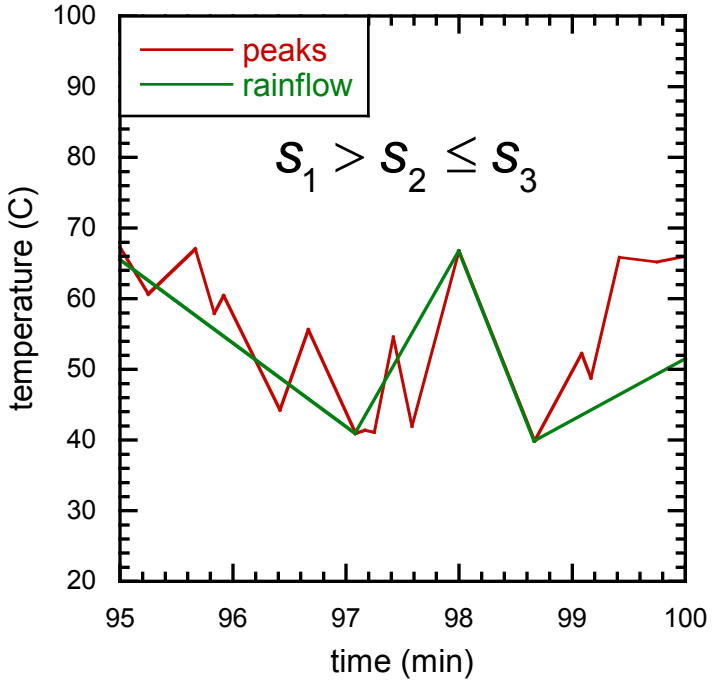
quantifying the weather: rainflow

As this temperature changes, how do we quantify those changes?

1. Peak and Valley



2. Rainflow count



- See and references [2&3] for more details on the rainflow counting algorithm.

1. maximum temperature $T_{\max}$
2. temperature change ΔT
3. transition time t_t

thermal fatigue modeling

Once known, how can we relate those changes to module damage?

Damage: Thermal fatigue of solder die attach

I :Engelmaier thermal fatigue model

$$N_f = \frac{1}{2}\left(\frac{\Delta\gamma_p}{2\varepsilon_f}\right)^{\frac{1}{c}}$$

where

$$\Delta\gamma_p = \frac{\sqrt{2}FL}{2h}\Delta\alpha\Delta T$$

$$c = -0.422 - 6\cdot10^{-4}T_{mean} + 1.74\cdot10^{-2}\ln\left(1+\frac{360}{t_d}\right)$$

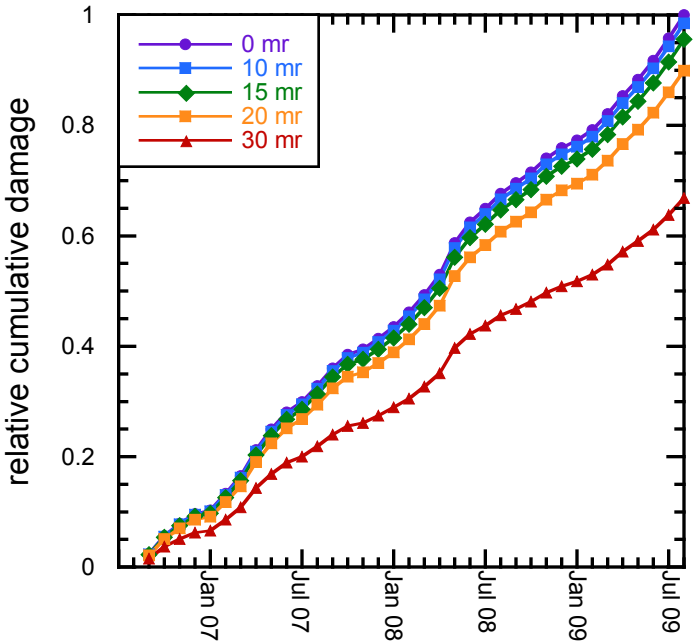
II: Palmgren-Miner rule

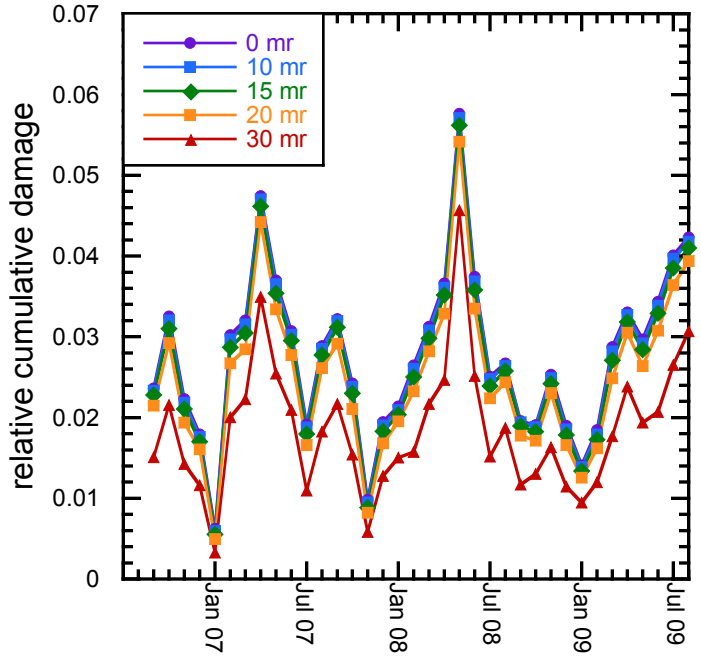
$$D = \sum_i \frac{n_i}{N_i}$$

$$D = \sum_i \Delta T_i^{-\frac{1}{c_i}}$$

damage analysis

3 years in Golden, CO: damage accumulation

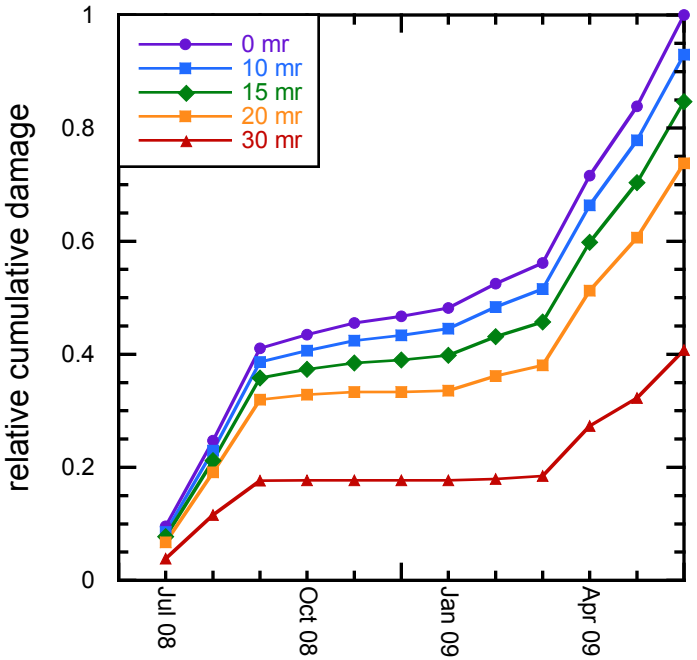


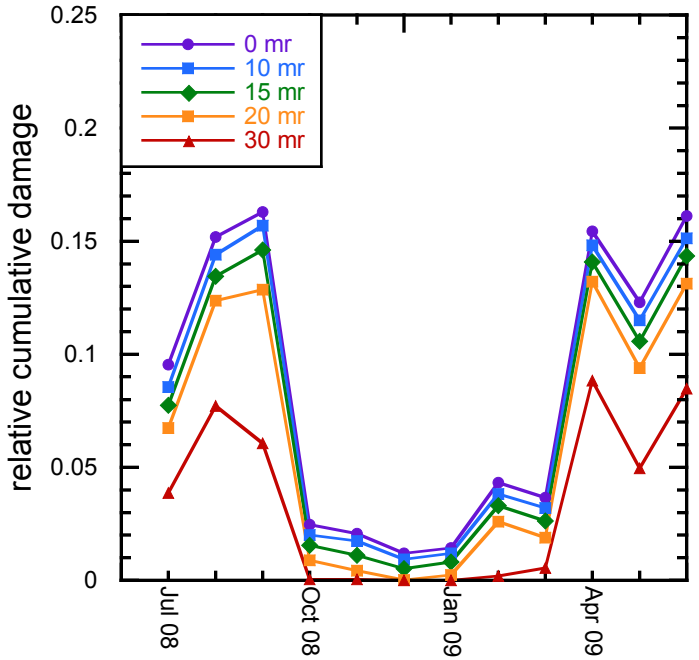


- Separate curves represent that only cycles with that minimum temperature range are considered in the calculation.
- For instance, ~67% of the damage is done by cycles with a temperature range of 30 C or greater (red curve).

damage analysis

1 year in Sanary, France*: damage accumulation

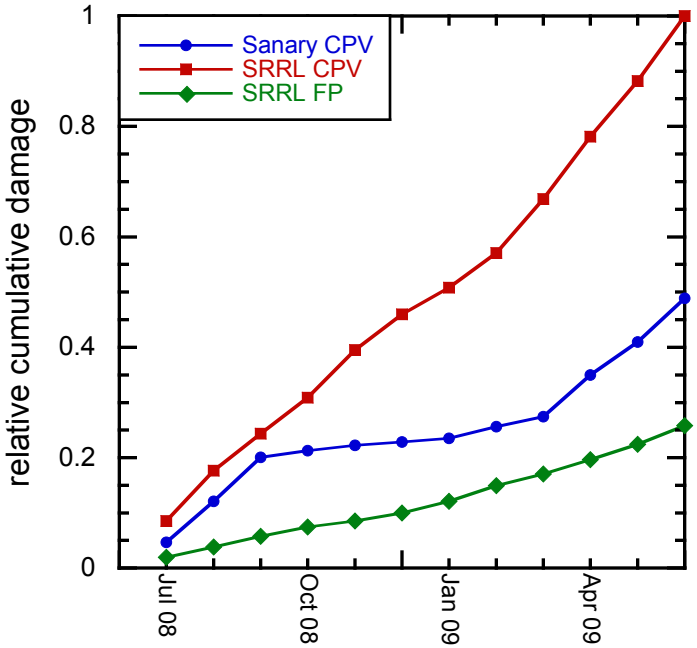


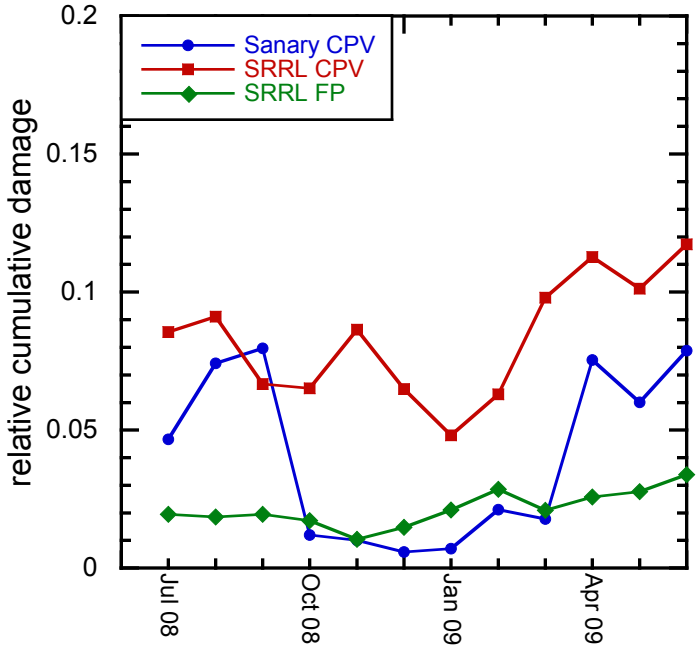


***Weather data courtesy of Atlas Testing Services, Atlas Material Testing Technology LLC.**

damage analysis

comparison: Sanary and Golden

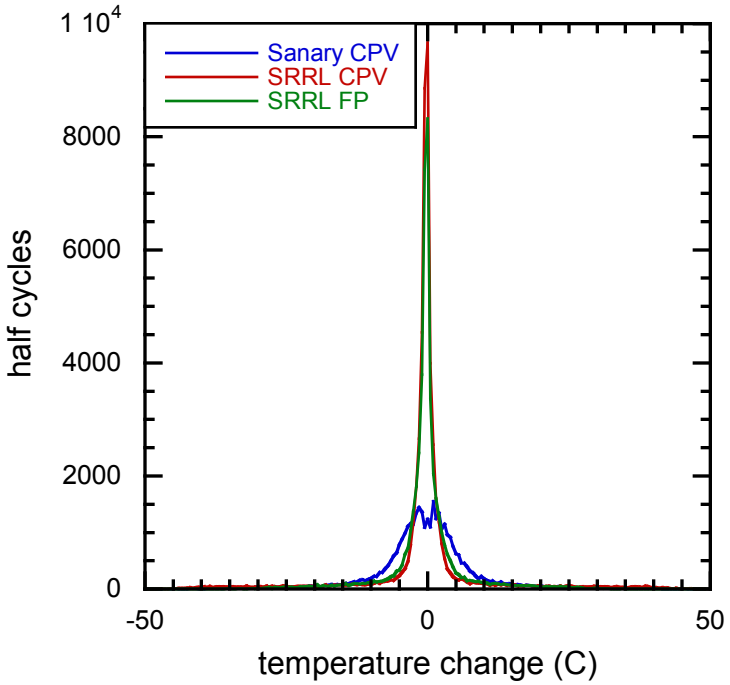


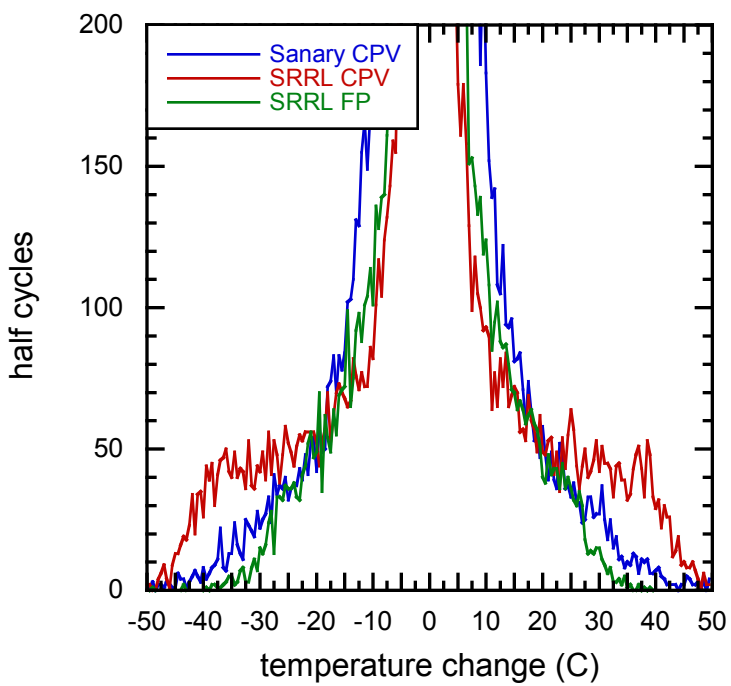


- Golden, CO is roughly twice as damaging to a CPV module as Sanary, France.
- A flat plate module will only accumulate ~25% of the damage of a CPV if both where deployed in Golden, CO.

rainflow count analysis

comparison: Sanary and Golden

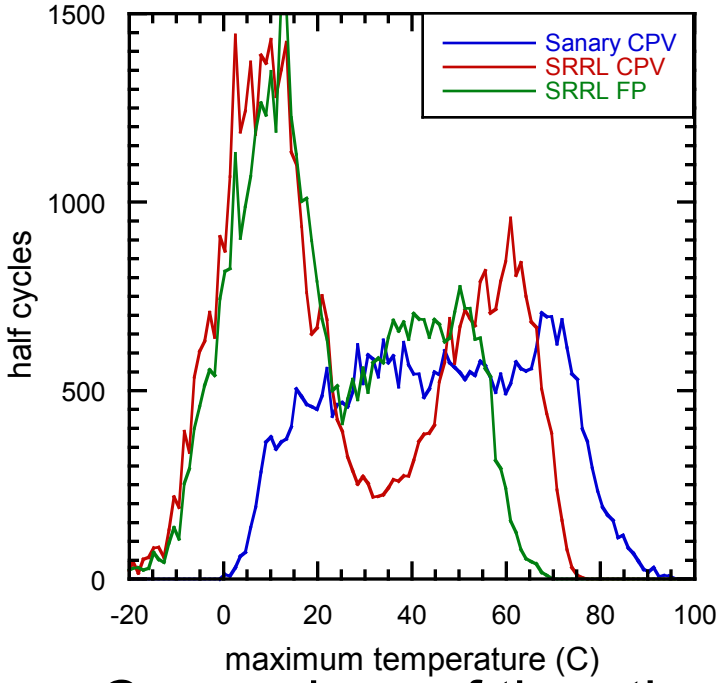


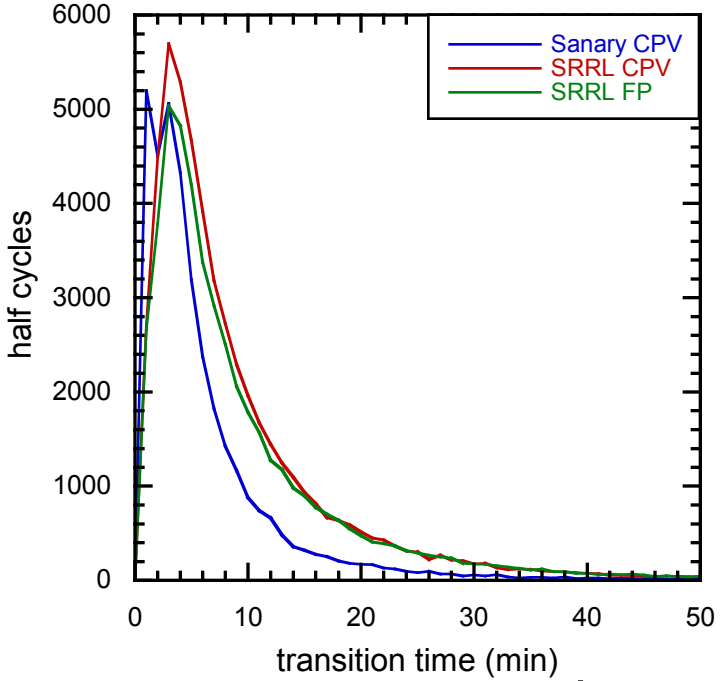


- Temperature range output from the rainflow count illustrates the higher number of large temperature ranges experienced in Golden, CO.

rainflow count analysis

comparison: Sanary and Golden

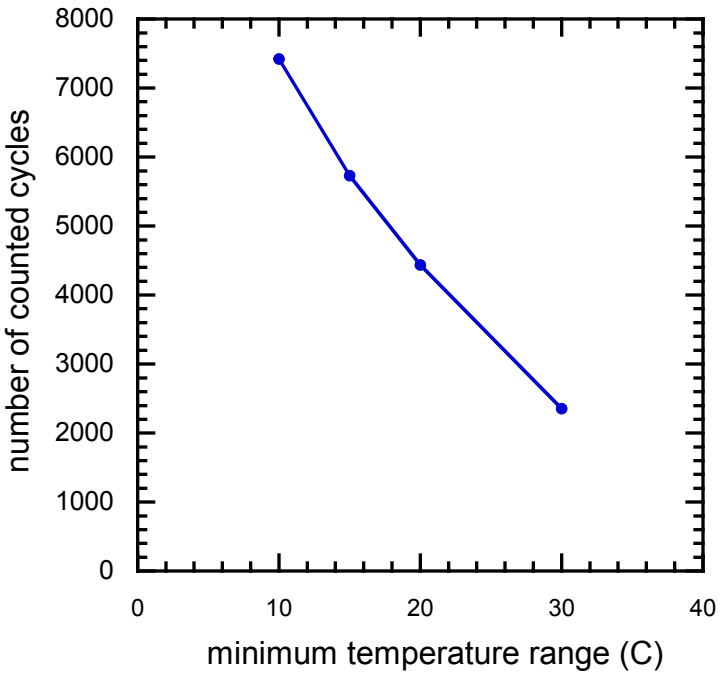




- Comparison of the other two rainflow count outputs: maximum temperature and transition time.

rainflow count analysis

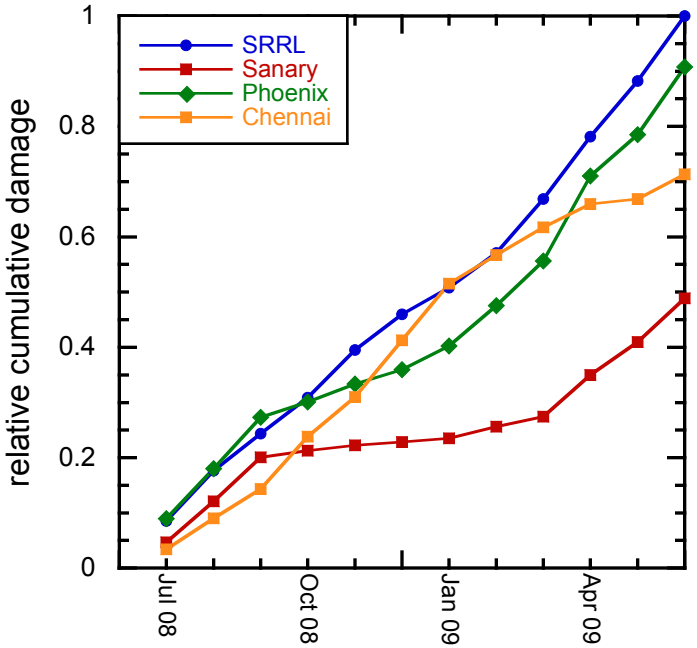
temperature cycles in one year in Golden

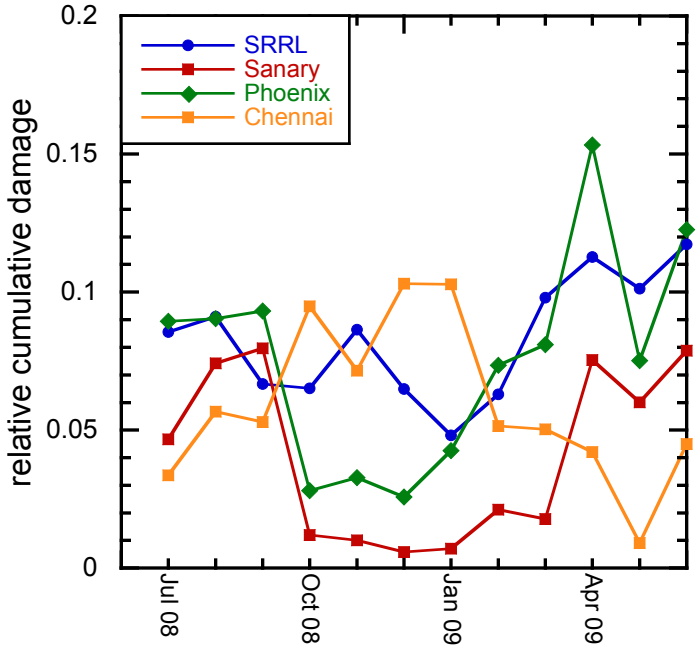


- Illustration of the number of cycles counted in the analysis.
- Roughly 20/day of a 10 C change or greater for the year considered.

rainflow count analysis

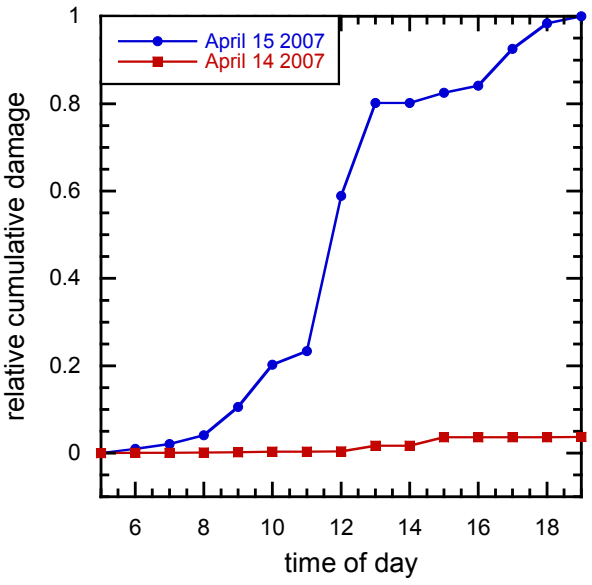
comparison

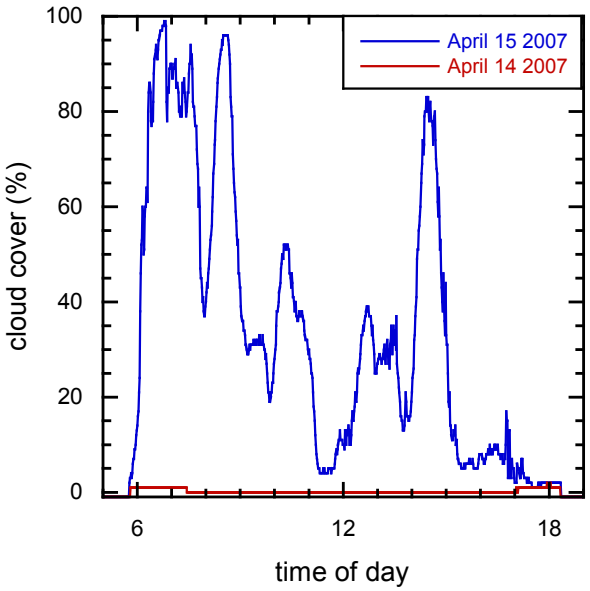


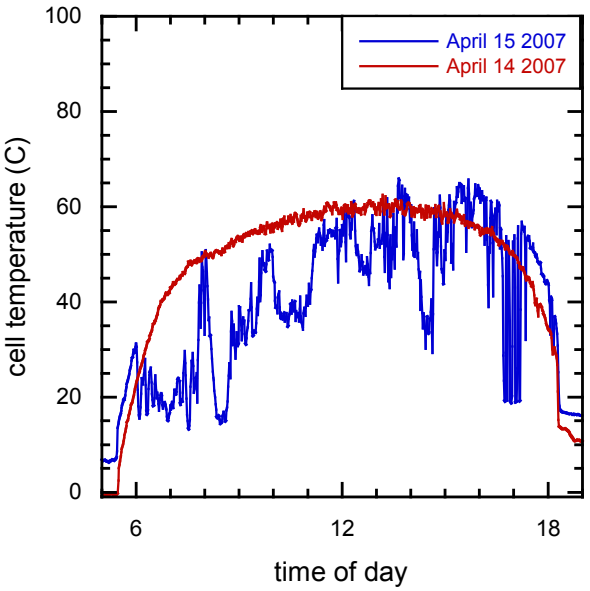


***Weather data courtesy of Atlas Testing Services, Atlas Material Testing Technology LLC.**

a really bad day

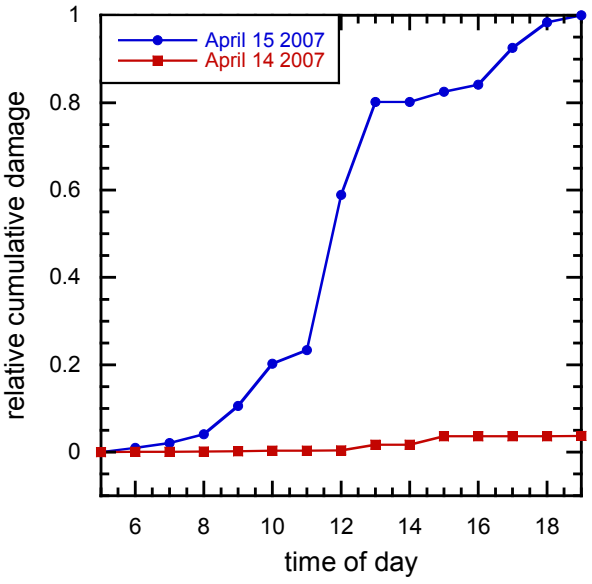


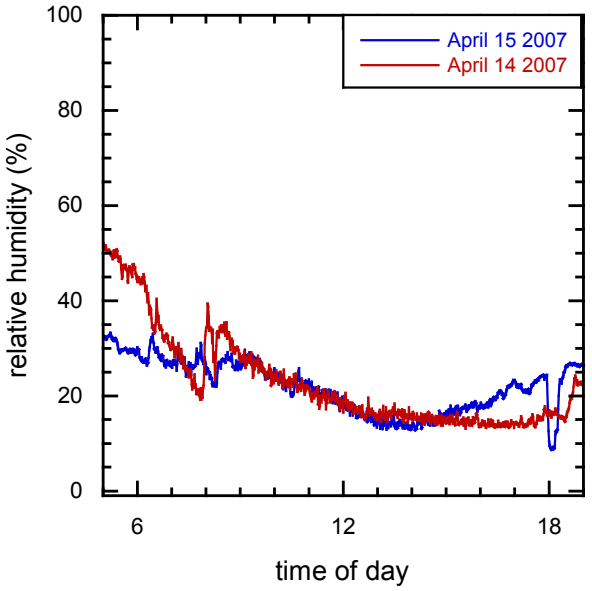


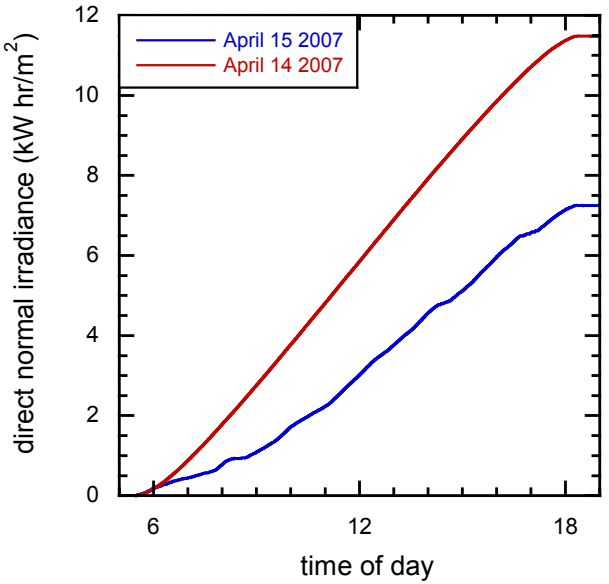


- Clouds are the key to a damaging day.

a really bad day





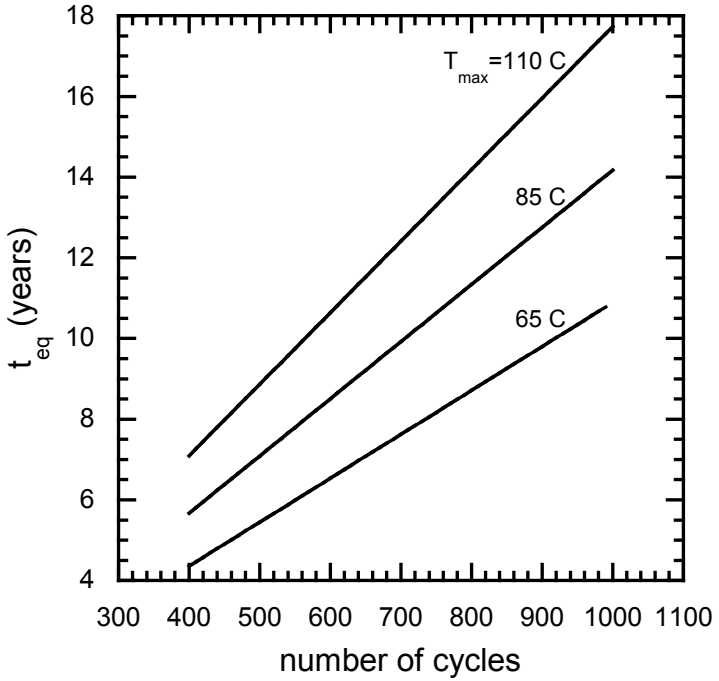


- It is difficult to determine if a day is damaging without high frequency data.

qualifications and predictions

If known, can we relate this damage to that incurred during accelerated testing?

Standard	Option	T_{max} °C	T_{min} °C	T_d min	n	t_{eq} SRRL years	t_{eq} Sanary years	observed years
IEC 62108	TCA-1	110	-40	10	500	8.9	18.2	
	TCA-2	85	-40	10	1000	14.2	29	
	TCA-3	65	-40	10	2000	21.8	44.6	
IEC 61215		85	-40	10	200	11		10*



*J. Wohlgemuth, D. Cunningham, D. Amin, J. Shaner, Z. Xia, and J. Miller, "Using Accelerated Tests and Field Data to Predict Module Reliability and Lifetime," *23rd European Photovoltaic Solar Energy Conference and Exhibition,* pp. 2663-2669, 2008

future work

- Outdoor testing to refine thermal fatigue and damage model.
- High frequency data.
- Analyze many locations: create a lifetime map.

1. Bosco, N.S., Sweet, C.,Kurtz, S., “Reliability Testing the Die-Attach of CPV Cell Assembles”, 34th IEEE Photovoltaic Specialists Conference, 7-12 June 2009, Philadelphia, Pennsylvania
2. A. Ramakrishnan and M. G. Pecht, "A life consumption monitoring methodology for electronic systems," *Components and Packaging Technologies, IEEE Transactions on,* vol. 26, pp. 625-634, 2003
3. "Standard practices for cycle counting in fatigue analysis," ASTM International Standard E 1049-85, West Conshohocken, PA 2005.

What Demonstration of Reliability Is Needed Before Investment?

PV Module Reliability Workshop – Feb. 18-19

Steve Voss – Director of Applied Engineering

SunEdison Fleet

- **SunEdison North American Fleet includes 95.9MW across 332 sites;**
- **Systems range from 30kW to 10MW;**
- **Lifetime energy production >200GWh;**
- **2009 fleet uptime was >98.5%;**
- **Predominately crystalline silicon but also includes a-Si and CdTe.**

MEMC 50
TECHNOLOGY IS BUILT ON US YEARS

SunEdison®
simplifying solar

How is a project valued?

- **All based on cash flows – no relationship to cost to build;**
- **Cash flows based on:**
  - Incentives and PPA rates;
  - Energy production (insolation, uptime, design, components);
  - OM&M costs;

- **Two module reliability metrics that most influence project valuation:**
  - Residual value – based on useful life at termination of contract;
  - Degradation rate;

Minimization of project risk

- Energy estimates performed by third party engineers;
- Coverage ratios are significantly below 100%;
- Portfolio or fund approach provides additional risk reduction;

- Investors are generally covered in the event of even severe underproduction on individual systems.

What Demonstration of Reliability Is Needed Before Investment?

- **Strong warranty backed by a strong balance sheet in the case of catastrophic failure.**

Building a bankability package

- **IEC qualification tests are the price of entry;**
- **Warranty and financial backstop (emerging alternatives);**
- **Building the story:**
  - General technology history;
  - Demonstration of fundamental understanding of the product and its application;
  - Specific manufacturer Quality Assurance programs;
  - Fielded history.



“ Consensus Guidelines For Quality Assurance and Their Role as a Foundation for Lifetime Prediction”

PV Module Reliability Workshop



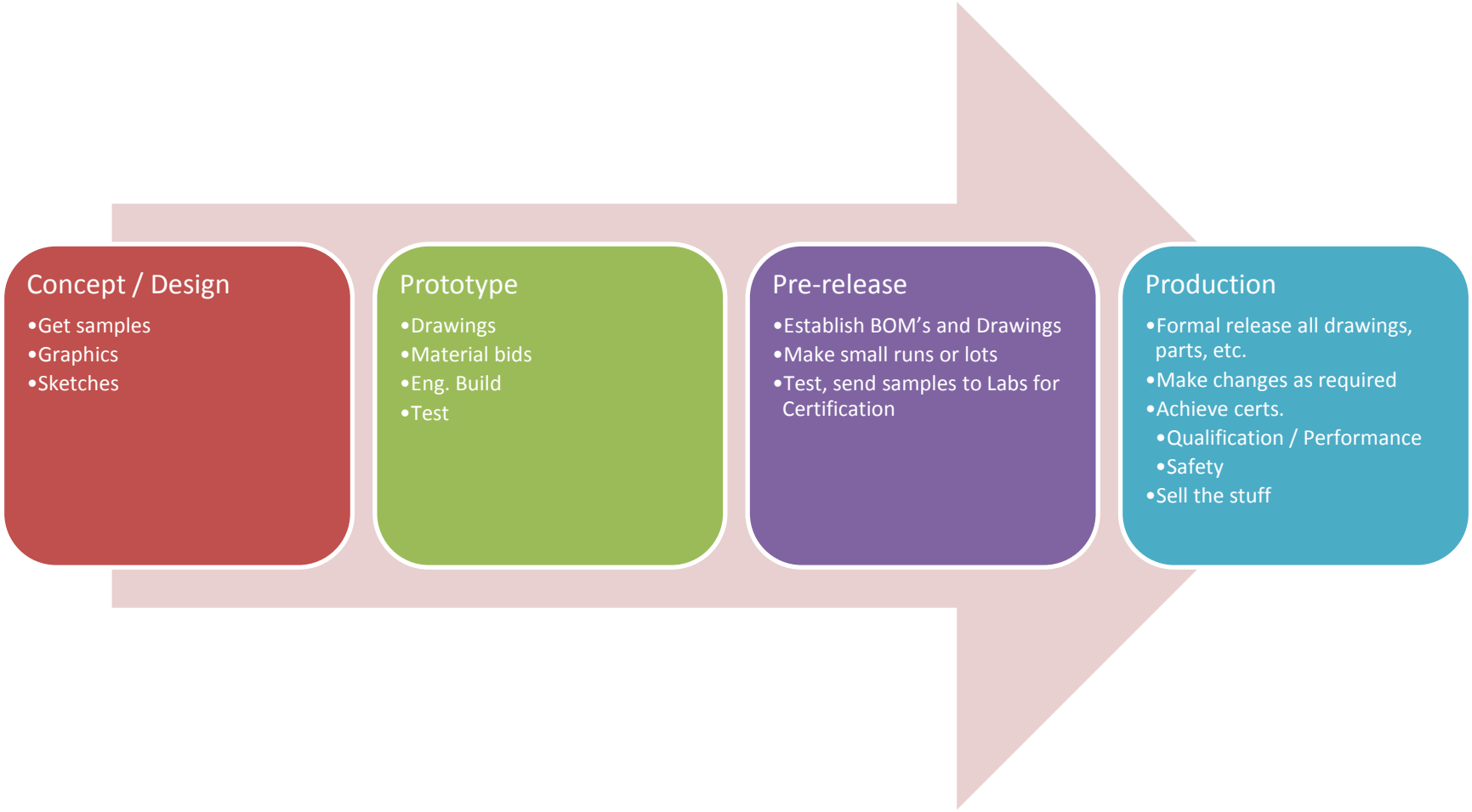
" Consensus Guidelines For Quality Assurance and Their Role as a Foundation for Lifetime Prediction"

or

"SAY WHAT"

PV Module Reliability Workshop

“The Birth of a Solar Module”





How does one assure they are good enough for an extended reliability test or “for my house”?

- Good Question
  - Test them?
  - Check warranty?
  - Ask Sales people?
  - Buy from reputable companies?
- Or request copy of their “Quality System”
  - QA manual
    - Test plans and performance measurements
    - Etc.

A Fair Response

"Is to insist on a Quality System

Or a Foundation"

- Policy
- Needs of customer (or requirements)
- Control of Processes
- Control of Documents
- Customer Feedback (warranty admin)
- Improve Everything (continuous improvement)



“Consensus” QA

- ISO-9000-2008 “Certification”
  - Is a consensus quality system
  - Has world recognition
  - Baseline Quality System
  - Requires compliance audits
    - Document control / configuration control
    - Calibration control
    - Supplier control
    - Training / qualification of employees
    - Corrective / Preventive action system

How does the “Quality System” Relate to Performance?

- Control of Processes (examples)
  - EVA in lamination process
  - Glass in handling, storage, and consistency
  - Backsheet for protection, safety etc.
  - Junction Boxes or connection schemes for connectivity
- Control of Suppliers
  - Monitor changes to their product

How does the “Quality System” Relate to Performance?

- Ongoing test and evaluation system
  - Continuously test samples of outgoing product
  - Frequently test samples of incoming material
  - Constantly monitor customer feedback for clues
- Bank warranty reserves and “pray”

" Consensus Guidelines For Quality Assurance and Their Role as a Foundation for Lifetime Prediction"

- In Summary;
  - The Industry as a whole needs to recognize the whole system (Quality / Business System) and educate the public
  - The Consumers (Big or Small) need to Demand the publication of lists of "certified companies" that supply under the ISO and IEC requirements etc.
  - It is the Quality System that Consistently delivers the "Goods"

&

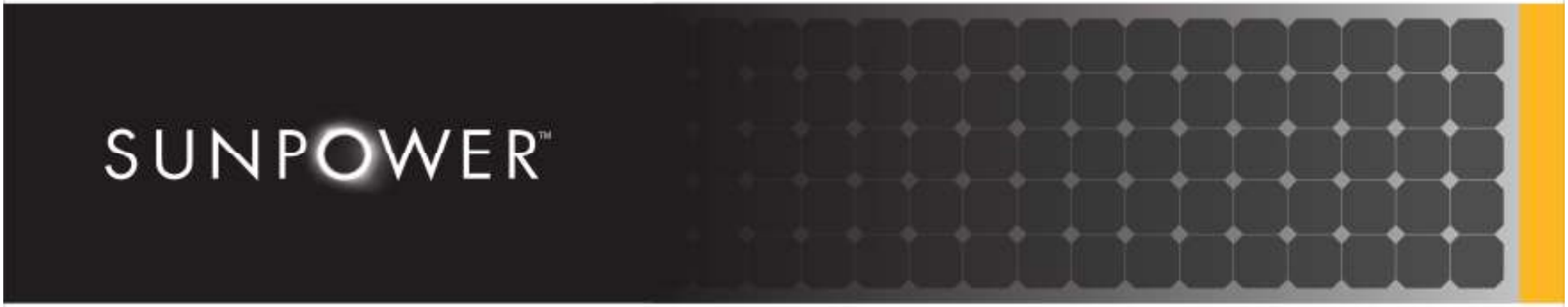
Finally

Thank You for your Time

(for luckily it is soon to be “Miller Time”)

“ Consensus Guidelines For Quality Assurance and Their Role as a Foundation for Lifetime Prediction”





Case study:
SunPower Manufacturing Quality Methods

Dr. David DeGraaff, SunPower Corp.

Presented at the NREL PV Module Reliability Workshop, Boulder, CO, 2/18/10

Permission to reprint or distribute any content from this presentation requires the prior written approval of SunPower Corporation.
Copyright © 2010 SunPower Corporation. All rights reserved.

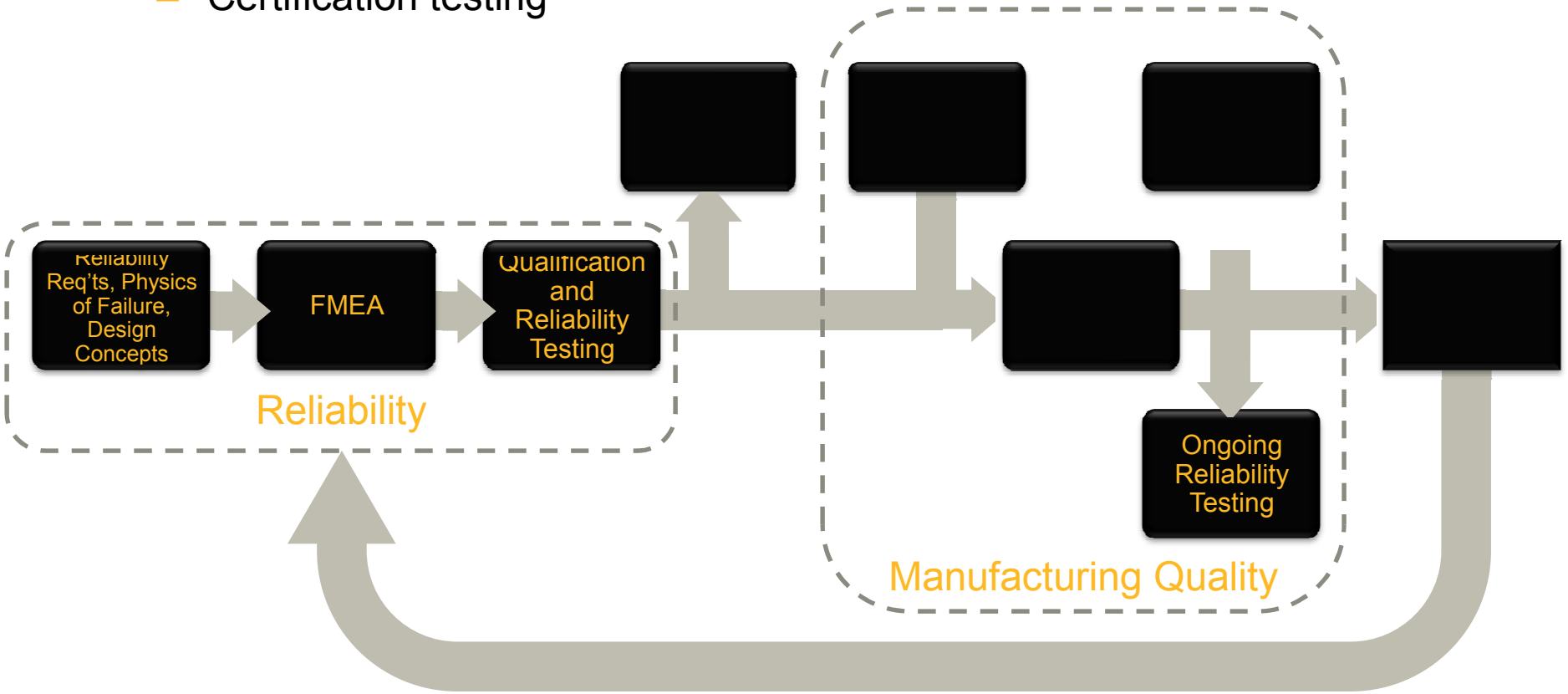
Safe Harbor Statement

This presentation contains forward-looking statements within the meaning of the Private Securities Litigation Reform Act of 1995. Forward-looking statements are statements that do not represent historical facts and may be based on underlying assumptions. SunPower uses words and phrases such as "expects," “believes,” “plans,” “anticipates,” "continue," "growing," "will," to identify forward-looking statements in this presentation, including forward-looking statements regarding: (a) plans and expectations regarding the company’s cost reduction roadmap, (b) cell manufacturing ramp plan, (c) financial forecasts, (d) future government award funding, (e) future solar and traditional electricity rates, and (f) trends and growth in the solar industry. Such forward-looking statements are based on information available to the company as of the date of this release and involve a number of risks and uncertainties, some beyond the company's control, that could cause actual results to differ materially from those anticipated by these forward-looking statements, including risks and uncertainties such as: (i) the company's ability to obtain and maintain an adequate supply of raw materials and components, as well as the price it pays for such; (ii) general business and economic conditions, including seasonality of the industry; (iii) growth trends in the solar power industry; (iv) the continuation of governmental and related economic incentives promoting the use of solar power; (v) the improved availability of third-party financing arrangements for the company's customers; (vi) construction difficulties or potential delays, including permitting and transmission access and upgrades; (vii) the company's ability to ramp new production lines and realize expected manufacturing efficiencies; (viii) manufacturing difficulties that could arise; (ix) the success of the company's ongoing research and development efforts to compete with other companies and competing technologies; and (x) other risks described in the company's Annual Report on Form 10-K for the year ended December 28, 2008, Quarterly Report on Form 10Q for the quarter ended Sept. 27, 2009, and other filings with the Securities and Exchange Commission. These forward-looking statements should not be relied upon as representing the company's views as of any subsequent date, and the company is under no obligation to, and expressly disclaims any responsibility to, update or alter its forward-looking statements, whether as a result of new information, future events or otherwise.

© 2009 SunPower Corp.

Big Picture

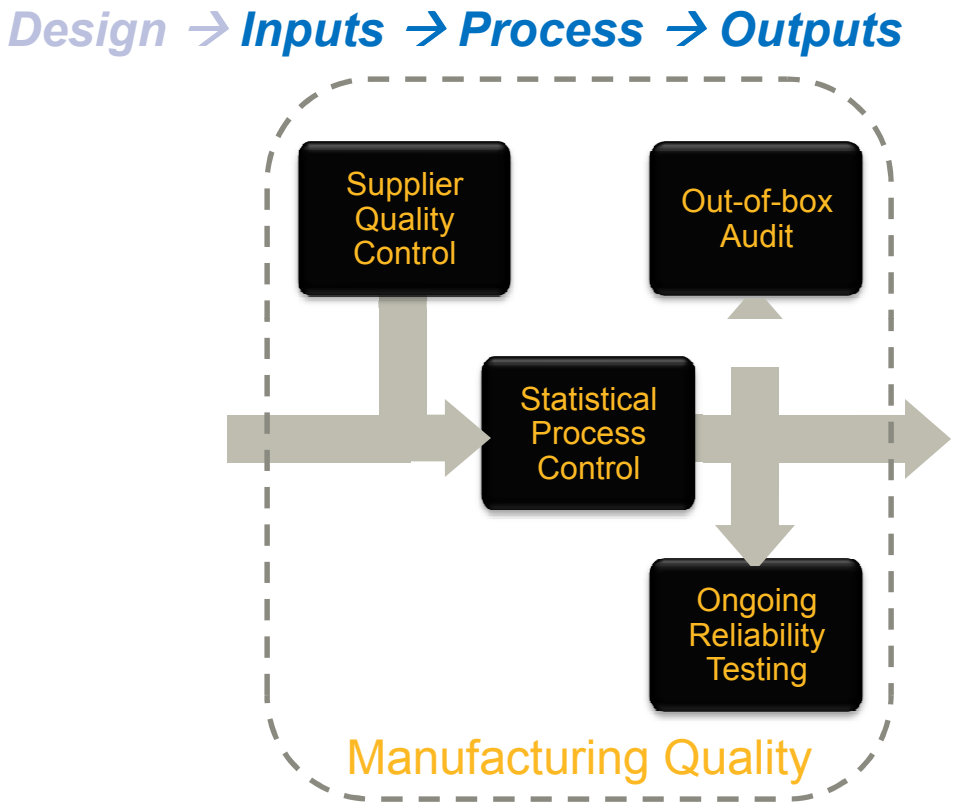
- Note difference between:
  - Qualification and Reliability testing
  - Ongoing Reliability Testing
  - Certification testing



© 2009 SunPower Corp.

Overview

- Focus today is on Manufacturing Quality
- Simple model:



© 2009 SunPower Corp.

Inputs: Supplier Quality Management

- Stage 1: Early engagement
  - Understand internal requirements, determine sourcing strategy and resources
- Stage 2: Planning and Preparation
  - Set expectations with supplier, analyze the current situation, develop a roadmap
- Stage 3: Qualification of supplier
  - Align expectations, data collection and analysis, conformance
    - Change Notification process
    - PSC audit
    - STARS score
- Stage 4: Supplier managed inventory
  - Self-assessment with validation, improvement plan, periodic review

PSC Audit:

- Prevention – Employee training, Statistical Process Control, FMEA usage, 8D usage, CAPA (Corrective and Preventive Actions) usage, Reliability program, Supplier Quality Program, etc.
- Standardize/Simplified/Scalable – high quality business processes.
- Customer Satisfaction – customer surveys, responsiveness to customer issues.

STARS – Supplier Total Achievement Rating System

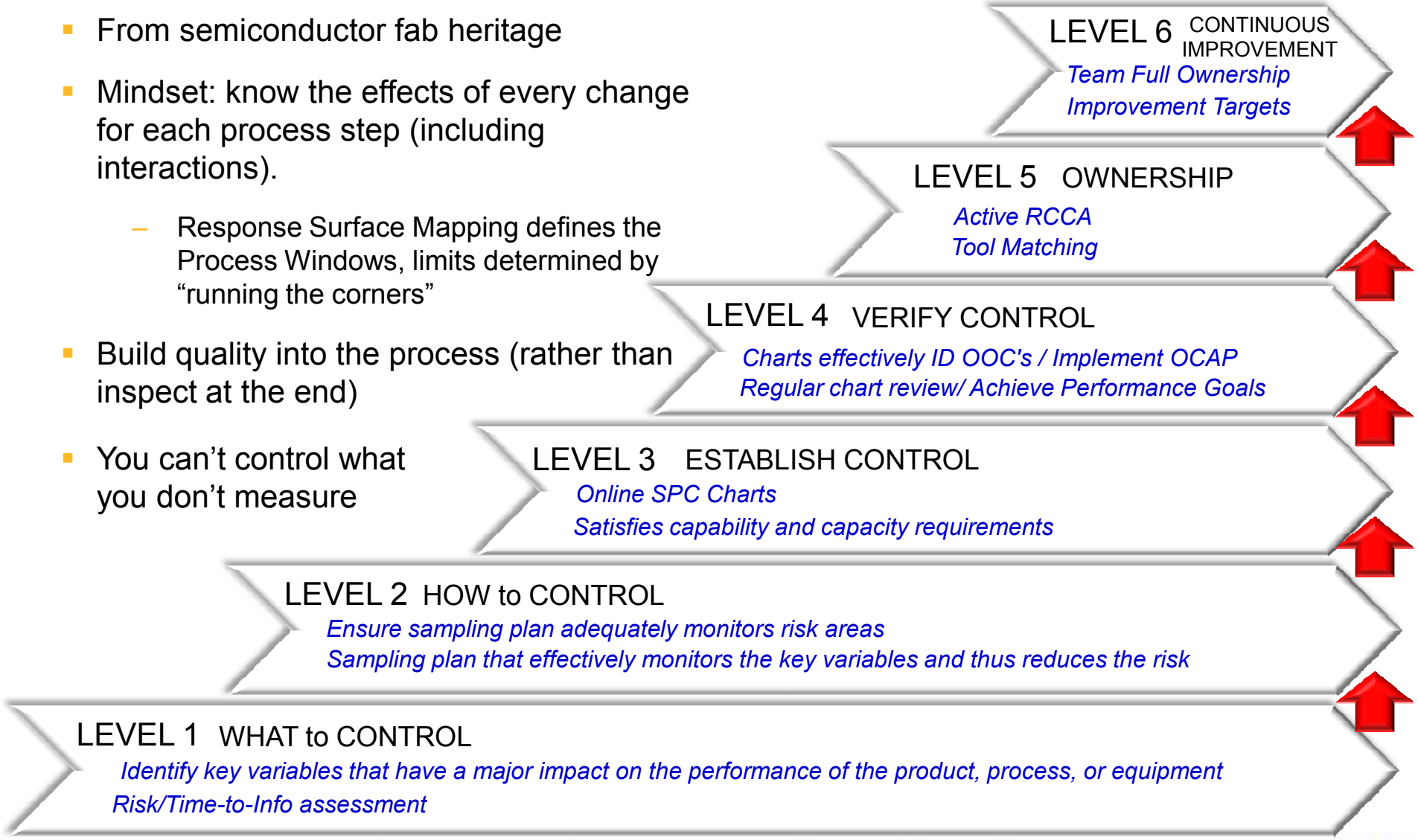
- Quality – customer issues, reliability, compliance to SunPower change requests, PSC Audit performance, problem recurrence rate
- Cost and cost reduction plan
- Availability – on-time delivery, lead time, etc.
- Technology

Must score more than 80% to be an approved supplier

© 2009 SunPower Corp.

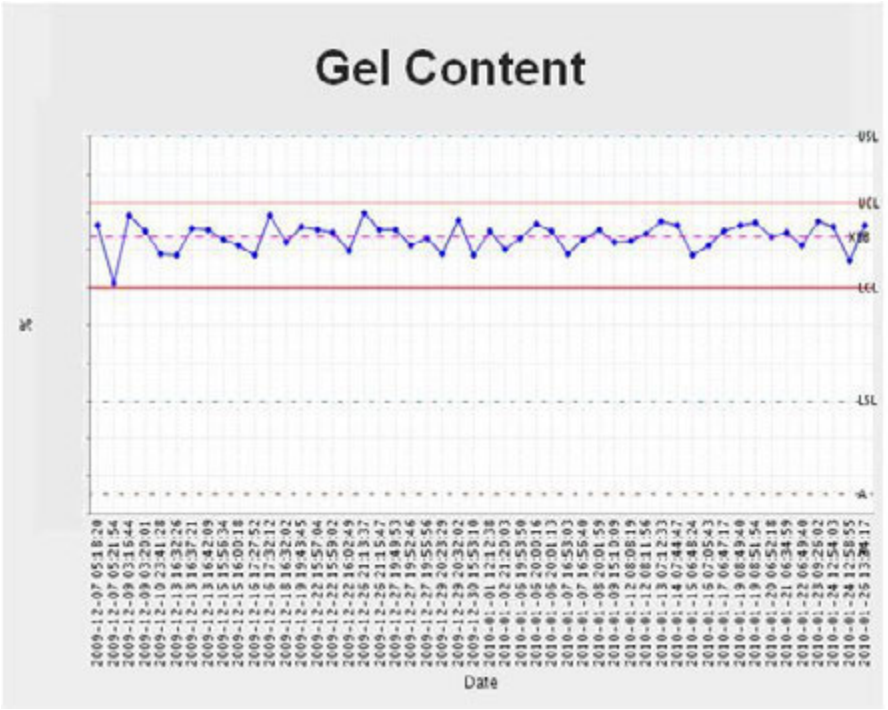
Process: Statistical process control (SPC)

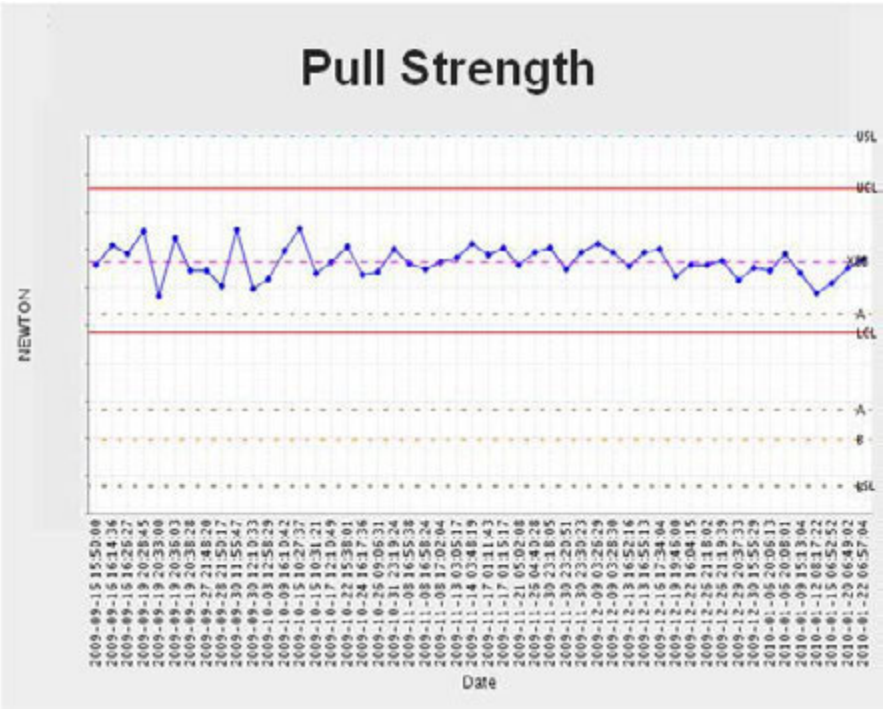
- From semiconductor fab heritage
- Mindset: know the effects of every change for each process step (including interactions).
  - Response Surface Mapping defines the Process Windows, limits determined by "running the corners"
- Build quality into the process (rather than inspect at the end)
- You can't control what you don't measure



© 2009 SunPower Corp.

SPC Example: Lamination Process





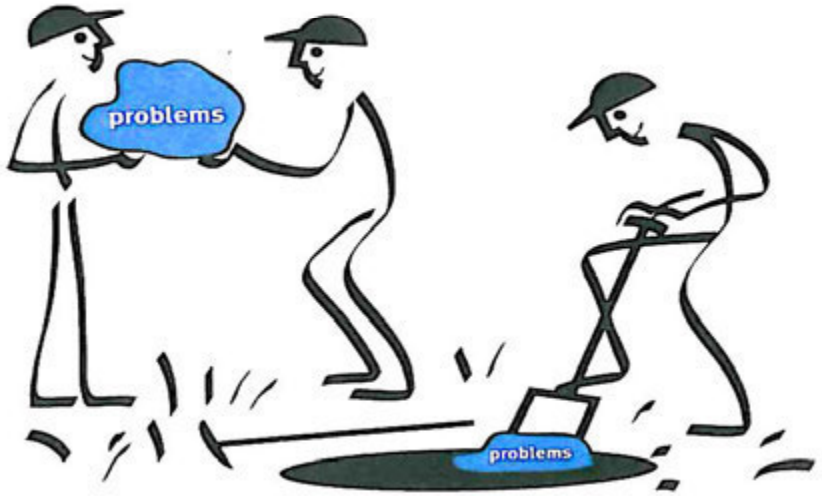
Each of these is considered a "chart" and is managed by the process engineers. There are over 100 charts encompassing the end-to-end manufacturing process.

© 2009 SunPower Corp.

Manufacturing Culture and SPC

Statistical Process Control can only be effective with an empowered organization structure

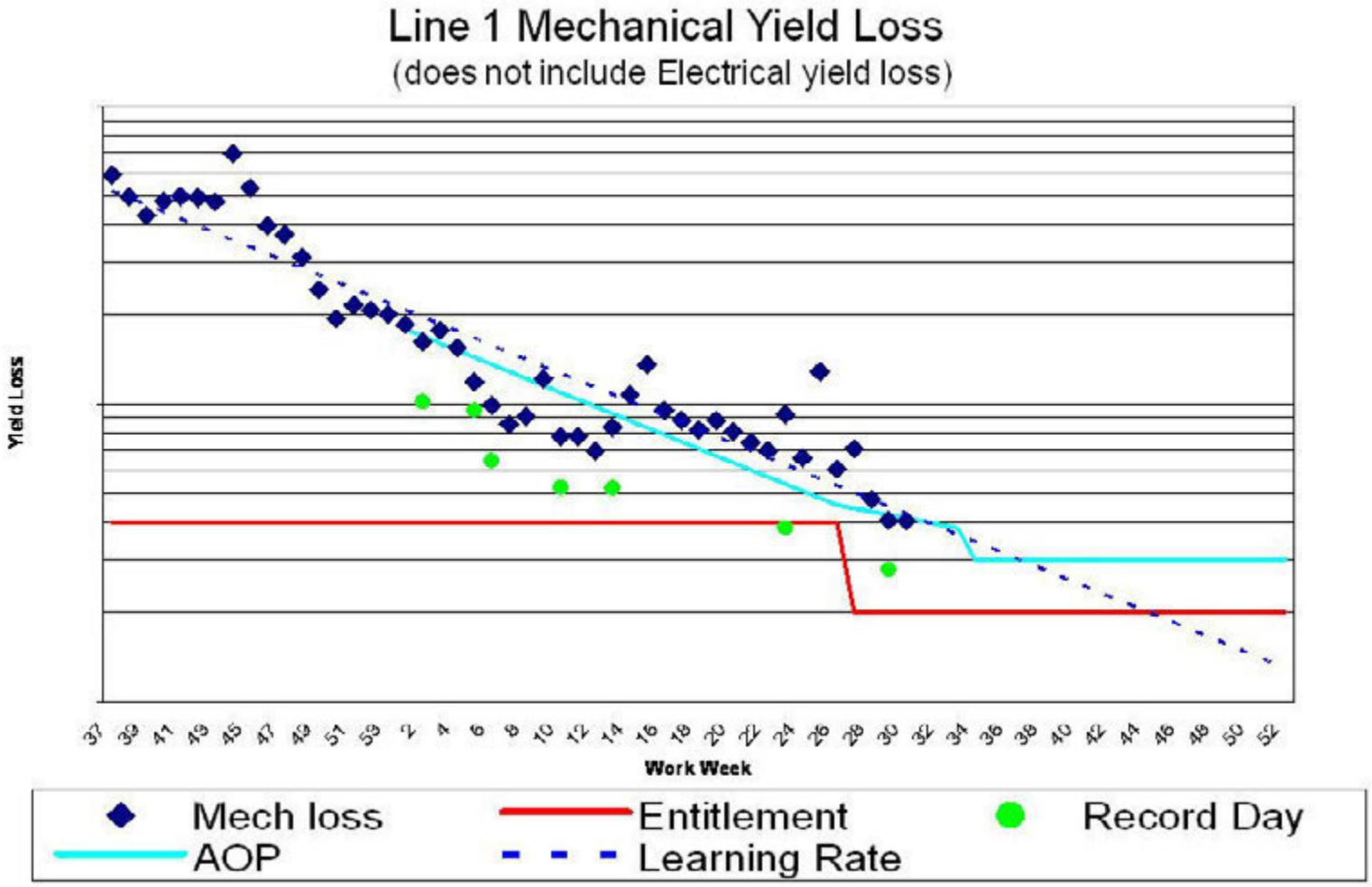
- People who do the work know best
- Pride of workmanship and quality at the source
- Continuous cycles of Learning and Improvement
- “Bright Ideas” come from everyone – all are welcome



Problems are Treasures

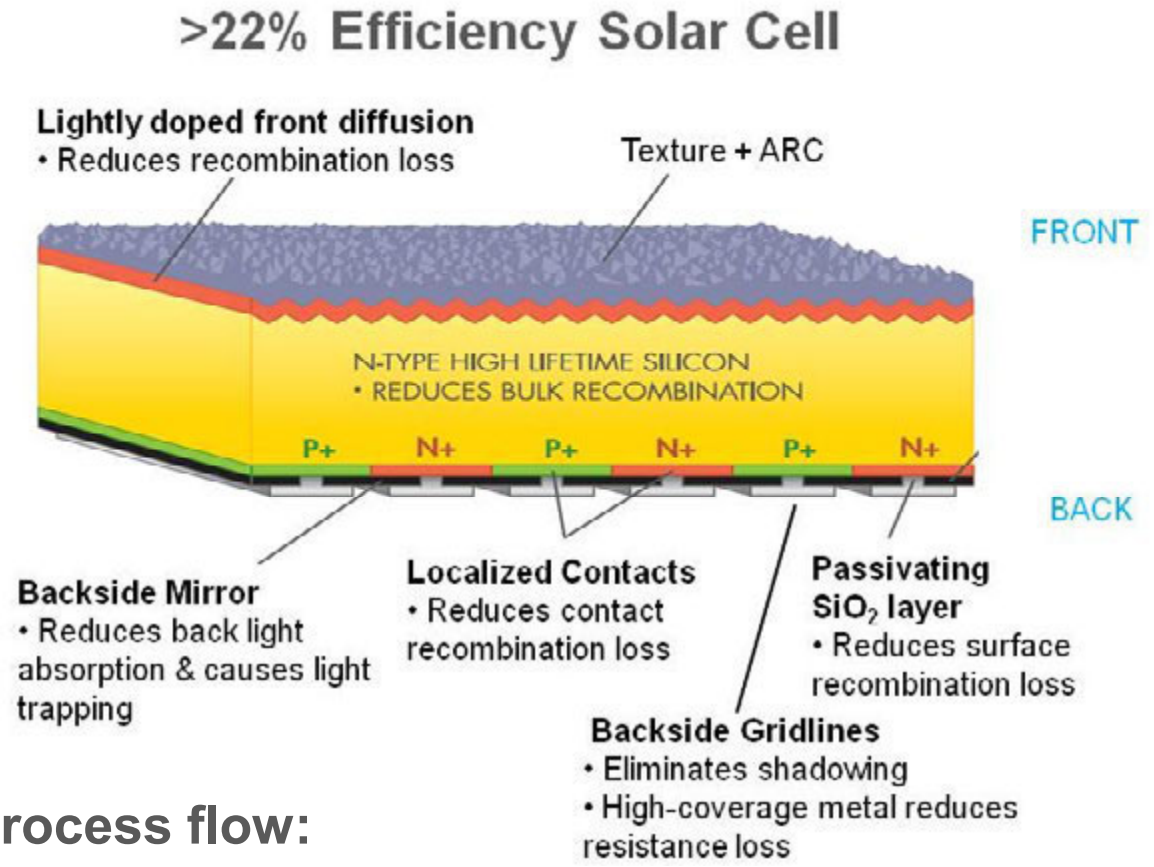
© 2009 SunPower Corp.

SPC Example: getting a process under control

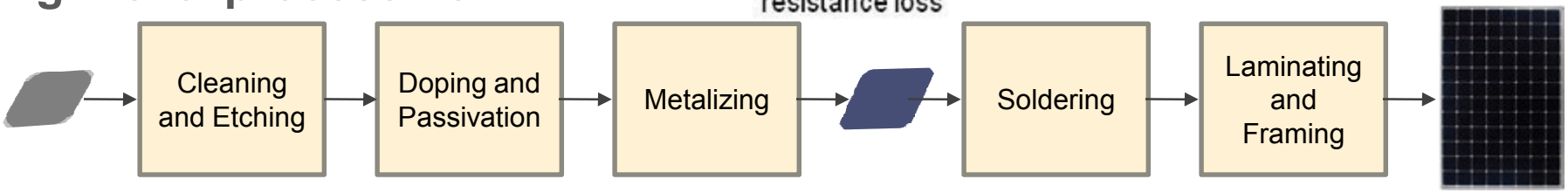


© 2009 SunPower Corp.

SunPower Manufacturing Process

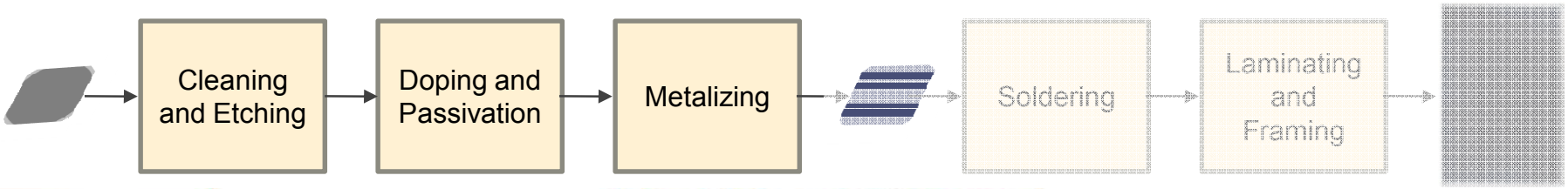


High-level process flow:

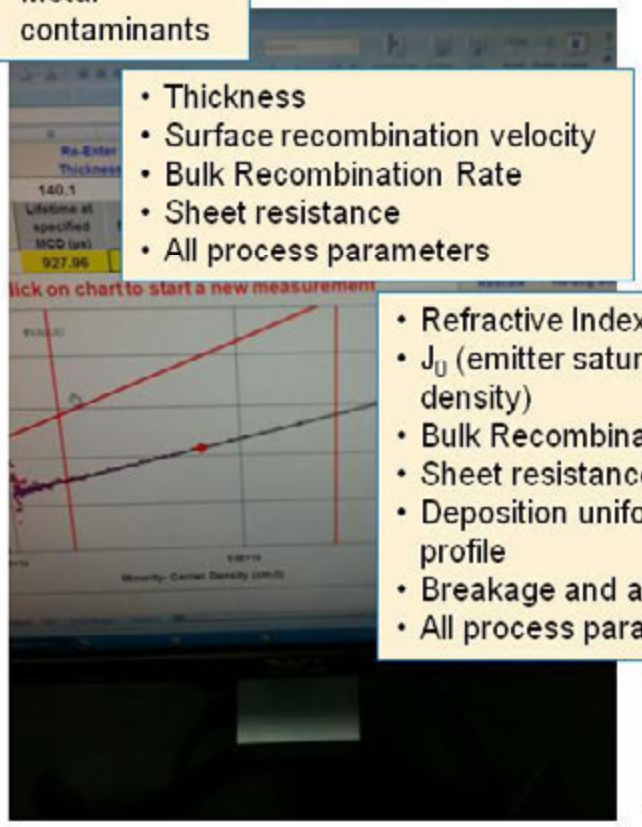


© 2009 SunPower Corp.

SPC Examples: major tests at each step

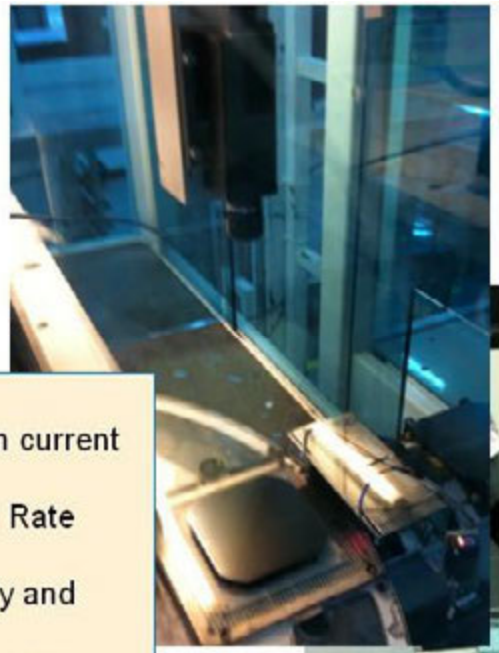


- Thickness
- Metal contaminants



- Thickness
- Surface recombination velocity
- Bulk Recombination Rate
- Sheet resistance
- All process parameters

- Refractive Index
- J_U (emitter saturation current density)
- Bulk Recombination Rate
- Sheet resistance
- Deposition uniformity and profile
- Breakage and alignment
- All process parameters



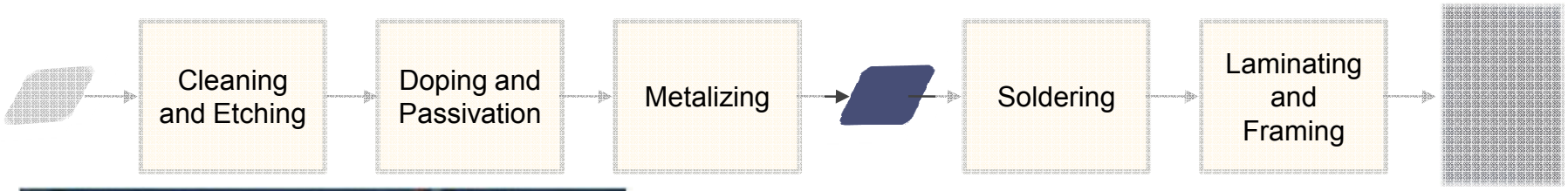


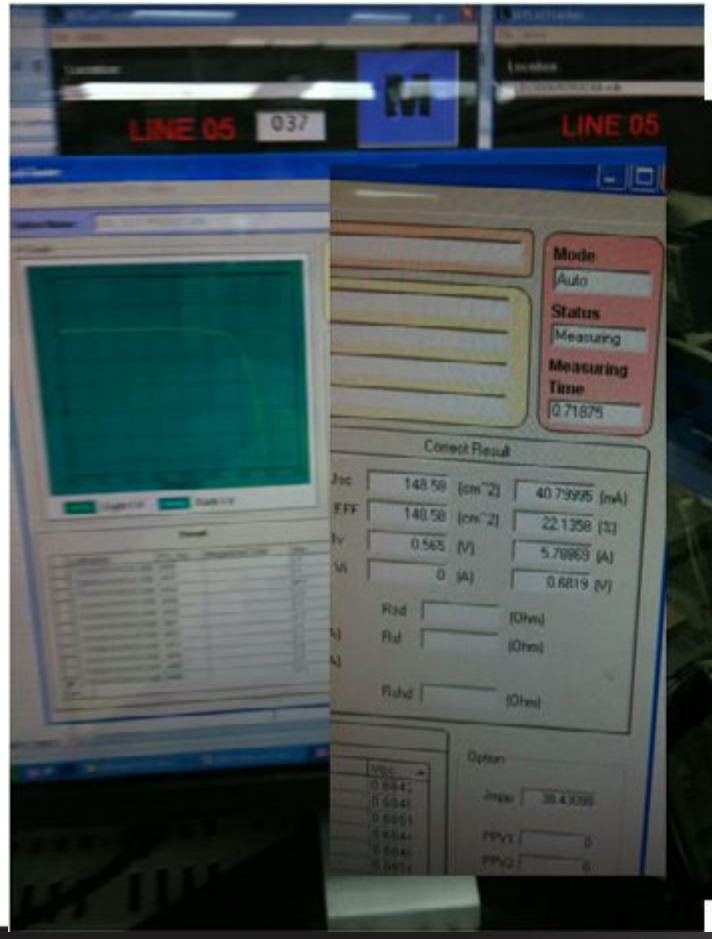


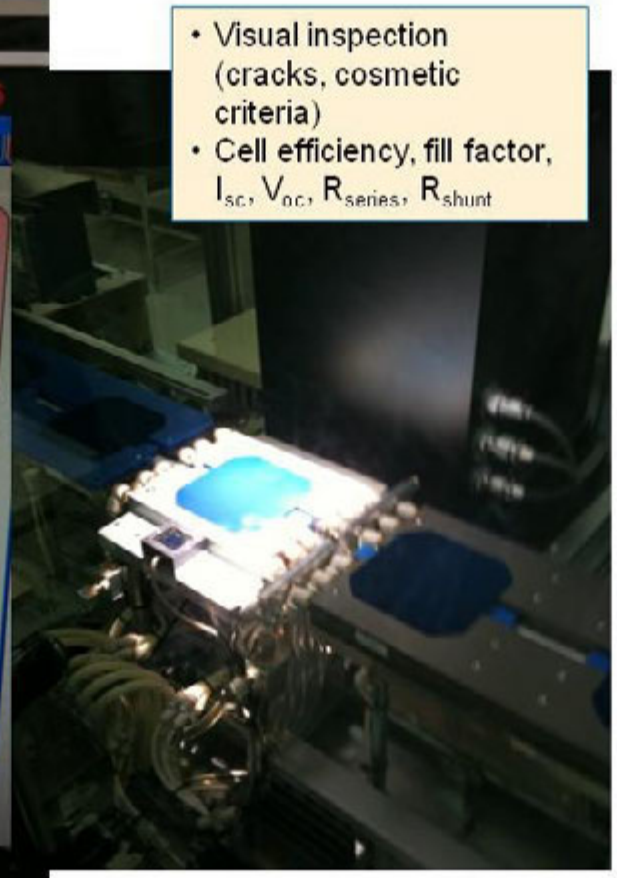
- Metal thickness
- All process parameters

© 2009 SunPower Corp.

SPC Examples: major tests at each step





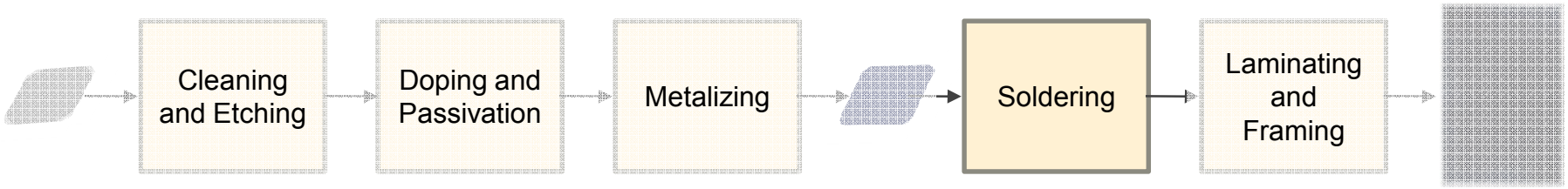


- Visual inspection (cracks, cosmetic criteria)
- Cell efficiency, fill factor, I_{sc}, V_{oc}, R_{series}, R_{shunt}

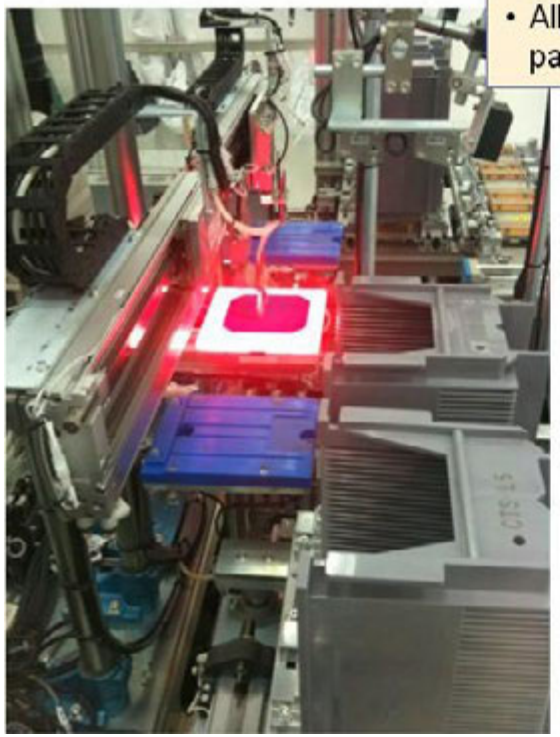


© 2009 SunPower Corp.

SPC Examples: major tests at each step



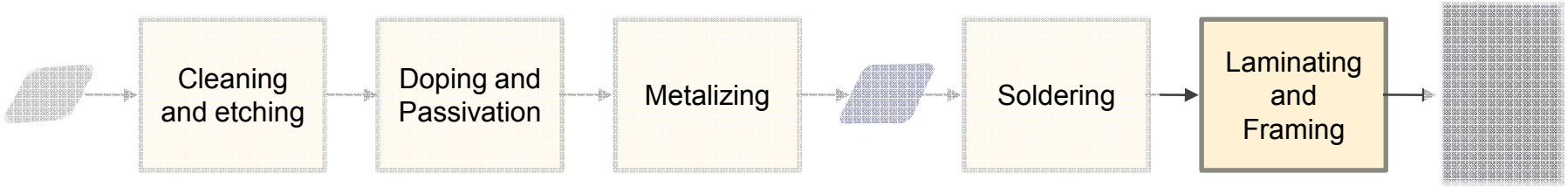
- Chips and shape
- Substring voltage
- All process parameters



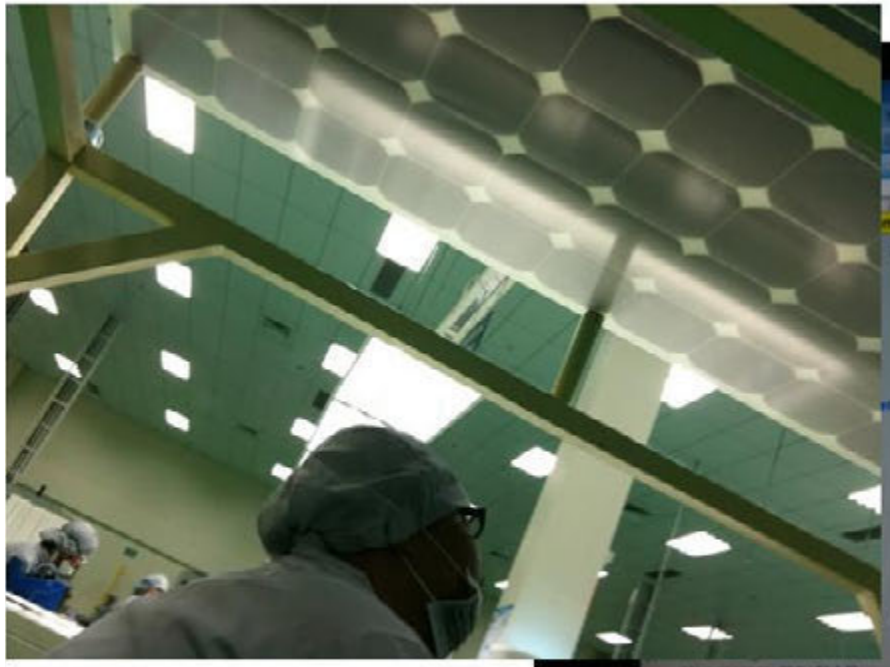


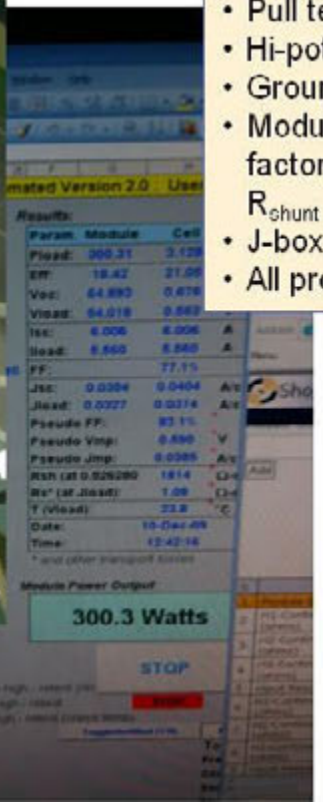
© 2009 SunPower Corp.

SPC Examples: major tests at each step



- Visual inspection
- Gel test
- Pull test
- Hi-pot
- Ground continuity
- Module efficiency, fill factor, I_{sc}, V_{oc}, R_{series}, R_{shunt}
- J-box test
- All process parameters







© 2009 SunPower Corp.

Outputs: Out-of-Box Audit

- Random sampling of boxes ready for shipment
- Check for:
  - Marking and documentation
  - Packaging
  - Cleanliness
  - Visual defects
  - Robustness
  - Electrical data (re-test)

© 2009 SunPower Corp.

Outputs: Ongoing Reliability Testing

- Cell Tests:
  - Autoclave test
  - UV
- 3-cell Laminate Tests and Module test:
  - 200 Thermal Cycles
  - 40 Humidity Freeze Cycles
  - 1000 Damp Heat Hours
  - Installation and outdoor exposure
  - Periodic longer durations and test-to-failure
- Cell Characterization:
  - Visual inspection
  - Performance test
  - Suns-Voc
  - Photoluminescence
- Laminate & Module Characterization:
  - Visual inspection
  - Performance test
  - High-Potential test
  - Electroluminescence

ORT is strictly a “sniff-test” to ensure no out-of-control manufacturing processes or inputs have impacted reliability. Qualification and Reliability Testing occurs at the design phase and is much more severe (and not pass/fail).

© 2009 SunPower Corp.

Ongoing Reliability Testing





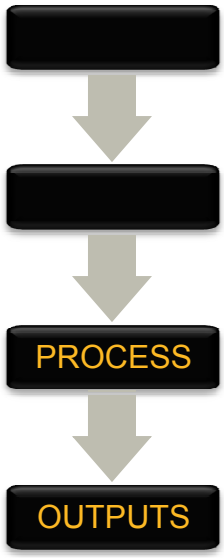






© 2009 SunPower Corp.

Conclusions



- Reliability – responsible for a reliable design
- SQC – supplier quality control – responsible for consistent manufacturing inputs
- SPC – statistical process control – responsible for ensuring robust and repeatable manufacturing output
- ORT – ongoing reliability testing – is responsible for ensuring no unanticipated changes have occurred

© 2009 SunPower Corp.





www.sunpowercorp.com



Breakout session: Silicon

Discussion leader: Peter Hacke

Scribe: David Miller

8:00 – John Wohlgemuth (BP Solar) – Failure Modes of Crystalline Si Modules and How to Eliminate Them

8:30 –Govindasamy Tamizhmani (Mani) (TUV Rheinland PTL) – Experience with Qualification and Safety Testing of Silicon Modules

9:00 – Discussion: Are there field failures that are not caught by the current qual test? Are there new failure modes that need to be studied? Do high system voltages cause new module failures?

9:30 – Break

10:00 – Dirk Jordan (NREL) – Degradation Rates—What Do We See?

10:30 – James Bing (New Energy Options) – Decades in the Installed Environment—Do Silicon Modules Really Last More than 20 Years?

11:00 – Discussion: Is the performance in the field adequate? If not, what is needed—better QA, qual test?

Failure Modes of Crystalline Si Modules

John Wohlgemuth, Daniel W. Cunningham, Andy Nguyen, George Kelly and Dinesh Amin

- **Broken interconnects – thermomechanical fatigue, stress concentration**
- **Broken Cells- need optical and mechanical test/inspection, multiple ribbons.**
- **Corrosion- need optical and mechanical test/inspection, strong interactions between moisture, metallization, and EVA**
- **Delamination and/or loss of elastic properties, control of materials, extensive accelerated testing**
- **Encapsulant discoloration – 6 mo 8x UV testing**
- **Solder bond failures – multiple solder bonds, for mechanical backup to j-box connection, do not depend on pottant**
- **Broken glass - Hot-spot, arcs, improper mounting**
- **Hot Spots – bypass diodes, screen cells with high leakage current**
- **Ground faults- avoid mounting behind the cell area**
- **Junction box and module connection failures- workmanship, QC, qualified parts**
- **Structural failures – follow mnf. Instructions, design to load**

Summary

bp solar

- **Crystalline Si Module reliability and performance**
  - **Very good but still with room for improvement**
  - **Not all modules are created equal, poor material selection, improper assembly and processing will yield different degradation rates and lifetimes**
- **New Module Technology**
  - **Can't test for 25 years before releasing commercial products**
  - **Strong accelerated test programs required.**
  - **Process controls required to assure production modules perform as well as test modules.**

John Wohlgemuth: Questions & Answers

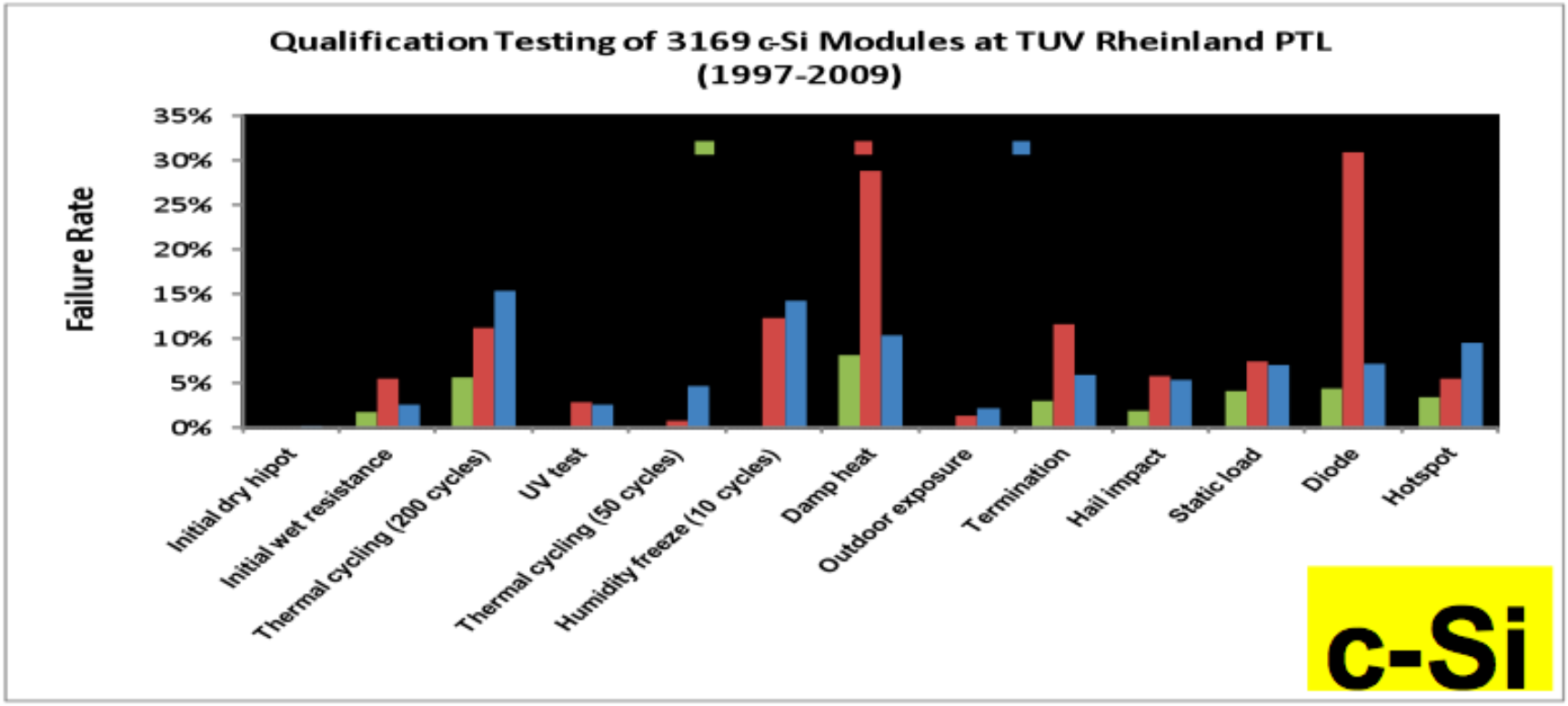
- **Q: pottant in j-box – how is this different than EVA and bus-bar**
- **A: you want another mechanical "hold" in addition to solder bond**
- **Q: new low cost encapsulants on the market … why stick to EVA**
- **A: not that significant cost savings; many are thermoplastics, and high T performance questions.**

Mani G. TamizhMani

Experience with Qualification and Safety Testing of Photovoltaic Modules

Test Results @ TUV Rheinland PTL

- **Qualification Test Results of PV Modules (IEC 61215/61646)**
  (3636 modules [87% c-Si]; 20 different countries; 1997-2009 [13 years of data])
  - c-Si: 1997-2005 *vs.* 2005-2007 *vs.* 2007-2009
  - Thin-film: 1997-2005 *vs.* 2005-2007 *vs.* 2007-2009
- **Safety Test Results of PV Modules (IEC61730; ANSI/UL1703)**
  - c-Si: Temperature test – 140 modules (2006-2009)



- 1997-2009 (13 years): Top 4 failure rates

- Damp heat failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Thermal cycling failure rates: 2007/2005 = increased; 2009/2007 = increased
- Humidity freeze failure rates: 2007/2005 = increased; 2009/2007 = increased
- Diode failure rates: 2007/2005 = increased; 2009/2007 = decreased

Out of the box (initial) wet resistance failure (!!!) : 2005 – 2%; 2007 – 5%; 2009 – 3%

Summary

Qualification Testing: c-Si

- Damp heat failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Thermal cycling failure rates: 2007/2005 = increased; 2009/2007 = increased
- Humidity freeze failure rates: 2007/2005 = increased; 2009/2007 = increased
- Diode failure rates: 2007/2005 = increased; 2009/2007 = decreased

Qualification Testing:Thin-Films

- Damp heat failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Thermal cycling failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Humidity freeze failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Static load failure rates: 2007/2005 = decreased; 2009/2007 = increased

Safety - Temperature Testing: Polymeric Substrate (c-Si)

- $T_{avg\text{-}norm\text{-}Voc}$: 84°C
- $T_{max\text{-}norm\text{-}Voc}$: 97°C

Mani:
Questions & Answers

- **Q: after hail test, wet resistance … why is that the case for c-Si in post-stress?**
- **A: not clear what after hail test, modules fail wet resistance; adhesion on back might be compromised?**
- **Q: where is damp heat failing?**
- **A: between j-box & laminate**
- **Q: Does that mean sealant at j-box not working properly**
- **A: Yes, bad adhesion there**
- **Q: In US only safety test is required… well what does CA use as crieria?**
- **A: IEC tests performance at STC required there, not full qual test**

National Renewable Energy Laboratory
Innovation for Our Energy Future

Degradation Rates



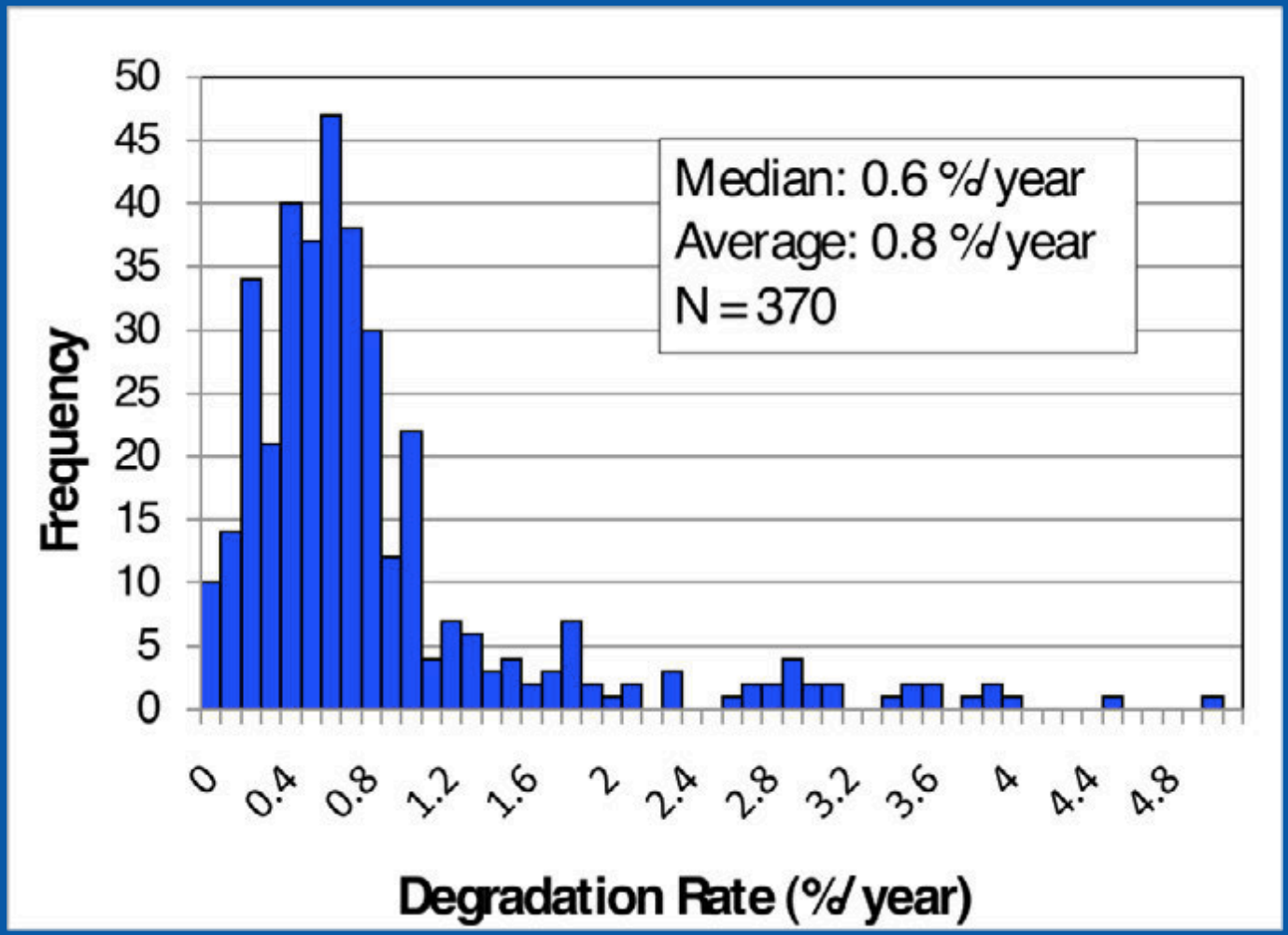
NREL

Dirk Jordan

Feb-19-2010

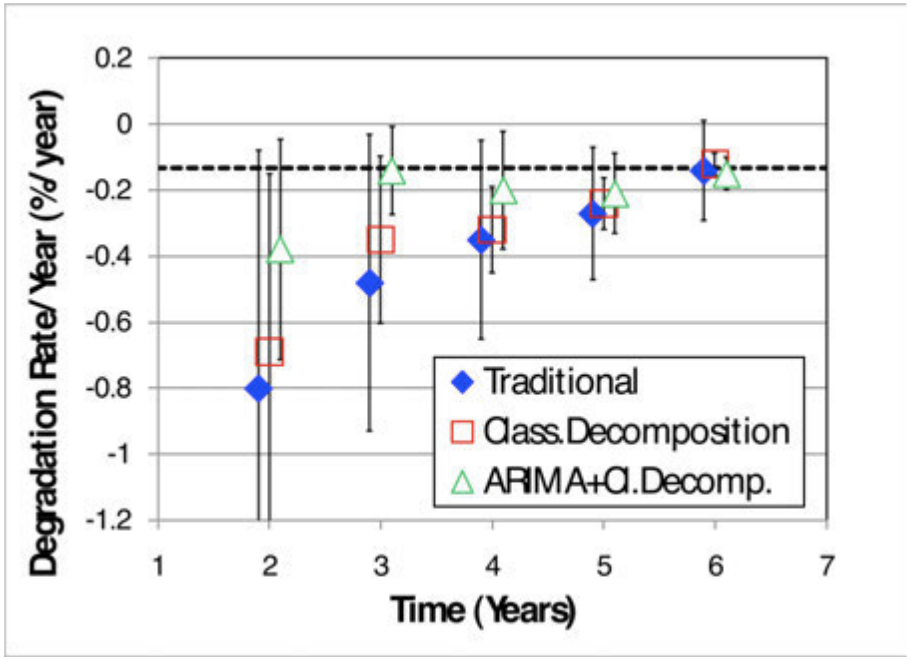
NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

Degradation Rates (R_d) most often reported

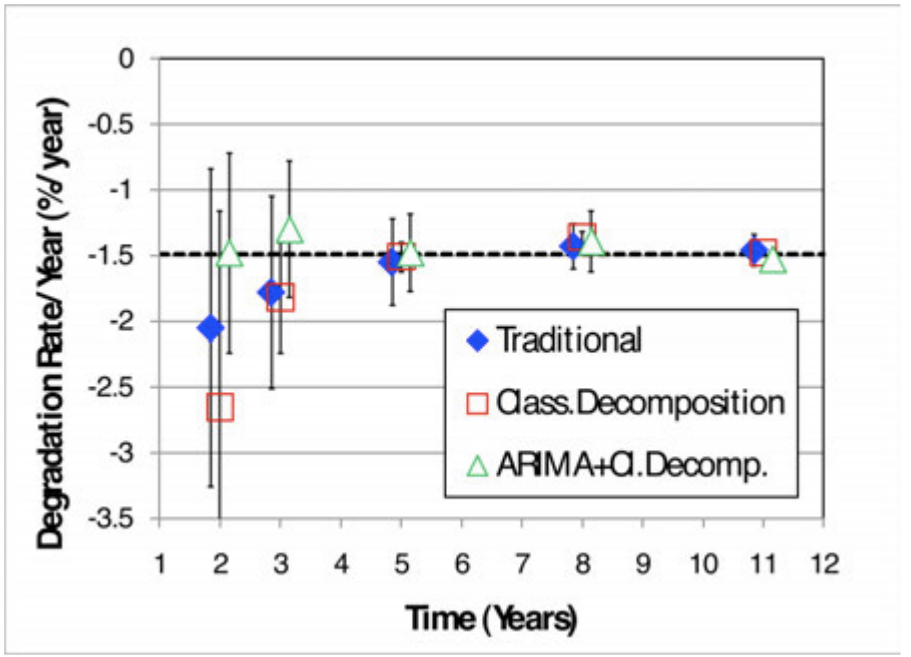


Degradation Rate in shorter Time

multi-Si



a-Si



- Degradation rates were calculated for each method starting with the first 2, 3 years etc.
- The a-Si module was in the field for over 6 months before data collection commenced.
- For longer times all three methodologies converge to the same rate.
- Traditional & Cl.Decomp. show increasing bias for shorter time but w/in uncertainty.

Conclusion

- Analysis of >40 modules showed why 3-5 years traditionally required to determine R_d
- Introduced 2 new methods to determine R_d (Class.Decomp., ARIMA+Decomp.)
- ARIMA most robust against outliers
- Introduced method to correct data shifts
- ARIMA seems to able to determine R_d more quickly → limited by numbers of degree of freedom → need more data points → sample weekly
- Using shorter time intervals increases noise but holds promise

Dirk Jordan: Questions & Answers

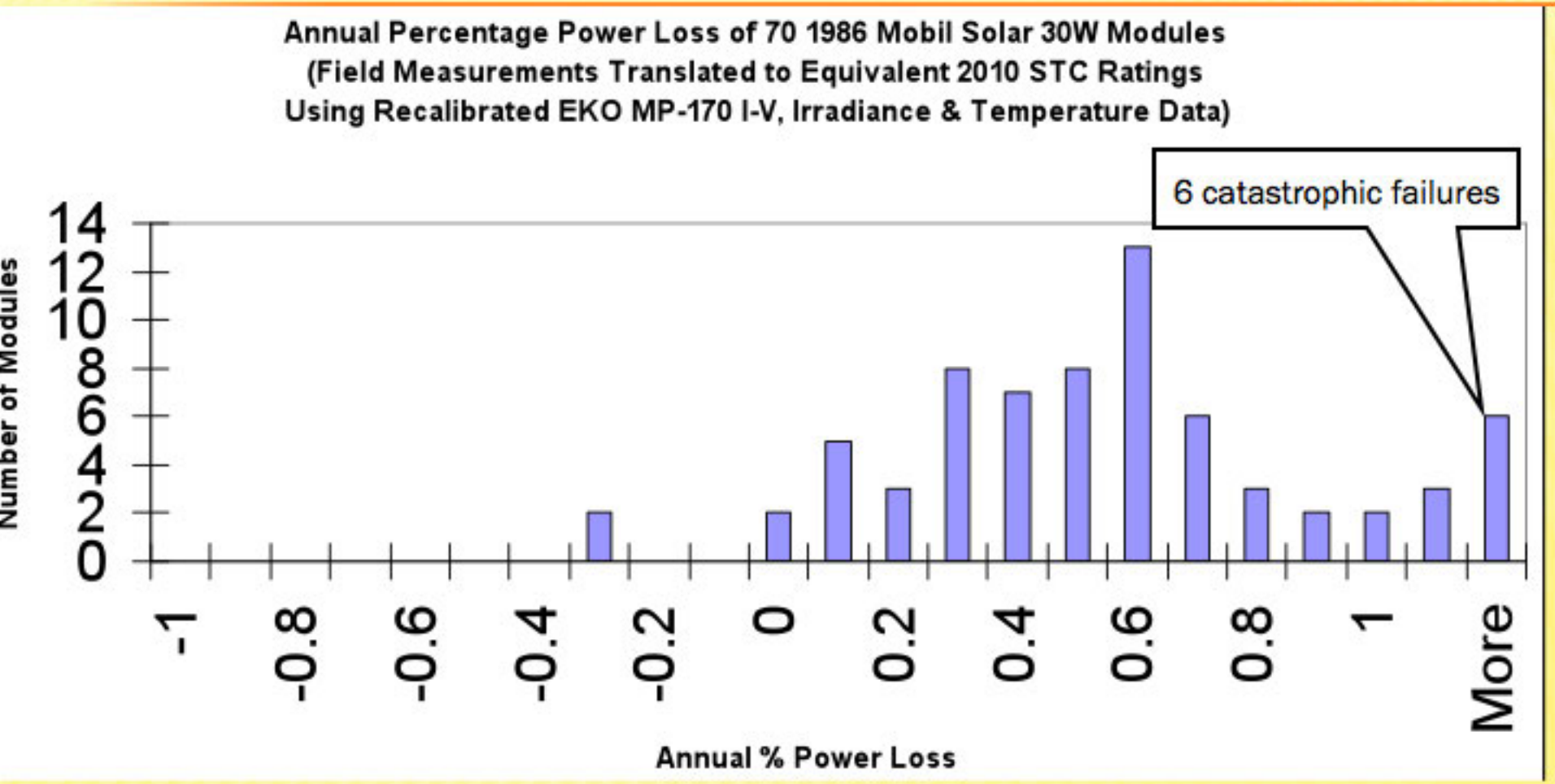
- Q: would some ‘true trends’ give you the opposite results? Would ARMIA ever render contradictory results?
- A: ARIMA does not handle sudden shifts very well. Can compensate this situation prior to analysis. Non-linear trends use a function rather than linear fits

Decades in the Installed Environment: Do Silicon Modules Really Last More than 20 Years? Preliminary Findings

NREL PV Module Reliability Workshop
2/19/2010

James M. Bing, PE
President
New Energy Options, Inc.
410 Great Road, B-6
Littleton, MA 01460
jbing@newenergyoptions.com

Percentage Power Loss Per Year
Mobil Solar Ra-30-12H Module Retest



Conclusions

- Yes, silicon modules –at least the ones that we looked at-- really do last more than 20 years.
- It may be the case that some of the Mobil Solar modules that we examined started out their lives with substantially higher STC ratings than their data sheets indicated.
- Quantifying a rate of power loss is difficult if you are not certain of the original rating. You can't tell how far you have come unless you know where you started from.
- Know your instruments.

James Bing: Questions & Answers

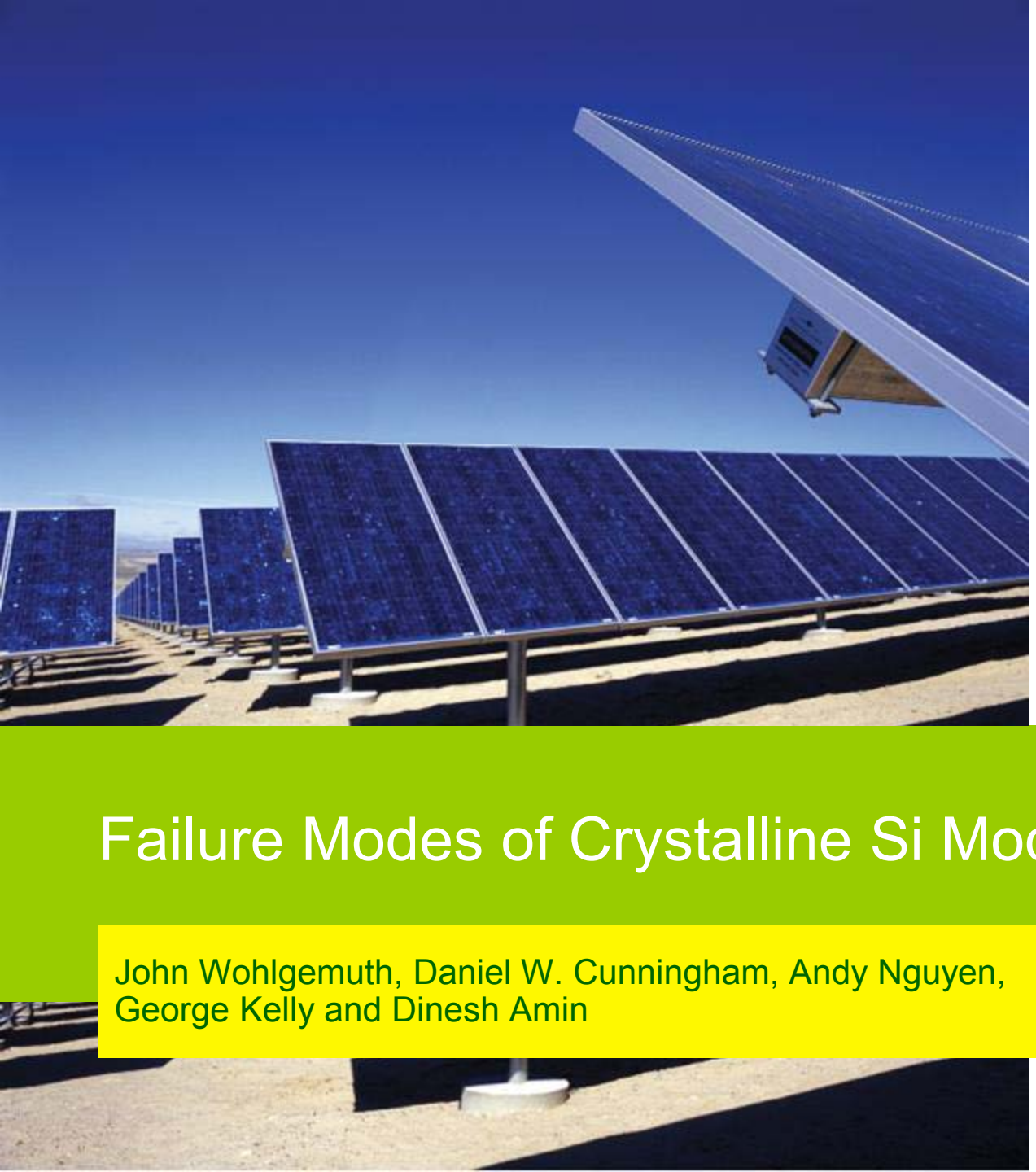
- Q: What was the module construction (encapsulant/backsheet)
- A: unknown, but being sent to NREL
- Q: Anything stand out from initial inspection
- A: Browning of encapsulant; c-Si modules look good;
- Q: what about catastrophic failures (poly-Si)?
- A: not clear why they were ½ power
- Q: cleaning procedure, where the modules dirty?
- A: c-Si – tilted at 60 deg, not “horribly” dirty, were measured before & after. procedure: windshield washer fluid, brush & squeegee

Discussion summary – Si module failures

- tests because the rate of damage is at a rate that is less than could be detected.
- Pr. M: Qual test captures catastrophic problems.
- A: J-box quality is **difficult** to assess on manufacturing line. J-box material or manufacturing issue.
- **A: Inverter box… operating life of 10 years vs. module life of 20-25 years.**
- **Pr. M: A lot of the instances are related to production quality.**
- **JW: No qualification procedure/test for inverter exists. Qualification mark (ISO) may or may not help with this issue**.
- **MQ: Inverters need a qual test. Examining commercial and residential inverters. Ranking concerns by risk. Currently investigating the performance (and excursions) at sites. Considering component-level issues (grease, capacitor).**
- Q: What about microinverters?
- MQ: Could be considered separately (centralized vs. distributor located inverters). Module scale inverters will likely interact w/ module itself. Centralized won't have same air-circulation issues. No electrolytic capacitors. Module scale… thermal management expected to be big issue within inverter & where it is attached on the module. Where and how mounted are important considerations.
- Pr. M: **Microinveter on module requires change in module qual test.**

Discussion summary – Si field performance (1)

- Q: what are main mechanisms of long term-degradation to focus upon?
- JW: 1. **quality**- occasional details may lead to catastrophic failure
- 2. **0.5%/year – mostly moisture driven** (improve encapsulation & metallization schemes)
- Pr. M: quality has improved over time; new IEC hot spot test (based on ASTM method) will be coming out soon – this may prove more difficult for manufacturers to pass, and should be helpful for module performance
- PH: Is performance adequate? Is soiling important? Mounting of module (installation) problems
- Q: Should the backsheet truly be breathable?
- JW: Most thin film manufacturers try to keep H2O out. In c-Si this has resulted in more problems (EVA continues to cure – delamination) than allowing the moisture in.
- PH: Outgassing renders bubbles. H2O can still get in through sides & j-box when a glass substrate is present.



bp solar

Failure Modes of Crystalline Si Modules

John Wohlgemuth, Daniel W. Cunningham, Andy Nguyen,
George Kelly and Dinesh Amin

Outline

- Review list of failure modes from yesterday's talk.
- Provide some detail on each of the failure mechanisms.
- Discuss methods utilized to either eliminate the failure itself or to minimize its effect of the module's long term performance.

Failure Modes of Crystalline Si Modules

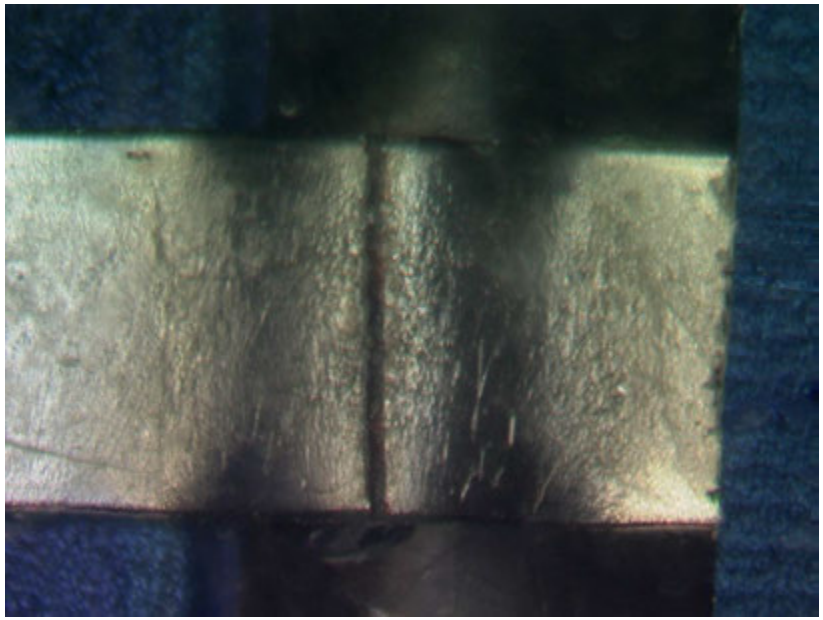
- Broken interconnects
- Broken Cells
- Corrosion
- Delamination and/or loss of elastic properties
- Encapsulant discoloration
- Solder bond failures
- Broken glass
- Hot Spots
- Ground faults
- Junction box and module connection failures
- Structural failures

Equal Opportunity Presentation

- This is an equal opportunity presentation
- Examples of module failures have been taken from many different module manufacturers, from most regions of the world.
- Many of these examples occurred during the early years of PV module manufacturing.
- It was this experience that lead to the reliable products we have today.

Broken Interconnects

- Interconnects break due to stress caused by thermal expansion and contraction or due to repeated mechanical stress.
- Early modules suffered open circuits due to broken interconnects.
- What makes it worse
  - Substrates with high thermal expansion coefficients
  - Larger cells
  - Thicker ribbon
  - Kinks in ribbon

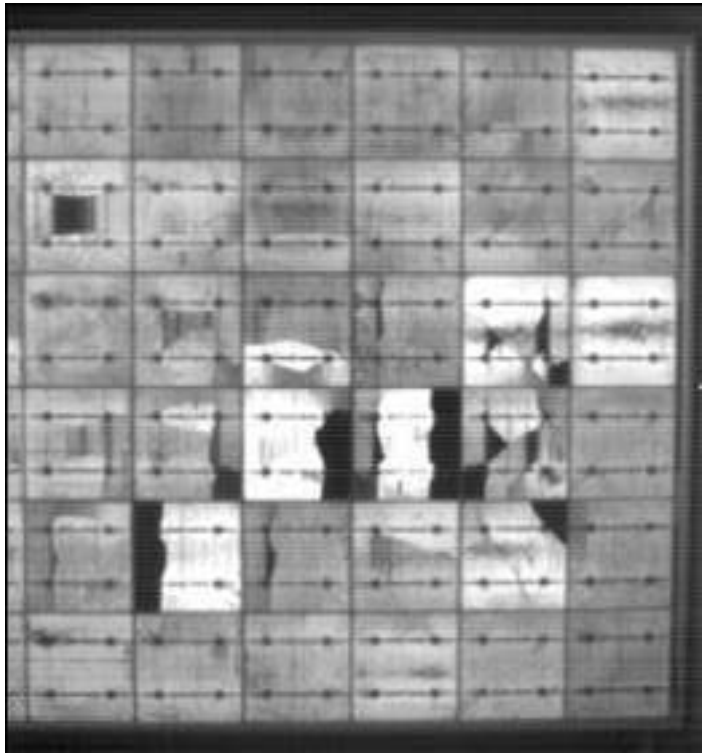


Solutions to broken interconnects

- Substrates with lower thermal expansion coefficients – that is one of the reasons why glass superstrate modules are so popular.
- Built in stress relief (But not kinks because they concentrate stress)
- Built in redundancy – if one fails the module continues to operate
- Thinner ribbon
- Softer more pliable material
- Discrete bonds versus continuous attachment

Broken Cells

- Crystalline Si cells can (and will) break due to mechanical stresses.
- Early modules suffered open circuits due to broken cells since there was only one attachment point for each polarity.
- What makes it worse
  - thinner cells
  - Single crystal especially if cleave plane is oriented along bus bar
  - Pre-stressed or chipped cells
  - Larger cells in large modules



Solutions to Broken Cells

- Build in crack tolerance using redundant interconnects and multiple solder bonds on each cell.
- Do not orient cleave planes along tabbing ribbons.
- Presorting of cells to remove those with cracks or chips.
- IR and NIR inspection.
- Dynamic mechanical load testing of new designs to determine the potential for cell breakage and whether the breakage leads to power loss.

Corrosion

- **Moisture induced corrosion of cell metallization.**
- **Key to survival is to minimize the ionic conductivity in the package, especially the encapsulant.**
- **Field failures of PVB encapsulated modules in 1980's was due to high ionic conductivity in moist PVB.**
- **What makes it worse**
  - **Metallization sensitivity to moisture**
  - **Encapsulant with humidity dependent conductivity**
  - **Encapsulant that absorbs a lot of moisture.**

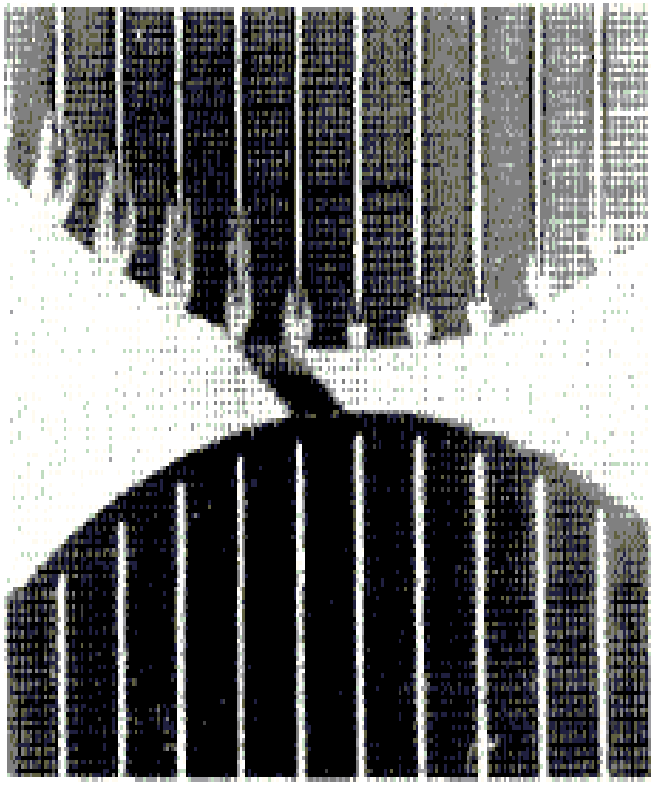


Figure 2. Solar-Cell Electrochemical Corrosion

Power Loss Due to Corrosion in PVB (JPL Picture and Data)

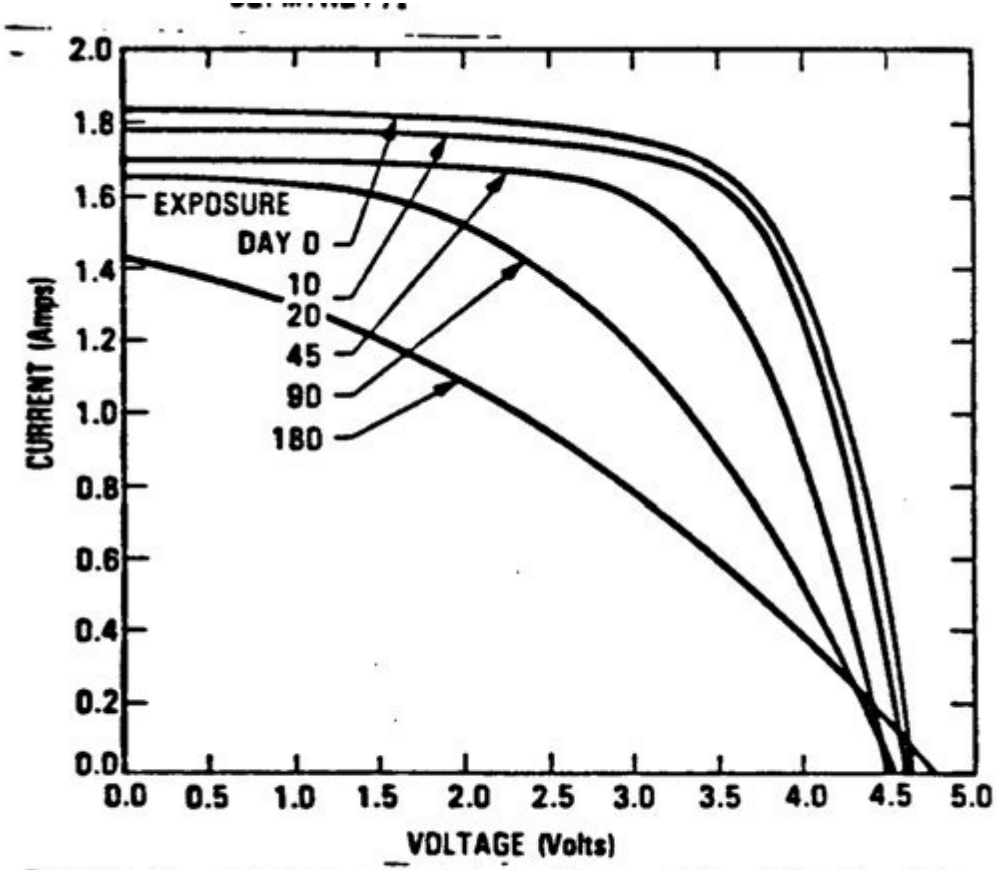


Figure 6. Module current-voltage data illustrating series resistance increase with exposure in 85/85/voltage-bias environment.

Corrosion

- For crystalline Si corrosion of front contacts is dependant on both the metallization system and the encapsulation system.
- Experience – with same cell metallization system, one EVA passed 1000 hours of damp heat (< 5% power loss) while modules with 2nd type of EVA degraded in power by close to 50% after 1000 hours.
- Performed testing of competitor's (IEC 61215 certified) crystalline Si modules through 1250 hours of damp heat testing (versus 1000 hours from IEC 61215). 8 out of 10 failed due to power loss in excess of 5%.

Solutions to Corrosion

- Utilize an encapsulant that does not increase in conductivity when it absorbs water vapor.
- Incorporate moisture barriers in superstrate and substrate.
- Utilize a metallization system that is compatible with the encapsulation system chosen.
- Do damp heat testing beyond 1000 hour.

Delamination

- Delamination observed to varying degrees in a small percentage of PV module types.
- Delamination can be between superstrate (ie. glass), substrate (ie. Backsheet) and encapsulant or between encapsulant and cells.
- Usually the result of an adhesive bond that is sensitive to UV, humidity, or contamination from the material (Excess Na in glass or dopant glass left on cell)

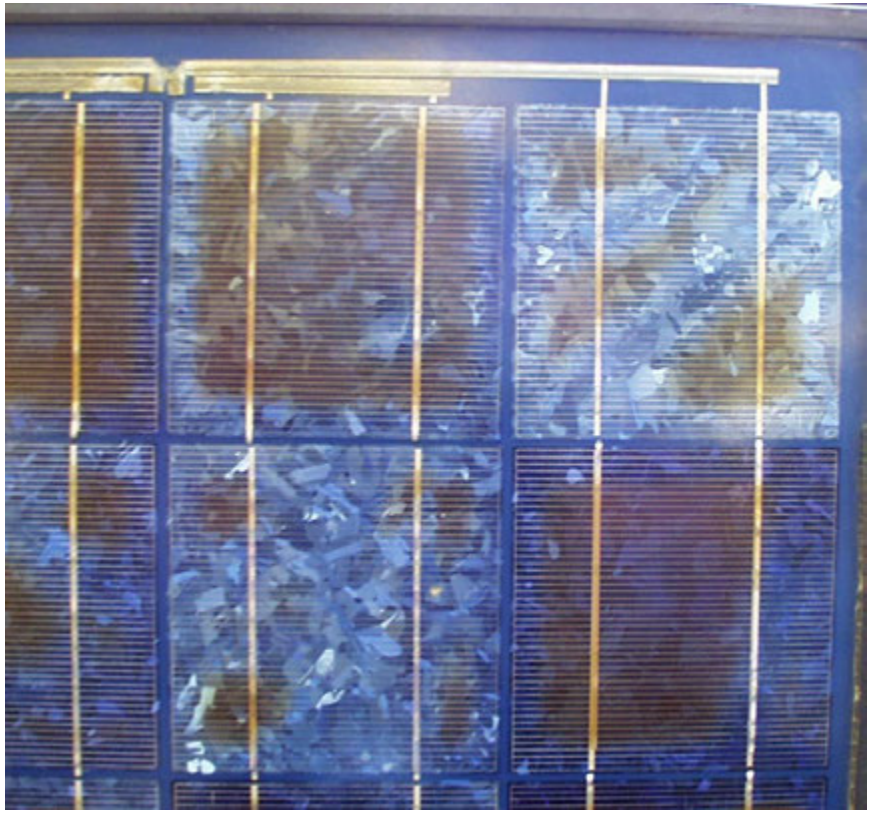


Solutions to Delamination

- Careful selection of adhesives and primers – Stable to UV and moisture.
- Control of raw materials and processes.
- Module testing to detect and eliminate any changes in materials or processes.

Encapsulant discoloration

- Will result in some loss of transmission and therefore reduced power.
- Worst reported case was in slow cure EVA caused by low concentration system at Carissa Plains.
- Standard cure EVA formulation A9918 does discolor.
  - Caused by heat and UV.
  - Bleached by oxygen
  - So with breathable backsheet center of cells discolor while outside ring remains clear.
  - Without concentration it takes 5 to 10 years to see discoloration and longer to start appreciably reducing output power.
- It was not EVA itself that discolored, but additives in the formulation



Eliminating encapsulant discoloration

- Make sure actual encapsulant package is tested to UV exposure at high temperature.
  - BP Solar does 6 months of UV testing for all encapsulants, backsheets and even labels.
- Original EVA yellowing alleviated via changes in EVA additive package and adding UV absorber (Cerium Oxide) to low iron glass.
- Most glass manufacturers have now removed Cerium Oxide from low iron glass so it is important to verify that the encapsulant being utilized is not sensitive to UV induced discoloration.

Solder bond failures

- Solder bonds can fail due to stresses induced by thermal cycling.
- Solder can creep when loads are applied at elevated temperatures.
- Solder fatigue can be caused by cyclic loading, e.g. thermal, mechanical or electrical repetitive stress.
- Early modules typically only had 1 solder bond per interconnect per cell so failure of this solder bond resulted in an open circuit failure of the whole module.
- Even today non-cell solder bonds often have no redundancy so failure of one of these bonds can lead to drop out of a cell string, a whole module or even a whole string of modules.

Alleviating Solder Bond Failures

- Utilize multiple solder bonds on each tabbing ribbon.
- Utilize softer ribbon and leave stress relief.
- Perform periodic pull tests to assure quality of solder bonds being made.
- Perform thermal cycle tests well beyond the 200 cycles from IEC 61215.
- Implement training and QA inspections to assure that non-cell solder bonds are being fabricated correctly.
- In critical areas (like termination wires) use both solder and mechanical connections.
- Do not rely on pottants as second attachment for termination wires. This can lead to arcing danger.

Broken glass

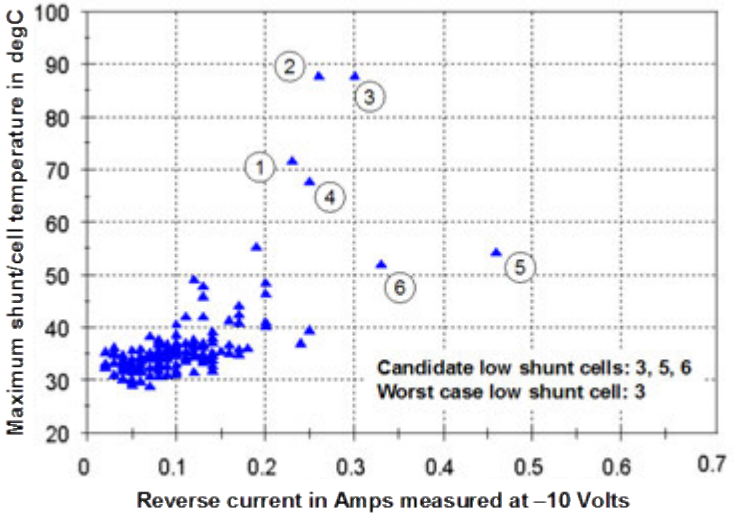
- Type of glass breakage is dependent on the type of glass used. (tempered, heat strengthened or annealed)
- High impacts like hail, rock or bullet will break glass. Can almost always identify spot where object hit.
- Mechanical loading from snow and/or wind can break glass.
- Failure of or misuse of support structure can lead to glass breakage
- High temperature (hot spot or arc) can break glass.
- Annealed glass can also break due to:
  - Stress built into the package during manufacture.
  - Stress applied by the framing/mounting system.
  - a temperature difference of as little as 25 C from center to edge.

How to keep glass from breaking

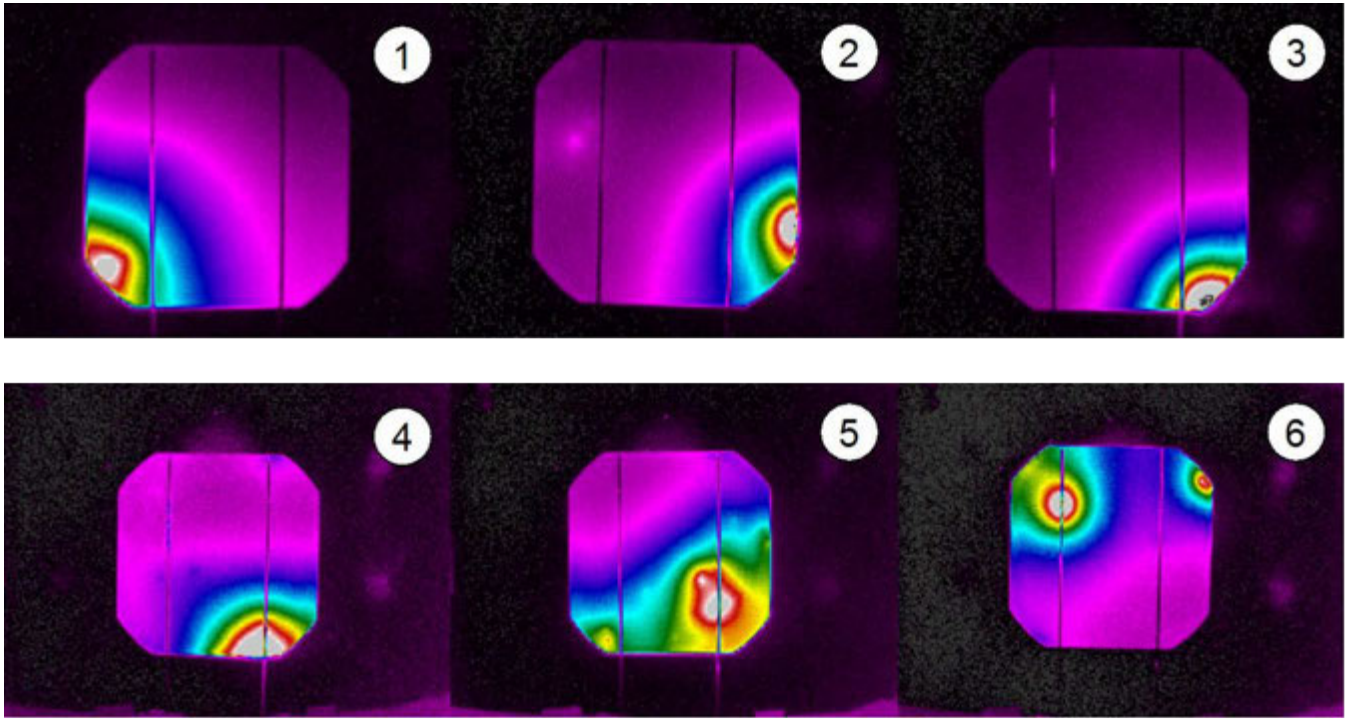
- Use tempered glass wherever possible.
- Pay attention to mounting method and mounting points.
- Test mounting system for snow load per IEC 61215.
- In high traffic areas try to protect glass (or any other superstrate) from direct impacts.
- Minimize hot spots and arcs.

Hot Spots

- Hot-spot heating occurs in a module when its operating current exceeds the reduced short-circuit current (Isc) of a shadowed or faulty cell or group of cells.
- When such a condition occurs, the affected cell or group of cells is forced into reverse bias and must dissipate power.
- If the power dissipation is high enough or localized enough, the reverse biased cell can overheat resulting in melting of solder and/or silicon and deterioration of the encapsulant and backsheet.



Hot Spots in Cells (From TUV)



How to avoid hot spots

- Most cells can be adequately protected by use of bypass diodes (say 1 diode every 20 cells).
- Still may have some cells with localized shunts that will heat excessively at the reverse bias level allowed by the bypass diodes.
- Solution is to screen out low shunt cells.

Ground faults

- PV modules are suppose to have high resistance stand-off between the electric circuit and the ground plane.
- Occasionally this protection is compromised.
- The consequences can be serious as there is nothing to stop the PV current from flowing in ground loops until one component gets so hot it melts or burns.
- Many ground faults are the result of poor installation practices.
- In picture the installer mounted modules with clips that penetrated the module insulation and contacted the solar cells at numerous locations.

Roof Fire Caused by Installer Ground Fault



Alleviating Ground Faults

- Mounting modules within the cell area should be avoided or done with extreme caution (and probably the addition of significant additional electrical insulating material like use of a glass substrate).
- Grounding of the array circuit actually increases the potential for this type of fault.
  - In a grounded array it only takes 1 ground fault to cause current flow in a ground loop.
  - For an ungrounded circuit it takes 2 ground faults to cause a problem, giving the system operator a chance to detect the first one and fix it before the second one occurs.

Junction box failures

- Single point for potential failure that can often be attributed to poor workmanship.
- Water ingress and subsequent corrosion can be a problem.
- How well is the J-box attached to the module back sheet?
- Some adhesive systems are good for short term pull but poor at maintaining long term adhesion.
- Picture from UL report.



Addressing junction box issues

- Use only qualified materials and boxes.
- Make sure boxes pass same set of tests that modules pass – damp heat, humidity freeze, thermal cycle, robustness of termination and wet high pot.
- Test adhesion well beyond qualification requirements.
  - At BP Solar we perform a boiling water test to verify adhesion under worst case conditions.
- Evaluate worst case failures – what happens if a wire comes detached?
- Quality control during manufacture.

Structural failures

- Often it is the way the module is mounted that determines whether it can survive a particular load.
- You want me to follow the manufacturers installation instructions?
- Snow load can deform the frame and break the glass.
- Sometimes the entire array structure is not capable of surviving high winds.

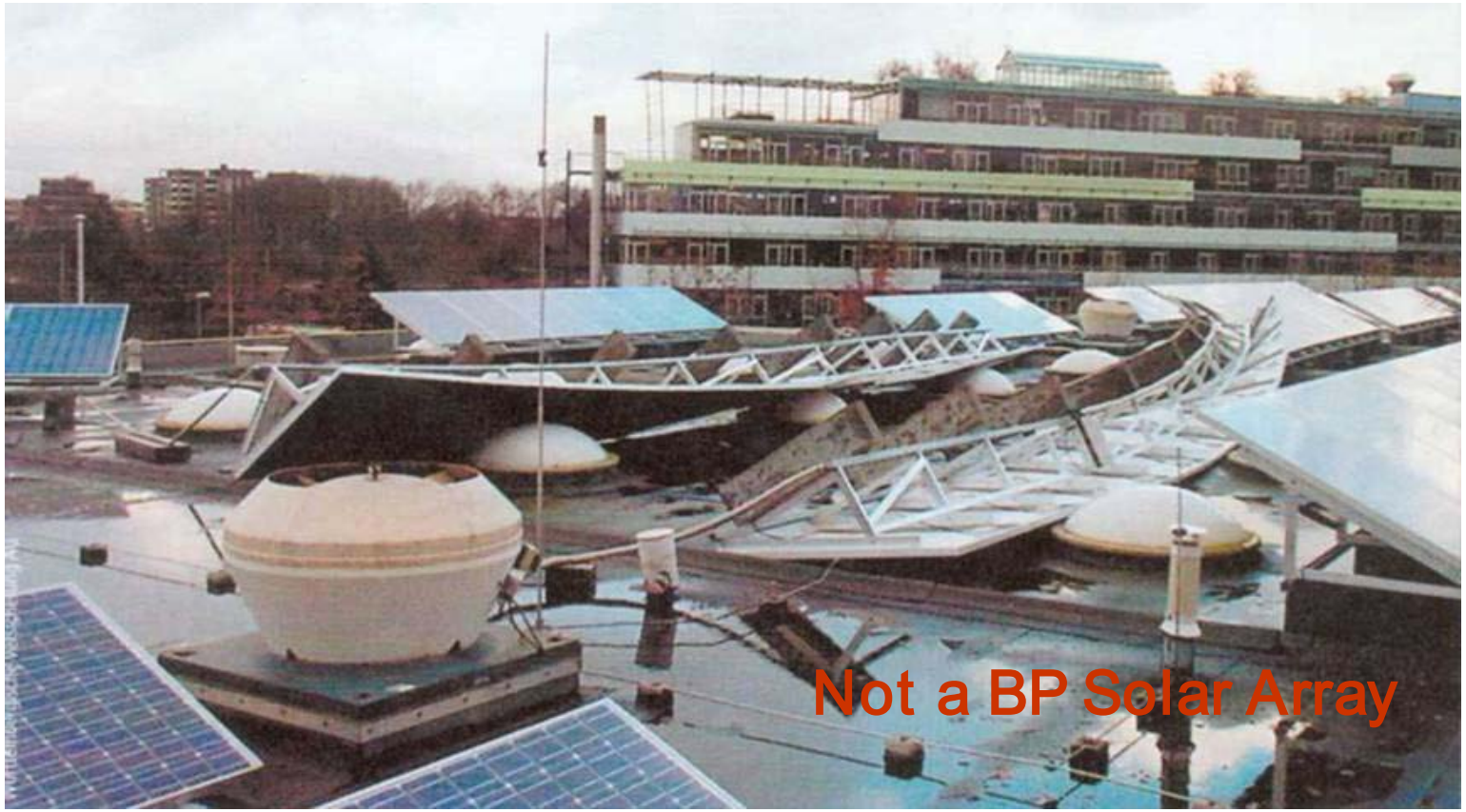
Difference in Mounting Method





Wind damage
(Hans Urban, from his presentation at TUV Sponsored Module Workshop, 2006)

bp solar



Avoiding Structural Failures

- Follow the module manufacturer's installation instructions.
- Follow local building codes where available as they are usually based on local weather history.
- Test new approaches (for example in a wind tunnel) before using them in the field.
- The best designed system built using the highest quality components will not work well and may be unsafe if it is installed improperly.
- Installer training and certification programs like the one run by BP Solar are critical to achieving highly reliable and safe PV systems.

Summary

- Crystalline Si Module reliability and performance
  - Very good but still with room for improvement
  - Not all modules are created equal, poor material selection, improper assembly and processing will yield different degradation rates and lifetimes
- New Module Technology
  - Can't test for 25 years before releasing commercial products
  - Strong accelerated test programs required.
  - Process controls required to assure production modules perform as well as test modules.

TÜV Rheinland PTL

Experience with Qualification and Safety Testing of Photovoltaic Modules

Mani G. TamizhMani

TUV Rheinland PTL

www.tuvptl.com

Outline

Test Results @ TUV Rheinland PTL

- **Qualification Test Results of PV Modules (IEC 61215/61646)**
  (3636 modules [87% c-Si]; 20 different countries; 1997-2009 [13 years of data])
  - **c-Si: 1997-2005 *vs.* 2005-2007 *vs.* 2007-2009**
  - **Thin-film: 1997-2005 *vs.* 2005-2007 *vs.* 2007-2009**
- **Safety Test Results of PV Modules (IEC61730; ANSI/UL1703)**
  - **c-Si: Temperature test – 140 modules (2006-2009)**

Qualification Standards for PV Modules

- IEC 61215: c-Si
- IEC 61646: Thin-film
- IEC 62108: CPV

Qualification Testing – Sequence – A Quick View

(Initial)
Visual Inspection
Insulation (dry & wet)
Performance (Pmax)

Stress 1

(Intermittent)
Visual Inspection
Insulation (dry & wet)
Performance (Pmax)

Stress 2

(Final)
Visual Inspection
Insulation (dry & wet)
Performance (Pmax)

Pass Verdict:

- Functional
- Safe

Safety Standards for PV Modules

- IEC 61730: Both technologies
- ANSI/UL 1703: Both technologies

Safety Testing – Test -A Quick View

(Initial)
Visual Inspection
Insulation (dry & wet)
~~Performance (Pmax)~~

Stress 1

(Final)
Visual Inspection
Insulation (dry & wet)
~~Performance (Pmax)~~

Pass Verdict:

- ~~Functional~~
- Safe

Accelerated Testing

• **Qualification Testing**: The qualification testing is a **short-duration** (typically, 60-90 days) accelerated testing and it may be considered as a **minimum requirement to undertake reliability testing**. The primary goal in the qualification testing is to identify the **initial short-term reliability issues** in the field.

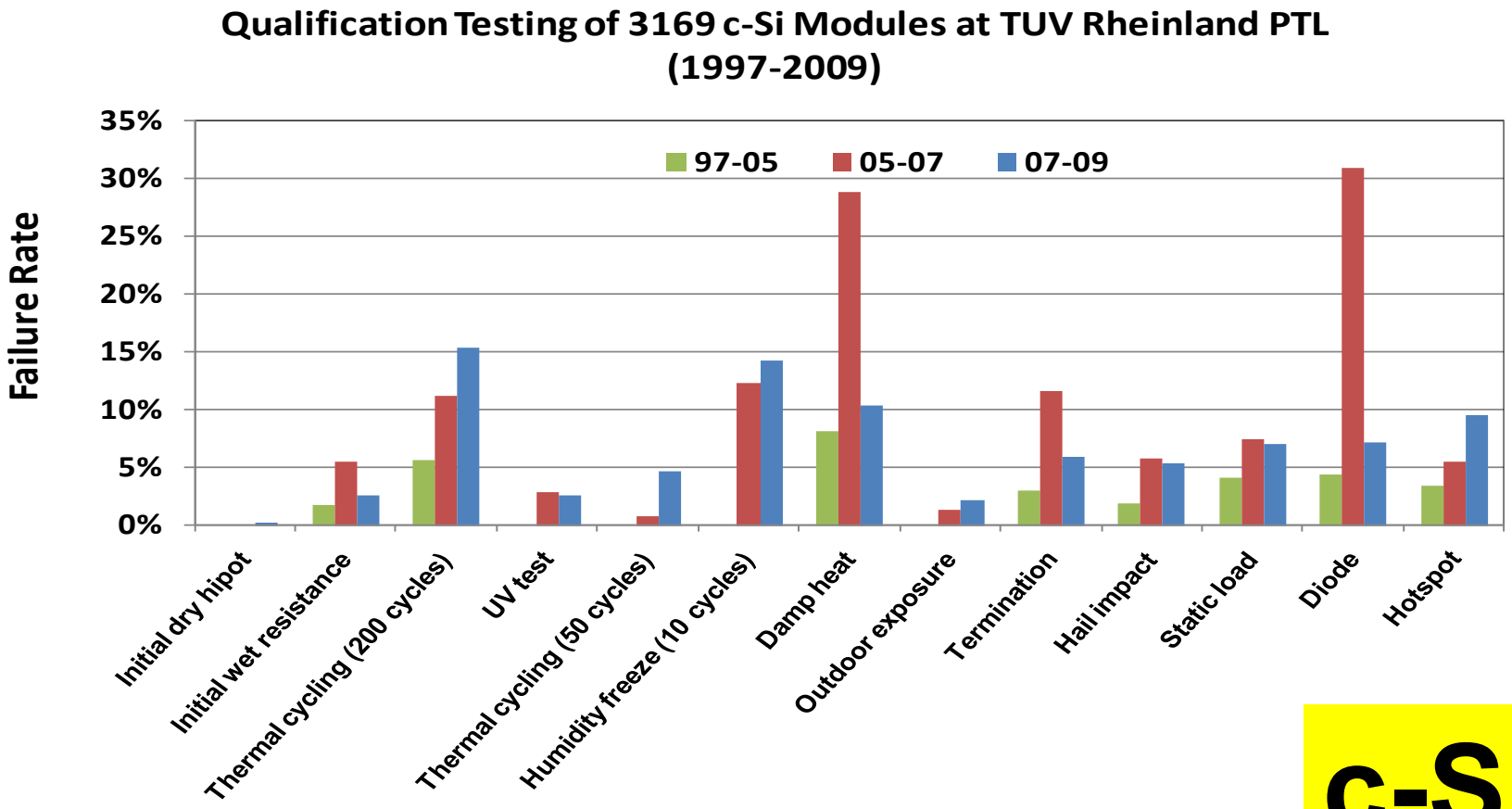
• **Reliability/Lifetime Testing**: The primary goal in the accelerated reliability or lifetime testing is to **identify the initial, use and ultimate reliability** issues in the field so that the lifetime can be predicted and warranty can be protected. A rigorous, **long-term** reliability testing of PV modules would be extremely time consuming and very expensive.

• **Test-to-Failure**: The test-to-failure (TTF) testing is a **compromise and it falls between** these two extremes of qualification testing and lifetime/reliability testing. The primary goal in the TTF testing is to **improve the current design as compared to previous or competitors' designs**.

➢ Qualification Test Results of PV Modules (IEC 61215/1646)

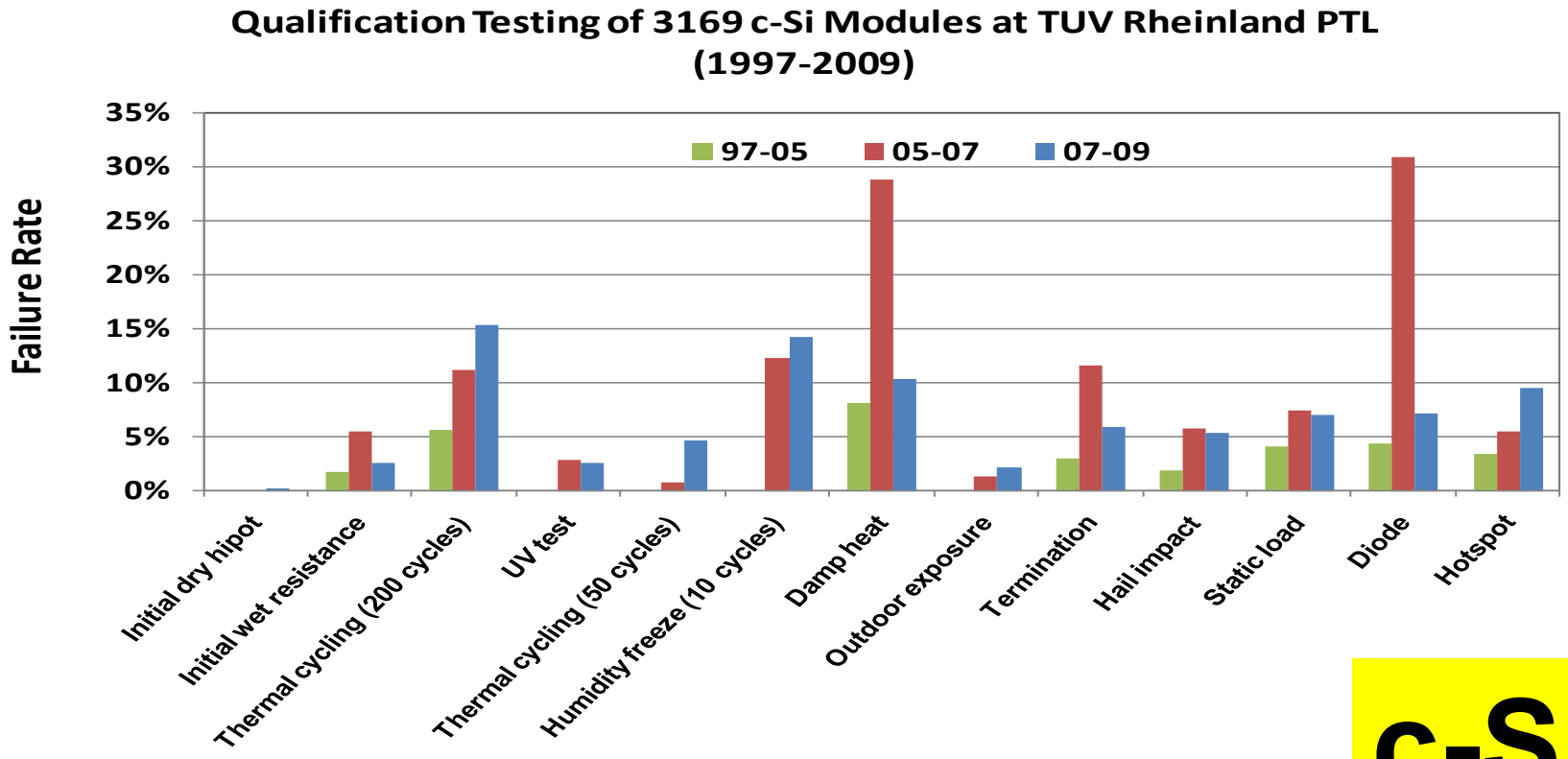
(3636 modules [87% c-Si]; 20 different countries; 1997-2009 [13 years of data])

- **c-Si: 1997-2005 *vs.* 2005-2007 *vs.* 2007-2009**
- **Thin-film: 1997-2005 *vs.* 2005-2007 *vs.* 2007-2009**



c-Si

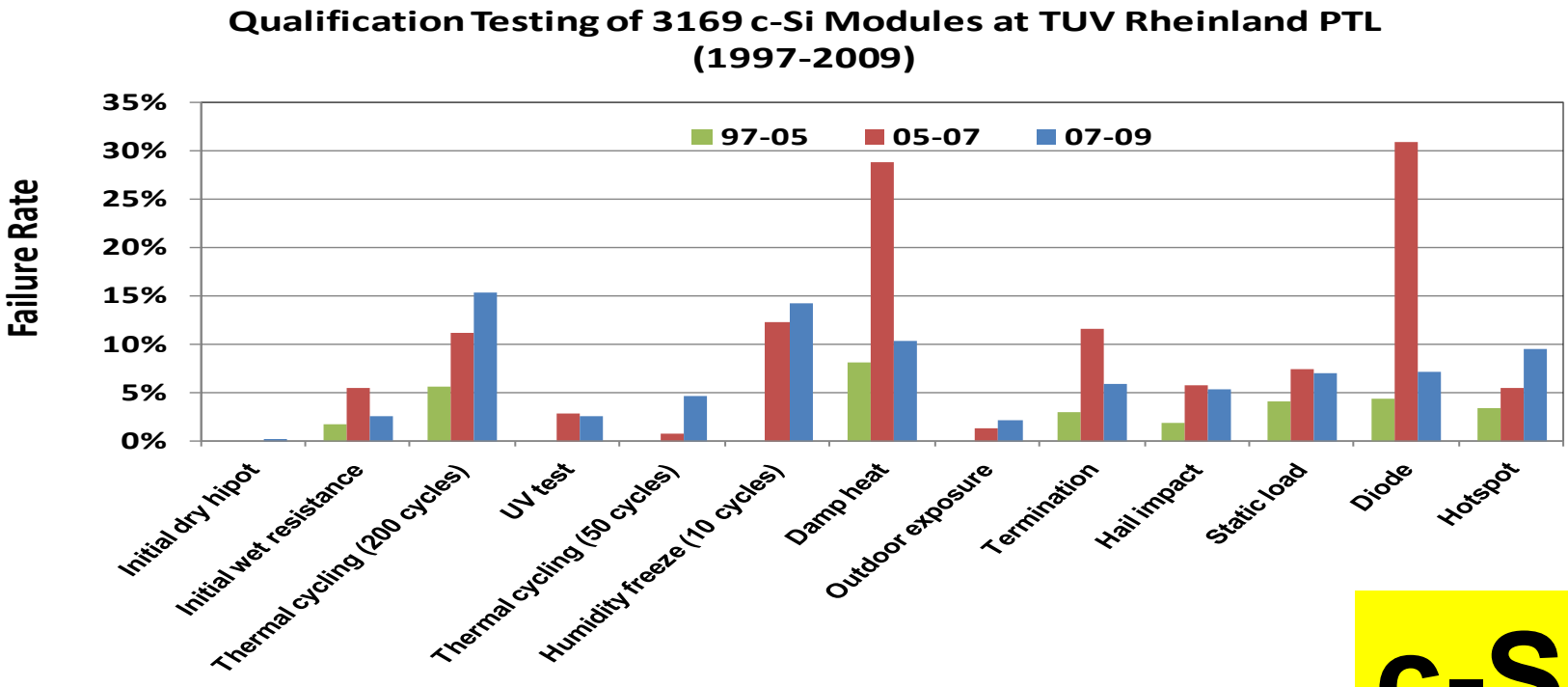
- 1997-2005: 1012 c-Si modules
- 2005-2007: 932 c-Si modules (New manufacturers in both c-Si and thin-film technologies: 52%)
- 2007-2009: 1225 c-Si modules (New manufacturers in both c-Si and thin-film technologies: 39%)



c-Si

Top 3 Failure Rates

- 1997-2005: # 1 Damp heat; # 2 Thermal cycling (200 cycles); # 3 Diode
- 2005-2007: # 1 Diode; # 2 Damp heat; # 3 Humidity freeze
- 2007-2009: # 1 Thermal cycling (200 cycles); # 2 Humidity freeze; # 3 Damp heat

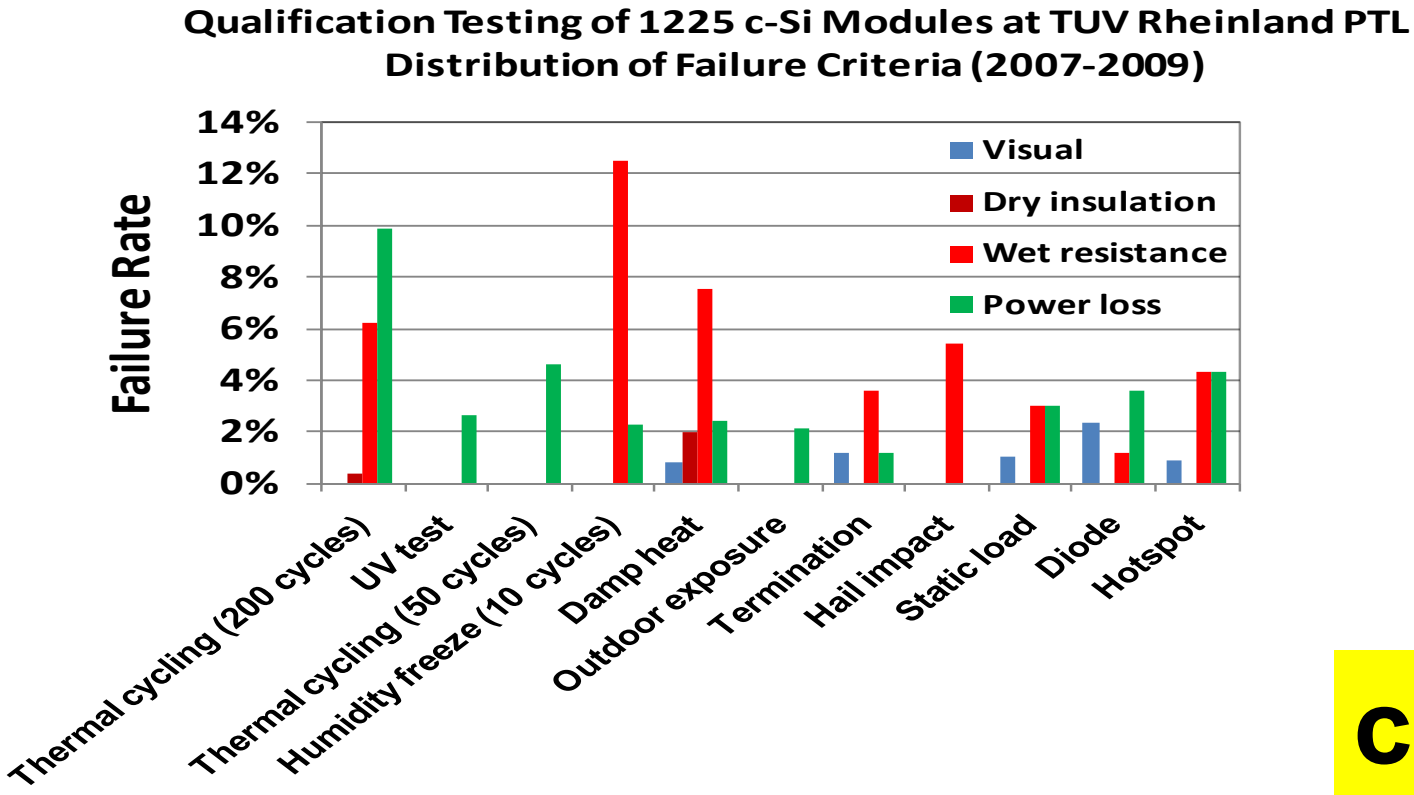


c-Si

- 1997-2009 (13 years): Top 4 failure rates

- Damp heat failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Thermal cycling failure rates: 2007/2005 = increased; 2009/2007 = increased
- Humidity freeze failure rates: 2007/2005 = increased; 2009/2007 = increased
- Diode failure rates: 2007/2005 = increased; 2009/2007 = decreased

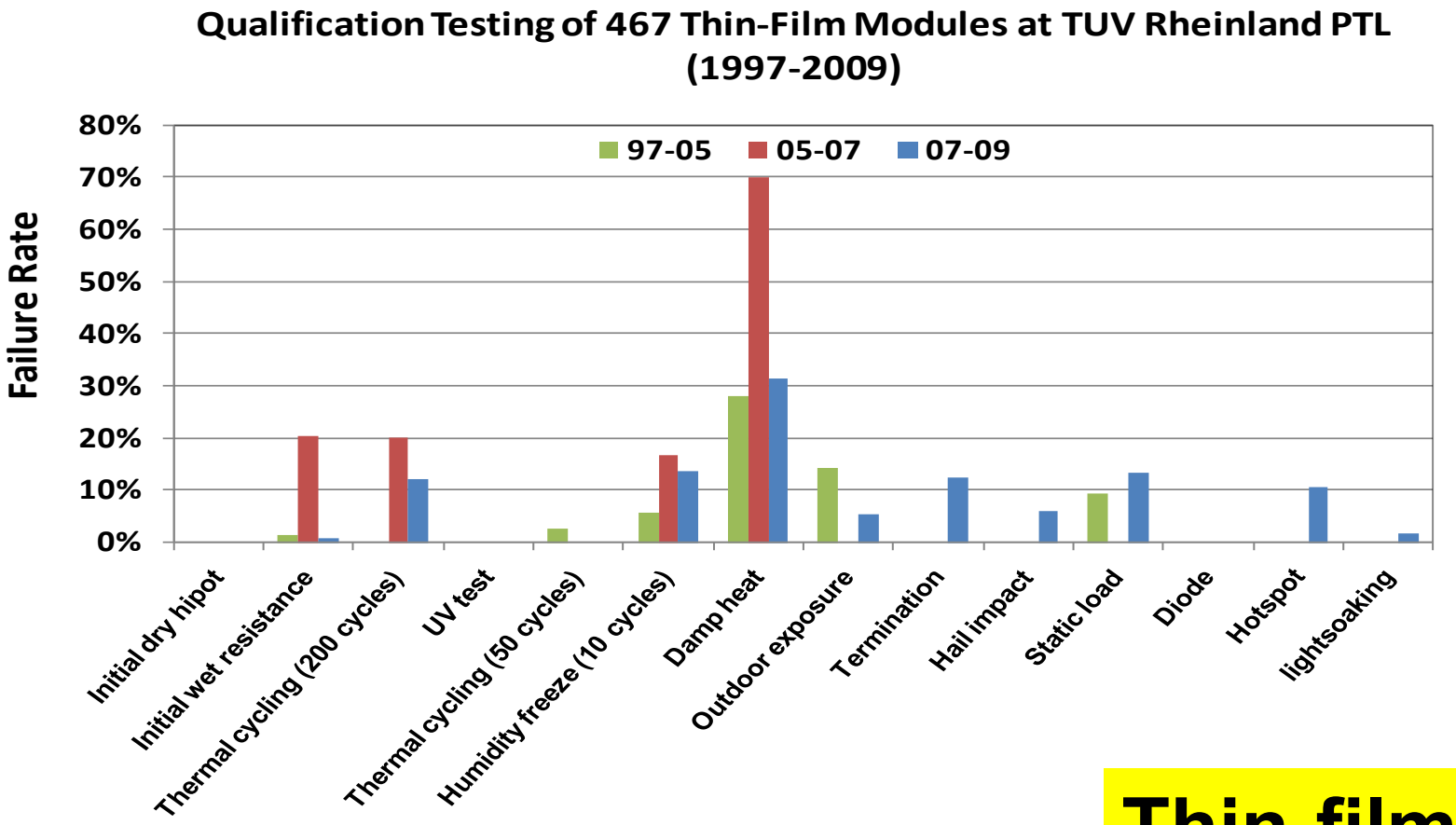
Out of the box (initial) wet resistance failure (!!!) : 2005 – 2%; 2007 – 5%; 2009 – 3%



c-Si

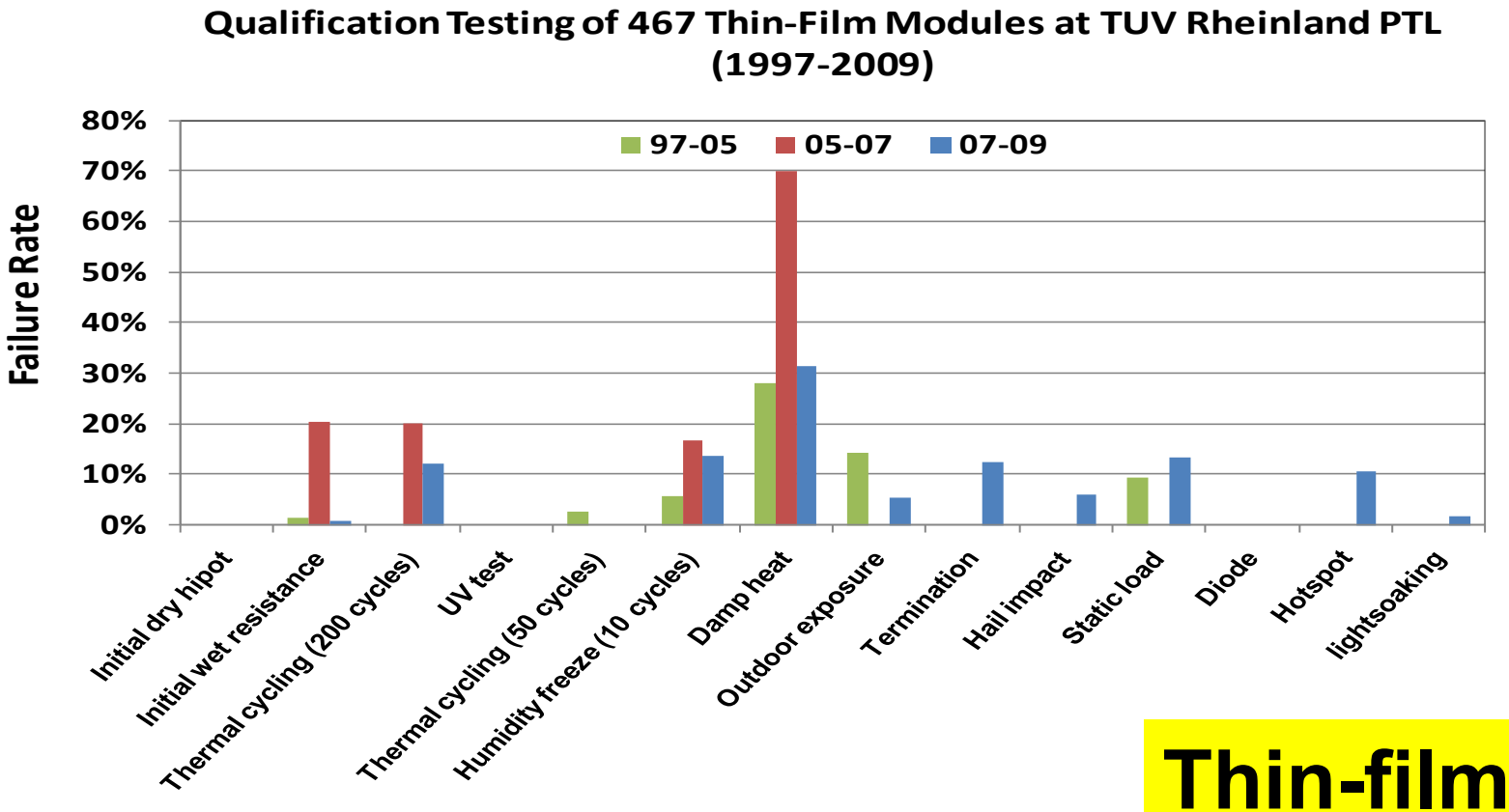
Order of post-stress failure

- **Visual:** Diode (2.4%) > Termination > Static load > Hot spot / Damp heat (0.9%)
- **Dry insulation:** Damp heat (2%) > Thermal cycling-200 (0.4%)
- **Wet resistance:** Humidity freeze (12.5%) > Damp heat > Thermal cycling-200 > Hail impact > Hot spot > Termination > Static load > Diode (1.2%)
- **Power loss:** Thermal cycling-200 (9.9%) > Thermal cycling-50 > Hotspot > Diode > Static load > UV > DampHeat ~ HumidityFreeze ~ OutdoorExposure > Termination (1.2%)



Thin-film

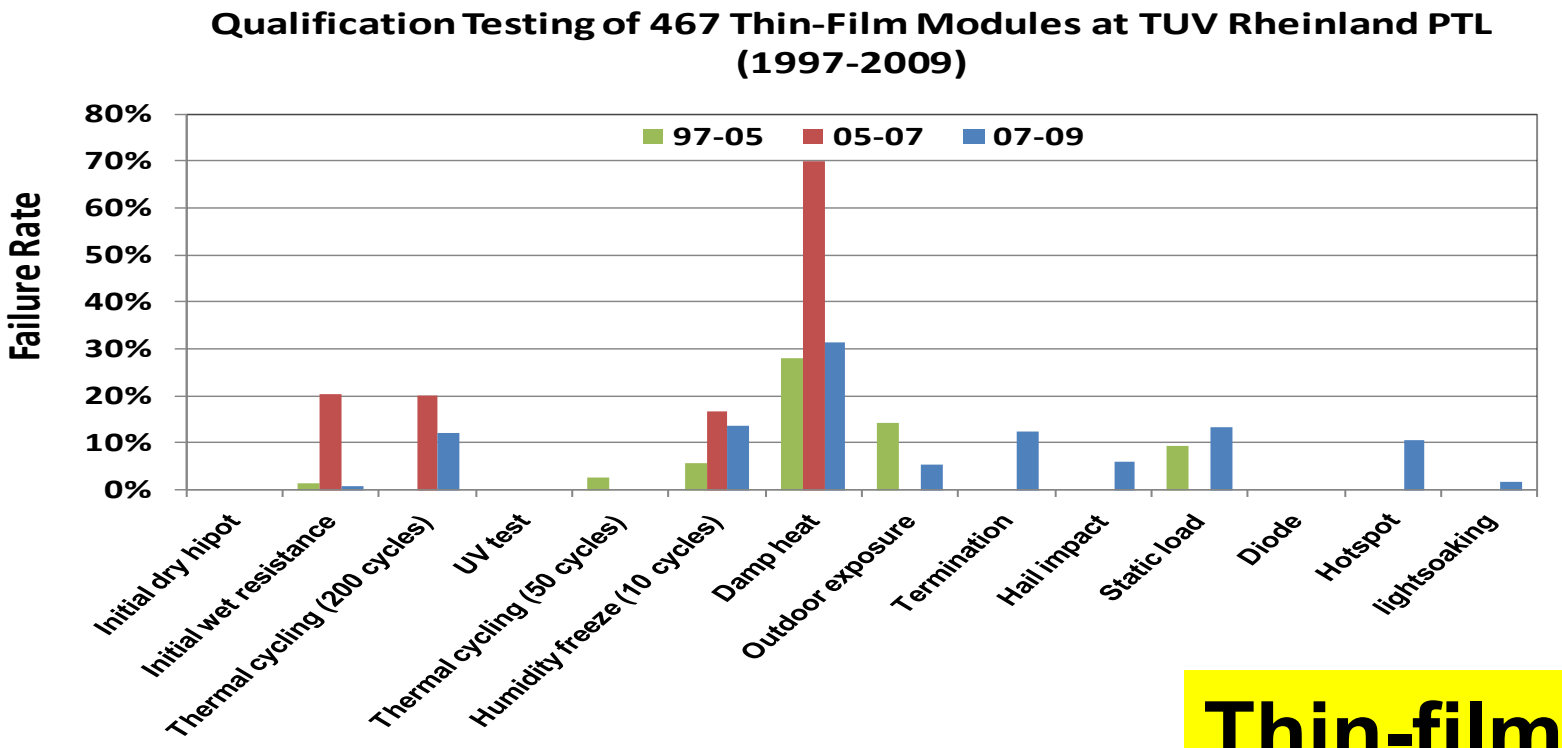
- 1997-2005: 150 thin-film modules
- 2005-2007: 69 thin-film modules (New manufacturers in both c-Si and thin-film technologies: 52%)
- 2007-2009: 248 thin-film modules (New manufacturers in both c-Si and thin-film technologies: 39%)



Thin-film

Top 3 Failure Rates

- 1997-2005: # 1 Damp heat; # 2 Outdoor exposure; # 3 Static load
- 2005-2007: # 1 Damp heat (disaster!) ; # 2 Thermal cycling (200); # 3 Humidity freeze
- 2007-2009: # 1 Damp heat; # 2 Humidity freeze; # 3 Static load



Thin-film

- 1997-2009 (13 years): Top 4 failure rates

- Damp heat failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Thermal cycling failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Humidity freeze failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Static load failure rates: 2007/2005 = decreased; 2009/2007 = increased

Out of the box (initial) wet resistance failure (!!!) : 2005 – 1%; 2007 – 20%; 2009 – 1%

➢ Safety Test Results of PV Modules (IEC61730; ANSI/UL1703)

- **c-Si: Temperature test – 140 modules (2006-2009)**

Purpose of Temperature Test:

This temperature test is designed to determine the maximum reference temperatures for various components and materials used to construct the module, in order to establish the suitability of their use.

Insulating polymeric material requirement:

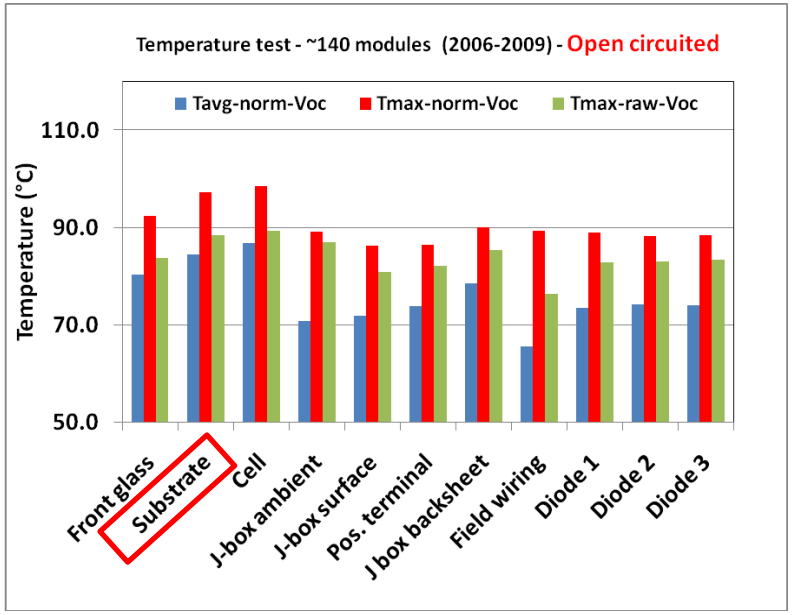
Relative thermal index > (T_{norm} + 20°C)

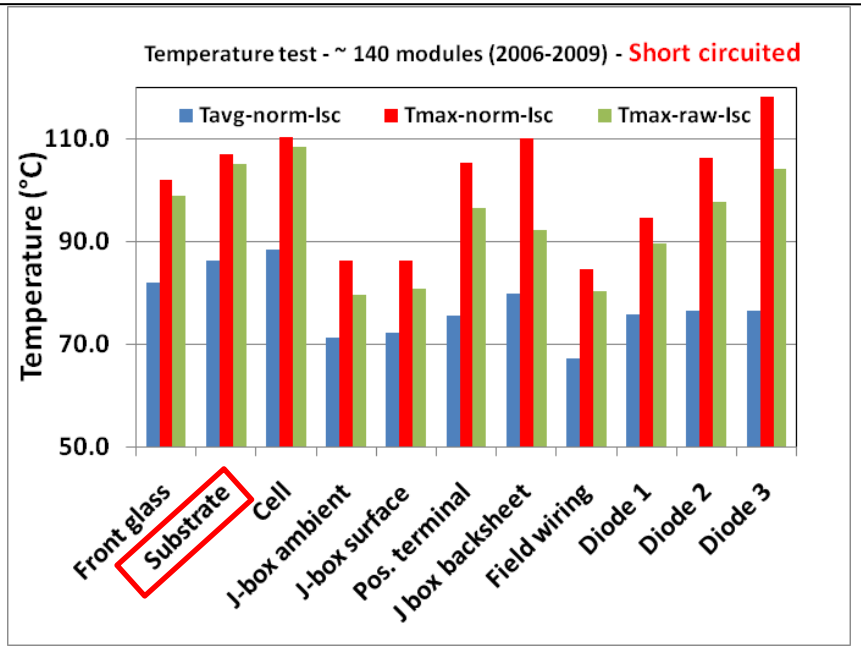
1	Front glass
2	Substrate
3	Cell
4	J-box ambient
5	J-box surface
6	Positive terminal
7	J-box backsheet
8	Field wiring
9-1	diode 1
9-2	diode 2
9-3	diode 3

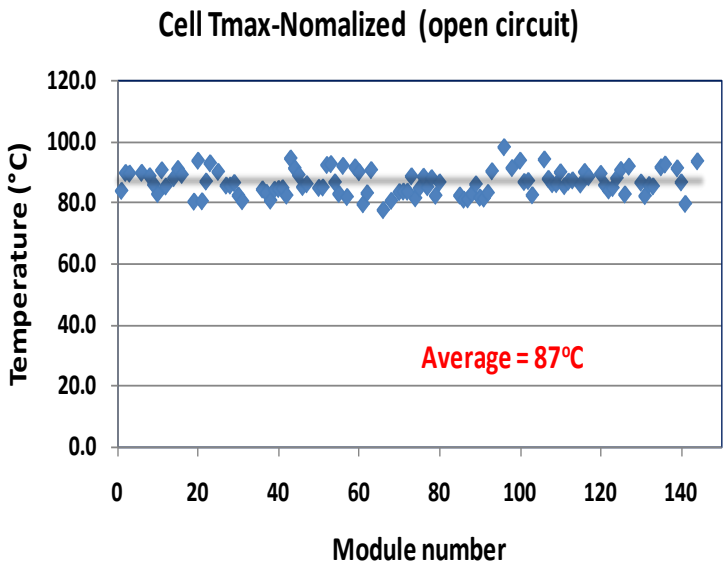
$$T_{norm} = (T_{max} - \text{Mean } T_{amb}) \times \frac{1000}{\text{Mean Irradiance}} + 40$$

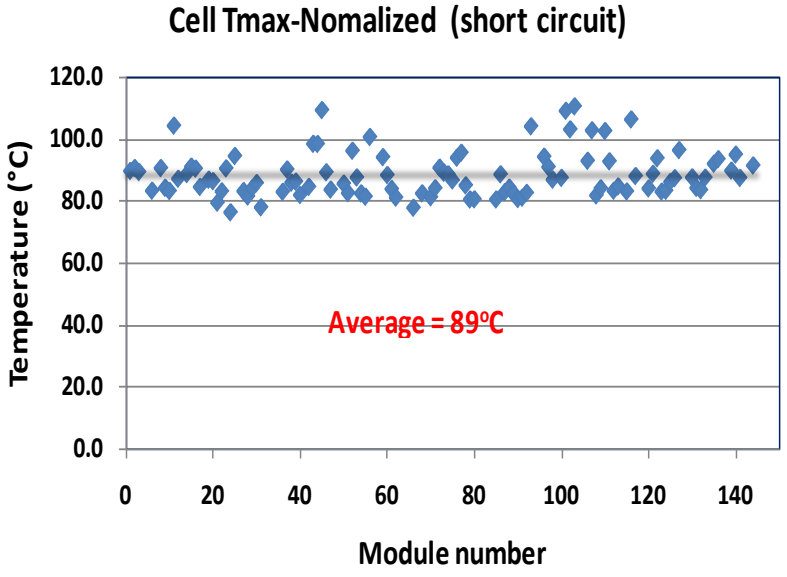
Where

T_{norm} is the normalized temperature, T_{max} is the maximum component temperature during the test, and T_{amb} is the ambient temperature during the test.


Temperature test - ~140 modules (2006-2009) - Open circuited
Tavg-norm-Voc
Tmax-norm-Voc
Tmax-raw-Voc
Temperature (°C)
110.0
90.0
70.0
50.0
Front glass
Substrate
Cell
J-box ambient
J-box surface
Pos. terminal
J box backsheet
Field wiring
Diode 1
Diode 2
Diode 3


Temperature test - ~ 140 modules (2006-2009) - Short circuited
Tavg-norm-Isc
Tmax-norm-Isc
Tmax-raw-Isc
Temperature (°C)
110.0
90.0
70.0
50.0
Front glass
Substrate
Cell
J-box ambient
J-box surface
Pos. terminal
J box backsheet
Field wiring
Diode 1
Diode 2
Diode 3


Cell Tmax-Nomalized (open circuit)
Temperature (°C)
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Average = 87°C
0
20
40
60
80
100
120
140
Module number


Cell Tmax-Nomalized (short circuit)
Temperature (°C)
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Average = 89°C
0
20
40
60
80
100
120
140
Module number

Summary

Qualification Testing: c-Si

- Damp heat failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Thermal cycling failure rates: 2007/2005 = increased; 2009/2007 = increased
- Humidity freeze failure rates: 2007/2005 = increased; 2009/2007 = increased
- Diode failure rates: 2007/2005 = increased; 2009/2007 = decreased

Qualification Testing:Thin-Films

- Damp heat failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Thermal cycling failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Humidity freeze failure rates: 2007/2005 = increased; 2009/2007 = decreased
- Static load failure rates: 2007/2005 = decreased; 2009/2007 = increased

Safety - Temperature Testing: Polymeric Substrate (c-Si)

- $T_{avg\text{-}norm\text{-}Voc}$: 84°C
- $T_{max\text{-}norm\text{-}Voc}$: 97°C

National Renewable Energy Laboratory
Innovation for Our Energy Future

Degradation Rates



NREL

Dirk Jordan

Feb-19-2010

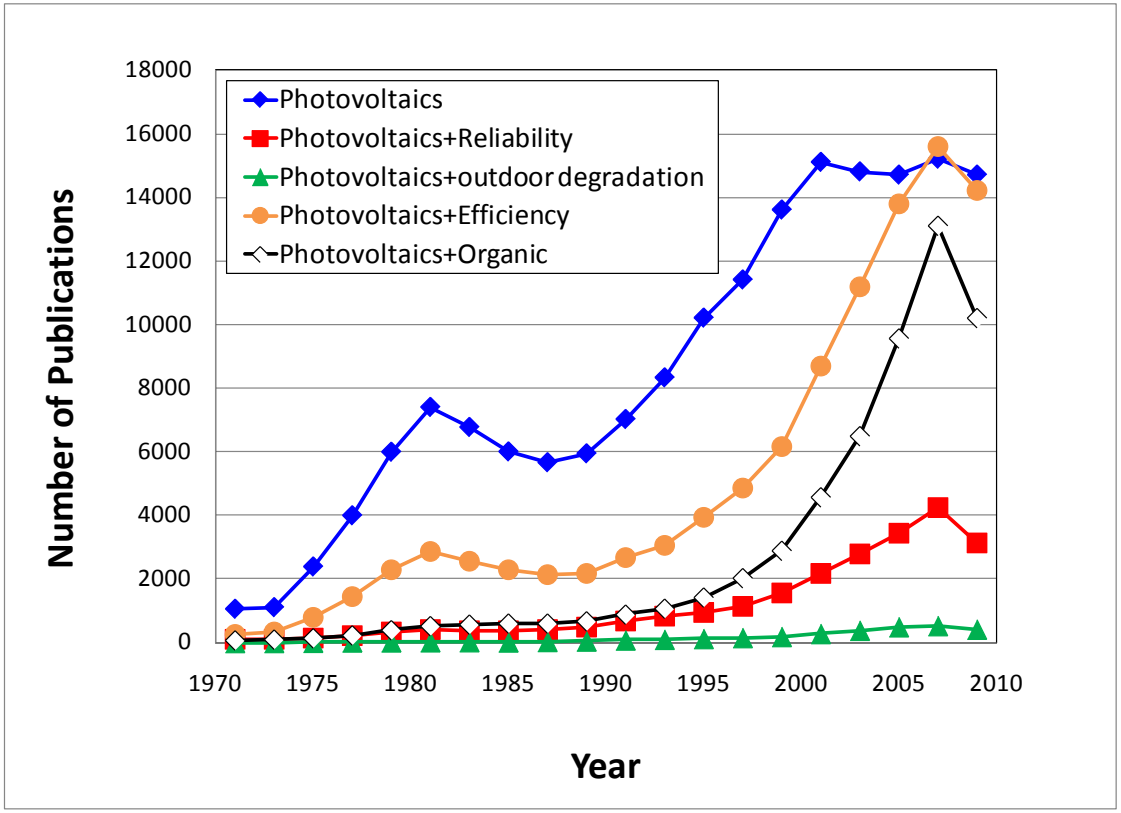
This presentation does not contain any proprietary or confidential information.

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

Outline

- Historical Degradation Rates (R_d)
- Importance of Uncertainty
- Traditional way to determine R_d
- Alternative methodologies - Classical Decomposition , ARIMA
- Impact of outliers, data shifts, missing data
- Correction for data shifts
- Determination of R_d in shorter time

Introduction - PV Publications

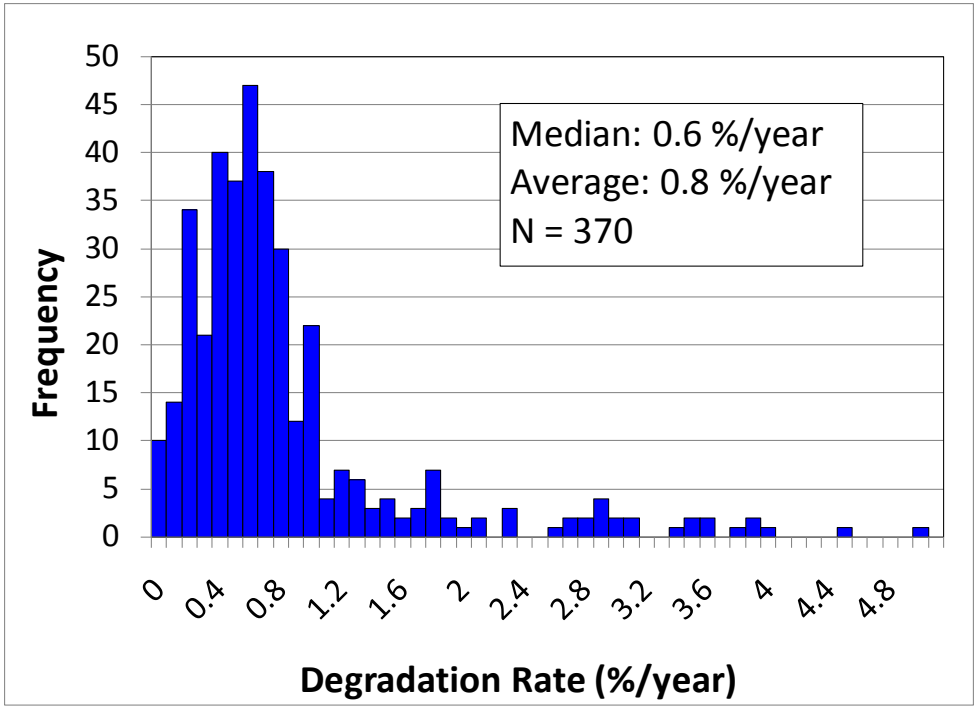


Number of Publications on Google Scholar

Different search engine. Web of Science, Scirus, INSPEC etc. → vertical axis will be different

Historical Degradation Rates

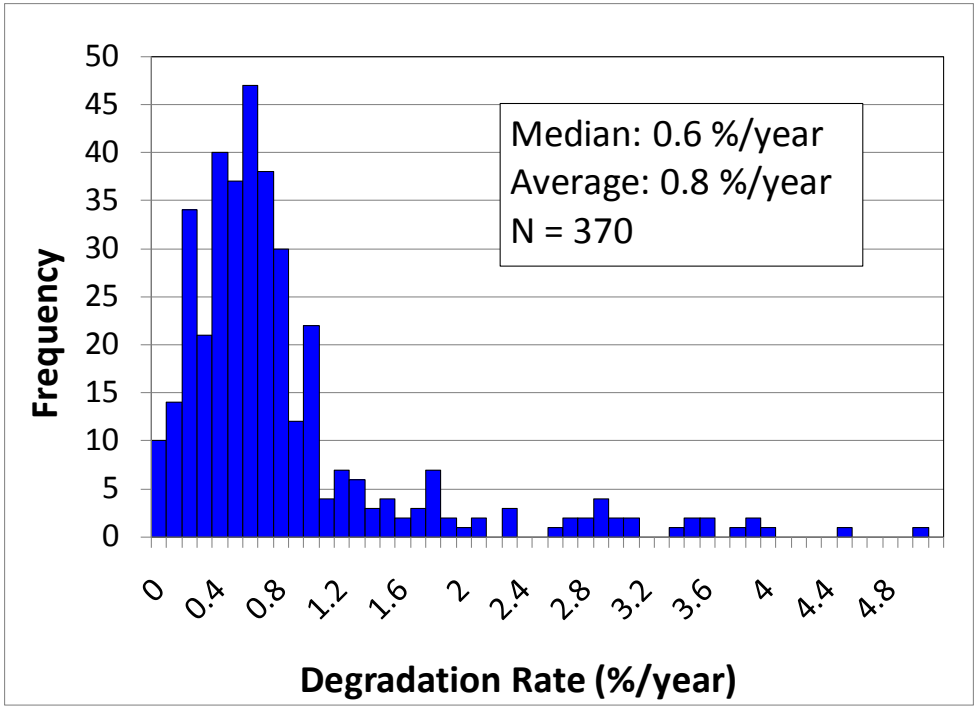
Degradation Rates (R_d) most often reported



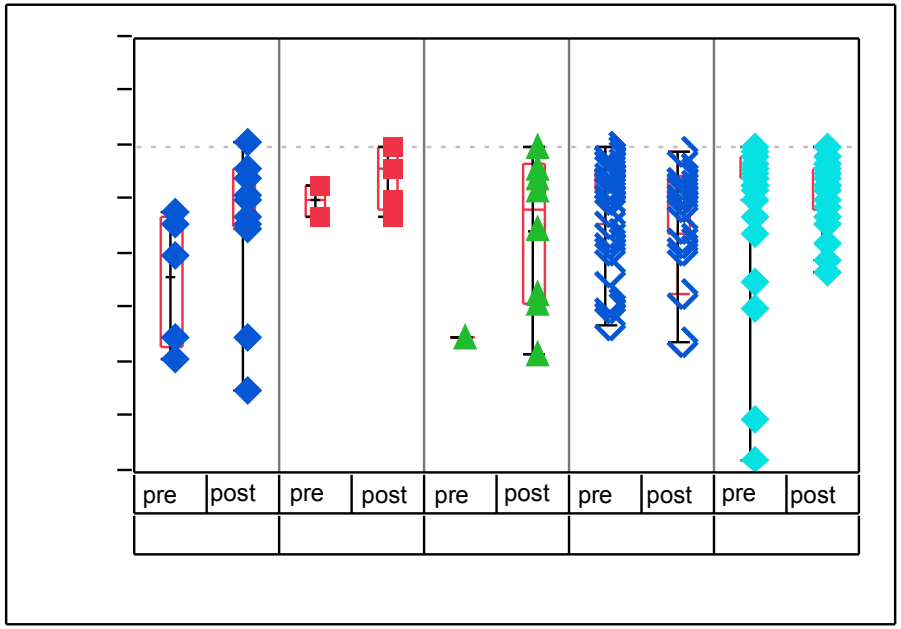
Ref
Perfor & Reliability_Adelstein_NREL_PVSC_2005
A-Si in Kenya_Jacobsen_Berkley_ASES_2000
Outdoor testing at ASU_Mani_ASU_2006
Measuring Degradation Rates without Irradiance Data_Pulver_UofA_PVSC_2010
DegRate for c-Si_Osterwald_NREL_2002
Outdoor PV on Cyprus_Makrides_Cyprus_2009
Field test in Mexico_Foster_New Mexico State_2005
PV Power production after 10 years_Cereghetti_Switzerland_2003
Predicted long-term PV performance_Muirhead_Australia_PVScienceConf_1996
Outdoor PV on Cyprus_Makrides_Cyprus_2009
CIGS Outdoor degradation_Jordan_NREL_2010
Measuring Degradation Rates without Irradiance Data_Pulver_UofA_PVSC_2010
Field PV reliability_Vazquez_Spain_2008
PV Power production after 10 years_Cereghetti_Switzerland_2003
DegRate for c-Si_Osterwald_NREL_2002
Long-term field age_Skoczek_Italy_2009
PV performance_Carr_Australia_2005
Outdoor testing at ASU_Mani_ASU_2006
PV Power production after 10 years_Cereghetti_Switzerland_2003
Predicted long-term PV performance_Muirhead_Australia_PVScienceConf_1996
PV performance_King_Sandia_2004
Outdoor PV on Cyprus_Makrides_Cyprus_2009
PV Korea_So_Korea_2006
PV Korea_So_Korea_2006
PV in Saxony_Decker_Germany_1997
25 yearold PV modules_Hedstroem_Sweden_2006
PV degradation_Vignola_UofOregon_2008
C-Si degradation_Morita_Japan_PVenergyconv_2003
PV degradation_King_Sandia_2003
Field test of c-Si in 1990_Sakamoto_Japan_PVenergyconv_2003
c-Si of 22 years_Dunlop_EU_2006
PV performance_Carr_Australia_2005
DegRate for c-Si_Osterwald_NREL_2002
PV Power production after 10 years_Cereghetti_Switzerland_2003
DegRate for c-Si_Osterwald_NREL_2002
DegRate for c-Si_Osterwald_NREL_2002
Long-term field age_Skoczek_Italy_2009
Outdoor testing at ASU_Mani_ASU_2006
Predicted long-term PV performance_Muirhead_Australia_PVScienceConf_1996
PV performance_Carr_Australia_2005
PV performance_Carr_Australia_2005
Outdoor PV on Cyprus_Makrides_Cyprus_2009
PV Korea_So_Korea_2006
PV Greece_Kalykakis_Greece_2009
PV degradation_Vignola_UofOregon_2008
Measuring Degradation Rates without Irradiance Data_Pulver_UofA_PVSC_2010
Long-term reliability_Wolgemuth_BP-1999
Common degradation mechanism_Quintana_Sandia_IEEE_2003
PV degradation_King_Sandia_2003
C-Si degradation_Morita_Japan_PVenergyconv_2003
C-Si degradation_Morita_Japan_PVenergyconv_2003
Field test of c-Si in 1990_Sakamoto_Japan_PVenergyconv_2003
PV performance_Carr_Australia_2005
Improved Power ratingsd_Kimber_PVSC_2009

Historical Degradation Rates

Degradation Rates (R_d) most often reported

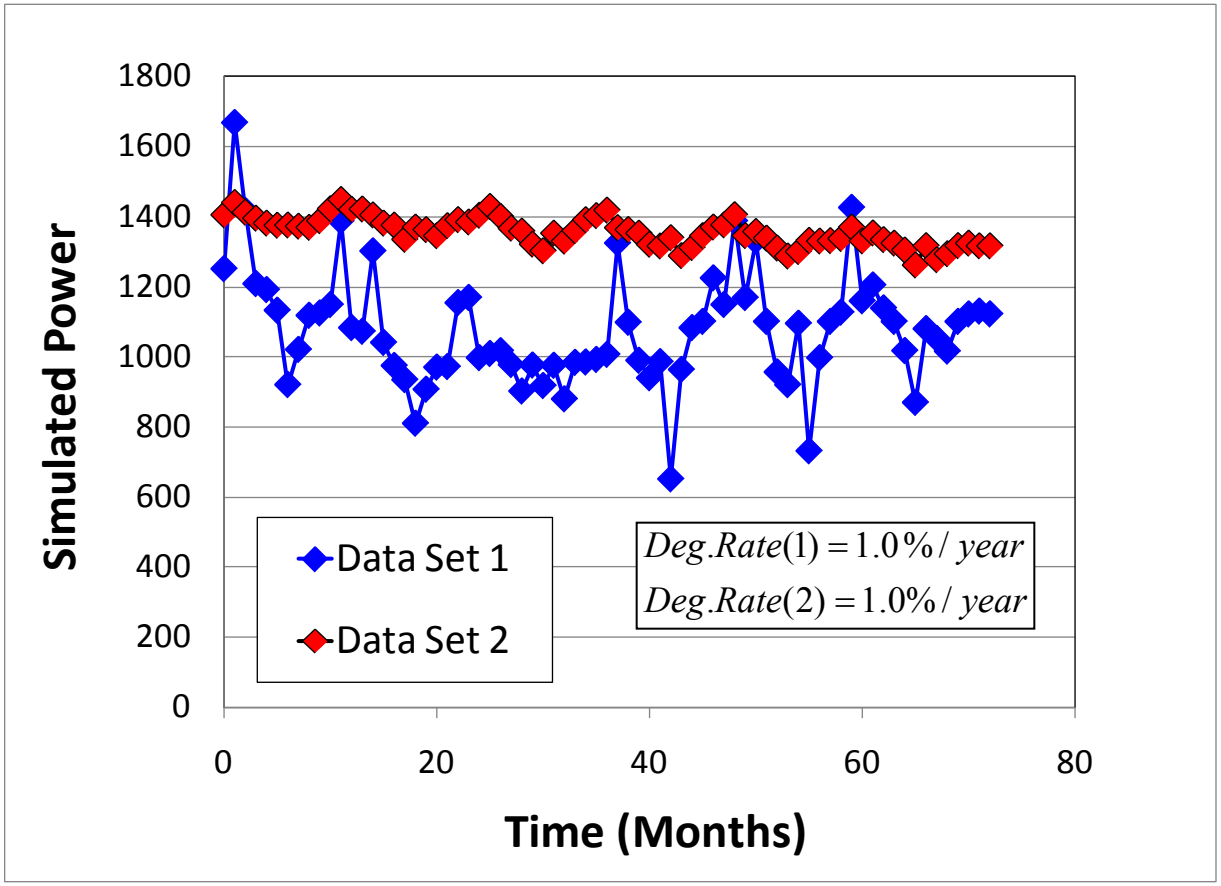


Installation
Pre: before 2000
Post: after 2000



All technologies show some degradation rates around 0 %/year for modules installed after 2000.

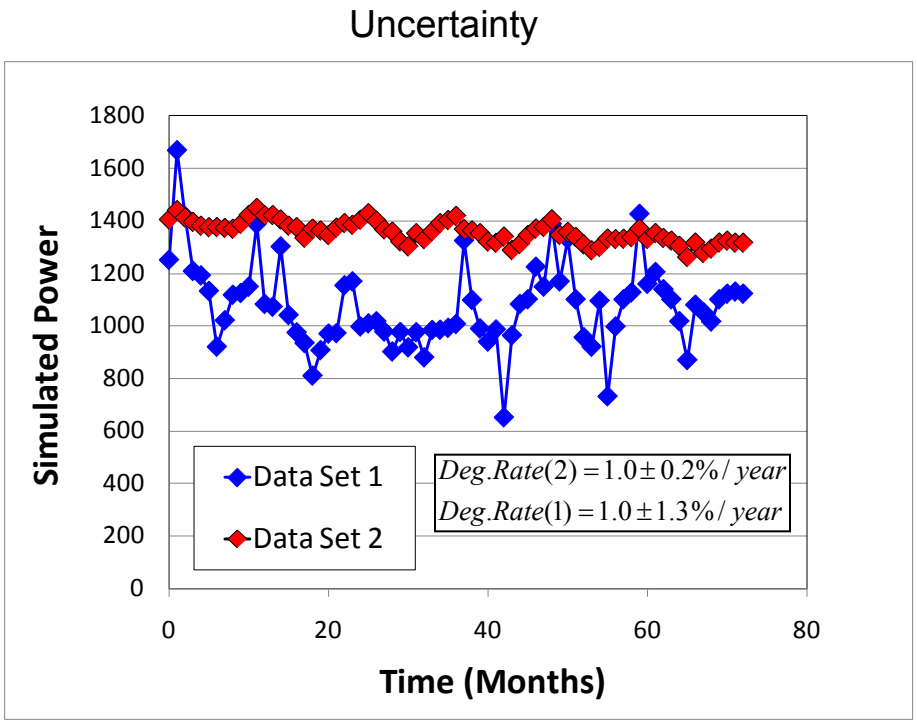
Degradation Rates



Both data sets have the same degradation rate!

How can you distinguish the 2 data sets?

Degradation Rate Uncertainty Impact

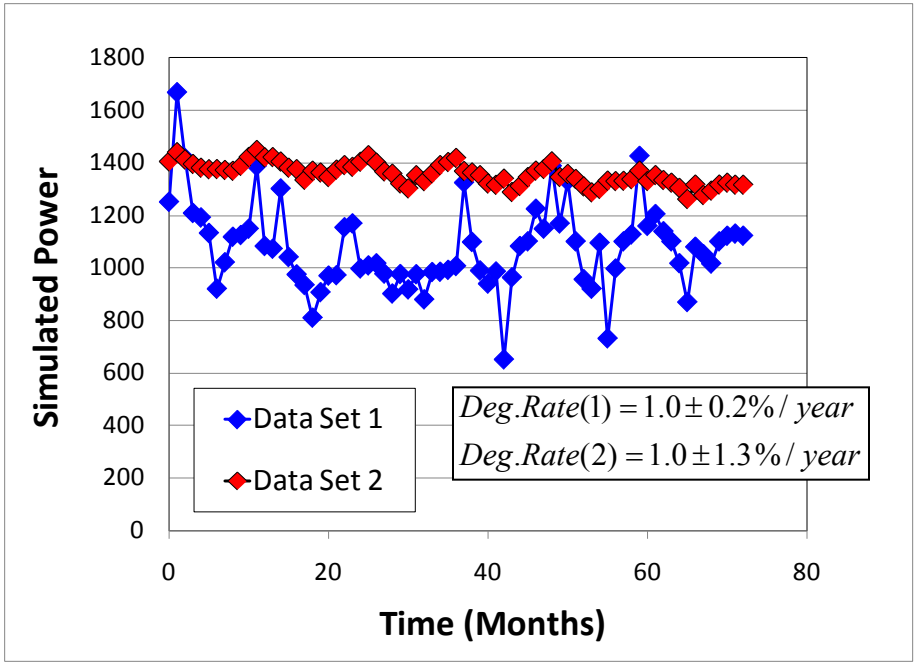


Uncertainty for Data set(1) small → R_d looks believable

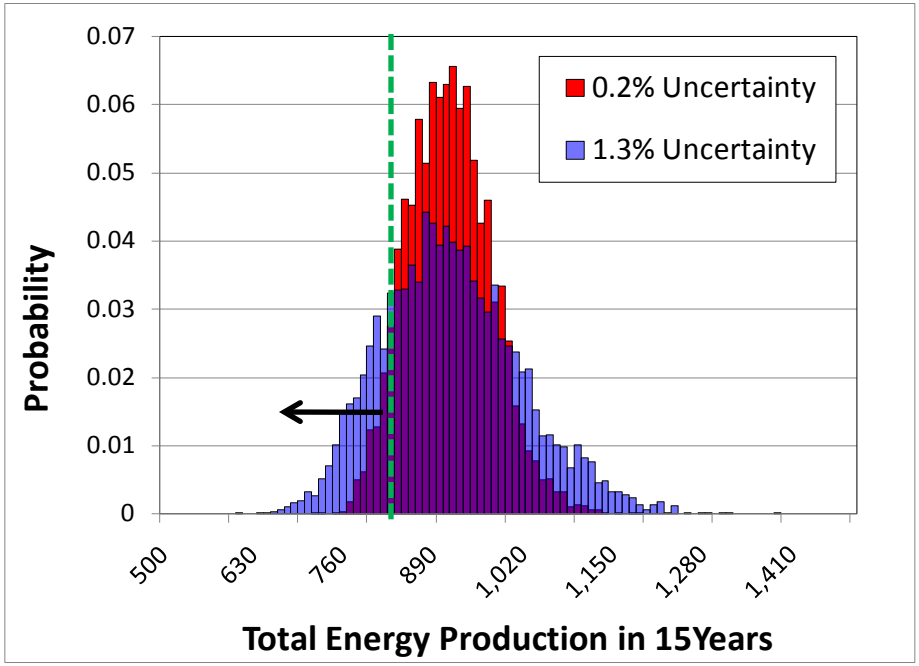
Uncertainty for Data set(2) large → 2 different slopes

Degradation Rate Uncertainty Impact

Uncertainty



Monte Carlo Simulation of Energy Production



Uncertainty for Data set(1) small → R_d looks believable

Uncertainty for Data set(2) large → 2 different slopes

$$Energy(Year_N) = \sum_{n=1}^{N} \frac{Energy(Year_1) \cdot (1 - R_D)^n}{(1 + r)^n}$$

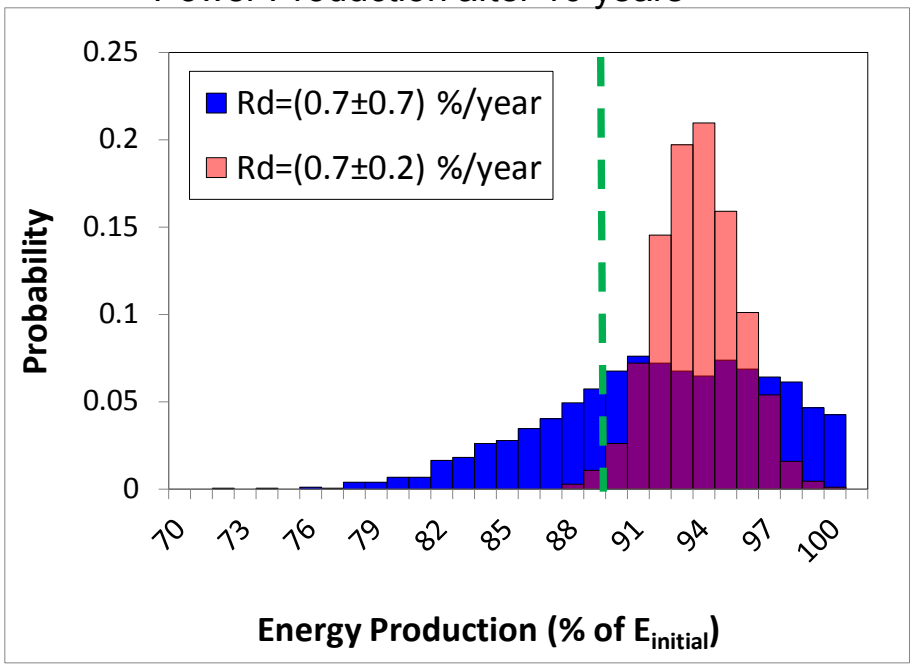
Energy production → Levelized Cost of Energy
Assumption:
Same Degradation Rate: 1.0%/year
Energy production for 15 year lifetime system
1st-year production 100%
Discount rate: 6%±1%

Larger Uncertainty leads to broader distribution → higher risk

R_D Uncertainty Impact on Warranty

Warranty often twofold: 90% after 10 years, 80% after 25 years

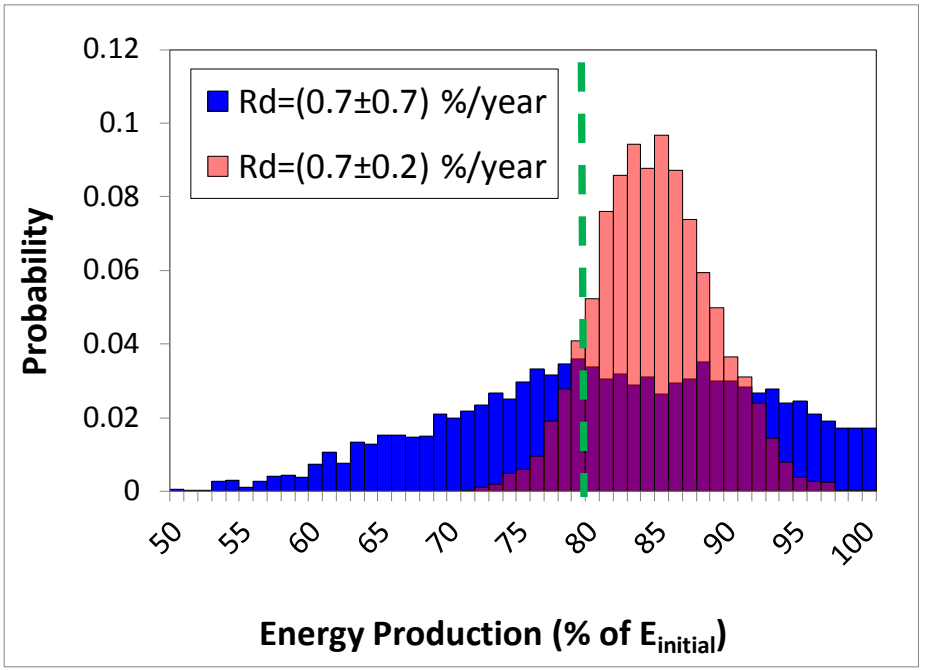
Power Production after 10 years



Chance to invoke warranty:

0.7 %/year uncertainty = 36%
0.2 %/year uncertainty = 4%

Power Production after 25 years



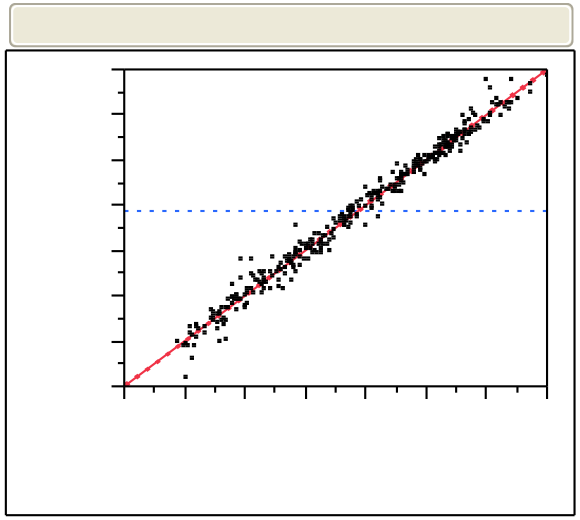
Chance to invoke warranty:

0.7 %/year uncertainty = 47%
0.2 %/year uncertainty = 16%

Degradation Rate Determination

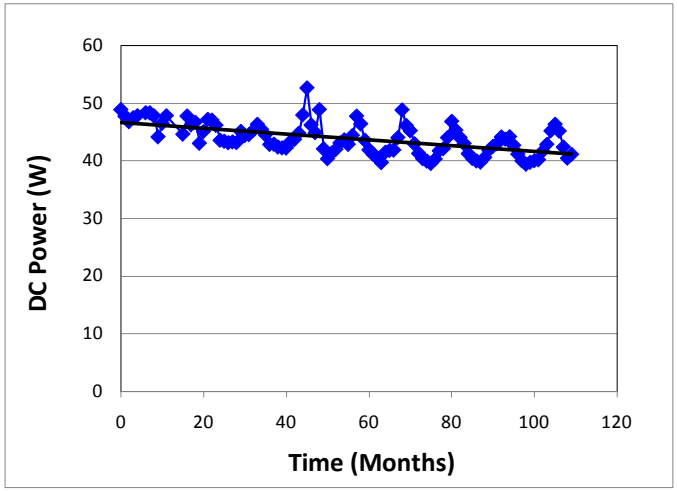
1. Step

Rating



2. Step

Time series + Linear Fit, Standard Least Squares



$$P = b + m \cdot t$$

$$m = \frac{n\left(\sum P \cdot t\right) - \left(\sum P\right)\left(\sum t\right)}{n\left(\sum t^2\right) - \left(\sum t\right)^2}$$

$$b = \frac{\left(\sum P\right)\left(t^2\right) - \left(\sum t\right)\left(\sum P \cdot t\right)}{n\left(\sum t^2\right) - \left(\sum t\right)^2}$$

$$SE_b = RMSE \cdot \sqrt{\frac{1}{\sum (x_i - \bar{x})^2}}$$

$$SE_m = RMSE \cdot \sqrt{\frac{1}{n} + \frac{\bar{x}^2}{\sum (x_i - \bar{x})^2}}$$

1. PVUSA equation

$$P = E \cdot \left(a_1 + a_2 \cdot E + a_3 \cdot T_{ambient} + a_4 \cdot ws\right)$$

PTC conditions:
E=1000 W/m^2, Tamb=20ºC, w=1m/s

2. Sandia Model

3. BEW Model

$$R_d = \frac{\left[\frac{P(t_0) - P(t)}{t} \cdot 12\right]}{P(t_0)} = \frac{m \cdot 12}{b}$$

$$\Delta R_d = \sqrt{\left(\frac{\partial R_d}{\partial m} \Delta m\right)^2 + \left(\frac{\partial R_d}{\partial b} \Delta b\right)^2}$$

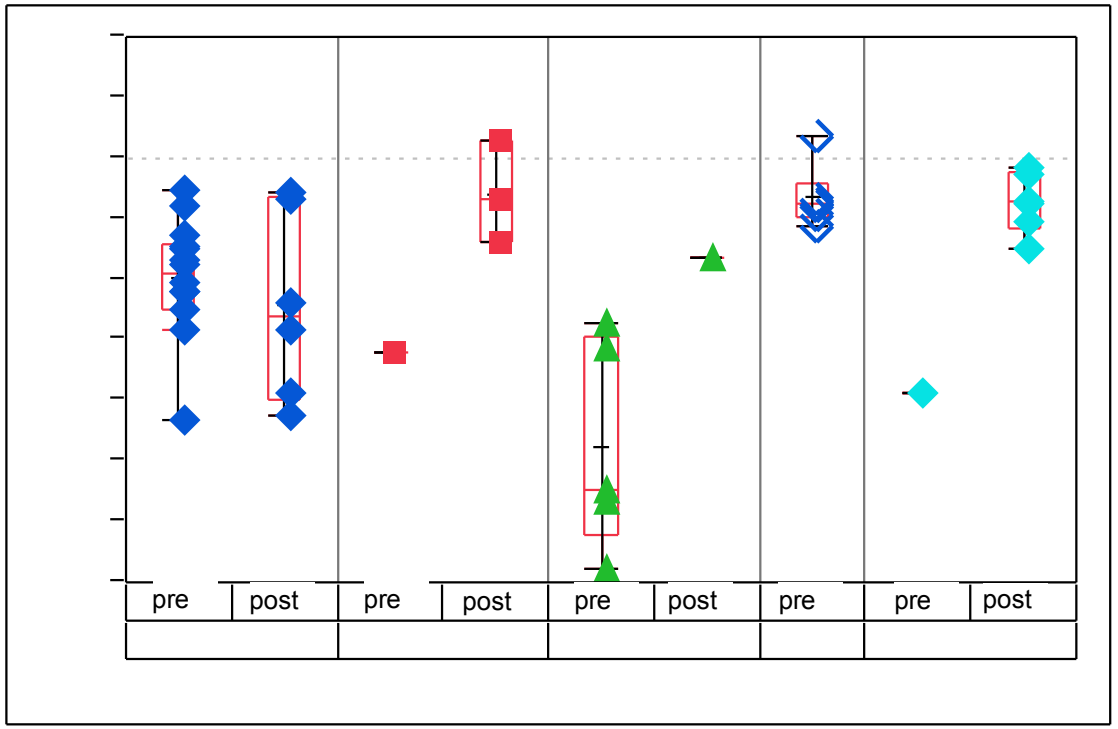
Linear Fit using Standard Least Square → Method 1

Kimber A, Dierauf T, Mitchell L, Whitaker C, Townsend T, Newmiller J, King D, Granata J, Emery K, Osterwald C, Myers D, Marion B, Pligavko A, Panchula A, Levitsky T, Forbess J Talmud F. Improved Test Method to Verify the Power Rating of a Photovoltaic (PV) Project. Proceedings of the 34th IEEE PV Specialist Conference, Philadelphia, 2009.

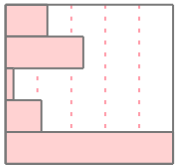
PERT – Degradation Rates

Performance Energy Rating Testbed = PERT





More than 40 Modules,
> 10 manufacturers,
Monitoring time: 2 yrs-16 yrs



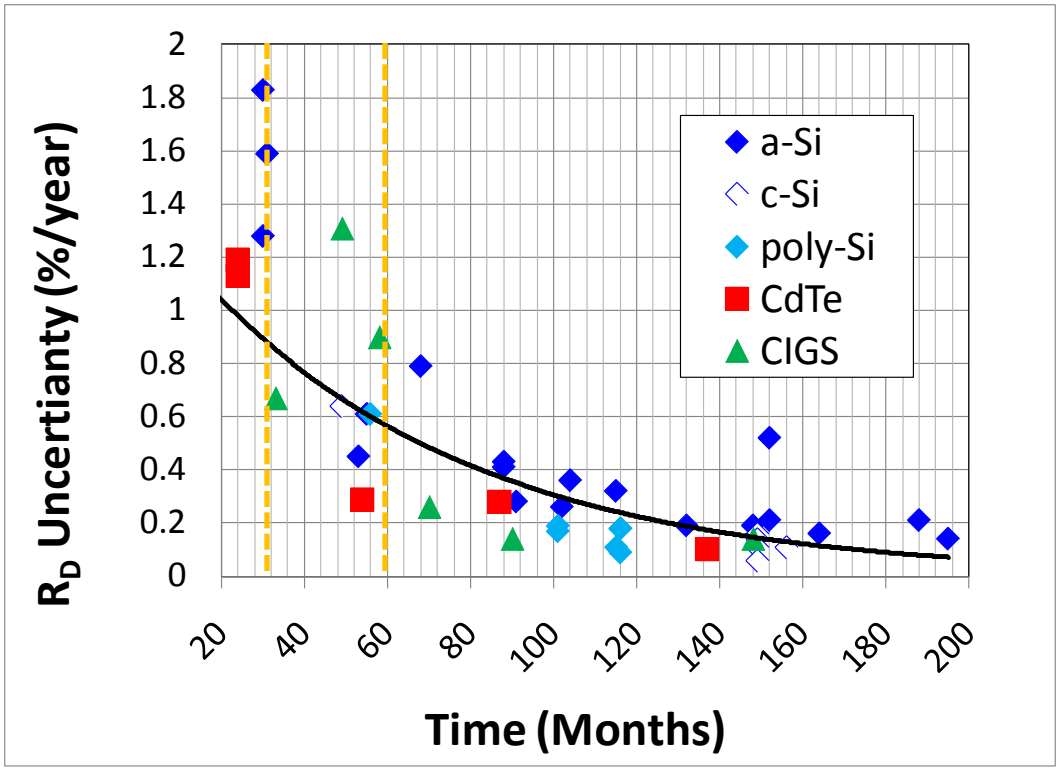
Appears that CdTe, CIGS & poly-Si improved, although sample size is small

PERT – Degradation Rate Uncertainty

Performance Energy Rating Testbed = PERT



Pmax + PVUSA multiple regression → Degradation Rate



Traditional Method → need 3-5 years to determine degradation rate*.

3-5 Years: Uncertainty is between (0.9-0.6) %/year

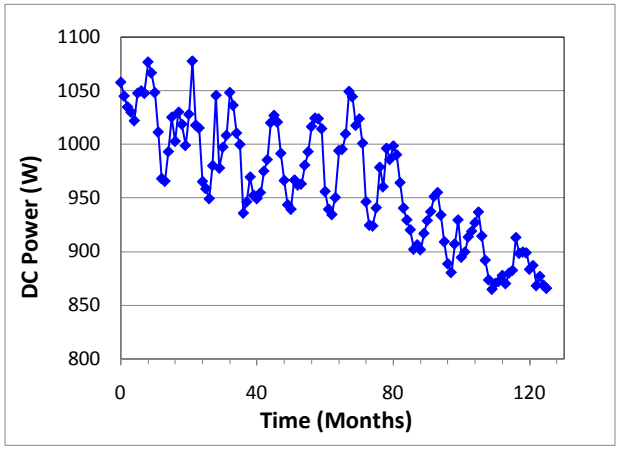
*Osterwald CR, Adelstein J, del Cueto JA, Kroposki B, Trudell D, Moriarty T. Proc. of the 4th IEEE World Conference on Photovoltaic Energy Conversion, Hawaii, 2006.

Classical Decomposition

Signal = Trend + Seasonality + Error

$$P_t = T_t + S_t + E_t$$ Additive Model

Original Data

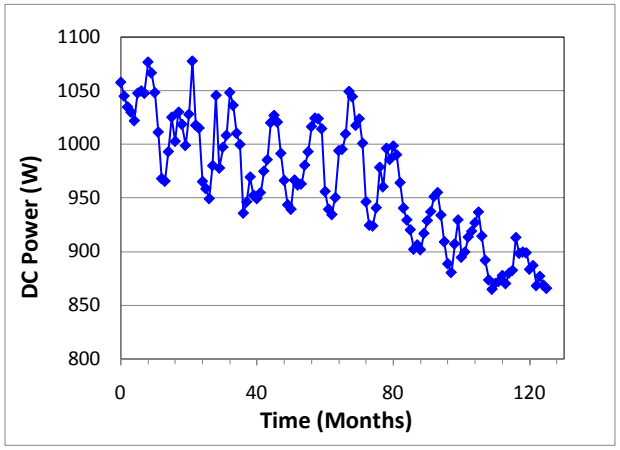


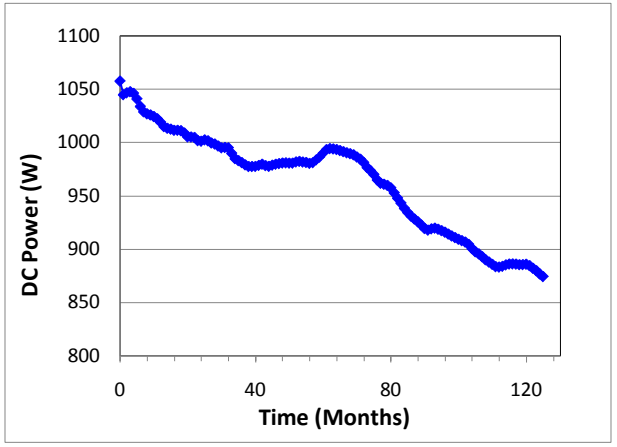
Classical Decomposition

Signal = Trend + Seasonality + Error

$$P_t = T_t + S_t + E_t$$ Additive Model

Original Data





Trend

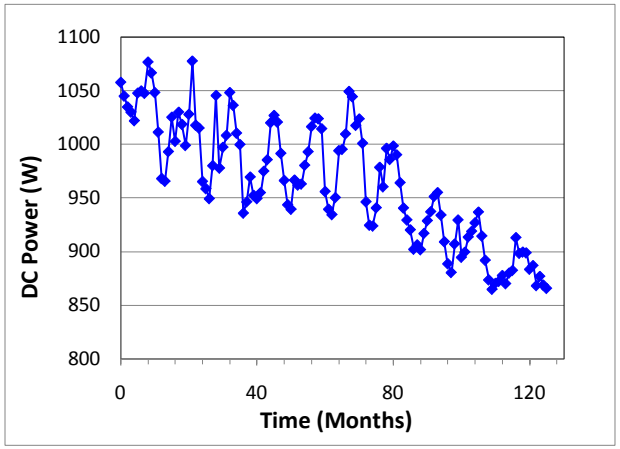
12-month centered-Moving Average

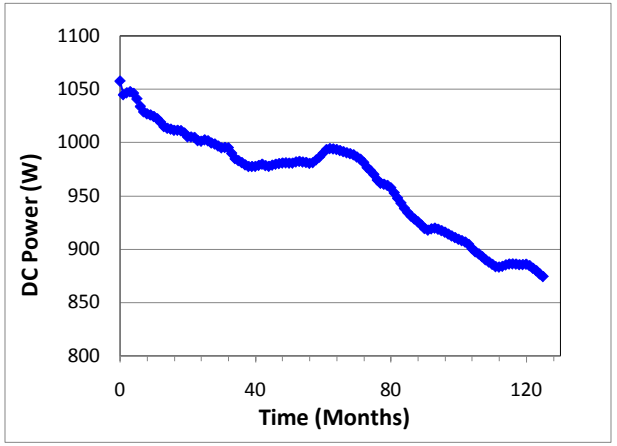
Classical Decomposition

Signal = Trend + Seasonality + Error

$$P_t = T_t + S_t + E_t$$ Additive Model

Original Data



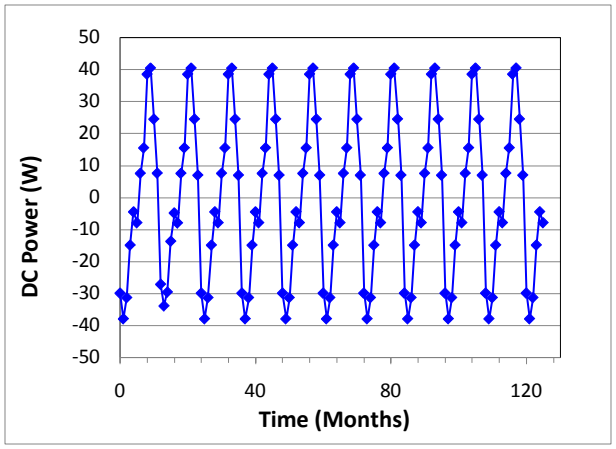


Trend

12-month centered-Moving Average

Seasonality

Average of each month for all years of observation

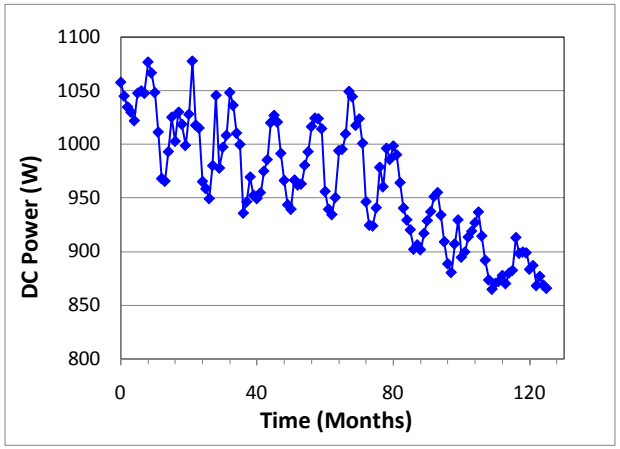


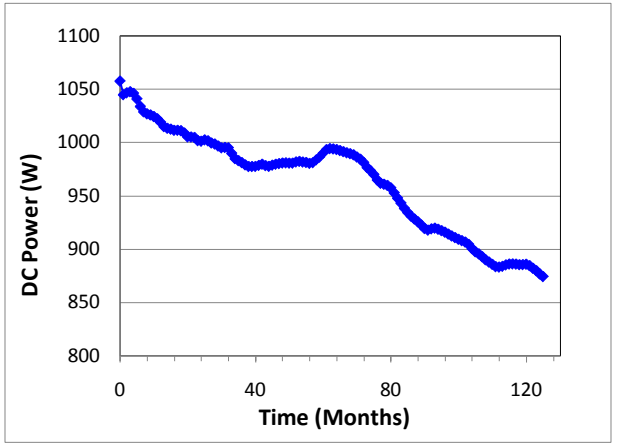
Classical Decomposition

Signal = Trend + Seasonality + Error

$P_t = T_t + S_t + E_t$ Additive Model

Original Data



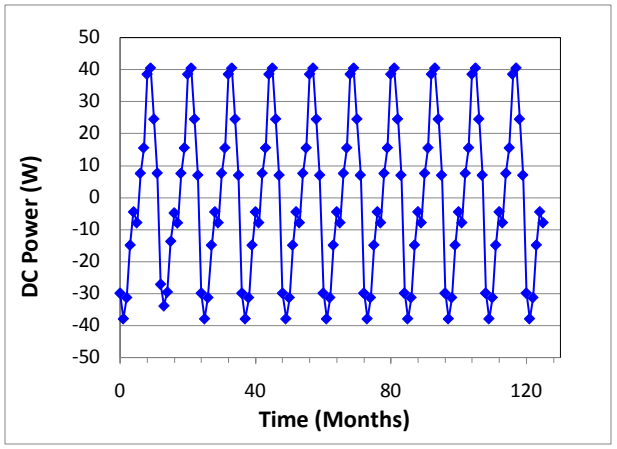


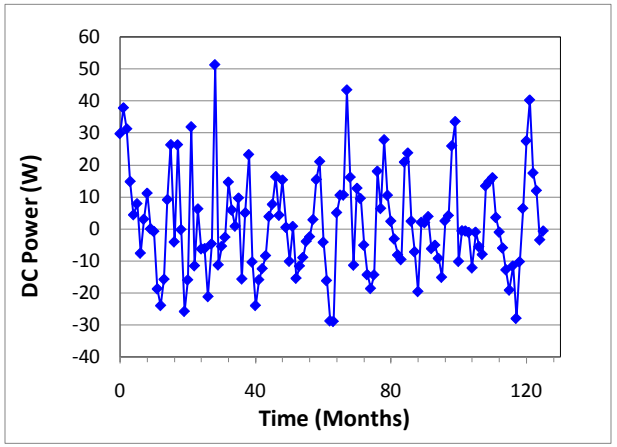
Trend

12-month centered-Moving Average

Seasonality

Average of each month for all years of observation





Error

Determine R_d from Trend graph only using SLS

Power Decline as Difference Equation

$$\frac{dP}{dt} = a_0 P(t) + c + e(t)$$

Stochastic differential equation

$$\left(P_t - P_{t-1}\right) = a_0 P_t + c + e_t$$

Discrete difference equation

$$P_t = \frac{1}{1-a_0} P_{t-1} + \frac{c}{1-a_0} + \frac{e_t}{1-a_0}$$

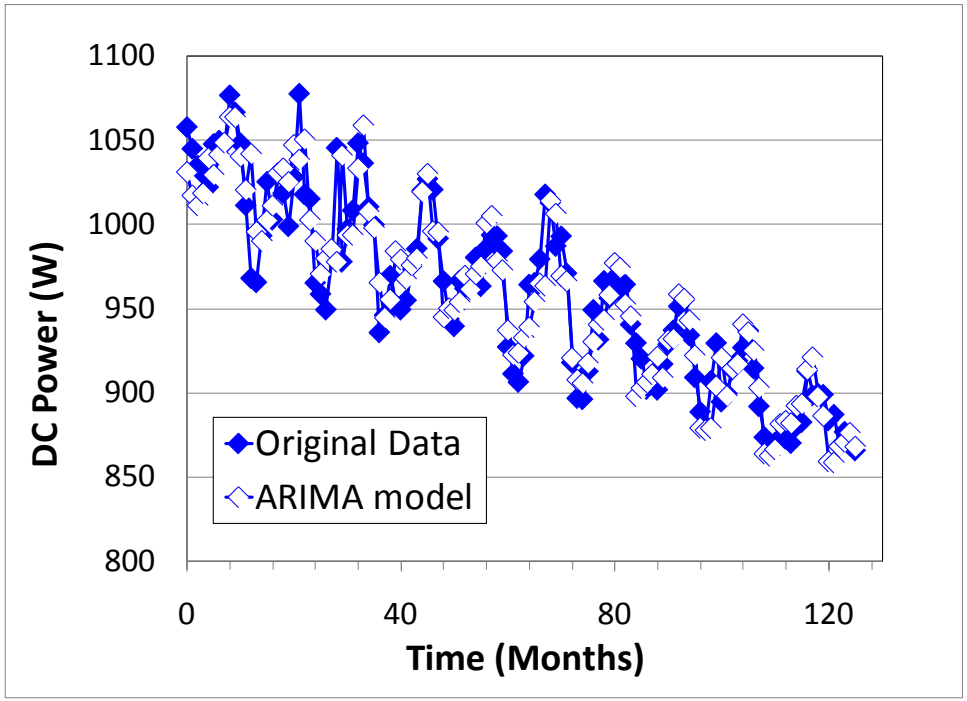
$$\phi = \frac{1}{1-a_0}, \quad \mu = \frac{c}{1-a_0}, \quad and \quad \varepsilon_t = \frac{e}{1-a_0}$$

$$P_t = \phi \cdot P_{t-1} + \mu + \varepsilon_t$$

- Regression of it's lagged self → auto-regression
- Because only 1 time lag is included → AR(1)

- AR(1) subset of larger class of ***A***uto***R***egressive ***I***ntegrated ***M***oving ***A***verage (ARIMA)

ARIMA + Decomposition



Commercial software:
(i) US Census Bureau
(ii) Bank of Spain
Complete solution

Statistical software:
User has to select model

Equation for ARIMA :

$$P_t - P_{t-12} - \phi \cdot P_{t-1} + \phi \cdot P_{t-13} = \varepsilon_t - \theta \cdot \varepsilon_{t-12}$$

Autoregressive coefficient

Seasonal Moving average coefficient

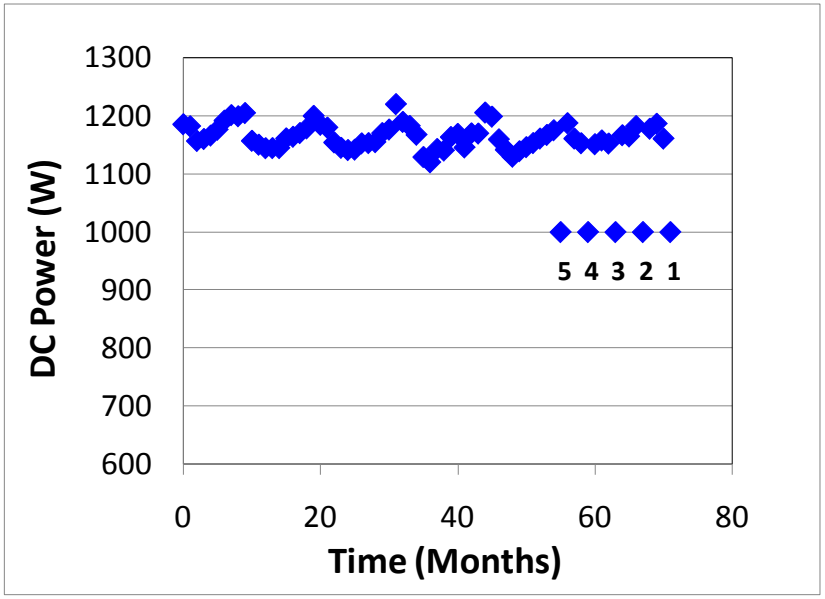
ARIMA(100)(011)

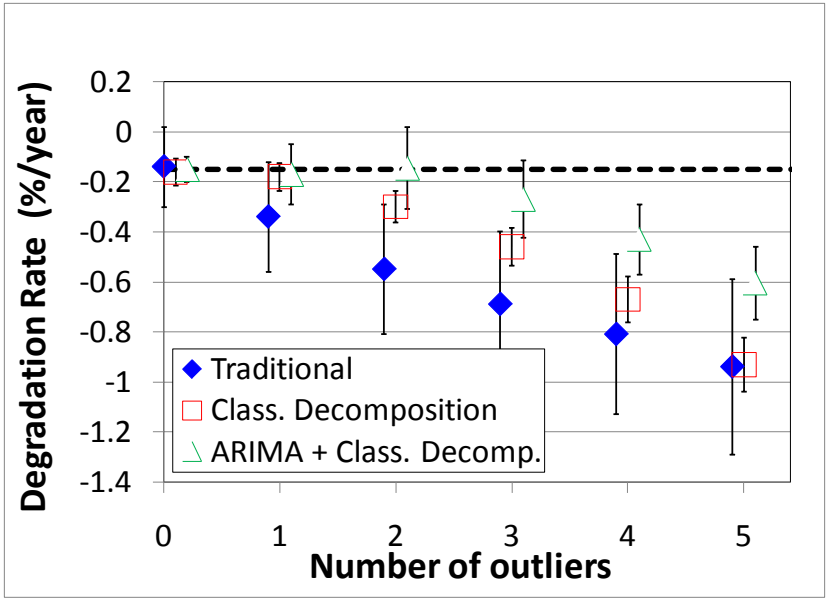
Analytical problems leading to longer observation times: Outliers, Data shifts, Missing Data

Outlier Sensitivity

Data set from OTF
Deliberately introduce outliers
Calculate Rd

(i) Linear Fit w/ SLS = traditional
(ii) Classical Decomposition
(iii) ARIMA + Decomposition





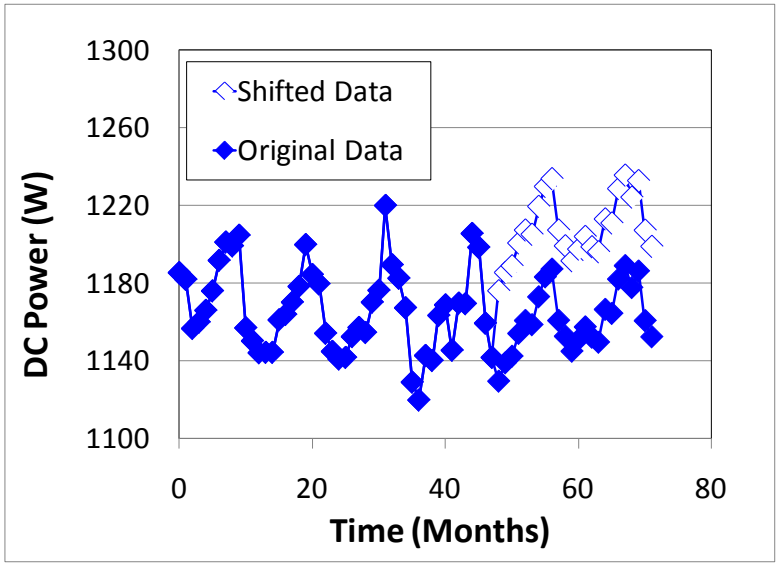
Traditional: 1 outlier → R_d changed significantly

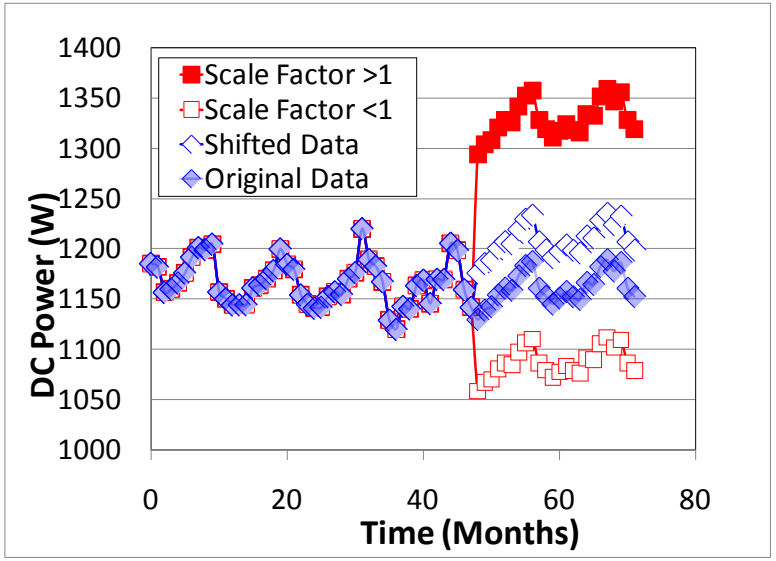
Class. Decomposition: 1 outlier → R_d does not change significantly, 2 outliers → significant change

ARIMA+Decomposition: Least sensitive to outliers → even 3 outliers

Method to correct Data Shifts

Data shifts often occur due to hardware changes



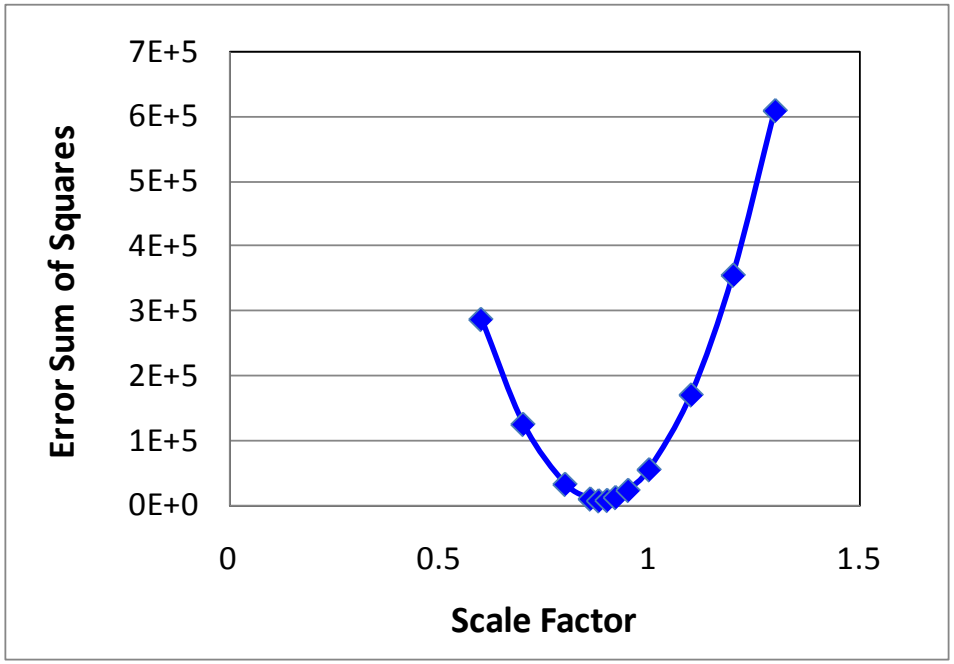


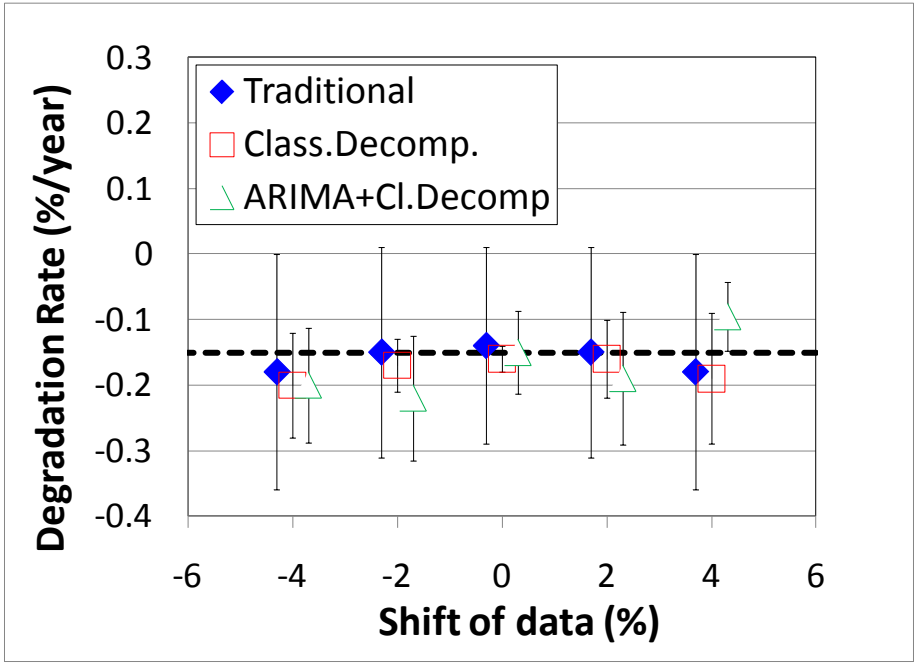
Method:

- Multiply shifted section by a scaling factor
- Plot Residual sum of squares vs. scaling factor

Method to correct Data Shifts

Example: Minimization of Error Sum of Squares of Errors (ESS)

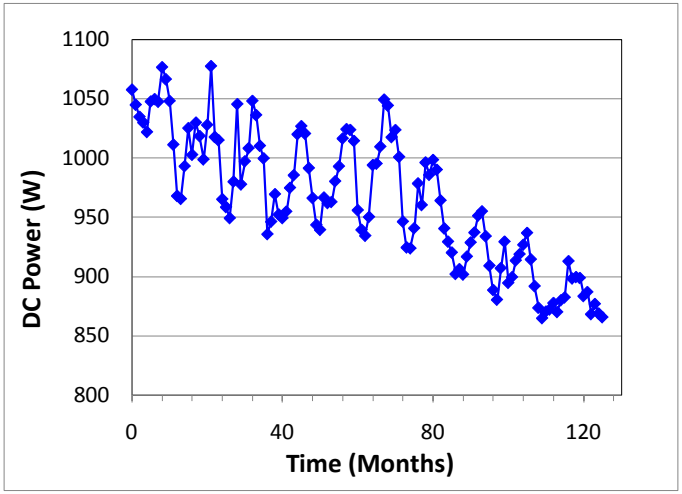




Data shift correction procedure is successful for all 3 approaches.

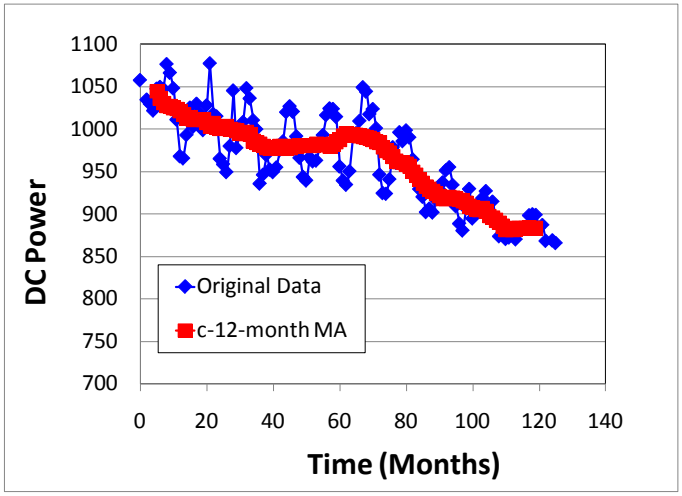
Data Shift – blind test

Data set with marked hump in the c-12-Month Moving Average



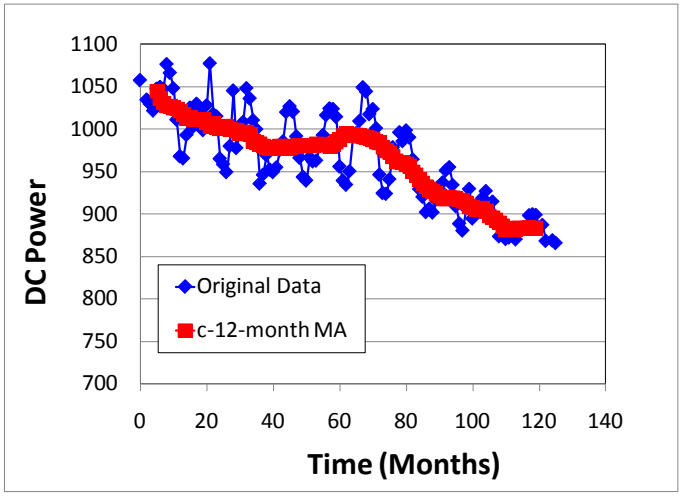
Data Shift – blind test

Data set with marked hump in the c-12-Month Moving Average

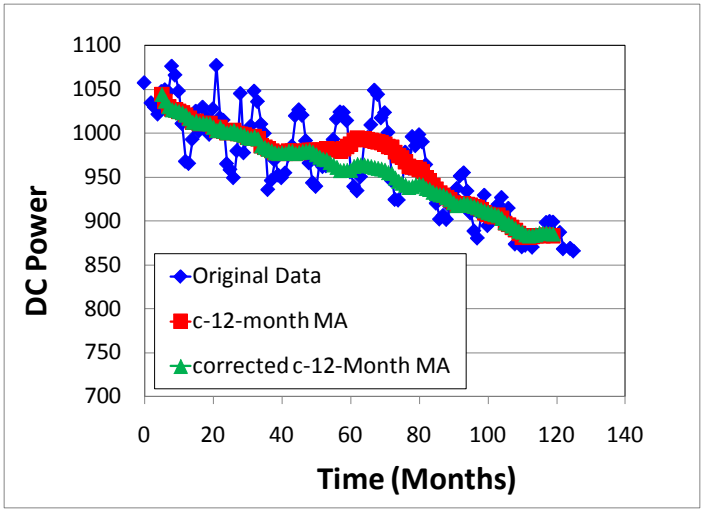


Data Shift – blind test

Data set with marked hump in the c-12-Month Moving Average

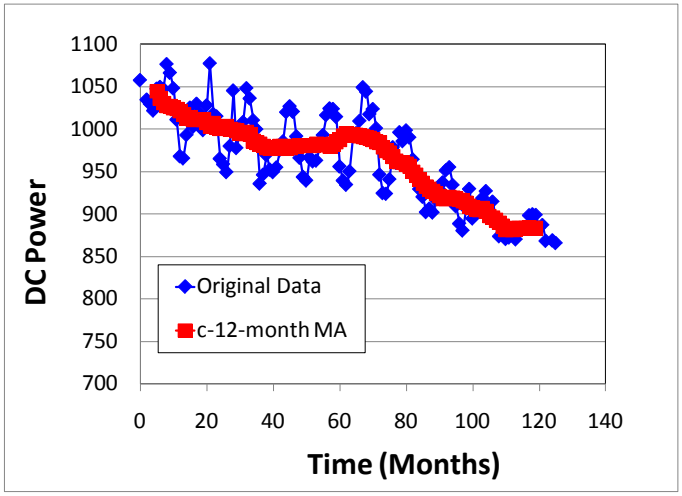


c-12-Month Moving Average after shift correction → no peak anymore

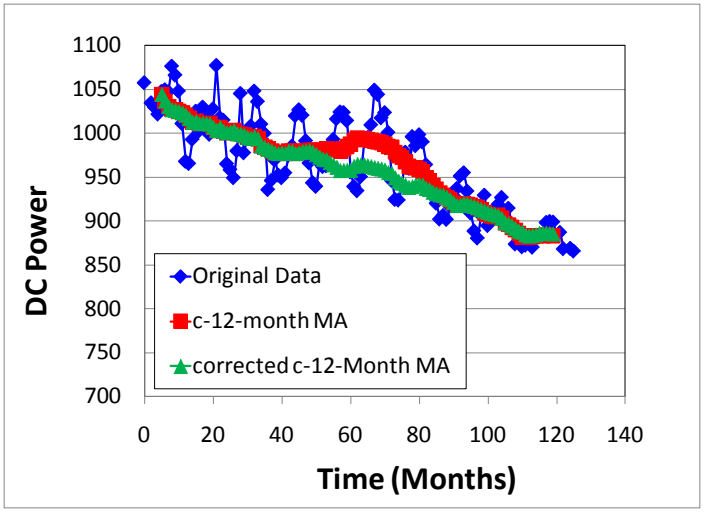


Data Shift – blind test

Data set with marked hump in the c-12-Month Moving Average



c-12-Month Moving Average after shift correction → no peak anymore



Methodology	Degradation Rate (%/year)	Error
SLS original	1.47	0.12
ARIMA+Classical Decomp.	1.44	0.06
SLS till 81 month (after hump)	0.86	0.24
SLS till 81 month (after hump) corr	1.41	0.22

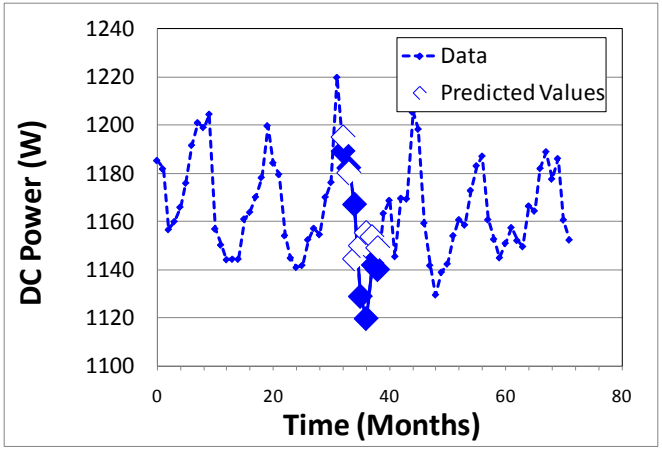
Cause: Ambient temperature sensor was reading erratically and was replaced.

Standard Least Square and ARIMA+Decomposition give the same result for degradation because almost 4 years of good data after shift.

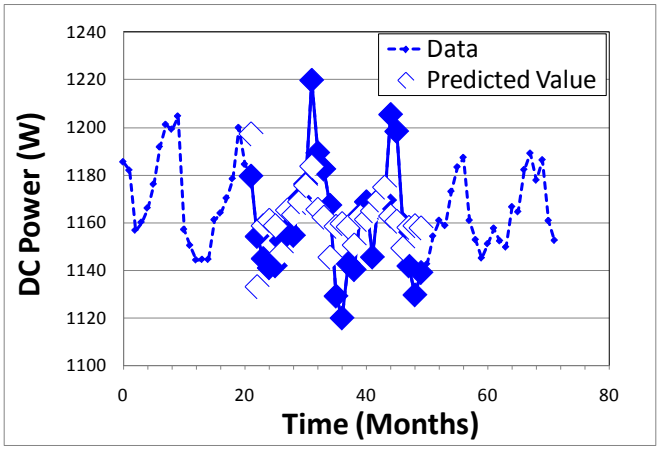
If degradation had been after shift, uncorrected → degradation rate would have been misleading.

ARIMA Modeling and Missing Data

10% missing data

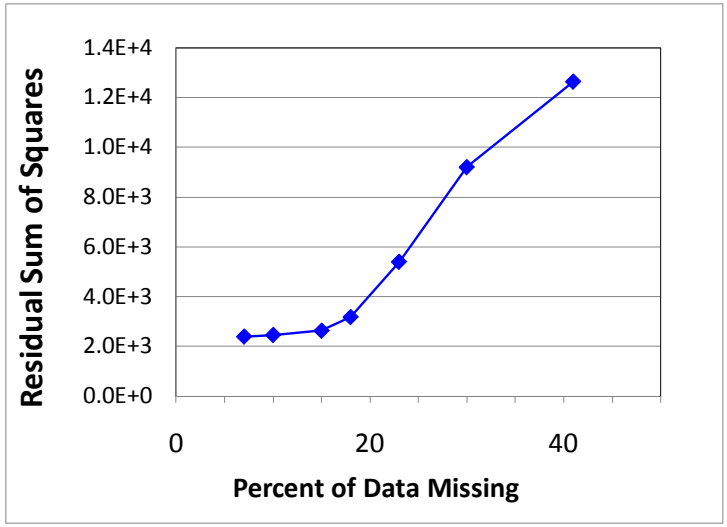


40% missing data



Actual data points: solid diamonds
Modeled points; open diamonds

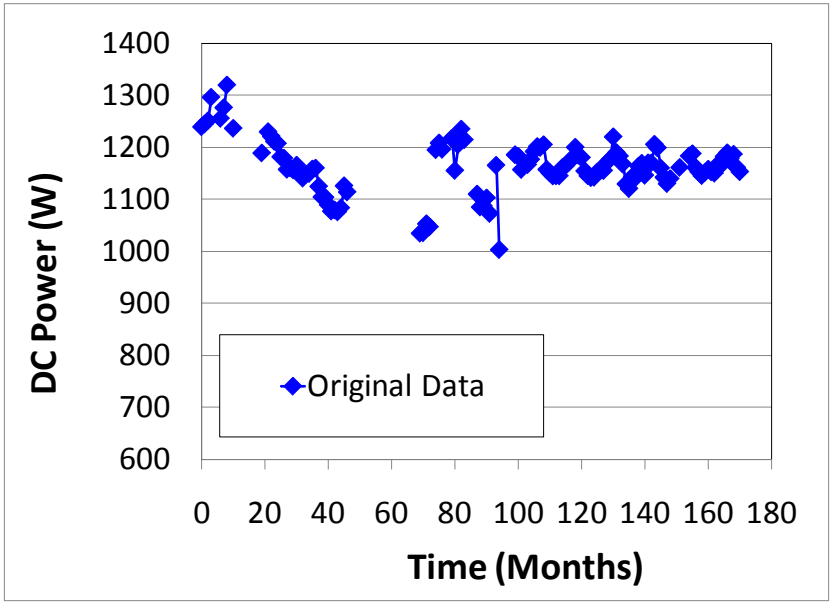
Procedure:
1. Remove x number of data points from time series.
2. Substitute w/ average value
3. Fit ARIMA model and predict missing data points
4. Compare with actual data points



Error does not increase significantly until >20% data missing (i.e. > 1 year of data missing)

Problematic Data Set

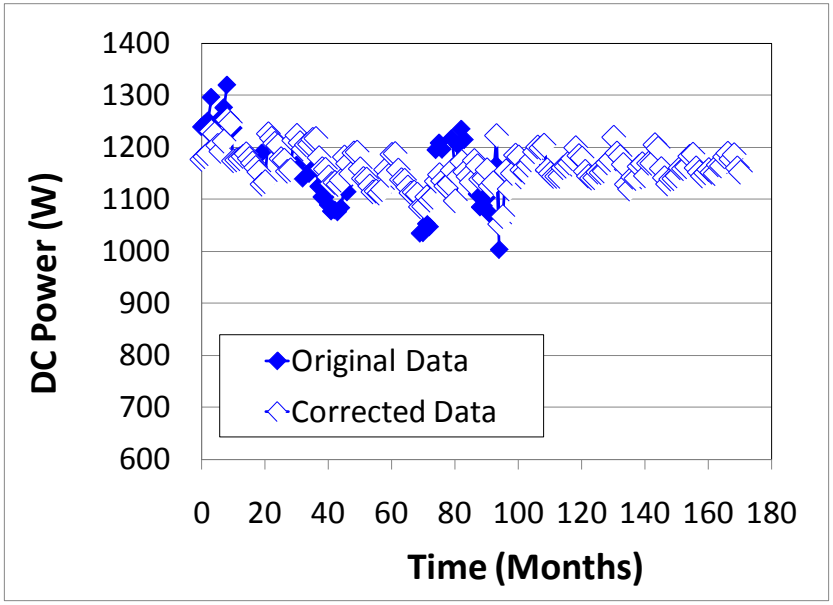
Degradation Rate determination difficult due to Data shifts, outliers & missing data



Data stabilize at > 100 months!

Data Shift - all data

Degradation Rate determination difficult due to Data shifts, outliers & missing data



Methodology	Degradation Rate (%/year)	Error
SLS, all data	0.14	0.13
SLS, all data Shift-corrected	0.14	0.07
Class.Decomp. Shift-corrected	0.13	0.07
ARIMA+Class.Decomp Shift-corrected	0.15	0.04

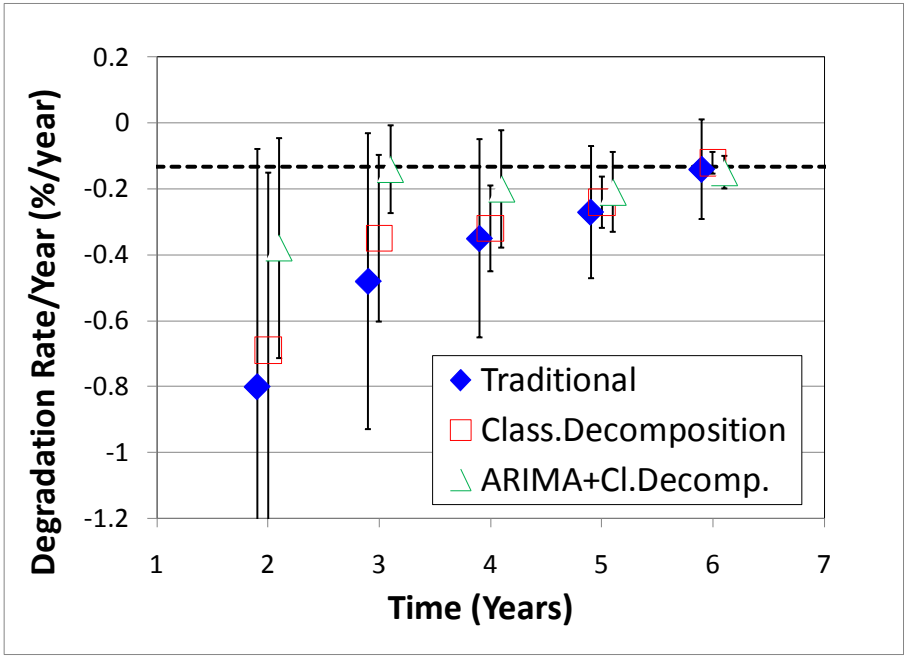
Data stabilize at > 100 months!

All 3 methodologies determine ultimate degradation rate after data are corrected.

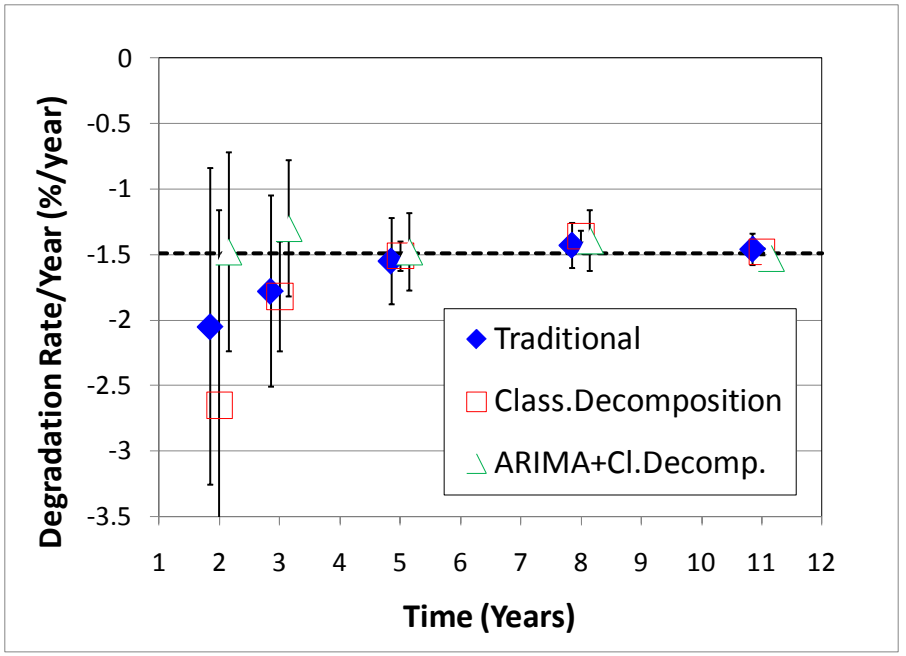
Correction procedure enables to determine degradation rate with small enough uncertainty

Degradation Rate in shorter Time

multi-Si



a-Si

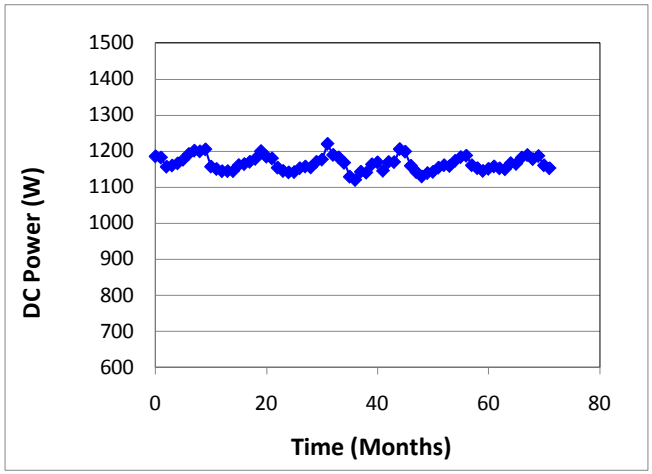


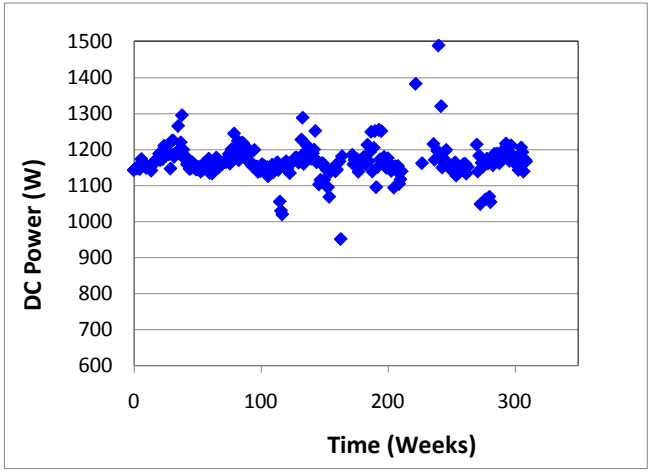
- Degradation rates were calculated for each method starting with the first 2, 3 years etc.
- The a-Si module was in the field for over 6 months before data collection commenced.
- For longer times all three methodologies converge to the same rate.
- Traditional & Cl.Decomp. show increasing bias for shorter time but w/in uncertainty.
- ARIMA approach shows lowest bias close to ultimate degradation rate.

PVUSA – Weekly Intervals

PVUSA Method – multi-crystalline Si

Monthly Intervals



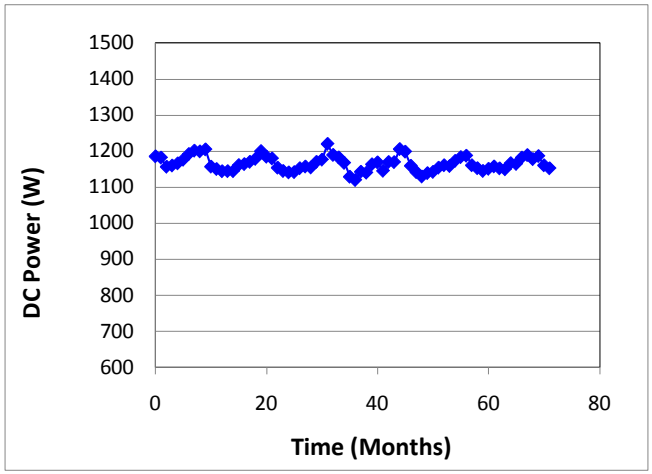


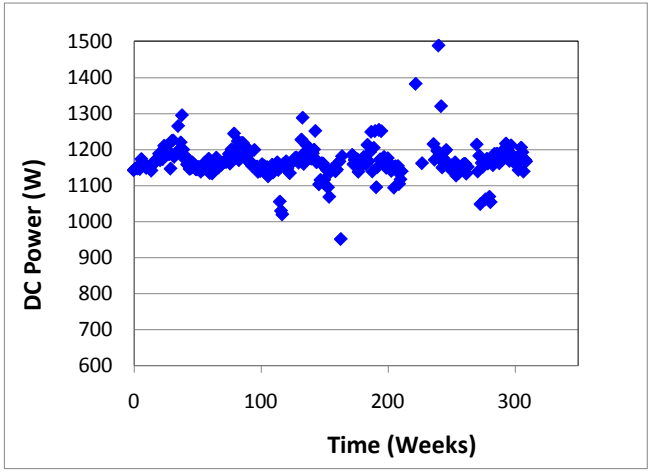
Weekly Intervals

PVUSA – Weekly Intervals

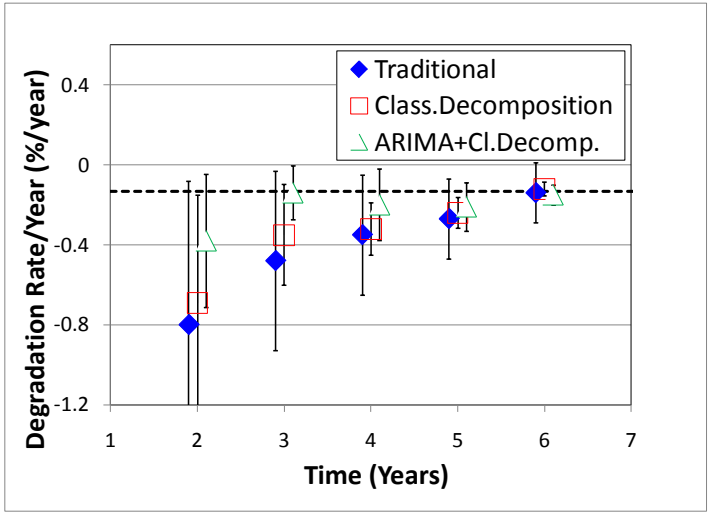
PVUSA Method – multi-crystalline Si

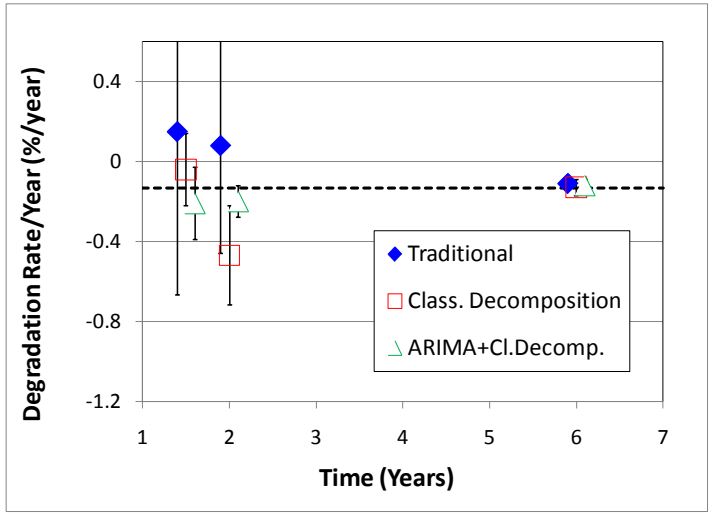
Monthly Intervals





Weekly Intervals





Weekly intervals → more data, degrees of freedom

Conclusion

- Analysis of >40 modules showed why 3-5 years traditionally required to determine R_d
- Introduced 2 new methods to determine R_d (Class.Decomp., ARIMA+Decomp.)
- ARIMA most robust against outliers
- Introduced method to correct data shifts
- ARIMA seems to able to determine R_d more quickly → limited by numbers of degree of freedom → need more data points → sample weekly
- Using shorter time intervals increases noise but holds promise

Conclusion

- Analysis of >40 modules showed why 3-5 years traditionally required to determine R_d
- Introduced 2 new methods to determine R_d (Class.Decomp., ARIMA+Decomp.)
- ARIMA most robust against outliers
- Introduced method to correct data shifts
- ARIMA seems to able to determine R_d more quickly → limited by numbers of degree of freedom
- Using shorter time intervals increases noise but holds promise

"All Models are wrong……but some are useful!"

-- G.P.P. Box

Decades in the Installed Environment: Do Silicon Modules Really Last More than 20 Years? Preliminary Findings

NREL PV Module Reliability Workshop
2/19/2010

James M. Bing, PE
President
New Energy Options, Inc.
410 Great Road, B-6
Littleton, MA 01460
jbing@newenergyoptions.com

TOPICS

- Two Modules & Two Arrays
- Test & Measurement Procedures
- Test Results
- Conclusions & Future Work

Two Modules
&
Two Arrays

Two Modules

- Beverly, Massachusetts
- Solar Power Corporation
- G12-331CT
- 30.2W NOCT

- Gardner, Massachusetts
- Mobil Solar
- Ra-30-12H
- 30.0W STC

Solar Power Corporation Module G12-361CT

(Beverly, Massachusetts)

- Single Crystal
- 36 Cell (36 series/1 parallel)
- Potted junction box
- Bi-pass diode
- Type SO cable w/two-pin molded connector
- Dimensions: 1057 x 424mm (41.5 x 16.75in)
- 84 modules tested

Solar Power Corporation Module G12-361CT

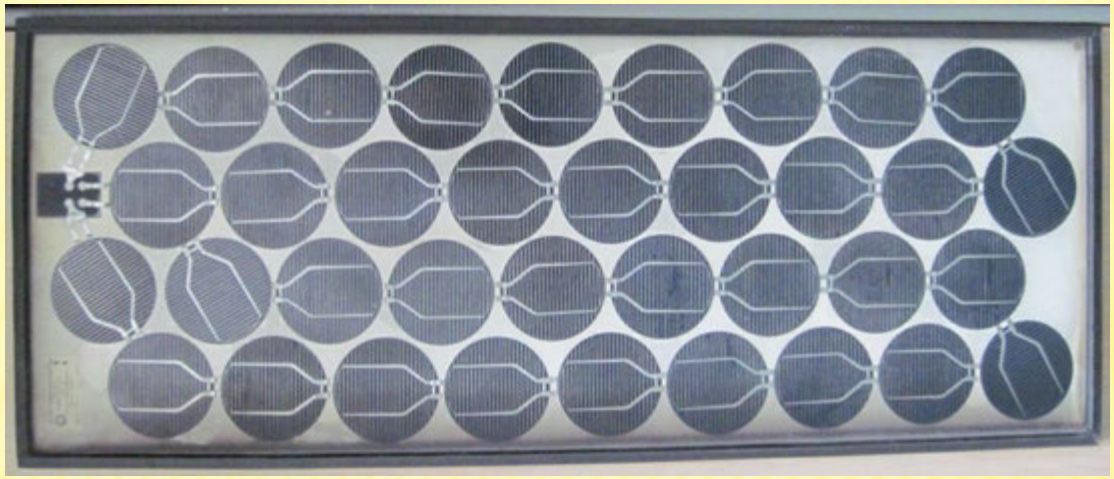
(Beverly, Massachusetts)

- Electrical Specifications:

Nominal Operating Cell Temperature (NOCT)	46°
Short Circuit Current at NOCT	2.15 Amp
Open Circuit Voltage at NOCT	19.6 Volt
Maximum Power Point Voltage at NOCT	15.1 Volt
Maximum Power Point Current	2.00 Amp
Maximum Power at NOCT	30.2 Watt
Total Module Power Density	6.19 Watt/ft^2
Temp Coefficient of Current	$\Delta I / \Delta T$= 0.46mA/ °C
Temp Coefficient of Voltage	$\Delta V / \Delta T$ =-78mV/ °C

Solar Power Corporation Module G12-361CT

(Beverly, Massachusetts)





New Energy Options, Inc.

Mobil Solar Module
Ra-30-12H

(Gardner, Massachusetts)

- Polycrystalline
- 72 Cell (36 series/2 parallel)
- Separately installed bi-pass diode
- Screw cover junction box with brass threaded post terminals
- Dimensions: 905 x 412mm (35.5 x 16.25in)
- 70 modules tested

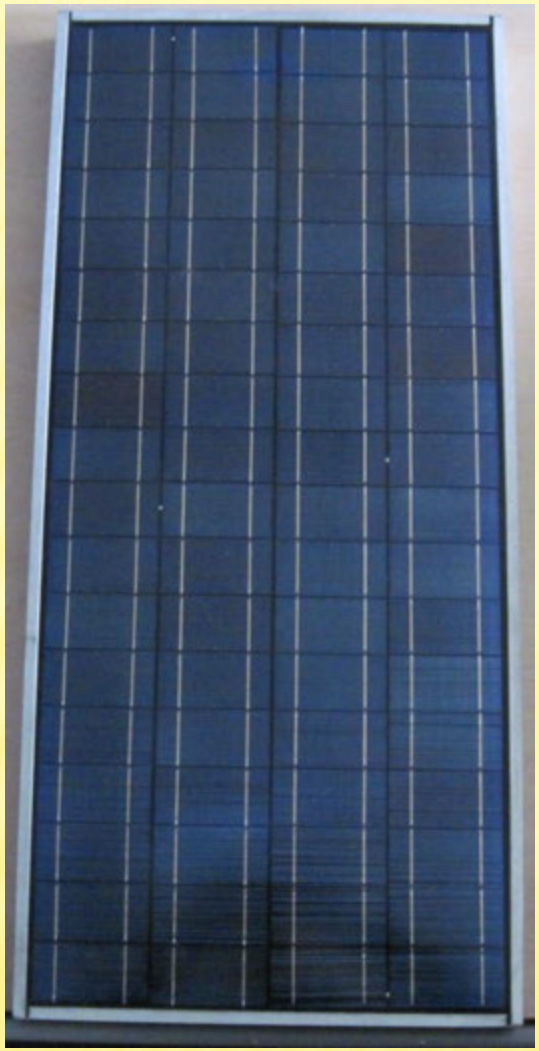
Mobil Solar Module
Ra-30-12H

(Gardner, Massachusetts)

- Electrical Specifications:
  - Isc at STC 2.2 Amp
  - Voc at STC 18.9 Volt
  - Vmp at STC 15.5 Volt
  - Imp at STC 1.94 Amp
  - Pmp at STC 27.0 Watts (Min) 30.0 Watt (Typ)
  - TCI_{SC} 1.60 mA/ °C/Cell (Parallel)
  - TCV_{OC} -2.18 mV/ °C/Cell (Series)

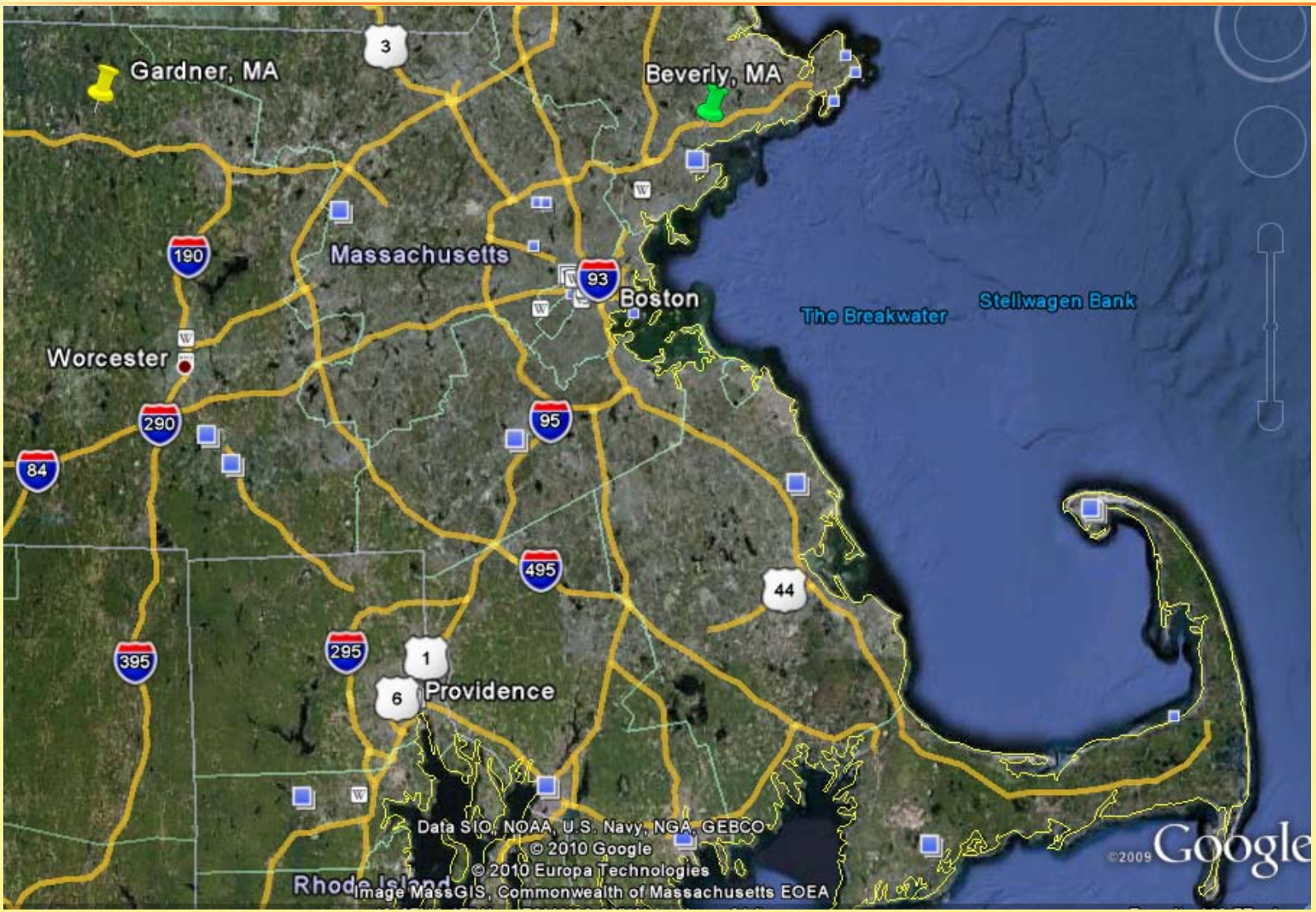
Mobil Solar Module
Ra-30-12H

(Gardner, Massachusetts)





Two Arrays



New Energy Options, Inc.

Two Arrays

- Beverly, Massachusetts
  - Record high temp: 38°C
  - Record low temp: -23°C
  - 20m above sea level
  - 3km to ocean
- Gardner, Massachusetts
  - Record high temp: 37°C
  - Record low temp: -37°C
  - 330m above sea level
  - 95km to the ocean

Two Arrays

- Beverly, Massachusetts
  - 100kW system
  - Solar Power Corp Modules
  - Ground mount
  - Open racks
  - Tilt 60° (approximate)
  - Azimuth 180°
  - 10 module panels in landscape
  - Six 15kW inverters (current configuration)
- Gardner, Massachusetts
  - 2.1kW system
  - Mobil Solar Modules
  - Open racks on flat roof mount
  - Tilt 60° (approximate)
  - Azimuth 165°
  - 5 module panels in portrait
  - Single Inverter

Two Arrays

- Beverly, Massachusetts
  - Commissioned 1981
  - 100kW system
  - One of 8 systems installed nationwide
  - Massachusetts Electric (now National Grid)
  - DOE Funded
  - Stone & Webster engineers
  - Current Status: Functioning with new inverters
- Gardner, Massachusetts
  - Installed 1986
  - 2.1kW system
  - One of 6 commercial & 28 residential systems
  - Massachusetts Electric (now National Grid)
  - EPRI Funded
  - Solar Design Assoc. eng.
  - Current Status: Decommissioned in 2007.

Beverly, Massachusetts 100kW PV Array 1980 to 2010

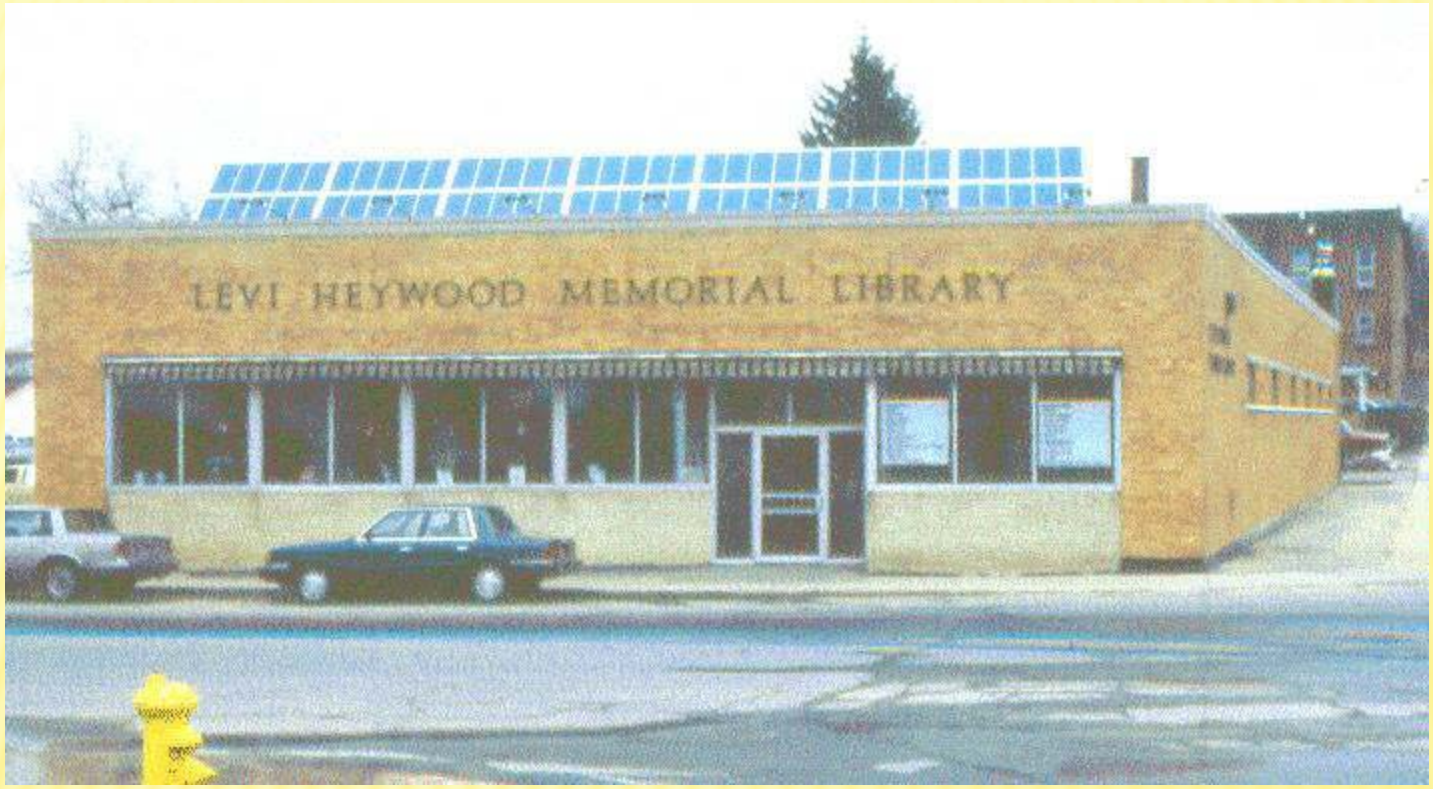




BEVERLY ARRAY



Gardner, Massachusetts 2.1kW PV Array 1986 to 2007



Gardner Massachusetts
Mobil Solar Ra-30-12H Modules



New Energy Options, Inc.

Test & Measurement Procedure

Test & Measurement Procedure

- EKO MP-170 I-V Curve Tracer
  - Sweeps I&V from Isc to Voc
  - Plane of array irradiance (POA)
  - Cell temperature (Tc)
  - Ambient temperature (Ta)
- Cleaning prior to measurement
- POA irradiance 700W/m^2 or greater
- Gardner retested with measurements confirmed with secondary data logger:
  - POA, Tc, Ta, Voc, Isc

EKO MP-170 I-V Curve Tracer





New Energy Options, Inc.

Module Testing

(Beverly, Massachusetts)

- Fixed tilt& azimuth (true south)
- Single thermocouple location
- Molded modular two pin connector for connection of module to EKO
- Modules with shattered glass or with “stuck” connectors were not tested.
- Nominal irradiance: 1000W/m2
- Ambient temperature: -5°C



Gardner Massachusetts

Module Testing

- Changed thermocouple for each 5-module panel
- Adjustable tilt & azimuth
- Alligator clips for EKO curve tracer

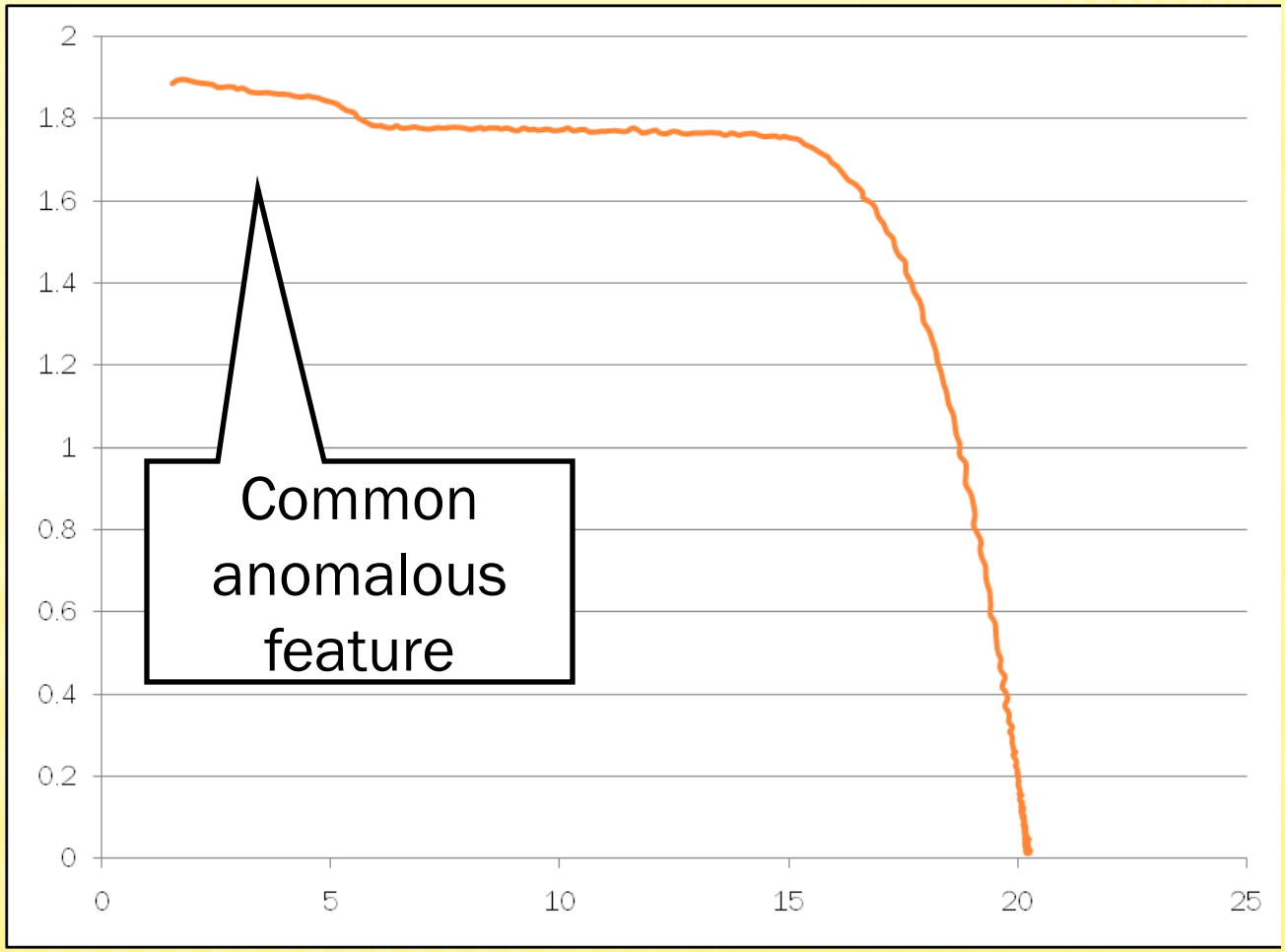


- For Retest:
  - Campbell Scientific CR800
  - Licor200SZ
  - Two type K thermocouples for Tc and Ta

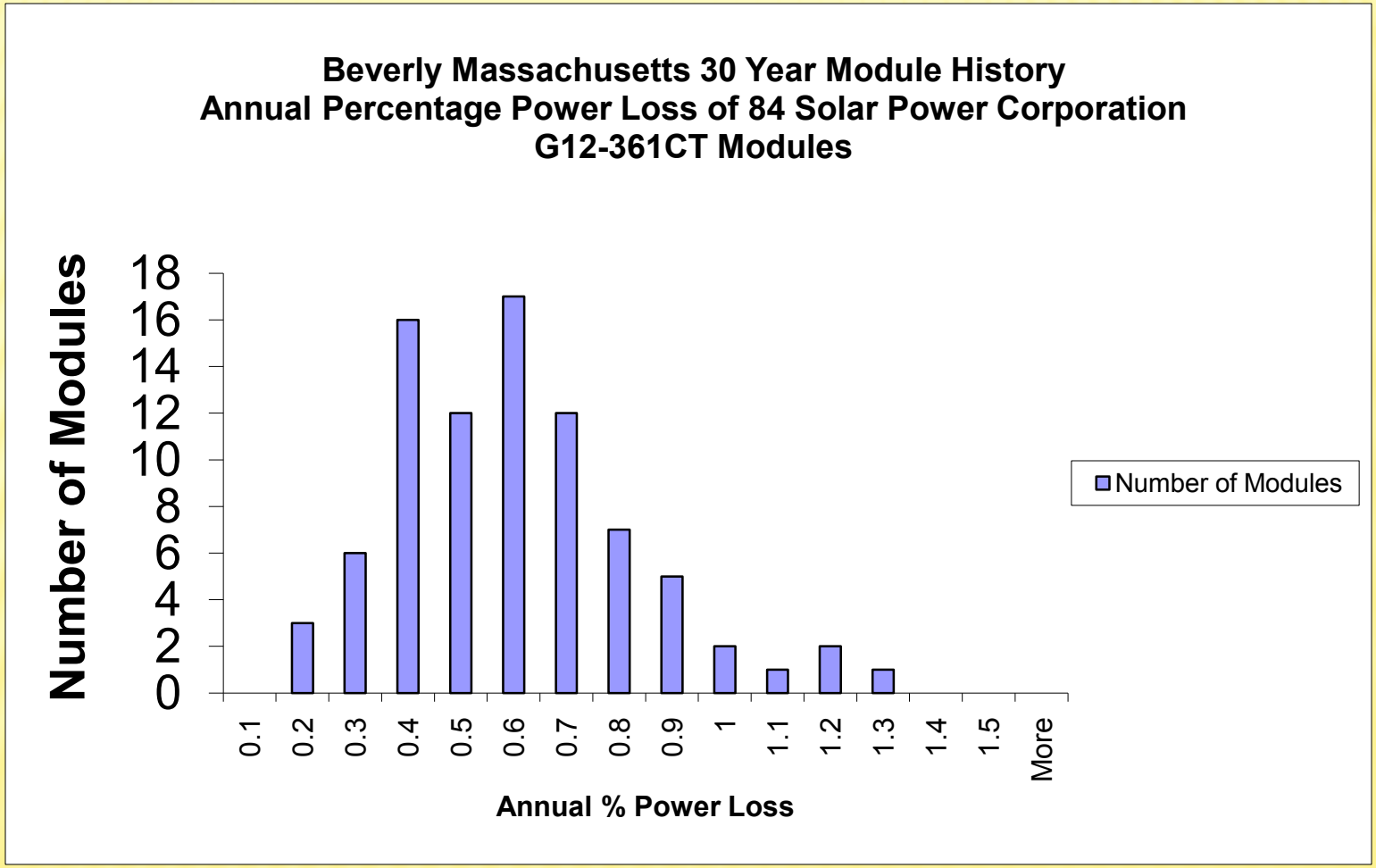
Test Results

Typical I-V Curves

Solar Power Corporation G12-361CT Modules



Percentage Power Loss Per Year
Solar Power Corporation G12-361CT Modules

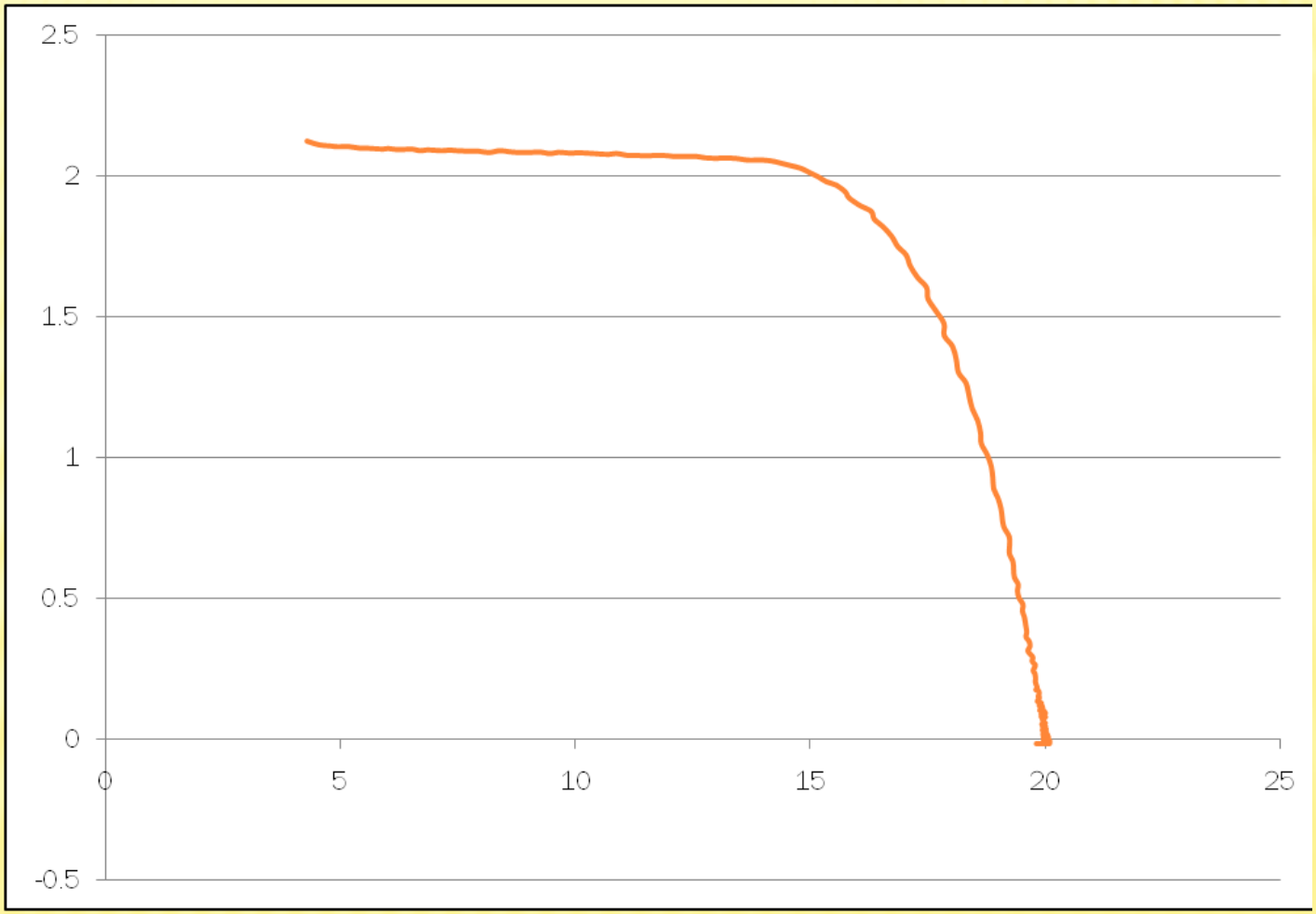


Percentage Power Loss Per Year
Solar Power Corporation G12-361CT Modules

(Beverly, Massachusetts)

- Average annual power loss from original NOCT rating for 30.2W for all tested modules: 0.539%
- Median annual power loss from original NOCT rating for 30.2W for all tested modules: 0.546%

Typical I-V Curve
Mobil Solar Ra-30-12H Modules

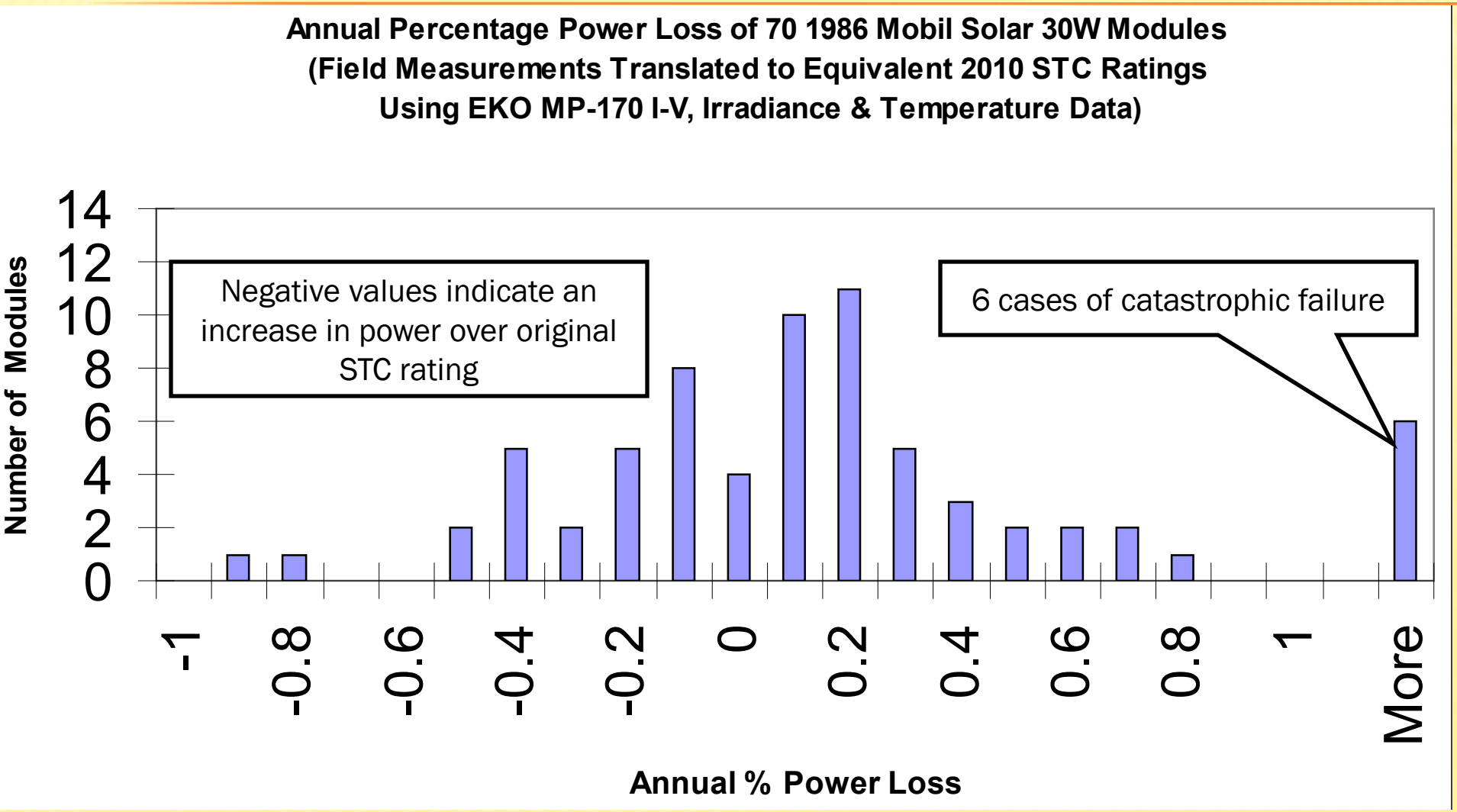


Percentage Power Loss Per Year
Mobil Solar Ra-30-12H Modules

(Gardner, Massachusetts)

- Average annual power loss from original STC rating for 30.0W for all tested modules: 0.180%
- Median annual power loss from original STC rating for 30.0W for all tested modules: 0.082%

Percentage Power Loss Per Year
Mobil Solar Ra-30-12H Modules



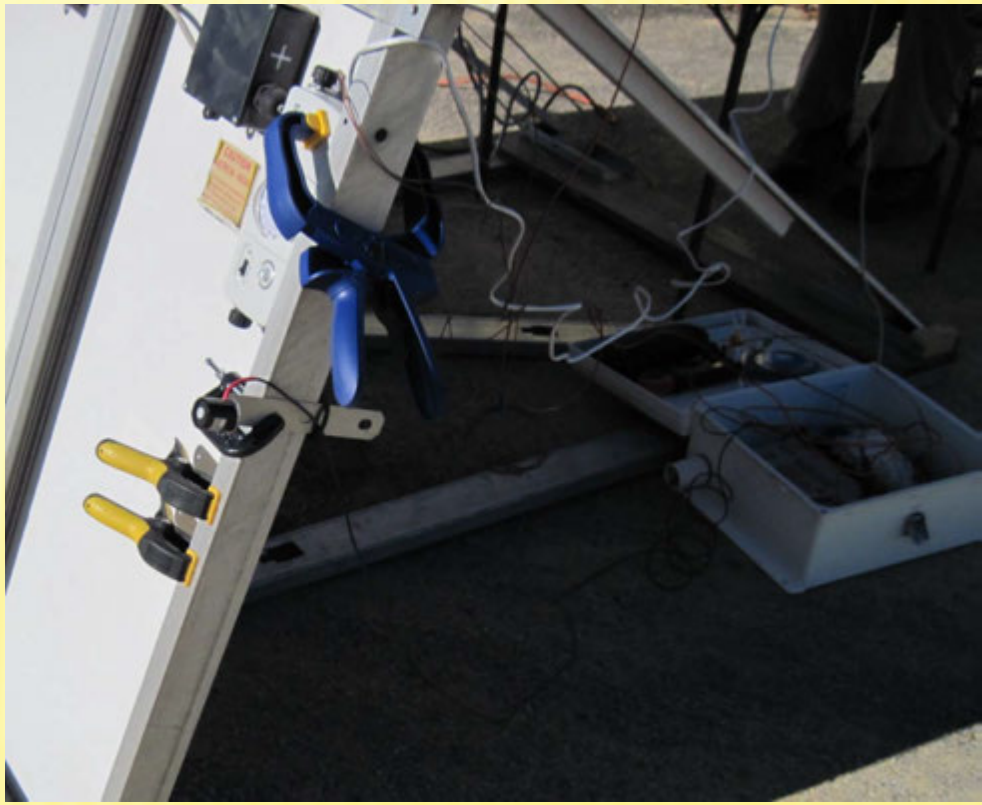
Mobil Solar Ra-30-12H Retest

New Energy Options, Inc.

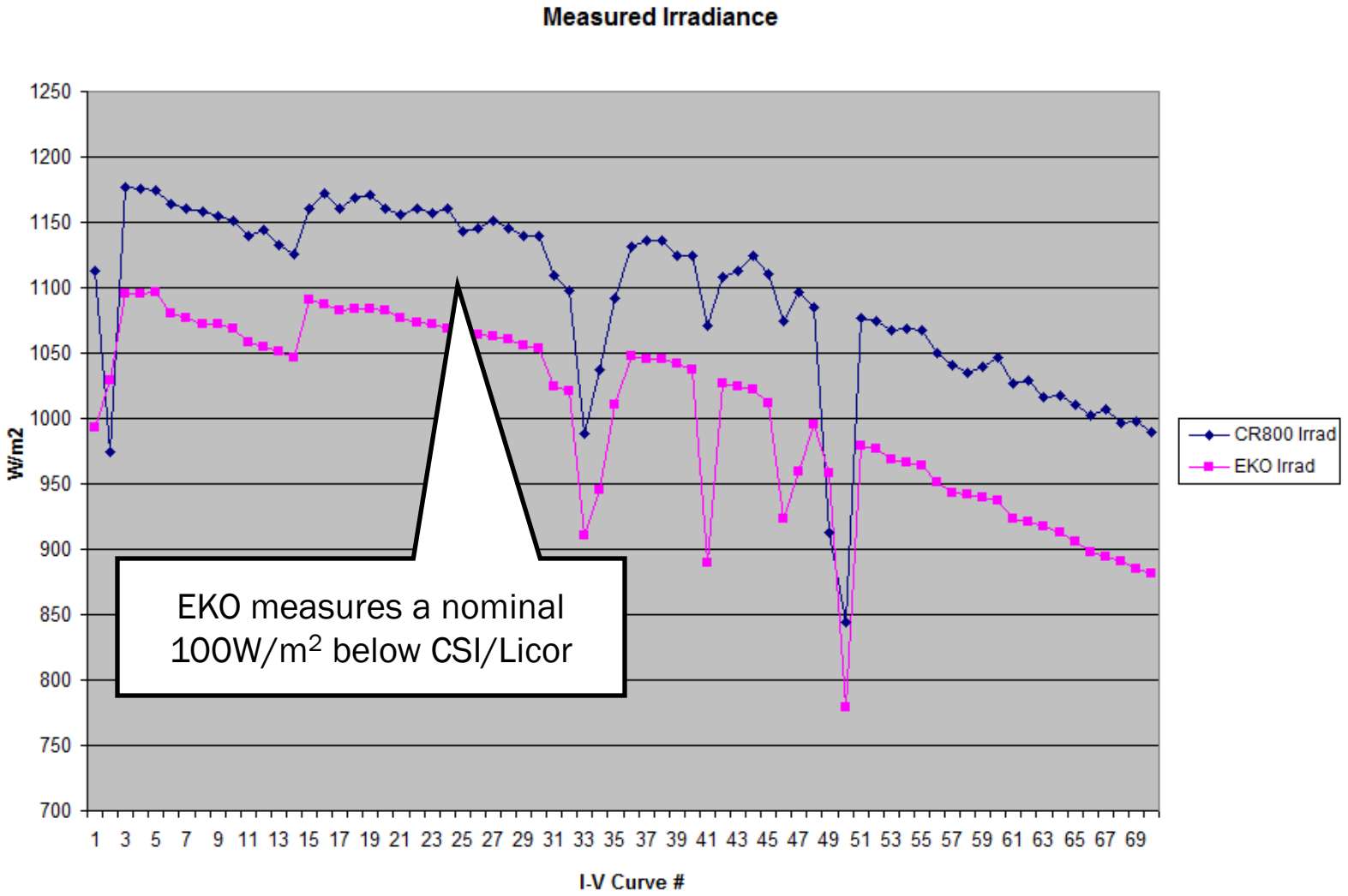
Gardner Massachusetts

Module Testing

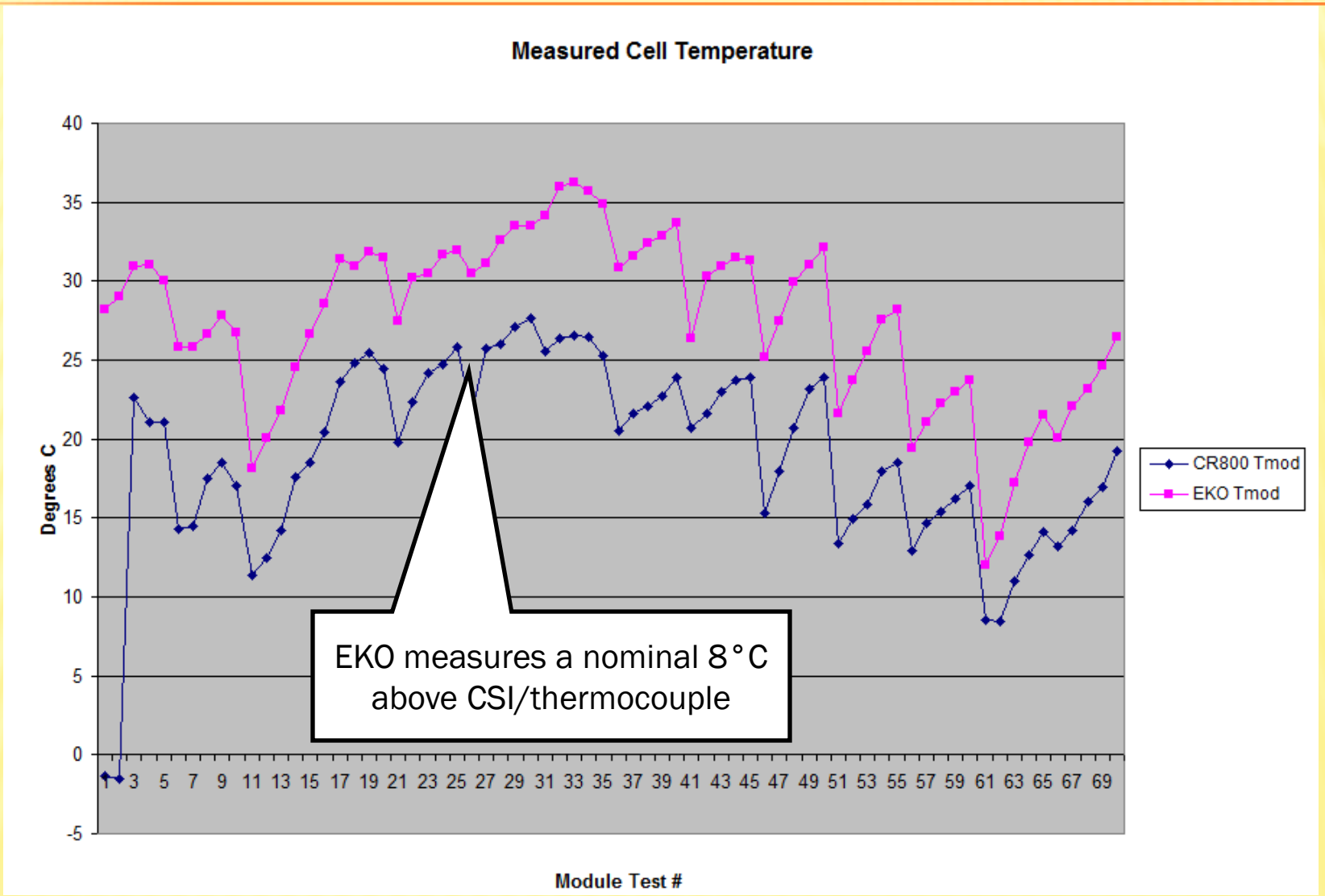
- For Retest:
  - Campbell Scientific CR800
  - POA Licor 200SZ
  - Two type K thermocouples
    - Cell temperature (Tc)
    - Ambient temperature (Ta)
  - Measure Isc & Voc



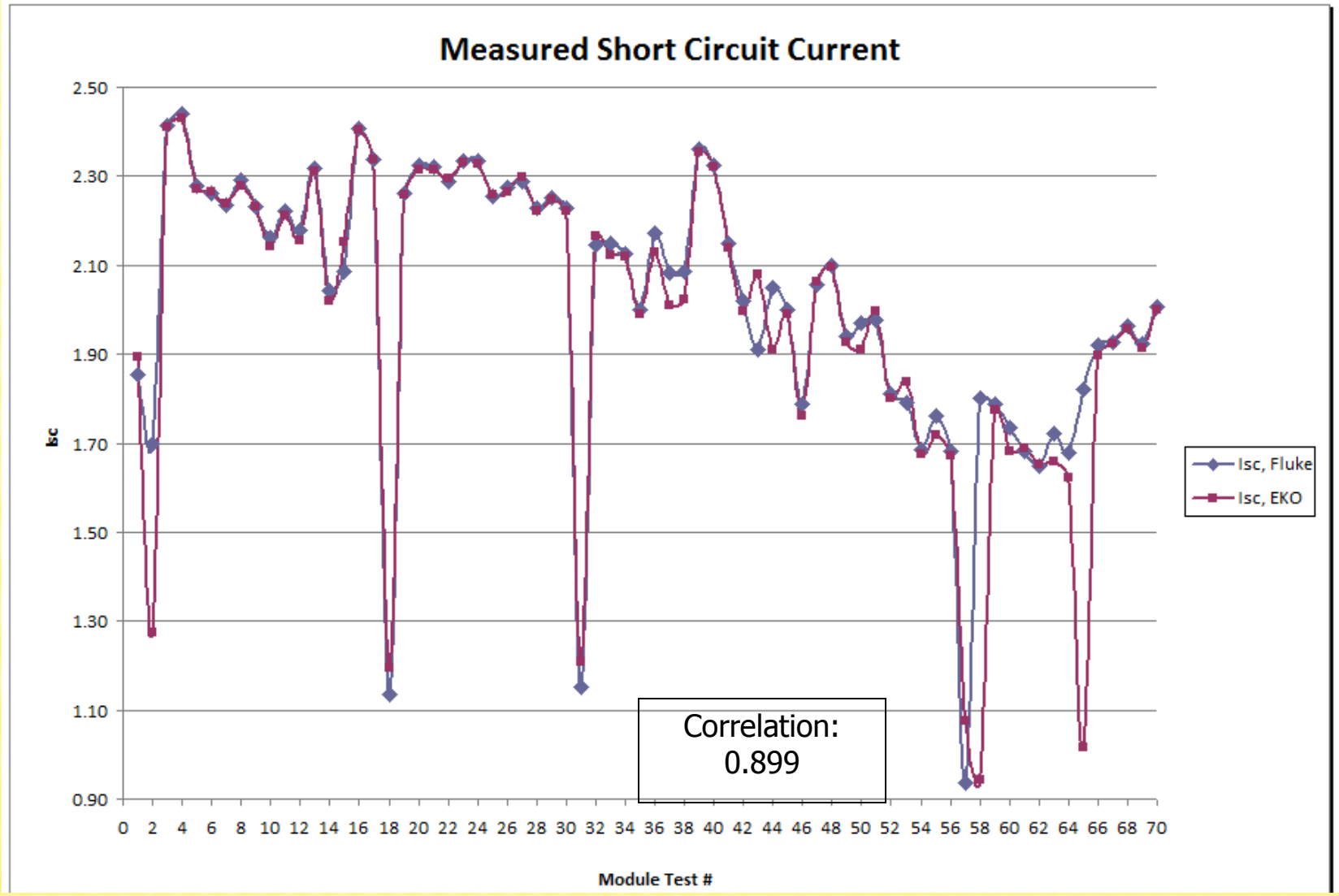
Comparison of Incident Irradiance: EKO I-V Curve Tracer vs. Campbell/Licor



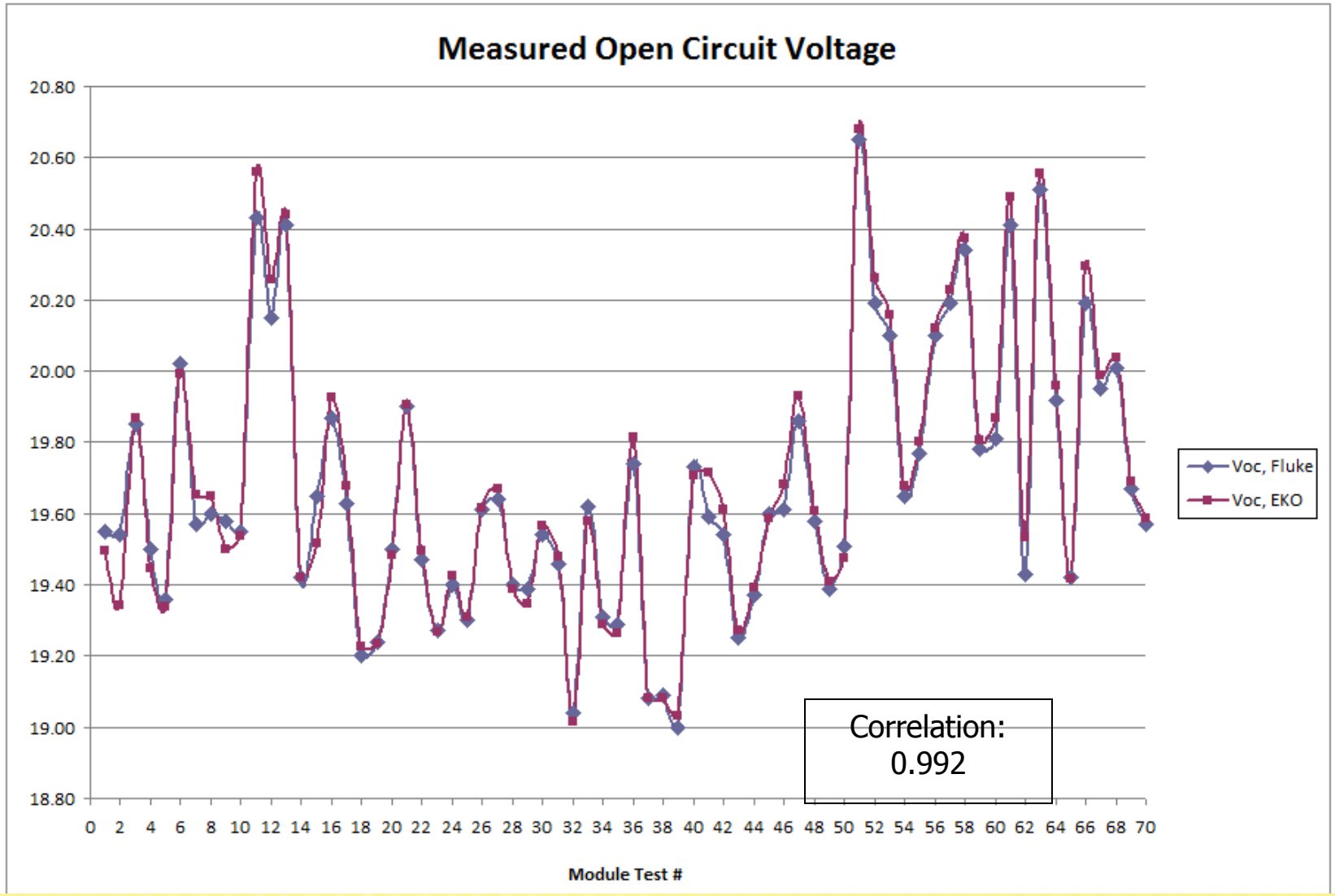
Comparison of Cell Temperature: EKO I-V Curve Tracer vs. Campbell/K Thermocouple



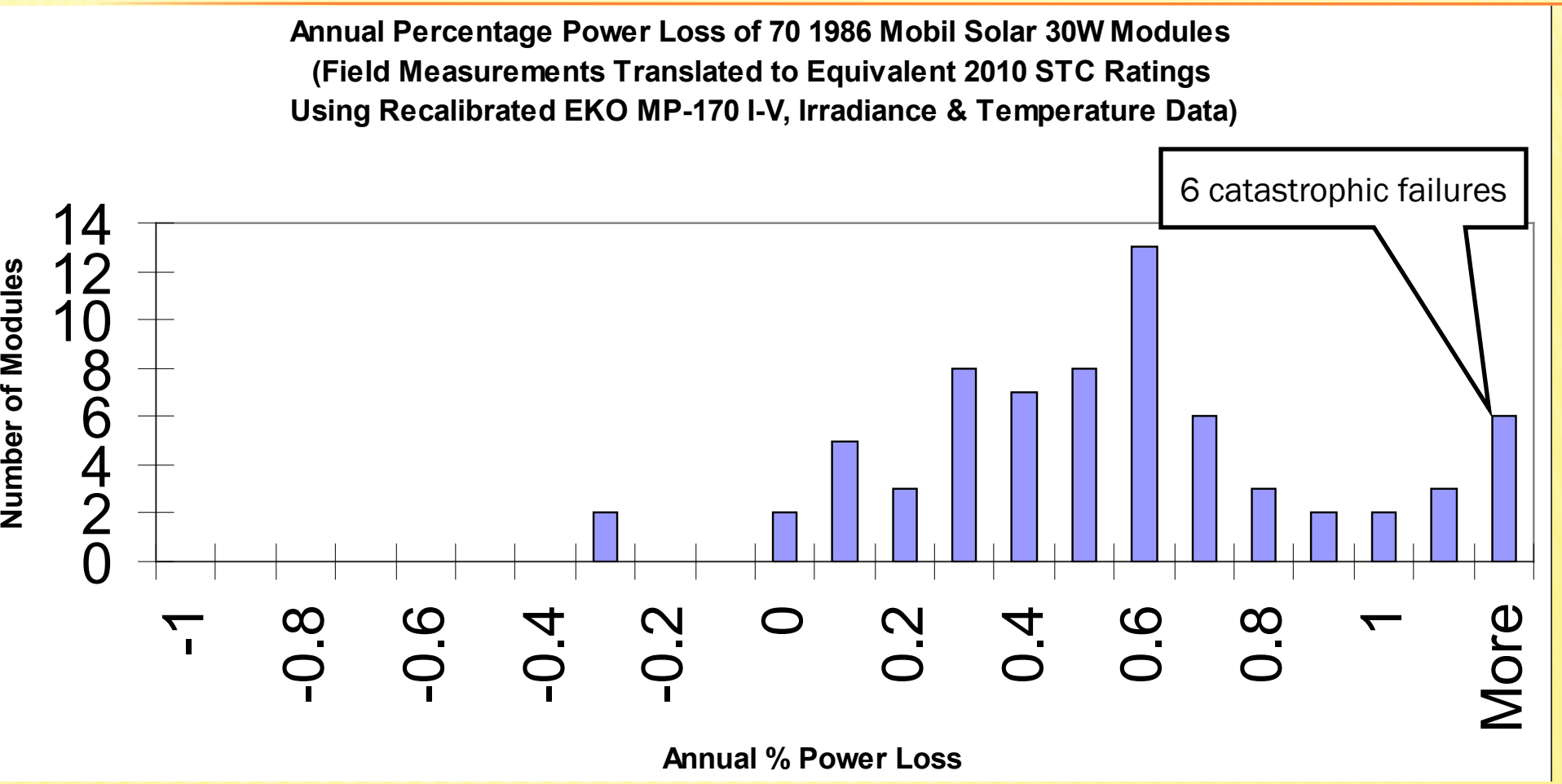
Comparison of Short Circuit Current: EKO I-V Curve Tracer vs. Fluke 83 III



Comparison of Open Circuit Voltage: EKO I-V Curve Tracer vs. Fluke 83 III



Percentage Power Loss Per Year
Mobil Solar Ra-30-12H Module Retest



Percentage Power Loss Per Year
Mobil Solar Ra-30-12H Modules

(Gardner, Massachusetts)

- Average annual power loss from original STC rating for 30W for all tested modules: 0.575%
- Median annual power loss from original STC rating for 30W for all tested modules: 0.499%

Conclusions
&
Future Work

Conclusions

- Yes, silicon modules –at least the ones that we looked at-- really do last more than 20 years.
- It may be the case that some of the Mobil Solar modules that we examined started out their lives with substantially higher STC ratings than their data sheets indicated.
- Quantifying a rate of power loss is difficult if you are not certain of the original rating. You can't tell how far you have come unless you know where you started from.
- Know your instruments.

Future Work

- Calibration of EKO and Licor pyranometers
- Recalculation of annual % power loss for Solar Power Corp single crystal modules using corrected irradiance data from calibration
- Recalculation of annual % power loss for Mobil Solar polycrystalline modules using corrected irradiance data from calibration
- Three samples of each module will be flash tested at NREL
- Possible destructive testing of sample modules at NREL

Decades in the Installed Environment: Do Silicon Modules Really Last More than 20 Years?

NREL PV Module Reliability Workshop

James M. Bing, PE
President
NEO Virtus Engineering, Inc.
410 Great Road, B-6
Littleton, MA 01460
jbing@newenergyoptions.com
www.newenergyoptions.com

Breakout session:
CPV1
Discussion leaders: Peter Hebert & Greg Flynn

8:00 – Daryl Myers (NREL) – Solar Resource Data for CPV

8:30 – Matthew Muller (NREL) – Spectral Effects in CPV Performance

9:00 – Discussion of Solar Resource Issues for CPV

9:30 – Break

10:00 – Ian Aeby (Emcore) – Failure Modes of CPV Modules and How to Test for Them

10:30 – Nick Bosco (NREL) – Thermal and Current Cycling for CPV Qualification

11:00 – Discussion of Failure Modes in CPV

MYERS SUMMARY

- Measured data SPARSE and EPISODIC
- Specialized Measured Data available
- Measured-Model broadband difference patterns ~ 10% - 15% Typical
- Uncertainty Function of Site, INPUT data and REFERENCE DATA uncertainties
- Data Sources PROLIFERATING; benchmarking is a RESEARCH project !!
- International Energy Agency Task 36 on Solar Radiation Knowledge Management
http://www.iea-shc.org/task36/index.html
- U.S. Satellite (SUNY) Uncertainty comparable European Estimates (state of the art)

NOTE: MODELS CONTINUOUSLY EVOLVING !

Measurements AND models: Similar Uncertainty Limits:

5% - 10% Global Month Mean Daily Total

10%- 15% Direct Month Mean Daily Total

Statistics help, but this is essentially WEATHER data!

Rating Conditions: DNI ~ 900 W/m^2 appropriate compromise with GNI, Flat Plate ~ 1000, and DNI Reference spectrum

Muller Summary

- CPV module performance data clearly shows spectral sensitivity
  - Clearly defined AM response peak
  - Relative sensitivity to changing AM can be determined
- PVUSA ratings taken on a monthly basis vary from 5-10%, most likely a result of spectral sensitivity
- Spectral sensitivity, as measured through an AM correction factor for 2009 data, results in significant deviations in energy production.
  - 2.2% deviation between modules
  - 7% deviation between spectrally sensitive module and a module with a fixed efficiency
- Future work will examine specific impact of AM, PWV, and Turbidity on Normalized Isc

Discussion summary – CPV Spectral Issues

- Module sensitivity very dependent on optics and optical transfer function
  - varies between manufacturers
- Open question as to the source of AM-sensitivity variation
  - aerosols
  - thermal expansion can change the focus
  - water absorption changes the optics
  - temperature

continued...

- Need to revisit standards for measurement conditions
  - eg. actual cell temp or heat-sink temp
  - isotype cells instead of multijunction cells
- Proposal to package MJ reference cells with appropriate optics and deploy around the country
  - develop a more applicable data set
  - Is the data transferable if the cell design changes?

Aeby - In Conclusion

- Rel Prediction is a tough business.
- CPV modules and systems are complex and opportunities for failure abound.
  - Examples:
    - EL can help discriminate shunting problems in the various subcells
    - Observations of “thermal runaway” following ESD damage
    - Electrolytic corrosion at contacts almost always seen in damp-heat tests

- The IEC 62108 suite of CPV module/system qualification tests provide an excellent baseline for beginning-of-life performance but little insight into long-term reliability.
  - Accelerated Life Tests at high concentration levels are difficult to implement.
- Hermeticity at the receiver subassembly level is critical.

summary: I and T cycling for CPV qualification

Nick Bosco, Cassi Sweet, Adam Stokes and Sarah Kurtz

- IEC 62108 Section 10.6: Thermal Cycling cannot be executed as written.
- Additional temperature excursions due to current cycling does not accelerate damage.
- Current application up to 4A/cm^2 is benign to the cell though will cause failure if large cracks/voids exist under bus-bar.
  - Are these representative of on-sun failures?
  - Unacceptable amounts of and sized voids/cracks not detected through failure.

- Proposed amendments to IEC 62108 Section 10.6: Thermal Cycling
  - Current application should be reduced to when T>25 C (similar to IEC 61215).
  - Cell current density level should be reduced to 4 A/cm^2 or J_{sc}.
  - Additional requirement should limit the percentage of voids/cracks as detected via an appropriate imaging technique. Alternatively, modules should be subject to an on-sun exposure for a designated time and irradiance.

Discussion summary – CPV failure modes/mechanisms

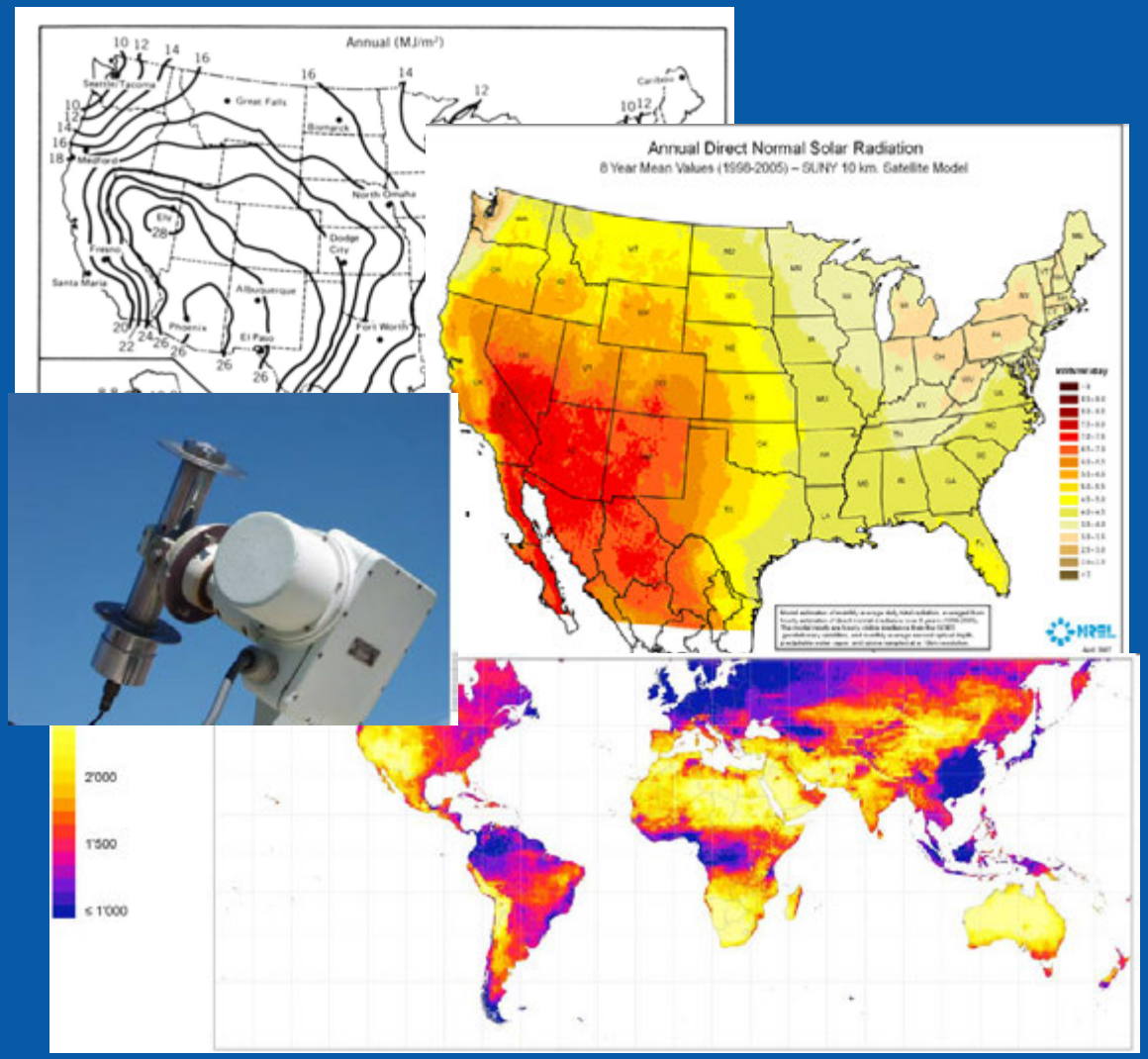
- Thermal stresses between cell and substrate/dye vs stresses within cell
- 62108 under revision
- “Hermiticity” - how is it defined for the module vs the receiver
  - do we need a better test than wet-insulation qual test?
  - biased damp-heat test would be more informative

continued...

- General observations that real cell/receiver damage may not be reflected in the IV curves
  - eg. EL or IR images show voids despite good performance of the cell
  - Future work to estimate on-sun lifetime of these damaged cells

National Renewable Energy Laboratory
Innovation for Our Energy Future

Solar Resources For Concentrating PV (CPV)



PV Module Reliability Workshop
Golden CO

Daryl R. Myers
National Renewable Energy Laboratory
Electricity, Resources, and Buildings Systems Integration Center

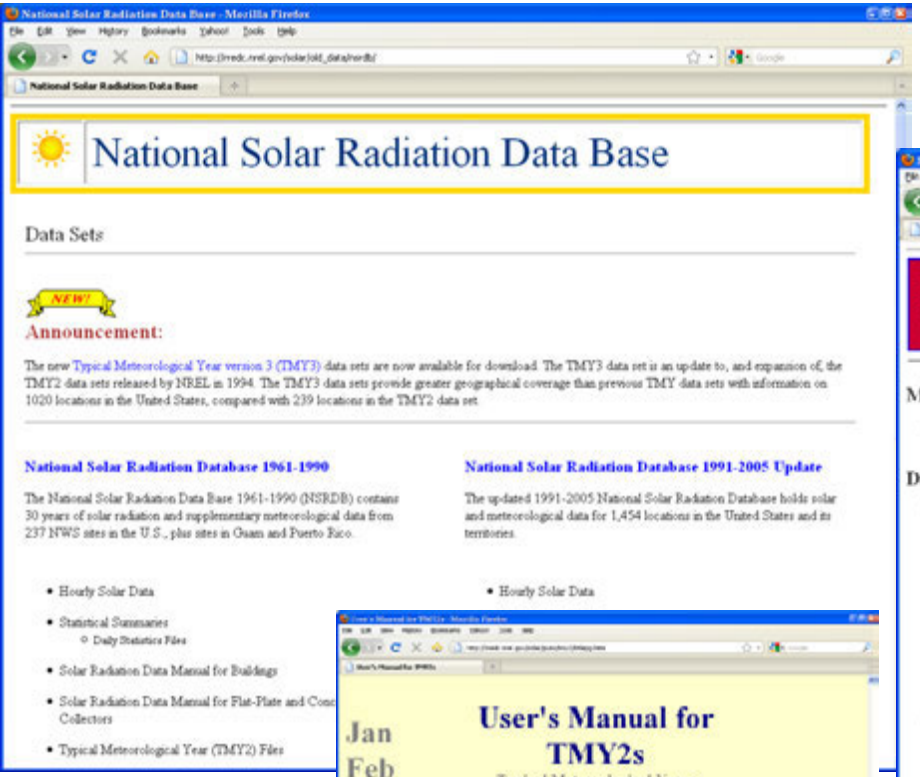
daryl.myers@nrel.gov
303-384-6768

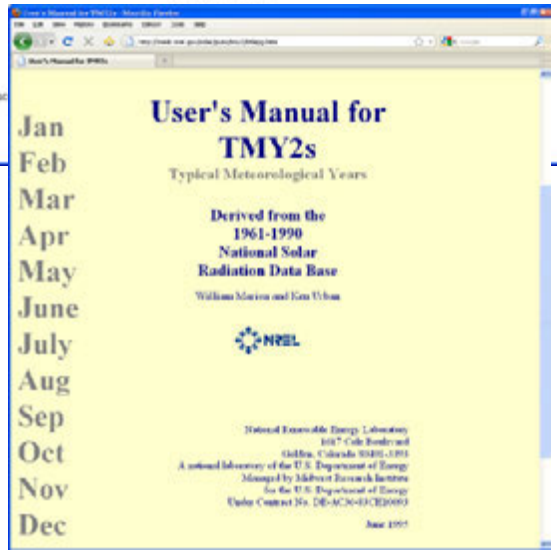
Feb 19 2010

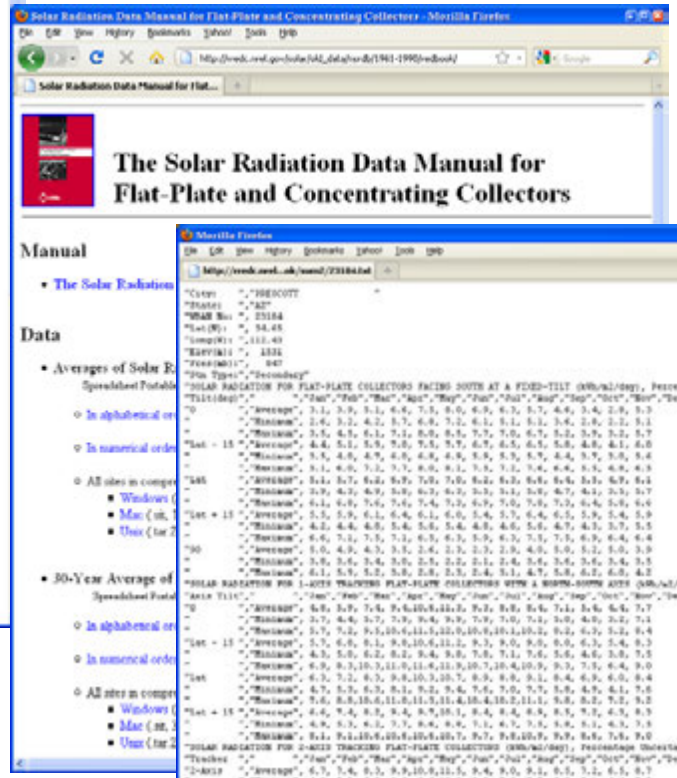
This presentation does not contain any proprietary or confidential information.

National Solar Radiation Data Base

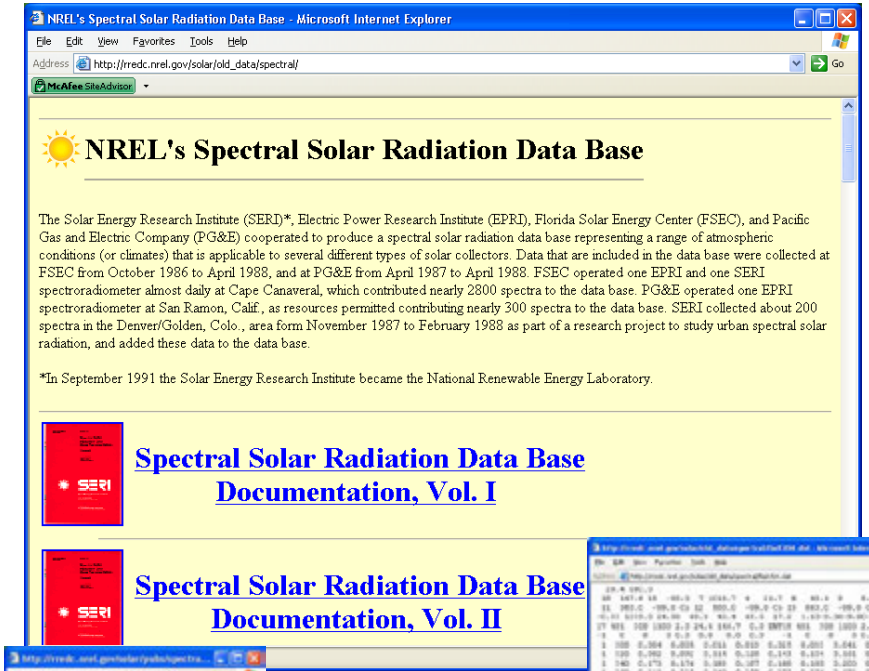
~ 97% modeled broadband hourly data
Collector modes: Perez Anisotropic Model
Global ~ ±10%, DNI ~±15%

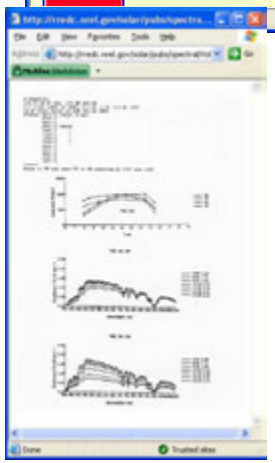




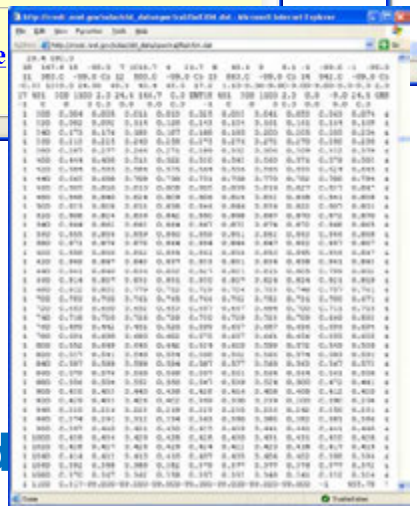


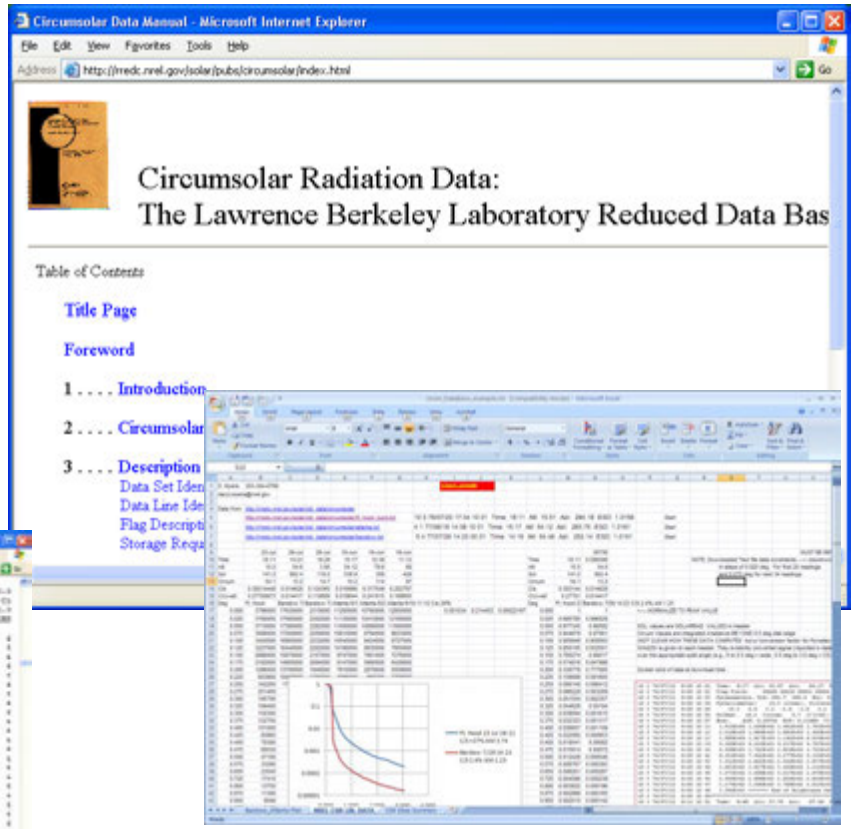
Special Data Sets: Circumsolar and Spectral





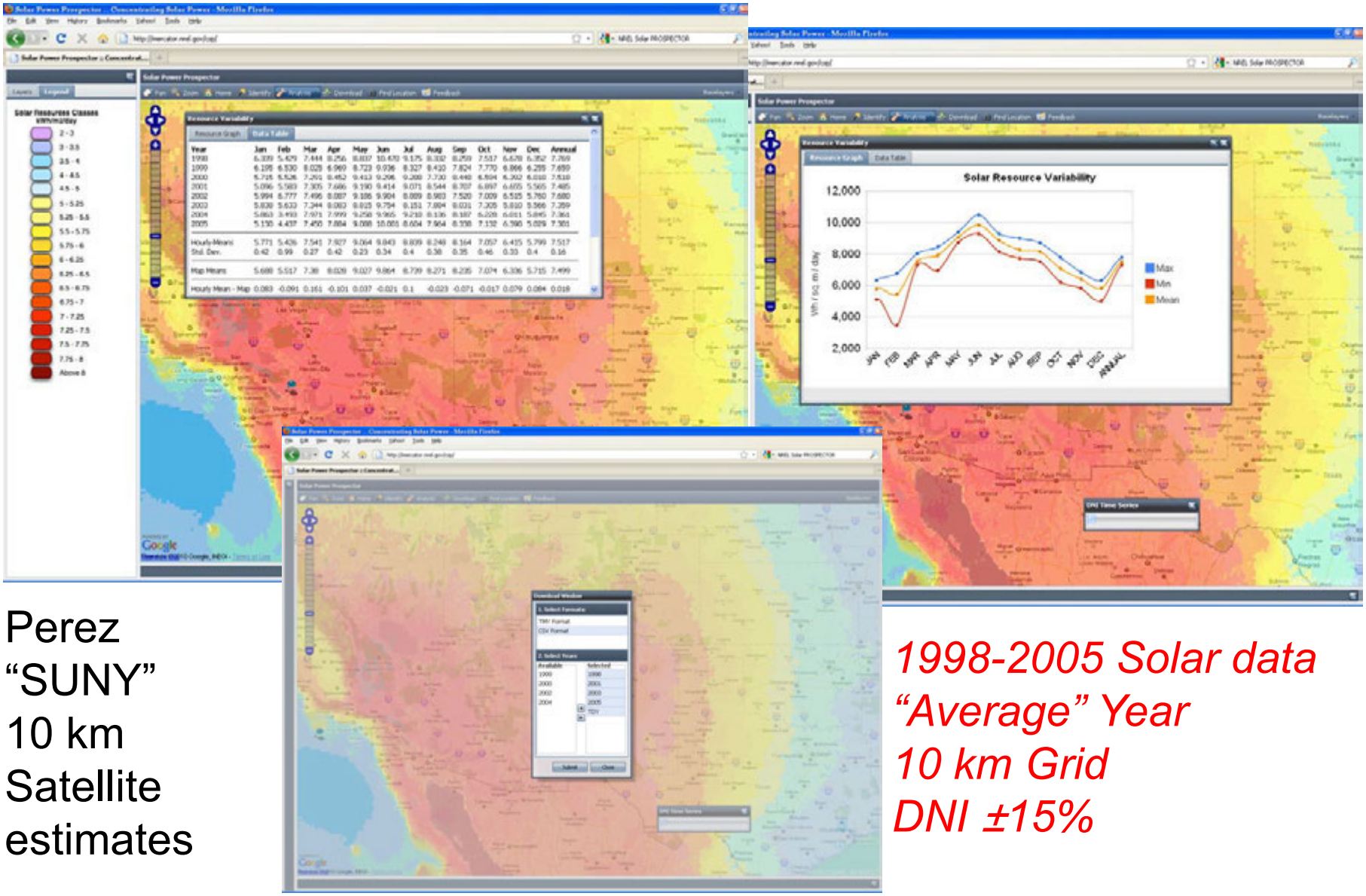
3000 spectra
CA, FL, CO
DNI, Global tilt,GNI, and GHZ





179,000 Circumsolar profile scans
0.025° steps
11 locations

NREL Solar Prospector: **http://mercator.nrel.gov/csp/**



Perez
"SUNY"
10 km
Satellite
estimates

1998-2005 Solar data
"Average" Year
10 km Grid
DNI ±15%

Typical GNI DNI Summary Data

(Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors)

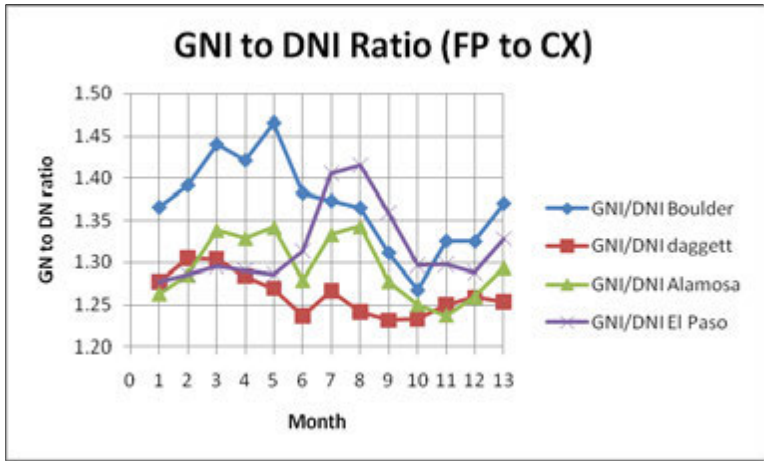
Entries for Boulder CO

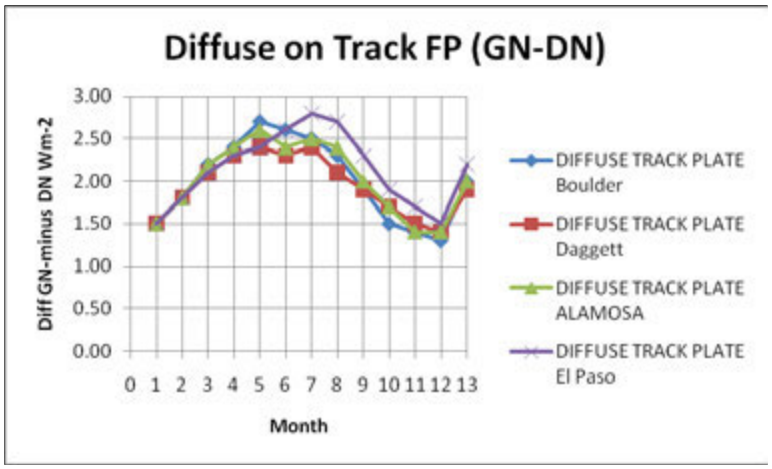
SOLAR RADIATION FOR 2-AXIS TRACKING FLAT-PLATE COLLECTORS (kWh/m2/day), Percentage Uncertainty = 9														
Tracker		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2-Axis	**Average**	**5.6**	**6.4**	**7.2**	**8.1**	**8.5**	**9.4**	**9.2**	**8.6**	**8**	**7.1**	**5.7**	**5.3**	**7.4**

DIRECT BEAM SOLAR RADIATION FOR CONCENTRATING COLLECTORS (kWh/m2/day), Percentage Uncertainty = 8														
Tracker		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2-X	**Average**	**4.1**	**4.6**	**5**	**5.7**	**5.8**	**6.8**	**6.7**	**6.3**	**6.1**	**5.6**	**4.3**	**4**	**5.4**

Example Ratios GNI/DNI

GNI/DNI Boulder	1.37	1.39	1.44	1.42	1.47	1.38	1.37	1.37	1.31	1.27	1.33	1.33	1.37
GNI/DNI daggett	1.28	1.31	1.30	1.28	1.27	1.24	1.27	1.24	1.23	1.23	1.25	1.26	1.25
GNI/DNI Alamosa	1.26	1.29	1.34	1.33	1.34	1.28	1.33	1.34	1.28	1.25	1.24	1.26	1.29
GNI/DNI El Paso	1.28	1.29	1.30	1.29	1.29	1.31	1.41	1.42	1.36	1.30	1.30	1.29	1.33





Previous Analysis: Kurtz et at. 1990

Summary of data observed for all of the sites studied[a]

Site	PPR DNI (W/m²)	Latitude (°)	Longitude (°)	Altitude (m)	# hours	GNI (kWh/m²)	DNI (kWh/m²)	DNI/GNI	Kt	PPR T (°C)	Annual T (°C)	PPR Wind (m/s)	Annual Wind (m/s)
Alamosa, CO	875	37.5	105.9	2297	13,734	8.8	6.8	0.773	0.638	16.1	5.1	3.1	3.8
Flagstaff, AZ	870	35.01	111.6	2135	10,974	8.4	6.4	0.762	0.607	16.7	7.7	4.1	2.7
Prescott, AZ	867	34.65	112.4	1531	11,980	8.7	6.8	0.782	0.627	21.8	11.7	4.1	3.6
Cheyenne, WY	865	41.15	104.8	1872	10,205	7.3	5.2	0.712	0.562	17.8	7.6	6.2	5.8
Elko, NV	863	40.83	115.8	1547	10,516	7.5	5.5	0.733	0.582	20.0	8.2	3.1	2.7
Ely, NV	861	39.28	114.9	1906	10,309	8.1	6.0	0.741	0.608	18.2	7.0	4.1	4.3
Kahului, HI	861	20.9	156.4	15	11,952	8.0	5.8	0.725	0.577	28.2	24.2	8.8	6.1
Daggett, CA	860	34.87	116.8	588	16,115	9.4	7.5	0.801	0.681	27.2	19.8	5.2	5.1
Cedar City, UT	853	37.7	113.1	1762	11,078	8.3	6.2	0.747	0.614	20.6	10.3	4.1	3.4
Winnemucca, NV	853	40.9	117.8	1323	11,205	7.7	5.6	0.727	0.596	22.2	9.5	4.1	3.7
Tonopah, NV	852	38.07	117.1	1653	12,852	8.6	6.7	0.779	0.638	20.2	10.6	4.1	4.1
Tucson, AZ	851	32.12	110.9	779	14,605	9.0	7.0	0.778	0.653	28.9	20.2	3.6	3.9
Reno, NV	849	39.5	119.8	1341	12,582	8.2	6.2	0.756	0.621	20.9	10.4	2.6	3.1
Rock Springs, WY	849	41.5	108.5	2056	10,319	7.6	5.4	0.711	0.587	18.3	5.9	5.2	4.8
Grand Junction, CO	845	39.12	108.5	1475	12,475	8.0	5.9	0.738	0.616	23.3	11.7	3.6	3.5
Lewiston, MT	843	47.05	109.5	1264	7,883	6.5	4.4	0.677	0.541	18.0	5.8	3.6	4.2
Tucumcari, NM	841	35.18	103.6	1231	12,266	8.3	6.1	0.735	0.616	24.1	14.3	5.2	4.4
Albuquerque, NM	836	35.05	106.6	1619	11,484	8.8	6.7	0.761	0.658	22.2	13.4	3.6	4.1
Anchorage, AK	836	61.7	150.0	35	2,847	4.0	2.3	0.575	0.427	14.4	2.2	2.6	3.1
Las Vegas, NV	834	36.08	115.2	664	12,804	9.1	7.1	0.780	0.675	26.7	19.5	3.6	4.4
Amarillo, TX	832	35.23	101.7	1098	11,518	7.9	5.8	0.734	0.595	24.4	13.8	6.7	6.0
Bismarck, ND	827	46.77	100.8	502	9,692	6.6	4.5	0.682	0.553	21.7	5.3	5.2	4.3
Lubbock, TX	825	33.65	101.8	988	11,191	7.9	5.7	0.722	0.594	25.8	15.6	6.2	5.6
El Paso, TX	821	31.8	106.4	1194	14,476	8.9	6.7	0.753	0.656	26.7	17.3	3.1	3.4
Abilene, TX	821	32.43	99.7	534	11,190	7.7	5.5	0.714	0.584	27.2	18.1	5.7	5.0
Wichita Falls, TX	821	33.97	98.5	314	10,973	7.4	5.2	0.703	0.572	27.4	17.2	6.2	5.2
Midland, TX	819	31.93	102.2	871	10,914	8.1	5.9	0.728	0.610	27.8	17.4	6.2	5.1
Santa Maria, CA	818	34.9	120.5	72	16,733	7.8	5.7	0.731	0.610	19.4	14.1	5.2	3.2
San Angelo, TX	817	31.37	100.5	582	11,191	7.7	5.5	0.714	0.584	28.3	18.3	5.2	4.6
Sacramento, CA	814	38.52	121.5	8	13,662	7.6	5.5	0.724	0.606	25.4	16.0	3.6	3.2
Phoenix, AZ	814	33.43	112.0	339	13,908	8.9	6.8	0.764	0.665	30.6	22.6	3.1	3.0
Bakersfield, CA	813	35.42	119.1	150	13,925	7.9	5.7	0.722	0.617	27.8	18.6	3.6	3.0
Honolulu, HI	810	21.33	157.9	5	10,966	7.7	5.2	0.675	0.569	27.8	25.1	6.2	4.9
Fresno, CA	806	36.77	119.7	100	14,548	7.8	5.6	0.718	0.622	27.2	17.4	3.1	2.9
Fort Worth, TX	806	32.83	97.05	164	11,188	7.2	4.8	0.667	0.564	27.9	18.6	5.2	4.9
Austin, TX	806	30.3	97.7	189	9,319	7.0	4.6	0.657	0.547	28.1	20.3	4.6	4.0
San Antonio, TX	789	29.53	98.47	242	9,984	7.0	4.5	0.643	0.554	28.9	20.3	4.6	4.1
Mean	**836**	**36.17**	**112.8**	**931**	**11,718**				**0.601**	**23.7**	**14.1**	**4.5**	**4.1**
Standard deviation	22	6.84	14.6	711	2405				0.047	4.4	5.9	1.4	0.9
Median	836									24.4		4.1	

[a]PPR DNI = median DNI for GNI between 975 and 1025 W/m²; # hours = number of data points. GNI and DNI = the average daily energy [14,15], and the DNI/GNI column shows their ratio; Kt is the global clearness index; PPR T and PPR Wind = median temperature and wind speed, respectively, for GNI between 975 and 1025 W/m². Annual T and Annual Wind = annual temperature and wind speed from the NSRDB [14,15].

S.R. Kurtz et al. / Solar Energy Materials & Solar Cells 62 (2000) 379–391

What is DNI for GNI at SRC?

Mean GNI
1000 ± 25 W^{-2}

Avg *MEDIAN*
DNI 836 Wm^{-2}

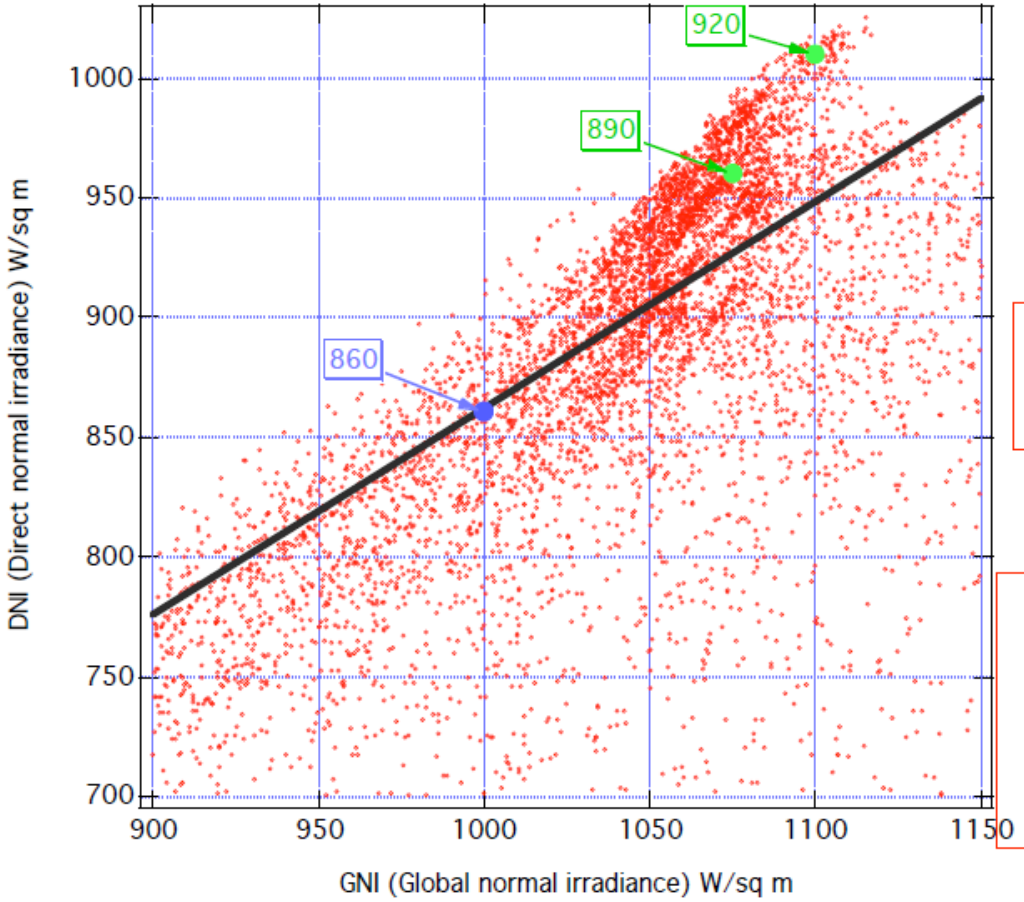
Power rating – 850 or 1000 W/m²?

Flat plate

- 1000 W/m²

CPV

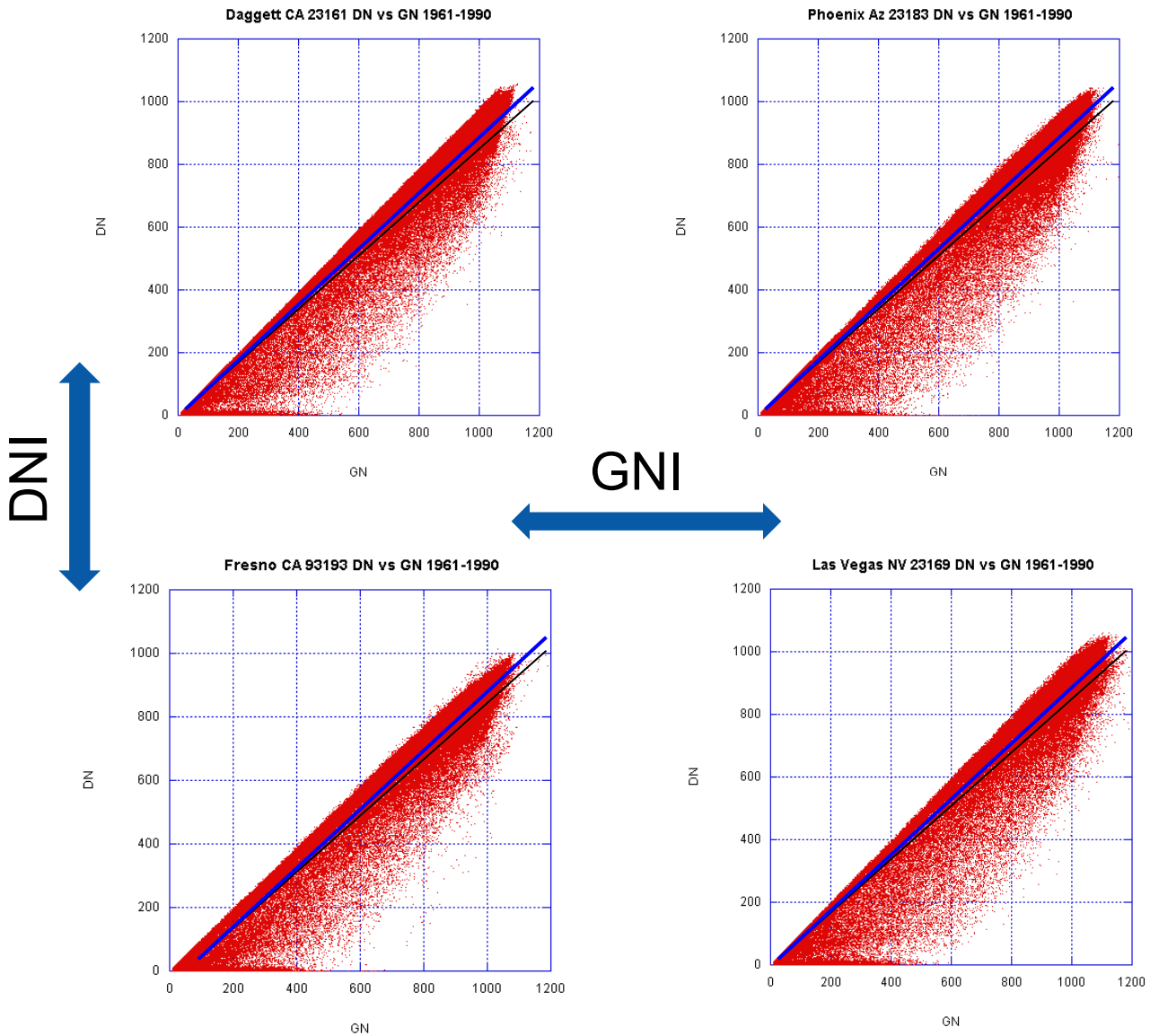
- 850 W/m²



Data taken in Golden, CO

Tags give ratio of DNI/GNI normalized to 1000 W/m²

Example DNI Vs GNI ALL Hours ~ 120,000

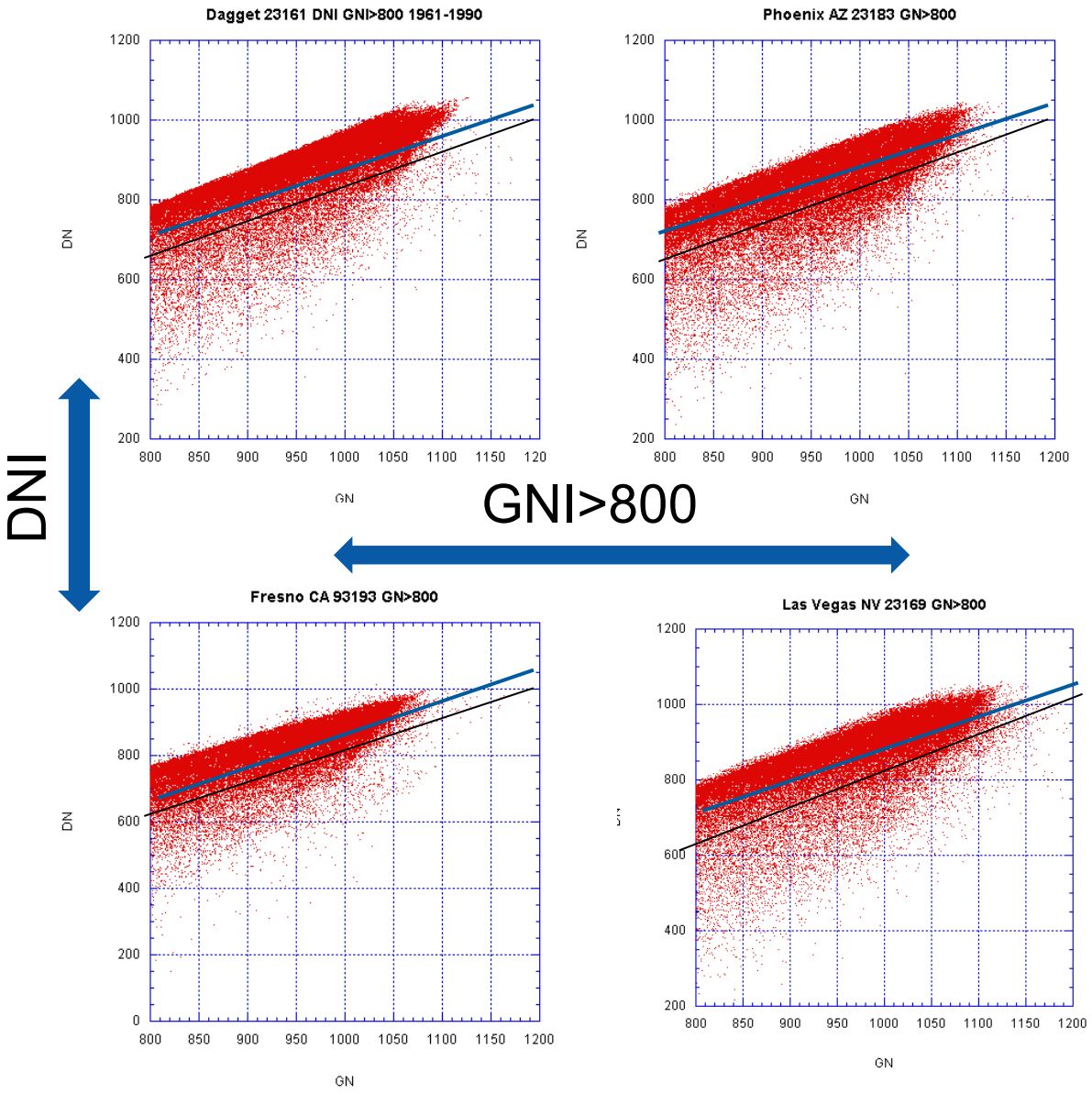


GNI model from NSRDB Glo,Beam, Diff with Perez Anisotropic model

DNI/GNI
0.874

DNI/GNI
0.836

Example DNI Vs GNI>800 Wm^{-2}



DNI/GNI
0.874

DNI/GNI
0.836

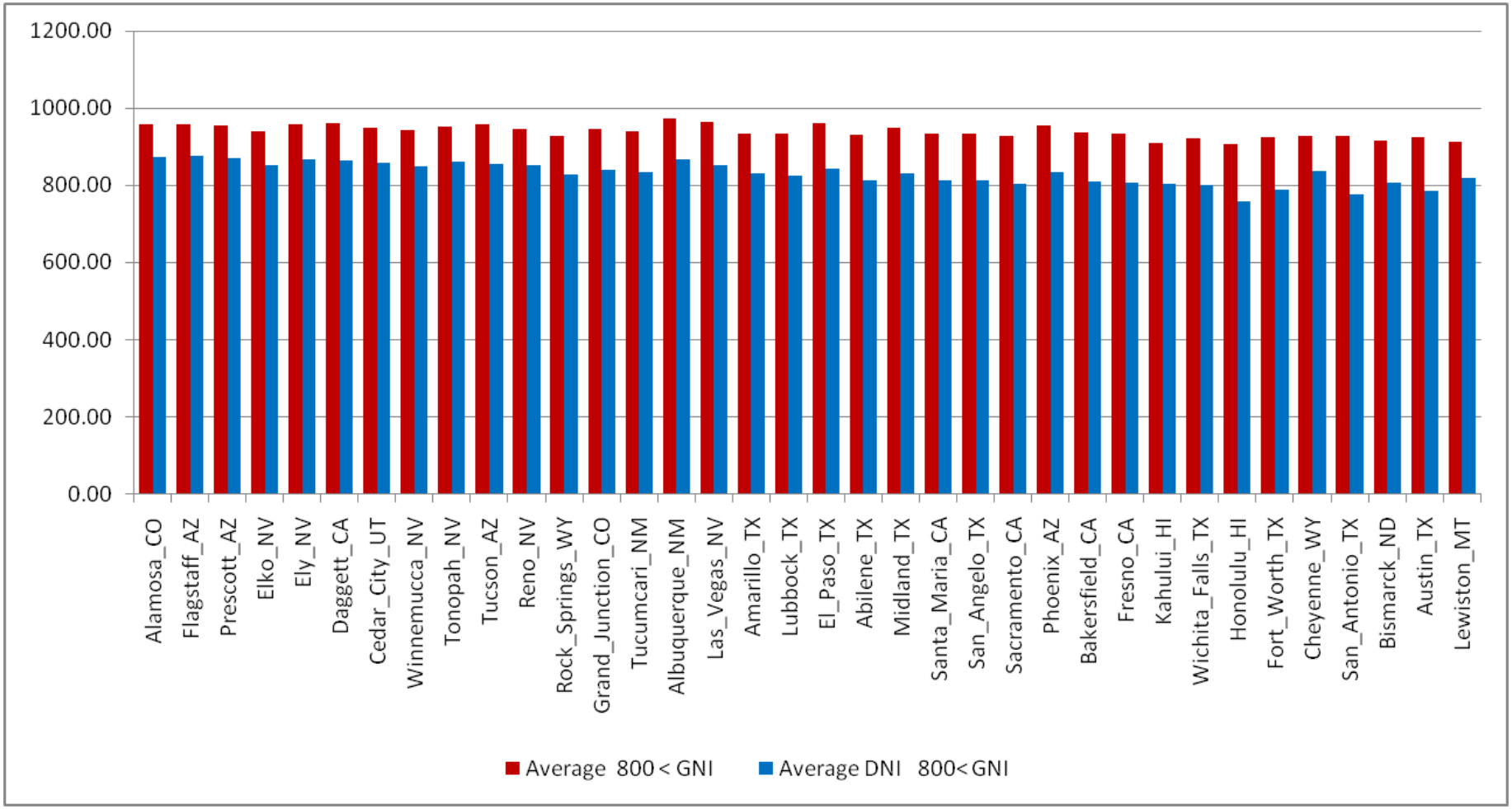
Averages 36 Sites, 30 yr hourly GNI> 800 Wm^{-2}

STATION	Lat	Long	AVG GNI > 800	Stdev GNI	AVG DNI GNI >800	V DNI GNI	GNI/DNI (GNI>	V G/D GNI	COUNT
Alamosa_CO	37.5	-105.8	956.94	82.05	874.75	115.83	1.11	0.11	57934
Flagstaff_AZ	35.1	-111.8	956.91	83.06	876.45	108.62	1.10	0.09	50947
Prescott_AZ	34.7	-112.5	955.27	81.19	870.39	107.92	1.11	0.10	56419
Elko_NV	40.8	-115.8	940.35	75.84	853.20	101.82	1.11	0.09	42136
Ely_NV	39.3	-114.9	958.01	82.76	868.63	116.97	1.12	0.13	49065
Daggett_CA	35.4	-119	959.86	77.04	864.55	101.02	1.12	0.11	67184
Cedar_City_UT	37.7	-113	949.10	79.31	856.71	108.39	1.12	0.11	50680
Winnemucca_NV	40.9	-117.8	944.09	76.03	849.57	101.24	1.12	0.10	44429
Tonopah_NV	38	-117.1	953.04	79.93	861.53	104.64	1.12	0.10	55544
Tucson_AZ	32.1	-110.9	956.73	77.68	856.41	105.95	1.13	0.12	62831
Reno_NV	39.5	-119.8	947.04	76.40	850.84	98.45	1.12	0.10	50218
Rock_Springs_WY	41.5	-109	927.86	74.73	826.72	109.85	1.13	0.12	38236
Grand_Junction_(	39.1	-108.5	946.55	78.10	841.33	114.10	1.14	0.15	48786
Tucumcari_NM	35.2	-103.5	939.32	75.42	833.42	109.66	1.14	0.12	47069
Albuquerque_NM	35	-106.5	972.12	83.31	866.24	117.12	1.14	0.14	61065
Las_Vegas_NV	36.1	-115.2	963.55	81.77	853.26	105.54	1.14	0.14	63730
Amarillo_TX	35.2	-101.7	934.41	72.50	829.96	105.01	1.14	0.11	47923
Lubbock_TX	33.6	-101.8	933.98	72.99	823.50	107.88	1.15	0.12	47198
El_Paso_TX	31.8	-106.5	959.59	78.95	843.60	113.65	1.15	0.16	60792
Abilene_TX	32.5	-99.8	931.70	71.50	812.27	109.19	1.16	0.13	45168
Midland_TX	31.9	-102.2	947.56	76.42	830.11	116.65	1.16	0.15	51542
Santa_Maria_CA	34.9	-120.5	935.33	68.42	814.10	91.70	1.16	0.11	50523
San_Angelo_TX	31.4	-100.5	933.04	72.03	813.77	109.71	1.16	0.13	45630
Sacramento_CA	38.5	-121.5	929.26	69.07	804.46	86.51	1.16	0.10	44286
Phoenix_AZ	33.5	-112	955.11	78.27	832.80	102.04	1.16	0.13	61909
Bakersfield_CA	35.5	-119	935.99	71.93	808.45	90.80	1.17	0.10	47259
Fresno_CA	46.6	-119.8	935.14	71.08	807.41	92.30	1.17	0.12	46850
Kahului_HI	20.9	-156.5	910.09	62.11	802.94	95.05	1.14	0.10	44970
Wichita_Falls_TX	33.9	-98.5	922.91	68.56	801.22	107.14	1.17	0.13	41522
Honolulu_HI	21.3	-157.9	905.50	63.44	758.18	105.06	1.21	0.15	36966
Fort_Worth_TX	32.8	-97.1	926.24	69.38	789.85	120.03	1.20	0.17	39765
Cheyenne_WY	41.2	-104.8	927.11	71.68	837.23	101.14	1.12	0.10	38131
San_Antonio_TX	29.5	-98.5	926.76	70.33	776.17	127.49	1.22	0.19	37249
Bismarck_ND	46.3	-100.8	914.89	65.22	806.72	96.15	1.15	0.12	31778
Austin_TX	30.3	-97.7	923.59	69.85	786.33	117.60	1.19	0.15	37194
Lewiston_MT	47	-109.5	911.32	66.28	818.68	93.57	1.12	0.09	27507
		Average	939.62		830.60				

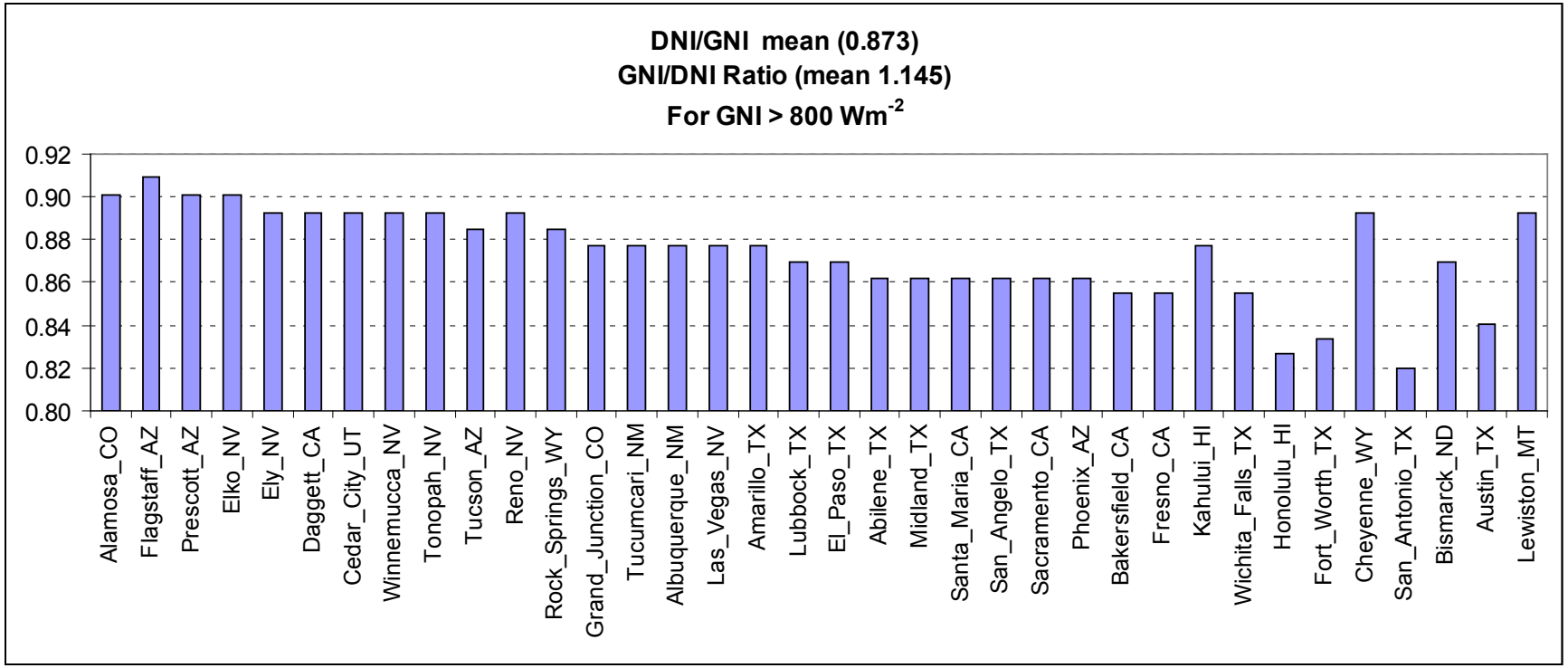
Mean GNI
939.6 ± 70

Mean DNI
830.6 ± 100

Summary GNI> 800 Wm^{-2}



Summary DNI/GNI for GNI> 800

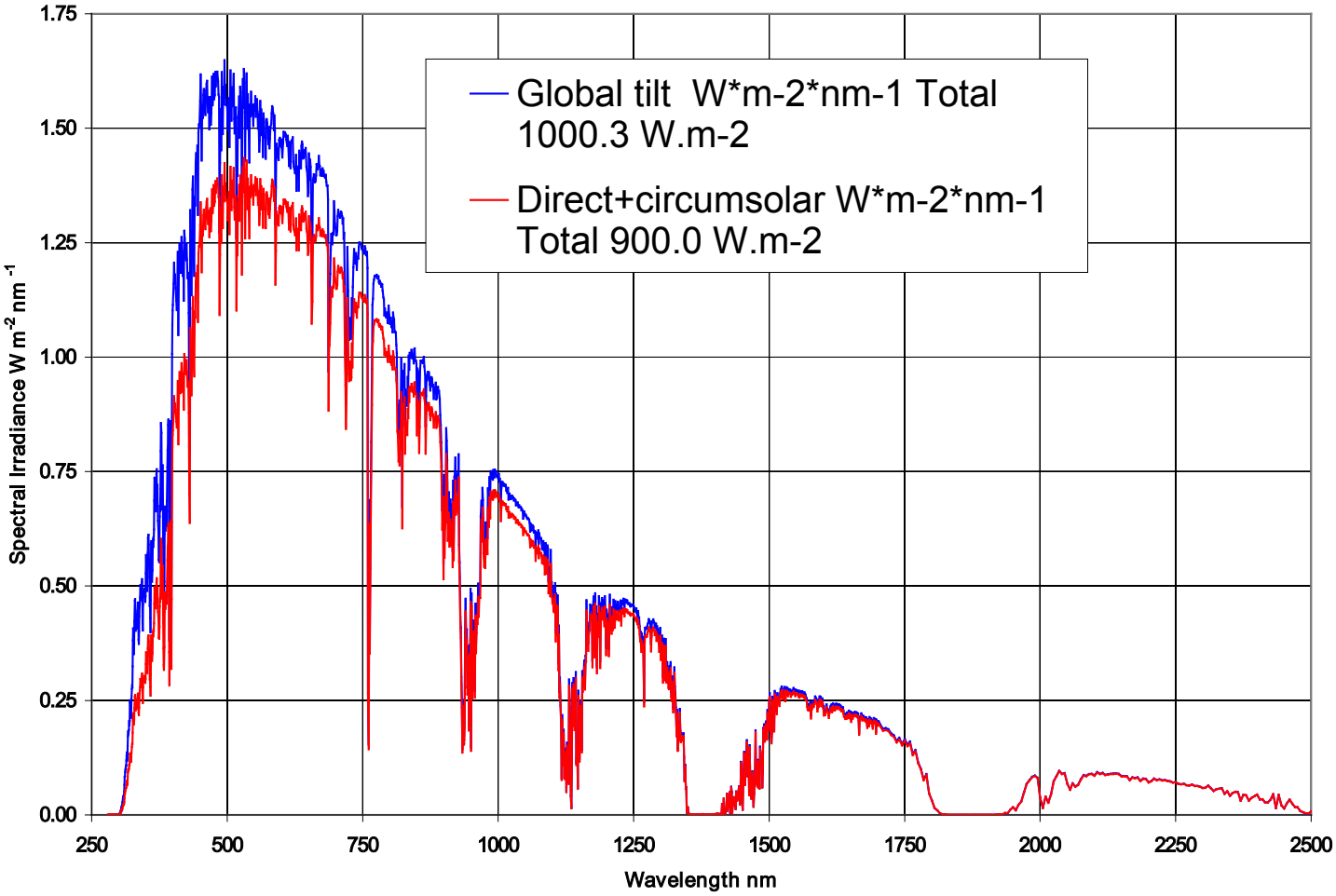


GNI ~ 1000 Wm^{-2}=> DNI ~ 873 Wm^{-2}

ASTM G 173 AND ISO REF SPECTRAL STD :

Global “Tilt = 37°” = 1000 Wm^{-2}

DNI for same conditions = 900 Wm^{-2}



Uncertainty

MEASUREMENTS

U_{meas} (±%)

Global	Direct	Diffuse
6	5	6

MODELS

U_{mod} (±%)

Model	Glo/Dif RMS (U_{mod})	Glo/Dif MBE (U_{bias})	Dir RMS (U_{mod})	Dir MBE (U_{bias})
METSTAT	8	2	15	4
SUNY	5	0	14	1

$$U_{opt} = (U_{meas}^2 + U_{mod}^2 + U_{bias}^2)^{1/2} \ (\pm\%)$$

U_{opt} (±%)

Model	Glo/Dif	Dir
METSTAT	10	16
SUNY	8	15

U_{add} Satellite (±%)

Condition	Additional Uncertainty
Time shifting	2
Ground snow cover	5
High latitude	10

U_{add} METSTAT (±%)

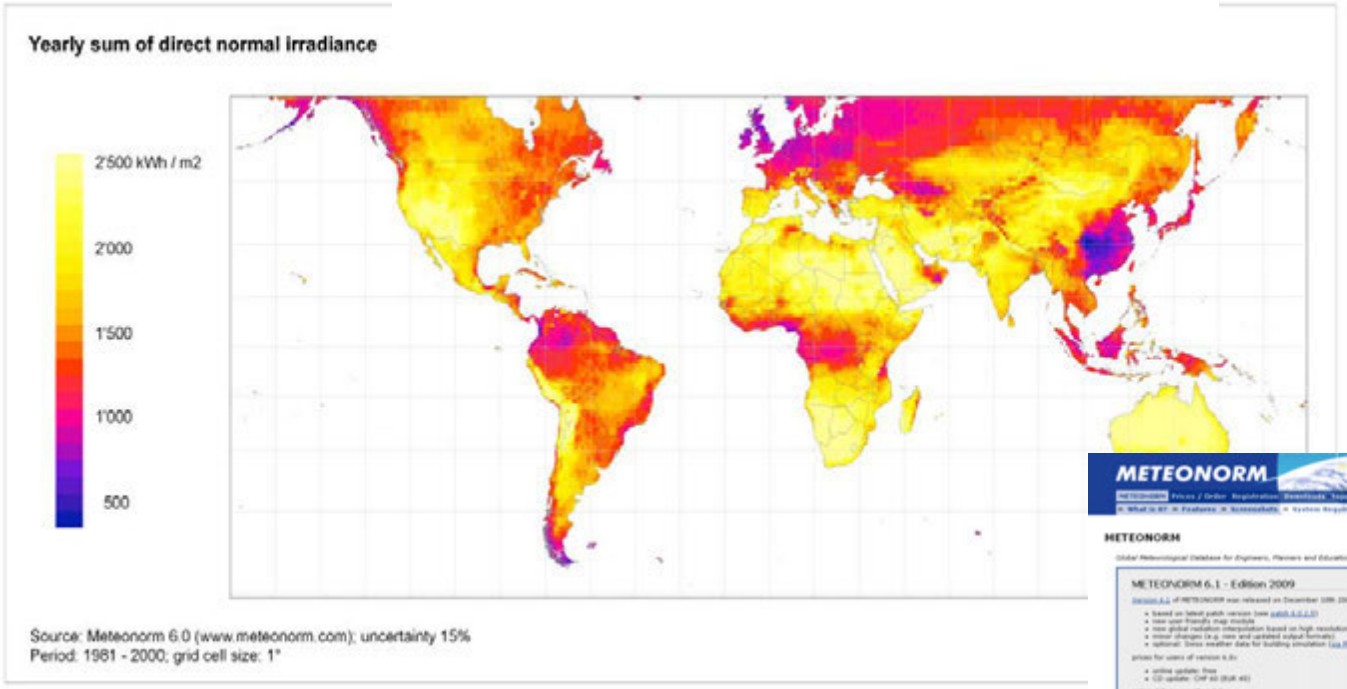
Condition	Additional Uncertainty
Short- and med-termfilling	4
Long-term filling	14
Cloud probability derivation	4
Cloud probability nearby site	4
ASOS-only	22

$$U_{95} = (U_{opt}^2 + U_{add1}^2 + U_{add2}^2 \ldots)^{1/2} \ (\pm\%)$$

Sanity Check: Other Methods; Meteonorm

DIRECT

Source: Meteonorm 6.0 (www.meteonorm.com); uncertainty 15%
Period: 1981 - 2000; grid cell size: 1°





Analysis 6 Solar Databases Europe

Šúri1, et al., "First Steps in the Cross-Comparison of Solar Resource Spatial Products in Europe" *Proceeding of the EUROSUN 2008,*

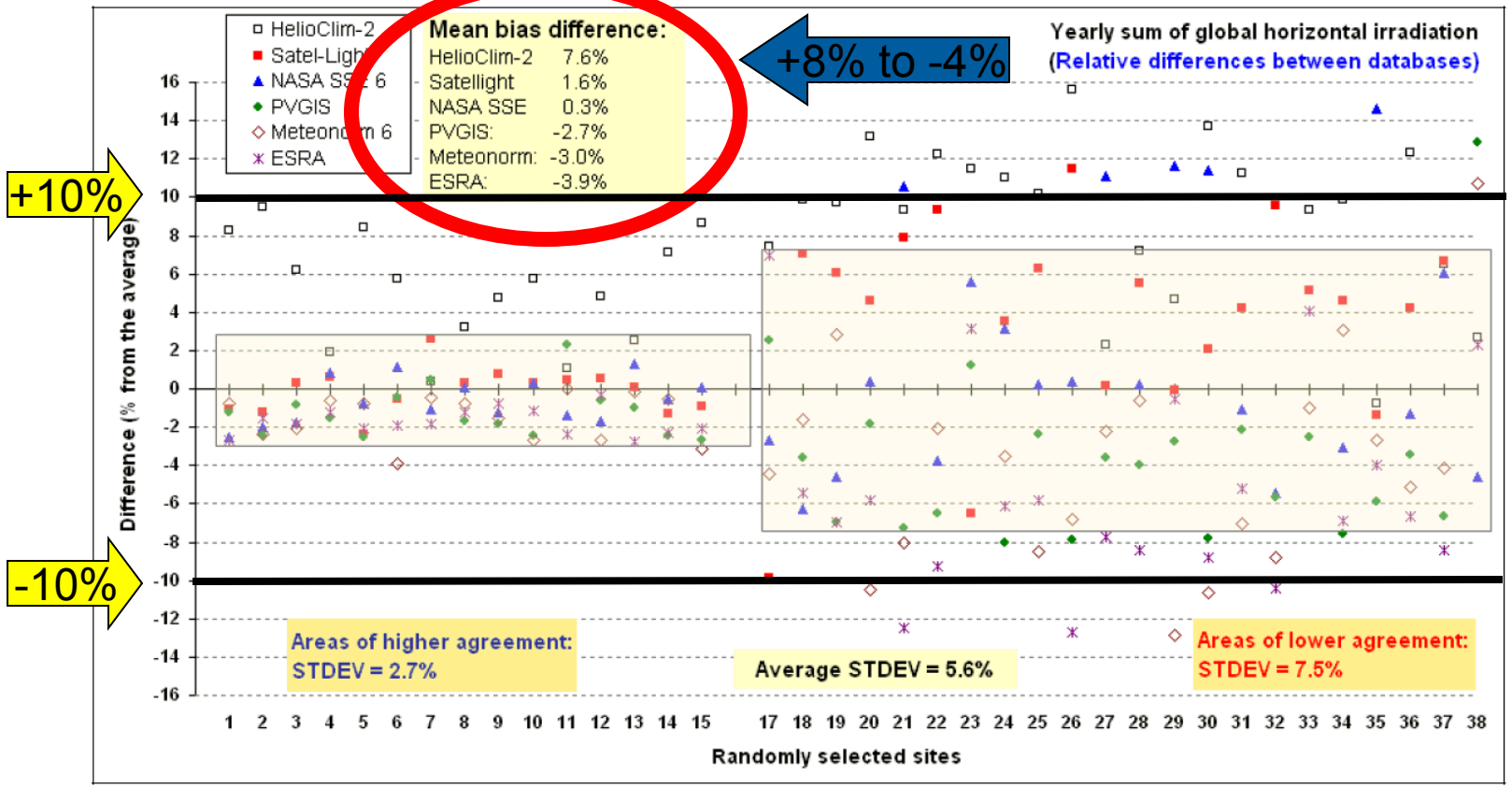
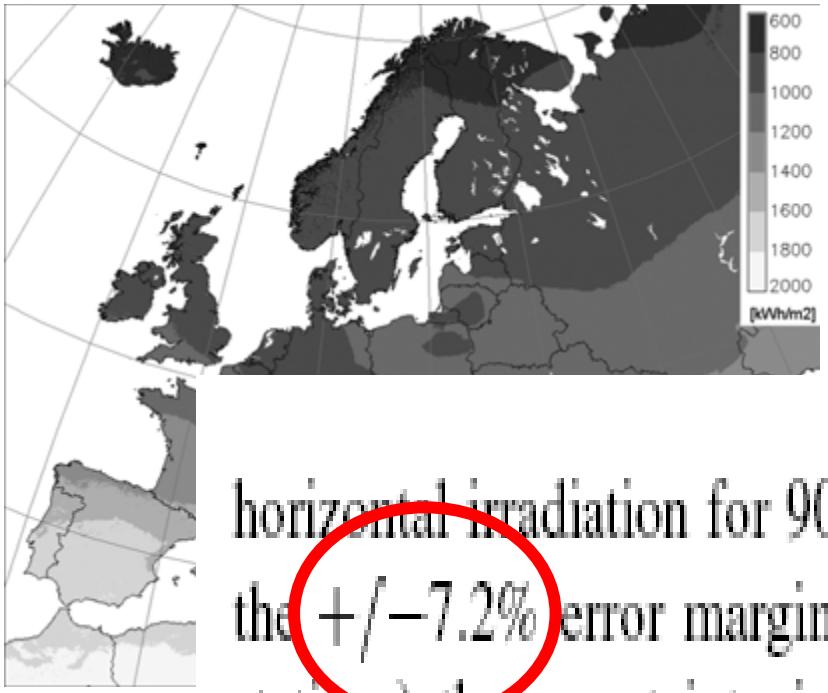


Fig. 3. Yearly sum of global horizontal irradiation – differences of the values from 6 databases relative to the overall average. First 15 points represent areas with higher agreement between databases; the other 22 points are randomly selected in areas where the difference between the databases is higher.

European PVGIS Uncertainty

Súri et al., "Geographic Aspects of Photovoltaics in Europe: Contribution of the PVGIS Website" *IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING*, VOL. 1, NO. 1, MARCH 2008



—the estimate of yearly global horizontal irradiation for 90% of station locations falls within the +/−7.2% error margin, and in 19 locations (3.5% of all stations) the uncertainty is higher than +/−10%.

PV system monitoring vs satellite based solar maps

A. Drews et al., “Quality of performance assessment of PV plants based on irradiation maps”, *Solar Energy* 82 (2008) 1067–1075

Modeled and measured annual yield of the 10 systems under inspection

Location	Modeled yield (kWh/kW)	Measured yield (kWh/kW)	Relative error (%)
Borna	928	998	−7.0
Seifennersdorf	926	930	−0.4
Starbach	942	930	1.3
Hartha	976	957	1.9
Zwickau	906	957	−5.3
Plauen	921	850	8.4
Berzdorf	1040	964	7.9
Freiberg	906	977	−7.3
Mittweida	912	958	−4.7
Dresden	966	989	−2.3

-7%

-5 to +8 %

Sample Results: European Benchmarking Satellite vs Ground (IEA Task 36)

Station	GHI av [W/m²]	nov	R^2	Bias%	RMSD%	KSI%	DNI av [W/m²]	nov	R^2	Bias%	RMSD%	KSI%
Camborne (BSRN, 2001-2003)	238.5	10815	0.95	-1.01%	29.77%		262.5	7655	0.83	-0.52%	60.98%	0
Carpentras (BSRN, 2000)	345.8	5618	0.98	2.82%	18.55%		482.4	4779	0.9	2.66%	31.41%	0
DeAar (BSRN, 2001-2003)	501.5	9168	0.97	3.44%	16.76%		673.9	8469	0.9	0.89%	23.80%	0
Geneva (IDMP, 2002-2003)	309.9	6560	0.95	7.74%	29.37%		372.9	5384	0.84	7.52%	52.58%	0
Lerwick (BSRN, 2001-2003)	174.1	12112	0.93	-1.72%	38.64%		187.2	7082	0.68	-9.43%	92.72%	0
Payerne (BSRN, 2000-2003)	383.6	11139	0.96	0.66%	18.84%		428.3	9886	0.87	-3.33%	36.88%	0
SedeBoqer (BSRN, 2003 - 2005)	561.5	10048	0.98	4.64%	12.96%		607.2	9934	0.78	-2.50%	30.37%	0
SolarVillage (BSRN, 2000 - 2002)	574	11640	0.98	-0.02%	10.84%		578.1	11418	0.81	-0.37%	31.09%	0
all	**387.3**	**77100**	**0.97**	**1.93%**	**18.79%**		**467.8**	**64607**	**0.87**	**-0.73%**	**36.83%**	**0**

Time scale	RMSD GHI %	R^2	RMSD DNI %	R^2
hour	18.79%	0.97	36.83%	0.87
day	11.08%	0.99	23.58%	0.95
month	4.95%	0.99	9.69%	0.99
year	3.66%	0.99	4.92%	0.99

SUMMARY

- Measured data SPARSE and EPISODIC
- Specialized Measured Data available
- Measured-Model broadband difference patterns ~ 10% - 15% Typical
- Uncertainty Function of Site, INPUT data and REFERENCE DATA uncertainties
- Data Sources PROLIFERATING; benchmarking is a RESEARCH project !!
  - International Energy Agency Task 36 on Solar Radiation Knowledge Management http://www.iea-shc.org/task36/index.html
- U.S. Satellite (SUNY) Uncertainty comparable European Estimates (state of the art)

NOTE: MODELS CONTINUOUSLY EVOLVING !

Measurements AND models: Similar Uncertainty Limits:

5% - 10% Global Month Mean Daily Total

10%- 15% Direct Month Mean Daily Total

Statistics help, but this is essentially WEATHER data!

Rating Conditions: DNI ~ 900 W/m^2 appropriate compromise with GNI, Flat Plate ~ 1000, and DNI Reference spectrum

National Renewable Energy Laboratory
Innovation for Our Energy Future

Spectral Effects in CPV Performance



NREL
Test & Evaluation

Matthew Muller

Feb 18-19, 2010
Reliability Workshop
Golden, CO

This presentation does not contain any proprietary or confidential information.

Outline

- Overview of NREL CPV testbed
- Overview of Spectral Variation as it relates to triple junction PV cells
- AirMass based Spectral corrections for 3 distinct modules on-sun @ NREL
- Baseline PV USA ratings for the same modules
- Predicted energy performance comparison for 2009 in Golden CO, based on the AM corrections specific to 2009 Golden, CO data
- Conclusions and continuing work

NREL CPV Testbed



- 2-axis tracker (+/-0.15 degree sun pointing error)
- Data acquisition provides module peak power tracking
- IV sweeps, 5 minute intervals
- DNI, GNI, wind speed, Tambient, Tmodule, and tracking error are measured and recorded with module electrical measurements
- Spectral data is available from SRRL (Mesa top adjacent tracker location)
- First CPV modules mounted in February, 2009
- All modules under measurement to this point contain III-V triple junction cells
- All modules are high concentration ~500 suns or greater

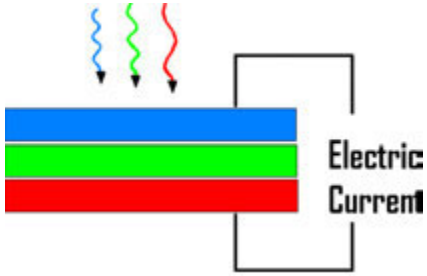
Triple Junction Cells and G173/AM1.5 spectrum

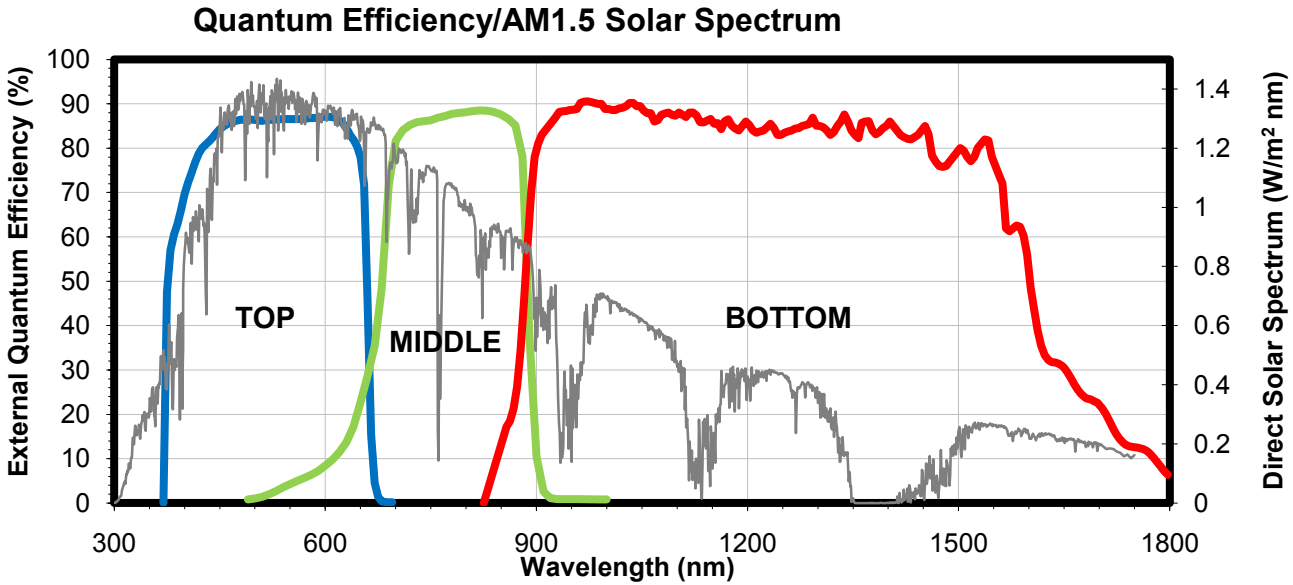
•Junctions are in series and therefore the cell must operate according to the junction with the lowest current

•Bottom junction produces excess current and typically will not be the limiting junction

•For G173-03/AM1.5 Top/Middle junctions are current matched for peak performance

•In a red rich spectrum the top junction limits while in blue rich the middle junction limits





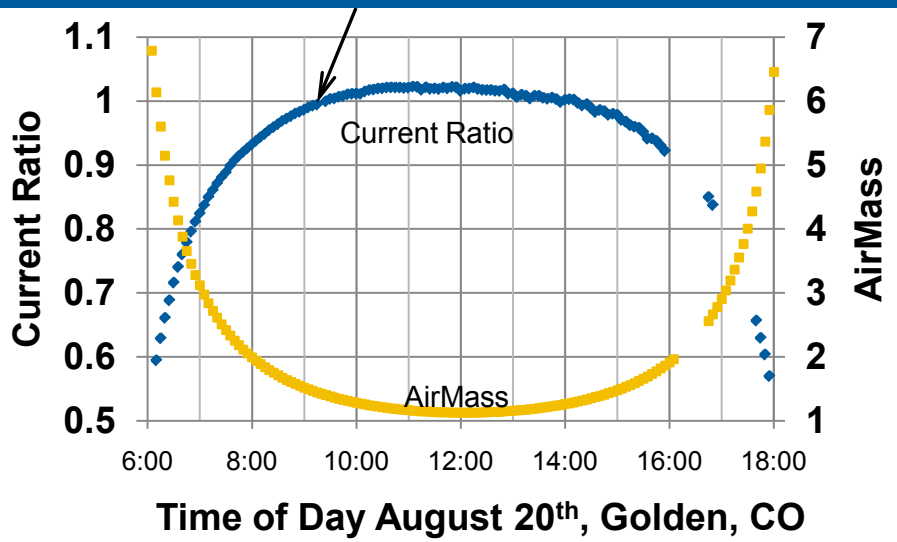
Factors Causing Deviations from G173 Spectrum

- **AirMass** (path length through atmosphere which is a function of the zenith angle) greater path length results in increased Rayleigh scattering of blue light.
  - Ranges from 1-5 when CPV produces significant power
  - AM1 blue rich spectrum (middle junction limits current)
  - AM5 red rich spectrum (top junction limits current)
- **Aerosols or Turbidity**, particles in the air that result in radiation attenuation in the range of 400 to 2000 nm. The rate of attenuation decreases with wavelength but is dependent on the quantity and size of particles.
  - G173 specifies a Turbidity of 0.084 @ 500 nm
  - 0.05 to .3 common range in U.S.
  - Boulder,CO ~0.05 winter months, ~0.09 summer months
- **Precipitable Water Vapor, PWV,** (cm of condensed water vapor in the vertical direction) Water vapor absorption bands (720, 820,940,1100, 1380, 1870, 2700, and 3200nm).
  - Absorption in the wavelengths corresponding with the bottom junction are the strongest. The bottom junction does not limit current and therefore PWV impacts performance primarily through efficiency measurements. (Efficiency = Pmax/DNI) As PWV increases DNI will decrease more than Pmax resulting in an increase in efficiency.
  - G173 specifies a PWV of 1.42 cm.
  - 0-4 cm is a common range of PWV
  - Boulder,CO ~0.6 cm winter, 1.7 cm summer
  - An increase from 0 to 0.4cm PWV decreases radiation by 10% while an increase from 0.4 to 4cm only decreases radiation an additional 10%.

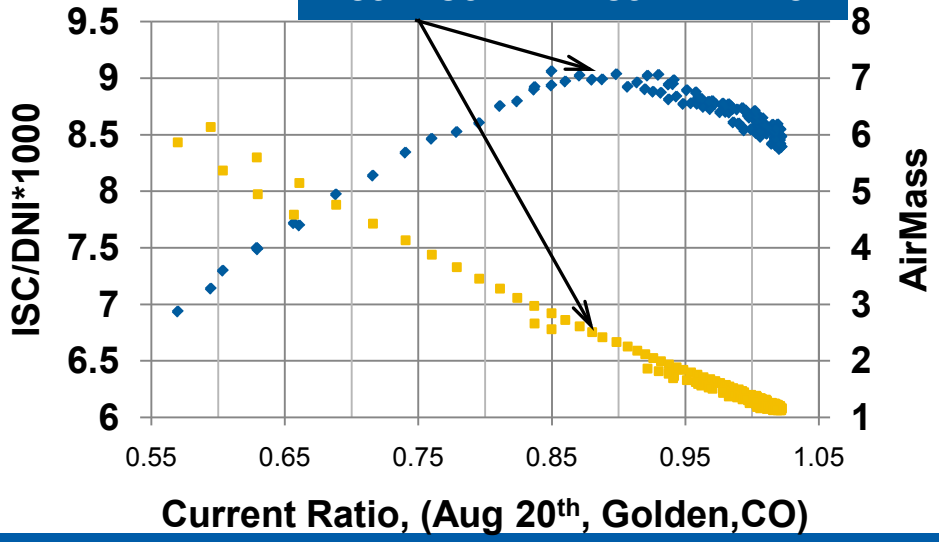
Performance of cell /module under measured spectral conditions

- Upper right graph, ratio of top junction current to the middle junction current calculated from Q.E. data and measured spectra
- Lower left graph, module Isc/DNI peaks at AM2.5
- Lower right graph, module efficiency also peaks near AM2.5
- Generally, plots are repeatable for varying spectrum, temperatures, and time of year
- Consider optics, multiple cells in series, cell QE deviation from manufacture specs

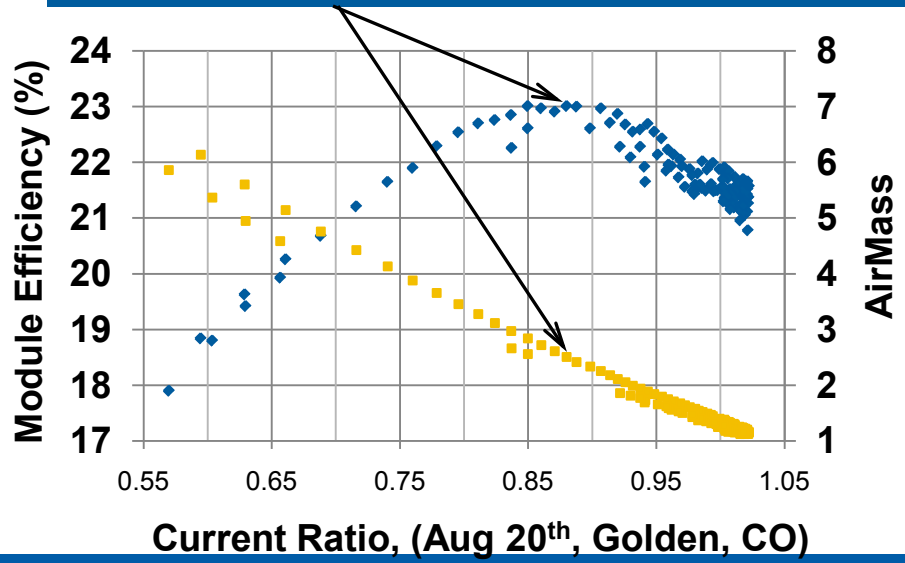
Middle cell begins to limit current @AirMass ~1.4



Peak Isc/DNI near AM 2.5



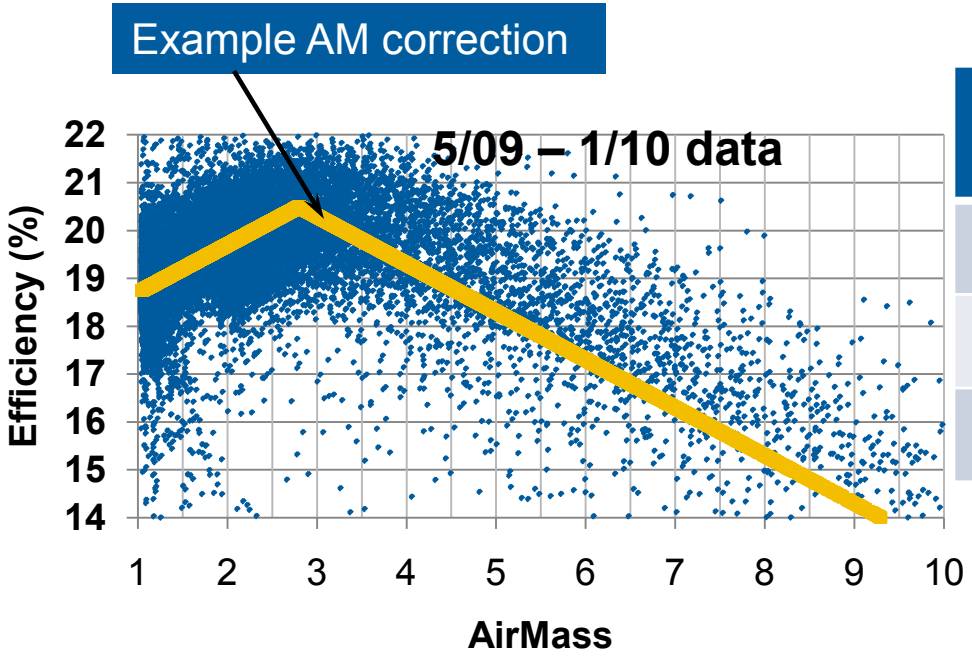
Peak Module efficiency occurs near AM 2.5



Multi-Month Data Analyzed to Predict Module Performance

- Performance variation was examined in terms of temperature and spectral effects
  - Ultimately AirMass was the only factor used in predicting performance variation
  - Issues such as heat sink variation make it difficult to accurately predict cell temperature
  - Uncertainty in turbidity measurement was often greater than day to day variation
  - PWV measurement device is in need of calibration that occurs in mid-2010
  - Spectroradiometer measurements are not available for the entire data set and the instrument is currently under repair
- AirMass Correction applied: $Rated\ Efficiency - a|AM - b|$

$a = rate\ efficiency\ changes\ with\ AM,\ \ b = AM\ at\ which\ the\ efficiency\ peaks$



Module	PVUSA Efficiency	AM Peak	Rate of Change
1	25.5	1.7	1.6
2	20	2.8	1
3	22.4	2.5	0.95

PVUSA Ratings for 3 Modules

PV USA Ratings (850 W/m2, 20C Ambient, 4m/s wind)													
Module #		March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	AVG
1	Power (W)	69.5	68.2	69.5	71.3	72	72.5	72	69.9	68.7	70.9	67.9	70.2
	%S.E. *	1.90%	3.50%	2.10%	2.40%	2%	1.00%	1.70%	2.80%	4.20%	3.70%	2.20%	
	# of data	111	339	227	734	466	499	176	932	1156	172	88	
2	Power (W)			77.2	78.4	78.9	79.3	82.1	79.1	78.1	81.1	75.9	78.9
	%S.E. *			2.50%	2.90%	1.70%	1.70%	1.50%	2.90%	2.50%	2.00%	2.20%	
	# of data			228	741	464	497	166	930	1157	172	87	
3	Power (W)			111	110	110	107	107	105	104	106	99.5	106.6
	%S.E. *			1%	2.60%	1%	0.80%	1.10%	1.9%	2.7%	1.9%	1%	
	# of data			112	702	465	502	179	939	1155	172	85	

*% standard error

Predicted Energy Comparison 2009 @ NREL

- AM corrections are used to gauge the impact of spectral variations
- To Normalize the comparison a 25% efficiency is applied to all AM corrections
- SRRL 1 minute average DNI data is used for the energy availability

2009, NREL	Module 1 25%-1.6|AM-1.7|	Module 2 25%-1|AM-2.8|	Module3 25%-0.95|AM-2.5|
Jan-March KWH	118.07	120.74	121.69
April-June KWH	113.70	113.22	114.52
July-Sept KWH	130.44	130.04	131.50
Oct-Dec KWH	97.84	101.96	102.55
2009 total KWH	460.05	465.95	470.27

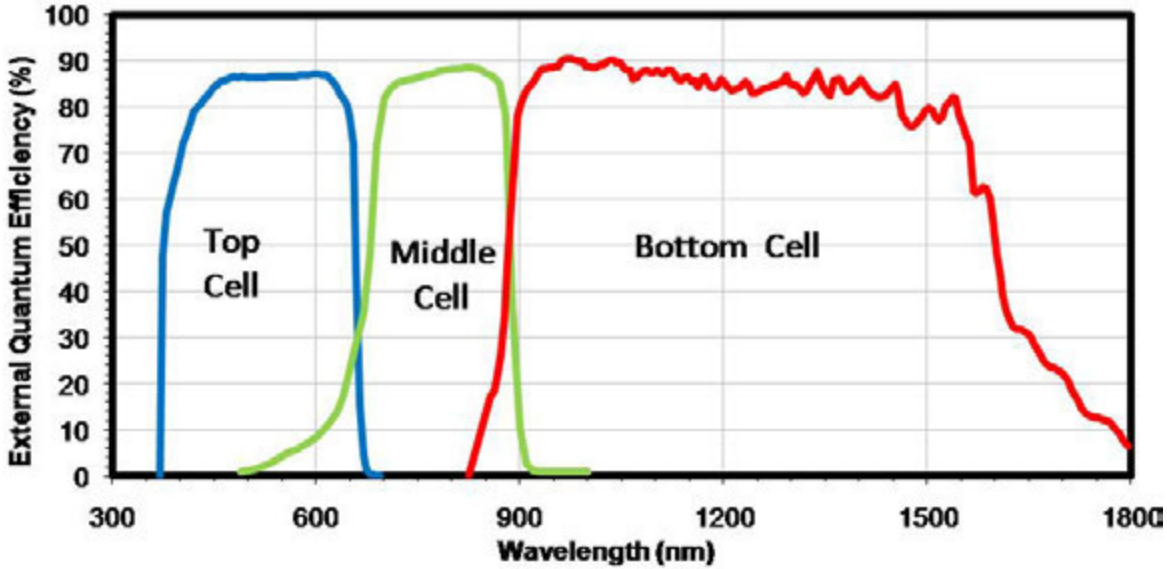
A fixed efficiency of 25% results in 493.5 KWH for 2009

~ 7% difference in energy produced between fixed efficiency and Module1

~2.2% difference in energy produced between Module 1 and Module3

Summary

- CPV module performance data clearly shows spectral sensitivity
  - Clearly defined AM response peak
  - Relative sensitivity to changing AM can be determined
- PVUSA ratings taken on a monthly basis vary from 5-10%, most likely a result of spectral sensitivity
- Spectral sensitivity, as measured through an AM correction factor for 2009 data, results in significant deviations in energy production.
  - 2.2% deviation between modules
  - 7% deviation between spectrally sensitive module and a module with a fixed efficiency
- Future work will examine specific impact of AM, PWV, and Turbidity on Normalized Isc


External Quantum Efficiency (%)
100
90
80
70
60
50
40
30
20
10
0
300
600
900
1200
1500
1800
Wavelength (nm)
Top Cell
Middle Cell
Bottom Cell

empower with light™

Failure Modes of CPV Modules and How to Test for Them

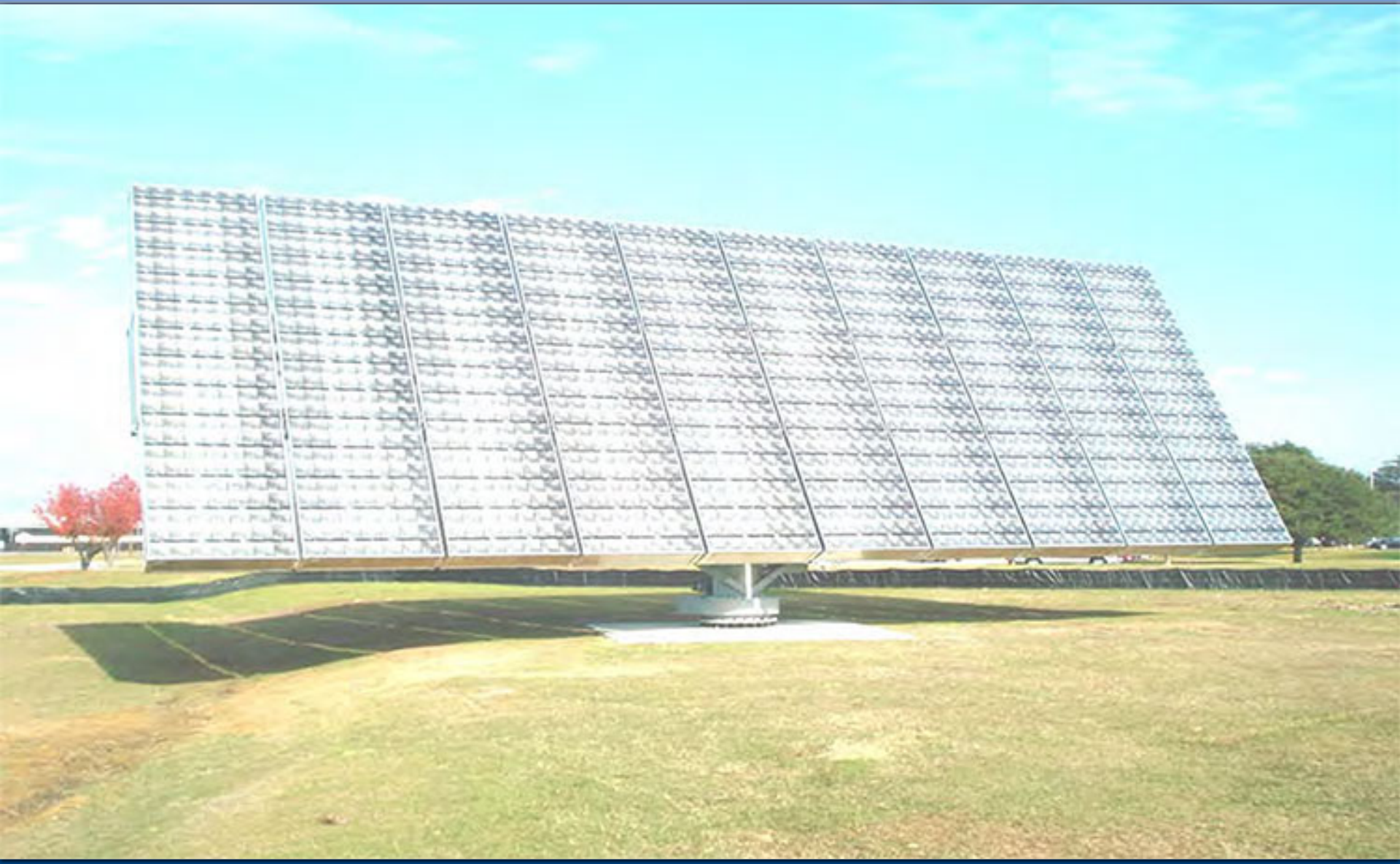
19-Feb-10

This presentation does not contain any proprietary or confidential information.

Outline

- Intro
  - This talk will include both failure modes we have detected at Emcore along with the techniques that we have used to reveal them.
  - The Issues Matrix will guide the discussion and is loosely modeled after the IEC 62108 CPV systems qualification standard.
- Damp heat cell failures
  - Easily detectable in EL.
  - Electrolytic corrosion (also a wet insulation issue).
  - Lens warp.
- Thermal Runaway
  - ESD
  - Thermography
  - Vaporized ribbons,
- Power Thermal Cycle
  - Many assume this means 1.25 X I_{SC} but this leads to very high junction temperatures
  - Also too hard on the DBC (CSLM failure)
- Melting Coverglass
- Summary

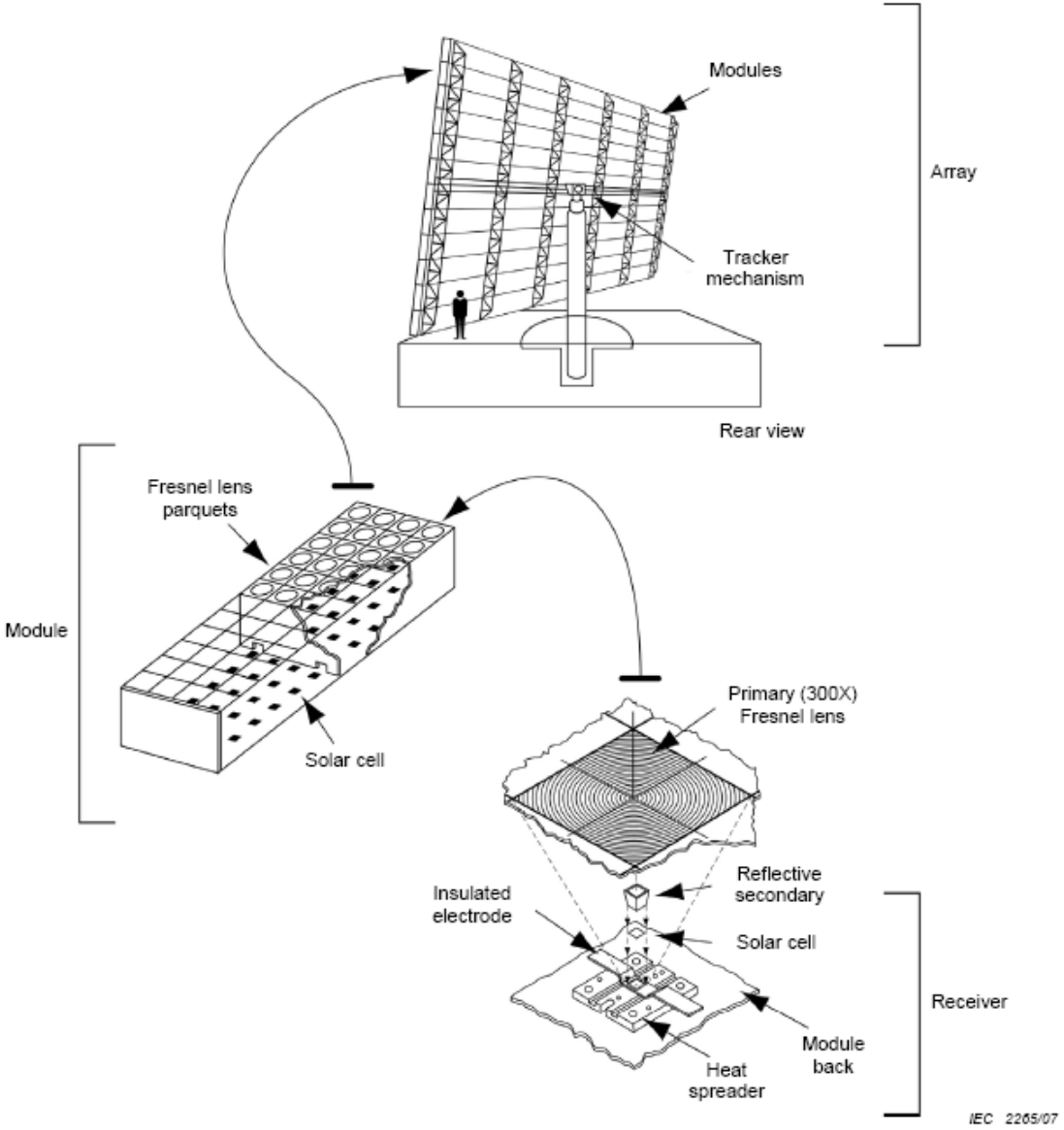
Emcore's Latest Gen II Installation



Gen III



Point-focus Fresnel Lens HCPV System (IEC 62108)



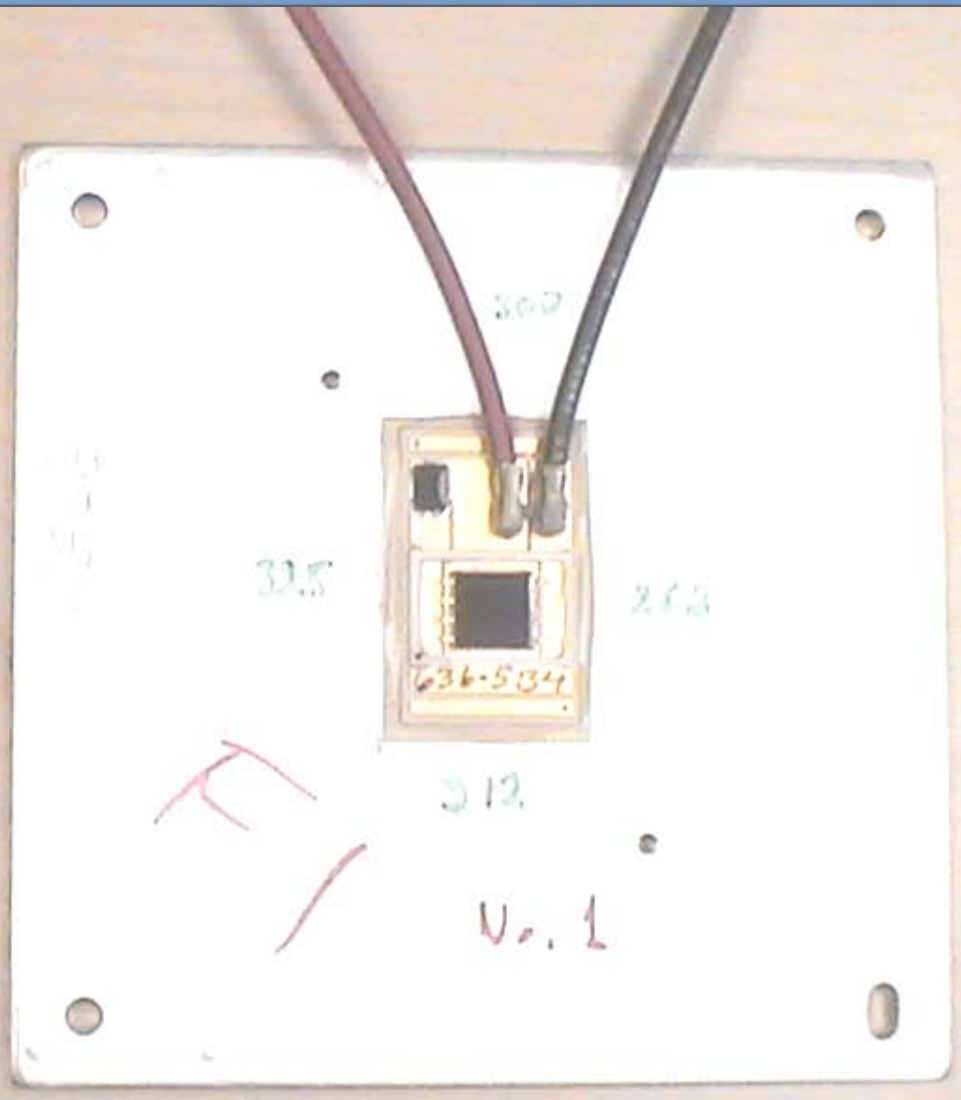
Definitions



Bare Cell
or
Device

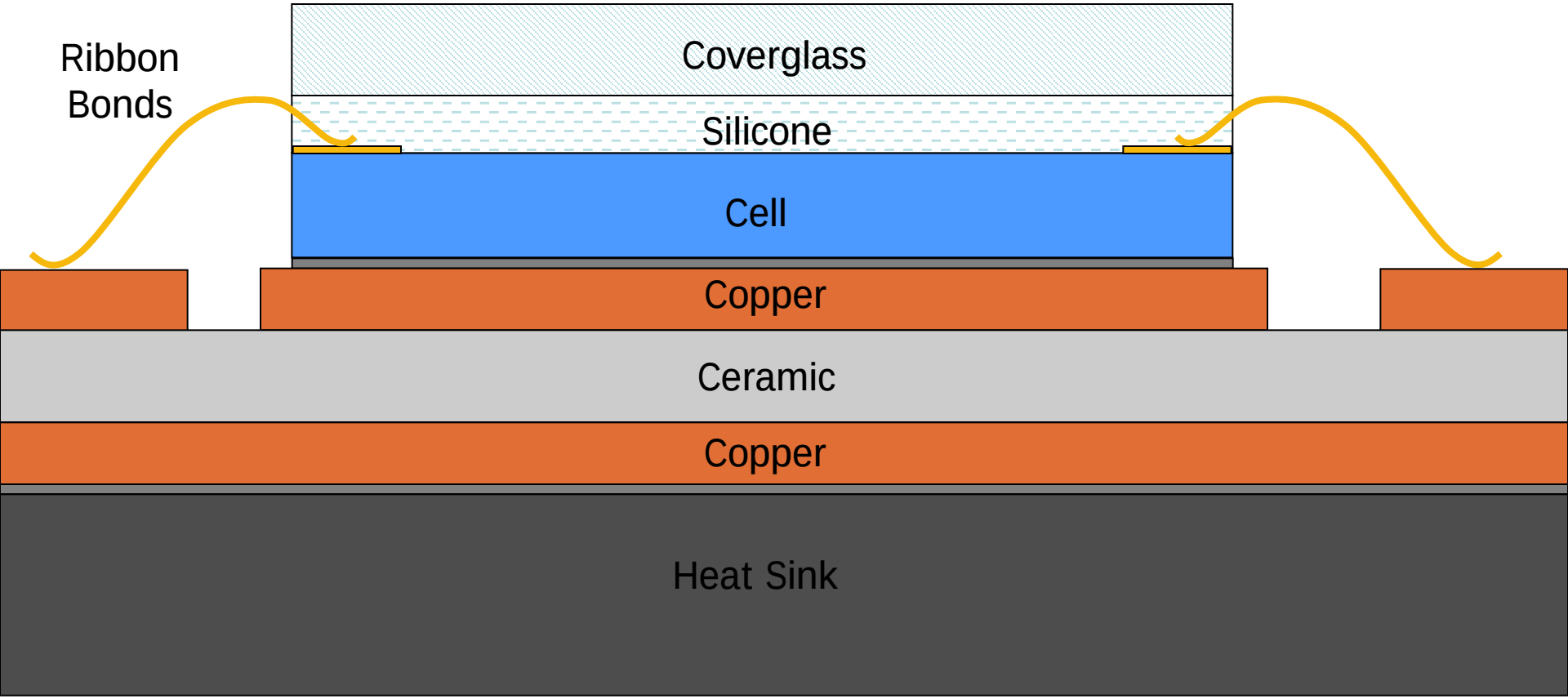


Receiver
(Rx)



Receiver Assembly

Rx Cross Section



CPV Module Reliability Issue Matrix

	Cell	Reciever	Reciever Subassembly	Module
Damp heat	Cell Corrosion		Electrolytic corrosion	Acrylic Lens Warp
Wet insulation			Must pass at Rx level for non-hermetic modules	
Dry Insulation				Hard Shorts
Outdoor Exposure		Melting coverglass	Yellowing of encapsulants	
Damp Freeze			Rx attach failures	
Power Thermal Cycle	Thermal Runaway	DBC Conchoidal Fracture		
ESD	Bare cells vulnerable			

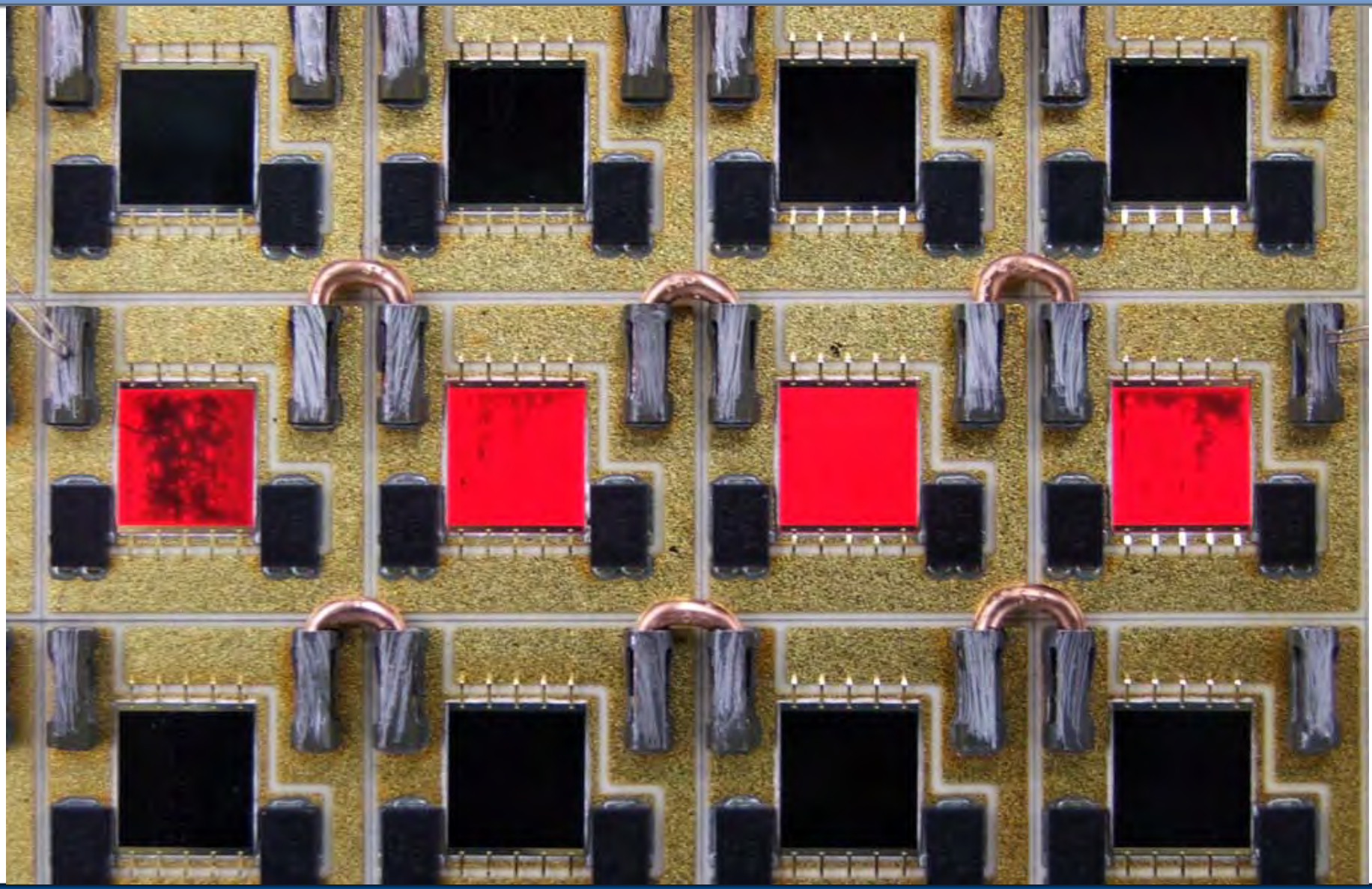
Electro-Luminescence (EL)

- One of the really cool features of current III-V compound semiconductor multi-junction solar cells is that if you run them backwards they make a pretty good LEDs!
- The top junction is the most spectacular because it is visible with the naked eye, but the other two junctions also emit.
- This makes EL a powerful analysis technique at all levels of CPV system assembly.

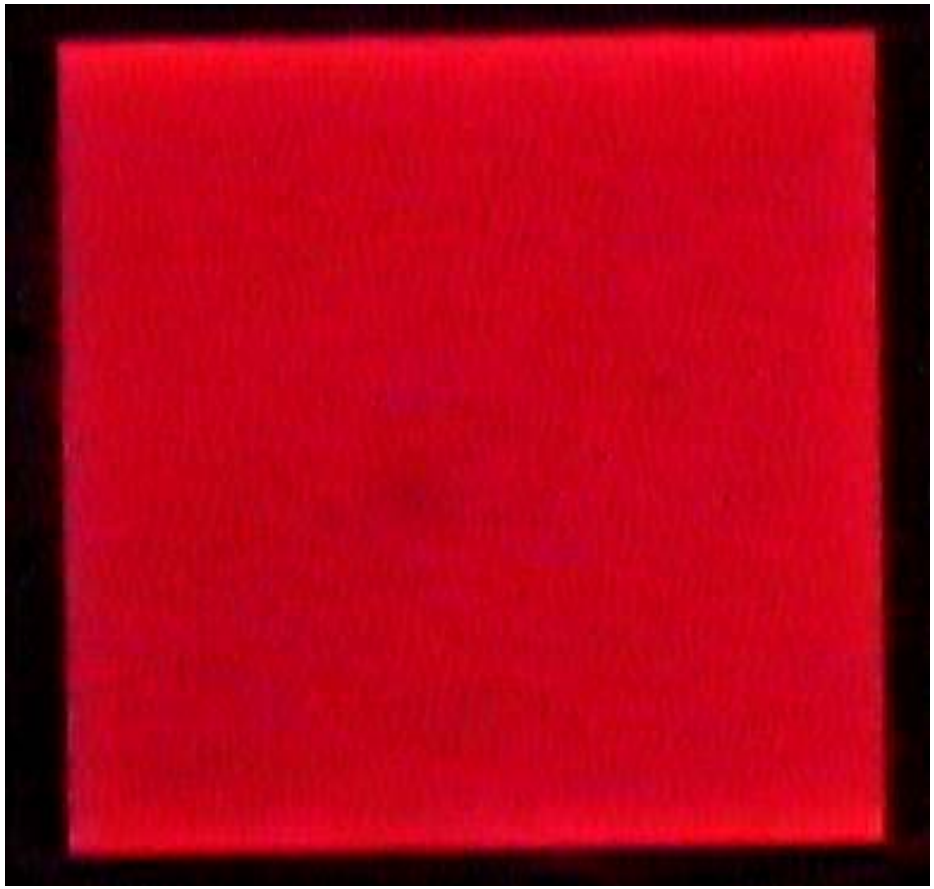


Damp Heat

TC EL After Damp Heat Exposure



Healthy Cell Top and Middle Junction EL



Top Junction

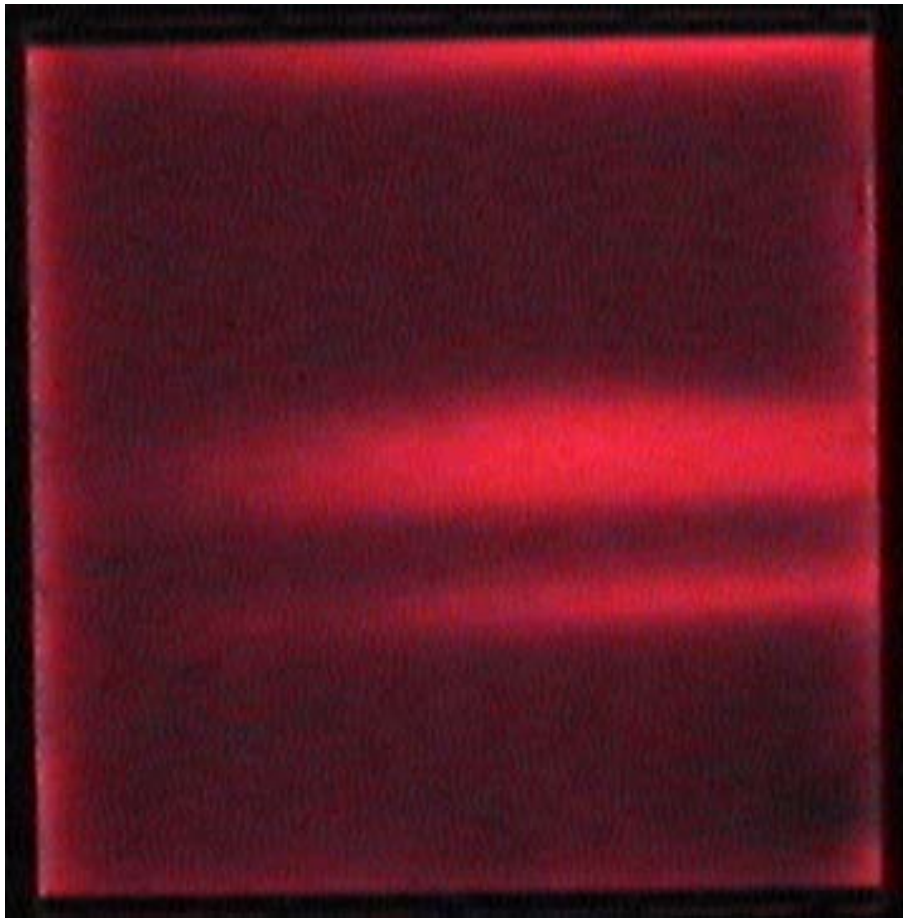


Middle Junction

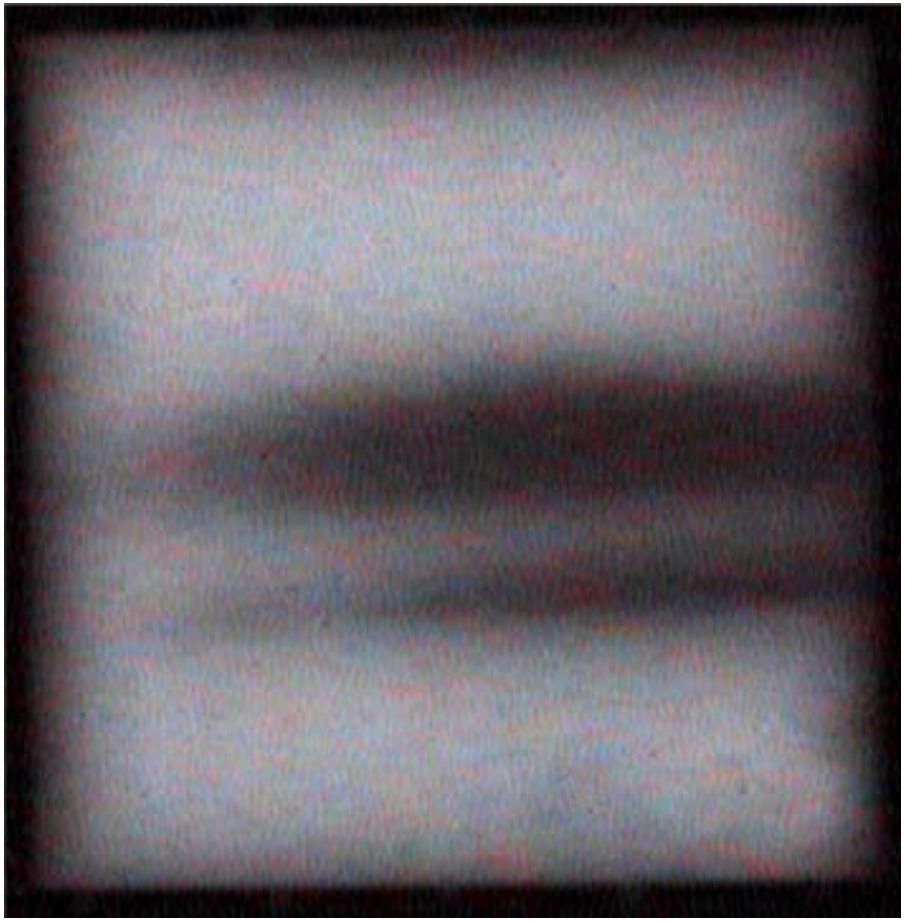
Likely Suspects

- Grid Finger Delamination.
  - Dark areas appear to be aligned along GFs.
- Degradation of Anti-Reflective Coating (ARC).
- Top cell shunting.
- Accumulation of opaque surface contamination.

EL Example of Counter-contrast in TC and MC

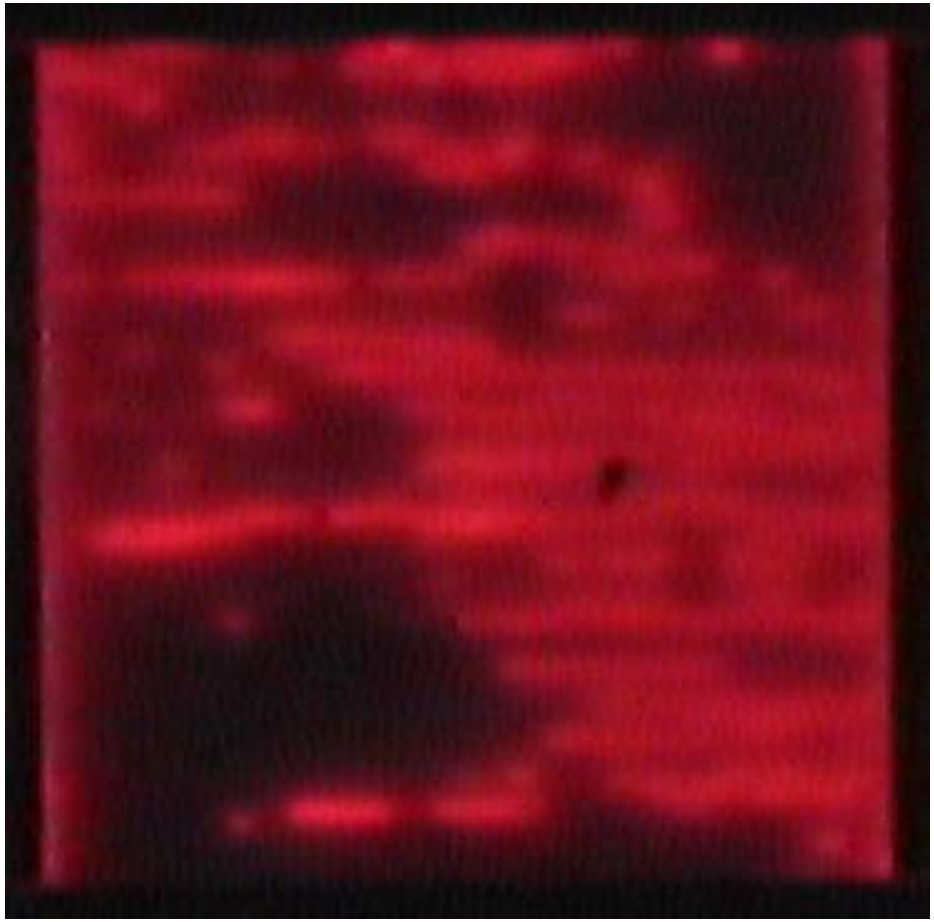


Top Junction

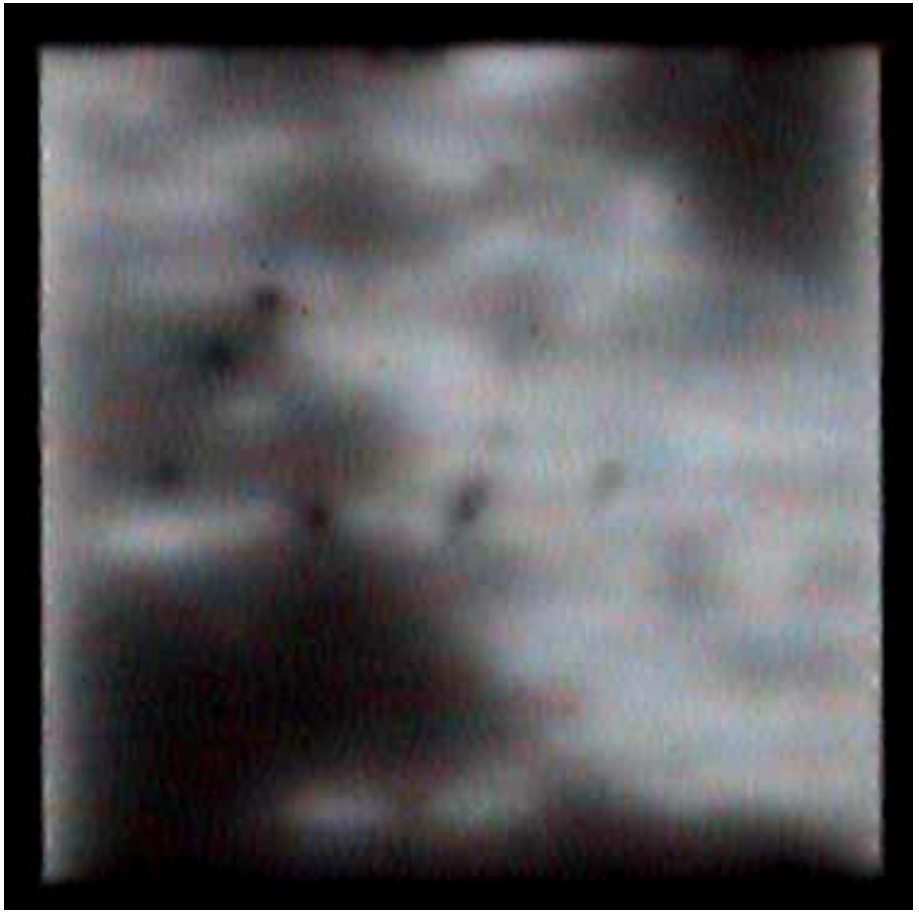


Middle Junction

Multijunction EL Signature of Grid Finger Failure



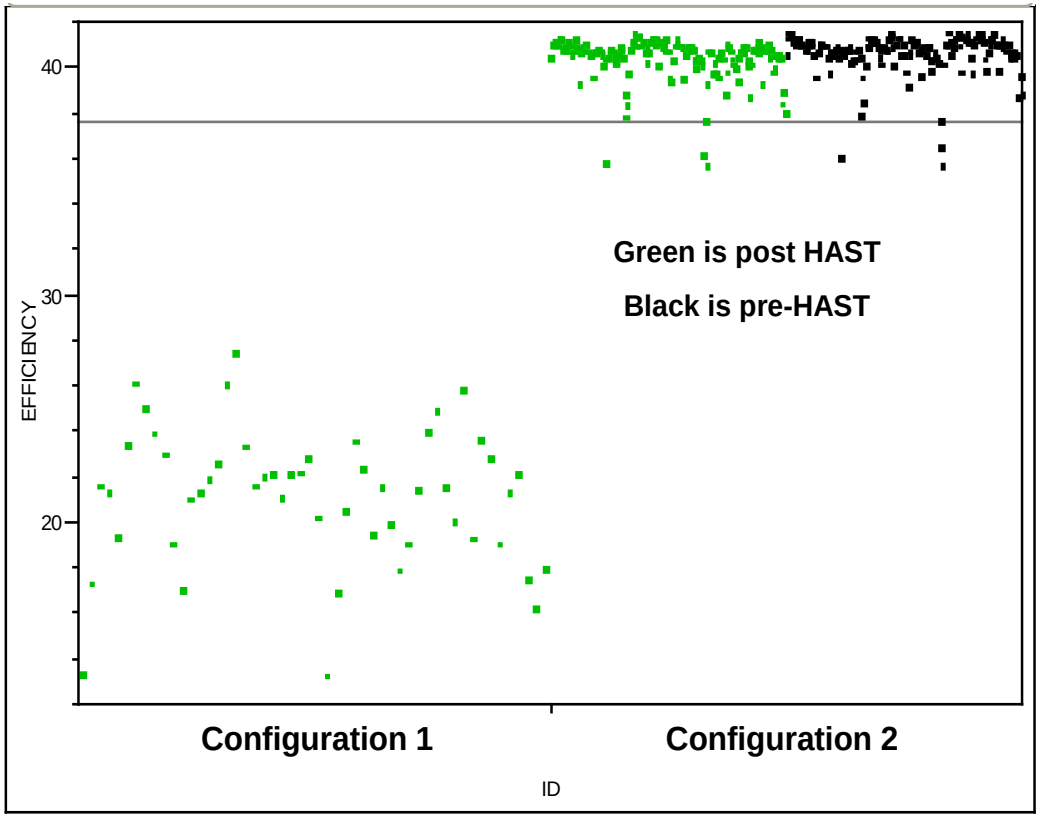
Top Junction



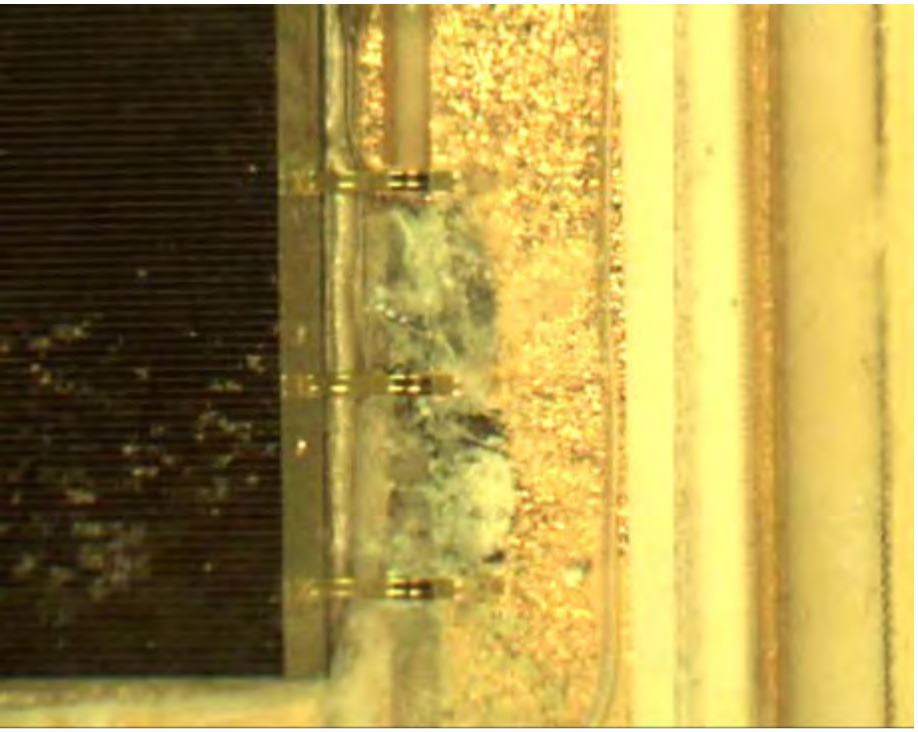
Middle Junction

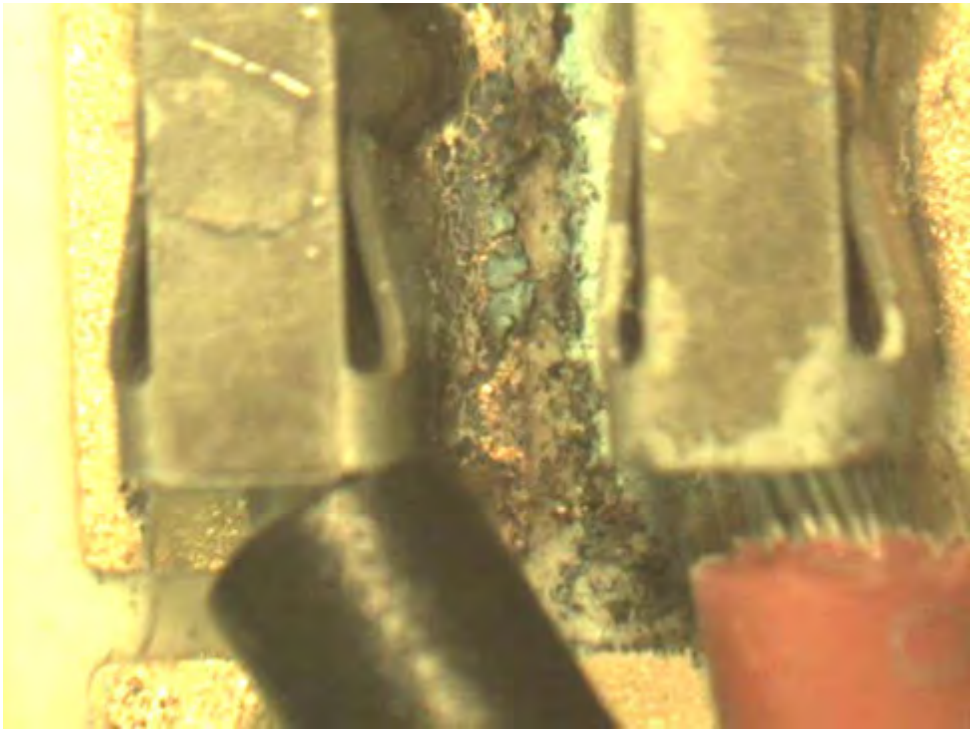
Bare Cells can now Pass 1k Hrs of 85/85 Exposure

- **Based on this experience, Emcore has improved our damp heat resistance at the device level.**
- **However, passing the 1000 hour IEC damp heat exposure test is no guarantee that bare cells will survive 20 years of exposure to uncontrolled environments.**



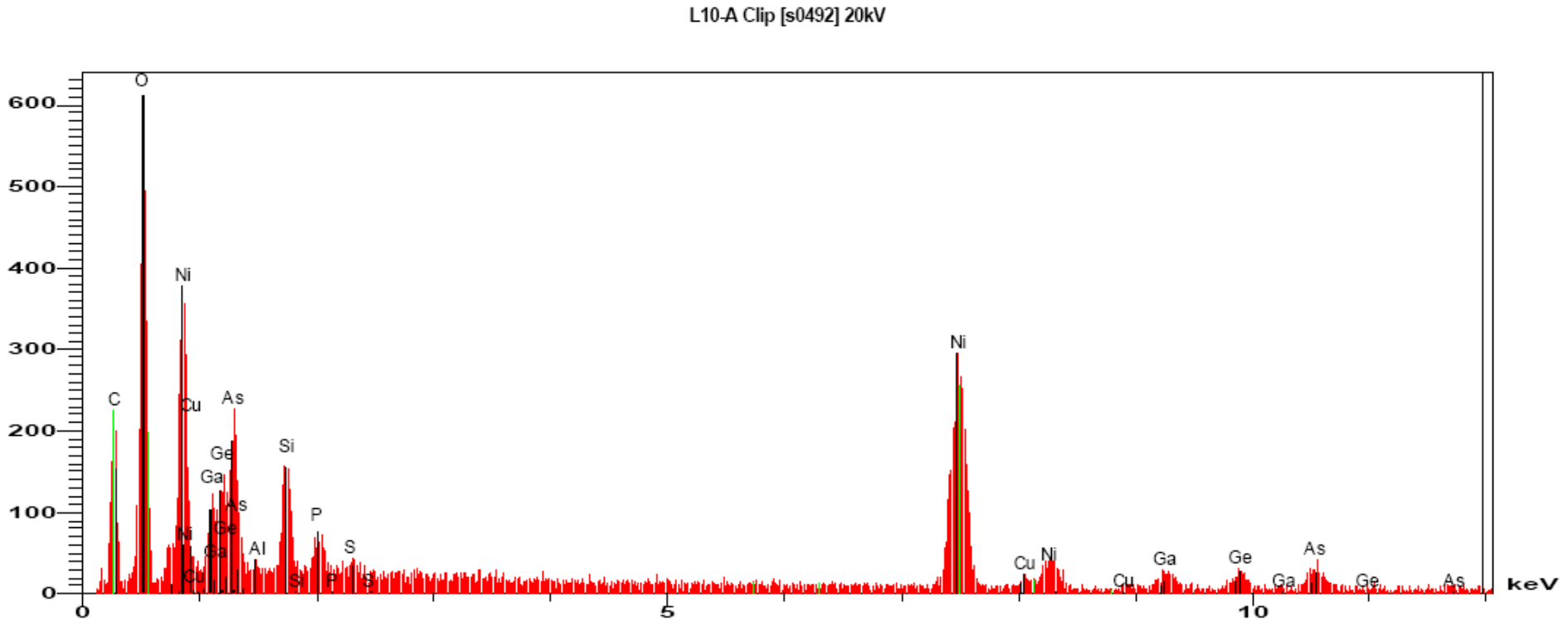
Robust Encapsulation is Critical





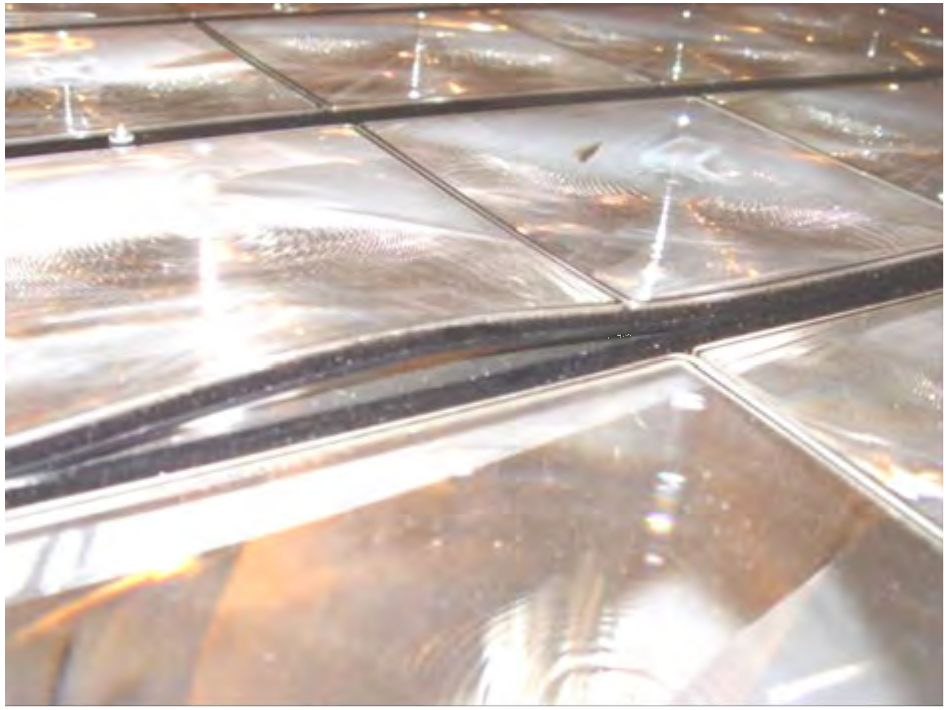
- It appears that this type of failure mode requires both moisture incursion as well as bias.
- For this reason we now add light bias to all our damp heat product reliability testing.
- Moisture incursion also makes it difficult to pass the IEC wet insulation test.

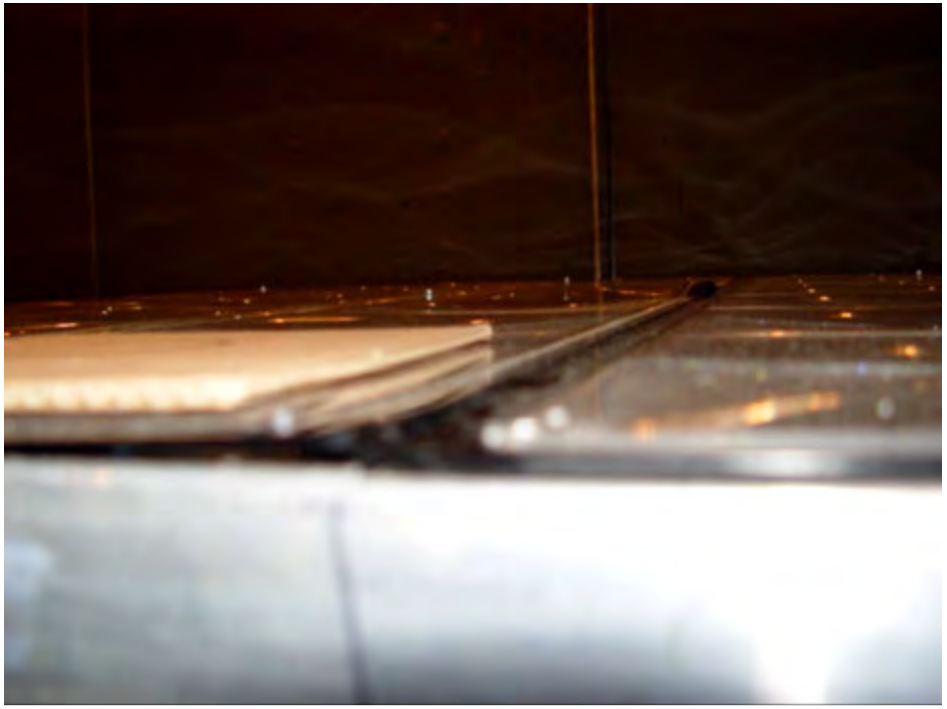
EDX Spectrum from the Blue Goo



Lens Warping

- We have also seen Acrylic lenses deform during damp heat testing.
- Besides the obvious impact to the optical performance of the module, in damp climates this further reduces the chances of passing the wet insulation test when the receiver in the bottom of the module finds itself under water from time to time.



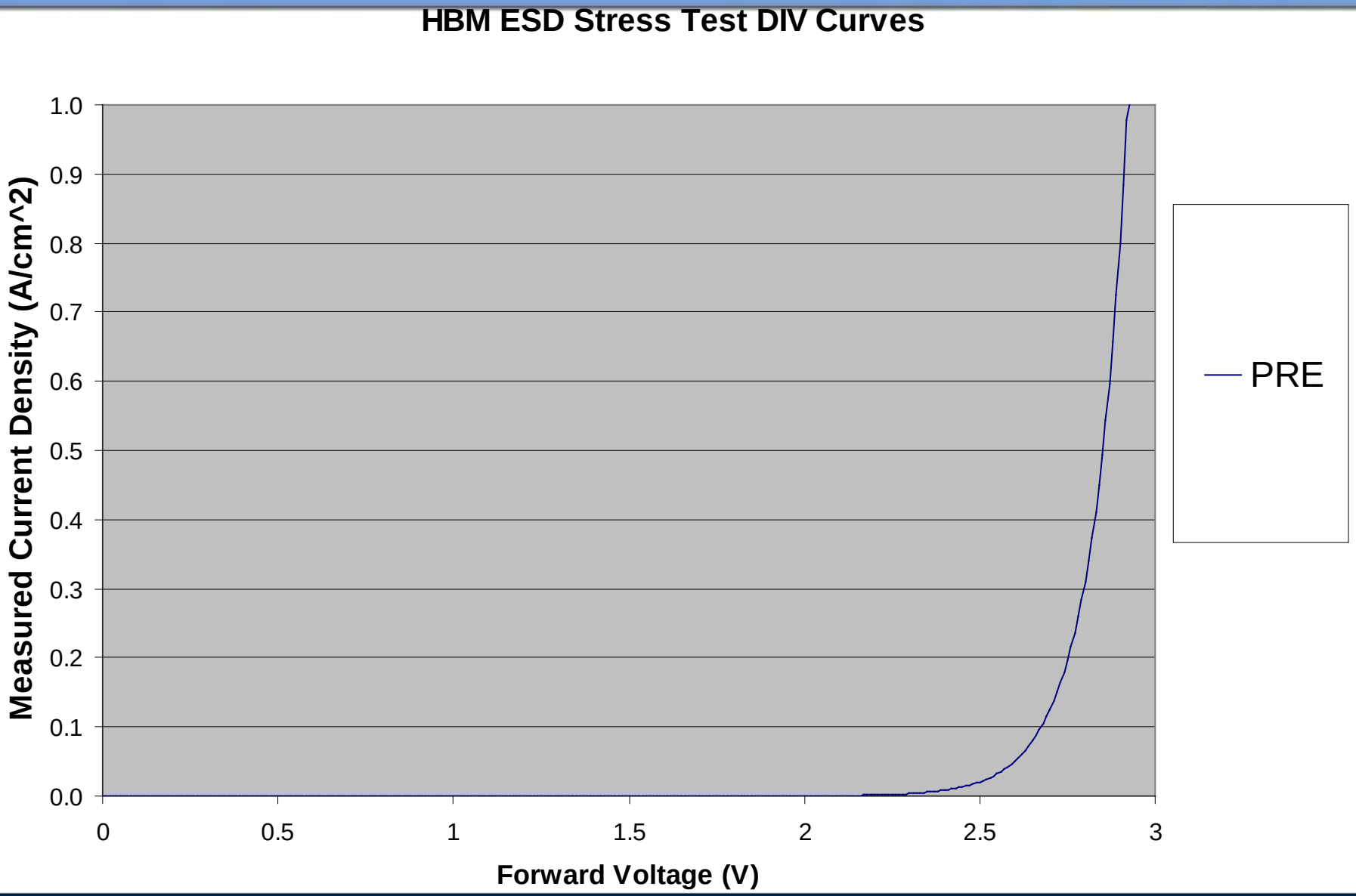


ESD

ESD Damage Threshold Test

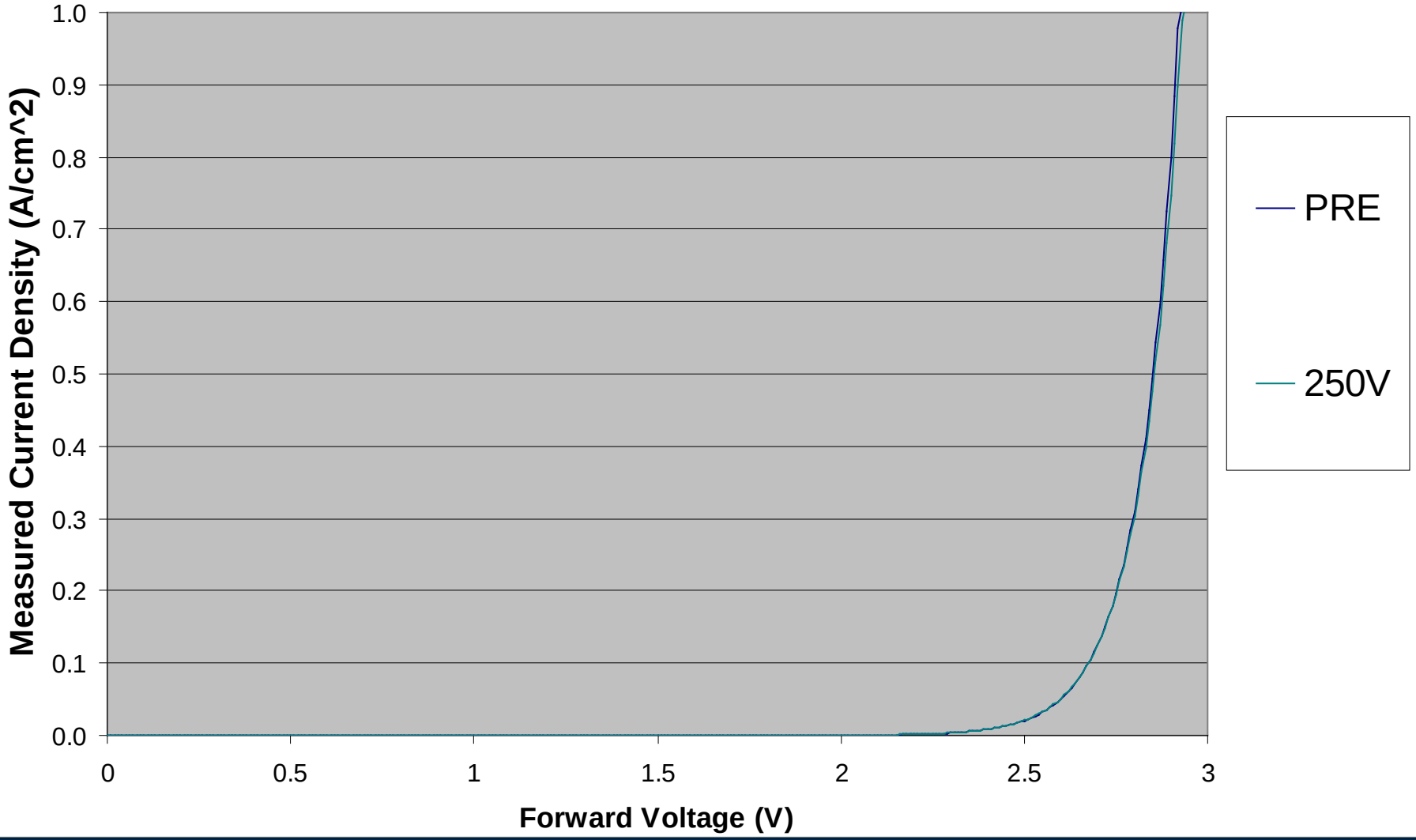
- Through not currently a requirement for IEC qualification of CPV modules, an understanding of the ESD damage threshold of the solar cell is important for establishing adequate ESD mitigation protocols.
- To establish the ESD damage threshold for CPV solar cells we have borrowed from the well established methods used throughout the semiconductor industry (e.g. Mil-STD-883 and JSTD-22a114).
- The following slides illustrate the technique through a series of non-illuminated (dark) current vs voltage characteristics (DIV) for a solar cell that has been subjected to increasingly medieval levels of ESD stress from a Human Body Model (HBM) simulator.
- The reason these data are presented here is mostly as background for the following section on thermal runaway, but ESD hay also be implicated in a reported low level infant mortality rate for multijunction solar cells in CPV applications.

Pre-Stress

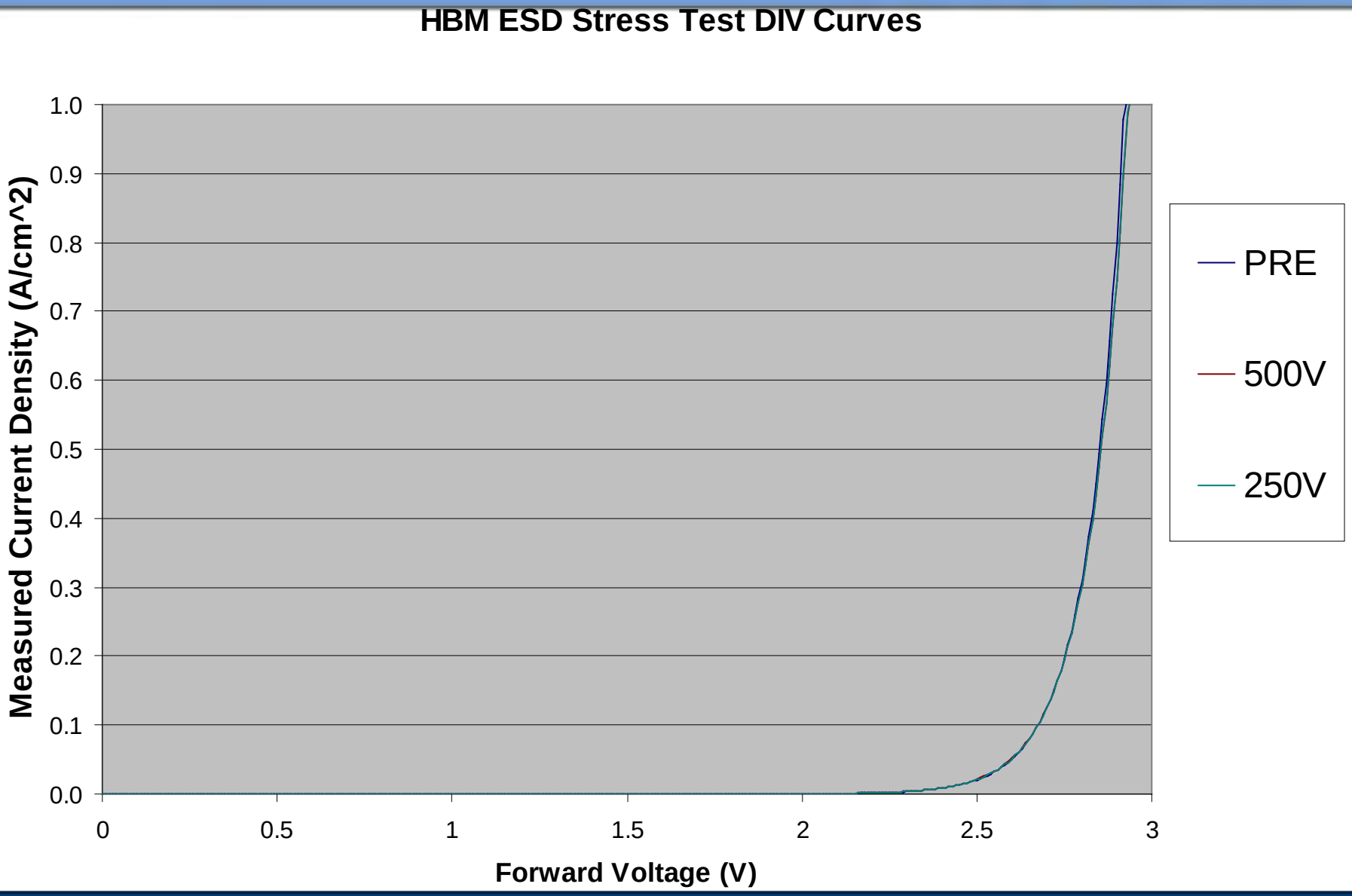

HBM ESD Stress Test DIV Curves
Measured Current Density (A/cm^2)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
0.5
1
1.5
2
2.5
3
Forward Voltage (V)
PRE

250 V

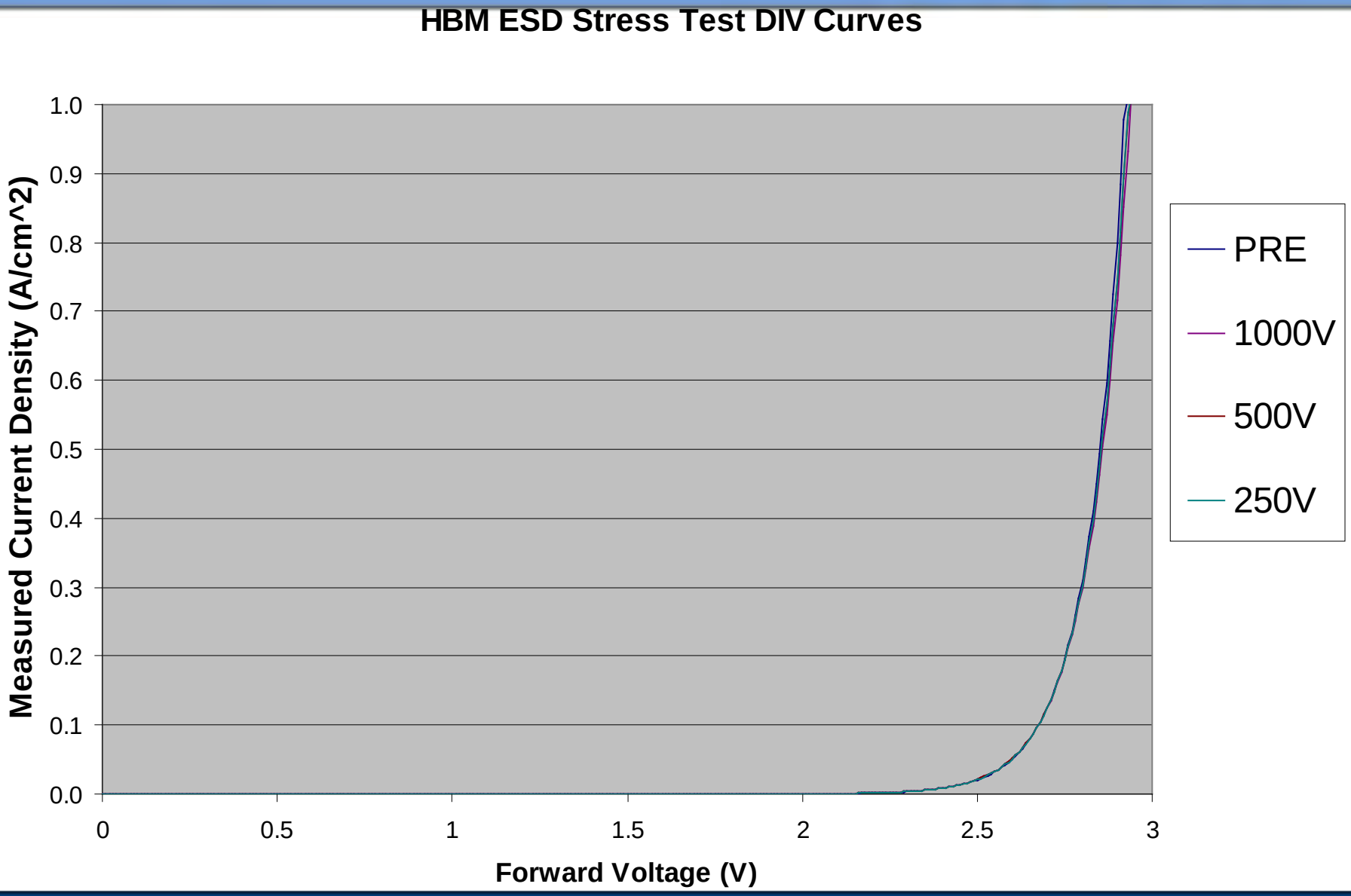
HBM ESD Stress Test DIV Curves



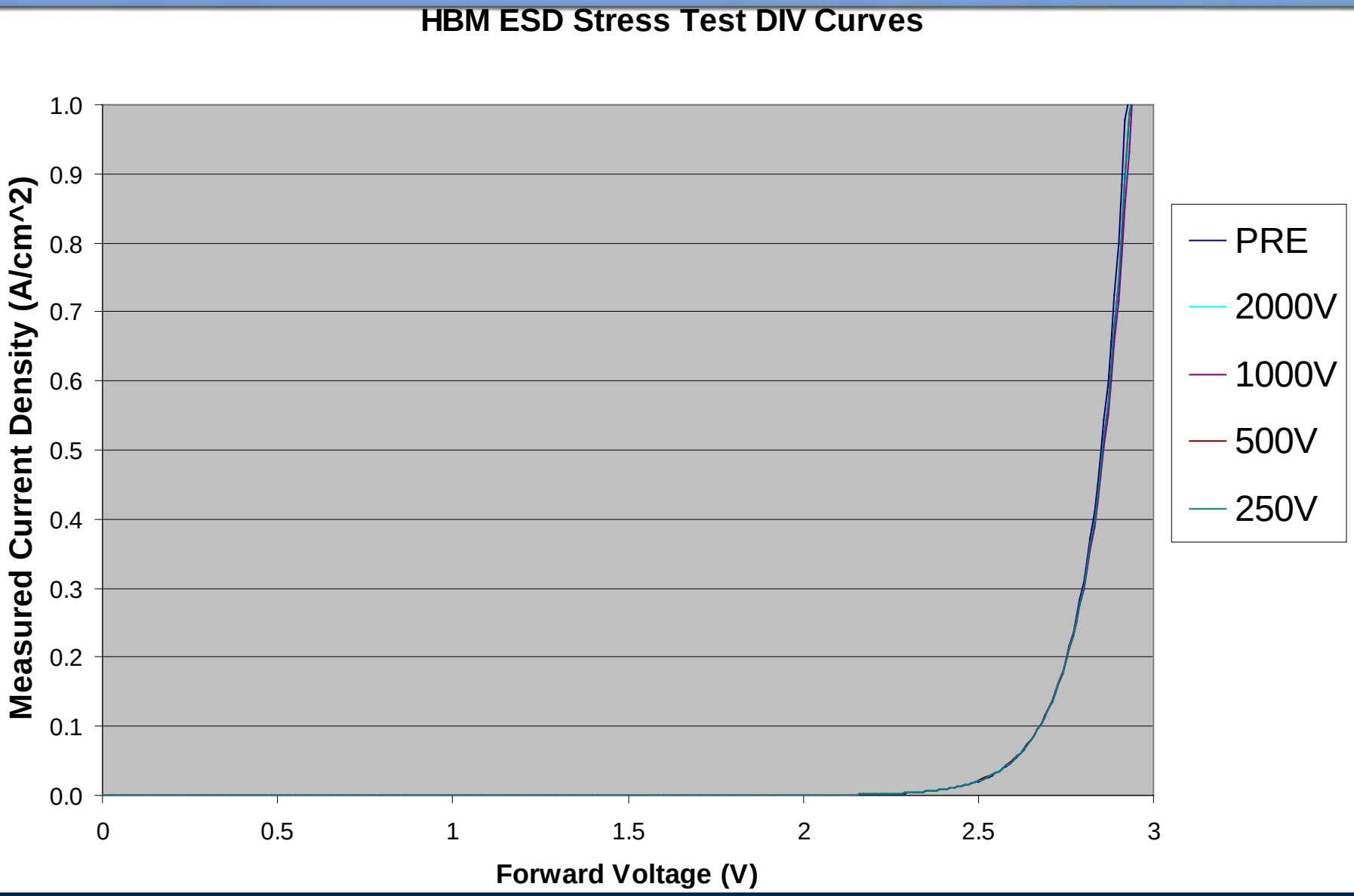
500 V


HBM ESD Stress Test DIV Curves
Measured Current Density (A/cm^2)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
0.5
1
1.5
2
2.5
3
Forward Voltage (V)
PRE
500V
250V

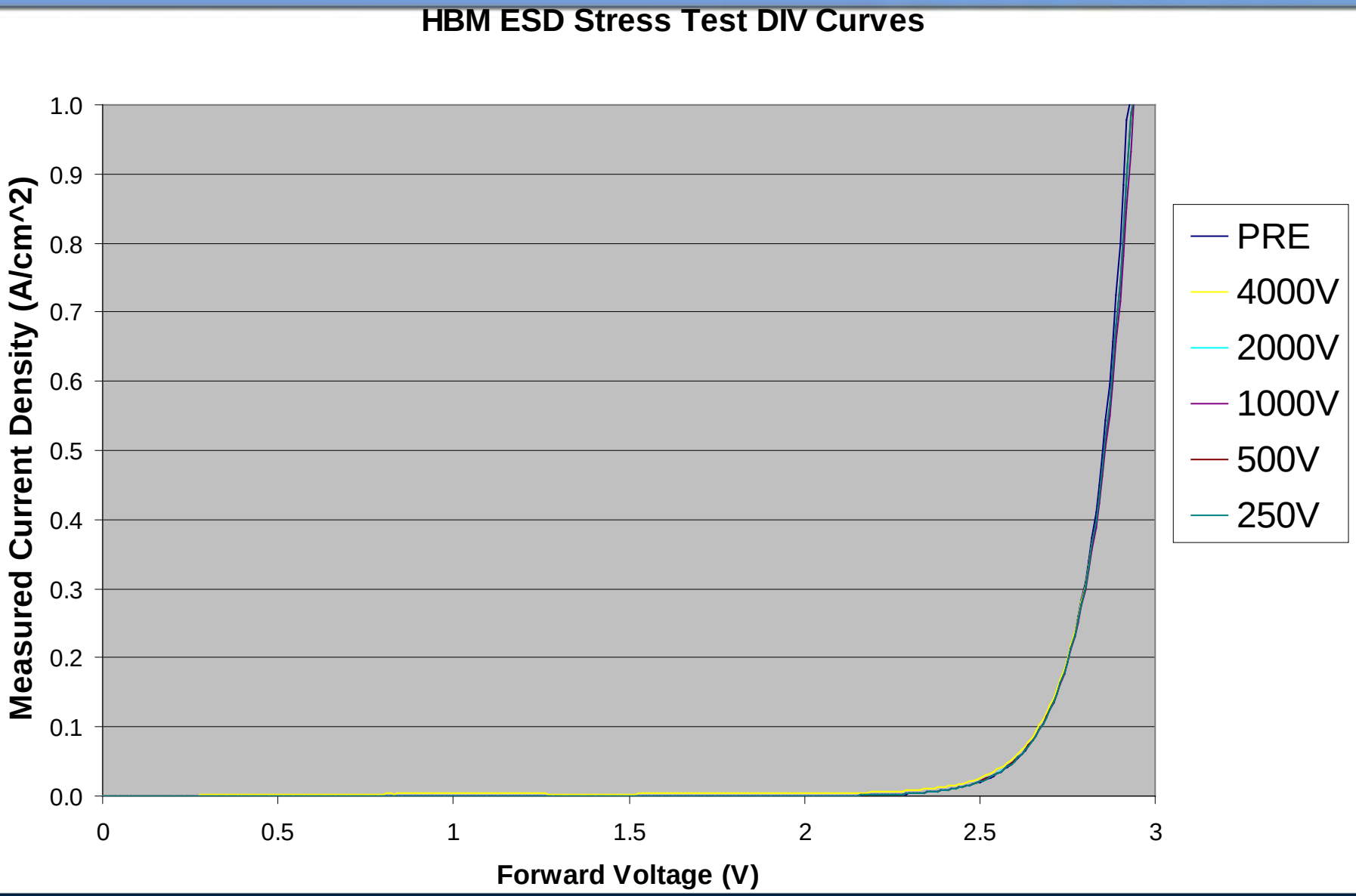
1 kV


HBM ESD Stress Test DIV Curves
Measured Current Density (A/cm^2)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
0.5
1
1.5
2
2.5
3
Forward Voltage (V)
PRE
1000V
500V
250V

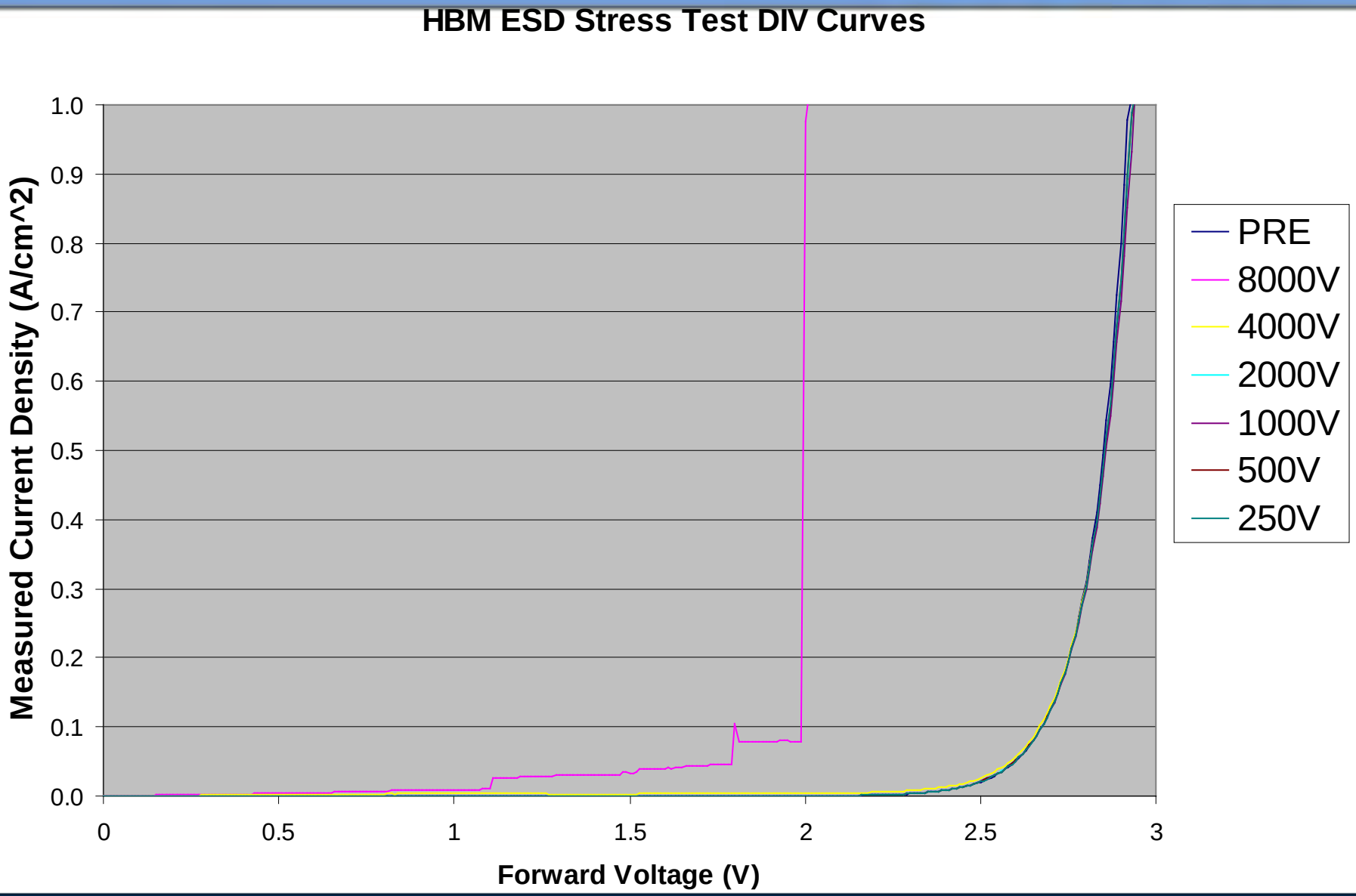
2 KV


HBM ESD Stress Test DIV Curves
Measured Current Density (A/cm^2)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
0.5
1
1.5
2
2.5
3
Forward Voltage (V)
PRE
2000V
1000V
500V
250V

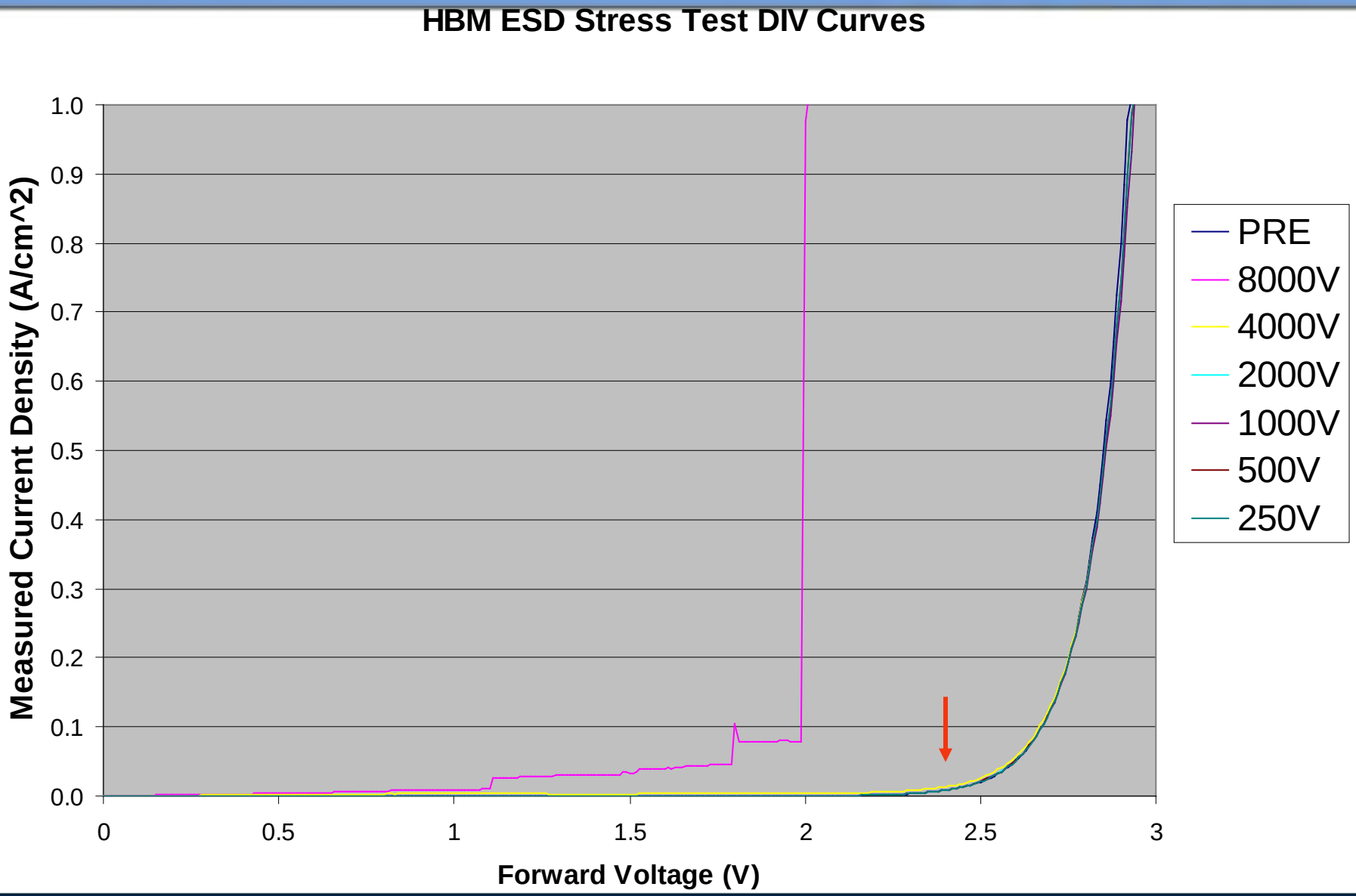
4 kV


HBM ESD Stress Test DIV Curves
Measured Current Density (A/cm^2)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
0.5
1
1.5
2
2.5
3
Forward Voltage (V)
PRE
4000V
2000V
1000V
500V
250V

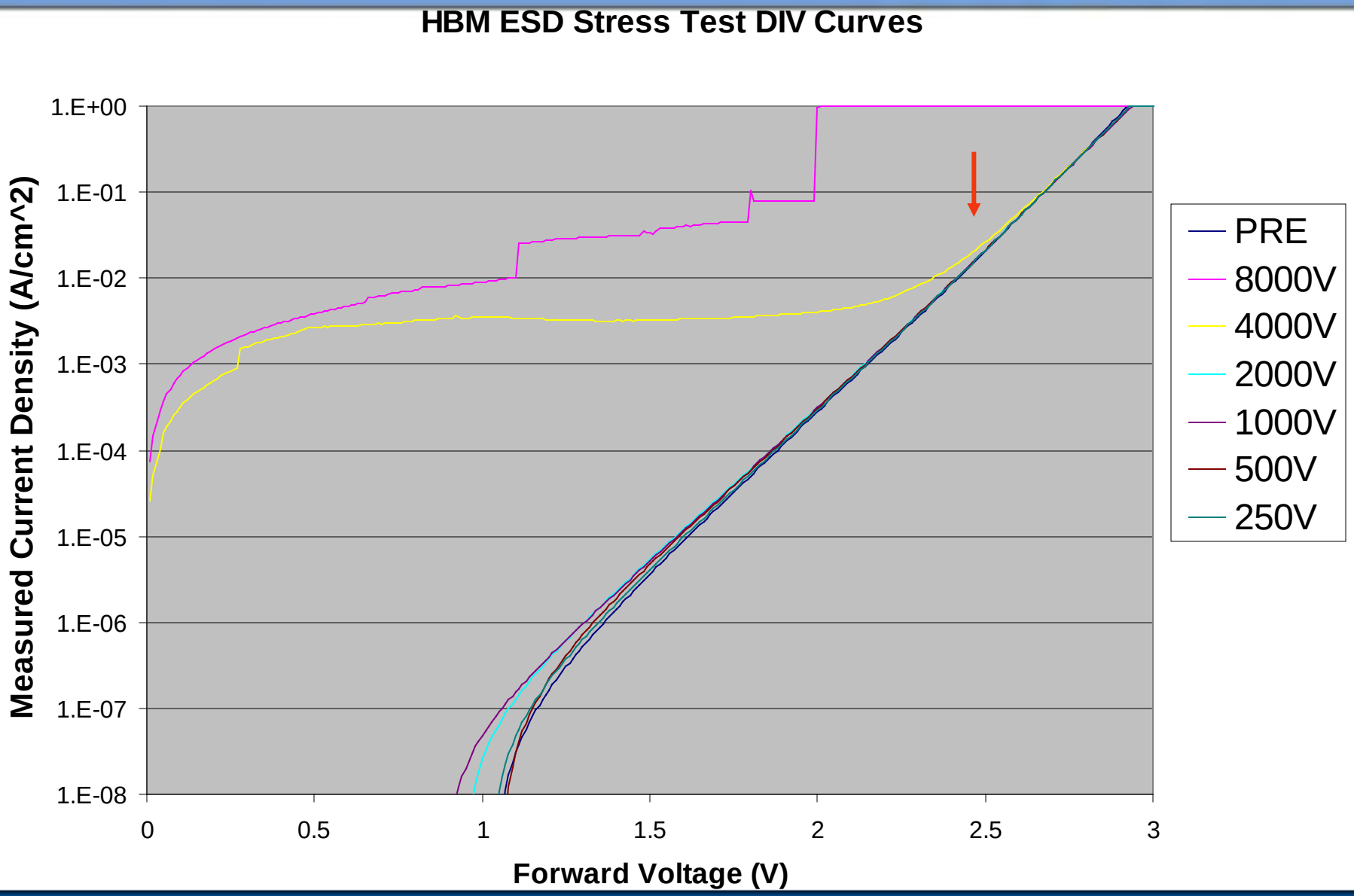
DIV Curves on a Linear Scale



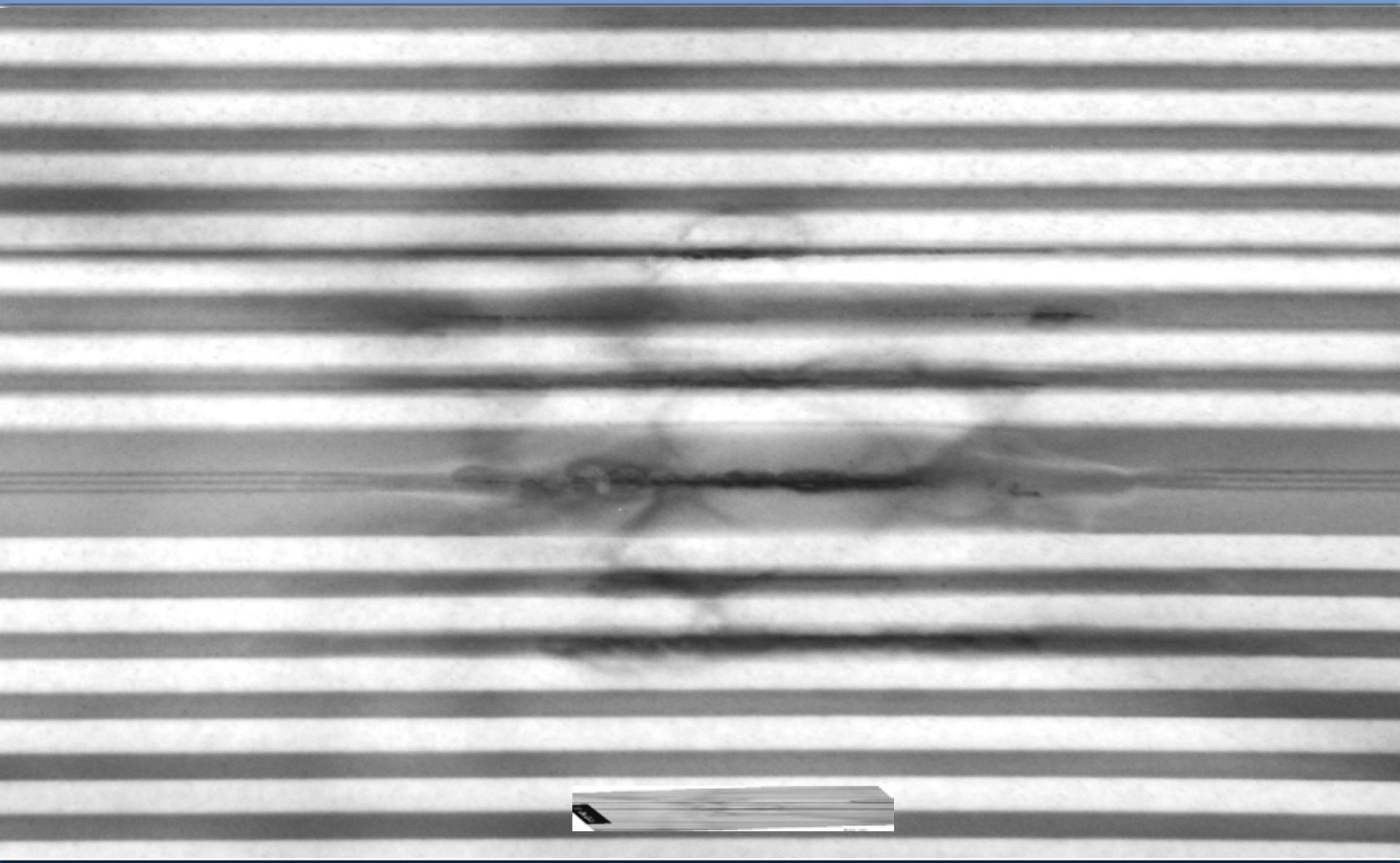
Typical In-process Pass/Fail Requirement



DIV Curves on a Log-Linear Scale



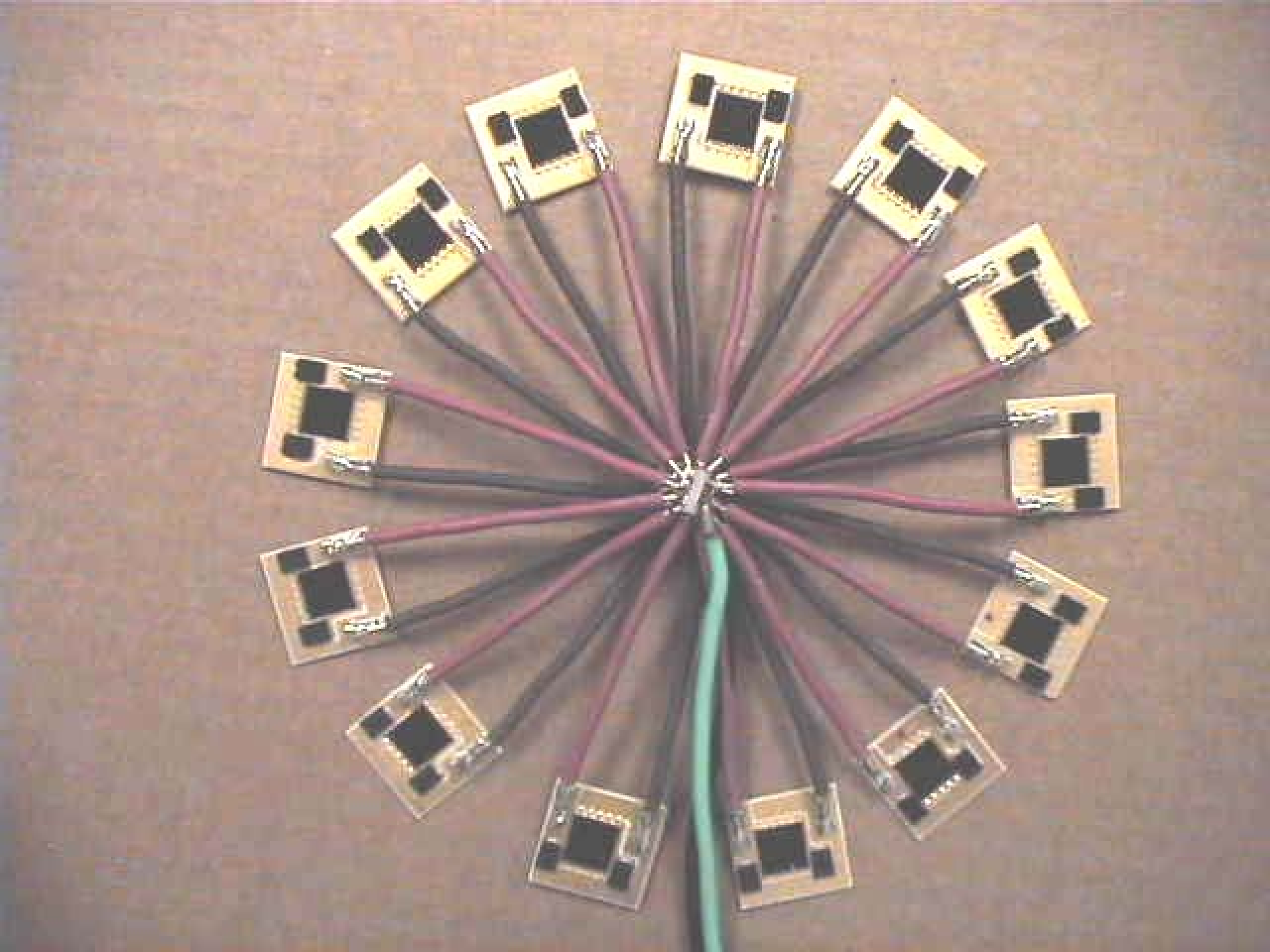
Cross Section TEM of ESD Damage (Laser Diode Structure)



Thermal Runaway

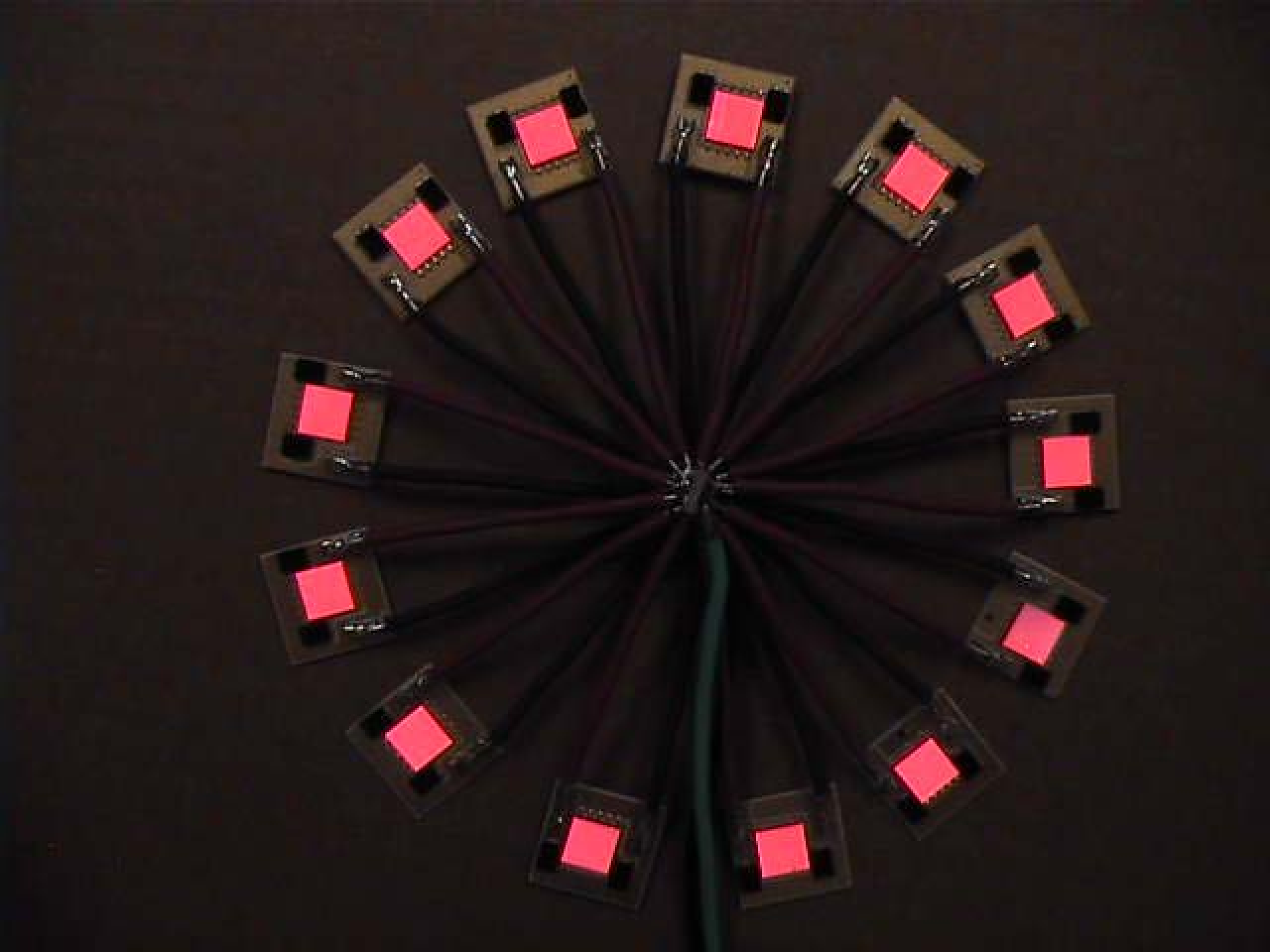
Thermal Runaway Demo

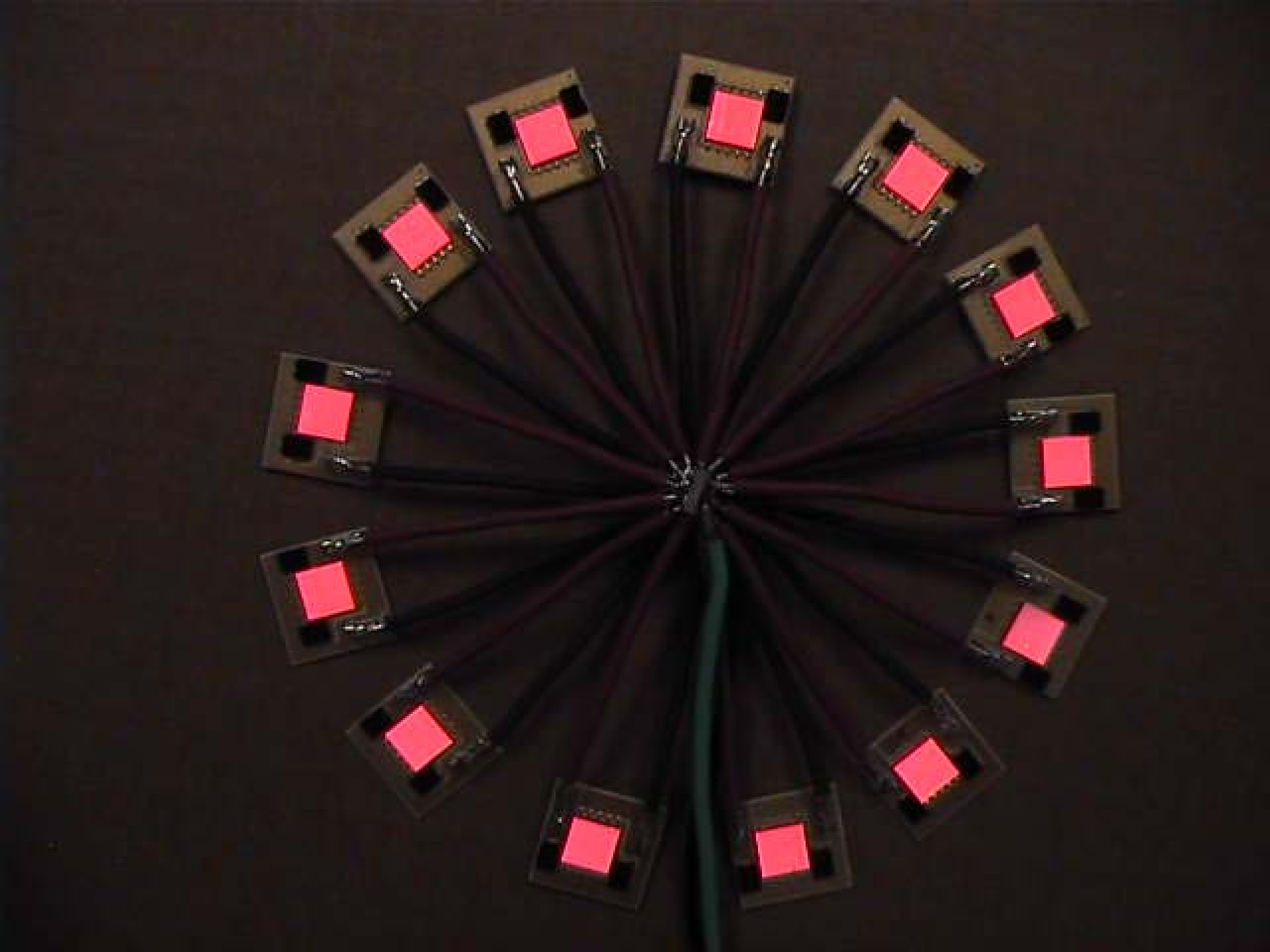
- The following slide sequence shows a baker's dozen of Rxs wired in parallel.
- A fixed voltage at 3 A total regulated current is applied in the forward direction.
- Each device sees the same voltage, but draws a slightly different current due to natural variations in the forward IV characteristics of the cells.
- The assembly is then allowed to heat up.
- As this happens, eventually one of the devices will heat a bit more than the others.
- This, in turn, causes a shift towards lower voltage of the IV characteristic of the hotter device.
- Which leads to an increase in current flow through that device.
- Which leads to it getting even hotter due to joule heating.
- Which causes the IV curve to shift even further.
- Etc., etc.
- Eventually, a single device in the array will draw the lion's share of the current.
- If this is allowed to continue, that device will eventually overheat and fail.









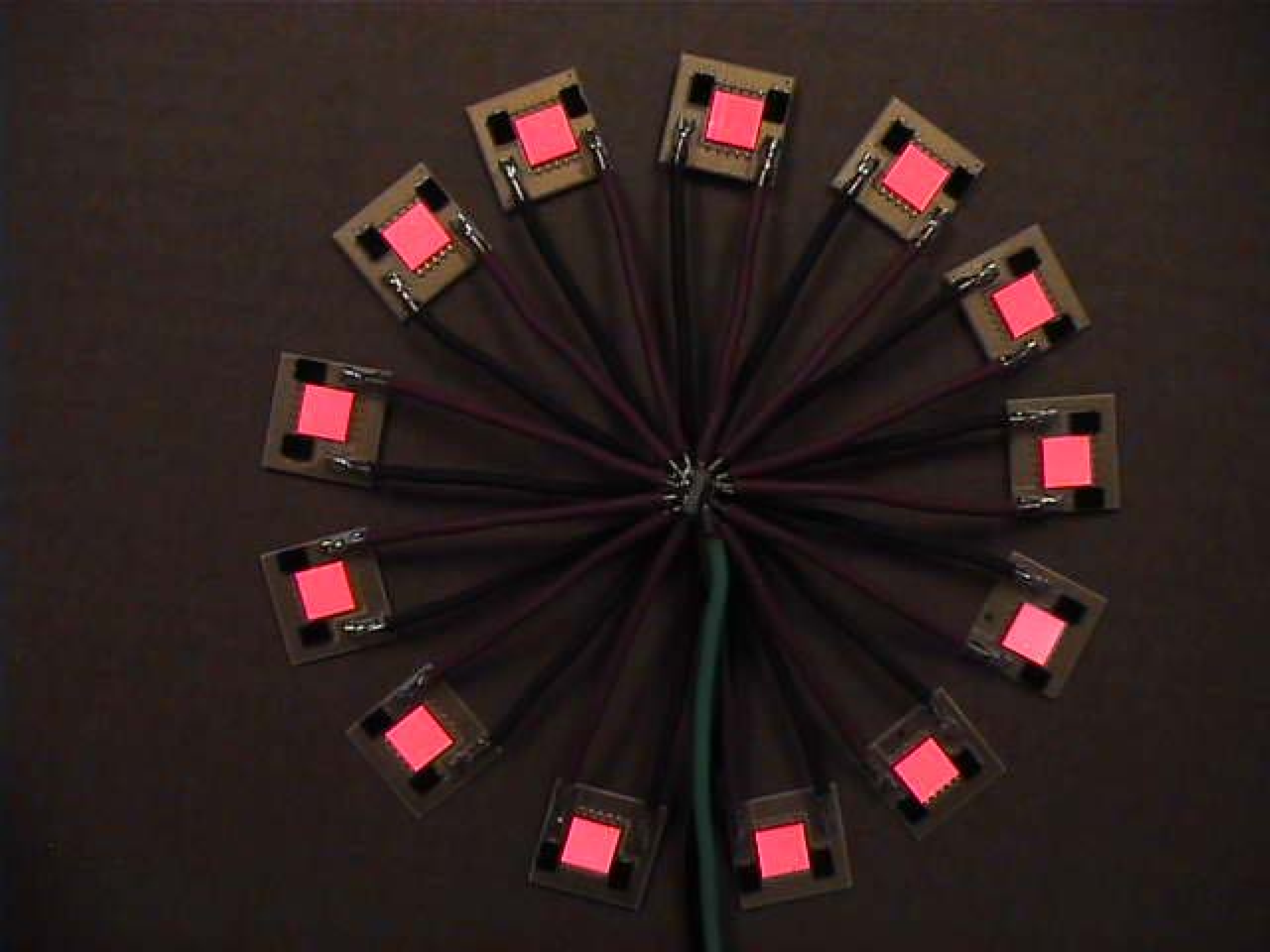


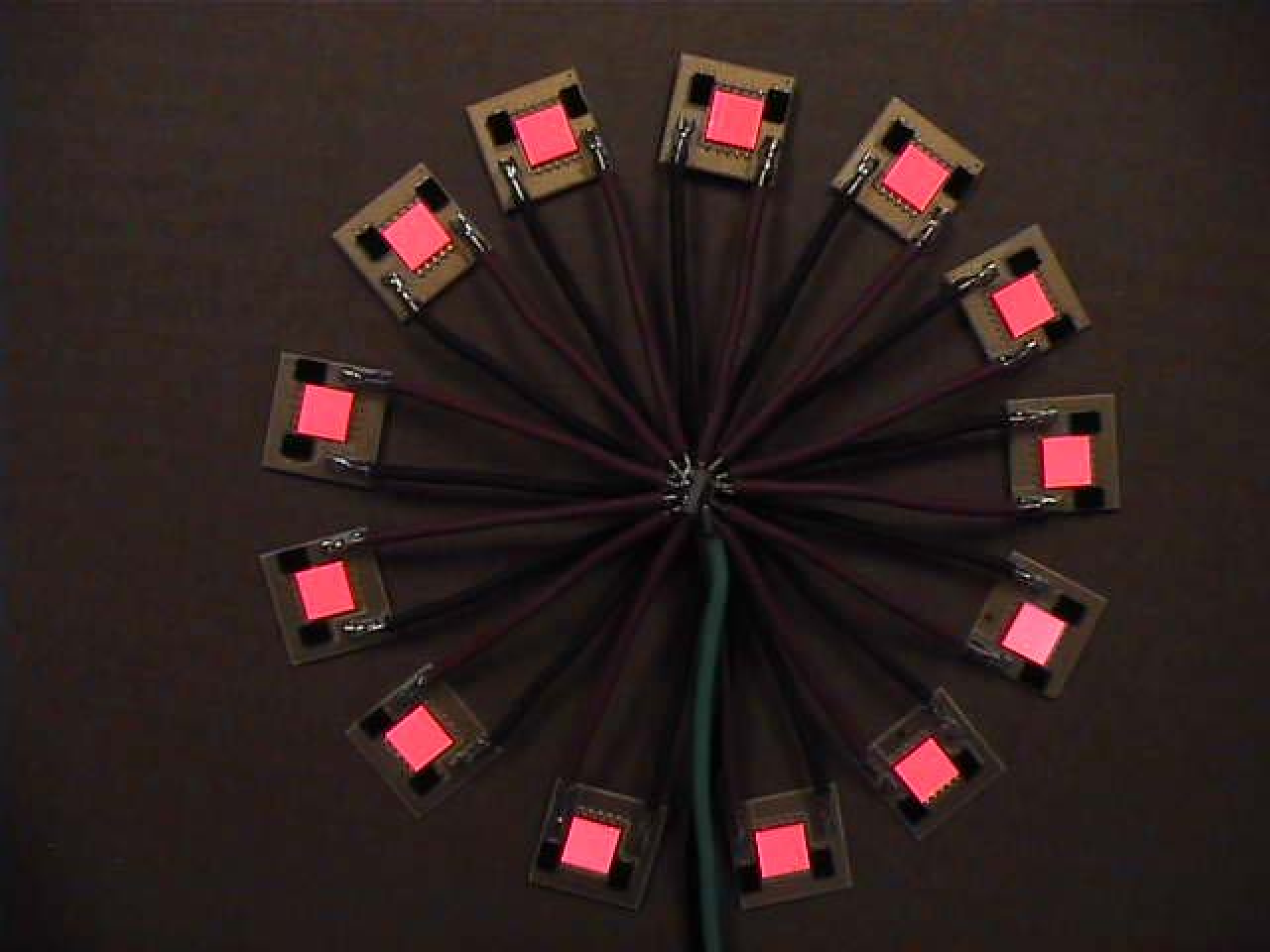










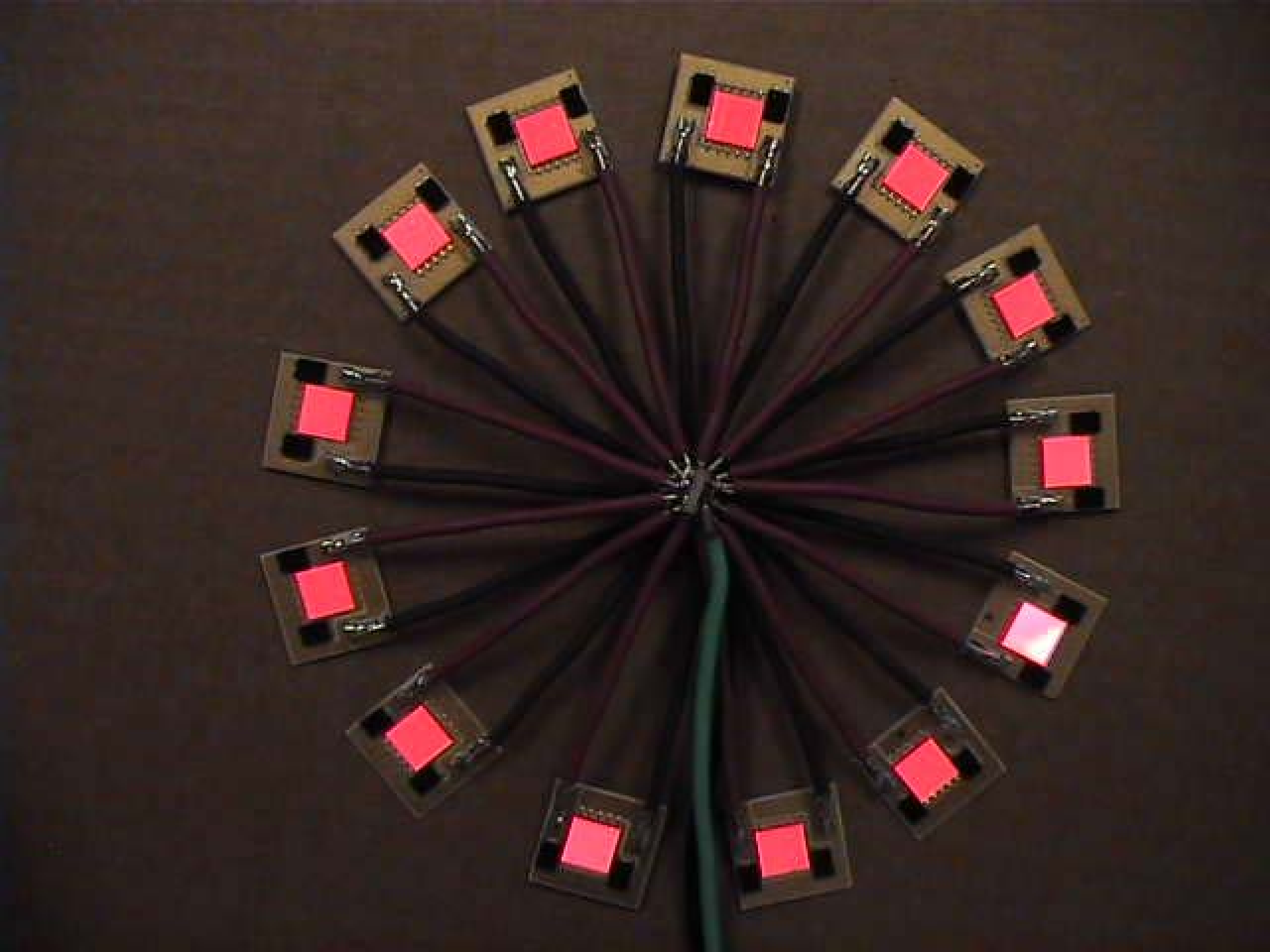


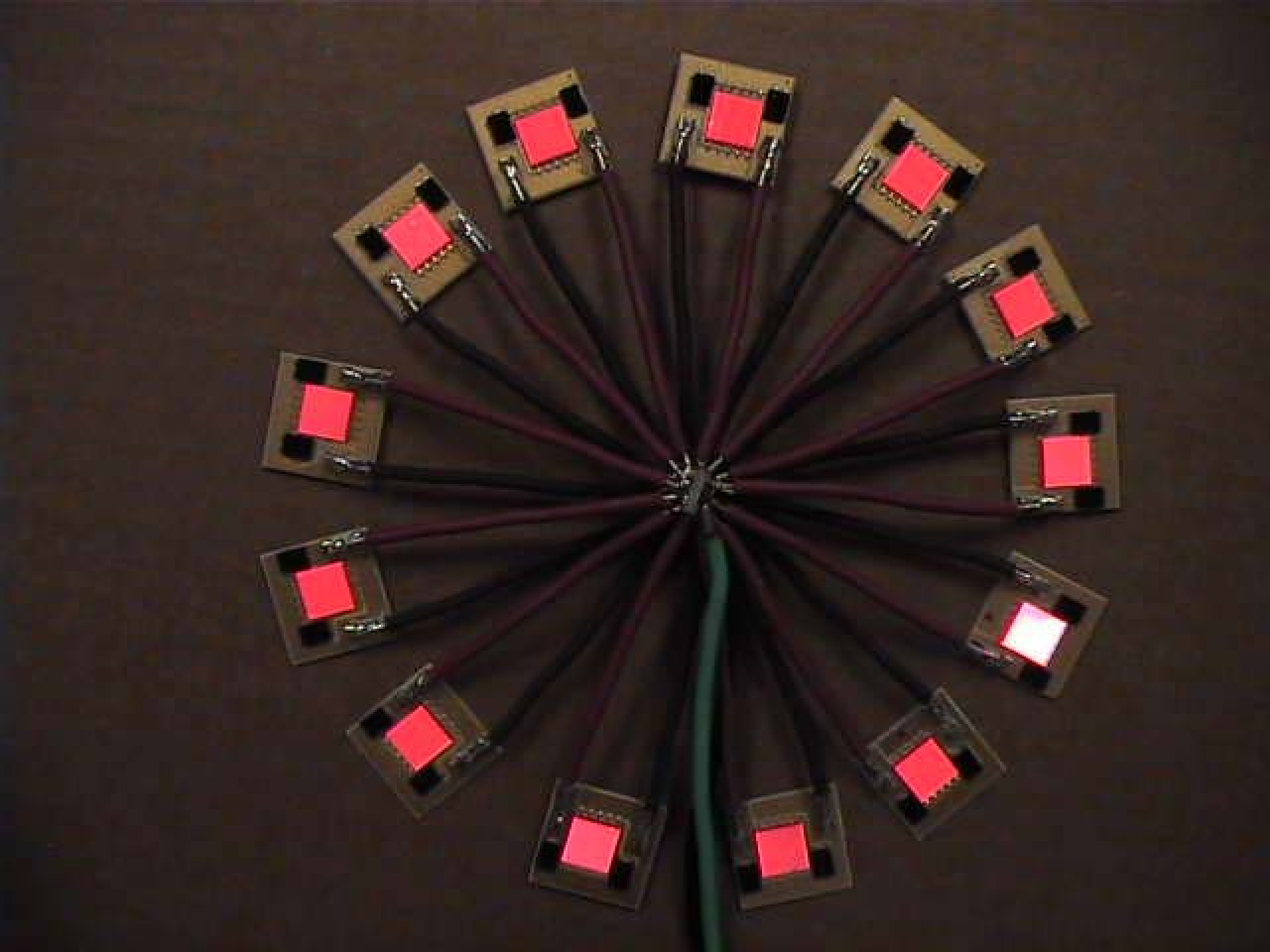


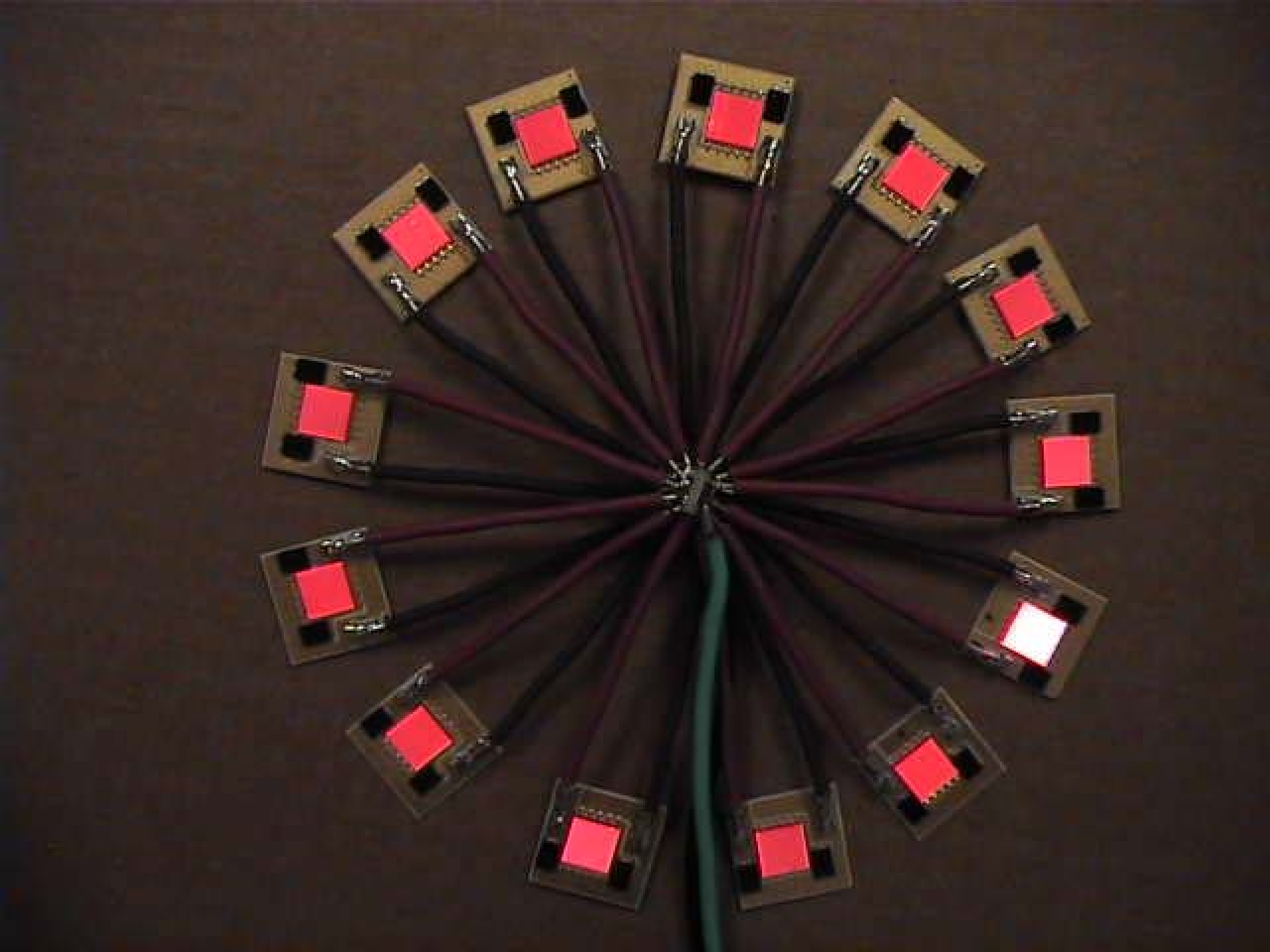


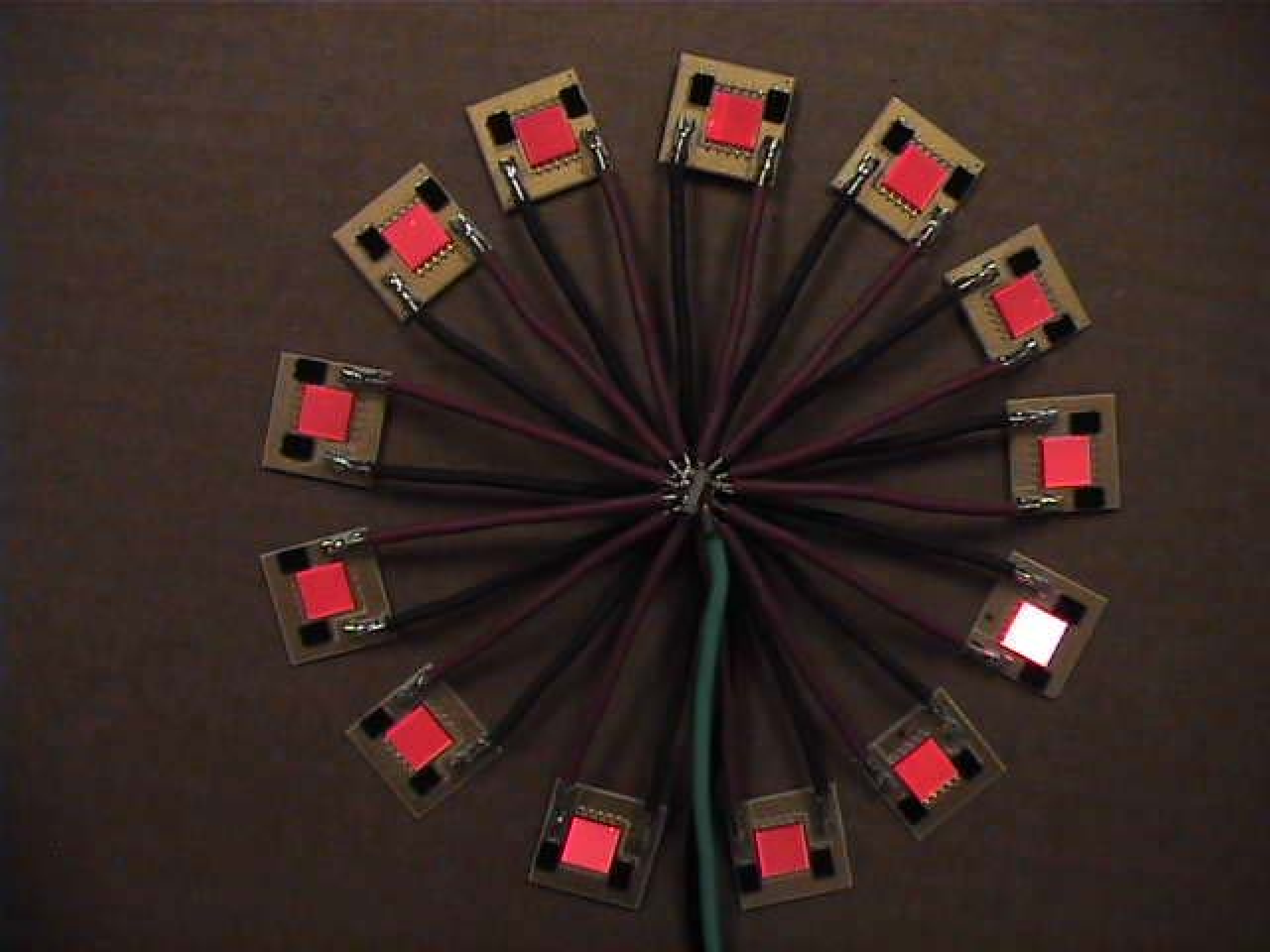


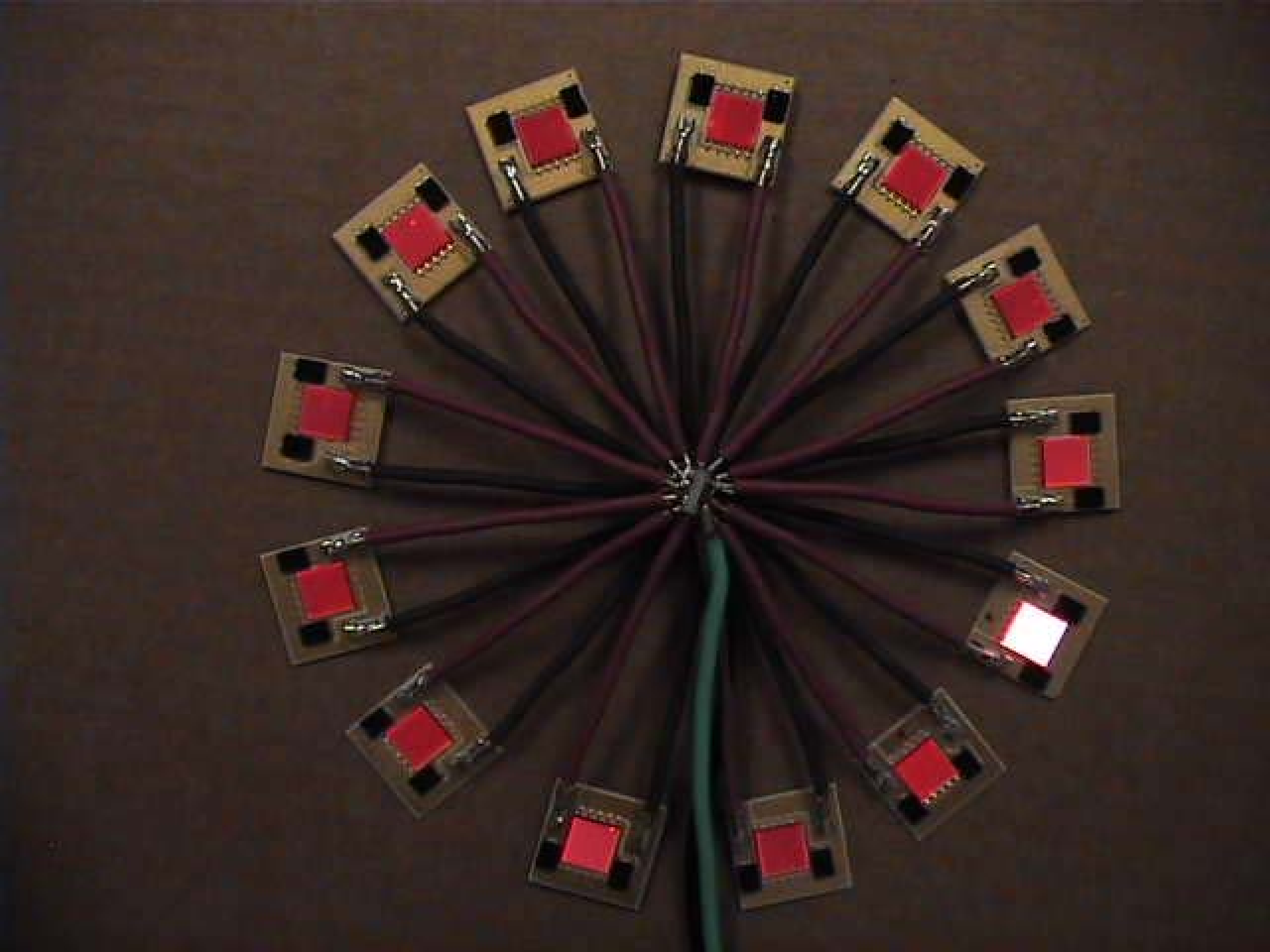


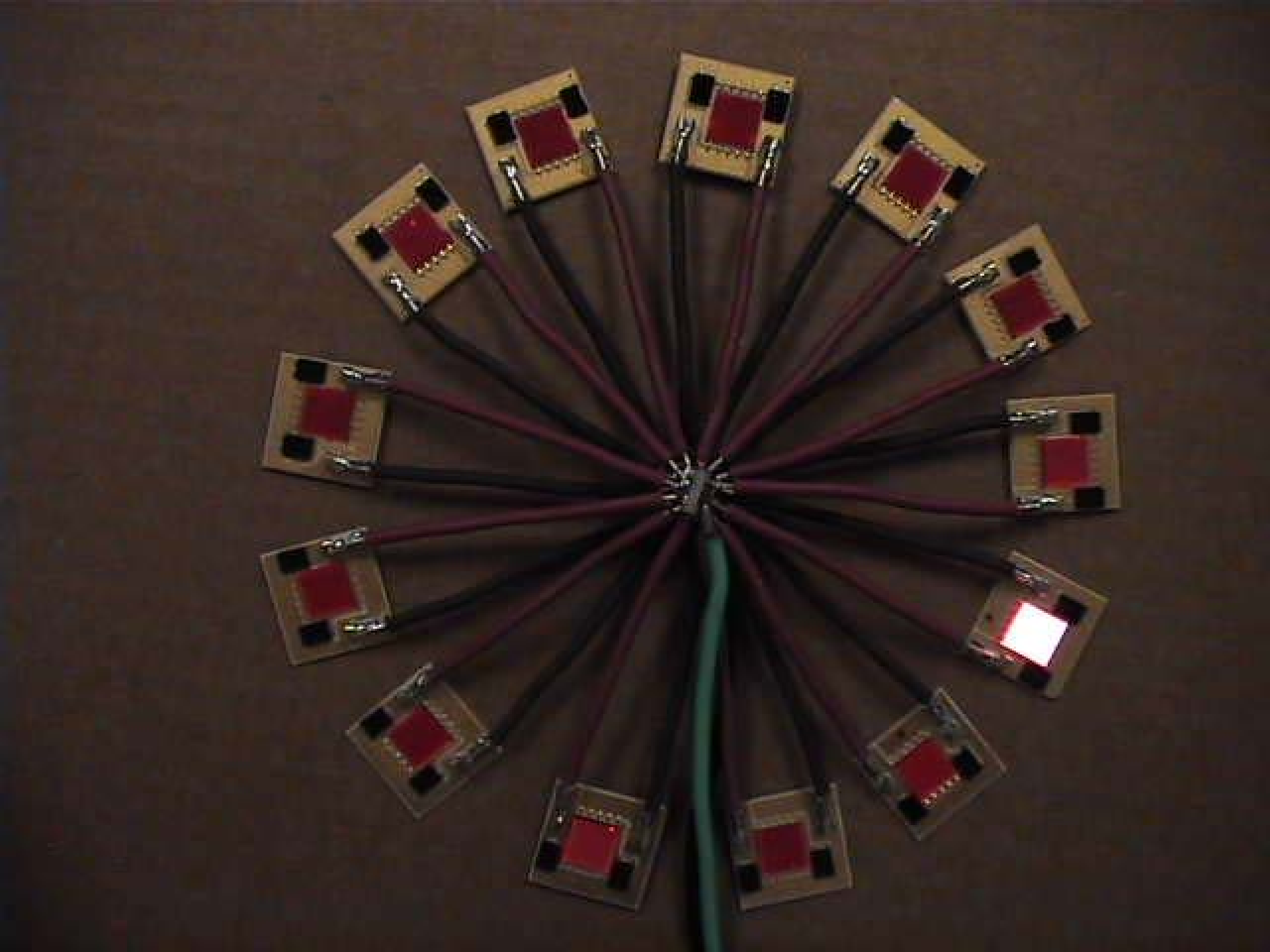




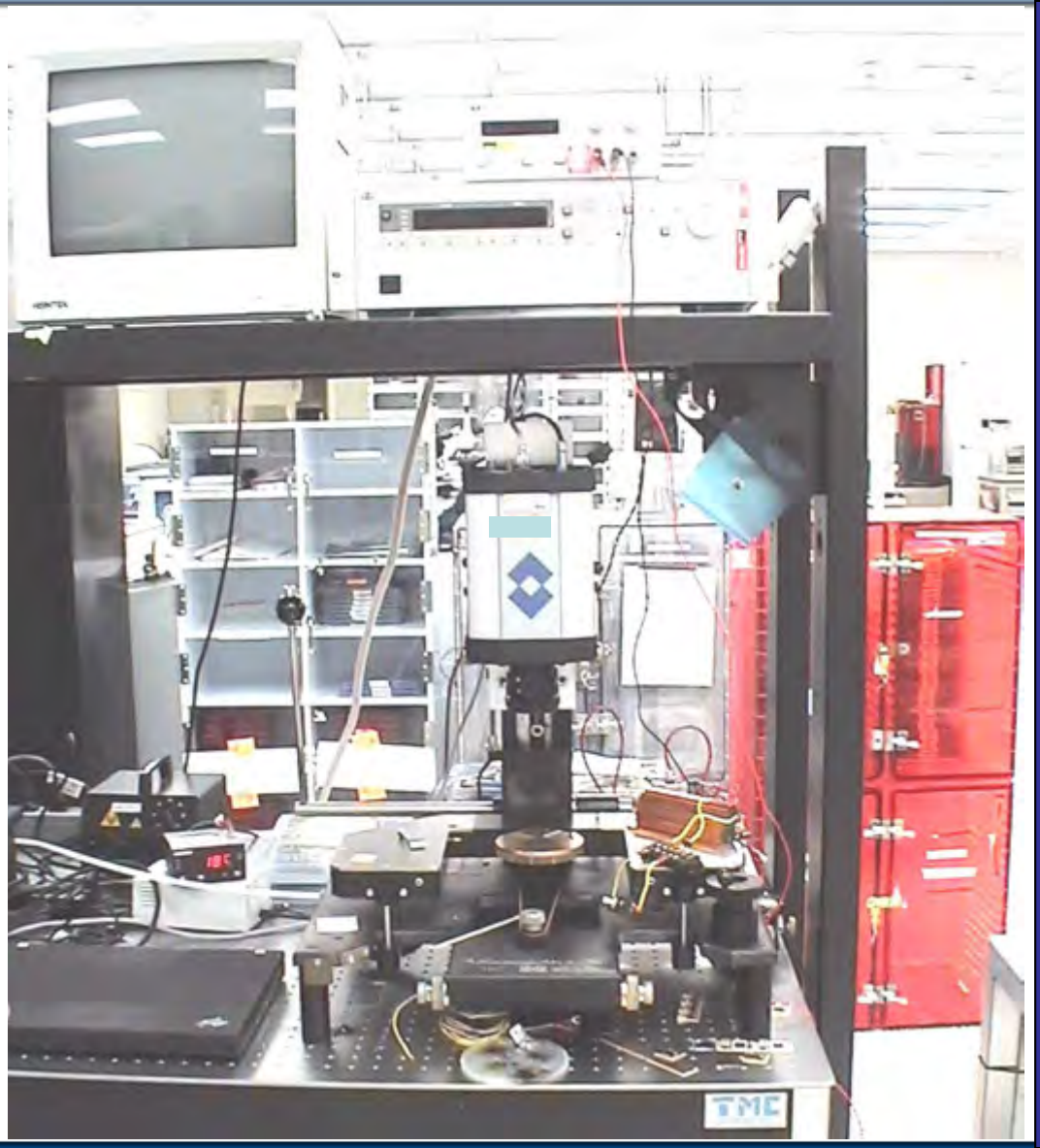


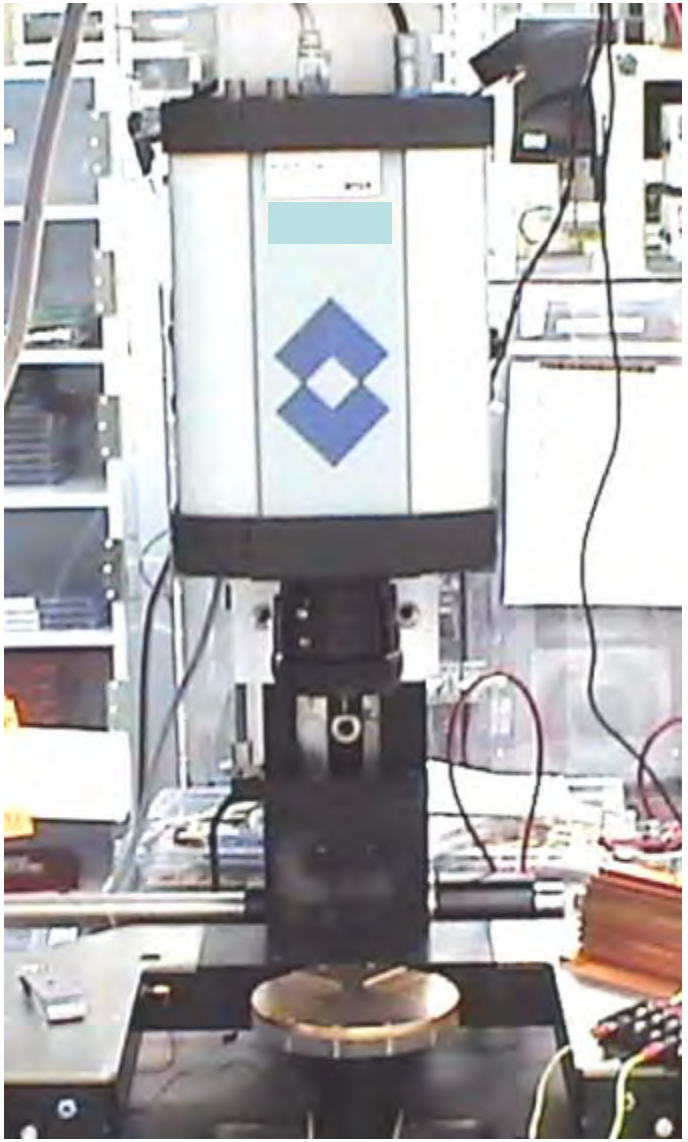






Thermal Imaging Setup



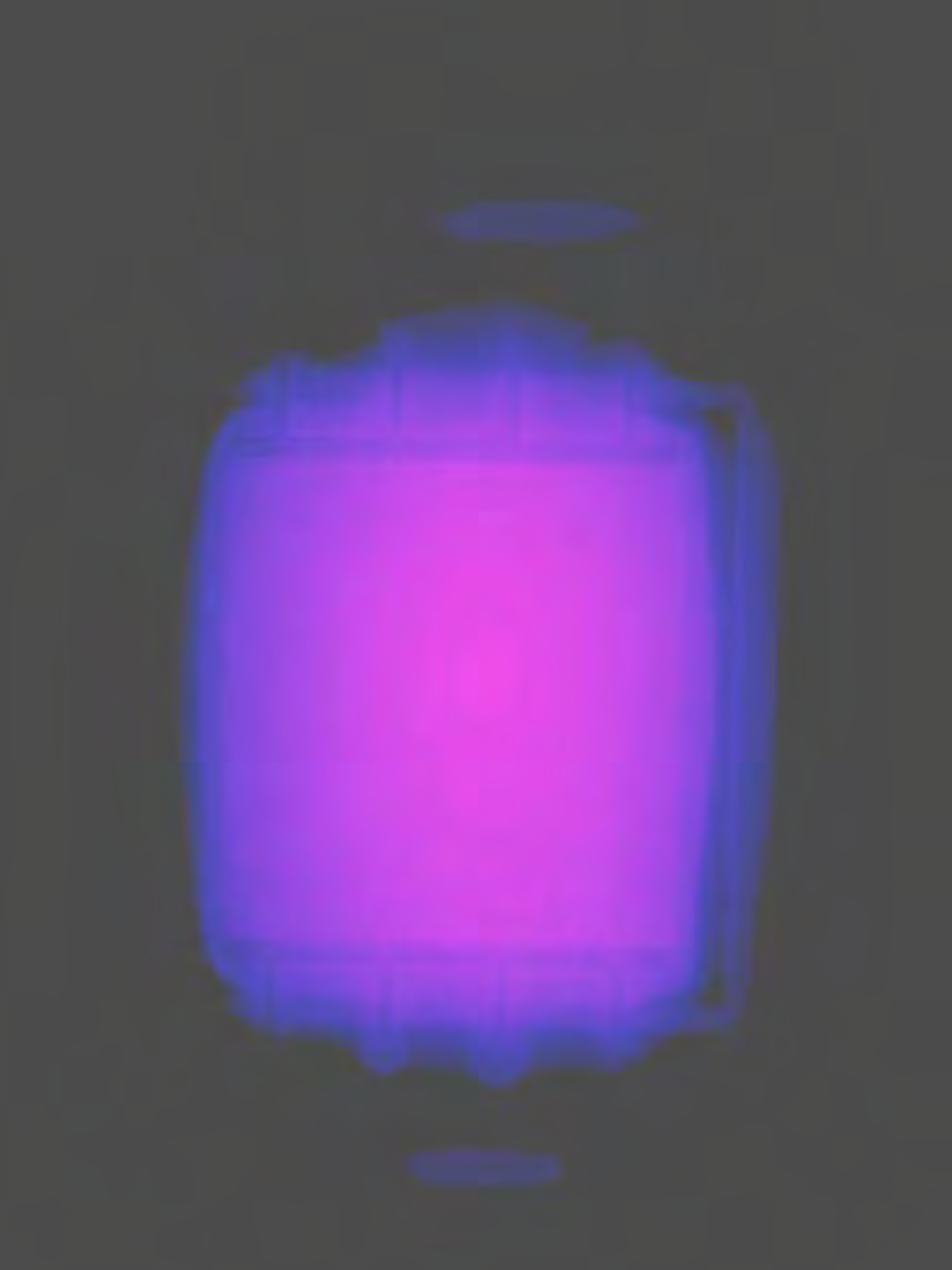


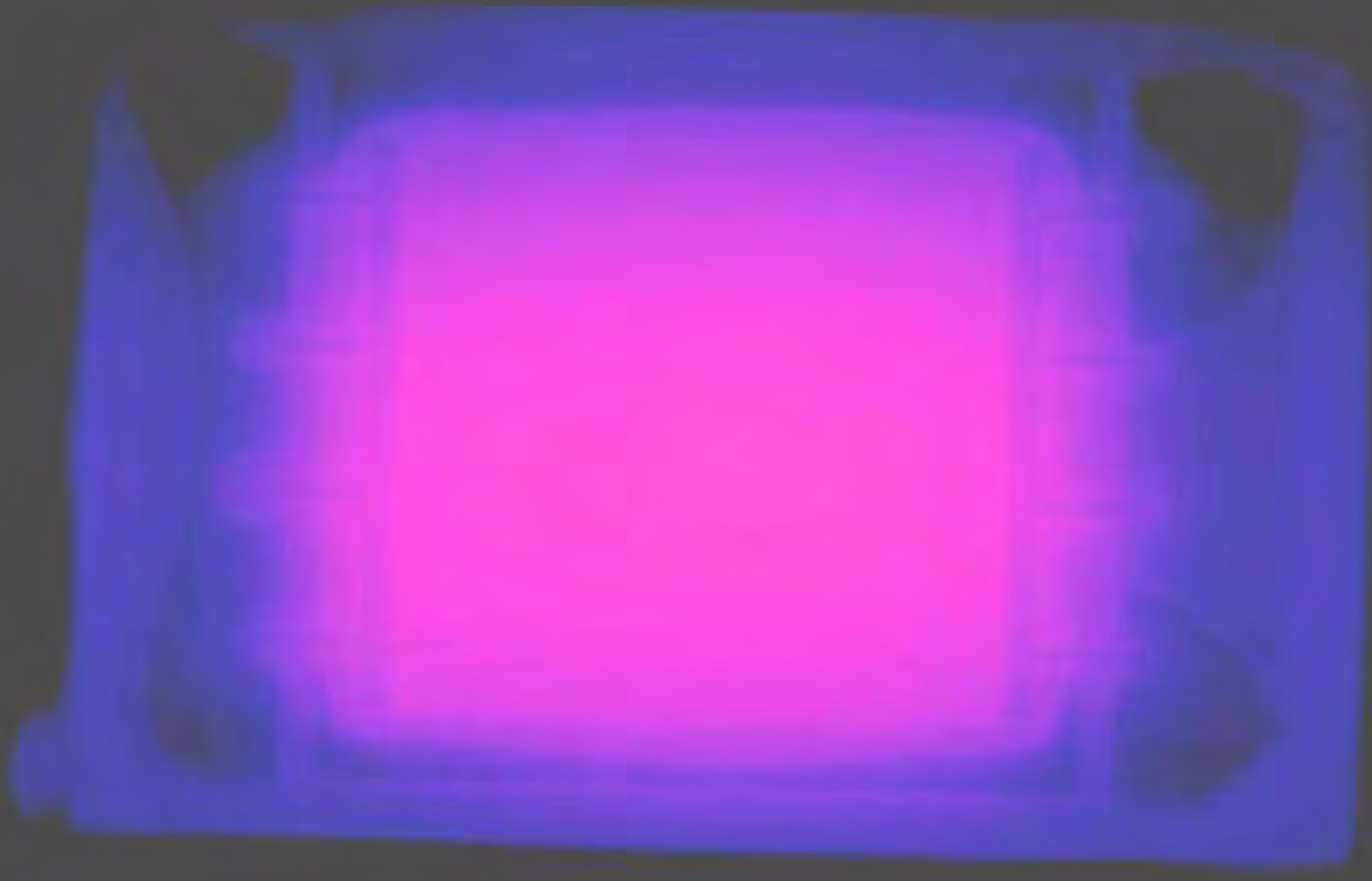
Thermography

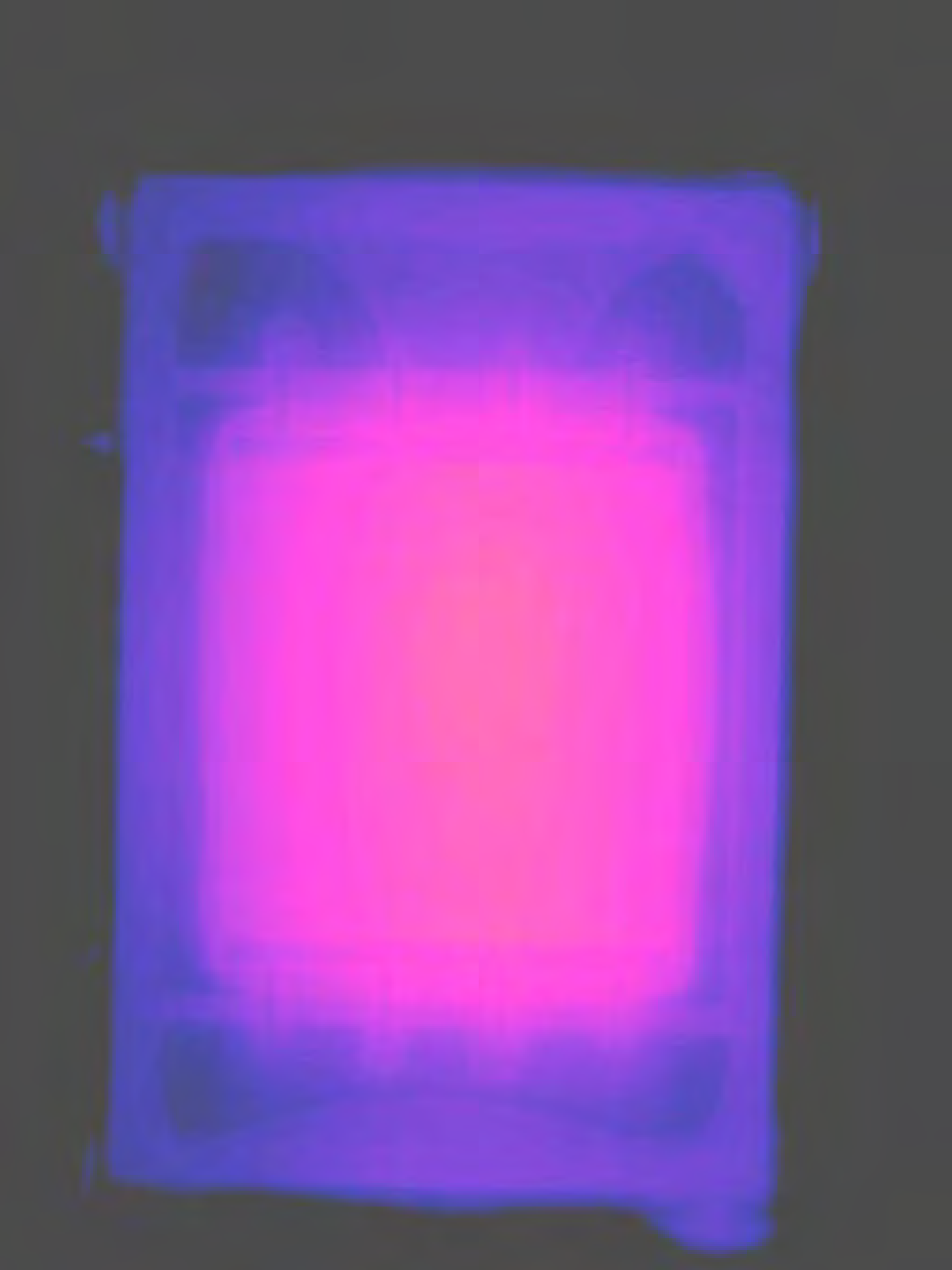
- The previous slide shows a pair of photographs of the FLIR Thermography set up used to capture the images in the following sequence.
- What you will see are thermal images of a single receiver that is stressed with progressively higher levels of forward current.
- The sequence runs from low bias to destruction of the cell by thermal runaway.
- The thermal scale runs from black = room temperature to white = hot, hot, hot (>350°C where the camera saturates).

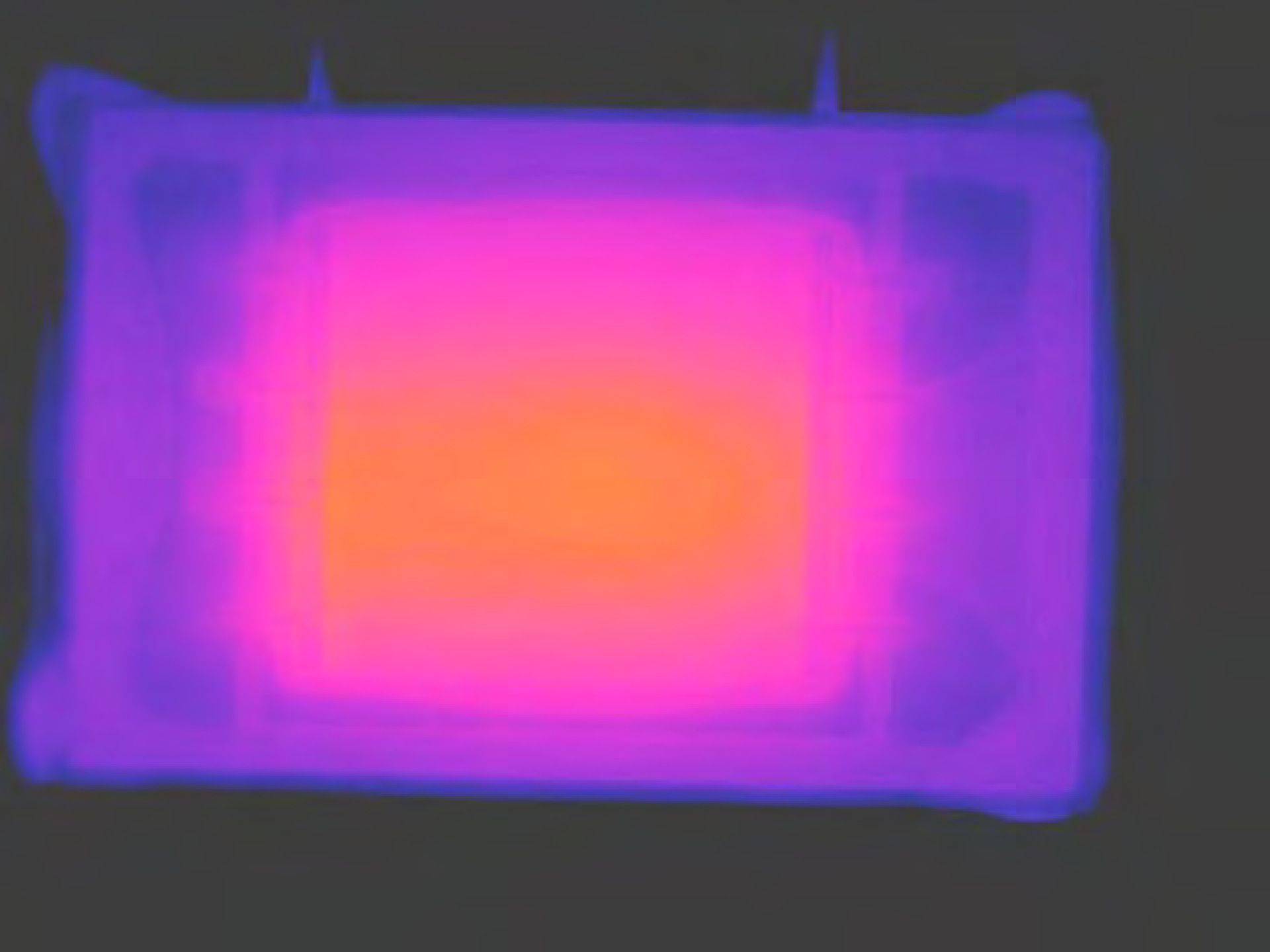


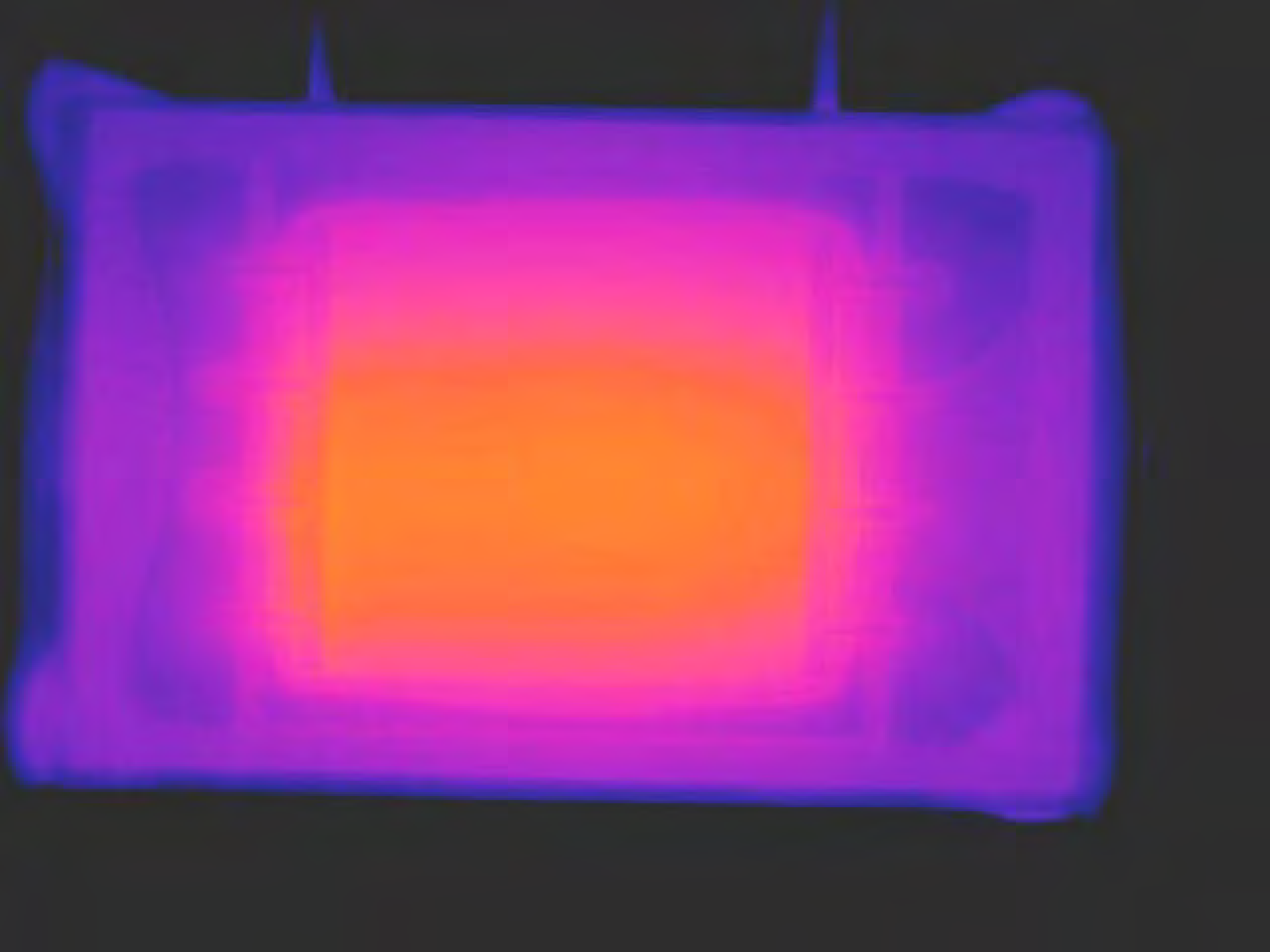
- These images were not corrected for emissivity variation between the various surface materials in the receiver.

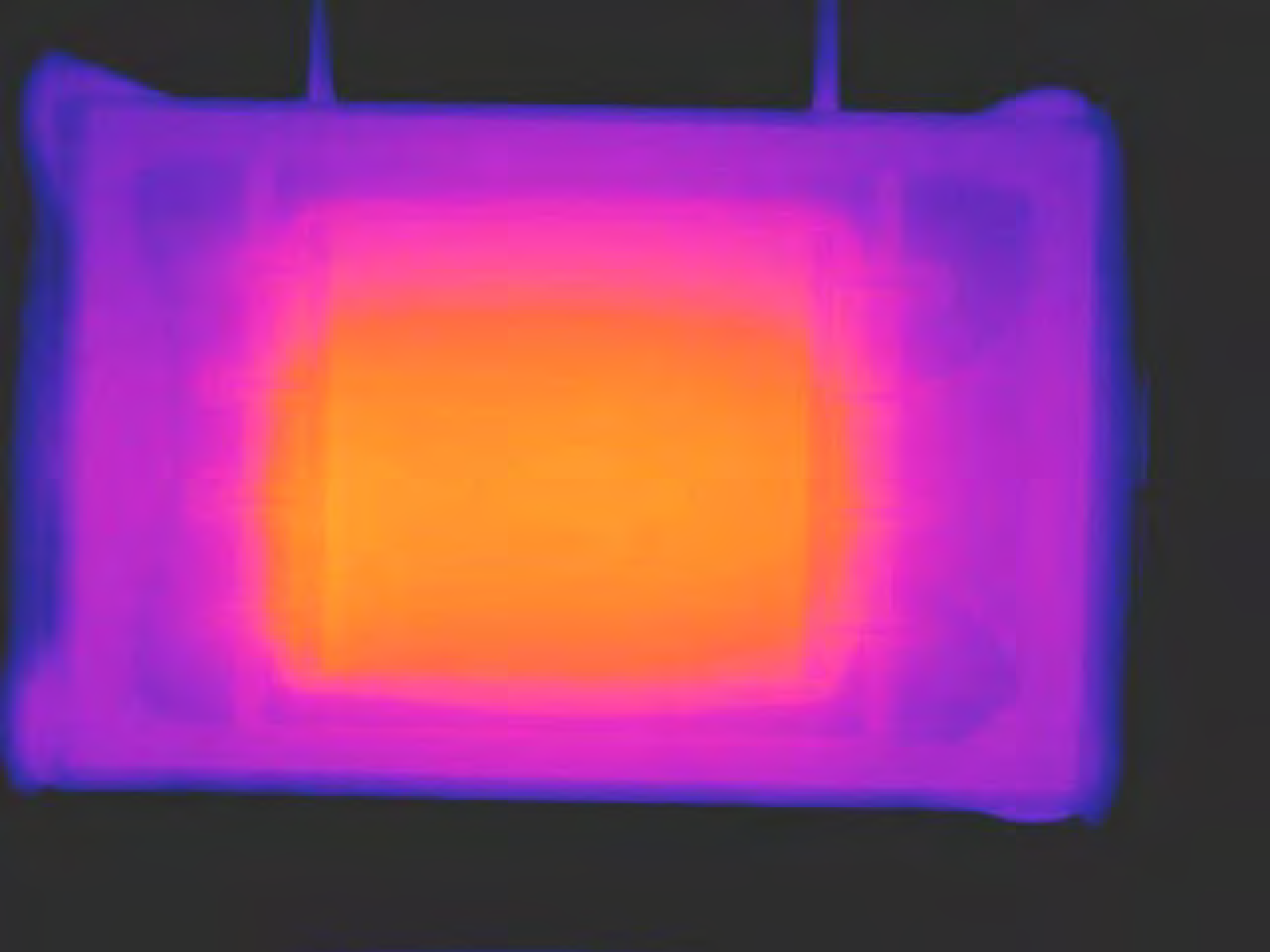


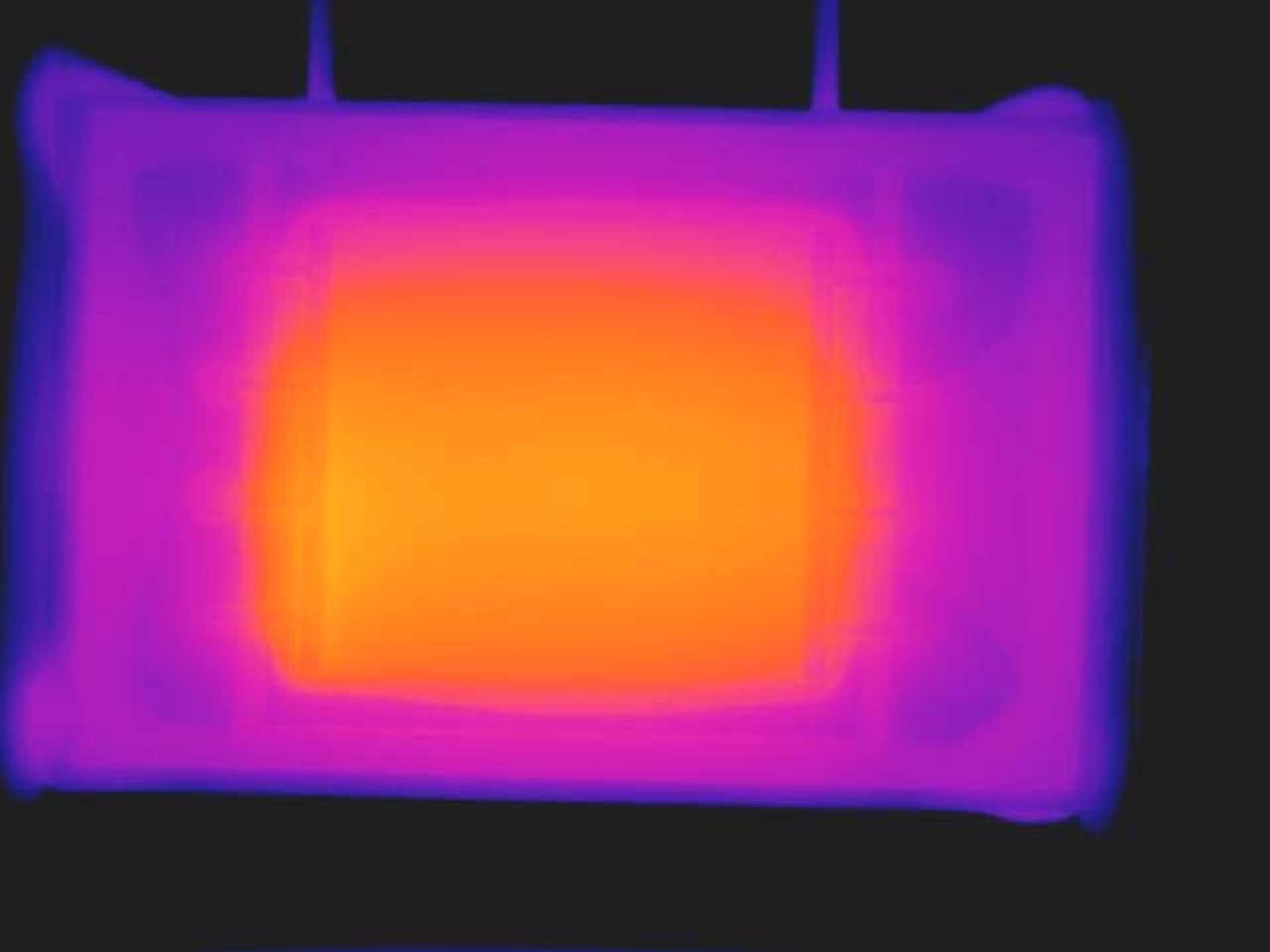


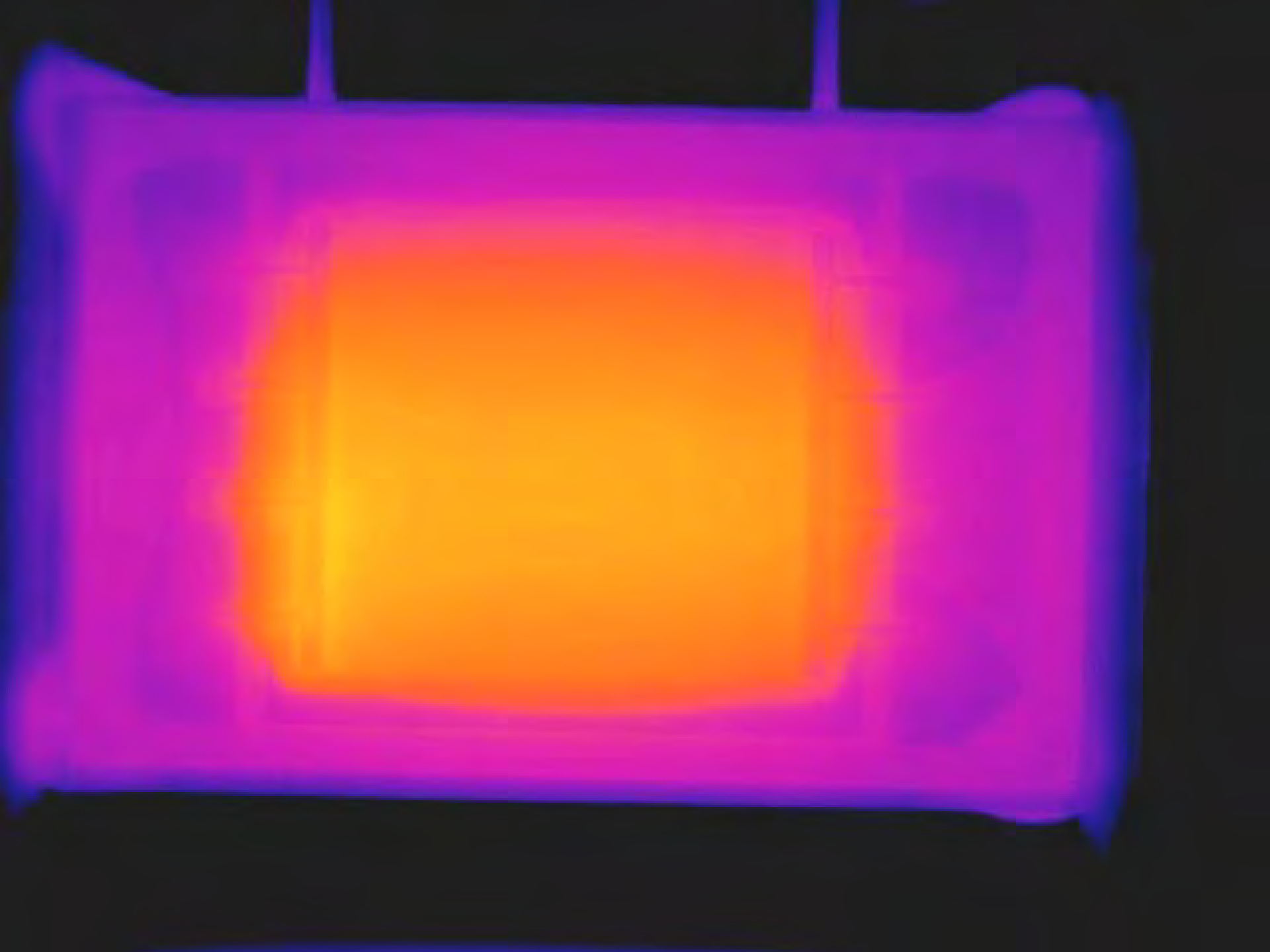


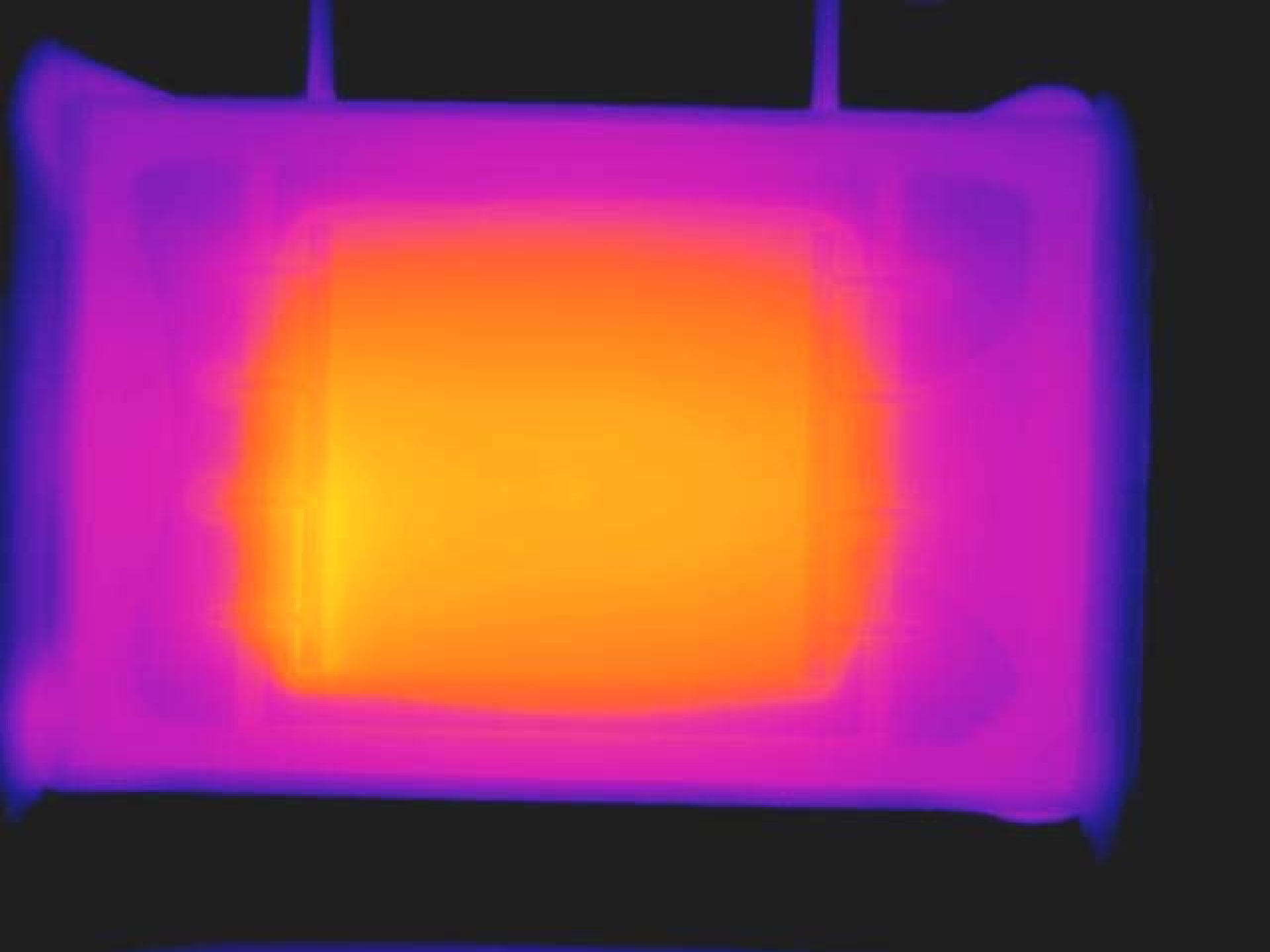


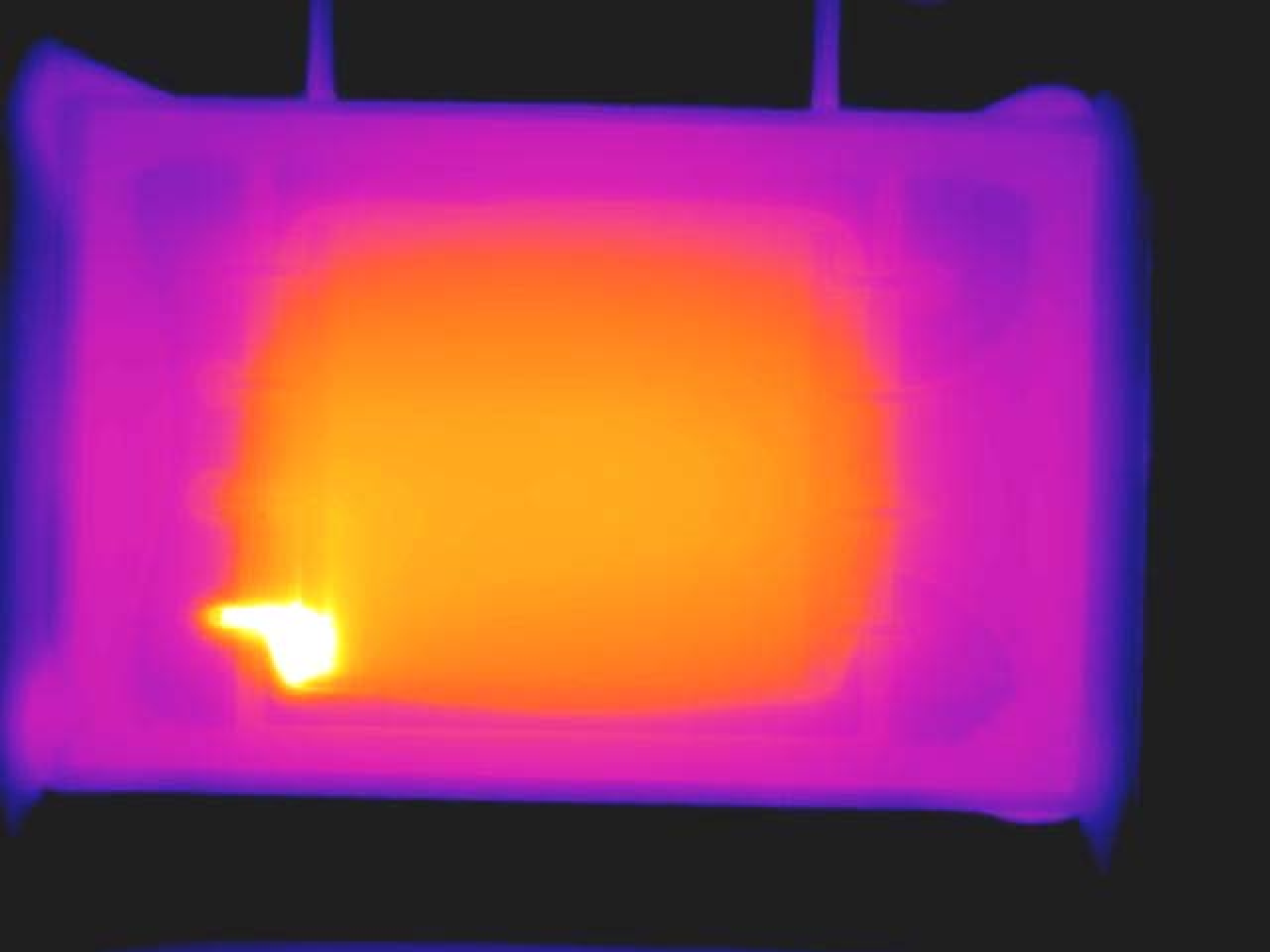


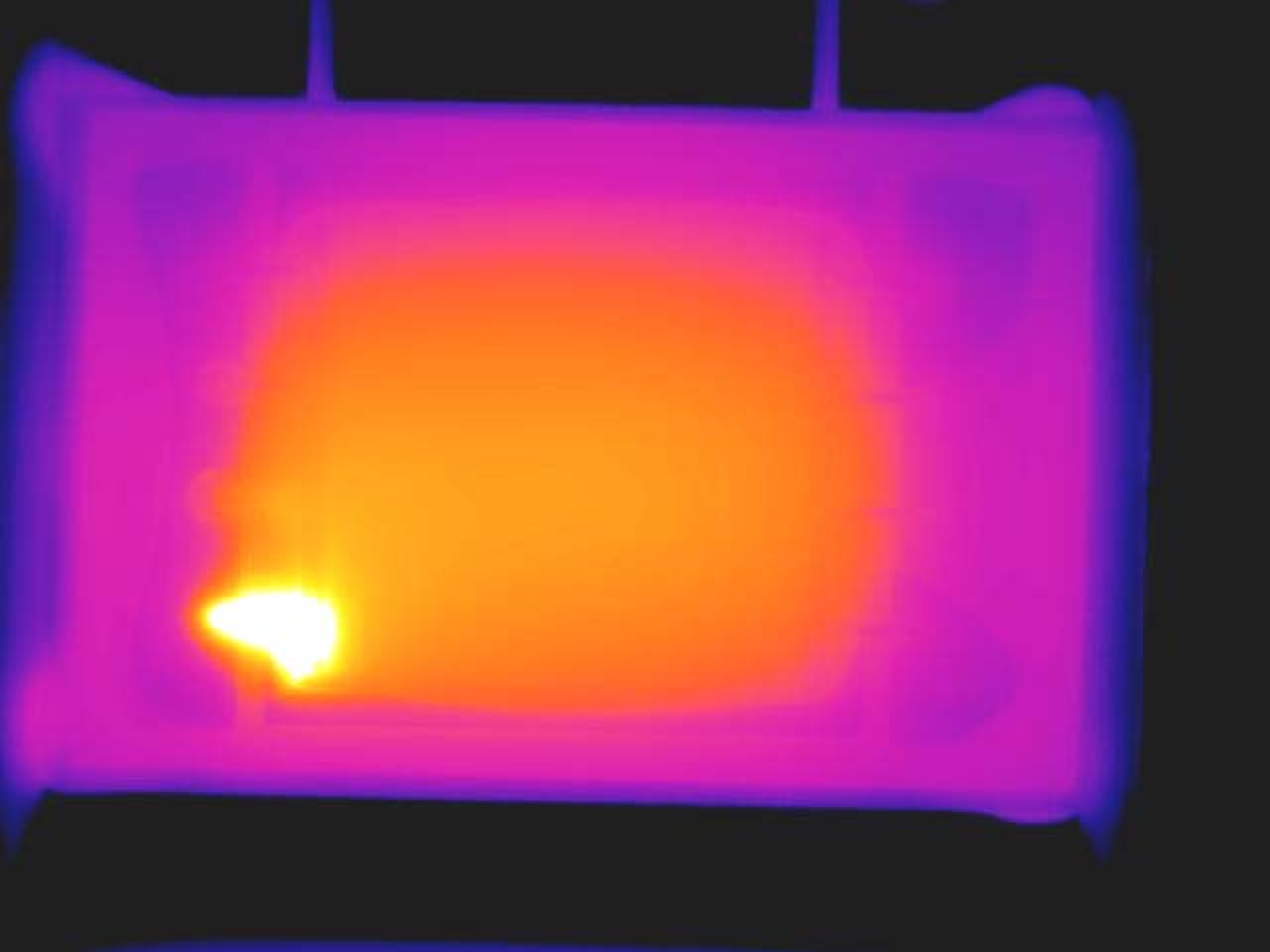


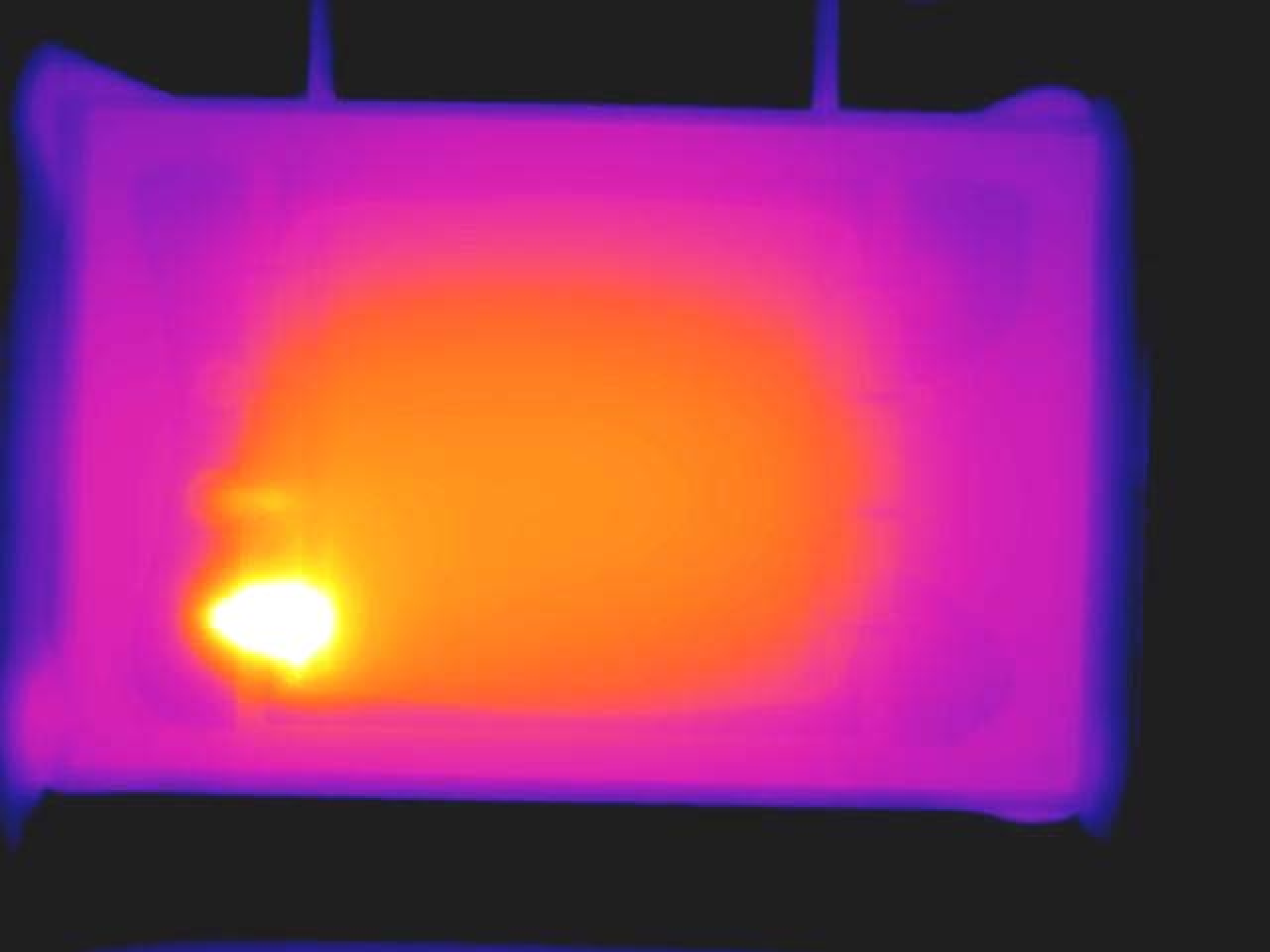




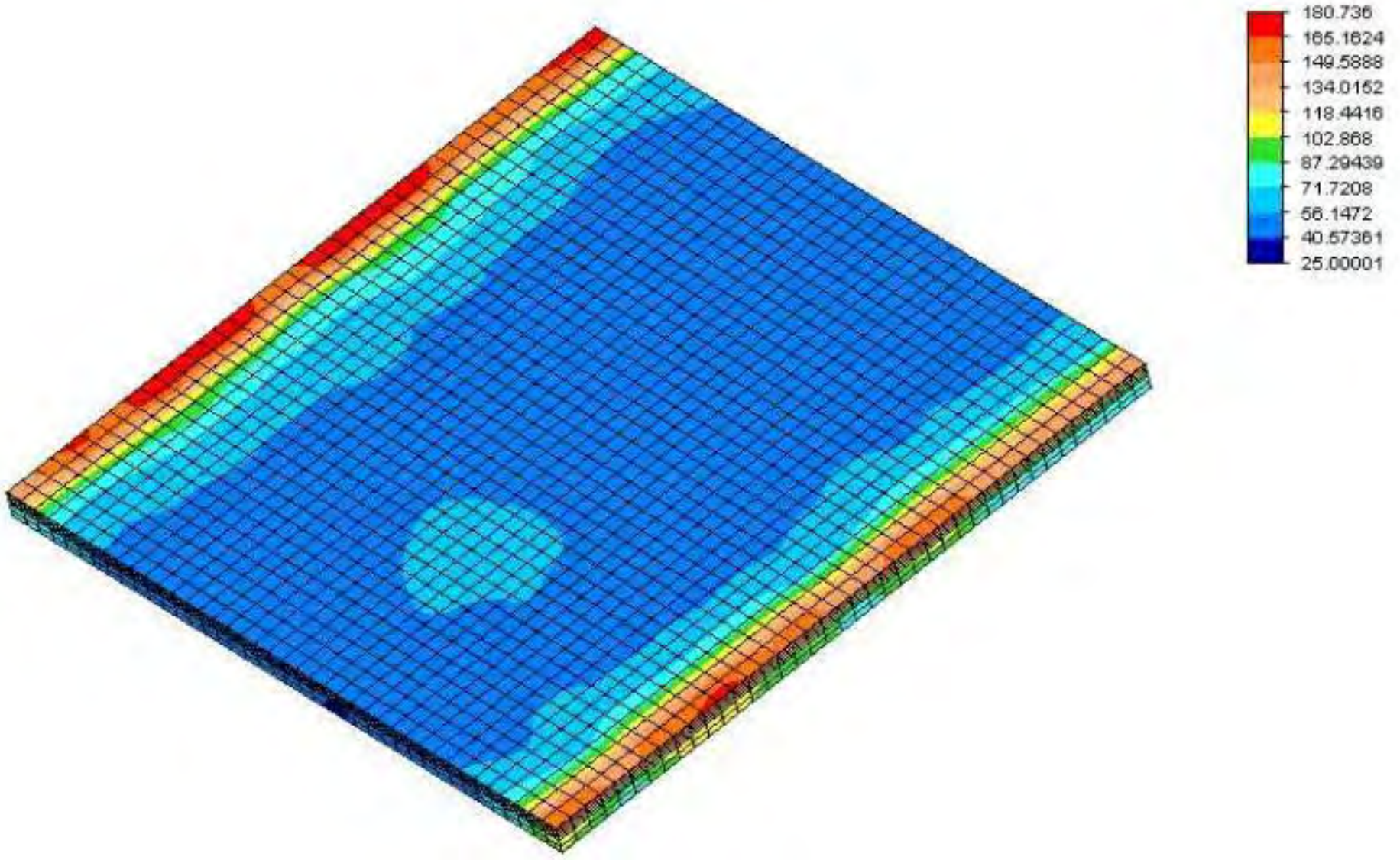








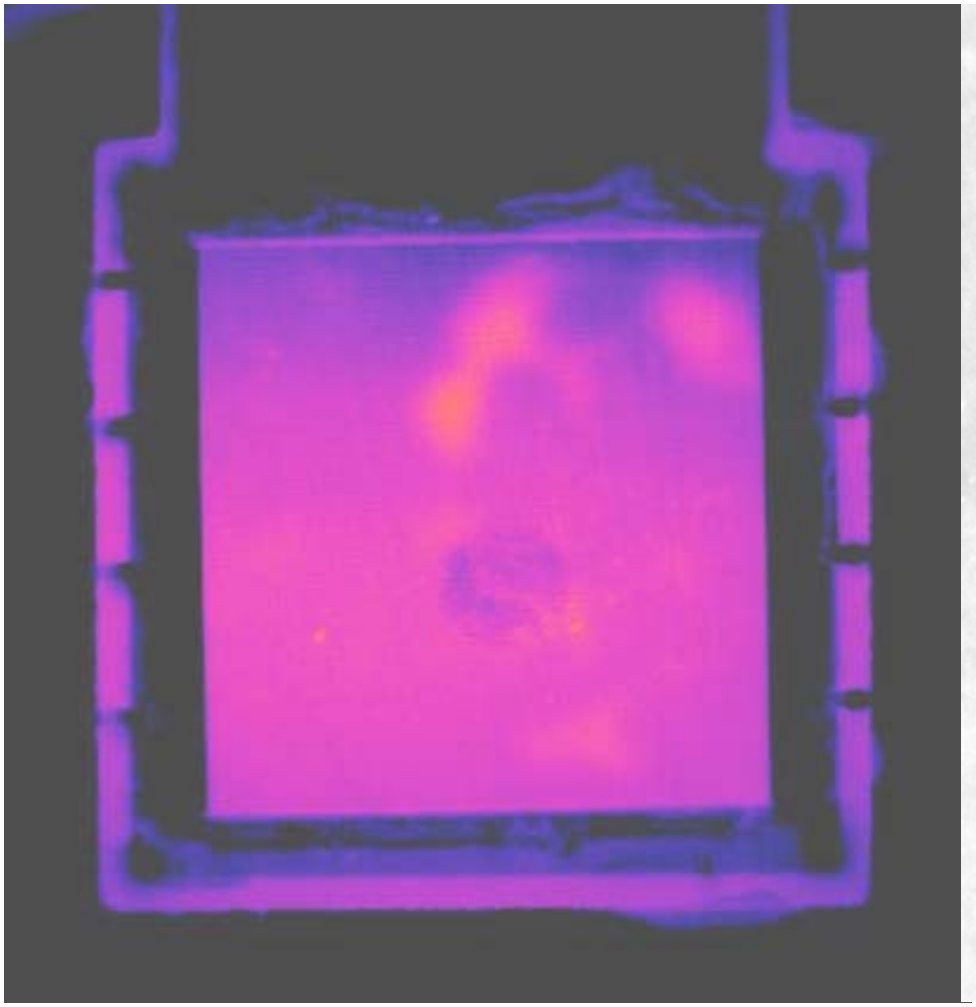
FEA Model (Current and Heat are Synonymous)

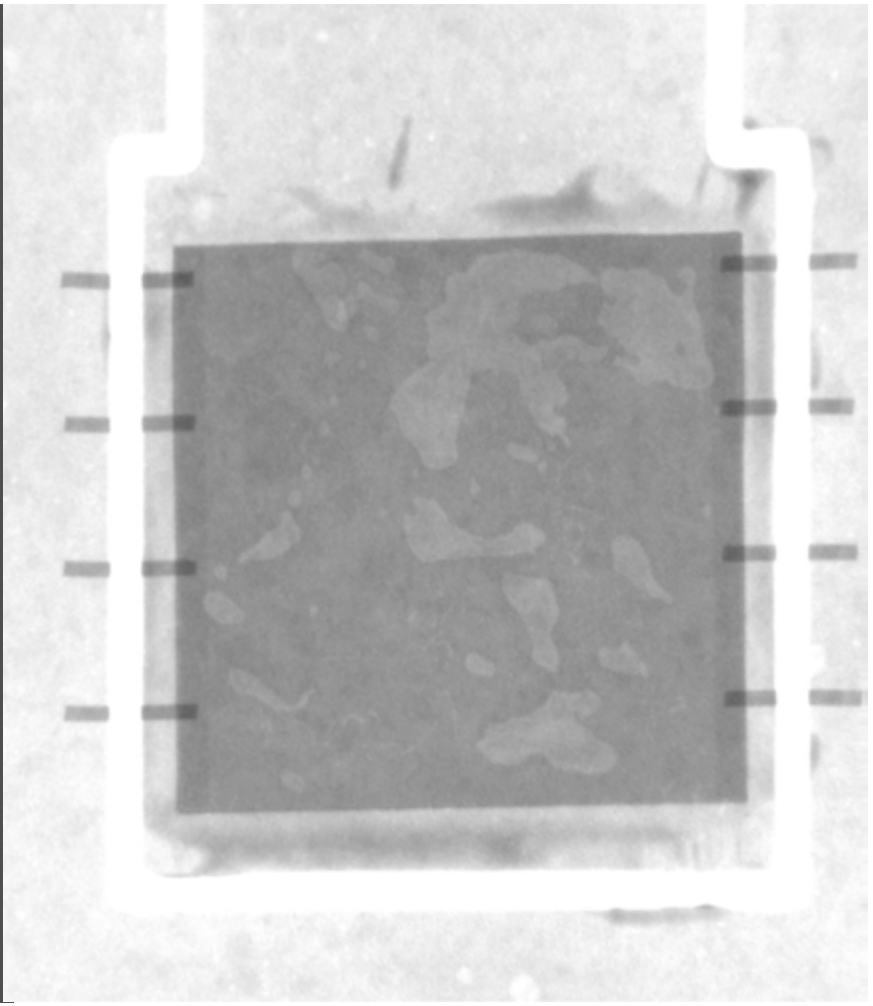


Potential Root Causes of Thermal Runaway

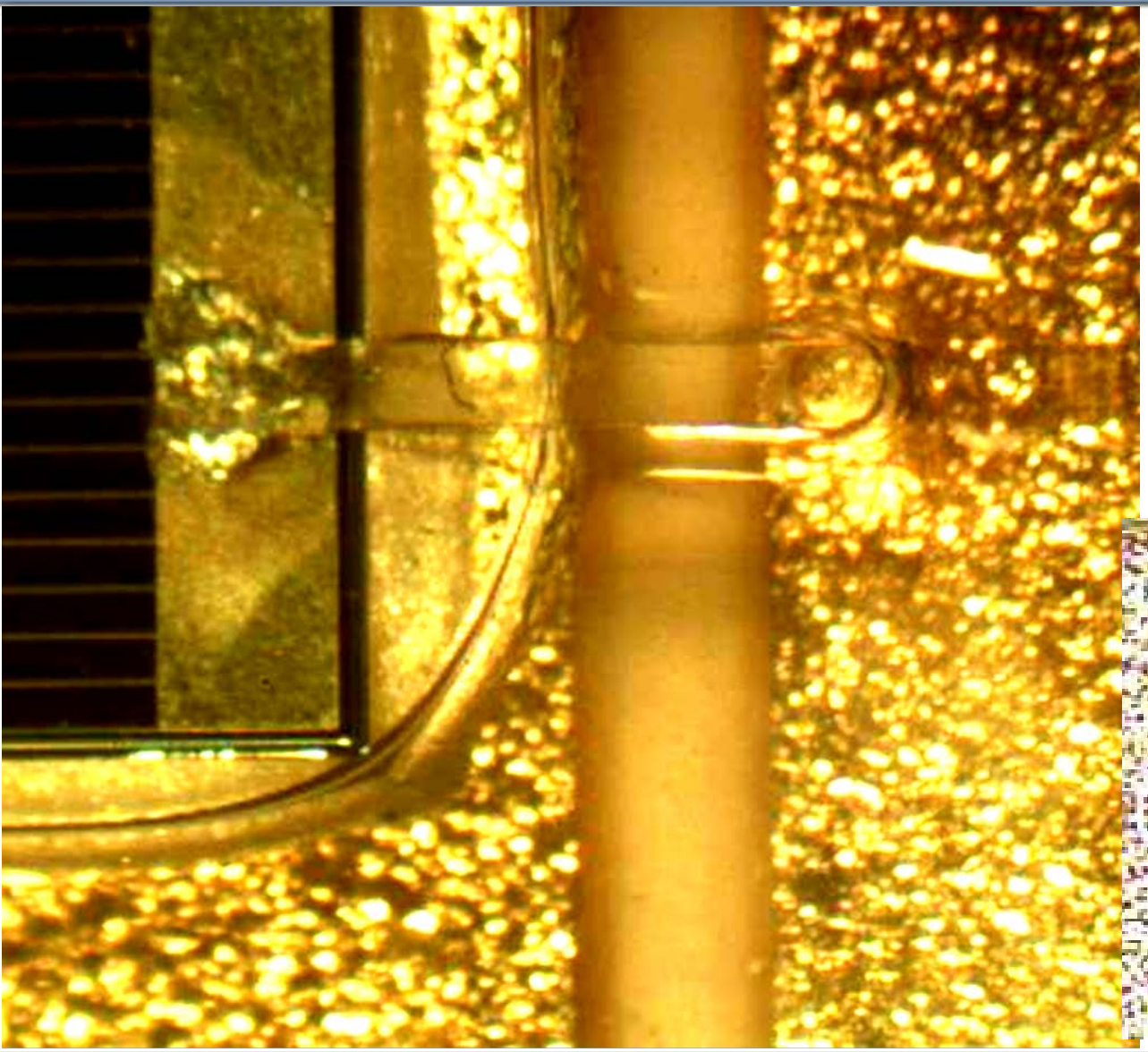
- Thermal Impedance Variations
  - Voids and other non-uniformities in the die attach
  - One corner of a rectangular cell is always higher than the other three
- Current crowding in forward bias
  - Under buss-bars
  - Near ribbon bonds
- Localized shunt current paths
  - Intrinsic crystalline defects
  - Edge shunts
  - EOS/ESD

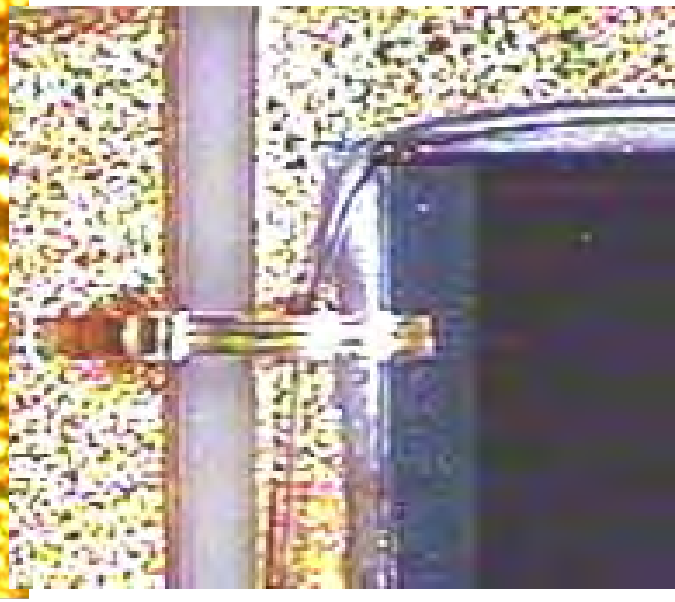
Die Attach Voids





Fused Ribbon Bonds

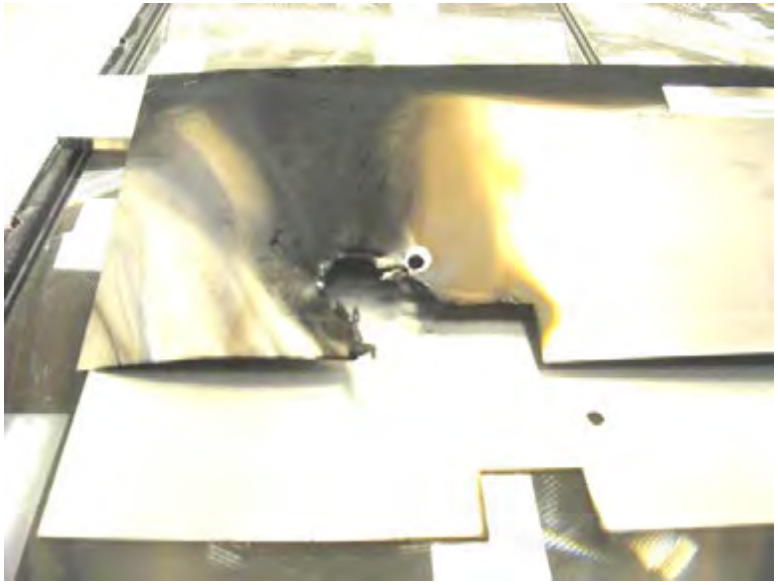




Highly Energetic Events







Power Thermal Cycling

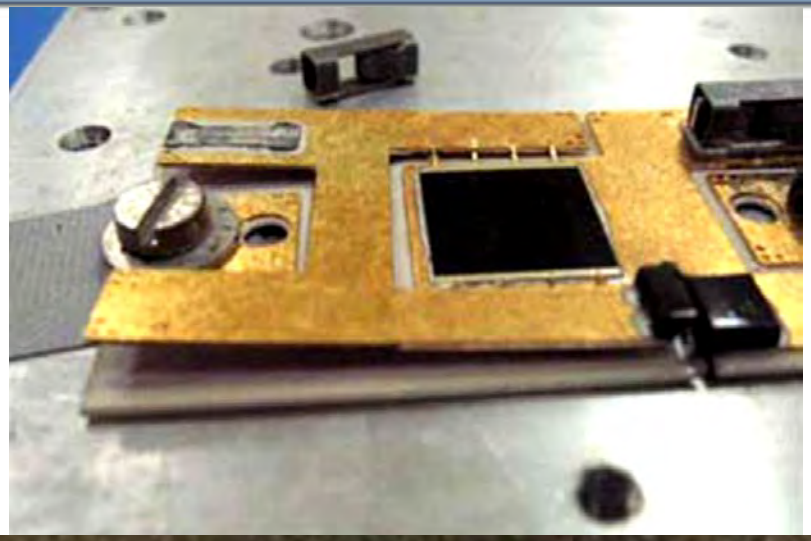
Power Thermal Cycle

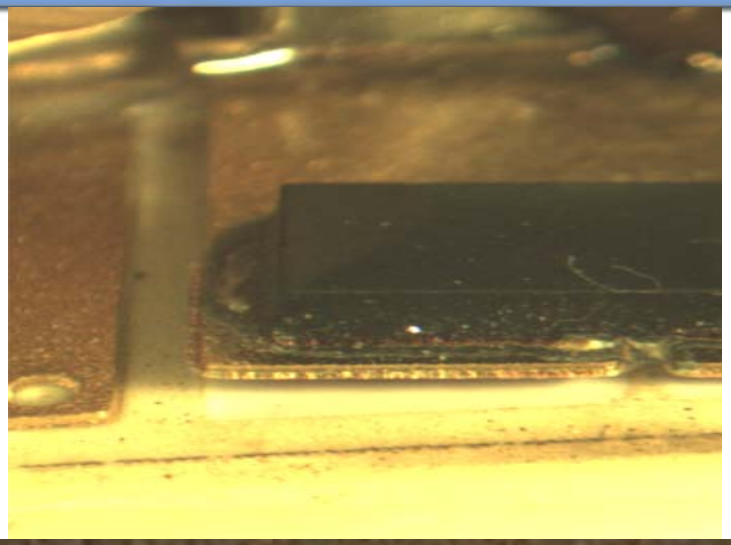
- IEC 62108 section 10.6 calls for a periodic forward bias current of 1.25 x I_{SC} through the cell (to simulate the optical thermal load in the application) while the device under test is cycled between -40 to 110°C CELL temperature.
- If one misses the fine points of this test and simply applies the current bias without monitoring (and controlling on) cell temperature some unexpected results may obtain.
  - Thermal Runaway.
  - Very high cell temperatures.
  - Unrealistic temperature gradients.
  - Receiver substrate failures.

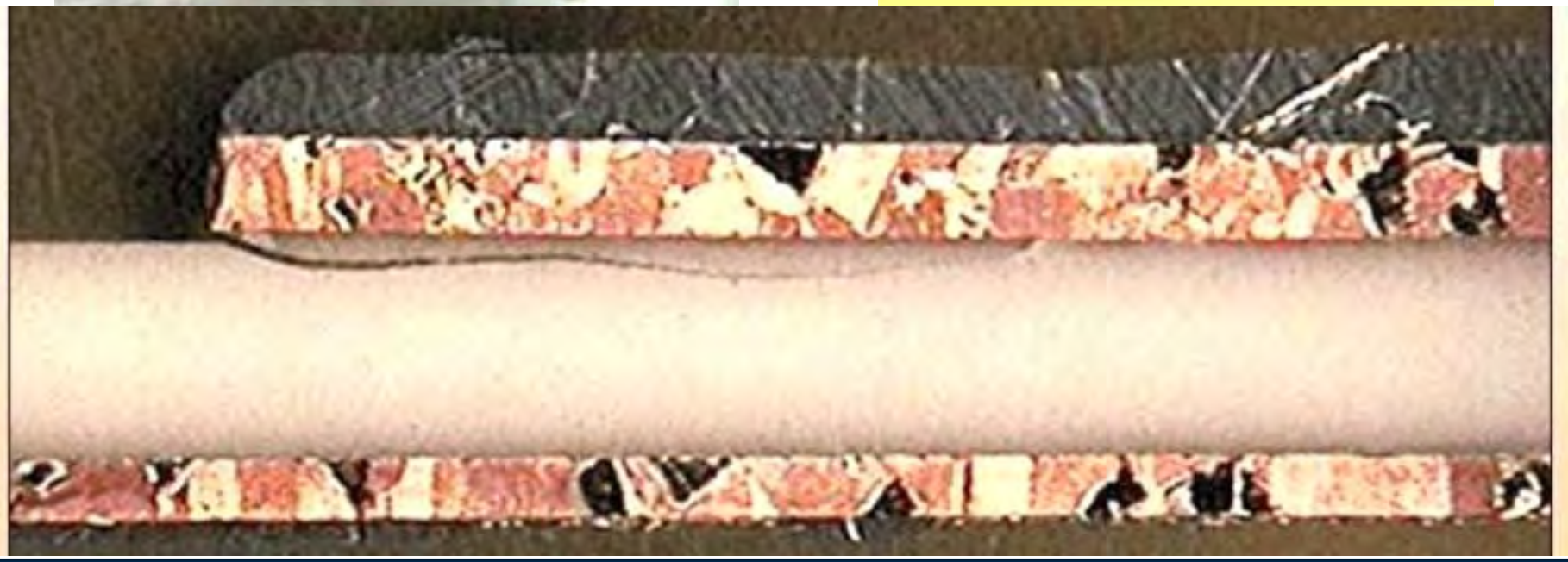
Powered Thermal Cycling



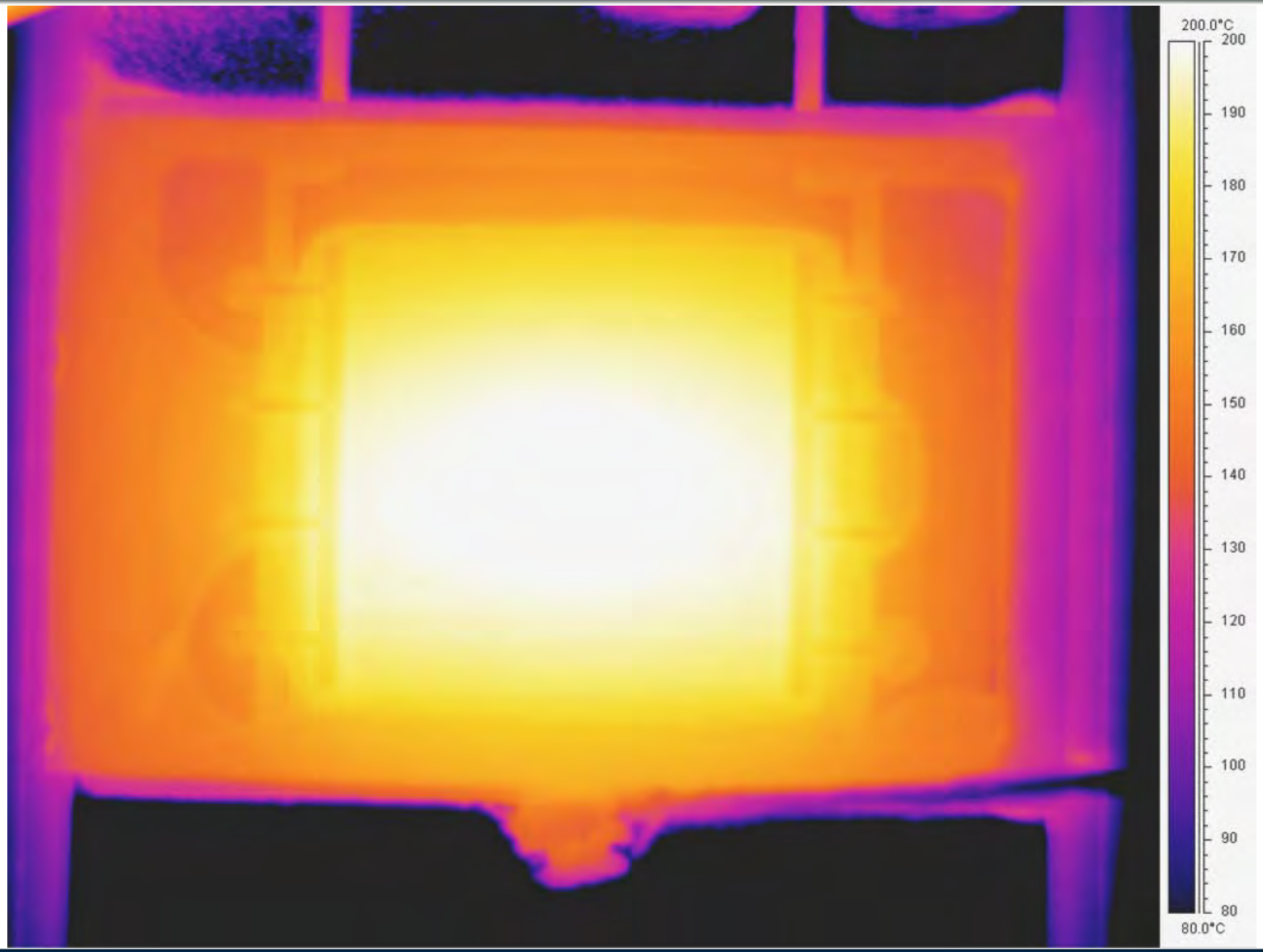
Ceramic Conchoidal Failures in PTC





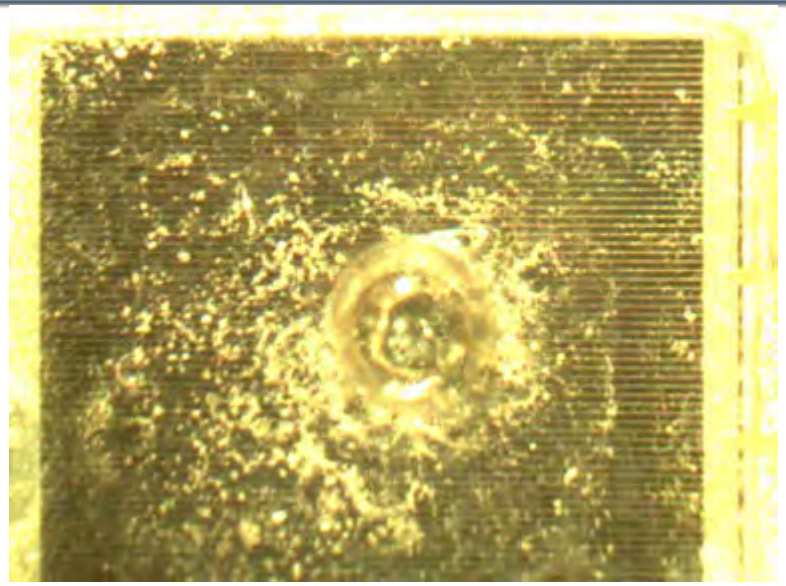


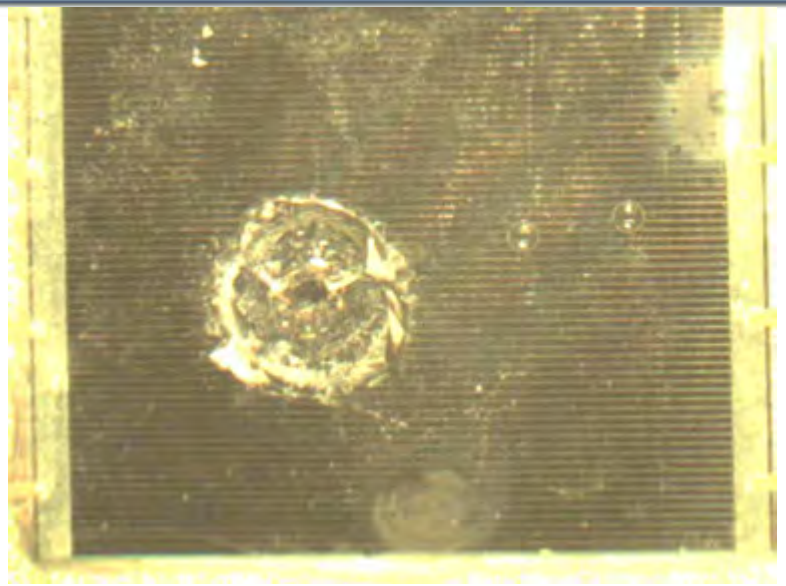
At 1.25 x I_{SC} the temperature of this cell is at least 120°C above ambient (heat sink).

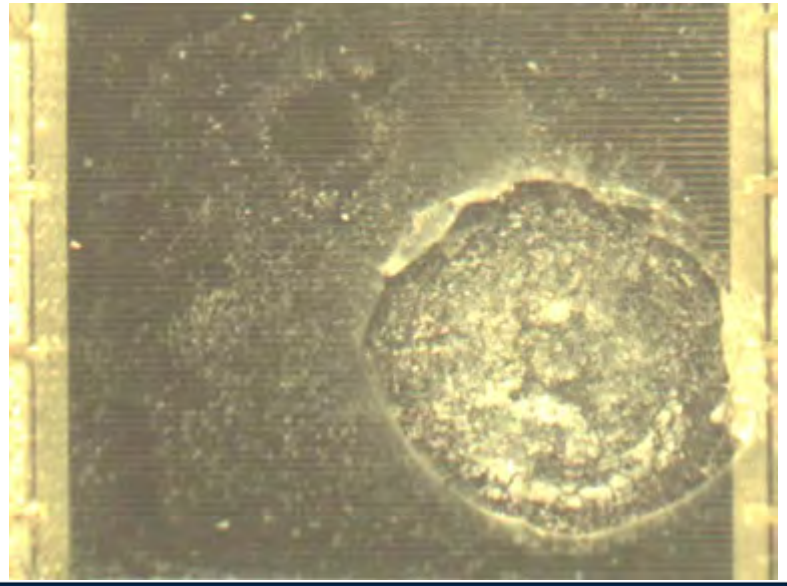


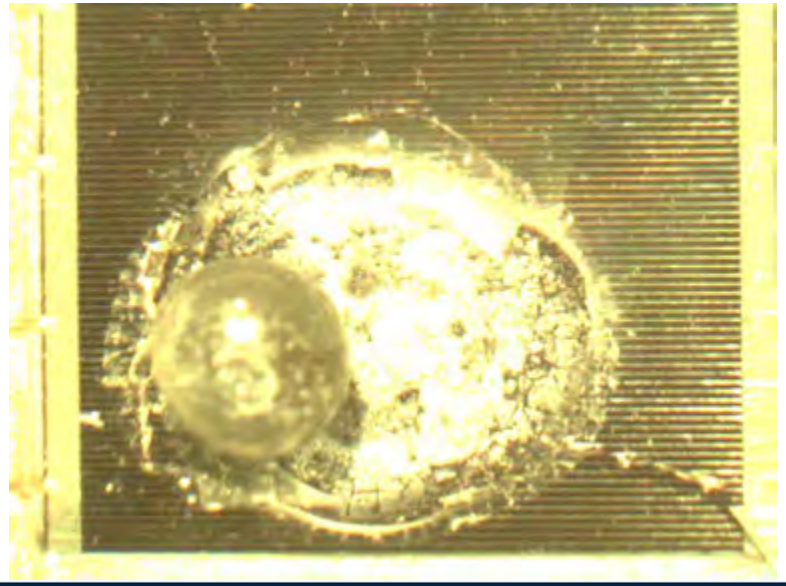
Coverglass Melting

Coverglass Failures

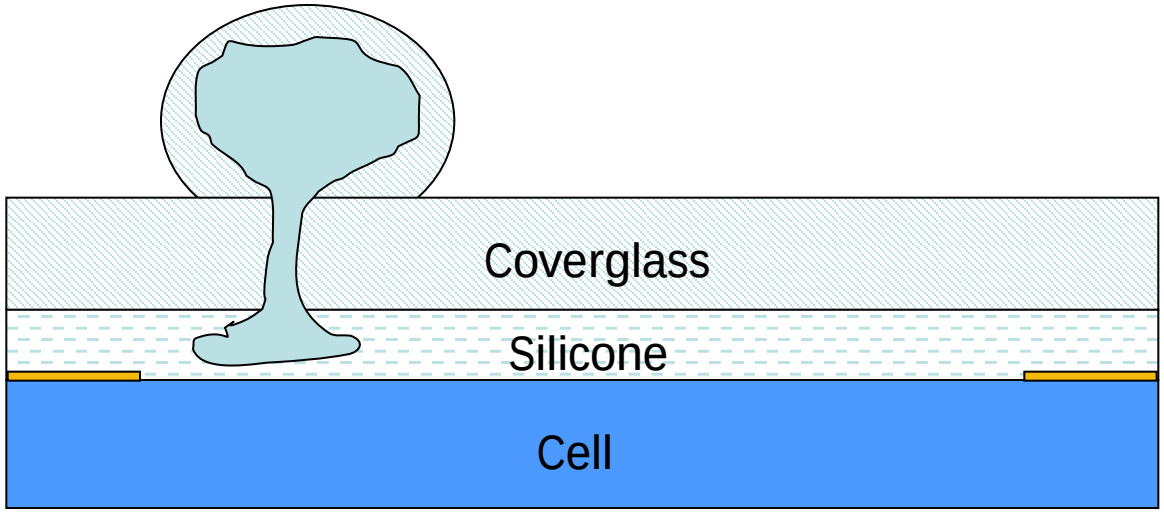




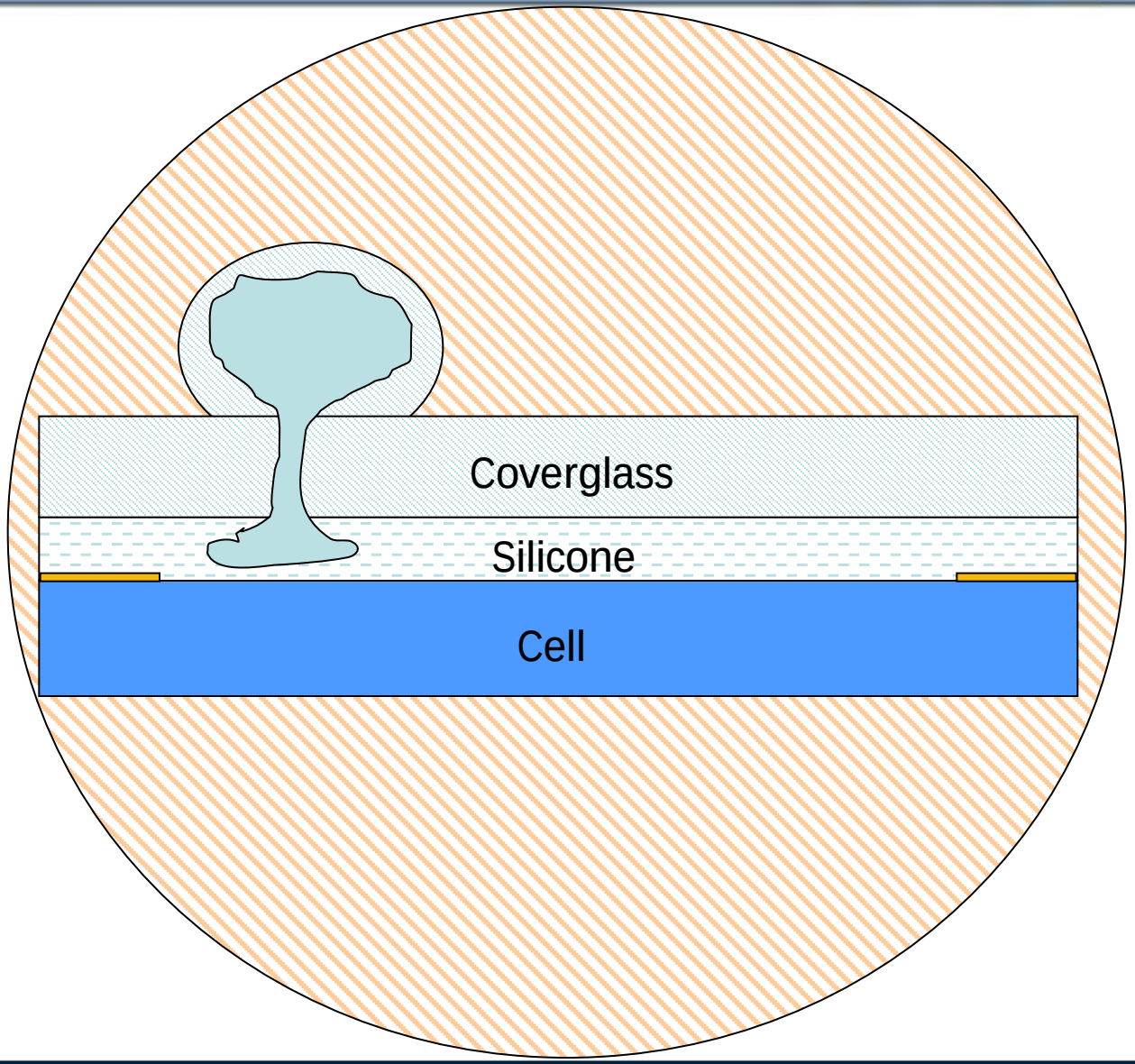




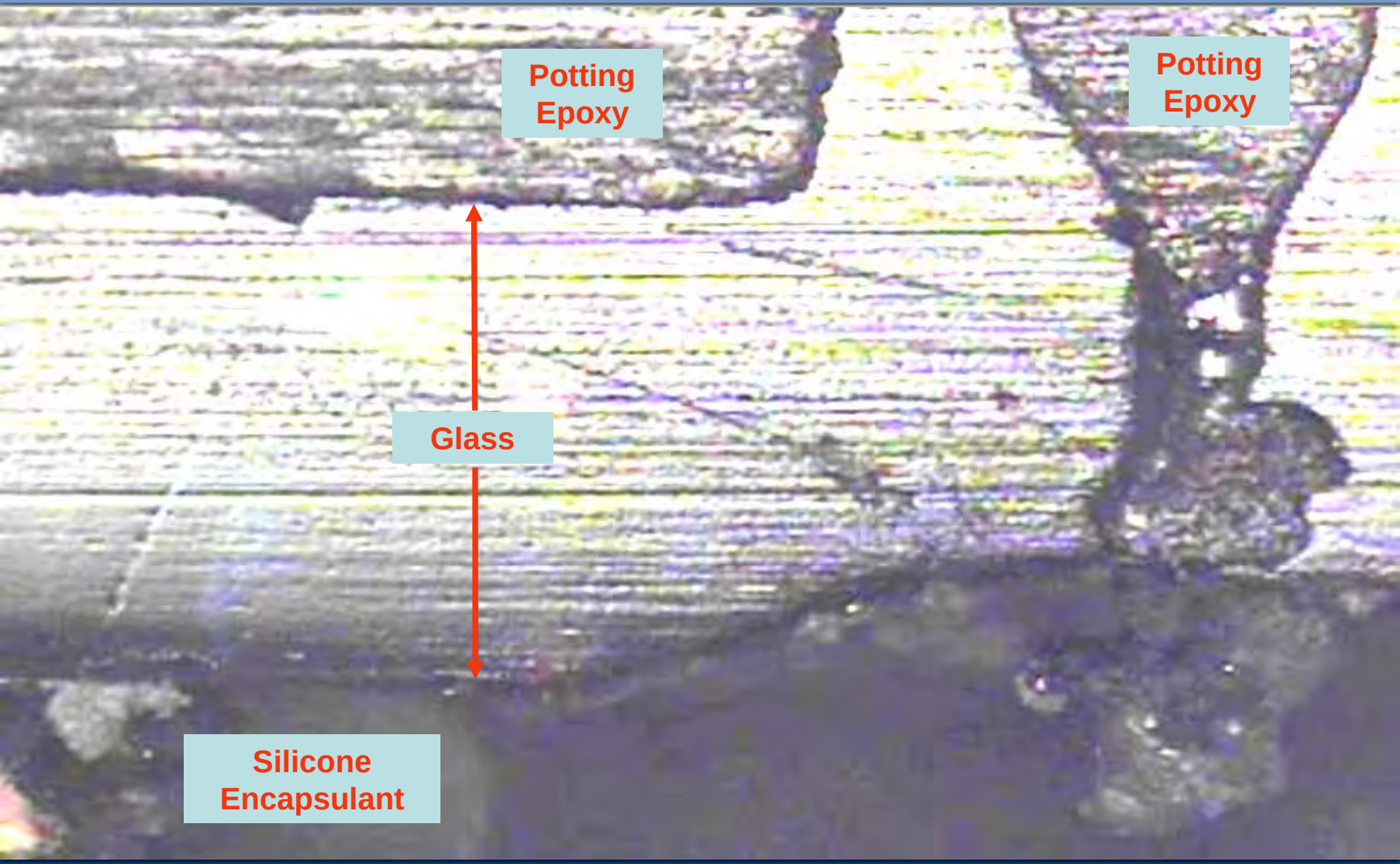
Cartoon Cross Section of Melted Coverglass



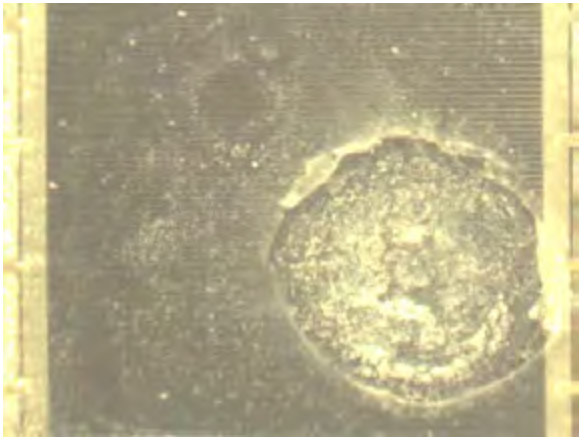
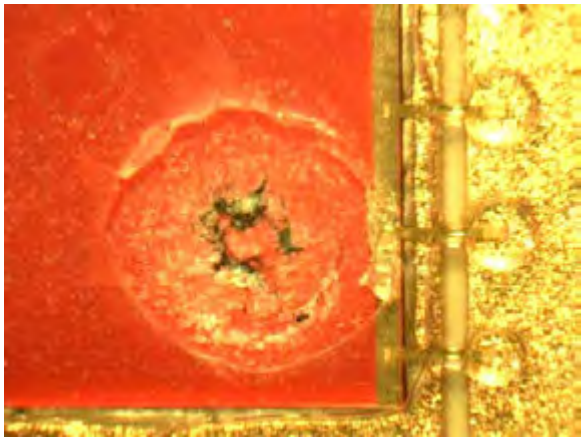
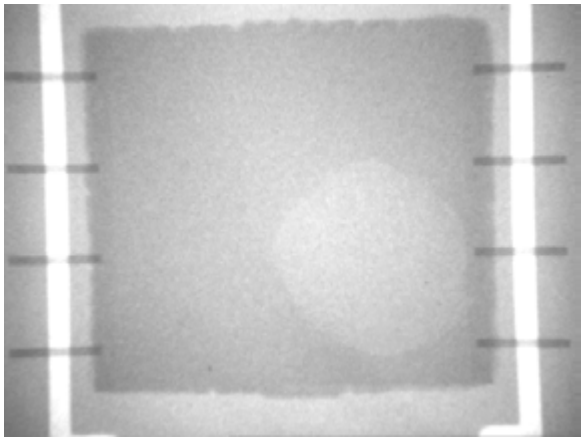
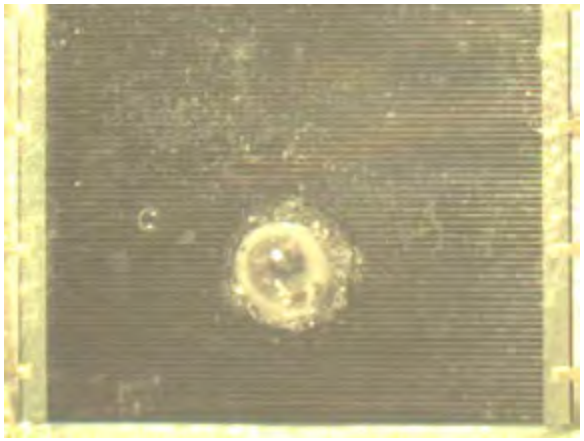
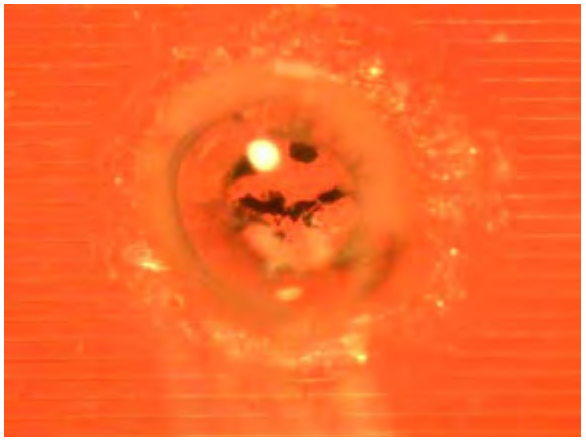
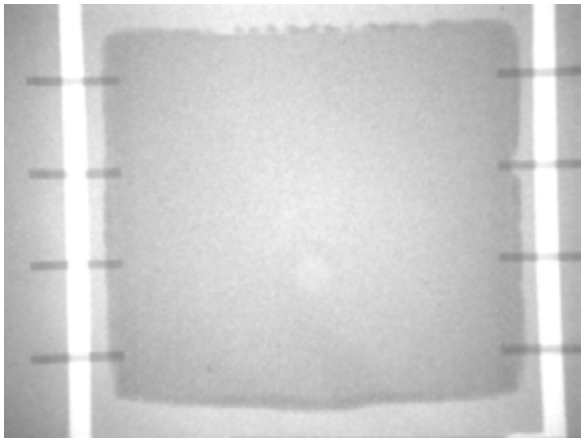
Cartoon Cross Section of Melted Coverglass



Mechanically Polished Cross-section



Closer Examination of Failures

Visual	TC EL	Xray
		
		

No apparent damage to cell

Xray contrast due to glass

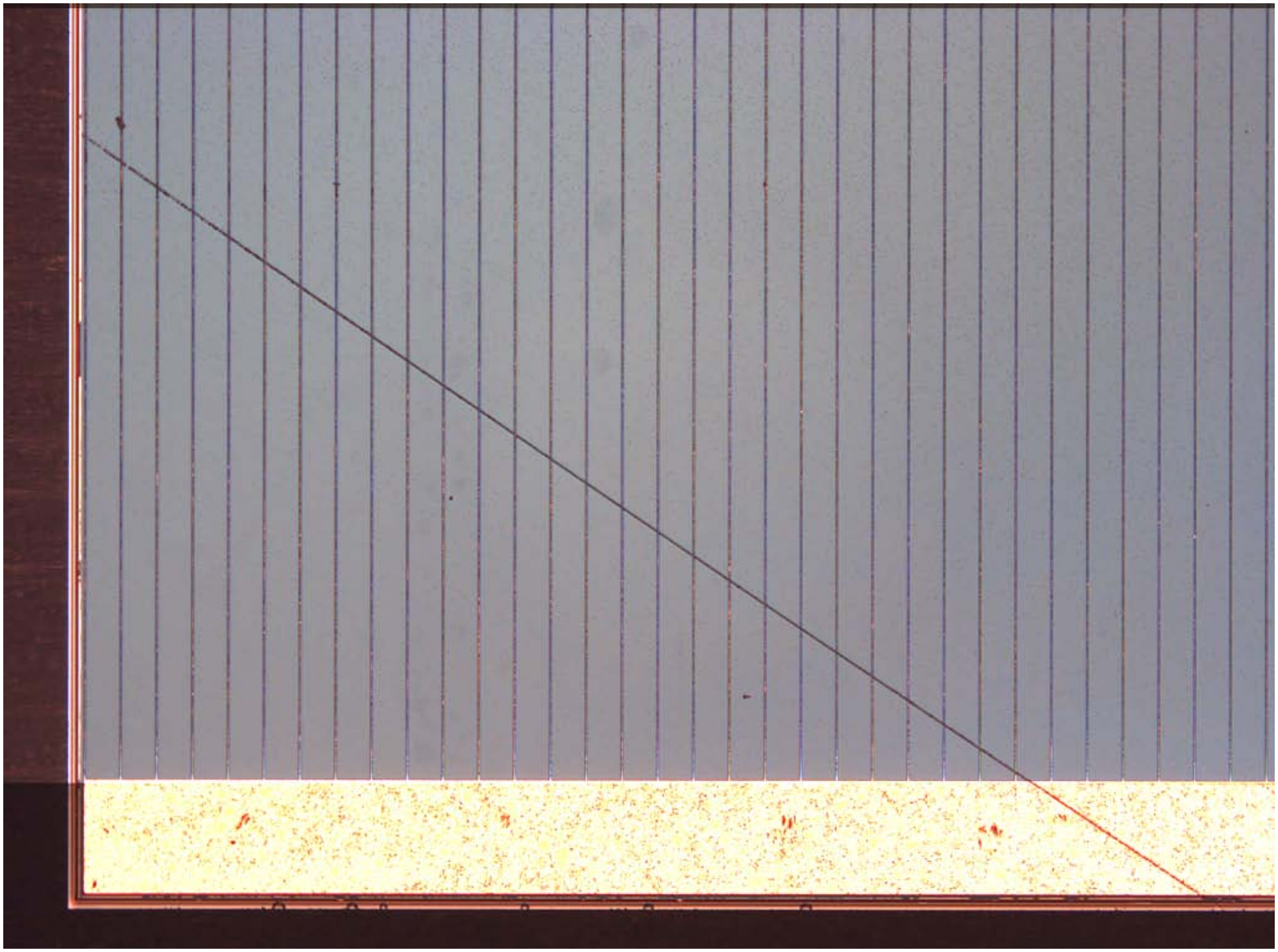
Possible Root Causes

- **Silicone beneath coverglass too thick**
  - Thinner silicone (1 – 2 mils) under coverglass has not exhibited the failure mode.
  - Silicone is not a good thermal conductor, but why is it absorbing?
- **Particulates trapped in silicone during fabrication**
  - Tools shedding metal particles.
  - Dust or lint particles.
- **Coverglass quality**
  - Inclusions.
  - Incorrect glass formulation.
- **Various “Greenhouse” effects**
  - Coverglass reflects IR emitted by cell.
  - Structure concentrates and preferentially absorbs energy re-radiated at the middle cell band-edge wavelength.
- **Misalignment of lens relative to cell**
  - Higher concentration (2000X?) if light pushed into corner of SOE.
  - Doesn’t explain failures near center of cell, or provide root cause.
- **Thermal impedance**
  - Better heat sinking reduces incidence of failure.

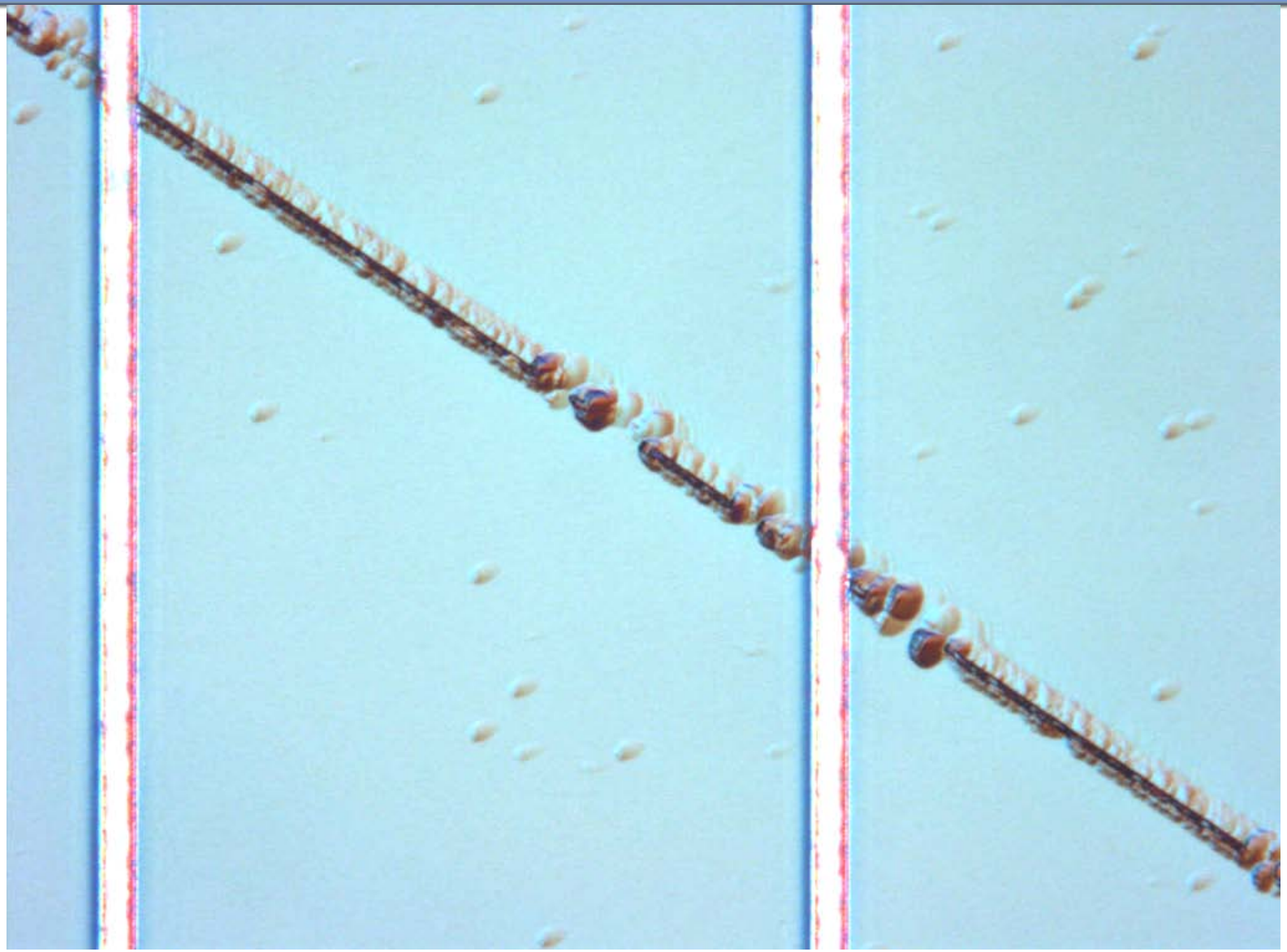
Other Things to (or not to) Worry About

- Visual Defects
- Current Density?
- Forward Bias Induced Effects

Scratch? Crack? Other?

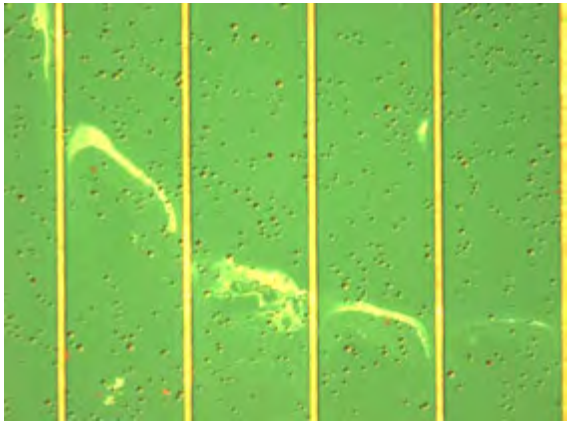


Slip Plane Dislocation

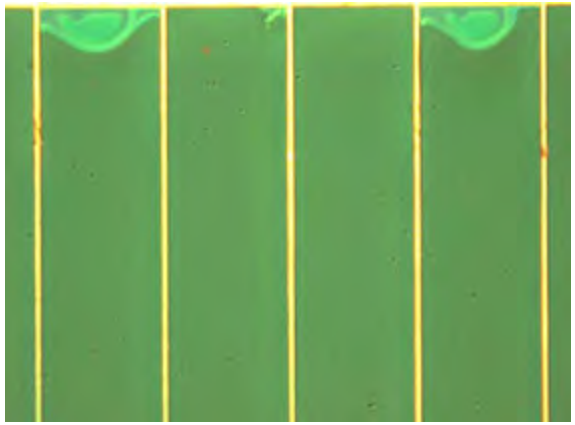


Microscopic Examination

- If you look closely enough, you will find all manner of “features” on the surface of CPV solar cells!



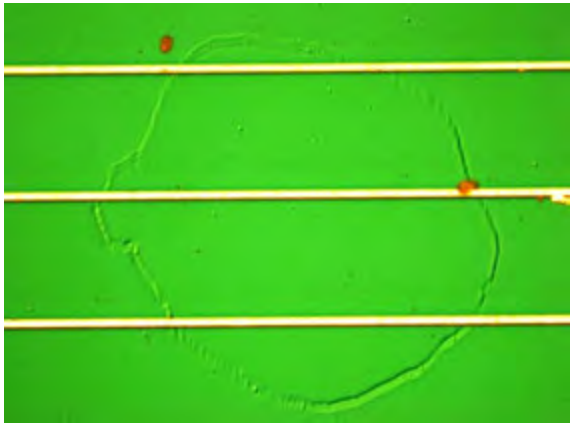
“Stacking Faults”



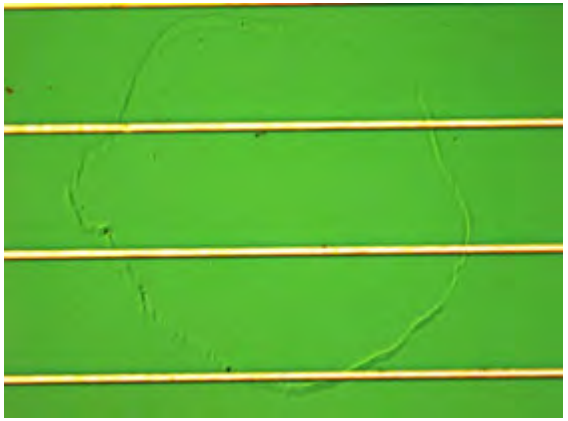
Etch Artifacts



Very Tiny Gold Wedding Rings?

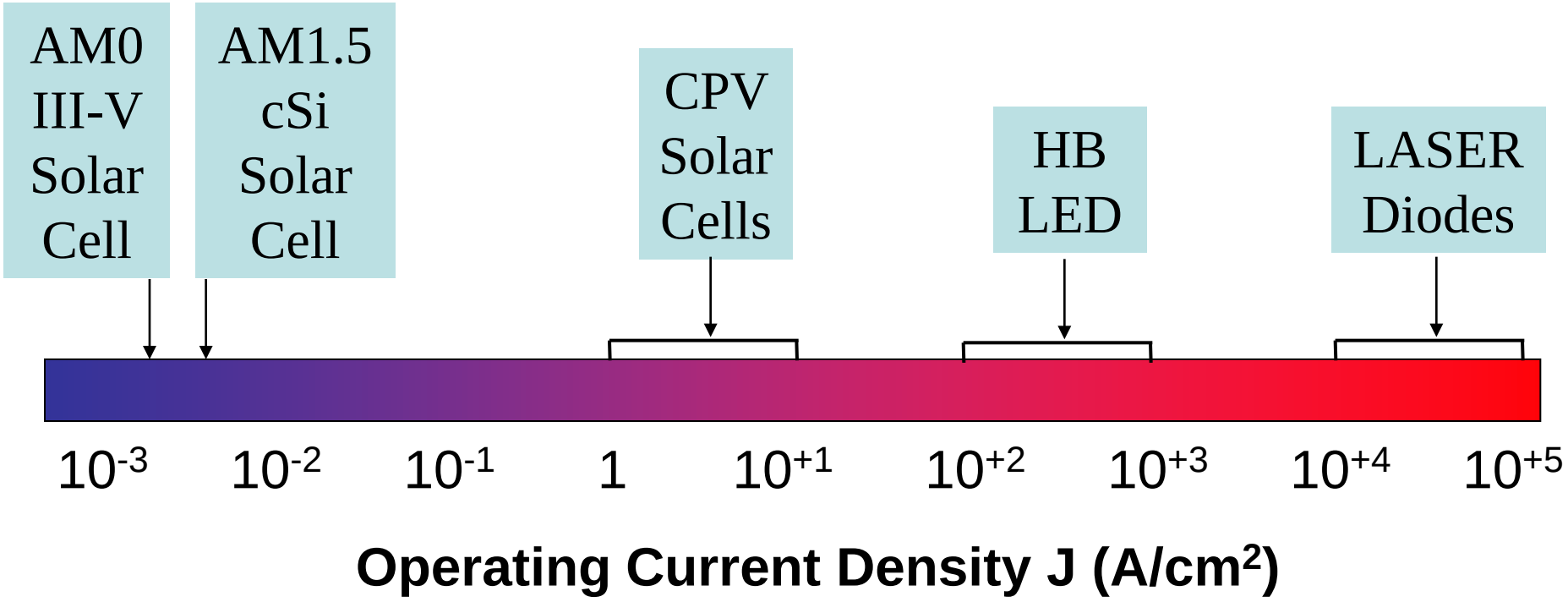






Handling/Litho Repeaters

Current Density in Optoelectronics Devices



Summary

Still Going



The Vagaries of Reliability Predication

- The photo in the next slide a pair of panels that were decommissioned from an ARCO PV plant In California and then reinstalled on a roof in Northern New Mexico ca. 1995.
- Many people in the room probably know a lot more about the pedigree and jaded history of these panels than I do, but these are the essential facts:
  - The panels were originally taken out of service after the encapsulation yellowed and reduced the output power by about 15%.
  - At the time they were reinstalled a misguided drywall screw shattered the tempered face glass on the upper panel.
  - Since then the both panels have been in continuous service powering a 12V DC service in an artist's studio.
  - Both have yellowed considerably more than when reinstalled but even the shattered panel is still generating power.
- I don't have hard numbers, but the main point is that at the time these panels were built, I am guessing that there were not many predictions that they would fail prematurely due to yellowing of the encapsulate and even fewer that they would still be generating power after thirty + years in service and a shattered coverglass.

In Conclusion

- Rel Prediction is a tough business.
- CPV modules and systems are complex and opportunities for failure abound.
- The IEC 62108 suite of CPV module/system qualification tests provide an excellent baseline for beginning-of-life performance but little insight into long-term reliability.
  - Accelerated Life Tests at high concentration levels are difficult to implement.
- Hermeticity at the receiver subassembly level is critical.

Acknowledgements

- I would like to sincerely thank all the contributors to this presentation, but especially the following current or former employees of Emcore:
  - Steve Seel
  - Hans Schoon
  - Jim Foressi
  - Dan Aiken
- And the following staff members at NREL:
  - Sarah Kurtz
  - Peter Hacke
  - Nick Bosco
  - Michael Kempe

National Renewable Energy Laboratory
Innovation for Our Energy Future

National Center for Photovoltaics

Thermal and Current Cycling for CPV Qualification



Nick Bosco, Cassi Sweet, Adam Stokes and Sarah Kurtz

NREL PV Module Reliability Workshop
February 18-19, 2010
Golden, CO

This presentation does not contain any proprietary or 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

outline

- Examination of IEC 62108 Section 10.6: Thermal Cycling
  - interpretation
  - consequence of current cycling
- Current ramp for failure detection
- Experiment and observations

IEC 62108 10.6 thermal cycling test

Table 3- Thermal cycle test options for sequence A

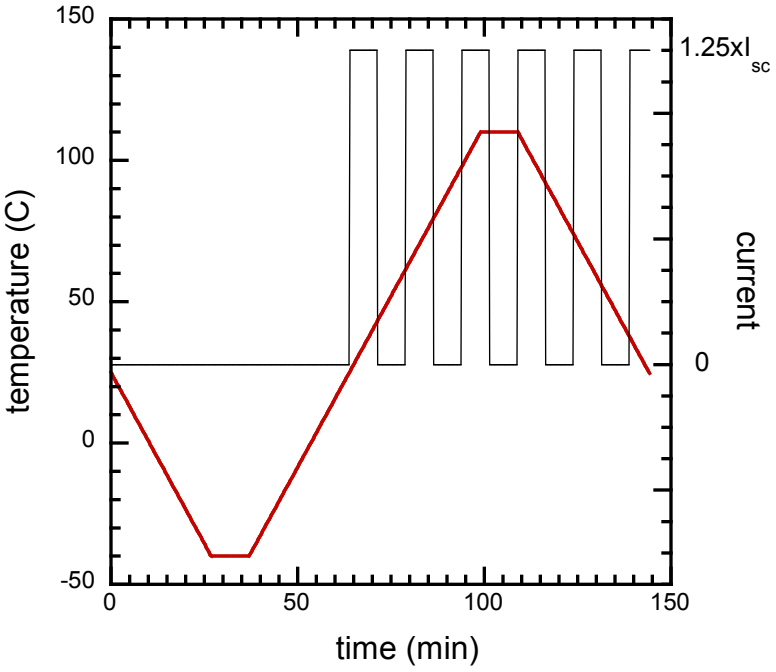
Option	Maximum cell temperature ºC	Total cycles	Applied current
TCA-1	85	1 000	Apply 1,25xI_{sc} when T>25 ºC, Cycle speed is 10 electrical/thermal
TCA-2	110	500	Apply 1,25xI_{sc} when T>25 ºC, Cycle speed is 10 electrical/thermal
TCA-3	65	2 000	Apply 1,25xI_{sc} when T>25 ºC, Cycle speed is 10 electrical/thermal

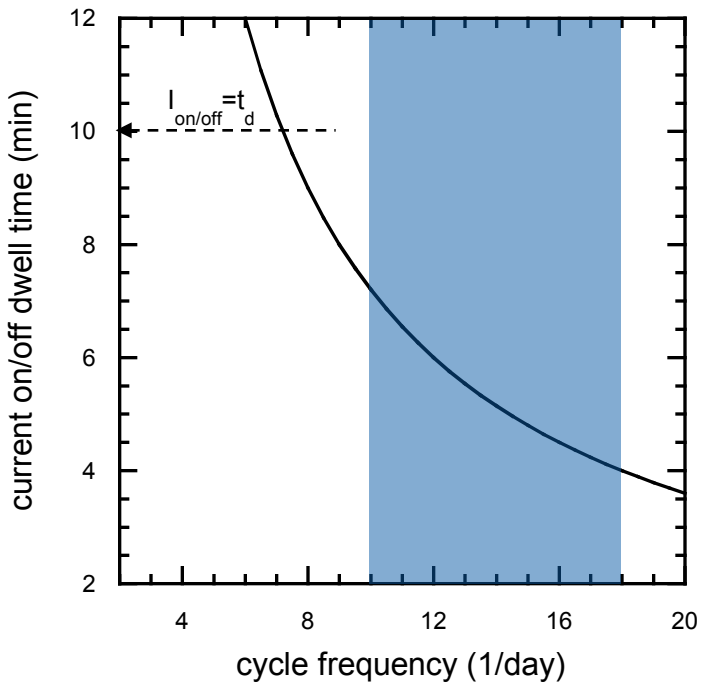
From text

“ A dwell time of at least 10 min within ±3 ºC of the high and low temperatures is required. The cycling frequency should be 10 to 18 cycles per day.”

IEC 62108 10.6 thermal cycling test

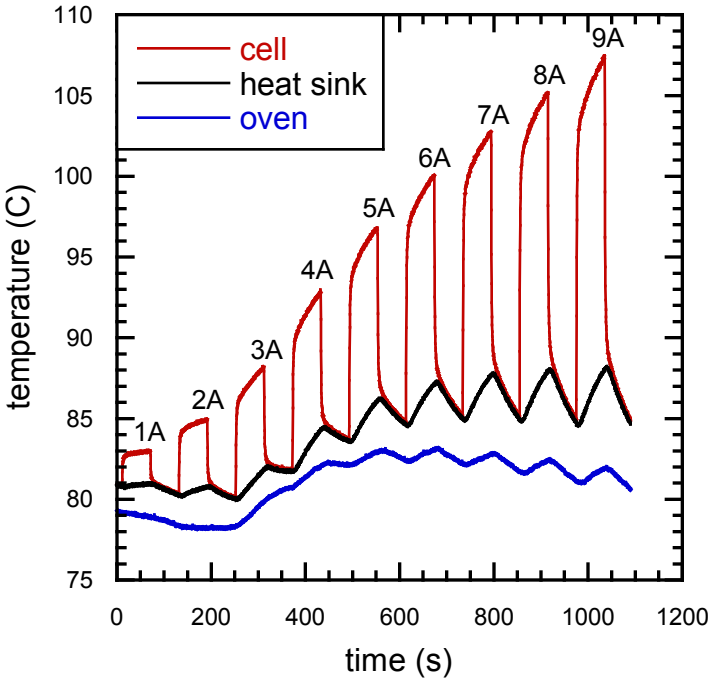
cycle frequencies

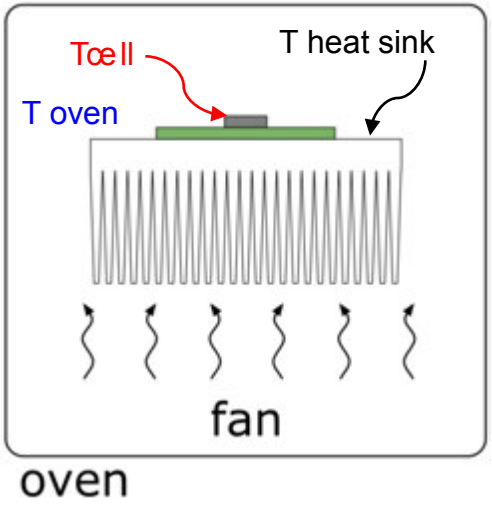




As the standard is composed, it is not possible to balance the dwell time and cycle frequency to have ONE current ON/OFF cycle coincident with the hot temperature dwell time.

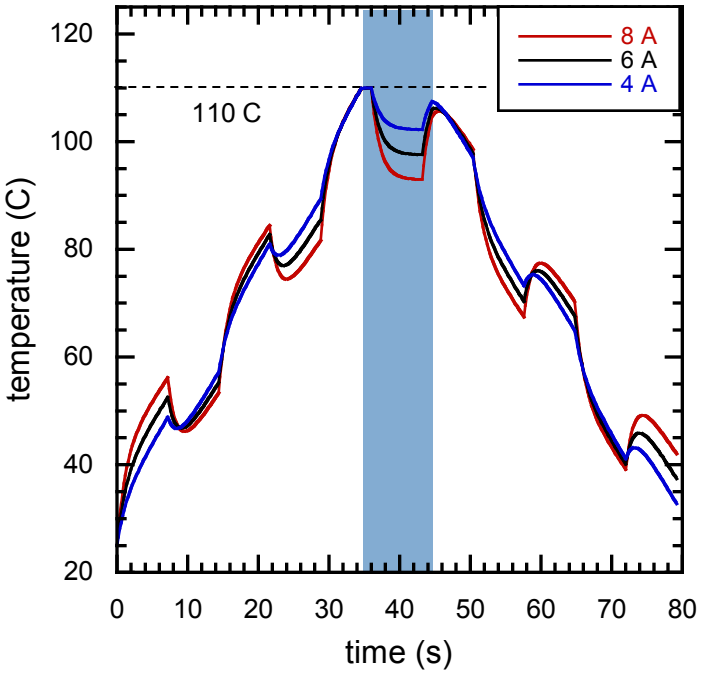
heating experiments

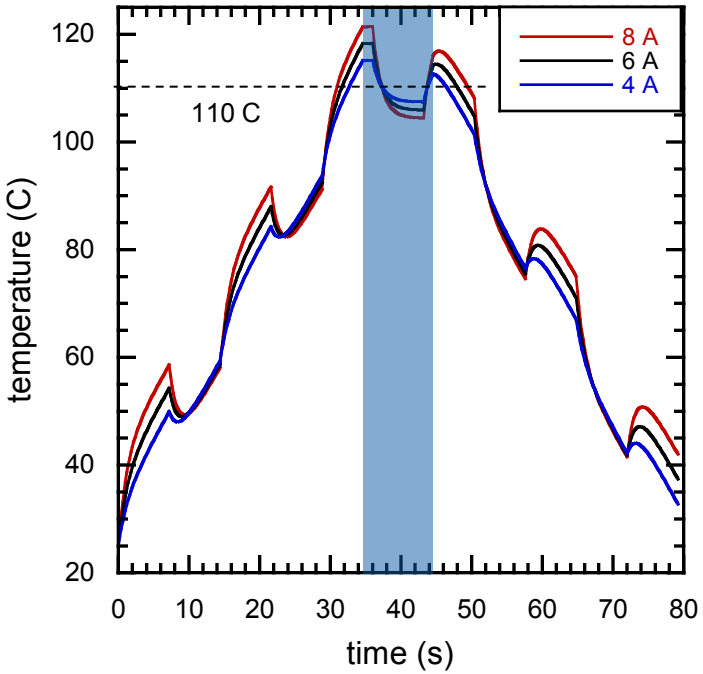




An immediate, and significant, temperature rise is experienced by the cell upon application of current.

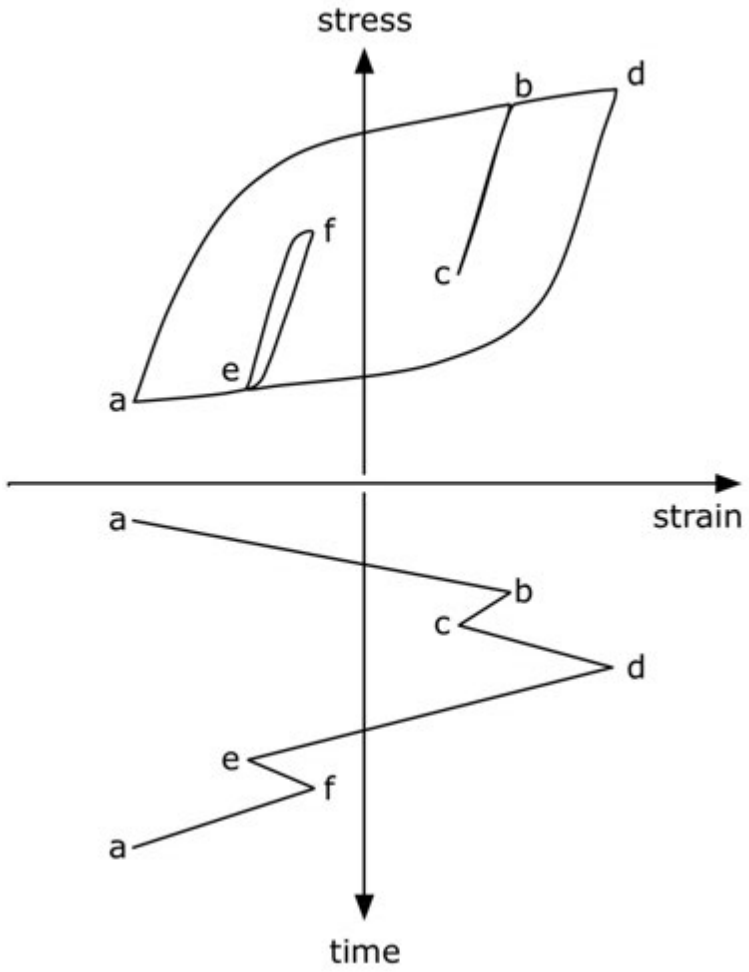
heating experiments





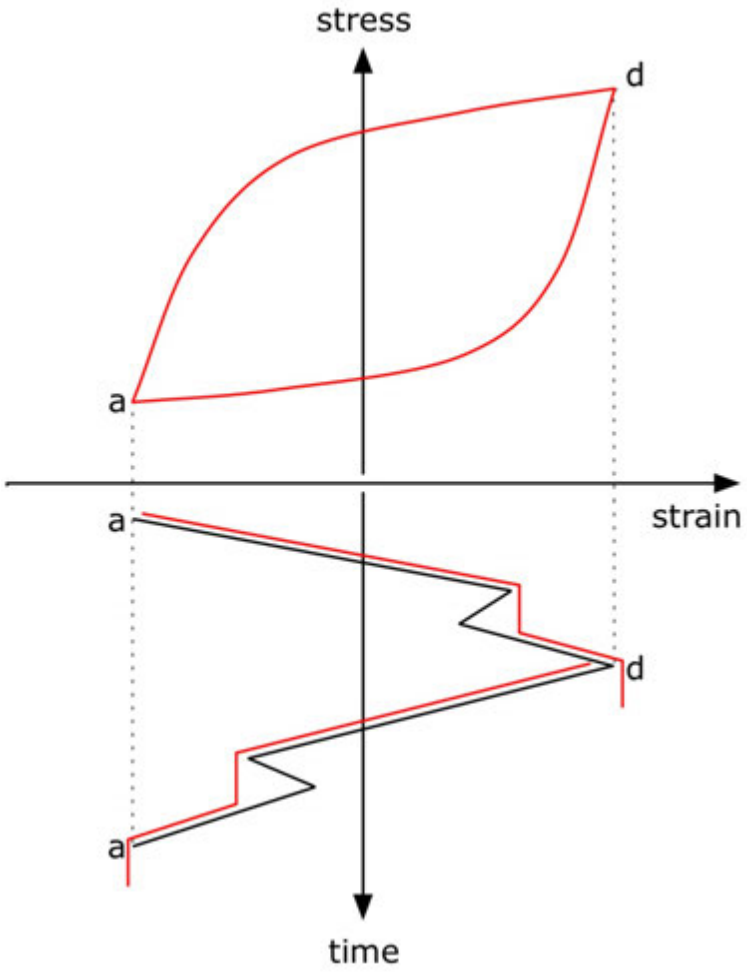
Cell temperature with current cycling is modeled for a dwell maximum and mean of 110 C at 4, 6, and 8A.

cycle damage



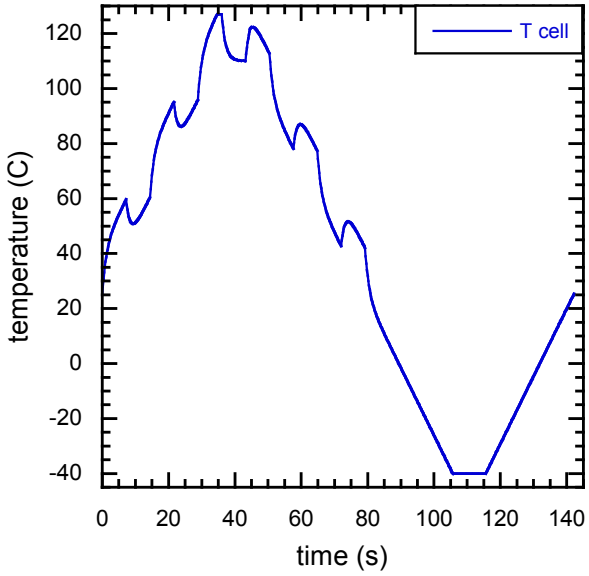
- Area within the stress-strain hysteresis is the work, or damage, imparted through the cycle.
- Small reverses in loading do not affect the hysteresis area and therefore the work done.

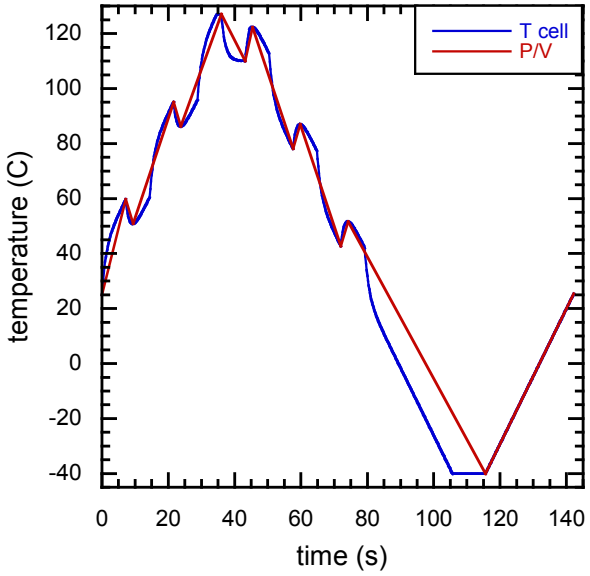
cycle damage

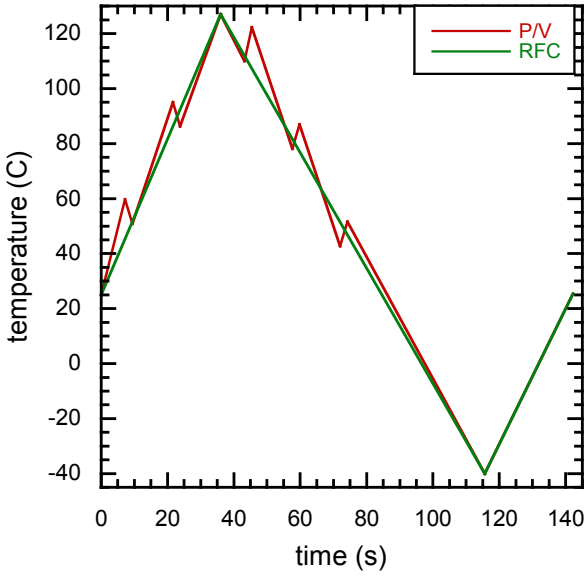


- Area within the stress-strain hysteresis is the work, or damage, imparted through the cycle.
- Small reverses in loading do not affect the hysteresis area and therefore the work done.
- The rainflow method “reaps” smaller cycles contained within larger ones,

cycle damage

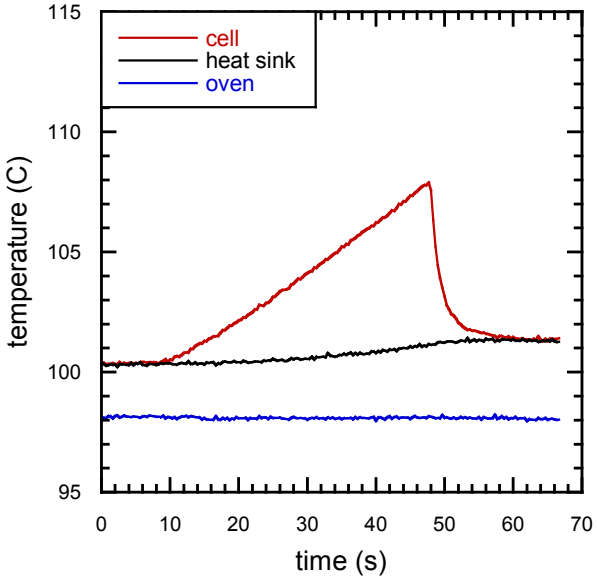


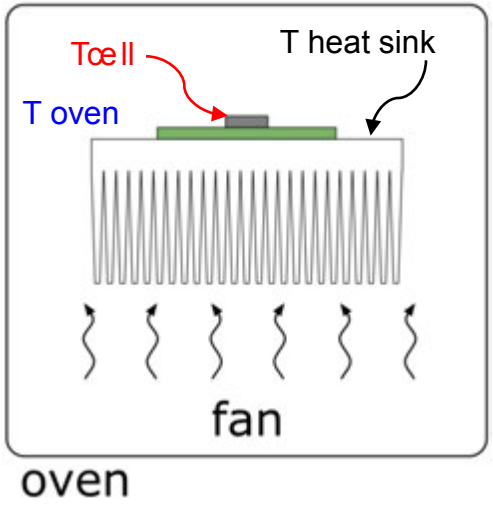


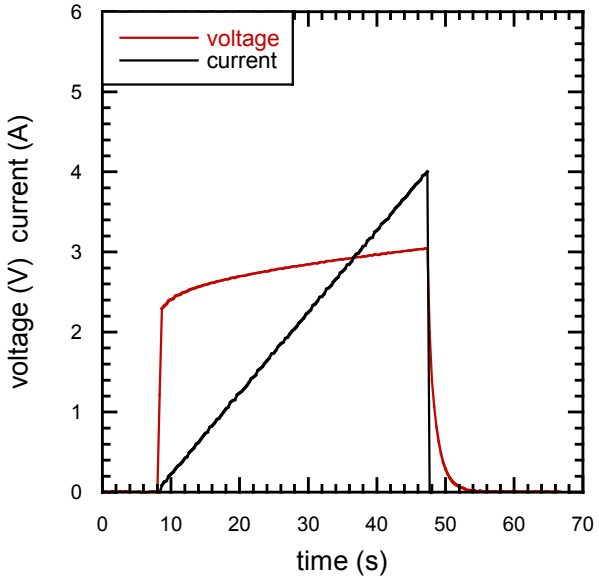


A rainflow count applied to the modeled temperature resulting from current cycling demonstrates no additional damage due to the extra fluctuations in temperature.

failure detection

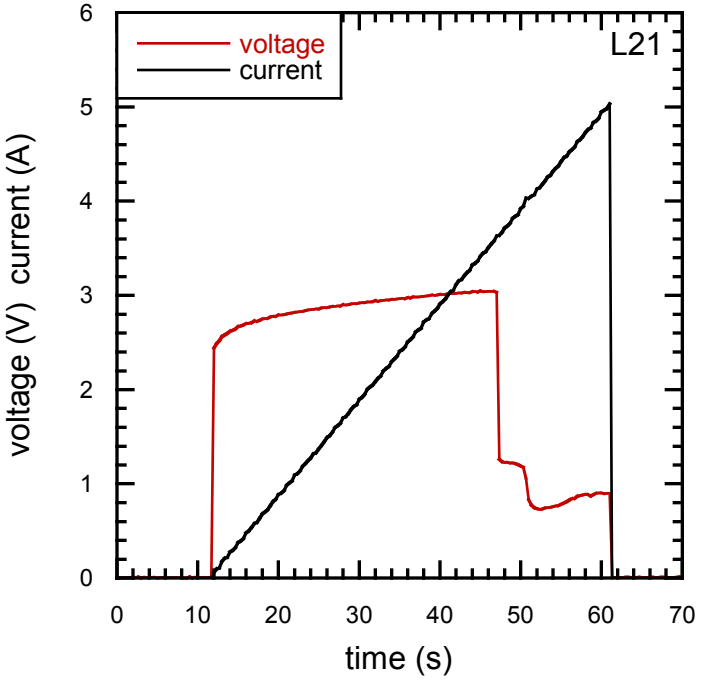






A 4A current ramp is designed to replicate thermal cycling conditions.

failure detection

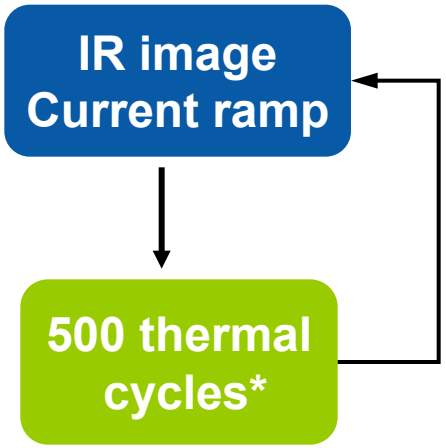


cell assembly survived 2175 NREL thermal cycles (3A max, no heat sink)

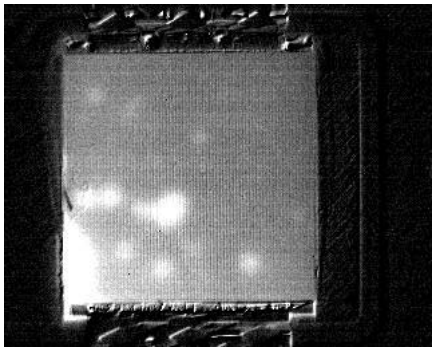
failure occurs at ~3.63A

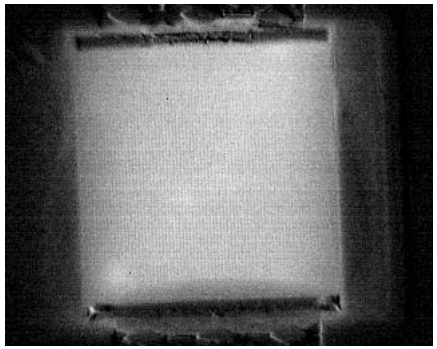
thermal cycling

Experiment:



Initial IR images show varying degree and location of voids





Non of the initial 17 assemblies failed the 4 A current ramp

$T_{min} = -40C$

$T_{max} = 110C$

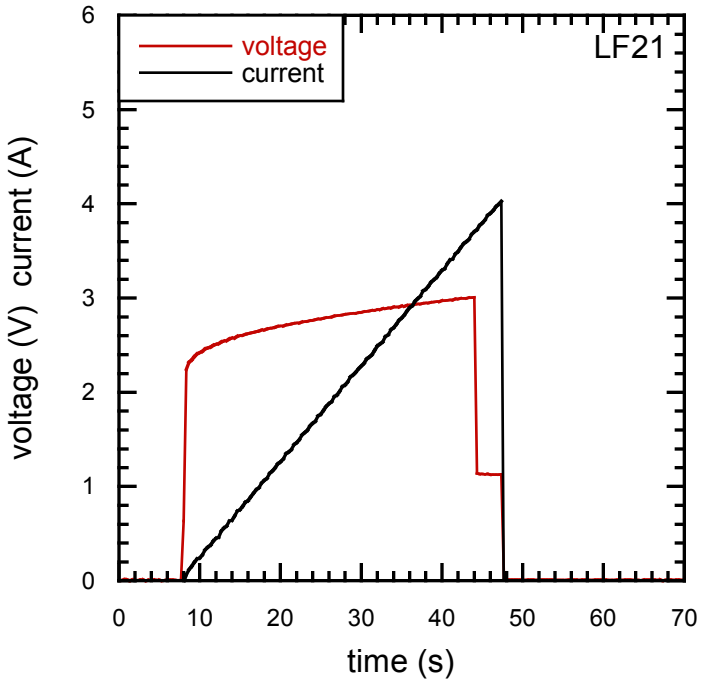
$t_d = 5\,\text{min}$

$f = 48/day$

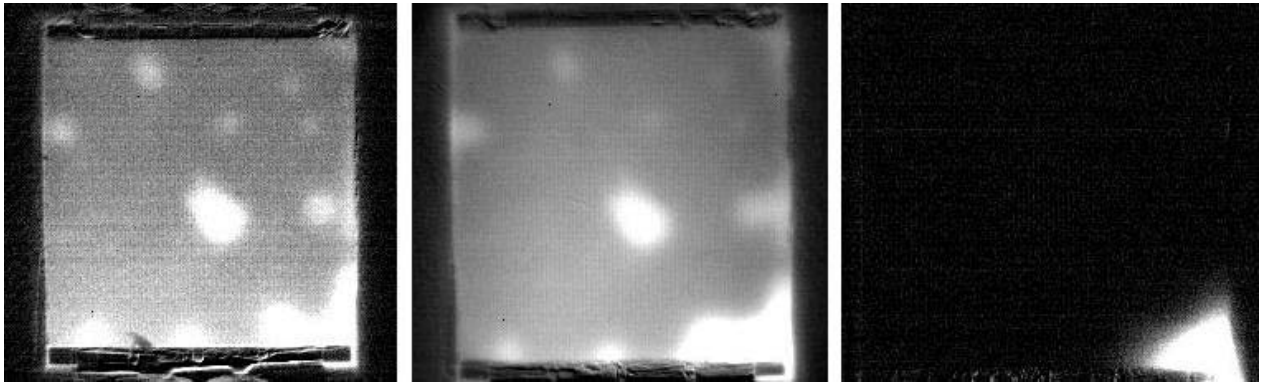
- Samples consist of ~ 1cm^2 multi-junction cell on ~2 x 2 cm substrate
- Cell assembly heating is via the application of forward bias current, I_{max} = 3A

*Bosco, N.S., Sweet, C.,Kurtz, S., "Reliability Testing the Die-Attach of CPV Cell Assembles", 34th IEEE Photovoltaic Specialists Conference, 7-12 June 2009, Philadelphia, Pennsylvania

thermal cycling

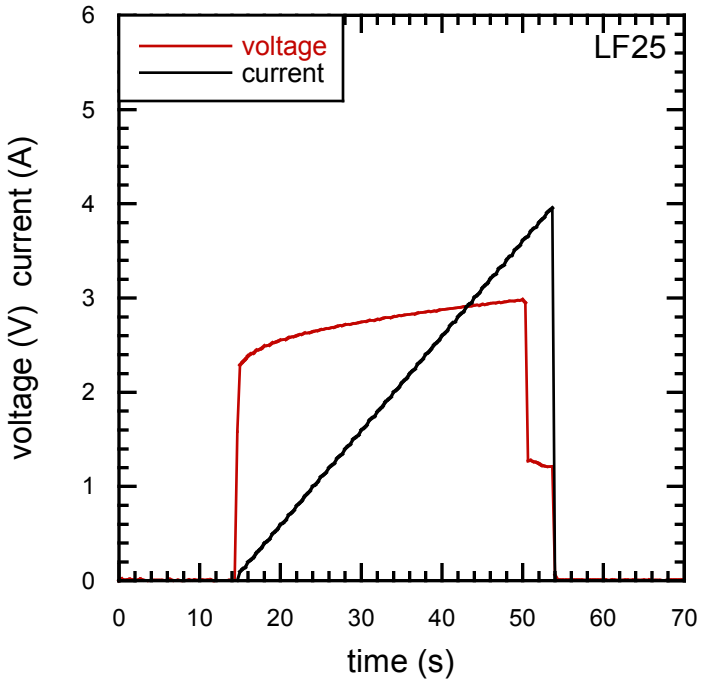


Following 500 cycles, one assembly failed the current ramp

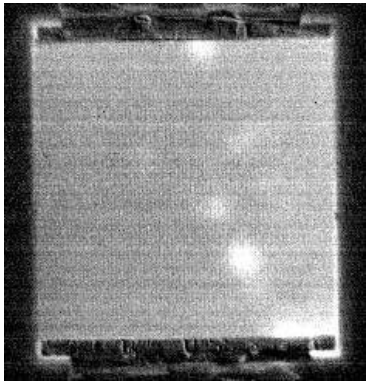


initial 500 cycles failure

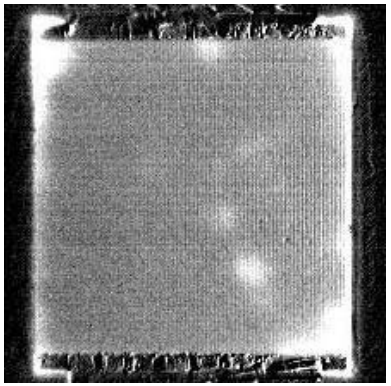
thermal cycling



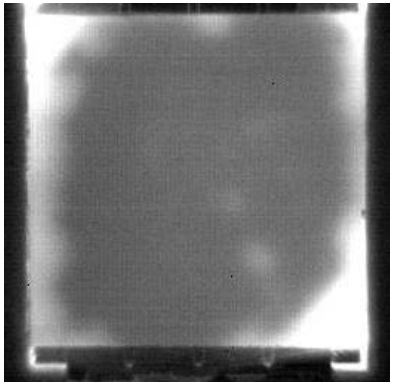
Following 1000 cycles, 4 assemblies failed the current ramp



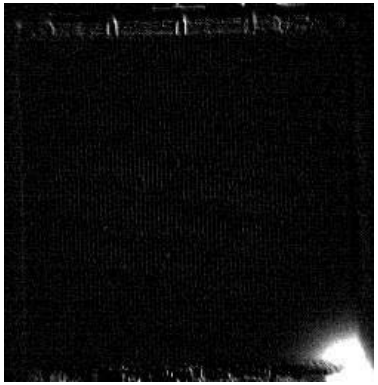
initial



500 cycles



1000 cycles

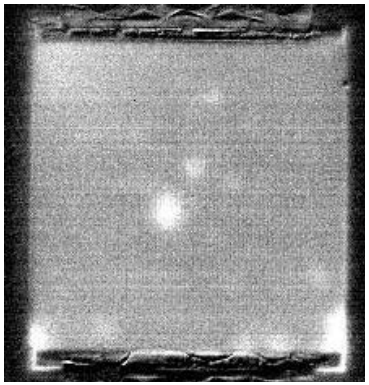


failure

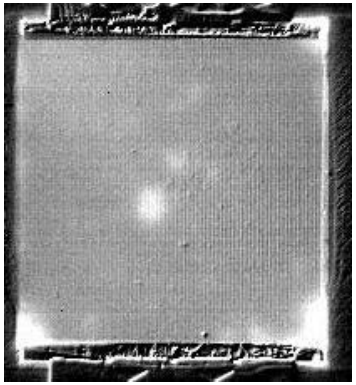
thermal cycling

Additional samples demonstrate increased cracking with cycling, though survive the 4A current ramp

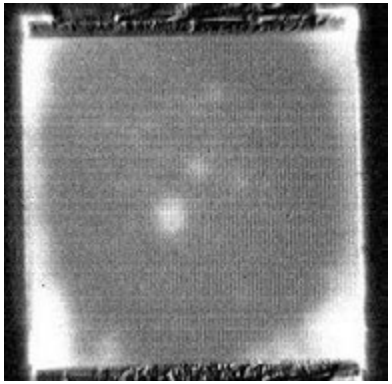
LF15



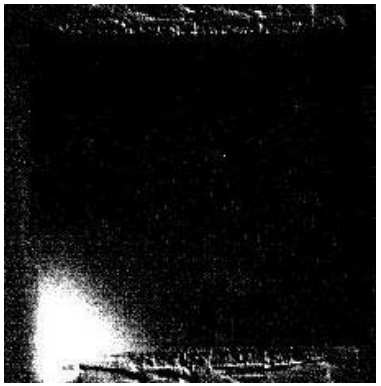
initial



500 cycles



1000 cycles

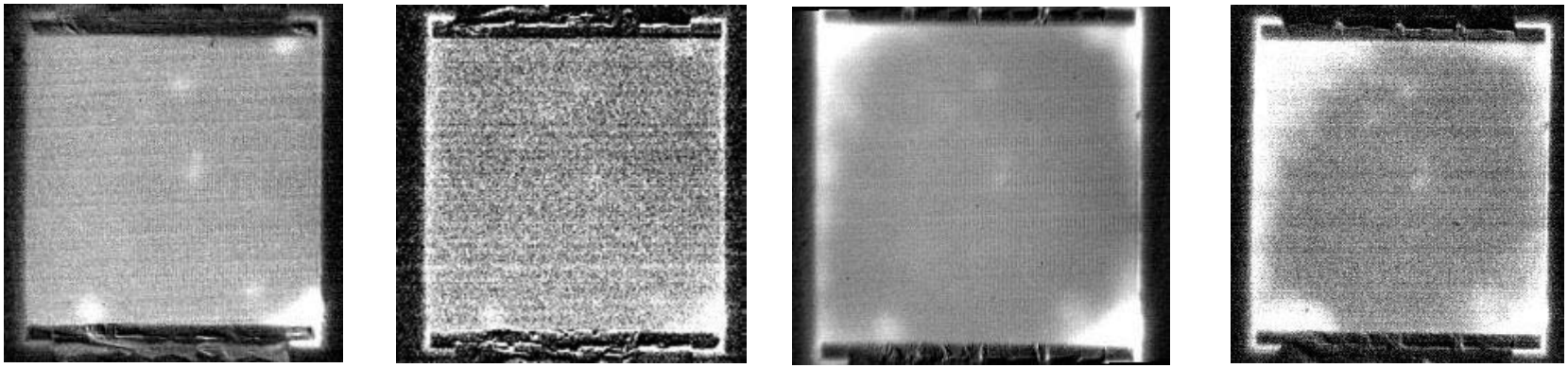


1303 cycles

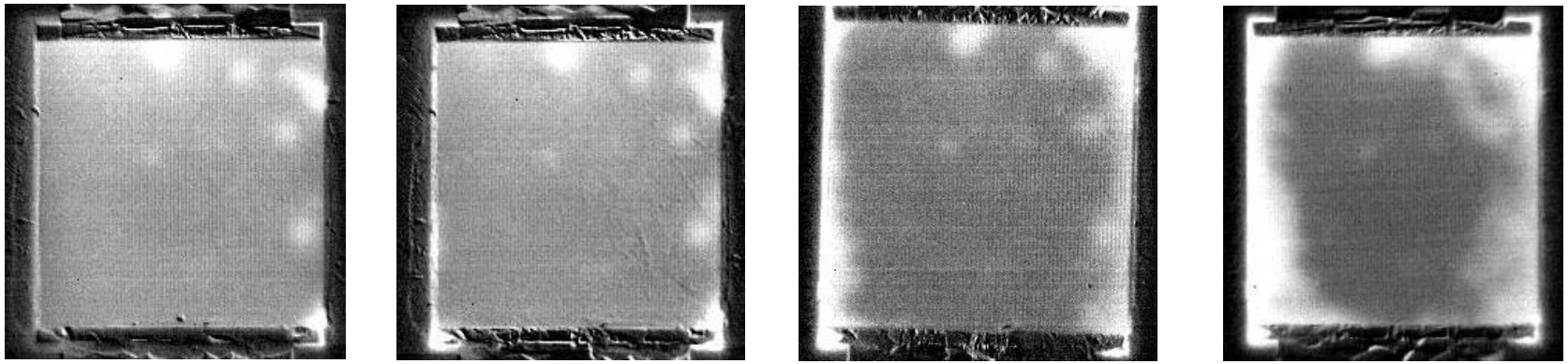
thermal cycling

Additional samples demonstrate increased cracking with cycling, though survive the 4A current ramp

LF4



LF10



initial | 500 cycles | 1000 cycles | 1500 cycles

conclusions

- IEC 62108 Section 10.6: Thermal Cycling cannot be executed as written.
- Additional temperature excursions due to current cycling does not accelerate damage.
- Current application up to 4A/cm^2 is benign to the cell though will cause failure if large cracks/voids exist under bus-bar.
  - Not representative of on-sun failures
  - Unacceptable amounts of and sized voids/cracks not detected through failure

proposals

- Proposed amendments to IEC 62108 Section 10.6: Thermal Cycling
  - Current application should be reduced to when T>25 C (similar to IEC 61215).
  - Cell current density level should be reduced to 4 A/cm^2 or J_{sc}.
  - Additional requirement should limit the percentage of voids/cracks as detected via an appropriate imaging technique. Alternatively, modules should be subject to an on-sun exposure for a designated time and irradiance.

and future work

- On-sun evaluation of voided and cracked die attach.

Breakout session:
CPV2
Discussion leaders: Robert McConnell & Ian Aeby

1:00 – Andy Hartzell (3M) – Durability of Optical Materials

1:20 – David Miller (NREL) – Durability of Poly(Methyl Methacrylate) Lenses Used in Concentrated Photovoltaics

1:40 – Discussion of Test Needs for Optics for CPV

2:00 – Mike Ludowise (SolFocus) – Questions about IEC 62108 Implementation

2:20 – Discussion of IEC 62108: Intentions, Interpretation, and Implementation

Durability of Optical Materials

Andy Hartzell (3M)

Testing protocols, especially outdoor, need be carefully planed

Uniform industry definition of Fresnel lens failure would be helpful for vendors

Grades of raw polymers matter

- Will effect crazing

A History of outdoor testing and results was preseented

Questions:

- Crazing near the edges?
- Has not been observed.

Spectra are useful for failure analysis?

- Yes

Abrasion in sandy environments?

- Yes, has been reported in Saudi Arabia and by Sandia

Test other material properties?

- Heading in the direction of combined effects testing and analysis

Durability of PMMA Lenses In CPV

David Miller (NREL)

NREL study:
- Identify key issues for contemporary specimens

Optical durability:
- Evolution of location & distinctness of cut-on frequency

Mechanical durability (K_{IC}, $\partial a/\partial N$):
- Fracture, fatigue strongly depend on M_w
- Embrittlement over time

Soiling:
- Complex issue that may vary significantly over time w/ location

Photodegradation:
- Chain scission $\Rightarrow$ decreased M_w

Thermal decomposition:
- Chain unzipping $\Rightarrow$ decreased mass

SOG:
- Probably physically robust against soiling; limited existing literature

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

Test Needs for Optics in CPV

Post Session Discussion

- Spectral degradation
- Progressive SOG Delamination?
- Over temperature characterization
  - Lens temp likely to follow ambient temperature
- Cleaning can be a significant source of degradation
  - Are there “standard” cleaning methodologies
  - Techniques may be dictated by geography
  - Extra care may be required for AR coated surfaces
- Is cleaning CPV different between flat plate and CPV?
  - Yes, due to light scattering that may actually be beneficial for PV but is a killer for CPV
- Standard moisture condensation resistance requirements for optics?
- AF for Xenon exposure
- Requirements for reflective optics?

Questions about IEC 62108 Implementation

Mike Ludawise (SolFocus)

- Presented from HCPV integrators viewpoint
- Reiterated that 62108 is the cost of entry for CPV
- PTC test is particularly puzzling
  - Options have not really been explored by the integrators who have executed the standard
- Compared CPV to Flat Plate PV
  - Noted that illuminated and forward biased cells have significantly different current distribution
- Difficulty comes from possible nascent damage that may only be detected in subsequent test legs
- Reiterated the suggestion to use resistive heating in grid lines.
- Recommended a cell qualification standard and a review of the total required qualification test time

IEC 62108 Intentions, Interpretation, and Implementation

Post Session Discussion

- Maybe specify cell temperature as opposed to the method of achieving it
- Need requirements for retest after engineering changes
  - Conflict of interest between test labs and system manufacturers
- Industry may be moving towards standard form factors
- Recommend 25 to 30 cycles per day, at least 10°C/min for thermal cycling
- Need recognition of actual system temperatures for setting stress limits
  - Where did 110°C come from? (IEC 61215 derivative)
- Very difficult to execute PTC on large area (higher power) cells while regulating cell temp within +/- 3°C
- Need test protocols for both cells and receiver packages
- Need to revisit the AFs for the temperature/# of cycles

Durability of Optical Materials



Andy Hartzell
3M Renewable Energy Division

© 3M 2009. All Rights Reserved.

Outline



- 3M Background
  - *Optical Products*
  - *Weathering Expertise*
- Considerations in setting up weathering testing
  - *Typical Test Regimens*
  - *Optical Testing of Samples*
  - *Definition of Failure*
- Example Outdoor Results

© 3M 2009. All Rights Reserved.

3M Optical Products for the Solar Market





Silicone on Glass
Fresnel Lens Panels



PV Backsheets



Mirror
Films



Acrylic
Fresnel Lens Panels



Barrier Films

© 3M 2009. All Rights Reserved.

3M Weathering Resource Center







Description:

- *The Weathering Resource Center is a 3M facility that provides testing and research services for the study of material failures resulting from exposure to light, heat, and moisture. Controlled outdoor weathering is conducted in a number of global locations. Accelerated weathering devices are operated in the WRC laboratory to provide similar environmental stresses on materials and constructions, but in a shorter time frame.*

Value Proposition:

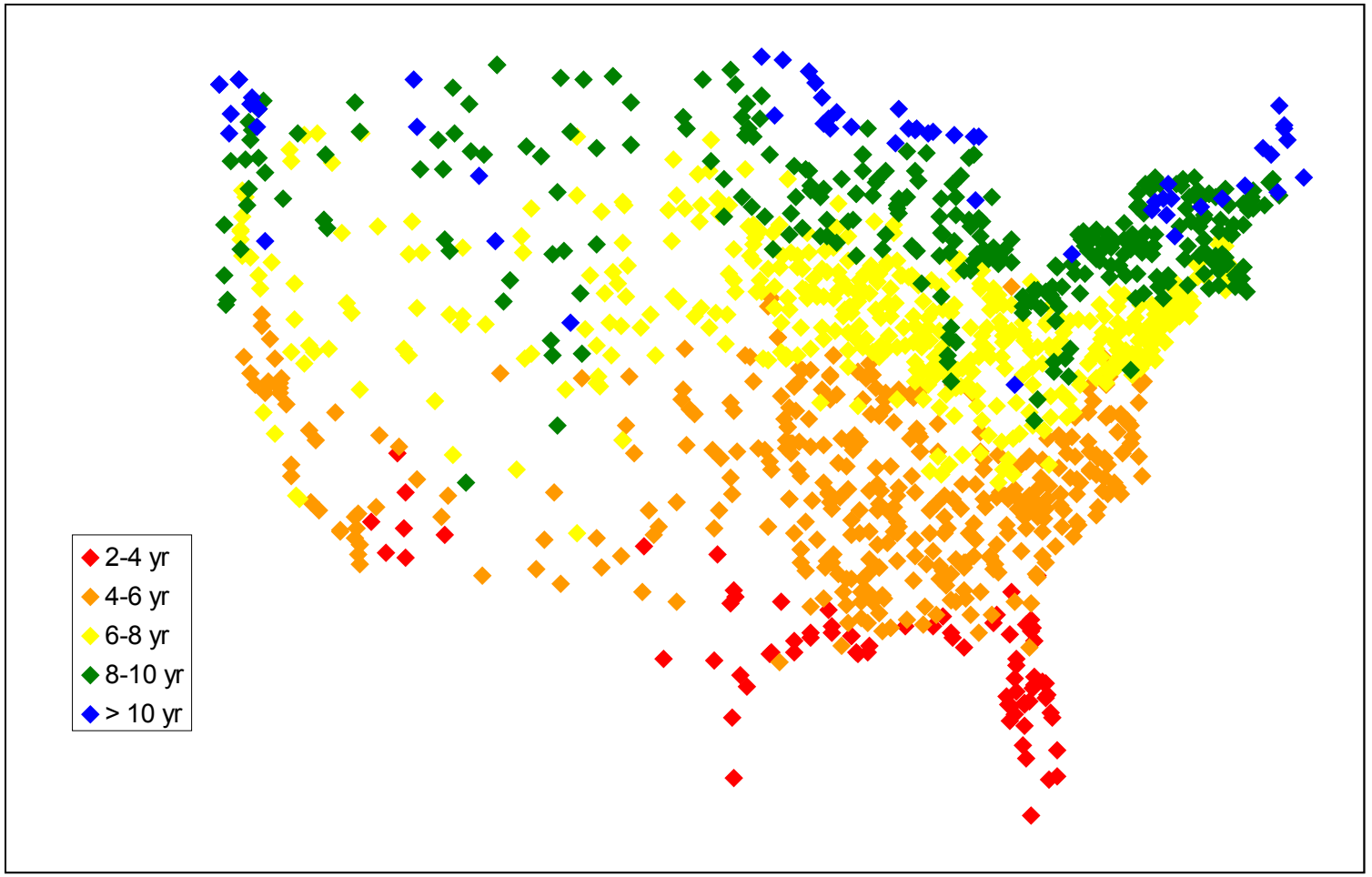
- *The WRC's unique ability to support research of the degradation effects and lifetimes of many product types across many 3M divisions leads to increased product durability and improved product reliability.*

Technical Benefits:

- *The WRC has developed a number of proprietary laboratory tests that exhibit very good correlation with natural weathering results. Faster tests are achieved through the use of patented light sources that yield higher levels of realistic solar radiation.*

© 3M 2009. All Rights Reserved.

Example Product Lifetime Map (Product Unknown)



Estimating material or product lifetimes. *By means of a series of proprietary accelerated weathering tests that determine the relative effects of light, heat, and moisture on degradation, mathematical models may be derived and used with climate data from specific locations in order to estimate lifetimes.*

© 3M 2009. All Rights Reserved.

Typical Test Regimen



New Products/New Material Sets

Accelerated Indoor Testing

- *Battery of tests for light, heat, & humidity responses*
- *Test to Failure, typically more than 10,000 hours (~15 months)*
- *IEC-62108*

Outdoor Testing

- *Locations: Arizona, Florida, and Minnesota*
- *Durations: 1 year, 5 year, 10 year periods & retest until failure*

Product Modifications

Accelerated Indoor Testing

- *Most aggressive accelerated test, with standard product as a control*
- *IEC-62108*

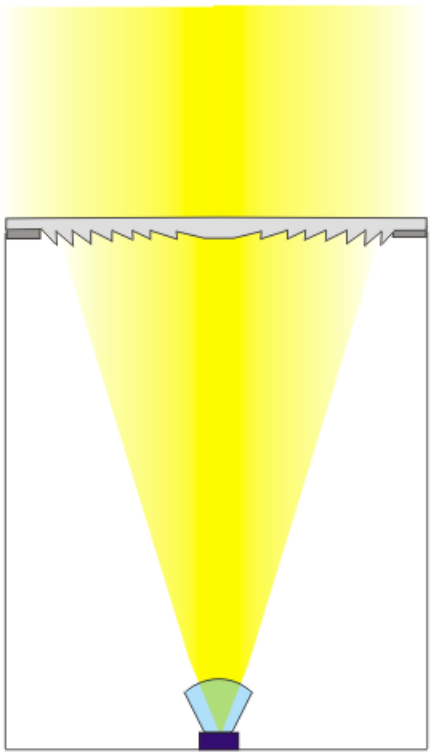
Outdoor testing

- *Same as for new products*

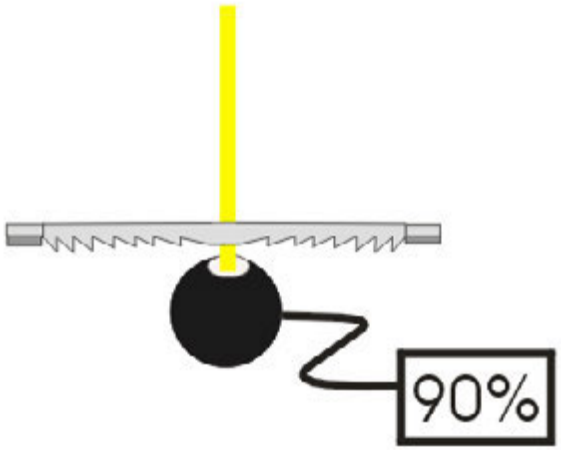
© 3M 2009. All Rights Reserved.

Testing Lens Transmission





Typical
Application



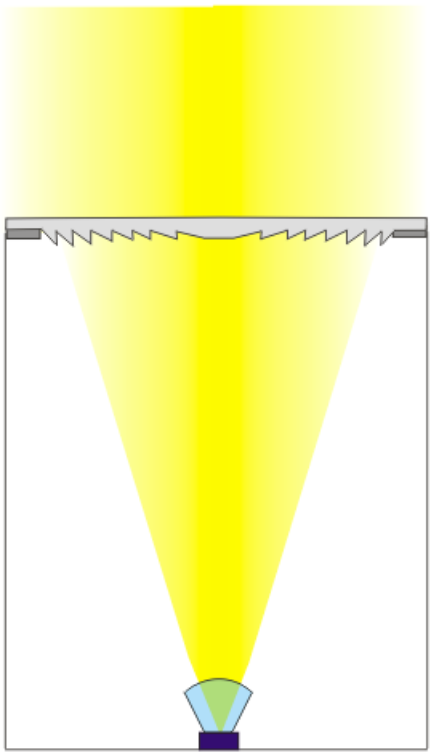
Diffuse
Transmission

Nearly all light that gets through the lens is included in measurement

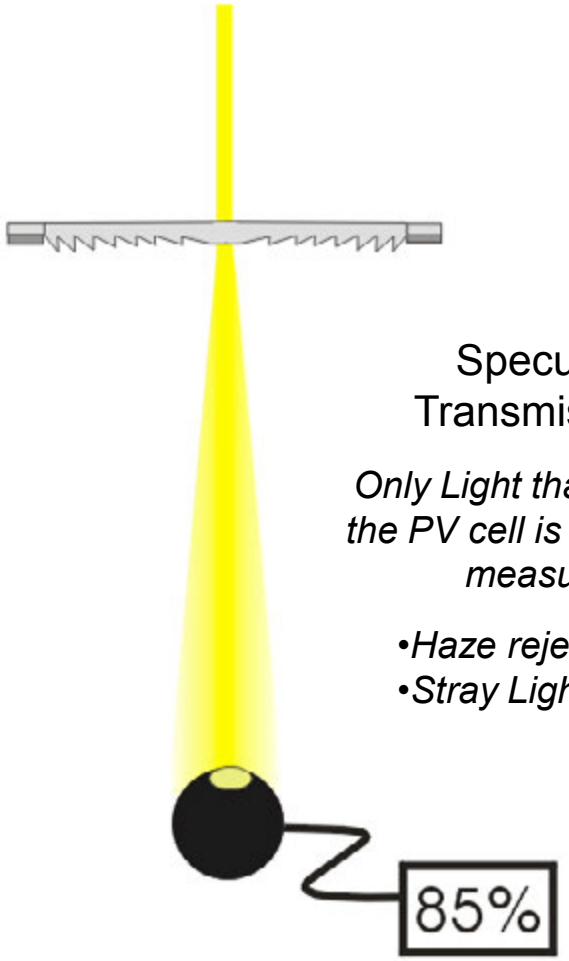
© 3M 2009. All Rights Reserved.

Testing Lens Transmission





Typical Application



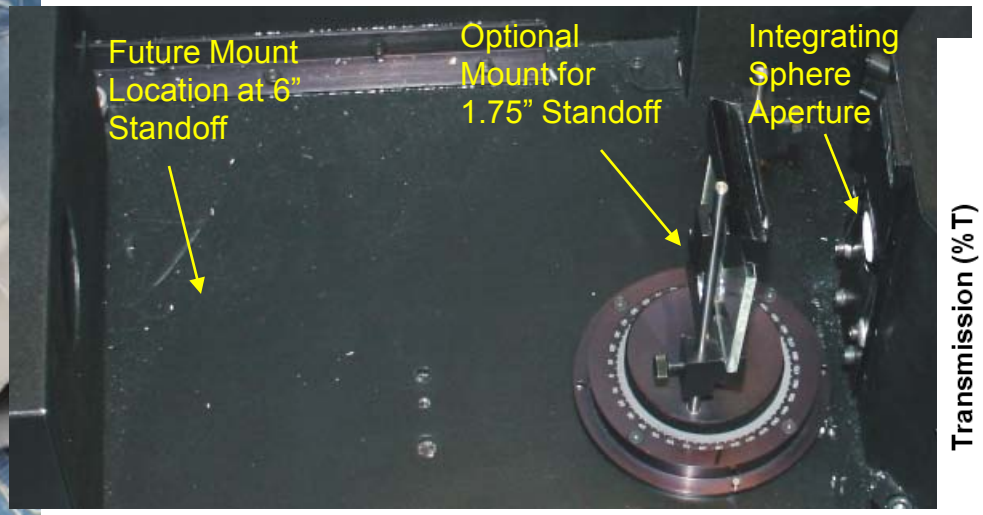
Specular Transmission

Only Light that would get to the PV cell is included in the measurement

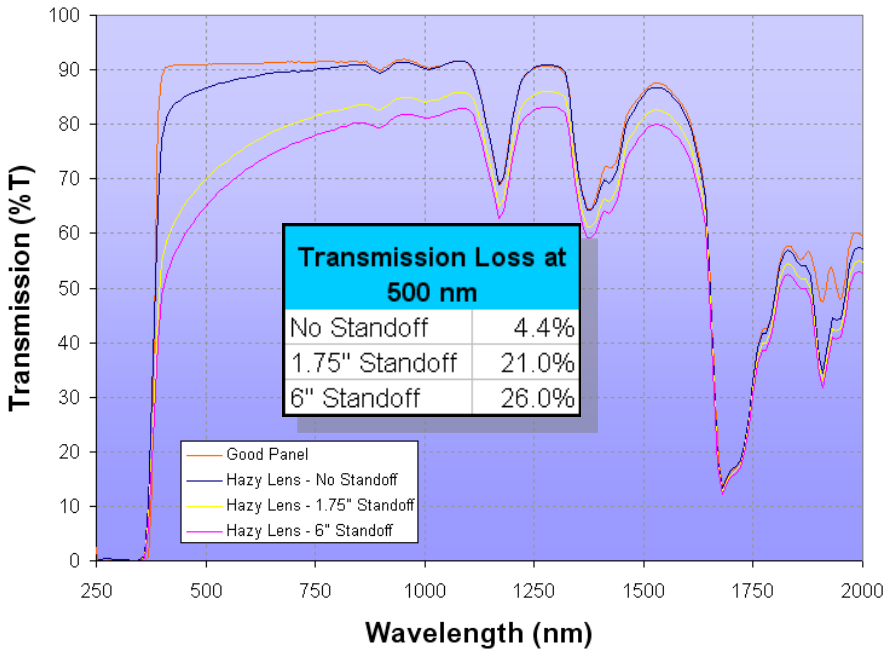
- *Haze rejection*
- *Stray Light Rejection*

© 3M 2009. All Rights Reserved.

Testing Lens Transmission



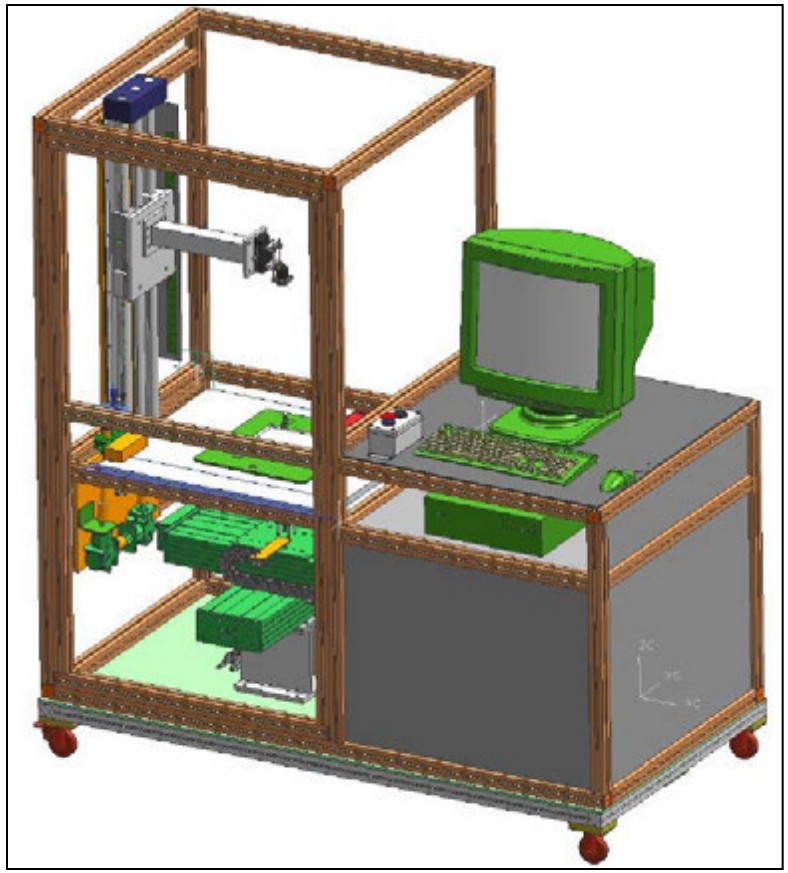
Inside of a Perkin Elmer Lambda 900 spectrometer, showing three locations where the sample was placed to get the results shown to the right.

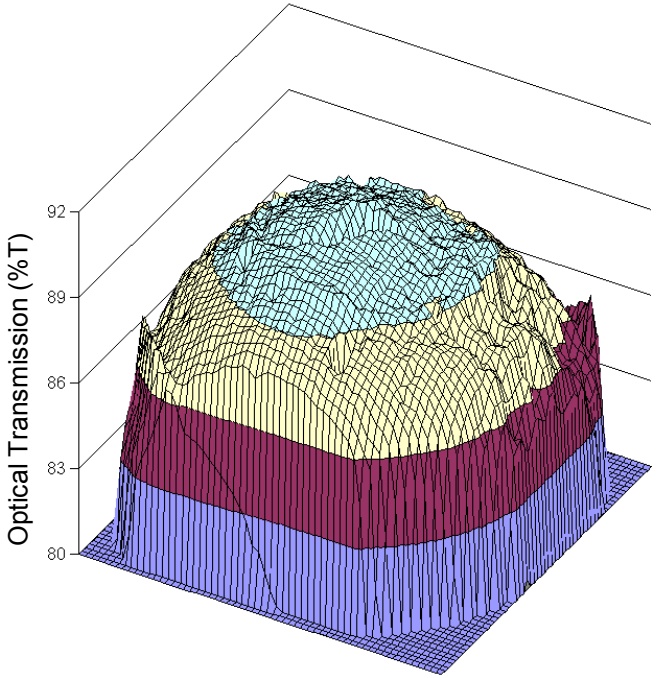


Lens Transmission as a function of detector standoff for a very hazy sample

© 3M 2009. All Rights Reserved.

Testing Lens Transmission





Surface plot of data measured on Lens Efficiency Tester pictured at left. This tester, which measures efficiency at discrete points across the lens, is helpful in highlighting non-uniformities in lens transmission.

© 3M 2009. All Rights Reserved.

Testing Methodology – Sample Cleaning



- Samples will be periodically washed in the application, should washing also be a part of testing?
- Some washing will occur in outdoor samples, and accelerated tests often have a wash cycle.

Factors to consider in washing

- *Use of detergent?*
- *Spray Pressure*
- *Cleaning materials and scrub pressure during use*
- *Polishing compounds*
- *Wash Period*
- *Use of solvents*
- *Purity of wash materials/sources of residue*

© 3M 2009. All Rights Reserved.

Outdoor Testing Considerations



Improper Control of Water

- *Can foster growth of Algae*
- *Excessive heat and water can lead to crazing*
- *Condensing/Evaporation cycles can leave residue*

Lens Mounting

- *Should be no pockets for dirt accumulation*
- *Should be sealed to prevent water intrusion*
- *Should be vented to allow escape of water*
- *Requires custom mounts*

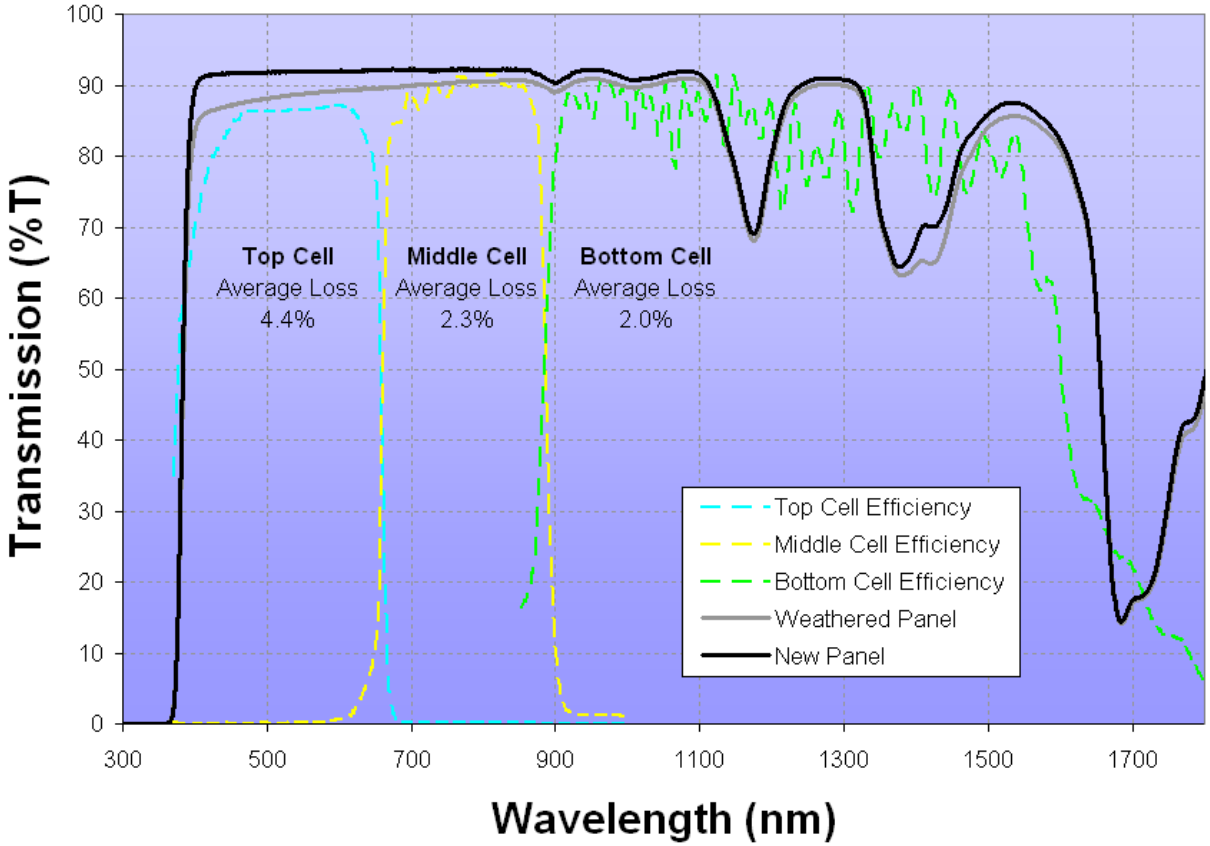
Outdoor testing considerations are similar to the considerations faced by CPV manufacturers and installed systems are probably the best source of outdoor weathered samples.



© 3M 2009. All Rights Reserved.

Definition of Failure – Optical Considerations





Transmission loss in a weathered panel leads to uneven losses in the three junctions of a triple junction cell. Should failure be written in terms of average transmission loss over the complete spectrum or average transmission loss across the top junction?

© 3M 2009. All Rights Reserved.

Definition of Failure – Mechanical Concerns

- Visual Inspection is still needed for anomalies that may lead to failure
  - *Crazing*
  - *Bubbles*
  - *Warping*
  - *Delamination*

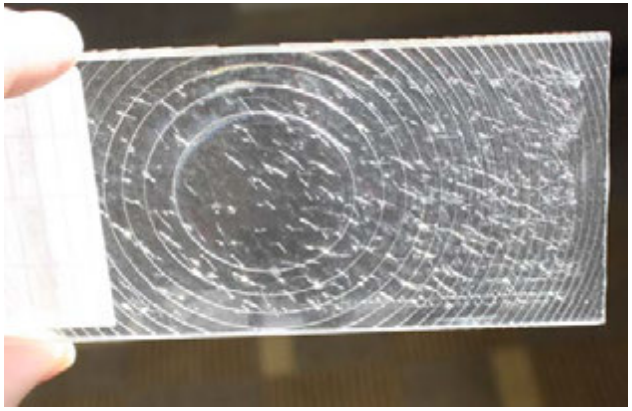


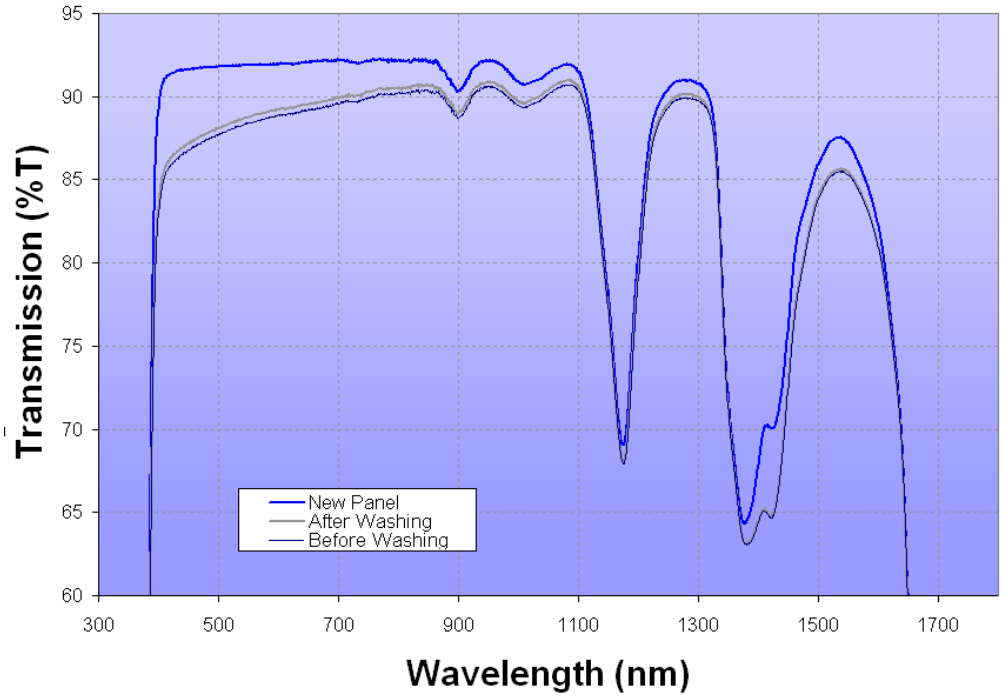
Image of a crazed injection molded lens (not produced by 3M) after time in an accelerated test. Not all PMMA lenses perform the same.

- Acceptable levels of anomalies like these still need to be defined, so it is unclear how they would be included in a definition of failure

© 3M 2009. All Rights Reserved.

Analysis of installed lens panels







Measured transmission of a linear Fresnel lens from the system pictured after 13 years in service in Minnesota. This system survived winds over 30 meters/second and temperatures from -30F to 90F with little or no cleaning of the optical surfaces.

© 3M 2009. All Rights Reserved.

National Renewable Energy Laboratory
Innovation for Our Energy Future

Durability of Poly(Methyl Methacrylate) Lenses Used in Concentrated Photovoltaics

David C. Miller*, Cheryl E. Kennedy, and Sarah R. Kurtz

***speaker**



PV
Reliability Workshop

Denver West Marriot

2010/02/19 1:20 PM

This presentation does not contain any proprietary or 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

Overview

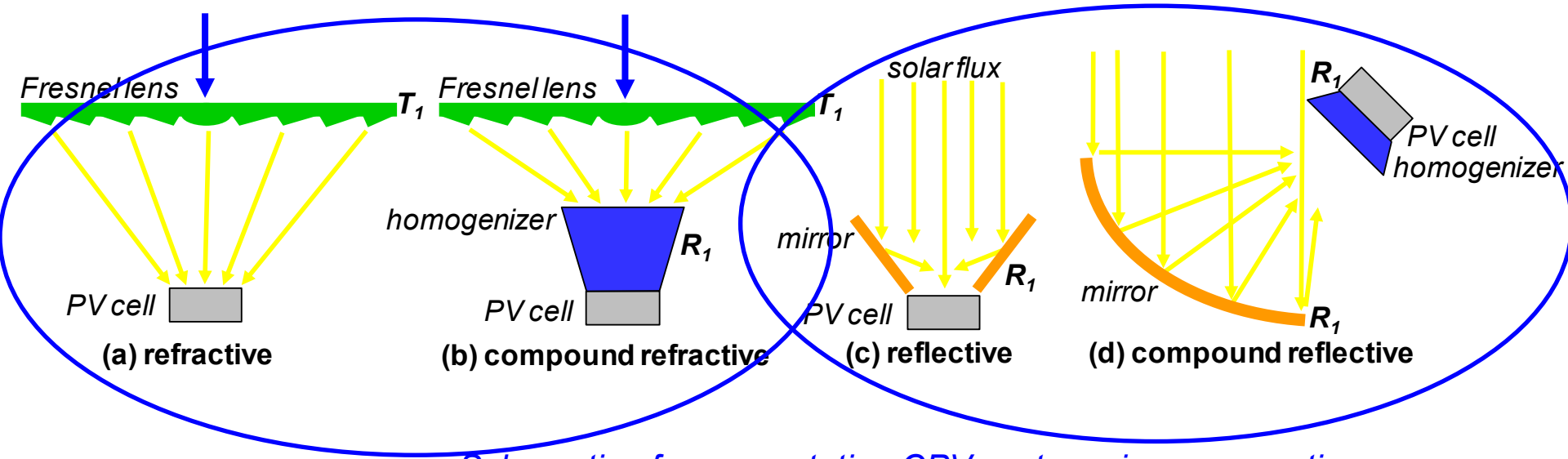
- Introduction/scope/terminology
- Experiment (@ NREL) vs. literature
- Failure *modes*
  - Optical durability
  - Mechanical durability
  - Soiling
- Failure *mechanisms*
  - Photodegradation
  - Thermal decomposition
- Summary

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

- Focus: Fresnel lens component in refractive CPV system
- Opto-mechanical component expected to last 30 years

- Direct solar resource (*for reference*)
  - solar disc: ±4.65 mrad (±0.27°)
  - circumsolar region: ±50 mrad (±2.9°)
  - reference spectrum: ASTM G173 direct

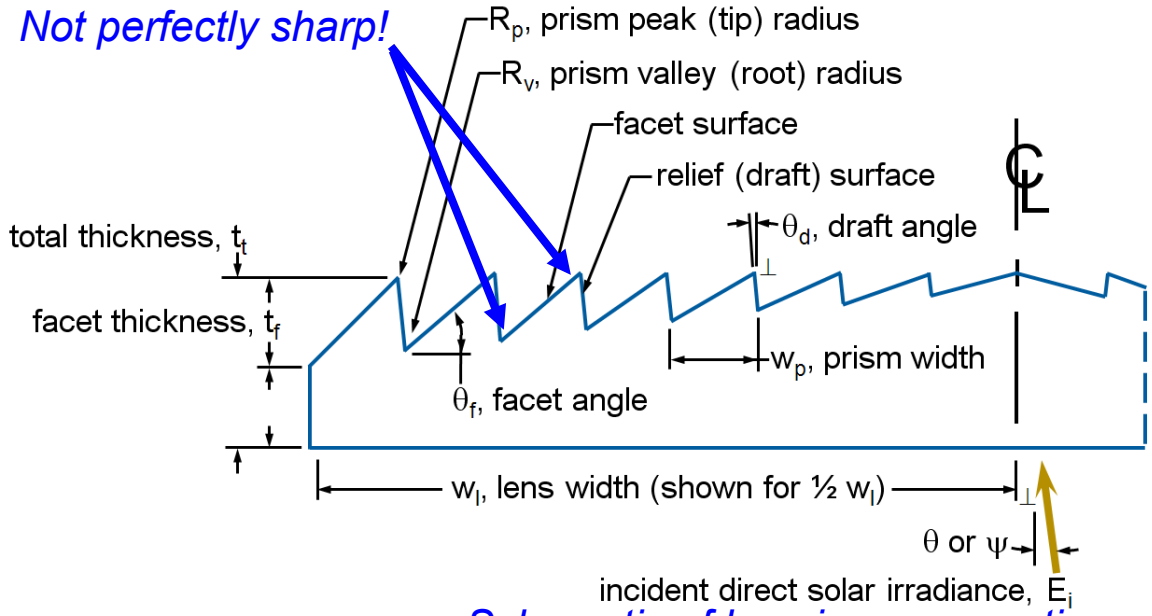


Schematic of representative CPV systems in cross-section

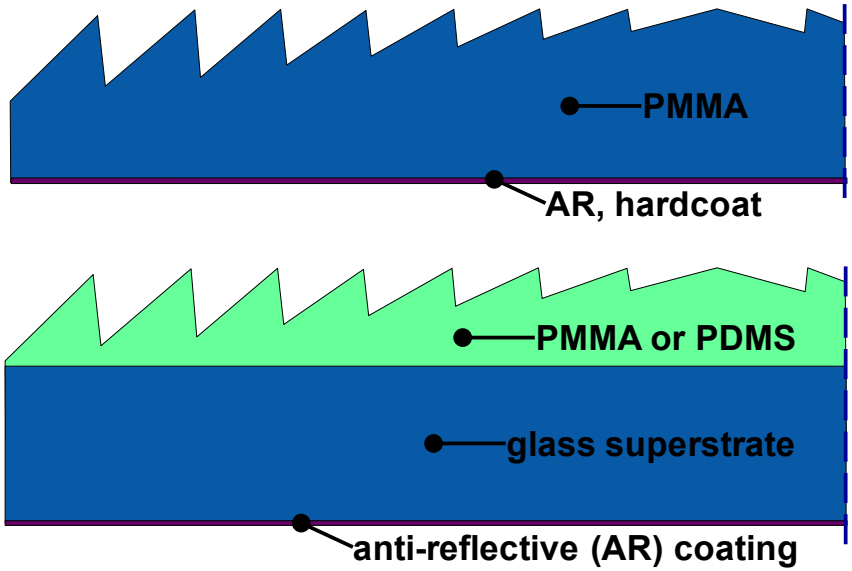
NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

Terminology

Fabrication methods:
hot-embossing *(low σ)*
casting
extruding
laminating
compression-molding
injection-molding *(low $)*



Schematic of lens in cross-section



Materials implementation (monolithic vs. composite)

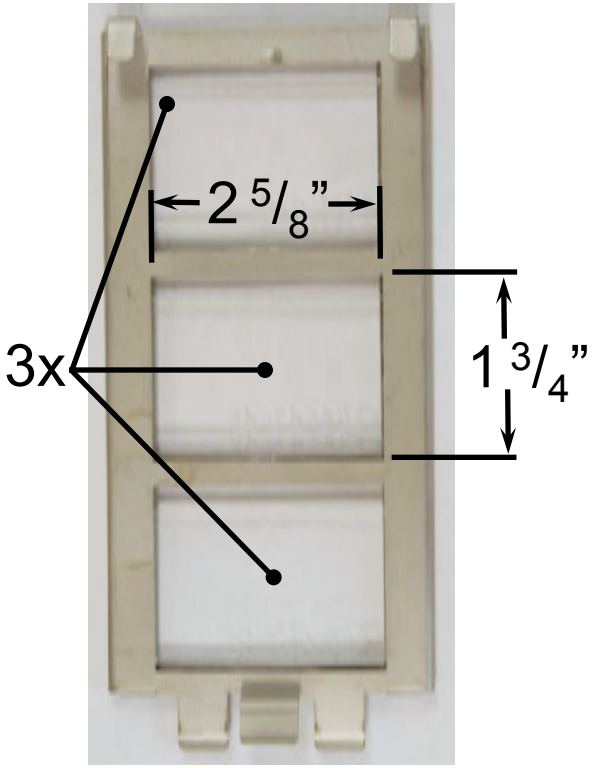
PARAMETER	REPRESENTATIVE VALUE
t_f	0.1-0.5 mm
t_s	2.0-5.4 mm
t_t	2.5-5.5 mm
R_p	2-30 μm
R_v	1-30 μm
θ_f	1.0-1.6 rad
θ_d	35-52 mrad
w_p	0.01-1.0 mm
w_l	2-30 cm
θ	±5-150 mrad
C	5-1000
f/	0.5-1.5
η	78-86%

*Figures of merit**

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 Screen Test (1)

- Literature ⇒ initiated ≥20 years ago
- Characterize the durability of a broad range of contemporary specimens subject to indoor HALT



Test specimens, (3) ea

DESCRIPTION	SPECIMEN TYPES
stock sheet	11
linear lens	1
spot lens	8
veteran lens	3

- Test instrument: ATLAS Ci4000 Weather-ometer (Xenon-arc lamp @ 2.5x UV suns. Chamber @ 60°C/60%RH)

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 Screen Test (2)

- Measurands:

  Periodic

  optical appearance
  → optical transmittance (hemispherical)
  mass
  → contact angle (sessile drop, 1st surface)

  "**End of life**"

  prism facet geometry (lenses: section then SEM)
  surface morphology (SEM or AFM)
  indentation (Vicker's hardness, toughness)
  ⇆ rheometry (E', E'', T_g)
  XPS or ESCA (surface chemistry)

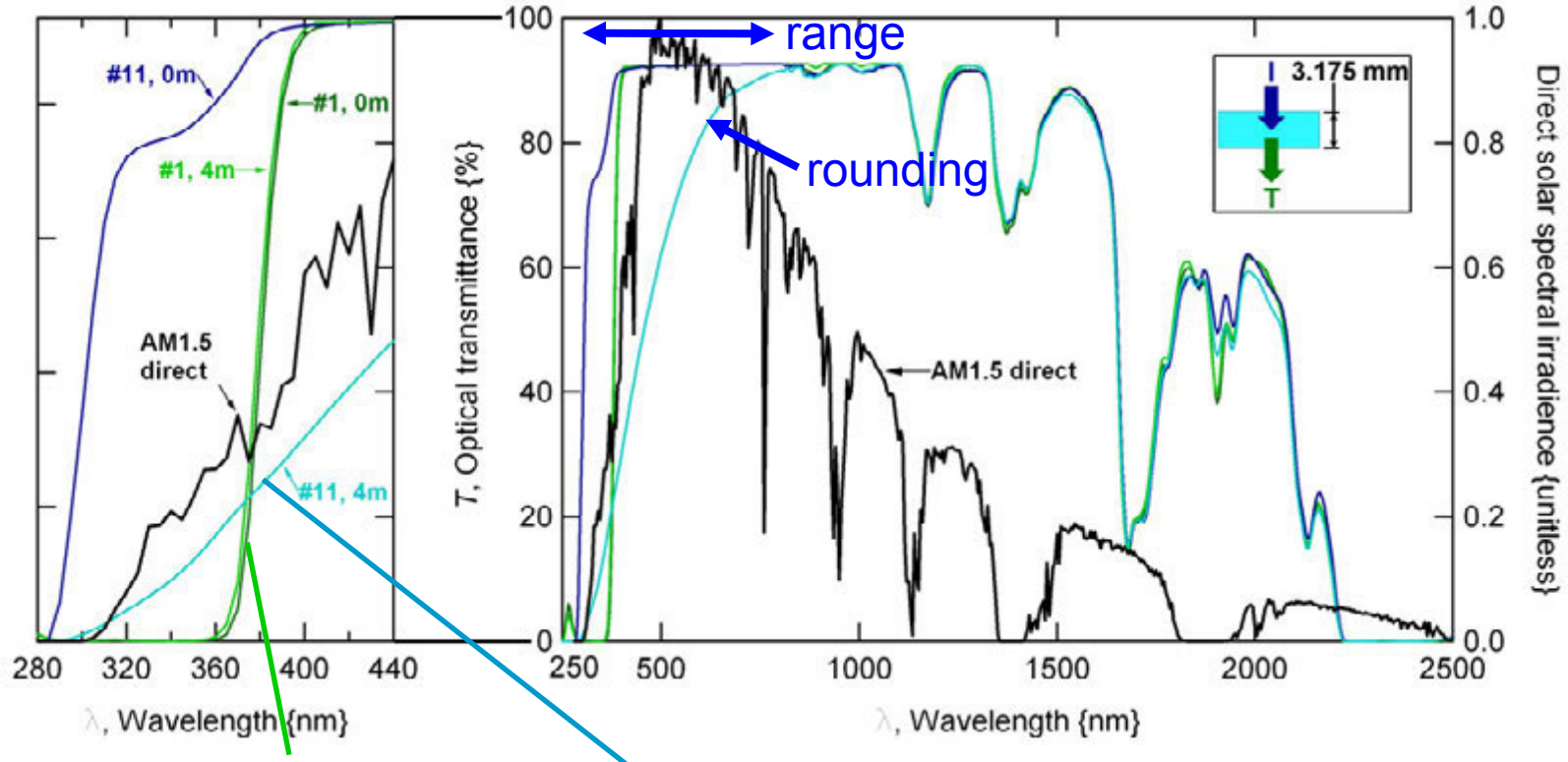
- Test schedule:

  0, 1, 2, 4, 6, 12, 18, 24, 30, 36, 42 months
  ≥8 acceleration factor

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

Optical Durability

- Transmittance of PMMA
- Lambda 900 (Perkin-Elmer) spectrophotometer (w/ I-sphere)





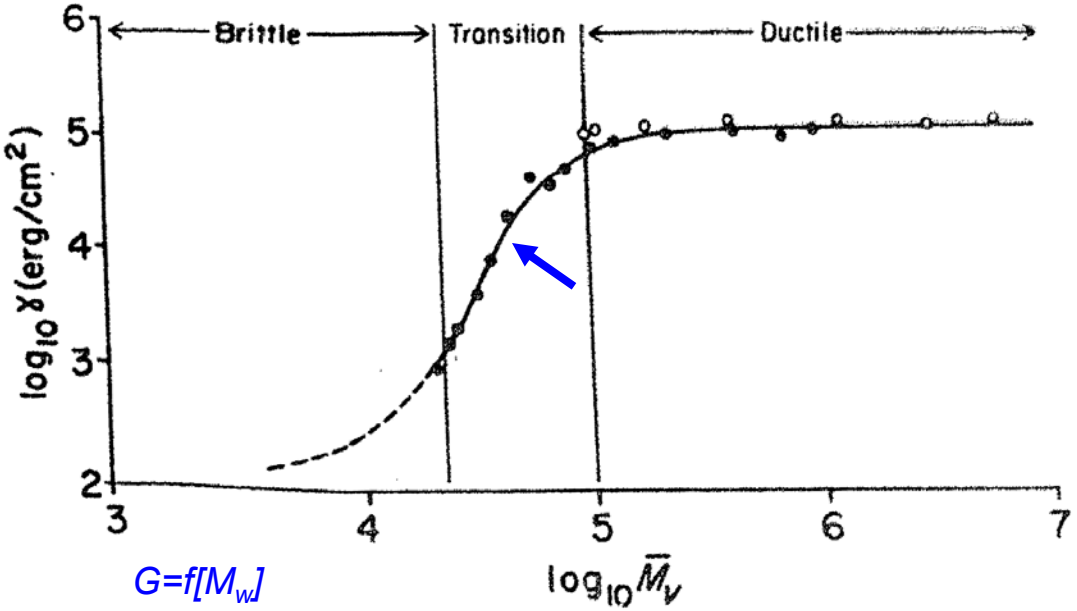


Yellowness index
(ASTM D65,1964)
YI: -1.1 → -0.9-18.4

Comparison of transmittance at 0, 4 months for best and worst sheet stock specimens

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

Mechanical Durability (Fracture/Toughness)



G=f[M_w]

Kusy, J. Non-Cryst. Sol., 24, 1977.

$$G = \frac{K_{IC}^2}{E} = \frac{\pi a_o Y^2 \sigma_f^2}{E} = 2(\gamma_s + \gamma_p)$$

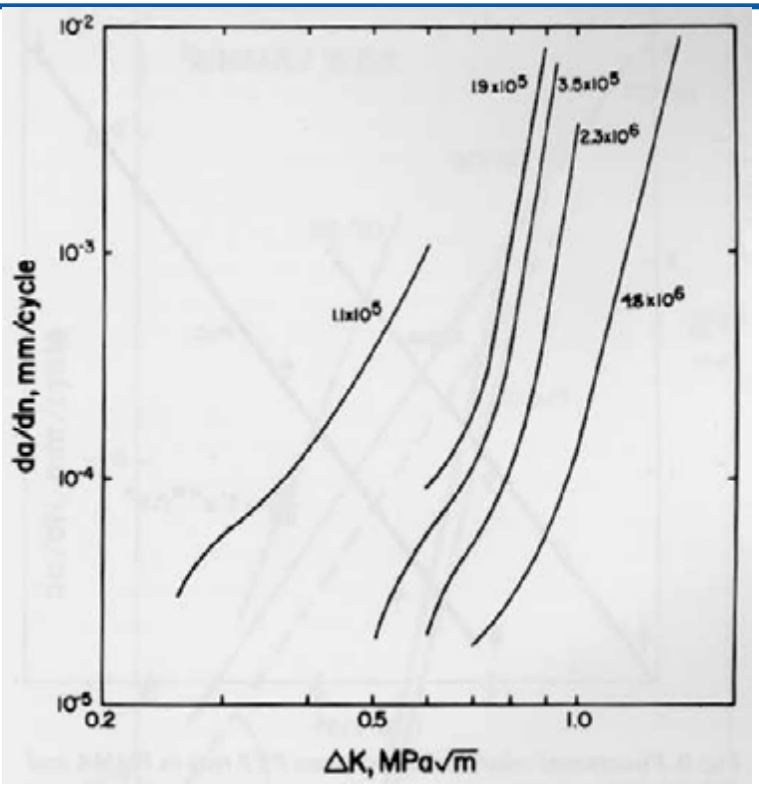
Fracture mechanics: Griffith representation

- Unstable crack propagation (σ_f) depends on toughness (K_{IC}), greatest critical flaw (a_o)
- Embrittlement: K_{IC} varies with M_w, which decreases over time in the field
- Critical molecular weight, M_w, 10,000-100,000 (<10^4 not machinable)
- Mirror/mist/hackle fracture morphology for M_w>10^5

- Related mechanical concerns:
  - Buckling $\Rightarrow$ fracture
  - Abrasion (tribology = *f*[*H*,*E*]); *H*=f[σ_y]; σ_y=f[M_w}

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

Mechanical Durability (Fatigue)



∂a/∂N=f[M_w]
Kim et. al., Polym. Eng. Sci., 19, 1977.

$$\frac{\partial a}{\partial N} = C\Delta K^m$$

"Paris law" for crack growth rate

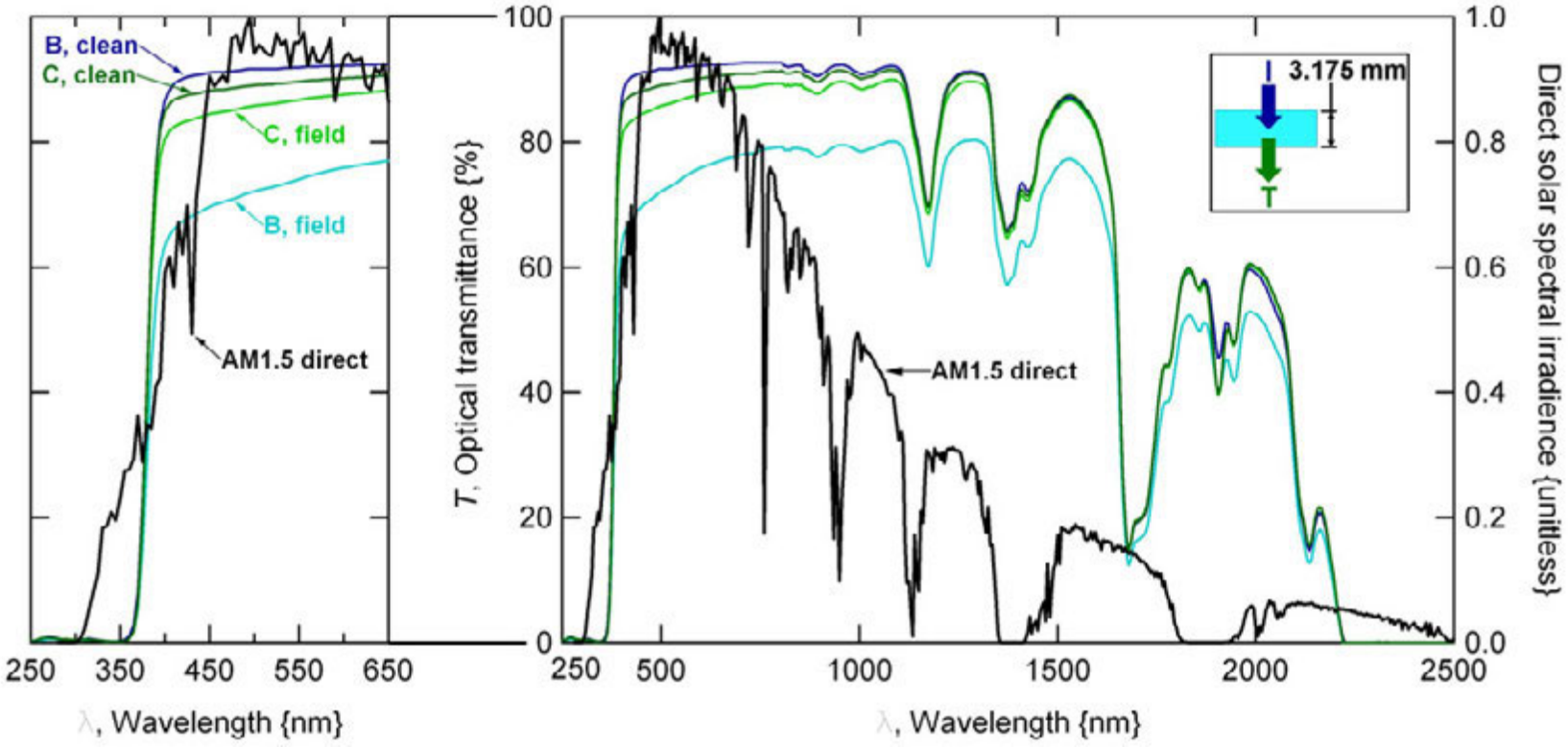
- Steady-state crack propagation modeled by log-linear relationship
- Hystertic heating above ~5 Hz
- Like unstable fracture, M_w & H_2O absorption can be influential

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

Soiling

- Contamination absorbs, scatters, and back-reflects light
- Effect most significant as $\lambda\downarrow$ (Mie scattering: $0.6/n<\pi\varnothing/\lambda<5$)
- Direct/specular light more severely affected than hemispherical

Contact angle (sessile drop) θ: 66 $\rightarrow$ 58 $\rightarrow$ 43°



Comparison of transmittance as-received and after cleaning for 19, 8 year old Fresnel lens specimens

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

Soiling (Literature Summary)

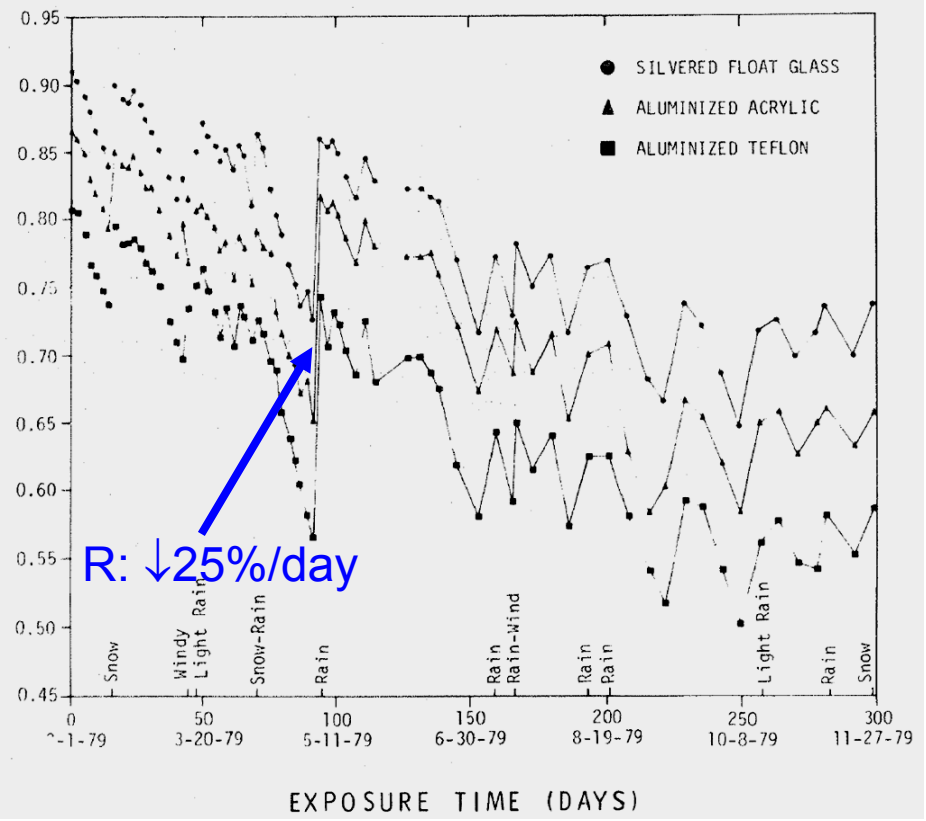
- Issue of soiling is significant (could compromise η_{module})!
- Data from: Baja Mexico (*ocean & desert*), Europe (Spain & Italy), North & South *Africa*, *Australia*, West China might add perspective

YEAR	REFERENCE	LOCATION	ENVIRONMENT	SPECIMEN(S) (FIRST SURFACE)	SPECIMEN TYPE	DURATION	↓T, typical {%}	↓T, max {%}	RECOMMENDED *f* CLEANING
1971	Hamberg []		laboratory	glass	mirror	N/A	3	42	
1974	Garg []	Roorkie, India	urban, continental	glass, PMMA	sheet	30 days	14	63	
1977	Pettit [], 1978 []	Albuquerque, NM, USA	rural, desert	glass, PMMA, Al	mirror	5 weeks	5	23	
1978	Berg []	Albuquerque, NM, USA	desert	glass	mirror	1 month	4	13	
1978	Blackmon [], []	CA, USA; NM, USA	rural, desert	glass, PMMA	mirror	1.5 years	7	14	
1978	Freese []	Albuquerque, NM, USA	desert	glass	mirror	7 months	5	11	
1979	Freese []	Albuquerqu					4		
1979	Nimmo []	Dhahran, S					15	N/A	
1979	Sheratte []	CA, USA; GA,					4	10	
1980, 1983	Cuddihy [], []	CA, U					9	19	
1980	Hoffman []	CA, NM, NY,					8	21	
1980	Pettit []	Albuquerqu					7.5	12	
1980	Roth [], []	Albuquerqu					10	18	
1981	Bethea []	Crosbyto					8	9.4	
1981	Morris []	A, HI, NM, NV,					15	100	
1983	Bethea []							44.5	
1984	Cuddihy []	AK, WA, U					6	19	
1984	Khoshaim []	Riyadh, Sa					22	33	
1985	El-Shobokshy	Riyadh, Sa					3	55	
1985	Sayingh []	Safat,					5	80	3 days
1986	Deffenbaugh []	TX,							
1987	Al-Busari []	Safat,					9	57	2/ month
1990	Nahar []	Jodphu					4	62	daily
1990	Said []	Dhahran, S					7	65	1 month
1992	Hasan []						16	35	
1992	Pande []	Jodphur, India	arid	glass	PV module	1 year	8	30	
1993	El-Shobokshy		laboratory	glass	PV module	N/A		90	
1995	Bonvin []	Morges, Switzerland	urban	glass	sheet	1 year	5	25	
1997	Becker []	Köln, Germany	urban	glass	PV module	5 years	4	24	
1997	Hammond [], []	Phoenix, AZ, USA	urban, desert	glass	PV module	3 years	1	3	
1998	Al-Hasan []		laboratory	glass	sheet	N/A		73	
1998	Haeberlin []	Burgdorf, Switzerland	urban	glass	PV module	3 years		10	
1999	Goosens []		laboratory	glass	PV module	N/A		90	
2001	Hegazy []	Minia, Egypt	rural, desert	glass	sheet	1 month	15	26	
2003	El-Nashar []	Abu Dhabi, UAE	urban, desert	glass	desalination plant	1 year		29	
2005	Sahm []	Las Vegas, NV, USA	urban, desert	PMMA	sheet	1 year	11	24	2-4 weeks
2006	Kimber []	CA, USA	urban, desert	glass	PV site	1 year	6	27	
2008	Ruesch [], []	Davos, CH; Raperswil, CH	urban + rural, temperate	glass, PMMA, others	sheet	20 years	4.5	14	
2008	Vivar []	Madrid, Spain	rural, continental	glass, PMMA	CPV module	4 months	12	26	
2009	Banchik []	Las Vegas, NV, USA	urban, desert	PMMA	sheet	1 month	10	12	

	↓T, typical {%}	↓T, max {%}
↓T, AVG {%}	9	34
↓T, ST DEV {%}	7	26
↓T, MAX {%}	35	100

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

Soiling (Over Time)



Pettit and Freese, Solar Energy Mat., 3, 1980.

- Asymptotic degradation w/ time

$$\left(\frac{1-T}{T_{clean}}\right) = d_1 erf\left[d_2 \omega^{d_3}\right]$$

(Hegazy, Renewable Energy, 22, 2001)

- T cannot be 100% restored to T_i
- Greater permanent retention for PMMA vs. glass

Subject to synoptic events:

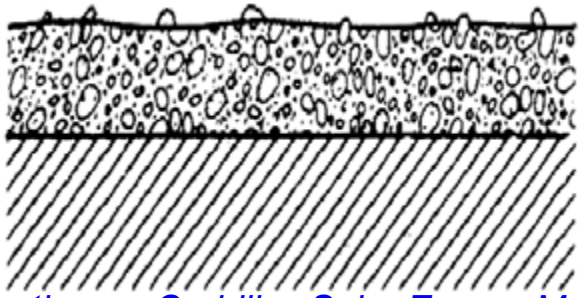
- Rain: intense vs. evanescent
- Scraping effect from snow

Subject to tilt angle:

- Horizontal inclination ⇒ most soiling; vertical ⇒ least soiling
- Relates to accumulation and natural cleaning processes
- Trackers: store them face down overnight
- Uniformity… accumulation at the bottom ⇒ partial shading

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

Soiling (Mechanisms)



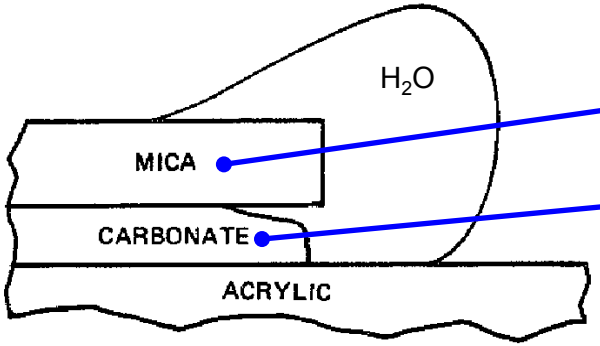
C: large ∅ (<50μm); inert; easily removed by rain
B: fine ∅ sediment; scrub to remove
A: 'cementing' matter; tenacious (abrasives)

In theory: Cuddihy, Solar Energy Mats, 3, 1980.

energetic gradients:
coarse ∅, non-polar organics, low γ
fine ∅, polar inorganics, high γ

CPV environment:

- Great insolation, little precipitation ⇒ more prone to soiling
- Alkaline (desert) vs. acidic (temperate) soils



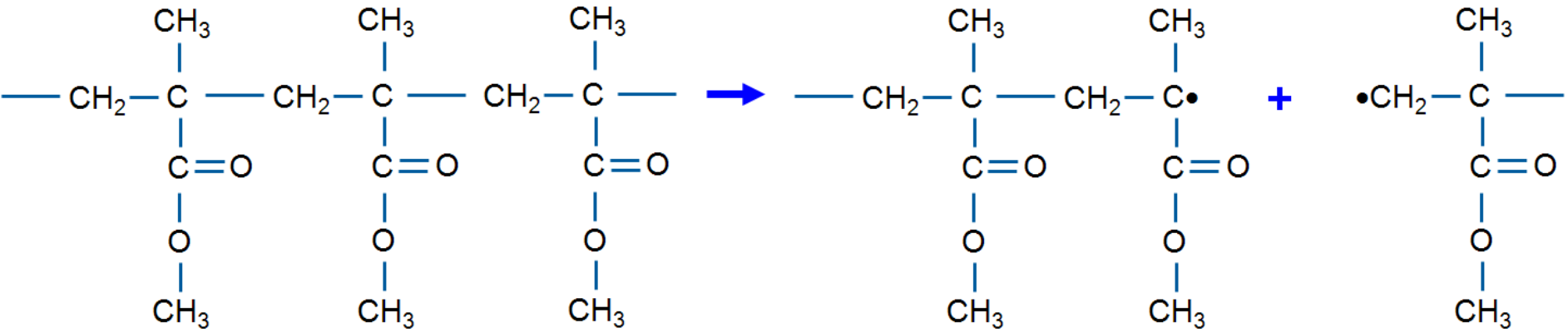
mica, quartz, feldspar

carbonates, sulfates (calcite, gypsum, halite, sylvite)
salts (external or from glass)
montmorillonoid clay

In practice: Sheratte et. al., SAND79-7052, 1979.

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

Photodegradation



main chain scission after Aboulezz and Waters, "Studies on the Photodegradation of Poly(Methyl Methacrylate)", 1978

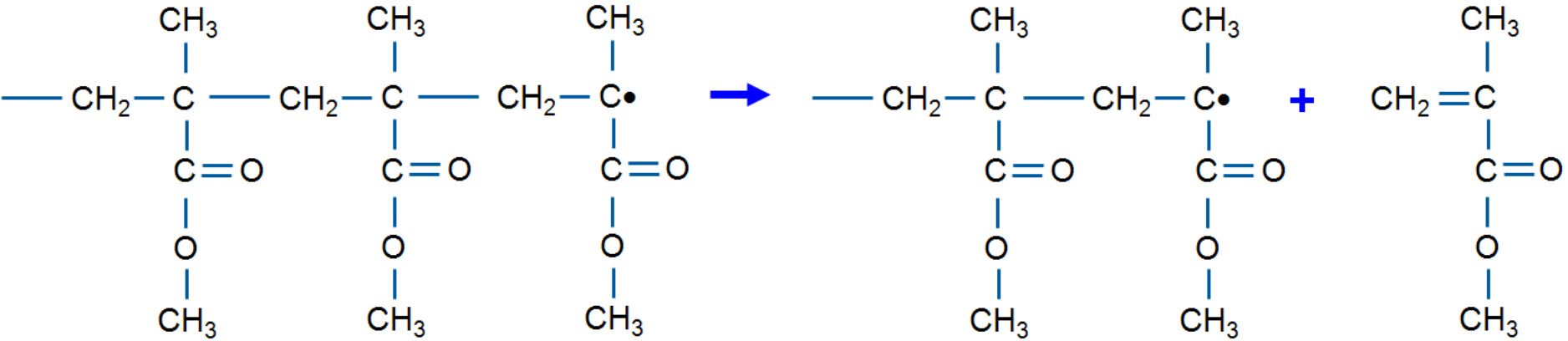
- Random main chain scission by UV (photolysis) $\Rightarrow M_w$ therefore T_g reduced
- T_g reduced $\downarrow$~5°C after 18 years outdoors

  L.G. Rainhart & W. P Schimmel, SAND 74-0241, 1974.
- Likewise affects mechanical durability: $K_{IC}\downarrow \Rightarrow \sigma_f\downarrow$ … $\partial a/\partial N\uparrow$

- Many classic studies of quantum yield vs. λ, atmopshere
- Volatile products (vacuum): methyl formate, methanol, methyl methacrylate, plus(in air): methane, hydrogen, carbon monoxide, carbon dioxide
- Potential chromophores: residual monomer, formulation additives, co-polymers

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

Thermal Decomposition



chain unzipping after Aboulezz and Waters, "Studies on the Photodegradation of Poly(Methyl Methacrylate)", 1978

- Unzipping of main chain in methyl methacrylate (monomer)
- Autocatalytic process (zip length on order of 1000)
- Significant weight loss (vs. minimal in chain scission)

- Occurs readily for T>200°C
- Synergistic effect w/ irradiation (UV)⇒occurs at T<200°C
- Many classic studies of E_a vs. heating rate, atmopshere
  - O_2 suppresses decomposition

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

Unknowns

- Mechanical (fracture & fatigue):
  - General material characteristics understood;
    - application specific data is not available
  - Size/morphology of field-developed critical flaws
  - Dimension stability, *e.g.* facets
- Soiling (lots!):
  - Comparison between key world sites
  - Solution methods (fluorination, roughening, or doping the first surface)
  - Tracking vs. fixed modules
- SOG:
  - No literature (concerning durability)
  - Significant $\Delta\alpha \Rightarrow$ delamination?

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

Summary

NREL study:
- Identify key issues for contemporary specimens

Optical durability:
- Evolution of location & distinctness of cut-on frequency

Mechanical durability (K_{IC}, $\partial a/\partial N$):
- Fracture, fatigue strongly depend on M_w
- Embrittlement over time

Soiling:
- Complex issue that may vary significantly over time w/ location

Photodegradation:
- Chain scission $\Rightarrow$ decreased M_w

Thermal decomposition:
- Chain unzipping $\Rightarrow$ decreased mass

SOG:
- Probably physically robust against soiling; limited existing literature

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

Acknowledgements

- NREL: Daryl Myers, Marc Oddo, Robert Tirawat, Bryan Price, Matt Beach, Christa Loux, Kent Terwilliger

- Others: Ralf Leutz (Concentrator Optics Inc.), John Wiedner, Michael Longyear, Scott Steele (Arizona Public Service, S.T.A.R. facility)

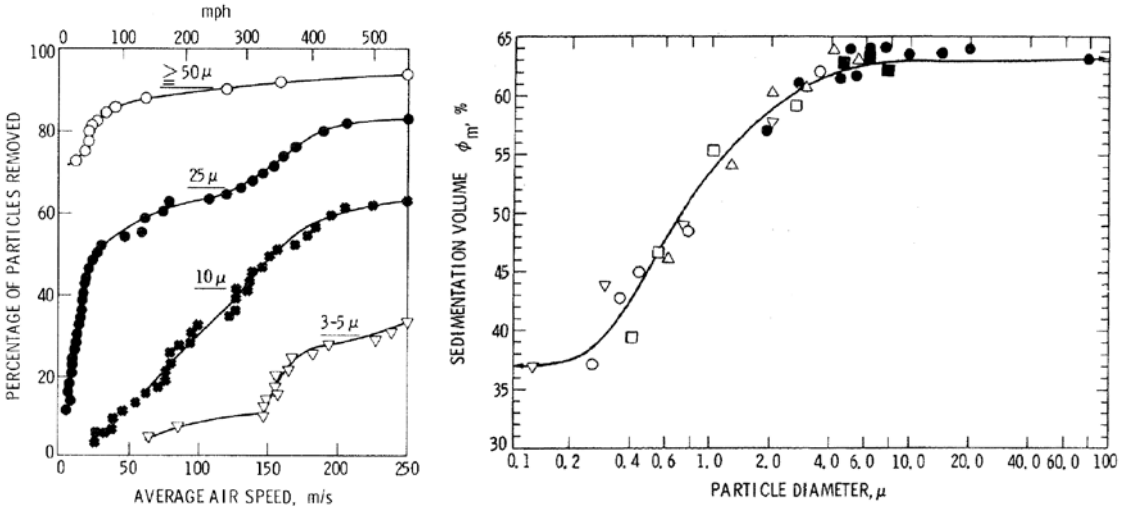


This work was supported by the U.S. Department of Energy under Contract No. DOE-AC36-08GO28308 with the National Renewable Energy Laboratory.

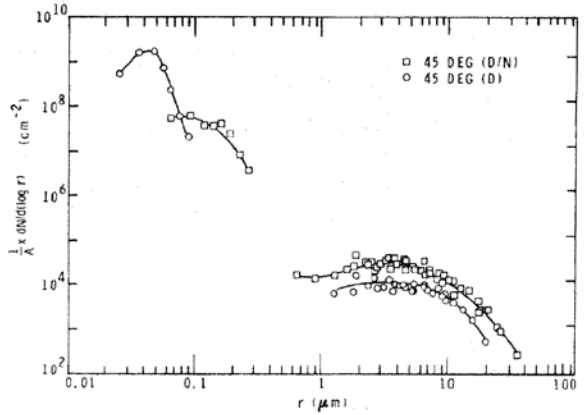
NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

Xtras

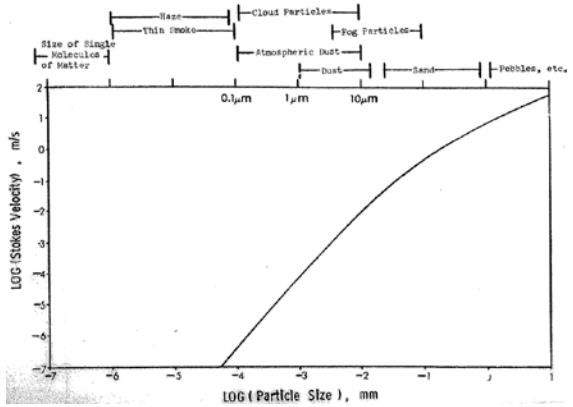
- Some useful additional figures…



Cuddihy, Solar Energy Mats, 3, 1980.



Particle size for natural cleaning; day only (152) vs. day & night (396 hr)
Roth and Anaya, Trans. ASME, 1980.



Berg, SAND78-0510, 1978.

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

Questions About IEC 62108 Implementation

NREL PV Module Reliability Workshop

Mike Ludowise, Feb. 18-19, 2010



This presentation does not contain any proprietary or confidential information

SolFocus™

Innovation Inspired by Nature

© SolFocus, Inc. 2009
Patents Pending

Outline



- Introduction
  - Intent of 62108 – “Concentrator Photovoltaic (CPV) Modules and Assemblies - Design Qualification And Type Approval”
  - Brief History
- Experience in Implementing 62108 from an HCPV manufacturer’s viewpoint
  - Design variations
  - Inappropriate cell tests
  - Vague directions, desired additions
  - Other Issues
- Conclusions & Questions

From the viewpoint of a newcomer in CPV interested in applying the standard in a balanced way within an industrial setting, but without the benefit of silicon PV experience.

© SolFocus, Inc. 2009; Patents Pending

SolFocus

Introduction

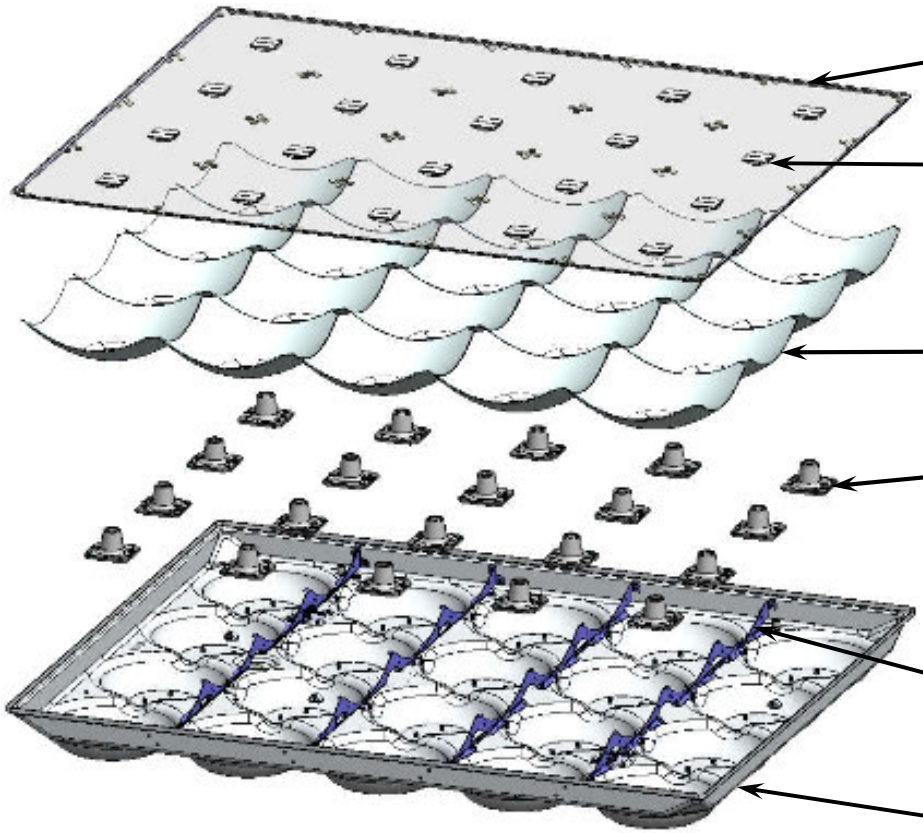


- Intent of 62108
  - To specify the minimum requirements for the design qualification and type approval of concentrator photovoltaic (CPV) modules and assemblies and receivers
- History
  - IEEE 1513 issued in 2001 as first CPV standard
    - Started in 1997, NREL led effort
    - Expired in 2006
    - Served as first draft of IEC 62108
  - IEC 62108 issued in 2007 as comprehensive CPV standard
    - Started in 2000, NREL led effort
    - Influenced by IEC 61215, “Design Qualification and Type Approval” aimed at flat plate terrestrial crystalline silicon PV modules
- Few HCPV system fabricators in 2002
  - HCPV is still a nascent branch of the PV industry
  - 2007 marked the entry of many companies into the HCPV space
  - Experience is “testing” 62108 against real world realities:
    - Widely varied HCPV system designs
    - Application to contemporary HCPV III-V cells
    - Tight funding, budget, and time-to-market constraints

© SolFocus, Inc. 2009; Patents Pending

SolFocus

Parts Identification - Module Assembly



Front glass panel, adhesively attached to backpan rim

Secondary mirror, adhesively attached to front glass

Primary mirror

Receiver - Contains:

- Cell
- Bypass diode
- Tertiary optic
- Thermal path
- Electrical connects

Spacer

Single piece drawn backpan

SolFocus SF1100 Panel

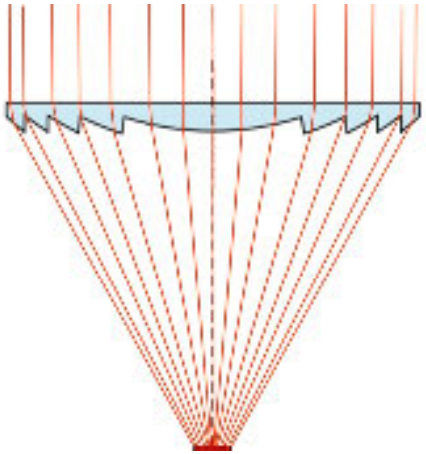
© SolFocus, Inc. 2009; Patents Pending

SolFocus

Two of Many Designs

Two Fundamental Approaches

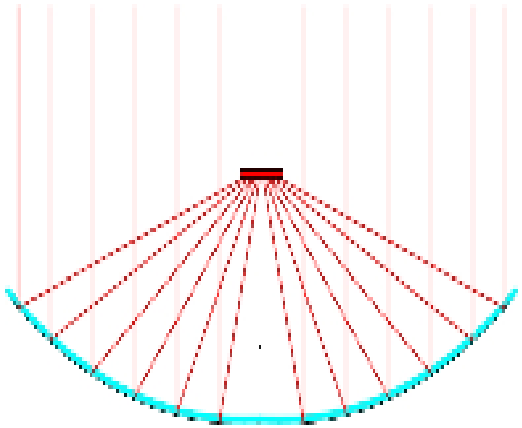
- Refractive: with lenses





Amonix, California

- Reflective: with mirrors





Solar Systems, Australia

© SolFocus, Inc. 2009; Patents Pending

SolFocus

Thermal Cycle Test



- Section 10: current cycling in the hi-T parts of thermal cycle test using one of:
  a) Driving the cell to1.25 x I_{sc} forward current using an external DC source
  b) Illuminating with full intensity light to generate 1.25 x I_{sc}
  c) Partial illumination combined with an external drive to generate 1.25 x I_{sc}

  - Pass:
    - No major visual defects
    - No interruption of current flow during the test
    - Insulation resistance passes per clause 10.4.

- Notes the above may be detrimental to cells – provides alternate and additional test:
  - Retain option a) above with no applied current
  - Drive additional "dead" cells to 1.25 x I_{sc} such that $\Delta T_{test} \geq \Delta T_{operation}$
    - Simulates operational thermal mismatch, fatigue, other stresses
    - Additional receivers pass $\Delta R_{receiver}$ < 2% (excluding the cell).

- Attempts to simulate on-sun stresses; tests the die attach bond line integrity, solder, and electrical connection reliability

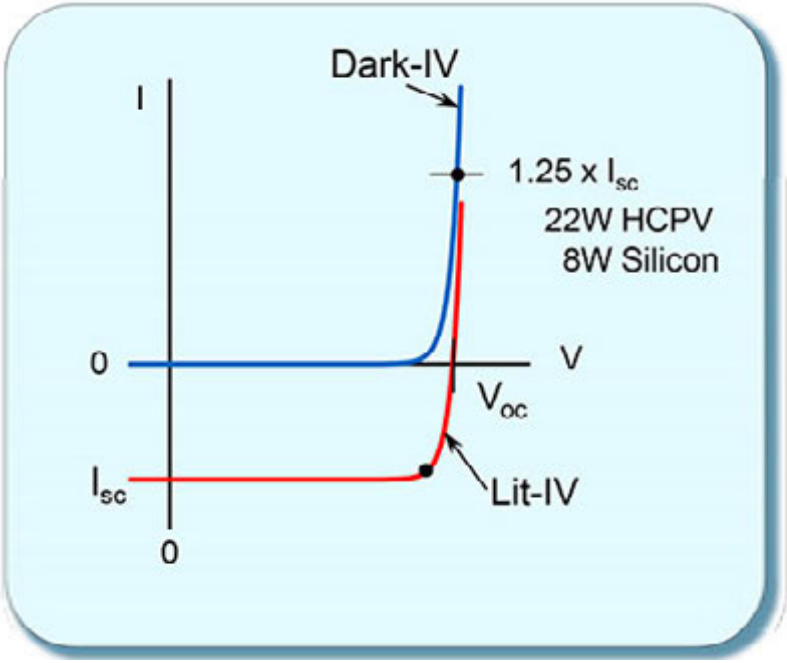
© SolFocus, Inc. 2009; Patents Pending

SolFocus

Dark IV and Light IV Comparison

Driven 1.25 · I_{sc} pushes the cell to a different operating point beyond the intended design range

Flat silicon conditions do not translate directly to III-V HCPV cells

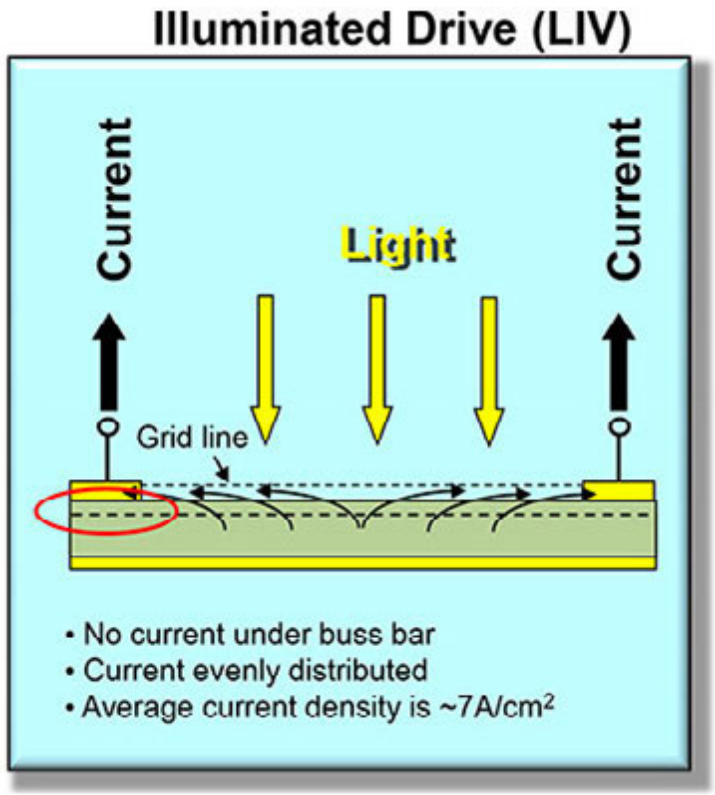


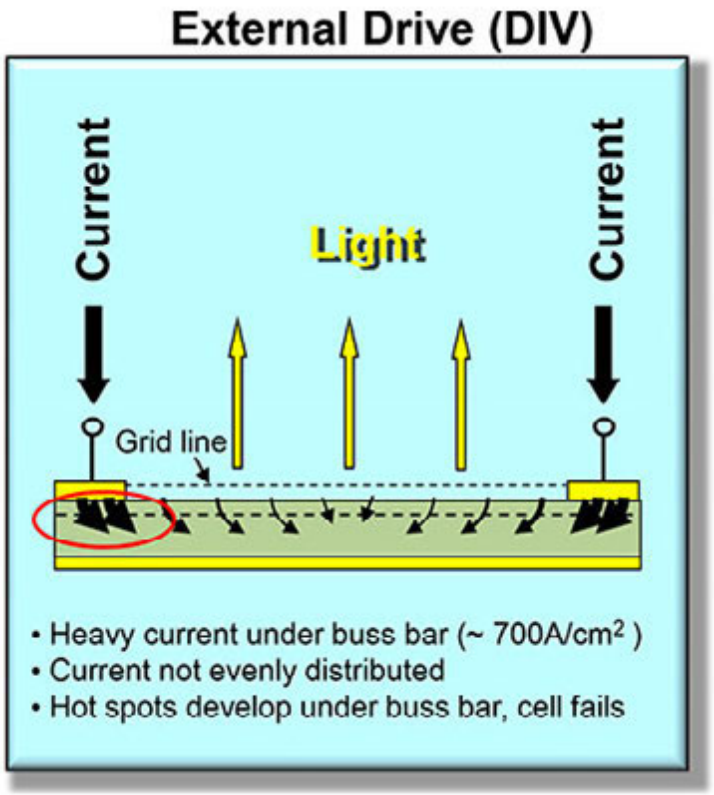
Silicon @ 1-sun	III-V HCPV Cell
V_{oc} = ~1V	V_{oc} = ~3V
I_{sc} = 6A (150cm² cell)	I_{sc} = 6A (1cm² cell)
J_{sc} = 40mA/cm²	J_{sc} = 6A/cm²
P = 40mW/cm²	P = 17W/cm²
P = 6W	P = 17W
1.25·J_{sc} = 50mA/cm²	1.25·J_{sc} = 7.6A/cm²
Monolithic	Epitaxial Construction

© SolFocus, Inc. 2009; Patents Pending

SolFocus

DIV vs LIV Stress





- Any small defects under the buss bar concentrate forward current
- Thermal run-away results

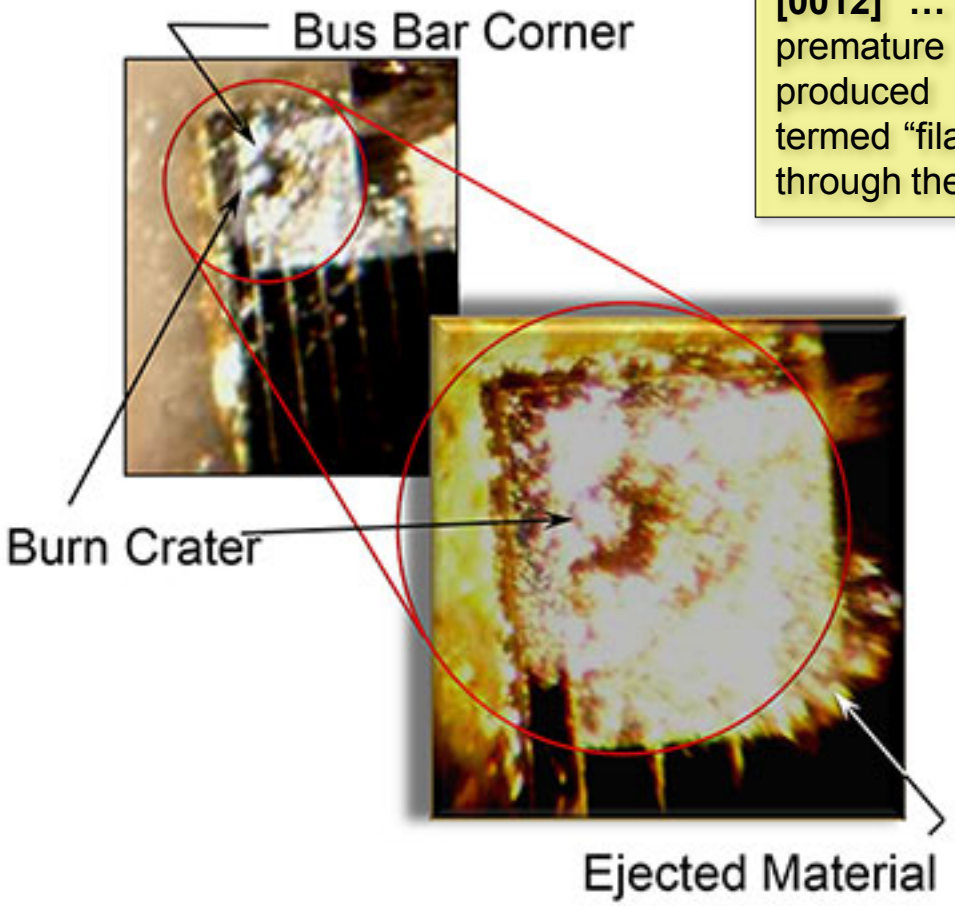
© SolFocus, Inc. 2009; Patents Pending

SolFocus

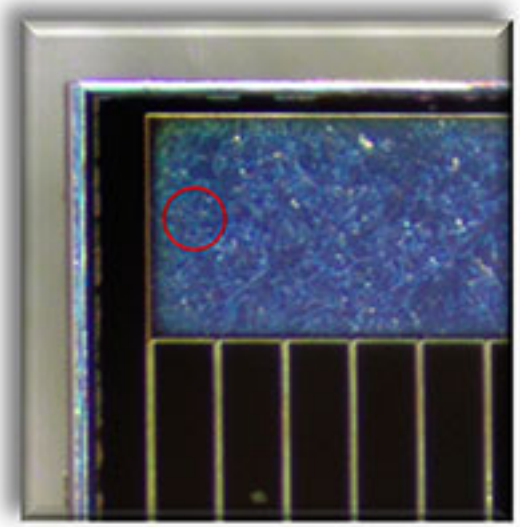
Cell Failures from Over-current Stress

US 2004/0261838 A1

[0012] … the cause of the current limitation and premature failure of … cells … is the result of the heat produced by tiny local current shunts (sometimes termed “filaments”) that short the metallic busbar layer through the underlying semiconductor material …



Burned Out Cell



New Cell

© SolFocus, Inc. 2009; Patents Pending

SolFocus

Vague Sections



- **Section 9: Modifications**
  - "Any changes in design, materials, components, or processing of the modules and assemblies may require a repetition of some or all of the qualification tests to maintain type approval. Manufacturers shall report to and discuss with the certifying body and testing agency every change they made."
  - Is the testing agency the best authority to make these decisions?
  - For example, sourcing cells from an alternate supplier:
    - Is there a way to handle identical form, fit and function cells from alternate manufacturers without triggering a re-test?
    - If the cell V_{oc} increases? Internal epi composition change? IMM Cells?
  - Is it more sensible for the IEC standard to be expanded to include major categories of changes that trigger re-testing, and specify the test section affected.

© SolFocus, Inc. 2009; Patents Pending

SolFocus

Other Issues Worth Addressing



- Cycle time for the full IEC 62801 tests suite is 6 to 9 months
  - Similar flat plate exposure is only about 3 months
  - Long term outdoor & UV exposure pace the tests; 1000kWhrs DNI required
  - Result: ~1yr. to certify against IEC 62108
  - CPV market and technology moves rapidly
  - Difficult for CPV to overcome cycle time handicaps
  - Valuable time to market can be lost owing to small changes
- Hundreds of thousands of dollars may be spent in the process
- Develop field data correlation to accelerated tests of IEC 62108
  - Standards may not identify all degradation modes
  - If CPV cells operate in hot, dry climates, 85°C/85% RH may be overkill
  - UV degradation of index-matching silicones not yet correlated with on-sun exposure
  - Humidity Freeze test does not necessarily mimic stresses found at any location on earth

© SolFocus, Inc. 2009; Patents Pending

SolFocus

Other Possible Revisions



- Thermal Cycling:
  - Probably cycles too slowly
  - 18 cycles/day => ~5C/min.
  - OK for 1-sun system, but slow for high intensity systems with rapid $\Delta T/\Delta t$
  - May result in under-testing of the receiver assembly

- Carry over test from flat panel
  - Tests carried over from flat panel should be consistent with flat-panel standards
  - E.g., flat panel humidity freeze is 10 cycles; 62108 requires 20 cycles

© SolFocus, Inc. 2009; Patents Pending

SolFocus

Beyond 62108



- Cell level testing
  - Reliability tests
  - Standards for cell interchangeability
- Enhanced outdoor exposure testing
  - Add a larger population requirement
  - Concentrated sunlight cannot be replicated in a chamber
  - Many degradation mechanisms unique to concentrated sunlight
  - Lends more confidence to customers, investors
- Pooled experience
  - CPV companies have collectively learned much about accelerated testing
  - Try to quantify tests in terms of years of field life
    - Differences in concentrator designs
    - Approximate accelerations for different component or material types would help
  - Quixotic hope of pooling knowledge base to enhance standards
- Vibration or mechanical shock testing
  - Shipping and installation damage
  - Well known correlations for adhesives to static system lifetimes

© SolFocus, Inc. 2009; Patents Pending

SolFocus

Questions



- What is the best method for simulating on-sun stresses during thermal cycle?
- How should new solar cells be introduced into the product under IEC 62108?
  - When is a re-test triggered, and when is it not?
  - Will solar cell qualification and reliability standards help?
- How to set uniform change thresholds for re-testing :
  - By sub-system, i.e. optics, cell, structural, electrical?
  - When substituted parts are “identical” without cross reference standards?

I would like to acknowledge the SolFocus staff, especially Mark Spencer, Steve Horne, and Nancy Hartsoch, and many others in the industry including Bob McConnell, Pete Hebert, Ian Aeby, James Foresi, Paul Lamarche, and Sarah Kurtz who shared their thoughts and comments on IEC 62108.

© SolFocus, Inc. 2009; Patents Pending

SolFocus

Breakout session:
Moisture sensitivity of thin films

Discussion leaders: Ryan Gaston & Mike Kempe

8:00 – Kent Whitfield (Miasole) – Common Failure Modes for Thin-Film Modules and Considerations Toward Hardening CIGS Cells to Moisture

8:30 – D.J. Coyle, H.A. Blaydes, J.E. Pickett, T.R. Tolliver, and R.A. Zhao (GE Global Research) – Packaging Requirements for ITO-Hardened CIGS

9:00 – Discussion: After Hardening, What Protection Do We Need?

9:30 – Break

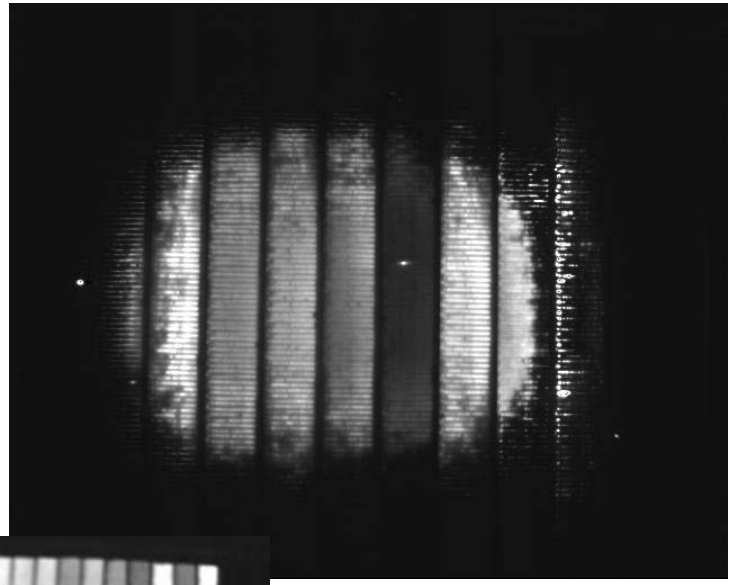
10:00 – Arrelaine Dameron (NREL) – Methods for Measuring Moisture Ingress and Requirements for Protecting Moisture Sensitive Cells

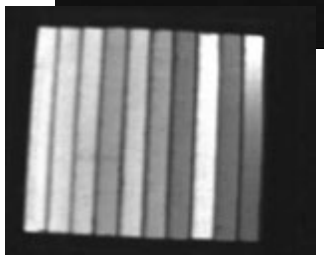
10:30 – Samuel Graham (Georgia Tech) – Approaches to Barrier Coatings for the Prevention of Water Vapor Ingress

11:00 – Discussion: Which aspects of the problem are solved? Where is more work needed?

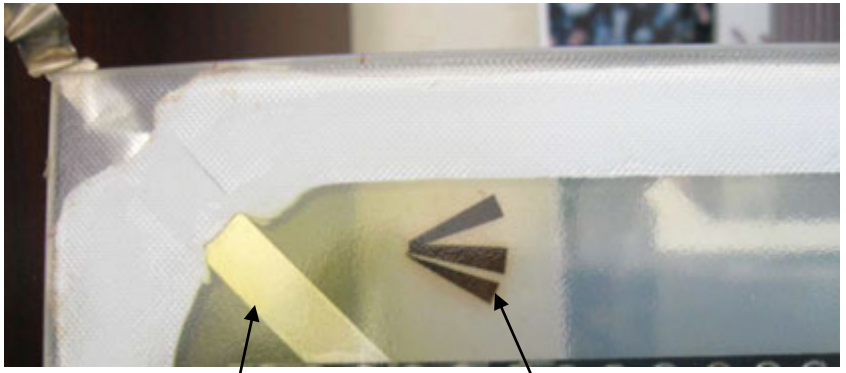
What to look for

- Moisture ingress almost always leaves very perceptible signs



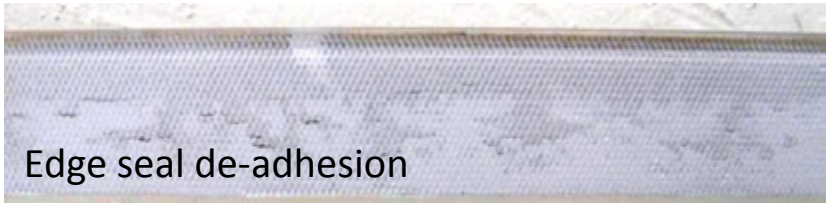


EL Image



Metallic corrosion
(in this case yellowing)

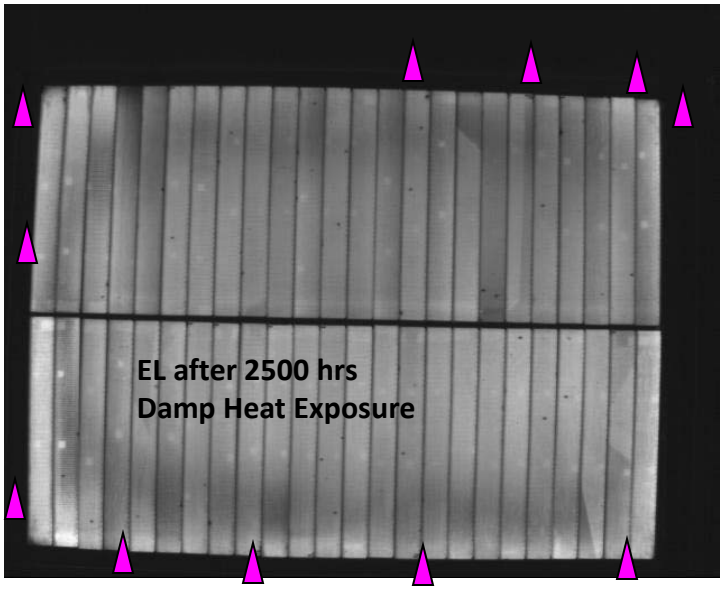
Color change
indicator



Edge seal de-adhesion

Whitfield summary

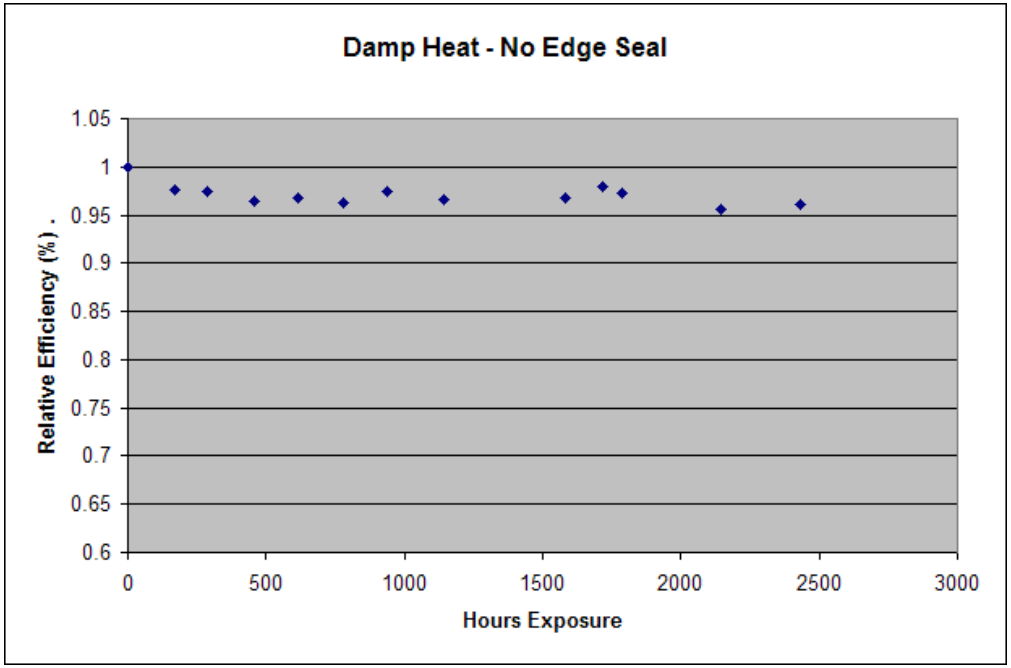
Can CIGS be Moisture Hardened?



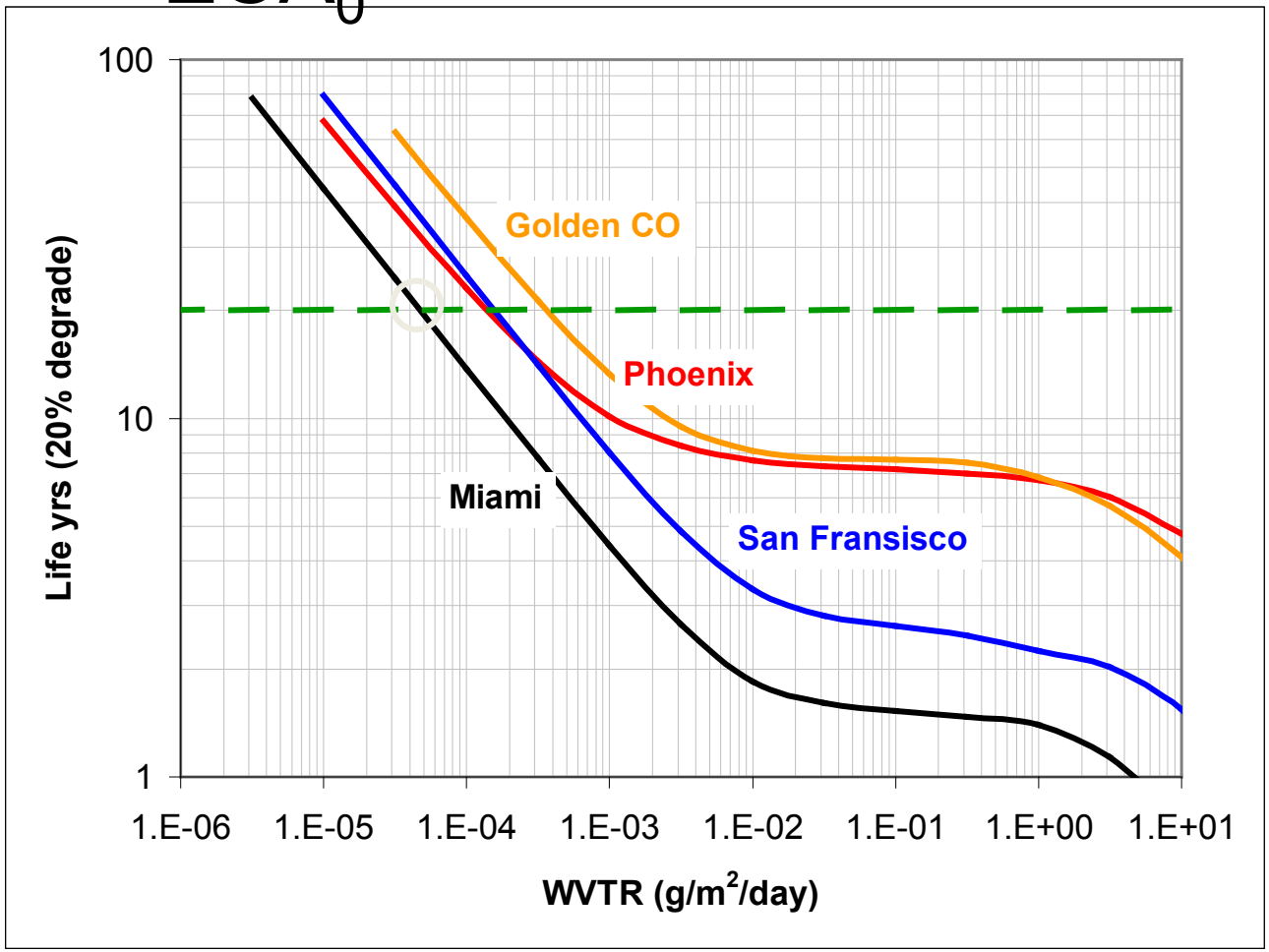
- Yes, but there are tradeoffs.
- I know that's unfulfilling, but that is the limit to what I can say…



No edge-seal



Life vs. Barrier: ITO-ECA$_0$



Need ~ 4×10^{-5} g/m^2/day package ~ 20 yr life

Conclusions, Plans & Acknowledgements

Conclusions

- AZO vs ITO CIGS degradation kinetics quantified – 25X
- Life model and accelerated test scaling developed
- Diffusion-controlled: Life ~$(t_c/R_D)^{1/2}$ or ~(diffusion-time*degrade-time)$^{1/2}$
- Significant moisture barriers required for 20 yr life – even for ITO
- Acceleration factor for damp heat smaller than assumed, highly nonlinear!
- Methodology can predict life for any moisture-sensitive module (once kinetic constants are measured)

Future Plans

1. Critical experiments to test model predictions
2. Experimental validation – Miami, FL & Arizona

Acknowledgements

Mike Kempe NREL

Steve Hegedus IEC

This work was supported by:

U.S. Department of Energy

Award DE-FC36-07GO17045

GE Global Research

GE Energy

Discussion summary – How far can the cells be hardened?

- Yes – cells can be hardened, but not a single solution, depends on packaging and location
- Window layers have a large impact on hardening of CIGS devices (ITO vs AZO)
- Some discussion on an industry acceptable level of degradation and percentage of samples allowed to fail – no consensus

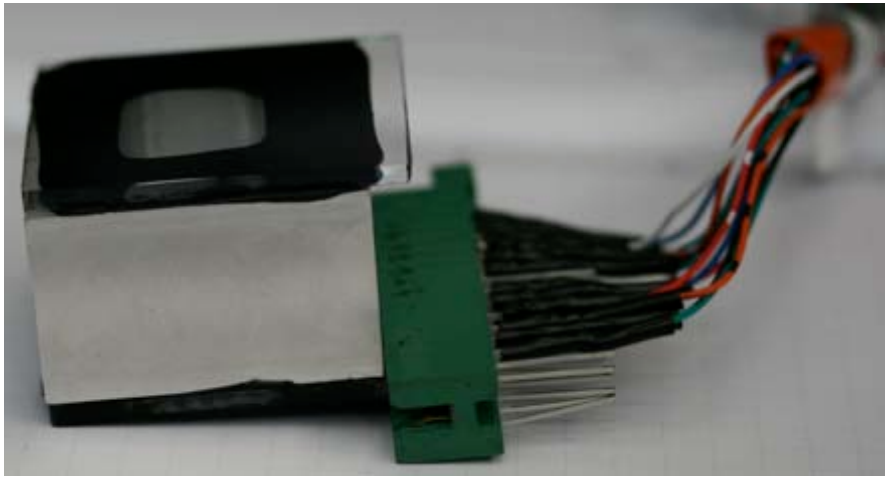
NREL's Ca Test

- Electrical Ca Test (0.1 mΩ resolution)

- Easily configurable test card & edge connector assembly
  - fast setup
  - no need to deposit Ca onto the barriers

- 16 tests simultaneously = high throughput

- Variety of environmental conditions possible

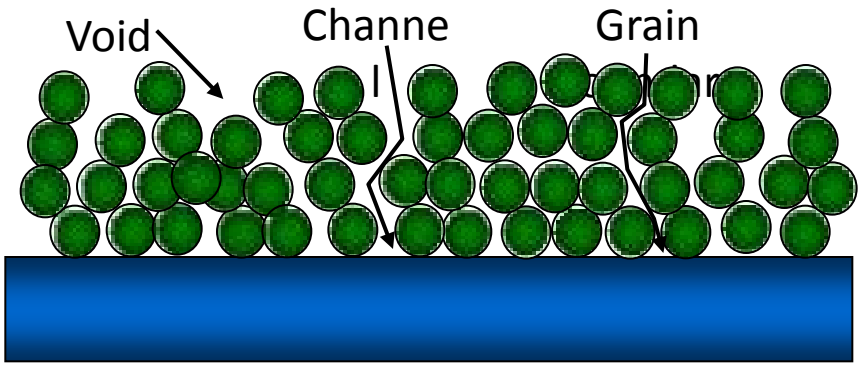


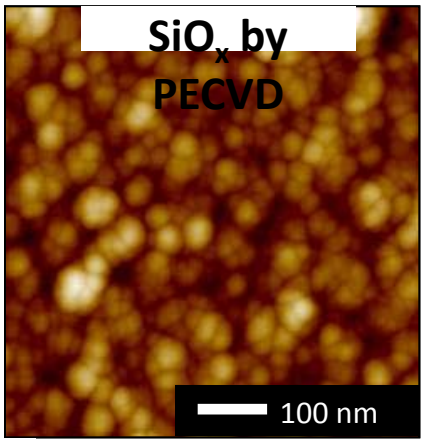
Conclusions

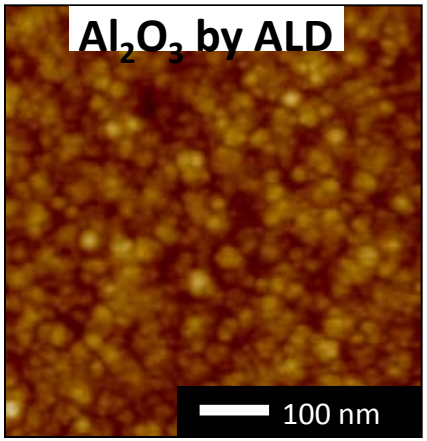
- There are several techniques to quantifiably measure moisture permeation through thin films

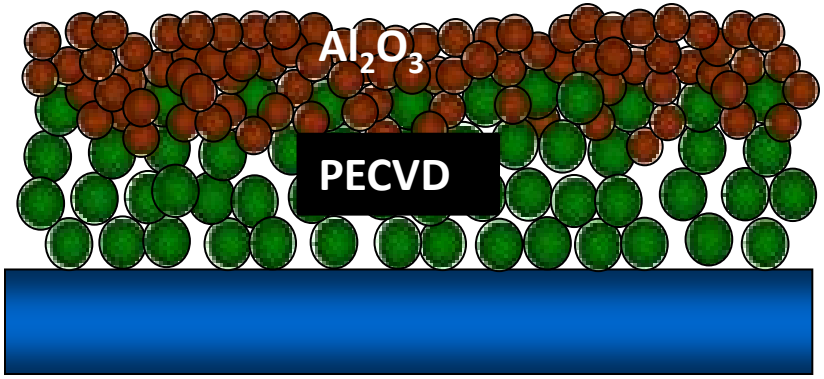
- At NREL we are working to improve existing barrier evaluation methods and developing routes to evaluate and compare edge seal materials in their applied environment

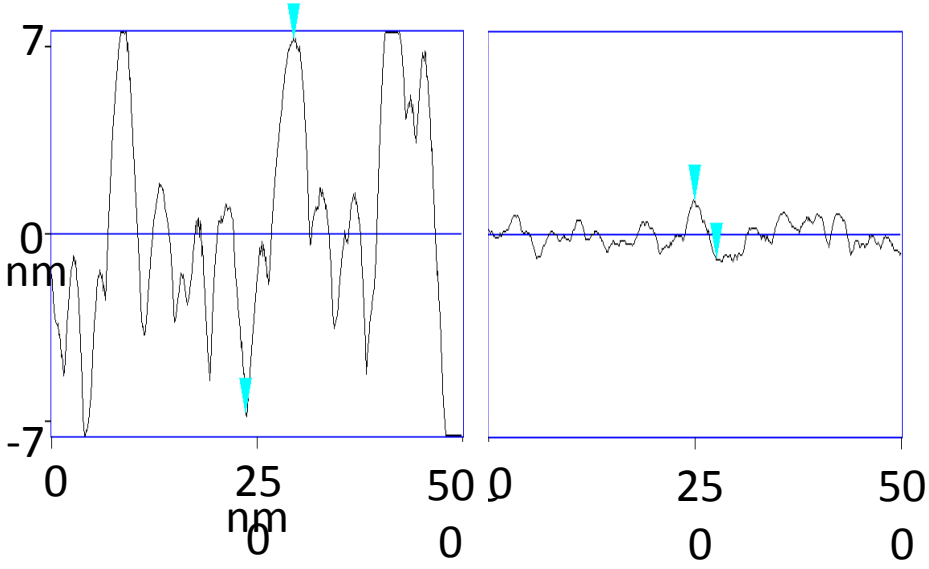
Combine rapid low temperature deposition by PECVD with high quality atomic layer deposition to simplify barrier architecture.











SiOx by PECVD Al2O3 by ALD

■ Multilayer Encapsulation

- Defect structure and solubility of polymer layer control laminate performance

- Reporting WVTR and lag time may be necessary for understanding barrier performance.

■ Hybrid Encapsulation

- Simplified Architecture provides ultralow barrier performance

- Promising opportunities exist for further reductions in processing time.

■ Device Integration

- Successful direct encapsulation of OPVs by hybrid thin films

■ Future Efforts

- Development of Edge Seals important for the packaging toolbox.

- Accelerated testing under harsh environments including light soaking!

Discussion summary – Moisture ingress – problem solved?

- Many potential solutions were discussed from multilayer vs single layer. ALD is a promising technology for eliminating pins holes and defects
- Commercial ALD technology exists and is being scaled up to roll to roll
- New testing methodologies allow for faster estimation of very low WVTRs and higher throughput
- Lag Times effects can be considerable and needs to be understood before a steady state WVTR can be calculated
- ~50% of the room believes that a commercially viable flexible CIGS based product with 20+ year lifetimes will be a reality within 5 years

MiaSolé
Thin-film solar

Common Failure Modes for Thin-Film Modules and Considerations Toward Hardening CIGS Cells to Moisture

A "Suggested" Topic

Kent Whitfield, Dir. Reliability

MiaSolé
Thin-film solar

Outline

- **Warnings, disclaimers and objective assessment**
- **Scope**
  - **Field experience (limited hard data, but anecdotal information abounds)**
    - Mechanical
    - Thermal
    - Electrical
  - **Qualification testing – building a transfer function**
  - **Where do the majority of thin-film modules encounter trouble in the qualification testing sequences?**
    - Mechanical
    - Thermal
    - Stress testing
  - **Damp Heat –**
    - Does it mean anything?
    - Dark vs. damp – is it distinguishable?
    - Is moisture hardening achievable?

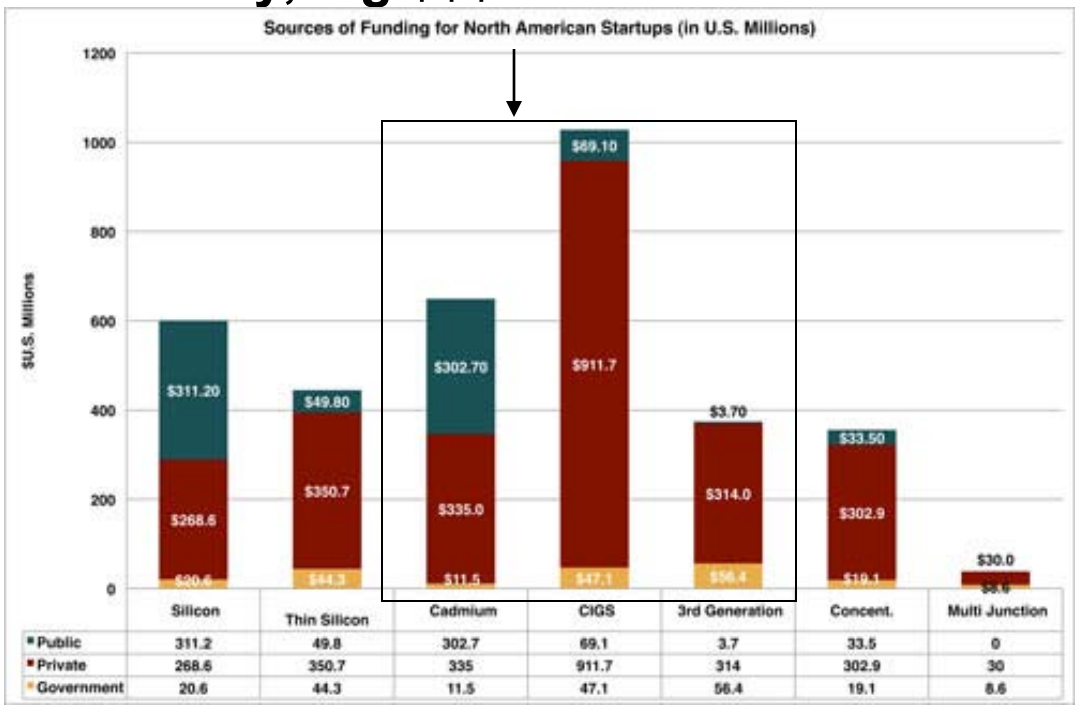
Warning!!

QUESTION	**RISK**/EVIDENCE
• **Do I have a bias?**	• **High**/Obvious
• **How objective can I really be?**	• **Medium**/Have participated in all sides on this issue.
• **How current is my information?**	• **Fairly Low Risk**/Attempt to stay on top of voluminous data on the subject.
• **Am I aiming at a particular manufacturer?**	• **Low.** No manufacturer has zero failure modes. The outcome is dictated 100% by their response to a finding.
• **Am I interested in casting a dark shadow on the thin-film industry?**	• NO!!! There are highly reliable thin-film products in the market today.

Field Experience – Thin-Film PV

- **Not a sterling history.**
- **Some high-profile issues (not dissimilar from crystalline Si's terrestrial start).**
- **Many manufacturers have come and gone.**

- **Through 2008 and even true today, big $$$ investment**



Changes since 2008?

Triumvirate of despair:

1. Financial conservatism
2. Softened demand
3. Oversupply of x-stal Si

Source GreenTech Media

MiaSolé
Thin-film solar

2002

		Thin-Film (Glass Substrate)	Crystalline Technologies	Approx. Sys. Cost Impact to Thin-Film
1	Module Power (to Edge)	4 to 7.5 W/Ft^2	10 to 15 W/Ft^2	$0.30/W - $1.25/W
2	Mechanical Strength	Annealed/ Heat Strengthened	Tempered (5 to 10X stronger)	$0.06/W - $0.30/W
3	Lamination QA/QC	Poor	Good	Included in #2
4	Module O.C. Voltage	45V to 100V typ.	20V to 50V typ.	$0.03/W - $0.33/W
5	Typical 'String' Power	200W to 750W	1500W to 3000W	Included in #4
6	Stability	Poor	Good (Not Great)	$0.30/W - $0.60/W
7	Voltage Isolation	Intermittent	Excellent	Included in #6
8	Module Design Flex.	Poor	Excellent	Not quantified
9	Blocking Diode Req'd	Yes	No	$0.02/W - $0.05/W
10	Opaque to UV?	No	Yes	$0.00/W - $0.10/W
11	End of Life Recycle?	Some	No	$0.00/W - $0.20/W
	Avg cost impact:	$1.77/W	TOTAL:	$0.71/W - $2.83/W

http://www.nrel.gov/pv/thin_film/docs/powerlight.pdf

The Past:
One somewhat controversial presentation made at NREL by a large system integrator indicated that thin-film had a LONG way to go to improve reliability.

Some have proven lessons learned from this experience.

F.E. Mechanical

- **Mainly packaging-related**
- **Inadequate glass strength, impact toughness.**
  - **Installation breakage**
    - Do not underestimate poor practices by installers.
  - **Cleaning damage and sometimes breakage**
    - Power washers
    - Mechanical brush damage (dragging grit along superstrate)
  - **Environmentally-related breakage**
    - Wind blown debris (tempered glass)
    - Hail
    - Module-to-array differential expansion



PI Photovoltaik-Institut Berlin AG

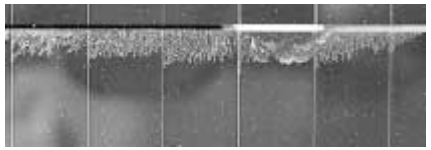
Now that's Texas hail! →



F.E. Thermal and Electrical

- **Main concerns – performance degradation**
  - **Leakage current rates (performance degradation and potential safety concern)**
    - High voltage stress → electro-chemical corrosion of contacts
      - **Both thick and thin-film PV have it, but thin tends to be more pronounced (10x).**
      - **Can lead to other issues.**

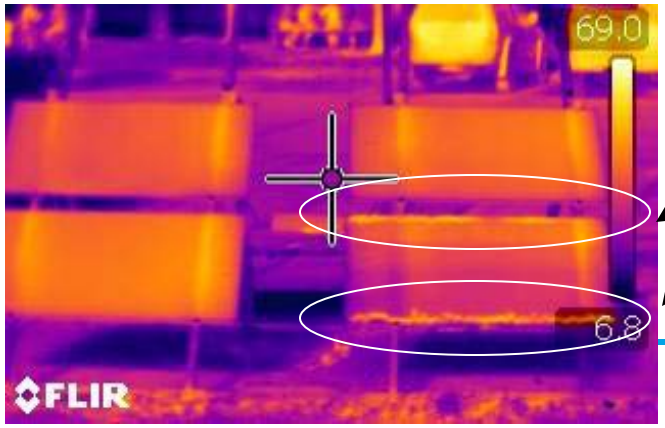
ye ol' bar-graph delamination failure



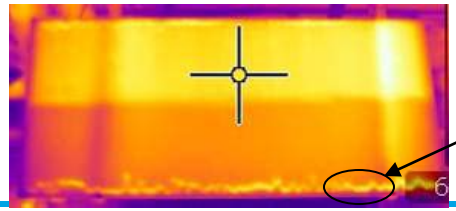
McMahon, 2004

- Leakage Currents:
  - Measured and characterized
  - Appear thermally activated
  - May point to potential corrosion problems in hot environments, where average daytime air temperatures are at, or exceed 25-30 °C for 200 days or more per year, after 10 years.

J.A. del Cueto, B.R. Sekulic NREL, 2006



But don't forget shade induced hot spot!!!

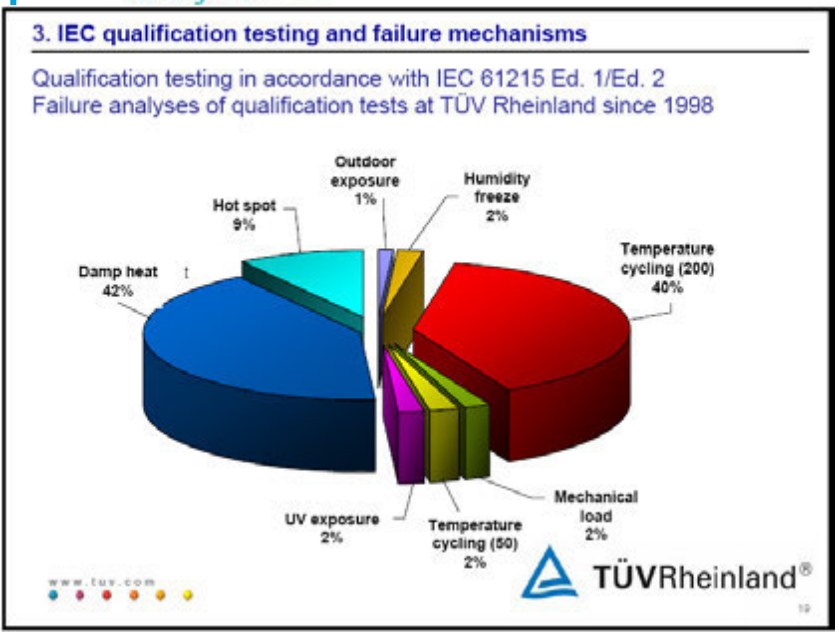


Trise~60°C

Qualification Testing

- **UL 1703, IEC 61646, IEC 61730**
  - **Don't be fooled…these are really standards built around crystalline PV failure modes with a dash of thin-film specific conditioning tests thrown in.**
  - **Nevertheless are remarkably good stress tests for identifying weaknesses with thin-film PV.**
    - *Should be thought of as hitting the product with different impact hammers and listening to the resonant response.*
    - Cannot alone provide useful failure probability information, but can clearly identify weaknesses requiring further investigation.
    - Are not Accelerated Lifetime Tests – but – thermal cycling and damp heat are particularly useful tests in a test-to-failure program for thin-film PV.

Where Do The Majority of Failures Occur?



Crystalline Si - Courtesy of Werner Herrmann

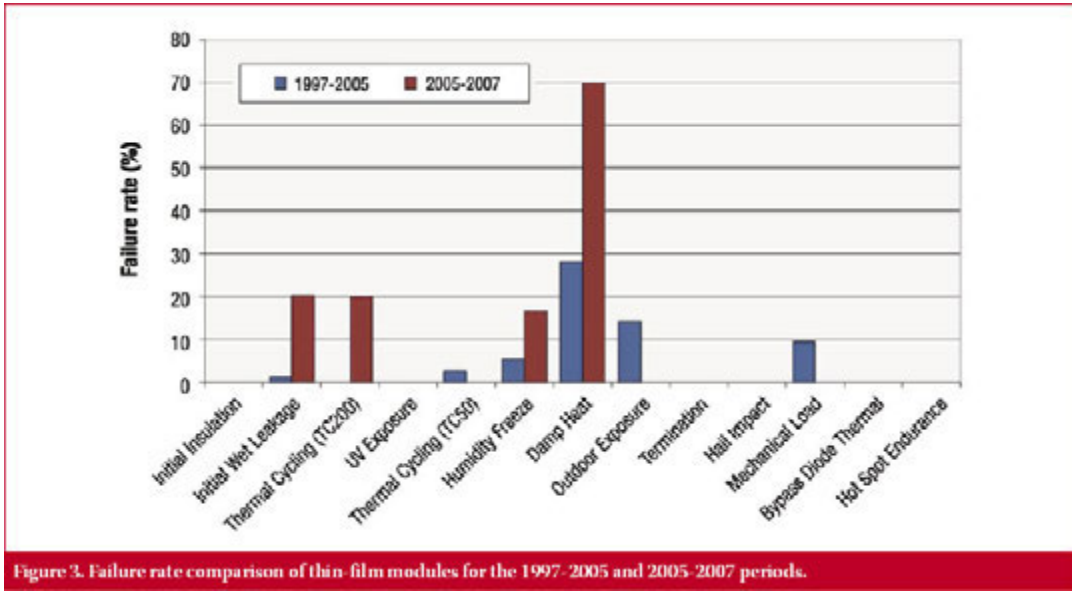


Figure 3. Failure rate comparison of thin-film modules for the 1997-2005 and 2005-2007 periods.

Failure analysis of design qualification testing: 2007 vs. 2005

G. TamizhMani, B. Li, T. Arends, J. Kuitche, B. Raghuraman, W. Shisler, K. Farnsworth, J. Gonzales, & A. Voropayev,
Arizona State University Photovoltaic Testing Laboratory (ASU-PTL), Mesa, Arizona, USA

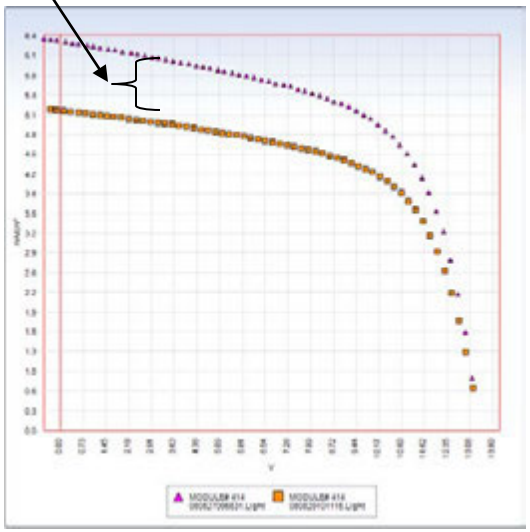
This article first appeared in *Photovoltaics International* journal's first edition in August 2008.

#1 for X-stal Si or thin-film – Damp Heat
#2 …Thermal cycling

Disturbing recent trends for thin-film:
Initially non-compliant wet leakage current values?

Non Pareto'ed – But Historical Issues

- **Mechanical**
  - **Hail Impact Test (IEC 61646 clause 10.17)**
  - **Static Load Test (IEC 61646 clause 10.16)**
    - Must use specified mounting system to be valid.
    - Optional 5400Pa positive load to cover extreme snow conditions for low (<20°) tilt angles.
  - **TC200 - Adhesive/cohesive stack damage (IEC 61646 clause 10.11)**
  - **TC200 w/current – interconnect/bus bar fatigue or run away series resistance change.**

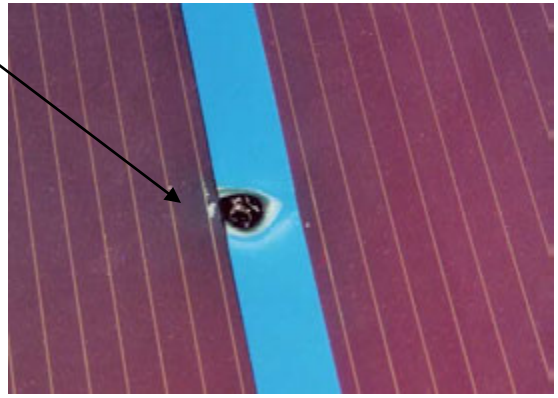


N.R. Sorenson, M.A. Quintana, et. al.
"Accelerated testing of metal foil tape joints and their effect of photovoltaic module reliability" Proc. SPIE, Vol. 7412, 74120R (2009); doi:10.1117/12.826876

Non Pareto'ed – But Historical Issues

- **Electrical**
  - **Outdoor Exposure (IEC 61646 clause 10.8)– usually just a ratings adjustment issue.**
  - **Reverse Current Overload (IEC 61730-2, MST 26)**
    - Caution – many integrators love to parallel modules. Not all know to de-rate the fuse accordingly!
  - **Hot Spot Endurance (IEC 61646 clause 10.9)**
    - Caution – Should use IR and should consider effects of multiple modules.





PI Photovoltaik-Institut Berlin AG, 2008



Reverse Current Failure

So about 1000 HR Damp Heat…

- **Does it mean anything?**
  - **Does not mean**
    - 20 years life regardless of location
    - A predictor of long-term electrical performance
    - Edge seal is hermetic
    - Chemical compatibility for module material set
    - No electrochemical corrosion issues will form (if conducting voltage biased testing)
  - **Does mean**
    - A significant milestone and check mark towards a certifiable product.
    - Tends to be a particularly grueling single-stress test for some thin-film modules.
      - **Will point to problem areas in construction, process or material choices**
  - **Can mean much more if part of a MULTI-STRESS TTF program and combined with many other diagnostics.**
    - Electroluminescence
    - Polymer characterization tools (DSC, TMA, Mocon, etc., etc.)

What to Look for

- **Moisture ingress has a classic electrical degradation pattern:**

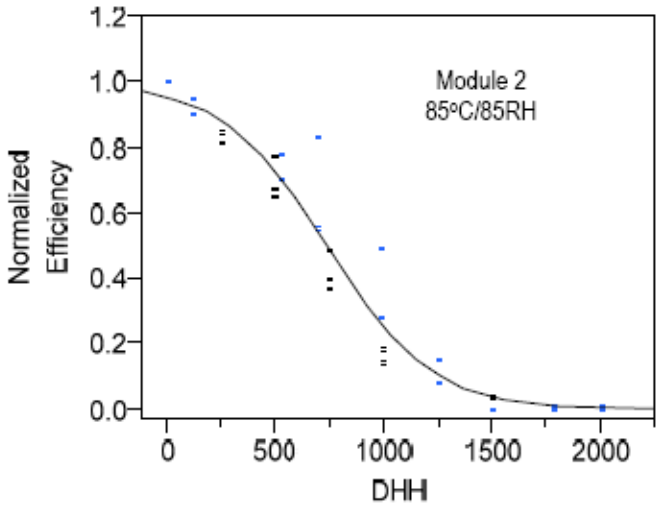
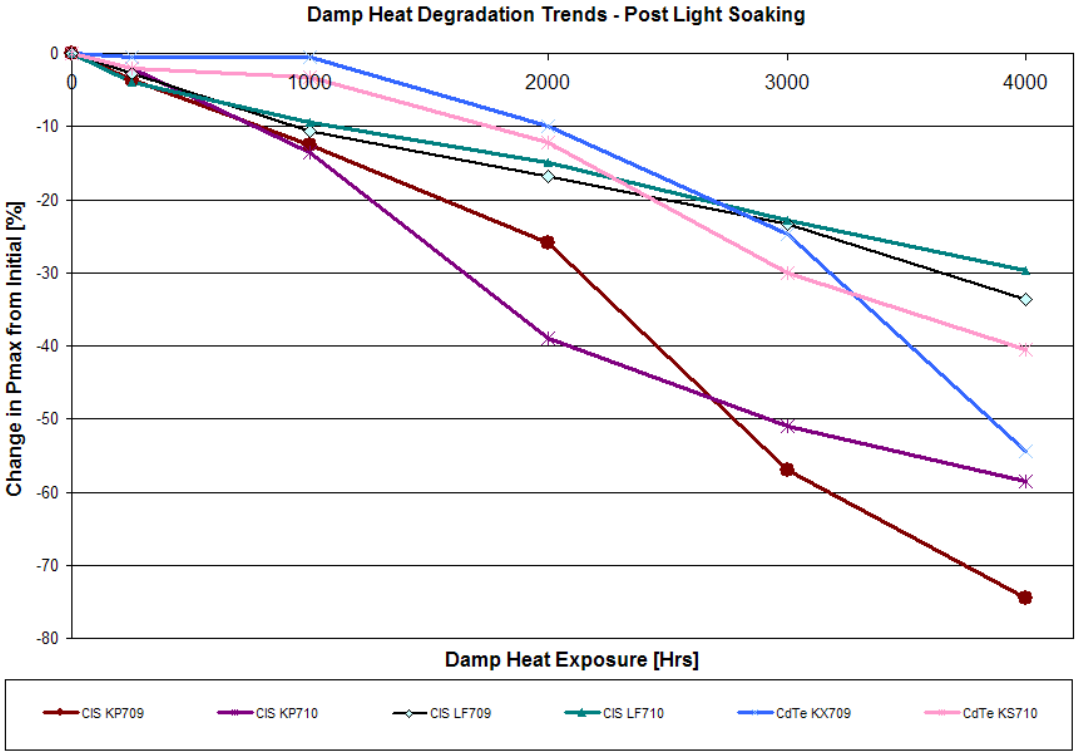


Fig. 9. Performance evolution in Module 2 at fixed EC 85°C, 85%RH.

V.A. Kuznetsova, R.S. Gaston, et. al. 2009

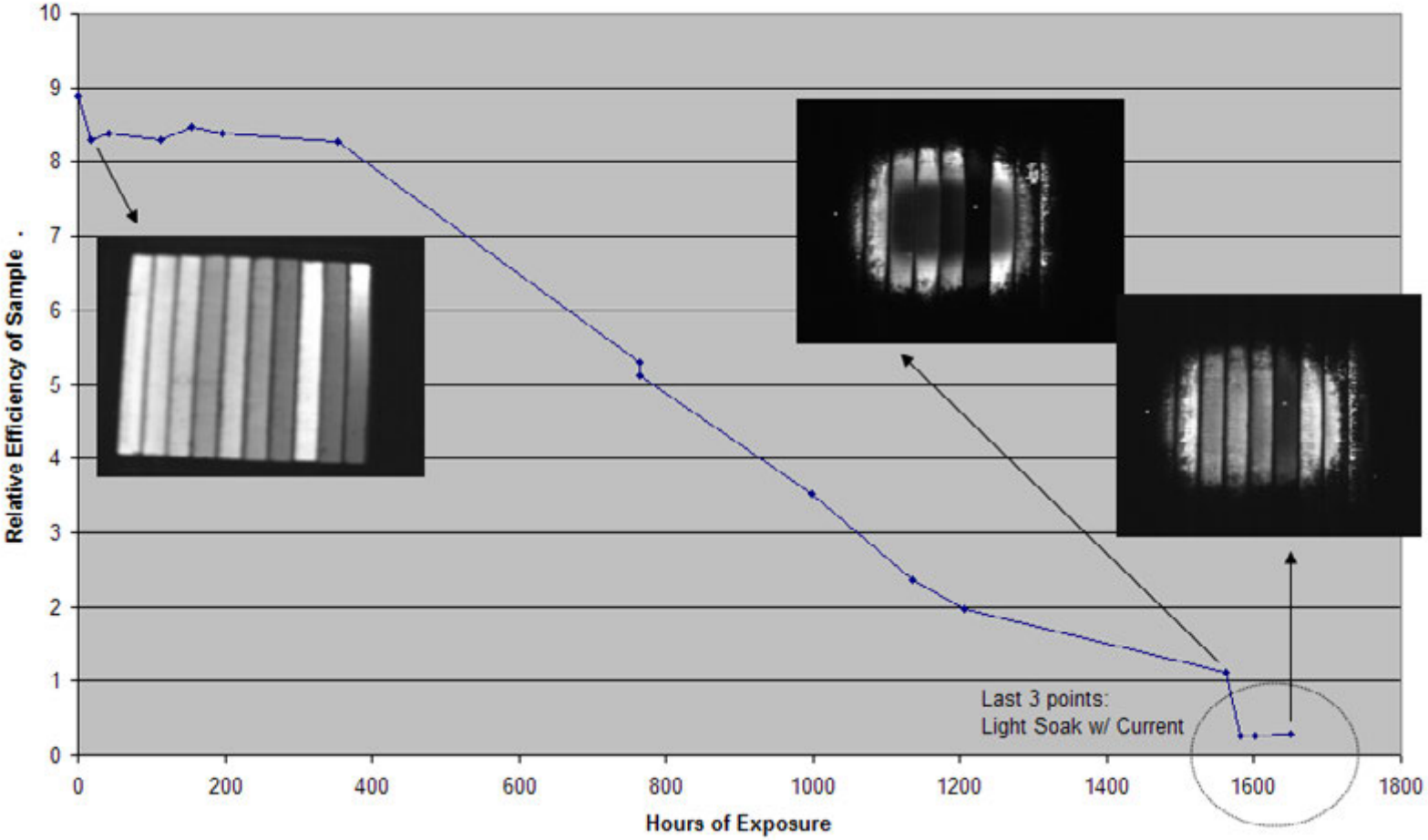


T. Sample, A. Skoczek, et. al. 2009

Bound the Problem

Damp Heat - Boundary Condition for Moisture Ingress
11-cell sample with 1000:1 WVTR encapsulant and no edge seal

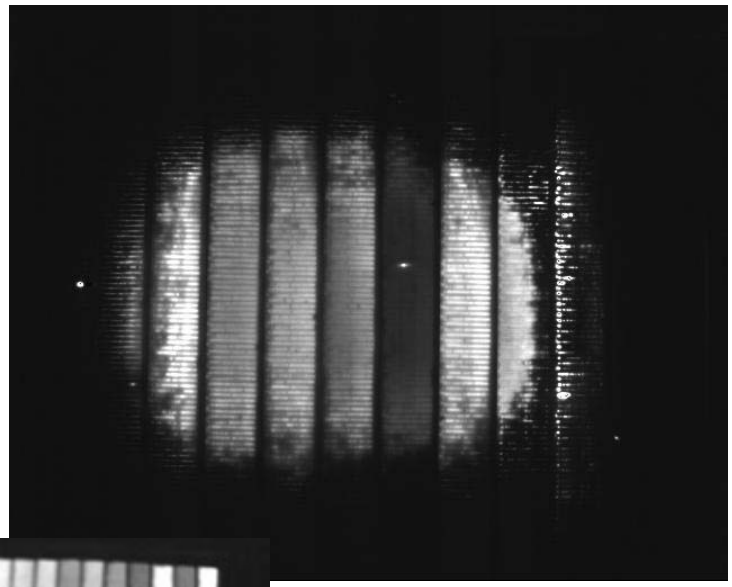
Ingress BC

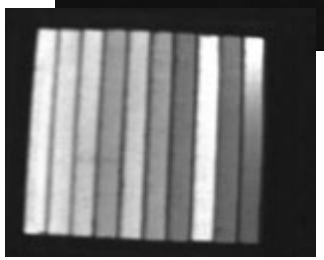


The other BC? "Dry", dark heat.

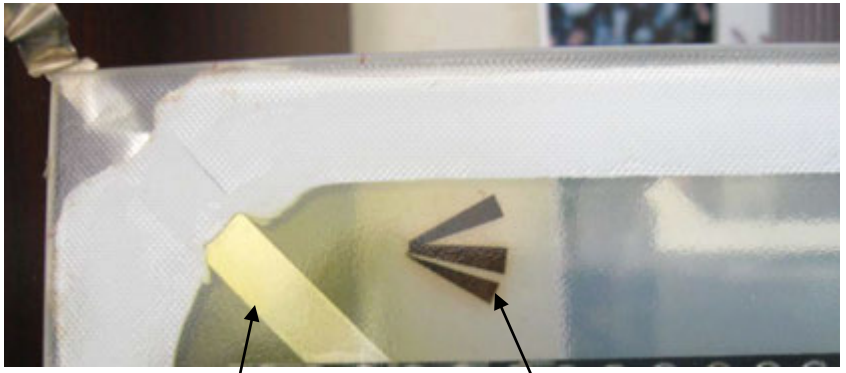
What to look for

- **Moisture ingress almost always leaves very perceptible signs**



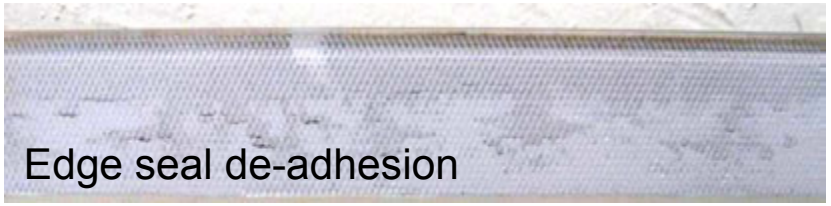


EL Image



Metallic corrosion
(in this case yellowing)

Color change
indicator



Edge seal de-adhesion

Dark Heat

- **Exponential behavior that "reaches" an asymptote and may also be reversible to some extent with light soak under load.**

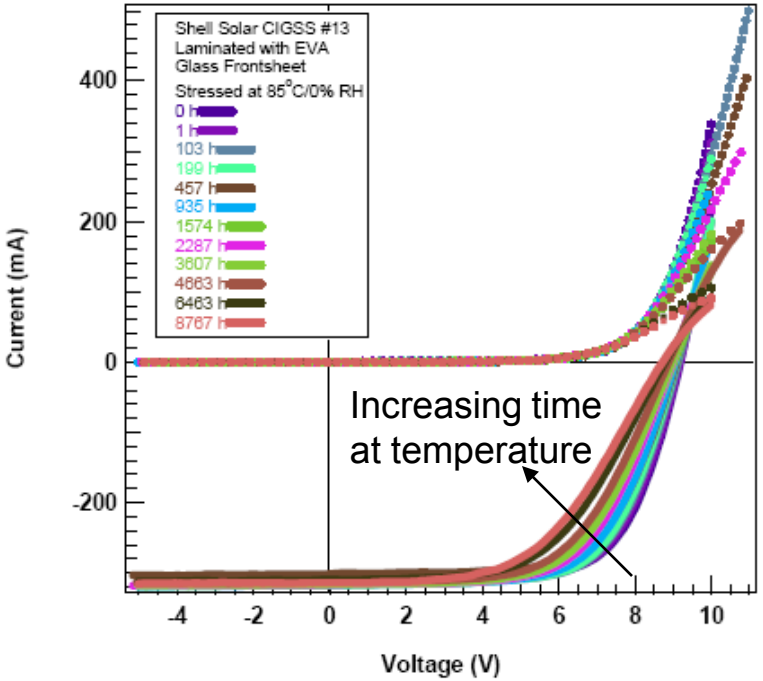


Fig. 5. Typical IV traces for a EVA/Glass encapsulated mini-module exposed to 85ºC and 0% RH.

M. Kempe, K Terwilliger, D Tarrant 2008

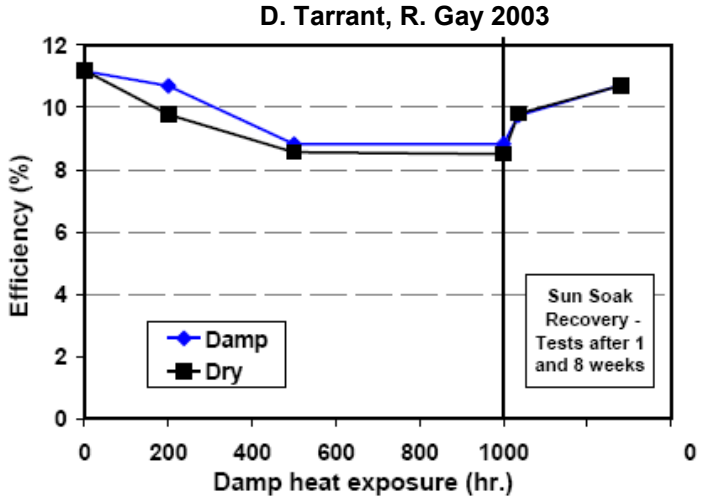
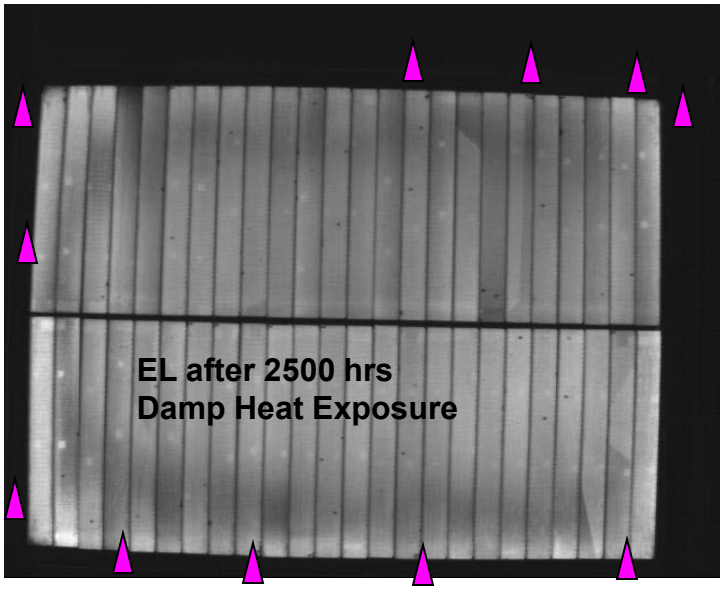


Figure 15. Recovery after the thermal exposure of damp heat accelerated tests with or without including high humidity in the tests.

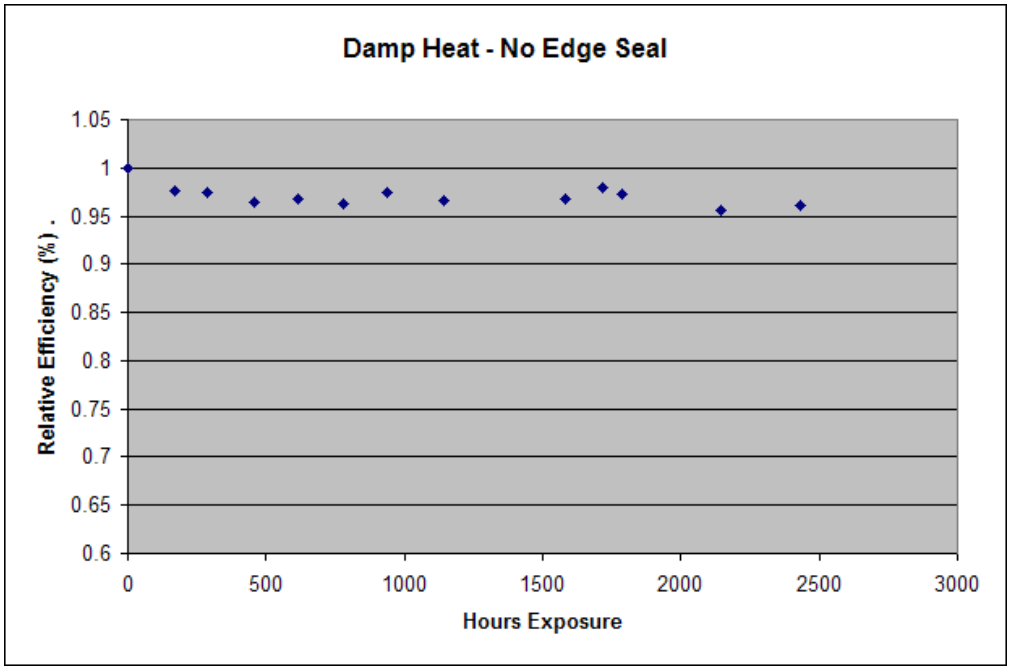
Leaves no signs of moisture ingress
EL shows "uniform" changes in cells

Can CIGS be Moisture Hardened?



- Yes, but there are tradeoffs.
- I know that's unfulfilling, but that is the limit to what I can say…





References

- J.A. del Cueto, B.R. Sekulic, "An Unlikely Combination of Experiments with a Novel High-Voltage CIGS Photovoltaic Array," 4thWorld Conference on Photovoltaic Energy Conversion, Waikoloa, Hawaii, 2006
- G. TamizhMani, B. Li, T. Arends, J. Kuitche, et. al.,"Failure Analysis of Design Qualification Testing: 2007 vs. 2005," Photovoltaics International, 1st Ed., 2008
- C.R. Osterwald, "Terrestrial Photovoltaic Module Accelerated Test-to-Failure Protocol," NREL/TP-520-42893, March 2008.
- T. J. McMahon, "Accelerated Testing and Failure of Thin-film PV Modules," PIP: Research and Applications, Prog. Photovolt: Res. Appl. 2004; 12:235–248
- N.R. Sorenson, M.A. Quintana, et. al., "Accelerated testing of metal foil tape joints and their effect of photovoltaic module reliability" Proc. SPIE, Vol. 7412, 74120R (2009); doi:10.1117/12.826876
- V.A. Kuznetsova, R.S. Gaston, et. al., "Photovoltaic Reliability Model Development And Validation," 34th IEEE PVSC, Philadelphia, PA, 2009.
- T. Sample, A. Skoczek, et. al., "Accelerated Ageing of Seven Different Thin-Film Module Types by Sequential Exposure to Damp Heat or Damp Heat with Either Additional Applied Voltage or Ultraviolet Light," 24 EU PVSEC, Hamburg, Germany 2009. Available via the Fraunhofer ISE website.
- M.D. Kempe and K.M. Terwilliger, D. Tarrant, "Stress Induced Degradation Modes in CIGS Mini-Modules," 33rd IEEE PVSC, San Diego, CA, 2008.
- D. Tarrant, R. Gay, "Process R&D for CIS-Based Thin-Film PV," NREL/SR-520-35684 Annual Technical Report 2003.

Packaging Requirements for ITO-Hardened CIGS

Dennis Coyle, Holly Blaydes, James Pickett, **Todd Tolliver**, Ri-An Zhao, and J.ames Gardner

GE Global Research
Niskayuna, NY, 12309

PV Module Reliability Workshop
Golden, CO
February 18-19, 2010



imagination at work

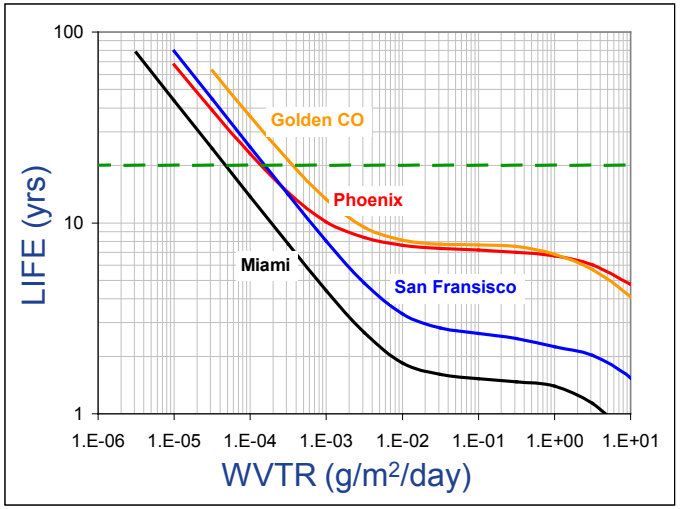
Flexible CIGS Module



Advantages

- Lightweight – no racking, no structural engineering, labor savings
- High efficiency – low-cost manufacturing (potential), high power density

→ ***ideal for commercial rooftop!***



Challenges

- Lifetime – moisture sensitive devices, UV degradation, interconnects
- Cost – low-scale production, expensive packaging materials

→ ***detailed understanding of degradation needed!***

Factors for Lifetime Prediction (CIGS Module)

This study focuses on moisture driven failure modes…

- Cell Construction/Materials
  - ITO vs AZO window layer
  - Type of ECA for interconnect

- Environment/Exposure
  - Accelerated testing (ovens with various temp, RH)
  - Real-world exposure (Miami, Phoenix, …)

- Package Materials
  - Barrier properties of topsheet and backsheet
  - Edge seals



Life Model – Moisture Sensitivity

1. CIGS Degradation Kinetics

- Degradation rate vs. Temp, humidity
- ITO vs AZO
- ECA - Interconnect degradation can play a role

2. Moisture Diffusion into Package

- Meteorological data – TMY3 from NSRDB
  - Hourly irradiance, air temp, ground temp, humidity, wind speed
- Heat transfer model of module
  - Radiation, free & forced convection
- Diffusion through barrier film, Saturation of encapsulant, no edge effects

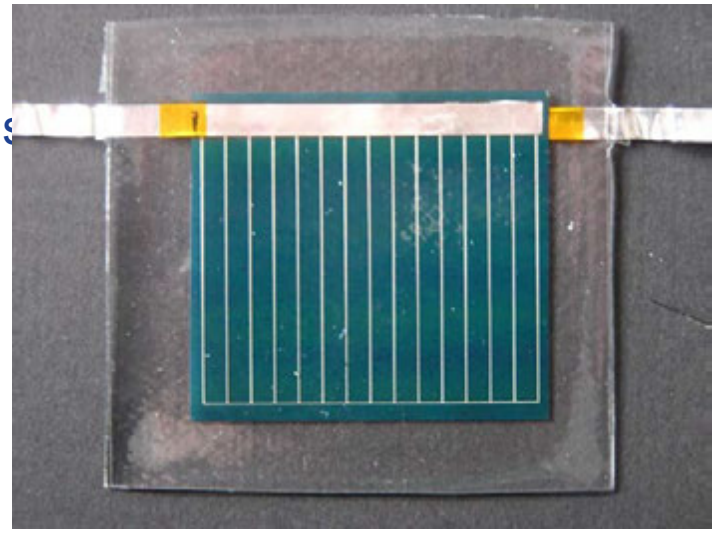
3. Coupled Model

- Cumulative degradation and average life vs. location and package design
- Tradeoffs between CIGS sensitivity and package design/cost
- Interpretation of accelerated tests results

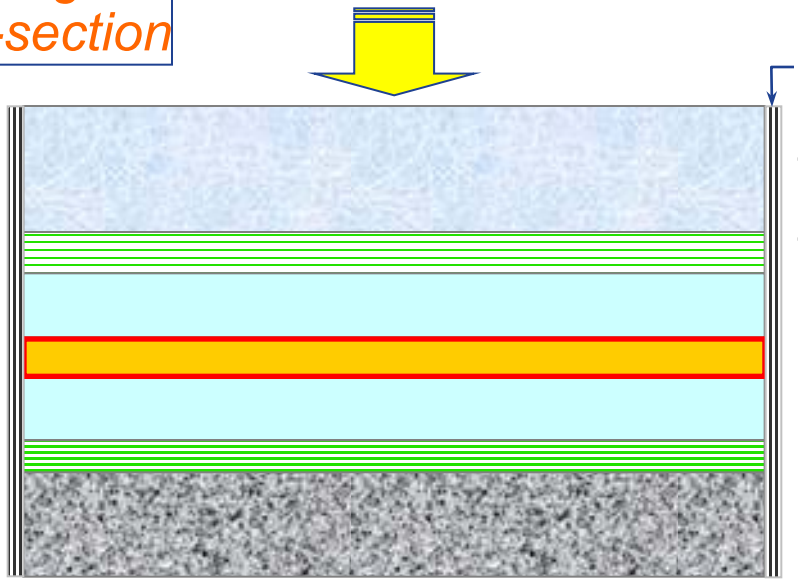


Test Structures/Package Configurations

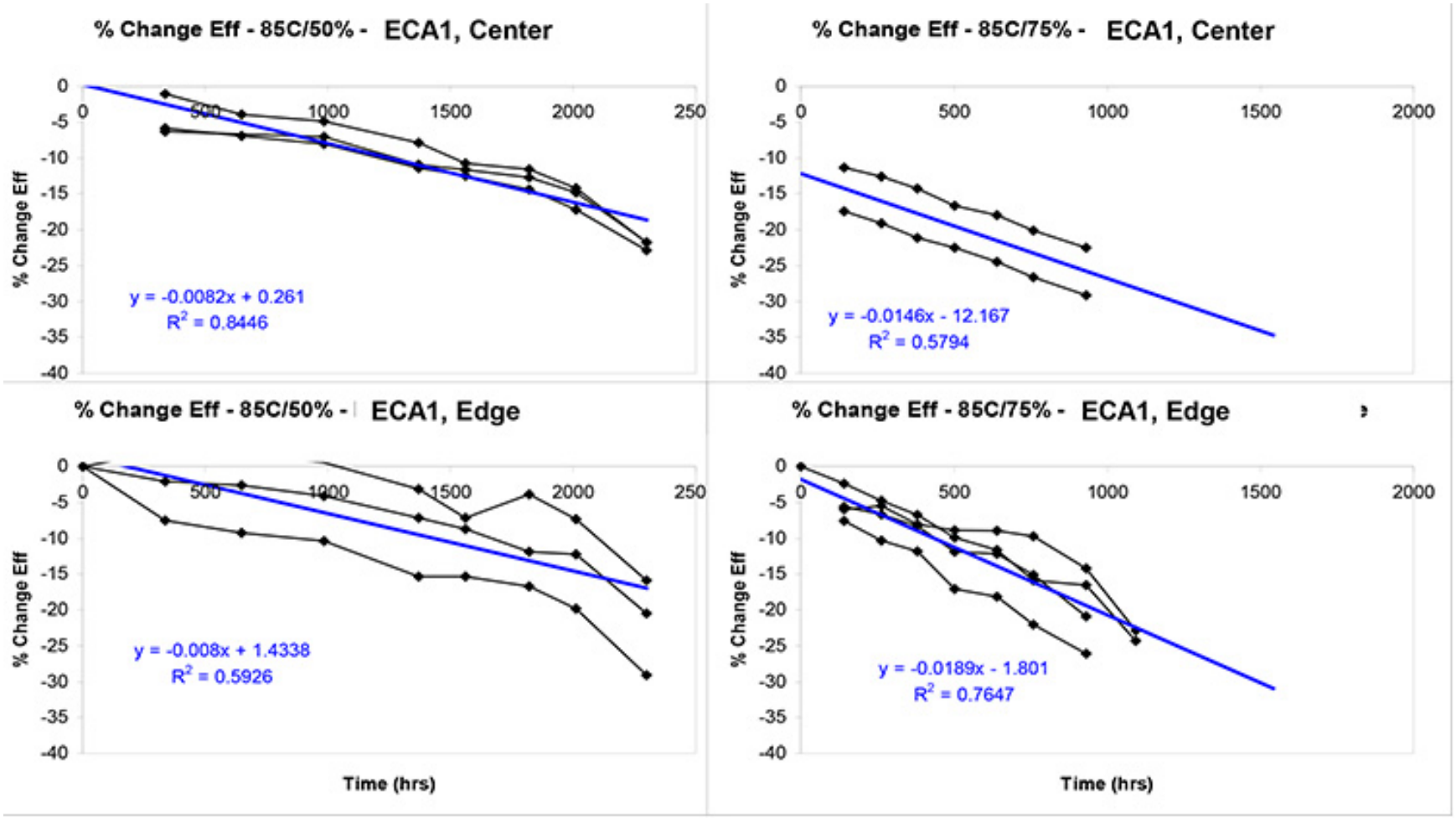
- Metal foil substrate
- Electrically conductive adhesive (2) + tabs/ribbons
- AZO/ITO window layer
- Nominal cell performance
  - Efficiency ~ 10 – 12.5%
  - Voc ~ 550 - 610 mV, Jsc ~ 28-33 mA/cm2
  - FF ~ 59 - 62%, Area ~ 16.5 cm2



Package Cross-section

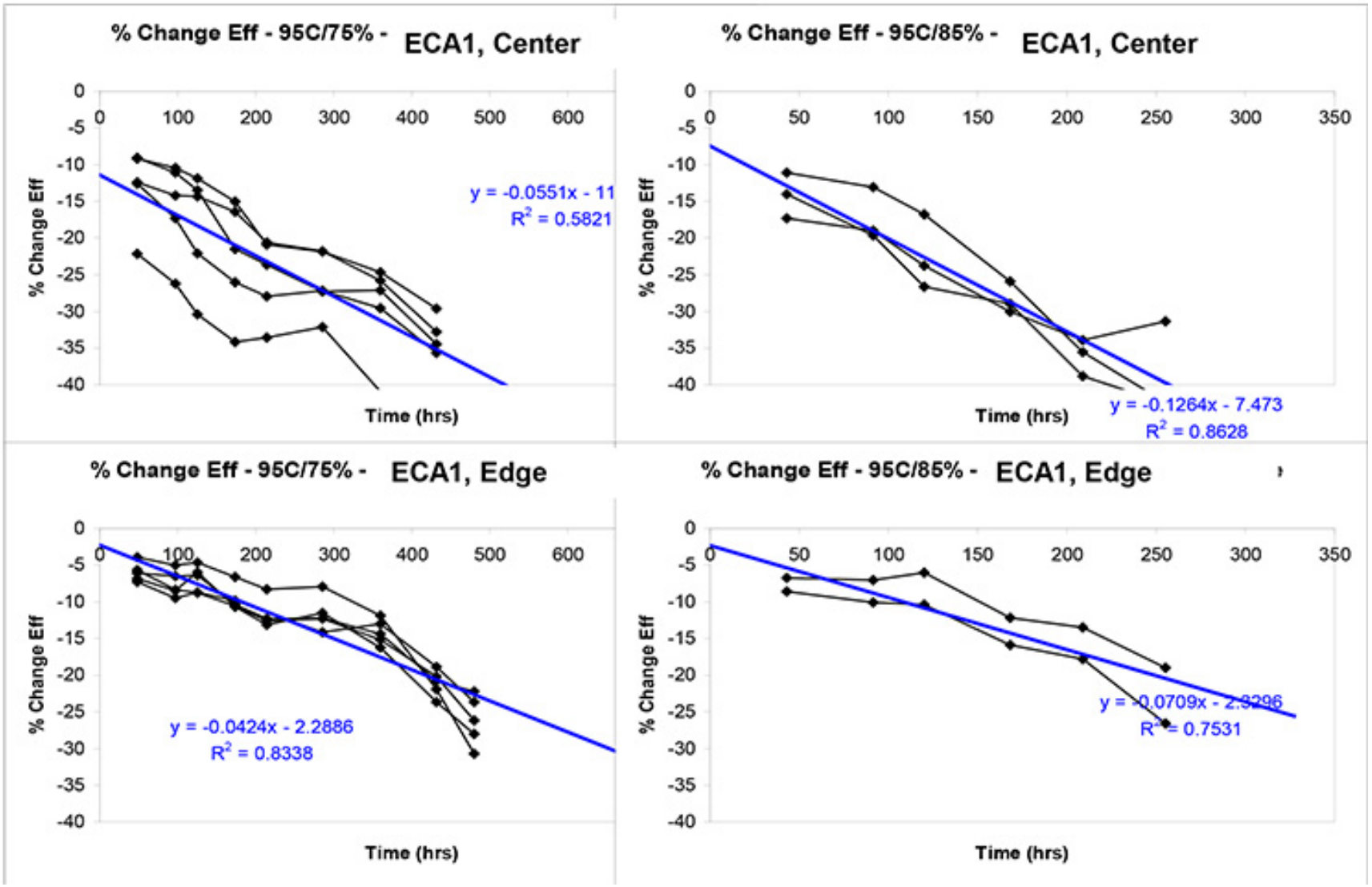


Degradation data – example (humidity)



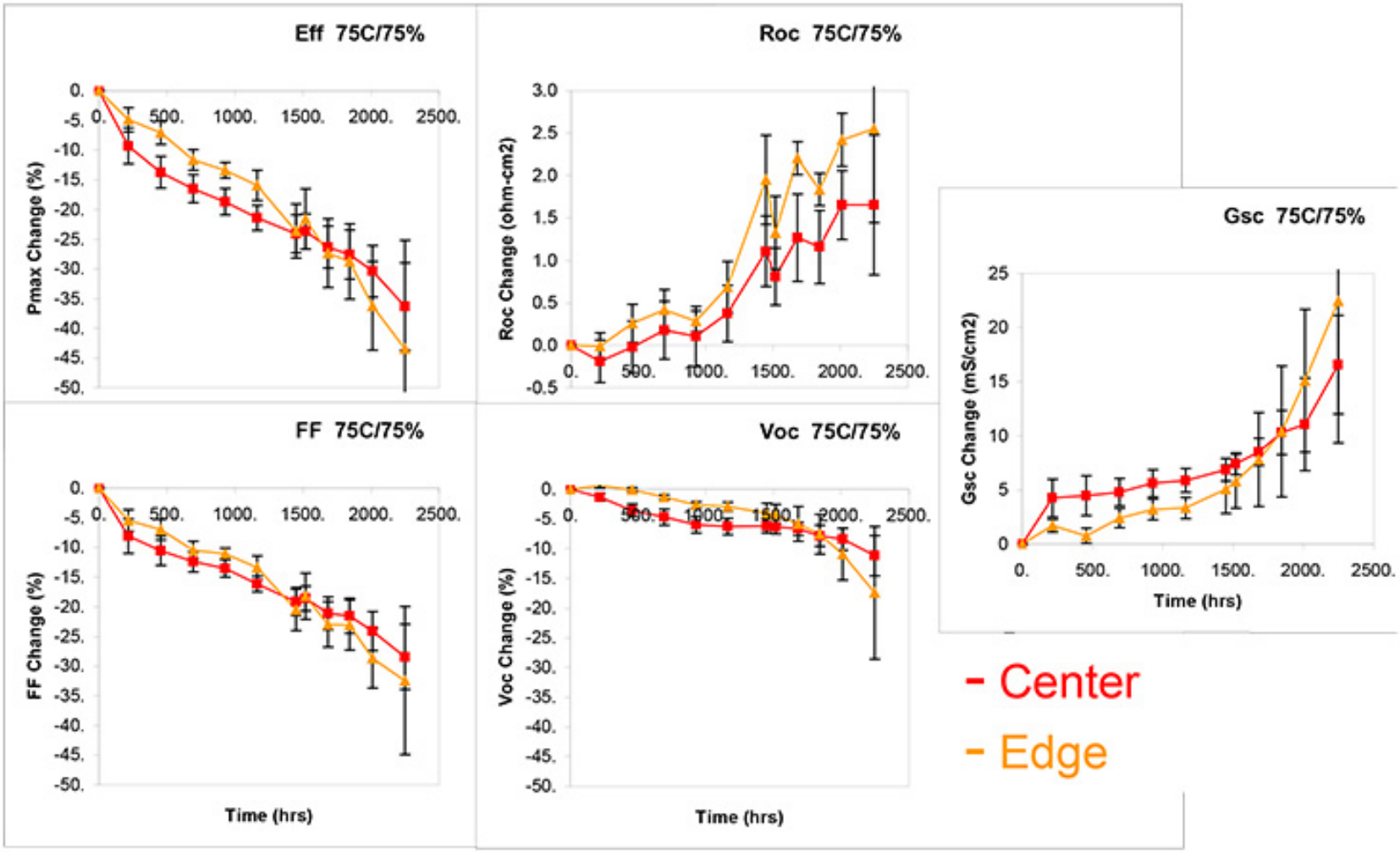
- High humidity faster
- Center cells rapid initial degradation
- Same long-term rate center vs edge

Degradation data – example (temperature)



- Center cells rapid initial degradation
- Same long-term rate center vs edge

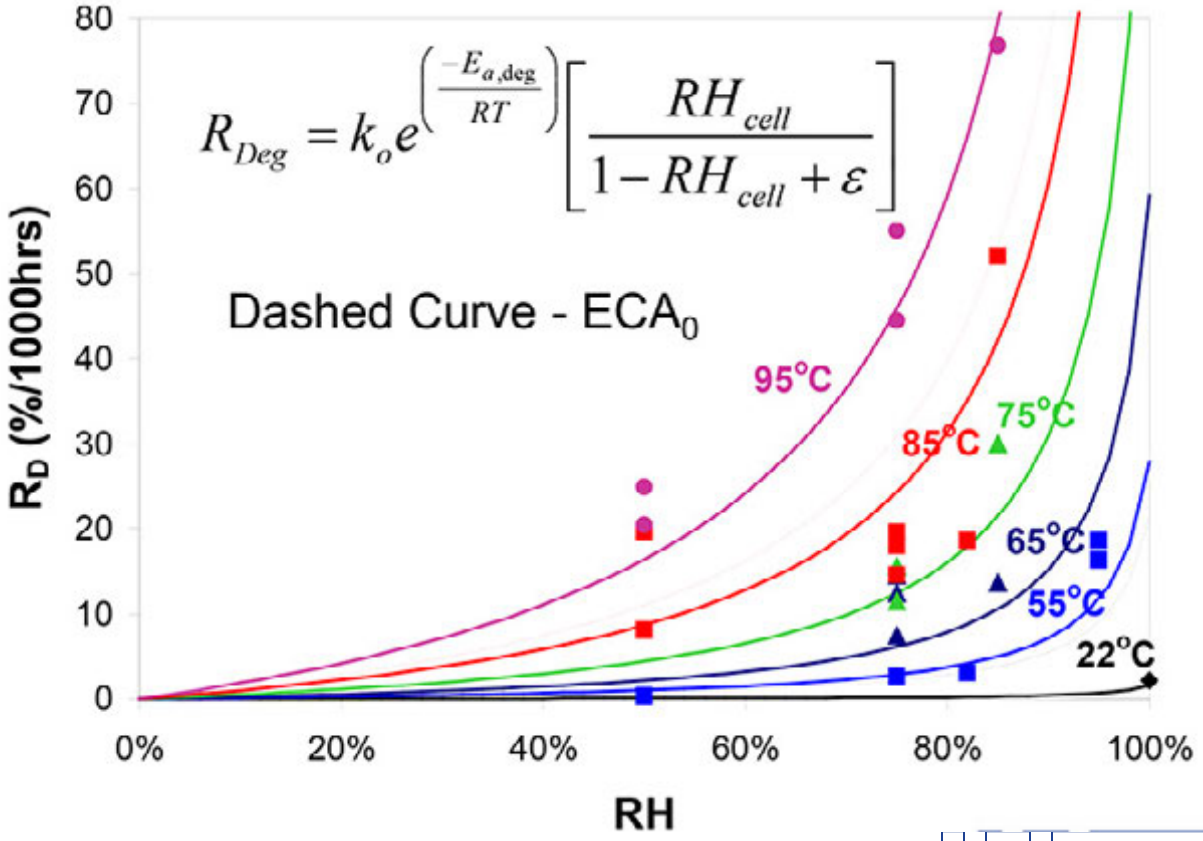
Which JV Parameter is the Driver?



- Steady degradation driven resistance - FF and Roc
- Initial drop driven by shunting - Gsc

CIGS Degradation Kinetics

(ITO-based test structures)

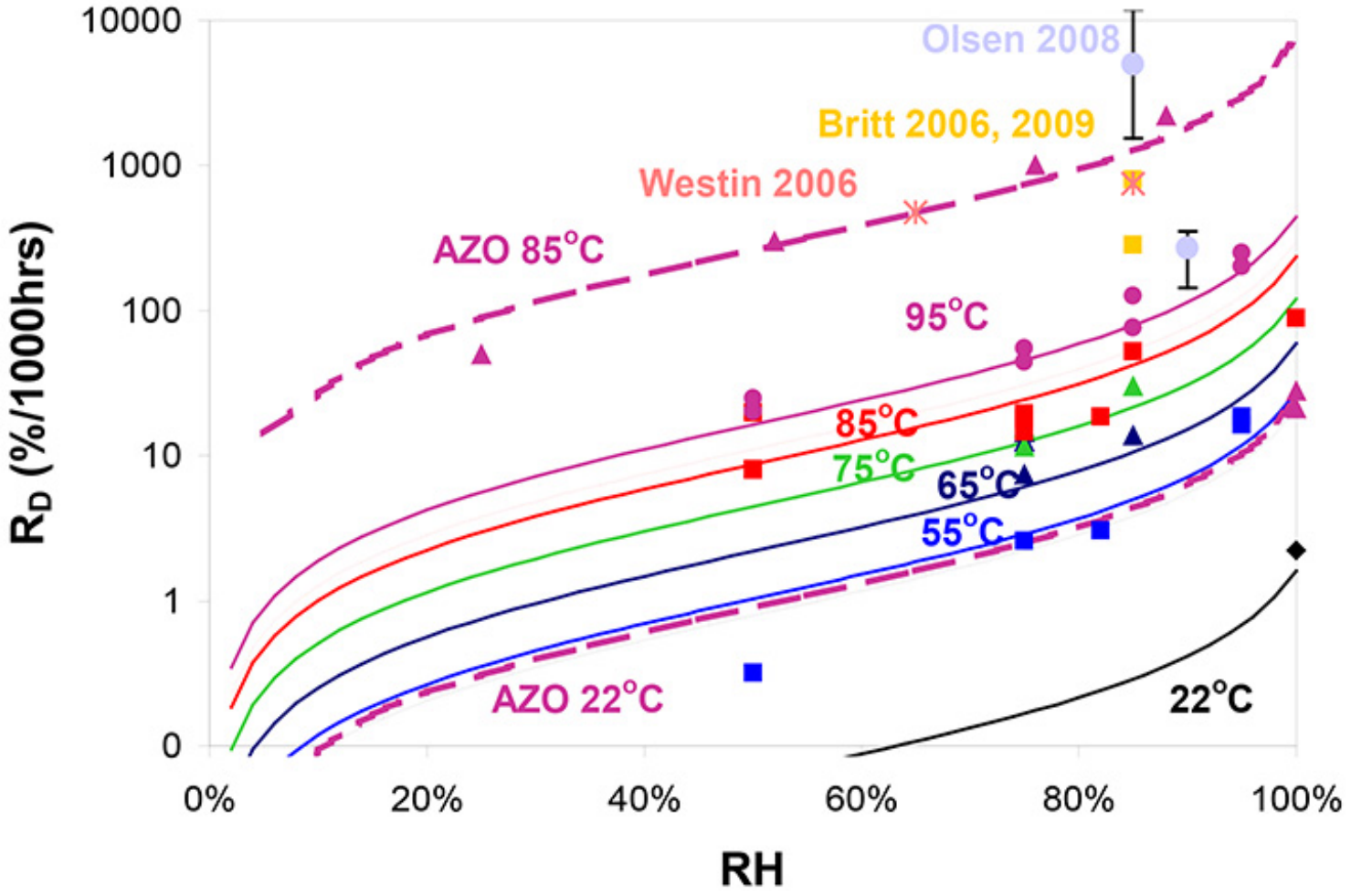


- For every Temp & RH, fit data to linear degradation rate (1st 20% of degradation)
- Fit rate of degradation vs Temp, RH to kinetic model
- Strong RH dependence at high RH
- ECA affects temperature dependence

Compare to AZO

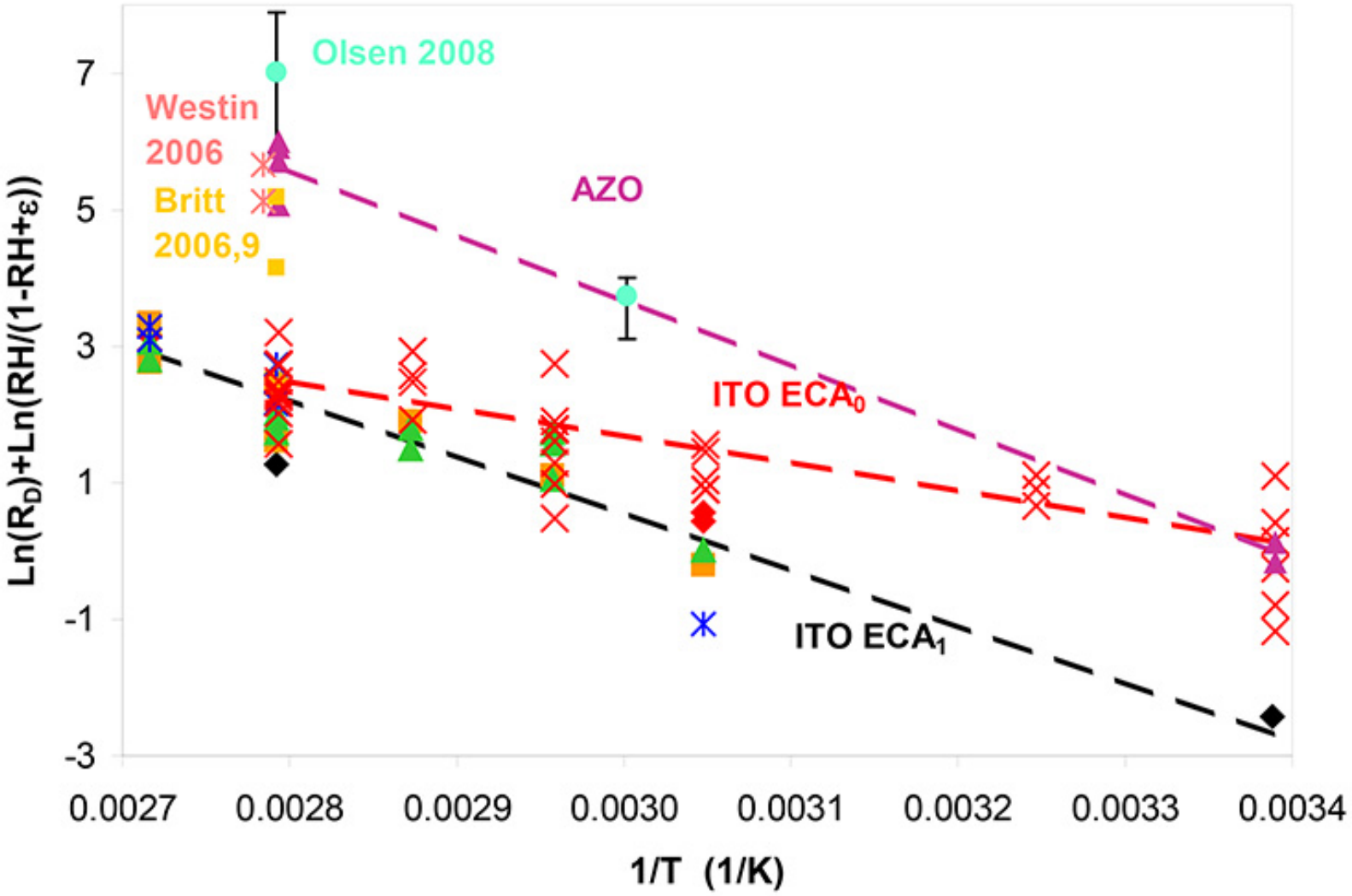
(Klinger, D. J., "Humidity acceleration factor for plastic packaged electronic devices", Quality and Reliability Engineering International. Vol. 7, 965-3711, 1991).

CIGS Degradation - AZO vs ITO



- Comparable to published data

Arrhenius Plot



Package Diffusion Model

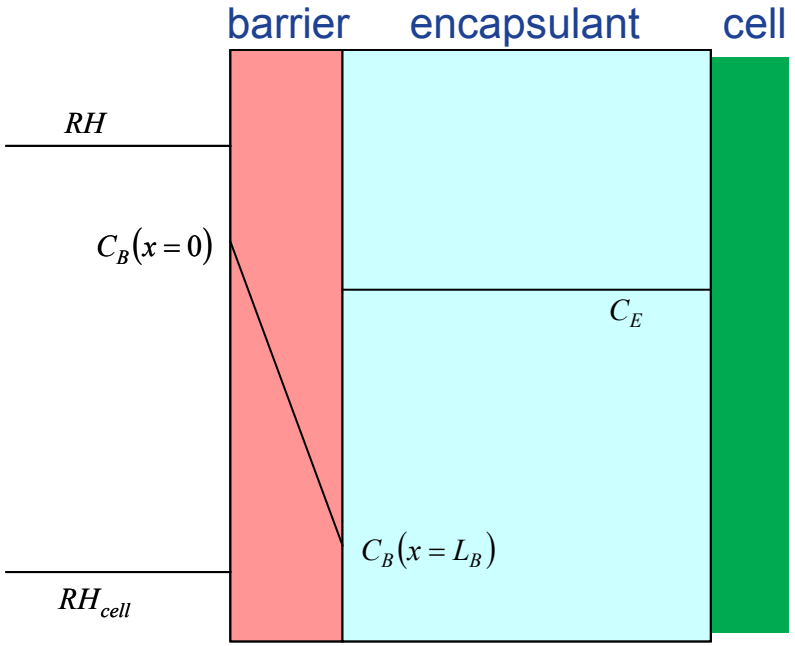
Mass Balance, Interfacial Equilibrium, Fickian Diffusion, $D_{barrier} << D_{encapsulant}$

$$\frac{\partial C_E}{\partial t} = \frac{S_E RH - C_E}{t_c}$$

$$t_c = \frac{L_E S_E}{WVTR_{\max}}$$

If initially dry:

$$\frac{C_E}{S_E} = RH\left[1 - e^{\left(-t/t_c\right)}\right]$$

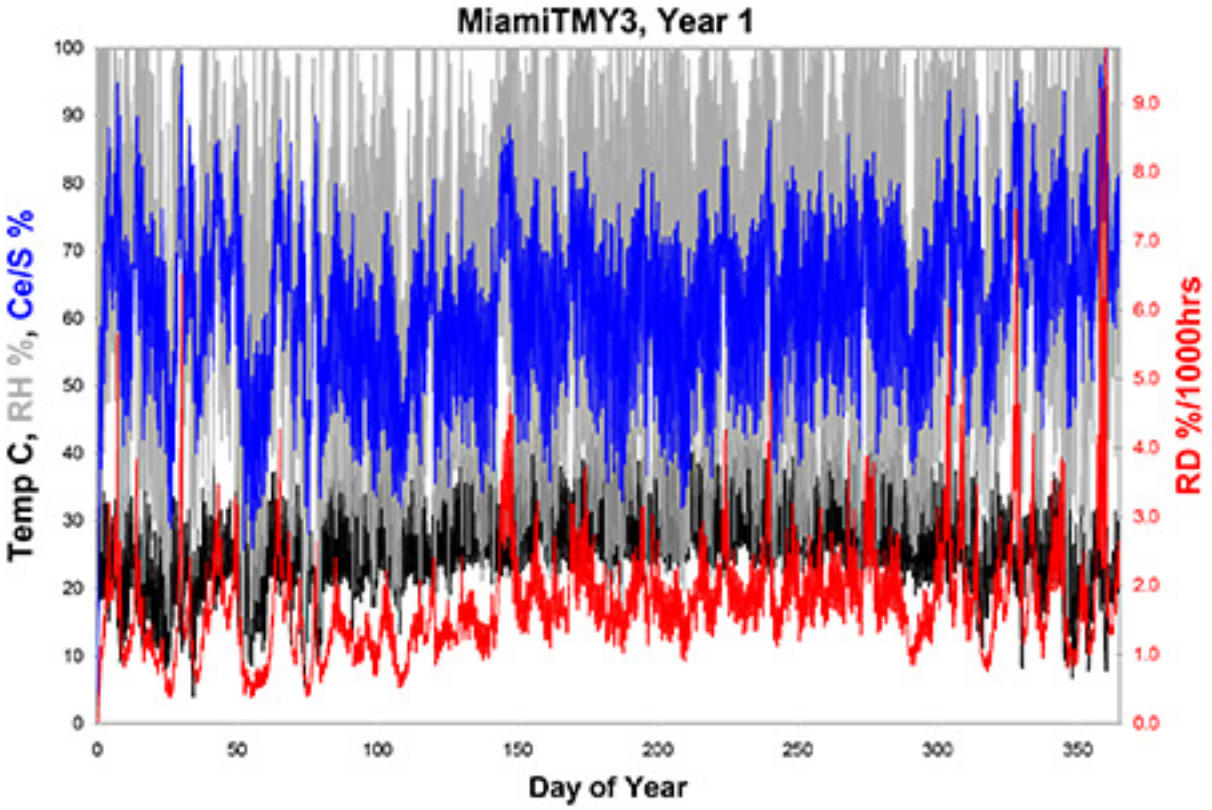


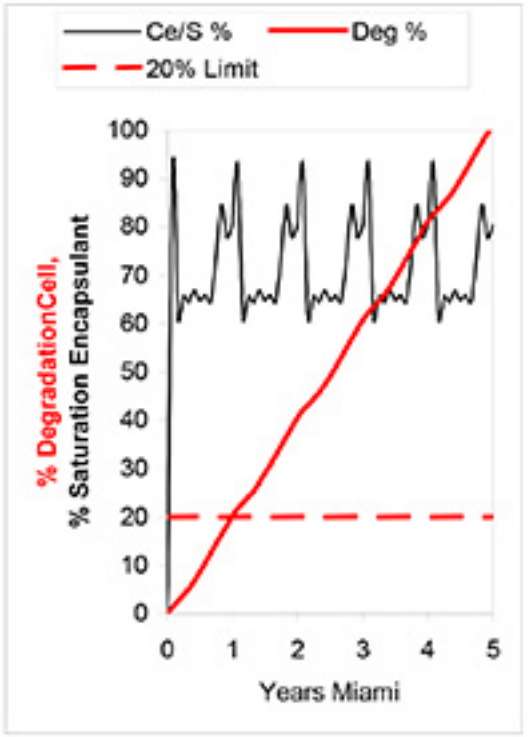
→ Integrate moisture ingress with hourly weather data (TMY3)

(Kempe, M.D., "Modeling of rates of moisture ingress into photovoltaic modules," Solar Energy Materials & Solar Cells, Vol 90 (2006) pp. 2720–2738).

Plastic Package (No Barrier)

WVTR = 10^0 g/m^2/day



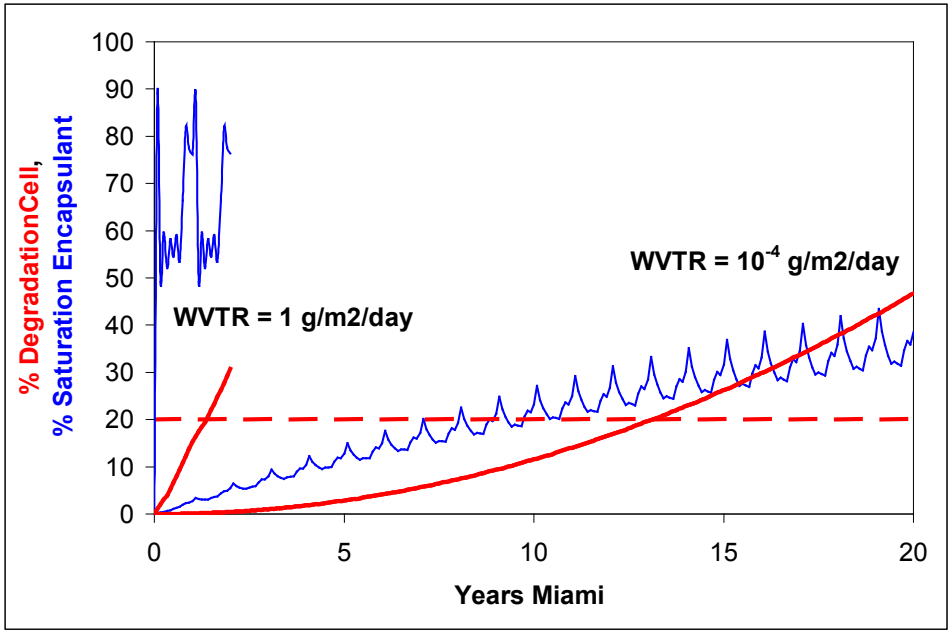


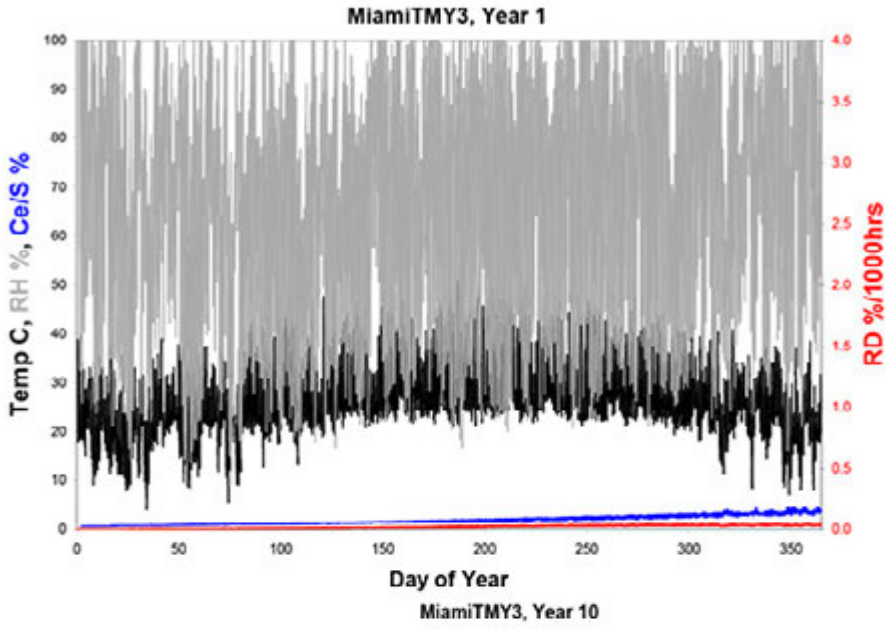
- Package equilibrates ~ $t_{1/2}$=0.7 days
- PV degrades ~ 1 year

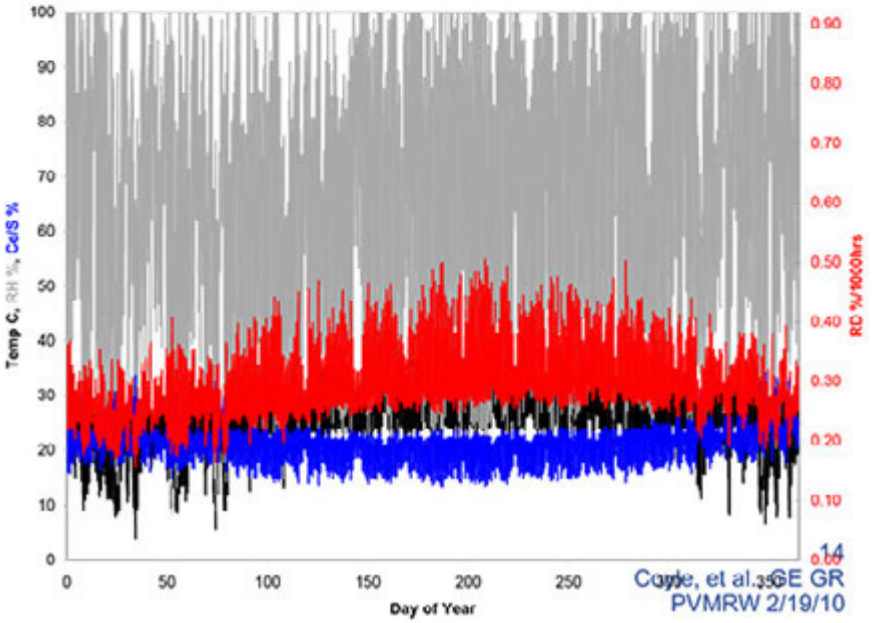
Barrier Package

WVTR = 10^{-4} g/m^2/day

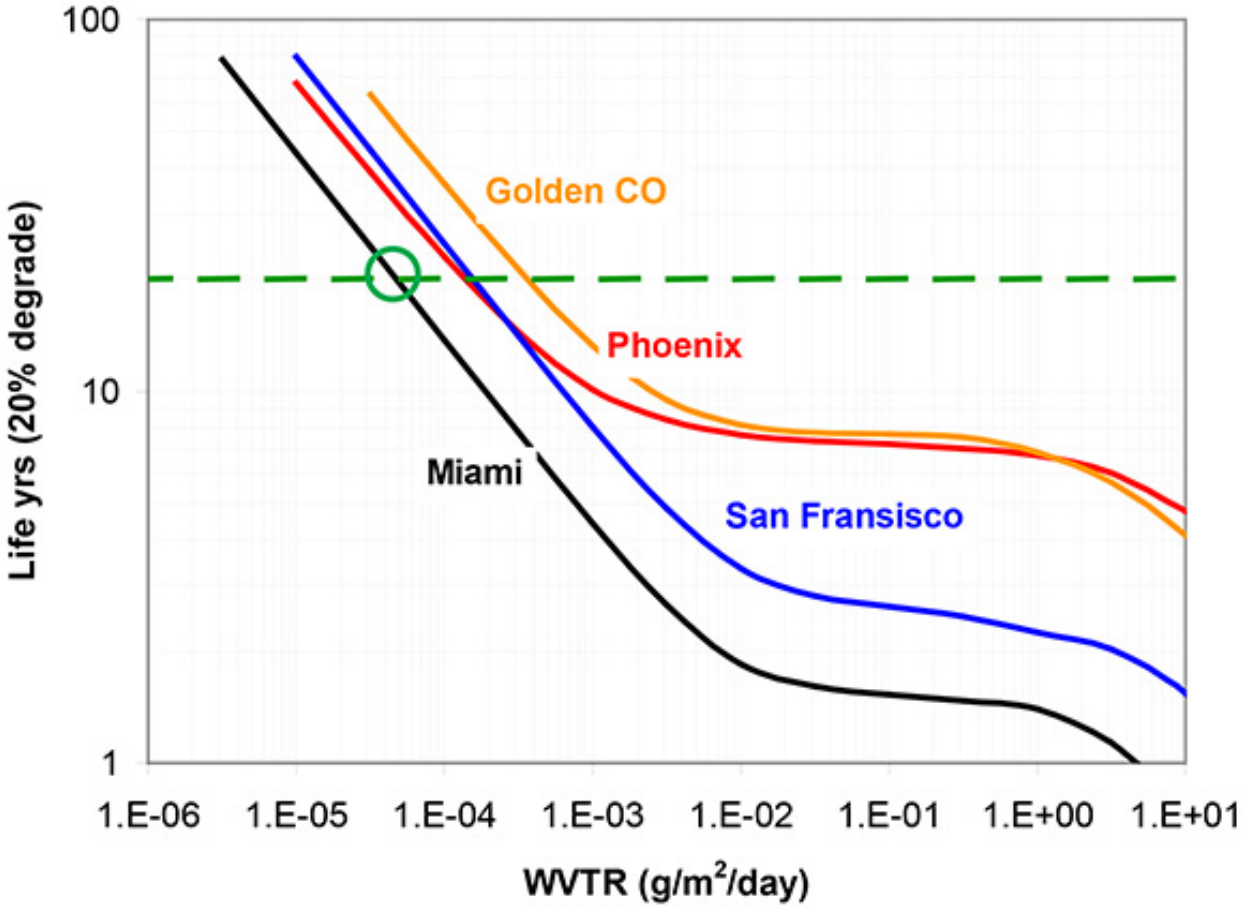
- Package equilibrates ~ $t_{1/2}$=20yrs
- Module Degrades < 13 yrs





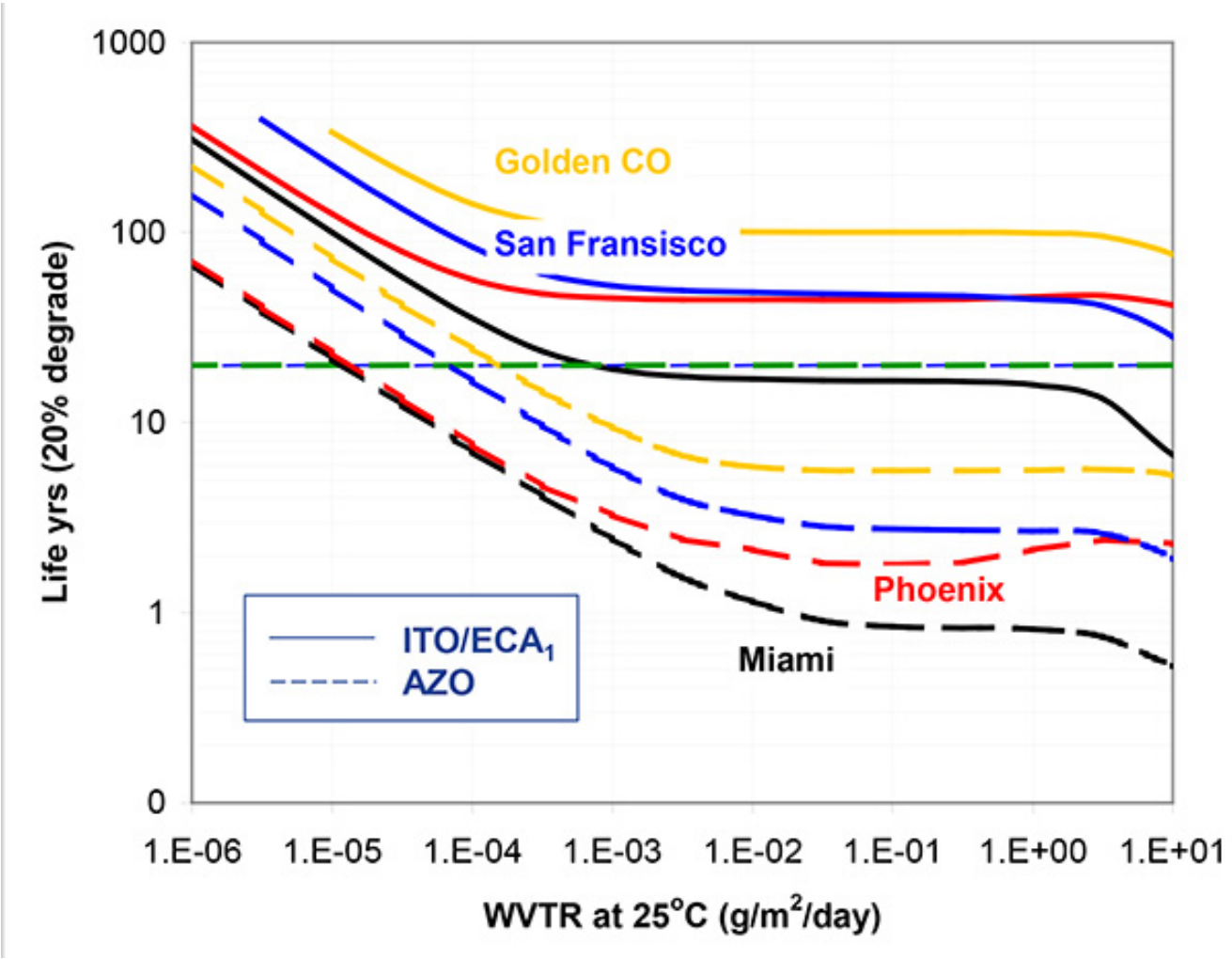


Life vs. Barrier: ITO-ECA$_0$



Need ~ 4x10^{-5} g/m^2/day package ~ 20 yr life

Life vs Barrier – ITO vs AZO

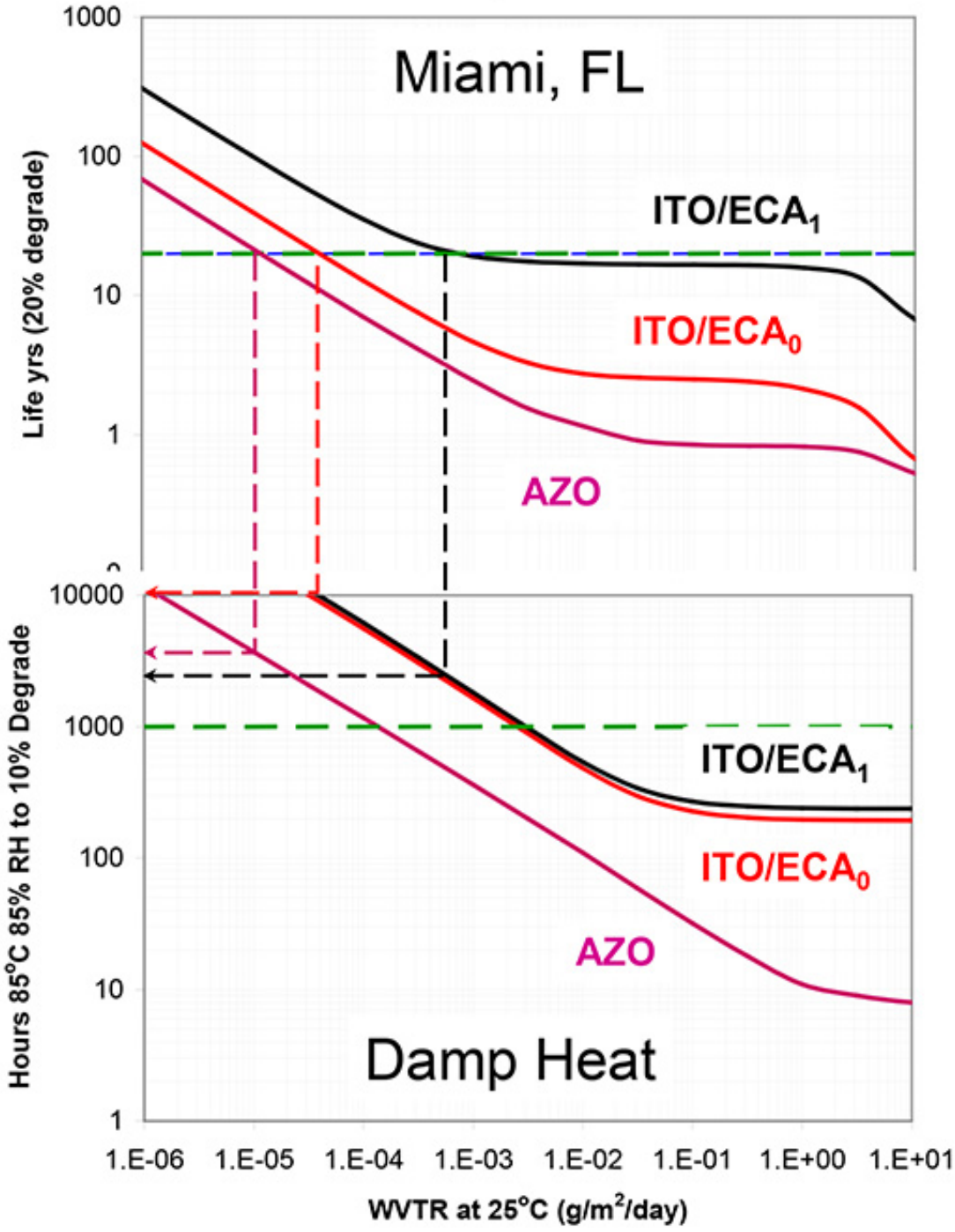


ITO Life 5-25X AZO Life

Connection to Accelerated Testing

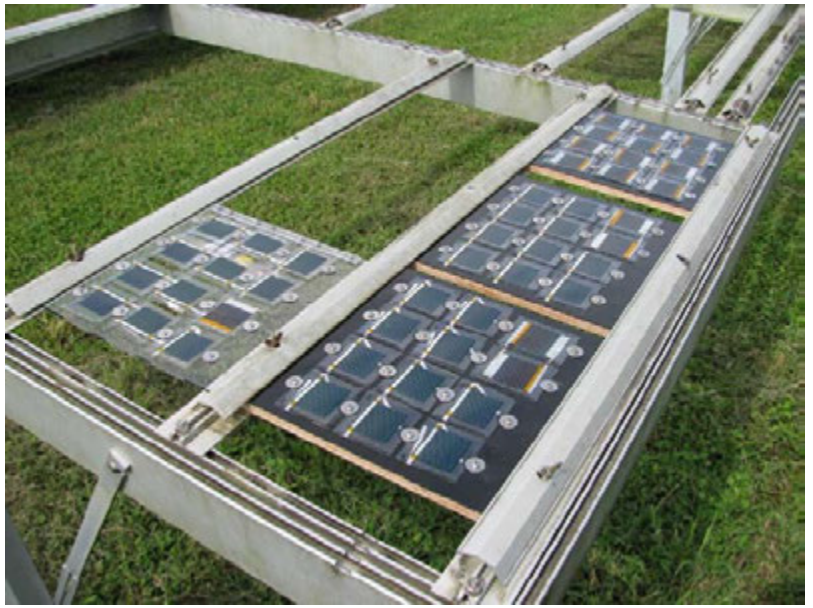
- Nonlinear relationship
- No simple scaling
- Depends on details of kinetics and package

~10,000 hrs
~4,000 hrs
~2,500 hrs



Outdoor Testing

- Generate real time degradation data to compare to life model
- Samples placed in Miami, FL and Phoenix, AZ

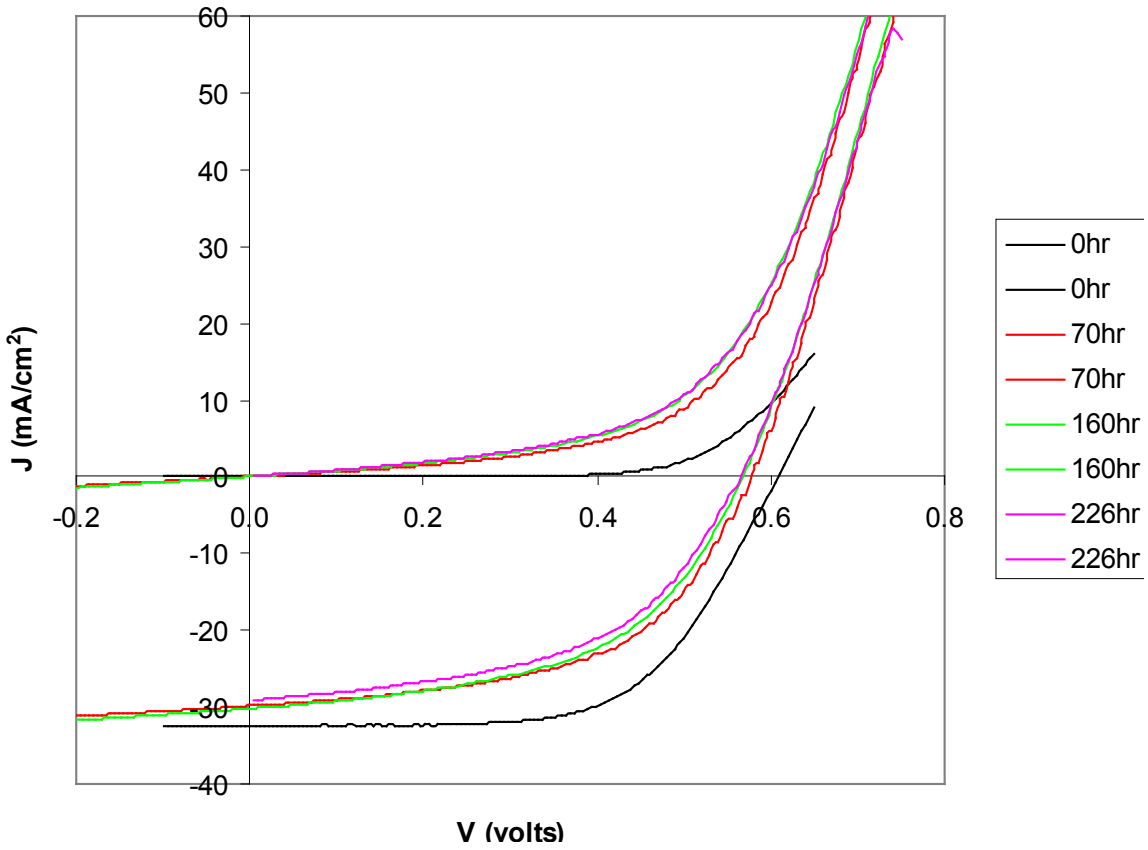


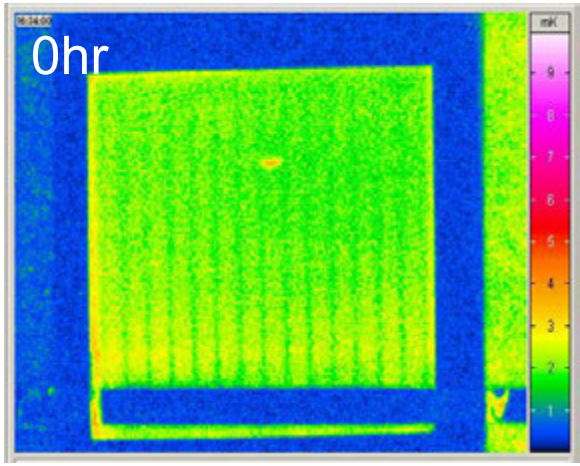
	Calc P_{max} change	Measured P_{max} change	Roc change	P_{max} change shunted
Phoenix ECA_1	-0.1%	-1% +-2%		
Miami ECA_1	-0.5%	-1% +-2%		
Miami ECA_0	-4.1%	-5% +-2%	29% +-7%	-30% +-5%

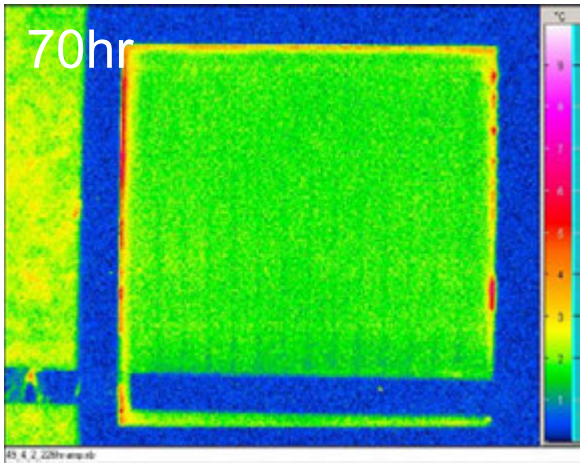
Results as expected after 3 months

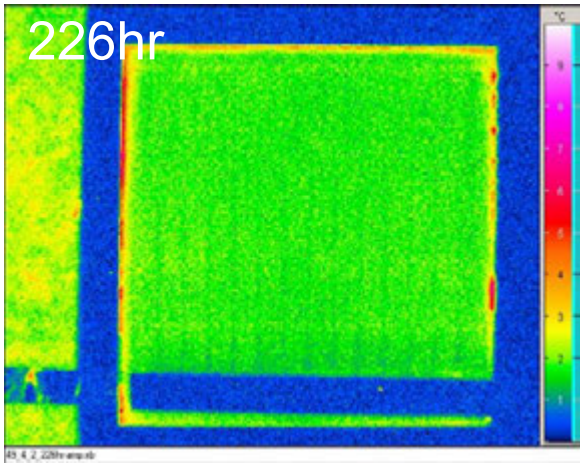
- ITO/ECA_1 not measureable yet – will continue
- ITO/ECA_0 ~ 5% down as expected

Root Cause Analysis: Shunting





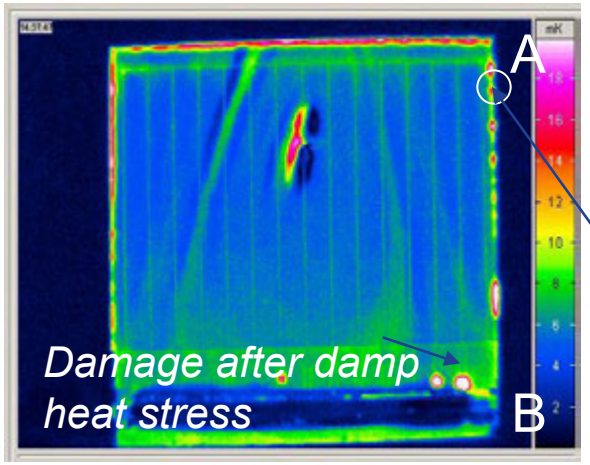




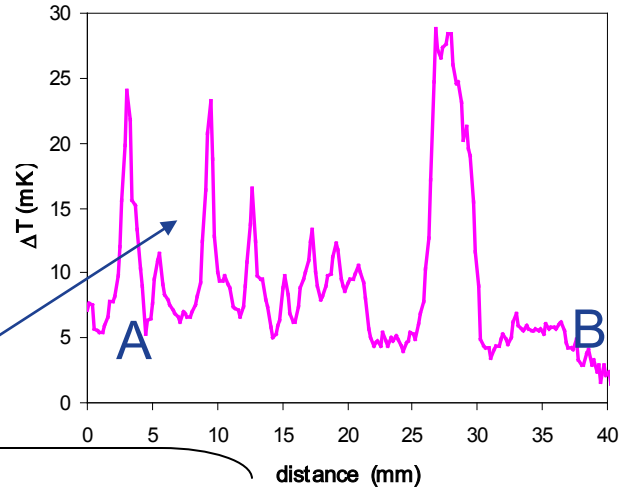
- Use lock-in thermography (LIT) to image shunting behavior
- Image at various stages of damp heat stress
- Initial degradation is dominated by edge shunting

Shunting Failure Analysis Deep Dive

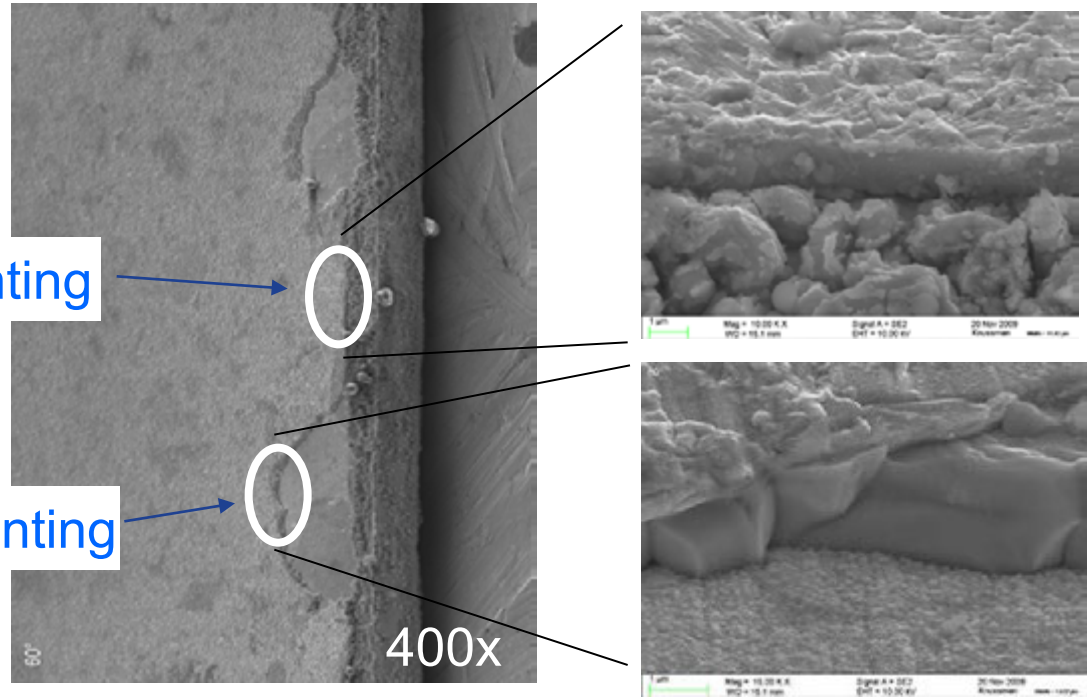
LIT Full Cell Image



LIT Line Scan of Cell Edge



SEM



- LIT line scan shows distinct localized shunt paths
- image with SEM to look at μ-structure
- Shunting caused by small CIGS edge clearance

Conclusions, Plans & Acknowledgements

Conclusions

- AZO vs ITO CIGS degradation kinetics quantified – 25X
- Life model and accelerated test scaling developed
- Diffusion-controlled: Life ~$(t_c/R_D)^{1/2}$ or ~(diffusion-time*degrade-time)$^{1/2}$
- Significant moisture barriers required for 20 yr life – even for ITO
- Acceleration factor for damp heat smaller than assumed, highly nonlinear!
- Methodology can predict life for any moisture-sensitive module (once kinetic constants are measured)

Future Plans

1. Critical experiments to test model predictions
2. Experimental validation – Miami, FL & Arizona

Acknowledgements

Mike Kempe NREL

Steve Hegedus IEC

This work was supported by:

U.S. Department of Energy

Award DE-FC36-07GO17045

GE Global Research

GE Energy

imagination at work



National Renewable Energy Laboratory
Innovation for Our Energy Future

Methods for Measuring Moisture Ingress



Arrelaine Dameron, Mathew Reese, Thomas Moricone, & Michael Kempe

This presentation does not contain any proprietary or 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.

Moisture Barrier Requirements

Next generation PV will require barriers with WVTR < 1× 10^{-6} g/m^2/day using materials with low defect density; Diffusivity <1× 10^{-18} cm^2/s

Material Goal: flexible & transparent material with these properties

General Strategy: alternating inorganic/organic thin films estimated ~12 dyads required

Measurement Goal: quantifiable means to evaluate, compare and improve materials

Device testing: demonstrates applicability but is not the best means to quantify moisture ingress

Lewis *et. al., IEEE Journal of Selected Topics in Quantum Electronics, vol.10 p. 44, 2004.*
G.L. Graff *et. al., Journal of Applied Physics*, vol. 96, pp. 1840, 2004.

How much water?

WVTR = 1 g/m^2/day

In a day:

X = ~1 um

In 20 years:

X = ~7.3 mm

~7.3 L collected

WVTR = 1× 10^{-4} g/m^2/day

In 20 years:

X = ~1 μm

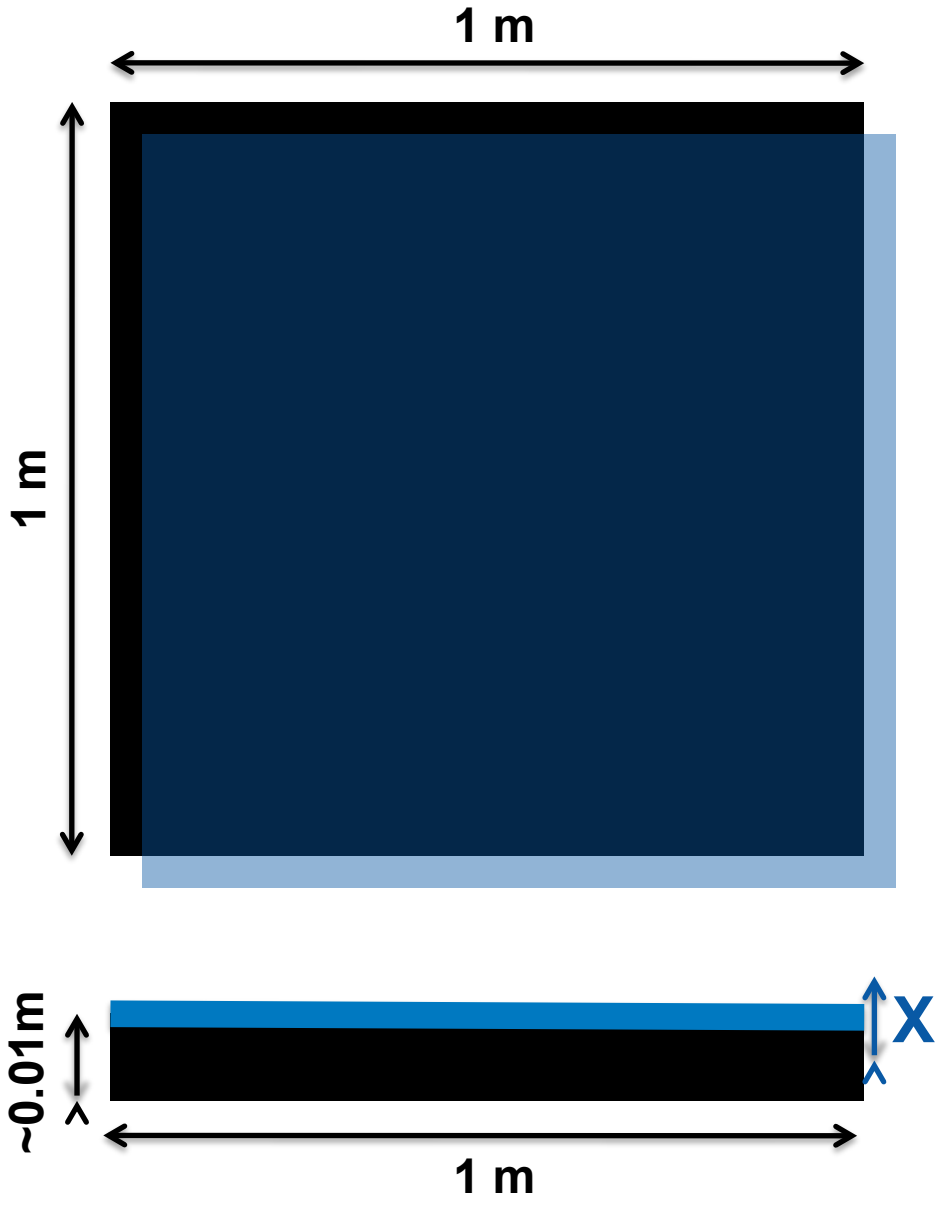
~7.3 mL collected

WVTR = 1× 10^{-6} g/m^2/day

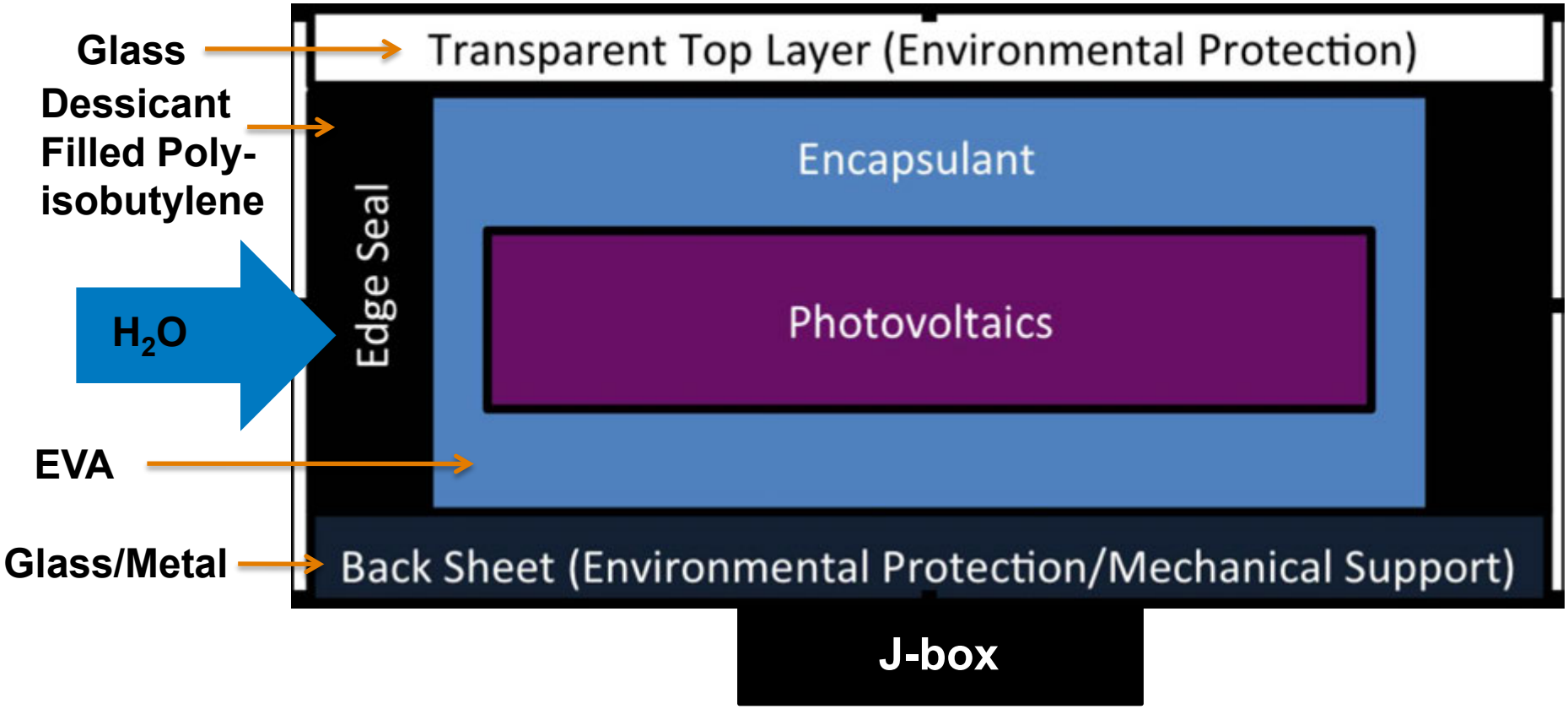
In 20 years:

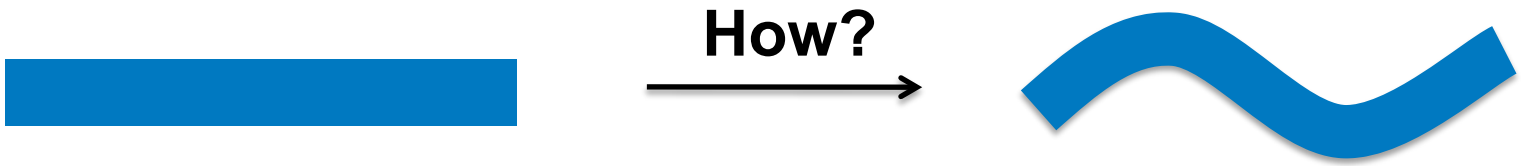
X = ~10 nm

~7.3 μL collected

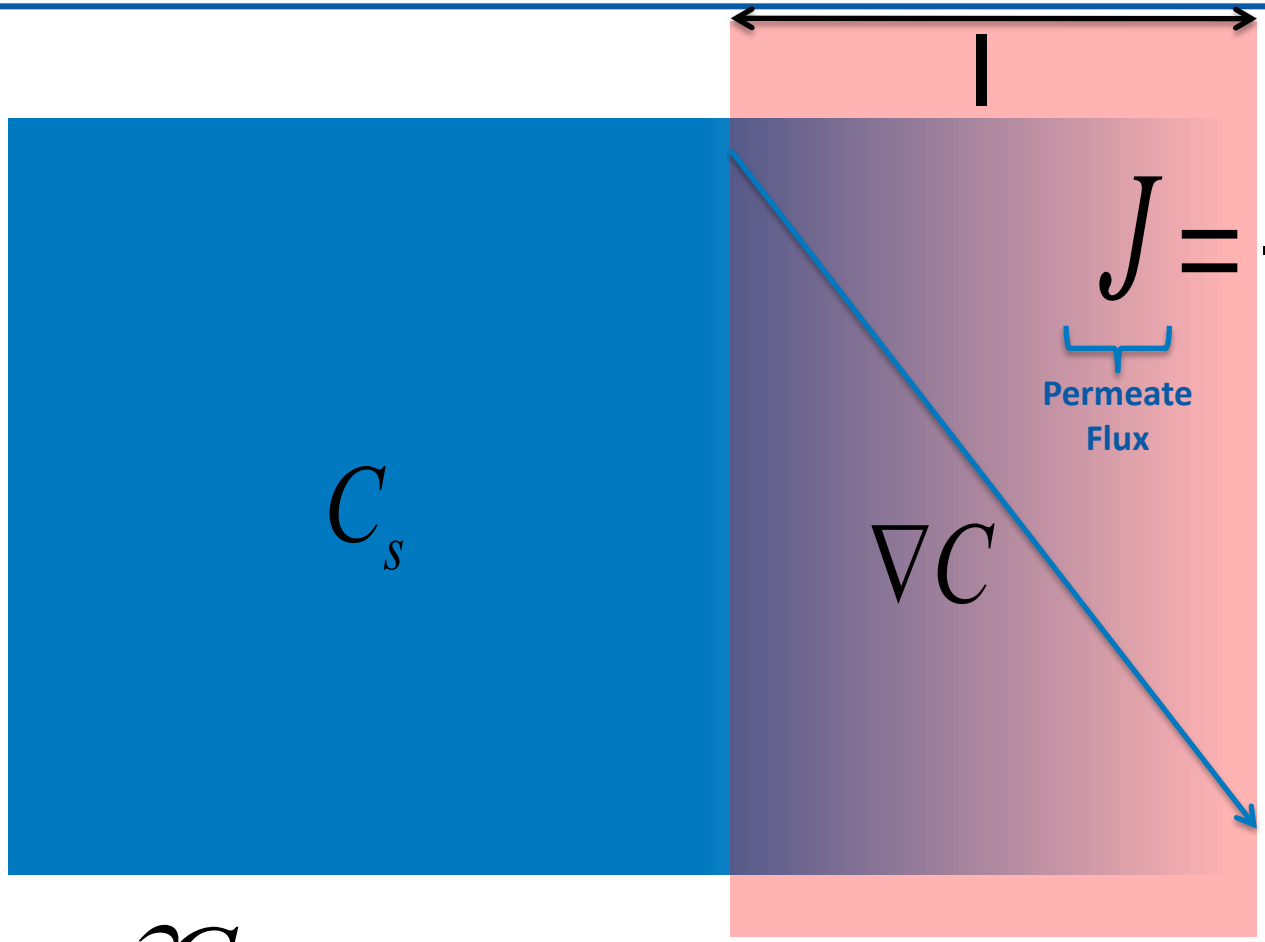


Entry Points





Diffusion



$$J = -D\nabla C$$

Concentration Gradient

Permeate Flux

Diffusivity

$$\frac{\partial C}{\partial t} = -\nabla J = \nabla(D\nabla C) \longrightarrow D\nabla^2 C$$

Assume Fickian: material has no dependence on concentration

WVTR, Permeability, Diffusivity and Solubility

$$WVTR(t) = \frac{DC_s}{l}\left[1 + 2\sum_{n=1}^{\infty}(-1)^n \exp\left(-\frac{Dn^2\pi^2 t}{l^2}\right)\right]$$

Thickness

$$Q(t) = \int_0^t WVTR(t)dt = \frac{DC_s}{l}t - \frac{lC_s}{6} - \frac{2lC_s}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\exp\left(-\frac{Dn^2\pi^2 t}{l^2}\right)$$

Permeability

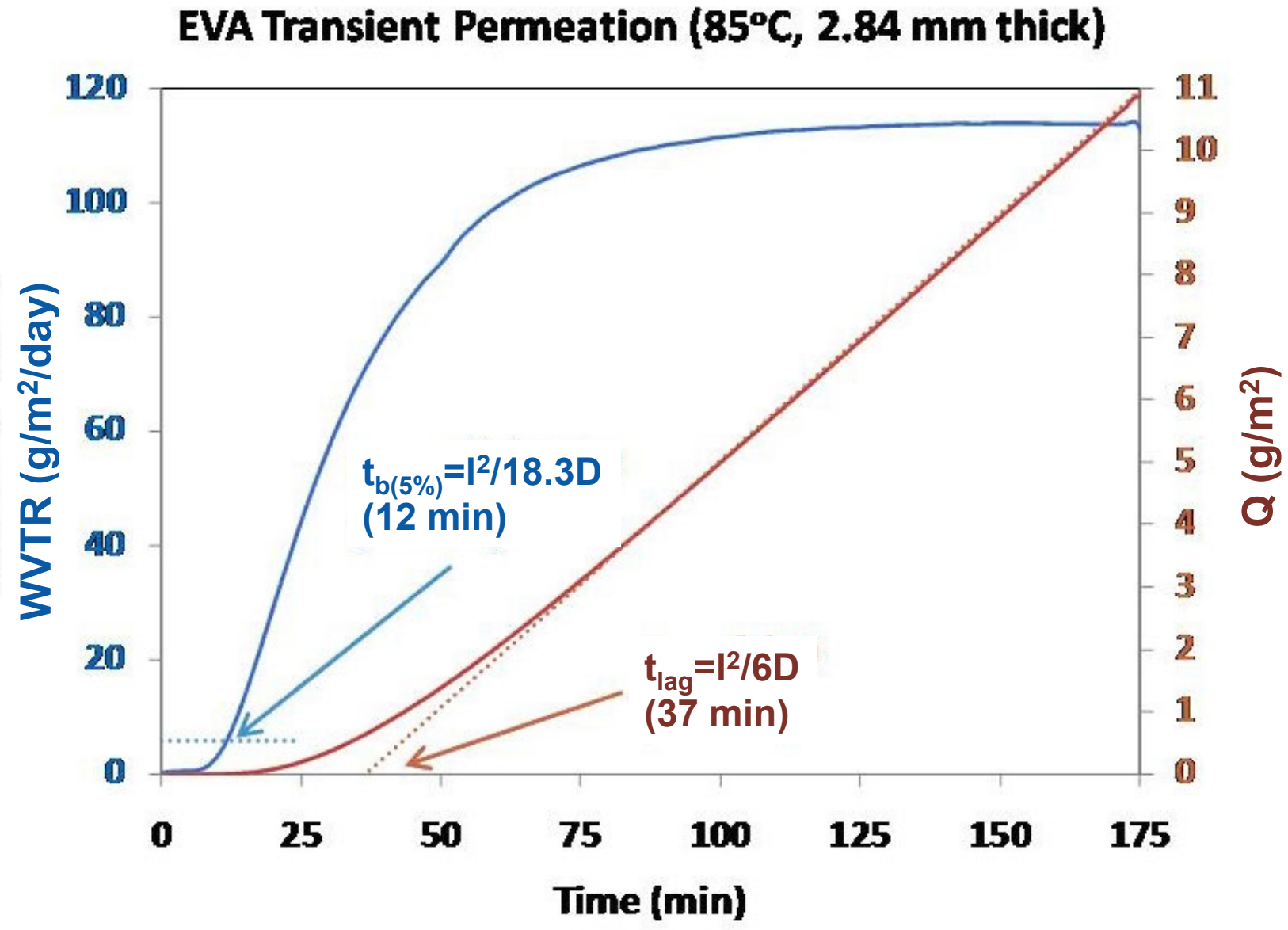
$$P = \frac{Ql}{At\Delta p} = DS$$

Solubility

Area

Partial Pressure

WVTR and Q


EVA Transient Permeation (85°C, 2.84 mm thick)
WVTR (g/m²/day)
Q (g/m²)
Time (min)
0
20
40
60
80
100
120
0
1
2
3
4
5
6
7
8
9
10
11
0
25
50
75
100
125
150
175
$t_{b(5\%)}=l^2/18.3D$
(12 min)
$t_{lag}=l^2/6D$
(37 min)

Barrier Testing Method Types

Scavenger Methods

a material that reacts with or absorbs water is used for quantification

Q(t)

Calcium Test

Radioactive Tracer Test

Gravimetric Cup test

Diffusion Cell Methods

water is directly quantified

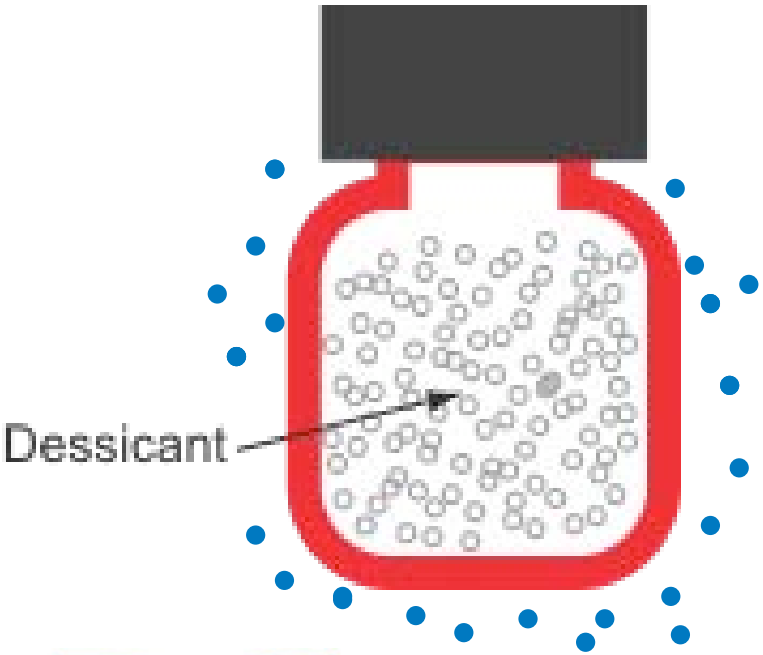
WVTR(t)

Isostatic Test (MOCON)

Radioactive Tracer Test

Mass Spectrometry

Gravimetric Cup Test





Standard: ASTM E96

Measurement:

$$\frac{\partial m}{\partial t} => WVTR(t)$$

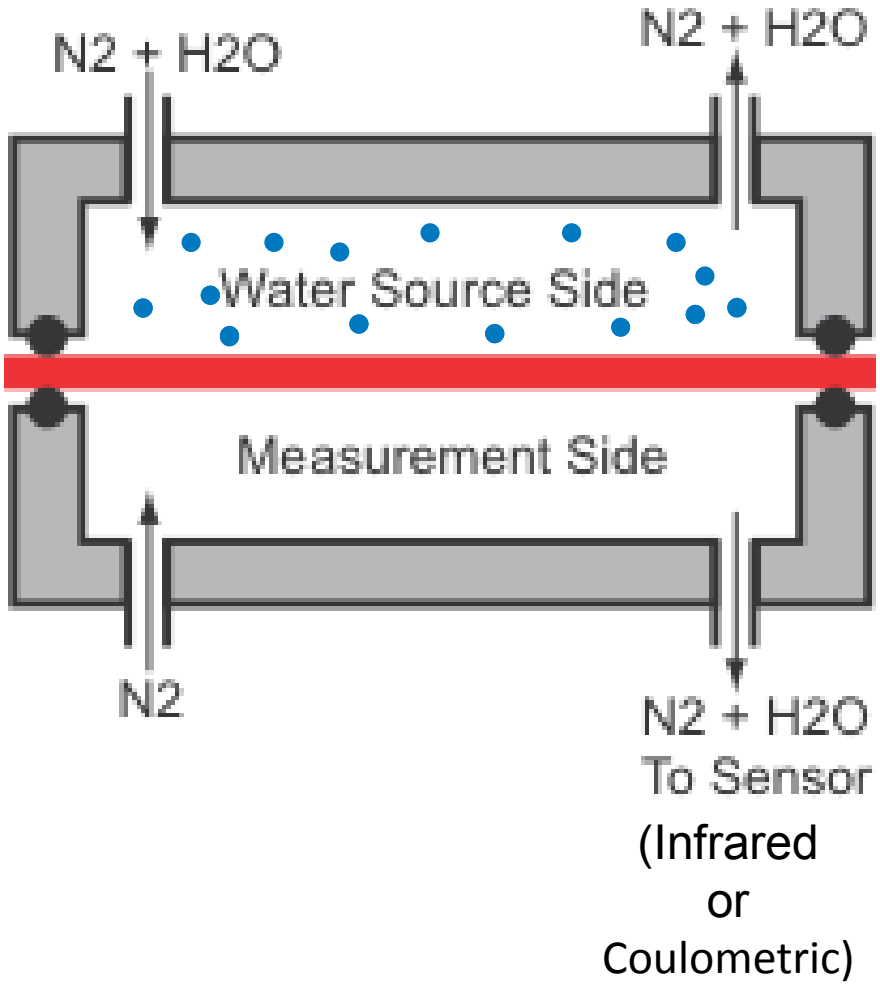
(assuming constant WVTR for Δt)

Sensitivity Limits:
>>1000 g/m^2/day – 0.1g/m^2/day

Pros: simplicity; throughput; controlled temp/humidity

Cons: sensitivity; no transients

Isostatic method (MOCON)



Standard: ASTM F1249

Measurement:

Infrared:

$$A_\lambda(t) => [H_2O]_{test}(t)$$

$$\frac{[H_2O]_{test}}{[H_2O]_{standard}}(t) => WVTR_{test}(t)$$

Coulometric:

$$\Delta R(t) => \Delta molH_2O(t) => WVTR(t)$$

Sensitivity Limits:

100 g/m^2/day – 5×10^{-4} g/m^2/day

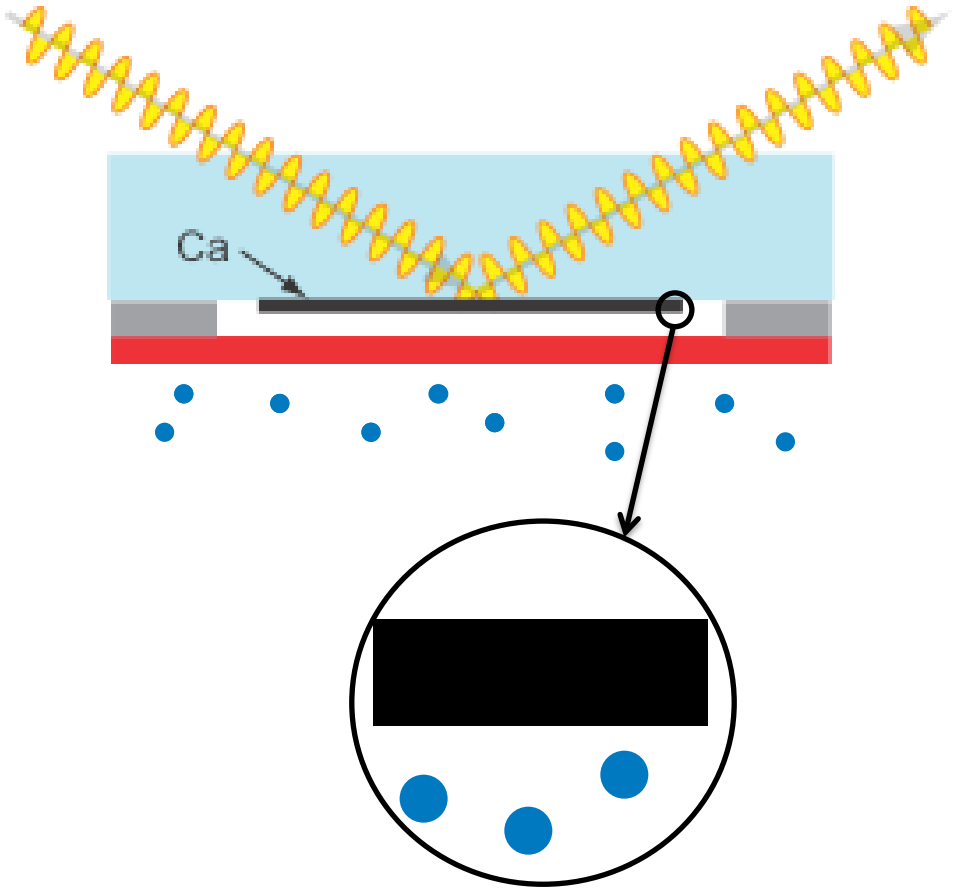
Pros: commercial availability

Cons: sensitivity; throughput; limited temp/humidity

Optical Ca Test

$Ca + H_2O \rightarrow CaO + H_2$

$Ca + 2H_2O \rightarrow Ca(OH)_2 + H_2$



Standard: None

Measurement:

$$A_\lambda(t) => molCa(t)$$

$$molH_2O(t) => WVTR(t)$$

Sensitivity Limits:

1×10^{-2} g/m^2/day – 1×10^{-6} g/m^2/day

Pros: sensitivity; visual evaluation

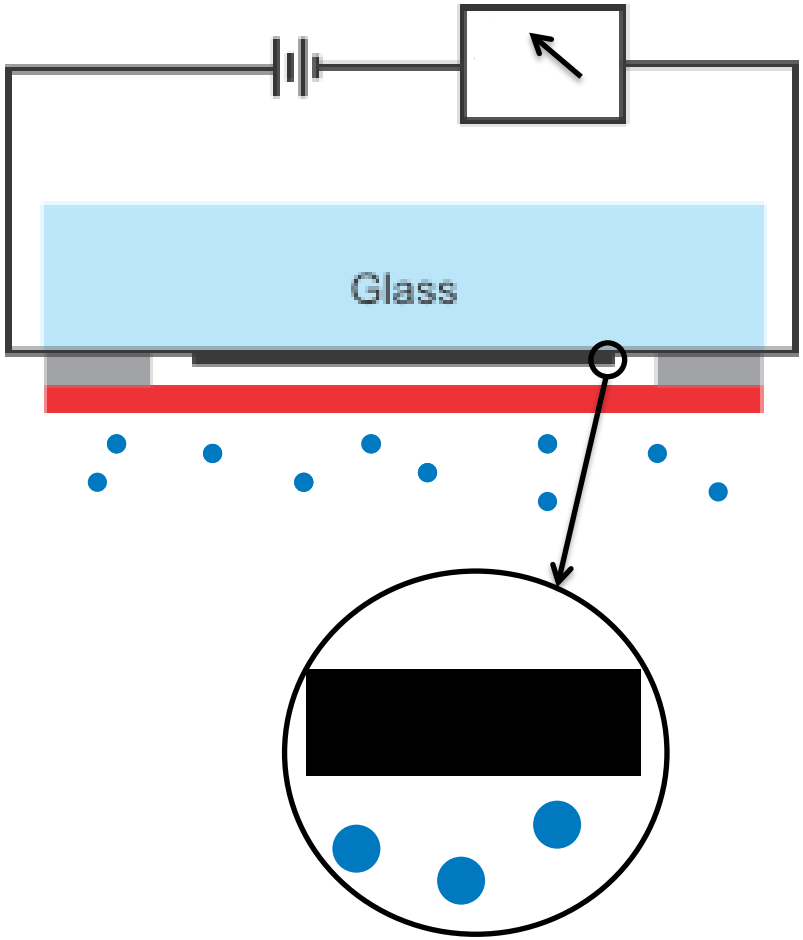
Cons: cost

G.Nisato *et al.*, *Proceedings Asia Display/IDW* pp. 1435, 2001.

Electrical Ca Test

$Ca + H_2O \rightarrow CaO + H_2$

$Ca + 2H_2O \rightarrow Ca(OH)_2 + H_2$



Standard: None

Measurement:

$$R(t) => molCa(t) =>$$

$$molH_2O(t) => WVTR(t)$$

Sensitivity Limits:

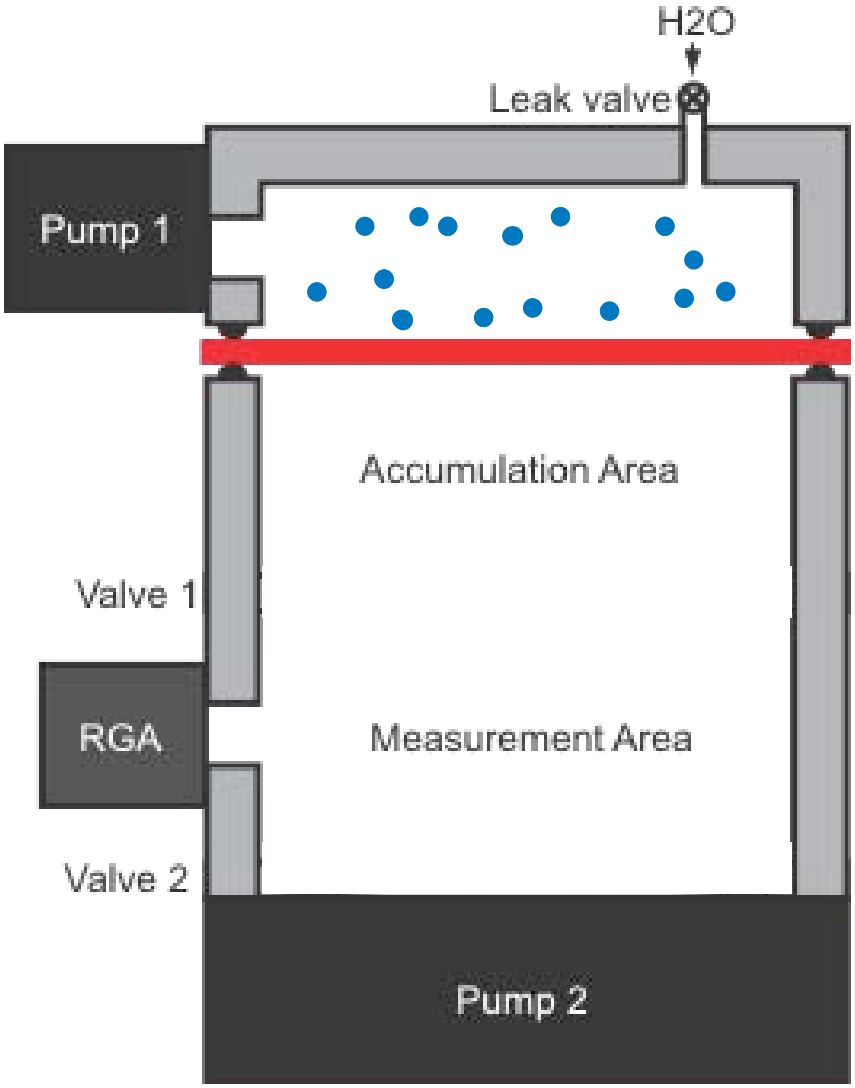
1 g/m^2/day – 1×10^{-6} g/m^2/day

Pros: sensitivity; throughput; controlled temp/humidity

Cons: cost

R. Paetzold *et al.*, *Review of Scientific Instruments*, vol. 74, pp. 5147, 2003.

Mass Spectrometry



Standard: None

Measurement:

$$\frac{\partial P_{H_2O}}{\partial t} => molH_2O(t) => WVTR(t)$$

Sensitivity Limits:

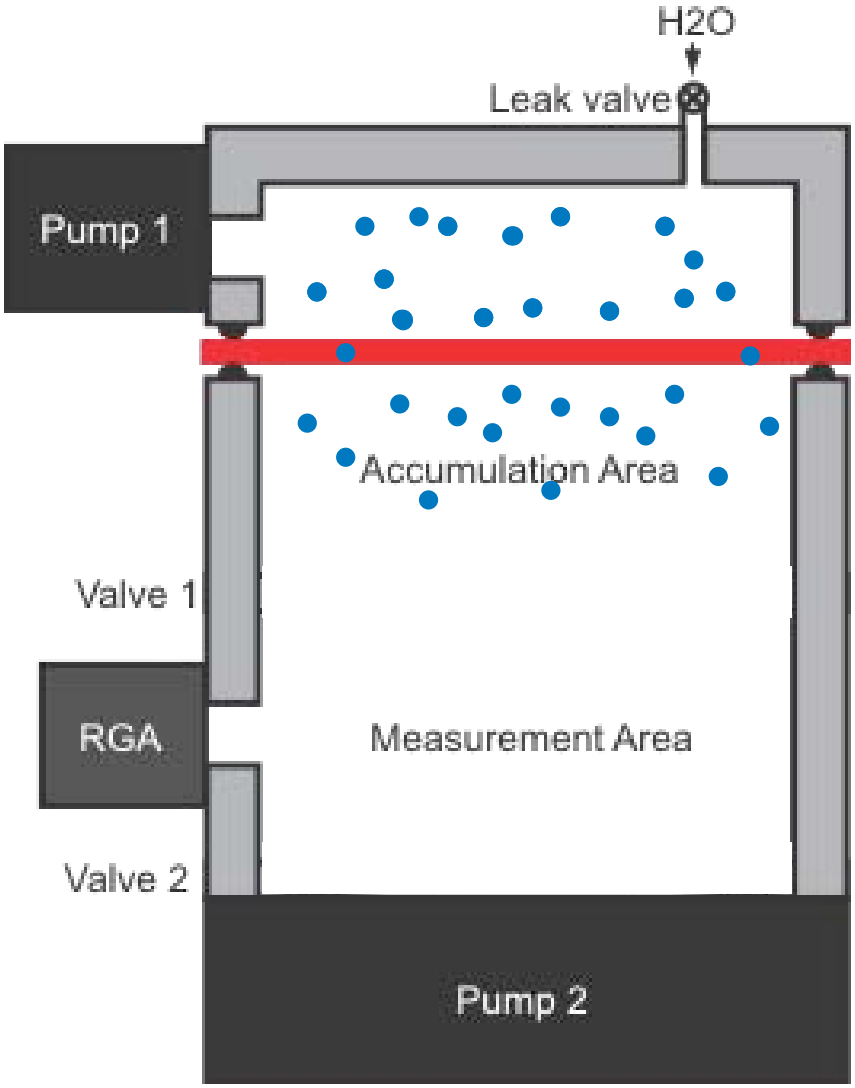
1 g/m^2/day – 1×10^{-7} g/m^2/day

Pros: sensitivity

Cons: cost; throughput; limited temp/humidity

A. Ranade *et al.*, Review of Scientific Instruments vol. 76, p. 013902, 2005.

Mass Spectrometry



Standard: None

Measurement:

$$\frac{\partial P_{H_2O}}{\partial t} => molH_2O(t) => WVTR$$

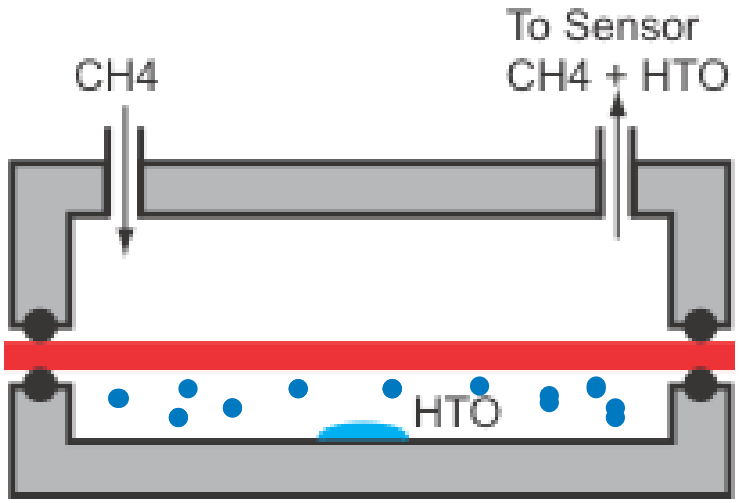
Sensitivity Limits:

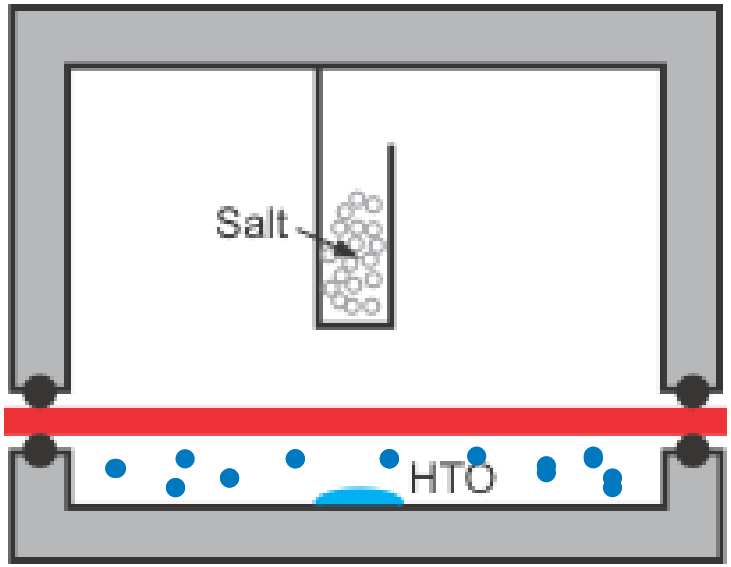
1 g/m^2/day – 1×10^{-7} g/m^2/day

Pros: sensitivity, multiple permeates simultaneously

Cons: cost; throughput; limited temp/humidity

Radioactive Tracer





Standard: None

Measurement:

Ionization: $i(t) => molT(t) => molH_2O(t) => WVTR$

Scintillation: $I(t) => molT(t) => molH_2O(t) => WVTR$

Sensitivity Limits:

1 g/m^2/day – 1×10^{-6} g/m^2/day

Pros: sensitivity; throughput

Cons: radioactivity; 100% RH

R. Dunkel *et al., Proceedings of the IEEE, vol. 93, p. 1478, 2005.*

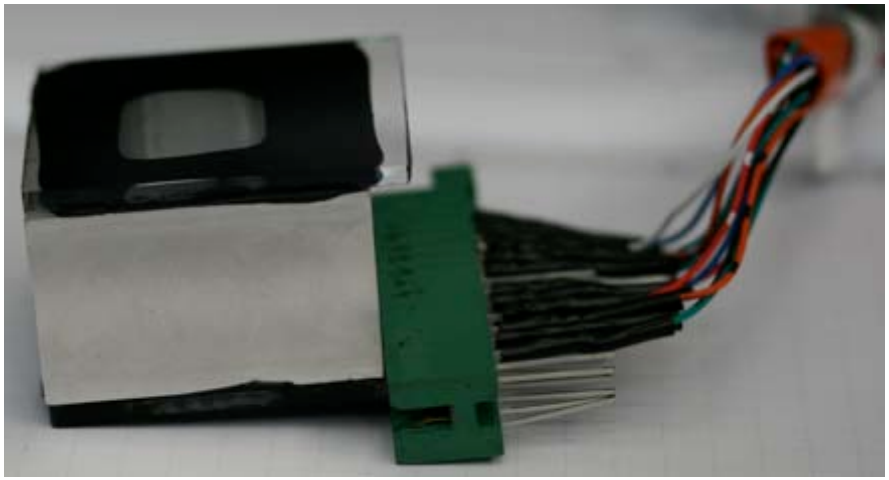
NREL's Ca Test

Electrical Ca Test (0.1 mΩ resolution)

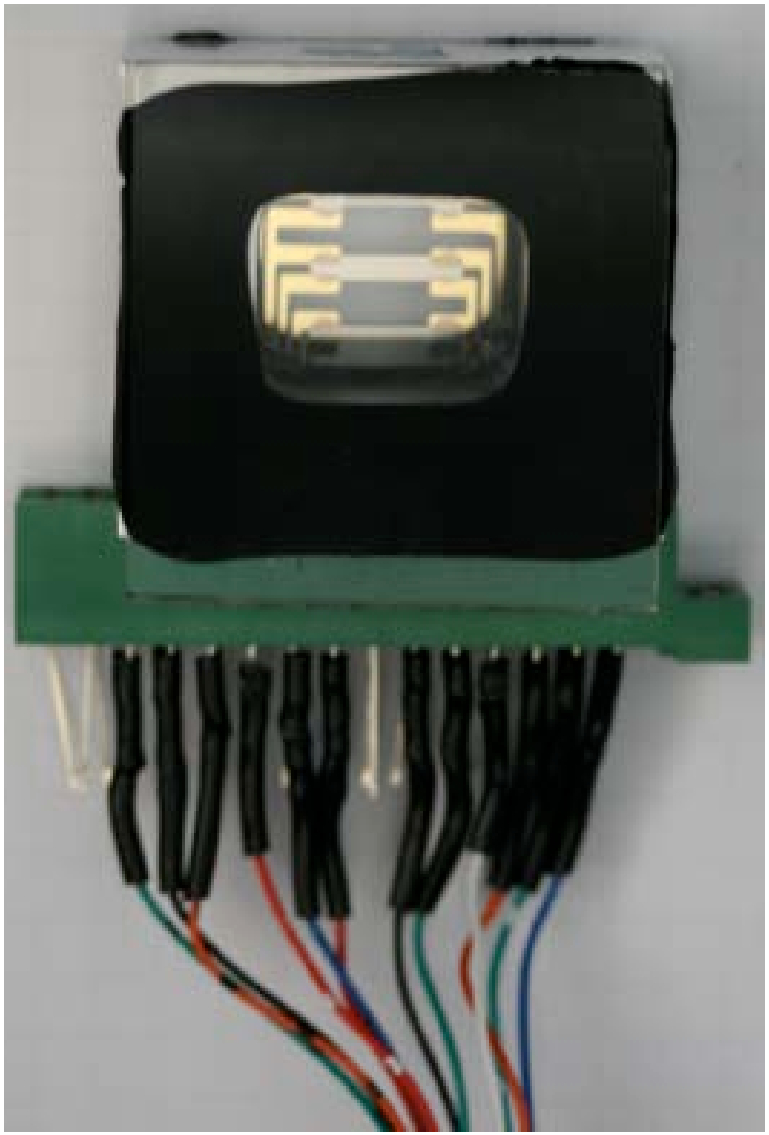
Easily configurable test card & edge connector assembly
- fast setup
- no need to deposit Ca onto the barriers

16 tests simultaneously = high throughput

Variety of environmental conditions possible



Limits/Sensitivity



Sensitivity Limits

Theoretical:

~1×10^{-7} g/m^2/day

Current Experimental:

~1×10^{-5} g/m^2/day

Can measure WVTR @ 1×10^{-5} g/m^2/day within 24 h (post lag time)

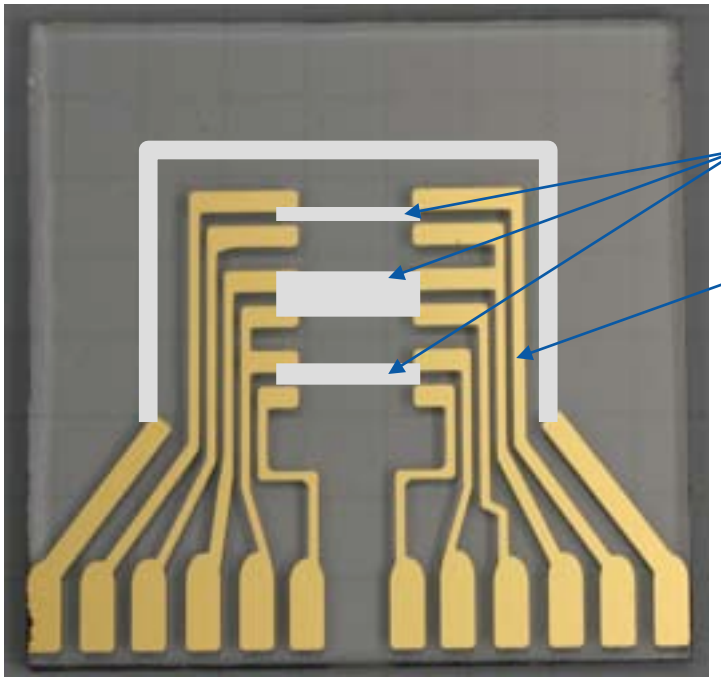
Test Setup

Each test card:

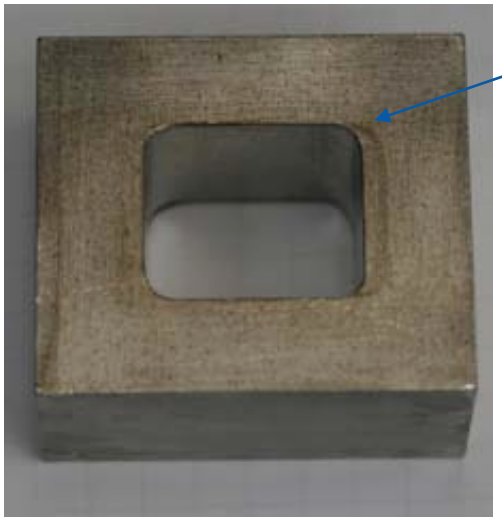
- Three 4-pt configured experimental traces
- 1 edge seal witness

Spacers:

- Variety of test areas possible
- Incorporated diffusion length to average out pinhole/defect effects

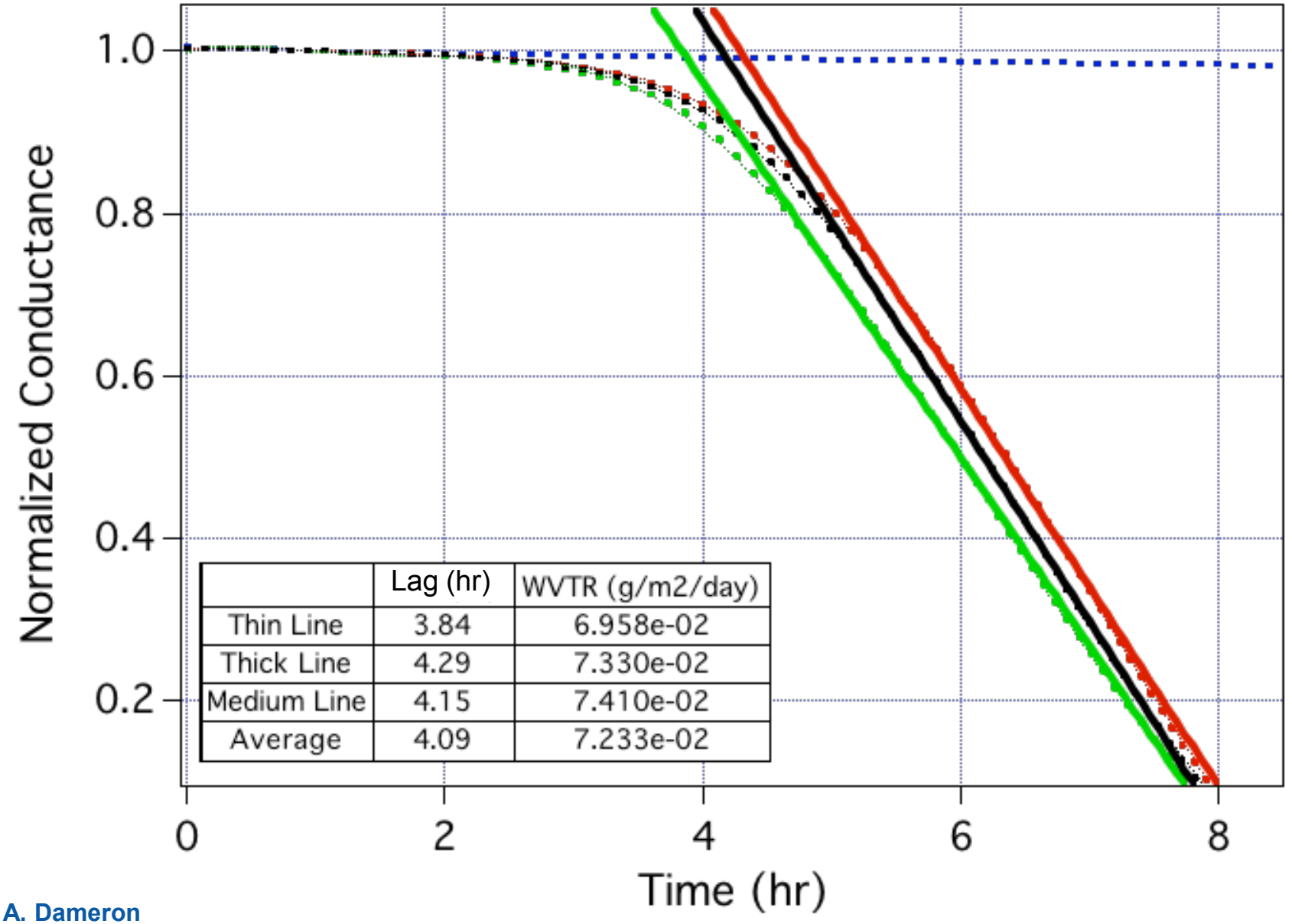


Spacers define the measured area





Example: 70 nm IZO on PEN 40C/85%RH



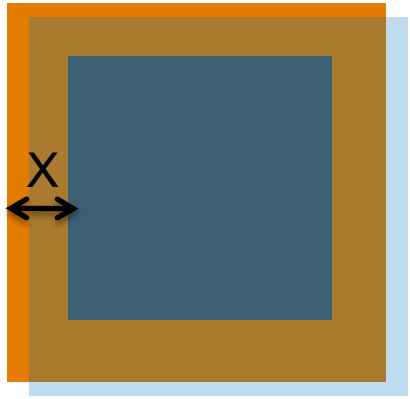
	Lag (hr)	WVTR (g/m2/day)
Thin Line	3.84	6.958e-02
Thick Line	4.29	7.330e-02
Medium Line	4.15	7.410e-02
Average	4.09	7.233e-02

Edge Seal Testing

Using the Ca Test concept as an effective means of evaluating edge seal materials similar to applied environment



Glass
100nm Ca
Edge Seal
Glass



Ca turns transparent appearing to shrink toward center

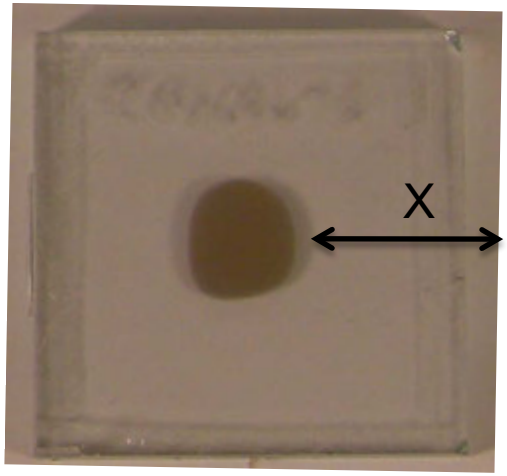
$$X = K\sqrt{t}$$

PDMS

85C/
85 %RH



0 h



3 h



4.5 h

Polyisobutylene 1



115 h

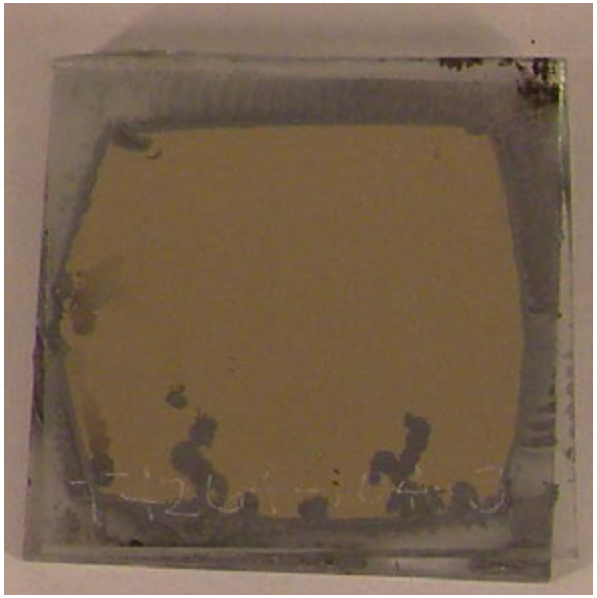
1488 h

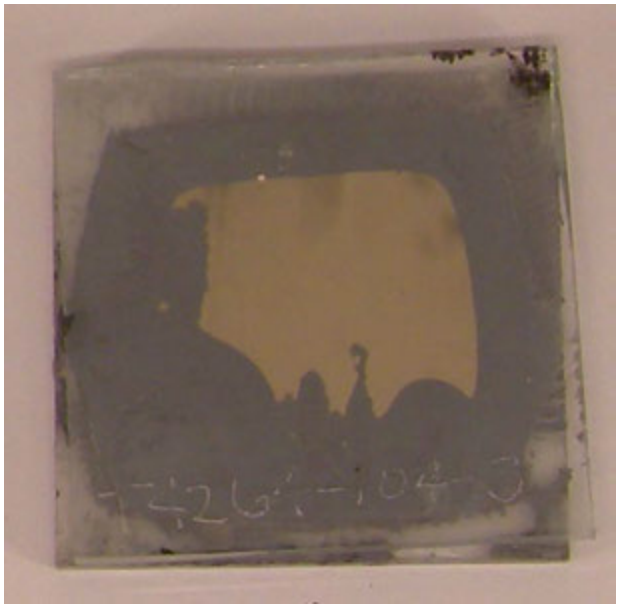
3509 h

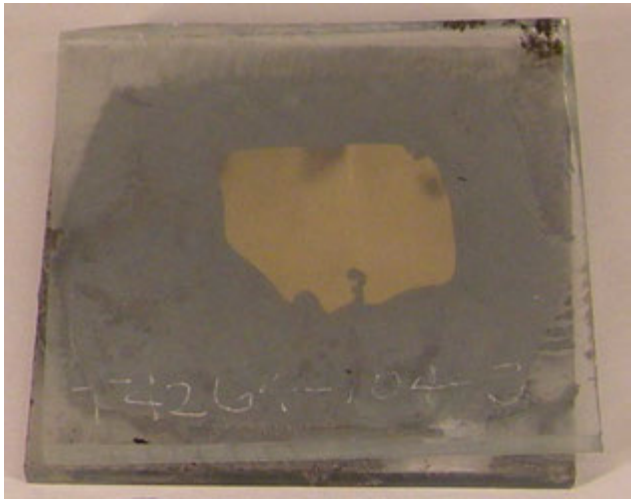


Glass
100nm Ca
Edge Seal
Glass

Polyisobutylene 2







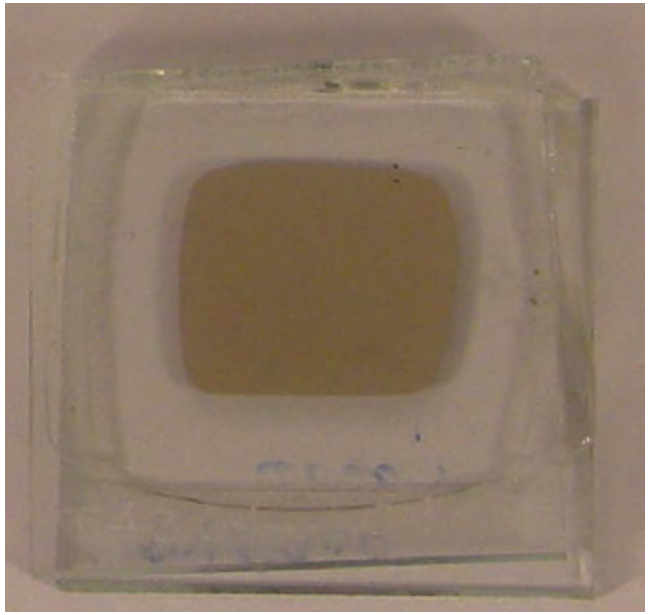
3 h **652 h** **1227 h**



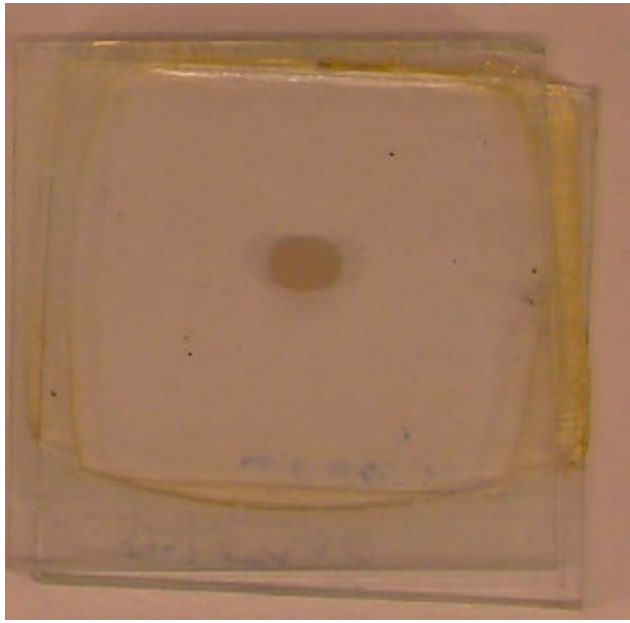
Ionomer



3 h



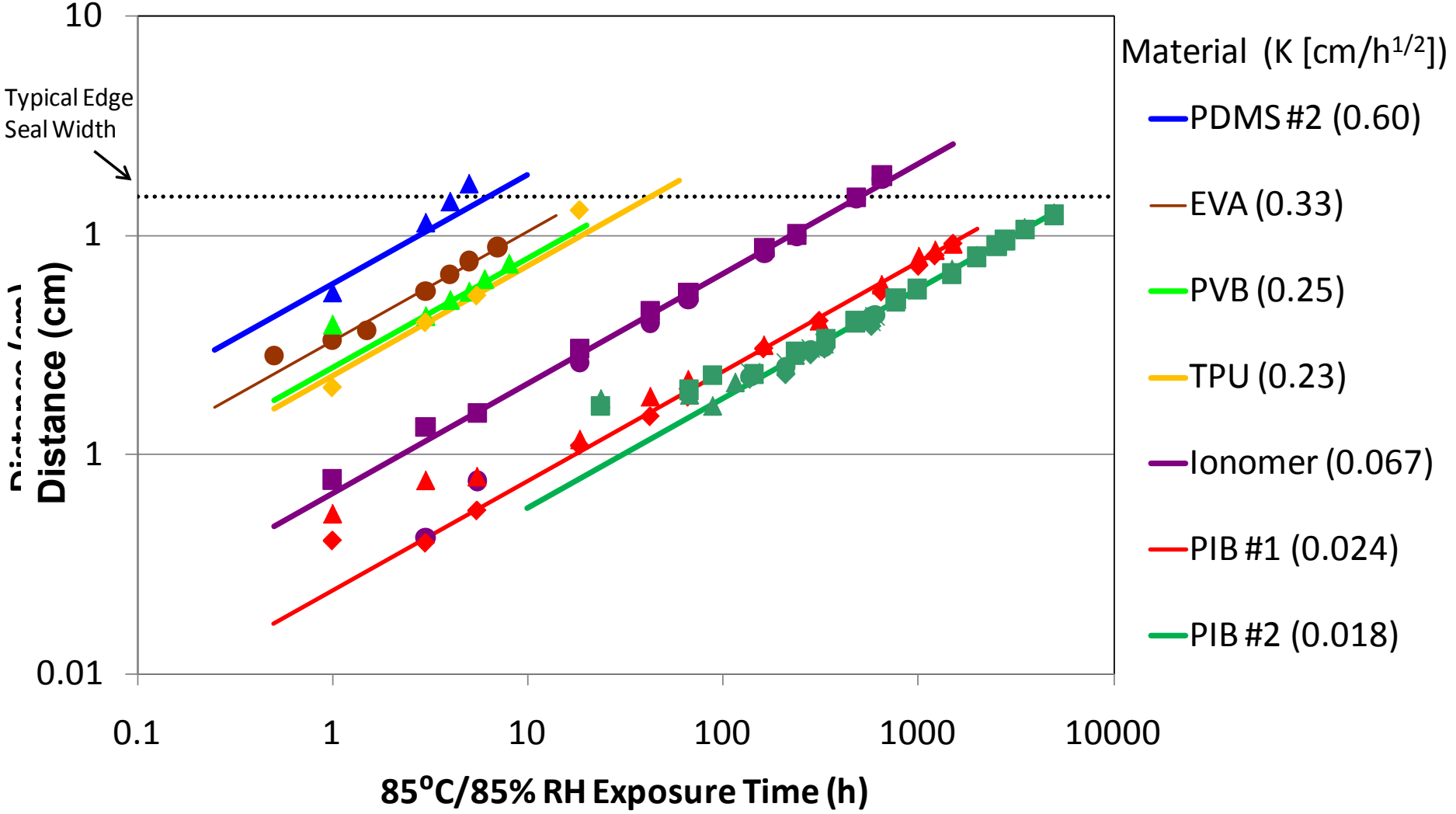
162 h



652 h



Relative Comparison of Materials



Conclusions

There are several techniques to quantifiably measure moisture permeation through thin films

At NREL we are working to improve existing barrier evaluation methods and developing routes to evaluate and compare edge seal materials in their applied environment

Georgia Institute of Technology

*E*lectronics *M*anufacturing and *R*eliability *L*aboratory

Approaches to Barrier Coatings for the Prevention of Water Vapor Ingress



Samuel Graham

Woodruff School of Mechanical Engineering
and the
Center for Organic Photonics and Electronics
Georgia Institute of Technology



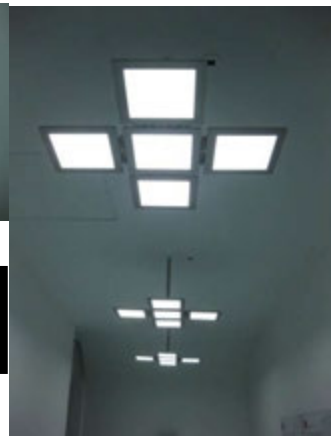
NSF MDITR

CIS:SEM
Center for Interface Science : Solar Electric Materials

COPE
Center for Organic Photonics and Electronics

Motivation for Thin Film Barrier Development





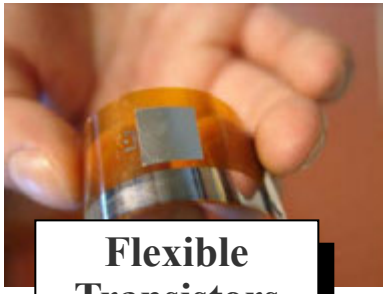
Solid State Lighting





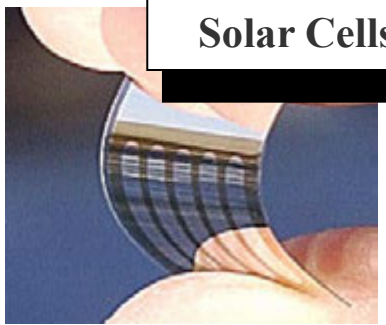
Displays



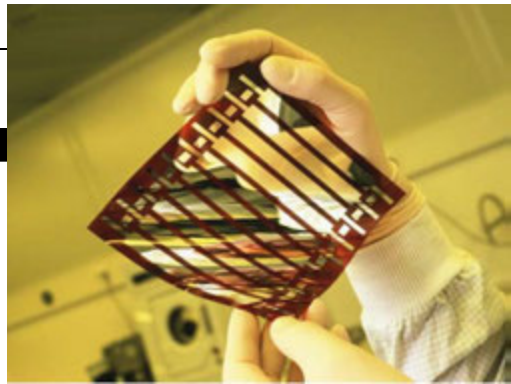




Flexible Transistors



Solar Cells



Reliability issues: device encapsulation

Need for Barrier Layers

• Highly reactive electrodes and active layers are very sensitive to water vapor and oxygen.

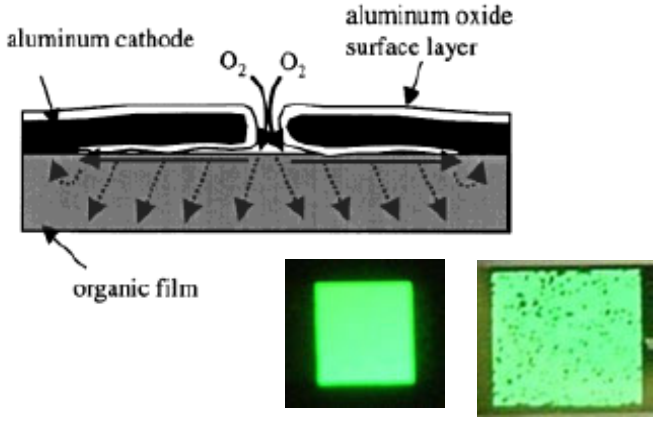
• Advancements in materials can reduce sensitivity, but not eliminate environmental degradation.

Must address:

⇒**Development of high barrier performance films.**

⇒**Process compatibility with device.**

⇒**Extending technology to large areas and devices with topography.**



Mechanical Concerns

• Inorganic layers found in encapsulation are generally very brittle and may crack during bending.

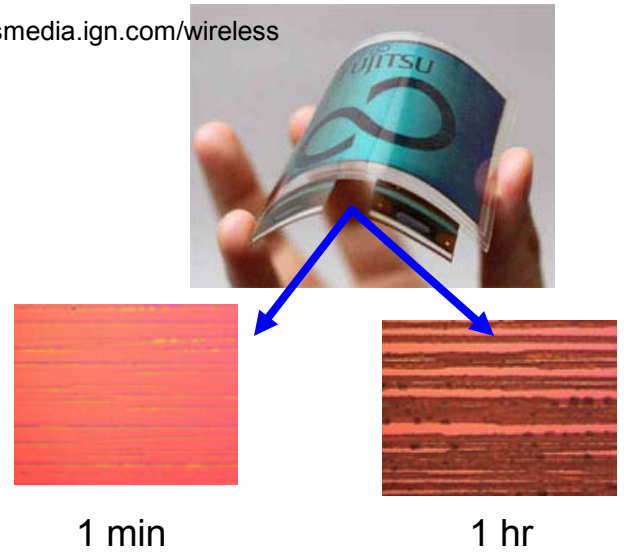
• Internal stresses from processing can impact the reliability of the encapsulation.

Must address:

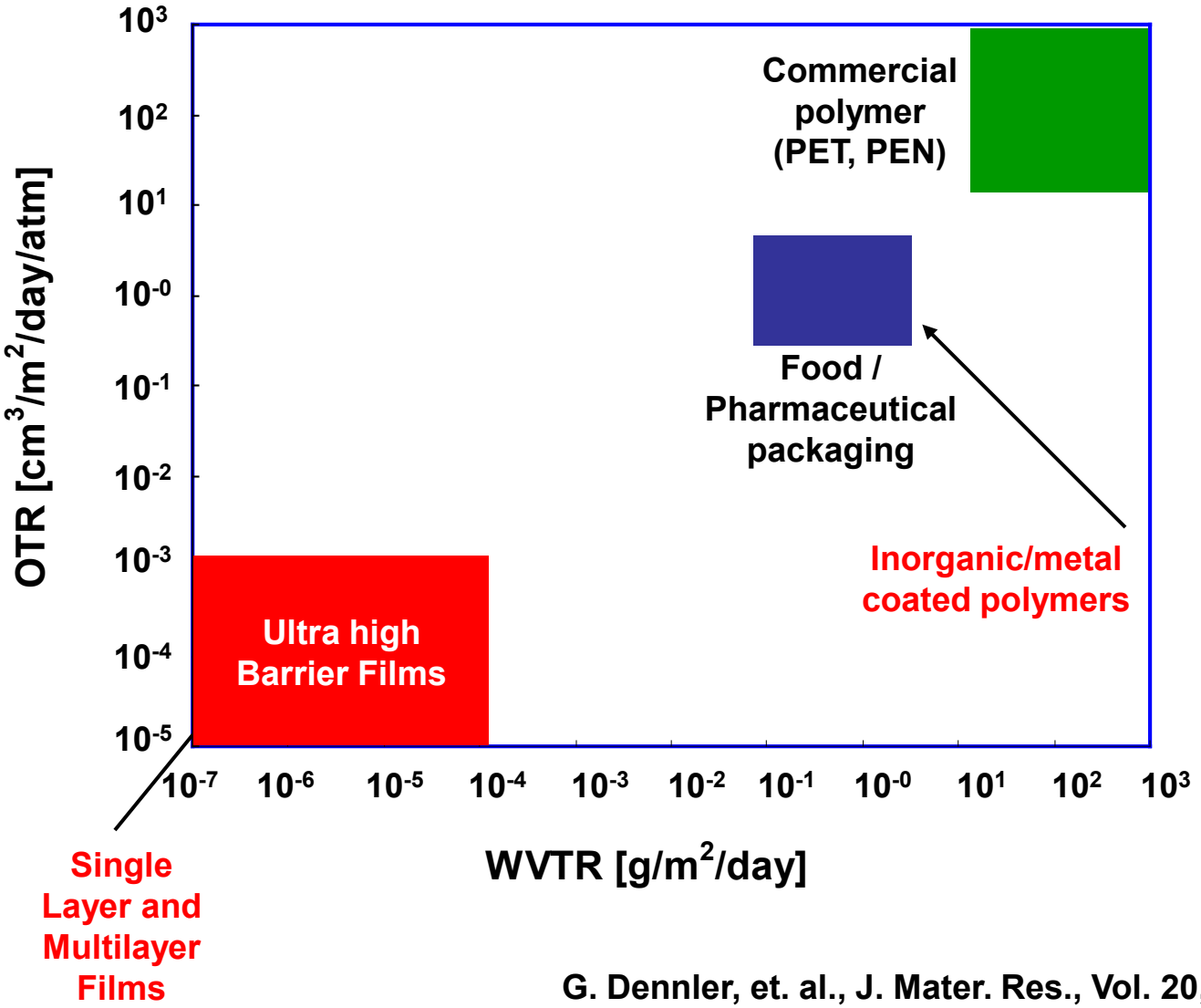
⇒ **Mechanically robust barrier layers.**

⇒**Adhesion and stress management.**

http://wirelessmedia.ign.com/wireless/image/article



Encapsulation Performance Needs





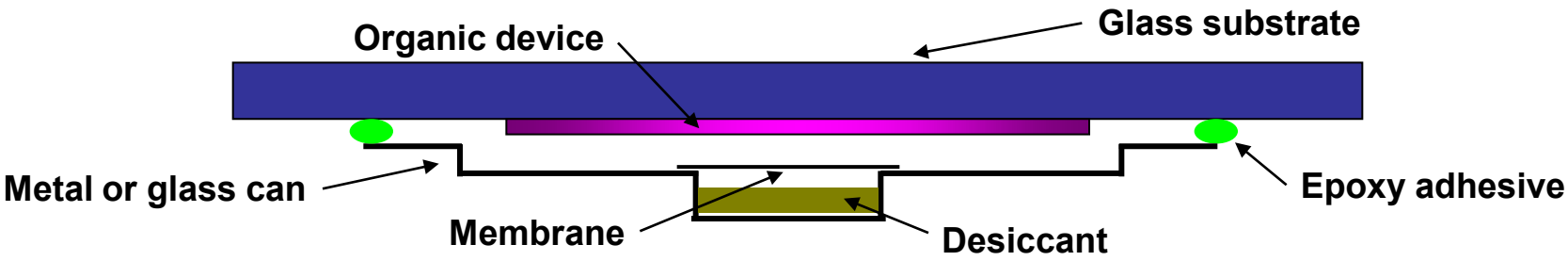


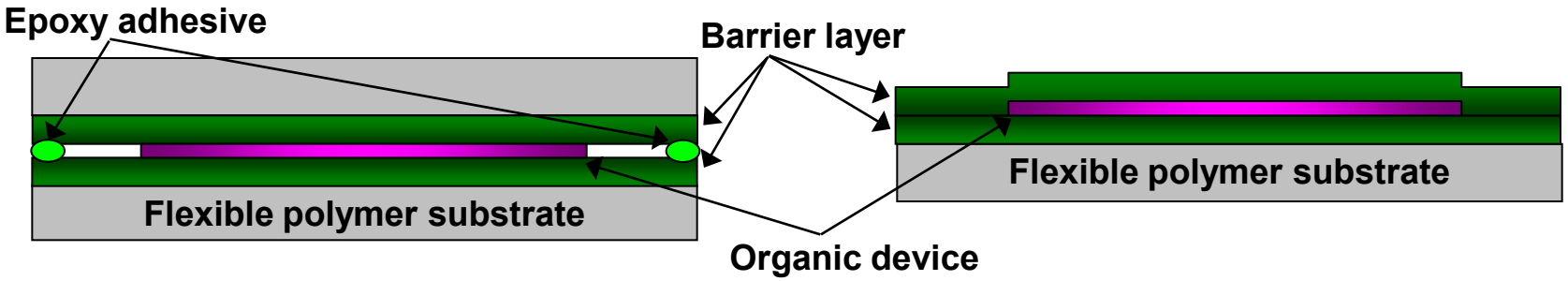


G. Dennler, et. al., J. Mater. Res., Vol. 20, No. 12, Dec 2005. Vol.20, 3224

Encapsulation Structures

heavy, thick, rigid,
side permeation through epoxy





+ : flexible, light

- : need to fabricate barrier layer on both substrates, side permeation

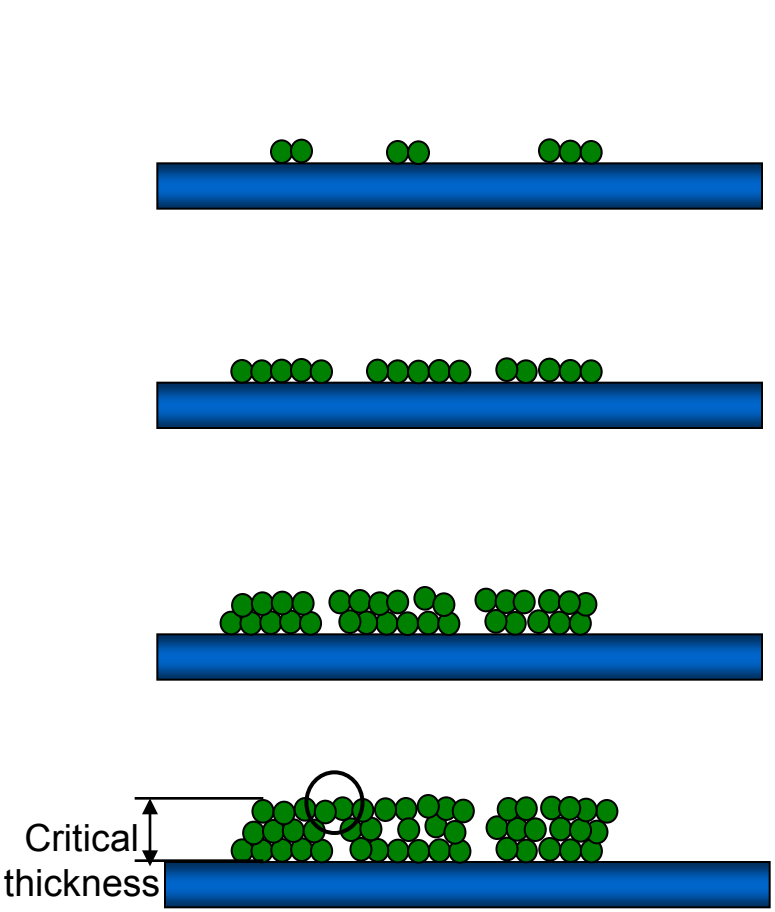
+ : thin, very flexible, light, no side permeation

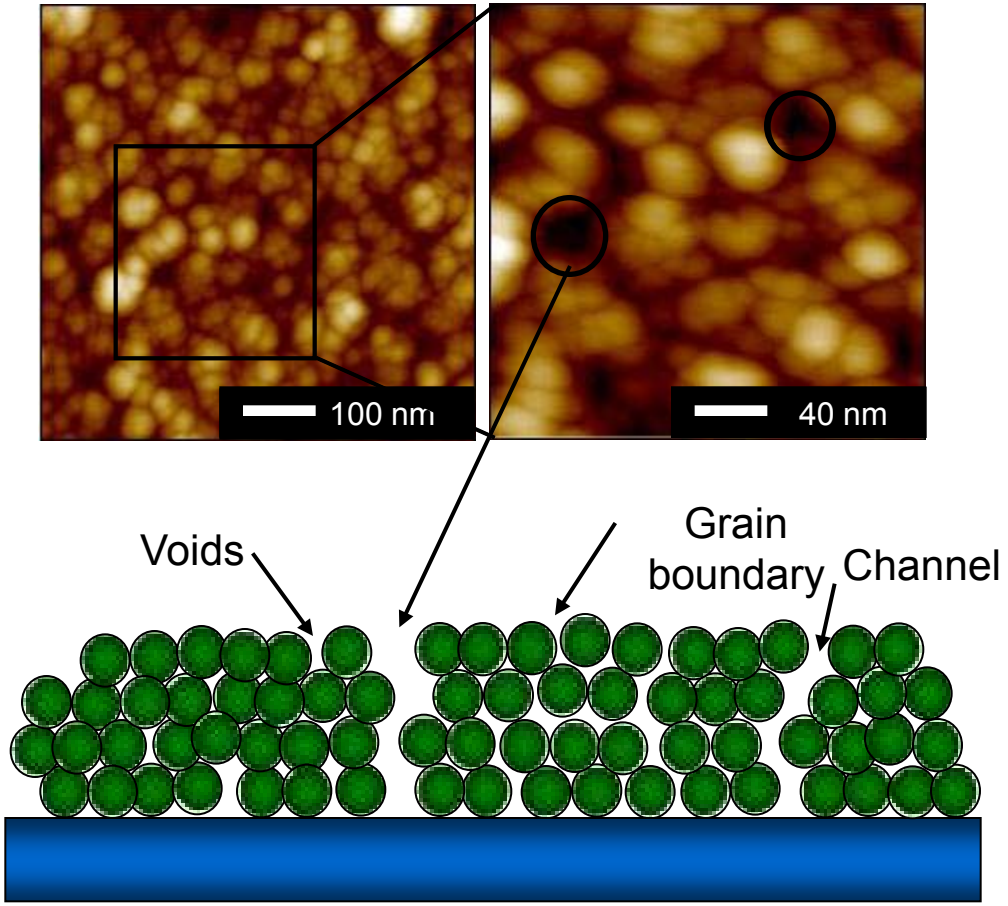
- : need to fabricate barrier layer

J. S. Lewis, et. al., *IEEE Journal of Selected Topics in Quantum Electronics* 2004, *10*, 45-57

Defects in Barrier Films

Single Layer Thin Films



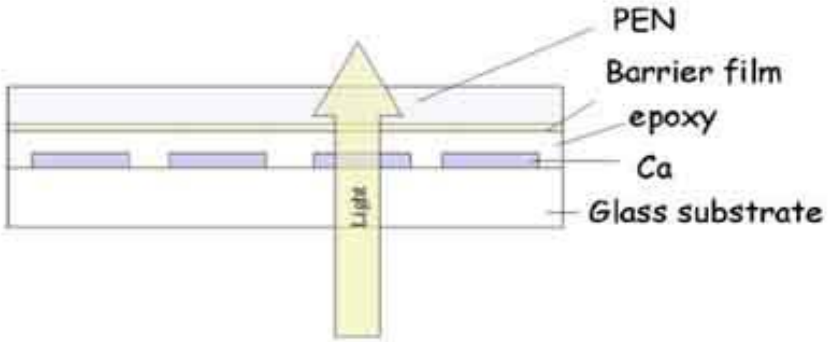


Thin Film Encapsulation Methods

High Quality Single Layer Encapsulation: Al_2O_3

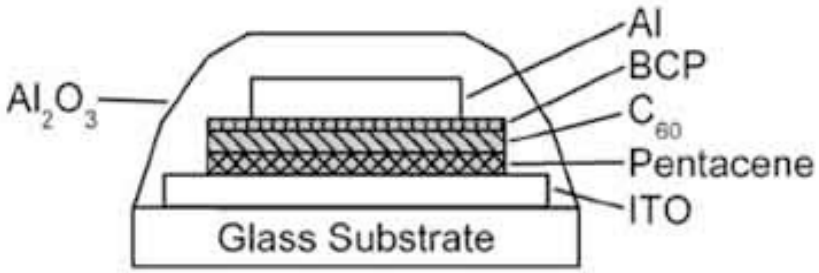
High density, pinhole free, conformal deposition

Permeation governed by nanoscale defects vs macrodefects.

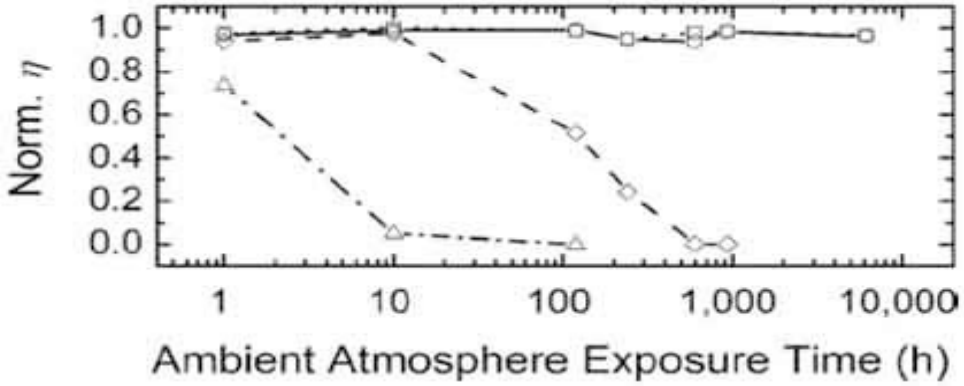


Structure	PEN/ Al_2O_3
Deposition	ALD
WVTR [g/m^2/day]	1.7x10^{-5}
Test condition	38°C and 85% R.H.

P. F. Carcia, R. S. McLean, M. H. Reilly, M. D. Groner, S. M. George, *Applied Physics Letters* **2006**, *89*, 031915.



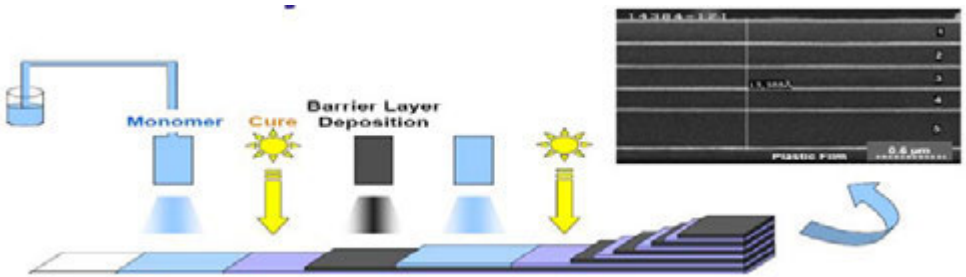
200 nm Al_2O_3 by ALD



W. J. Potscavage, S. Yoo, B. Domercq, B. Kippelen, *Applied Physics Letters* **2007**, *90*, 253511

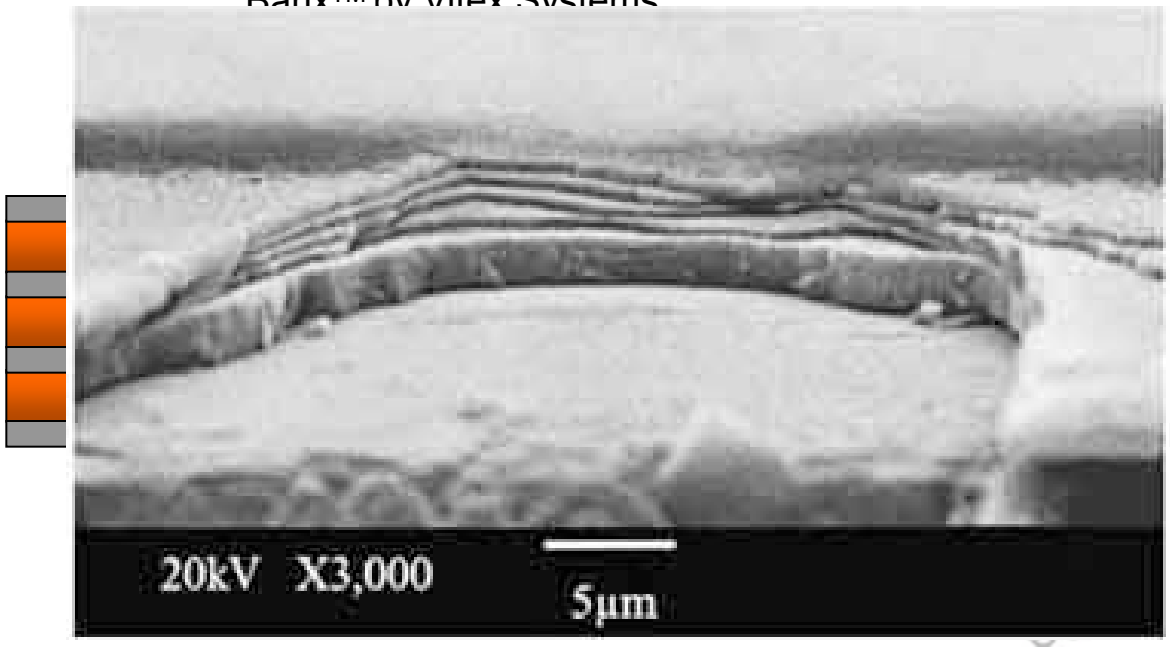
Thin Film Encapsulation Methods

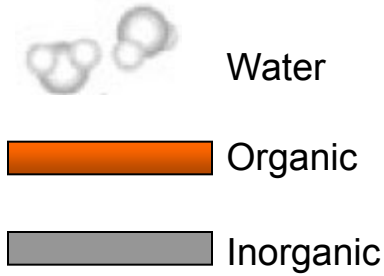
Multilayer Encapsulation



Barix™ by Vitex Systems

Structure	Al_2O_3/ Polyacrylate
Deposition	DC Sputtering, Evaporation/ UV curing
WVTR [g/m^2/day]	Maximum: 2.1×10^{-6}
Test condition	20°C, 50% R.H.

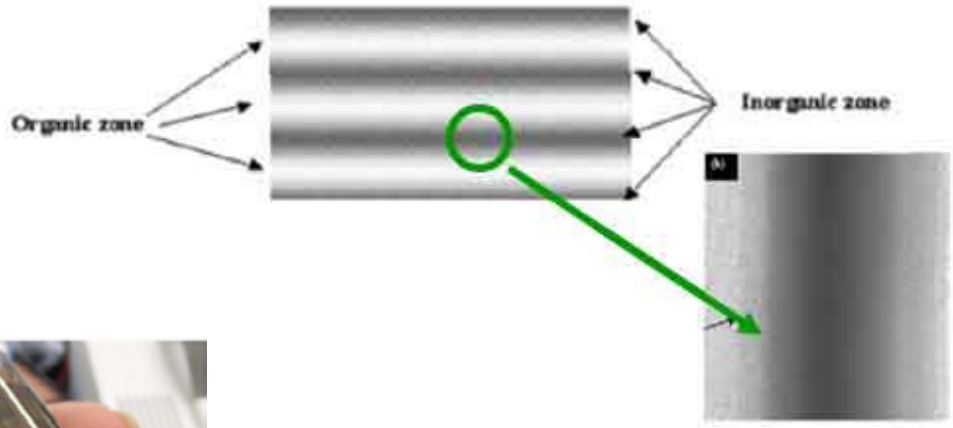




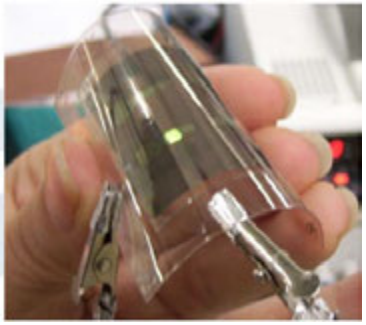
M. S. Weaver, L. A. Michalski, K. Rajan, M. A. Rothman, J. A. Silvernail, J. J. Brown, P. E. Burrows, G. L. Graff, M. E. Gross, P. M. Martin, M. Hall, E. Mast, C. Bonham, W. Bennett, M. Zumhoff, *Applied Physics Letters* **2002**, *81*, 2929.
G. Nisato, *Prod. Soc. Info. Display Symp., Digest Tech, Papers* **2003**, *34*, 550.

Thin Film Encapsulation Methods

Graded organic and inorganic layer (GE, Shaepkens, et al., JVST 2004)

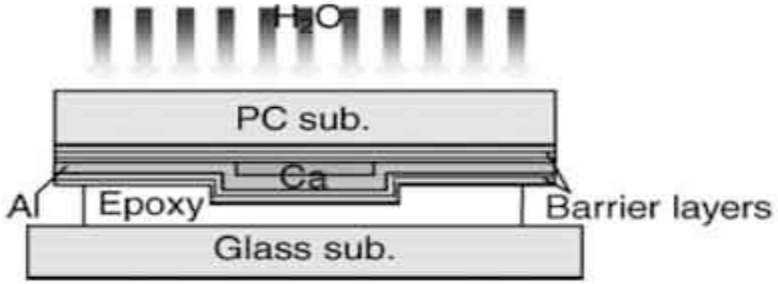


Structure	SiOxNy/ SiOxCy
Deposition	PECVD
WVTR [g/m^2/day]	5x10^{-5} ~ 5x10^{-6}
Test condition	23°C, 50% R.H. for 20 days



IMRE, Singapore

Multi layer Plus Bonding (Chen, et al., Plasma Process and Polymers 2007)



Structure	3 pairs SiOx/SiNx/ + Parylene + 3 pairs SiOx/ SiNx
Deposition	PECVD, PVD
WVTR [g/m^2/day]	Maximum: 2.5x10^{-7}
Test condition	23°C and 40% R.H. for 75 day

Processing of Barrier Films

Materials Used



PECVD: SiOx, SiNx



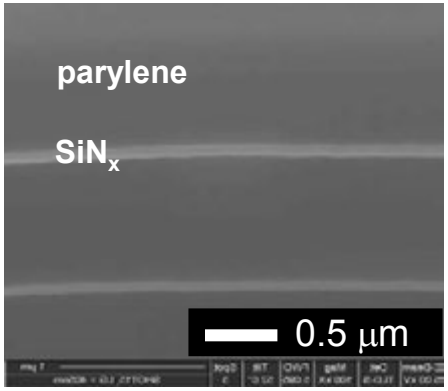
PVD: Parylene

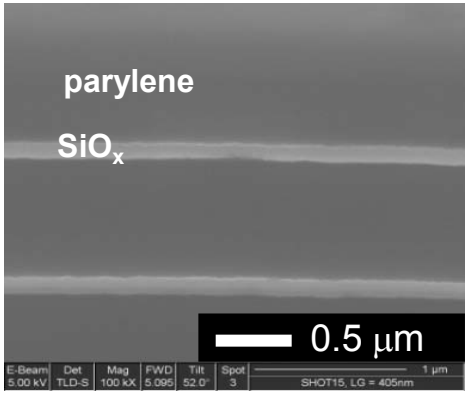


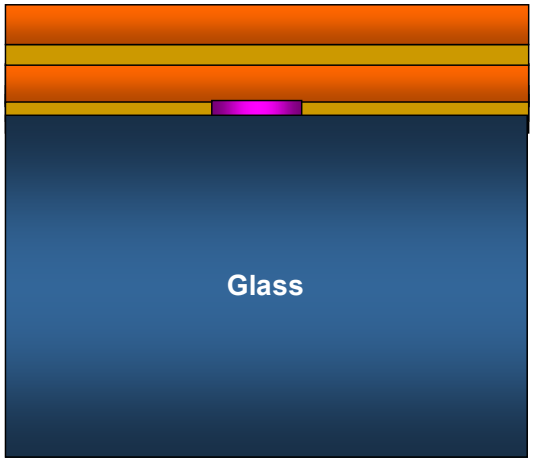
ALD: Al_2O_3



Environmental Chamber

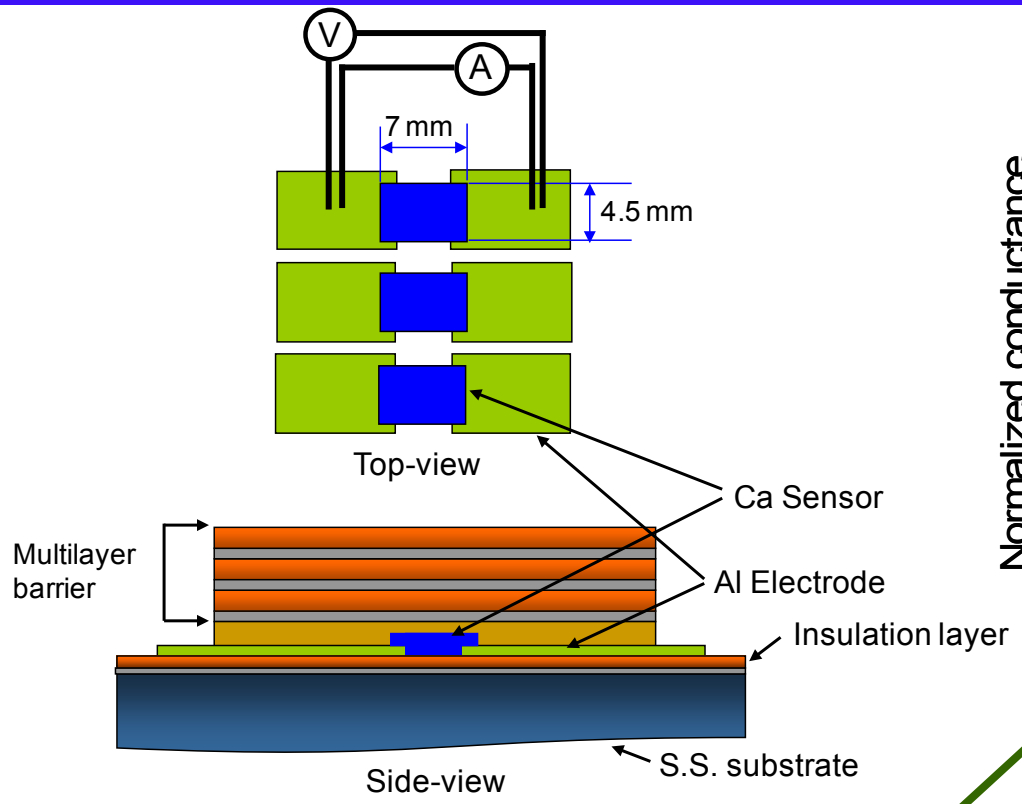


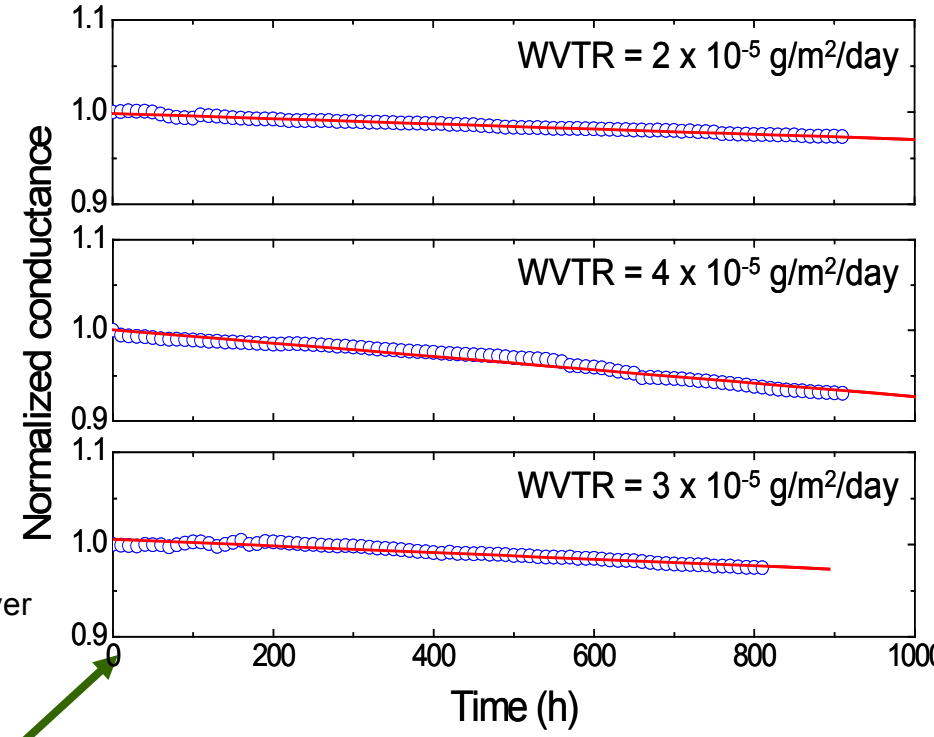




Measured by Ca Corrosion Method at 50 % R.H. and 20 °C

Ca Corrosion Tests





$$WVTR[g/m^2/day] = 2\delta_{Ca} \times \rho_{Ca} \times \frac{dG_S}{dt} \times \frac{M(H_2O)}{M(Ca)} \times \frac{Ca_Area}{Window_Area}$$

ρ_{Ca} 1.55 g/cm^3

δ_{Ca} 3.4*10^{-6} cm Ω

$G_s = 1/R_s = (W/L)*(1/R)$

L : Length of Ca

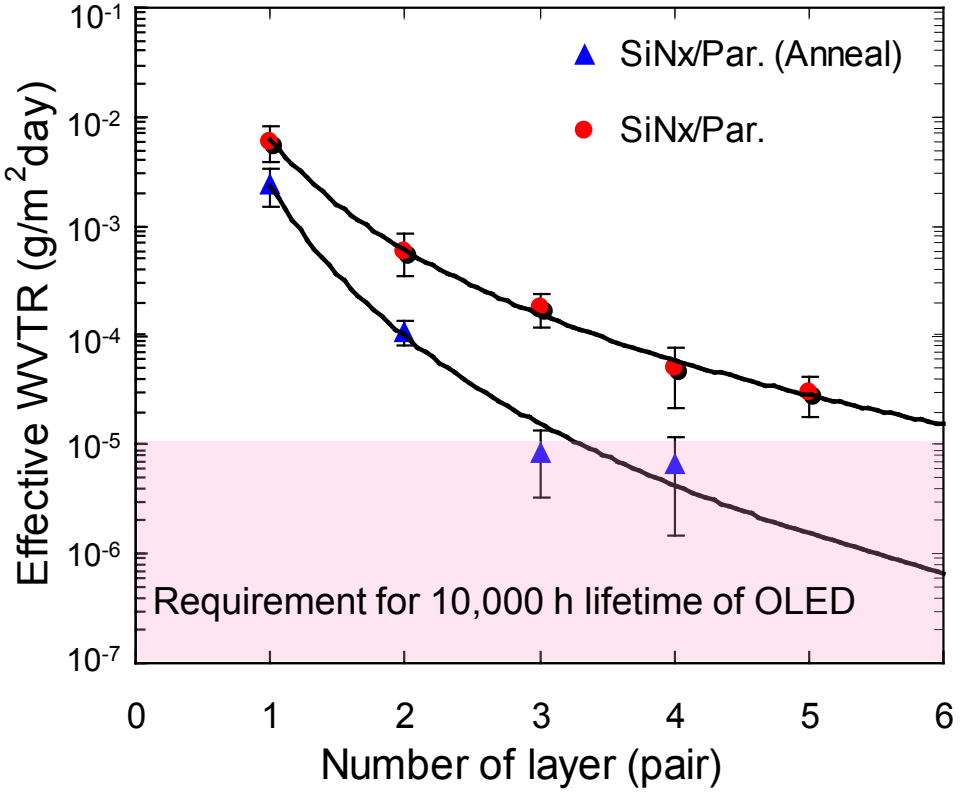
W : Width of Ca

$M(H_2O)$ 18 amu

M(Ca) 40.1 amu

R. Paetzold, et. Al., Rev. of Sci. Inst., 2003, 74, 5147

Multilayer Results



No. of Layers [pairs]	WVTR [g/m²/day]		Decrease in WVTR [%]
	Before annealing	After annealing	
1	4.3×10^{-3}	2.4×10^{-3}	**44**
2	4.4×10^{-4}	1.3×10^{-4}	**70**
3	1.3×10^{-4}	7.3×10^{-6}	**94**
4	4.4×10^{-5}	6.6×10^{-6}	**85**

SiOx/ Parylene (3 pairs)

8.4×10^{-4} ► 6.6×10^{-5} (g/m²/day), (85 %↓)

Mass Transport in Barrier Films

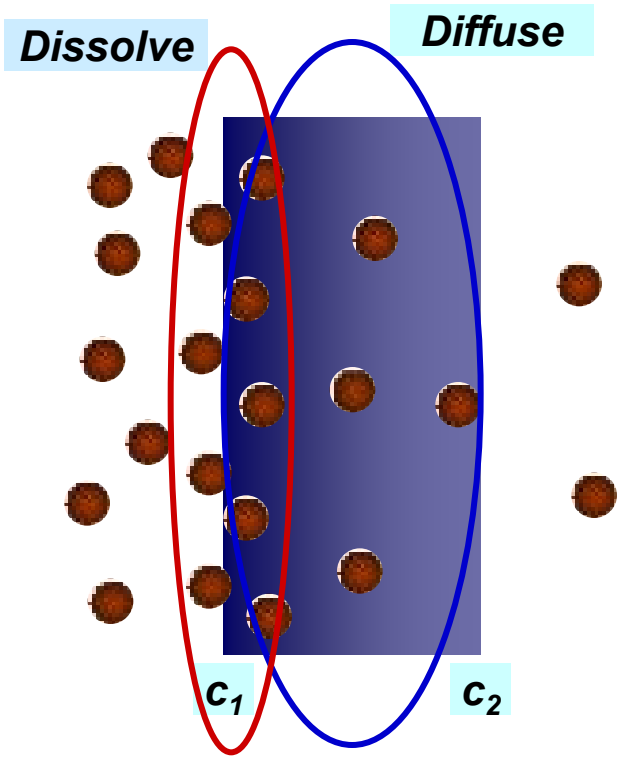
Principles of permeation

$$P = DS$$

P : Permeation coefficient (permeability)

D : Diffusion coefficient, determines how **fast** the permeant can **move** in the media

S : Solubility coefficient, determines how **much** of the permeant can **be dissolved in in the film**



Driving force

$$J = -D(\frac{\partial c}{\partial x}) \qquad \textit{Fick's first Law}$$

$$\rightarrow c = Sp \qquad \textit{Henry's Law}$$

$$J = DS\frac{\Delta p}{l}$$

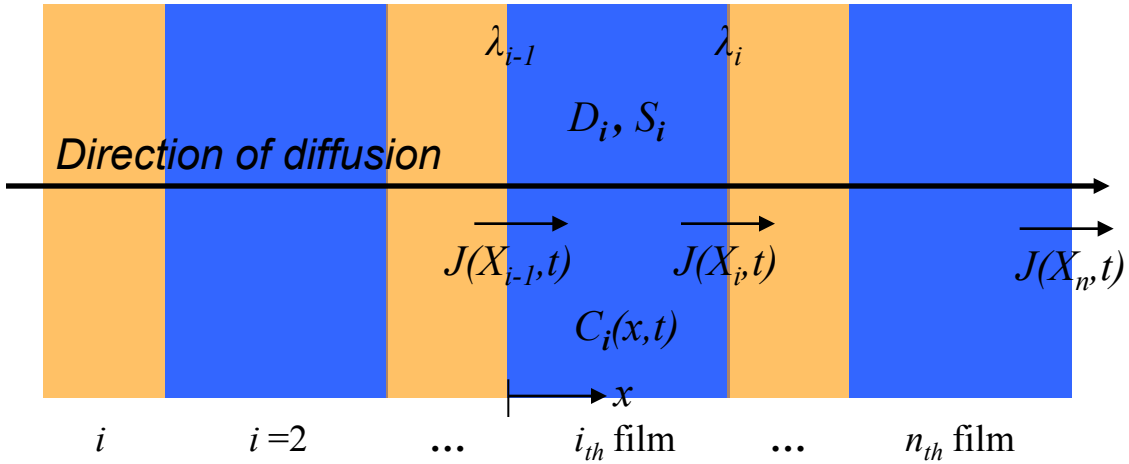
J : Flux of permeant

$\partial c / \partial x$: concentration gradient

p : Partial pressure of permeant

Mass Transport in Barrier Films

Diffusion in multilayer structure



D_i (diffusivity),
S_i (Solubility),
L_i (thickness)-fixed
Defect spacing

WVTR, Lag time

WVTR calculation

$$WVTR \Leftrightarrow \frac{P_{total} \cdot \Delta p}{L_{total}}$$

Δp : pressure drop
L_{total} : thickness

For inorganic layers, use effective permeability

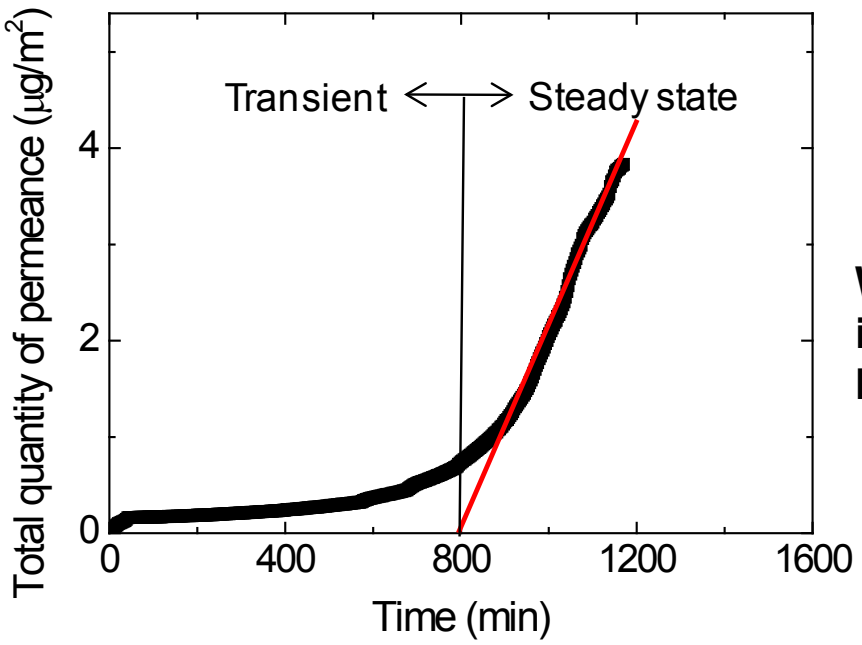
$$\frac{L_{total}}{P_{total}} = \frac{1}{\frac{L_1}{P_1} + \frac{L_2}{P_2} + \frac{L_3}{P_3} + \cdots + \frac{L_n}{P_n}}$$

Lag time calculation

$$L = \left(\sum_{i=1}^{n} \frac{L_i}{D_i} \prod_{j=1}^{i-1} k_j\right)^{-1} \sum_{i=1}^{n} \left\{\frac{L_i^2}{2D_i} \sum_{i=1}^{n} \left[\frac{L_m^2}{D_m} \prod_{j=1}^{i-1} k_j\right] - \frac{L_i^3}{3D_i^2} \prod_{j=1}^{i-1} k_j\right\} + \sum_{i=1}^{n} \left\{\frac{L_I}{D_I} \prod_{j=1}^{i-1} k_j \sum_{\beta=i+1}^{n} \left[\frac{L_\beta}{\prod_{j=1}^{\beta-1} k_j} \sum_{m=\beta}^{n} \left(\frac{L_m}{D_m} \prod_{j=1}^{m-1} k_j\right) - \frac{L_\beta^2}{2D_\beta}\right]\right\}$$

$$where, k_j = \frac{k_j}{k_{i+1}}$$

Mass Transport in Barrier Films



We have seen lag times greater than 1000 hours in our films.
Impacts the WVTR measured.

Lag Time: 1300 hours

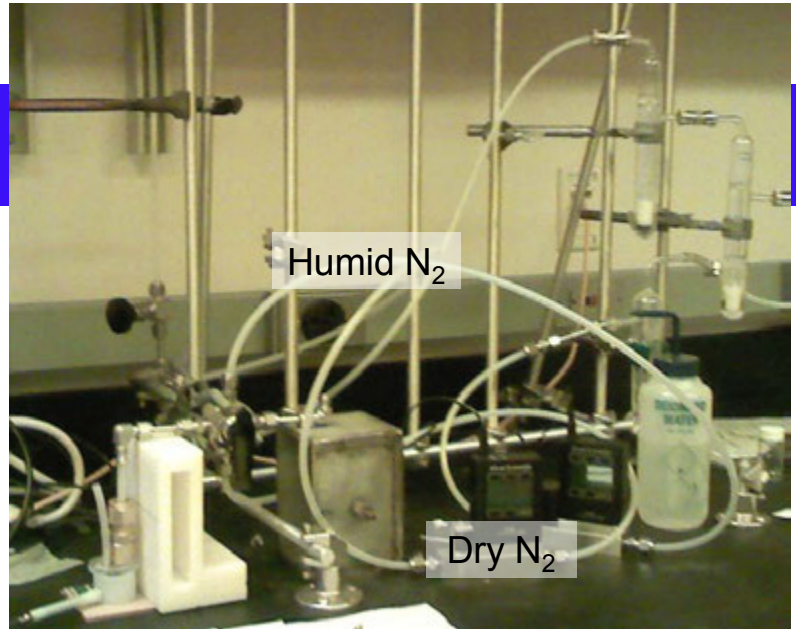
Transient WVTR: 8×10^{-6} g/m^2/day

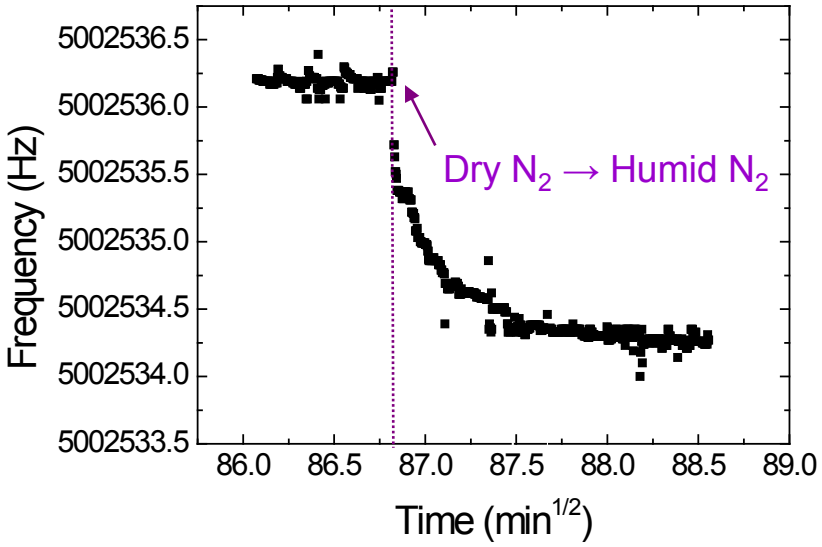
Steady State: 2×10^{-3} g/m^2/day

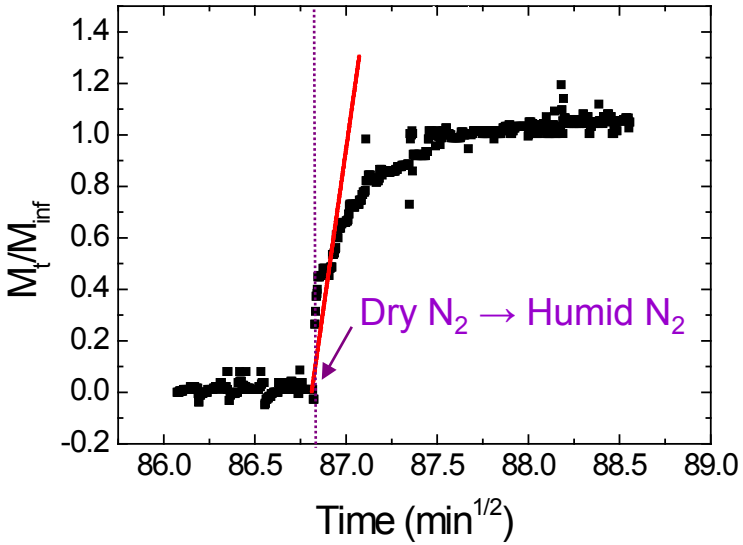
(Data not obtained from graph on left)

QCM









$$\frac{M_t}{M_\infty} = \frac{2}{L}\left(\frac{Dt}{\pi}\right)^{1/2}$$

M : Mass uptake

D : Diffusion coefficient

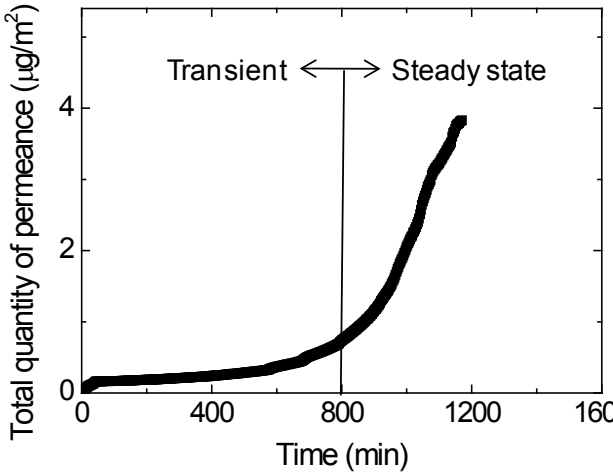
L: Thickness of film

Solution to Fick's 2nd law for short times (Valid only $M_t/M_\infty < 0.6$)

Diffusion Coefficient and Solubility

Diffusion Coefficient (cm^2/s)

Test #	Before Anneal	After Anneal for 10 min
Average	3.27×10^{-9}	2.06×10^{-9}
STDV	4.29×10^{-9}	1.01×10^{-10}



Solubility coefficient measurement

$$S = \frac{M_\infty}{M_0} \frac{\rho_{polymer}}{MW_{penetrant}} \times \frac{22,414}{p}$$

M_∞ : *Equilibrium mass uptake*
M_0 : *Mass of the water –free polymer*
$MW_{penetrant}$ *molecular weight (g/mole)*
p : *Vapor pressure [atm]*
22,241 : Conversion from moles to cm^3*(STP)*

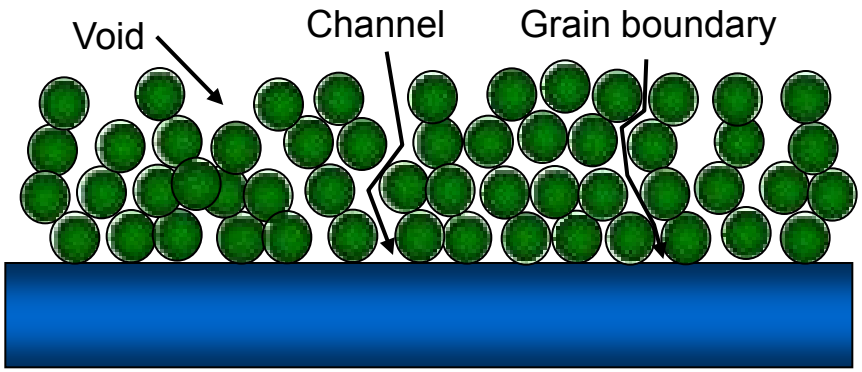
Solubility ($g/cm^3 atm$)

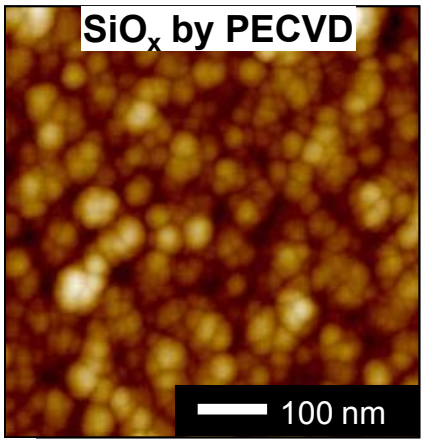
Test #	Before Anneal	After Anneal for 10 min
Average	0.286	0.140
STDV	0.054	0.044

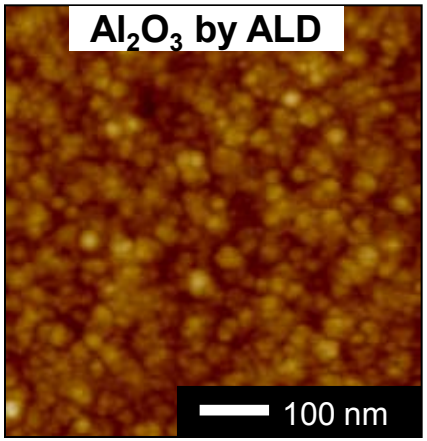
Initial water content in sample impacts the lag time and WVTR observed unless measured for a long time.

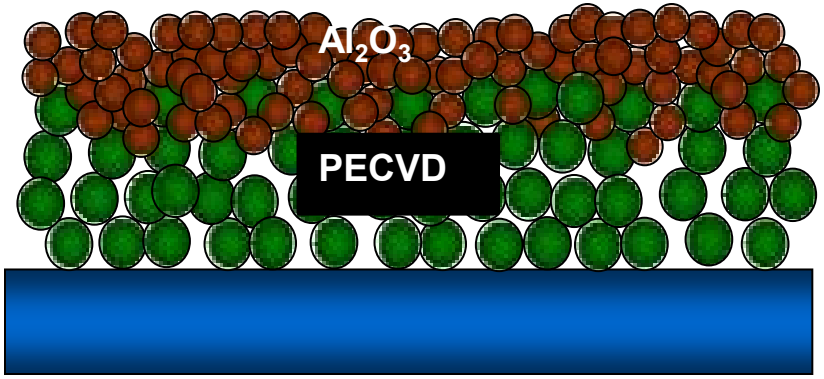
New Approach: Hybrid Architecture

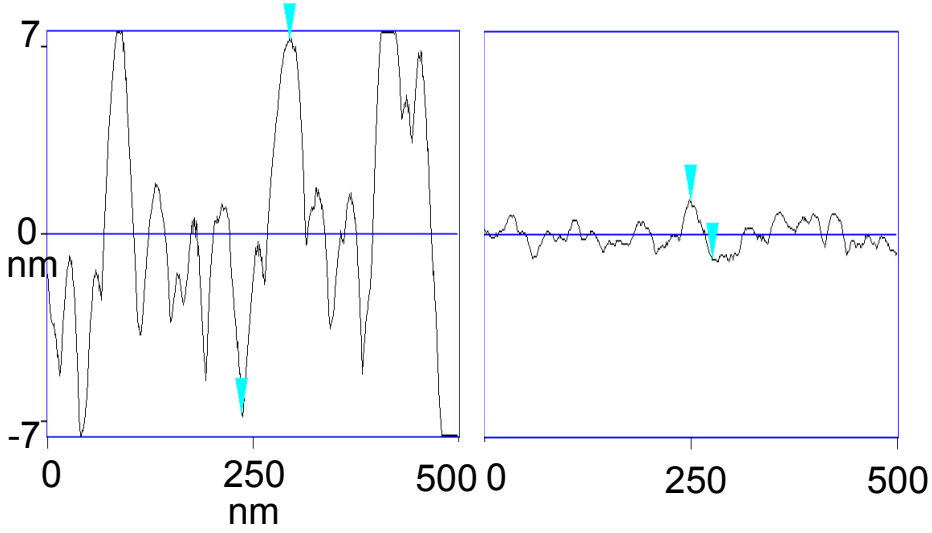
Combine rapid low temperature deposition by PECVD with high quality atomic layer deposition to simplify barrier architecture.







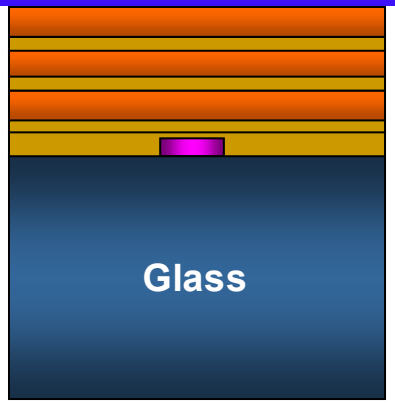




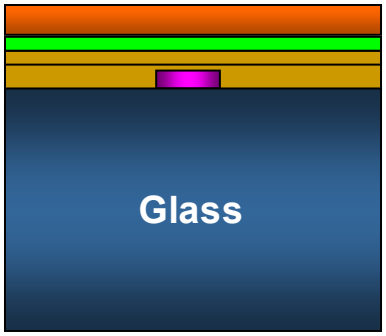
SiO_x by PECVD Al_2O_3 by ALD

Comparison of Results

Multilayer Film	**WVTR** ($g/m^2/day$)
3 dyads of SiOx/Parylene	$6 \pm 2 \times 10^{-5}$
3 dyads of SiNx/Parylene	$7 \pm 2 \times 10^{-6}$



Hybrid Architecture	**WVTR** ($g/m^2/day$)*
$SiOx/Al_2O_3$/Parylene	$2 \pm 1 \times 10^{-5}$
$SiNx/Al_2O_3$/Parylene	$3 \pm 2 \times 10^{-5}$



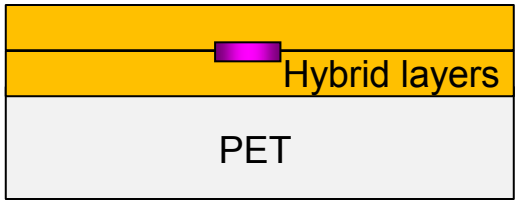
***Films contain 50 nm of Al_2O_3**

****Al_2O_3 layer 3 x 10^{-4} $g/m^2/day$**

Reducing ALD thickness: minimal impact!!!

Al_2O_3 thickness : 10 nm

SiO_x/Al_2O_3 /Parylene : **4 ± 0.5 x 10^{-5} $g/m^2/day$**



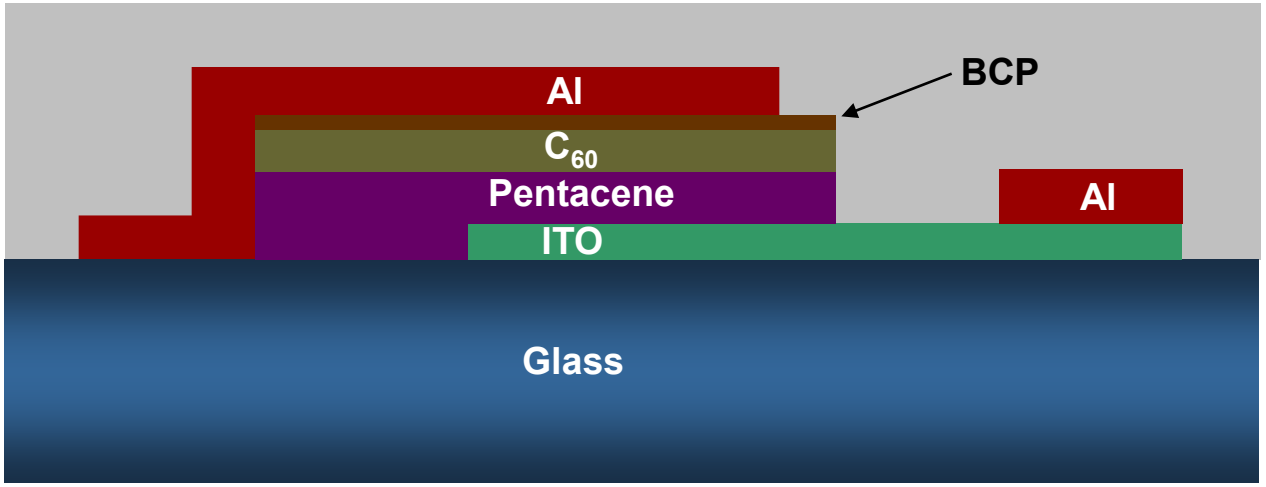
Coated PET Substrate

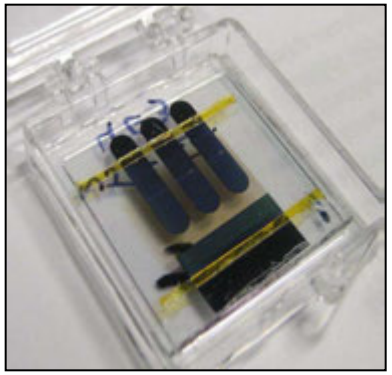
Al_2O_3 thickness : 50 nm

SiO_x/Al_2O_3 /Parylene : **2.5 ± 1.5 x 10^{-5} $g/m^2/day$**

Integration with OPVs

Device fabrication and encapsulation

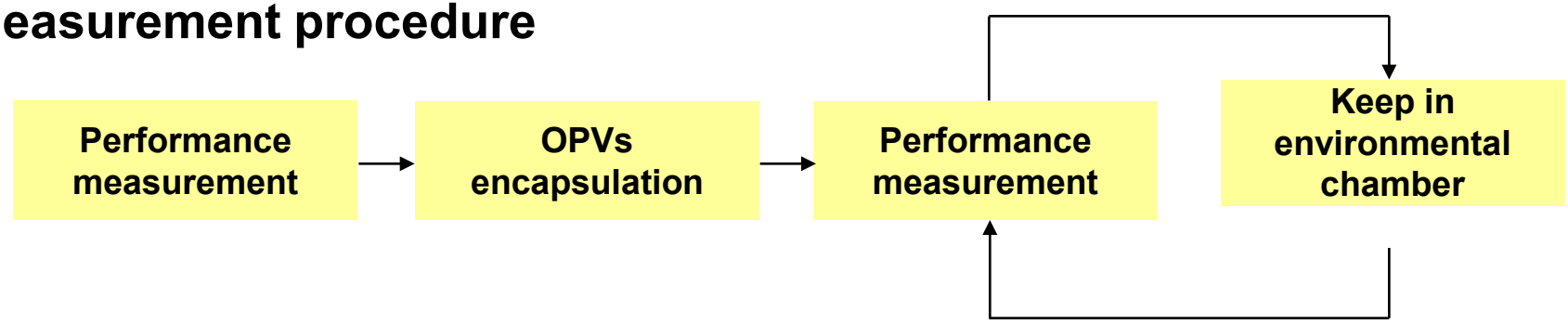




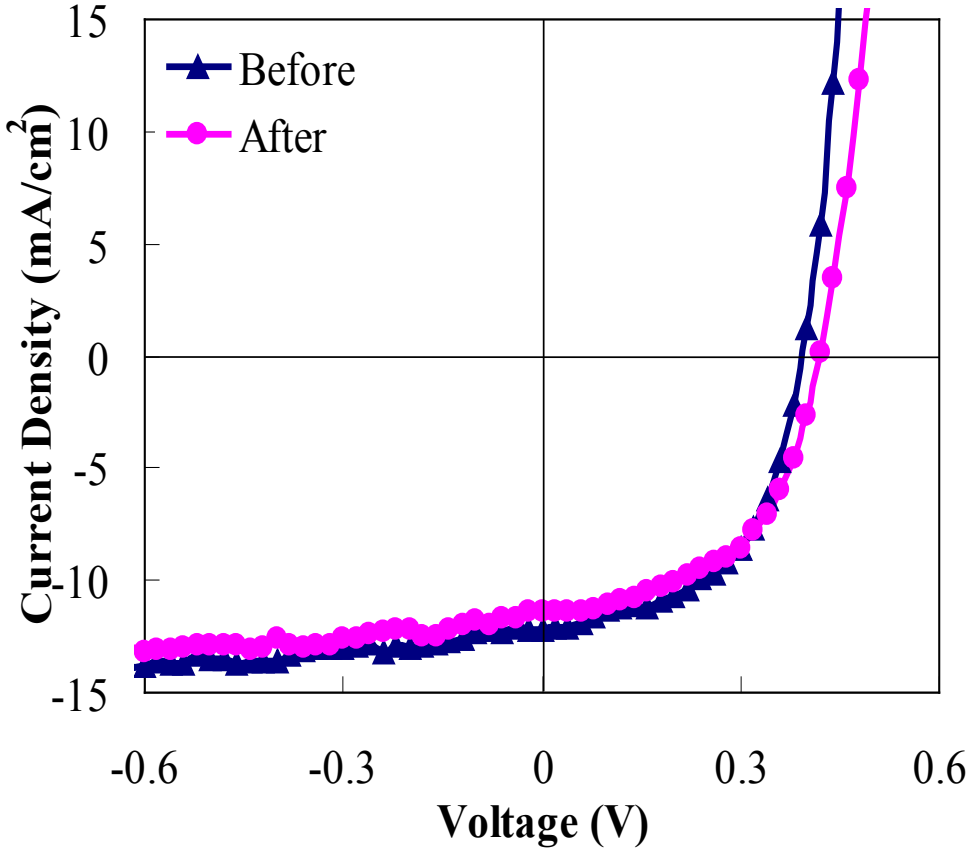
ITO/ Pentacene (50 nm)/ C_{60} (45nm)/ BCP (8 nm)/ Al

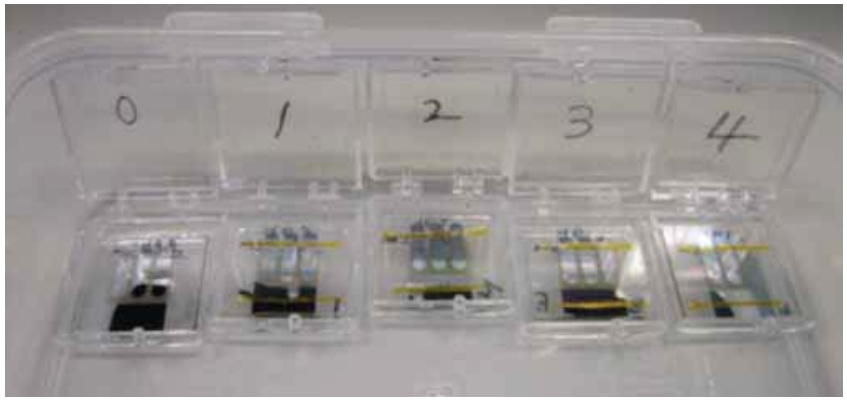
S. Yoo, et., Al., Appl. Phy. Lett., 2004, 85, 5427

Measurement procedure



Process Impact on OPVs



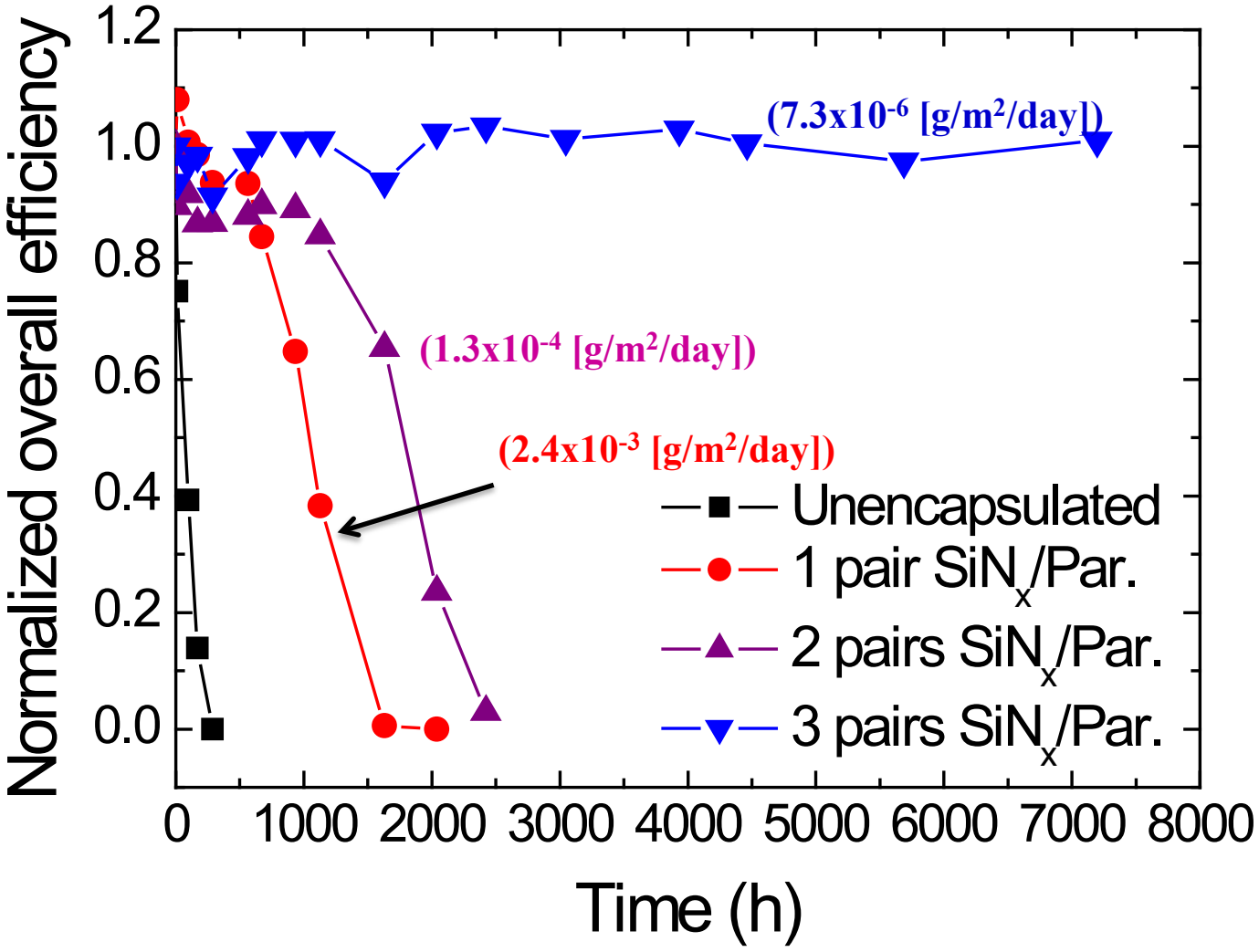


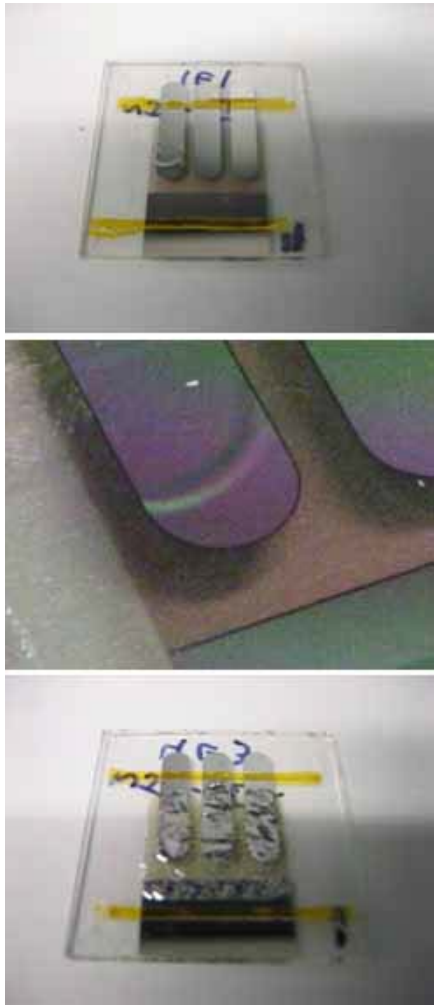
	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	η (%)	Average (%)
Before	0.39	-12.19	0.54	3.3	3.4
After	0.41	-11.40	0.54	3.3	3.3

- Average is based on 12 devices
- Light source : 175W Xenon Lamp

Device Performance Vs. Time

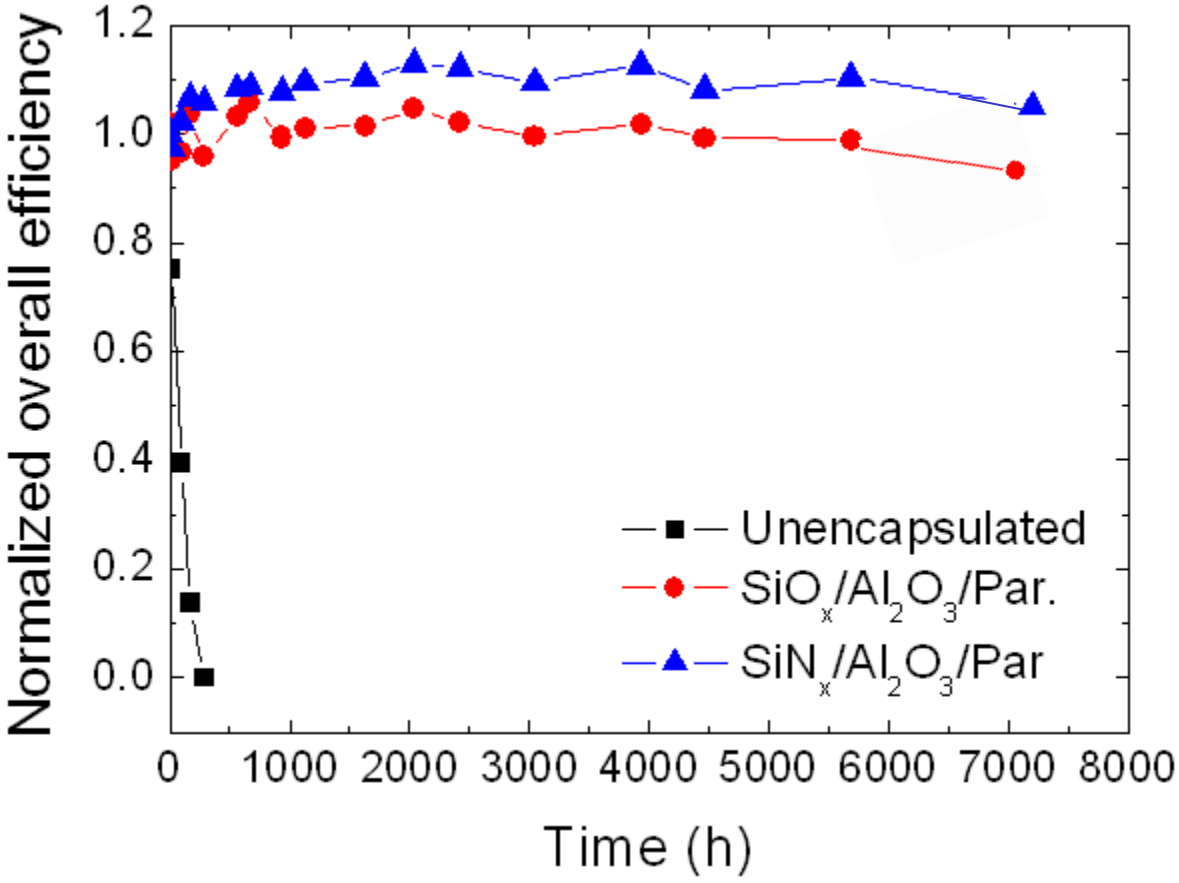
Overall device efficiency (Oriel 91160, AM 1.5G)





Hybrid Encapsulation Architecture

Overall device efficiency (Oriel 91160, AM 1.5G)



Excellent performance for simple architecture. (WVTR~10^{-5}).

Reduction in deposition time by a factor of 5.

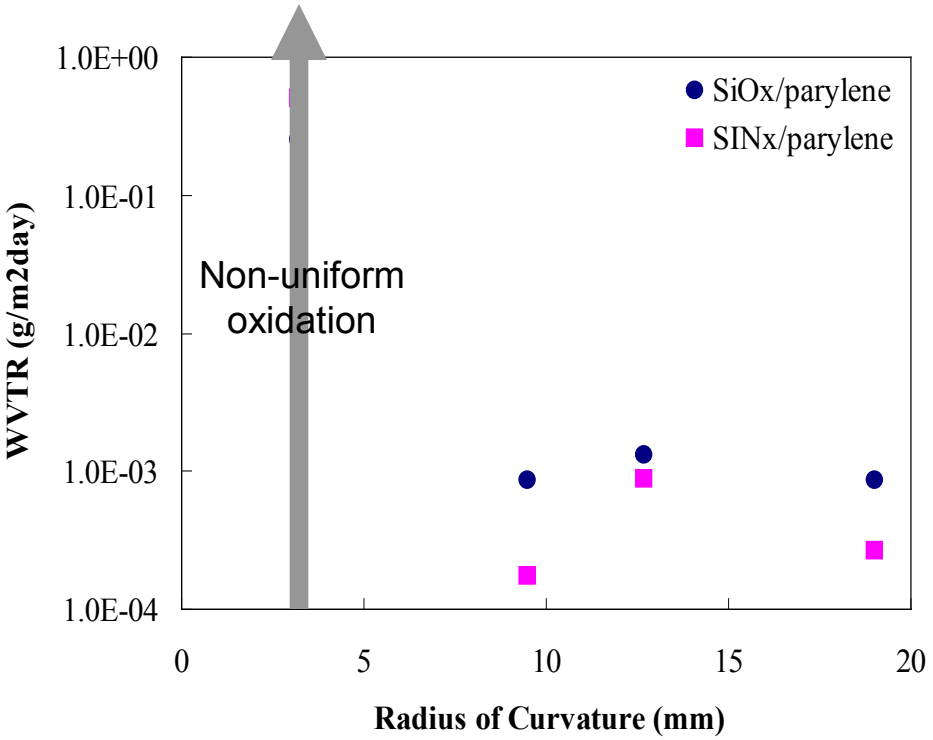
Delamination and buckling were eliminated

Additional work on reducing processing time by an order of magnitude are underway.

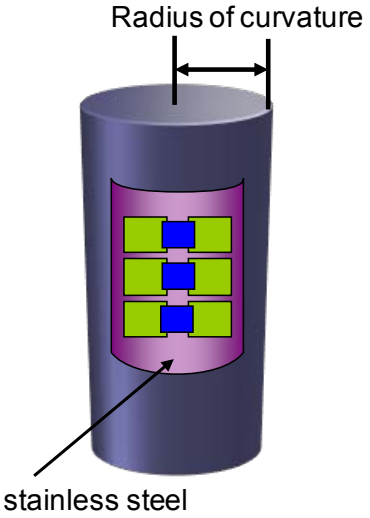
(N. Kim, et al., Applied Physics Letters, 2009)

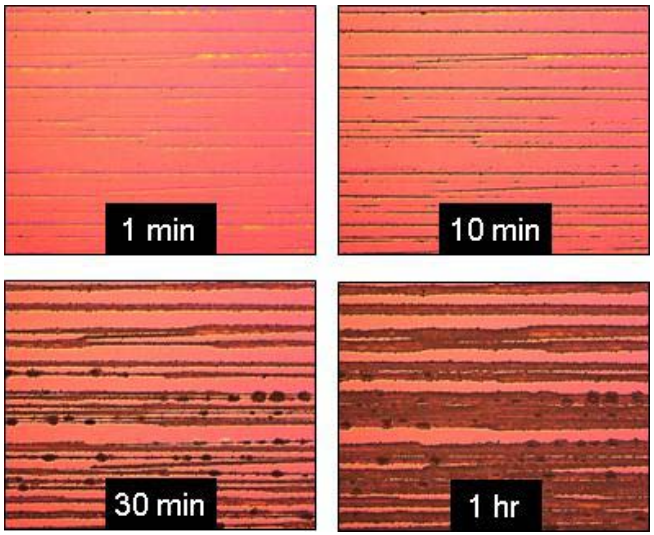
Barrier Performance under Bending

Results



WVTR as the function of the radius of curvature



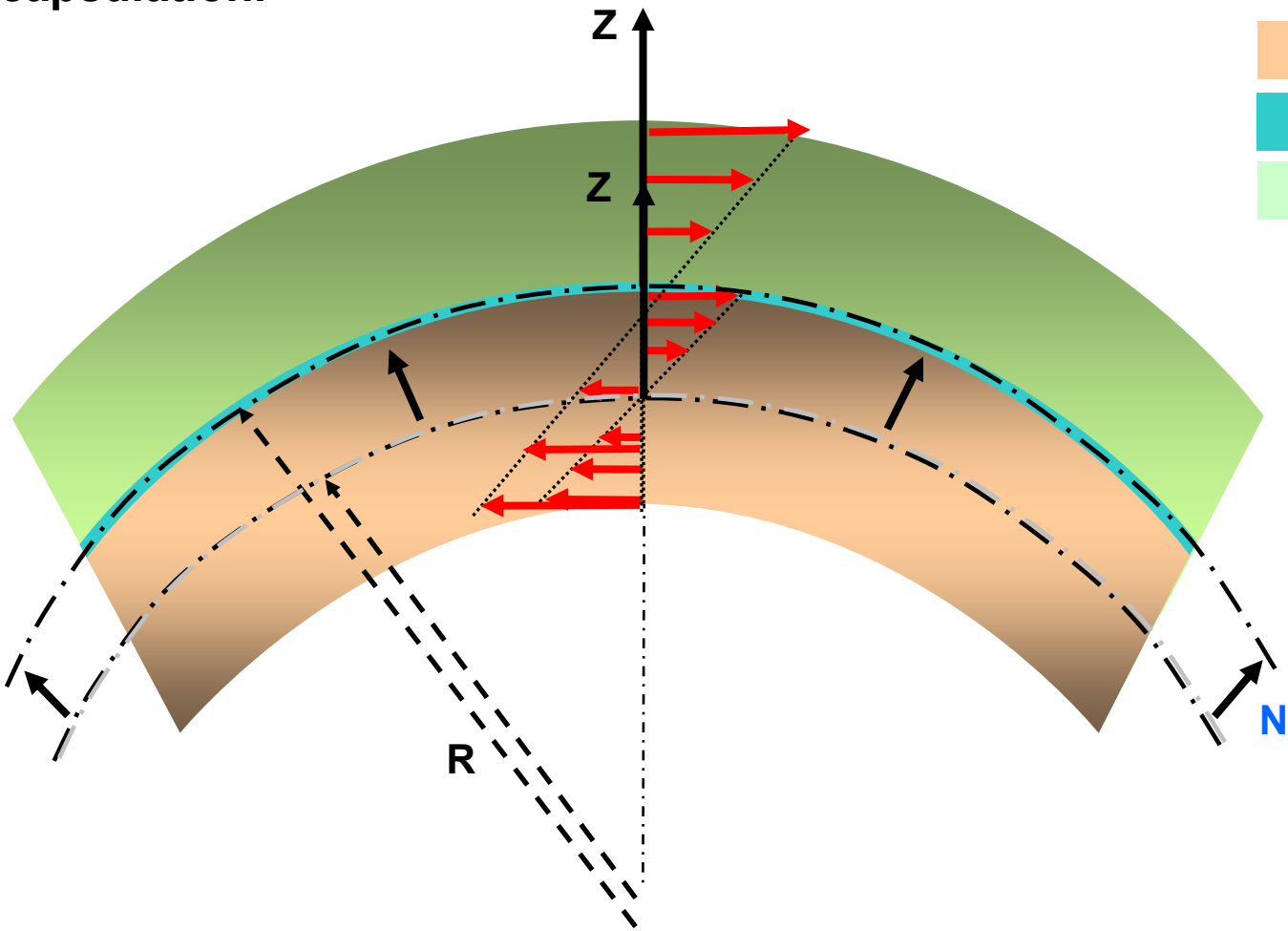


Oxidation through cracks in inorganic layer

Improving Flexibility

Flexibility is limited by the failure strain of the inorganic layer (0.5-2%).

Must improve failure strain without reducing WVTR or reduce strain on the encapsulation.



PET substrate

Hybrid barrier layer

Epoxy

$$\varepsilon_z = \left(\frac{z - z_n}{R}\right)$$

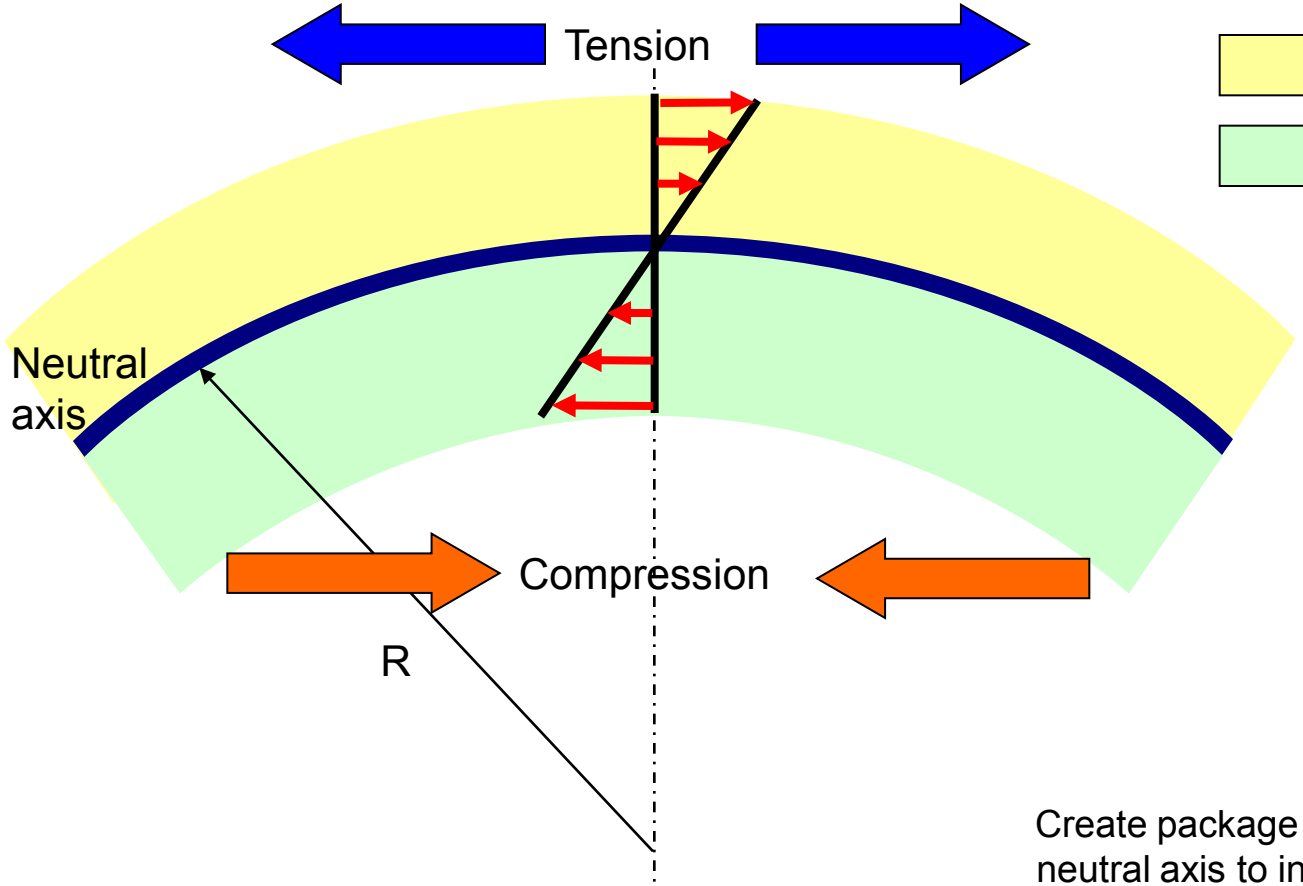
$$Y_1 d_1^2 = Y_2 d_2^2$$

Neutral axis shift

Improving Flexibility

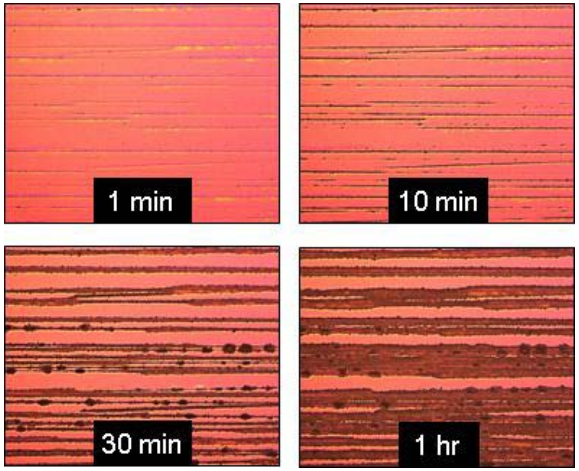
Flexibility is limited by the failure strain of the inorganic layer (0.5-2%).

Must improve failure strain without reducing WVTR or reduce strain on the encapsulation.



Tensile stress

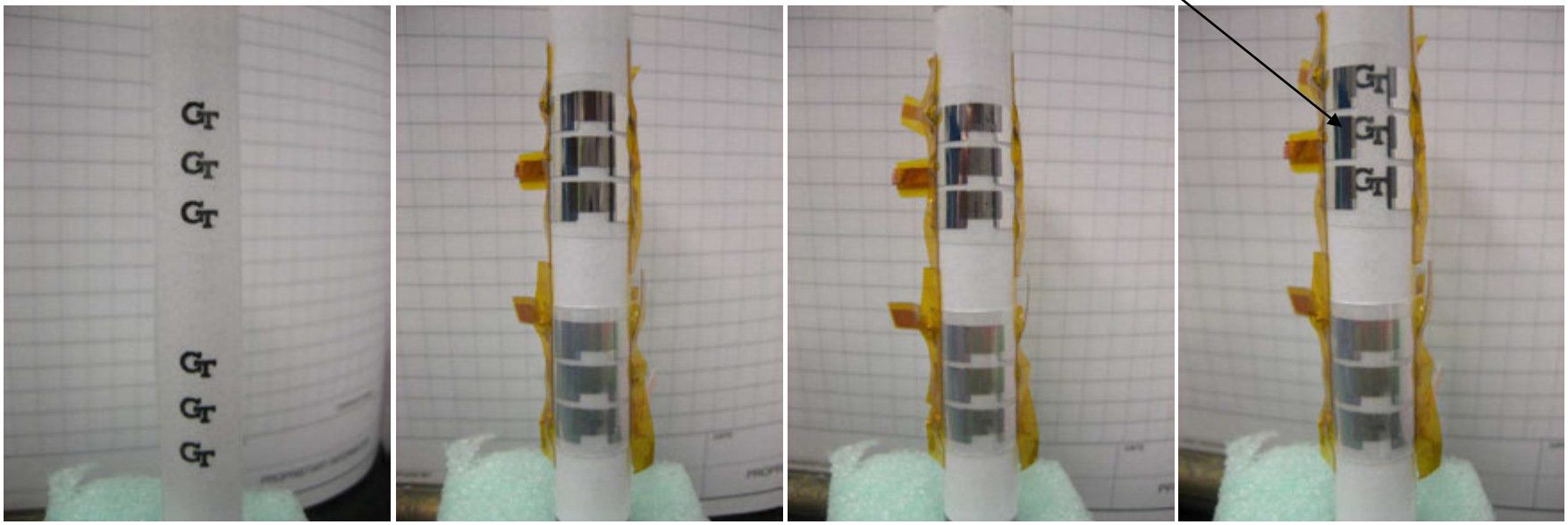
Compressive stress



Create package which places the device on the neutral axis to increase durability under flexural deformation.

Improving Flexibility

Preliminary results



GT logo was used for visual qualitative comparison and not WVTR measurement.

Summary

- **Multilayer Encapsulation**

  - Defect structure and solubility of polymer layer control laminate performance

  - Reporting WVTR and lag time may be necessary for understanding barrier performance.

- **Hybrid Encapsulation**

  - Simplified Architecture provides ultralow barrier performance

  - Promising opportunities exist for further reductions in processing time.

- **Device Integration**

  - Successful direct encapsulation of OPVs by hybrid thin films

- **Future Efforts**

  - Development of Edge Seals important for the packaging toolbox.

  - Accelerated testing under harsh environments including light soaking!

Acknowledgements

- **Graduate Students: Namsu Kim, Yongjin Kim, William Potscavage**
- **Post Doc: Anuradha Bulusu**
- **Bernard Kippelen and Benoit Domercq (Georgia Institute of Technology)**
- **Neal Armstrong (U. Arizona)**

Q & A

Technology Specific Issues
Packaging Session

Mike Kempe, NREL

Types of Encapsulant Materials and Physical Differences Between Them

- Cost / performance must be balanced
- Silicones were used almost exclusively in early module designs
  - Showed no degradation (%transmission) in current tests
- Shift away from silicones in the 80s
  - Move to EVA and PVB
  - PVB more conductive than EVA and led to higher leakage currents
- Backsheet water ingress rate of 10^{-4} g/m^2/day for a 20 year half time
- Edge seals are usually PIB (Butyl Rubber)
  - Ca test can be used to quantify moisture ingress

Mike Kempe, NREL – Q&A

- **Q:** PDMS cracking issues, sensitive to moisture
- **A:** Decomposes at temperature and has low tear strength. Polymerization catalyst cleanup can decrease susceptibility. Early modules had issues with soiling and tearing (birds eating) because PDMS was exposed. [Mani] – Testing on old exposed modules showed failure of wet resistance due to cracking of encapsulant
- **Q:** Acetic Acid: is it inherent and is it a bad actor? Does it contribute to yellowing?
- **A:** Yes it is present; bad actor question is up in the air at this point. Small impact over long time frame may contribute. Yellowing is due to additives. Acetic acid may accelerate changes in the additives but no good publications on this question yet.

Tim Zgonena, UL

Safety Concerns Related to PV Polymeric Materials

- Qualification test may not be a good predictor of long-term field performance.
- PV modules manufactured up to 2005 used similar construction and materials
  - More recent modules use new materials and methods that need to be thoroughly tested
- Current thermoplastic concerns
  - J-boxes (adhesion, creep, delamination, etc.)
  - Electrical connections that open or short
  - Mounting methods (loss of mechanical integrity)
- Creep in thermoplastics can lead to shock, fire and mechanical risks
  - Current tests may not meet or exceed actual field conditions in some cases
- IEC PV Materials Characterization Project Team (TC82 WG2) is in place
- Efforts are underway to harmonize IEC61730 and UL61730
  - Minimize national differences

Tim Zgonena, UL – Q&A

- **Q:** J-Box under stress. Will there be a new J-box adhesion test?
- **A:** Looking at updates to apply loads during certain portions of the tests.

- **Q:** [SK] Has there been an example where the entire front glass creeps off?
- **A:** Not the whole front glass. But it could theoretically happen and

- **Q:** Have you seen an uptick in occurrence of J-box problem due to use of thermoplastics?
- **A:** Example shown in presentation was to indicate that electrical problems can occur. None seen yet. [JW] Hot melt adhesives hove shown this issue. [] Adhesives used to attach mounting rails have shown creep issues as well when at operating temperatures.

Discussion of New Polymeric Materials & Testing Needs

- Q: [ZX] What are needs for new materials (material properties) in PV industry. What new testing methods are needed?
- A: [MK] Methods have been tried to do in-situ measurements of gel content of encapsulants. [Dupont] No in-situ method yet seen to be viable.
  - EVA film is generated from EVA resin and additives. Processing of film cannot be too hot because it will crosslink before PV manufacture can use it.
- Q: Methods to quantify crosslinking.
- A: Gel content and crosslink density. Solvent extraction is a primary method to determine gel content.
- A: Currently evaluation of lamination can show differences in crosslink density depending on location on the module.
  - DSC is quick but solvent extraction can take up to 24 hours including prep.
  - [DUPONT] There is no consensus on what the crosslink density should be.
  - [MK] Gel content is not what you want but correlates to what you want which is that the EVA does not flow. [DUPONT] Gel content method existed long before PV.
- Q: What kind of variability is observed in gel content
- A: [MK] Not investigated thoroughly but curing will continue for some time.
- A: [ZX] Higher variability in solvent extraction than in DSC.

- Q: [ZX] What about new materials for PV? Something better than EVA?
- A: [RD] How much viscoelasticity is needed in these materials?
- A: [MK] Enough to eliminate cracking and prevent internal stresses that could damage cells.
- A: [RD] In plane stress?
- A: [JW] Has to allow for spreading due to temperature changes. Low modulus is needed.

Discussion of New Polymeric Materials & Testing Needs

- A: [RD] A classic thin films mechanics problem.
- A: [PH] Correct in that stresses are more extreme at the edges of the module. Requires some give in the frame.
- A: [RD] A different material could be used in the center than in the edge of the cell.
- A: [JW] Difficult to do. Cost is a major issue which is why only a limited number of materials are looked at.

Christopher Barry, Pilkington

Why Glass Sometimes Breaks

- Was the load too high or the glass too weak?
- Strength of glass is a probability function.
- Glass strength will also depend on treatments and coatings (chemical, soft vacuum, and hard CVD types)
- Fractographics can find the cause of glass breakage.
  - Single cracks indicate low stress – weak glass
  - Multiple cracks indicate high stress
- On rare occasions heat-treated glasses can break spontaneously due to small inclusions.
- Soda-lime glass can be corroded by alkalis. Small amounts of water can leach Na creating an alkali solution which attacks the silicate structure. Large amounts (rain) dilute the alkali solution and are not generally an issue.

Christopher Barry, Pilkington – Q&A and Discussion

- Q: Can cut edges be fired?
- A: Laser cuts result in a strong edge. Or fire the edge to take off the sharp edge (but be careful when you cool the edge)

- Q: Reduction of warpage in glass?
- A: Window glass manufacturers are not as worried about warpage. Make sure that you define the maximum amount of acceptable warpage when ordering glass. The float process can result in very flat glass with vary parallel surfaces. [JW] Lamination process results in warpage anyway.

- Q: [PH] Thin film manufacturers have seen issues with conductivity through glass due to sodium content. What goals are there for sodium content and this problem?
- A: Sodium is used to adjust the melt point. Films can be deposited to block sodium. Electrical conductivity in glass is not a general concern from our customers. Large quantity orders would be needed to adjust the glass from current formulations.

- Q: Comment on low-Fe glass
- A: Low-Fe allows for more IR to pass. AR coatings are readily available (on one surface).

- Q: How long do coatings last?
- A: CVD coatings are fully oxidized and we have seen no degradation or change with outdoor weathering. Abrasion can happen with commercial cleaners. There is a slight texture so soiling can be more apparent.

National Renewable Energy Laboratory
Innovation for Our Energy Future

Types of Encapsulant Materials and Physical Differences Between Them



Michael Kempe, Matt Reese, Arrelaine Dameron, Thomas Moricone

National Renewable Energy Laboratory

This presentation does not contain any proprietary or 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.

Purposes of Polymer Materials in PV

Helps Protect Cell Materials From Environmental Stress

- Must Provide Good Adhesion.
- Resistant to Heat, Humidity, UV Radiation, and Thermal Cycling.

Electrical Isolation

Control, reduce, or eliminate moisture ingress.

Optically Couples Glass to Cells

- High Photon Transmission.

Cost Must Be Balanced With Performance.

Outline

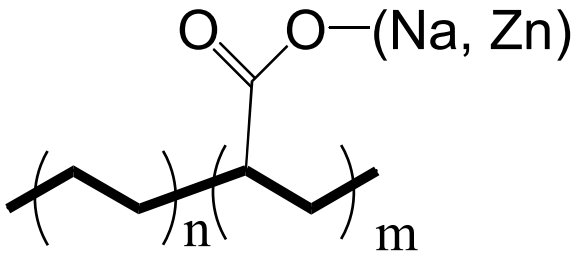
Encapsulant Chemistry

Optical Transmission

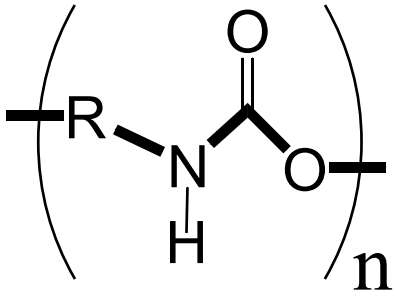
Electrical insulation

Moisture ingress

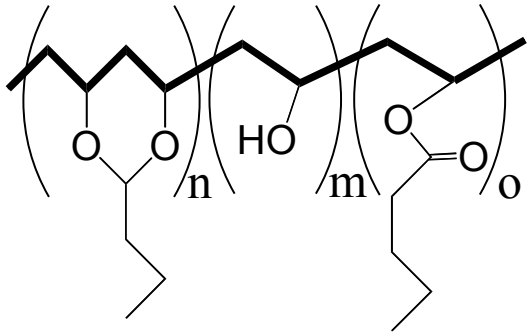
Encapsulant Materials Structures



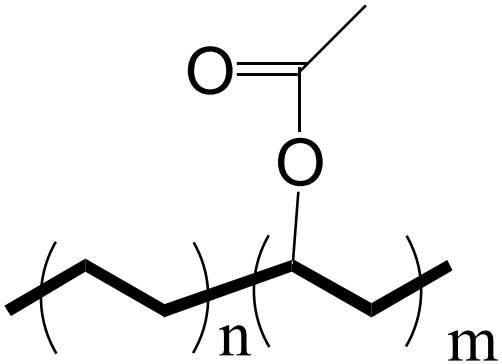
Ionomer



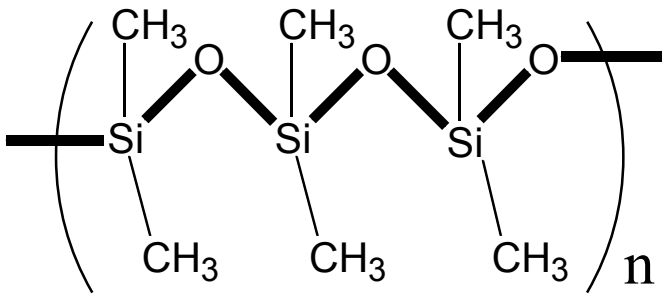
Thermoplastic Polyurethane (TPU)



Polyvinyl Butyral (PVB)

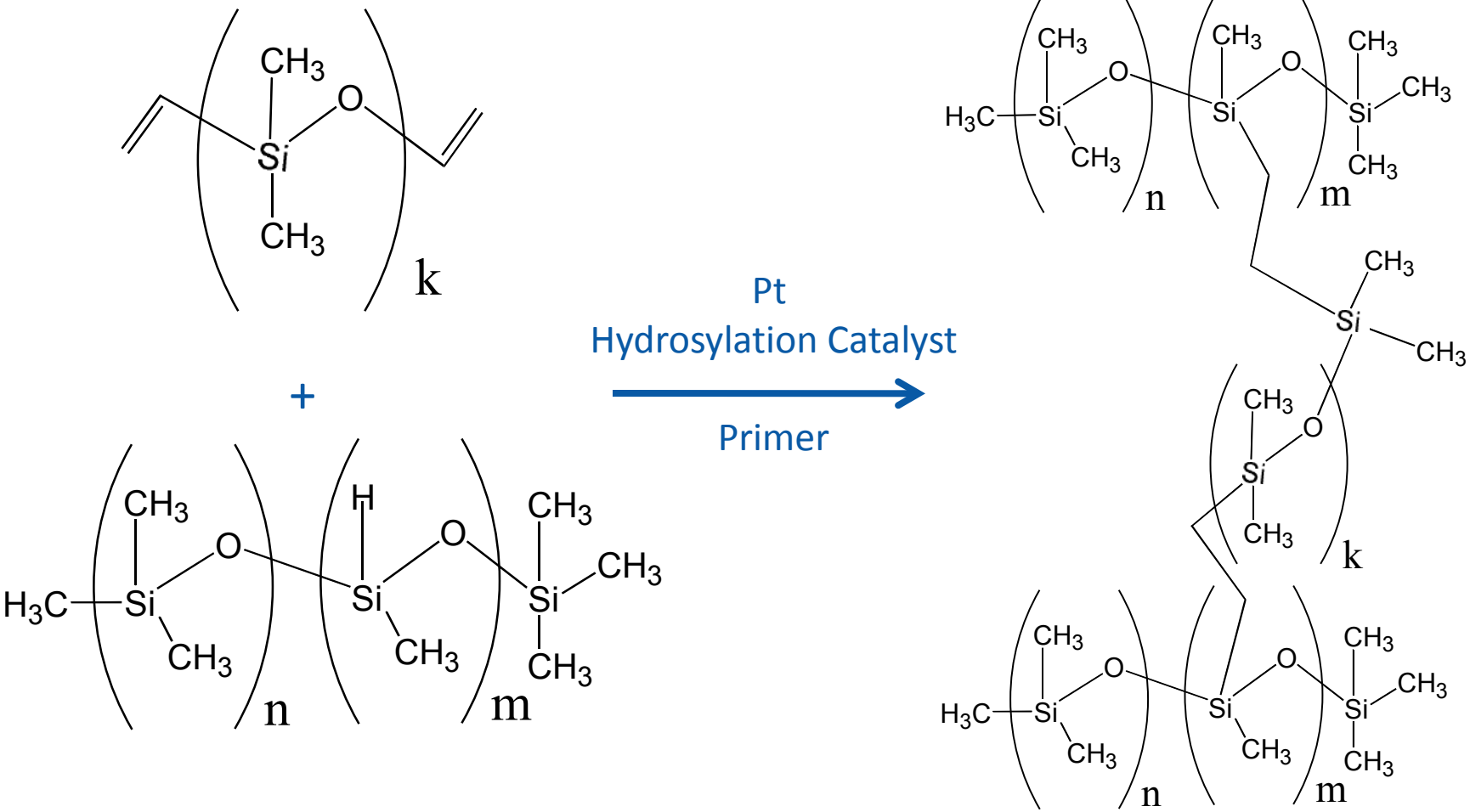


Ethylene Vinyl Acetate (EVA)



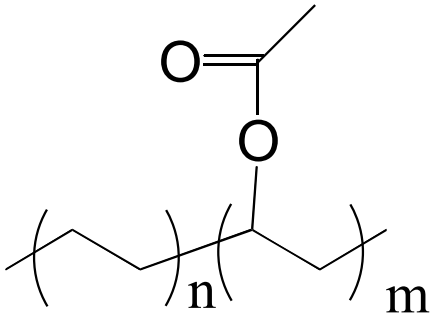
Polydimethyl Silicone (PDMS)

Early PV Modules Used PDMS

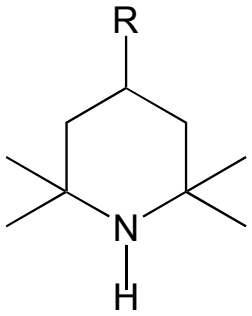


Dow Corning Corporation, "Develop silicone Encapsulation Systems for Terrestrial Silicon Solar Arrays", Doe/JPL954995-2 (1978).
M. A. Green, "Silicon Photovoltaic Modules: A Brief History of the First 50 Years", Prog. Photovolt: Res. Appl. **13,** (2005) 447-455.

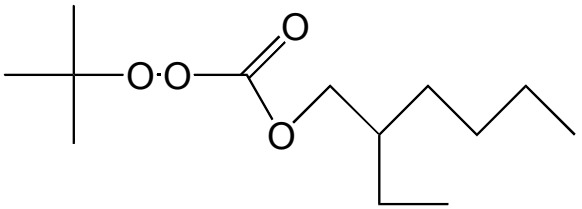
EVA Film Composition



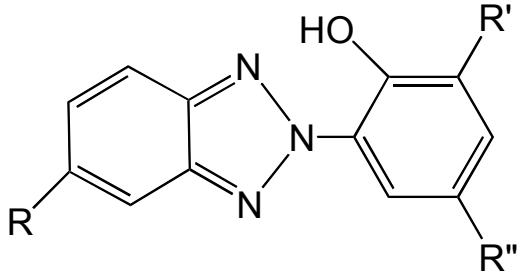
Ethylene Vinyl Acetate
(EVA, 96% to 98%)



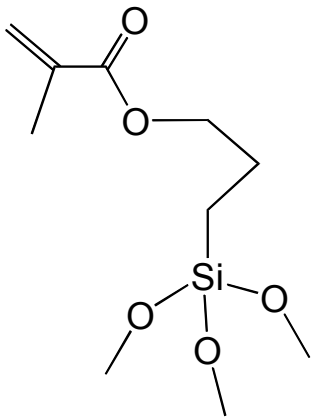
Hinder Amine Light Stabilizer
(HALS, 0.1% to 0.2%)
Decomposes Peroxide Radicals



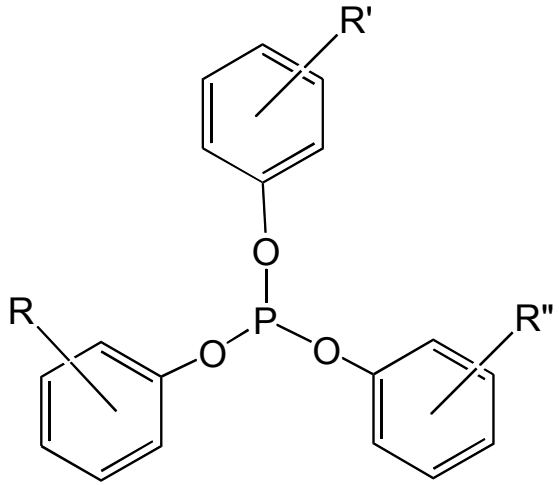
Peroxide
(1% to 2%)
Cross-Linker



Benzoltriazole
(0.2% to 0.35%)
UV Absorber



Trialkoxy Silane
(0.2% to 1%)
Adhesion Promoter

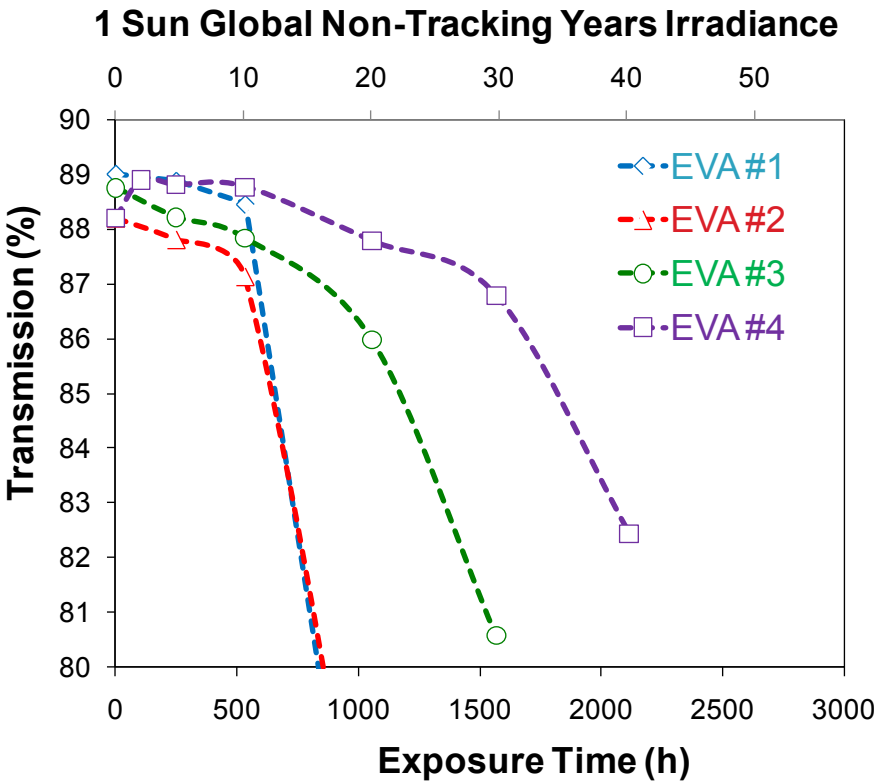


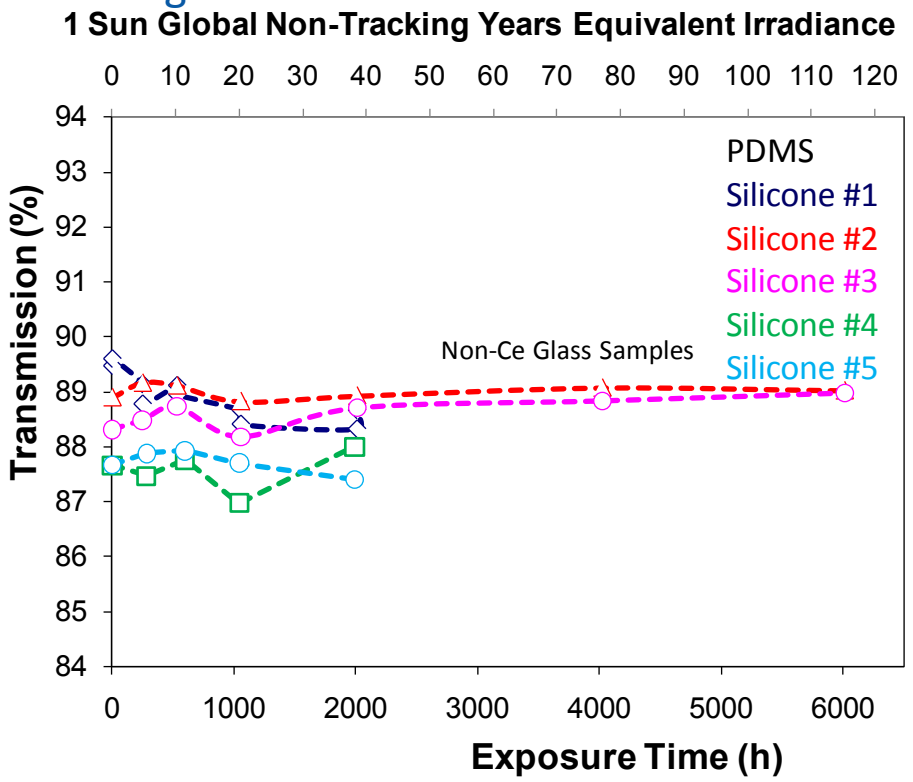
Phenolic Phosphonite
(0.1% to 0.2%)
Peroxide Decomposer/
Radical Scavenger

F. J. Pern, "Composition and Method for Encapsulating Photovoltaic Devices", Patent# 6,093,757, (2000).
P. Klemchuk, M. Ezrin, G. Lavigne, W. Holley, J. Galica, S. Agro, "Investigation of the Degradation and Stabilization of EVA-Based Encapsulant in Field-Aged Solar Energy

The PDMS Samples Did Not Degrade

Exposure of encapsulant materials to 42 UV suns at 80°C to 95°C.
Samples between 3.18mm low Fe non-Ce glass.





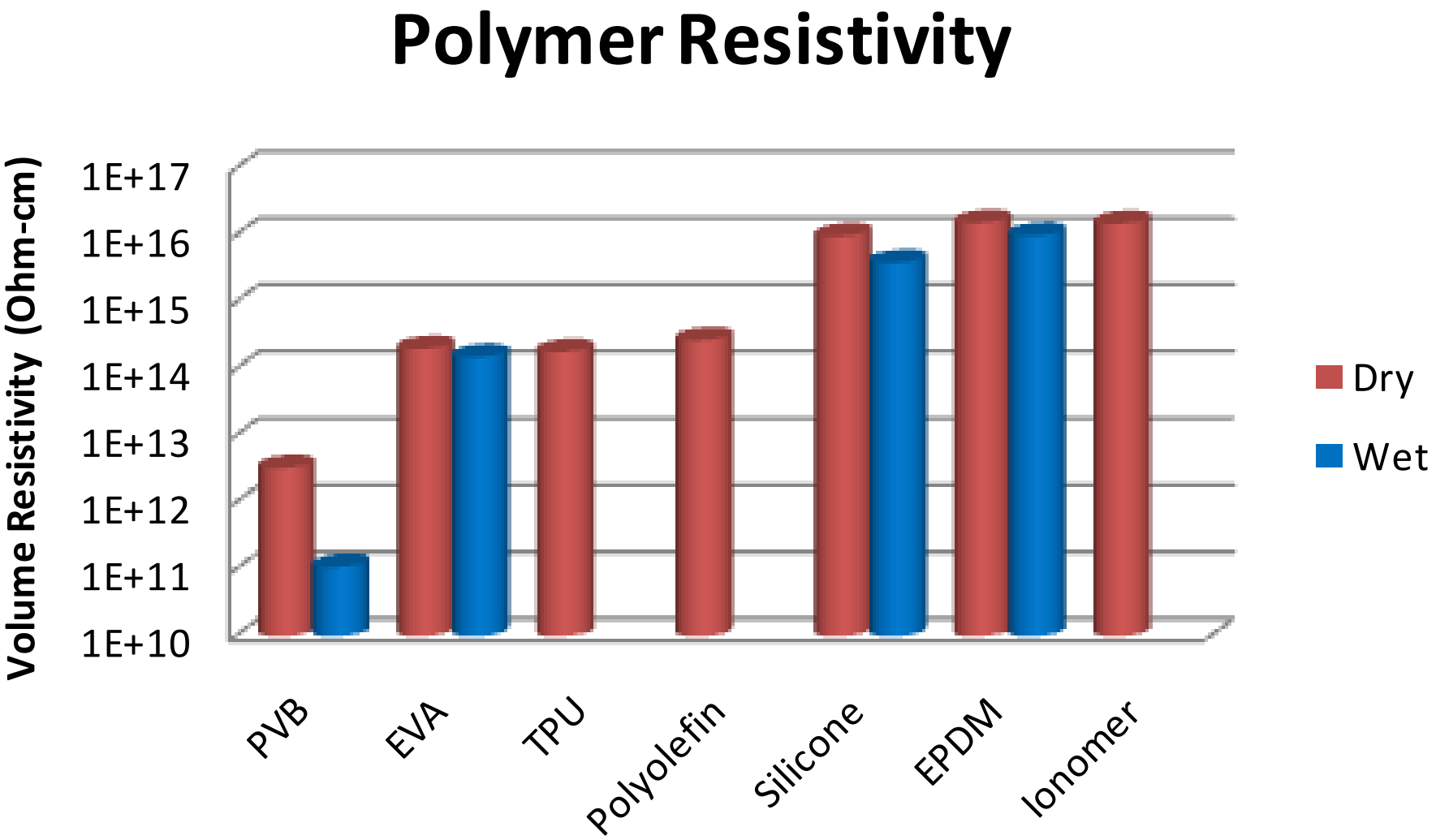
M. D. Kempe, T. Moricone, M. Kilkenny, "Effects of Cerium Removal from Glass on Photovoltaic Module Performance and Stability", *SPIE,* San Diego, Ca, August 2-7, 2009.

EVA Has Good Optical Transmittance

Encapsulant	Transmission to Cells through 3.18 mm glass and 0.45 mm Encapsulant	Comments
	%	
Momentive RTV615	94.5 ± 0.3	PDMS, Addition Cure
Dow Corning Sylgard 184	94.4 ± 0.3	PDMS, Addition Cure
Dow Corning 527	94.4 ± 0.3	PDMS, Addition Cure
Polyvinyl Butyral	93.9 ± 0.4	
EVA	93.9 ± 0.4	
NREL Experimental	93.4 ± 0.4	Poly-α-olefin
Thermoplastic Polyurethane	93.3 ± 0.3	
Thermoplastic Ionomer #1	92.3 ± 0.4	Copolymer of Ethylene and Methacrylic acid
Dow Corning 700	91.7 ± 0.3	PDMS, Acetic Acid Condensation Cure
Thermoplastic Ionomer #2	88.4 ± 0.4	Copolymer of Ethylene and Methacrylic acid

Solar photon-weighted average optical density determined from transmittance measurements through polymer samples of various thickness (1.5 to 5.5 mm) between two pieces of 3.18 mm thick Ce doped low Fe glass.

Electrical Conductivty Varies Greatly



Resistivity measured at 22°C using alternating polarity DC current a +/- 700V.
"Wet" samples were soaked in water at 40°C.

PVB, 1000 Times more Conductive than EVA

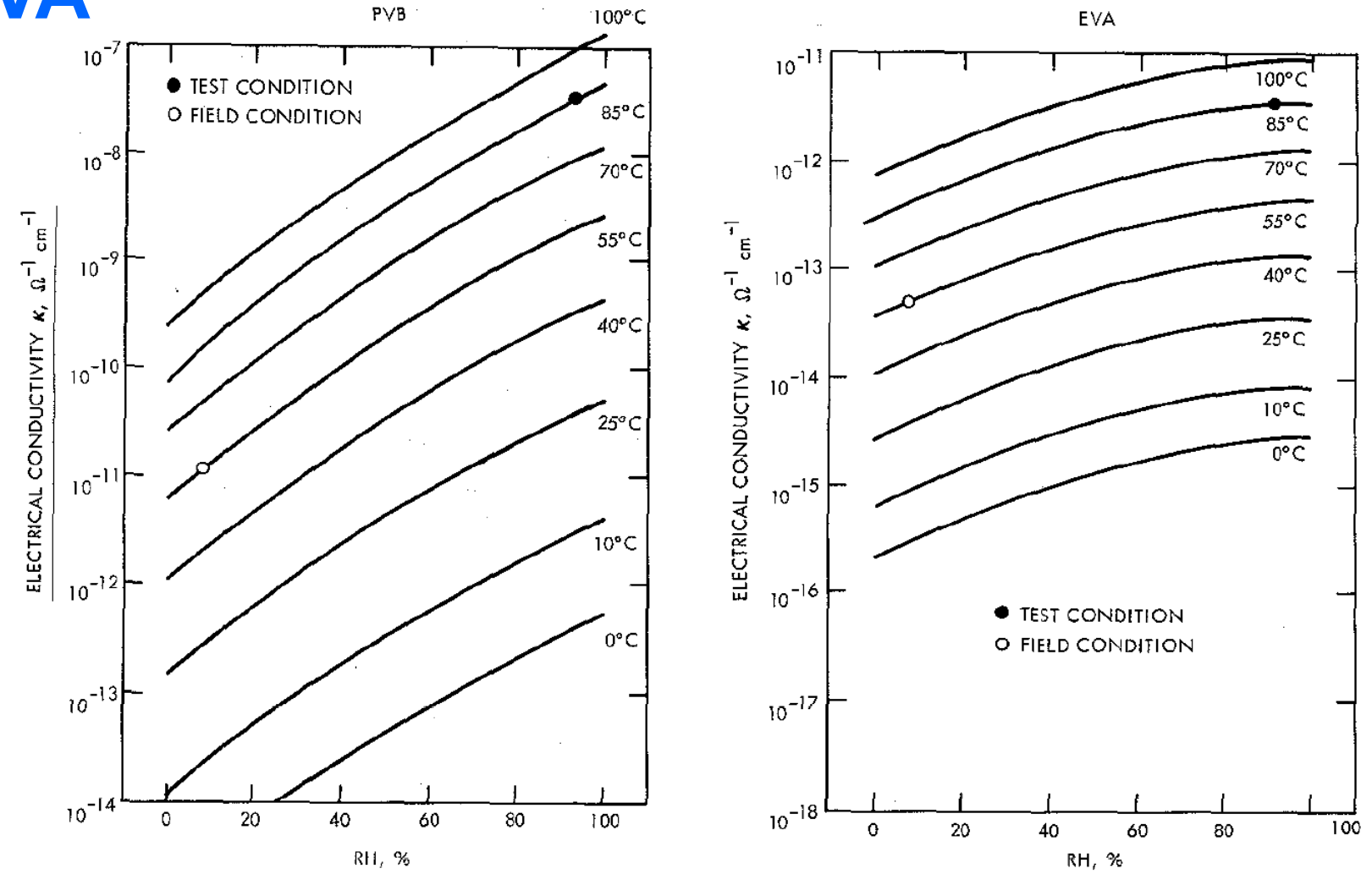


Figure 2. Bulk Electrical Conductivity of PVB and EVA

G. R. Mon, R. G. Ross, "Electrochemical degradation of amorphous-silicon photovoltaic modules", 18th PVSC, Las Vegas, NV, October 21-25, (1985) p. 1142-1149.

Leakage Current Correlates With Performance loss

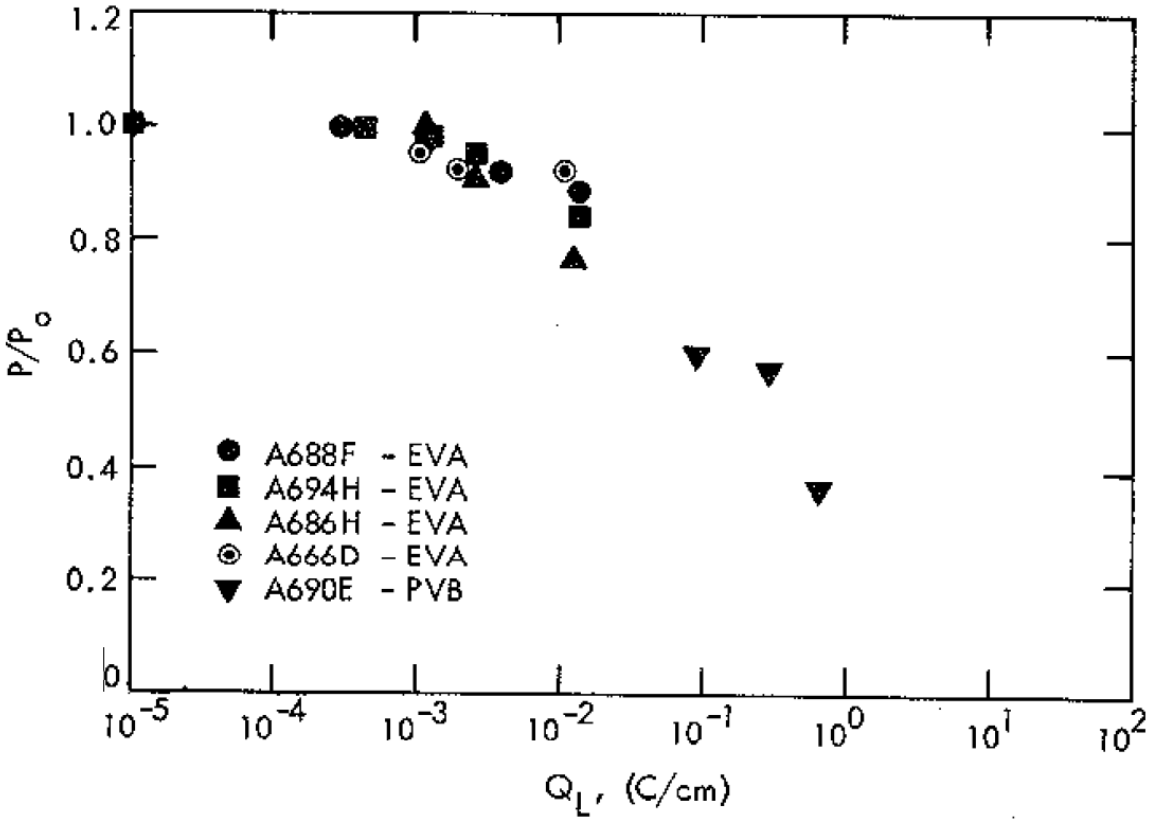


Figure 8. Power Output Reductions Versus Accumulated Unit Charge Transfer for α-Si Cells

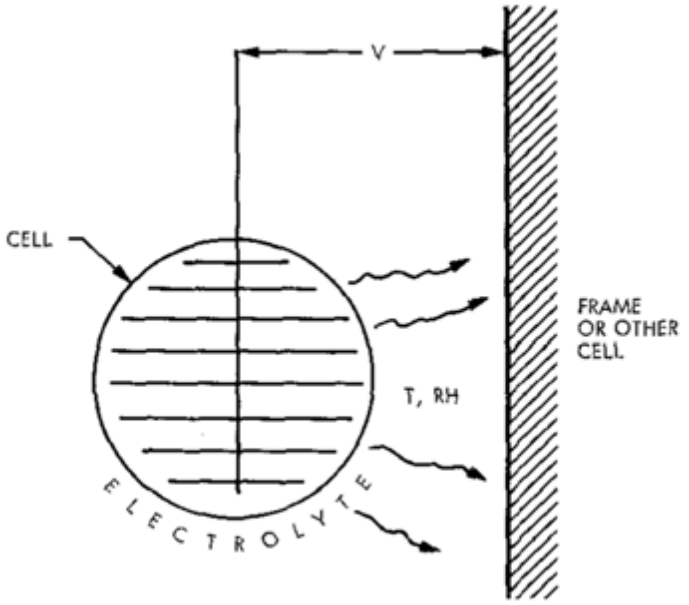
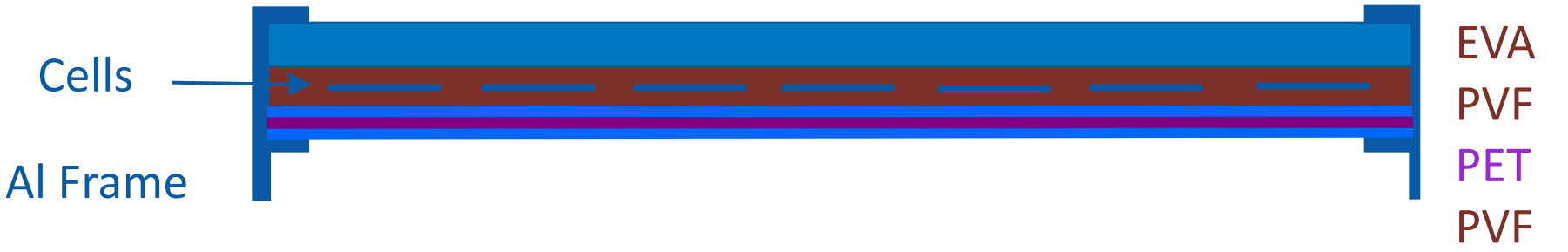


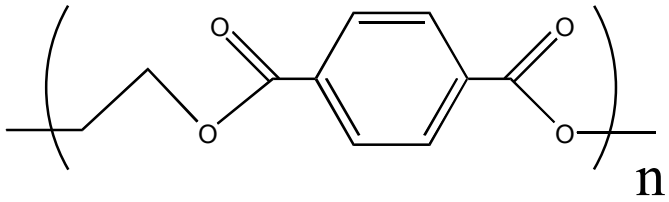
Figure 1. Corrosion Mechanism Overview

G. R. Mon, R. G. Ross, "Electrochemical degradation of amorphous-silicon photovoltaic modules", 18th PVSC, Las Vegas, NV, October 21-25, (1985) p. 1142-1149.

Backsheets Protect Against Electrical Shock

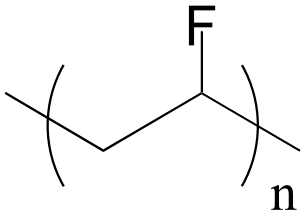
Framed Silicon Wafer Module





PolyEthylene Terepthalate (PET)

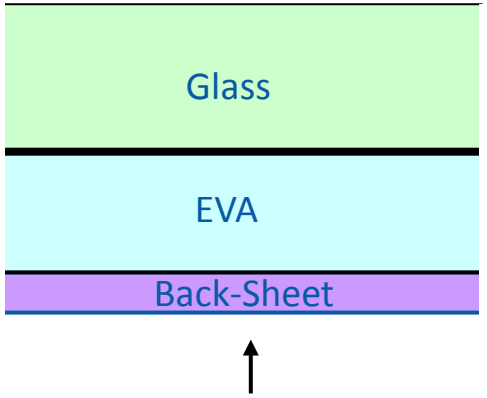
PET
provides Electrical insulation.



Poly Vinyl Floride (PVF)

PVF
provides UV stability

Time Constant for Water Ingress



$$C(t) = C_O\left(1 - e^{-\frac{WVTR_{B,Sat}\,t}{C_{Sat,EVA}\,l_{EVA}}}\right)$$

$$\tau_{1/2} = 0.693\frac{C_{Sat,EVA}\,l_{EVA}}{WVTR_{B,Sat}} = 0.693\frac{Amount\ of\ water\ EVA\ can\ hold}{Rate\ of\ moisture\ ingress}$$

l_{EVA}=18 mil, T=27 °C, $C_{Sat,EVA}$=0.0022 g/cm^3

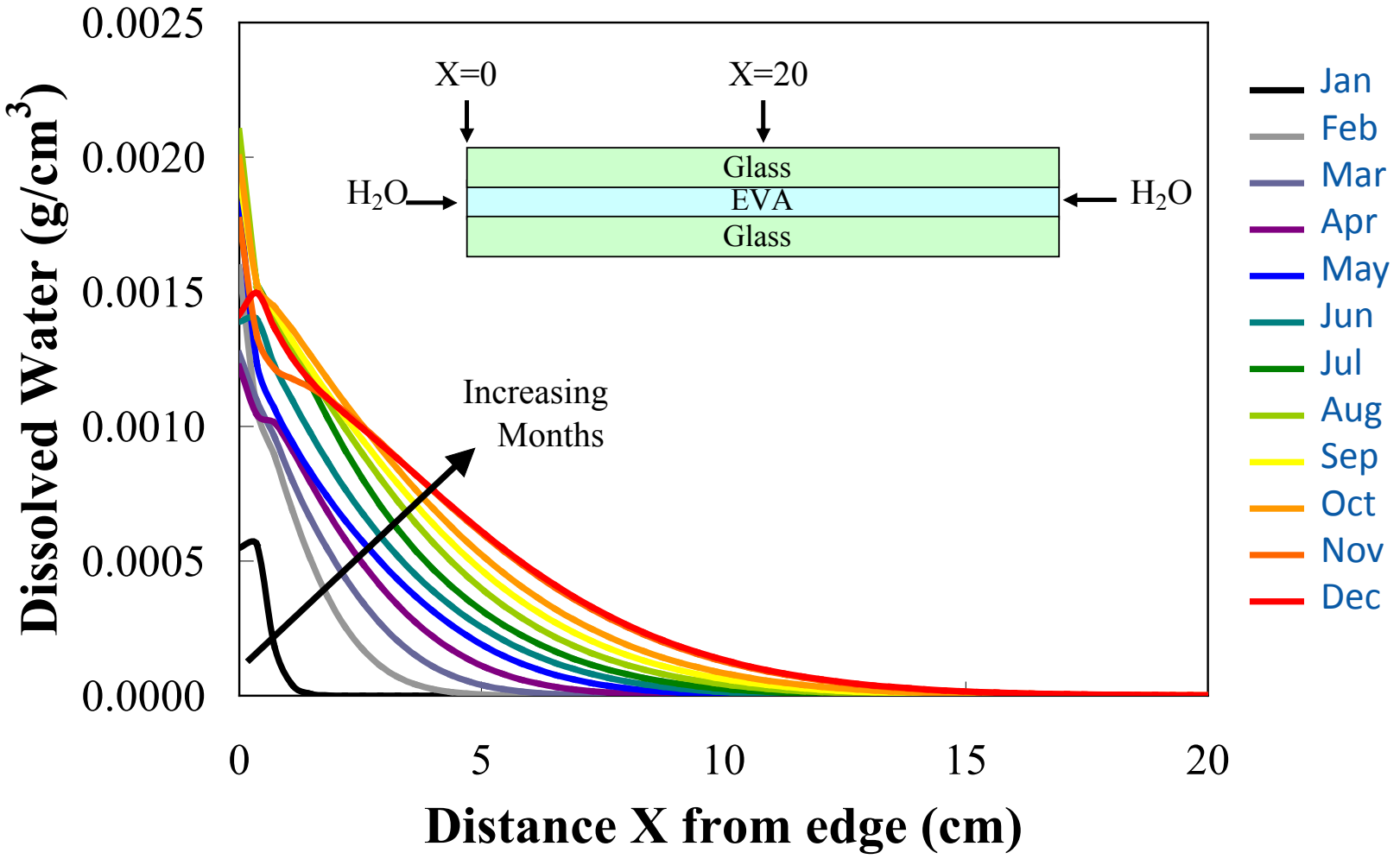
	PVF	ETFE	PVF/PET	PET	PCTFE	
$\tau_{1/2}$ =	0.0741	0.223	0.457	1.78	6.87	(day)

For $\tau_{1/2}$=20 years need 10^{-4} g/m^2/day

M. D. Kempe, "Modeling of rates of moisture ingress into photovoltaic modules," *Solar Energy Materials and Solar Cells,* vol. 90, pp. 2720-2738, 2006.

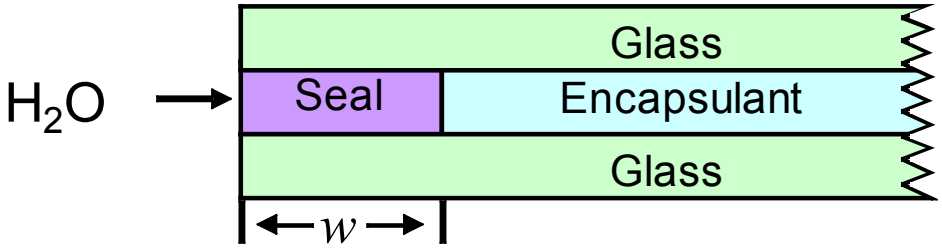
Even a Glass/Glass Module Will Let in Moisture

Finite element analysis using meteorological data from Miami Florida 2001



Edge Seals Can Keep Moisture Out

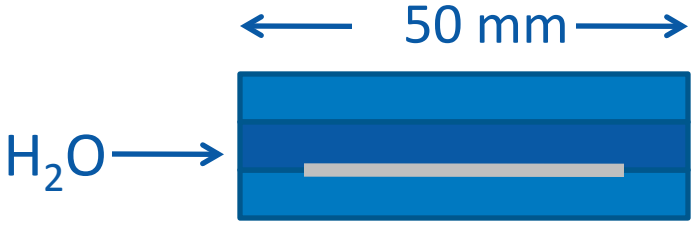
Schematic of module edge





PIB test sample after 3500 h
85°C and 85% RH

Schematic of Test sample



Glass (3.18 mm)
Butyl Rubber (0.3 mm)
Ca (100 nm)
Glass (3.18 mm)

Conclusions

Packaging materials are formulated to:

- Resist to Heat, Humidity, UV Radiation, and Thermal Cycling.
- Provide Good Adhesion.
- Optically Couples Glass to Cells
- Electrically isolate components
- Control, reduce, or eliminate moisture ingress.

Choices made by Balancing cost With Performance.

the standard in safety

Safety Concerns with New PV Polymeric Materials

Tim Zgonena
Underwriters Laboratories Inc (UL)

February 19, 2010

Copyright© 1995-2007 Underwriters Laboratories Inc. All rights reserved. No portion of this material may be reprinted in any form without the express written permission of Underwriters Laboratories Inc. or as otherwise provided in writing.

Connector Materials

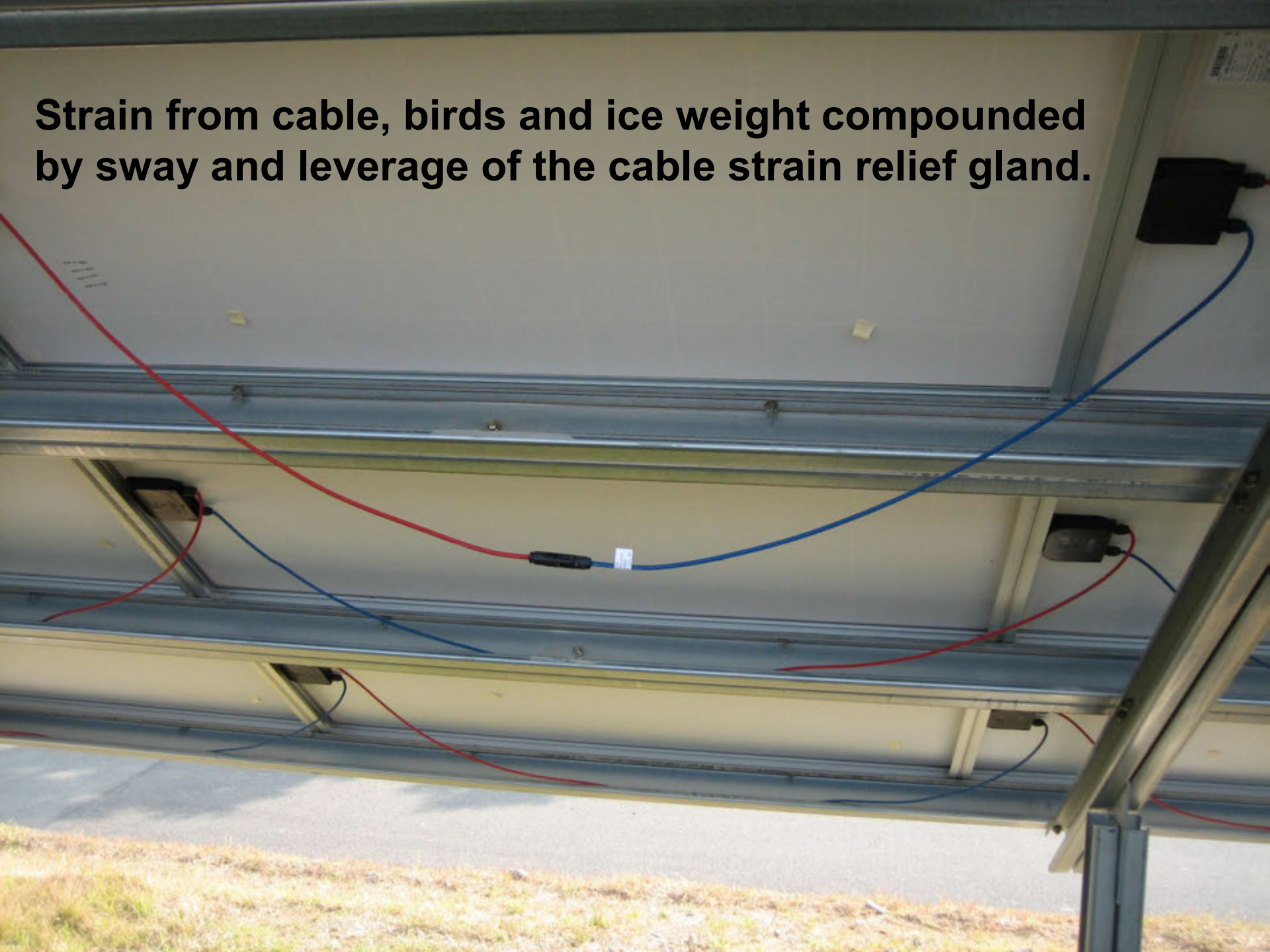


This passed qualification test.
This is after 8 years operation in AZ

Underwriters Laboratories

This could happen to any PV connection or connector that is unmated under load. 150Vdc and 6A.




Strain from cable, birds and ice weight compounded
by sway and leverage of the cable strain relief gland.

I just need a little more cable …..

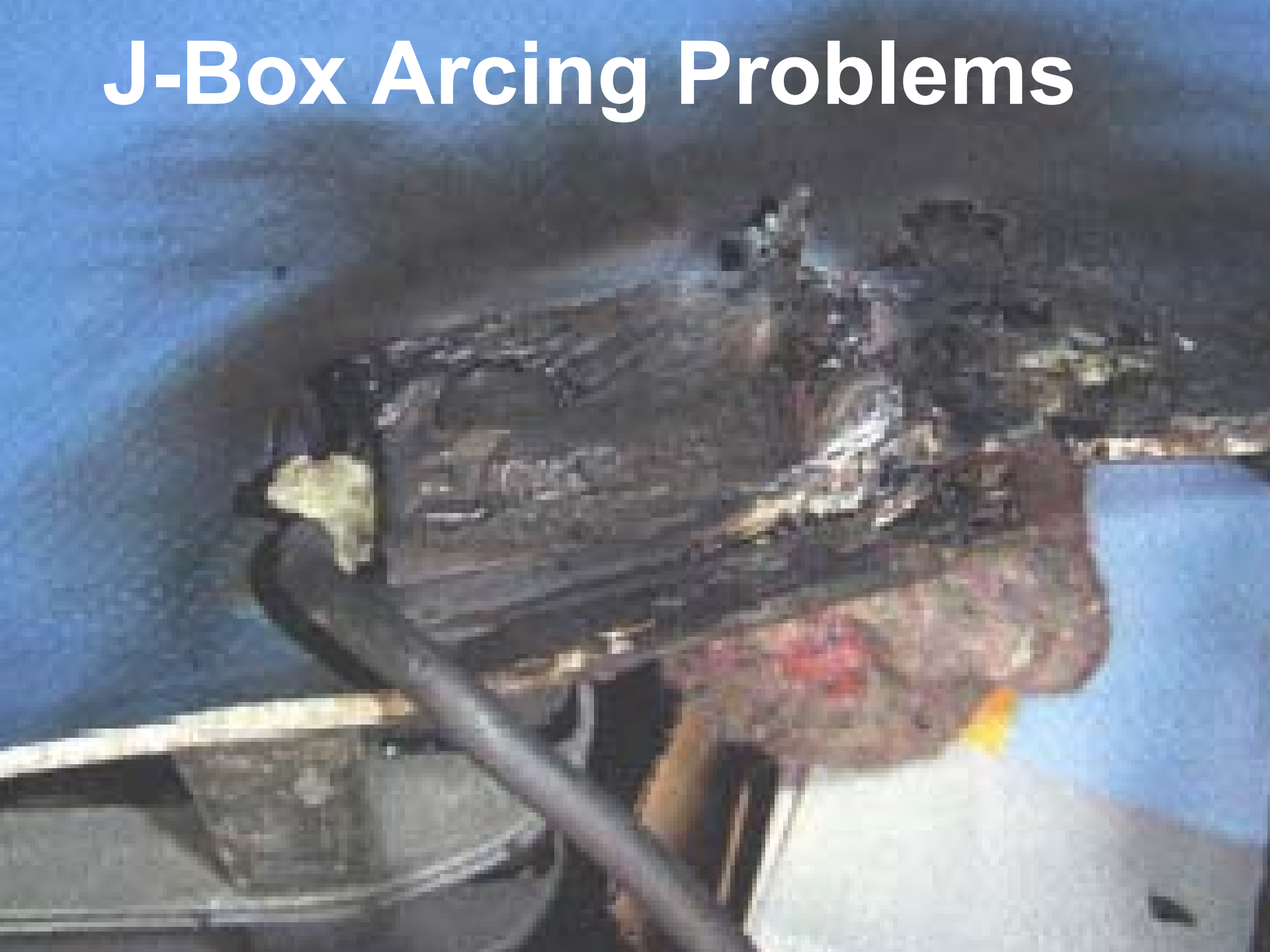


Delamination or creep can can cause these ribbons to open or short circuit




Terrible Tabbing Tether!!!

J-Box Arcing Problems



The Changing PV Landscape

- Most PV modules produced between 1990 and 2005 share similar construction, materials and manufacturing processes.
- This traditional PV module recipe was developed over years of research and testing and it has a good track record.

Past Performance is Not Necessarily Indicative of Future Results

- New players, mfrs with little or no PV experience.
- New PV module configurations and applications
- Significantly new construction techniques
- Many new construction materials
  - Thermoplastic and other new encapsulants and adhesives with low softening / melt temps
  - Conductive adhesives to replace solder
  - Polymer mounting
- New manufacturing processes

Recent Thermoplastic Concerns

- J-box – adhesion, delamination, creep or flow. Any movement can be very very bad!
- Electrical connections short or open circuits
  - Displacement of electrical conductors or components
  - Loss of contact pressure
- Mounting means delamination, creep or flow
  - Loss of mechanical integrity
  - Falling modules or falling glass

PV Polymeric Material Creep

We are seeing a transition away from crosslinked EVA based PV encapsulants toward thermoplastic encapsulants materials in the construction of PV modules.

These thermoplastic materials can flow or creep over time when exposed to the high operating temperatures.

Some of these new materials have melt temperatures less than 100C.

Existing temperature tests are normalized to 40C and chamber cycling is done at 90C max and will not always address worst case modules temperatures experienced from high ambients, high irradiance and shading conditions that can raise temperatures well above 90C.

This flow or creep of critical PV polymeric materials can result in a risk of shock, fire or mechanical hazards.

Challenge!

- **Existing evaluation programs do not address all concerns as demonstrated by increased product testing failures**
  - **New generation of PV modules,**
  - **New components and**
  - **New materials**

IEC 61730 Scope and Object

IEC 61730 describes the fundamental construction requirements for photovoltaic (PV) modules in order to **provide safe electrical and mechanical operation during their expected lifetime.** Specific topics are provided to assess the prevention of electrical shock, fire hazards, and personal injury due to mechanical and environmental stresses.

International Information Transfer

IEC PV Plastics
Project Group

IEC61730

UL61730

IEC PV Material Characterization Project Team
(TC82, WG2)

- Scope - Developing PV material property characterization requirements
  - Start with Backsheets, then Encapsulants and Front Sheets
  - 21 companies participating

- Arkema
- Atlas
- BP Solar
- Dow Chemical
- Dow Corning
- DuPont
- eTimax-Solar
- First Solar
- Fraunhofer
- Isovolta
- JEMA
- JET
- Krempel
- Madico
- NREL
- Sharp
- Solarwatt
- TUV Germany
- Tyco Electronics
- VDE
- UL

Underwriters Laboratories

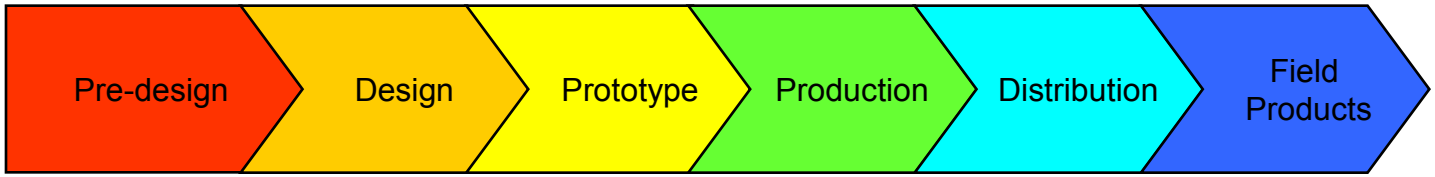
Hazard	Failure Mechanism	Test	Test Method
Electric Shock	Electric strength – dielectric breakdown due to degradation of insulating material	Dielectric Strength	IEC 60243, IEC 60216-5 (thermal aging)
	Voltage tracking – voltage causing a permanent electrically conductive carbon path after application of wet contaminants.	CTI	IEC 60112
	Material electrically conductive	Volume Resistivity	IEC 60167
	Insulation thickness consistency	Partial discharge	IEC 61730-2
	Mechanical protection from tearing	Tensile Strength, Tear Resistance, Cut Test	ISO 527-3, ASTM D1004, IEC 61730-2
	Mechanical protection from punctures due to installation tools	Puncture Properties	ASTM D7192
	Mechanical support of junction box due to movement or stretching of backsheet	Tensile Creep	ISO 899
	Superstrate / Glass movement/creep	Creep/flow test,	D6382
	Substrate / Encapsulant movement from J-box and cable weight	Dynamic Mechanical Analysis (DMA)	
	Interfacial Delamination/adhesion	Bond strength,	??
	Common failures include crazing (micro scale) that grow to cracking and mechanical failures. SEM or TEM optical microscope to view	Peel strength, Intra-layer adhesion	SAE Automotive or IEC 60950-1 (2.10.11)
	Water ingress from delamination	Water Absorption	ISO 62
Flammability	Additional fuel for the fire	Flammability test, Radiant Heat Ignitability (Cone Calorimeter test)	IEC 60695-11-10, ISO 5657
	Insulated or uninsulated wire attaining red heat during a fault causing possible ignition	HWI or Glow Wire	IEC 60695-2-20
	Loose connections and broken leads in the vicinity of the polymer material causing arcing	HAI	IEC 60695-1-1
Mechanical	Mechanical failure due to degradation of insulating material	Tensile Strength and Tensile Elongation	ISO 527-3, IEC 60216-5 (thermal aging)
	Thermal stress due to material expansion	Thermal Expansion (CTE)	ISO 11359-2
	Adhesion to glass and backsheet	Bond strength, Peel strength	?? SAE Automotive or IEC 60950-1 (2.10.11)
	Inter-layer adhesion of backsheet	Bond strength, Intra-layer adhesion	?? SAE Automotive or IEC 60950-1 (2.10.11)
	Surface treatment, chemical, corona treatment	Surface finish rating scale for machined metals?	??

Certification and Performance Certification and the Product Development Cycle

Performance Certification

One time 61215 or 61646 evaluation Follow Up Not Required

Without Follow Up modules, component and materials can change and invalidate performance certification



Safety Certification

Consulting

Preliminary Investigation

Certification

Manufacturing Follow Up Inspection & Testing

Product failure Investigation Field Reports



Harmonization of IEC 61730 & UL61730

- Goal to minimize national differences
  - IEC 61730 Amendment
- Revisions include
  - Standardized PV material characterization tests
  - Module level tests to address creep, flow, displacement and delamination failures
- International effort
  - Growing participation
  - Now is the time to get involved!

Thank You
for your attention
and future participation!

Tim Zgonena

Underwriters Laboratories Inc (UL)

Underwriters Laboratories

NSG GROUP

Why Glass Sometimes Breaks

PV Module Reliability Workshop

NREL, Golden, CO 2010/02/19

Chris Barry, Dir. Tech. Services. Tel. 419 247 4203

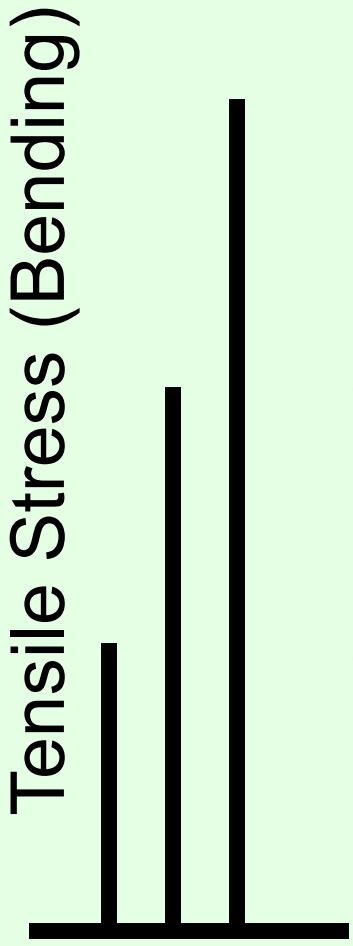
Breakage Causes

Glass breaks when an applied load exceeds the strength of the glass

The big question is:

Was the load too great, or was the glass too weak?

How Strong is Annealed Glass?



— 9,000 psi 992 Broken (8 not broken)

– 6,000 psi Half (~500) Broken

– 3,000 psi 8 of 1,000 Samples Broken

– 0 psi 1,000 Identical Test Samples

Conclusion: Don’t use glass for Rupture Disks

Glass Strength

1. **Heat-Strengthened Glass is ~ 2 times Stronger than Annealed**

2. **Tempered Glass is ~ 4 times Stronger than Annealed Glass**

3. **Chemically Strengthened Glass can be > 4 times Stronger than Annealed**

How does Coating Glass Affect its Strength?

- Coating Types:

- "Soft" Vacuum Sputtered –
  - Applied post glass manufacture
  - No change to glass strength – damage already done
  - Moisture & Temperature Sensitive

- "Hard" CVD (Chemical Vapor Deposition)-
  - Applied during glass manufacture
  - Small improvement ~20% by protecting top side only
  - High temperature (650+C) resistance
  - Durable - weatherproof
  - Temperable, Bendable

Breakage Causes

1. **Tensile Stress**: 1.a. Bending
   1.b. Thermal
   1.c. NiS inclusion expansion in FT or HS
2. **Impact**: 2a. Hard Body – Hail Stones
   2b. Soft Body – Snow Slide
3. **Crushing**
4. **Acts of God**? *God doesn't break glass – we do*
5. **Mother Nature**? '*Hurricanes Happen'*
   – don't blame your mother

Finding Breakage Causes

FRACTOGRAPHICS can find the cause.

It only takes: enough time; enough money;

and having all the broken pieces near the fracture origin

See: ASTM C1256-93 "Interpreting Glass Fracture Surface Features“

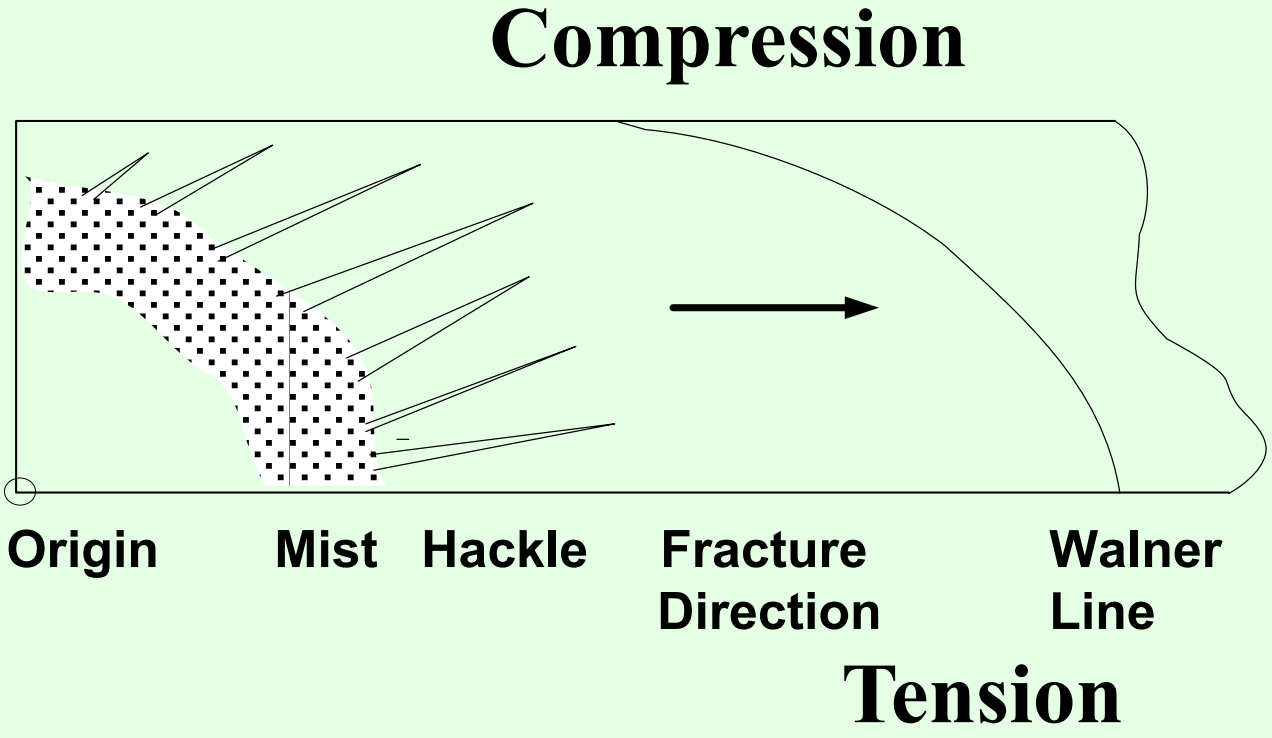
ASTM C1678-07 “Standard Practice for Fractographic Analysis”

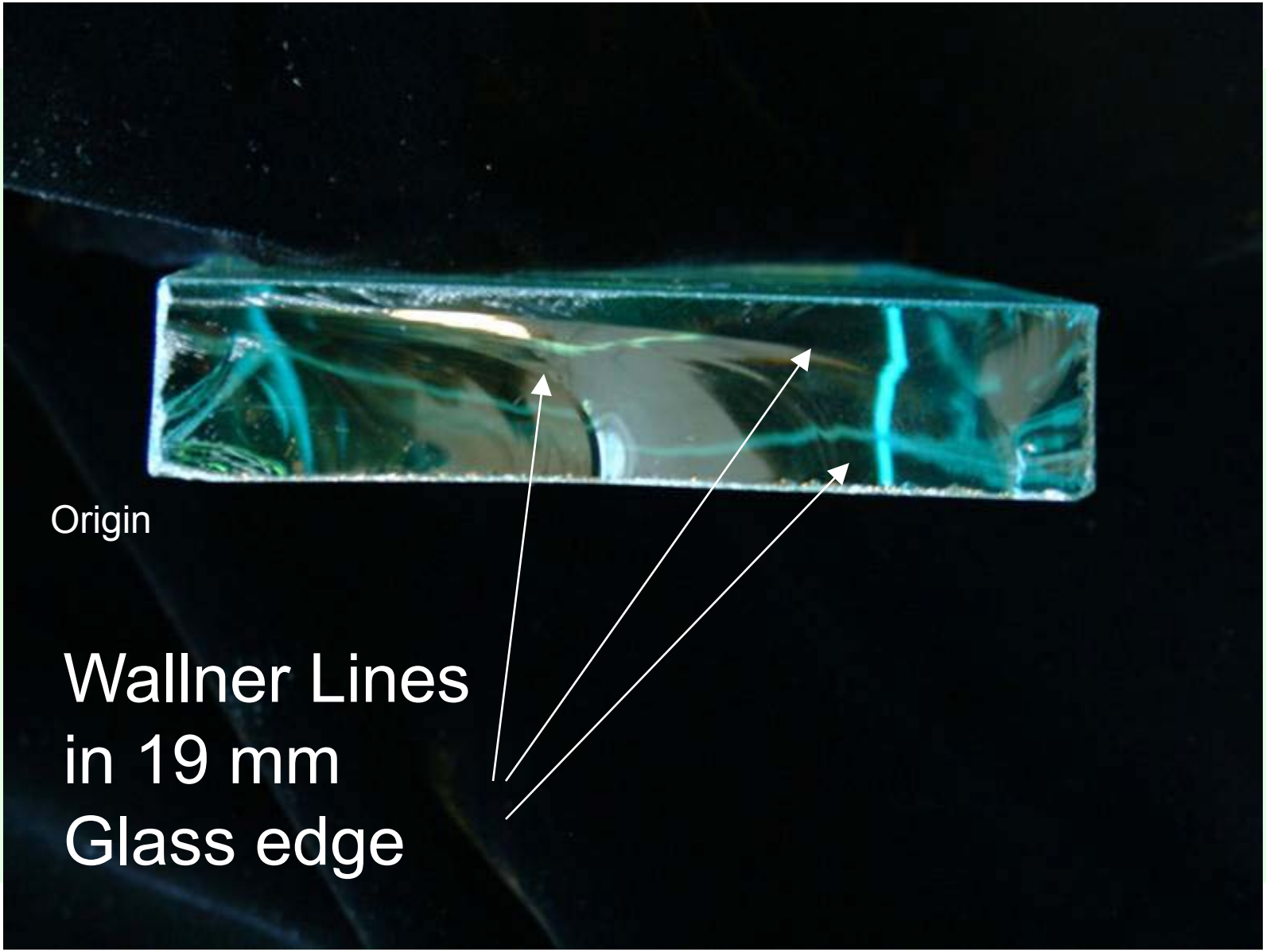


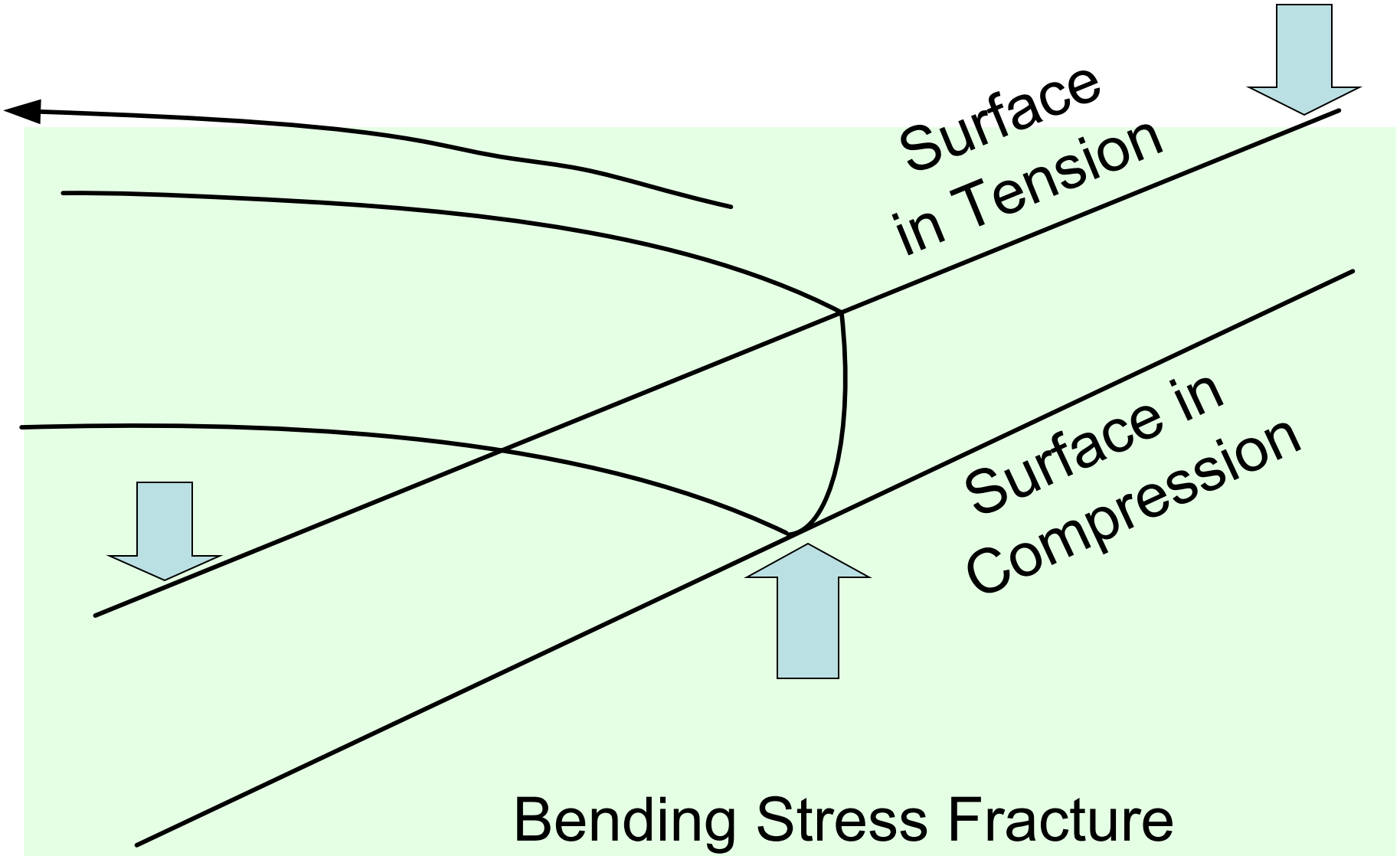
“White Boat Rock”

Bending or Thermal Cause

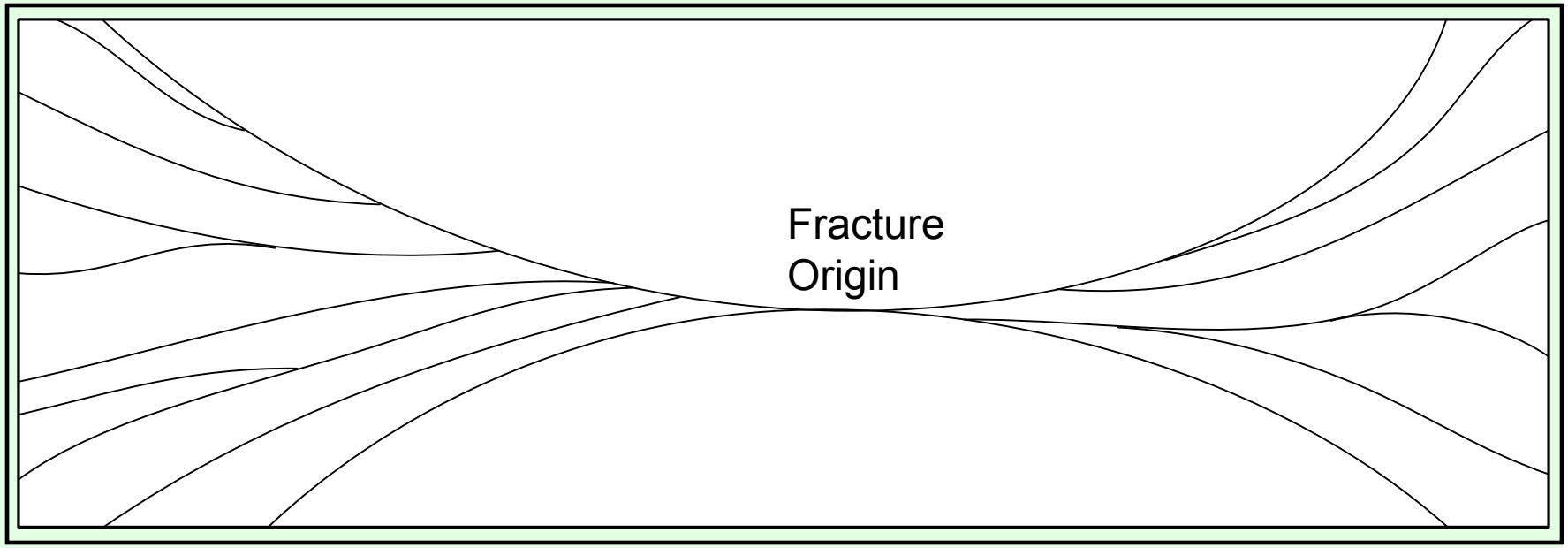
First, find the fracture origin




Origin
Wallner Lines
in 19 mm
Glass edge



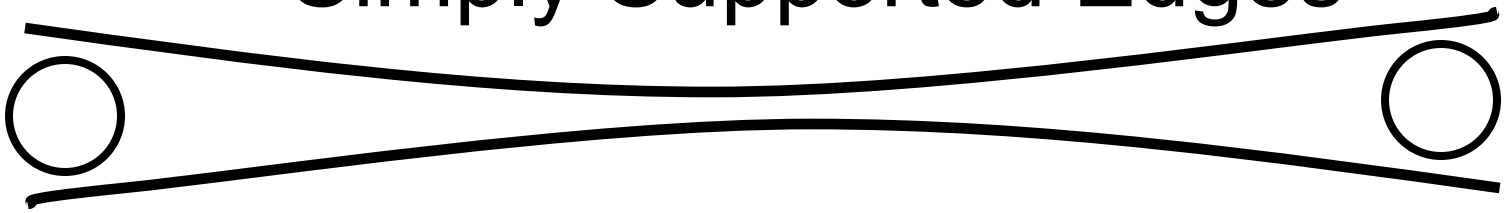
Bending Stress Fracture
Fracture starts in tension zone



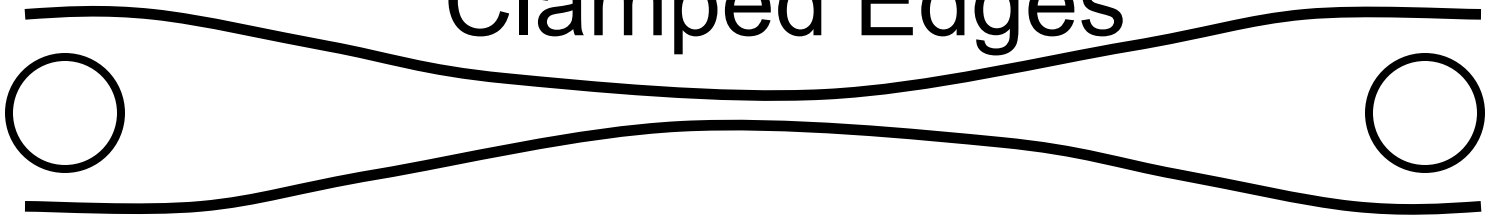
Properly glazed High Aspect Ratio Sealed Insulating Glass.

Breakage from too High or too Low air space pressure

‘Saucer’ shape
Simply Supported Edges

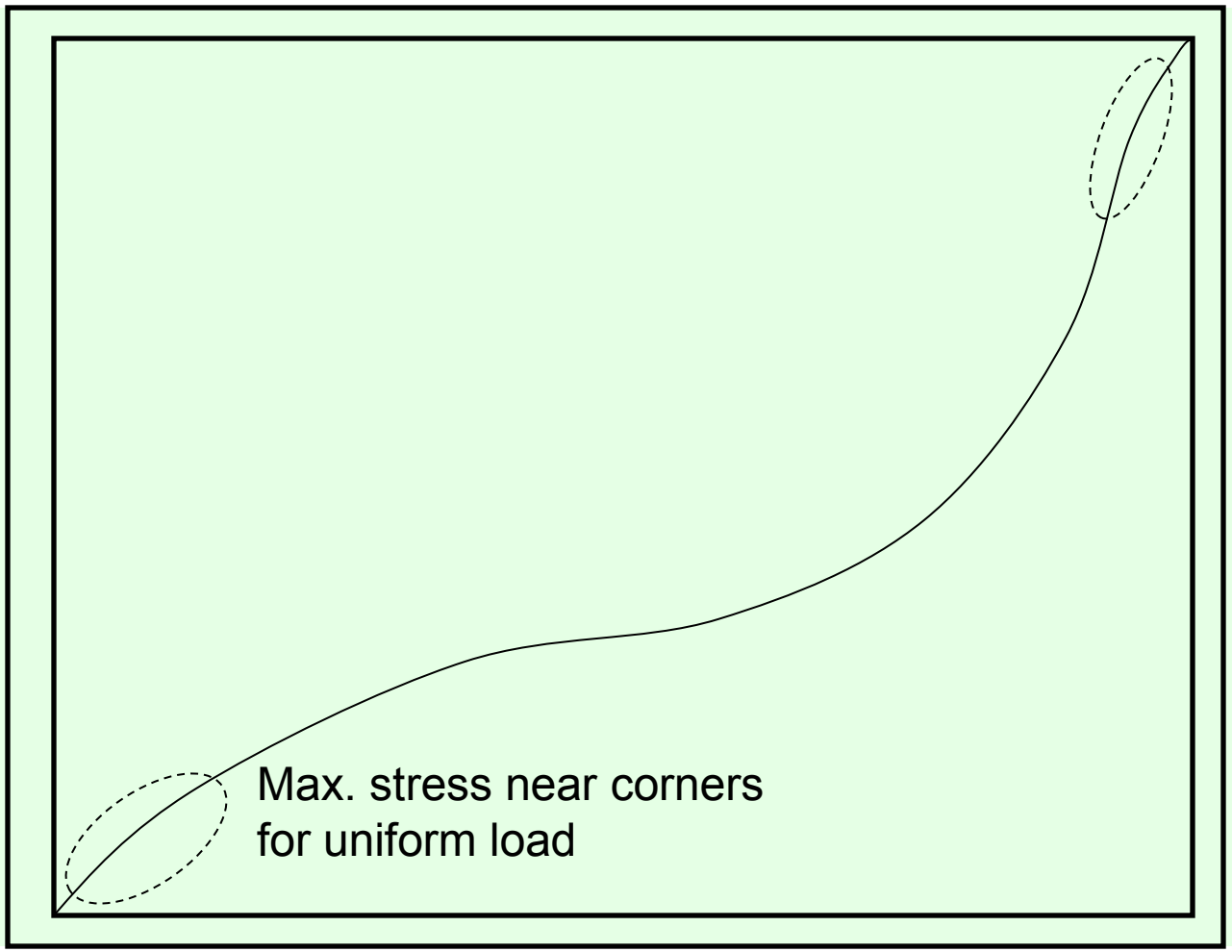


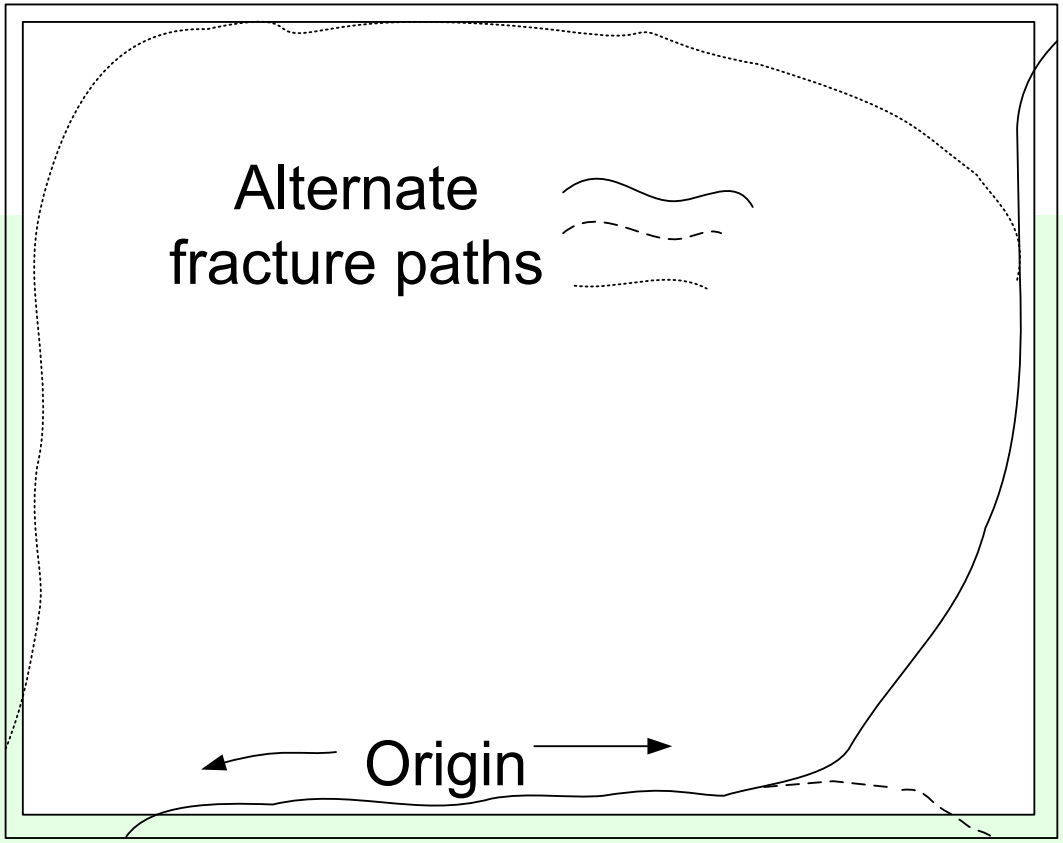
‘Soup Plate’ shape
Clamped Edges



4 x stress under IG air space
± pressure load

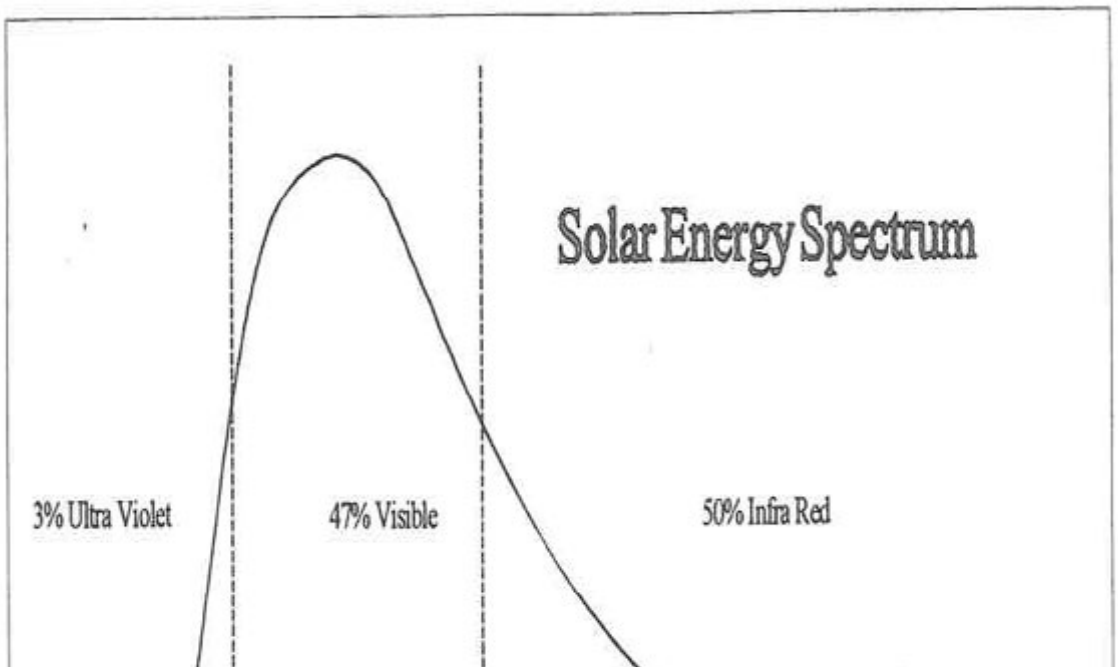
Sealed Insulating Glass
Simply Supported Edges.
Break caused by excessive ±∆Pressure in sealed air space.





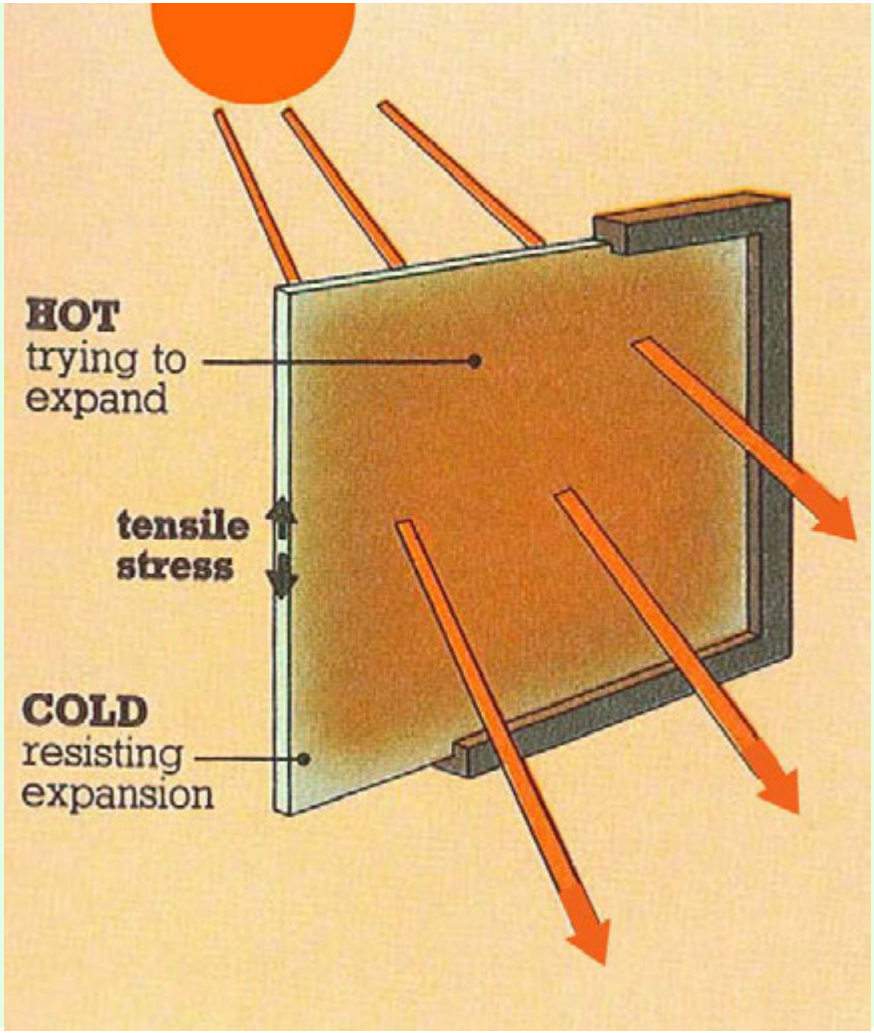
Incorrect ‘Clamped Edges’ create very high bending stresses at low temperatures in Insulating Glass. Fracture origin at a scratch.

Thermal Loads

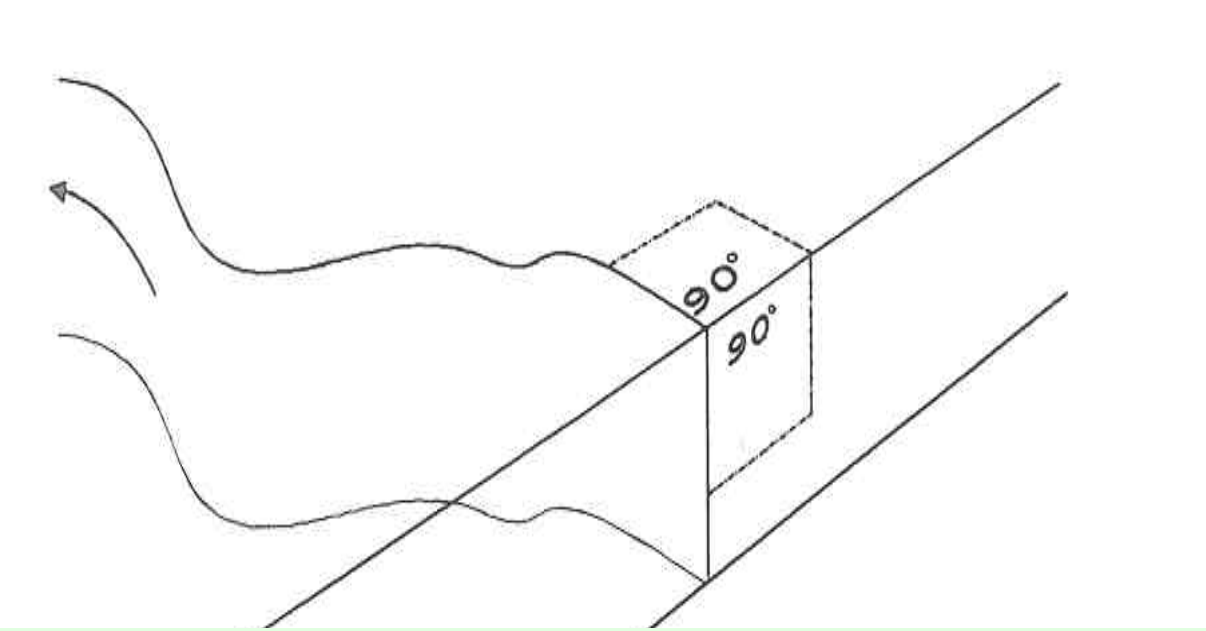


A glass or coating can appear clear yet absorb a large amount of invisible Solar IR energy and so incur significant stress

Thermal Stress Generation

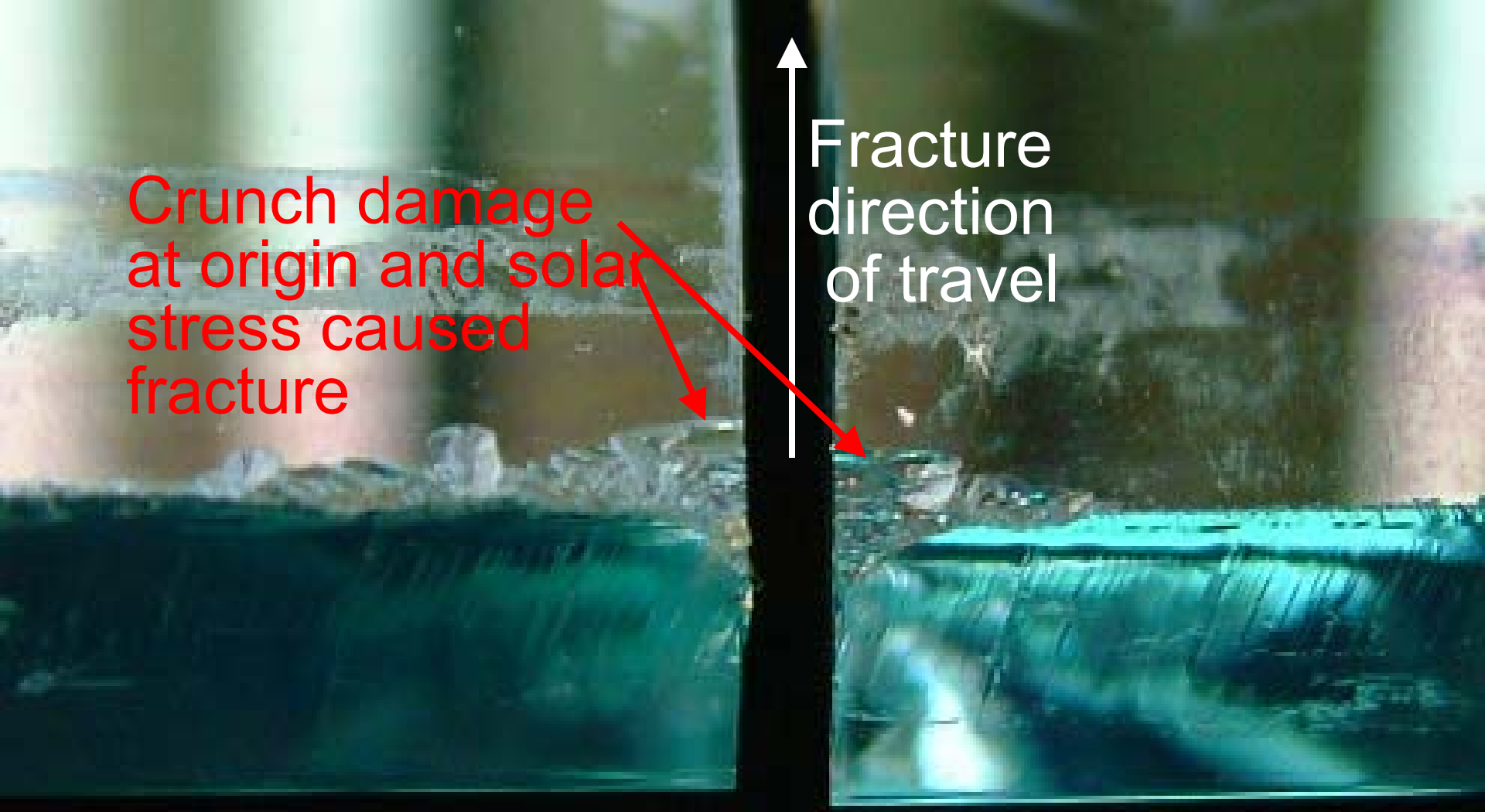



2004 3 12



Classic Thermal Stress fracture origin.

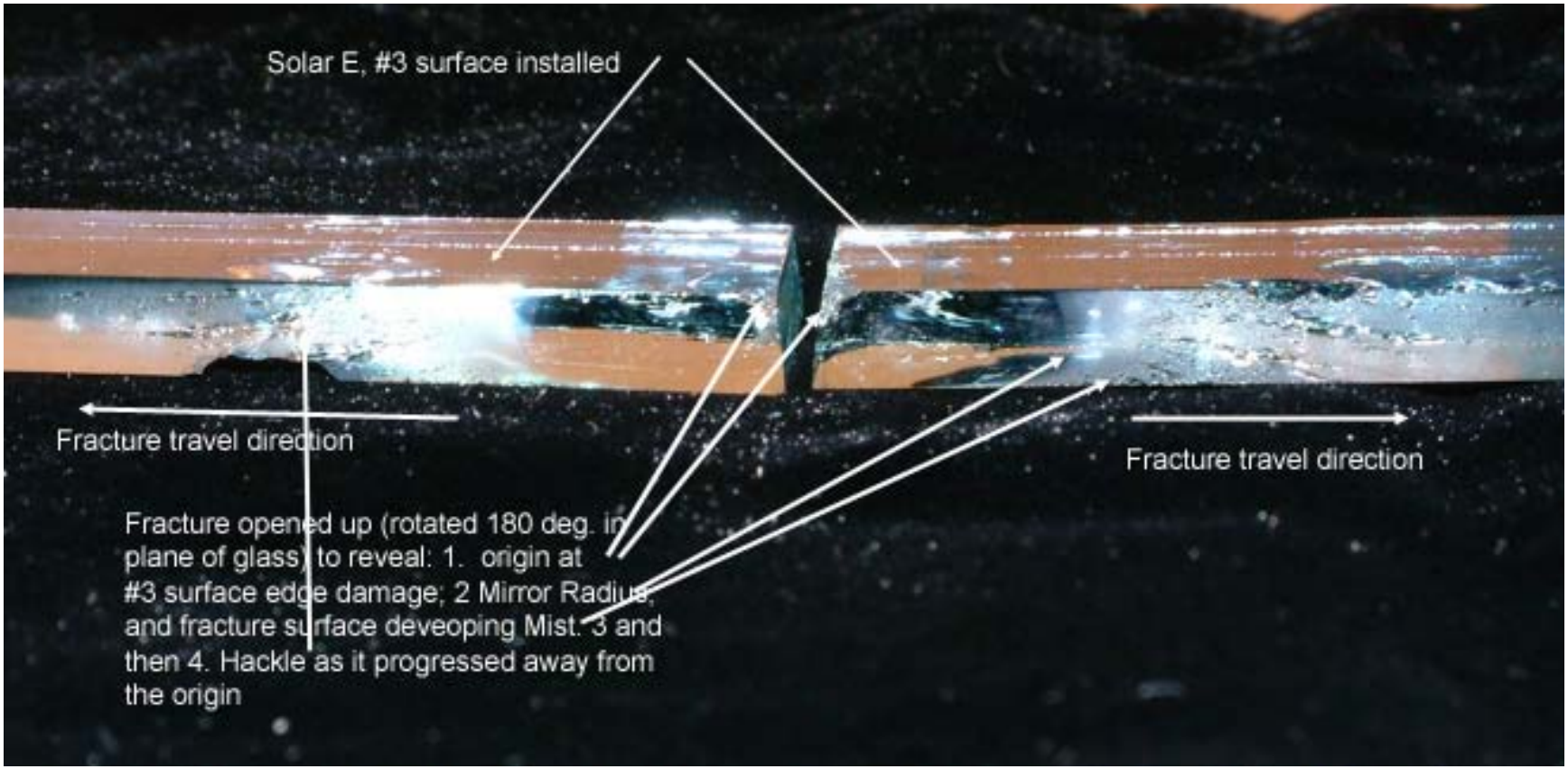
Break typically starts in the central ¾ of the edge length and not at a corner.

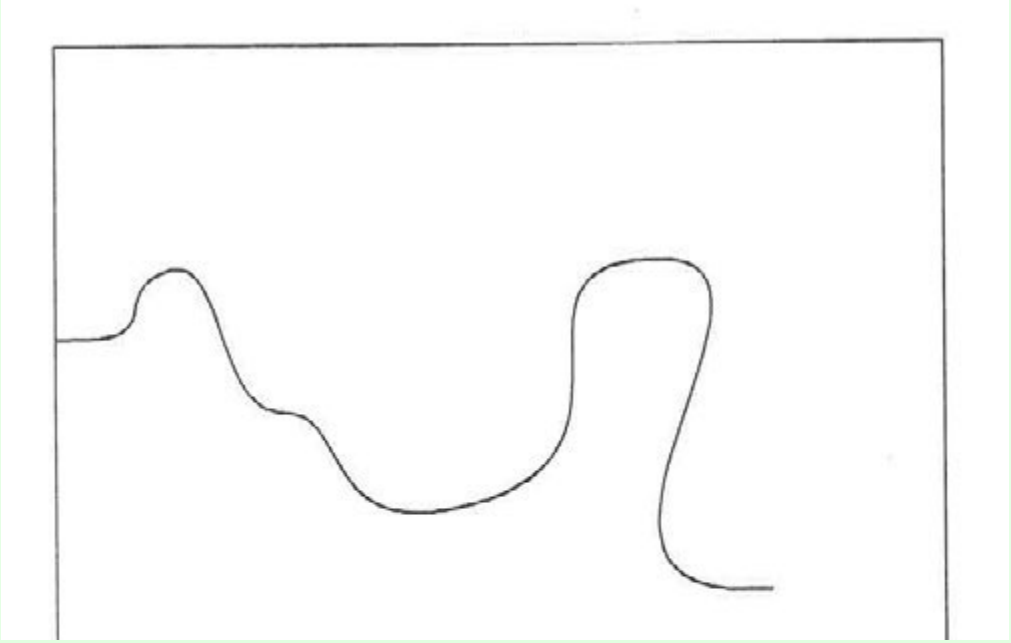


Cut edge – poor quality

Solar E (solar absorbing Low E coating) incorrectly used on #3 Surface (should be #2).

Energy Advantage Low E can be correctly used on either #2 or #3 Surface

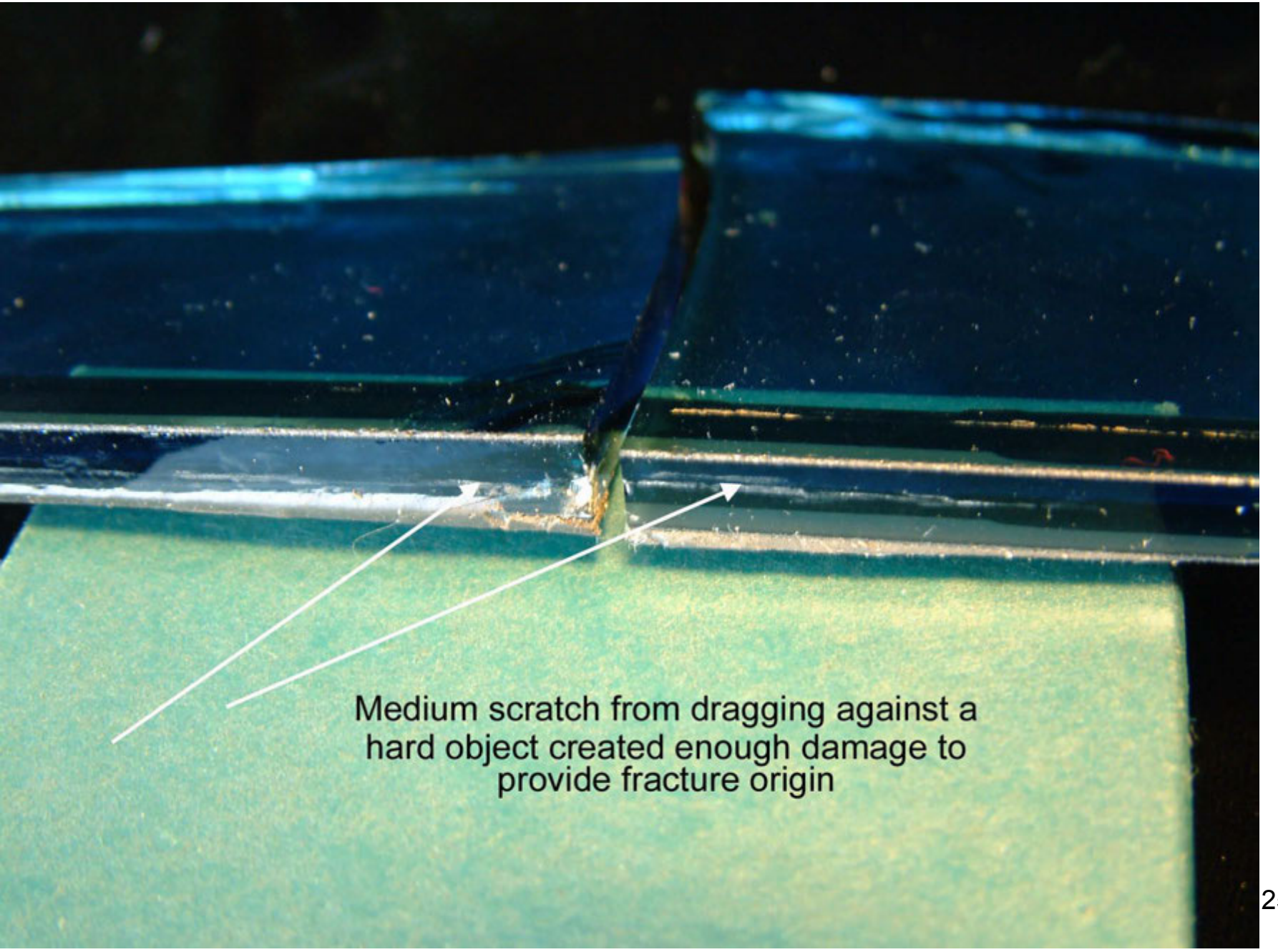

Solar E, #3 surface installed
Fracture travel direction
Fracture travel direction
Fracture opened up (rotated 180 deg. in plane of glass) to reveal: 1. origin at #3 surface edge damage; 2 Mirror Radius; and fracture surface deveoping Mist. 3 and then 4. Hackle as it progressed away from the origin

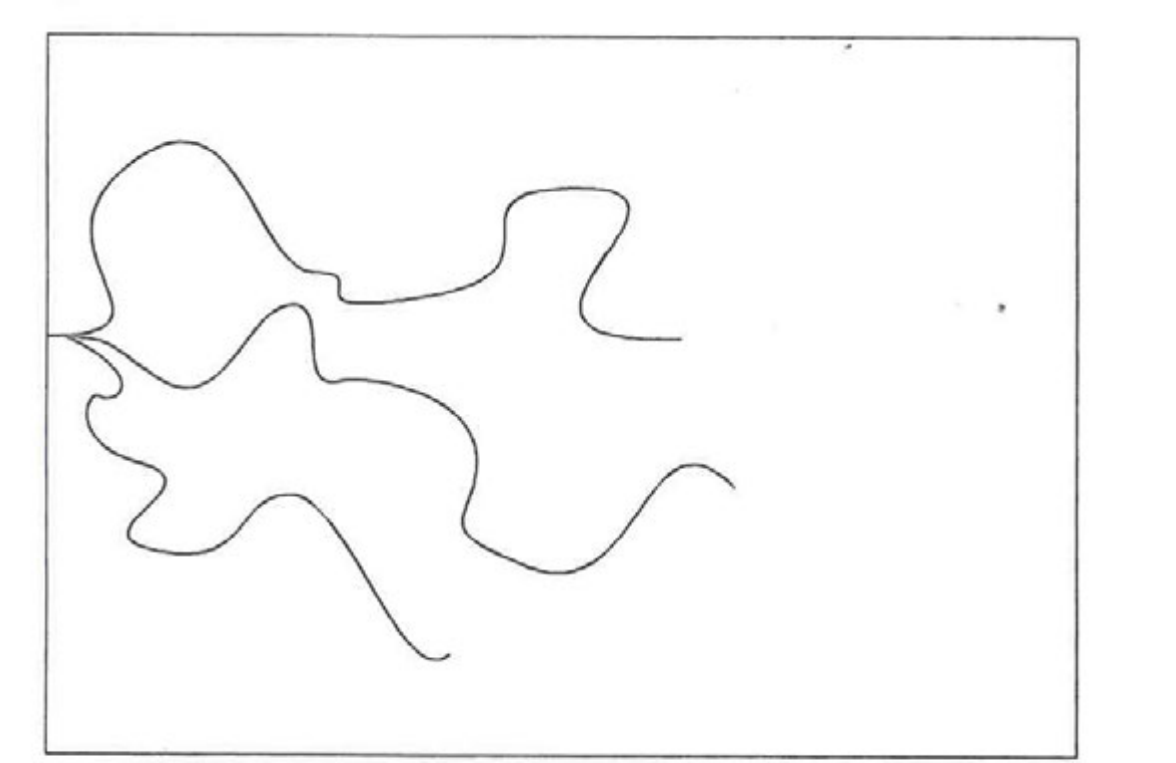


Low Stress: Single crack suggests a weaker glass edge. Less energy was needed to propagate the crack





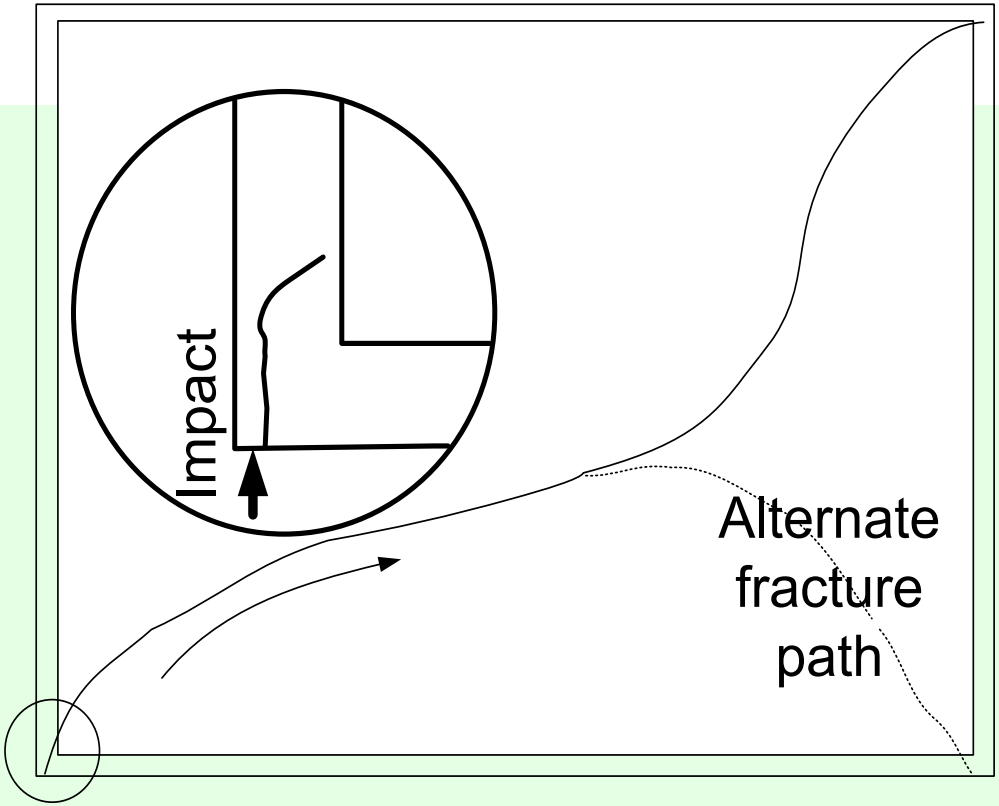

Medium scratch from dragging against a
hard object created enough damage to
provide fracture origin



High Stress: Multiple crack surfaces were needed to absorb excessive energy.

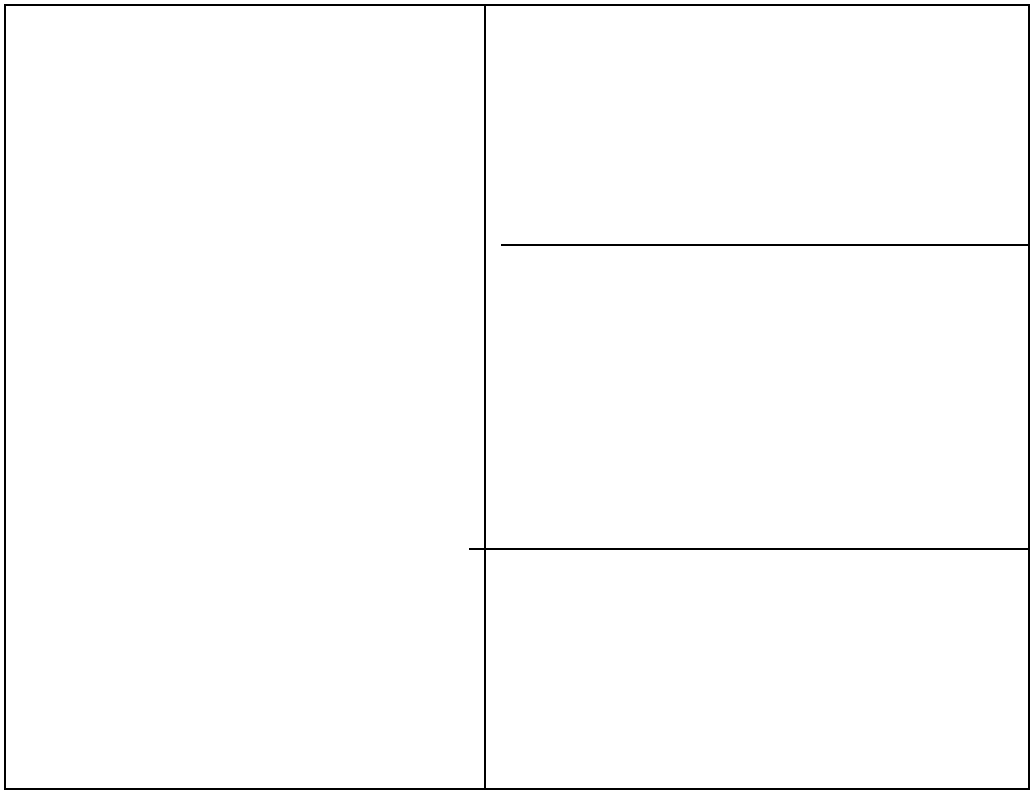






A corner impact easily creates a 10 or 20 mm long crack which waits for a high stress situation to make it run. Here low winter temperature contracts the sealed air space and creates a large bending stress.

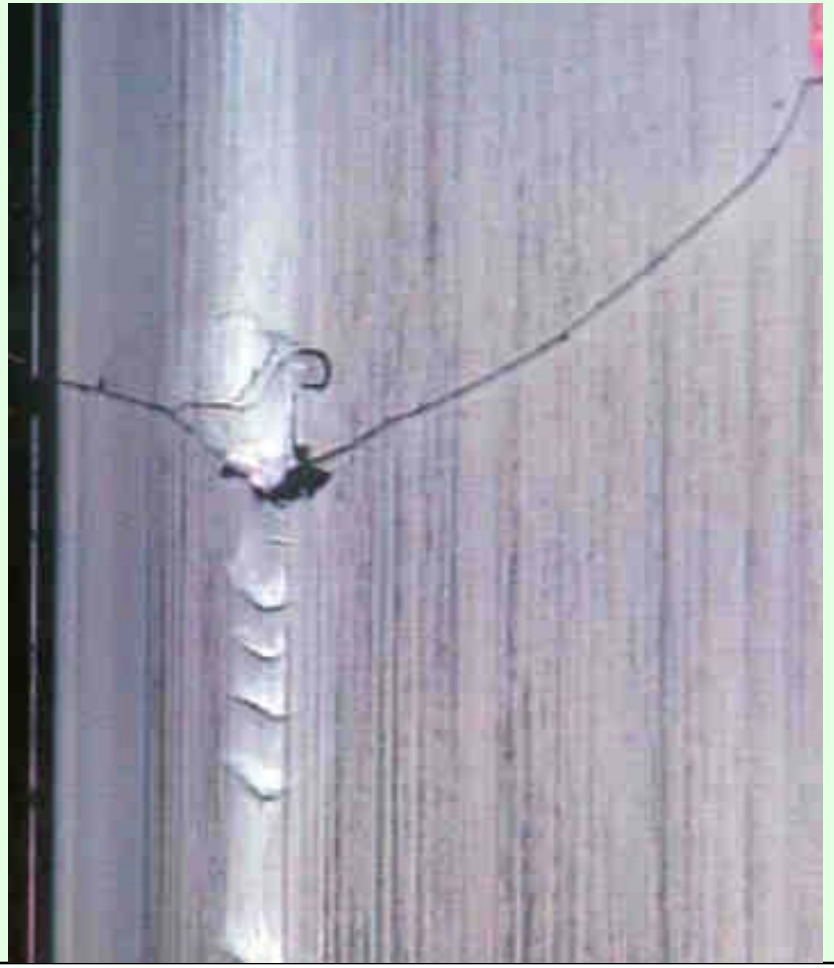
Over-running
Interrupted Cut Score Line



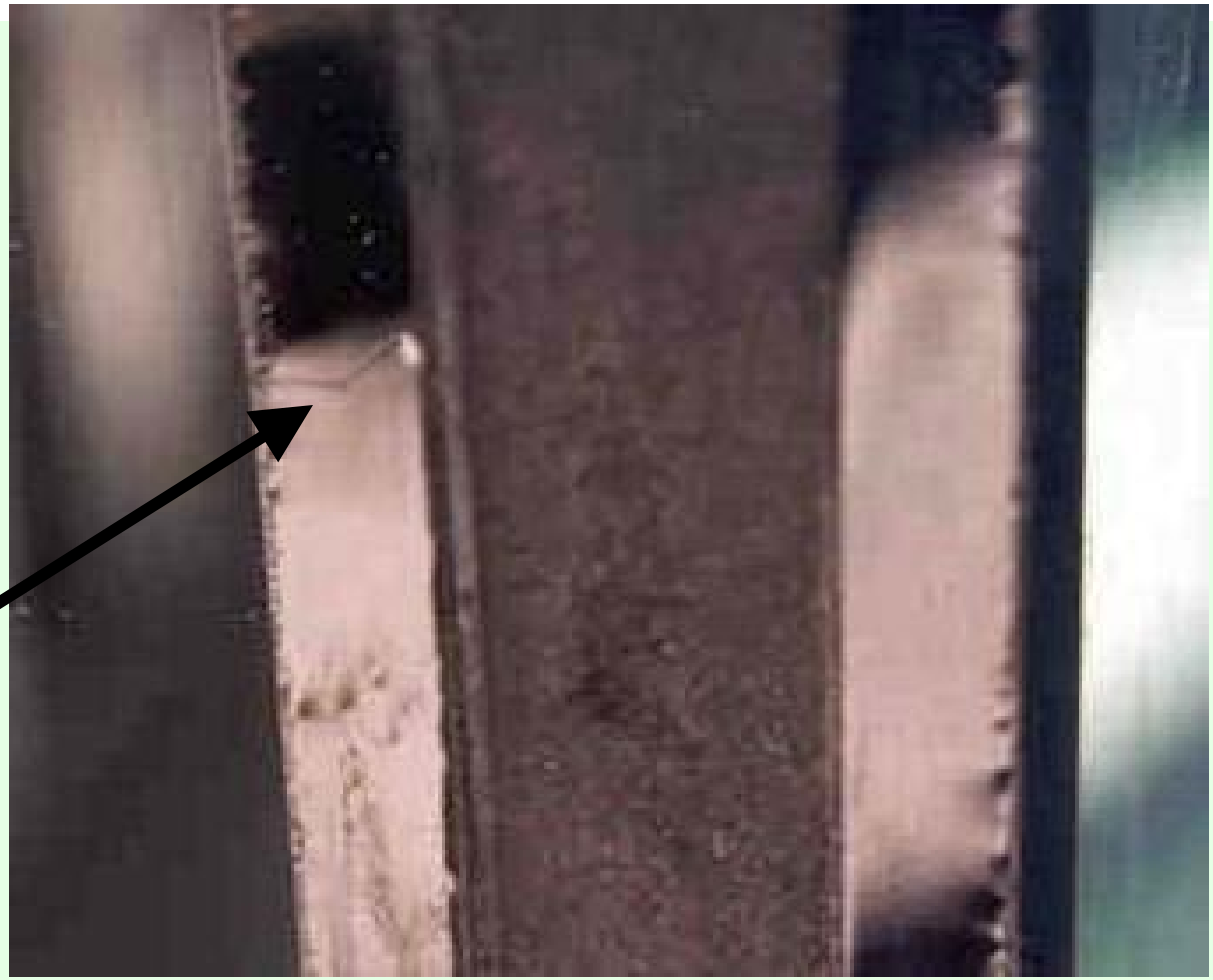
Weld Splatter Damage



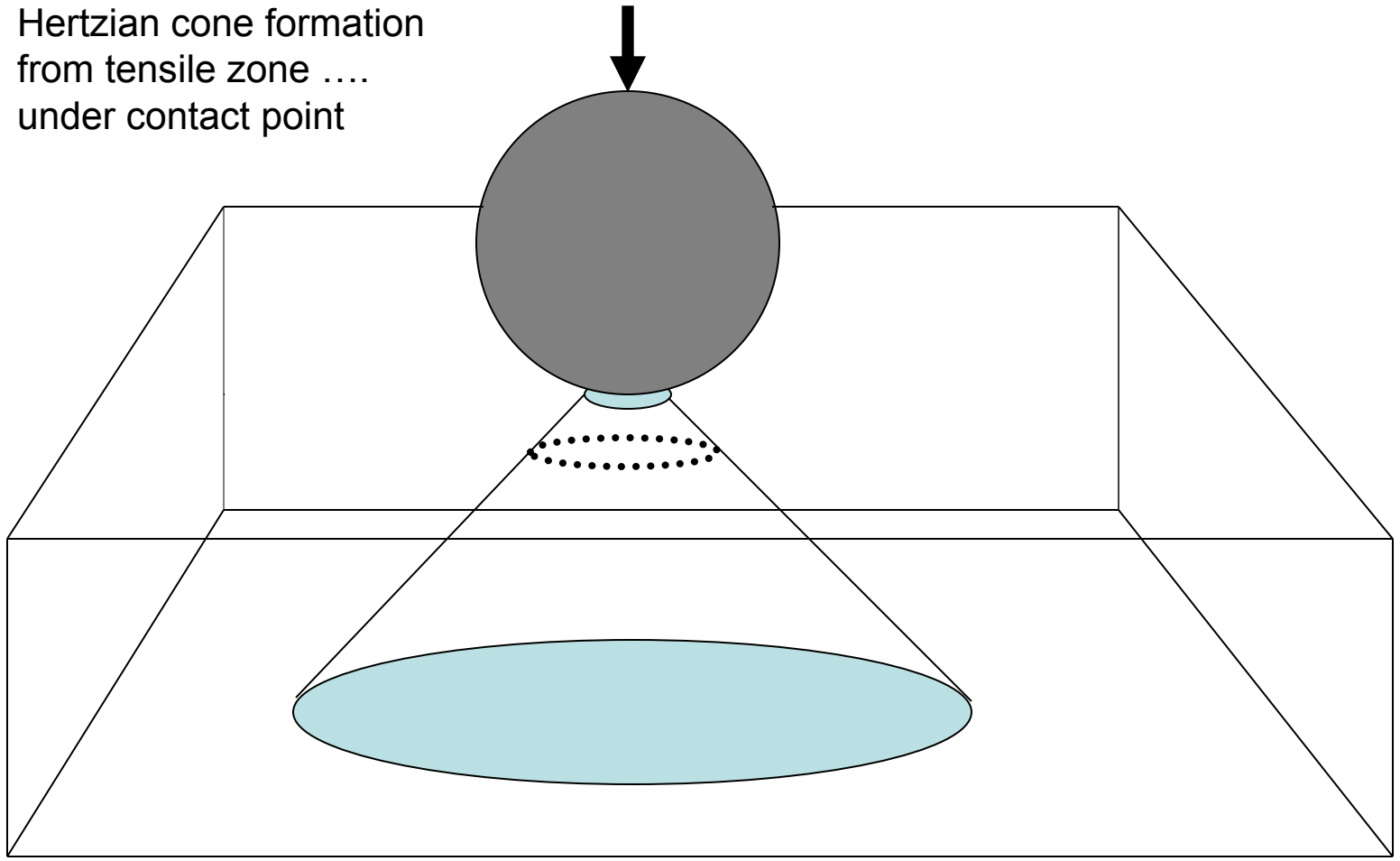
Insufficient sealant in IG gun head made rub marks causing many vents of sub-millimeter size in glass cut edge



Fracture Origin at rub mark on IG cut edge. Thermal stress caused the small vent to run



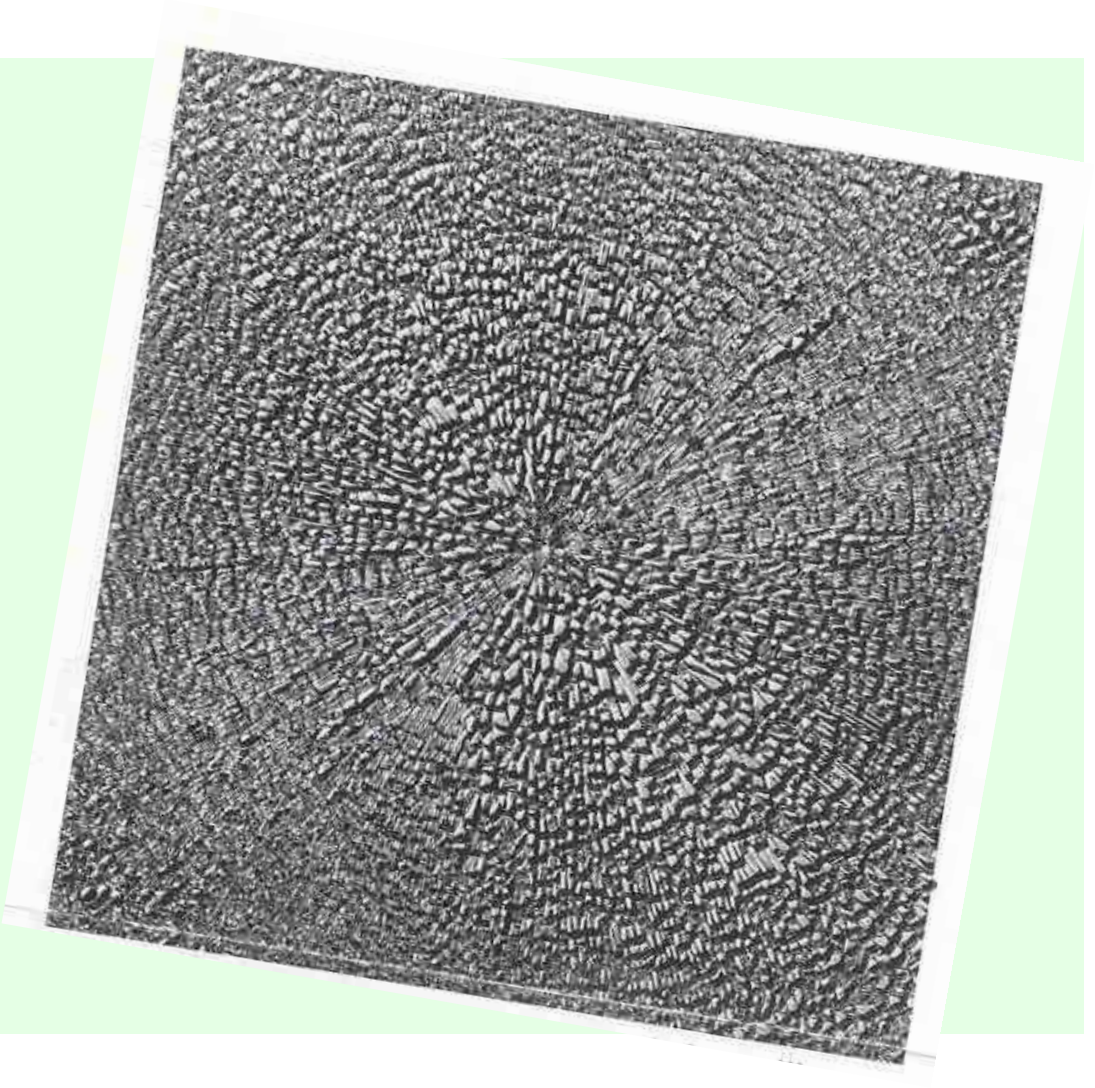
Impact Cause



Tempered Glass

Fracture origin at plate center

Look for surface damage or very small inclusion in glass at origin









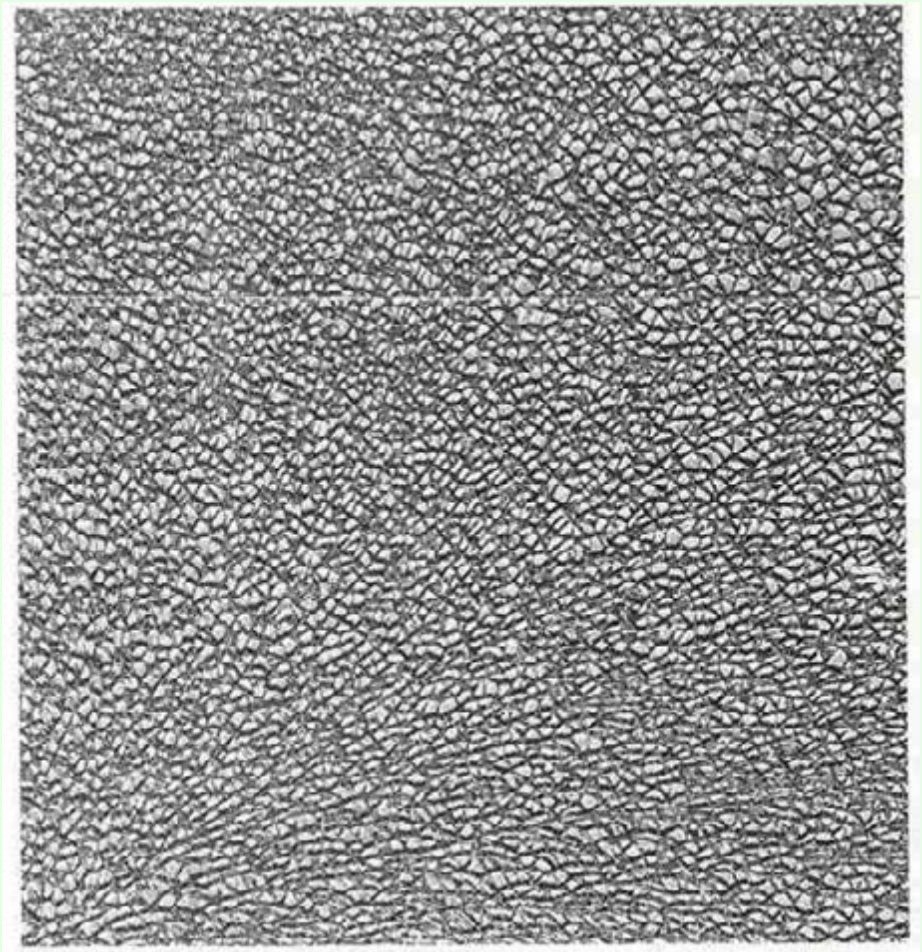
TEMPERED GLASS

– On rare occasions, heat-treated (tempered and sometimes even heat-strengthened) glass can break spontaneously, without any applied load, due to small inclusions that may be present in all float glasses.

Tempered Glass

Corner origin of fracture.

Look for corner-crunch damage



Wind Loads

Wind Loads used to be 60 second duration gusts.

Now the building codes use 3 second duration gusts.

3 second gusts are greater than those of 60 sec.

But Glass is stronger when the load duration is shorter so there was little change when the codes changed.

Other Considerations

1. Condensation Damage

Soda-Lime window glass can be corroded by alkalis. Small amounts of water (dew?) leach sodium making an alkali solution which attacks the silicate structure. See drinking glasses washed too often in domestic dish washers.

Other Considerations

2. Solarization

Some glass compositions show slight yellowing when exposed to strong UV light for extended periods of time.

Summary

Will my glass break?

Nobody knows for sure. You can't tell how strong it is, until it was.

Design glass not to break (low probability), but if it does, the consequences must be acceptable.

What to Do

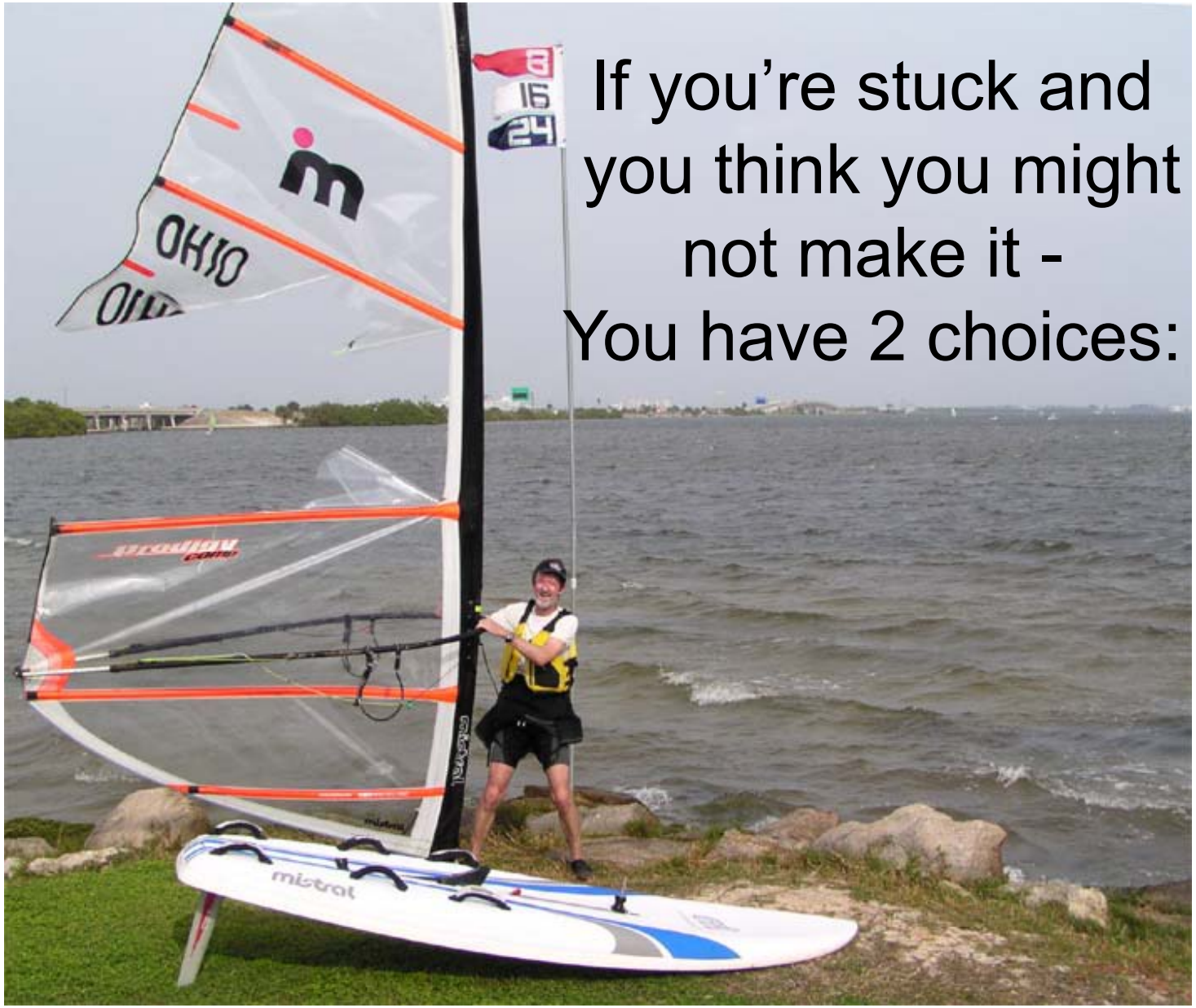
Was the load too great?

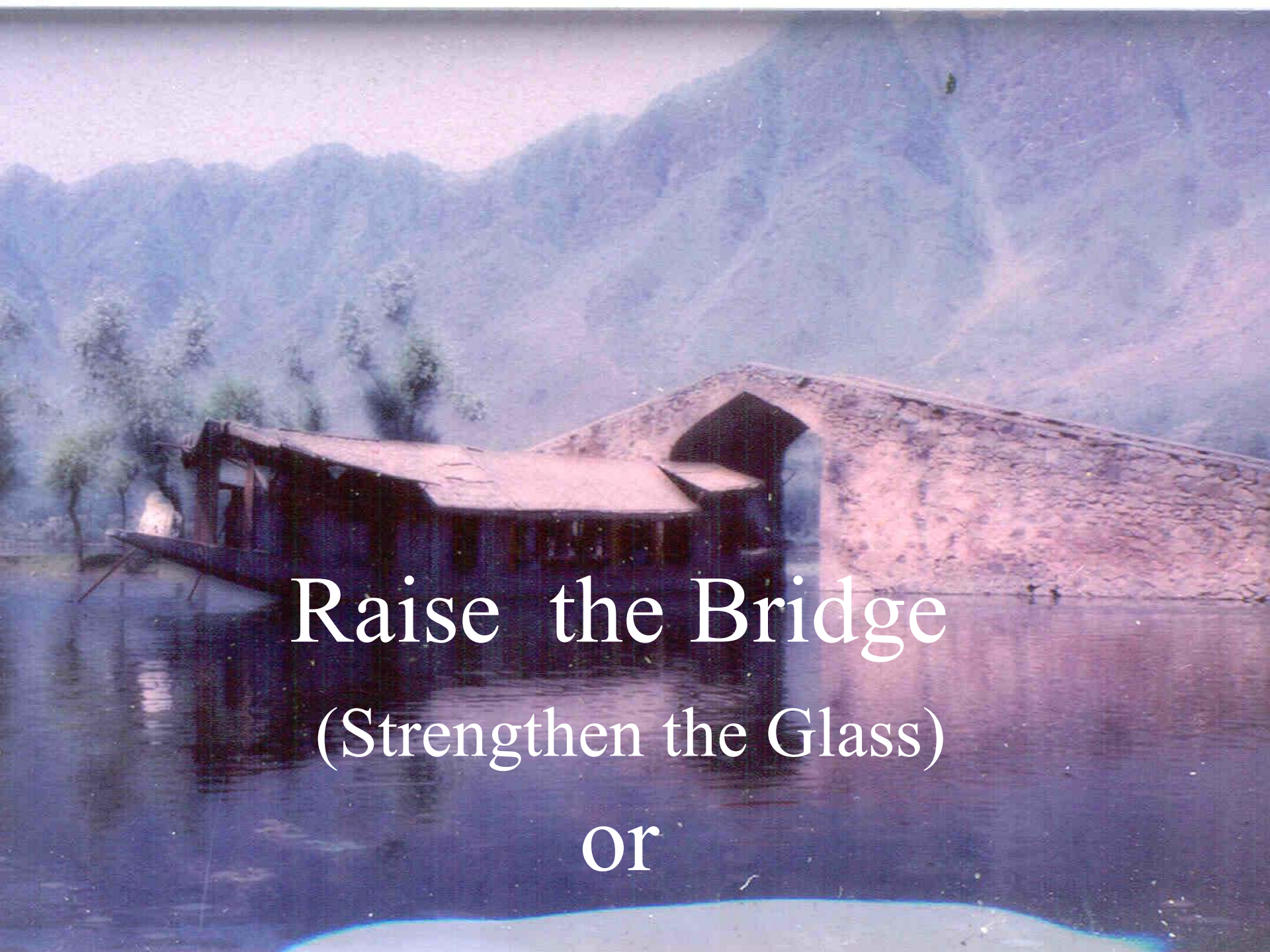
Reduce the load or stress

or

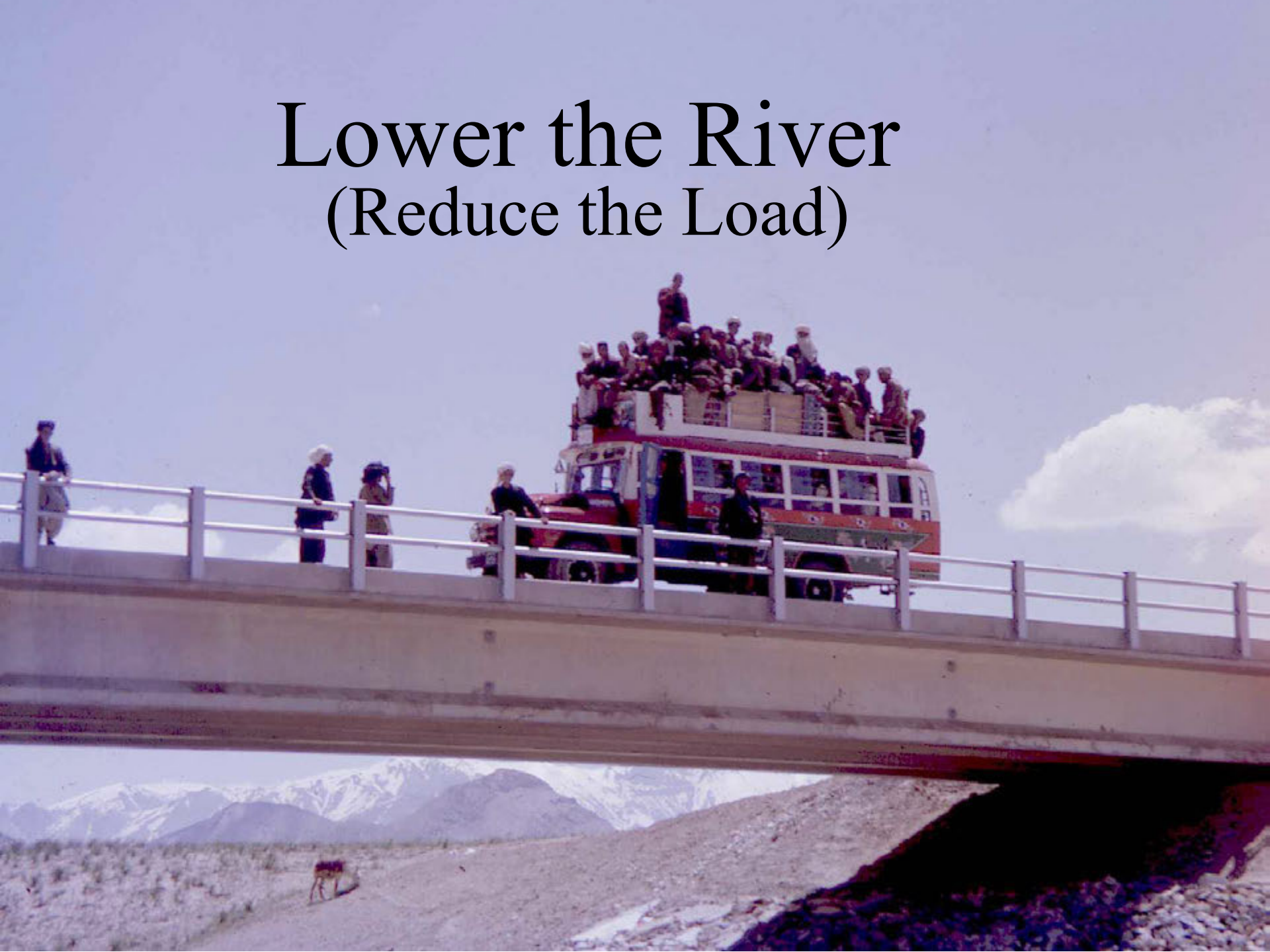
Was the glass too weak?

Strengthen the glass


If you're stuck and
you think you might
not make it -
You have 2 choices:
OHIO
mistral


Raise the Bridge
(Strengthen the Glass)
or

Lower the River
(Reduce the Load)



Breakout session: Metastabilities of Thin Films

Discussion leader: Jim Sites

1:00 – Jeff Yang (Uni-Solar) – Metastability of Amorphous Silicon – Historical Perspective and Real-Life Performance

1:30 – Dave Albin (NREL) – Metastable Effects in Polycrystalline Thin Film Cells and Correlations with Performance and Reliability

1:50 – Joe delCueto (NREL) – Comparison of Injection of Carriers Through Light Soaking and Forward Bias in Dark

2:10 – Discussion: How do we differentiate reversible from irreversible changes? How does a-Si experience with the Staebler-Wronski effect help with CIGS/CdTe issues? Can we use the same pre-conditioning test for all thin-film modules?

Jeff Yang summary slide

The **Staebler-Wronski effect** is reversible with thermal annealing

The **triple-junction structure** with high quality material results in improved module performance featuring higher kWh/kW

Reliability has been much improved; **25-year warranty** is being offered

Long-term degradation still exists and needs better understanding

Performance prediction should include thermal annealing to reflect real-life conditions

Dave Albin summary slide

NREL **CTO/ZTO** CdTe cells superior to SnO_2-based cells in initial performance, but some fundamental durability problems

C-V hysteresis for CdTe cells increased with stress in cells using "infinite" sources of dopant (Cu).

Additional **hysteresis in CTO/ZTO** cells strongly suggests "decomposition" of the CTO/ZTO layers

C-V hysteresis also increased in **industrial cells**, but decreasing hysteresis observed at longer stress times and higher temperatures.

C-V during ALTs easily implemented as a non-destructive technique to better identify degradation mechanisms in cells and modules

Joe del Cueto summary slide

Both **CIGS and CdTe** show metastable behavior in performance

IEC61646 stabilization, defined as $\Delta\eta \leq 2\%$ between successive increments, may be inadequate to define stability for polycrystalline thin-film PV.

Will deploy same module set outdoors for 6-10 weeks to compare light- and dark-exposure Will start testing **newer CdTe and CIGS** module sets

Implemented **stabilization/preconditioning procedures** for (1) light soak at 1-sun, and (2) voltage-biased dark-soak, at 65°±5°C

CV profiling:

Changes in depletion width and hysteresis with light or thermal anneal

Quantifiyng link to stability is likely different between CIGS and CdTe

For some modules, capacitance profiles are different in light and dark

Discussion summary – Thin-film metastabilities

- What differentiates stability and reliability issues for a-Si, CdTe, and CIGS? Different mechanisms: electronic states, possible ionic movement.
- Seasonable effects: (Joe) 45% phase lag with CdTe
- How does one focus in quickly of metastable effects? Systematic pre-conditioning before measurments recommended.
- Any merit to using biases significantly above V_{MP} for stress tests? Probably, but need care with associated thermal effects.
- Why does a-Si not need a moisture barrier, even though similar TCO's are used? Seems to be true at both Uni-Solar and NREL, and is a mystery.

Metastability of Amorphous Silicon

Historical Perspective and Real-Life Performance

Jeffrey Yang & Subhendu Guha

United Solar Ovonic

PV Module Reliability Workshop

Golden, CO

February 19, 2010

Outline

- Staebler-Wronski effect and mitigation
- Flexible light-weight triple-junction laminates for roofing applications
- Outdoor behavior and energy yield
- Annual degradation
- Reliability
- How do we predict performance?
- Real life performance
- Summary

Staebler-Wronski Effect (1977)

UNI-SOLAR

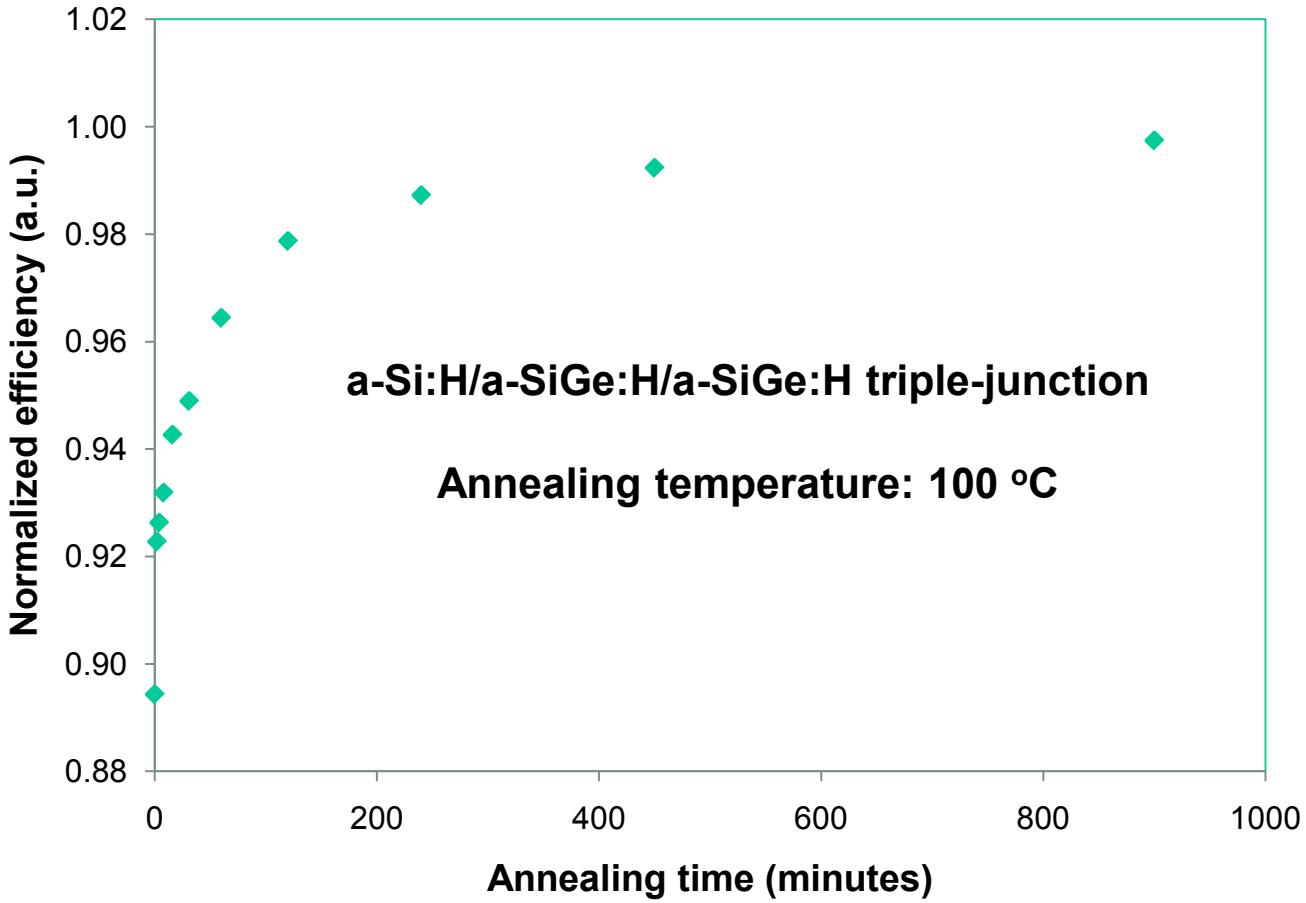
Reversible conductivity changes in discharge-produced amorphous Si[a)]

D. L. Staebler and C. R. Wronski

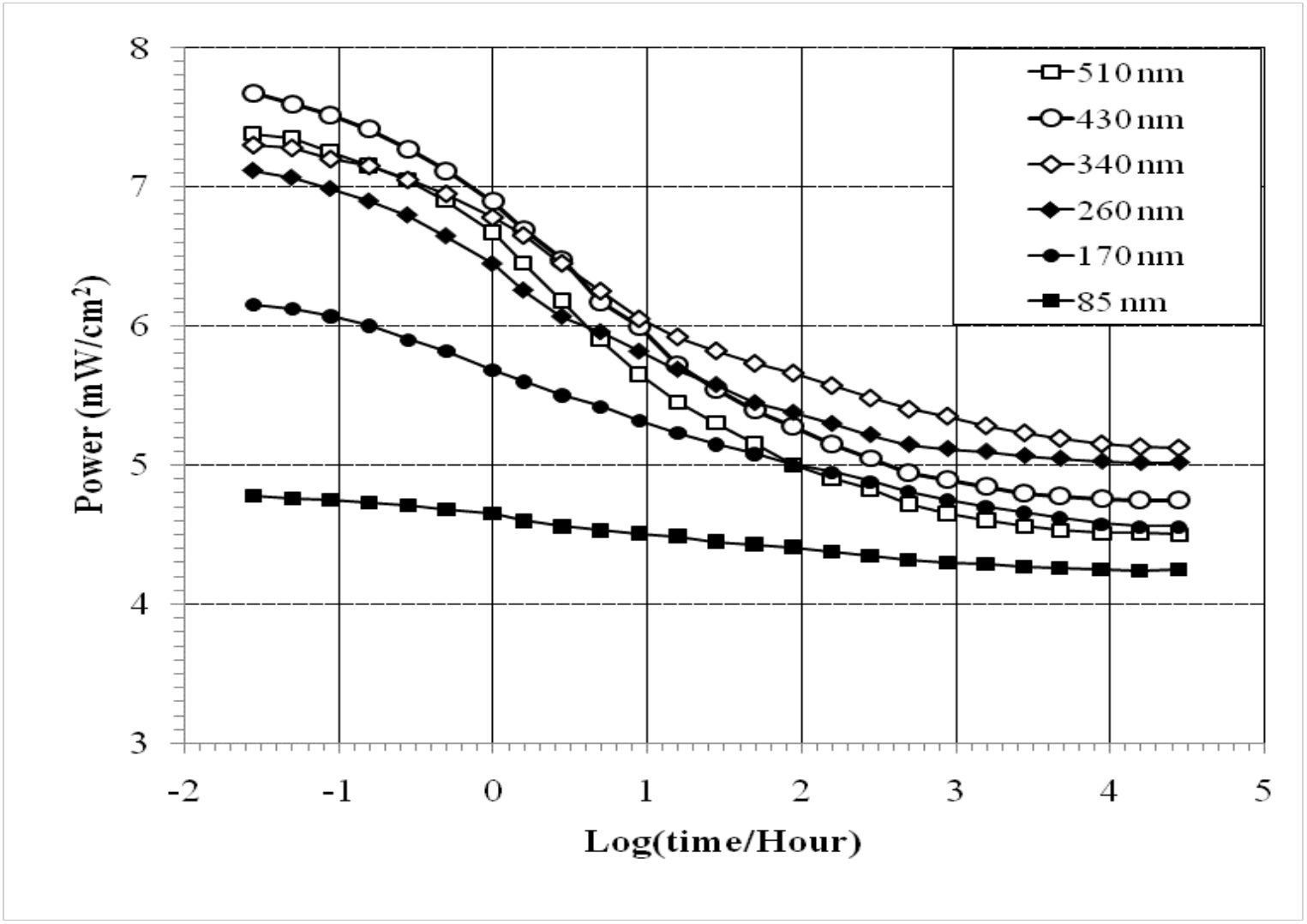
RCA Laboratories, Princeton, New Jersey 08540
(Received 9 May 1977; accepted for publication 17 June 1977)

A new reversible photoelectronic effect is reported for amorphous Si produced by glow discharge of SiH_4. Long exposure to light decreases both the photoconductivity and the dark conductivity, the latter by nearly four orders of magnitude. Annealing above 150°C reverses the process. A model involving optically induced changes in gap states is proposed. The results have strong implications for both the physical nature of the material and for its applications in thin-film solar cells, as well as the reproducibility of measurements on discharge-produced Si.

Effect of Thermal Annealing



Thick a-Si layer causes more degradation



Approaches for Improving a-Si cells

UNI-SOLAR

- Improve materials using hydrogen dilution during film growth
- Incorporate light trapping in cell design
- Adopt multi-junction cell structures
- Rate products at their stabilized power

Effect of hydrogen dilution on a-Si cells

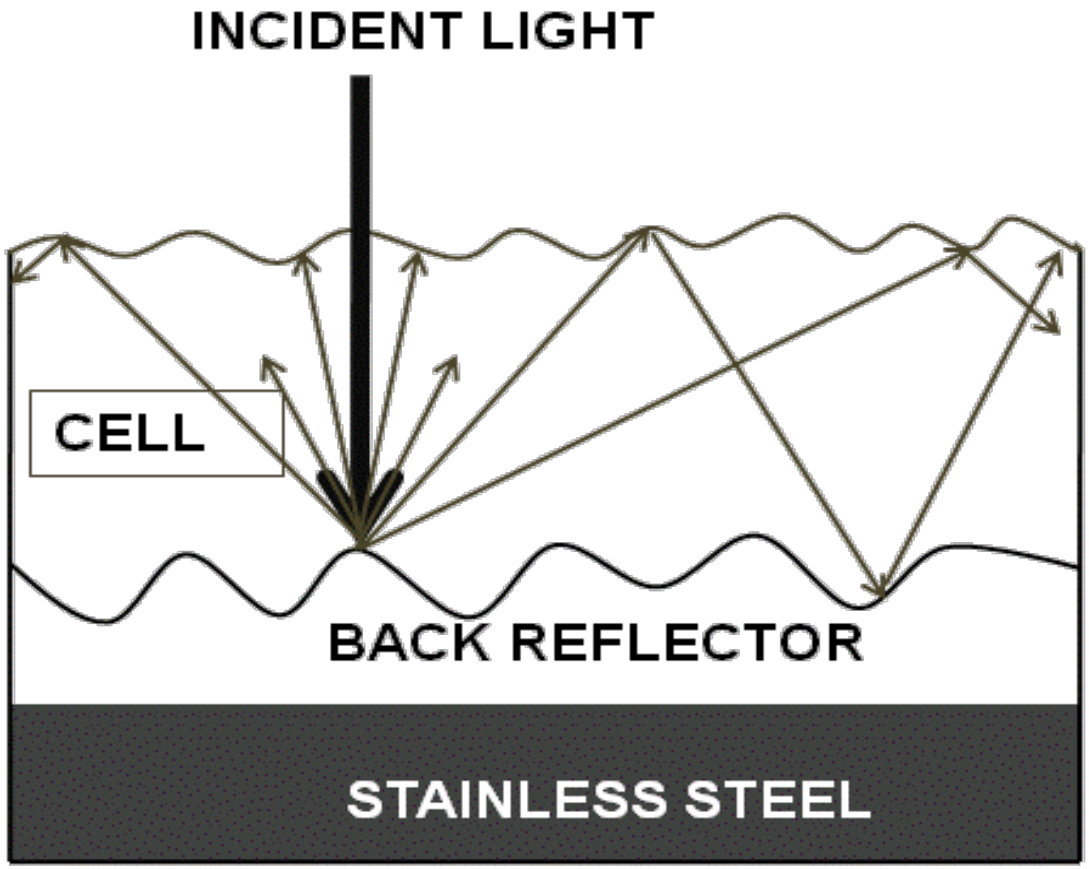
UNI-SOLAR

Hydrogen dilution	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	Eff. (%)
Near-optimum	10.04	1.018	0.732	7.48
Optimum	*9.88*	*1.028*	*0.761*	*7.73*
On-the-edge	9.82	0.624	0.426	2.61
Over-the-edge	8.95	0.459	0.562	2.31

Effect of Hydrogen Dilution

Description	State	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	Eff. (%)
a-Si, low dilution, 300 °C	Initial	12.3	0.94	0.65	7.5
	Degraded	11.6	0.91	0.55	5.8
a-Si, high dilution, 300 °C	Initial	11.6	0.96	0.68	7.6
	Degraded	11.2	0.94	0.61	6.4
a-Si, low dilution, 175 °C	Initial	11.4	0.96	0.64	7.0
	Degraded	9.5	0.91	0.46	4.0
a-Si, high dilution, 175 °C	Initial	10.9	1.00	0.69	7.5
	Degraded	10.5	0.97	0.60	6.1
a-SiGe, low dilution	Initial	17.6	0.72	0.55	7.1
	Degraded	14.9	0.64	0.41	3.9
a-SiGe, high dilution	Initial	18.0	0.74	0.59	8.0
	Degraded	16.3	0.69	0.45	5.1

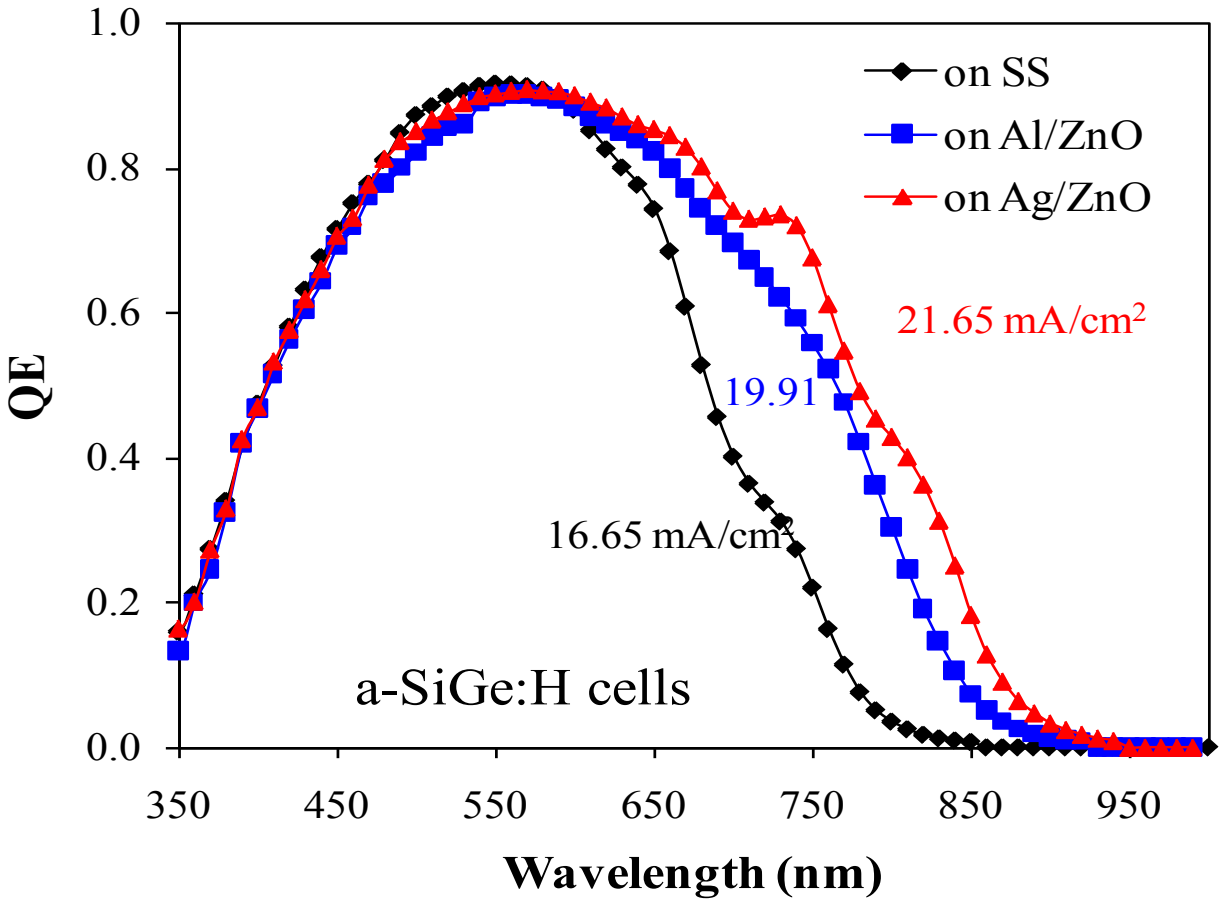
Light Trapping



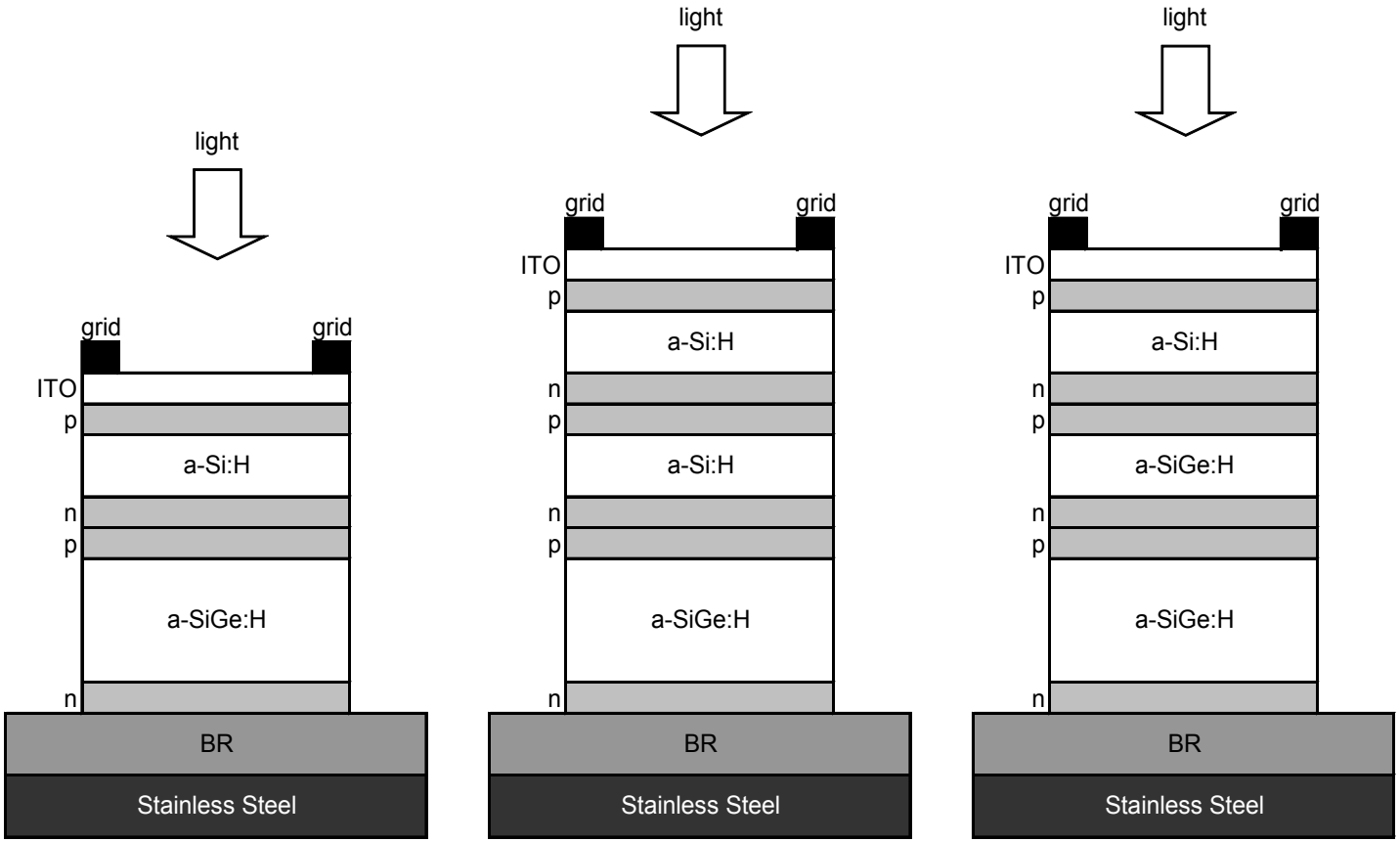
Light Trapping Effect

UNI-SOLAR

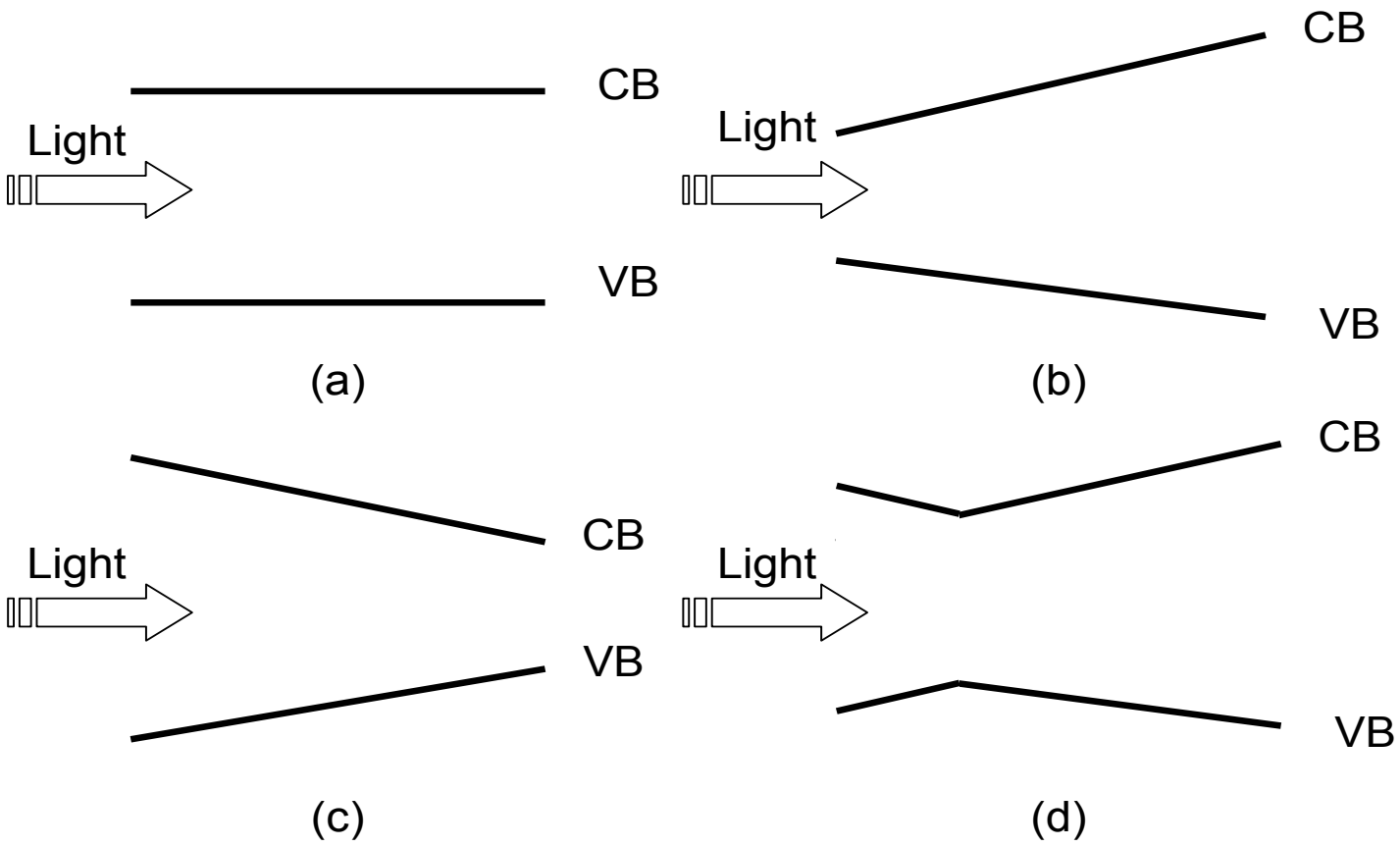
a-SiGe:H cell on ss, Al/ZnO, & Ag/ZnO



Multi-junction cells using a-Si:H & a-SiGe:H

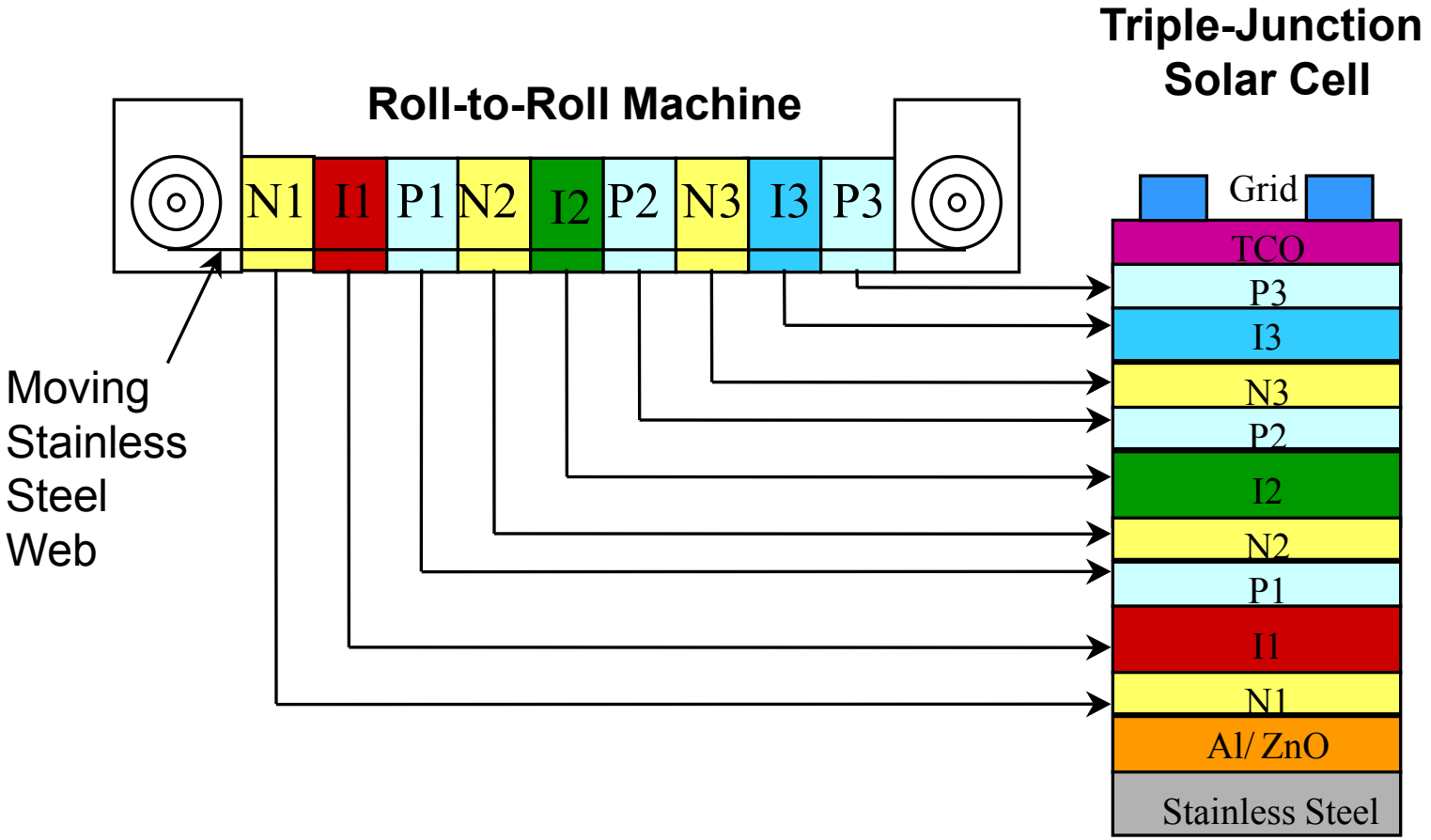


Ge profiling in a-SiGe:H cells



UNI-SOLAR

ROLL-TO-ROLL DEPOSITION PROCESS



UNI-SOLAR Laminates are Unique

UNI-SOLAR

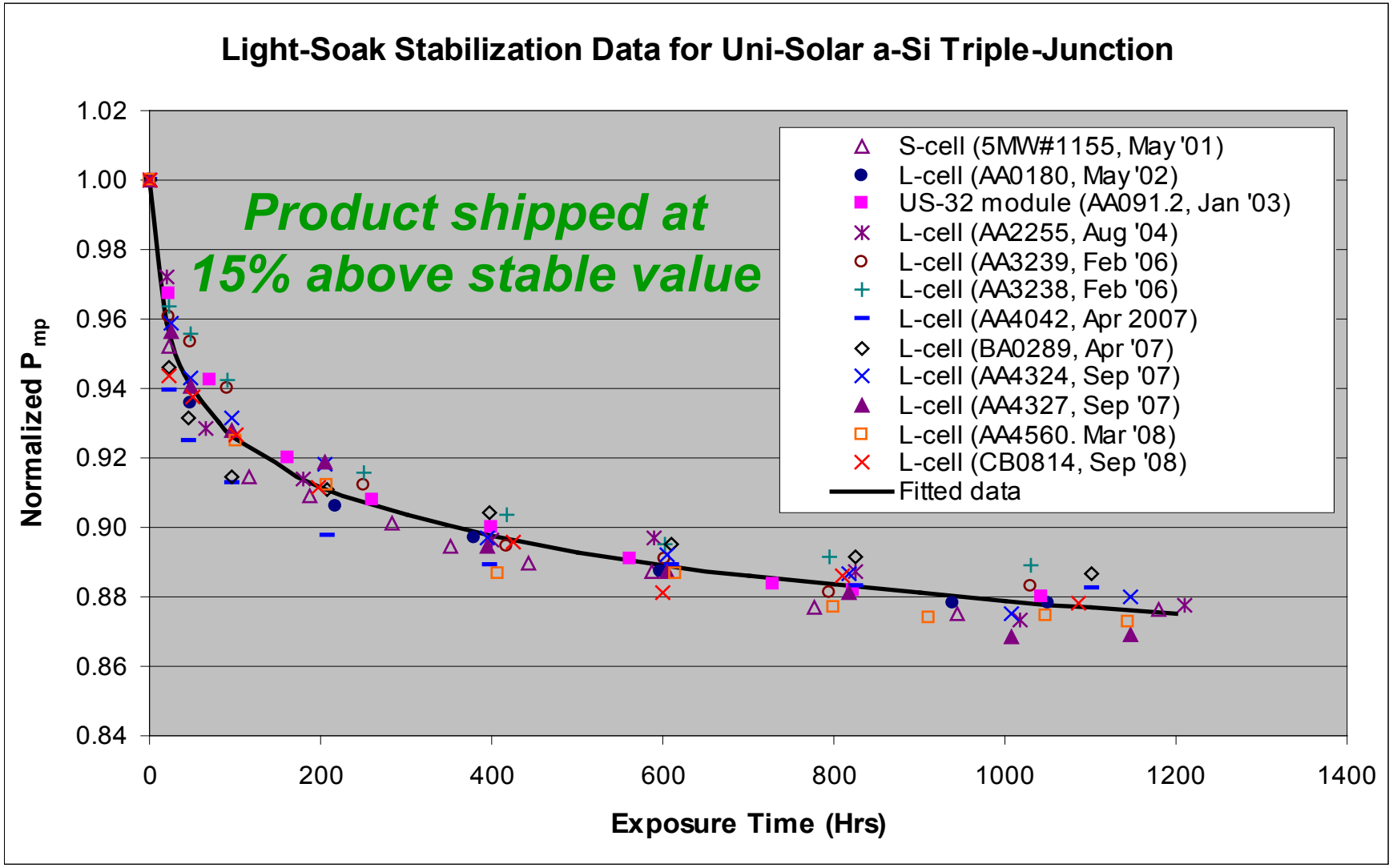
Conventional Solar Cells



UNI-SOLAR® Laminates



Historical indoor light-soak data



A DIFFERENTIATED PRODUCT

UNI-SOLAR

Rome, Italy
Rome Trade Fair



A DIFFERENTIATED PRODUCT

UNI-SOLAR

Commune St. Georges de Montaigu



A DIFFERENTIATED PRODUCT

UNI-SOLAR

Coca-Cola Plant
Los Angeles, California



A DIFFERENTIATED PRODUCT

UNI-SOLAR

Yuba City School District

Yuba City, California



A DIFFERENTIATED PRODUCT

UNI-SOLAR

New 25MW Project with Enel Green Power



Buildings owned by CIS-Interporto di Nola in Italy

A DIFFERENTIATED PRODUCT

UNI-SOLAR

The World's Largest Rooftop Installation
12MW - Zaragoza, Spain

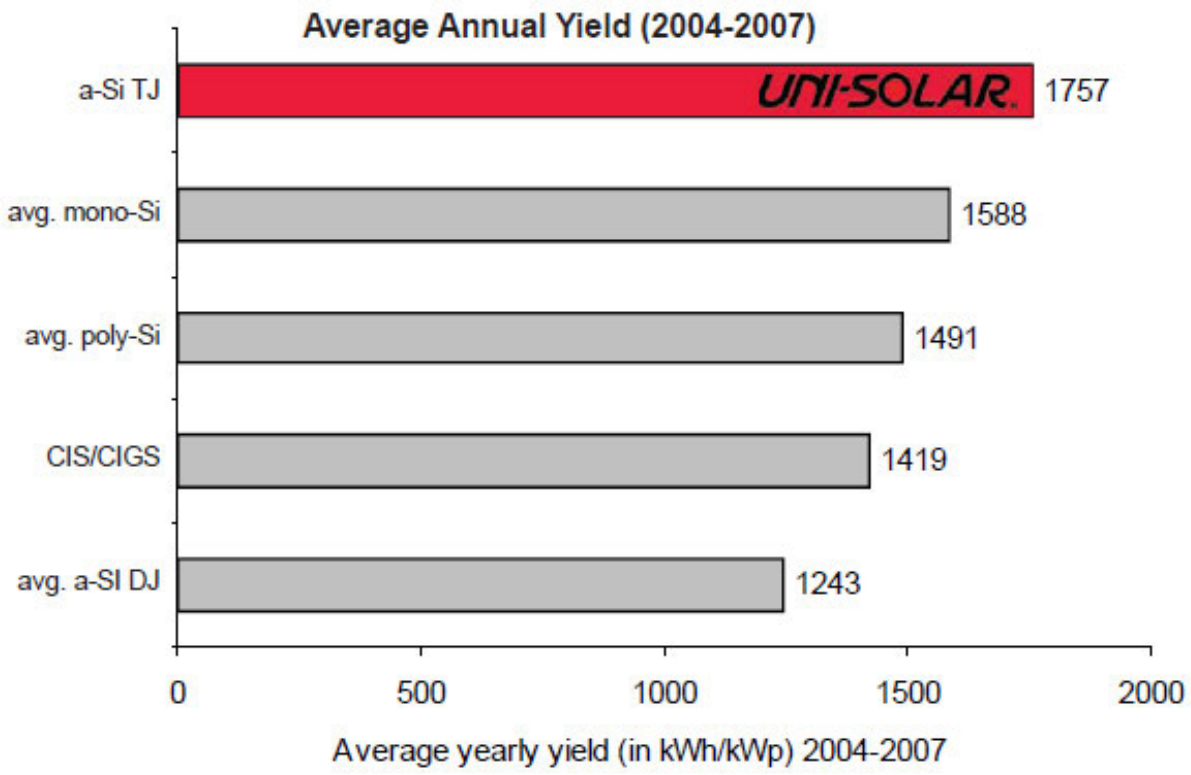


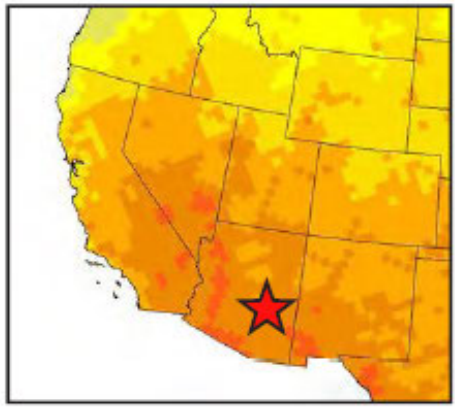
Uni-Solar
PRODUCT FEATURES

Higher Energy Yield (kWh/kW)

UNI-SOLAR

Site: Tucson, Arizona, USA
Source: Tucson Electric Power, Arizona, USA



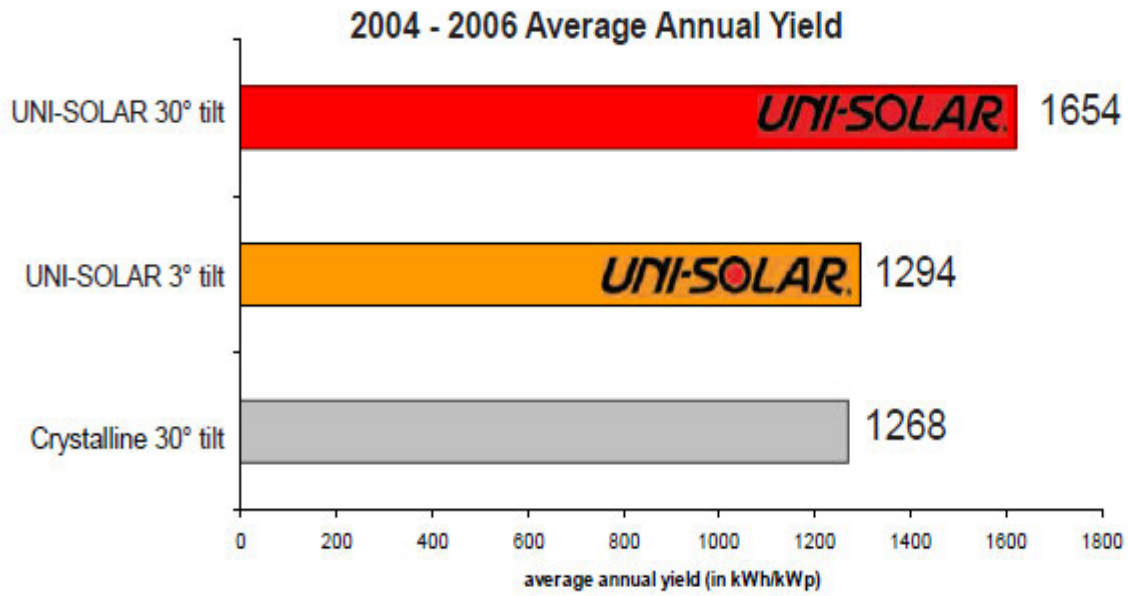


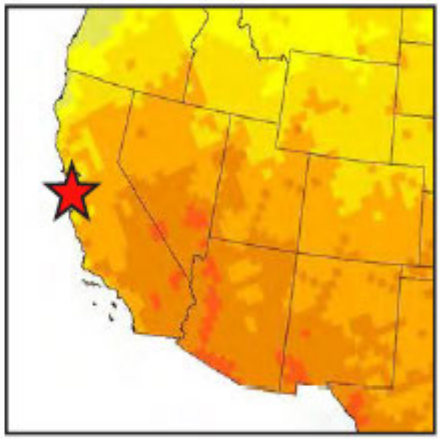
USO Surplus versus:
Avg. mono-Si: +11%
Avg. poly-Si: +18%
CIS/CIGS: +24%
Avg. a-Si: +41%

Higher Energy Yield (kWh/kW)

UNI-SOLAR

Site: Santa Cruz, California, USA
Source: Solarquest Report



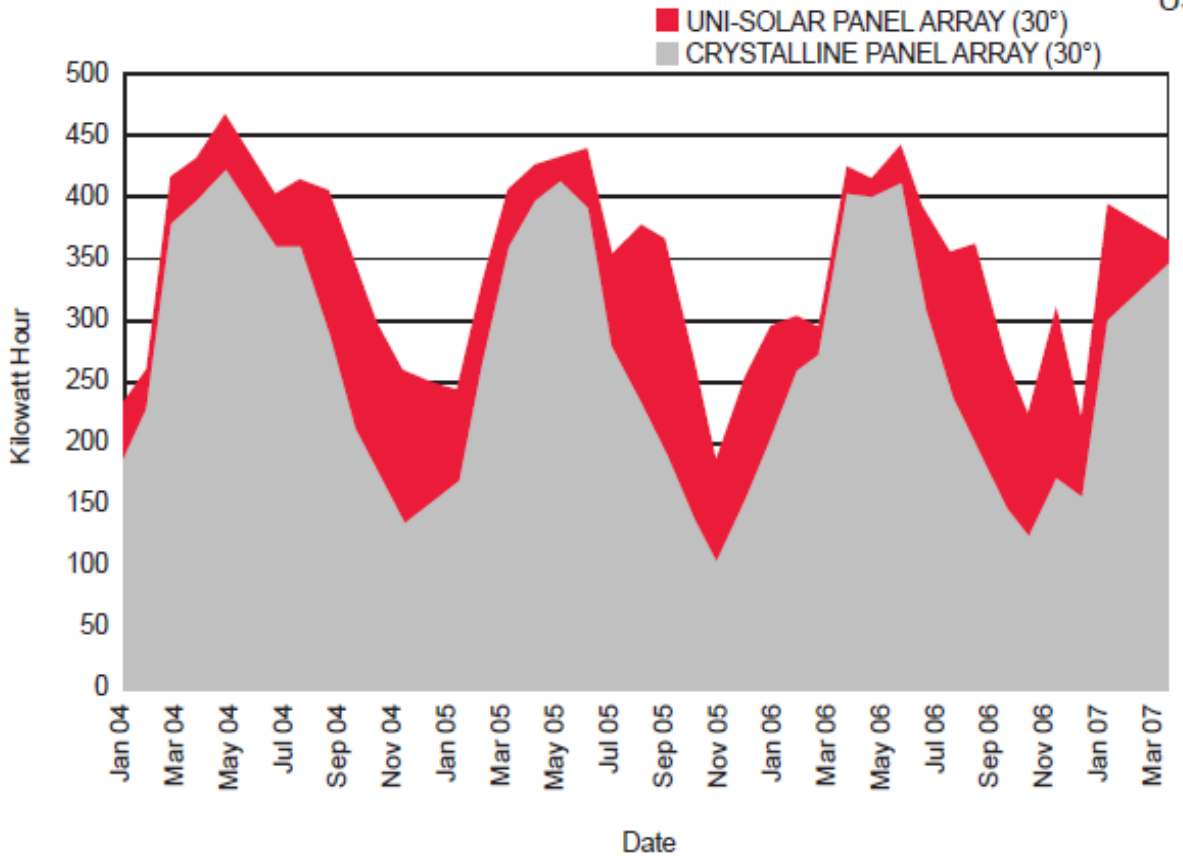


USO 30° Tilt Surplus versus:
USO 3° Tilt: +28%
Crystalline 30° Tilt: 31%

Higher Energy Yield (kWh/kW)

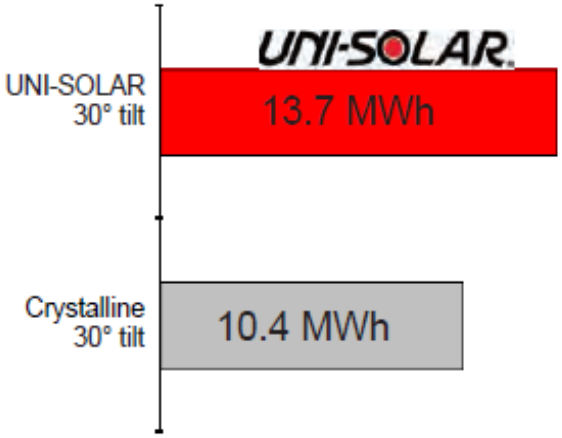
UNI-SOLAR

Santa Cruz Test Site
Energy Production Performance Summary



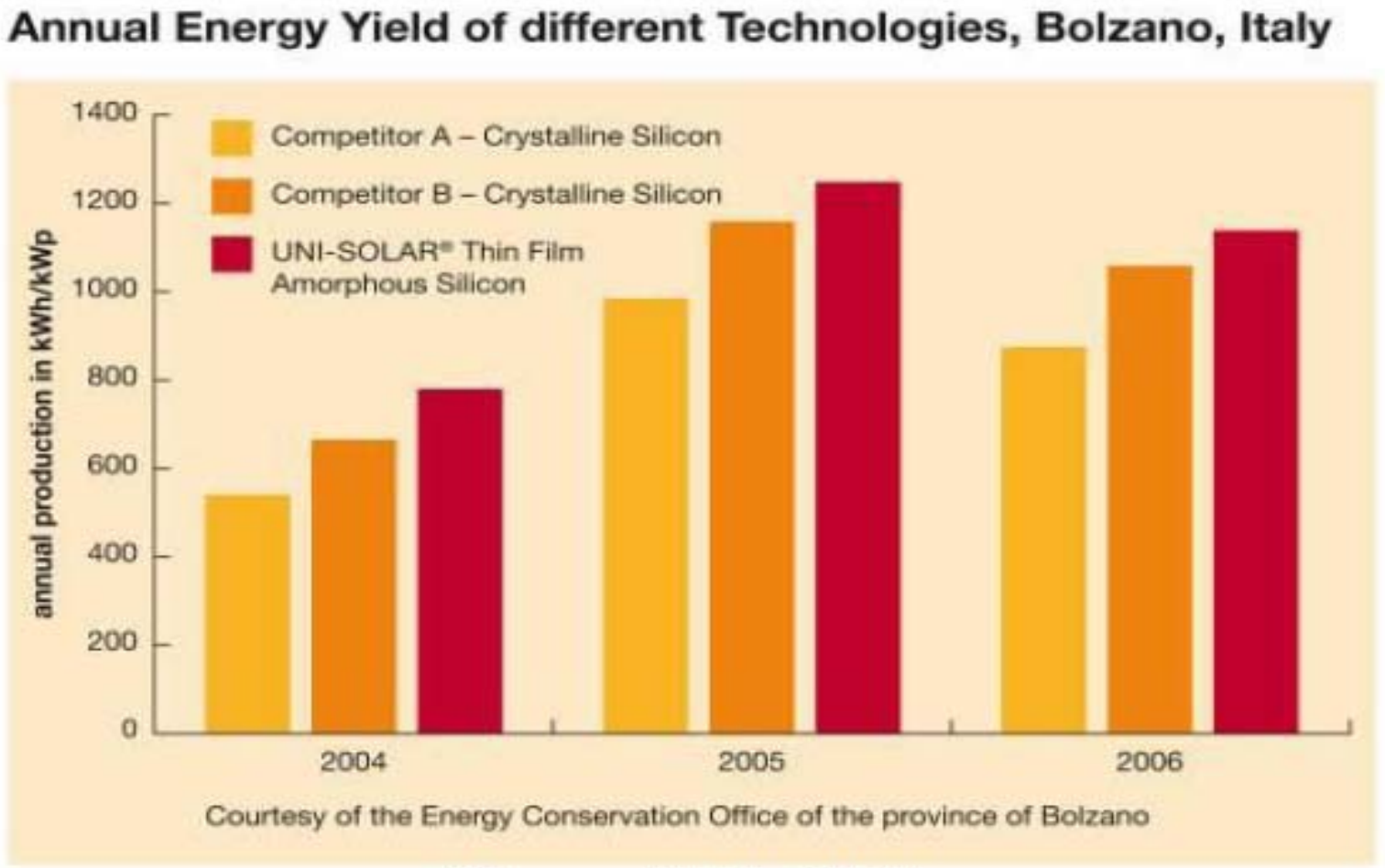
Cumulative Power Production
November 2003 - March 2007

USO Surplus versus Crystalline: +31%



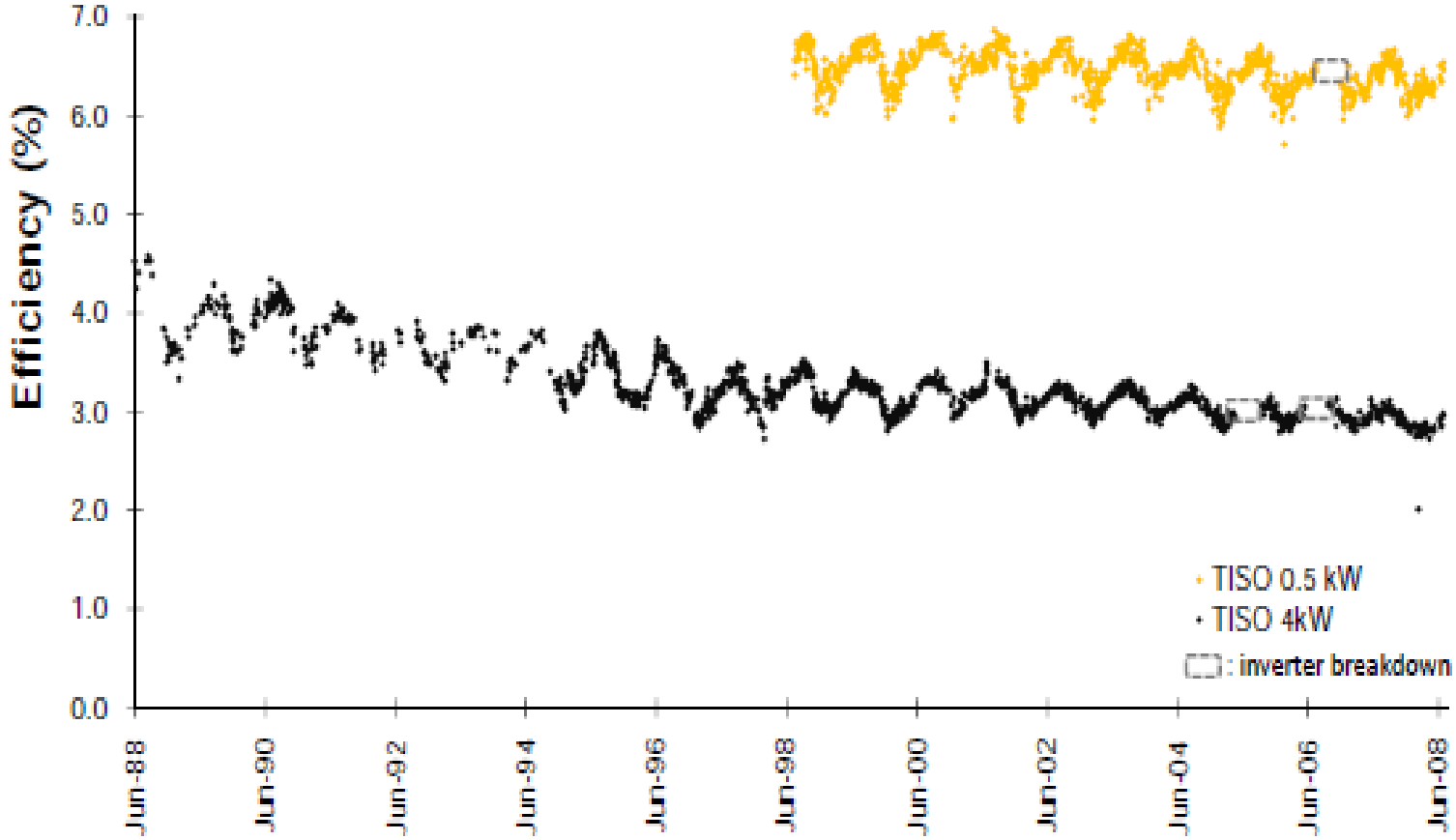
Higher Energy Yield (kWh/kW)

UNI-SOLAR.



More kWh/kW

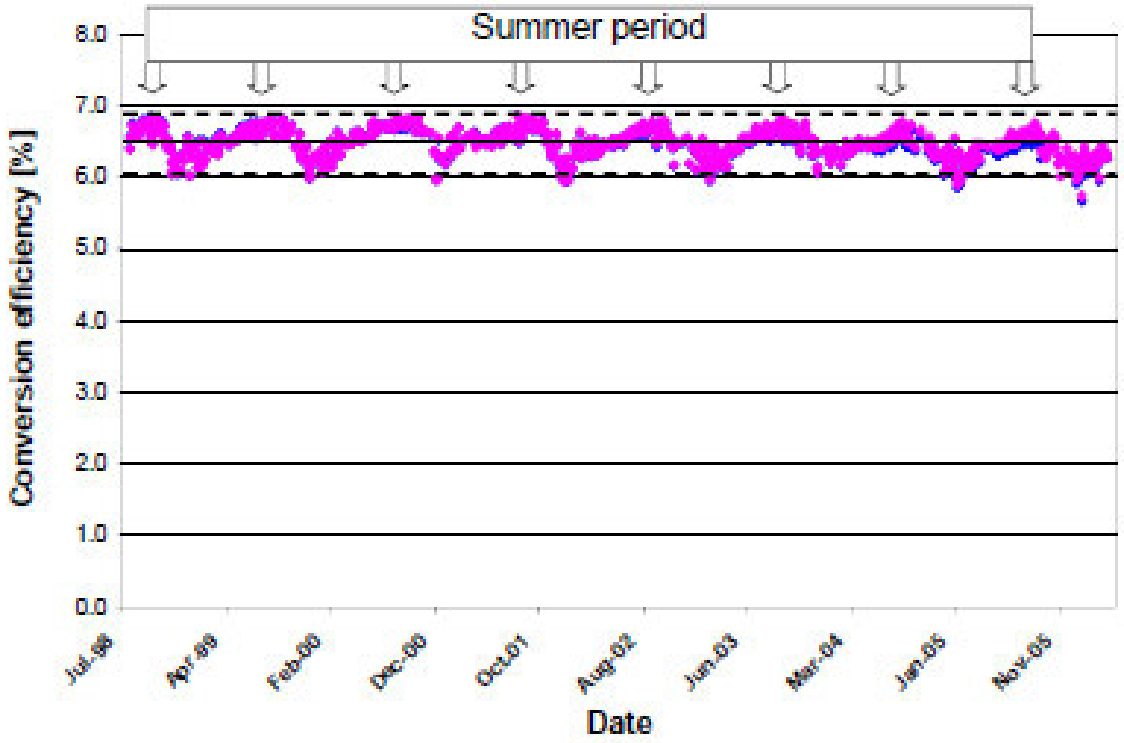
Long Term Behavior (single vs. triple junction)



Annealing effect improves summer performance

UNI-SOLAR

Results in Switzerland

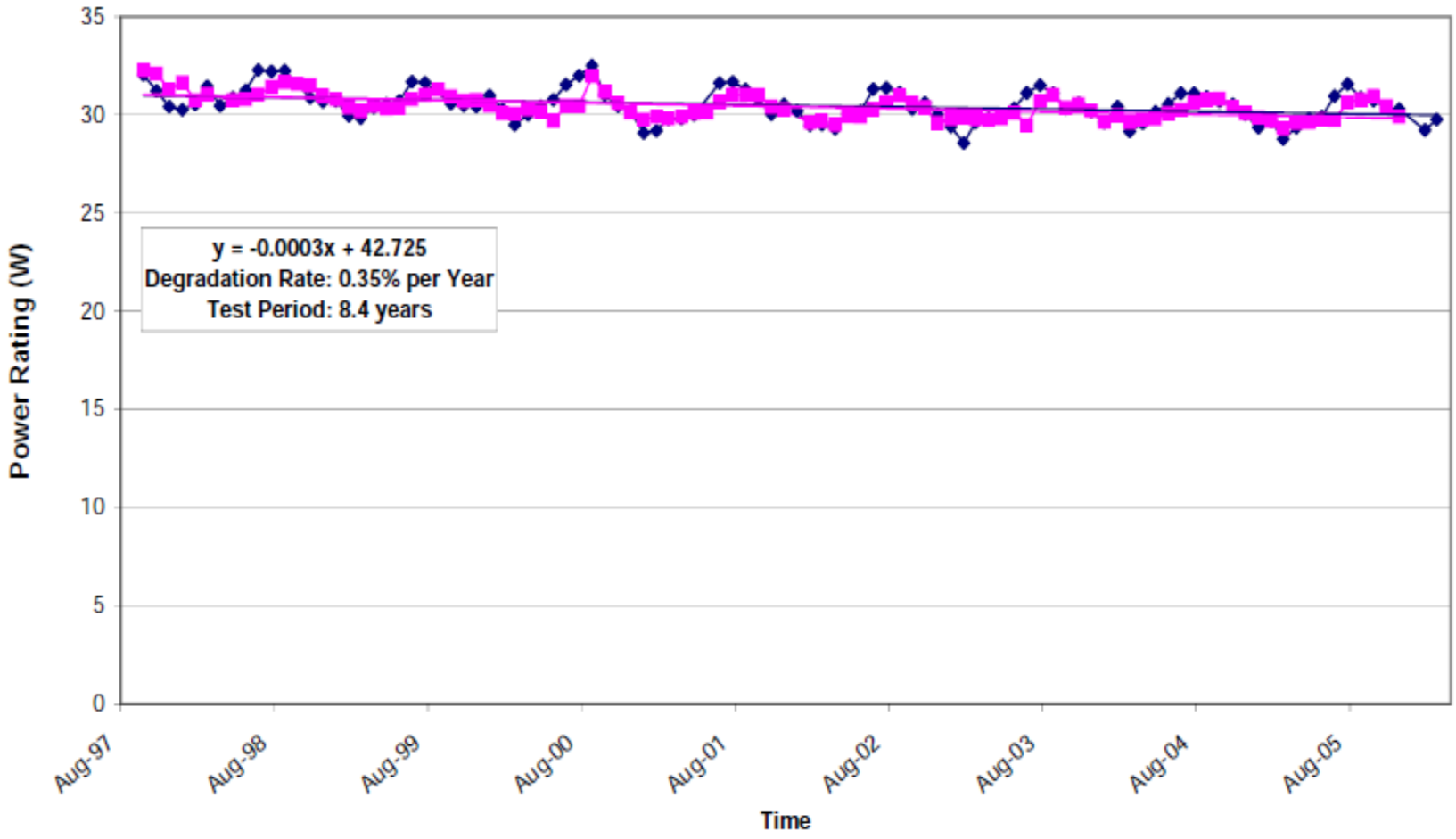




Site: Lugano, Switzerland
Horz. Irradiance: 1234 kWh/m2
Tilt: 30°
Size: 0.5 kWp
Inverters: Dorfmueller
Installed Year: 1998
Source: TISO – ISAAC Institute - SUPSI – University of Ticino, Switzerland

UNI-SOLAR modules typically show their peak in efficiency during SUMMER periods, opposite to crystalline modules. This is due to the annealling effect of a-Si, which gradually improves the conversion efficiency in the warm period of the year.

Long Term Degradation, Golden, CO (1997 – 2006)



Long Term Degradation Studies

UNI-SOLAR

3rd party studies on Triple Junction installations

Location	Climate	Test Institute	Size	First Year	Data Range	Annual Degr. (%/Yr)
Golden, CO, USA	Hot & Dry	NREL	0.032 kWp	1997	1997-2006	0.39
Juelich, Germany	Temperate	KfZ-Juelich	0.032 kWp	1998	1998-2004	0.14
Lugano, Switzerland	Temperate	TISO-ISSAC	0.5 kWp	1998	1998-2007	0.33
Freiburg, Germany	Temperate	ISE-Freiburg	2 kWp	2001	2002-2007	0.10
Cocoa, FL, USA	Hot & Humid	FSEC	1.2 kWp	2003	2005-2007	0.58
Golden, CO, USA	Hot & Dry	NREL	1.2 kWp	1998	1998-2004	0.98
Average Degradation Rate: 0.42% per year Weighted Average Degradation Rate: 0.49% per year						

- *UNI-SOLAR* products have been extensively tested for long durations at third party sites
- The degradation rates are: 0.42% per year average; 0.49% per year weighted average

Long-term Degradation

UNI-SOLAR

What causes the 0.3% -- 1% annual degradation?

- **EVA yellowing?**
- **Dirt?**
- **Contacts?**

Reliability

UNI-SOLAR

- **What causes the field failure?**

  Accelerated tests, such as IEC 61646, has improved reliability significantly

- **Manufacturing defects**
  - **Contacts**
  - **Shunts**
  - **Poor encapsulation**
- **Improper installations**
- **Manufacturers and installers need to be more vigilant**

Predict System Performance

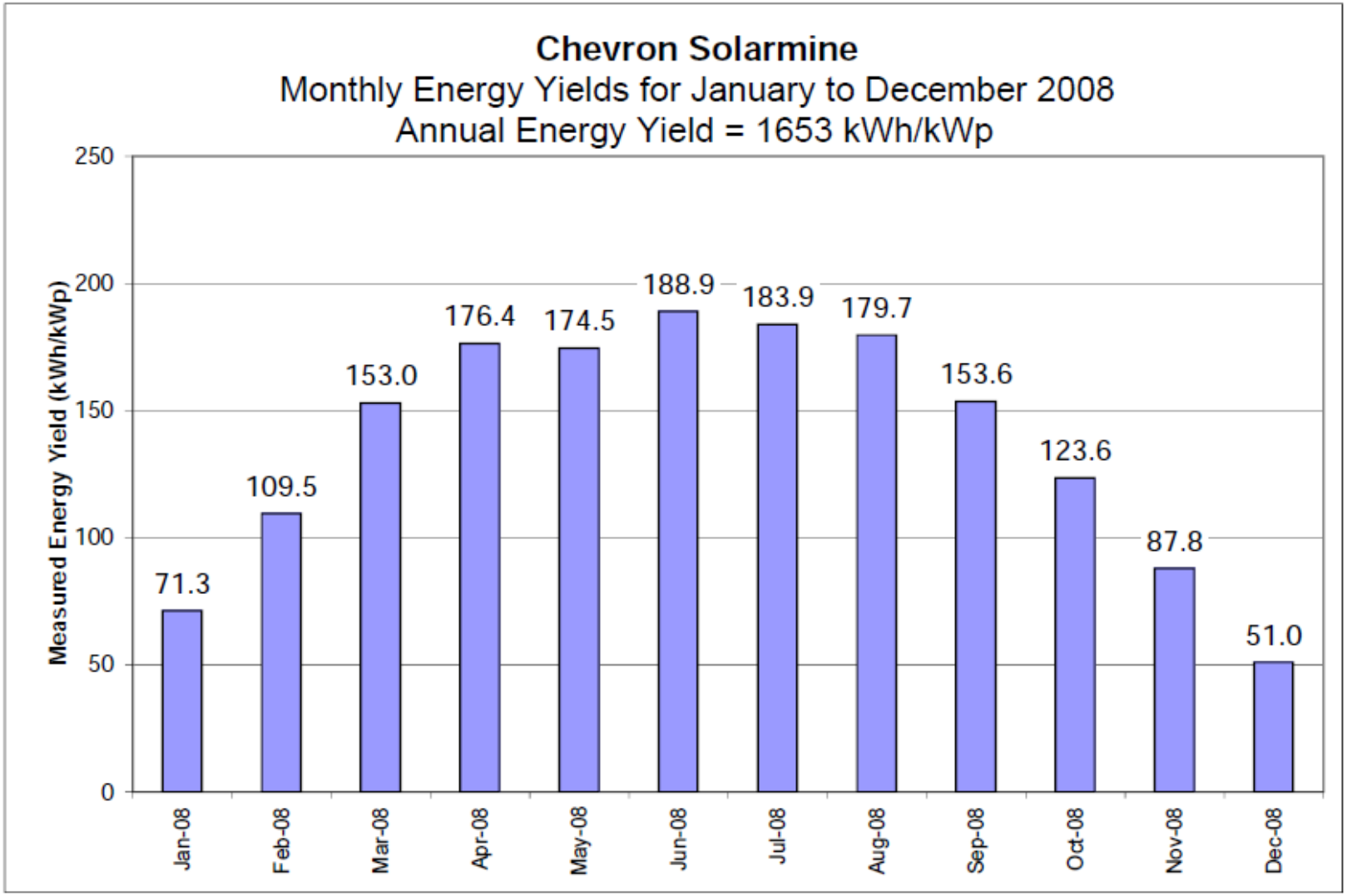
- SAM
- PVSYST
- None considers the annealing effect
- Real life temperature dependence is flat rather than -0.2%/ ^{O}C

Chevron Solarmine, California



Chevron Solarmine
Fellows, CA (near Bakersfield)
614 kWp

Real Life Data



Models

UNI-SOLAR

	PVWATTS Energy Yield (kWh/kW_p)	PV*SOL Energy Yield (kWh/kW_p)	PVSYST Energy Yield (kWh/kW_p)	Measured Energy Yield Chevron Solarmine Jan. 2008 to Dec. 2008 (kWh/kW_p)
Tilt: 20°	1457	1669	1629	1653
Losses	• Soiling: 5% • Mismatch: 2% • Spectral & Climate: 0% • Diode: 0.5% • Cable: 3%	• Soiling: 2% • Mismatch: 2% • Spectral & Climate: 1% • Diode: 0% • Cable: 2%	•Soiling: 2% •Mismatch: 2% •Spectral & Climate: 1% •Diode: 0% •Cable: 2%	-

Used default values for PVWATTS

Summary

UNI-SOLAR

- Staebler-Wronski effect is reversible upon thermal annealing
- The triple-junction structure with high quality material results in improved module performance featuring higher kWh/kW
- Reliability has been much improved; 25 year warranty is being offered
- Long-term degradation still exists and needs better understanding
- Performance prediction should include thermal annealing to reflect real-life conditions

National Renewable Energy Laboratory
Innovation for Our Energy Future

Metastable Effects in Polycrystalline Thin Film Cells and Correlations with Performance and Durability



PV Module Reliability Workshop

Feb. 18-19, 2010
Golden, CO 80401

D.S. Albin

Contributors:
J. del Cueto, R. Dhere, S. Glynn, J. Li, X. Li, T. Gessert
Industry Collaborations

This presentation does not contain any proprietary or confidential information.

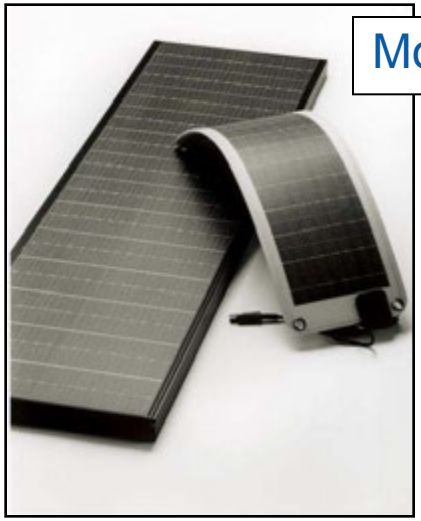
NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

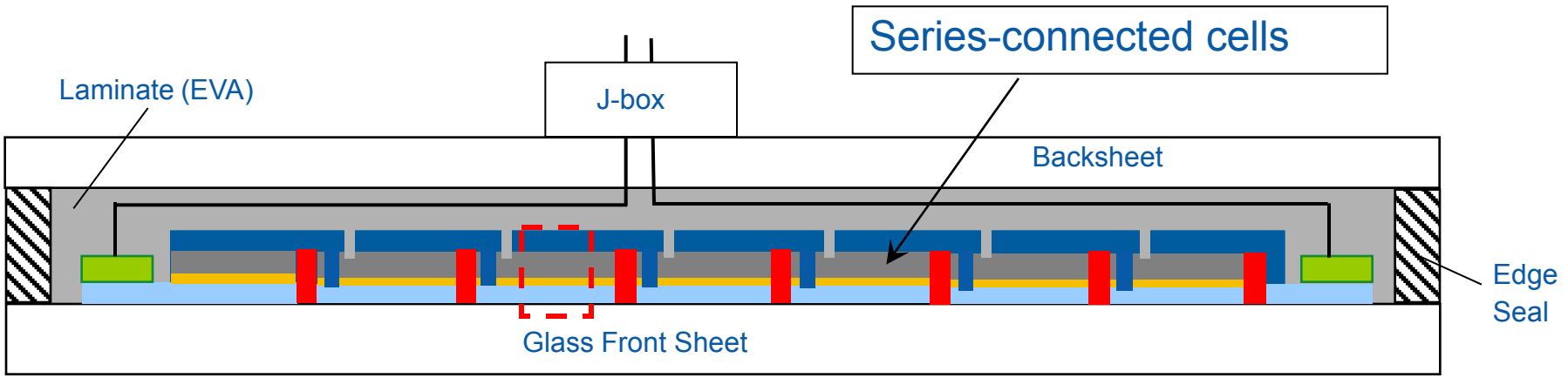
Cell durability fundamental to module durability

Systems

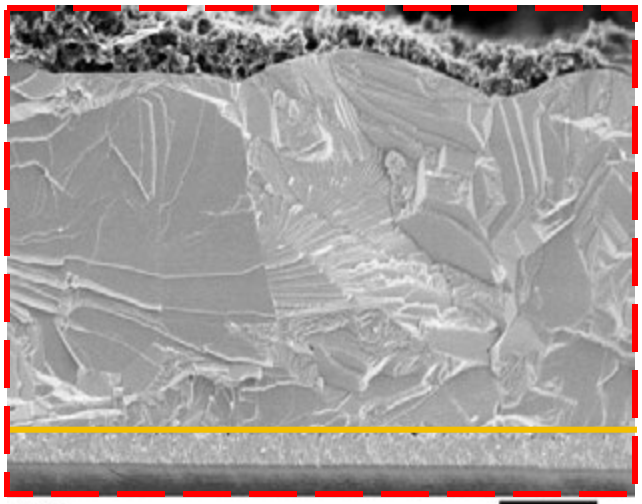


Modules





Cell durability is a function of cell fabrication





light

back contact

back contact

p-layer

n-layer

TCO

glass

metallization (ZnTe, metals, dag-pastes)

Cu-doping

back contact Surface Prep (acid etch, dry etch)

$CdCl_2$ (soln, vapor)

CdTe (CSS)

CdS (CSS, sputter, CBD)

650 ºC – CdS+He anneal

Zn_xSnO_x (ZTO, sputter)

650 ºC – CdS+He anneal

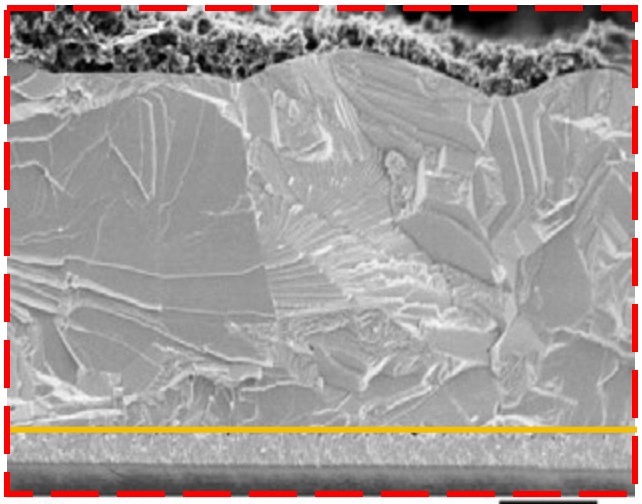
Cd_2SnO_4 (CTO, sputter)

i-SnO_2 (MOCVD)

F-doped n-SnO_2 (MOCVD)

Glass Superstrate (borosilicate vs sodalime)

Past Cell Durability Studies





light

back contact

back contact

p-layer

n-layer

TCO

"**Pre-contact Surface Chemistry Affects on CdS/CdTe Solar Cell Performance and Stability**", Albin, et al., 28th IEEE PVSC, 583-586 (**2000**)

"**Stability study of CdS/CdTe solar cells made with Ag and Ni back-contacts**", Demtsu, et al., Sol. Energy Mat. & Solar Cells, 90, 2934-2943 (**2006**)

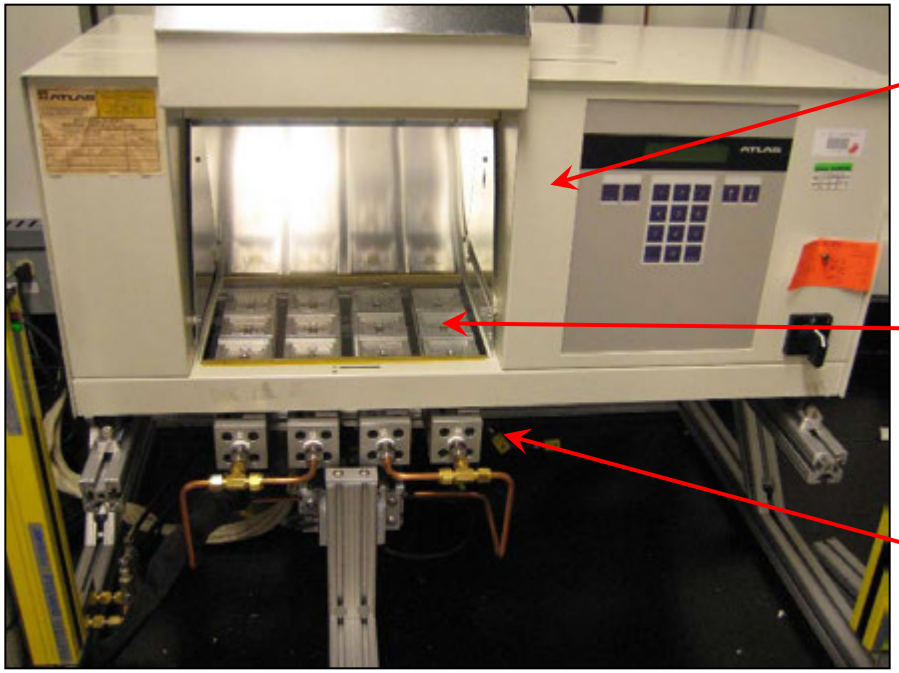
"**Film thickness and chemical processing effects on the stability of cadmium telluride solar cells**", Albin et al., Thin Solid Films, 2659-2668 (**2006**)

"**Accelerated Stress Testing and Diagnostic Analysis of Degradation in CdTe Solar Cells**", Albin, in Reliability of Photovoltaic Cells, Modules, Components, and Systems ed. N. Dhere, SPIE Proceedings Vol. 7048 (**2008**)

"**Degradation and Capacitance-Voltage Hysteresis in CdTe Devices**", Albin et al., , in Reliability of Photovoltaic Cells, Modules, Components, and Systems II ed. N. Dhere, SPIE Proceedings Vol. 7412 (**2009**)

"**Striving for a standard protocol for preconditioning or stabilization of polycrystalline thin film photovoltaic modules**", del Cueto et al., , in Reliability of Photovoltaic Cells, Modules, Components, and Systems II ed. N. Dhere, SPIE Proceedings Vol. 7412 (**2009**)

Cell Accelerated Lifetime Testing (ALT)



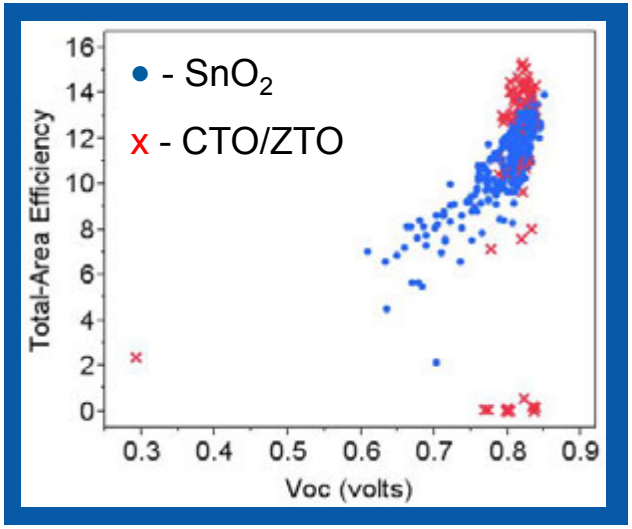
Atlas Suntest CPS solar simulator
- Solar-matched spectrum
- 1500 hrs continuous
- V_{oc} bias

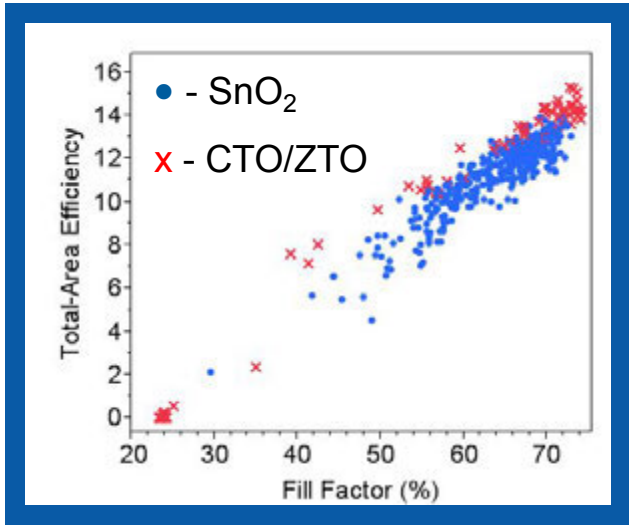
Aluminum-milled cell holders
- Cells oriented TCO up
- No Shunting
- Good thermal uniformity

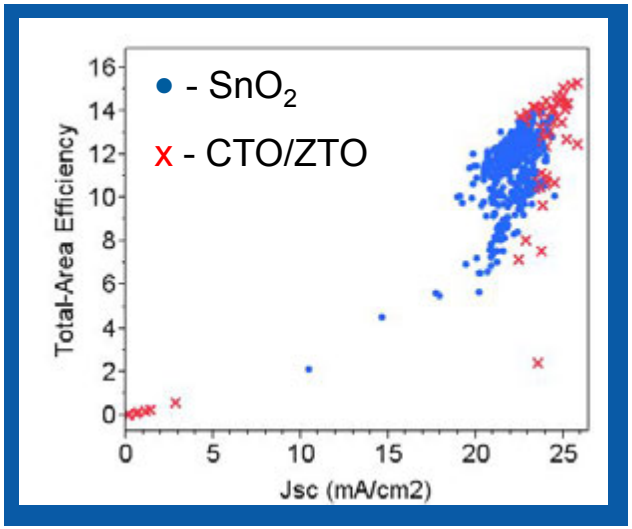
Independent heating/cooling zones
- T_{sample} controlled to ±1 ºC
- Irradiance can affect T_{sample}

Experimental Procedure:
- Make initial, t=0 measurement
- Expose cells for some t
- Remove cells, store in the dark (12-24 hrs)
- Measure cells (J-V, **C-V**, Q-E, etc.)
- Repeat

SPIE 2009 Study –Performance of CTO/ZTO vs $nSnO_2/iSnO_2$





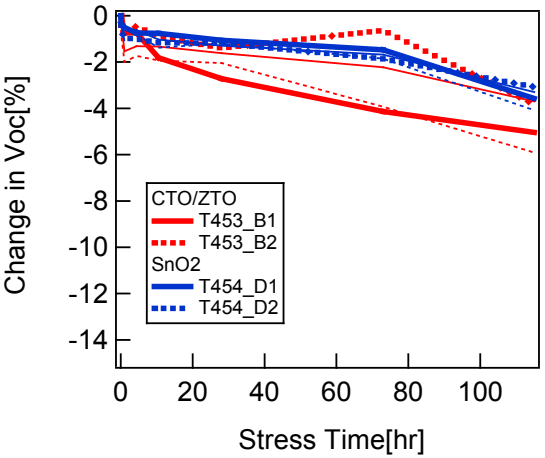


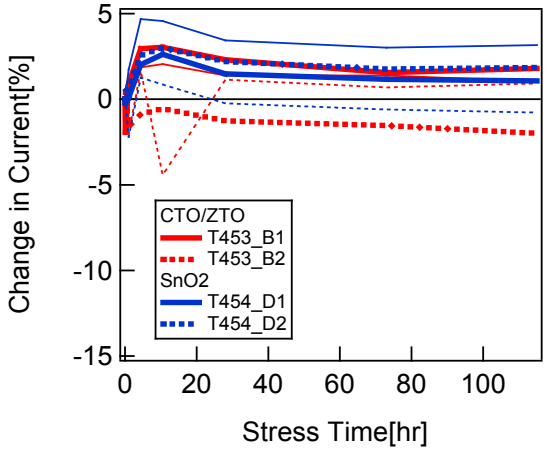
FF increases about 1 to 1.5 % pts.

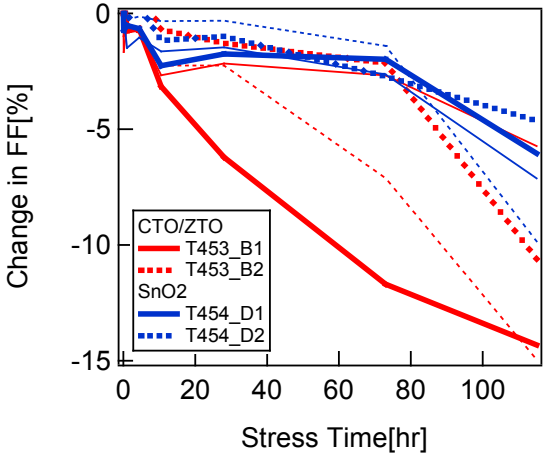
No difference in V_{oc}

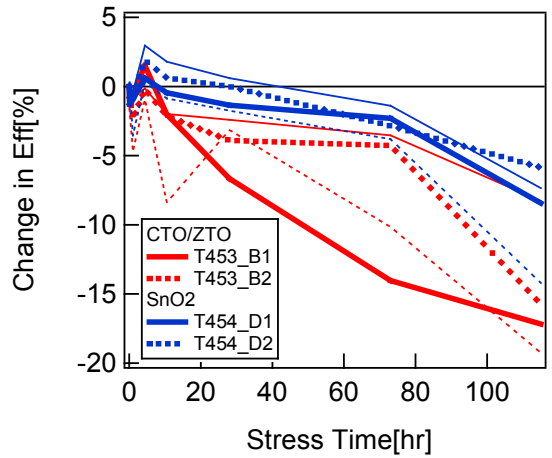
~ 1.0 - 1.5 mA/cm^2 increase in J_{sc}

SPIE 2009 Study –Durability of CTO/ZTO vs $nSnO_2/iSnO_2$









Cells fabricated identically except for TCO

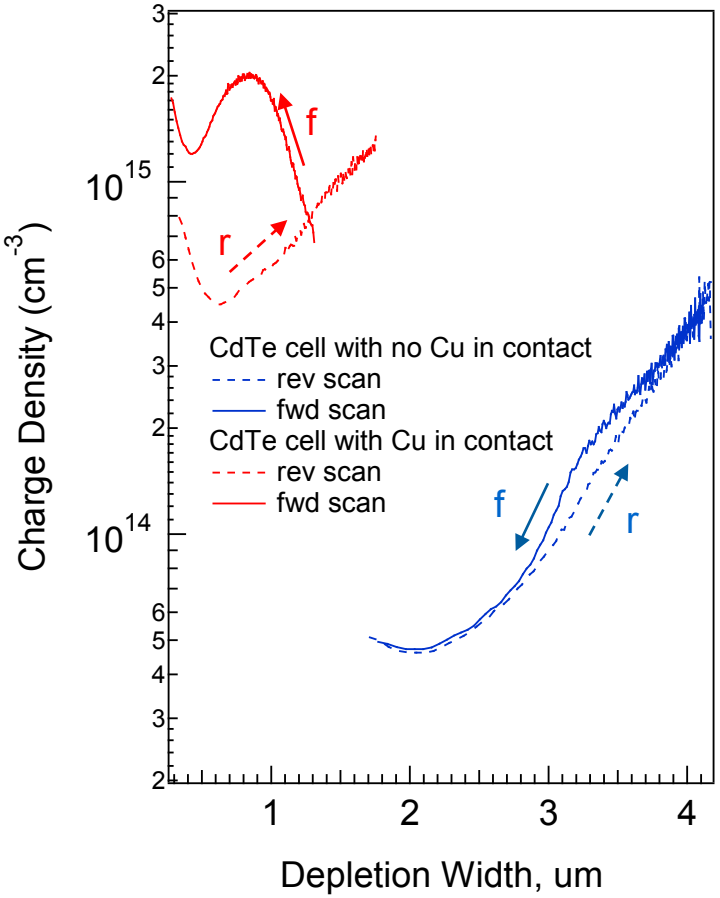
(Cu,Hg) doped BC	(Cu,Hg) doped BC
CdTe	CdTe
CdS	CdS
$ZnSn_xO_y$	**$i\text{-}SnO_2$**
Cd_2SnO_4	**$n\text{-}SnO_2$**
glass	glass

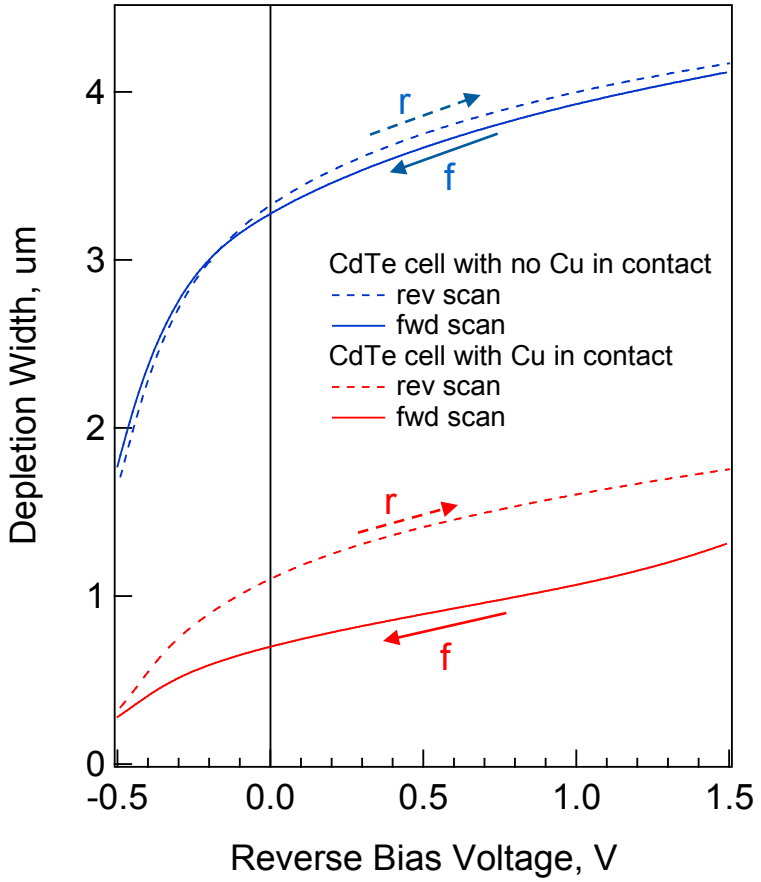


Stressed identically (100 ºC, V_{oc}, 1-Sun)

Differences in degradation due to different TCO layers

C-V hysteresis (metastability) during ALT

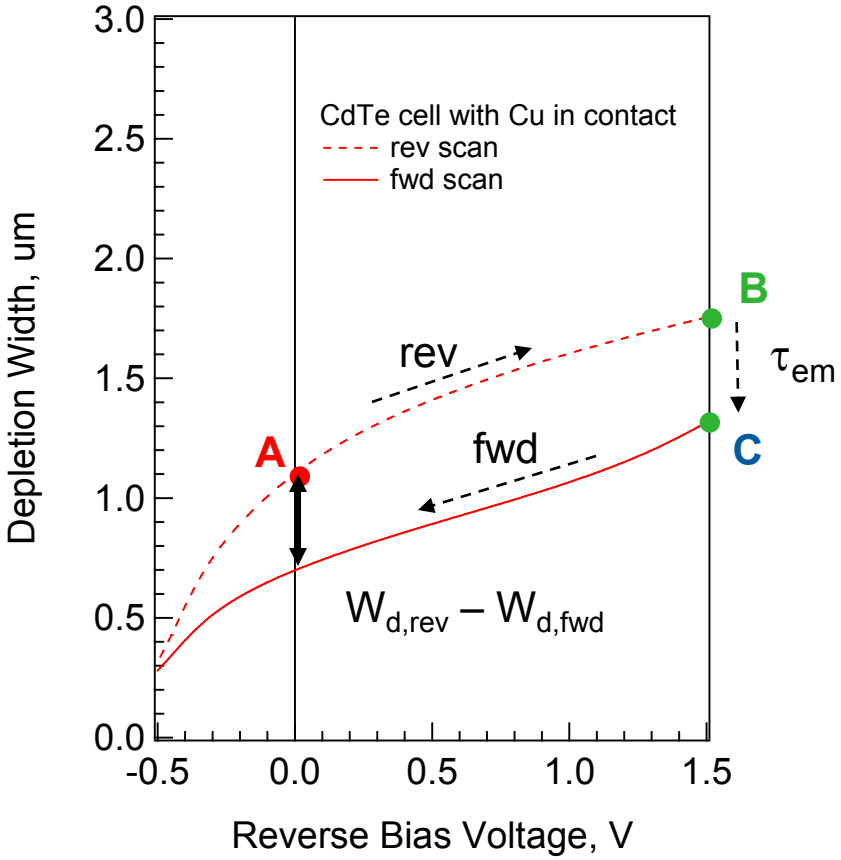


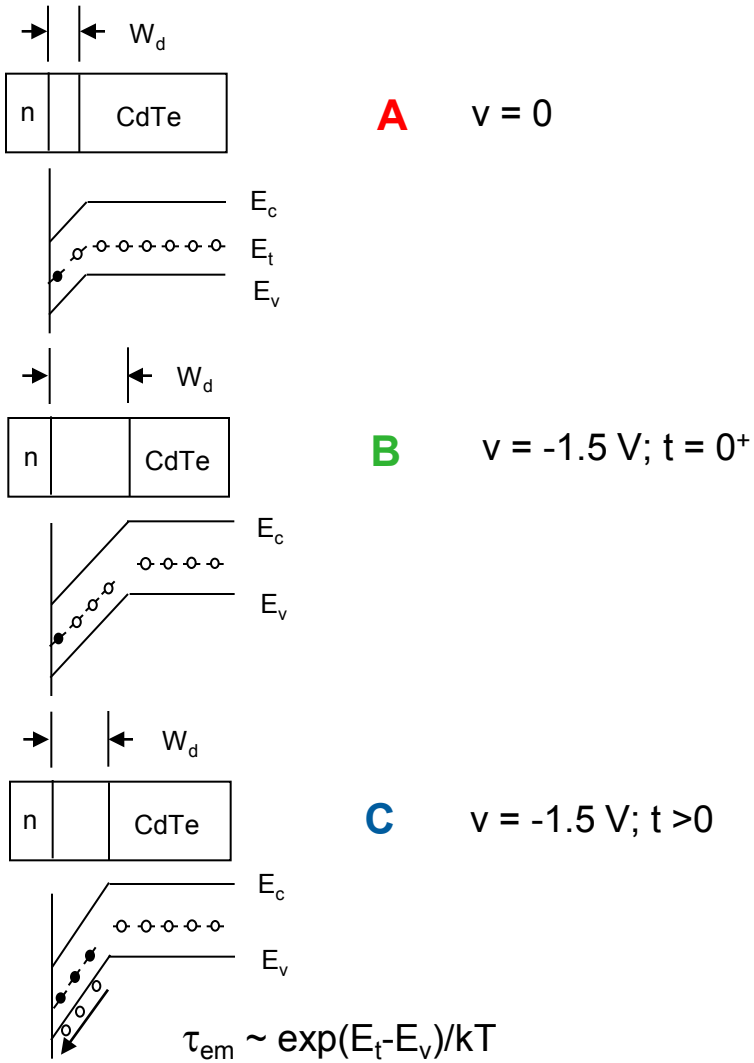


"rev scan" → +0.5 V to -1.5 V

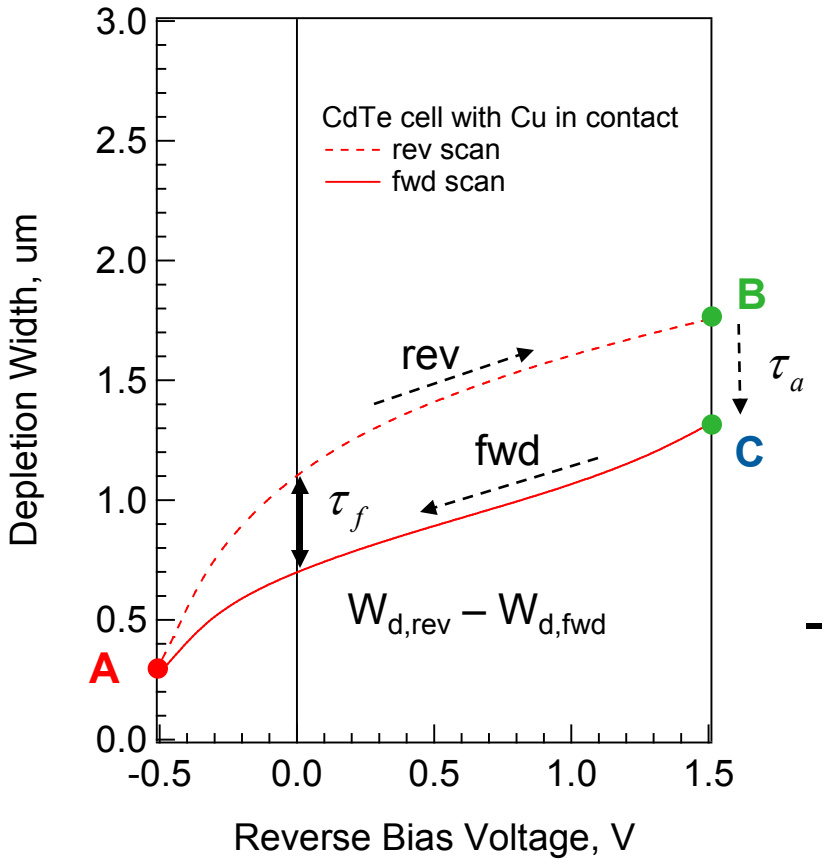
"fwd scan" → -1.5 V to +0.5 V

C-V hysteresis (electronic processes) during ALT





C-V hysteresis (ionic processes) during ALT



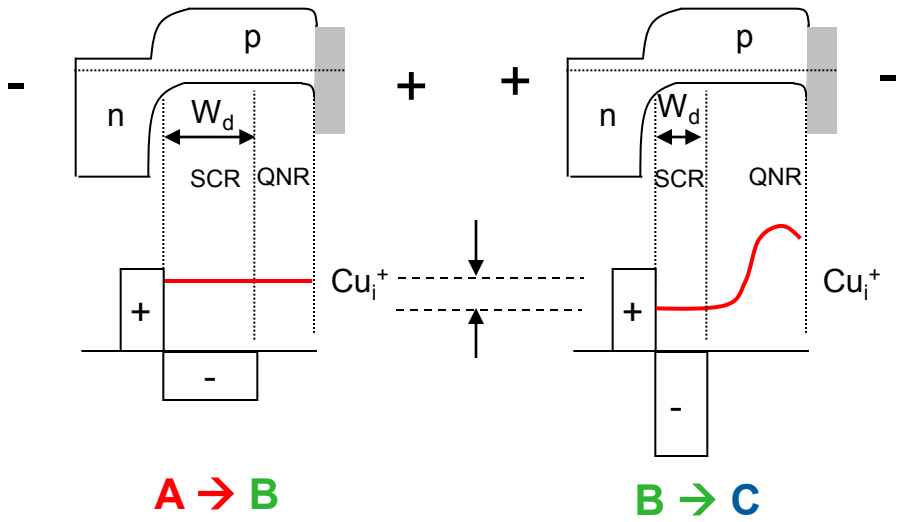
Perform "rev" scan

- *Measure SCR with Cu_i^+ screening N_a^-*

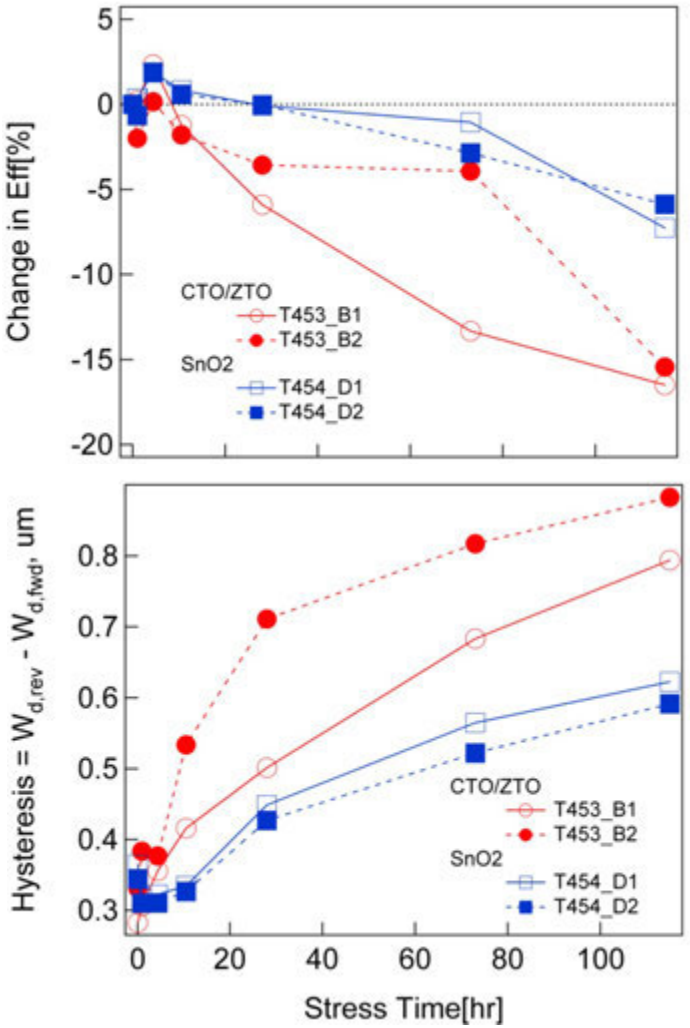
Hold cell at rev-bias for 5m (τ_a)

Perform "fwd" scan

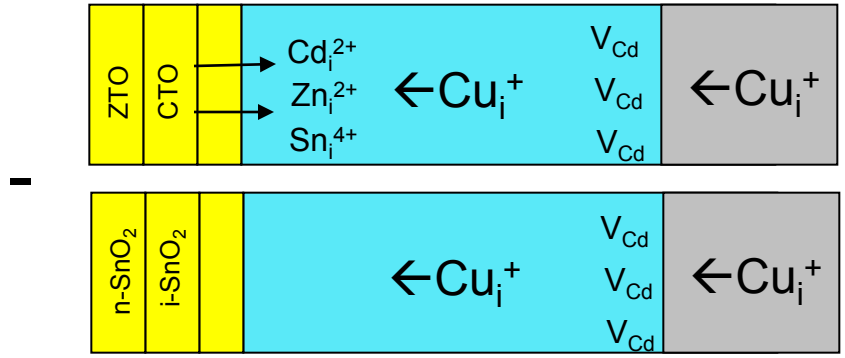
- *Measure SCR with Cu_i^+ removed from SCR*



CV-hysteresis correlates with performance during stress test

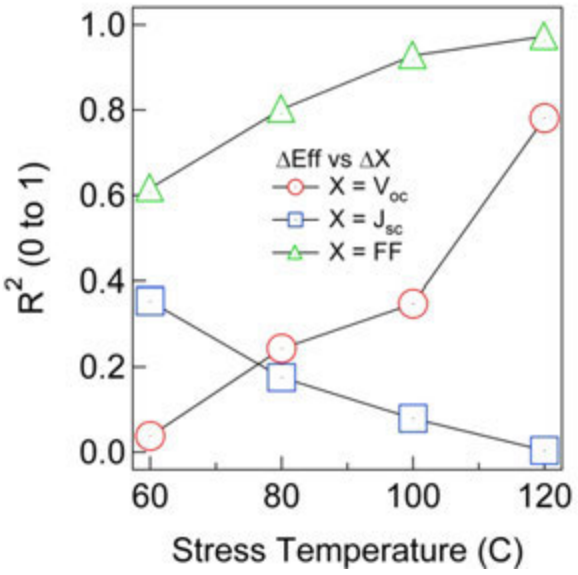


- CdTe cells grown on CTO/ZTO transparent conducting oxides *degrade faster*
- Magnitude of degradation proportional to hysteresis
- For all cells, increasing hysteresis partly due to continuous diffusion of Cu from the back contact.

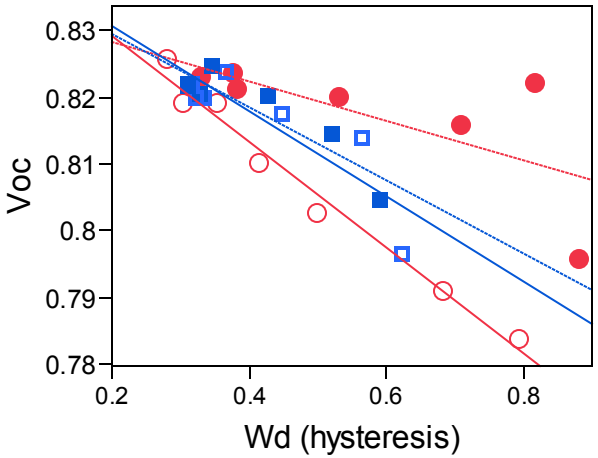


- Additional hysteresis indicative of “decomposition” of the CTO/ZTO layers

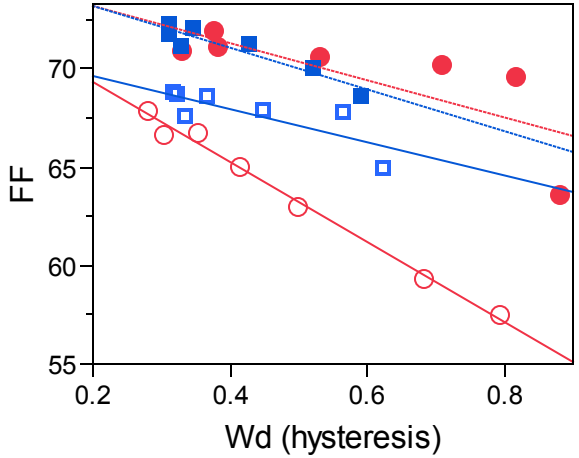
CV-hysteresis correlates with performance during stress test



•At 100 ºC; cell stability is determined by changes in FF and V_{oc} (SPIE-2008)

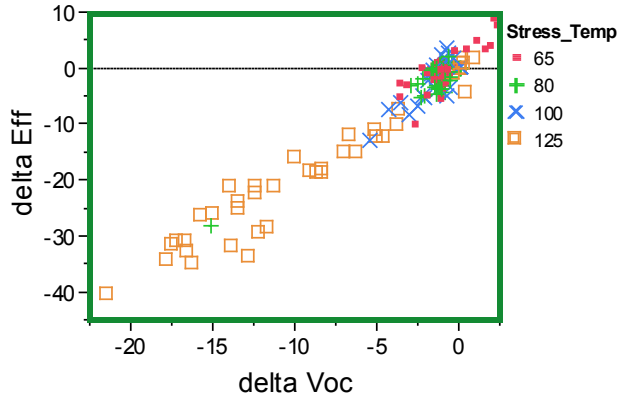


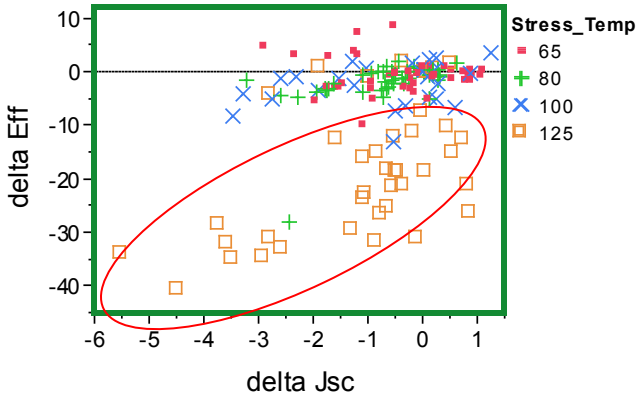
$0.46 < R^2 < 0.98$

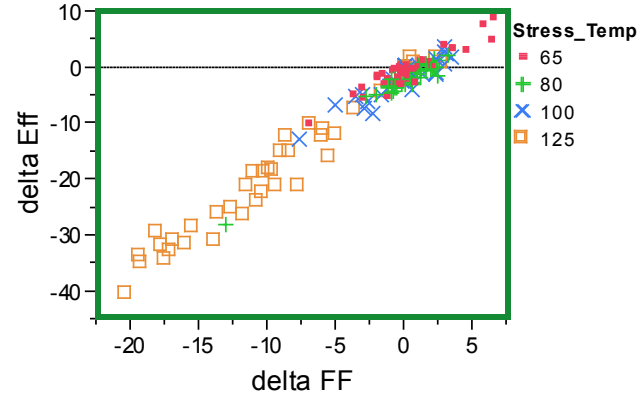


$0.58 < R^2 < 0.99$

C-V hysteresis in industrial CdTe cells and mini-modules







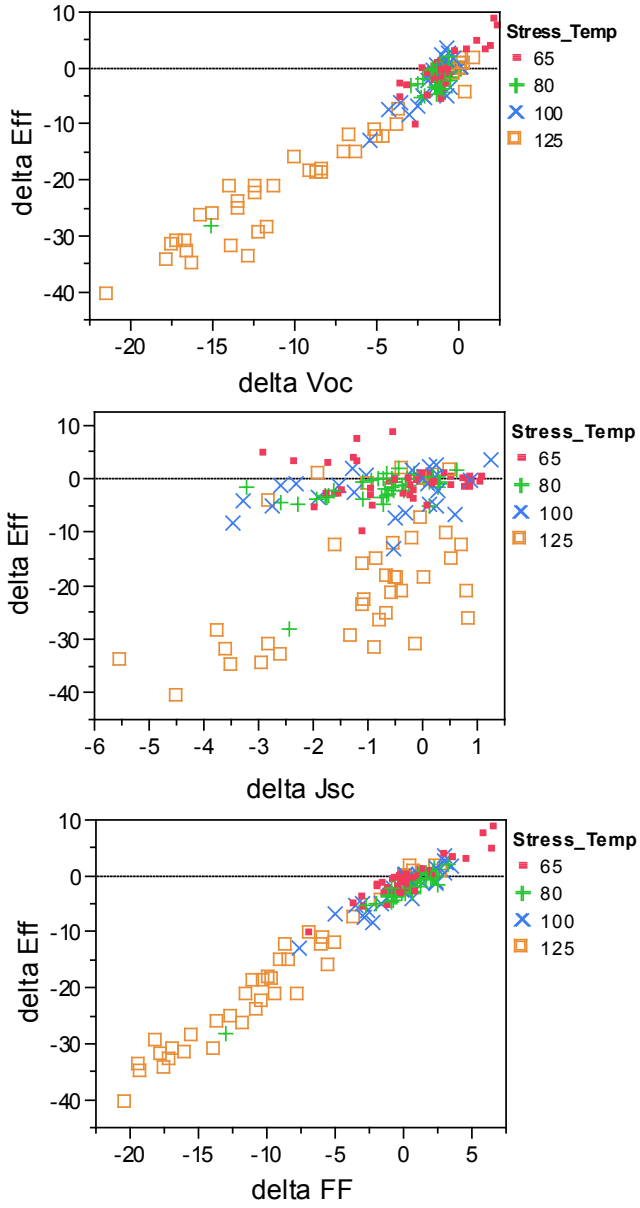
- Cells "cut" from mini-modules and full-size modules
  - ALT performed at 65, 80, 100, and 125 ºC
  - 1-sun illumination and V_{oc} bias
  - Correlate ΔEff vs ΔV_{oc}, ΔJ_{sc}, and ΔFF

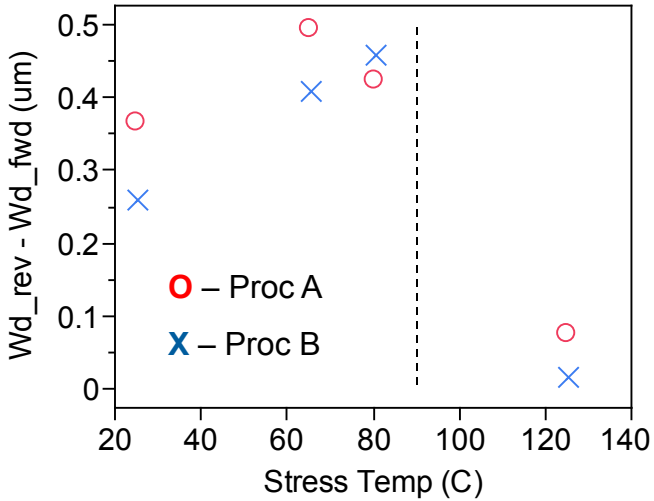
- Strong correlations between ΔEff and (V_{oc} , FF)

- Cell and mini-module reliability good at 65-80 ºC

- Higher stress temperatures (125 ºC) see "outliers" in Eff vs J_{sc} curve not associated with series resistance

C-V hysteresis in industrial CdTe cells and mini-modules

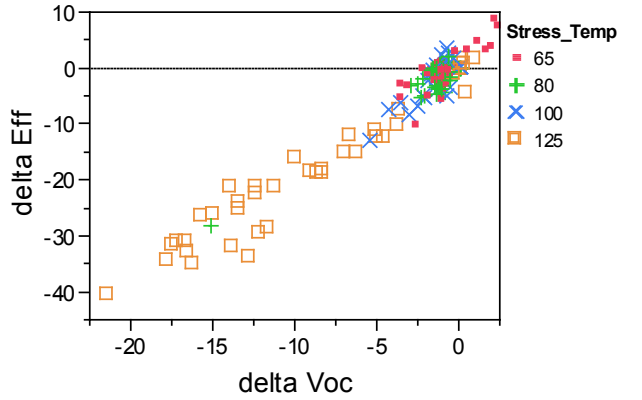


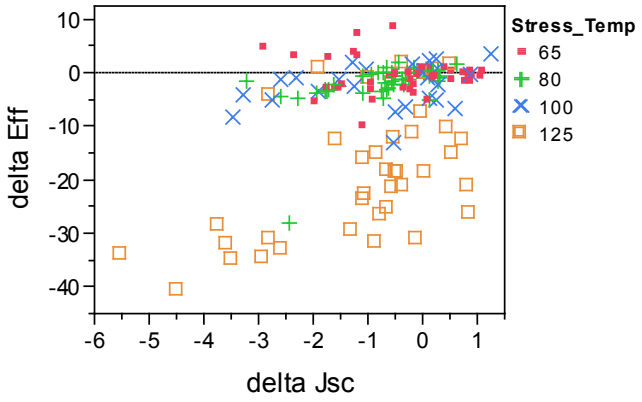


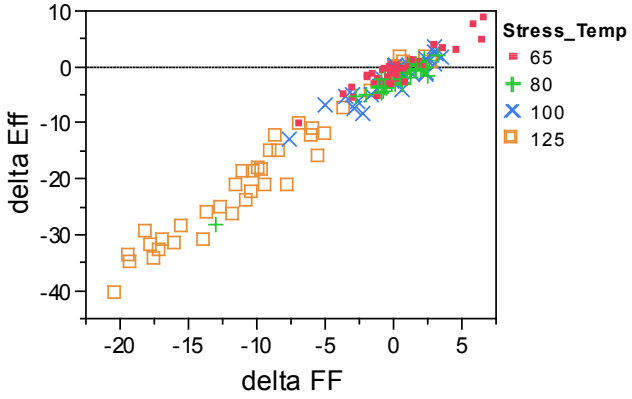
At lower stress temperatures see increasing hysteresis but begins to decrease at longer stress times

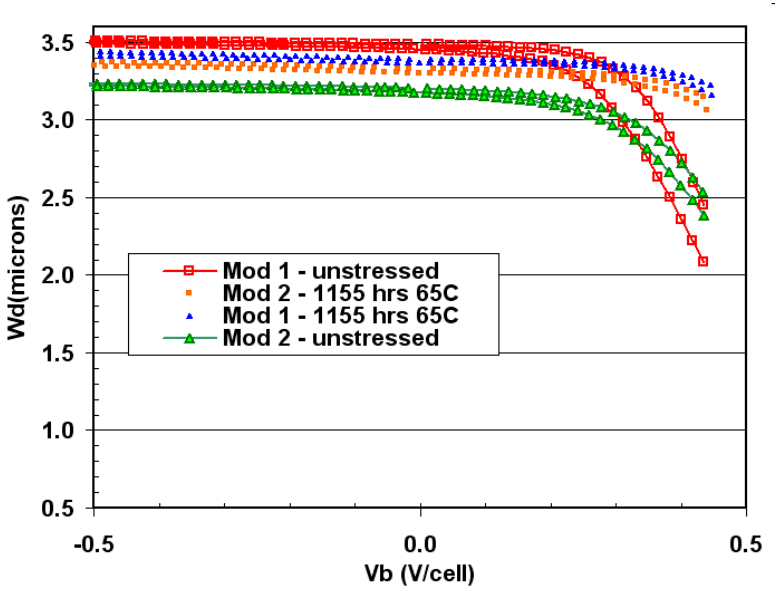
At higher stress temperatures (and longer times) see decreasing hysteresis

C-V hysteresis in industrial CdTe cells and mini-modules









- Indoor ALT of series-connected mini-modules (unencapsulated)
- After 1155 hrs at 65 ºC observe a decrease in hysteresis
- Also observed in individual “cells”

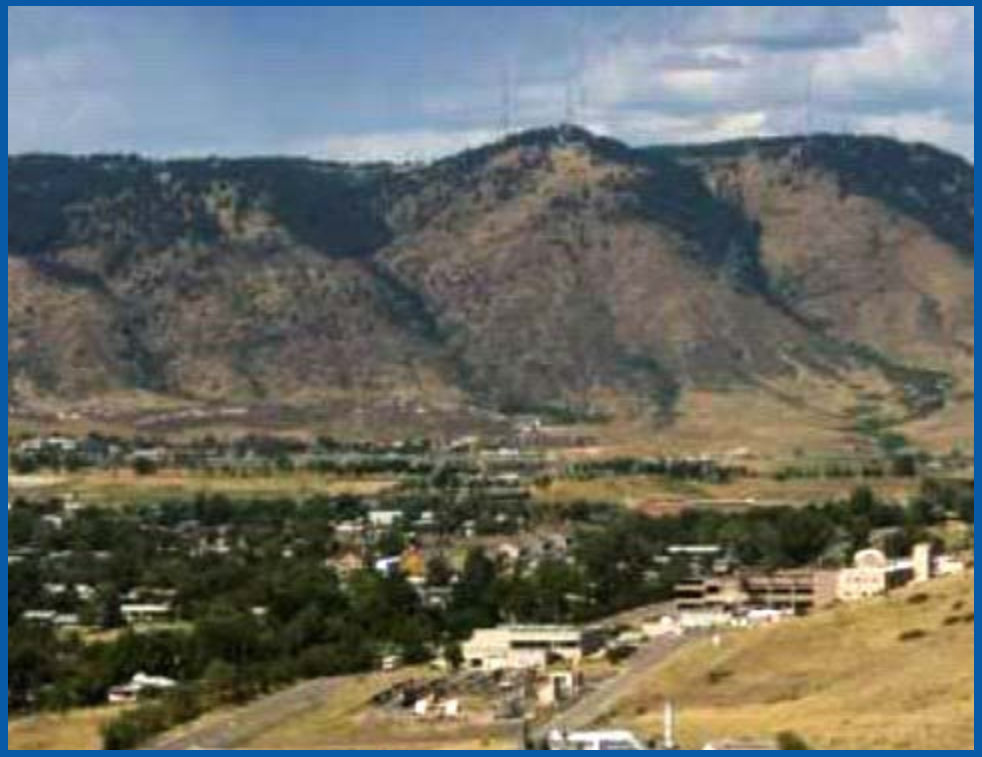
Conclusions

- NREL CTO/ZTO cells are superior to SnO_2-based cells in initial performance but have some fundamental durability problems
- C-V *hysteresis* has been observed to increase with stress in cells using “infinite” sources of dopant (Cu).
- Additional *hysteresis* in CTO/ZTO cells strongly suggests a “decomposition” of the CTO/ZTO layers
- C-V hysteresis also observed to increase in industrial cells. Observe decreasing hysteresis at longer stress times and higher temperatures.
- C-V measurements easily implemented during ALTs as a non-destructive technique to better identify degradation mechanisms in cells and modules

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

National Renewable Energy Laboratory
Innovation for Our Energy Future

Comparison of injection of carriers through light soaking and forward bias in dark (In Stabilization of polycrystalline thin film photovoltaic modules)



J.A. del Cueto, C.A. Deline

February 19, 2010
Reliability Workshop
Denver West Marriott

Testing, Evaluation and Reliability Team

Outdoor Test Facility (OTF)

This presentation does not contain any proprietary or 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

Outline

- Rationale: Metastability of CIGS & CdTe
- Study plan to probe metastable behavior
- Modules used in study
- Value of C-V profiling as signature
- C-V profile data
  - Carrier concentrations, depletion widths on CIGS & CdTe modules
  - 1 of each that went dark ⇨ light & light ⇨ dark
- Performance changes in CIGS & CdTe modules with exposure
- Summary

Rationale: Metastability of CIGS & CdTe

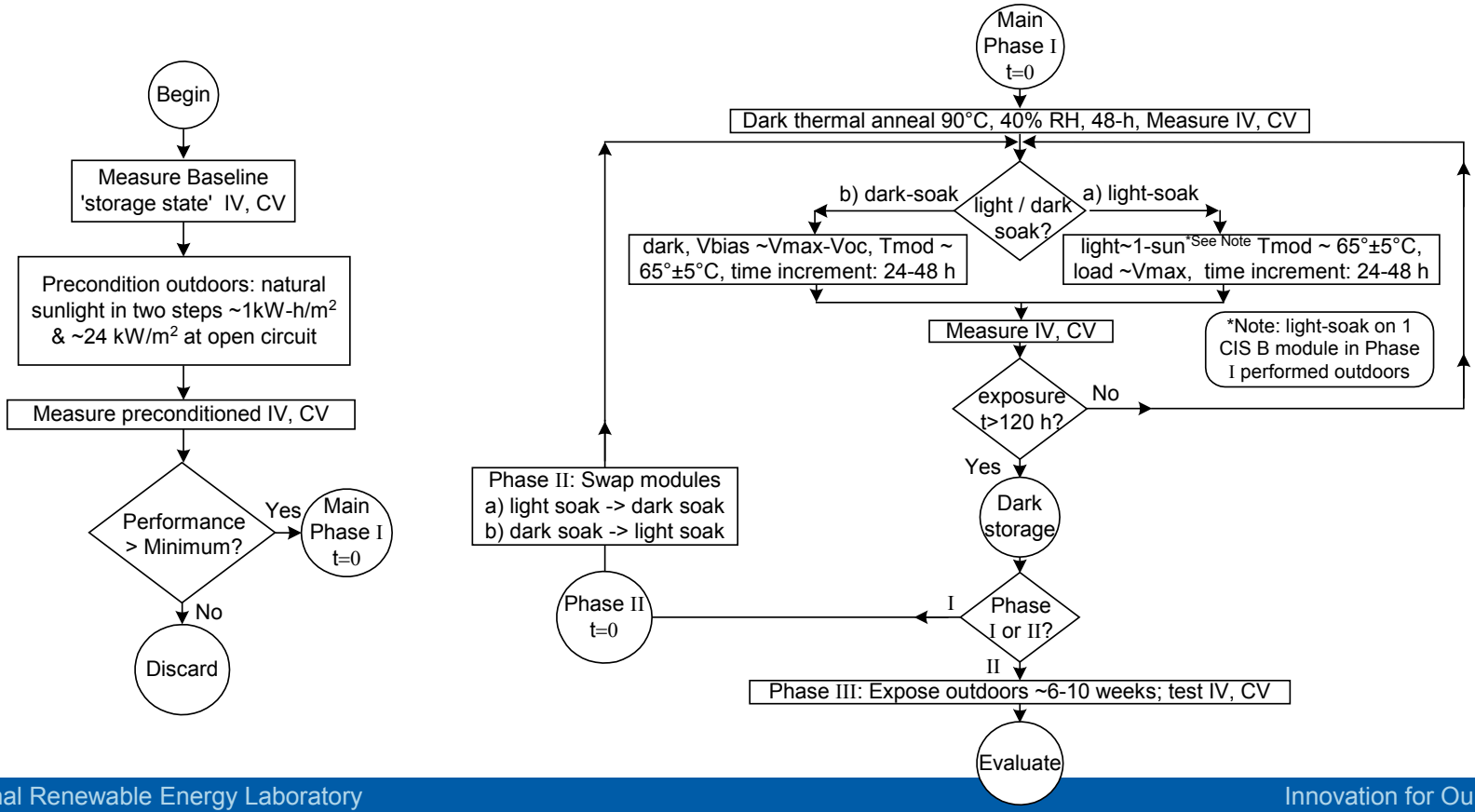
- High Performing CdTe & CIGS PV exhibit transient/metastable changes in performance that pose challenges in assessing accurate performance:
  - prior exposure history, time between exposure and I-V measurement critical

- Current standard for stabilization in thin-film PV certification (IEC 61646):
  - Light-soaking until change in power ≤ 2% is achieved, after successive periods of at least 43 kW-h/m^2 of integrated irradiance
  - designed for amorphous silicon where defect mechanism is light-induced Staebler-Wronski effect
  - CIGS or CdTe devices most likely have different defect mechanisms
    - ❖ current procedure probably inadequate for CIGS or CdTe (e.g. ions)

- Beckons preconditioning / stabilization steps prior to performance testing
  - reduced error in assessing consistent performance and
  - impacts accuracy of models for long-term energy yield, and/or reliability.

Preconditioning /Stabilization Study Plan

- Preconditioning steps:
  - ascertain minimum quality, emulates NREL preconditioning prior to IV measurements STC
- Main Stabilization Sequence: Phase I and II
  - dark 90°C anneal, emulates a short version of 85C/85% RH, 1000h certification test
  - consists of two branches: light exposure & biased dark exposure, both ~65°±5°C
  - Biased dark exposure is advantageous if successful because of ease and lower cost
  - Swap light/dark-soak modules in Φ–I ⇔ dark/light-soak modules Φ–II , no dark anneal



Modules Studied

- Diverse set of CdTe & CIGS modules
  - Some nascent or new, not used, or stored as controls
  - Some pre-exposed outdoors
  - Some light-soaked indoors
- All (except CIGS B) are glass(substrate/superstrate)/glass monolithically interconnected

Module Type	Quantity	Configuration	Pre-existing exposure conditions
CdTe A	2	Glass-superstrate-glass laminate, monolithically interconnected	Yes, outdoors 3 years
CdTe B	2	Glass-superstrate-glass laminate, monolithically interconnected	No, nascent
CdTe C	1	Glass-superstrate-glass laminate, monolithically interconnected	Yes, indoor light-soak, 1130 kW-h in 2002
CIGS A	3	Glass-substrate-glass laminate, monolithically interconnected	Nascent: 3 controls from 2003
CIGS B	2	Glass-flexsubstrate-glass laminate, solder bond interconnect	No, nascent

Module characterization tests

- I-V
  - Used large area continuous solar simulator (LACSS) apparatus
  - Dark & light (STC),

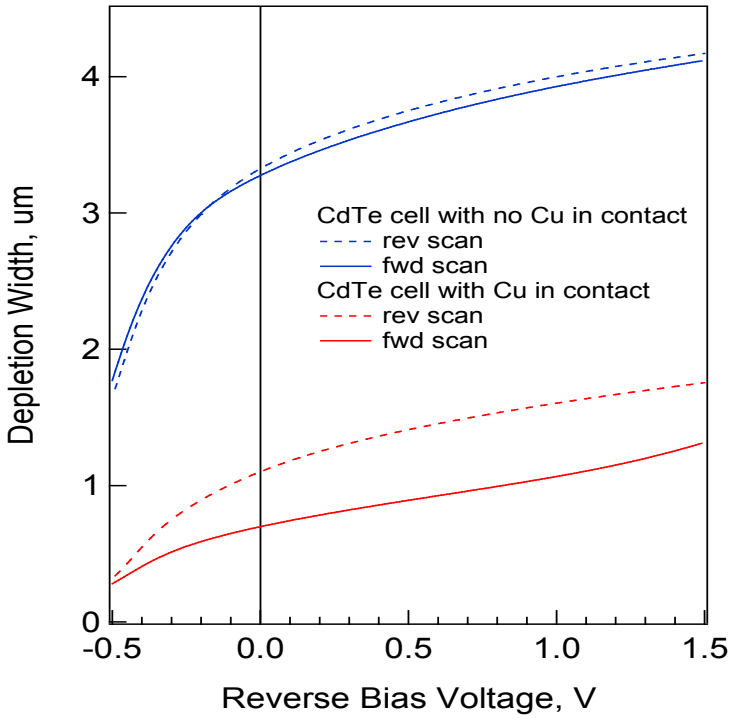
- C-V profiling
  - If module cells are uniform, measuring CV profile on module with N_C number of series cells each with cell area A_C, produces signal as if the device under test were a cell sized 0.5-3 cm^2, due to magnitude cancellation of A_C divided by N_C

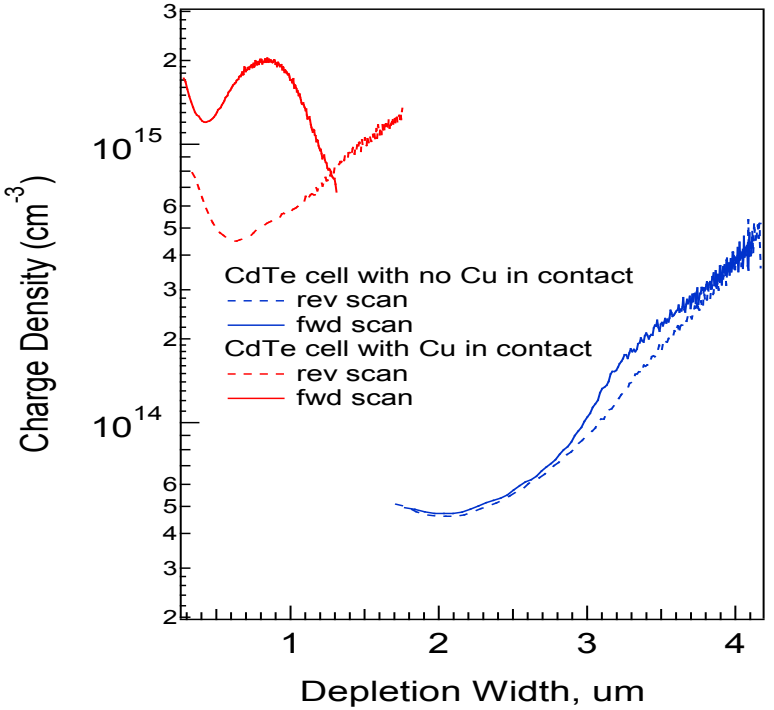
$$\frac{1}{C_{Mod}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_j} \ldots + \frac{1}{C_{Nc-1}} + \frac{1}{C_{Nc}} \quad \Rightarrow \quad C_{Mod} \approx \varepsilon \cdot \varepsilon_0 \cdot \frac{1}{w_D} \cdot \frac{A_C}{N_C}$$

$$N(W_D) = \frac{2}{q\varepsilon\varepsilon_0} \cdot \frac{1}{d(1/C^2)/dV} \quad \Leftrightarrow \text{ Carrier density}$$

Value of C-V profiling in CdTe devices

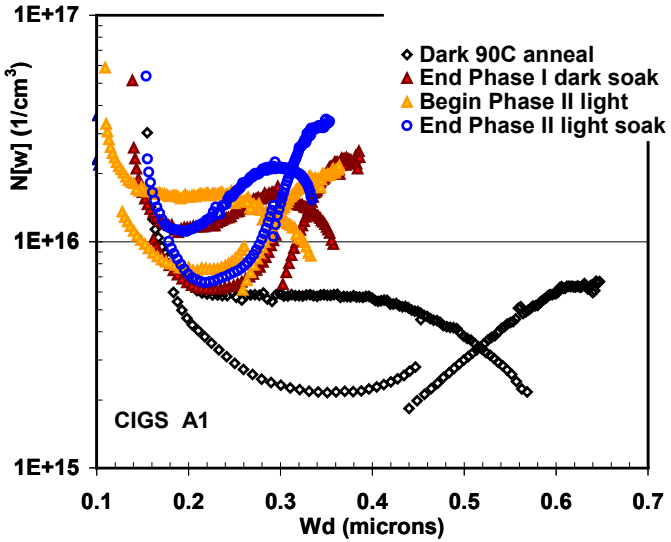
- Hysteresis & change in depletion width vs. bias ⇔signature to potential metastability
  - D. Albin et al., "Degradation and Capacitance-Voltage Hysteresis in CdTe Devices," paper 7412-18, Proc. SPIE 2009 Optics & Photonics Conf., San Diego, CA, Aug. 2009.
- depletion width and derived carrier densities as one sweeps into reverse then up to forward bias appears correlated to amount of Cu in devices
  - No Cu in back contact ⇨ little hysteresis in C-V profile, lower carrier densities
  - Cu in back contact ⇨ hysteresis in depletion width between reverse & forward bias

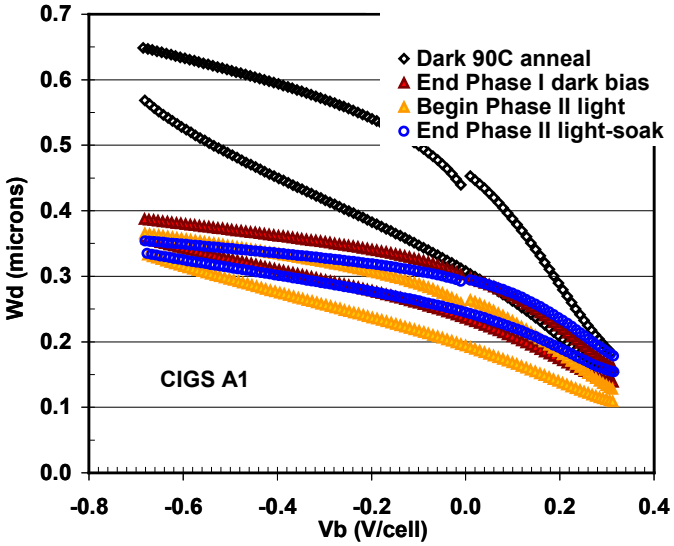




CV profiles CIGS A1: phase I dark soak ⇨phase II light soak

Carrier Concentration N(W) top, depletion width W_d bottom

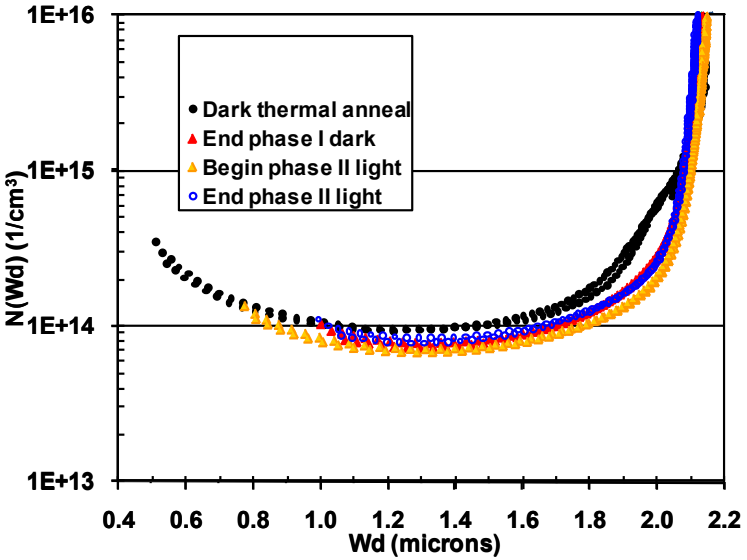


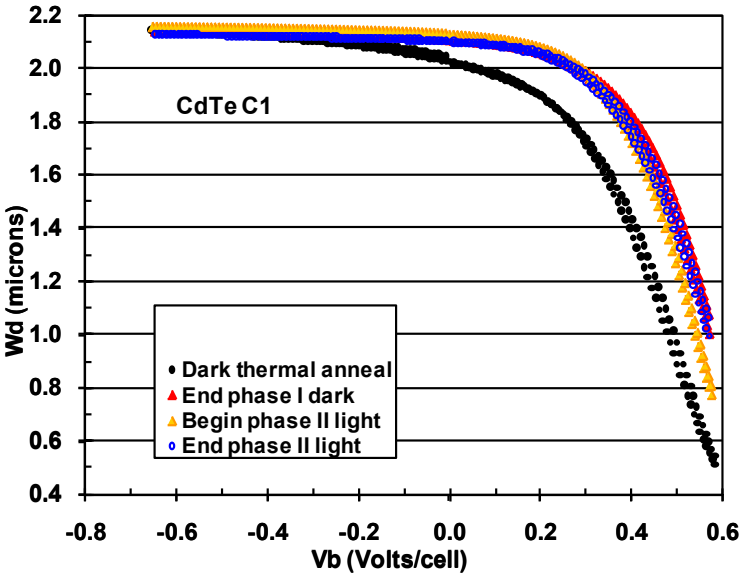


- Phase I (indoor dark soak)
  - Baseline, N ~ 1-3 *10^{16}
  - outdoor precondition 27 kW-h/m^2, slight shift of W_d upwards from baseline
  - dark anneal: drops N~2-7 *10^{15}, large shift up of W_d, large hysteresis ~50% at v=0
  - End of 3 dark soak steps (24h, 48h & 48 h)
    - restores N & Wd profiles closer to data after outdoor precondition, partway between precondition & anneal
- Dark storage ~ 3-4 months
- Phase II (indoor light soak)
  - Begin light soak after dark storage
    - N, Wd profiles relax slightly to state after outdoor precondition
  - End 3 light soak steps (48h, 30h & 48 h)
    - moves N, W_d data slightly between states after outdoor precondition and end of phase I

CV profiles CdTe C1: phase I dark soak ⇨phase II light soak

Carrier Concentration N top, depletion width W_d bottom

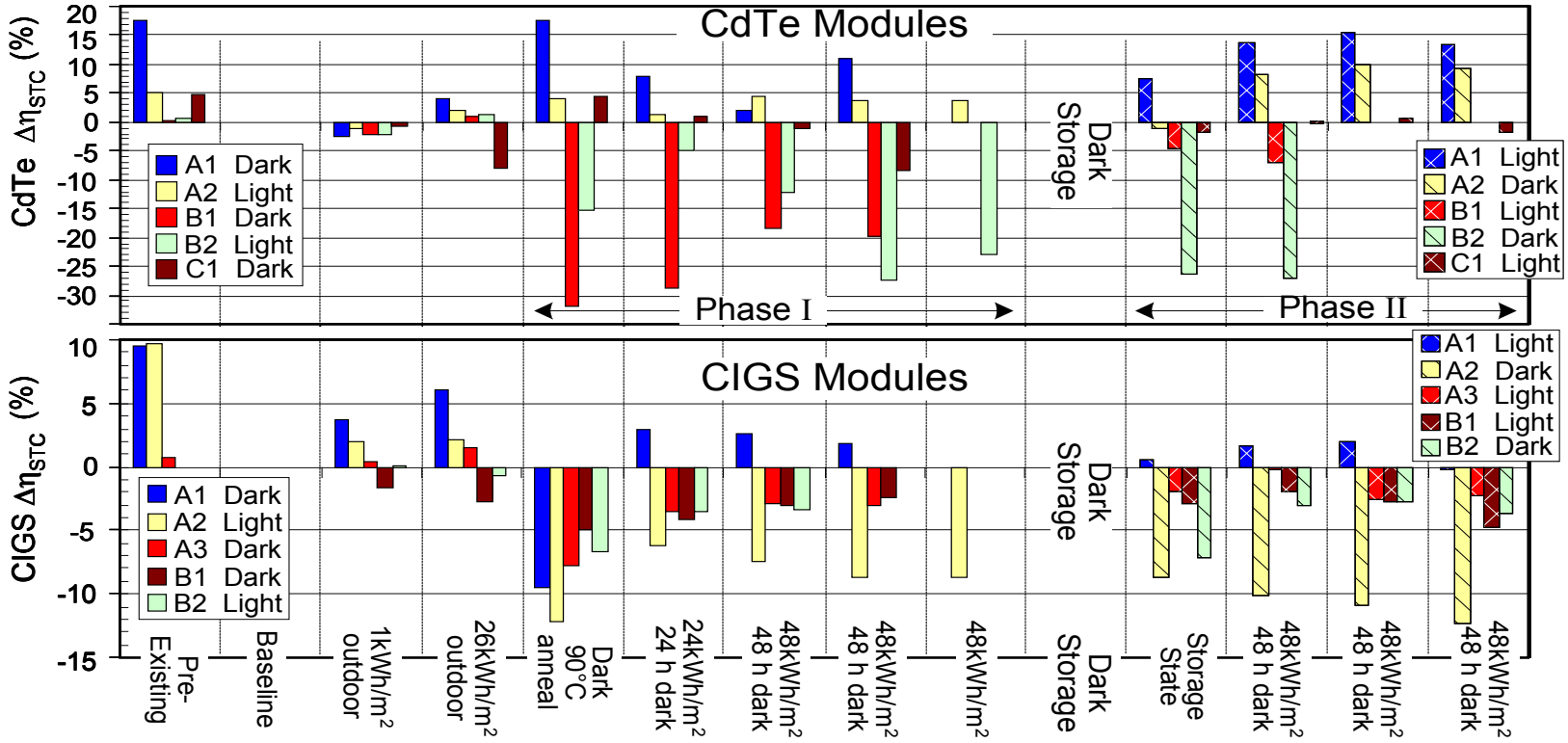




- Phase I (indoor dark soak)
  - Baseline, (valley) N ~ $7*10^{13}$-$1*10^{14}$
  - outdoor precondition 27 kW-h/m^2: some change in W_d upwards in forward bias, Δ N small
  - dark anneal: raises N~1-5 $*10^{14}$, large shift down of W_d, small hysteresis ≤5% at v>0
  - End of 3 dark soak steps: 24h, 48h, 48h
    - restores N close to outdoor precondition state,
    - W_d midway between baseline and outdoor state
- Dark Storage ~ 3 months
- Phase II (indoor light soak)
  - Begin light soak after dark storage
    - N, Wd profiles relax close to state at baseline
  - End 3 light soak steps (48h, 30h & 48 h)
    - returns N, Wd data profiles close to that just after end of phase I biased dark soak

Performance changes vs. exposure relative to baseline

- Phase I
  - Baseline = 0 Δ, some pre-existing higher
  - outdoor precondition 1 & 26 kW-h/m^2
    - CIGS A, CdTe A & B improve
    - CIGS B, CdTe C drop
  - dark thermal anneal
    - All CIGS + CdTe B drop,
    - CdTe A & C improve to preexisting performance
- Phase I (cont)
  - Exposures: 4 light /3 dark soak steps
    - CIGS seem to stabilize (Δ η ≤ 2%) in light or dark
    - CdTe mixed, some stabilize (B1, A2)
- Phase II swap: dark storage ~3-4 months
  - Some CdTe recover, CIGS change some
  - 3 light/dark steps 48 h each
    - CIGS mostly stabilize (Δ η ≤ 2%)
    - CdTe: type A stabilize as per pre-existing, C stabilizes near baseline, type Bs fail



Details of performance changes

- Dark thermal (90°C, 48h OC) anneal
  - CdTe A2, B1, B2 & all CIGS
    - FF loss is largest source of degradation
  - All CdTe Voc improve ~ 2%-8%
  - All CIGS Voc degrade ~ 2%-3%

- Biased dark soak phase I
  - V_{bias} chosen ~ halfway between Vmax & Voc,
  - I_{bias} <20% I_{max},
  - might have stifled stabilization

- Biased dark soak phase II
  - V_{bias} closer to Voc than phase I
  - I_{bias} ~ Imax
  - probably accelerated stabilization or changes in performance

Summary

- Polycrystalline CIGS & CdTe PV show metastable behavior in performance

- Implemented stabilization/preconditioning procedures using two types exposures light soak at 1-sun and voltage-biased dark-soak, at 65°±5°C
  - If stabilization is defined as $\Delta \eta \leq 2\%$ between successive increments
    - both (light/dark) capable of driving stabilization for most CdTe & CIGS modules
    - some modules did seem to behave differently with light vs. dark exposure
  - Capable of driving performance of CdTe back to incipient values before exposure
  - Biased dark exposure should be performed with setting $I_{bias} \sim I_{max}$ for acceleration

- IEC61646 stabilization defined as $\Delta \eta \leq 2\%$ between successive increments may be inadequate to ascertain actual stability in polycrystalline thin-film PV

- Will soon deploy same module set outdoors for 6-10 weeks to ascertain which one of light- or biased dark- exposures comes closest to outdoor stabilization performance level

- Will soon start testing newer CdTe & CIGS module set

Summary

- CV profiling:
  - Changes in depletion widths (Wd) & its hysteresis upon exposure or thermal anneal provide signature to metastability
  - Quantifiyng link to stability is likely different between CIGS and CdTe
  - For some modules CV / Wd profiles exhibit different behavior in light vs. dark exposure

Acknowledgements

- Dave Albin, for discussions & insight
- Steve Rummel, Allan Anderberg IV measurements

	Title, Author(s)	Affiliation
	Testing Methodologies	
1	*Accelerated electro-chemical delamination test for the durability of transparent conductive oxide* David Strickler, Yu Wang, and Satoshi Tanaka	NSG
2	*Analysis of CPV Optical Components Using an LBIC System (Light Beam Induced Current)* Mike Sumner, Damien Buie, Igor Kozin, and James Foresi	EMCORE Corp.
3	*Approaches Towards Light and Heat Management in PV Modules* Matthias Duell, Biao Li, Matthieu Ebert, Joachim Jaus, Carola Voelker, Dan M. J. Doble	Fraunhofer Center
4	*Characterization and Reliability of Polymeric Components in PV modules* Shuying Yang, Abhay Maheshwari, and Shirish Shah	Solaria
5	*Comparative Study of the Long-Term Performance of 3 Photovoltaic Systems installed in Florida* Nicoleta Hickman, Albert Leyte-Vidal, Kris Davis, Sarah Kurtz, Dirk Jordan	FSEC-U of Central Florida & NREL
6	*Displacement Test Protocol Considerations* Sam L. Samuels	DuPont Photovoltaic Solutions
7	*Extended Life Testing of multi-crystalline Silicon PV Modules* Vivek Gade	Evergreen Solar
8	*Faster and Adaptable Accelerated Solar PV/Thermal Durability Testing Solution* Jacob Zhang, Richard Schultz, Richard Donato, and Kurt Scott	Atlas Materials Testing Technology
9	*High Volume Light Soaking and UV Testing of Photovoltaic Modules* Lawrence Dunn and Michael Gostein	Atonometrics Inc.
10	*Impedance Measurement as a Diagnostic Tool for Device Degradation* Xin Jiang, Sean Shaheen, Sergey Li, and Srinivas Gowrisanker	Plextronics & Denver University
11	*OPV Lifetime Testing* Srini Balasubramanian, Elsa Kam-Lum, and Stephen Wicks	Konarka
12	*Pulsed Valve Mass Spectrometry Film Permeation Tool* Mark Roehrig, Dana Reed, Alan Nachtigal, Mark Weigel, and Robert Messner	3M Company
13	*PV Module Reliability and Durability Studies at the FSEC PV Materials Lab* Neelkanth G Dhere, Shirish V. Pethe and Ashwani Kaul	FSEC-U of Central Florida

Testing Methodologies cont.

14	*PV Module Weather Durability Testing - A Comprehensive Approach* Allen Zielnik and Kurt Scott	Atlas Material Testing Technology LLC
15	*PV Standards. What does the IEC have for you?* Barikmo Howard	Sunset Technology Inc
16	*Recommended Protocol for Accelerated Aging Testing: A Literature Search* Mani G. Tamizh-Mani	Arizona State University
17	*Sandia's PV Reliability Program* Rob Sorensen, Michael Quintana, Jennifer Granata, Mike Mundt, Jeff Mahn, Elmer Collins, Chad Staiger	Sandia National Laboratories
18	*Short and Long Term Spectral Stability over the Life of Tool* Serreze Harvey	Spire Solar Inc.
19	*Solar Logistics* Herb Schueneman	Westpak
20	*Split-Plot Design: Characterizing 10 factors in "12" runs* Rob Ong	Solexel Inc
21	*Thermalreflectance Imaging for High Reslolution Defect Inspection through Glass* Glenn Alers, Dustin Kending and Ali Shakouri	U of California at Santa Cruz

Thin-film Photovoltaics

1	*A Single Layer Thin-film Moisture Barrier for CIGS Solar Cells* P.F. Carcia, R.S. McLean, and S. Hegedus	DuPont/U. Delaware
2	*CIGS Cell-Level Reliability Task and Studies at NREL* F. J. Pern, R. Sundaramoorthy, S. H. Glick, B. To, X. Li, I. Repins, J. Li, C. DeHart, S. Glynn, L. Mansfield, M. Contreras, R. Noufi, T. Gessert	NREL
3	*Cohesion and Phase Separation in Organic PV Heterojunction Layers* Vitali Brand and Reinhold Dauskardt,	Stanford University
4	*Effects of Various Module Preconditioning Procedures on CdTe Pmax Measurements* Michelle Propst, Keith Goshia, and Jason Hevelone	Abound Solar
5	*Electrically Conductive Adhesive Reliability in Thin Film Photovoltaic Modules* Stephen Ruatta, Louis Rector, Anja Henckens, Hilde Goossens, and Gunther Dreezen	Henkel

Thin-film Photovoltaics cont.

6	*Frozen Light Soak Test: Simulating the Dawn Effect* Lei Chen and Delphine Bayon	Nanosolar Inc.
7	*Reliability of CIGS Modules* Deepak Nayak, Norbert Staud, Burak Metin, Eric Lee, and Mustafa Pinarbasi	SoloPower
8	*Thin Specialty Glass for Reliable Thin Film PV Modules* James Webb	Corning

Packaging

1	*Aging of c-Si PV module packaging material* Zhiyong Xia	BP Solar
2	*Benefits of a Desiccated Edge Seal in TFPV"* J. Baratuci, V. Bodnev, S. Hummel, and L.Postak	Truseal
3	*Comparative Performance and Reliability of Backsheets for Photovoltaic Modules* W. J. Gambogi	DuPont
4	*Degradation and Molecular Bond Rupture Kinetics in Organic PV Transparent Barriers* Fernando Novoa and Reinhold Dauskardt	Stanford University
5	*Lessons learned regarding failure modes of glass/glass modules in the field* Forrest Collins, Beth Copanas	Juwi Solar Inc.
6	*Momentive Performance Materials: Silicone Solutions for the Solar Industry* Markus Putzer and Clarissa Miller	Momentive Performance Materials
7	*Partial discharge testing* Pleydon Robert	Saint-Gobain Performance Plastics
8	*Relation of Wet Leakage Resistance with Module Front Glass Resistivity* Adam Brand and Renhe Jia	Applied Materials
9	*Solar Edge Sealants with a Better Balance of Properties* Rahul M Rasal and Paul E Snowwhite	ADCO
10	*The Reliability and Durability of Novel Silicone Materials for Photovoltaic Encapsulation* Yi Kang, Chrisopher Shirk, Barry Ketola, Ann Norris, Keith Mclntosh, Mary Kay Tomalia	Dow Corning Corp.

Concentrating Photovoltaics

1	*Characterization of an Aggregated Total Internal Reflection Optic* Kevin Fine and David Schultz	Banyan Energy
2	*Concentrating Solar Resource Tools and Data at NREL* Daryl R. Myers	NREL
3	*Design Verification Testing* Clay Stevenson and Doug Williams	Entech Solar Inc.
4	*Durability of Thermally Cycled ELO Solar Cells* Rickey Pastor and Noren Pan	MicroLink Devices
5	*Insuring and Predicting the Reliability of Concentrated Photovoltaics: Interconnect Structures* Craig Hillman (DfR), Greg Caswell (DfR), Jordan Ross (Indium)	DfR Solutions and Indium Corp
6	*Mechanically induced microfractures* Paul Lamarche	Solar Junction
7	*Overview of Aspects of Long-Term Optical Stability of HCPV Fresnel Lenses* J. Berrios, A. Carlson, and J.P.D. Cook	OPEL Solar
8	*Proposed CPV Bare Cell Thermal Cycle Qualification Test Procedure* Peter Hebert	Spectrolab
9	*Reliability considerations for a 7kW incident CPV monolithic concentrator module* Leo Baldwin and Tony Chen	Cool Earth Solar
10	*Reliability through Field Testing in Real World Conditions* Robert McConnell, Adi Nayak and Geoff Kinsey	Amonix
11	*Spectral dependence of CPV current generation in the San Gabriel Valley* Neil Fromer	Soliant Energy
12	*The Reliability and Qualification Program at Amonix* Adi Nayak and Geoff Kinsey	Amonix
13	*Thermal Runaway Failures of CPV Solar Cells* Steve Seel, Bruce Furman, Matt Meitl, Sal Bonafede, Scott Burroughs	Semprius

Characterization of an Aggregated Total Internal Reflection Optic

Kevin Fine; David Schultz

Supported by NREL Pre-Incubator Program – Subcontract # NEU-0-99010-11

INTRODUCTION:

Aggregated Total Internal Reflection (ATIR) is a new optics design space for solar concentration pioneered by Banyan Energy Inc. The primary advantages of ATIR are: a compact profile, wide acceptance angles, uniform energy distribution across the focal area and a direct cell mate.

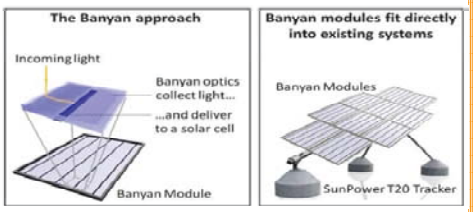


Figure 1: (Left) Rendering of a 'Banyanized' solar panel. Line-focus optics within the panel will reduce area costs and allow production to scale with fewer constraints. (Right) Existing tracking systems can be used. No downstream modification to solar infrastructure is needed.

Banyan's optics are approximately ten times flatter than conventional concentrators, and can therefore fit like a sheet within a standard module construction. This allows module mfrs. to leverage their existing silicon capacity to produce 5-10x as much product.



Figure 2: Isometric view of an early ATIR lens prototype (Left) that has an aspect ratio of 7:1 and produces a line-focus silhouette (Center). A single-unit module prototype demonstrates module integration and direct cell mate (Right).

ATIR SPECIFIC RELIABLITY CONSIDERATIONS:

- Cell temps ~5-10C hotter than 1-sun panel
- CTE decoupling between cell, backplane, and optic
- UV weathering performance of all optic and adhesive materials – especially with concentrated flux inside waveguide material
- ATIR design space allows (but does not require) optical features on the front surface of a module. Are any features allowable from a soiling perspective?

MEASURING OPTICAL EFFICIENCY – J_{sc} METHOD:

Short circuit current (J_{sc}) is proportional to exposed cell area and the intensity of incident light. Optical Efficiency (OE) is measured by comparing the J_{sc} of a bare cell to that of a cell coupled with an optic and controlling for the area and source intensity.

$$OE = \frac{J_{sc,final}}{J_{sc,initial}} = \frac{J_{sc,2}}{\left(J_{sc,1} * \frac{A_{optic\ input\ t}}{A_{mask}} * \frac{DNI_2}{GNI_1}\right)} = \frac{J_{sc,2}}{J_{sc,1}} * \frac{A_1}{A_{input}} * \frac{GNI_1}{DNI_2}$$

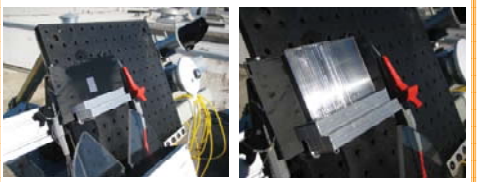


Figure 3: Detail of the outdoor test bed. (Left) Setup for input J_{sc} reading. A bare NaREC cell with precise area mask is mounted on the 2-axis tracking platform. Kipp and Zonen DNI and GNI sensors are visible. (Right) Setup for output J_{sc} reading. The Lens Step optic is coupled to the masked cell with Sylgard 184 base (n=1.42, non curing).

PREDICTED RESULTS: 84.2%

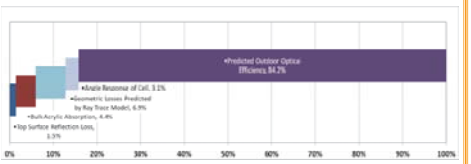
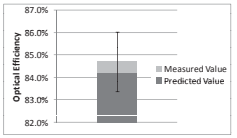


Figure 4: Predicted Optical Efficiency of prototype optic (84.2%) shown with the expected loss mechanisms. Loss mechanisms include spectral absorption by the acrylic optic and the angular response of the cell.

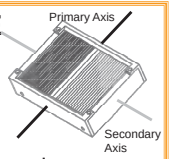
MEASURED RESULTS: 84.7%



Temperature	0.50%
Spectrum	0.50%
GNI sensor	3.60%
DNI sensor	0.54%
Mask area	0.02%
Repeatability	1.34%
Total Uncertainty (RSS)	3.94%

Figure 5: Measured optical efficiency of 84.7% is shown relative to the modeled optical efficiency of 84.2% (Left). The difference between modeled and measured performance is statistically insignificant due to the measurement uncertainty of ±3.9% (Right). Measurement uncertainty is driven largely by the large uncertainty in the GNI sensor reading. For future optical efficiency measurements, the GNI sensor is being upgraded from the Kipp and Zonnen CMP-3 to the CMP-11. This change reduces the total measurement uncertainty to ±1.8%.

ACCEPTANCE ANGLE CHARACTERIZATION:



The wide acceptance angle of ATIR optics allow a mid-concentration panel to be mounted on an existing low cost fixed tilt single axis tracker, making it a drop-in replacement for a one-sun panel.

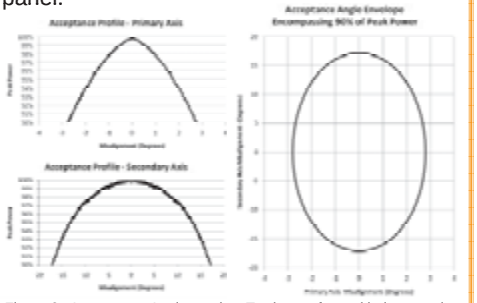


Figure 6: Acceptance Angle results. Testing performed indoors under a solar simulator with an encoder measuring degrees of misalignment. Primary axis: ±2.8˚ Secondary Axis: ±17.2˚

The measured AA's of ± 2.8˚ in the primary (tracked) axis and ± 17.2˚ in the secondary (seasonal) axis are sufficient for cost effective performance on a fixed tilt tracker. Broader AA's exceeding ± 3˚ and ± 22.5˚ are possible with greater manufacturing control and larger module sizes. Some new ATIR designs may even be effective on a horizontal axis tracker.

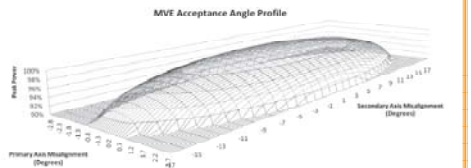


Figure 7: Minimum Volume Ellipsoid (MVE) fit to on-sun acceptance angle data illustrates expected power output given a specific misalignment

CONCLUSIONS:

Banyan's ATIR optics have demonstrated the necessary performance for effective commercialization. To reach the market successfully, proven manufacturability and reliability will be just as important.

Solar Radiation Resource Tools and Data Sources

Daryl R. Myers
National Renewable Energy Laboratory, 1617 Cole Blvd, Golden CO 80401

ABSTRACT

Many solar radiation resource tools and data are available from several NREL and other world wide web sites. We show examples for NREL modeling tools, including on-line interactive (Google Earth interface based) 10 km gridded solar resource data (global, direct, diffuse) from the NREL SOLAR PROSPECTOR; photovoltaic system energy production models based on PVFORM such as IN MY BACK YARD (IMBY), and two versions of interactive PVWATTS photovoltaic system energy calculators. Downloadable tools include the Solar Advisor Model (SAM) for detailed technical and financial analysis of solar conversion systems. Simple broadband and spectral clear sky models and a global horizontal to direct beam conversion model are available. Historical broadband measured data sets and a database of 3000 spectral measurements under all sky conditions and in various configurations are available. For concentrator applications, the Lawrence Berkley National Laboratory data based of 179,064 circumsolar radiation profile measurements are available. The U.S. National Solar Radiation Data Based (NSRDB) contains measured (less than 1% of the total) and modeled hourly solar data for 239 sites for 1961-1990, for 1140 sites from 1991-2005, and derived Typical Meteorological Years (TMY) for those sites. For 1998-2005 solar data on a 10 km grid derived from satellite imagery is available for the U.S. Free public access solar data is available from other government (NASA, DOE) or university sources. Several commercial providers have a variety of modeled, and sometimes measured, data available.

http://www.nrel.gov/rredc/models_tools.html

http://www.nrel.gov/rredc/solar_resource.html

http://www.nrel.gov/rredc/solar_data.html



Design Verification Testing

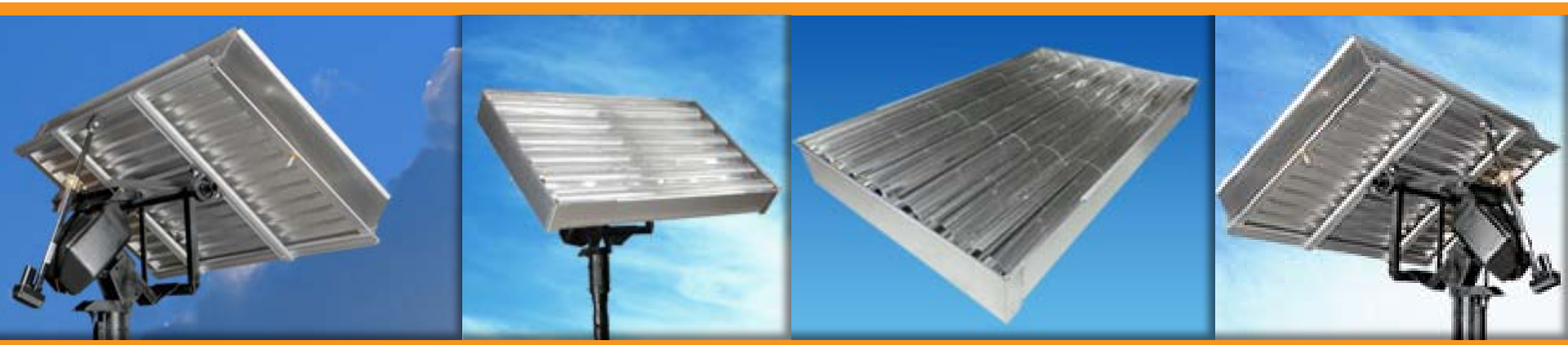
NREL PV Module Reliability Workshop

Entech Solar, Inc.

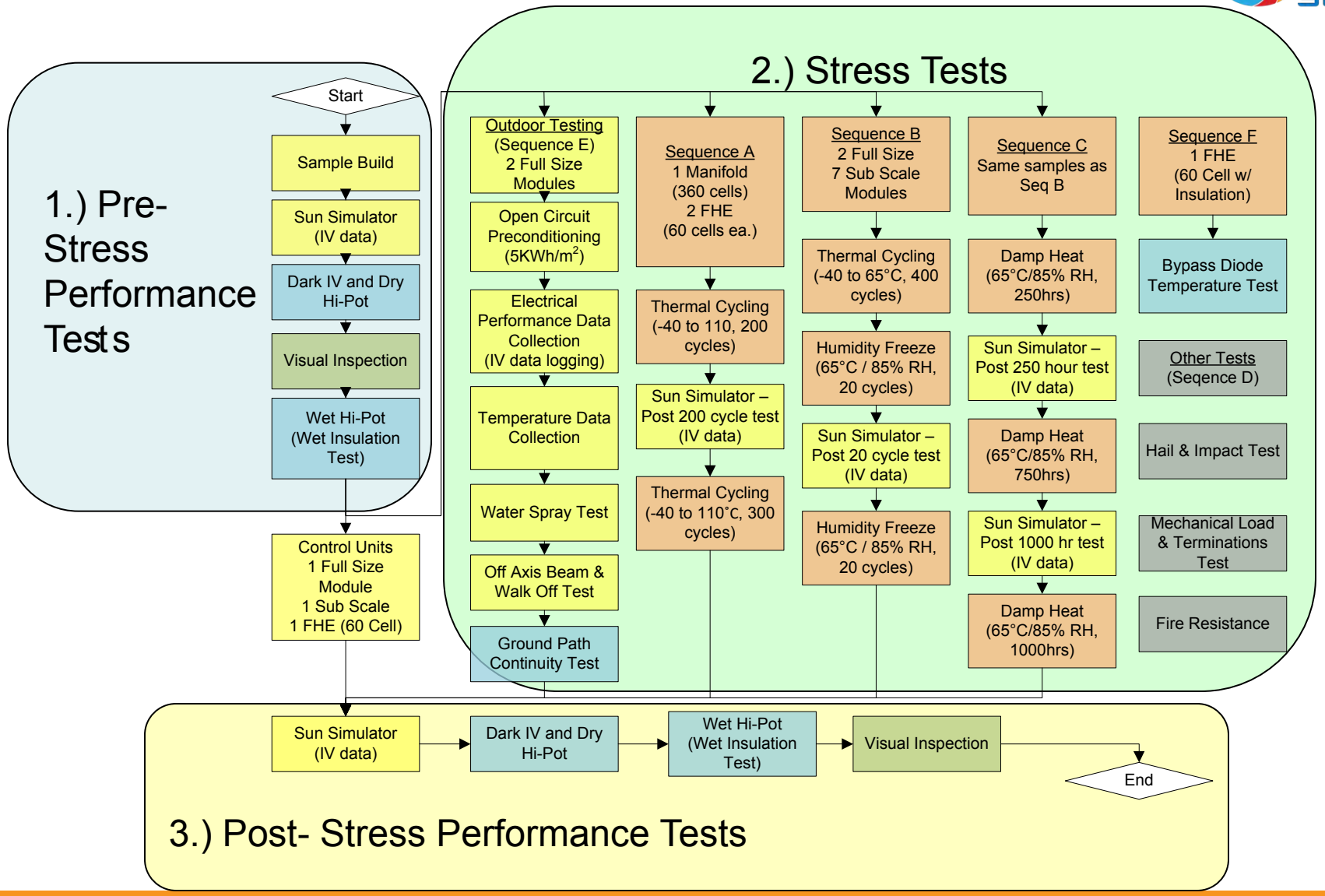
Clay Stevenson

Doug Williams

2-18-10

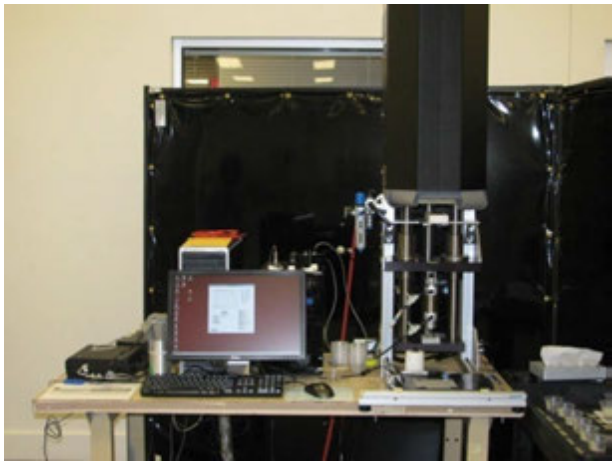


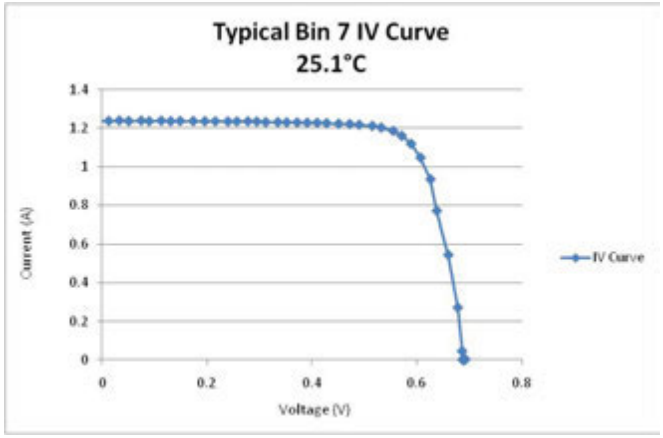
DVT Testing Sequence



Concentrated Solar Cell Testing

Custom Cell Tester



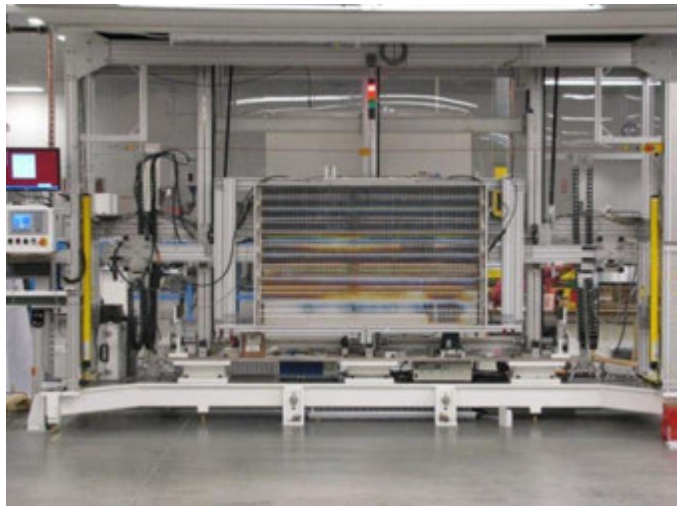


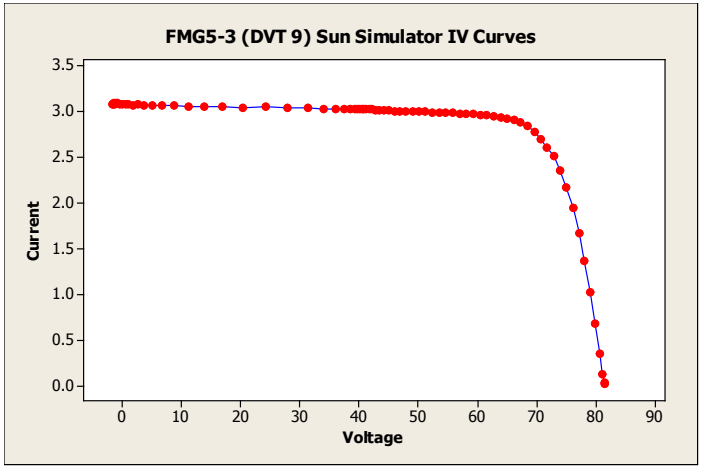
Cell Testing

- Description: Uses an e-load to sweep an IV curve from Voc to Isc under concentration.
- Purpose: To match cells in a receiver by ILoad. This will ensure max power, and prevent any one cell from limiting the series current.
- Concentration:
  - Flash intensity is set to
    - Flash concentration = Geometric Concentration ÷ Cell Width x gridline pitch ÷ bare silicon width between gridlines
  - Light level is calibrated to an NREL standard reference cell
- Common failure modes:
  - Shunting, cracked cells

World's Largest Sun Simulator

Sun Simulator with ThermaVolt II Module



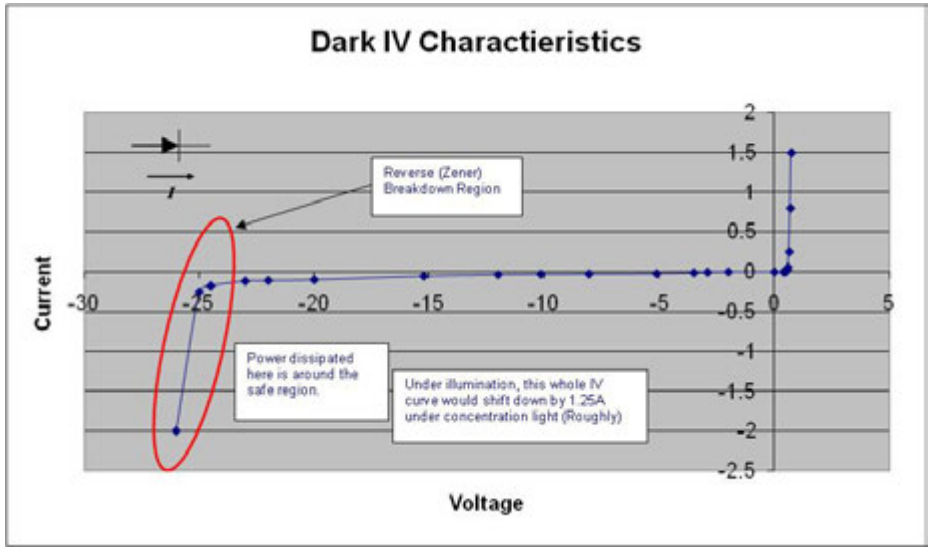


Sun Simulator IV Curve

- Description: Same as cell tester, but 110' Long, twice the light output, and capable of testing 12'x 3' CPV modules with 1 sun over full aperture.
- Purpose: Measure the performance of a module, without having to test outdoors.
- Simulating the Sun:
  - The Sun tunnel is set to 110' limiting all incident light angles at the CPV lens down to 3° for the 12' modules and 1.5° for the 5' modules.
  - Intensity is calibrated back to an NREL standard Reference cell
  - Uniformity: Spacial, Temporal, and Angular uniformity are considered to achieve Class B simulation.

Dark IV

Diode Characteristics



Dark IV Testing

- Description: Measures the series resistance through the cells and diodes. Applies 1.25*Isc through the cells and diodes and measures the voltage drop across the receiver or module.
- Purpose: Would identify defects such as broken wire bonds, broken cells, bad electrical contacts or connectors, etc.

Dry and Wet Hi-Pot

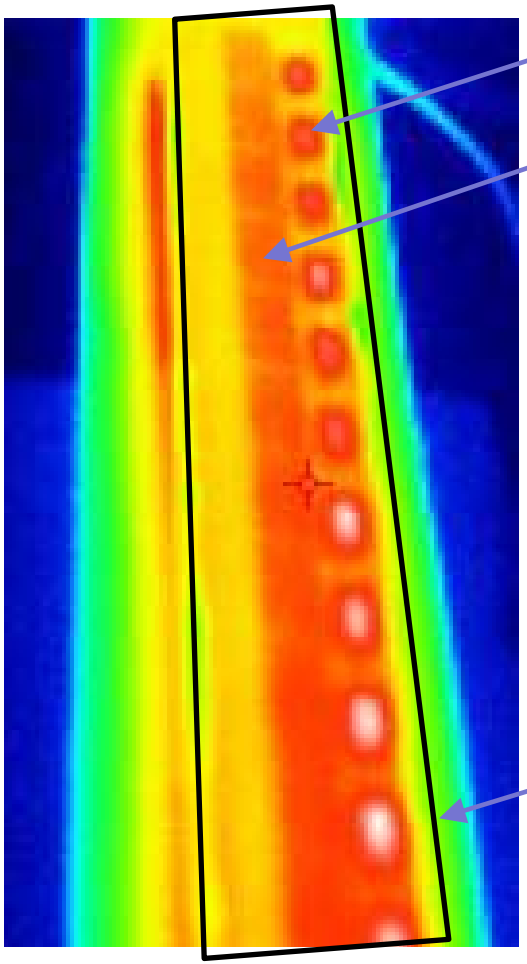
Dry and Wet Hi-Pot Station



Dielectric Testing

- Description: Test the electrical insulation of the module and receivers by applying a voltage between the electrical circuit and the ground plane.
- Purpose: Useful for identifying defects in the encapsulation, dielectric layers, wire insulation, etc.

Thermal Testing

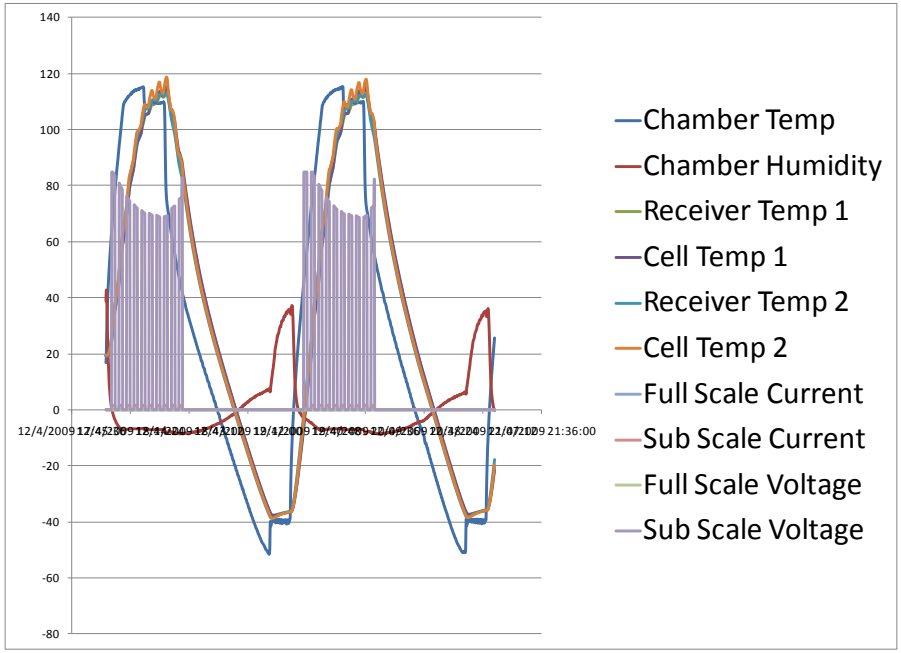


Thermal Imaging
Description: Infrared images are taken to look for hot spots of both the cell and diode with current flowing through them.

Purpose: Useful for identifying defects such as thermal bonding issues, open cells or diodes, delamination.

Sequence A: Thermal Cycling

Thermal Cycle Profile

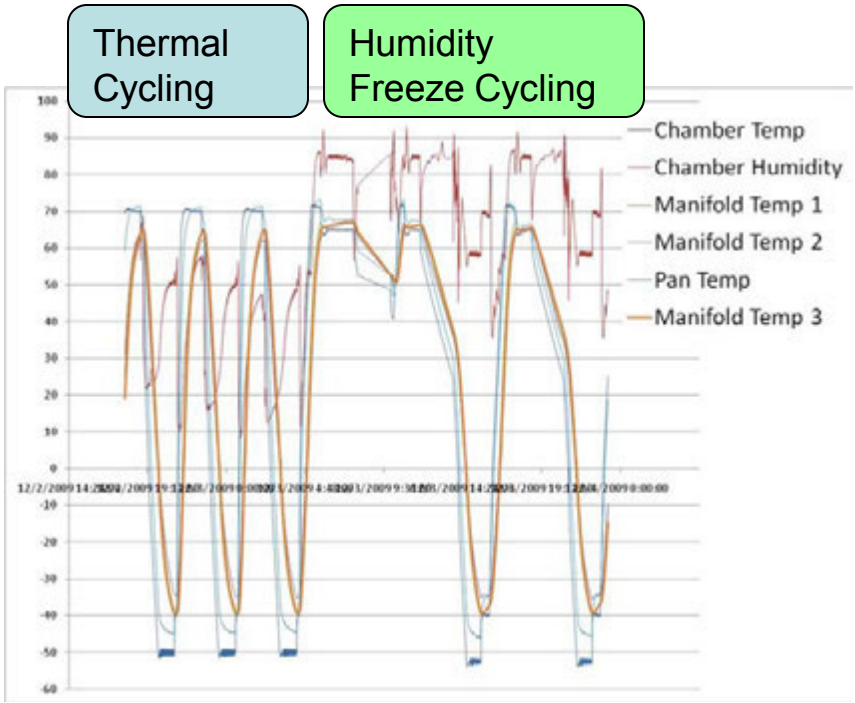


Thermal Cycling

- Description: An accelerated stress test. It cycles receivers in a 110°C to -40°C environment, for a total of 400 cycles. During the hot cycle (>25°C) a forward current (1.25*Isc) is applied off and on through the cells to further heat up the receivers.
- Purpose: To stress the design, and identify failures such as dielectric breakdown, loss of electrical continuity, cracking, delamination, etc.

Sequence B: Humidity Freeze

Humidity Freeze Profile



Humidity Freeze Test

- Description: An accelerated stress test consisting of a series of 400 thermal cycles (65°C to -40°C) followed by forty 24 hour long cycles in a high humidity environment. The Humidity Freeze profile consist of a 20 hour soak in a 65°C and 85% Relative Humidity followed by a 4 hour cycle at -40°C.
- Purpose: To stress the design and identify failures such as corrosion, loss of electrical continuity, shorting, cracking, delamination, etc.

Outdoor Testing

Outdoor Test Setup



Outdoor Testing

- Description: Measure electrical and thermal efficiency in real environment, and test the design against real world conditions per below.
- Purpose: To test the safety and performance of the modules, tests include: Beam Walk Off Test, Off Axis Beam Test, Material Temperature test, Dry Receiver Test, Water Spray, and Ground Path Continuity Test.

Other Test

Hail Test – Passed



Flame Test – Passed



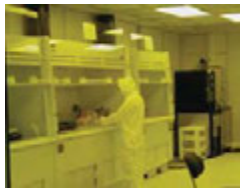
Durability of Thermally Cycled ELO Solar Cells

MicroLink Devices, Inc.

MicroLink Background

- Established in 2000
  - ISO 9001 certified manufacturer
  - Revenue is a mix of commercial and government contracts
  - Profitable, positive cash flow
- Technology leader
  - Core competence is MOCVD growth
  - InGaP HBT structures for wireless communications
  - GaAs and InP-based solar cells
  - Epitaxial liftoff process for solar cell manufacturing



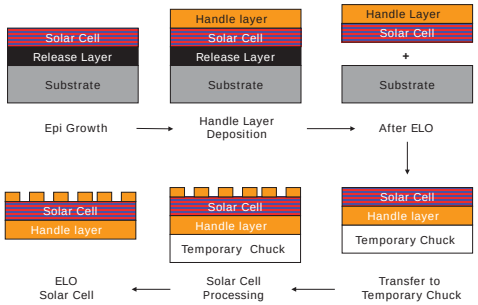


MicroLink Devices MOCVD reactors and solar cell fabrication and processing area.

What are ELO Solar Cells?

- ELO is epitaxial liftoff
- In ELO, the solar cell is completely removed from the GaAs substrate upon which the solar cell is epitaxially grown
- A release layer is grown between the GaAs substrate and the solar cell.
- Selective etches completely remove the solar cell from the substrate
- Proprietary to MicroLink

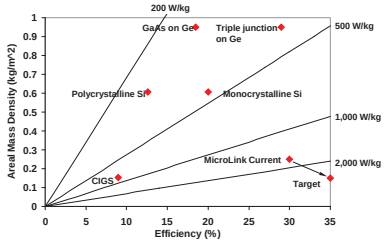
ELO Solar Cell Process Flow



Advantages

- Lightweight and flexible
- Low thermal impedance – reduces device operating temperature
- Works for GaAs, InP and other III-V materials
- Radiation-resistant InP-based cells are possible
- Substrate can be reused -- 3 x reuse demonstrated





Contact Information:
Dr. David McCallum, dmccallum@mldevices.com
MicroLink Devices, Inc., 6457 W. Howard St., Niles, IL 60714

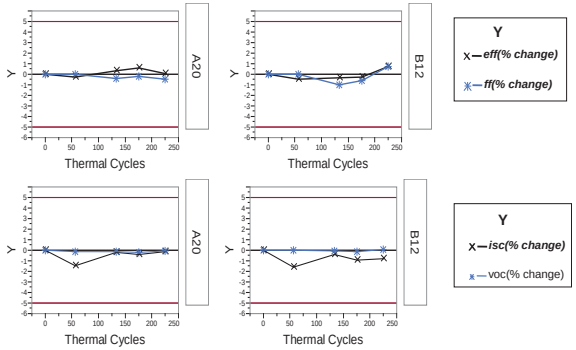
Durability and Reliability

- Manufacturing ELO solar cells requires new processing and handling procedure that may impact durability and reliability
- **Objective:** Differentiate between know solar cell durability issues and those that may be introduced by the ELO process and the extreme flexibility of the ELO solar cells
- Subject unpackaged ELO solar cells to various stresses and compare the durability of the unpackaged cells to those of packaged cells

Thermal Cycling Durability

Unpackaged ELO Solar Cell Advantages

- Cycle –40 °C to 110 °C
- Measure critical-to-quality output parameters at multiple read points
  - Efficiency
  - Fill Factor
  - Open Circuit Voltage
  - Short Circuit Current



Conclusion

- The ELO solar cell technology offers multiple advantages related to its low areal mass density and flexibility.
- A battery of environmental tests are scheduled to determine if the ELO technology introduces durability and reliability issues different from those of other solar cell technologies
- After 225 thermal cycles, -40 C to 110 C, no degradation is observed in key critical-to-quality output parameters.

DfR Solutions

reliability designed, reliability delivered

Ensuring and Predicting the Reliability of Concentrated Photovoltaics (CPV): Interconnect Structures

Jordan Ross
Indium Corporation

Greg Caswell and Craig Hillman
DfR Solutions

March 5, 2010

5110 Roanoke Place, Suite 101 College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

© 2004 - 2009

Reliability Challenges in CPV Interconnects

- Current material selection for CPV interconnects are insufficient
  - Filled epoxy is cheap 'temporary' solution
  - Poor thermal conductivity prevents migration to higher concentration levels, greater efficiencies
    - Inappropriate above 1000 Suns
  - Insufficient reliability to meet 25-year lifetime
- Extensive life requirements, short product development cycle demands 'proof-of-concept' before hardware build
  - Waiting till test to validate reliability requirements is high risk proposition
  - Requires reliability prediction of interconnect structures in the concept and design stages
- New materials by Indium Corporation and new reliability algorithms by DfR Solutions provide direct solutions to these industry-limiting issues

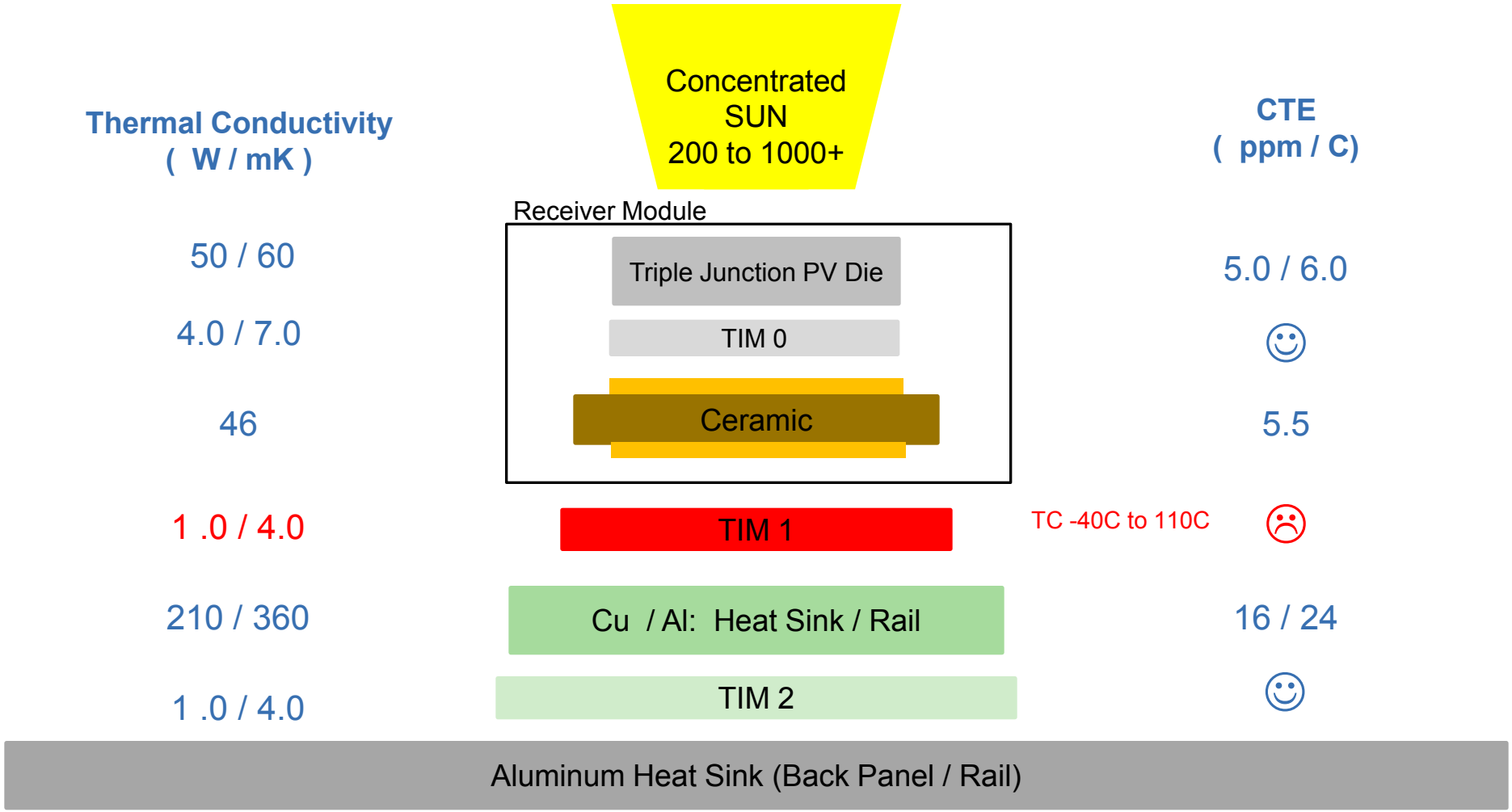
5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com
© 2004 - 2009

Typical CPV Receiver - Material Stack-Up

Material Comments		Design Comments
Fresnel Lens, Cassegrain Mirror Parabolic Mirror	Concentrated SUN 200 to 1000+	200 to 1000+ Suns
	Receiver Module	
III- IV, 10 x 10 x 0.2 mm Metalized Backside	Triple Junction PV Die	Tj,max <100C to Meet 25 Year Life and Efficiency
E / T Conductive Die Attach Epoxy	TIM 0	Better Thermal Conductivity Can Improve Efficiency
24x24 x0.38mm: Alumina, BEO, ALN Cu Ni Au Both Sides	Ceramic	Good CTE Match to Die OK Thermal Conductivity Electrical Insulator – High Pot Test
Non Conductive Adhesive	TIM 1	Absorb CTE Mismatch Al2O3 / Cu or Al
Heat Spreader	Cu / Al: Heat Sink / Rail	Good Thermal Conductor
Non Conductive Adhesive	TIM 2	Thermal Path to Baseplate
	Aluminum Heat Sink (Back Panel / Rail)	

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com
© 2004 - 2009

Typical CPV Receiver - Thermal View



5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

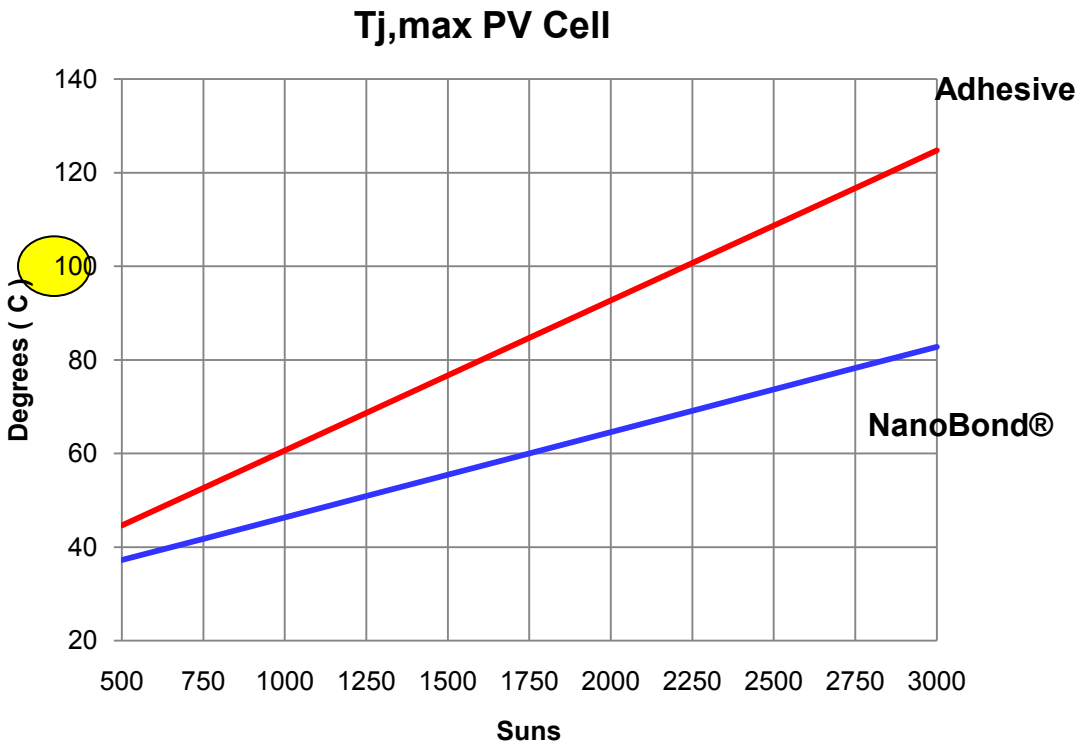
© 2004 - 2009

CPV Cell Performance NanoBond vs. Adhesive

1 Sun = 85 mW/mm2 x 500 = 425 mW/mm2
Die Surface Area = 100mm2
Power Incident Die Surface = 42.5W
Conversion Efficiency = 35%
Pdc = 14.9 W
Pdiss = 27.6 W – Thermal Management

Tj,max
Conversion Efficiency ~ 0.5% / 10° C
Maintain < 100°C to Meet 25 Year Life Time

Sun Concentration Levels
Typically ~ 500 X (Suns)
CPV Roadmaps – X will Continue to Increase



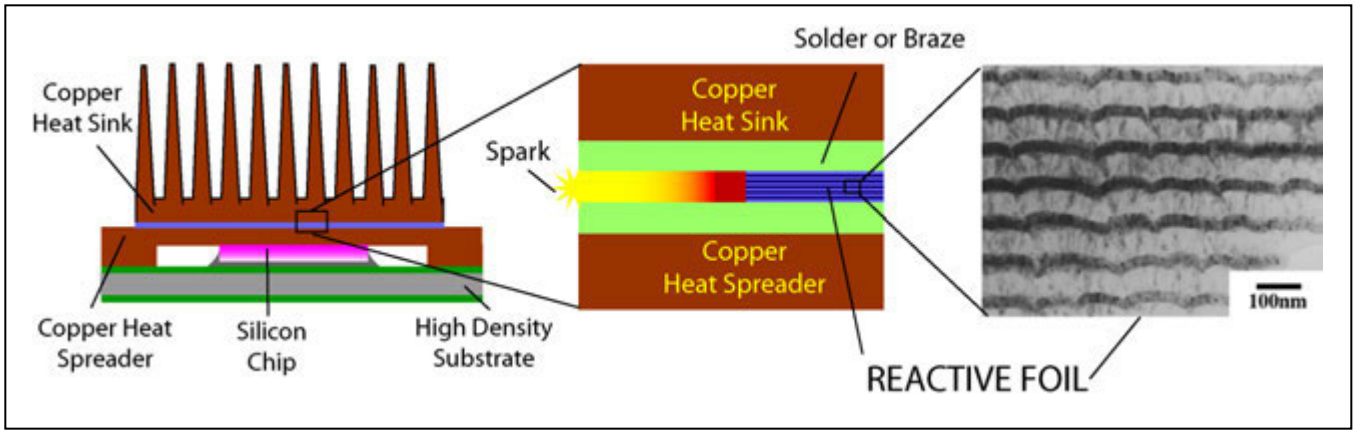
Delta Tj,max Increase vs. Suns
•Lower Tj,max - Increase Lifetime
•Or More Sun Headroom

DNI 850 W/m2
Efficiency 35%
Base Plate Held 28C

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com
© 2004 - 2009

NanoBond® Soldering Approach

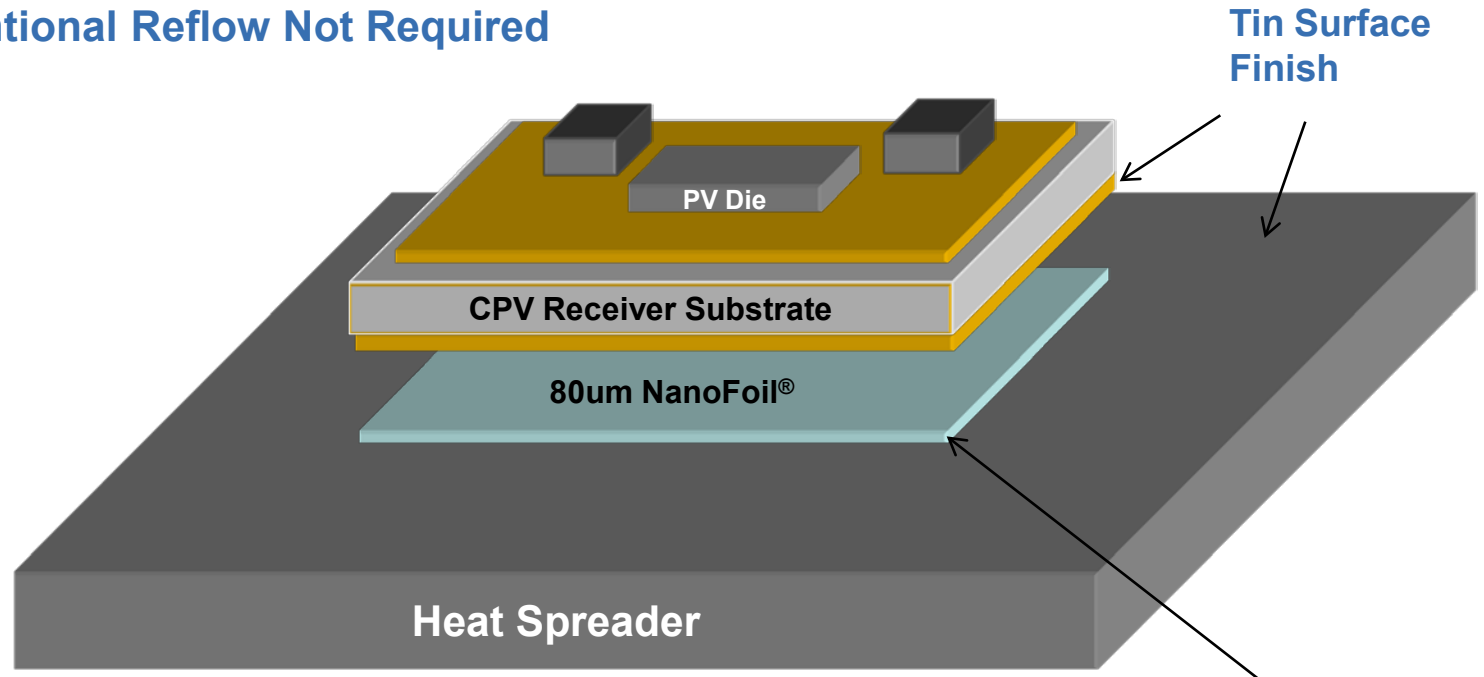
- A foil with thousands of nanoscale layers of aluminum and nickel.
- Heat generated by intermixing of aluminum and nickel layers.
- Foil acts as a controllable, rapid, local heat source.
- Heat of mixing melts the adjoining solder layers.
- Melted layers lead to formation of metallic bond



5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com
© 2004 - 2009

NanoBond® Configuration for CPV Receiver Modules

Tin Surface Finish
- Bottom of CPV Module
- Top of Heat Spreader
- **Conventional Reflow Not Required**



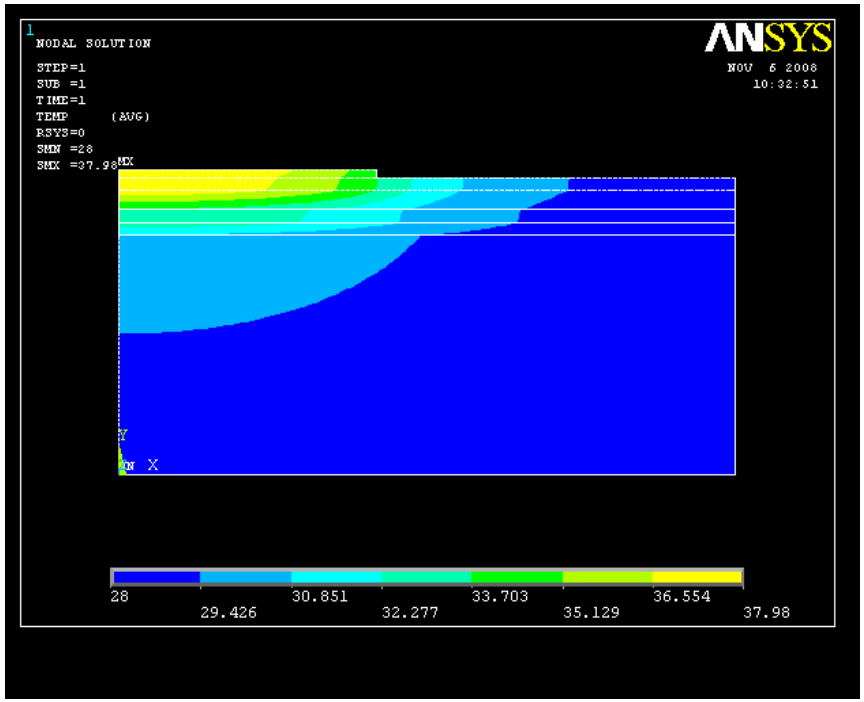
Cu vs. Al Heat Spreader
- Cu is Better TCE Match to Receiver Module
- Also Better Thermal Conductor

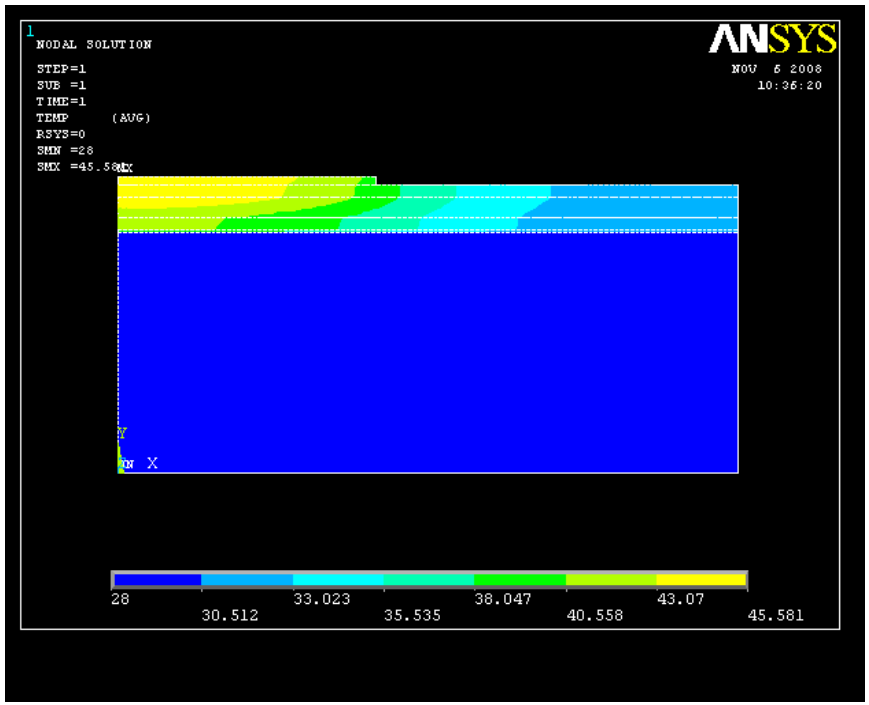
NanoFoil® Replaces TIM1 Adhesive
- Lower Tjmax
- Increased Efficiency
- Improved Lifetime

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

© 2004 - 2009

Solder vs. Adhesive Thermal FEA Model – 30W Heat Flow





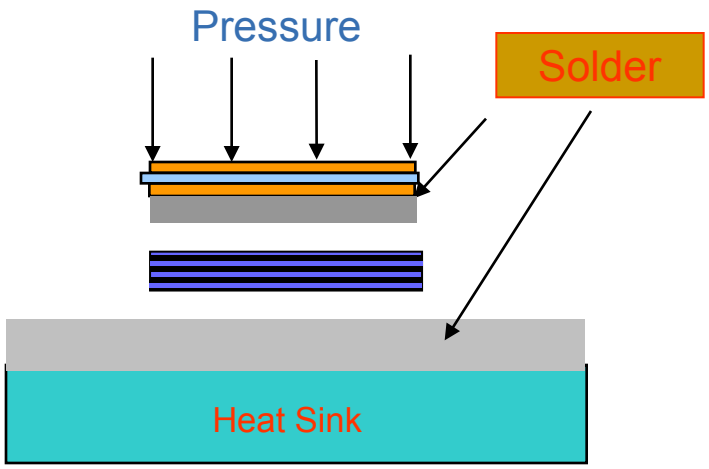
- T_{jmax}= 38C
- BLT=250um
- K=25 W/Km

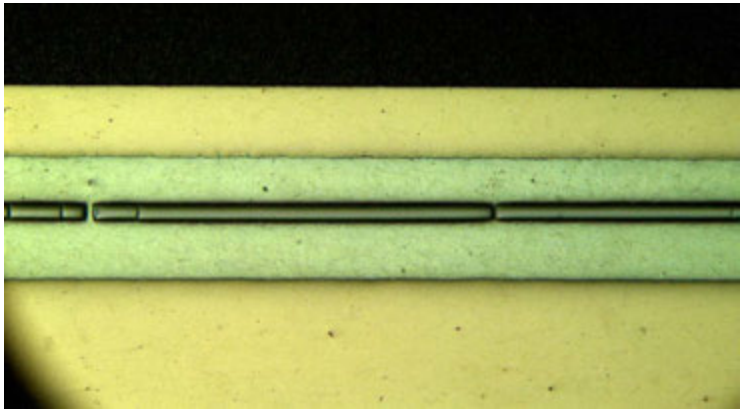
- T_{jmax}= 46C
- BLT=50um
- K=1W/Km

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

© 2004 - 2009

NanoBond®
Solder Solution





Post 1000 Cycles

NanoBond® Solder Bond

- Cu Heat Sink and Receiver Module
- >1000 cycles completed, no degradation
- -25 to +125C (8.5C per minute ramp)

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com

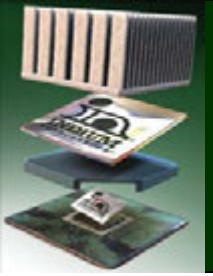
© 2004 - 2009

Laser Flash Analysis

Bonding Method	Bondline Thickness (µm)	Original Bond		After 540 cycles		After 940 cycles	
		*Thermal Cond. (W/Km)	***Thermal Resist. (Kmm2/W)**	*Thermal Cond. (W/Km)	***Thermal Resist. (Kmm2/W)**	*Thermal Cond. (W/Km)	***Thermal Resist. (Kmm2/W)**
NanoBond Screen printed DBC	447	42.2	**10.6**	42.3	**10.6**	41.0	**10.9**
NanoBond Spray coated DBC	467	30.7	**15.2**	32.4	**14.4**	32.0	**14.6**
Epoxy1 (3M)	50	0.85	**58.96**	0.81	**61.9**	0.76	**65.86**
Epoxy 2 (Epo-Tek)	50	2.83	**17.6**	Bonds started falling apart at 400 cycles	**-**	--	**-**

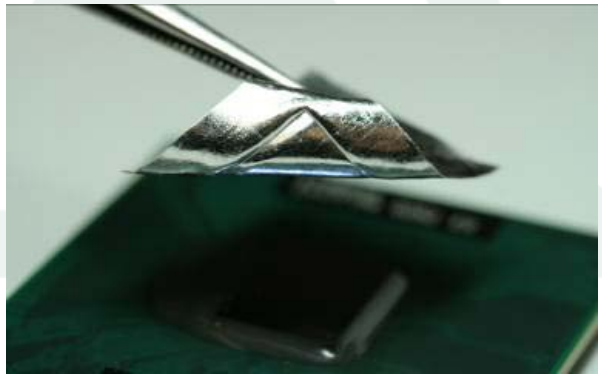
- Bond size 24 mm x 24 mm
- DBC material properties have been corrected using laser flash
- Copper thickness 1.6 mm

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com
© 2004 - 2009



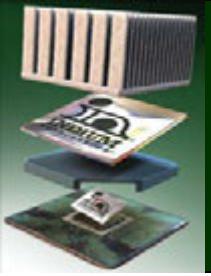
Heat-Spring®: What is it?

- **Material Description**
  - Made from Indium or Indium Tin as standard alloys
  - Custom Alloys available
  - We alter the surface so contact resistance is reduced
  - We use high conductive metal 86w/mk
  - We custom package for your application
  - We standard pack in Tape and Reel
  - We can recycle it and reclaim it
  - We can offer you a credit on un-used material
  - It's a "green" TIM



Information Property of Indium Corp.

INDIUM CORPORATION®



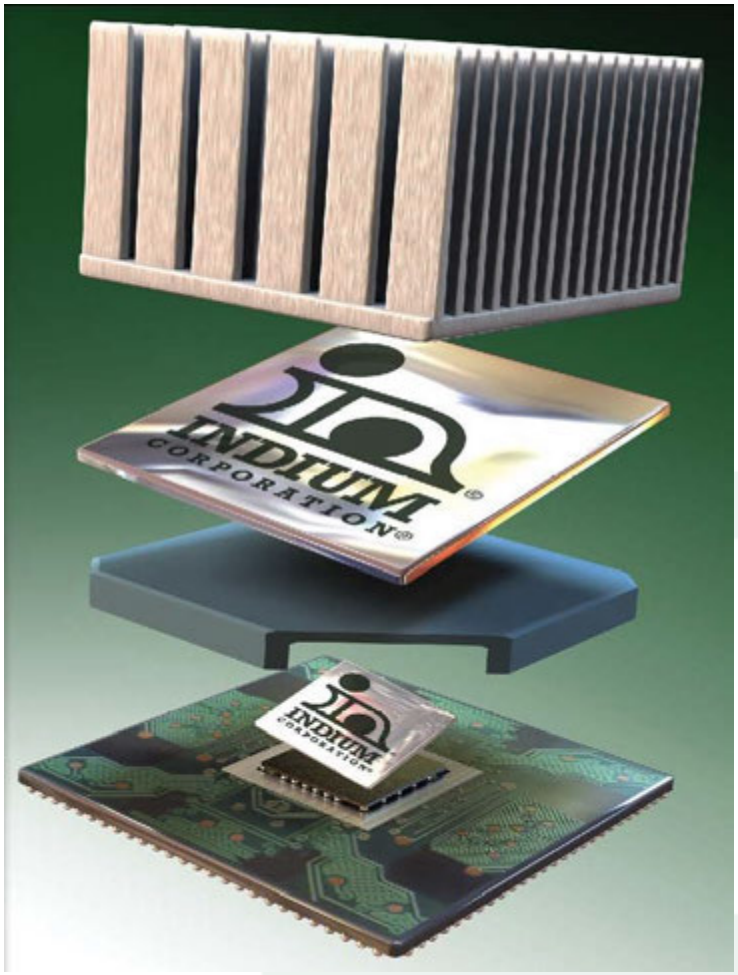
Soft Metal TIM Attributes

- **High thermal conductivity 86W/mK**
  - Low bulk resistance—insensitive to BLT
  - Heat spreading
- **Conformability**
  - Plastic deformation provides low contact resistance path, especially after time zero (burn-in period)
  - Inherent gap filling for co-planarity issues:
  - HSD: +/- .003”
  - HSG: +/- .010”
  - Complies with CTE mismatch
- **Stability/ Advantages**
  - No out-gassing
  - No bake-out or pump-out
  - Easy to handle
  - Reclaimable/ recyclable
- **Thickness**
  - HSD pattern, minimum thickness before Patented Heat-Spring Process is 75um, after the HSD process thickness will increase 75um.
  - HSG pattern, minimum thickness before Patented Heat-Spring process is 150um, after HSG is 300um
  - HSG pattern can be applied to a 250um preform and after HSG process will be 500um thick.
  - Max Thickness is well over .25 inches if necessary.

Information Property of Indium Corp.

INDIUM CORPORATION

Stack-up Pictorial



TIM1: Indium Solder Preforms, or conceptual Liquid Metal.

TIM1.5: Heat-Spring®, Liquid Metal

TIM2: Heat-Spring®, Liquid Metal

Burn-in and Test: Heat-Spring® and Aluminum Indium Clad preforms.

Information Property of Indium Corp.

Interconnect Reliability Prediction

Overview

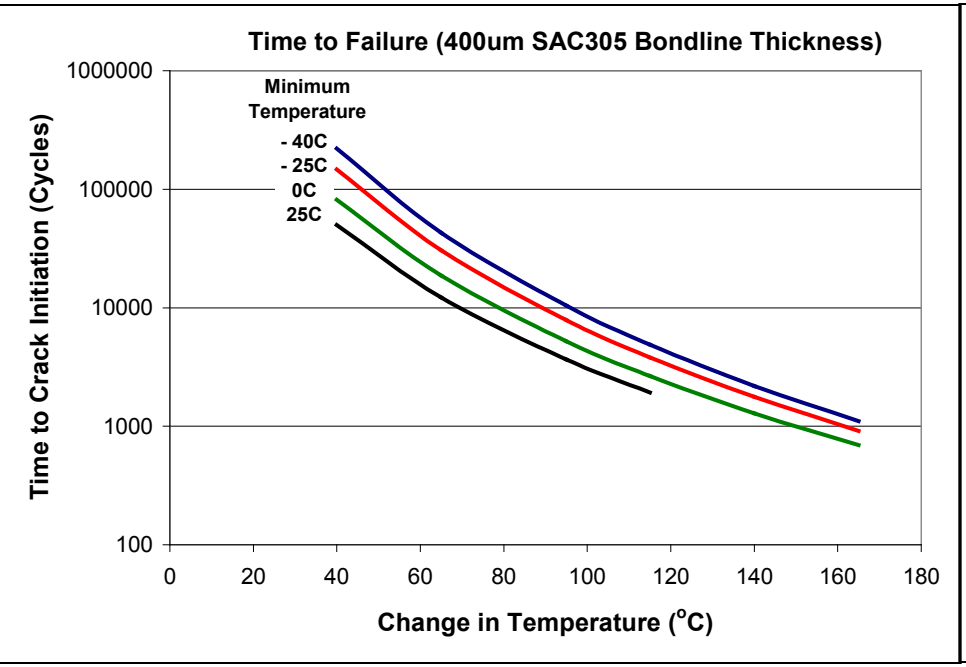
- DfR has extensive experience in developing material degradation algorithms for electronics applications
- These models have been adapted to assess cycles to failure for Concentrated Photovoltaic (CPV) modules
- Typical CPV architecture
  - 25 mm square CPV receiver
  - DBC on alumina
  - Heatsinks are copper and aluminum
  - Solder is SAC305

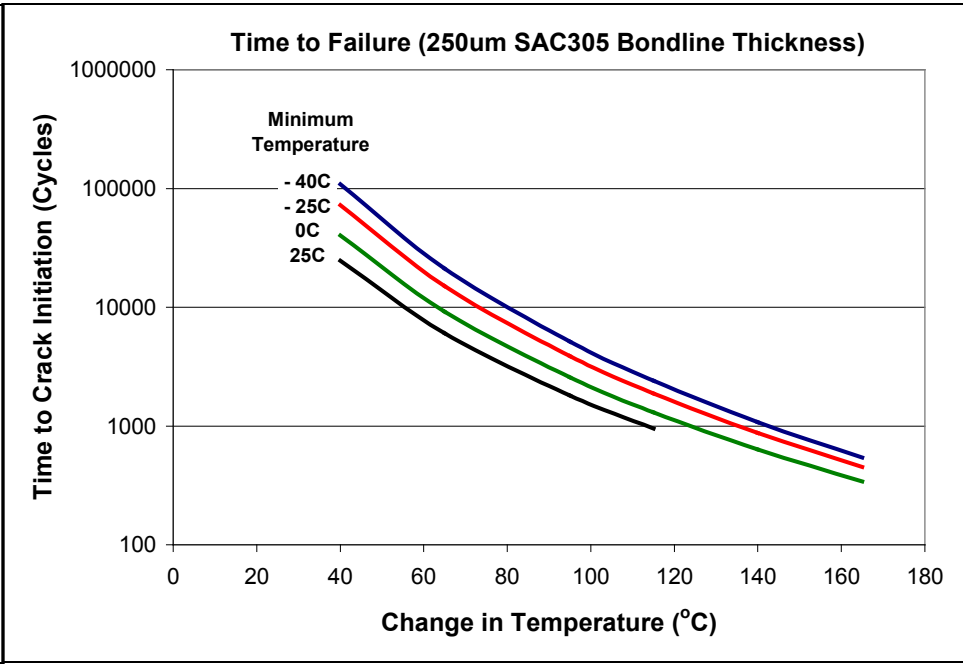
Model Inputs

- Environment
  - Max temperature
  - Min temperature
  - Dwell times
- Direct Bond Copper (DBC) Architecture
  - Thicknesses
- Interconnect Material
  - Composition (SAC305, etc.)
  - Material Properties
- Heatsink Material
  - Composition (Cu, Al, etc.)
  - Material Properties

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com
© 2004 - 2009

Reliability Prediction: Results





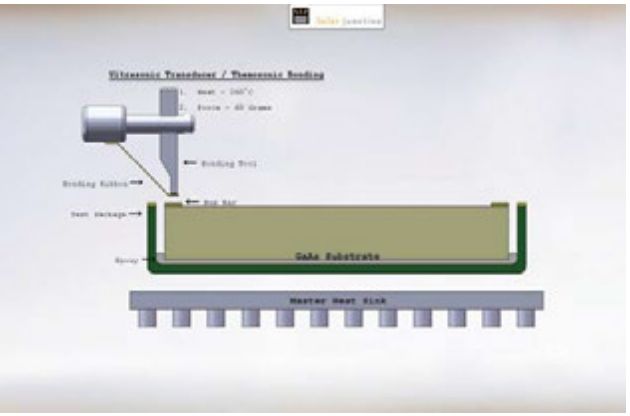
- Clearly demonstrates influence of minimum temperature (mountain vs. desert), change in temperature, and bondline thickness
- Allows for tradeoff analysis and rapid assessment of existing interconnect materials and architecture

5110 Roanoke Place, Suite 101, College Park, Maryland 20740
Phone (301) 474-0607 Fax (240) 757-0053
www.DfRSolutions.com
© 2004 - 2009

Summary

- DfR and Indium provide a turn-key solution for the reliability assurance of CPV modules
- New materials and technology for radical improvement in interconnect robustness
  - Commercially available NanoBonding and Heat Spring
- Interconnect reliability algorithm adapted to assess cycles to failure for Concentrated Photovoltaic (CPV) modules

© 2004 - 2009



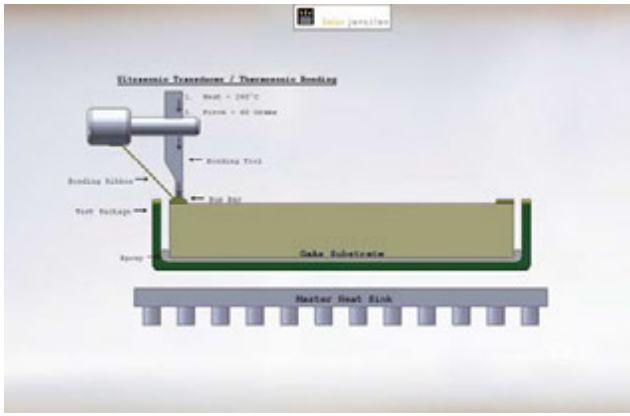
Solar Junction

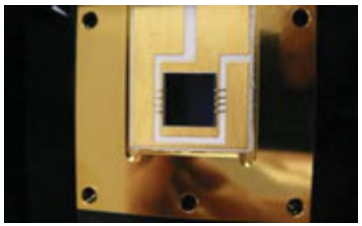
Mechanically Induced Microfractures

It is critical when doing high volume interconnects to Semiconductors that the process be defined, controlled, repeatable, scalable and most importantly RELIABLE!

One method to define the upper and lower limits of the bond cycle is to monitor the critical parameters: Force, Temperature, Ultrasonic energy. Changing one variable at a time and doing large sampling sizes evaluate the impact of each change by doing ribbon bond pulls, visual inspections, thermal resistance measurements, temperature cycling, snap on/ snap off tests and under-bias testing.

By doing failure analysis and corrective action it is possible to arrive at optimum parameters for your bond cycle that supports high volume throughput an assures a good and reasonable level of reliability.





Solar Junction

Latent failures / Reliability issues

Failure even temp due to bond separation

Failure after snap on / snap off

Low or poor pull test

Under bonded

10 Grams

Good bond

Optimum bond parameters

Little if no microfractures

100 Grams

Overbonded

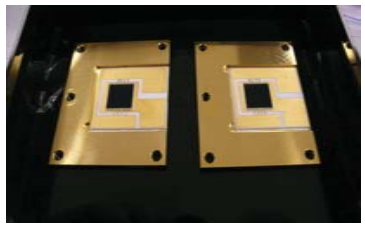
Microfractures

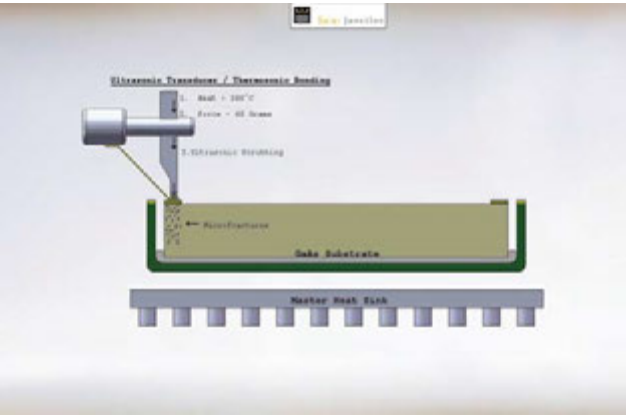
Localized heating

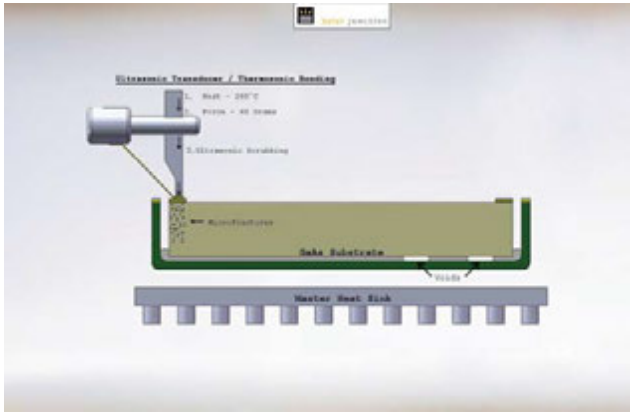
Catastrophic failures

Latent failures / Reliability issues

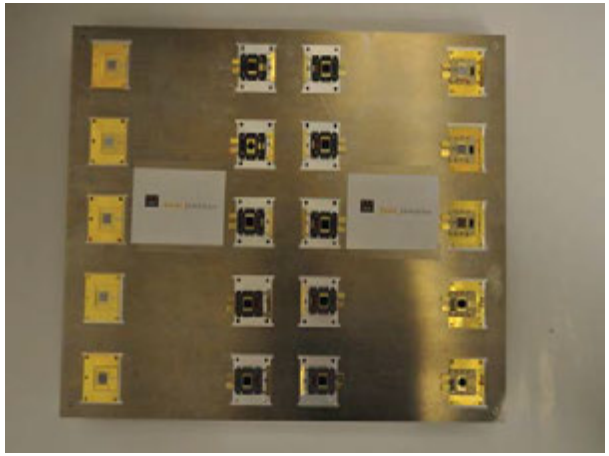
- After completion of optimization implement "Process Signature Technology"

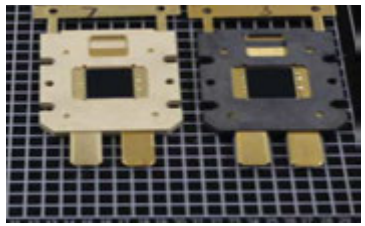












coolearth



reshaping solar energy

NREL

PV Reliability Workshop

February 18, 2010

Leo Baldwin

Problem Statement:

World annual energy consumption (2008):
474 exajoules (10^{18})(i.e.:15 terawatts (10^{12}) x 1 year)

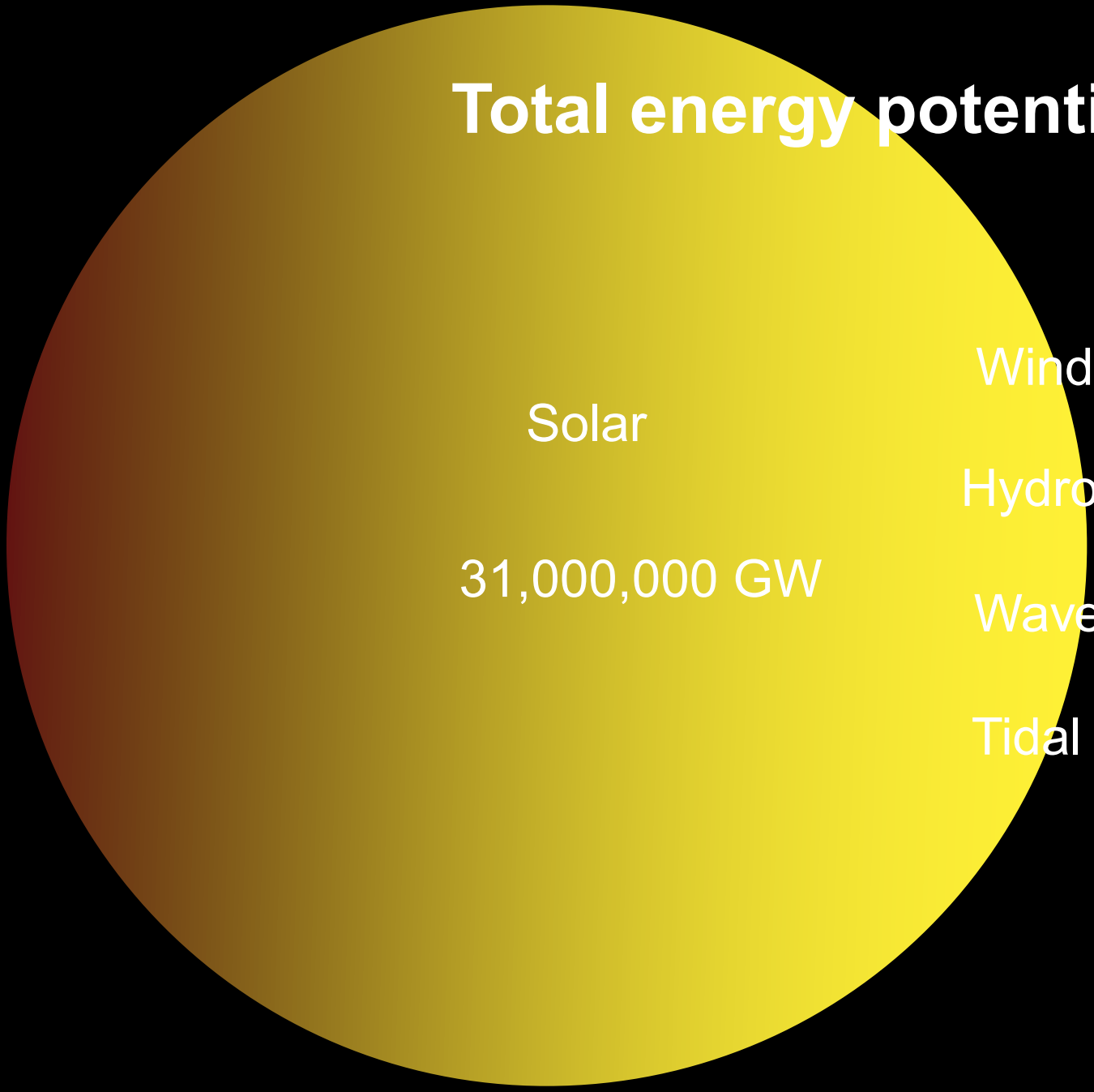
U.S. annual power consumption (2008):
105 exajoules (3.3 TW x 1 year)

>90% from fossil fuels

Projected world annual power consumption by 2030:
1 zettajoule (10^{21} joules)
1,000,000,000,000,000,000,000 JOULES

Replace carbon based energy with clean renewable energy

Total energy potential



Wind	72,000 GW
Hydro	6,000 GW
Wave	5,000 GW
Tidal	4,000 GW

Information courtesy of Dr. Mark Jacobson, Stanford University

Area needed to meet US 2030 demand:

coolearth

The Problem

What material is abundant enough to cover the surface area needed to supply all U.S. electricity?



Materials solution: Plastic



- Massively abundant - scales to 100%
- Inexpensive
- Easy to handle and ship

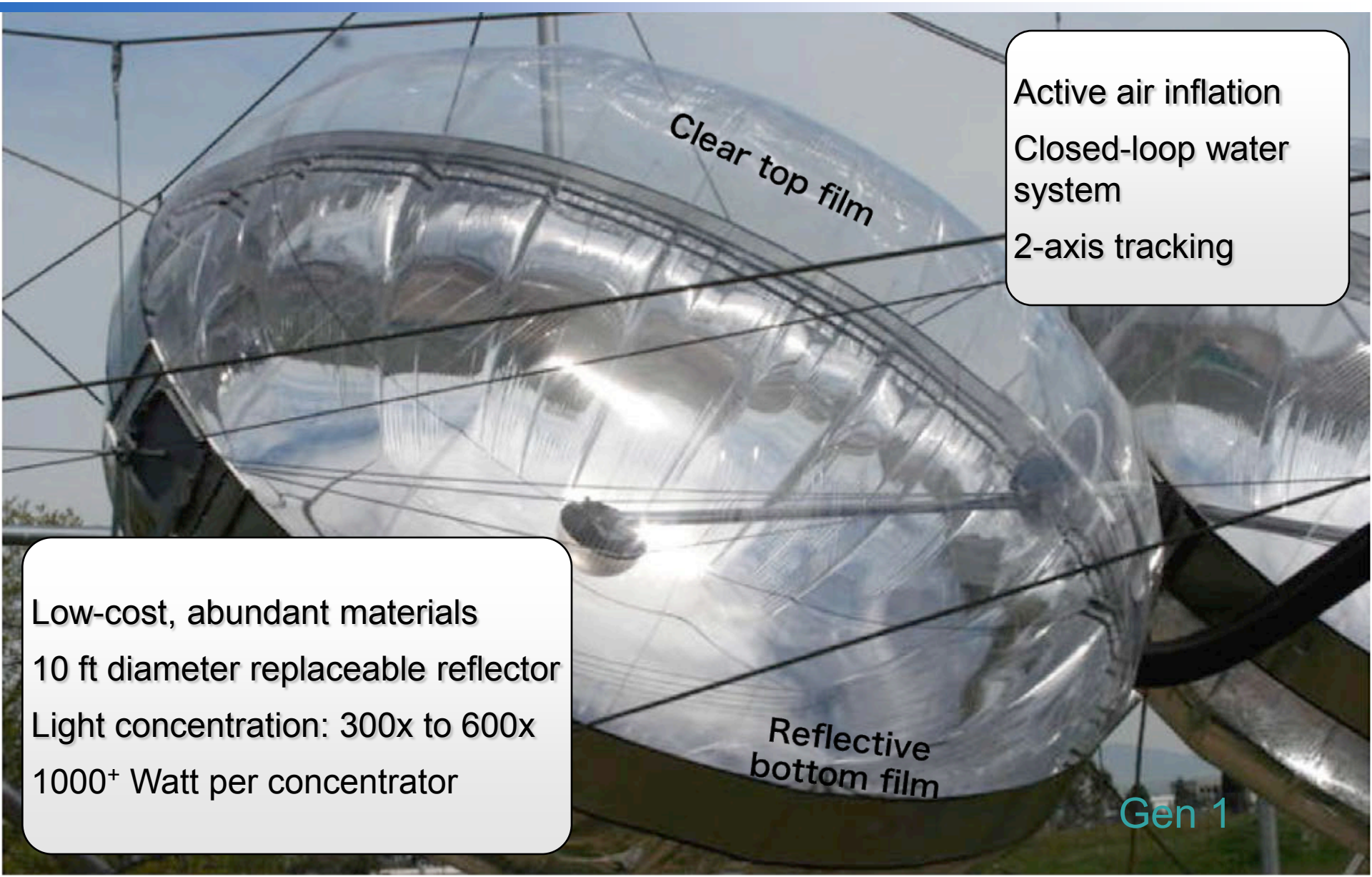
Scalable

Enough film produced globally each year to roll out to the Moon and back 28 times



We lower costs and get to scale by minimizing materials

coolearth



Active air inflation

Closed-loop water system

2-axis tracking

Low-cost, abundant materials

10 ft diameter replaceable reflector

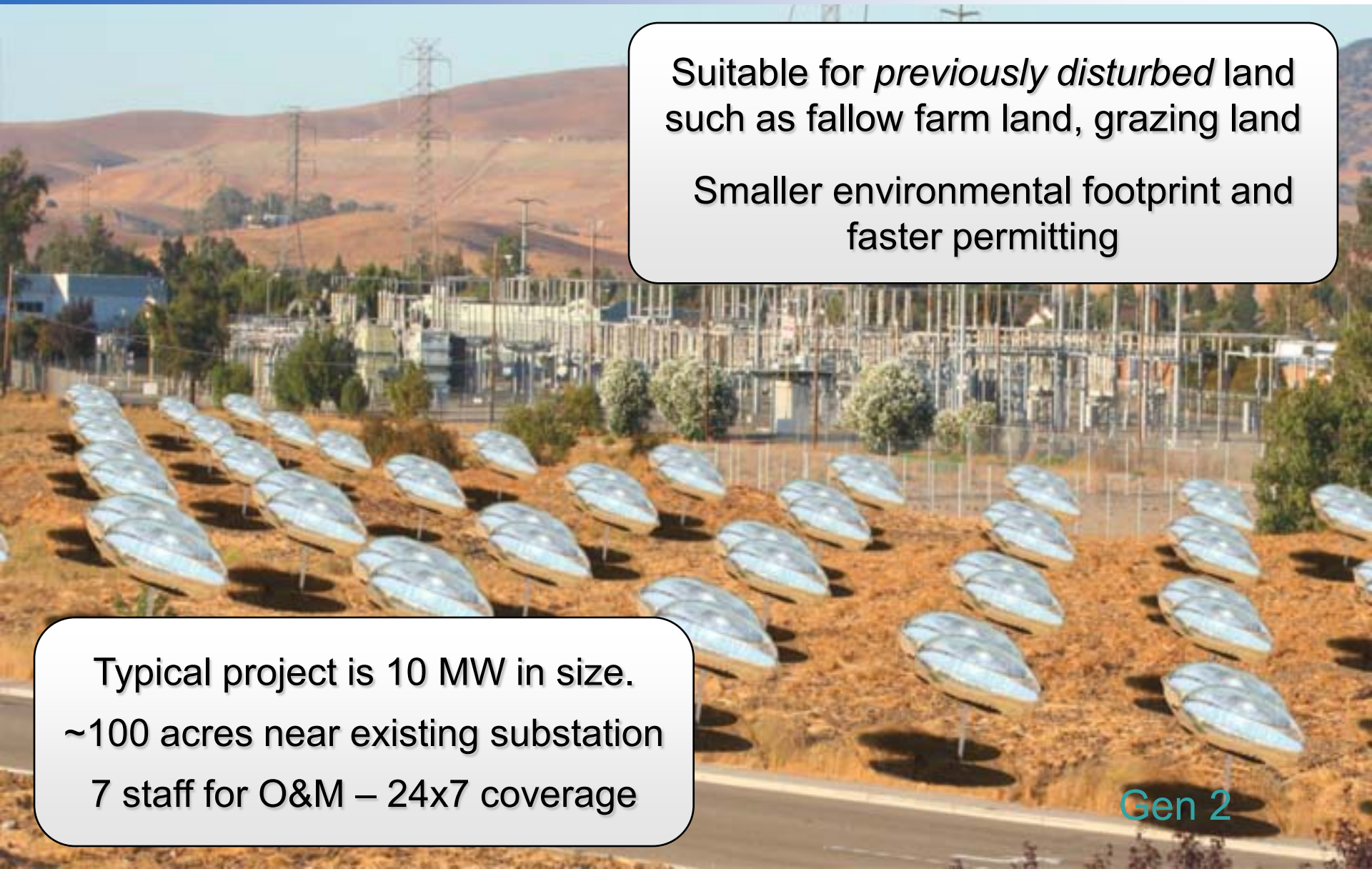
Light concentration: 300x to 600x

1000+ Watt per concentrator

Gen 1

We will own and manage our own solar power plants

coolearth



Suitable for *previously disturbed* land such as fallow farm land, grazing land

Smaller environmental footprint and faster permitting

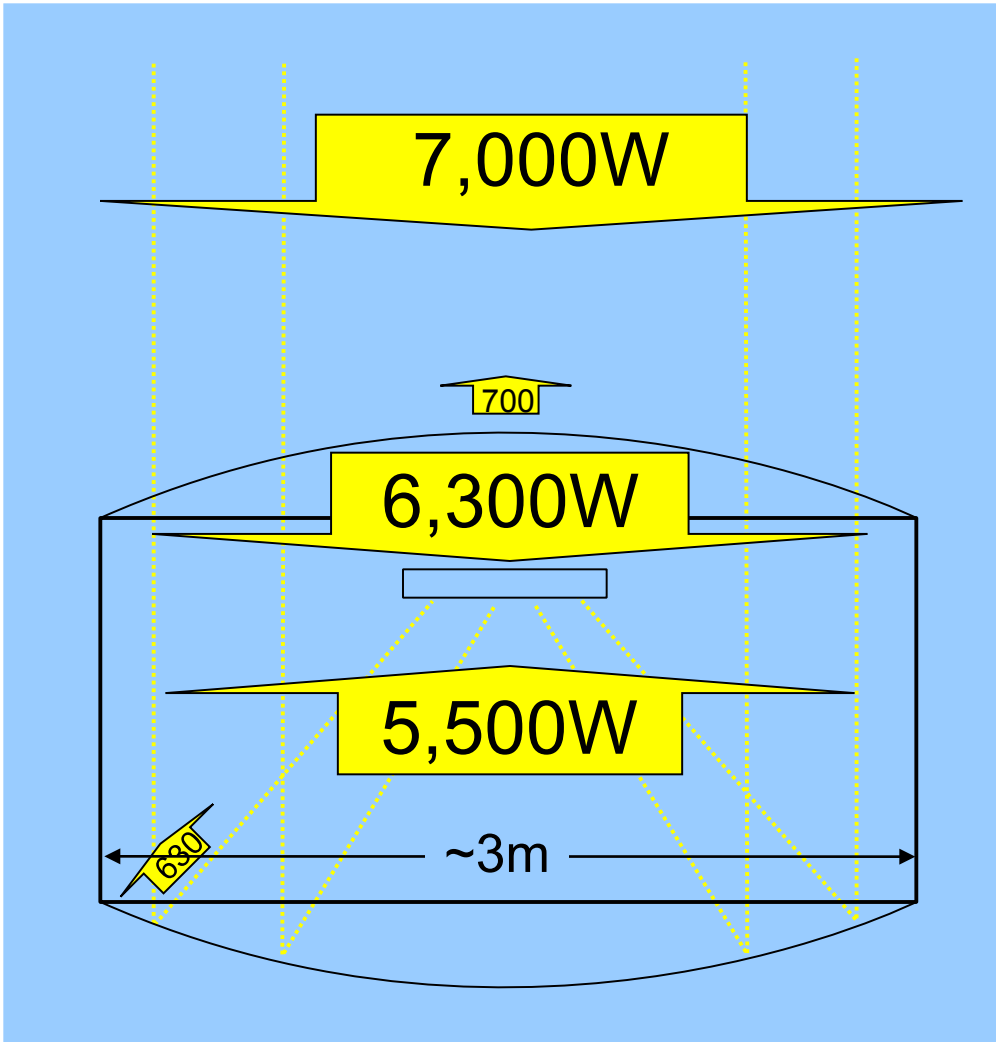
Typical project is 10 MW in size.

~100 acres near existing substation

7 staff for O&M – 24x7 coverage

Gen 2

Technology Summary



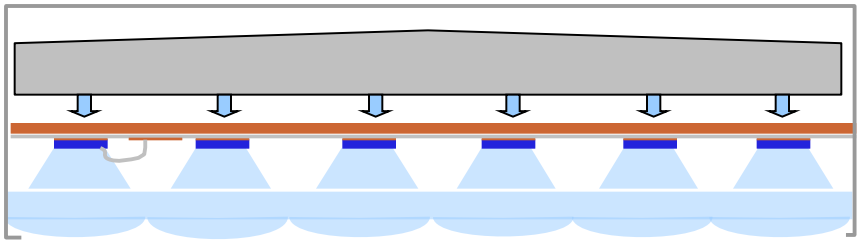
1,000 W/m^2
x 7 m^2

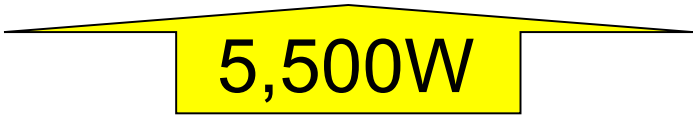
Fresnel and adsorption losses: front film (clear)

Scatter & adsorption losses: rear film (Al coated)

Technology Summary

Monolithic water-cooled receiver module



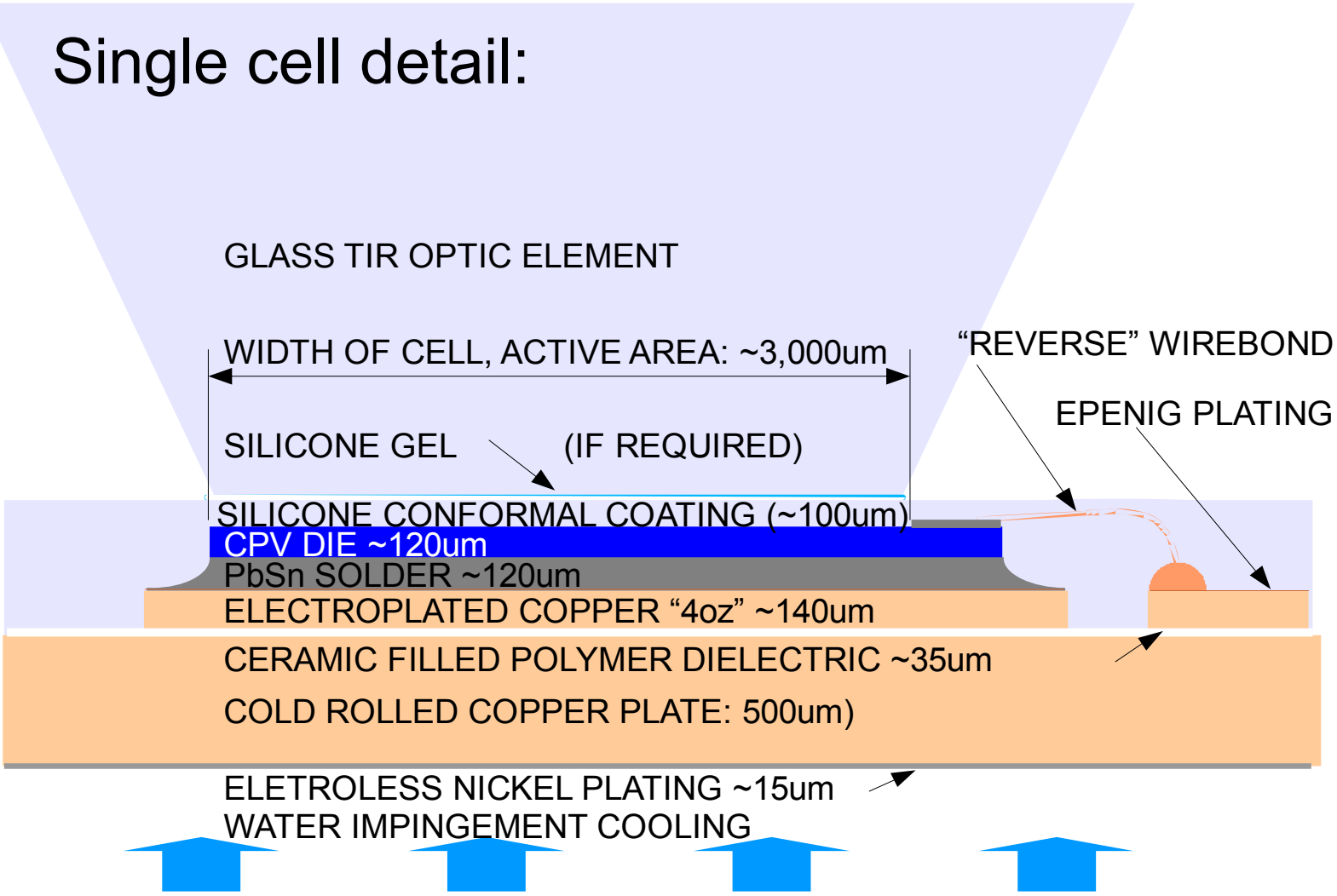


Average irradiance on receiver: 68kW/m^2

Average irradiance per cell: 350kW/m^2

Technology Summary

Single cell detail:



Technology Challenges

Front film degradation in UV:
~1.5 suns max (direct + backscattered)
Incorporate commercial UV inhibitors
Transmit <10% of UV
Require ~12 month lifetime
Well understood problem with commercial solutions

Rear film degradation:
~1 sun visible & ~0.1 sun UV
Protected by >99% opaque aluminum
Require ~12 month lifetime

Technology Challenges

coolearth

Secondary optic degradation:
~100 suns IR & visible
~10 suns UV exposure
Dry and clean environment (inside balloon)
Requires 25 year lifetime.
Some solarization may occur
    (greater attenuation of UVA)
Low risk item

Technology Challenges

coolearth

Silicone based optical coupling agents:
Up to 500 suns visible exposure
Up to 50 suns UVA exposure
UVB and UVC attenuated by glass
Requires 25 year lifetime:
- Clarity
- Resilience
- Glass optical contact

Data exists for PV, less for CPV
Must accommodate CTE mismatch between glass lens array and CPV cell array
High risk item

Technology Challenges

Die attachment to substrate:
Silver-filled epoxy or soft (PbSn) solder
Prefer soft solder
Must isolate CPV die from strain due to CTE mismatch between die and substrate
Must maintain electrical and thermal contact.
Requires 25 year lifetime
High risk item
Some helpful background in both aerospace and automotive industries


Thank you
lbaldwin@coolearthsolar.com
coolearth
reshaping solar energy
www.coolearthsolar.com

Reliability Through Field Testing in Real World Conditions

AMONIX
Powering Our Future™

Neither Wind…



NVEnergy

…Nor Ice…



APS

…Nor Rainstorm…



PG&E Corporation

…Nor Earthquake…



Southern California Edison
An EDISON INTERNATIONAL Company

…Nor Lightning…



AEP TEXAS
A unit of American Electric Power



Soliant

Energizing commercial rooftops

Spectral dependence of CPV current generation in the San Gabriel Valley

Neil Fromer, Soliant Energy

2/18/2010

Outline

- Measured and Modeled Solar Spectra in Monrovia
  - Is there a way to directly correct for spectrum in a power measurement
- Transmission of the Optical Path
- Measurements of Isotype CPV units and comparison with full TJ current production

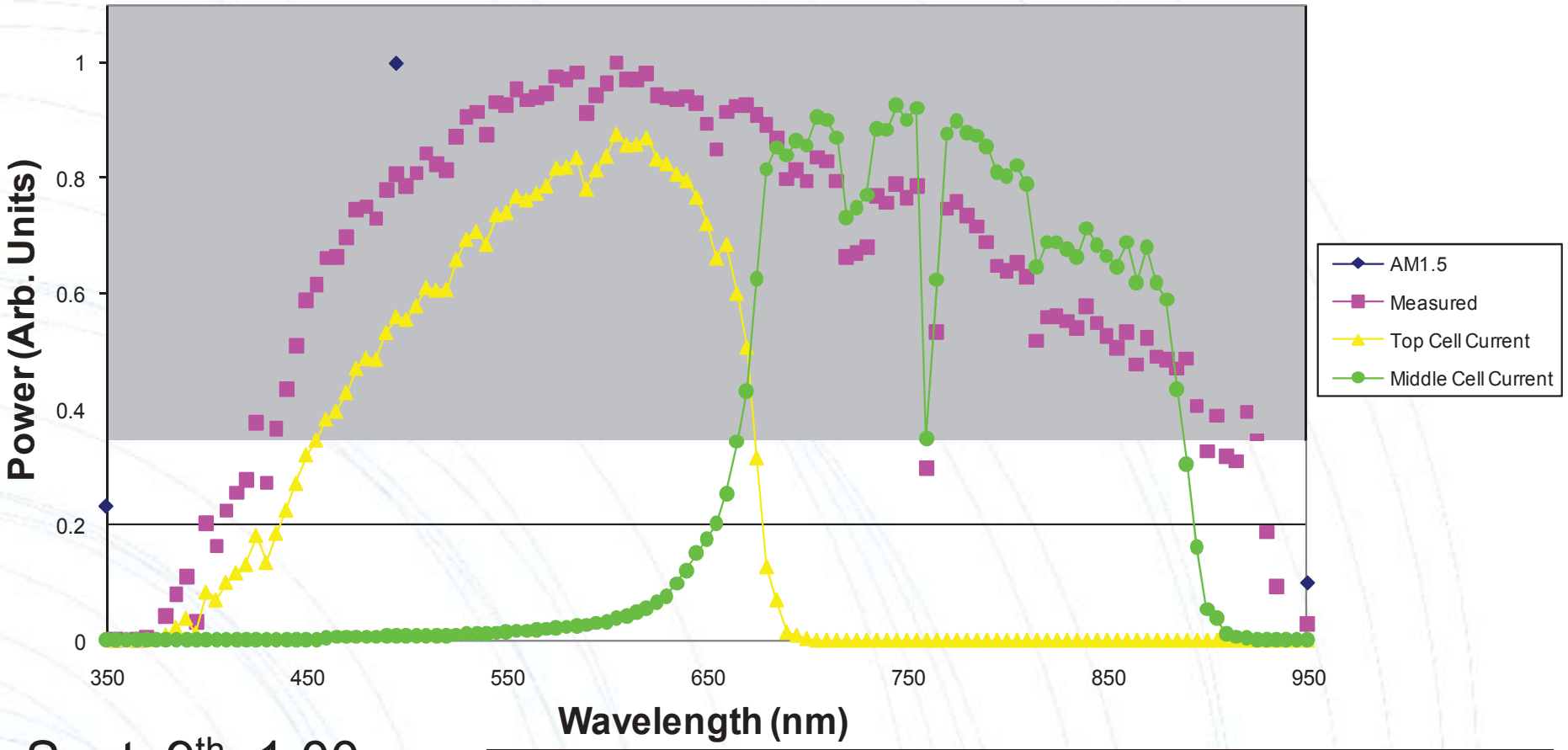
Soliant
Energizing commercial rooftops

Direct Spectrum Measurements

- Performed using Ocean optics fiber-coupled USB spectrometer
- Spectrometer outfitted for 350-1000nm operation
- Fiber input is calibrated using spectrally calibrated light source, ‘collimated’ using baffles
- Calibrated output can be directly compared to AM1.5D spectrum, integrated with QE to give expected current generation of top/middle junctions
- Generate a correction factor to estimate spectral effects on current generation

Soliant
Energizing commercial rooftops

Measured Solar Spectrum

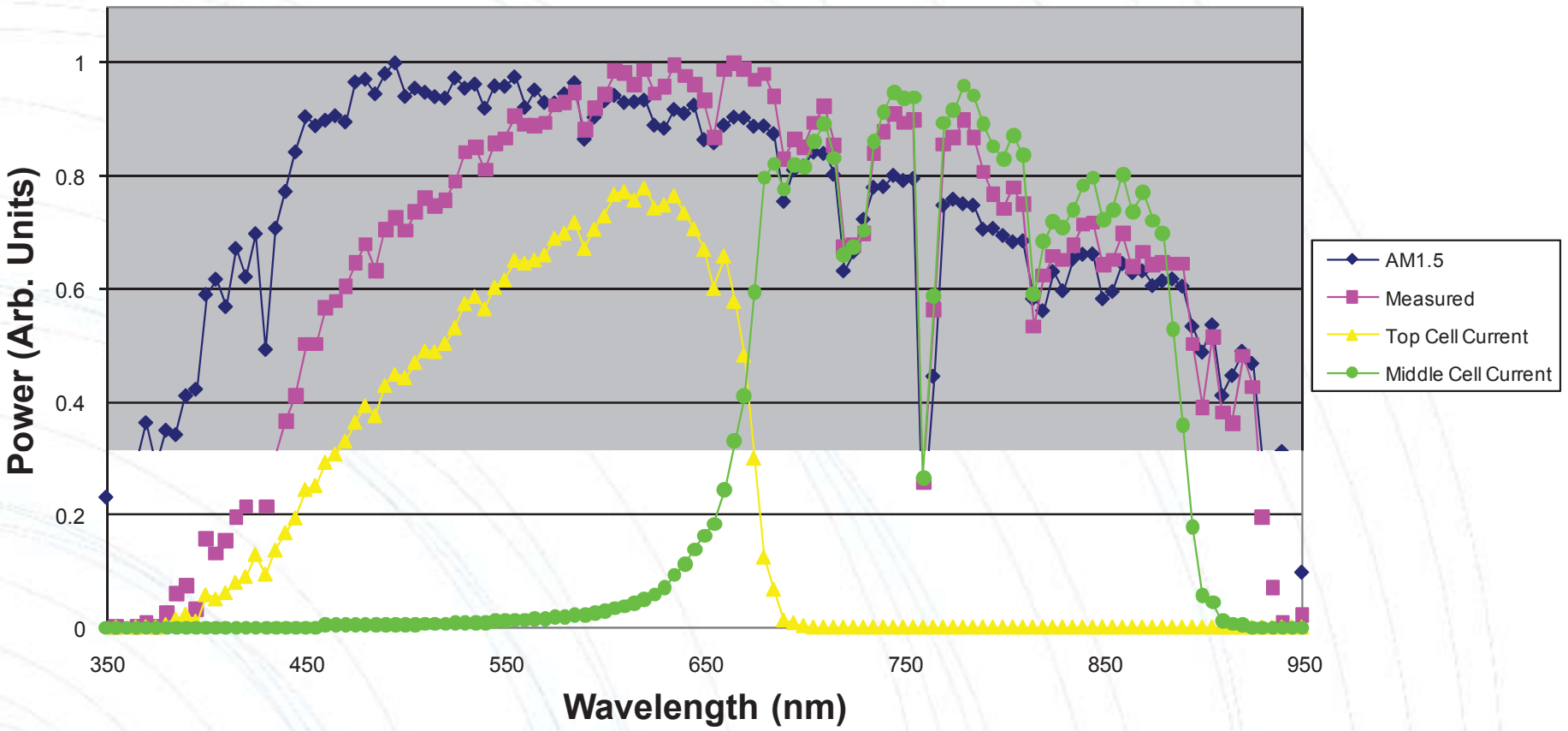


Sept. 9th, 1:00 pm

Direct				Through Optics			
	Top	Middle	Ratio		Top	Middle	Ratio
AM1.5	6.110183	6.326033	0.982643	AM1.5	5.4470991	5.684606	0.978663878
Measured	9.770425	10.81377	0.949313	Measured	8.8365355	9.721431	0.952317219
				Output Correction Factor			**1.03**

Soliant
Energizing commercial rooftops

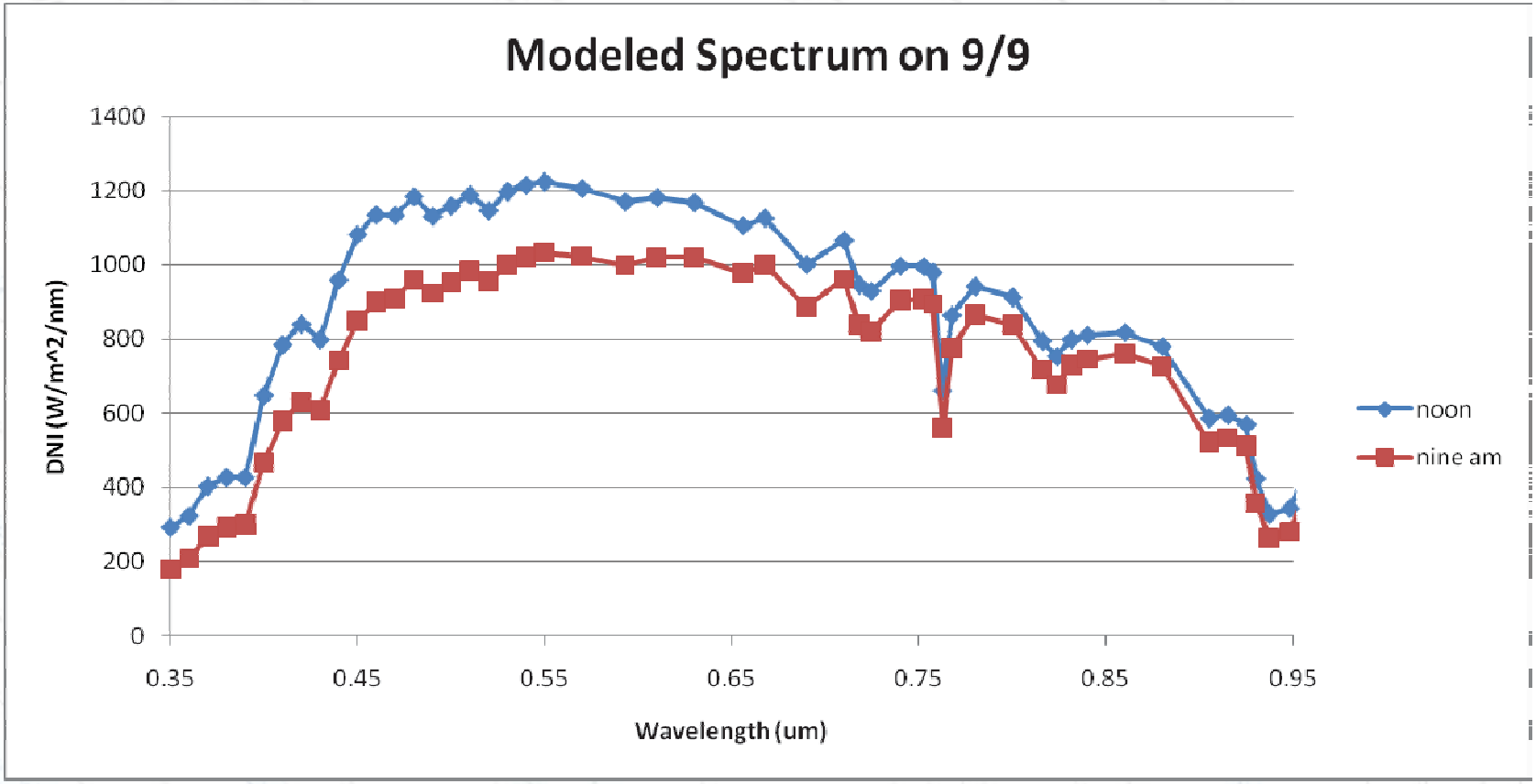
Measured Solar Spectrum



Sept. 9th, 9:30 am

Direct				Through Optics			
	Top	Middle	Ratio		Top	Middle	Ratio
AM1.5	6.110183	6.326033	0.982643	AM1.5	5.4470991	5.684606	0.978663878
Measured	5.536455	7.361426	0.858506	Measured	5.0085128	6.61561	0.861744643
				Output Correction Factor			**1.14**

Soliant
Energizing commercial rooftops



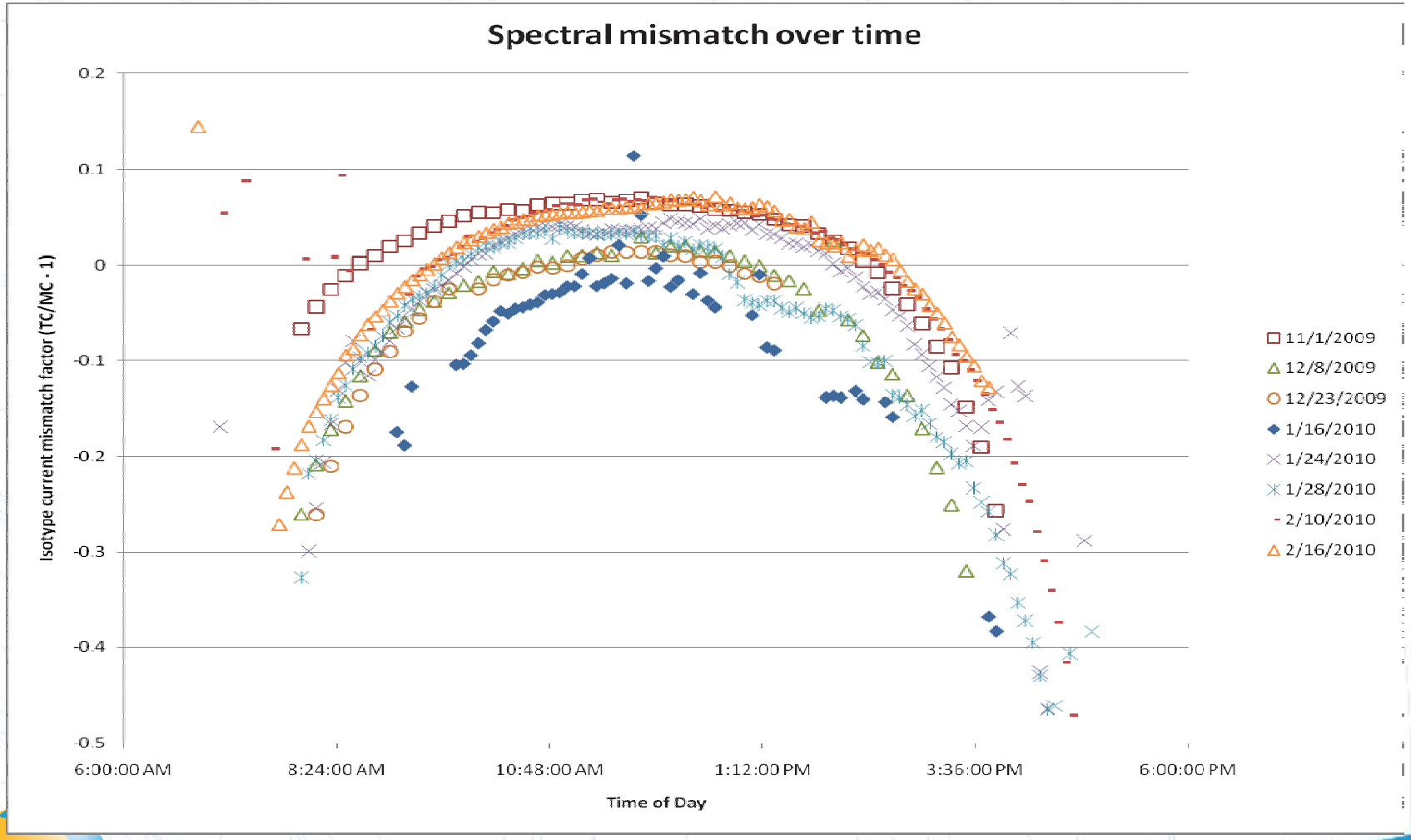
Soliant
Energizing commercial rooftops

Issues with Direct Spectrum Measurements

- Difficulty in calibrating
- Processing the spectral data was somewhat time consuming as a result
- Correction factors were not always well correlated with on sun measurements (see point 1)
- This technique was left, in favor of measurement of isotype cell current generation under Soliant Energy optics

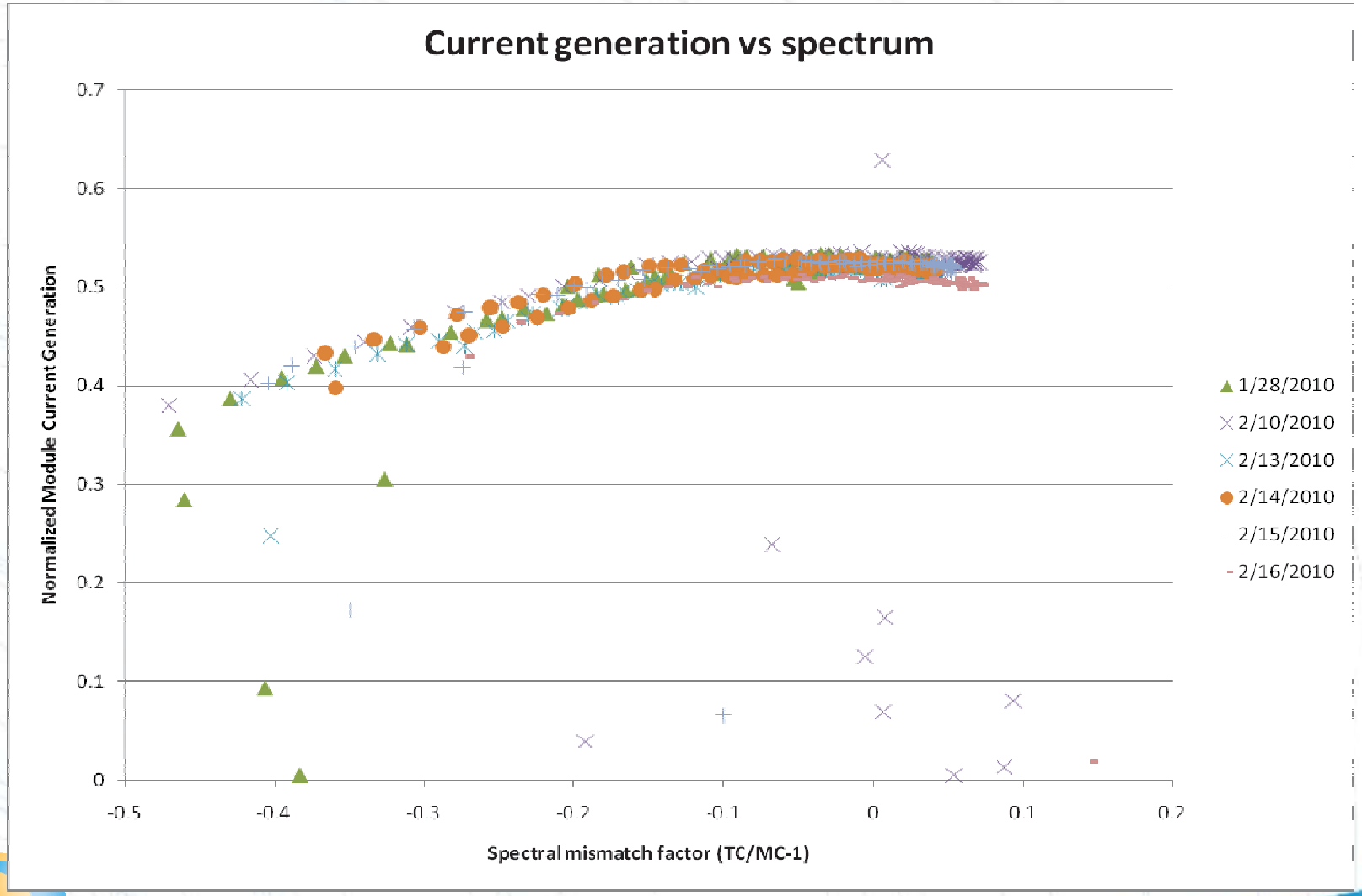
Soliant
Energizing commercial rooftops

Isotype module current production



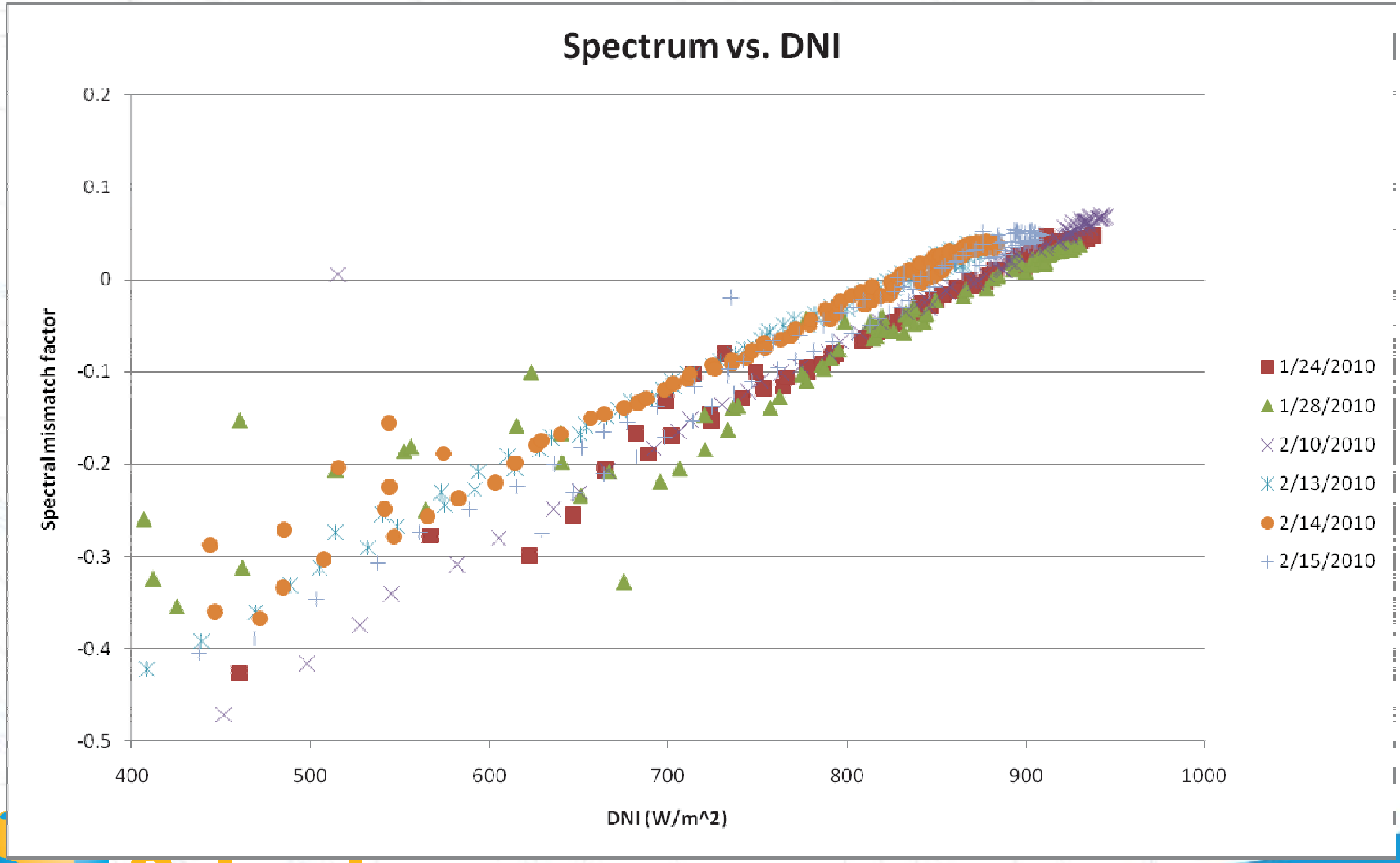
Soliant
Energizing commercial rooftops

Current Production vs. Isotype current ratio



Soliant
Energizing commercial rooftops

Spectral mismatch vs. Incoming DNI



Soliant
Energizing commercial rooftops

Next Steps

- Generate proper model for effects of spectrum on CPV module performance
  - Is the isotype module measurement robust?
  - Can the spectrometer give us more/better information?
- Look for site dependence in performance due to spectral variations



Soliant
Energizing commercial rooftops



Soliant

Energizing commercial rooftops

AMONIX
Powering Our Future™

Reliability and Qualification of Amonix Solar Power Plants

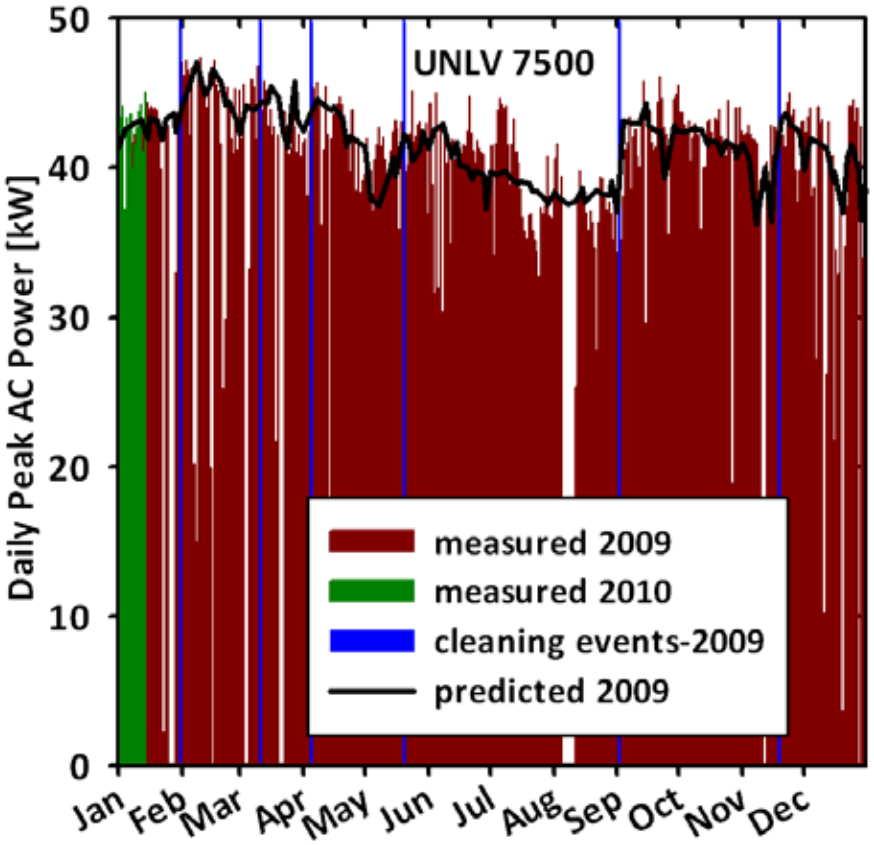


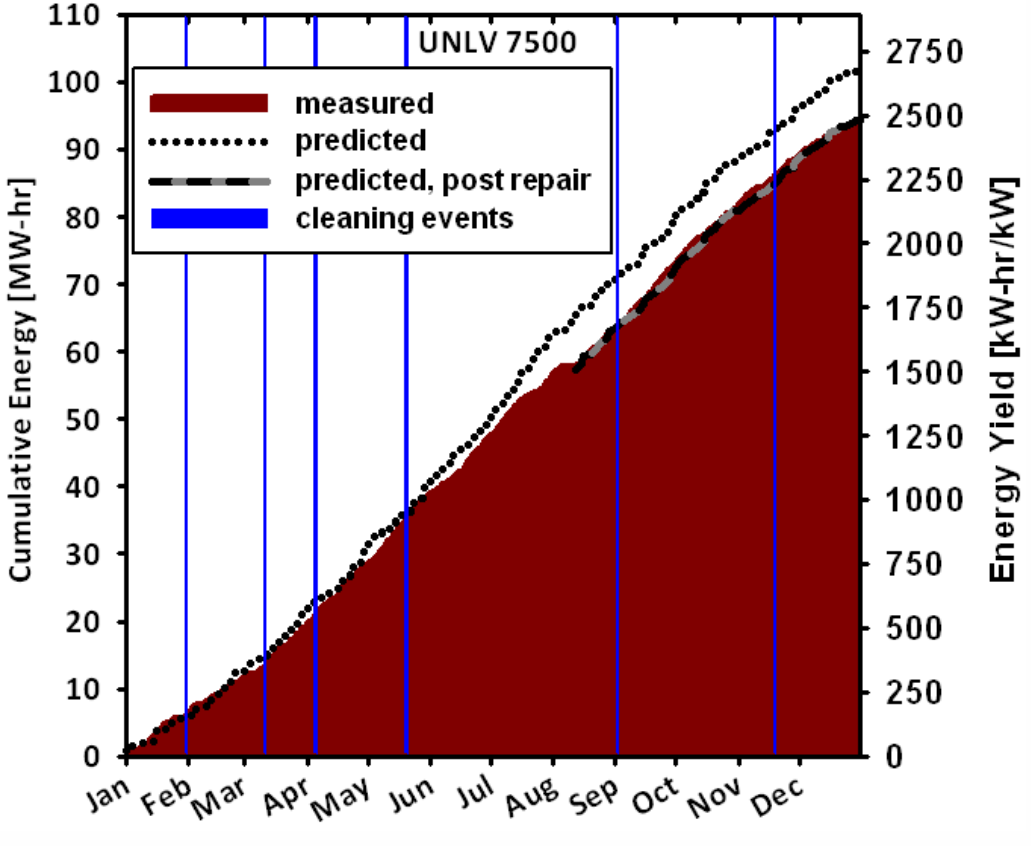
Field testing: Amonix technology in over 70% of world's installed CPV

WORLDWIDE COMMISSIONED SOLAR CPV INSTALLATIONS[a]				
PROJECT	LOCATION	CAPACITY	DEVELOPERS	COMMISSIONED
Guascor Fotón Navarra CPV Plant - Phase II & III	Spain	5.8 MW	Guascor Fotón (Amonix)	2008
Abengoa Casaquemada CPV Project	Spain	2.0 MW	Solucar Energia	2008
Guascor Fotón Navarra CPV Plant - Phase I	Spain	2.0 MW	Guascor Fotón (Amonix)	2007
GuascorFotón Murcia CPV Plant	Spain	2.0 MW	Guascor Fotón (Amonix)	2009[b]
Guascor Fotón Tecnohuertas CPV Plant	Spain	1.5 MW	Guascor Fotón (Amonix)	2006
Alsanbo Santa Pola Solar CPV Plant	Spain	1.0 MW	Electricidad Alsanbo	2007
Guascor Fotón Energias del Tietar	Spain	1.0 MW	Guascor Fotón (Amonix)	2008
Flix Solar Ramon Escriche Solar CPV Plant	Spain	0.8 MW	Flix Solar	2008
SolFocus and ISFOC Almoguera CPV Project	Spain	0.3 MW	ISFOC, SolFocus	2008
Concentrix and ISFOC Puertollano CPV Project	Spain	0.2 MW	Concentrix Solar	2008
SolFocus and ISFOC Puertollano CPV Project	Spain	0.2 MW	SolFocus	2008
Yitai Ordos grid-connected CPV power Project	China	0.2 MW	Inner Mongolia Yitai Group	2007
Amonix Solar CPV Plant (APS STAR Center - West) - Demonstration	United States	0.2 MW	Amonix	2003
Amonix Prescott CPV Plant - Demonstration	United States	0.2 MW	Amonix	2003
Amonix Solar CPV Plant (APS STAR Center - East) - Demonstration	United States	0.1 MW	Amonix	2002
Amonix Glendale CPV Plant - Demonstration	United States	0.1 MW	Amonix	2001
Total		**17.6 MW**		

Source: New Energy Finance

UNLV 7500 performance in 2009





- Model uses historical meteorological data to adjust for temperature, spectrum changes, etc.
- Model is deterministic: the only adjustable parameter is the cleaning schedule
- Energy generation is variable, but *predictable*

Installed III-V multijunction systems: 2009



UNLV



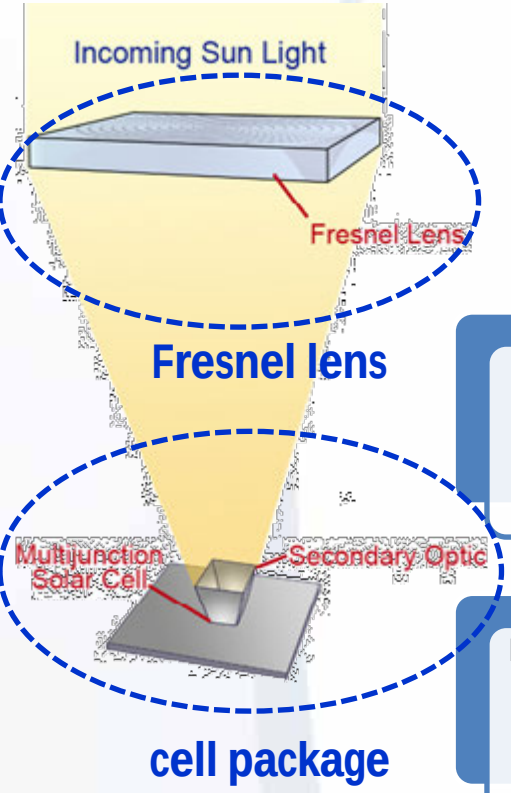
UNLV CENTER FOR ENERGY RESEARCH (LAS VEGAS, NV)
one 7500, one 7700
91 kW

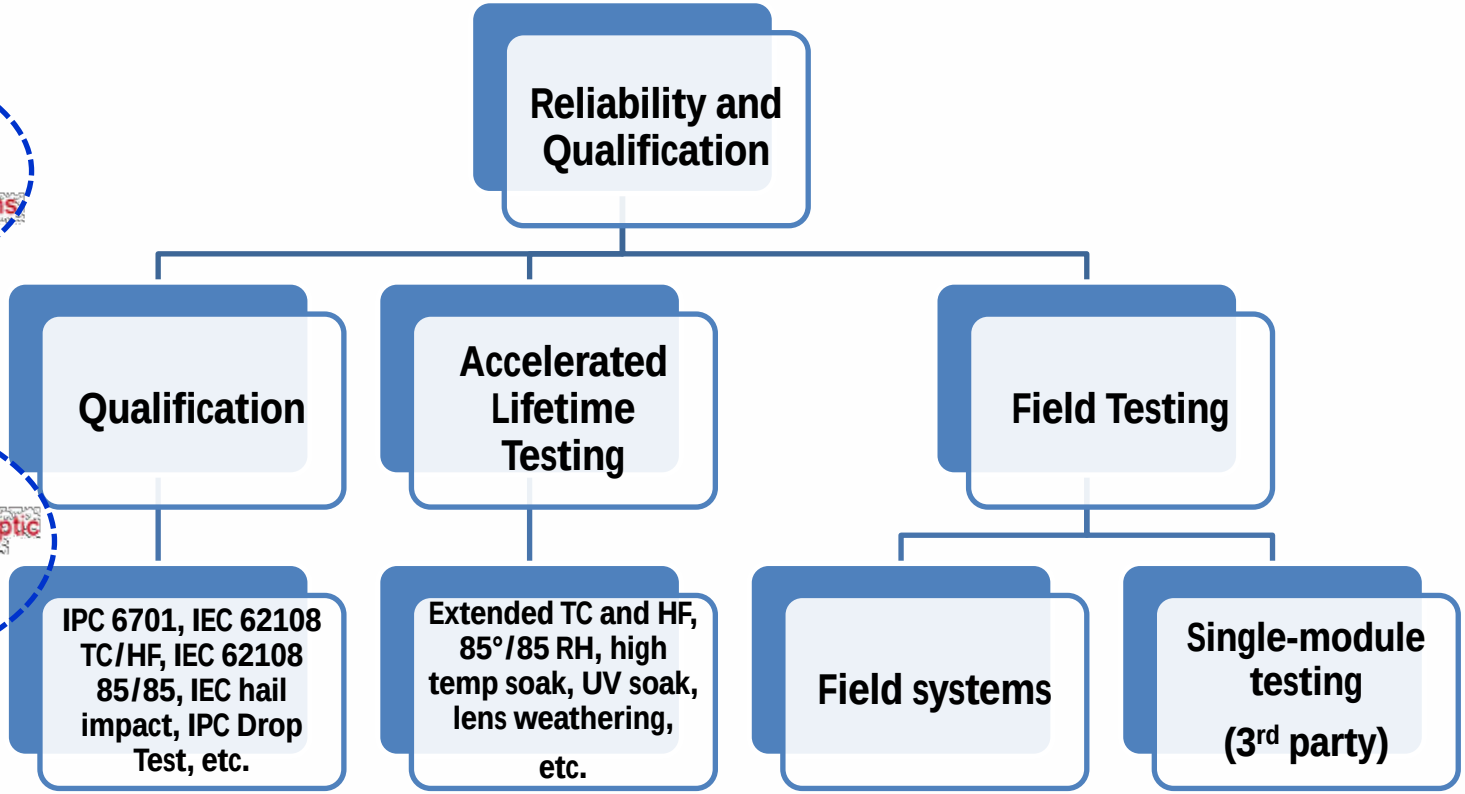


RIVER MOUNTAIN WATER TREATMENT FACILITY (HENDERSON, NV)
Six 7500s
228 kW

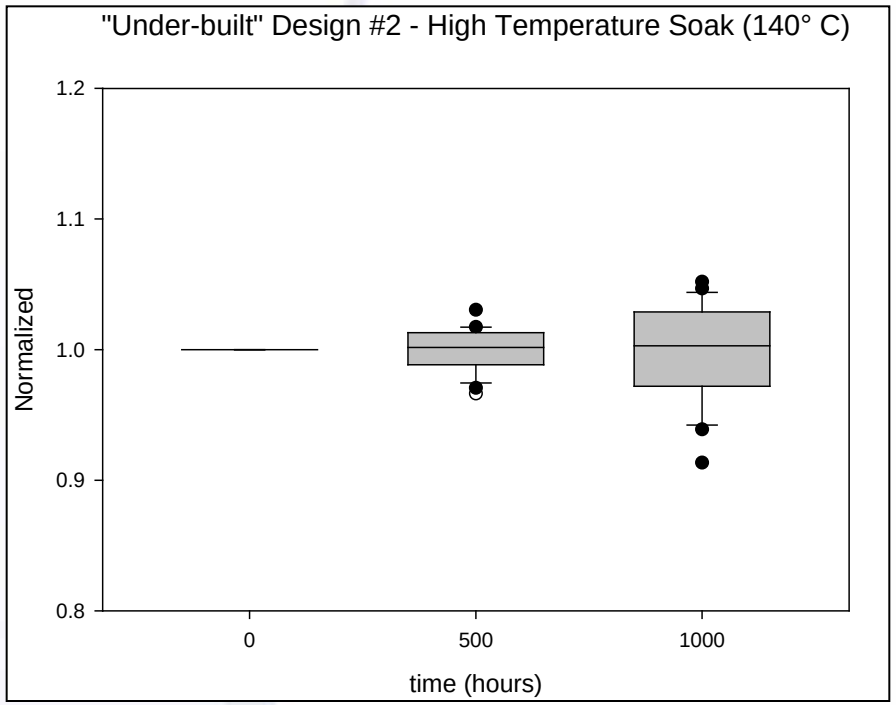
Southern Nevada Water Authority

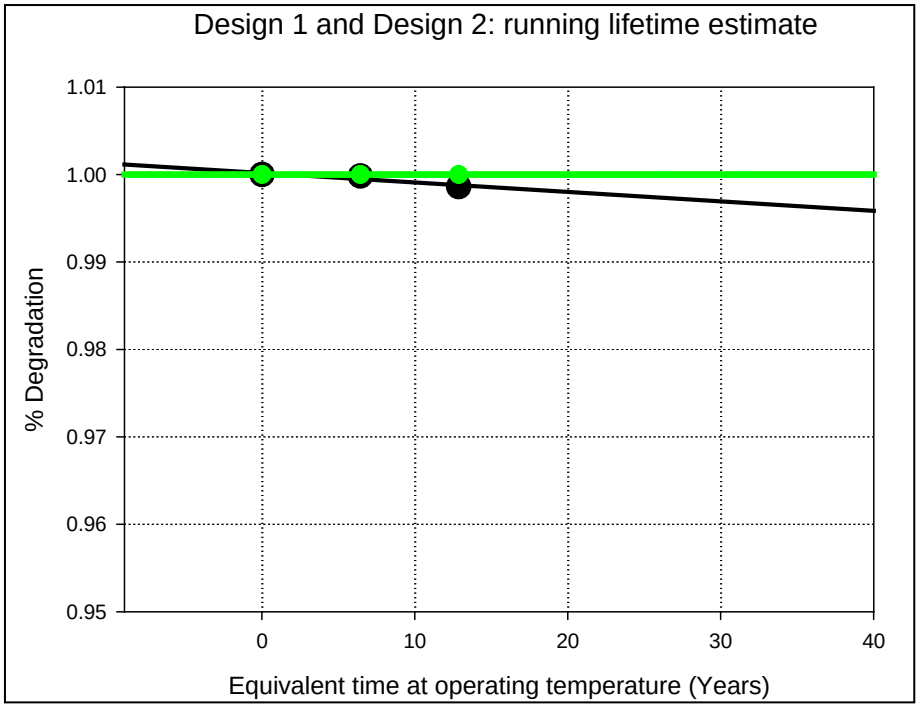
Reliability and qualification program: areas of focus





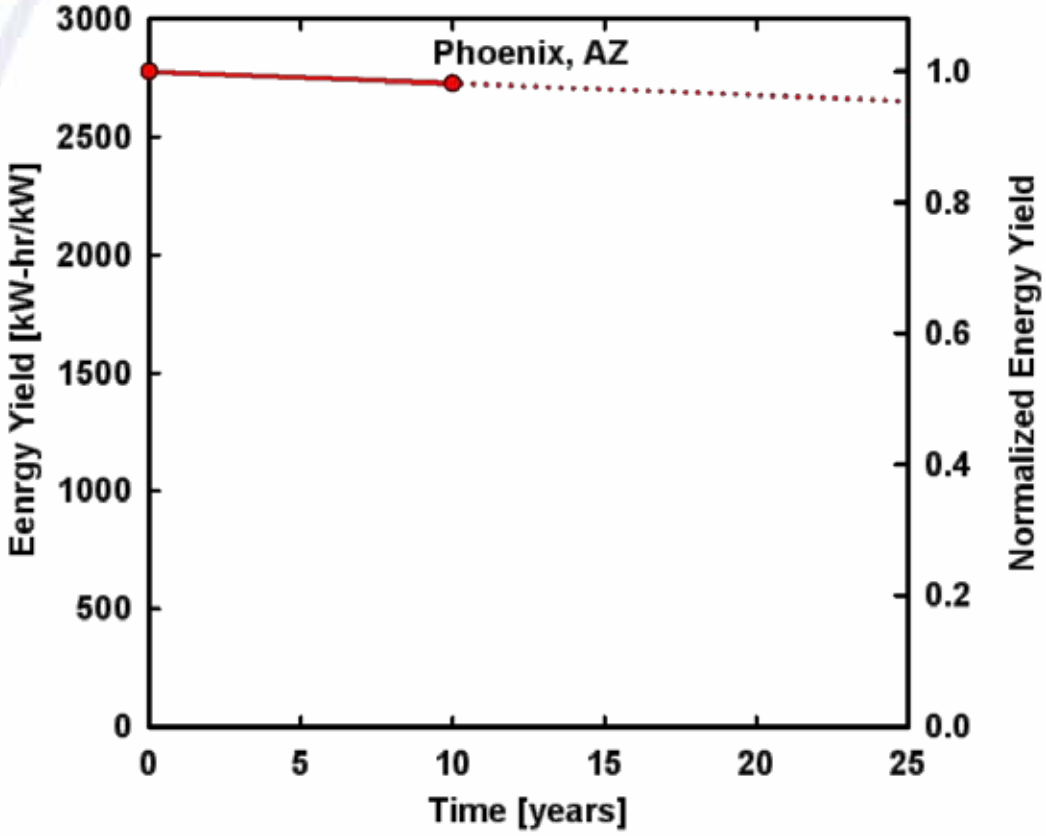
Cell package: lifetime estimate via high-temperature soak





- Assumes exponential degradation with temperature
- Only the (intentionally) under-built design shows measurable degradation as yet
- Tests are ongoing, including additional temperatures and designs

Fresnel lens: lifetime estimate via outdoor exposure



- Transmission of plastic lens materials changes over time
- Performance model can be applied to assess the impact on energy generation: ~0.2% per year for this material (assuming linear degradation)
- Accelerated testing in progress



Thermal Runaway Failures of CPV Solar Cells

Steve Seel*, Bruce Furman, Matt Meitl, Sal Bonafede, and Scott Burroughs

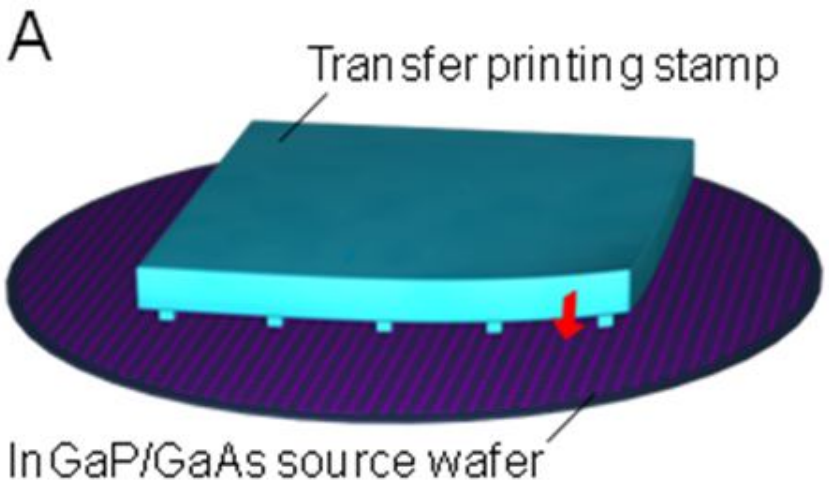
*steven.seel@semprius.com, 919-314-7708

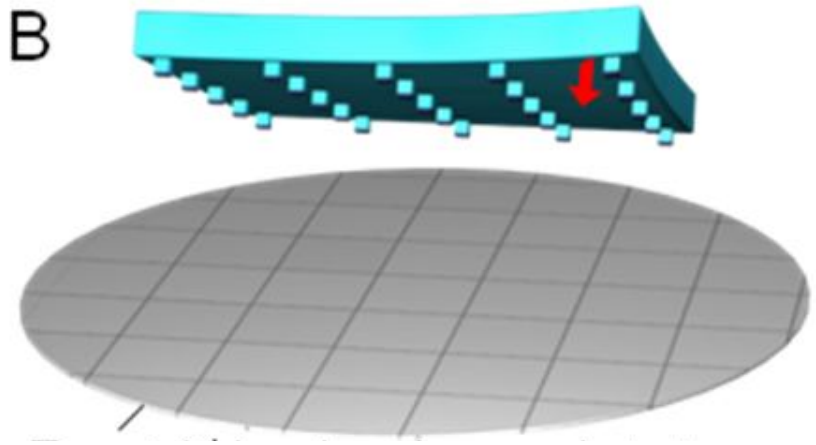
Semprius Background

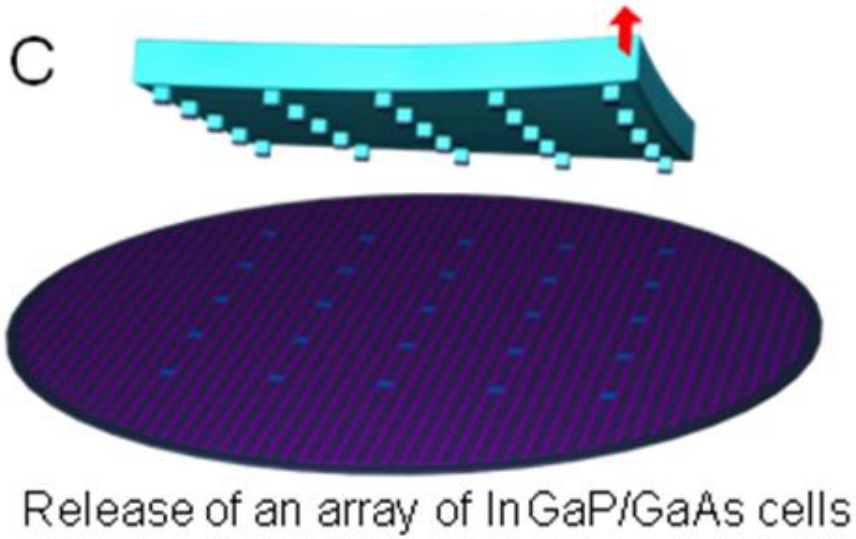
- Semprius is developing low cost, high performance concentrator photovoltaic (CPV) modules to make solar power generation economically viable in sunny, dry climates. The company's unique micro-transfer printing technology enables CPV modules with high performance, high reliability and low cost with scalability to high-volume production.

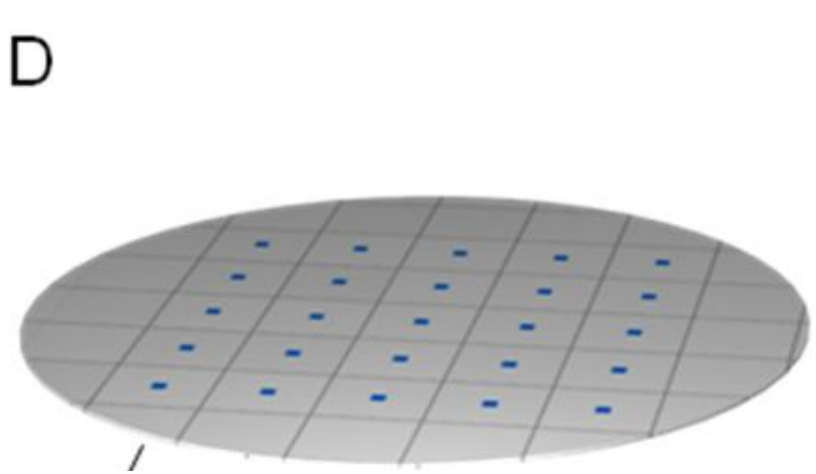
- Semprius is also licensing its micro-transfer printing technology for non-solar applications to enable a wide variety of new products requiring large-area, thin, lightweight form factors, unprecedented performance, high reliability and low cost. Applications include flat-panel displays, flexible electronics, large-area sensors, RF devices and other applications requiring heterogeneous integration of high-performance semiconductors.

Transfer Printing Process

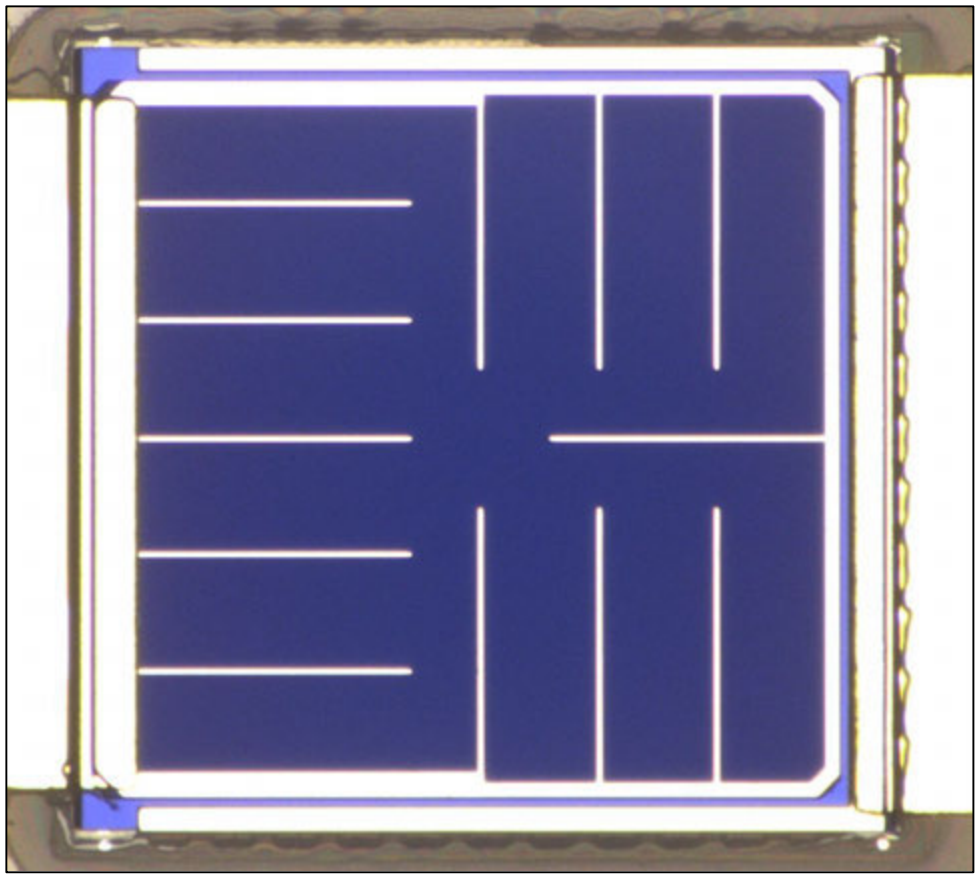






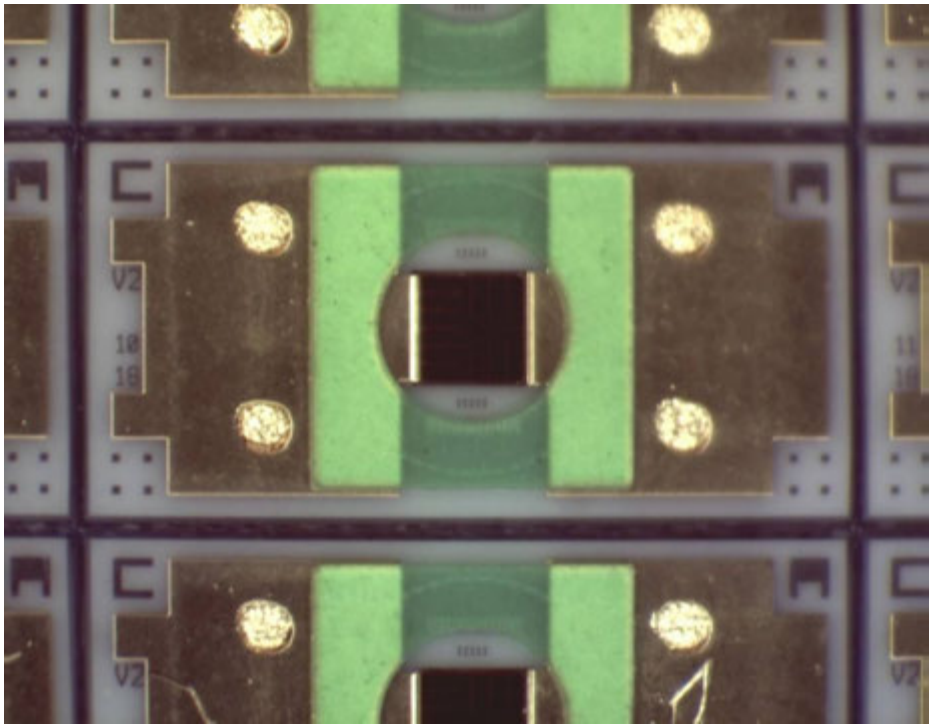


Cell Geometry & Interconnection



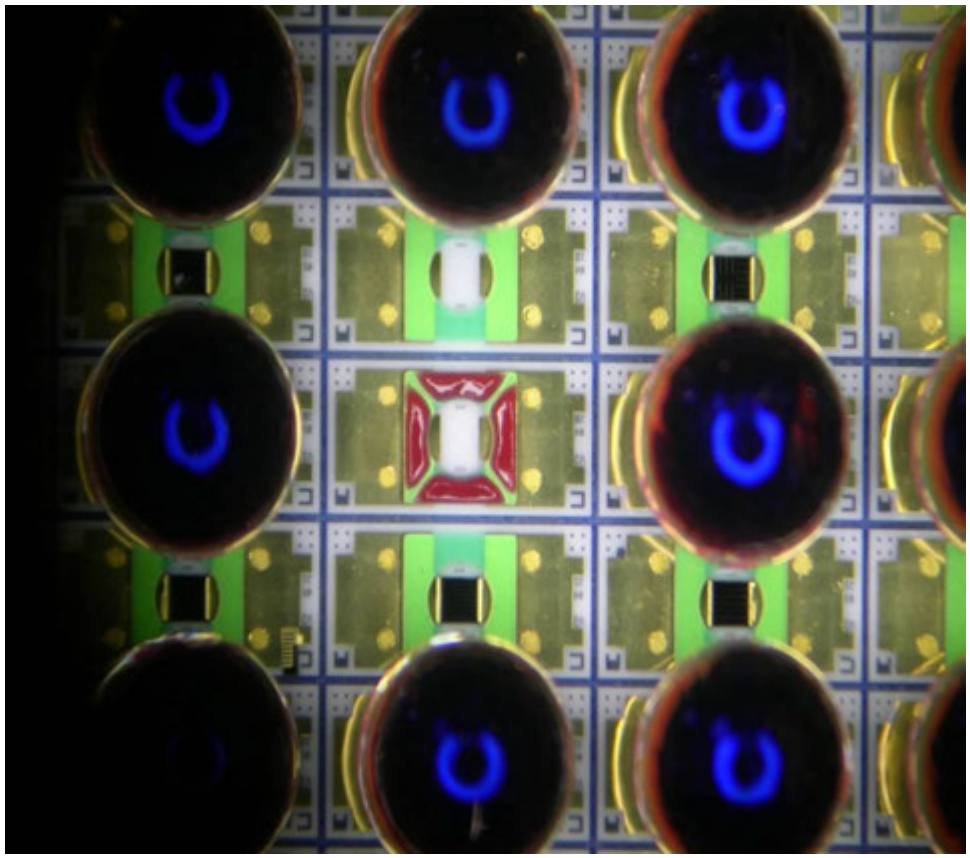
- 650um dual-junction unifacial GaInP/GaAs cell
- Thin film metallization creates anode/cathode interconnection
- 800 suns concentration at cell results in ~10 A/cm^2 current density

Thermal Stack: Cell to Backplane



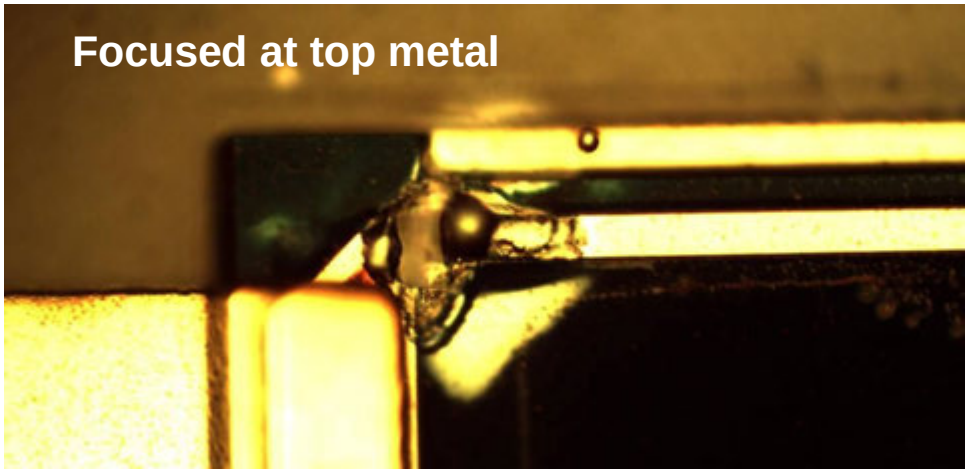
- ~5um-thick GaInP/GaAs solar cell
- Cell printed onto thin photo-imageable epoxy
- Evaporated + plated thin film interconnection
- Alumina interposer with thru-wafer vias
- Interposer soldered to Cu-dielectric-Al backplane

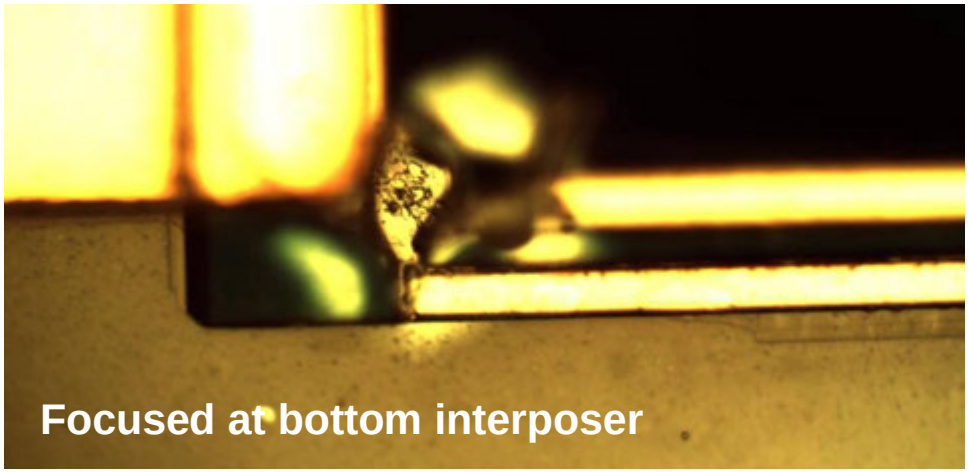
Secondary Optical Element

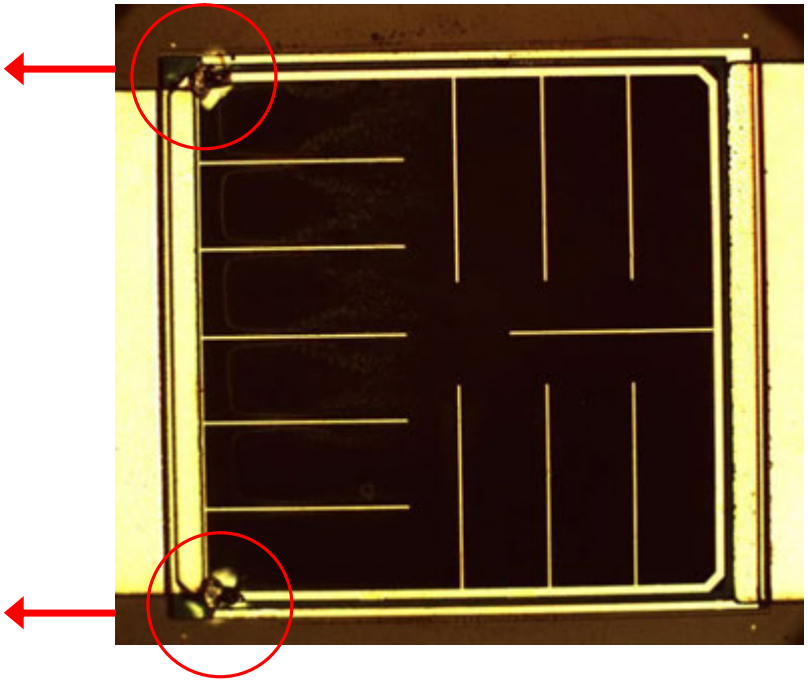


- Spherical ball lens attached to spacer with correct ball-to-cell distance
- Secondary optical element (SOE) provides uniform illumination across cell

Cell at 1000-Suns Failed Within Hours On-Sun

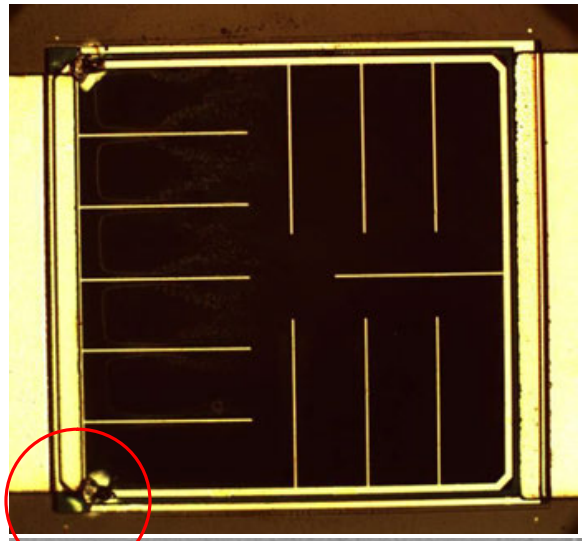




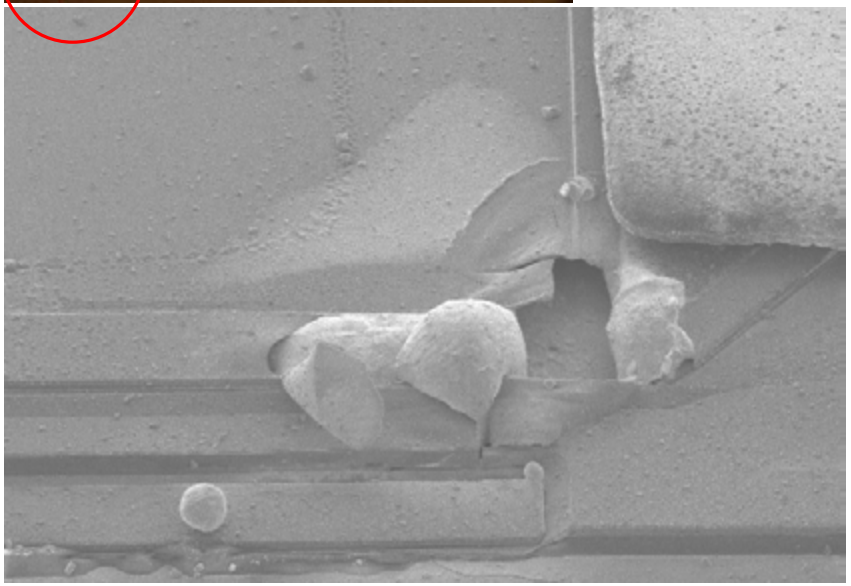


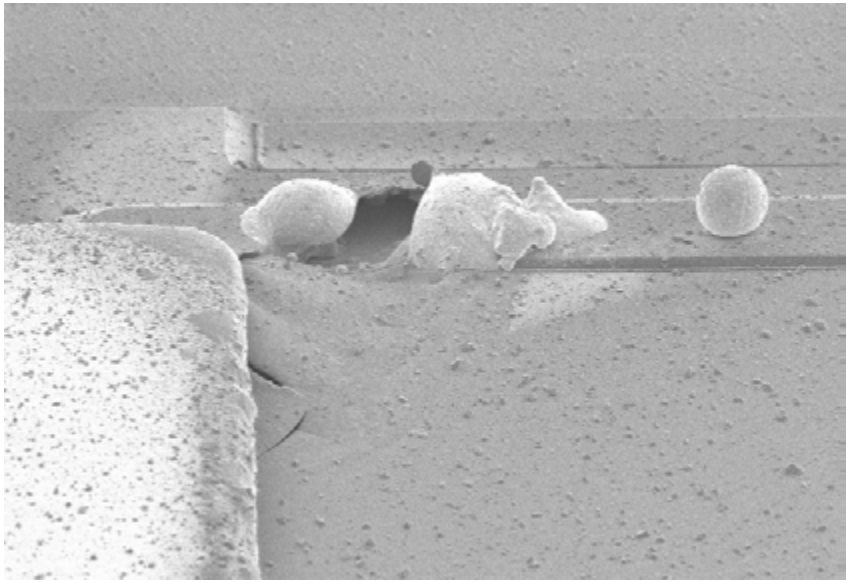
On-Sun Failures

SEM of Failed Cell on Interposer

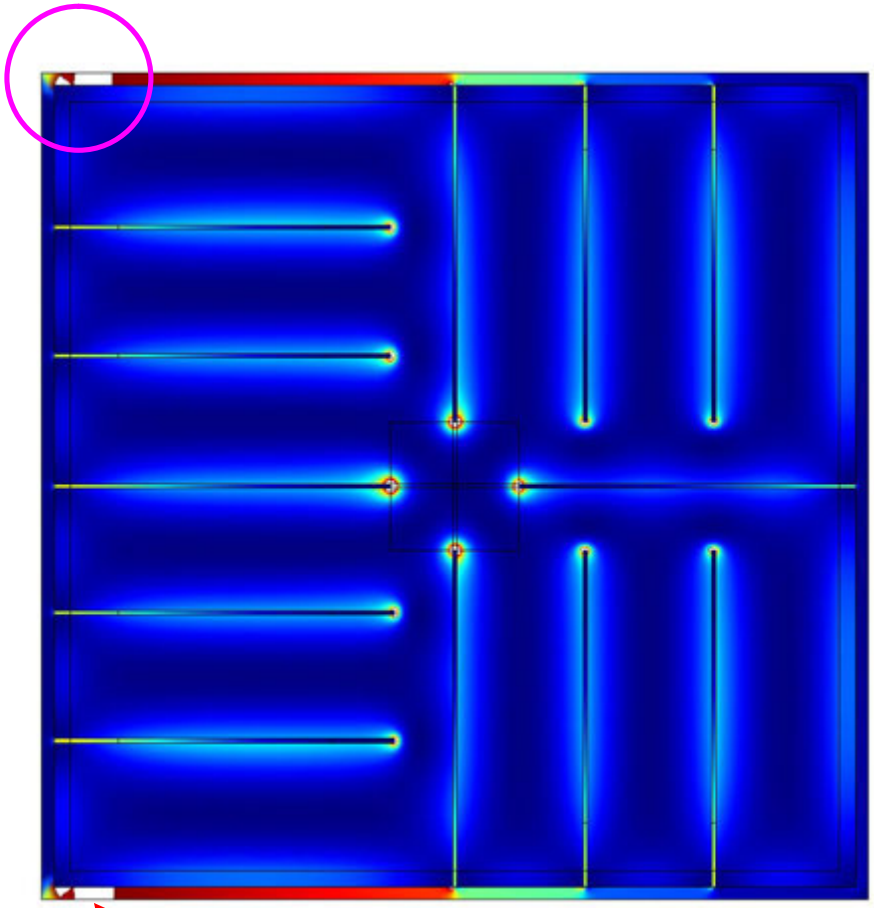


- SEM and XPS: metal and semi have melted together during on-sun failure!
- Failures almost always near junction of grid finger with busbar.





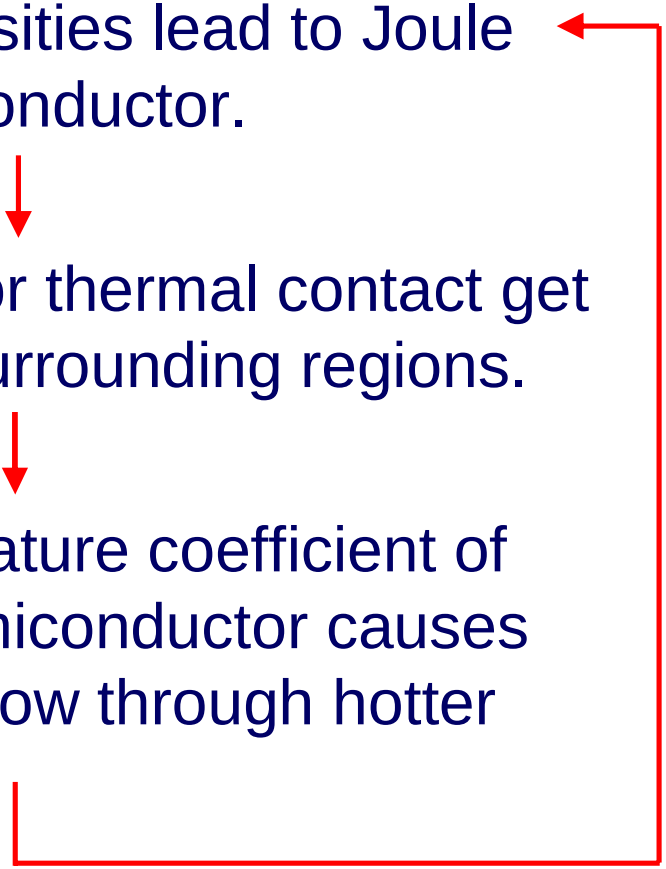
FEA of Surface Resistive Heating



- Highest current density and heating in same location as failures.
- Regions with highest current density are also potentially locations with poor thermal contact.

Thermal Runaway Mechanism

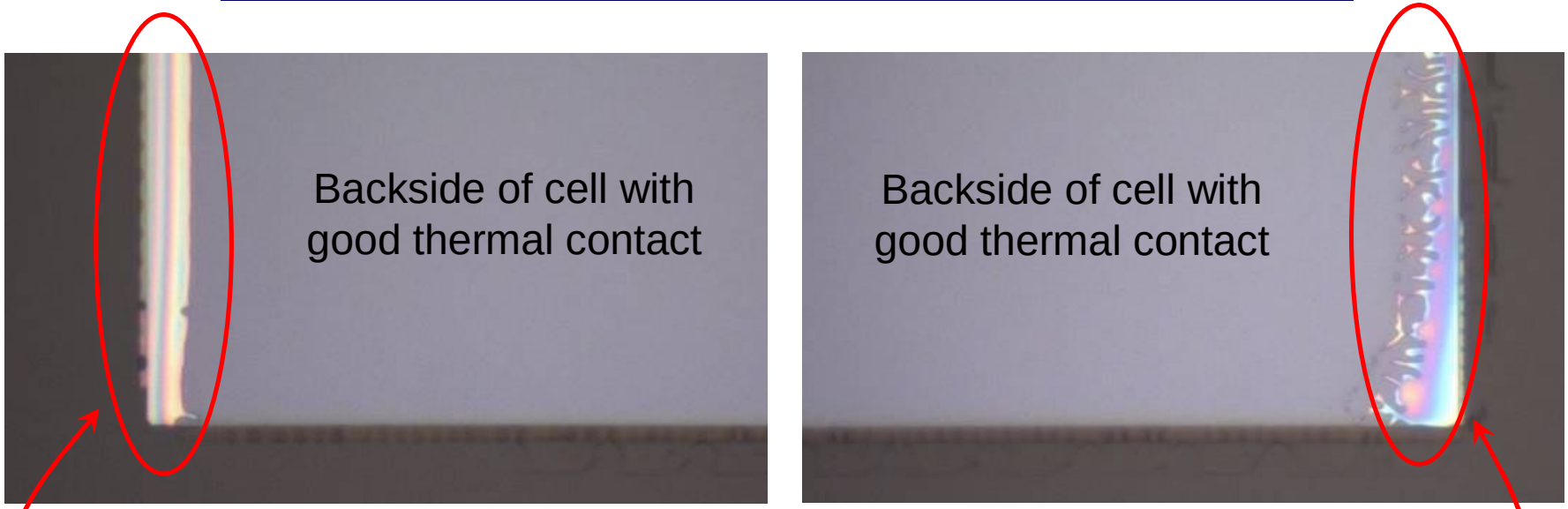
- High current densities lead to Joule heating of semiconductor.
- Regions with poor thermal contact get hotter than the surrounding regions.
- Negative temperature coefficient of resistance in semiconductor causes more current to flow through hotter regions.



Feedback loop results in catastrophic failure

Root Cause Determination

Transfer Print of Cell to Glass Wafer



- Printing cells onto glass allows backside observation.
- Poor thermal contact between epoxy and cell observed along edges under busbar locations.

Root Cause of Failure

- Unwanted removal of photo-imageable epoxy during photo develop step and oxygen plasma clean resulted in undercut of epoxy under cell and subsequent thermal runaway failure.

- Review of process traveler indicated that post-exposure bake (PEB) of epoxy had been inadvertently skipped.

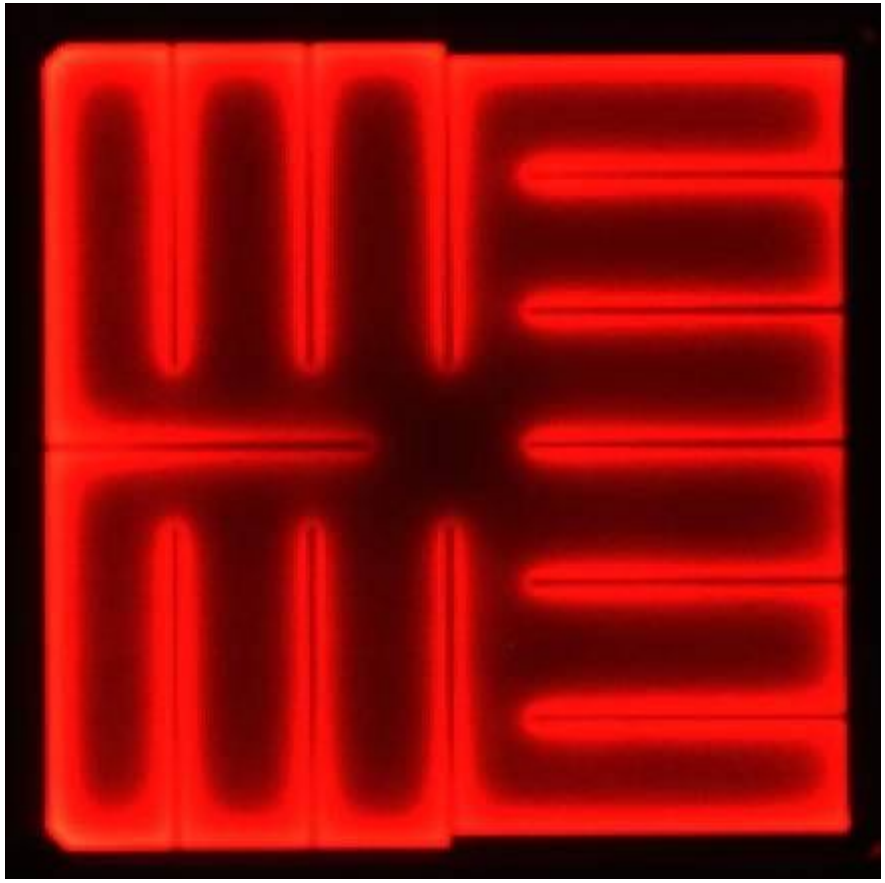
- Next lot processed with PEB did not show any signs of epoxy undercut even with extended periods in developer and extensive oxygen plasma ashing.

- On-sun failure due to this failure mode has not been observed since corrective actions were implemented.

Forward Bias to Failure

100 A/cm^2 Forward Bias

Electroluminescence of top cell

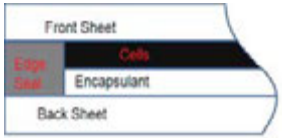


- Cells with poor thermal attach failed under forward bias at ~1A/cm^2 current density.
- After corrective action, >100 A/cm^2 for minutes without thermal runaway which is 10X normal operating conditions.

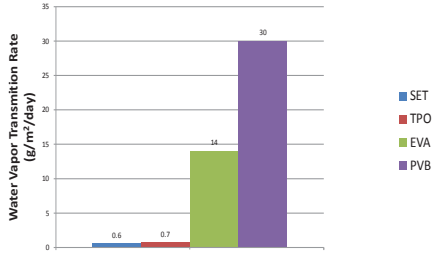
Benefits of a Desiccated Edge Seal in TFPV

1 Purpose of Packaging

- Protect TFPV device from environmental damage
  - Corrosion due to water inflow
  - Maintain water concentration in encapsulant below threshold level for 25+ years
- Protect Environment from TFPV device
  - Electrically insulate TFPV device from environment for 25+ years



2 Steady-State WVTR Comparison commonly Used Encapsulants vs. Truseal Solargain™ Edge Tape (SET)

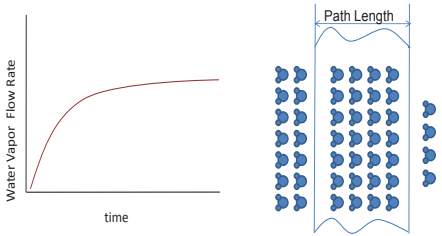


Actual Truseal laboratory results using MOCON Permatran-W equipment, Method ASTM F1249, 1.52mm (60 mil) film at 37.8° C, 100% RH. Various material suppliers. Steady-State conditions were achieved after materials were saturated with moisture.

3 Free Water Vapor Permeation Into PV Module

Without desiccant, water penetrates the edge seal quickly

In a non-desiccated edge seal water diffuses freely through the seal

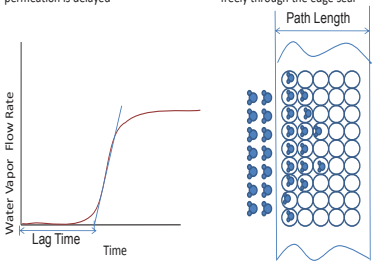


Paul, D.R. & Kemp, D.R. "The Diffusion Time Lag in Polymer Membranes Containing Adsorptive Fillers" *Journal of Polymer Science*, Vol. 41, pp 79 – 93 (1973)

4 Delayed Water Vapor Permeation Into PV Module

In a desiccated edge seal, water permeation is delayed

Water captured and not allowed to move freely through the edge seal

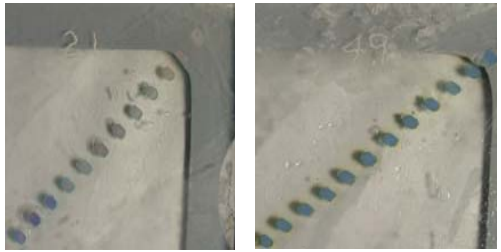


Paul, D.R. & Kemp, D.R. "The Diffusion Time Lag in Polymer Membranes Containing Adsorptive Fillers" *Journal of Polymer Science*, Vol. 41, pp 79 – 93 (1973)

5 Water Vapor Permeation into PV Module

Non-desiccated edge seal, 13 weeks at 60 °C/100%RH. Path length 15 mm.

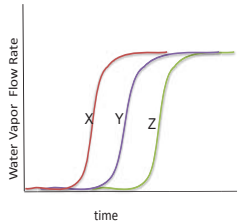
Desiccated Edge Seal, 13 weeks at 60 °C/100%RH. Path length 15 mm.



In non-desiccated seal moisture indicator dots changed color from blue to pink indicating that moisture went through the seal

6 Path Length Effect on Lag Time

- Lag time depends on presence of desiccant
- Lag time also depends on path length of a seal
- X, Y and Z represent different path lengths of the same sealant where X < Y < Z



7 Desiccated Edge Seal Effectively Reduces Water Ingress

- Reduced water concentration in TFPV increases module life
- Desiccated edge seal is necessary to provide adequate protection for TFPV from water
- Incorporation of desiccant into and an edge seal increases lag time

8 Desiccated Edge Seal Effectively Reduces Water Ingress

- Increasing lag time delays water penetration into a module
- Desiccated edge seal + Longer path length = Longer lag time = Longer module life

tru seal technologies

Address: 6680 Parkland Blvd
Solon, Ohio 44139
Web: Truseal.com

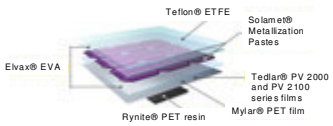
Comparative Performance and Reliability of Backsheets for PV Modules

William J. Gambogi, DuPont Photovoltaic Solutions

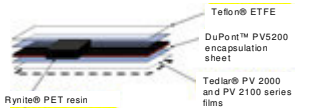
Solar Technologies – Long Life Required

- Rapid growth of commercial and utility segments
- Strong need for improved module reliability
- DuPont focused on partnerships, enabling technologies, and end market requirements
- Tedlar® film enables long-term, reliable module performance

Crystalline Si (c-Si) PV cells & modules



Amorphous Si (a-Si) thin film PV modules

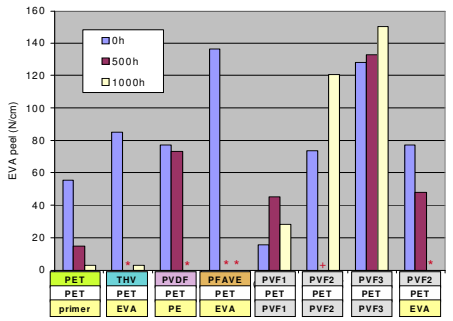


Critical Backsheet Properties Tested

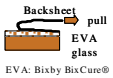
Physical Properties	*Sample Structure*	*Test Standard*
Structural Analysis	FILM	internal
Thickness	FILM	ASTM D374
Reflectance	FILM, LAMINATE	ASTM E1164
Color	FILM, LAMINATE	ASTM E308
Dielectric Breakdown Voltage	FILM	ASTM D1868
Tensile Strength (MD, TD)	FILM	ASTM D882
Elongation (MD, TD)	FILM	ASTM D882
Peel Strength to EVA (180deg, 0.2in/min peeling)	LAMINATE	ASTM D1876
Cut Susceptibility	LAMINATE	UL1703
Coefficient of Thermal Expansion	FILM	internal
Dimensional Stability (150C, 30m)	FILM	ASTM D1204
Visual Inspection	FILM, LAMINATE, MODULE	internal
Water Vapor Permeability	FILM	ASTM 1249

Exposure Tests	*Sample Structure*	*Test Standard*
Damp Heat (85C, 85%RH, 1000h))	FILM, LAMINATE, MODULE	IEC 61215
UV aging (xenon, UVA, UVB)	FILM, LAMINATE, MODULE	IEC 61345, ASTM
Thermal Cycling (50 and 200cyc, -40C, 85C)	FILM, LAMINATE, MODULE	IEC 61215
Thermal Cycling/Humidity Freeze (50 cyc, 10cyc)	FILM, LAMINATE, MODULE	IEC 61215

Backsheet Adhesion to Encapsulant After Damp Heat



Loss of EVA adhesion for PET and other fluoropolymer based backsheets

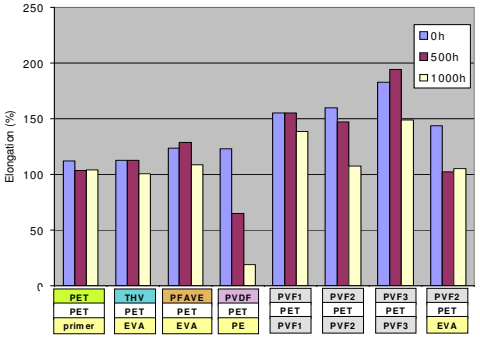


EVA: Bixby BixCure®

* Adhesion not measurable due to backsheet break
\+ EVA peel from glass indicating strong EVA/backsheet adhesion

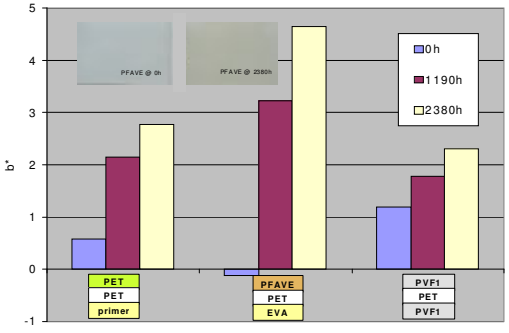
PFV1=PV2000 series
PVF2=PV2100 series
PVF3=PV2400 series

Backsheet Elongation After Damp Heat



Embrittlement of PVDF based backsheet

Color Change in Glass/EVA/Backsheet Laminate

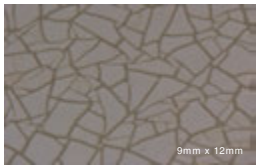


Exposed under xenon (ASTM G155) from glass side and measured from glass side of laminate

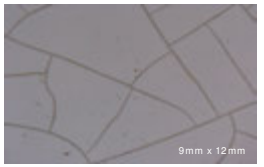
2380h xenon exposure ~630 days in Florida (< 2 years)

Degradation - Glass/EVA/backsheet laminate after UV Exposure (ASTM G155) at 1190h

Cracking observed on PET backsheet in laminate exposed on backsheet side



Cracking observed on PET backsheet in laminate exposed through glass



Coefficient of Thermal Expansion (CTE)

Backsheet	Direction 1 (um/°C*m)	Direction 2 (um/°C*m)
PVF1/PET/PVF1	41	29
PVF2/PET/PVF2	39	30
PVF3/PET/PVF3	41	30
PVF2/PET/EVA	116	178
PET/PET/primer	347	184
PVDF/PET/PE	82	34
THV/PET/EVA	114	28
PFAVE/PET/EVA	326	258

- CTE measured in two orthogonal directions (1 and 2) from -40°C to 90°C
- TPT structures have lower CTE and more isotropic expansion
- Other backsheets show higher CTE and more anisotropic expansion
- Two PET backsheets showed same or greater CTE as shown
- Higher expansion and anisotropy may lead to delamination, cracking and failure

Summary

- DuPont has and will continue to demonstrate its commitment to meet increasing demand for reliable backsheet materials.
- DuPont is recognized as a global leader in materials and technologies for the PV industry.
- Tedlar® PVF film based backsheet consistently outperforms alternative products.
- Tedlar® PVF film based backsheet is the only material that has successfully protected PV modules for more than 25 years.

energy for a thriving world™

DUPONT

NREL PV RELIABILITY WORKSHOP, 2/18/2010

Molecular Bond Rupture Kinetics in Organic Photovoltaic Transparent Barriers

F. Novoa and R. H. Dauskardt

STANFORD MATERIALS SCIENCE AND ENGINEERING

CAMP Center for Advanced Molecular Photovoltaics STANFORD UNIVERSITY

KAUST King Abdullah University of Science and Technology

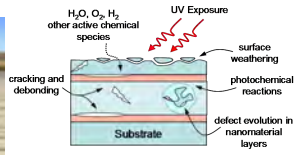
Objective

- The Lifetime of a Photovoltaic device is dictated by the loss of adhesion and defect evolution.
- The objective of this research is to develop quantitative methods to characterize basic thermomechanical properties (e.g. adhesion, cohesion), and photochemical and environmental degradation processes in organic solar cells.
- Kinetic models of damage evolution need to be developed as the basis for life prediction and accelerated testing (effect of operating temperature and environments, solar flux, etc.)

Degradation and Reliability of Photovoltaic Devices

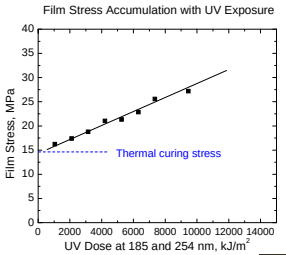


Keele University



Locations with the highest solar irradiance are also the most severe operating environments

Exposure to moisture, chemically active environmental species, thermal cycling and UV radiation leads to device failure.



Kamer and Dauskardt - 2009

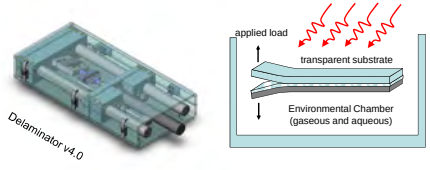
Driving force for damage:

$$G = \frac{Z_i \sigma_f^2 h_f}{E_f}$$

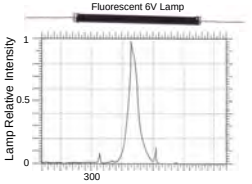


UV radiation on a polysiloxane film provides the driving force for defect propagation.

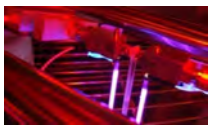
Assessing UV & Environment on Debonding Kinetics



Adhesive debonding in Organic Layer

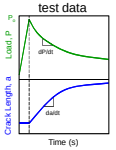


Low heating UV radiation



UV-Mechanical Delaminator

- An experimental setup was implemented to simulate effects of simultaneous environmental, mechanical and uv irradiation
- Load relaxation curves characterize the molecular bond rupture kinetics of transparent protective barriers



automated load relaxation debond growth analysis

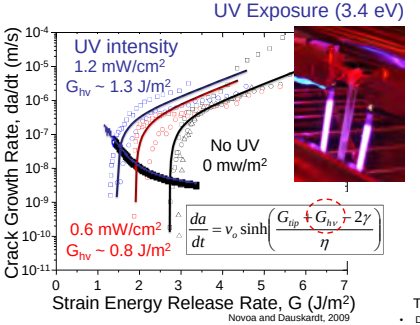
compliance analysis

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

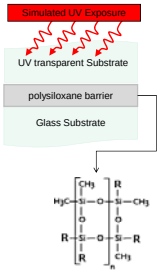
Debonding Kinetics explore role of:

- UV flux
- humidity, O_2, OH^-, ...
- temperature
- mechanical loading

UV Effects on Barrier Debonding Kinetics

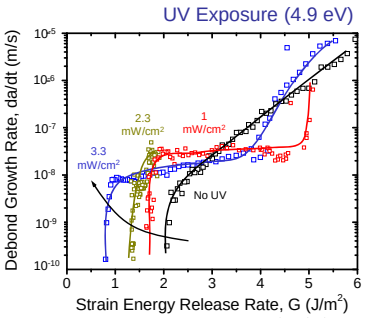


3.4 eV UV light exposure accelerates debonding rates between glass and the polysiloxane barrier



Transparent Polysiloxane Barrier

- Dip coated polysiloxane coatings
- Substituted methylsiloxanes polymer with organofunctional polysiloxanes



4.9 eV UV light exposure accelerates adhesive failure while increasing bond density in the polysiloxane film

Modeling Bond Rupture Kinetics

- Interaction of moisture with strained debond tip bonds

$$nH_2O + B(\text{debond tip}) \xrightarrow{h\nu} B^*(\text{activated complex})$$

- Atomistic crack-growth models:

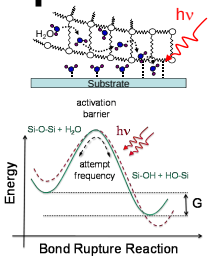
$$rate = f_o\left[\exp\left(\frac{-U_1^*}{kT}\right) - \exp\left(\frac{-U^*}{kT}\right)\right]$$

$$\frac{da}{dt} = v_o \sinh\left(\frac{G_{tip} + G_{hv} + 2\gamma}{\eta}\right)$$

$$v_o = \frac{2 f_o}{Nw} \exp\left(\frac{-u_1}{kT}\right)$$

Bond Rupture Parameters

N - bonds per unit area
u_o - work of rupture
2γ - N u_o
w - crack width
f_o - attempt frequency
u_1 - energy barrier
η - 2NkT



UV photons cleave highly strained bonds and accelerate the rate of defect evolution

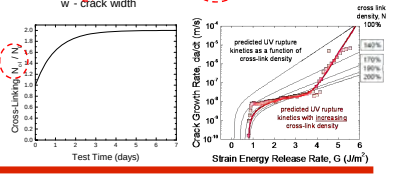
- Damage growth rate with increasing bond density:

$$\frac{da}{dt} = v_o \sinh\left(\frac{G_{tip} + G_{hv} + 2\gamma}{\eta}\right)$$

$$v_o = \frac{2 f_o}{Nw} \exp\left(\frac{-u_1}{kT}\right)$$

Bond Rupture Parameters

N - bonds per unit area
u_o - work of rupture
2γ - N u_o
w - crack width
f_o - attempt frequency
u_1 - energy barrier
η - 2NkT



Conclusions and Future Work

- Degradation of a transparent protective barrier was shown to be caused by the simultaneous effect of moisture, chemically active environmental species and UV radiation
- UV exposure accelerates debonding rates and lowers the threshold loads for bond rupture
- More experiments on UV, humidity, environmental species and mechanical loads on bond rupture kinetics will be performed.
- Atomistic modeling to reveal bond rupture processes is under way.
- Reliability modeling and life prediction studies will be performed.

Acknowledgement

This work was supported in part by the Center for Advanced Molecular Photovoltaics (Award No KUS-C1-015-21), and by the Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy (Contract No. DE-FG02-07ER46391). FN was partially supported by a Roberto Rocca Education Program Fellowship.

Lessons Learned Regarding Failure Modes of Glass/Glass Modules in the Field

by Forrest Collins and Beth Copanas
juwi Solar, Inc.

Introduction

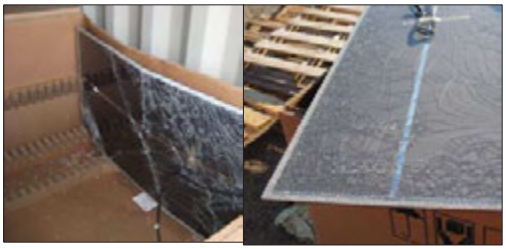
Module failure in the field is a reliability issue from both a manufacturing and Balance of System (BOS) installation perspective for most PV module types. Utilizing data from thin film glass /glass installations totaling 236 MW DC of installed capacity, the modes of module failure in the field are examined.

Materials and Methods

The 236 MW DC of installed capacity represents 520 installations with a total of 3,324,220 modules ranging in project size from 2kW DC to 38MW DC. The data represents projects beginning operation in 2005 through present day. Module Failure Modes in the field have been divided into five categories for the company's identification, tracking and warranty replacement purposes. Once a failed module is identified and classified a return request is filed with the manufacturer.

Installation Company Module Failure Mode Classification	
Classification	Description
Shipping/Packaging	Out of the box damage including glass breakage from transport
Installation and Handling	Glass breakage and cracks as a result of incorrect handling or installation
Diminished Module Output	Module output power is low.
Intrinsic Module Damage After Deployment	Module has defective wires, glass breakage or cracks or no power output.
Externally Caused Module Damage After Deployment	Module has been damaged by external source.

Shipping/Packaging



Installation and Handling



Externally Caused Module Damage After Deployment

Intrinsic Module Damage After Deployment



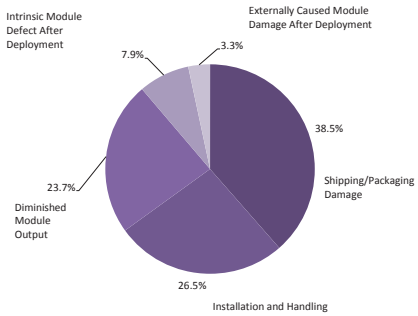
Results

Once the return report has been filed, the manufacturer evaluates if the return request meets the warranty specifications and authorizes the return. At this point the failed modules are returned and the manufacturer performs a technical assessment of the failure. The manufacturer determines the module failure and whether the module qualifies for warranty replacement.

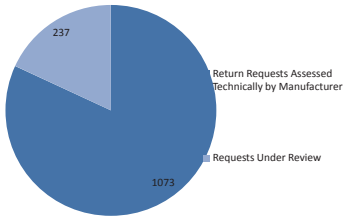
Manufactuer Failure Mode Designations After Technical Assessment
Defect/Damage Covered by Warranty Replacement
Damage due to Handling or Installation: Damage through mounting system (glass scratches) Damage due to bad module clip position
Glass Crack due to Thermal Cycling
Damage Due to External Source

Of the 1310 Return Requests filed, 1073 have been accepted and reviewed technically by the manufacturer .

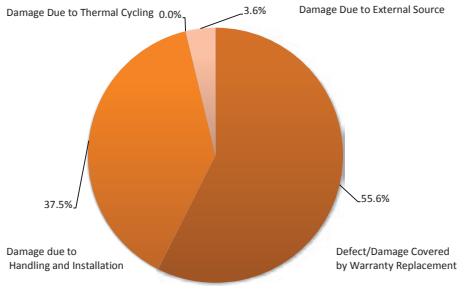
Company Failure Mode Designations for Installed Projects



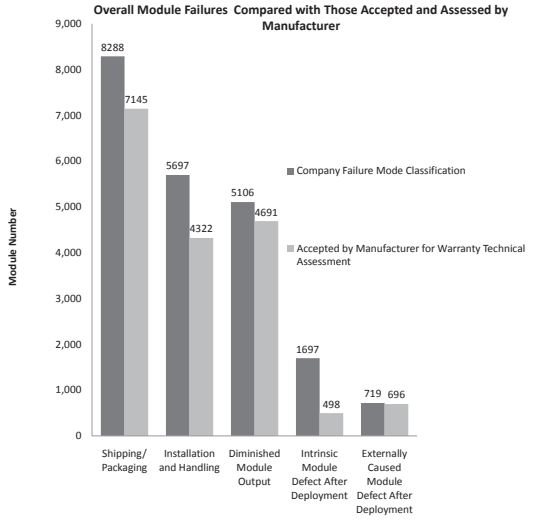
Return Requests Assessed by Manufacturer



Manufacturer Failure Mode Designations Based Upon Technical Assessment of Returns



Overall Module Failures Compared with Those Accepted and Assessed by Manufacturer



Conclusions

Shipping/Packaging and Handling and Installation are the greatest mechanisms of module failure in the field for these installations.

How *Lessons Learned from the Field:*

How modules are packaged and handled during shipment is important.

The difference between the company and manufacturer designation of module failure due to handling and installation indicates that installations can benefit from increased attention to how modules are installed .

Minimizing the number of times a module is handled during installation may help to reduce this risk.

Operation and Maintenance requires special attention to prevent externally caused damage to modules by maintenance crews and rocks kicked up during mowing,.

Relation of Wet Leakage Resistance with Module Front Glass Resistivity



Lizhong Sun, Adam Brand, Tracy Yang and Maxwell Yang

Applied Materials, Santa Clara, CA 95054

02/2010

think it. apply it.

APPLIED MATERIALS

Introduction

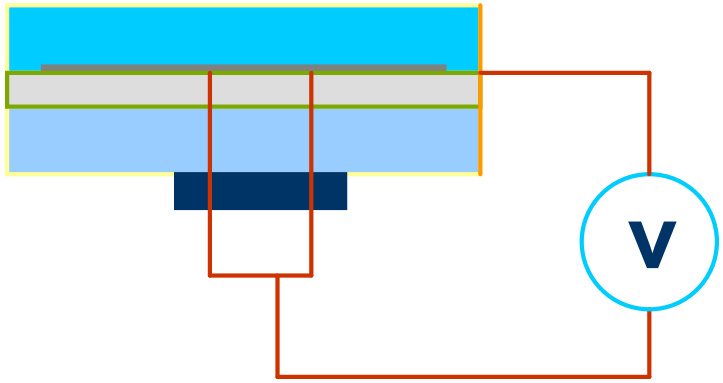
- **Wet Leakage Resistance (WLR)**
  - **An important module safety measure**
- **Criteria of Certification Standard**
  - **IEC 61646 ed. 2.0 10.15**
    > 40 MOhm.m^2 under 1000 v bias if module area > 0.1 m^2
  - **UL 1703**
    > 40 MOhm. m^2 under 500 v bias if module area > 0.1 m^2
- **Determination Factors**
  - TCO front glass (FG)
  - Back side (BS)
  - Edge deletion area
- **This Work**
  - **Explored the front glass resistance on thin film modules by using a resistance segmentation technique;**
  - **Characterized the WLR variation of the modules with different front glass bulk resistivity and the temperature dependence of glass resistivity;**
  - **Observed the correlation of WLR pre and post stress test;**
  - **Provided a criteria for front glass bulk resistivity to get an appropriate margin for WLR passing standards after stress tests.**

Applied Materials Confidential

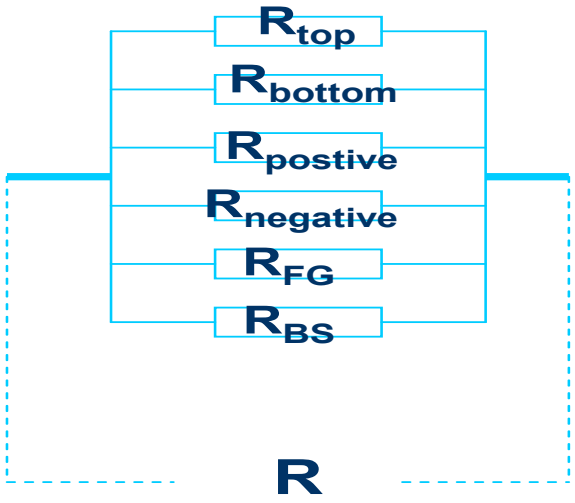
APPLIED MATERIALS

Equivalent Circuit and Resistance

- Measurement Set-up



- Equivalent Circuit



$$R_{parallel} = 1 / (1 / R_{top} + 1 / R_{bottom} + 1 / R_{positve} + 1 / R_{negative})$$

$$R_{FG} = 1 / (1 / R_{dry\ back} - 1 / R_{parallel})$$

$$R_{BS} = 1 / (1 / R_{module} - 1 / R_{dry\ back})$$

Applied Materials Confidential

APPLIED MATERIALS

Measurement Methodology

- **Measure WLR of individual panel edges**
  - Damp probe or 4mm wet solution can be used
  - Use parallel resistance addition to calculate total edge WLR term
- **Measure WLR of FG with 4 edges combined**
  - Use parallel resistance subtraction to extract FG WLR term
- **Measure WLR of full panel**
  - Use parallel resistance subtraction to extract BS WLR term

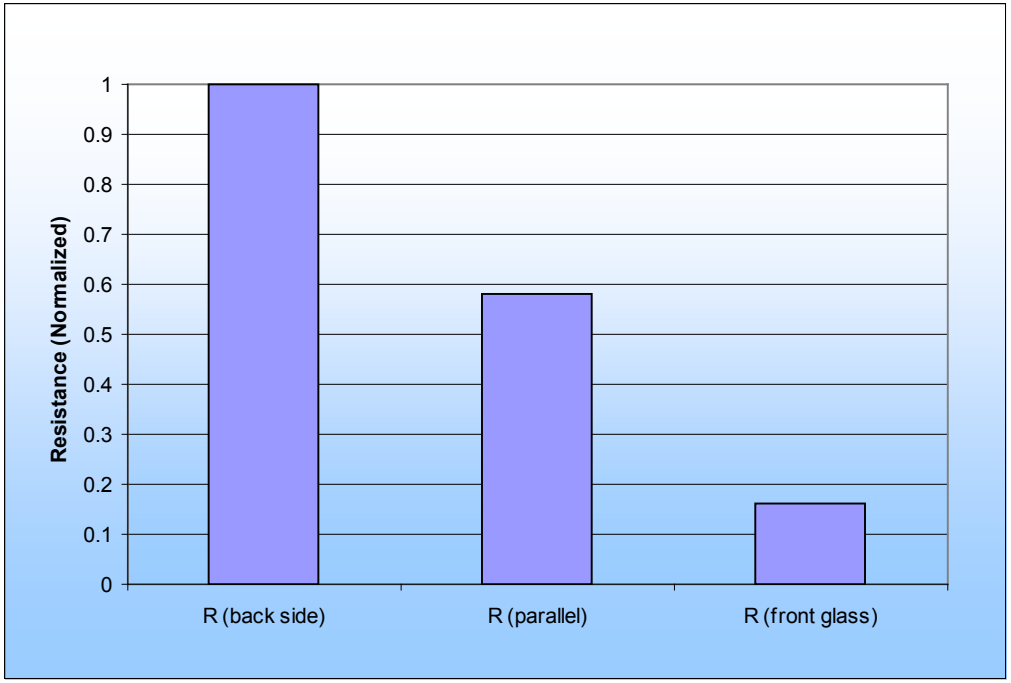
Applied Materials Confidential

Segmentation of Initial Resistance

- For Initial Leakage Resistance:

$$R_{BS} > R_{parallel} >> R_{FG}$$

- Front Glass → dominant *leakage path* of initial WLRs



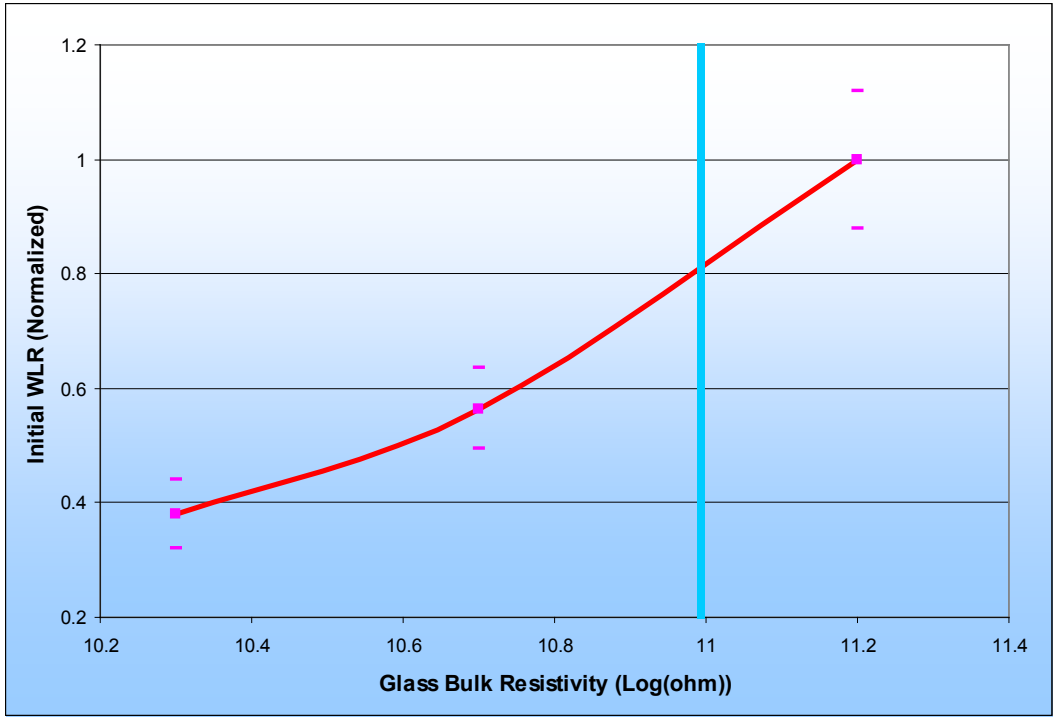
Initial leakage resistance of each part of a module

Applied Materials Confidential

APPLIED MATERIALS

Dependence on FG Resistivity

- A set of glass materials were evaluated over a range of resistivity typical in the solar industry
- Module WLR performance evaluated as a function of resistivity



Initial WLR of the modules vs FG bulk resistivity

Applied Materials Confidential

APPLIED MATERIALS

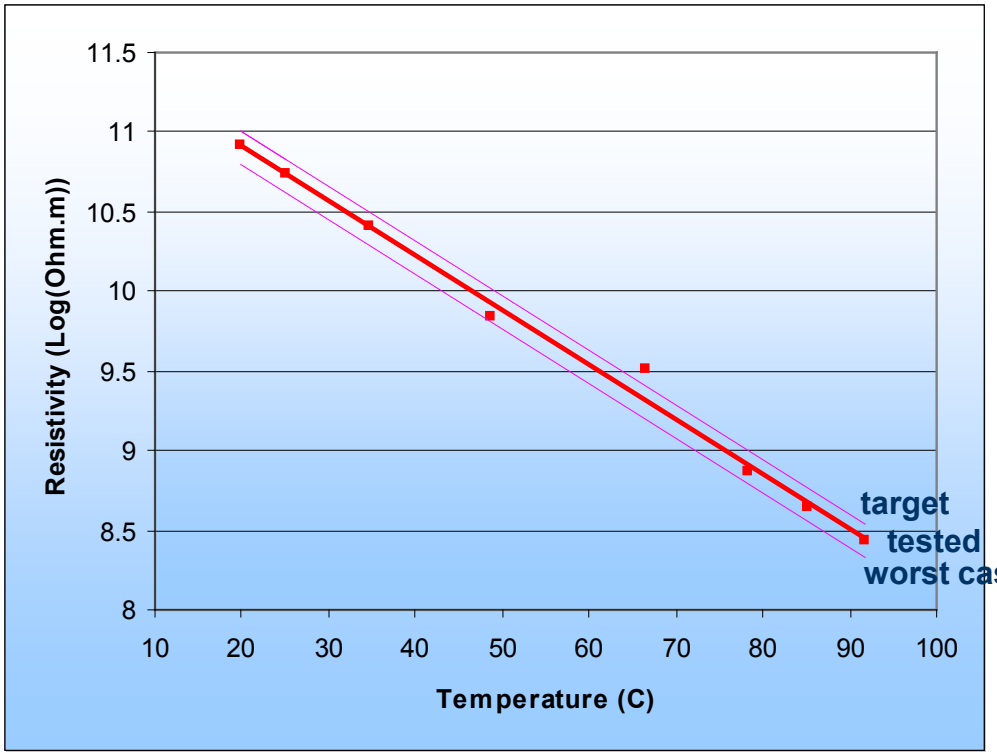
Dependence on FG Resistivity (cont'd)

- Front glass bulk resistivity can be the dominant term controlling WLR
- Requirement to front glass (FG)
  - High resistivity: >1e11Ohm·m recommended
  - Validated tight run-to-run quality control
    - Requires composition control and resistivity monitoring

Applied Materials Confidential

T Dependence of FG Resistivity

- FG resistivity is known to have an exponential temperature dependence[1]
  - Roughly, every 25 degree temperature variation results in a 10x glass resistivity change



Glass resistivity vs. temperature

[1]E. Guyer, Electrical Glass, Proceedings of the IRE, December 1944, p. 743-750

Applied Materials Confidential

APPLIED MATERIALS

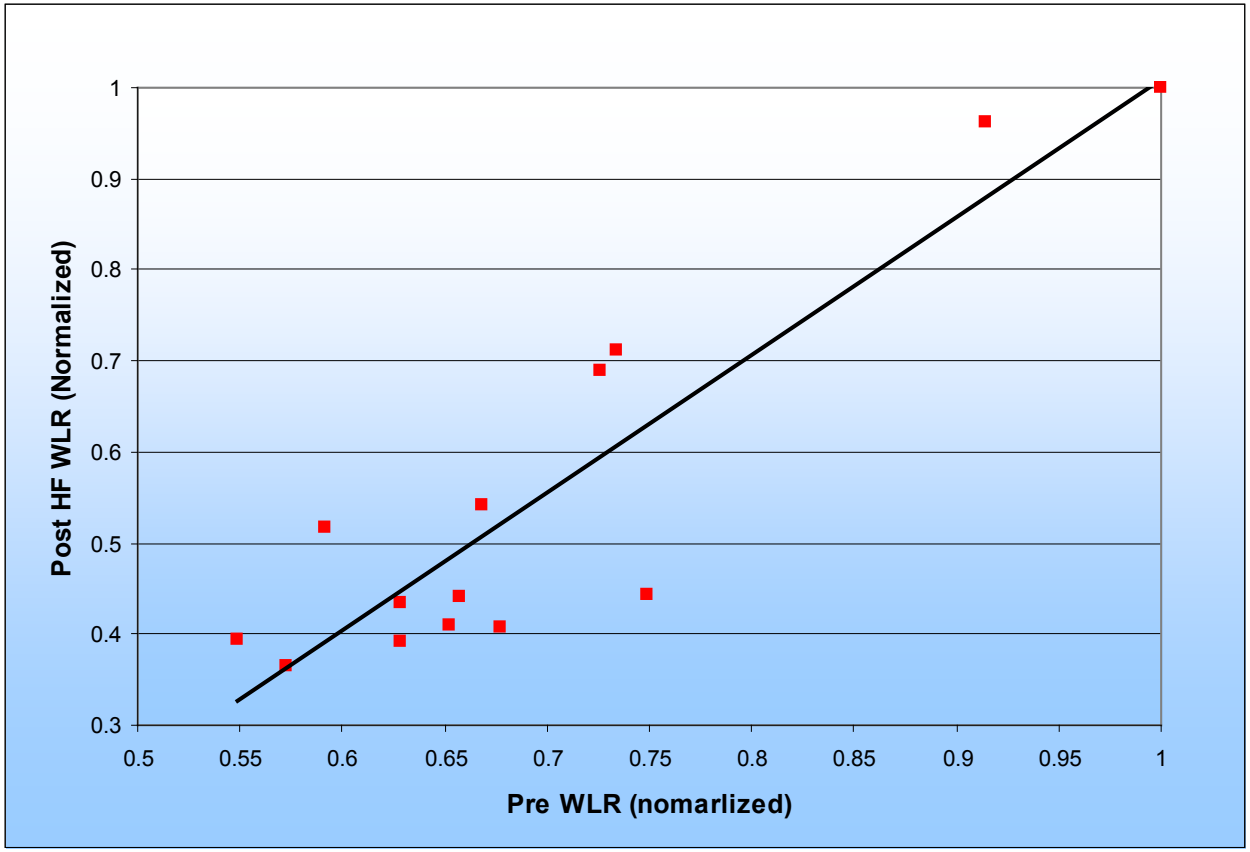
FG Resistivity Spec Considerations

- **IEC spec mandates all components meet 40 MOhm.m^2 at 25°C**
  - If FG were the only component w.c. value of $10^{10.1}$ will apply
- **FG resistivity spec needs to allow for several components:**
  - Partitioning of the leakage budget across all leakage paths
    - Reserve 1/3 of conductivity budget each for FG, edges and BS ($10^{0.5}$).
  - Margin for drift in resistivity over environmental exposure ($10^{0.2}$)
  - Margin for process variation
    - 2X variation margin is recommended ($10^{0.2}$).
  - **Net spec is $10^{(10.1 + 0.5 + 0.2 + 0.2)} = 10^{11 \pm 0.2}$**

Applied Materials Confidential

APPLIED MATERIALS

Degradation post HF Stress Test



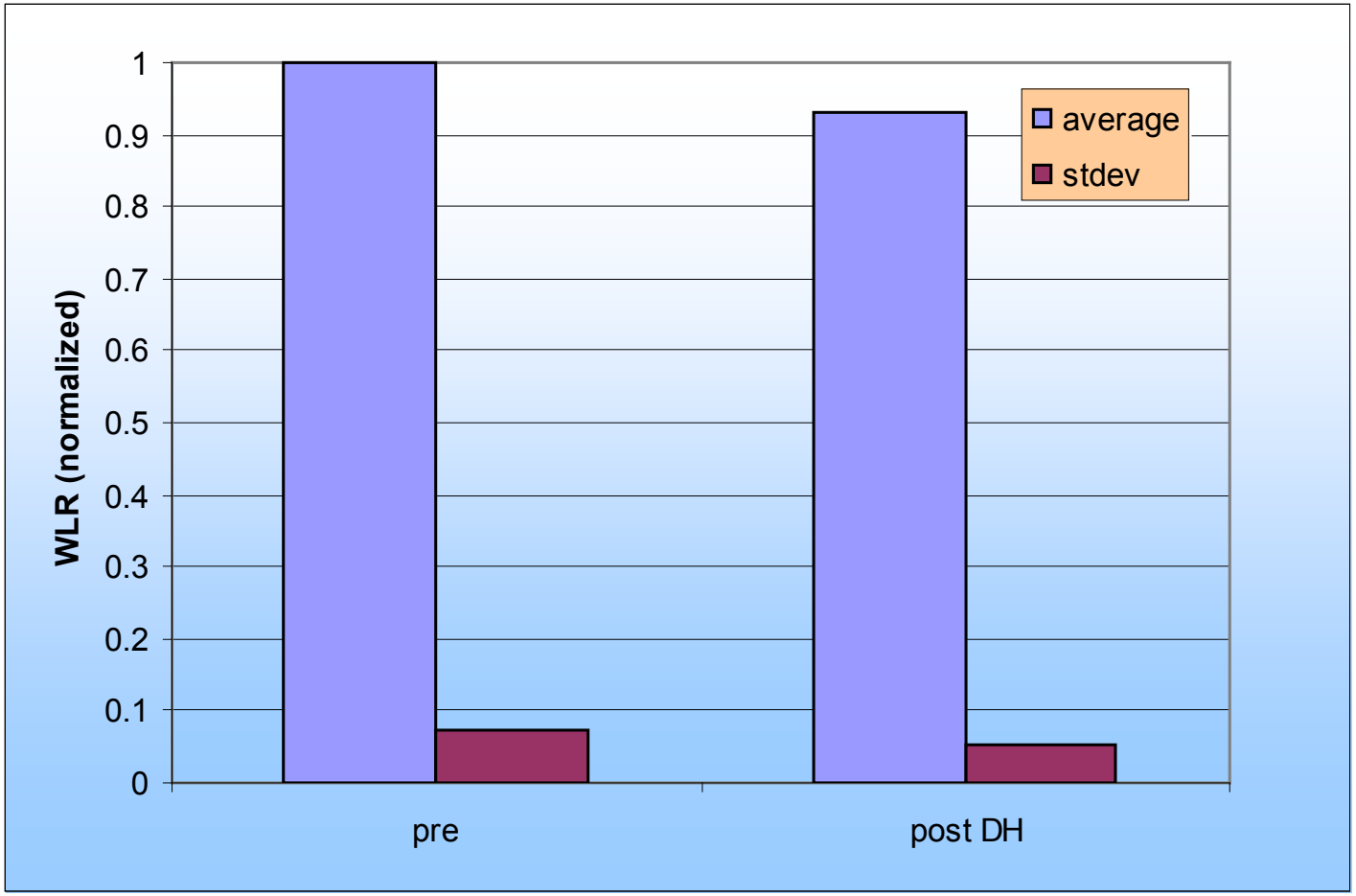
Correlation of WLR pre and post HF

Higher initial WLR correlated to higher post stress WLR

Applied Materials Confidential

APPLIED MATERIALS

Degradation post DH Stress Test



WLRs of the modules (front glass bulk resistivity = 10.7 log(MOhm.m)) post DH

Applied Materials Confidential

APPLIED MATERIALS

Degradation post Stress Tests

- **WLR degradation post stress tests from moisture uptake**
  - **~ 10% WLR reduction post DH**
- **Higher initial WLRs → more margin for environmental exposure**
- **Higher FG resistivity → higher initial WLRs**
- **Recommendation: FG bulk resistivity: > 11.0 Log(Ohm.m)**
  - ***Delivers WLR with an appropriate margin passing industrial standards after stress tests.***

Applied Materials Confidential

Conclusions

- *WLR is an important safety indicator, which is affected by all encapsulating components of the module*
- *The segmentation test can be used to identify the component leakage paths for initial WLR*
- *Initial WLR has a strong correlation with front glass resistivity, which is highly temperature accelerated*
- *WLR degraded after stress tests due to moisture penetration and the modules with higher initial WLRs resulted in higher post stress WLR*
- *Front glass with bulk resistivity higher than 10.8 Log(Ohm.m) is expected to have module WLR with an appropriate margin passing the industrial standards*

Applied Materials Confidential



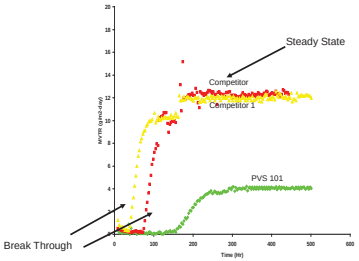
Solar Edge Sealants with a Better Balance of Properties

Rahul M Rasal and Paul E Snowwhite
ADCO Products Inc.

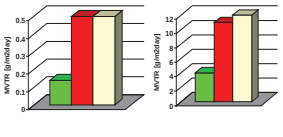
INTRODUCTION

Photovoltaic (PV) modules demand solar edge sealants with a better balance of surface (tack and reactivity) and bulk (thermal, mechanical, and barrier) properties. The major objective of this research was to develop solar edge sealants that chemically react with glass and show better thermal stability, mechanical properties, and moisture vapor transmission resistance (MVTR). The glass – edge sealant chemical adhesion was characterized using lap shear testing. Thermal stability was characterized using gravimetric method and mechanical properties were characterized using tensile testing. MVTR was measured using MOCON.

WATER INGRESS



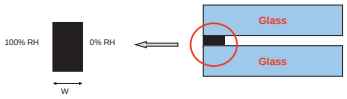
Sample spectra at 85 ºC and 100% RH



MOCON Method
Surface Area: 38 ºC: 50 cm²
85 ºC: 20 cm²
Thickness: 0.060 - 0.080 inch

Longer break-through time and lower steady state MVTR for PVS 101.

FICKIAN 1-D DIFFUSION MODEL



Boundary Conditions

at X = 0; $C_w = C_s$
at X = W; $C_w = 0$

Fickian 1-D Diffusion Model

MVTR = D (dc/dx)
MVTR = D (Cs/W)

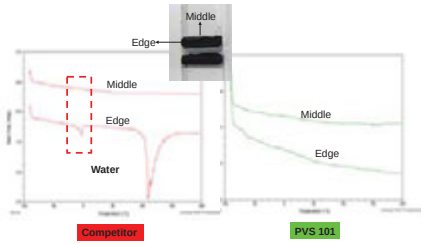
MOCON PVS 101 ⟹ **Steady state 38 ºC diffusivity for PVS 101 = 5.6E-7 cm²/sec**

MOCON Competitor ⟹ **Steady state 38 ºC diffusivity for competitor = 2.0E-6 cm²/sec**

~42% reduction in width will theoretically match performance of competition assuming a linear relationship in temperature. We recommend 25% as a conservative buffer.

DSC: MOISTURE INGRESS CHARACTERIZATION

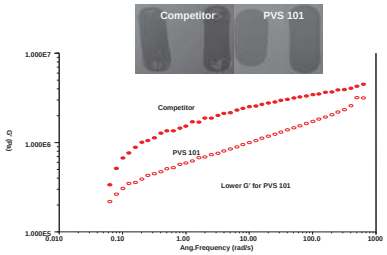
Lap shear samples, aged 4 weeks in a damp heat chamber
DSC: Differential Scanning Calorimetry



Longer break-through time for PVS 101.
Differential Scanning Calorimetry verified MOCON results.

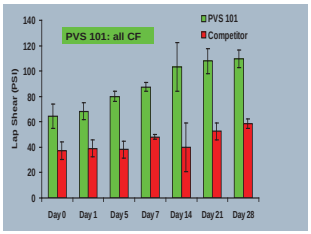
RHEOLOGY: WET OUT

Small Amplitude Oscillatory Stress Experiment: 100 Pa Shear Stress using 8mm diameter plates at 80 ºC

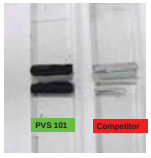


PVS 101 rheology has been engineered to exhibit improved wet out.

ADHESION TO GLASS



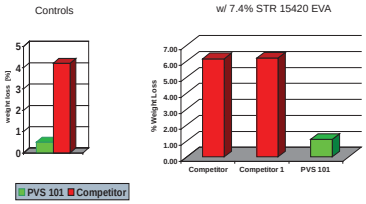
CF = Cohesive Failure



PVS 101 rheology and surface properties have been tuned to result in cohesive failures.

PVS 101 – EVA COMPATIBILITY

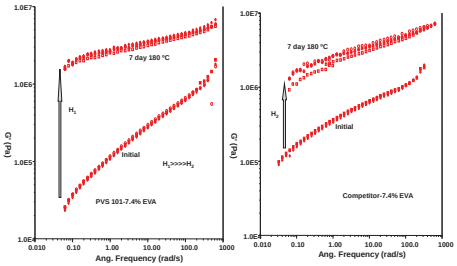
% weight loss upon 180 ºC air circulated oven treatment for 72 h



PVS 101 exhibited superior thermo-oxidative stability by itself as well as in the presence of fast cure EVA.

RHEOLOGY: PVS 101 – EVA COMPATIBILITY

Small Amplitude Oscillatory Stress Experiment: 100 Pa Shear Stress using 8mm diameter plates at 80 ºC



PVS 101 showed a greater potential to crosslink when exposed to EVA at 180 ºC.

CONCLUSIONS

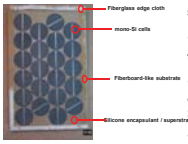
- PVS 101 has been designed to exhibit a superior MVTR as characterized using MOCON and DSC
- PVS 101 binds chemically with glass and the bonding strength increases with time
- PVS 101 rheology has been engineered to exhibit improved wet out
- Superior compatibility with EVA

ACKNOWLEDGEMENTS

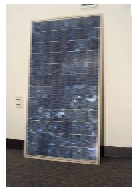
The authors thank Justin Bates, Harald Becker, Dennis Booth, Jim Wood, Kathy Lamb, Haewon Uhm, Paul Ruede, Lindsay Walliczek, Sam Ward, and Heike Brücher for their help.

The Reliability and Durability of Novel Silicone Materials for Photovoltaic Encapsulation

Yi Kang, Barry Ketola, Keith McIntosh, Don Juen, Ann Norris, Mary Kay Tomalia, Christopher Shirk,
Dow Corning Corporation, Midland, Michigan USA



- Module encapsulated by Silicone rubber as superstrate, fiberglass as substrate with potted junction box.
- Modules operated over 27+ years in the hot desert condition.
- ~70% of modules still functional operating, average power drop about 30% from its power rating.
- No notable delamination of the superstrate and busbar corrosion observed even after additional stress tests applied.



- Module from solar array at BP Solar in Frederick, Maryland.
- These modules were encapsulated with silicone only without backsheet.
- Modules still delivery > 90% of nameplate rating after 15 years operating and 10 years storage.
- No evidences show corrosion and yellowing.

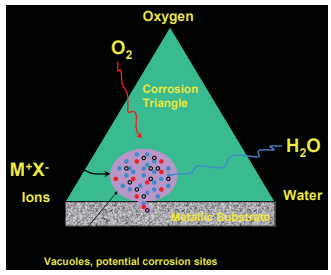


- SunPower Module with PV-6100 Series encapsulant made by 2009
- Fully-automated dispensing & cell-placement

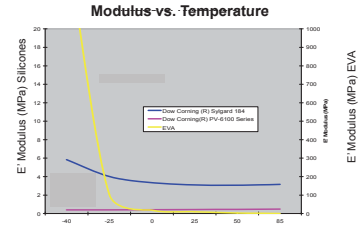
Silicone properties make them ideal candidates as encapsulants for photovoltaic modules

General Silicone Composition and Optical Properties

• Excellent UV-visible transmittance	250 to 900 nm
• Good near-IR transmittance	1000 to 1600 nm
• Tunable refractive index	1.38 to 1.58
• Range of dn/dT	–2 … –5×10⁻⁴ °C
• Low modulus/Low T_g	
• Variety of cure chemistries available	
• Addition cure, Pt catalyzed	
• Condensation cure	
• Excellent environmental stability, no change in properties:	
•High temperature stability (150 °C continuous)	
• Low moisture pick-up (<0.05%)	



Modulus vs. Temperature



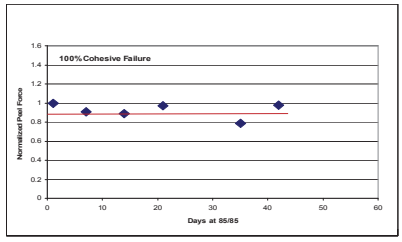
Silicones can be formulated to be low modulus over a very wide temperature range due to the very low T_g. Whereas EVA and other organic polymers have higher modulus at low temperatures.
Low modulus promotes stress relief in encapsulation applications.

Dielectric Properties-Silicones are known for having good electrical insulating properties

Material	Dielectric strength, V/mil	Thickness, mils (mm)	Break through voltage, kV
PV-6100 Series	720	21 (0.53)	15.1
EVA	907	17 (0.43)	15.4

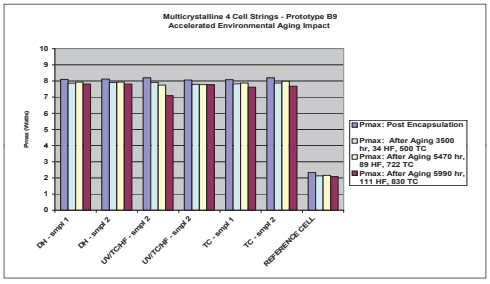
Partial Discharge Test For Silicone Encapsulation

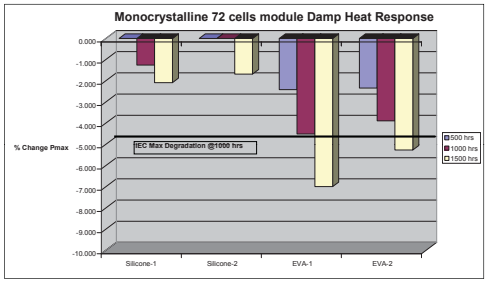
Sample	Corrected Extinction Voltage	Results
Tedler (25 micro) /Polyester(15mil)/Silicone #1	1220	> EU Rated
Tedler (25 micro) /Polyester(15mil)/Silicone #2	1058	> EU Rated
PET Backsheet (50 micro)/Polyester(15mil)/Silicone #1	1098	> EU Rated
PET Backsheet (50 micro)/Polyester(15mil)/Silicone #2	1165	> EU Rated
Silicone #3/Polyester (15mil)	1019	> EU Rated
Silicone #3 (30mil)	No Break Down	> EU Rated
Silicone #2 (30mil)	No Break Down	> EU Rated

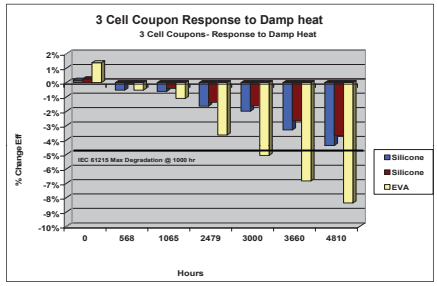


Silicones can be formulated to show only cohesive failure after 1000 hours of 85/85 exposure, no drop in peel force

Silicones encapsulant has better reliability and durability over EVA







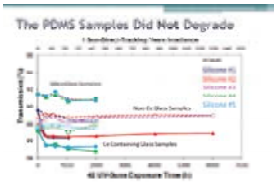
IEC 61215 Certification

- Passed UV Exposure/Temperature Cycling 50/ Humility Freeze 10 in TUV-PTL.
- Passed Damp Heat (85C/85%) 1000 hours in TUV-PTL.
- Passed Mechanical load after DH1000 test in TUV-PTL.
- Passed Thermal Cycling 200 cycles internally.
- Passed Outdoor exposure/ Hot spot tests in TUV-PTL.
- Passed Fire Test (Class C) in Western Fire Center Inc.
- Full IEC 61215/61730/UL1703 engineering evaluation on going in TUV-PTL.

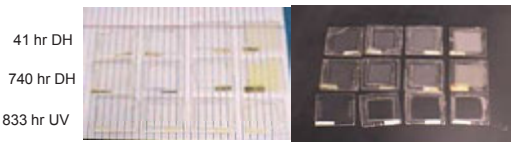
Extended Aging Beyond Certification

- The Dow Corning® PV-6100 Encapsulant Series has passed IEC 61215 specifications even up to 500 Thermal Cycles on full size modules.
- The Silicone encapsulant has been approved under "Fast thermal cycling (-30C ~ 60C)" test up to 2000 cycles on 2 cells coupons and will continue to end.
- Silicone encapsulated PV modules have been passed up to 4800 hours damp heat (85C/85%) on 3 cells coupons and passed 1500 hours on full size modules.
- Two Silicone encapsulated PV systems are operation in Michigan's four season climate. Other installations are planned in other regions.



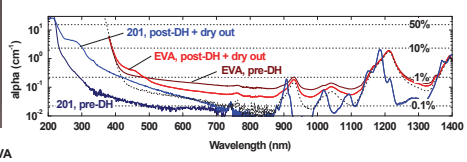


* By Michael Kempe's (NREL) presentation at ATLAS conference

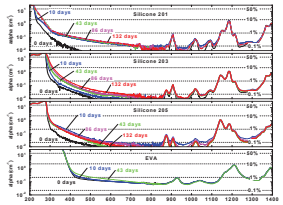


Silicone A Silicone B Silicone C EVA Silicone A Silicone B Silicone C EVA

Comparison of alpha before and after damp heat aging



Alpha Response to 30X roof top concentrator @ ANU





EVA charred after 86 days on 30X tracker

The information provided in this presentation does not constitute a contractual commitment by Dow Corning. While Dow Corning does its best to assure that information contained in this presentation is accurate and fully up-to-date, Dow Corning does not guarantee or warranty the accuracy or completeness of information provided in this presentation. Dow Corning reserves the right to make improvements, corrections and/or changes to this presentation in the future.

DOW CORNING Solar Solutions

Unleash the power OF SILICON

www.dowcorning.com/solar



Accelerated electro-chemical delamination test for the durability of transparent conductive oxide (TCO) glass

Yu Wang[1], Satoshi Tanaka[2], and David Strickler[1]

NSG Group, Building Products R&D, On-Line Coating Technology

[1]Pilkington, Northwood, OH, USA; [2]NSG, Itami, Japan

Introduction

The electro-chemical delamination (ECDL) test was developed as an accelerated method to evaluate the propensity of the TCO delamination from the glass substrate. [1],[2] The test (~ 0.5 hour) involves heat and voltage bias to rapidly drive Na^+ ion from the glass to the TCO layer to generate stress, which eventually results in cracking of the coatings (Fig. 1.) The ECDL performance relies on test temperature, humidity, and polarity, which also affect the durability of a PV system. The objective of this test is to evaluate if TCO glass can survive the 20 years of warrantee time of the PV module. [3],[4] However, non-standardized test procedure and a lack of database relating the ECDL results to TCO long-term performance make it difficult to fulfill this goal. Future work with the collaboration between TCO glass manufacture and PV module developer is a necessity to improve this TCO adhesion test.

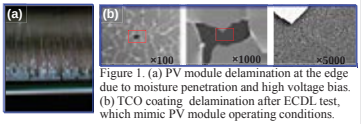


Figure 1. (a) PV module delamination at the edge due to moisture penetration and high voltage bias. (b) TCO coating delamination after ECDL test, which mimic PV module operating conditions.

Test methodology

The schematic diagram of ECDL test equipment is shown in Fig. 2, which includes a hot plate and a voltage source to rapidly drive Na^+ ion from the glass substrate to the TCO layer. The general test procedure includes the following steps:

- the sample is heated at 185 ˚C and a 100 V positive bias voltage is applied to the non-coated side for 15 min;
- the sample is then kept at room temperature within a humidity chamber (50% RH);
- after 5 min in the humidity air, the TCO coating is scratched with a razor blade to generate a path for water vapor to reach the TCO/glass interface. Scratching also creates defects that initiate delamination in damaged coatings;
- observation of the scratched coatings within the following 10 min differentiates coatings with bad adhesion from the good ones.

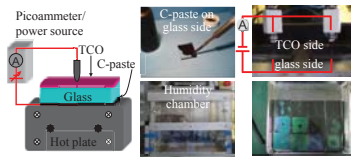
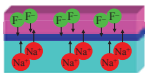


Figure 2. (a) Schematics of ECDL test instrument. (b) Photographs of the ECDL setup and the test procedure.

Results

❖ **Analysis of delaminated samples reveals the weak interface:**

Why coating delaminates after ECDL test?



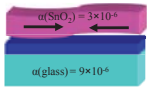
Under positive bias, alkaline ions in glass and F^- in SnO_2:F were driven towards TCO/glass interface:

(a) Chemical reactions at interface decrease interface adhesion: [1]

$$F^- + H_2O \rightarrow HF + OH^-$$
$$6HF + SiO_2 \rightarrow H_2SiF_6 + 2H_2O$$
$$Na + H_2O \rightarrow NaOH + H$$
$$SnO_2 + 4H \rightarrow Sn + 2H_2O$$

(b) Due to different thermal expansion coefficient ($\Delta\alpha$) between glass and SnO_2, compress stress is built up in the coating when it is cooled down, for instance, from ~550 ºC to ~20 ºC.

When compression stress in the TCO coating becomes larger than the interfacial adhesion, coating delaminates: [5]

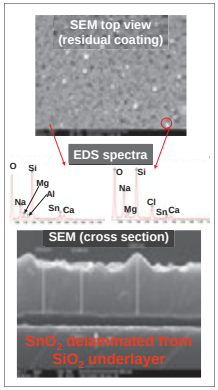


Mismatch strain:

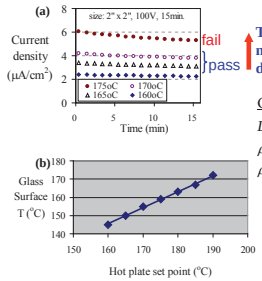
$$\varepsilon = \Delta\alpha \cdot \Delta T$$

Mismatch stress is ~0.98 GPa:

$$\sigma_{therm} = E \cdot \varepsilon / (1 - \nu)$$



❖ **ECDL test result is sensitive to test conditions that determine the total amount of charge passing through the TCO/glass interface (Fig.3.)**



Temperature ↑, mobility of alkaline ion↑, delamination current↑.

Glass resistivity vs. Temp:

$$Log\rho_{(T)} = A + B/T$$

$\rho_{(T=175\,^oC)} \sim 6.3 \times 10^8$ ohm-cm

$\rho_{(T=160\,^oC)} \sim 3.2 \times 10^8$ ohm-cm

Figure 3. (a) Delamination current density at different glass surface temperature. (b) Temperature difference between glass surface and hot plate surface.

❖ **Improve reliability of the test results:**

- standard equipment setup with regular calibration;
- consistent test procedure;
- clear definition of failure;
- optimized procedure, such as scratching the coating [6] after ECDL test (Fig. 4.).

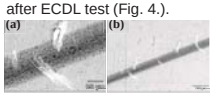


Figure 4. (a) SEM of razor blade scratch after ECDL. (b) SEM of the same area of the coating after 7 days.

❖ **Enhance the TCO adhesion to glass substrate:**

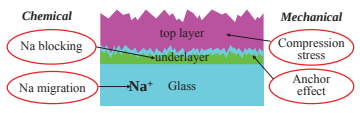
- Chemical approach to minimize alkaline ion transfer – glass resistivity (Fig. 5), Na blocking layer; [7]
- Mechanical approach to increase interface strength (Fig. 6), and decrease stress in TCO coating.

Sample	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	CaO	MgO
clear	72.0	1.9	0.1	**13.0**	**1.2**	7.6	4.0
low iron	72.0	1.8	0.0	**14.0**	**0.0**	7.6	3.8

SiO_2/ITO by sputtering

ITO
SiO_2
glass

resistivity	low iron	mixture	clear
	low	medium	high
100V	fail	pass	pass
50V	pass	pass	pass



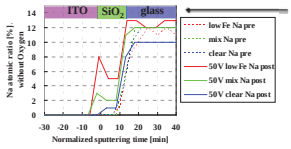


Figure 5. XPS step profile of Na distribution before and after ECDL test on different glass substrate.

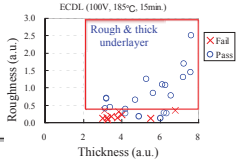


Figure 6. Effect of underlayer thickness and roughnesss on SnO_2 adhesion. [8]

Conclusions

ECDL test has been demonstrated to be an effective method for screening TCO/glass adhesion property (Fig. 7), especially in the case when the TCO glass is subjected to high voltage during normal PV module operation. SEM and XPS analysis on delaminated coating shows Na^+ migration from glass to TCO layer plays a key role in diminishing interfacial bonds, which eventually leads to the detachment of the coating from glass substrate. Based on the understanding on delamination mechanism, two approaches were proposed from chemical and mechanical perspectives to limit Na^+ transport, and to increase interface strength. The high sensitivity of the test results to ECDL test conditions, especially to temperature, also reveals the challenge in establishing a common base for direct comparison of TCO adhesion.

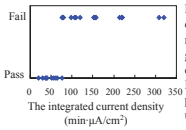


Figure 7. Integrated current density per unit area shows how much charge passes through the glass/TCO interface. A threshold charge can be calculated from the ECDL test, which can be used to predict the lifetime of the coating under normal condition.

Literature cited

[1] K.W. Jansen, and A.E. Delahoy, *Thin Solid Films* 423 (2003), 153–160.

[2] D. E. Carlson, R. Romero, F. Willing, D. Meakin1, L. Gonzalez, R. Murphy, H. R. Moutinho and M. Al-Jassim, *Prog. Photovolt: Res. Appl.* 11 (2003), 377–386.

[3] C.R. Osterwald, T.J. McMahon, and J.A. del Cueto, *Solar Energy Materials & Solar Cells* 79 (2003), 21–33.

[4] B. Nghiêm, and D. Le Bellac, *Int. J. Nanotechnol.*, Vol. 6, No. 9, 2009, 870-878.

[5] J. Chen, Z. Lin, S.J. Bull, C.L. Phillips, and P.D. Bristowe, J. Phys. D: Appl. Phys. 42 (2009), 214003.

[6] K.W. Jansen, A. Varvara, E. Twesmea, T. Berensa, and N.G. Dhereb, *Proc. of SPIE* Vol. 7048 (2008), 70480M-1.

[7] R.-Y. Tsai, F.-C. Ho, and M.-Y. Hua, *Opt. Eng.* 36 (8) 1997, 2335-2340.

[8] A.Fujisawa, M. Nara, M. Hirata, K. Kiyohara and M. Hyodo, Proc. of 3rd World Conference on Photovoltaic Energy Conversion (2003), 1745.

Acknowledgments

The authors thank Dr. K. Jansen for his suggestions on optimizing test procedure, Dr. N. McSporran for providing glass resistivity data, Dr. P. Warren for stress estimation, and Dr. M. Soubeyrand, Mr. G. Nichol, Dr. M. Hirata for inspired discussions.

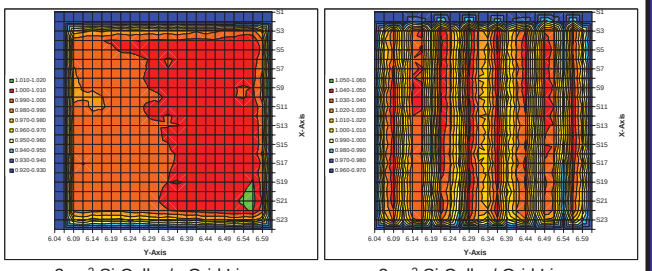
For further question

Please contact Yu Wang at: *yu.wang@nsg.com.*

Analysis of CPV Optical Components Using an LBIC System

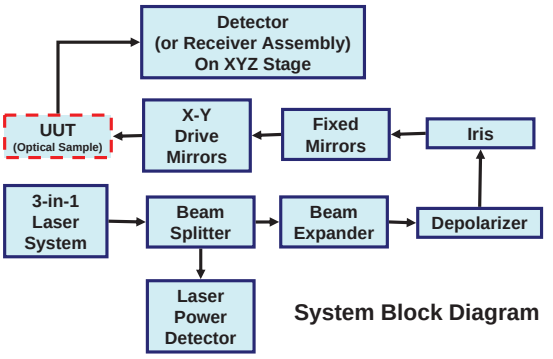
(LBIC: Light Beam Induced Current)

by Mike Sumner, Damien Buie, Igor Kozin & James Foresi (EMCORE Corp.)



2cm² Si Cell w/o Grid Lines — 2cm² Si Cell w/ Grid Lines

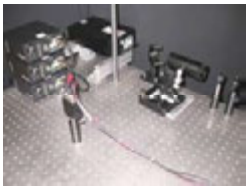
Demonstration of System Resolution



System Block Diagram

Potential Uses of an LBIC Measurement System

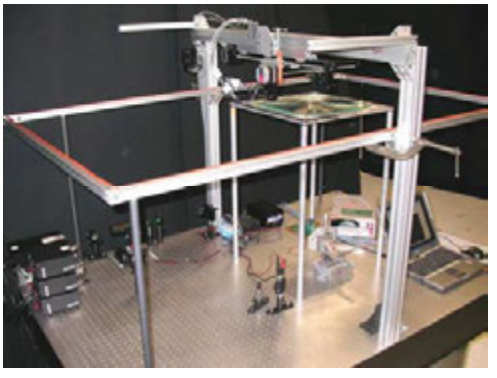
- Measuring performance and locating defects in a Fresnel lens
- Measuring performance and locating defective regions in a triple junction cell
- Measuring the performance of an optical component before and after stress or exposure tests
- Physical measurements of optical assemblies to validate optical models and designs



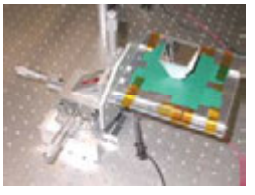
Laser, Splitter, Depolarizer & Iris



A/D Unit, PS & Motor Drive



LBIC System

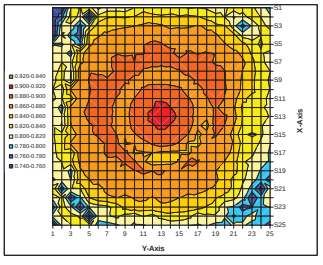


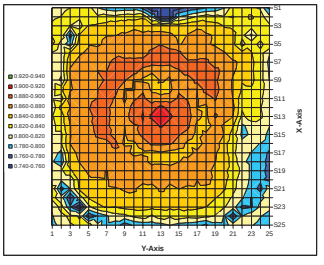
Detector (Receiver Assembly)

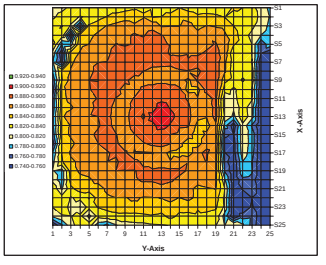


Beam Measurement H/W

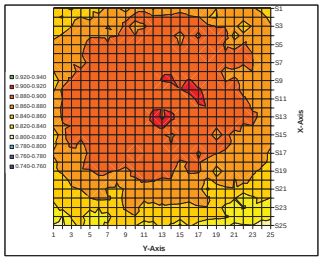








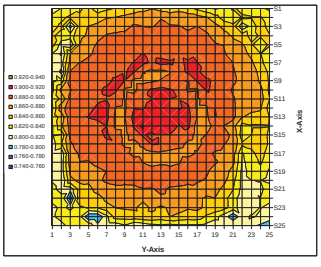
Examples of two "normal" Fresnel lenses and one "bad" Fresnel lens in a 3x5 module size parquet.

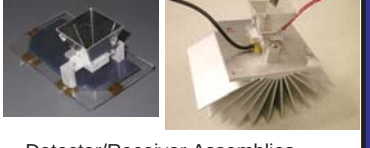


Acrylic Fresnel Lens ←

LENS	Transmission @ Center (%)	Transmission Grand Avg.
Acrylic Design	90.9	87.4
SoG Design	91.6	86.4

Silicone on Glass Fresnel Lens →





Detector/Receiver Assemblies

(used in validating optical models & designs)

Center for Sustainable Energy Systems (CSE)

25 First Street, Cambridge, MA 02141

Fraunhofer USA

An Approach Towards Light and Heat Management in PV Modules

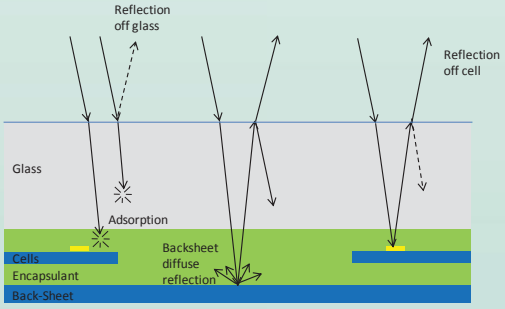
Matthias Dűll, Biao Li, Matthieu Ebert, Joachim Jaus, Carola Völker, and Dan M. J. Doble

Motivation – Quantification of Optical and Temperature Losses

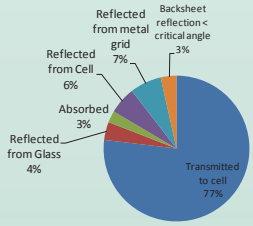
- PV Module energy output is limited by several factors on the module level.
  - Optical losses
  - Temperature losses
  - I^2R losses

Adsorber Type	Typical Temperature Coefficient % P_{max}/°C
mc-Si	-0.47
x-Si	-0.31
CIGS	-0.60
CdTe	-0.20
a-Si (triple junction)	-0.31

- Most modules have nominal operating cell temperatures (NOCT) in the region 50 to 60 °C
- Result is a significant loss in energy yield



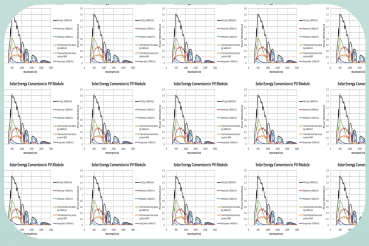
- A significant portion of light does not enter cells

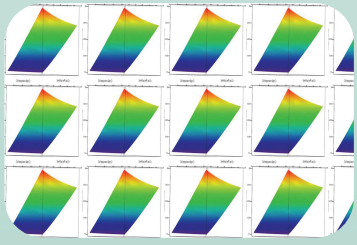


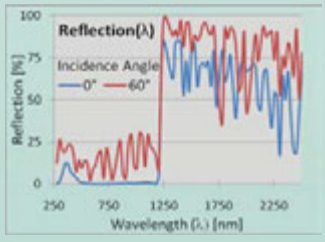
Assumptions: Incident sunlight, No ARC on glass, 4mm low Fe glass, 0.5mm EVA encapsulant, SiN ARC on untextured cells, 7.5% of cell area is metallization, 93% cell packing factor in module. Excludes frame and edges.
Note: Actual transmission to cell = 65% to >90% depending upon technology, architecture and orientation
References: S. Krauter, Solar Electric Power Generation, Springer 2005. K. McIntosh et al, 2009 PV IEEE, Philadelphia.

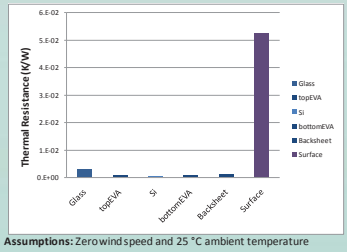
Computational Simulation and Testing of Solutions - Electromagnetic Wave Modeling

- Use computational model of electromagnetic waves from Maxwell's equations to predict light propagation and resulting energy dissipated in each layer.









Assumptions: Zero wind speed and 25 °C ambient temperature

- Optical losses are highly dependant on angle of incidence
- Greatest thermal resistance is at module surface

Experimentation - One Approach to Addressing Optical and Temperature Losses – Structured Glass

Module Temperature



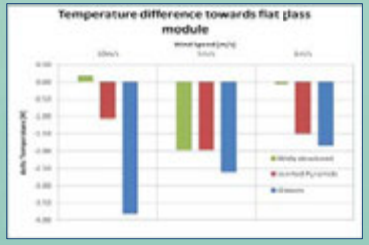
Module Fabrication

- Cells measured and sorted.
- Mini-modules assembled for the various glass structures using tabber –stringer and laminator
- Special modules fabricated that include foil heaters for wind tunnel testing.

Wind Tunnel Testing

- Constant power applied to heater in modules
- Module temperature measured as a function of wind speed and module tilt angle.

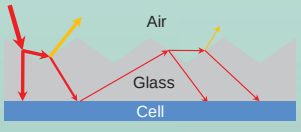




Results

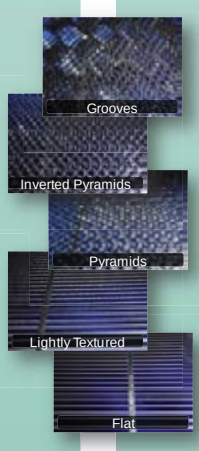
- Significant cooling observed for structured glass.
- Effect is highly dependent upon wind speed

Light Management



Theory

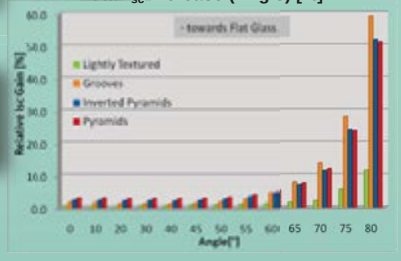
- Reflections are redirected by the structure, so that more light hits the cell.



Experimentation

- Module holder with tilt capability.
- Flasher with electronic load.
- Mini modules were tilted from 0˚ to 80˚
- I_{sc}, V_{oc}, FF, Eff. and angle were measured.





Results

- Structured glass has the has the capability of trapping more light.
- Effect becomes more pronounced at higher angles of incidence.

®2010 Fraunhofer CSE

25 1st St, Cambridge, MA 02141

Characterization and Reliability of Polymeric Components in PV Modules

Shuying Yang
SOLARIA CORPORATION
46420 Fremont Blvd.
Fremont, CA 94538
www.solaria.com



NREL Reliability Workshop

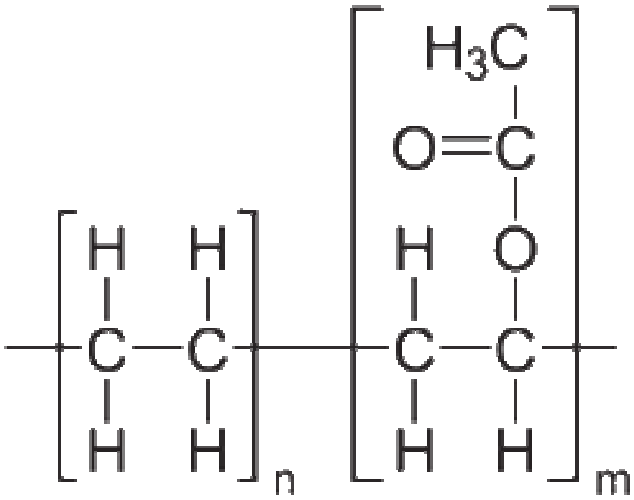
Feb 18-19, 2010

Reliability Requirement of PV Modules

- Normal warranty of PV modules
  - Varies per manufacturer. **Typical is 20-30 yrs* OUTDOOR**
- Harsh Environment. One or several combinations of following:
  - Direct Sunlight Exposure;
  - High Operating Temperature;
  - High Environment Temperature (hot area/deserts);
  - High Humidity;
  - Wind/Snow Load Stress;
  - Low Environment Temperature;
  - Thermal Cycling;
  - Salty Atmosphere in Coastal Area.

Critical Polymeric Components of PV Module Packaging

— Encapsulant (EVA, Ethylene Vinyl Acetate)



— Backsheet

- A multilayer protective back cover often contain PET and PVF or PVDF films.

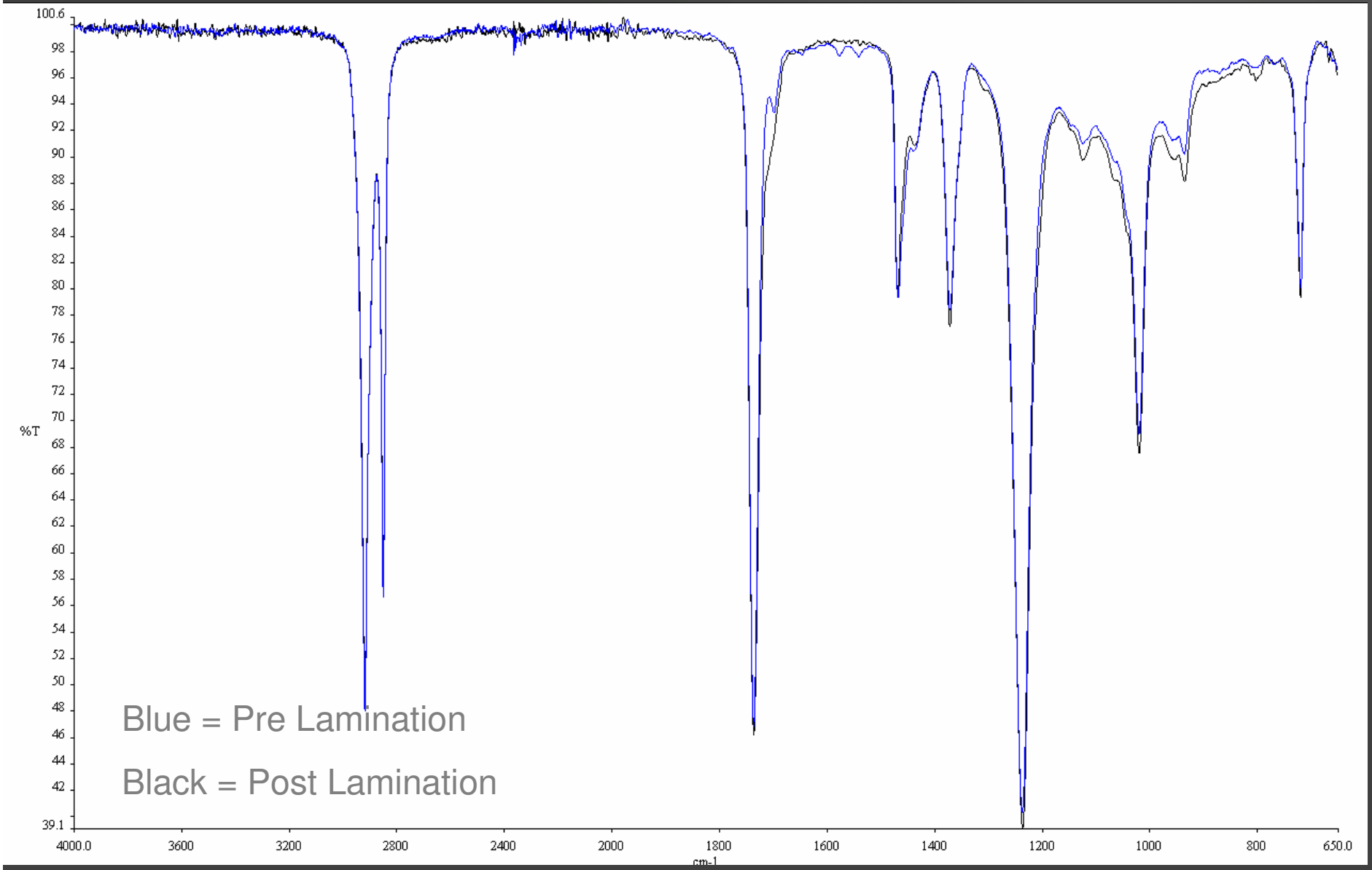
Characterization Techniques for EVA and Backsheet

- FTIR (Fourier Transform Infrared)
  - Chemical Compositions
  - Easy Technique for IQA;
- DSC (Differential Scanning Calorimetry)
  - Melting Points, Degree of Curing and Crystallization Behavior
  - Quick and Easy Technique for Production Control
- TGA (Thermo gravimetric Analysis)
  - Thermal stability
- Spectrophotometry
  - Transmission, Reflection, Haze, Yellow Index

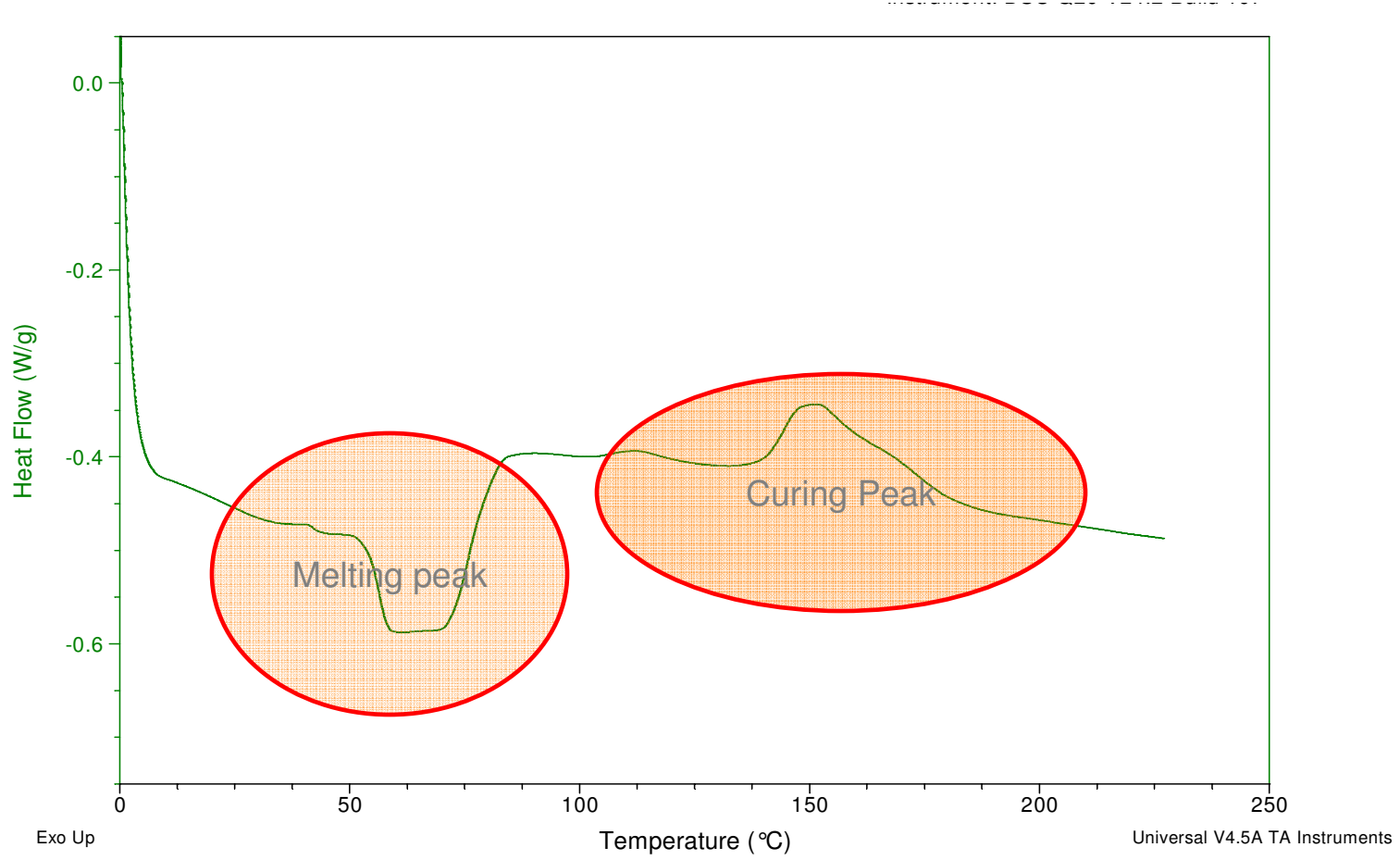
Other Characterization Techniques

- **Refractive Index**
  - For EVA
- **Mechanical Testing**
  - Tensile Testing (modulus, elongation to break);
  - DMA (Dynamic Mechanical Analysis);
  - TMA (CTE)
- **Peel Test**
  - For Adhesion Strength to Glass & Backsheet after lamination
  - Inter-layer Peeling Testing for Backsheet

Sample FTIR Curve of EVA

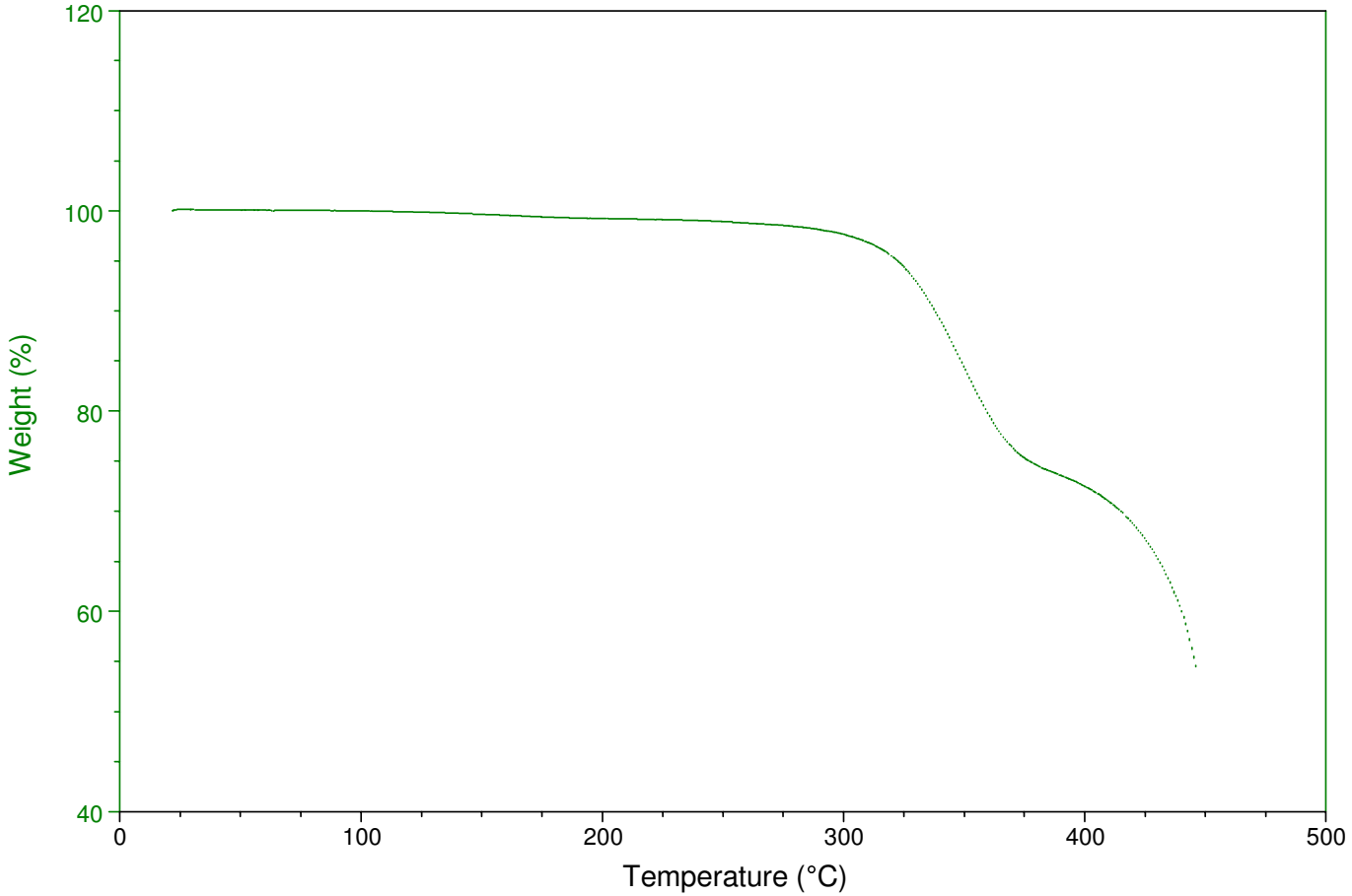


Sample DSC Curve of EVA



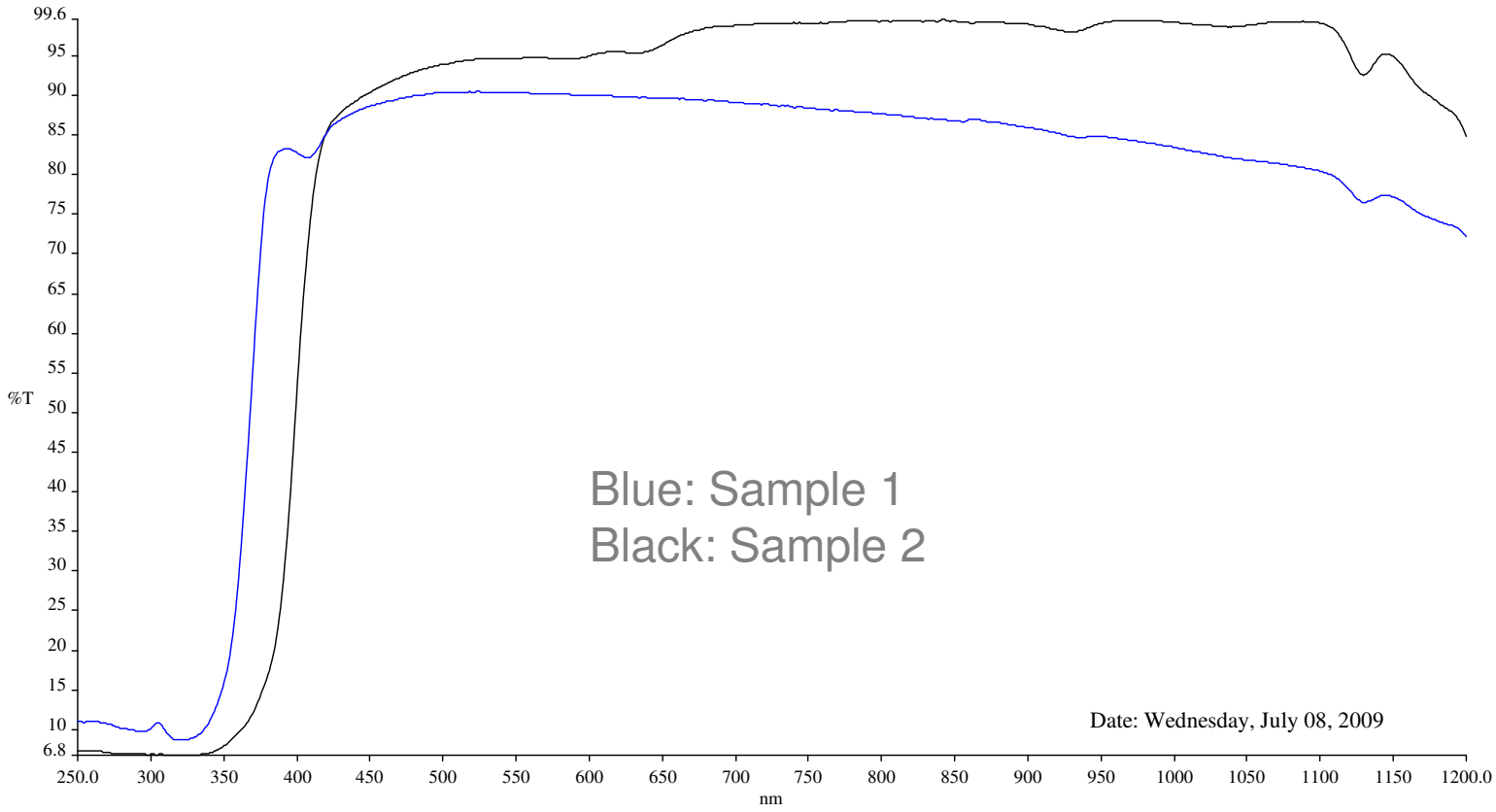
Replacement to Gel content measurement.
Melting peak will indicate batch to batch consistency.
Curing peak after lamination will shrink and determine degree of curing.

Sample TGA Curve of EVA: Thermal Stability



Proprietary and Confidential

Sample Backsheet Reflection Curves



Selection of material is based on higher reflectivity of a backsheet

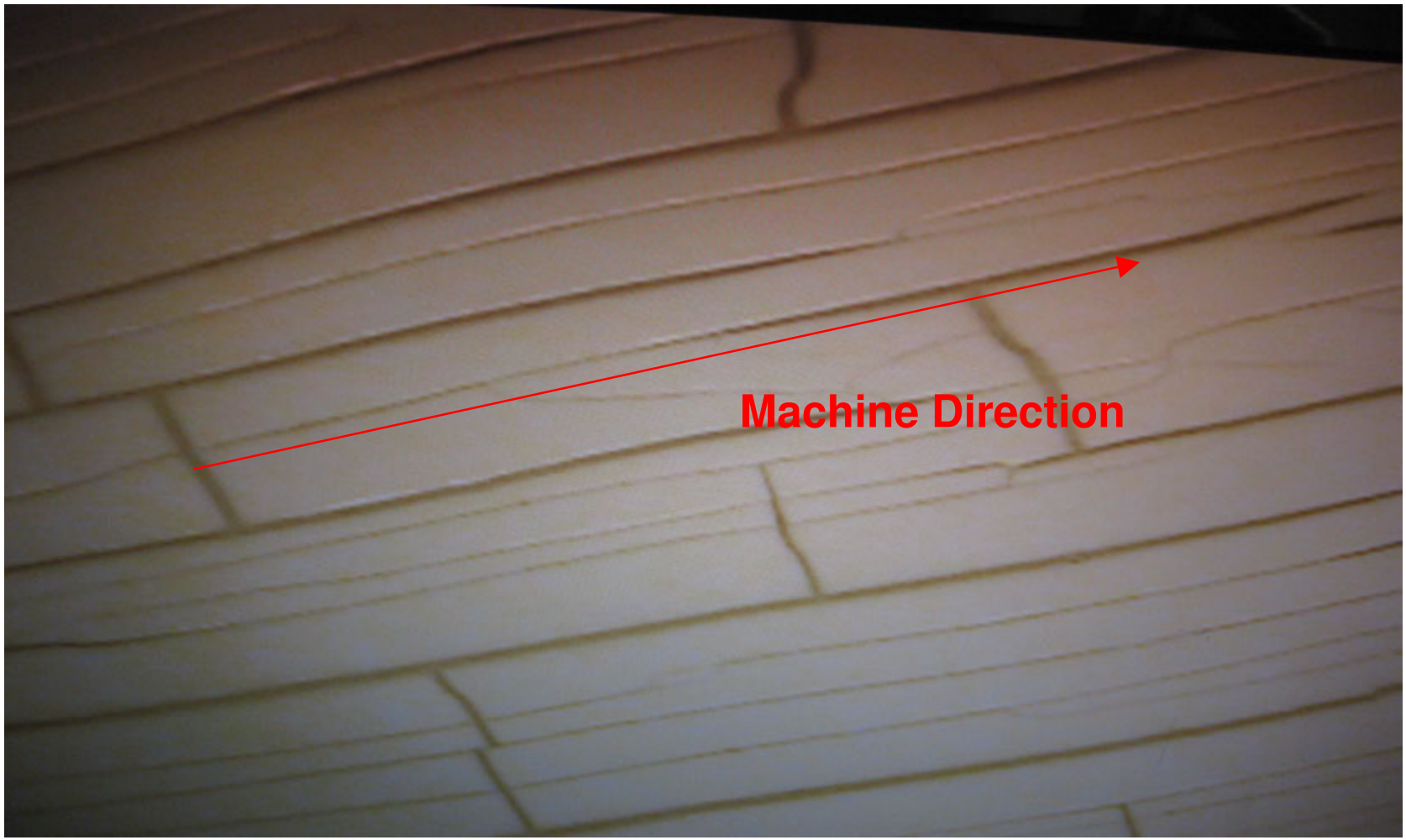
Aging / Reliability Study

- **Thermal Aging**
  - 95 ^{0}C – 105 ^{0}C. Long Term Bake of ~ 1000 hrs.
  - Used to differentiate quality of materials.
- **Damp Heat (DH)**
  - 85 ^{0}C / 85 % RH for >1000 hrs
- **UV aging**
  - 0.72W/m^2 for 1000 hrs @ 60 ^{0}C
- **Temperature Cycling**
  - -40 ^{0}C – 85 ^{0}C for >200 Cycles
- **Outdoor exposure**
  - For >6 months in CA sun

Typical Failure Phenomena After Aging

- Common Aging tests are UV Exposure, Damp Heat, Temperature Cycling and Humidity Freeze
  - EVA
    - Yellowing Index ⇧
    -
    - Cracking; ⇧
    - Haze: haze value ⇧
    - Transparency: ⇩
  - Backsheet
    - Inner layer Yellowing; ⇧
    - Inner layer& PET layer crack; ⇧
    - Reflection decreases; ⇩

Cracked Backsheet After UV Aging



Conclusion

- IEC tests does not help differentiate reliability performance of different components in a solar module.
- Through multiple test conditions and combination of these test, which are realistic in replicating actual environment, it is possible to differentiate reliability performance of materials from different vendors.

Comparative Study of the Long-Term Performance and Reliability of three different Photovoltaic Systems installed in Florida

FSEC

Nicoleta Sorloaica-Hickman, Kris Davis, Albert Leyte-Vidal, Florida Solar Energy Center
Sarah Kurtz, Dirk Jordan, National Renewable Energy Laboratory

NREL

Introduction

Accurate and consistent evaluations of photovoltaic (PV) system performance are critical for the continuing development of the PV industry. Scientists from NREL and FSEC developed a strong collaboration in order to improve the operation, sizing, electrical and economical output of photovoltaic power systems and subsystems by analyzing and disseminating information on their performance and reliability, providing a basis for their assessment, and developing practical recommendations. The collaborative project between NREL and FSEC is focusing on utilizing FSEC's existing PV system database to establish degradation rates of the PV modules and validate the energy rating models.



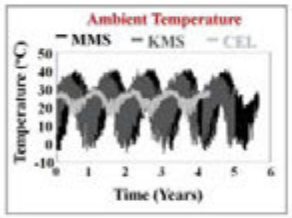
Measurement Selection

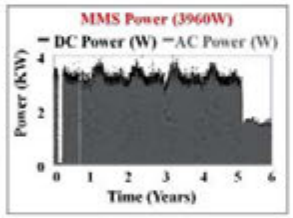


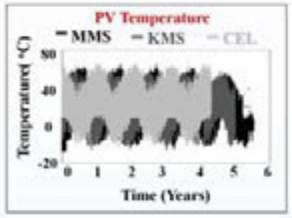
CR10 Datalogger for all PV systems with:
- Type-T Thermocouple wire
- Licor LI200 pyranometer
- Empro current shunt - DC current
- Voltage divider- DC Voltage
- IMS meter with pulse output - AC Power

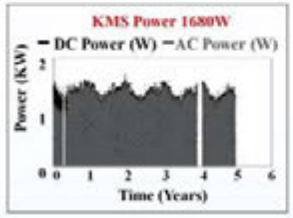
Photovoltaic Systems Characteristics

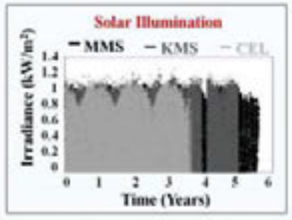
PV System	Location	Size (W)	Technology	Install Date	PV Manufacture	Inverter	Years	Azimuth and Tilt
MMS	Florida	3960	multi Si	2/5/03	Sharp NEQ5E2U	SMA-2500U	6	180° South; 25°
KMS	Florida	1680	mono Si	1/15/04	Shell solar SP 140	SMA-2500U	5	180° South ; 17°
CEL	Florida	3960	multi Si	12/8/03	Sharp NEQ5E2U	SMA-2500U	4	225°West of South ; 15°

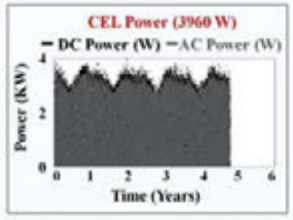












PVUSA power rating analysis (AC, DC)

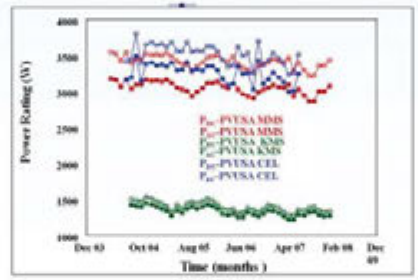
$$P = I_{POA}(a + bI_{POA} + CT_{amb} + dW)$$

Collect $T_{Ambient}$, Irradiance, DC and AC Power on all PV Systems data one-month blocks of 15-minute intervals

500 W/m²<Irradiance<1200 W/m²
-10 °C <T_a<60°C
P_{AC}>(75% of the P_{STC}) *Irradiance

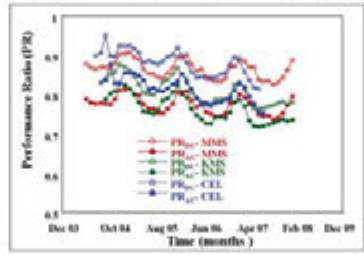
Ignore Data

Calculate the regression coefficients and the Power Rate (W) at Illumination of 1000 W/m² and temperature of 20°C



Performance ratio analysis

The performance ratio is defined as the relationship between the actual returns and theoretically potential energy returns of a Photovoltaic system. The performance ratio is an appropriate valuation criterion for determining the quality of the solar system.

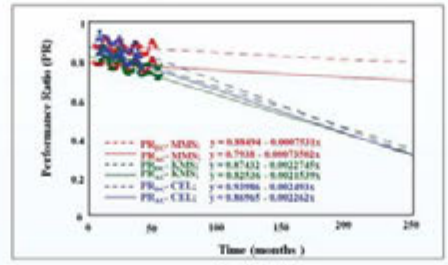


$$Y_f\left(\frac{kWh}{kW}\right) = \frac{E_{array}(kWh)}{P_{STC}(kW)};$$

$$Y_r(hours) = \frac{H_{POA}(kWhm^{-2})}{G_{STC}(kWm^{-2})};$$

$$PR = \frac{Y_f}{Y_r};$$

Linear Fit of Performance Ratio

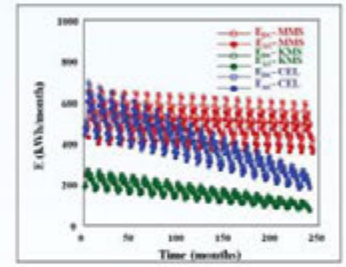


1. D. Myers, *"Evaluation of the performance of the PVUSA rating methodology applied to dual-junction PV technology"*, NREL Conference Paper 550-45376, (2009)
2. B. Marion et al., *"Performance parameters for grid-connected PV systems"*, Proc. 31st IEEE Photovoltaic Specialist Conference and Exhibition, Orlando, (2005)
3. K. Lynn, J. Szaro, W. Wilson, M. Healey, *"A review of PV system performance and life-cycle cost for the SunSmart school program"*, Proceedings of the ASME International Solar Energy Conference 2006, Denver, (2006)

Estimating Energy Output

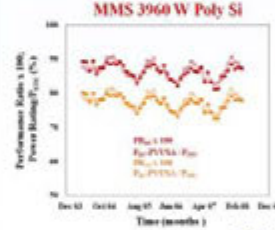
$$E\left(\frac{kWh}{month}\right) = H\left(\frac{KWhm^{-2}}{day}\right)N\left(\frac{days}{month}\right)P_{STC}PR$$

The energy output of each systems has been modeled using a straightforward technique that utilized the PR values and degradation rates established from the experimental results. Equivalent levels of incident solar irradiation are assumed for all three arrays to allow for a fair comparison

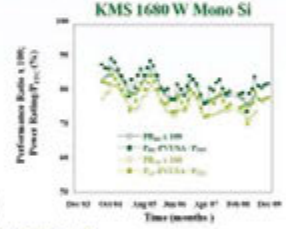


Comparison

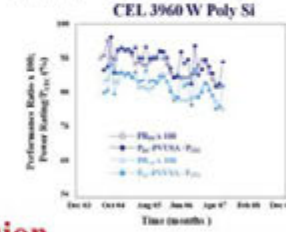
MMS 3960 W Poly Si



KMS 1680 W Mono Si



CEL 3960 W Poly Si



Conclusion

- The analysis of data of the three PV systems from the FSEC database led to increased understanding of the performance and degradation rates - expressed in terms of performance ratio and power rate.
- There is a typical winter power increase for all three systems when using both methods
- Season variation was found to be about 9 % (PR method) and 8 % (PVUSA method)

System	PR Array Degradation (DC)/year		Total Estimated DC Energy Production 20 Years	PR Array Degradation (AC)/year		Total Estimated DC Energy Production 20 Years	Total DC/ Total AC
	PR	PVUSA		PR	PVUSA		
MMS	-0.49%	-0.89%	126,836 kWh	-0.57%	-0.97%	112,922 kWh	89 %
KMS	-2.34%	-2.54%	39,563 kWh	-2.38%	-2.61%	37,135 kWh	94 %
CEL	-2.28%	-2.28%	97,537 kWh	-2.35%	-2.26%	90,682 kWh	93 %

Acknowledgements

- NREL for funding this project
- Kevin Lynn, William Wilson, Steve Barkaszi, and all our colleagues from the Solar Energy Division at FSEC involved in systems installing and data collections.

Displacement Test Protocol Considerations

Sam L. Samuels
DuPont Photovoltaic Solutions

DUPONT
The miracles of science™

Why develop new “creep” tests?

- **Assure safety of installed modules**
  - Collect evidence of existing problems due to displacement at elevated temperature
  - Prevent future failures due to displacement

- **Predict and prevent module failure due to relative displacements of components under load at elevated temperature**
  - Define “Module Failure”
  - Quantify “Load”
  - Define “Elevated Temperature”

- **Provide additional support for lifetime warranty**

This presentation does not contain any proprietary or confidential information

The case for MODULE testing/qualification

- **Safety and performance are dependent on module design**
- **Loading conditions are well defined *and meaningful***
  - Temperature exposure conditions
  - Load/geometry
    - Gravity
    - Other
- **Straightforward method development**
  - Mount and load module under severe (TBD) test conditions and measure displacements vs. time
  - Define failure criteria
- **Issue: How to accelerate and be assured that response mechanism(s) are relevant to field performance.**
    - Avoid introduction of new failure mechanisms, e.g.:
      - Melting
      - Flow
    - Continuous exposure vs. intermittent (real-world) exposure can significantly accelerate without changing mechanism

This presentation does not contain any proprietary or confidential information

The case against MATERIAL qualification

- **Module design, not material properties, determines observed displacement**
  - Dimensions
  - Support
- **Material properties can change during lamination**
  - Orientation
  - Morphology
  - Structure
- **Material characterization can provide physical property information useful in proper module design**
  - Define engineering properties of interest.
  - Define relevant test methods
- **Results are configuration and load dependent**
  - Test acceleration can introduce unrealistic creep/flow mechanisms

This presentation does not contain any proprietary or confidential information

Material Characterization (I)
Zero shear viscosity

- **Estimate stresses on module/encapsulant and calculate lifetime displacement assuming viscous flow**
  - Measure zero-shear viscosity vs. temperature.
  - Couple measured viscosity to real-world temperature history and assumed load to calculate displacement over the lifetime of the module
- **Issues**
  - Temperature dependence of viscosity may not follow simple activation energy model.
  - Extrapolation through material transitions (e.g., crystallization) is NOT valid. New/unrealistic deformation mechanisms are introduced. Results cannot be generalized.
  - Thermoplastic encapsulants are designed to flow during lamination but “solidify” below maximum use temperature by one or more mechanisms

This presentation does not contain any proprietary or confidential information

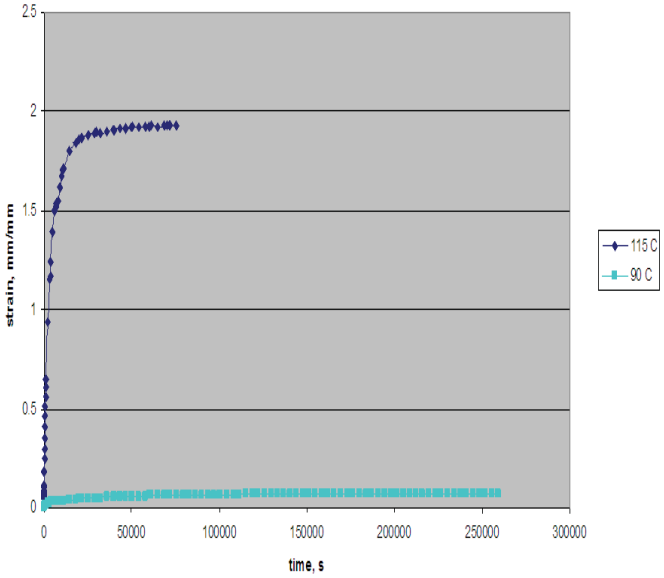
Material Characterization (II)
Creep

- **Estimate stresses on module/encapsulant and calculate lifetime displacement assuming viscoelastic creep**
  - Measure creep response over accessible range of time and temperature
  - Establish retardation spectrum using time-temperature superposition
  - Couple creep behavior to exposure history to determine lifetime displacement
- **Issues**
  - Test results dependent on specimen configuration and load
  - Phase transitions (e.g. crystallization) complicate data gathering and interpretation
    - Time-temperature superposition established for amorphous materials near glass transition
  - Establishing maximum test temperature

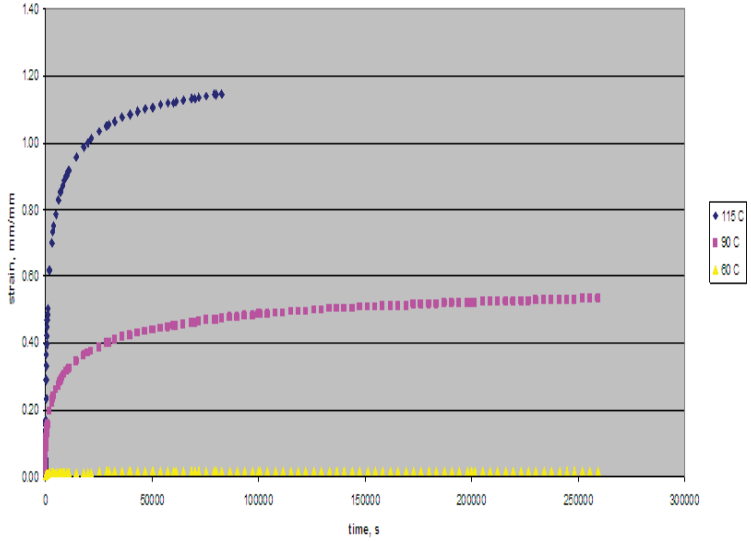
This presentation does not contain any proprietary or confidential information

Creep under high load (~7X glass weight)

Encapsulant A



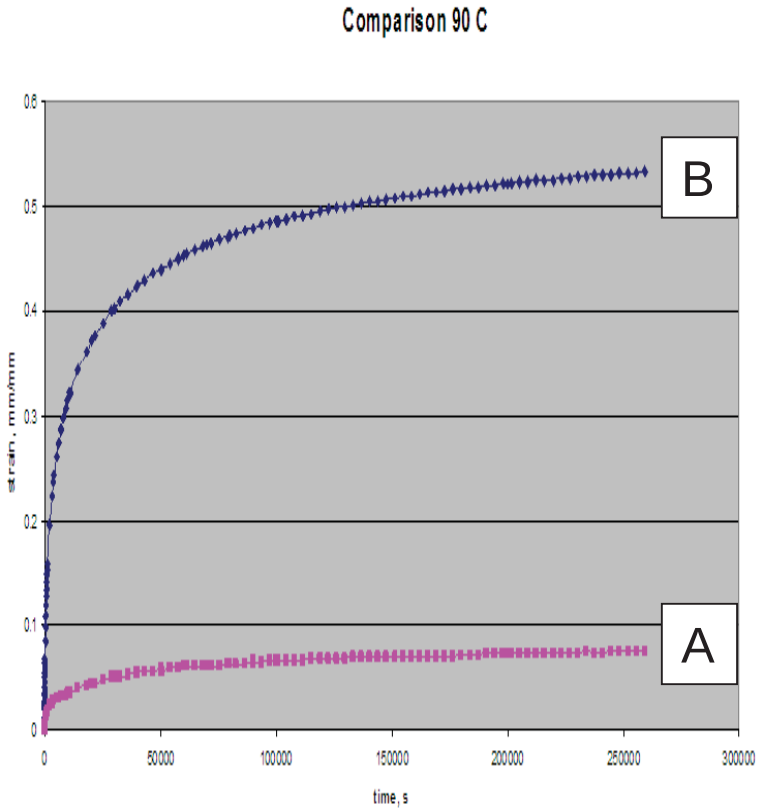
Encapsulant B

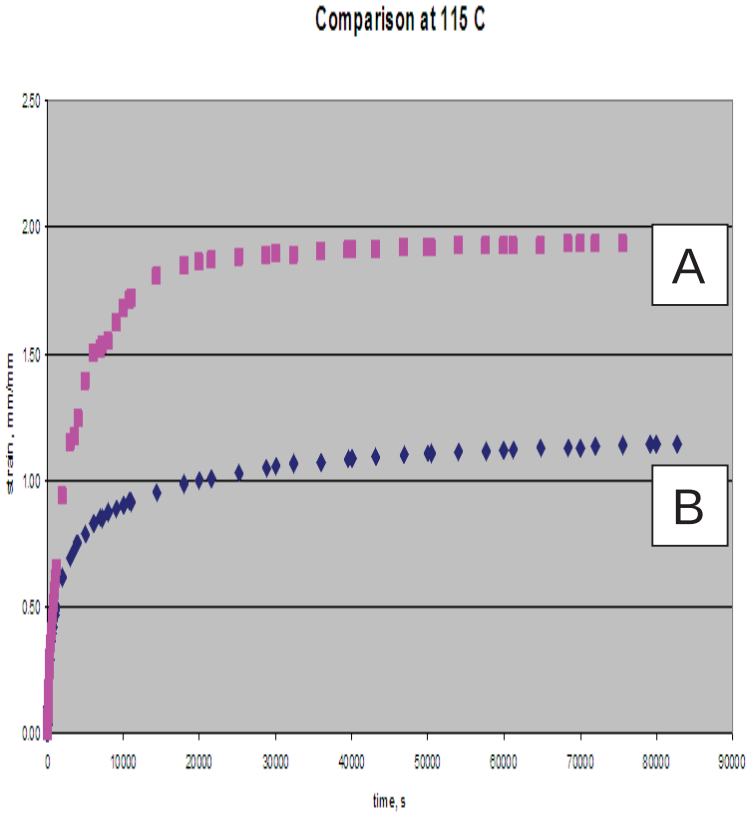


Thermoplastic encapsulants will creep under some temperature/stress loading conditions.

This presentation does not contain any proprietary or confidential information

Effect of Test Temperature on creep
(High load – 7X glass weight)

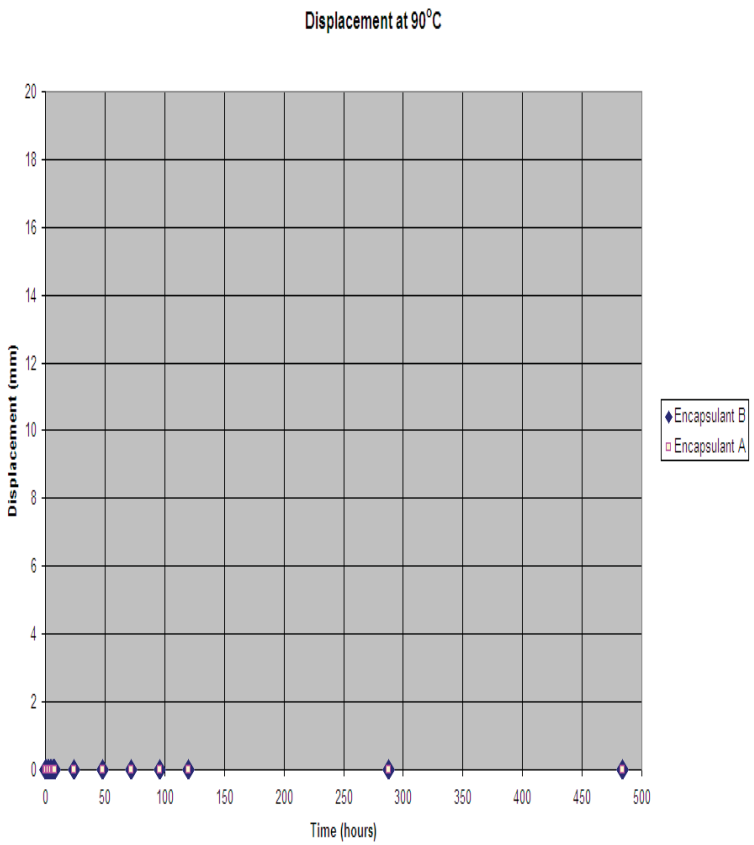


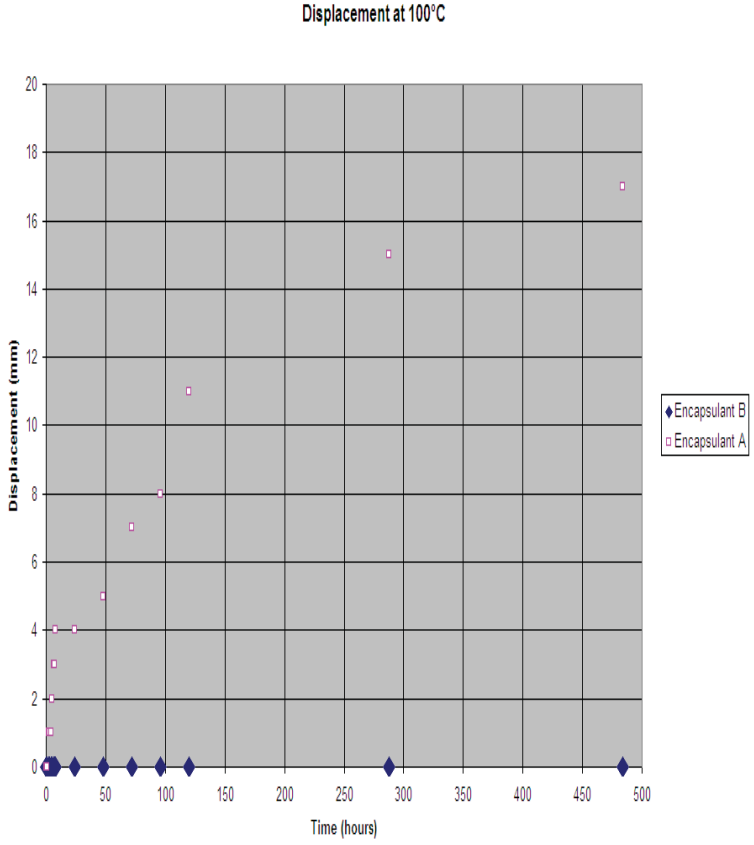


Performance depends critically on test temperature

This presentation does not contain any proprietary or confidential information

Effect of Test Temperature on creep
(Normal load – 1X glass weight)





Performance depends critically on test temperature

This presentation does not contain any proprietary or confidential information

Module Test Result

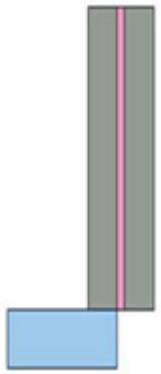
Method:

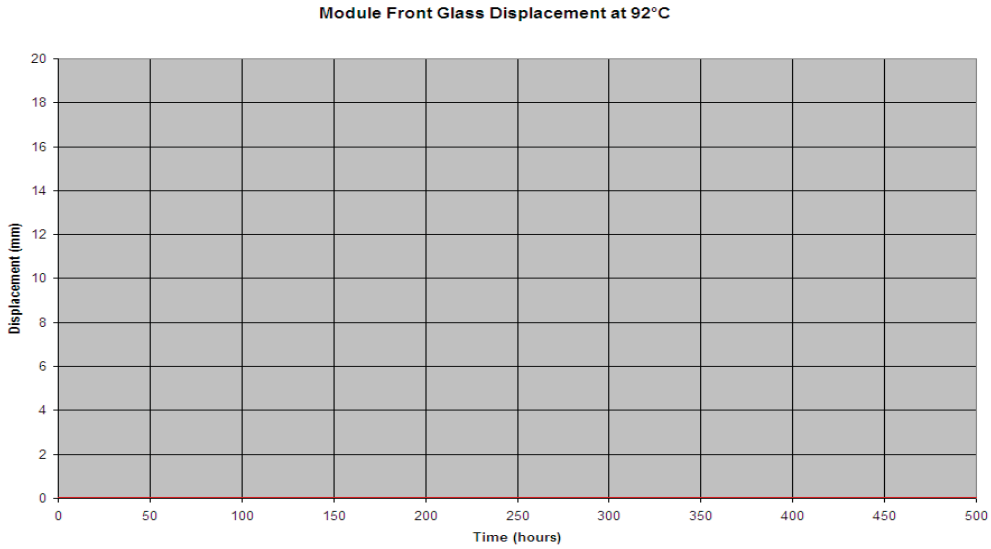
Mount module vertically supporting only back glass

Measure displacement of front glass after 500 hours at 92℃

Result:

No displacement observed





This presentation does not contain any proprietary or confidential information

Recommendations

- **Only module tests should be used to assess acceptability of displacement over lifetime**
  - Load to extreme, but PHYSICALLY MEANINGFUL, conditions, e.g.,
    - Vertical configuration
    - T_{max} (TBD)
  - Measure contact distortion, internal displacement, etc.

- **Identify failure mechanisms and define material characterization tests (e.g., viscosity, creep, DMA, TMA) to provide data useful in the design of safe modules.**

This presentation does not contain any proprietary or confidential information

Acknowledgements

The author would like to thank the following colleagues for valuable discussions and experimental data:

Donald Huang, DuPont Central Research and Development

Anthony Smith, DuPont Packaging and Industrial Polymers

Rebecca Smith, DuPont Packaging and Industrial Polymers

Jane Kapur, DuPont Packaging and Industrial Polymers

This presentation does not contain any proprietary or confidential information



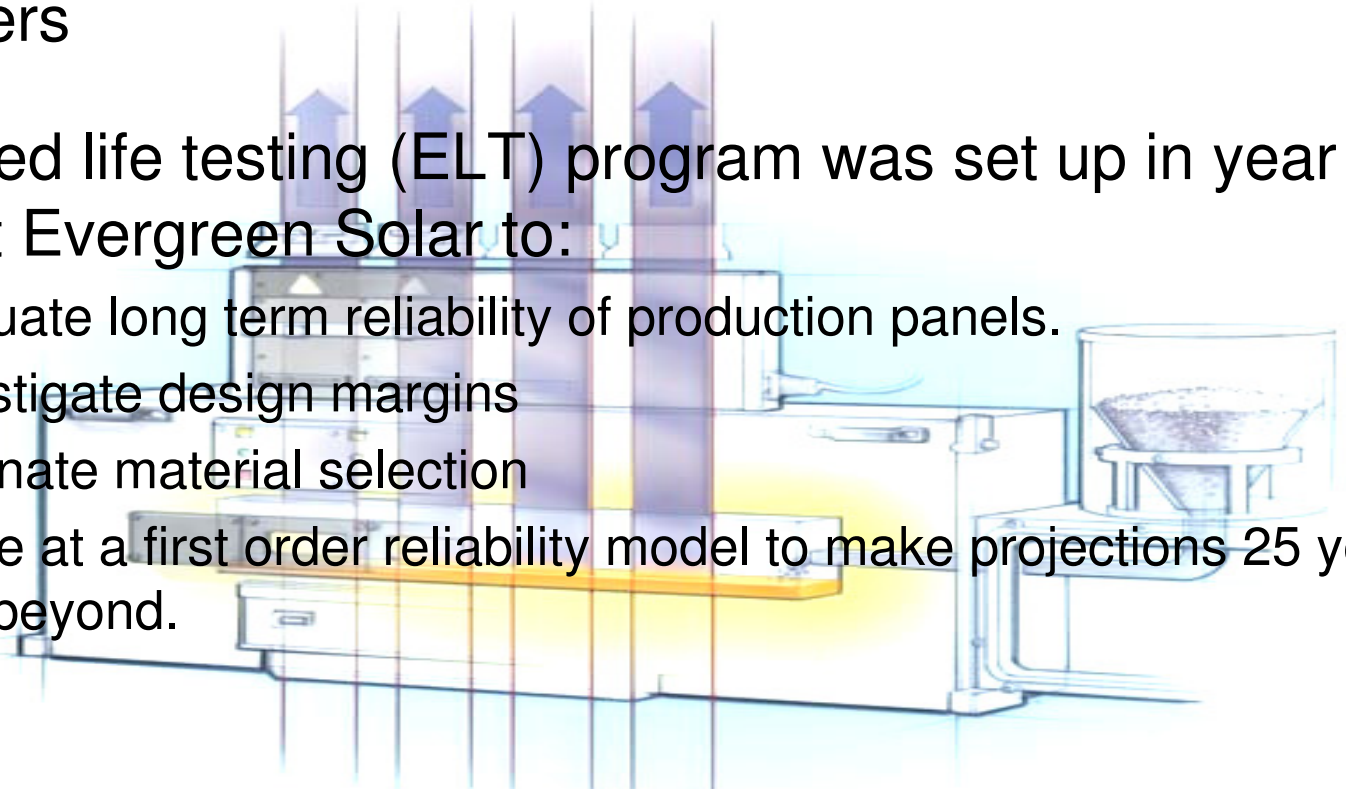
Extended Life Testing of multi-crystalline Silicon PV Modules

Vivek Gade
John Wilson

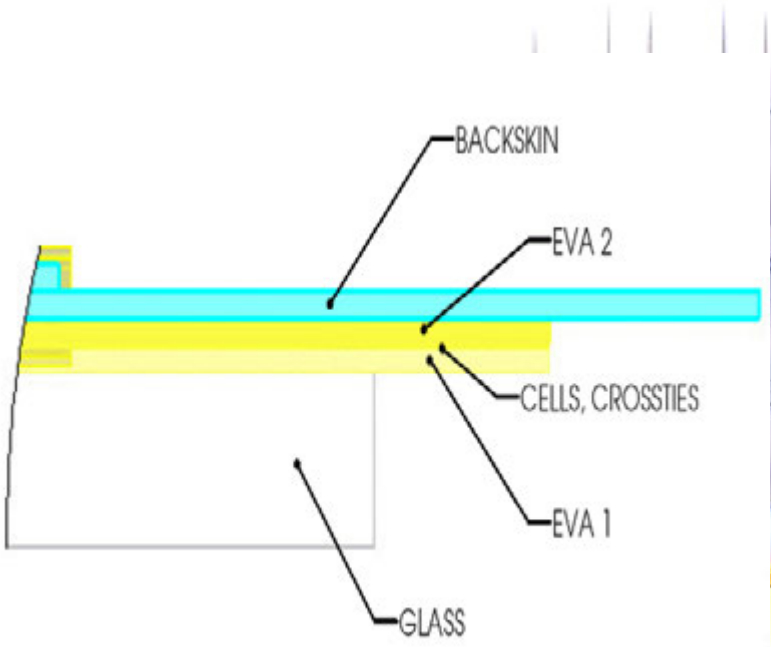
Goal & Background

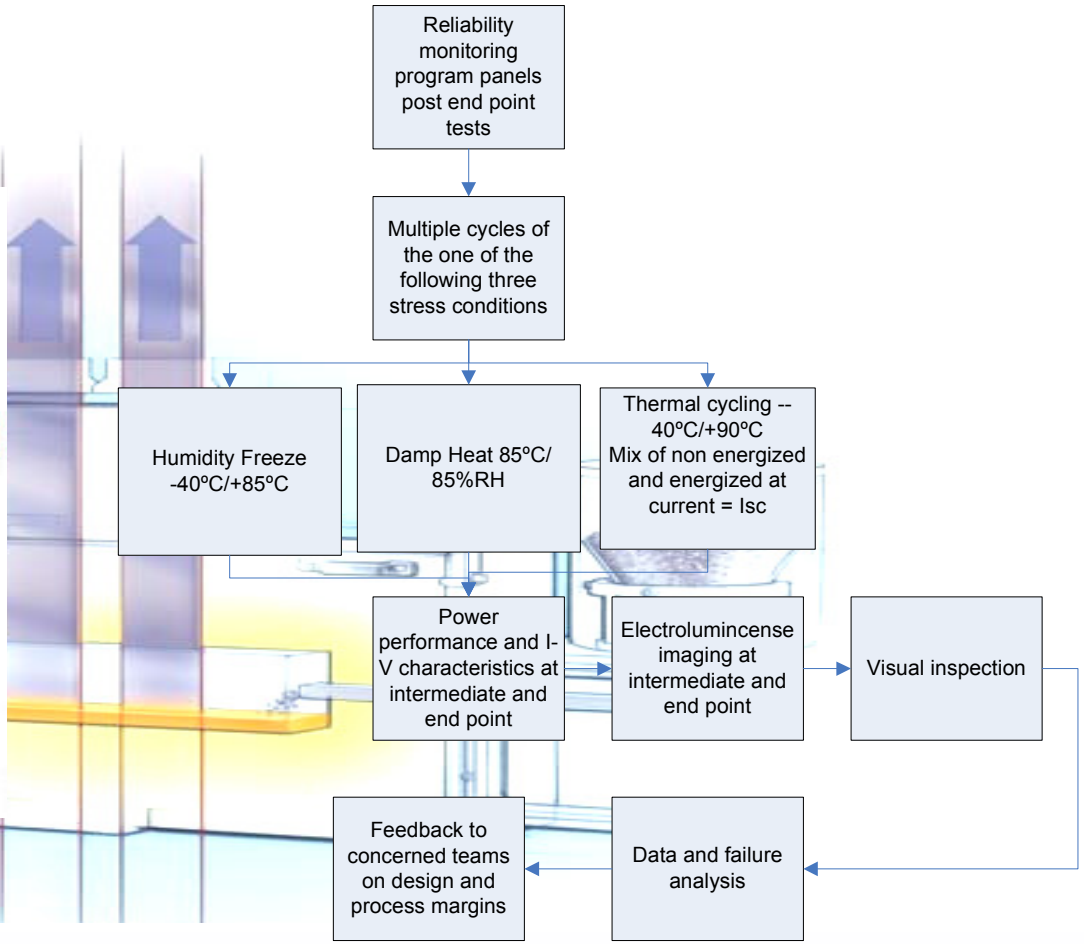
- Obtain quantitative information about long term reliability of Crystalline Si photovoltaic (PV) modules using accelerated testing in environmental temperature-humidity chambers

- Extended life testing (ELT) program was set up in year 2009 at Evergreen Solar to:
  - Evaluate long term reliability of production panels.
  - Investigate design margins
  - Alternate material selection
  - Arrive at a first order reliability model to make projections 25 years and beyond.



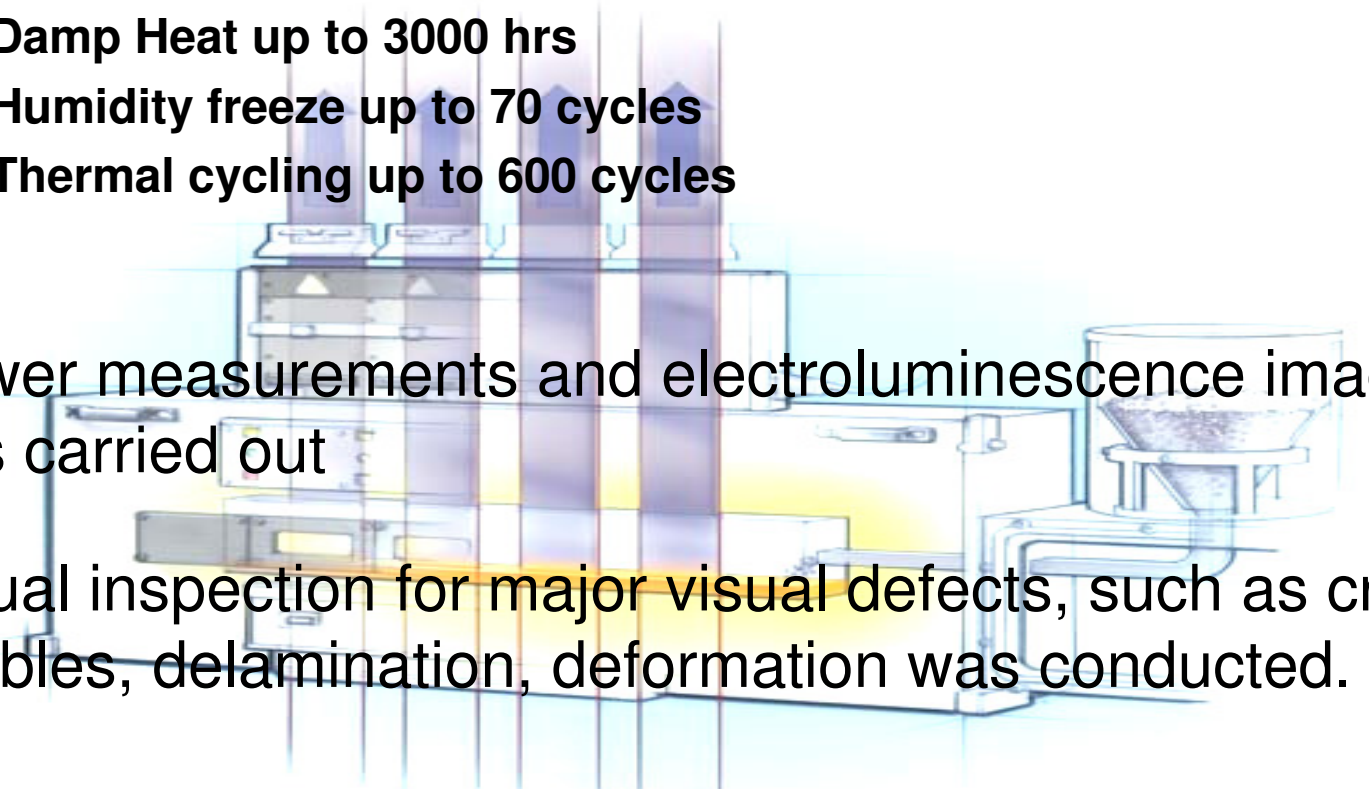
Solar module stack up and ELT flowchart





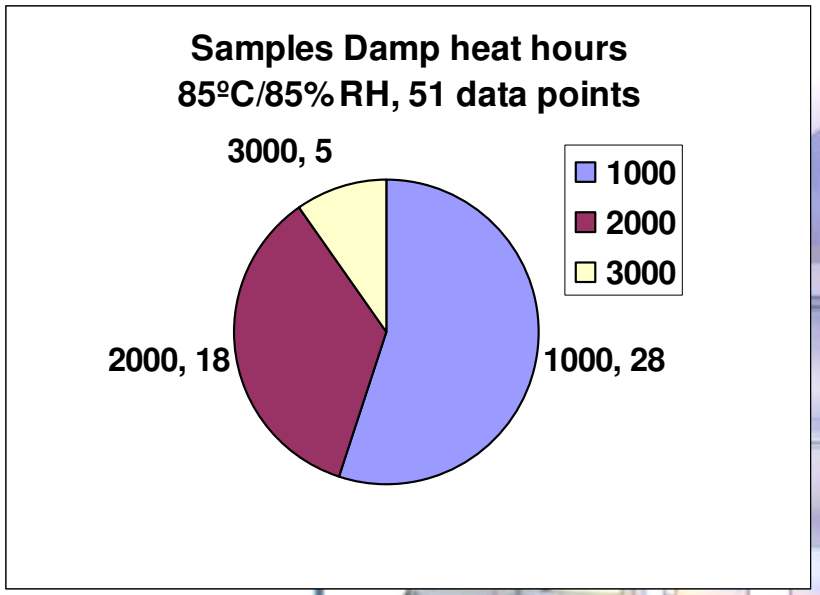
Experiments

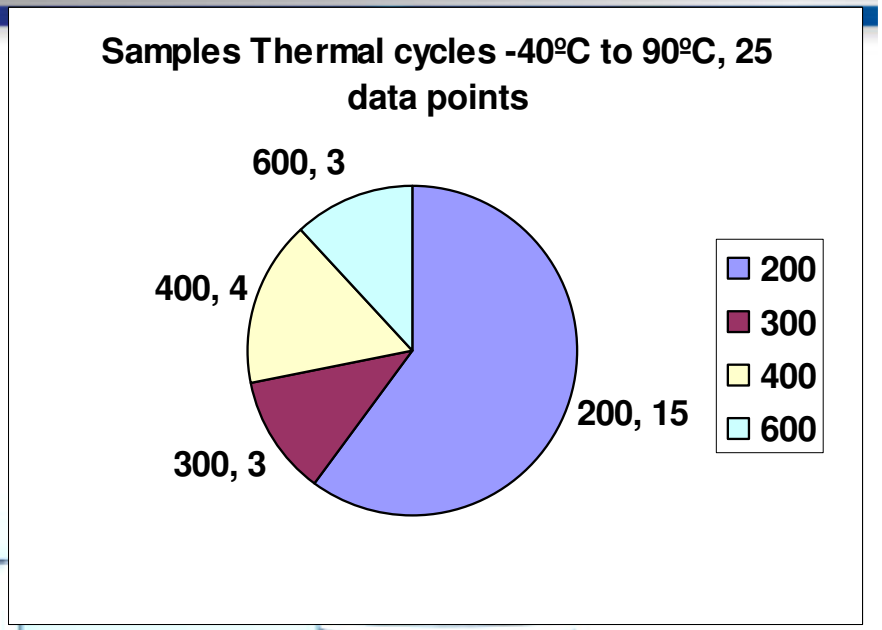
- Panels picked at random from production line were subjected to following tests as a part for extended life testing program at Evergreensolar:
  - **Damp Heat up to 3000 hrs**
  - **Humidity freeze up to 70 cycles**
  - **Thermal cycling up to 600 cycles**

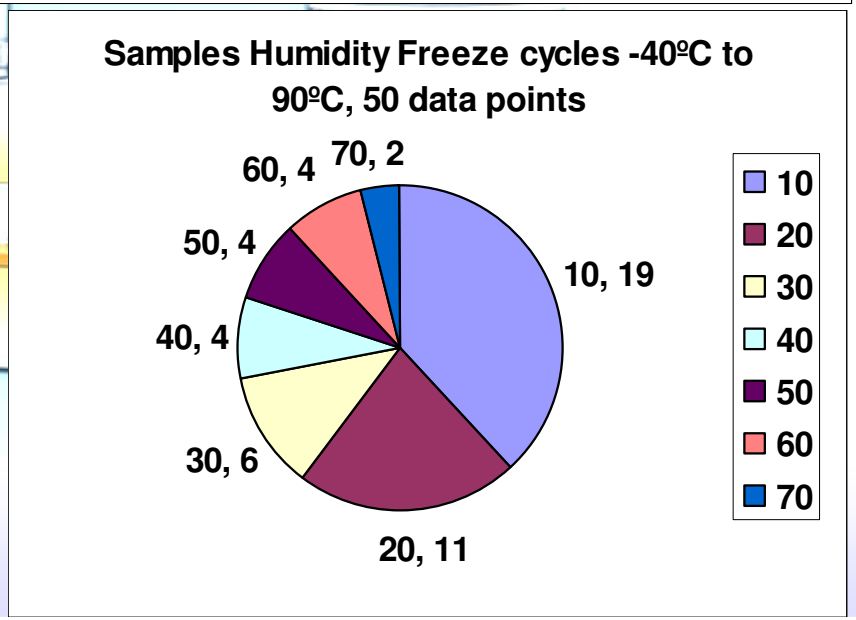


- Power measurements and electroluminescence imaging was carried out
- Visual inspection for major visual defects, such as cracks, bubbles, delamination, deformation was conducted.

Sample data points for model







Evergreen Solar Confidential

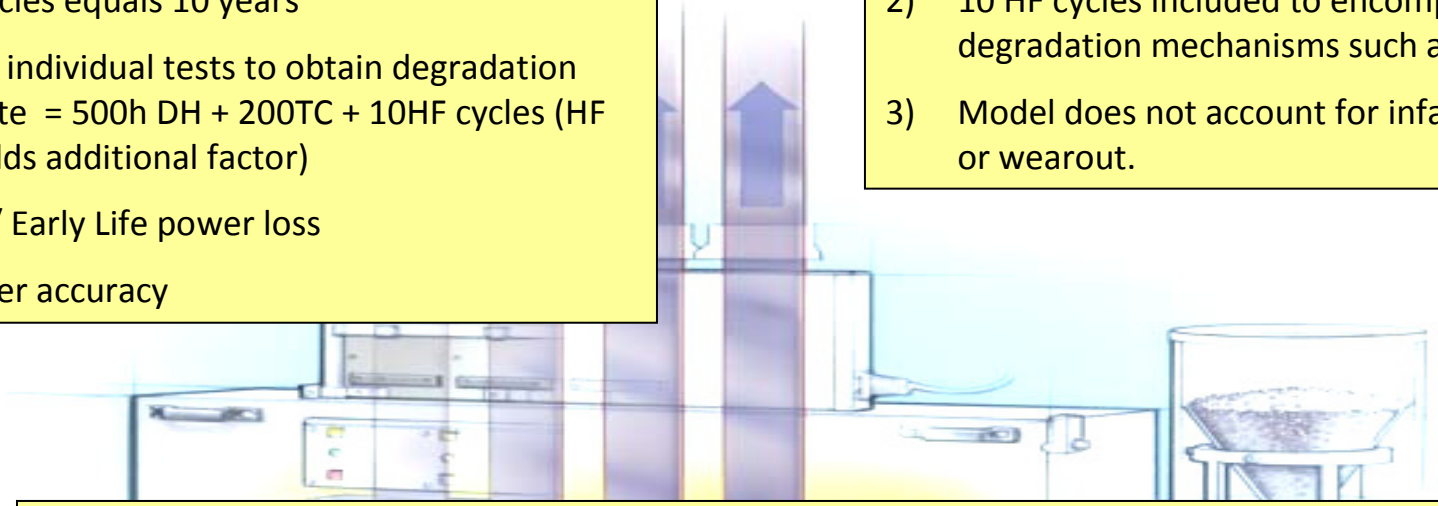
Degradation model

Model details:

1) From JPL study: 500 hrs DH equals 10 years
2) Per Industry available literature: 200 TC cycles equals 10 years
3) Sum individual tests to obtain degradation rate = 500h DH + 200TC + 10HF cycles (HF adds additional factor)
4) LID / Early Life power loss
5) Tester accuracy

Assumptions:

1) Model is based on best available industry and academic results.
2) 10 HF cycles included to encompass other degradation mechanisms such as UV
3) Model does not account for infant mortality or wearout.

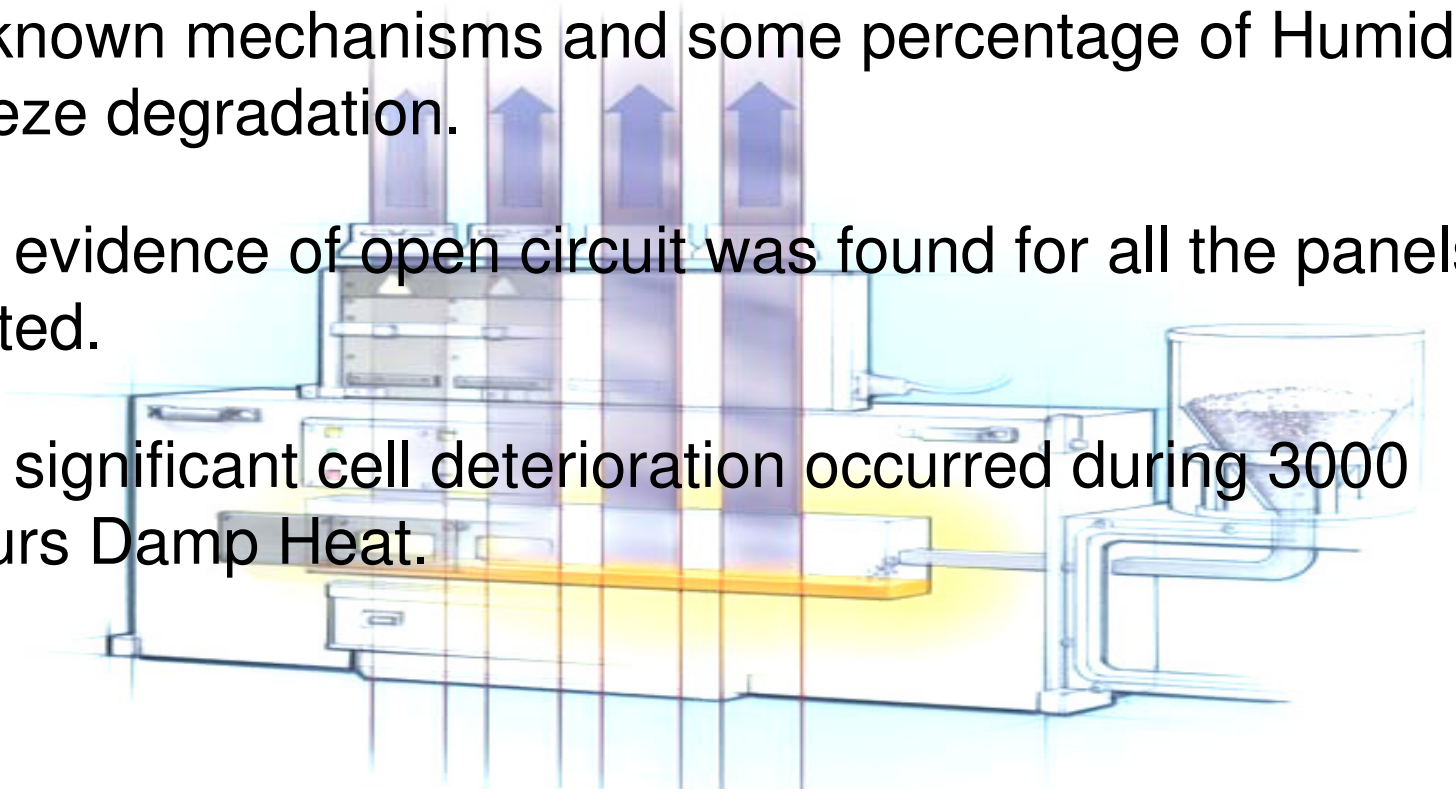


Risks & Limitations

1) Limited accelerated test data and field data on evergreen panels.
2) Data is continental / subtropical based; not to be applied to tropics
3) Model that relates accelerated tests to outdoor exposure not yet available in the industry.
4) Other unknown mechanisms may arise over the course of 25 years in field.

Conclusion and discussions

- Worst case scenario is considered in arriving at the model.
- UV related photodegradation is covered by factor for unknown mechanisms and some percentage of Humidity freeze degradation.
- No evidence of open circuit was found for all the panels tested.
- No significant cell deterioration occurred during 3000 hours Damp Heat.

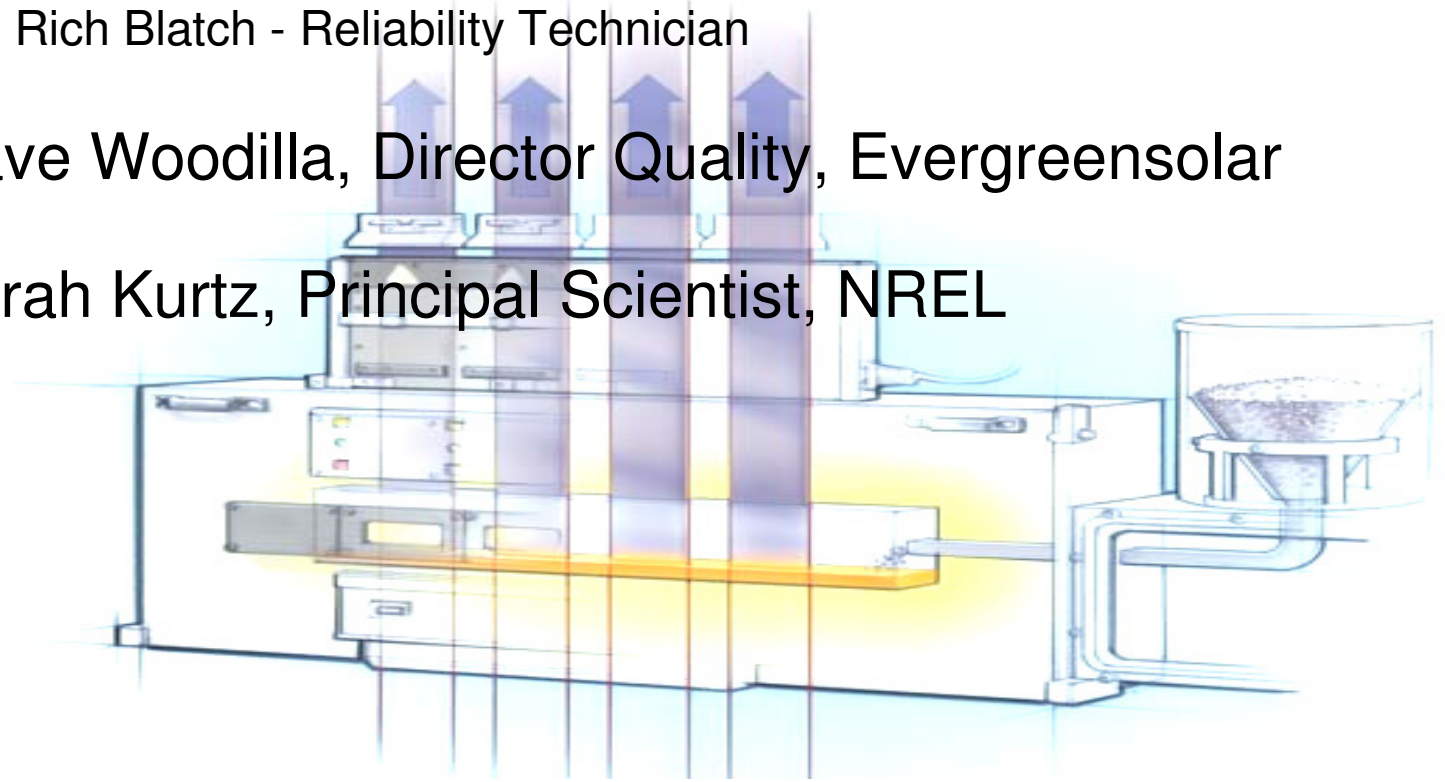


Further studies

- FA is being conducted utilizing analytical techniques to investigate degradation modes.
- Cell extraction technique development is in progress to obtain complete cell for FA.
- Temperature, Humidity & Bias (THB) - Accelerated life testing including power being incorporated into program.
- HAST/HALT studies are being conducted to cut down the time and arrive at an acceleration factor.
- Combination of DH, TC and UV testing on panels is planned for year 2010.

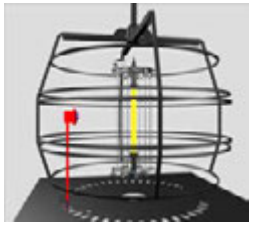
Acknowledgement

- Reliability and certification team, Evergreensolar
  - John Wilson - Group manager
  - Al Mendonca - Certification Engineer
  - Rich Blatch - Reliability Technician
- Dave Woodilla, Director Quality, Evergreensolar
- Sarah Kurtz, Principal Scientist, NREL

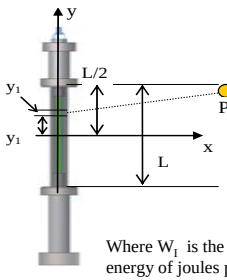


Faster and Adaptable Accelerated Solar PV/Thermal Durability Testing Solution





Atlas Weather-Ometer® equipped with a xenon arc lamp



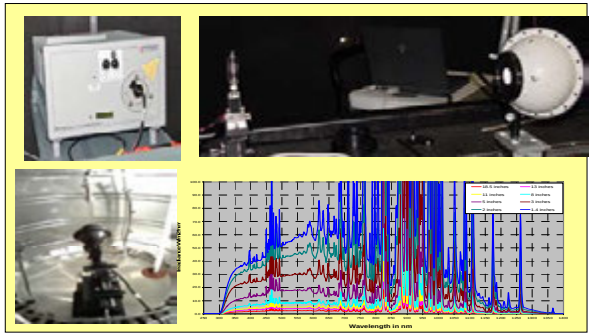
$$I = \frac{W_I}{4\pi L}\int_{-L/2}^{L/2}\frac{1}{x^2+(y-y_1)^2}\,dy_1$$

$$y = \sqrt{\frac{L^2}{4}+\frac{xL}{\tan(cx)}-x^2}$$

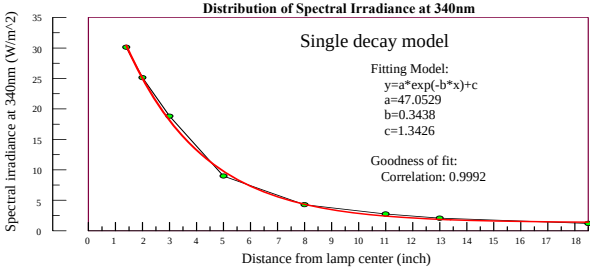
$$c = \frac{4\pi L I}{W_I}$$

Where W_I is the radiant flux of the lamp in terms of radiant energy of joules per unit time

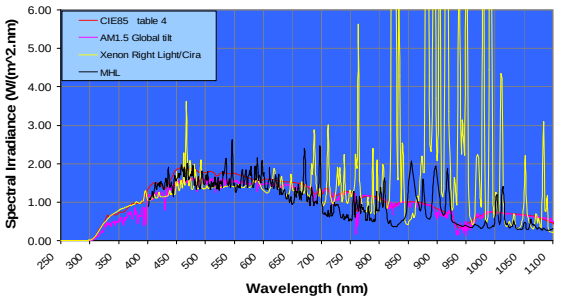
Modeling of light source



NIST-traceable irradiance calibration and measurement capability



Modeling of acceleration factor matches experimental data

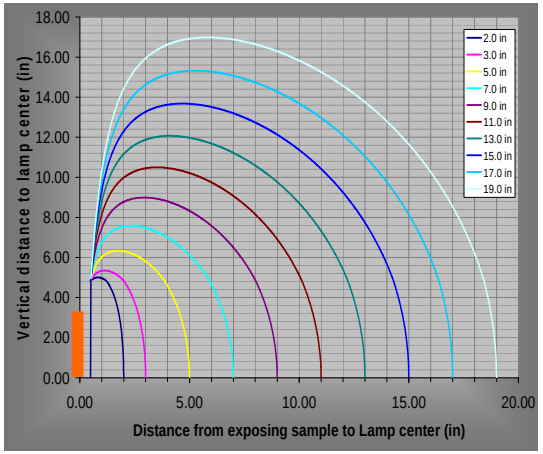


Comparison of Spectral Power Distribution of Atlas light sources and two prevalent references

Xenon lamp provides: Spectral match (with filter option): Class A –IEC 60904-9

Uniformity: <=2% on designated areas

Temporal instability - STI: up to 0.5%; LTI: up to 1%



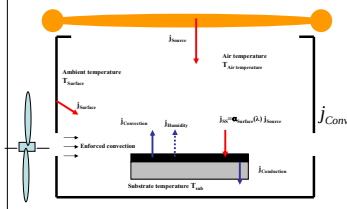
Equal irradiance lobes for various lamp geometry define sample mounting scheme to achieve the optimal uniformity

Temperature Control (Left: EVA as encapsulation in PV module is mounted in cold plate. Middle: direct air cooling on EVA. Right: use auxiliary refrigeration unit to reduce the air temperature)



Determine the Sample Surface Temperature

Theoretical consideration



$$j_{SS} = a_{surface(\lambda)}.\int_{\lambda_0}^{\lambda_1} E_{e\lambda}\,.d\lambda$$

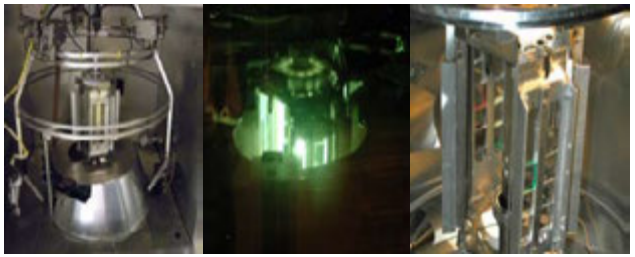
$$j_{IR} = \alpha_{Surface}\cdot\sigma\cdot\left(T^4_{Ambience}-T^4_{Surface}\right)$$

$$j_{Convection} = \alpha_{Convection}\cdot\left(T_{Surface}-T_{Air-temperature}\right)$$

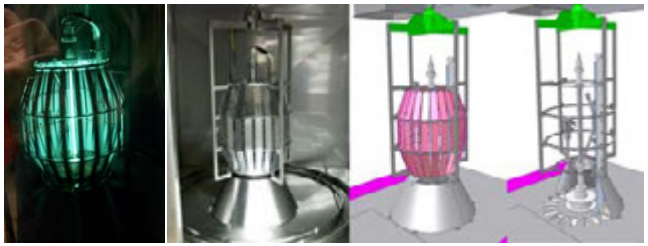
$$j_{Conduction} = \lambda\cdot\frac{\left(T_{Surface}-Tsub\right)}{d}$$

$$j_{stored} = j_{SS} + j_{IR} - j_{Convection} - j_{Conduction} - j_{Humidity}$$

$j_{(source)}$ = Energy flux density of source (radiant, conduction, convection, etc.)



Customized testing instrument using an Atlas xenon Weather-Ometer for high-flux stress test of encapsulants for medium-concentration concentrating photovoltaic (CPV) system at National Renewable Energy Laboratory (NREL)



A customized interior instrument design on 12kW xenon lamp for accelerated materials durability test

Jacob Zhang , Richard Schultz, Richard Donato and Kurt Scott

Atlas Materials Testing Technology, LLC
4114 Ravenswood Avenue
Chicago Illinois, 60613
Fro more information please visit:
http://www.atlas-mts.com

PV Module Reliability Workshop (NREL), February 18-19, 2010. Golden, Colorado

High Volume Light Soaking and UV Testing of Photovoltaic Modules

Lawrence Dunn[†,] and Michael Gostein[*]*
[†]lawrence.dunn@atonometrics.com
[*]Atonometrics, Inc., 8900 Shoal Creek Blvd., Suite 116A, Austin, TX 78757

Atonometrics Light Soaking System with *in situ* I-V



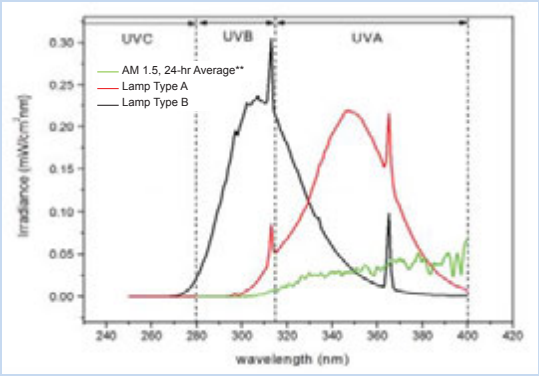


Capable of simultaneous testing of 4 to 6 standard size PV modules

Atonometrics UV Exposure System



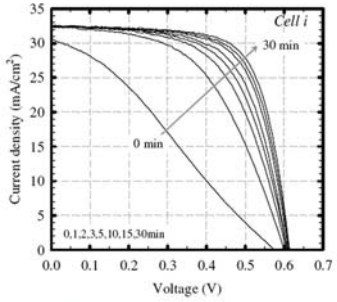
Capable of simultaneous testing of 4 to 6 standard size PV modules



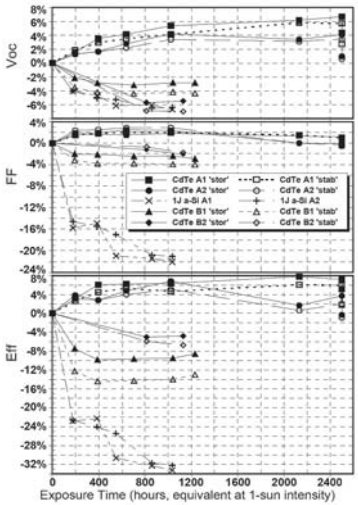
Light Soaking results from Literature

CIGS[1]

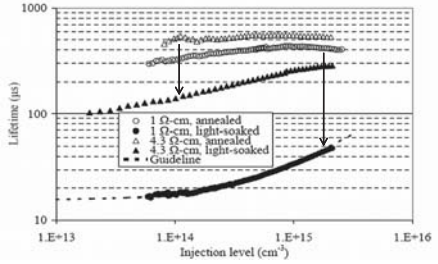
ZMO/CdS/CIGS (CBO: 0.24 eV)



a-Si and CdTe[2]



B-Doped Cz C-Si[3]



[1]"Variable Light Soaking Effect of Cu(In,Ga)Se2 Solar Cells with Conduction Band Offset Control of Window/Cu(In,Ga)Se2 Layers", T. Minemoto *et. al.*, Mater. Res. Soc. Symp. Proc. Vol. **1012** (2007).

[2]"Advanced Indoor Light-Soaking Facility", J. A. del Cueto, *et. al.*, Presented at the 2004 DOE Solar Energy Technologies Program Review Meeting

[3]"Fundamental Research and Development for Improved Crystalline Silicon Solar Cells", A. Rohatgi, NREL Subcontract Report NREL/SR-520-42324 (2007).

ATONOMETRICS

Impedance Measurement as a Diagnostic Tool for Device Degradation

Xin Jiang, **Sean Shaheen**, Denver University

Sergey Li, **Srinivas Gowrisanker**, Plextronics

Acknowledgements:

Nick Bosco, **Matthew Reese**, NREL

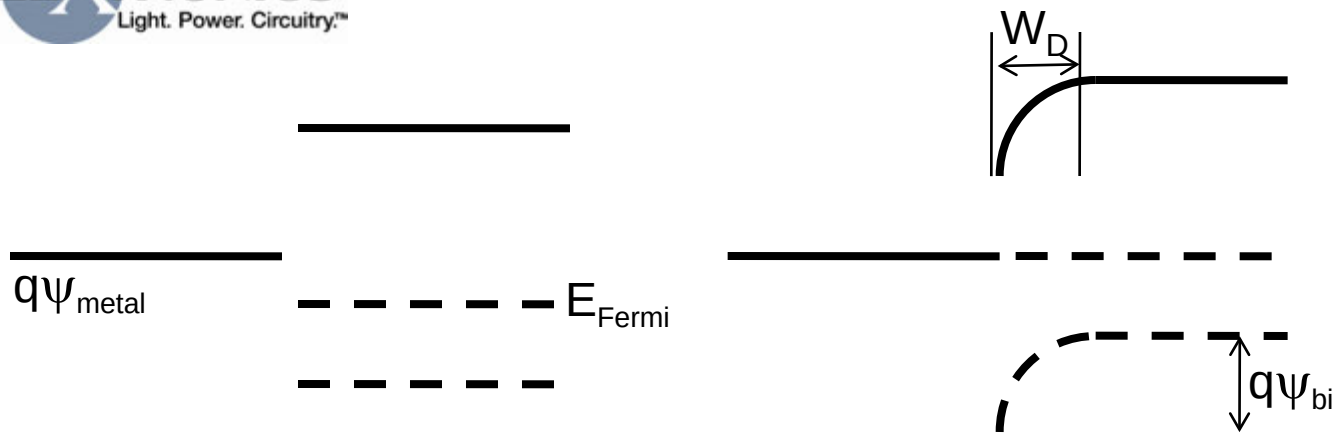
Min Xiao, **Jan Bernkopf**, **Darin Laird**, Plextronics

What We Can Learn From Impedance Measurements

Measurement	Analysis	What is Learned
Impedance under dark vs. bias voltage	Nyquist plot: Im(Z) vs. Re(Z)	• Number of capacitances in the device becomes apparent. • Extract fitted values of C, R.
	C vs. bias voltage (C-V)	• Origin of capacitance (e.g. geometric vs. chemical) is revealed by bias dependence.
	Mott-Schottky plot: $1/C^2$ vs. bias voltage	• Build-in potential. • Concentration of intrinsic dark carriers.
Impedance vs. light	C vs. Voc	• Chemical capacitance, derived from the photo-carriers, is probed. • Carrier lifetime.

Not included in this study but possible: impedance vs. temperature.

Mott-Schottky Analysis*



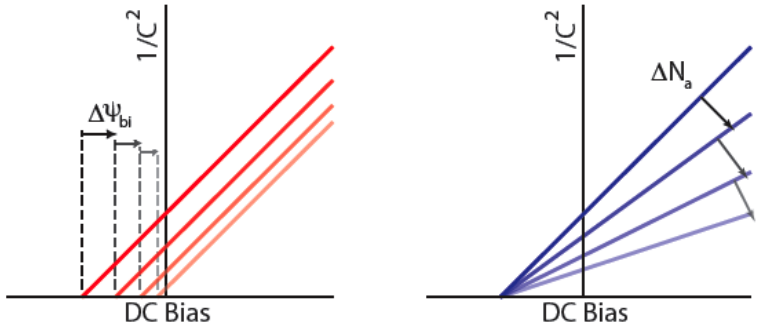
$$\frac{1}{C_D^2} = \frac{2\left(\Psi_{bi} - V - \frac{q}{kT}\right)}{q\varepsilon N_A}$$

W_D: depletion width
ψ_{bi}: built-in potential of the barrier
C_D: depletion layer capacitance per unit area
N_A: charge carrier density in the barrier

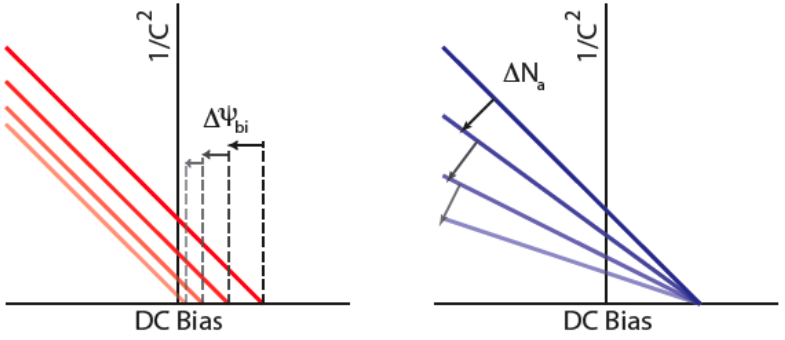
$$N_A = \frac{2}{q\varepsilon}\left[-\frac{1}{d(\frac{1}{C_D^2})/dV}\right]$$

*S. M. Sze, *Physics of Semiconductor Devices*, 2nd Ed. John Wiley & Sons, New York, 1981.

Depletion region at hole extracting electrode

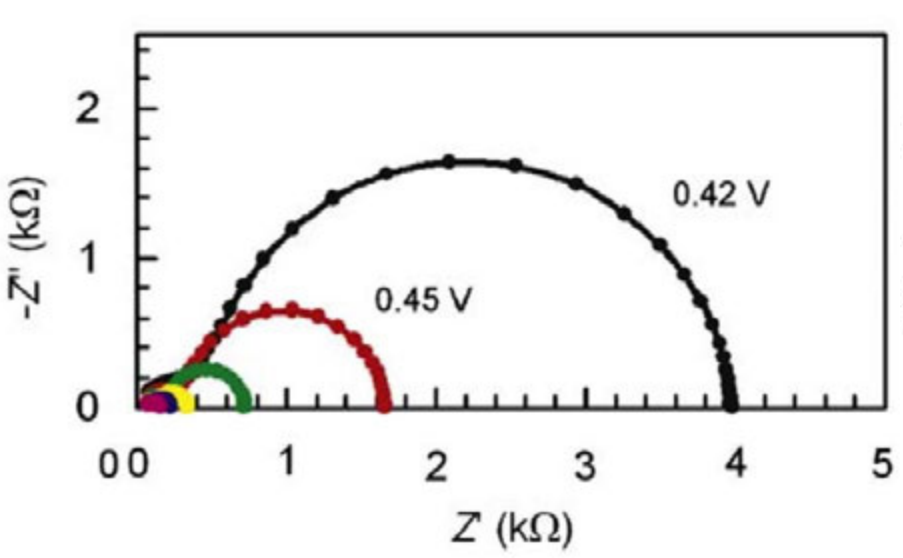


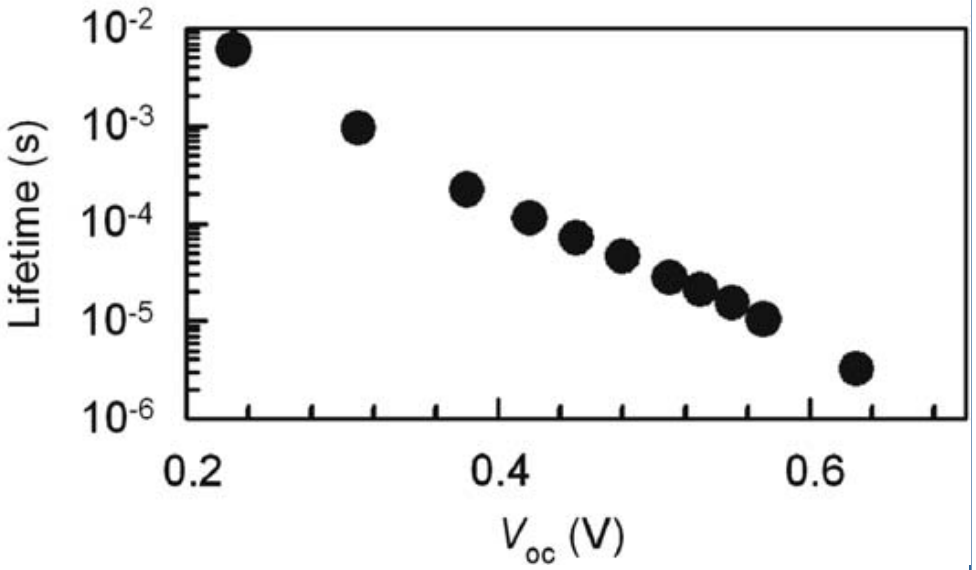
Depletion region at electron extracting electrode



Carrier Lifetime Calculation

- Photo-carrier lifetimes can be measured by impedance spectroscopy of devices under illumination*.
- Photo-generated carriers result in a photo-capacitance that is analyzed as a RC circuit, where C is the photo-capacitance, R is recombination resistance.
- In this analysis, the RC time-constant is the photo-carrier lifetime.

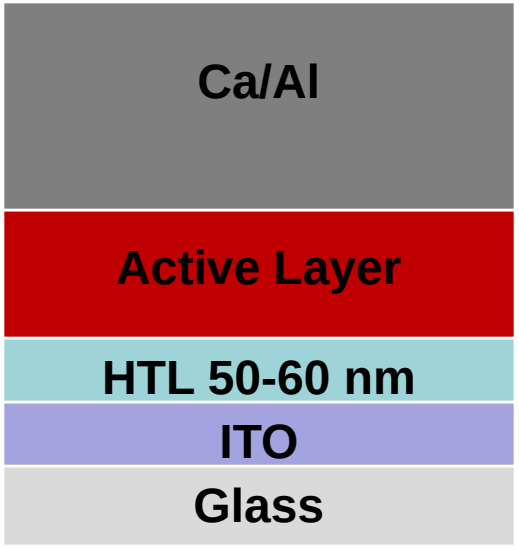




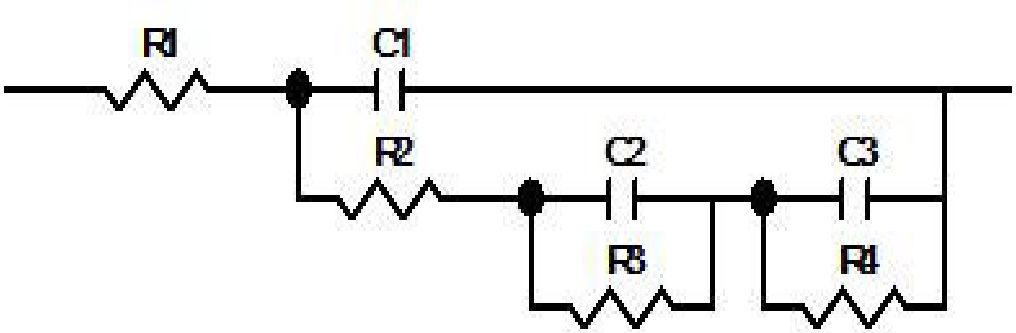
*G. Garcia-Belmonte, P. P. Boix, J. Bisquert, M. Sessolo, H. J. Bolink, "Simultaneous determination of carrier lifetime and electron density-of-states in P3HT:PCBM organic solar cells under illumination by impedance spectroscopy", Solar Energy Materials and Solar Cells (2009).

Experimental Methods

- **Measurement Instruments**
  - Impedance Analyzer: Agilent 4294A.
  - Solar Simulator: NREL's user facility XT-10.
- **Devices** (encapsulated with getter and cap glass)
  - 5323-2, Plexcore® PV1000
  - 5323-6, Plexcore® PV2000
  - 5409-2, Plexcore® PV2000 (294 nm, active layer + HTL)
  - 5409-6, Plexcore® PV2000 (193 nm, active layer + HTL)
  - 5409-8, Plexcore® PV2000 (129 nm, active layer + HTL)
- **Accelerated Tests**
  - 1 Sun Xe
    - 5409-2, measurement points: 2, 24, 96 hours,
  - 2.5 Sun Xe 60°C / 60% RH Weathometer
    - 5409-6, measurement points: 2, 24 hours.
  - ~0.8 Sun Sulfur
    - 5409-8, measurement points: 2, 47, 191 hours.



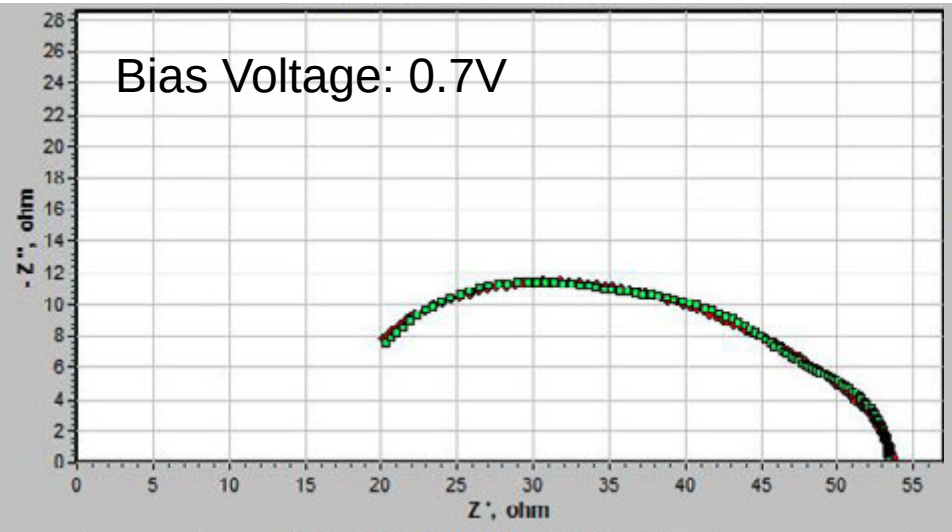
Establish Equivalent Circuit*

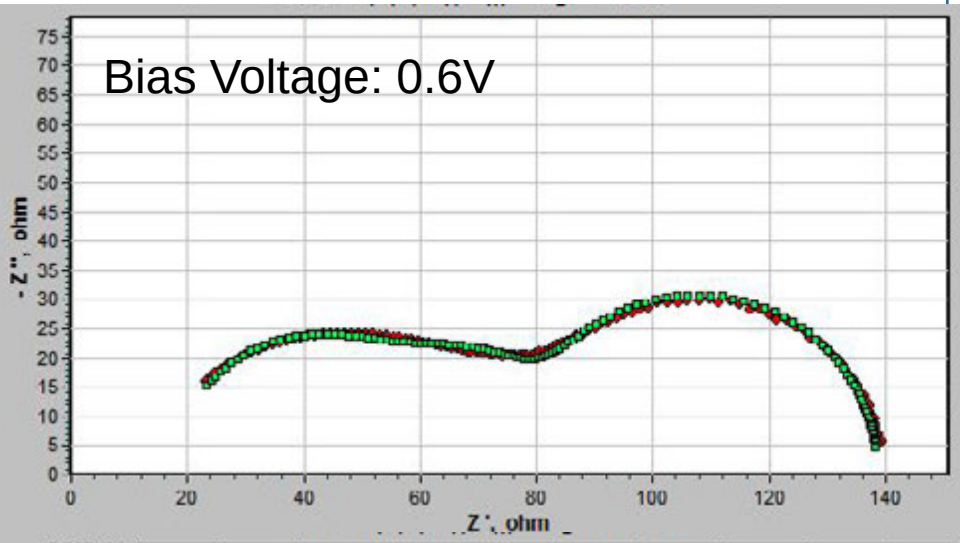


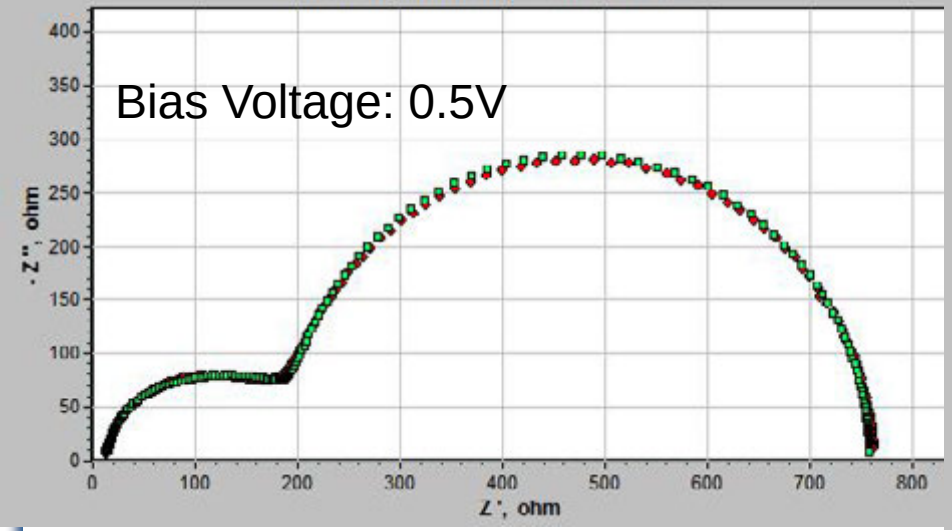
- C1: geometric capacitance of the active layer
- C2: depletion capacitance at HTL / active layer interface
- C3: depletion capacitance at active layer / metal interface

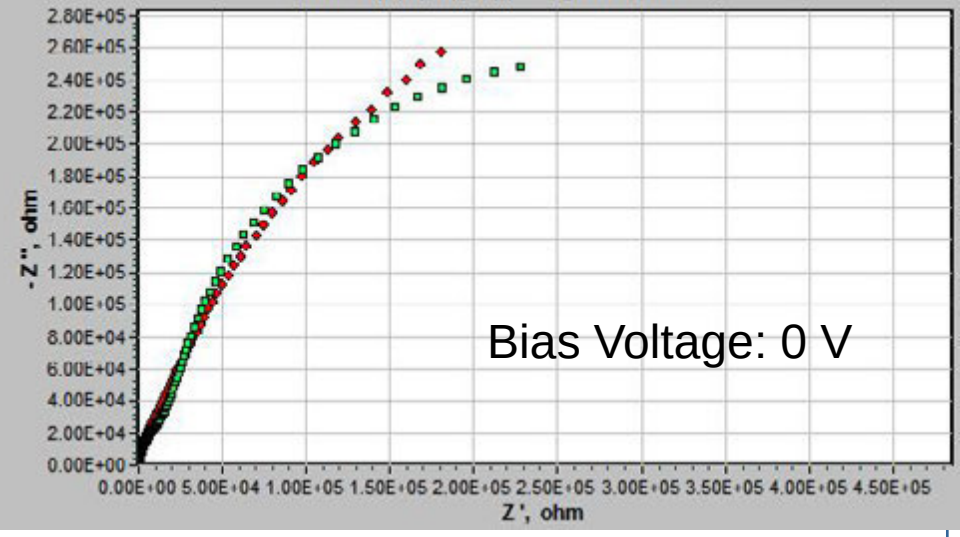
* A similar equivalent circuit has been reported: M. Knipper, J. Parisi, K. Coakley, C. Waldauf, “Impedance spectroscopy on polymer-fullerene solar cells”, Z. Naturforsch, 62a, 490-494 (2007).

Nyquist Plots and Fitting





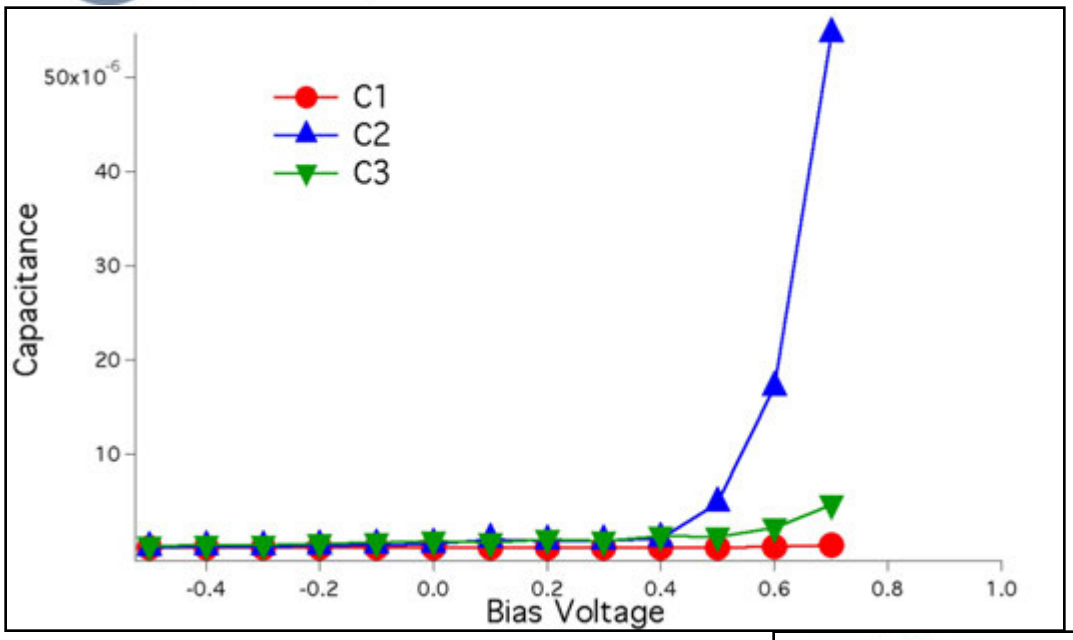


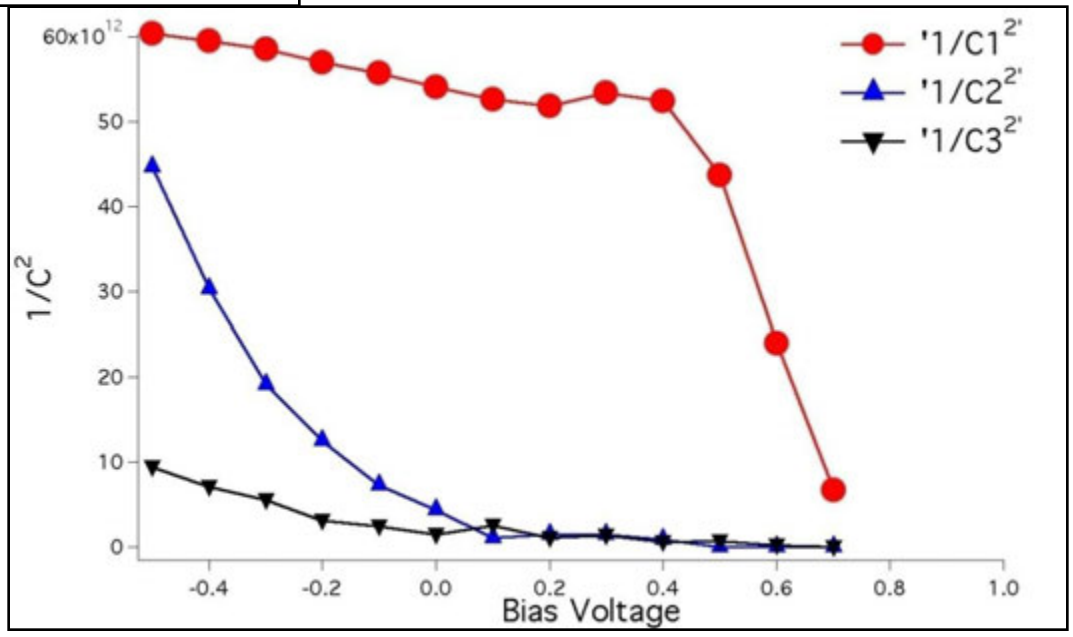


5232-2

- Measured
- Calculated

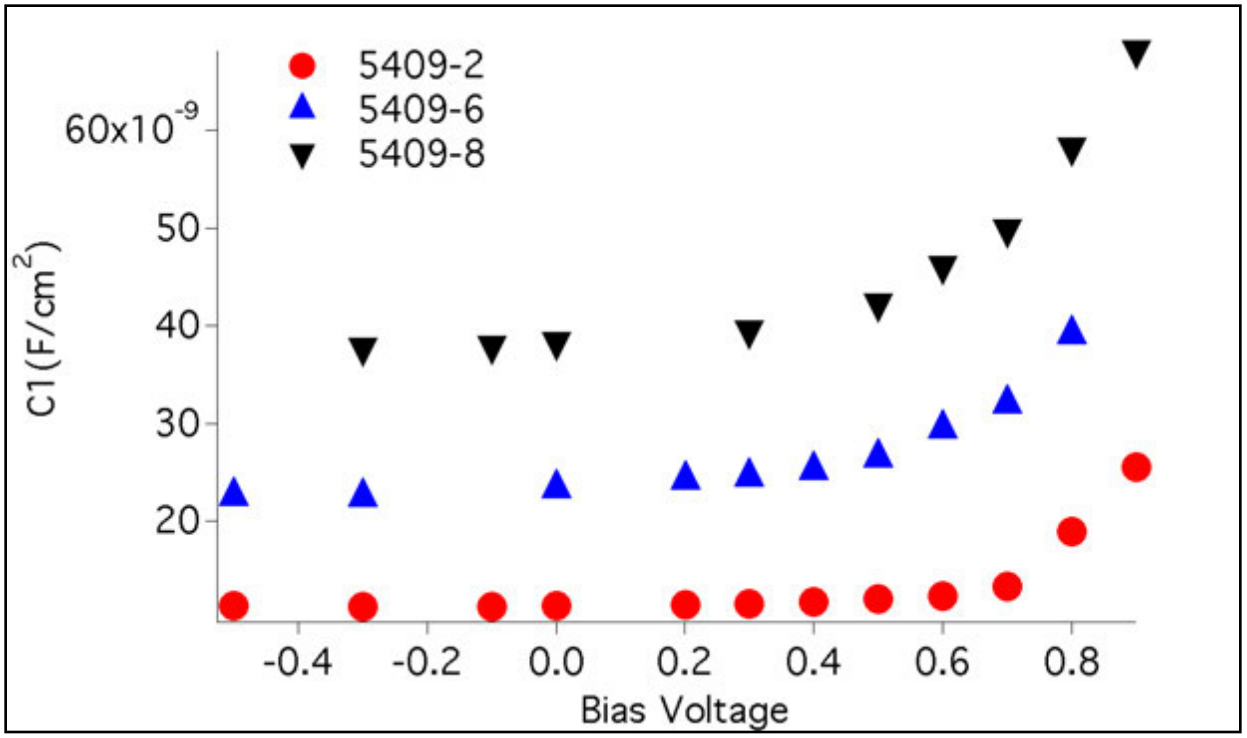
C-V and Mott-Schottky Plots





5232-2

Thickness Dependence_C1



Geometric capacitance did not change much with bias voltage.

Geometric Capacitor C1	5409-2 (239 nm)	5409-6 (138 nm)	5409-8 (74 nm)
Calculated	1.17E-8	2.03E-8	3.77E-8
Fitting data	1.13E-8	2.3E-8	3.8E-8

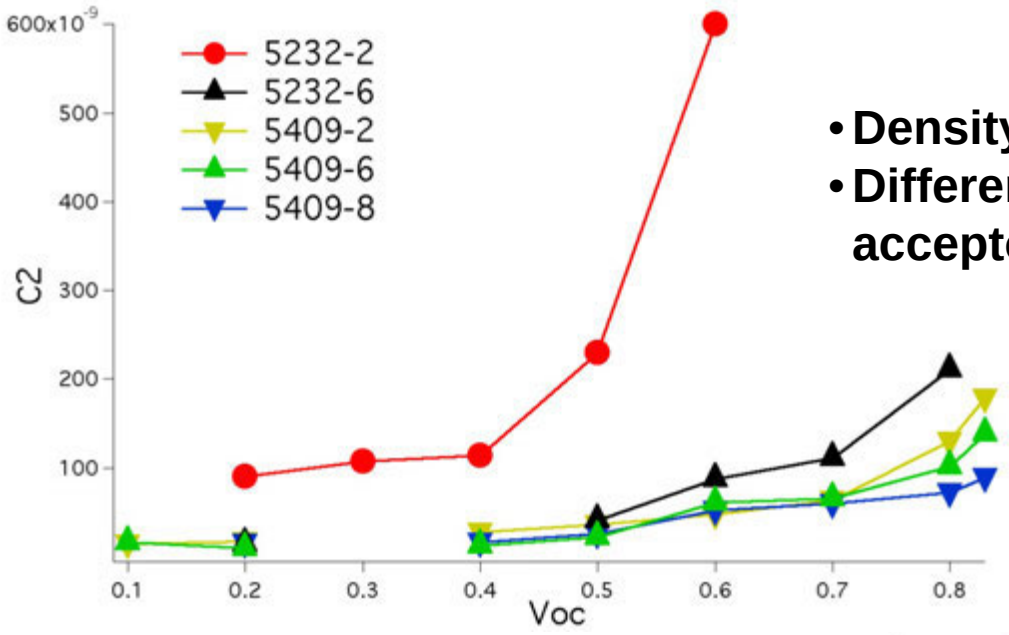
- HTL is considered part of the electrode.
- Calculated values assume relative dielectric constant of 3.5.

Thickness Dependence_C2, C3

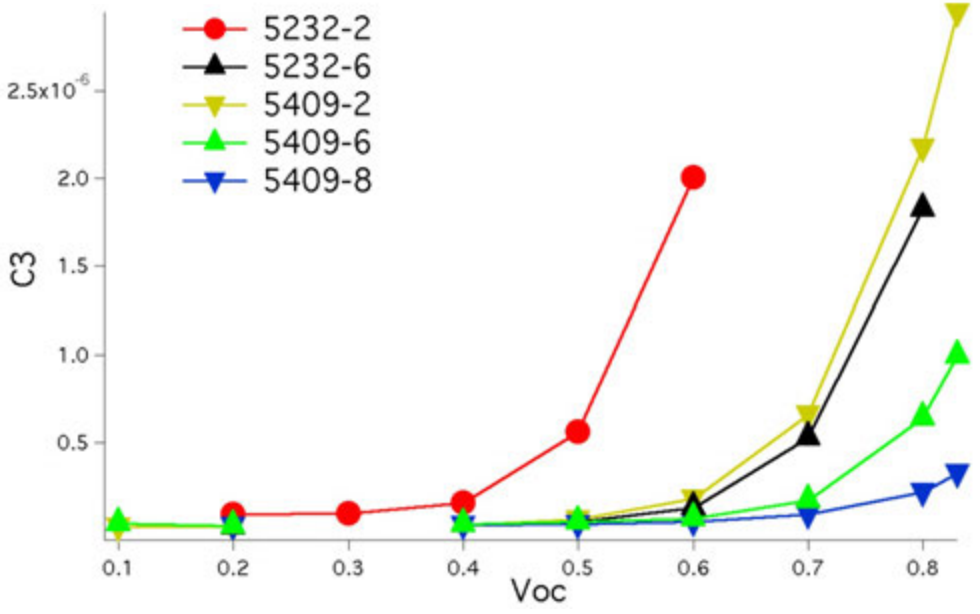
	C2_N_A (cm^{-3})	C2_V_{bi} (V)	C3_N_A (cm^{-3})	C3_V_{bi} (V)
5409-2	1.34E+15	0.462	8.68E+15	0.606
5409-6	1.45E+15	0.595	1.78E+16	0.697
5409-8	2.71E+15	0.604	1.51E+16	0.776

Dark carrier density appears to increase as the active layer becomes thinner.

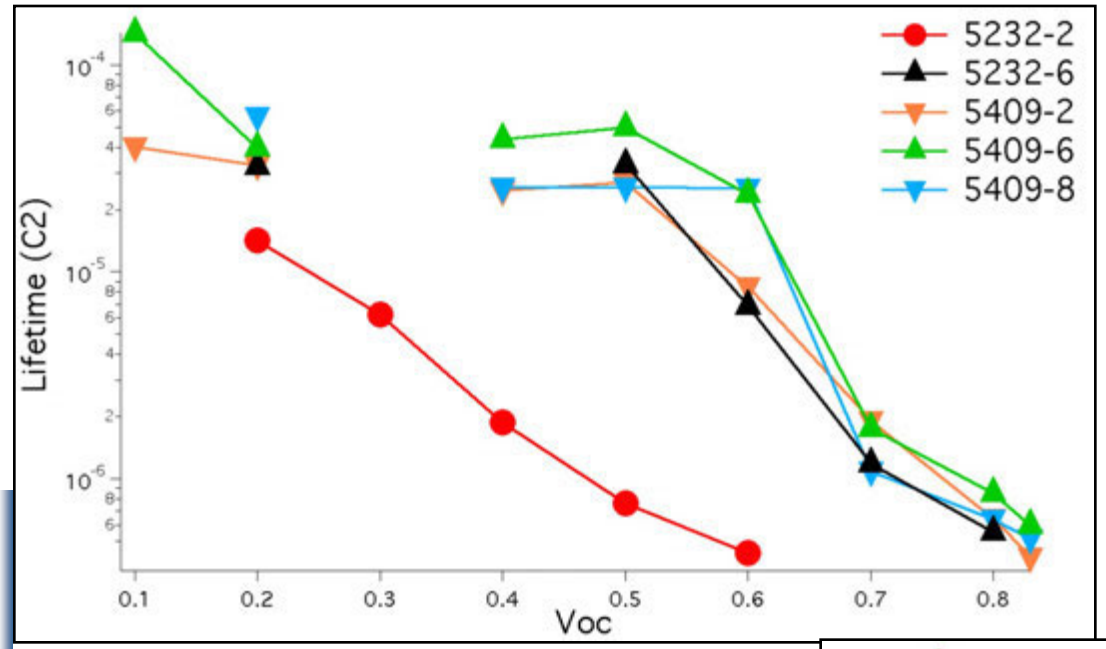
Thickness and Light Dependence_C2, C3



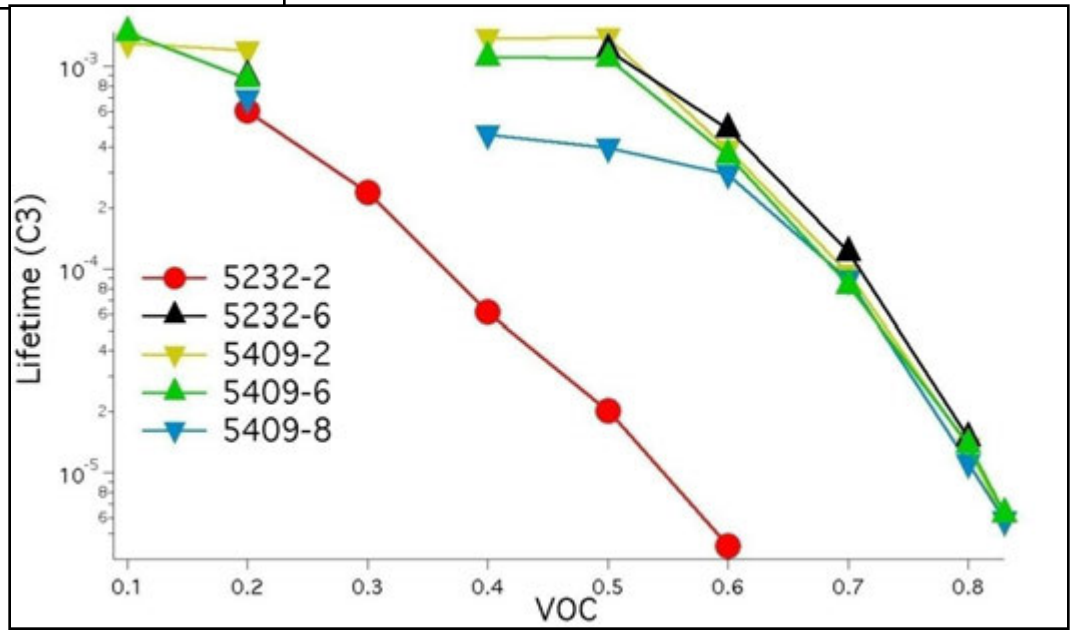
- **Density of states: 5409-2 > 5409-6 > 5409-8**
- **Different morphologies of the donor-acceptor blend?**



Carrier Lifetime_C2, C3



Reasonable carrier lifetimes are extracted from the light-induced capacitance.



Apply to Device Degradation

Cause of Degradation	Impact on the Device	Measurement
Delamination / dark spots	Active area effectively lowered. Jsc ⬇.	
Electrode oxidation	Rs ⬆. Change in depletion capacitance or Vbi possible. An extra capacitor could potentially form if oxidation is severe.	Nyquist dark, Mott-Schottky
Active layer chemical decomposition or morphology changes	Recombination ⬆. Carrier lifetime ⬇. Voc, Jsc, and FF ⬇.	Nyquist light
Active layer doping. Source of dopants can be either extrinsic (i.e. oxygen ingress) or intrinsic (diffusion from electrodes)	Rs ⬇. Depletion capacitance ⬆. Voc, Jsc and FF could go ⬆ or ⬇.	Nyquist dark, Mott-Schottky
Shunting of device due to electromigration of metal	Rp ⬇. Voc, Jsc, and FF ⬇.	Nyquist dark

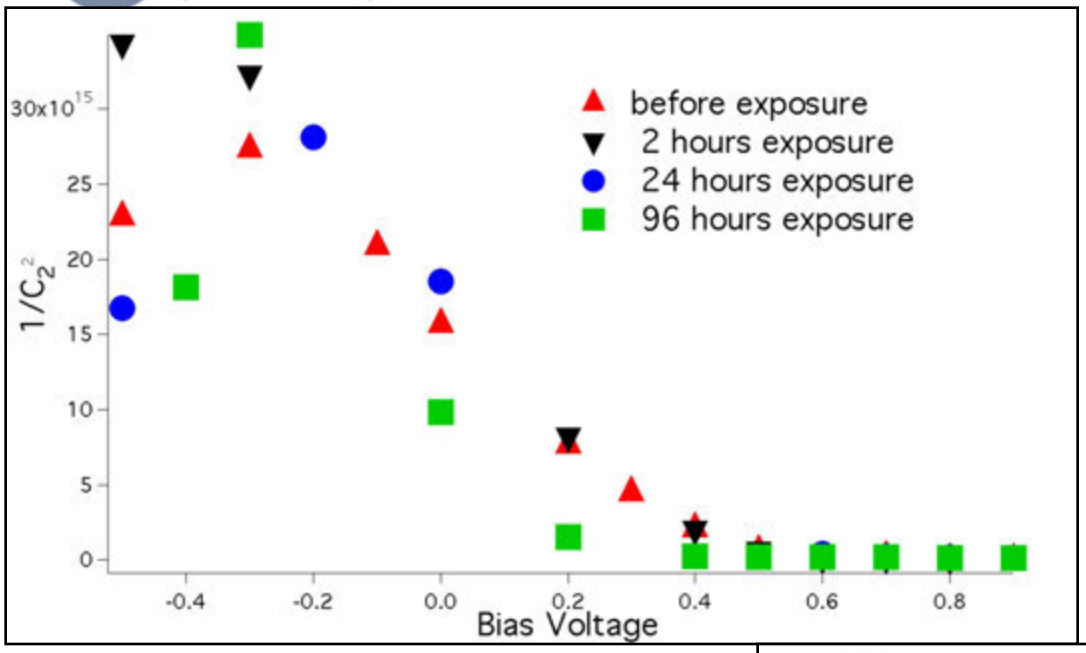
J-V Characteristics

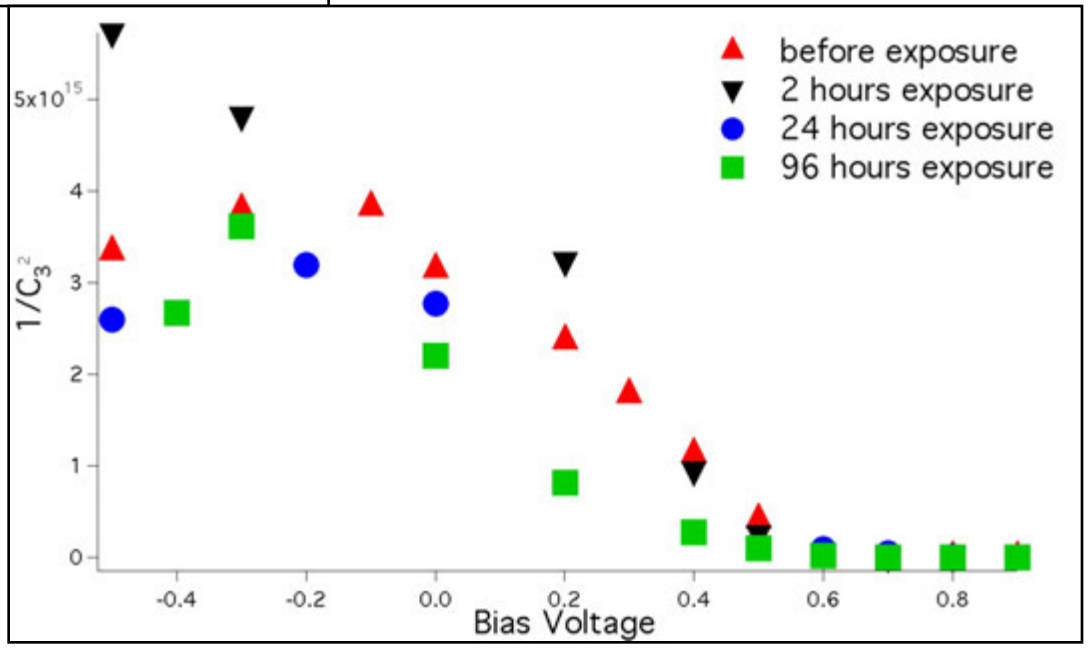
5409-2	Voc (V)	Jsc (mA/cm^2)	FF	PCE	R@Voc (Ω)	R@Jsc (Ω)	Rs (Ω) Spice	Rp (Ω) Spice
Before exposure	0.8076	10.01	64.9%	5.25%	124	9.85E3	40	12.5E3
2 hours	0.8102	11.20	61.6%	5.59%	135	8.06E3	56	11.2E3
24 hours	0.7066	9.891	55.7%	3.89%	182	5.85E3	116	8.35E3
96 hours	0.6345	8.640	51.8%	2.84%	238	3.91E3	116	6.15E3

5409-6	Voc (V)	Jsc (mA/cm^2)	FF	PCE	R@Voc (Ω)	R@Jsc (Ω)	Rs (Ω) Spice	Rp (Ω) Spice
Before exposure	0.8188	5.401	59.4%	2.63%	231	9.07E3	55	12E3
2 hours	0.7084	5.943	56.4%	2.37%	240	7.09E3	79	11.8E3
24 hours	0.5950	5.598	54.9%	1.83%	238	7.31E3	64	11.2E3

5409-8	Voc (V)	Jsc (mA/cm^2)	FF	PCE	R@Voc (Ω)	R@Jsc (Ω)	Rs (Ω) Spice	Rp (Ω) Spice
Before exposure	0.8499	5.176	58.0%	2.55%	230	6.84E3	64	9E3
2 hours	0.8557	5.158	58.1%	2.56%	228	7.56E3	72	9.65E3
47 hours	0.8315	5.635	50.2%	2.35%	313	5.40E3	152	6.25E3
191 hours	0.7748	5.391	55.2%	2.31%	291	6.32e3	140	7.45E3

Mott-Schottky Plots_5409-2





Mott-Schottky Analysis

5409-2	C2_N_A (Carrier Density)	C2_V_{bi} (Built-in Voltage)	C3_N_A	C3_V_{bi}
before stress	1.34E+15	0.462	8.68E+15	0.606
2 hours	3.45E+15	0.463	2.69E+16	0.629
24 hours	4.20E+15	0.6	3.52E+16	0.636
96 hours	2.08E+15	0.193	2.84E+16	0.422

5409-6	C2_N_A	C2_V_{bi}	C3_N_A	C3_V_{bi}
before stress	1.45E+15	0.595	1.78E+16	0.697
2 hours	6.88E+15	0.721	1.17E+17	0.683
24 hours	7.16E+15	0.506	1.07E+17	0.572

5**409-8**	C2_N_A	C2_V_{bi}	C3_N_A	C3_V_{bi}
before stress	2.71E+15	0.604	1.51E+16	0.776
2 hours	1.09E+16	0.682	5.27E+16	0.713
24 hours	1.17E+16	0.657	9.95E+17	0.885
191hours	2.69E+16	0.806	4.39E+17	0.798

Carrier density increased after initial stress, suggesting doping.

Carrier Lifetime_5409-2

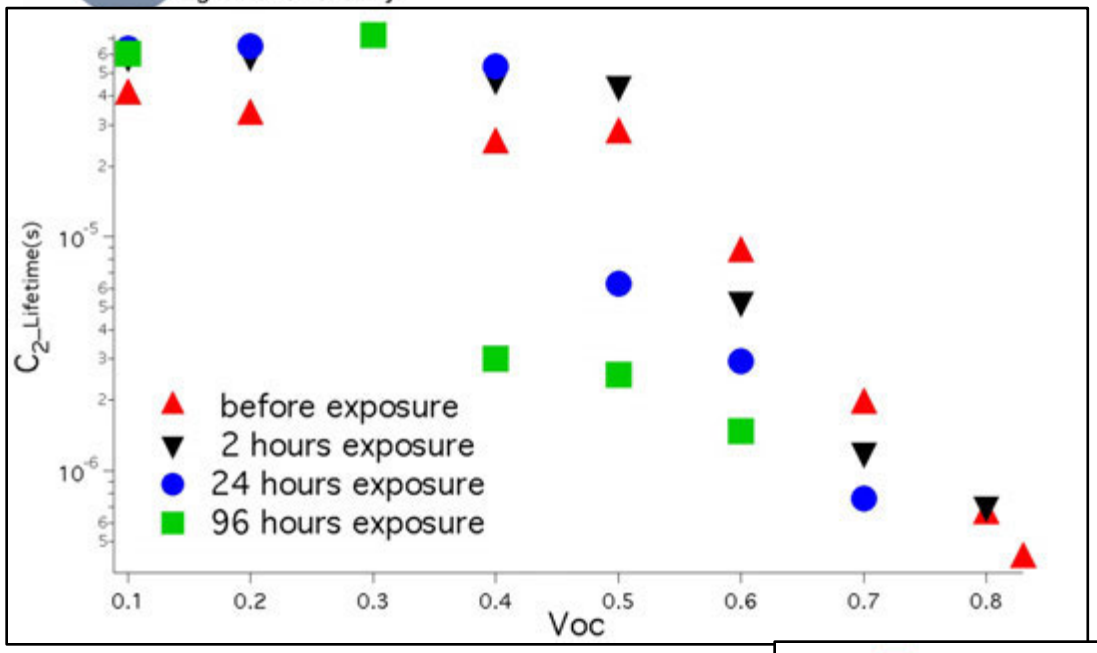
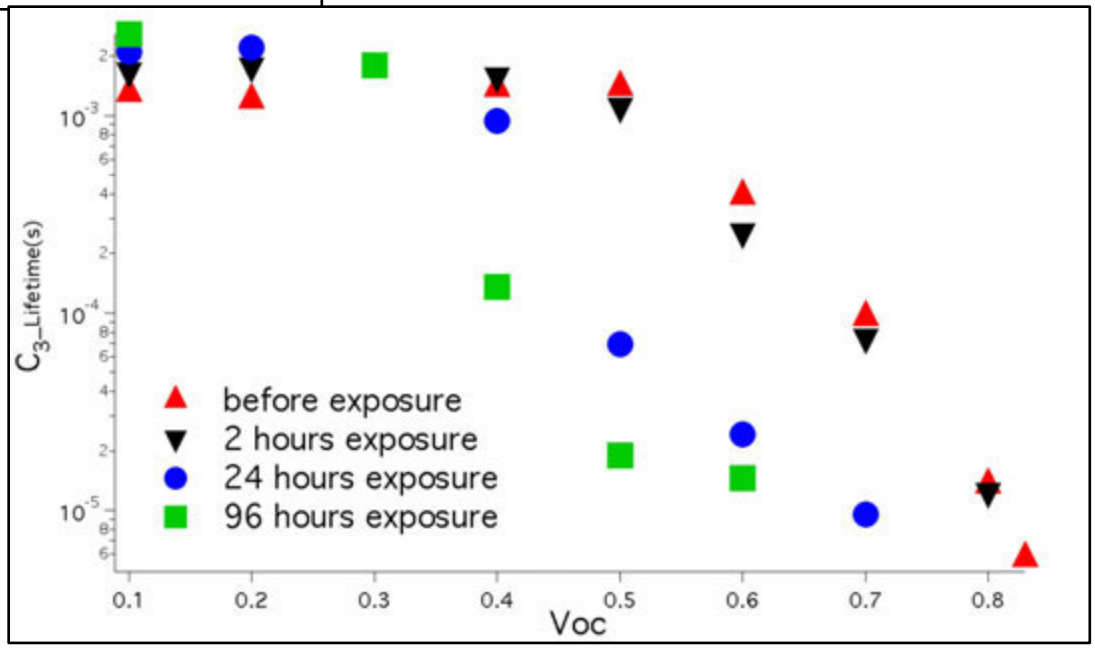


Photo-carrier lifetime decreased by order of magnitude upon Xe stress.



Carrier Lifetime_5409-6

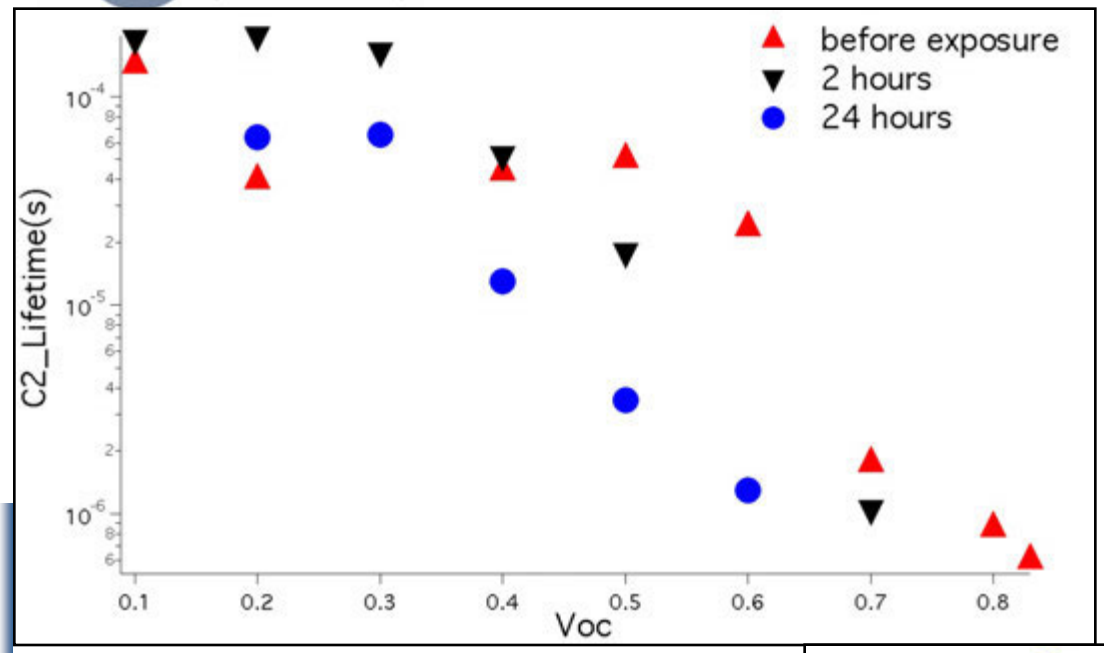
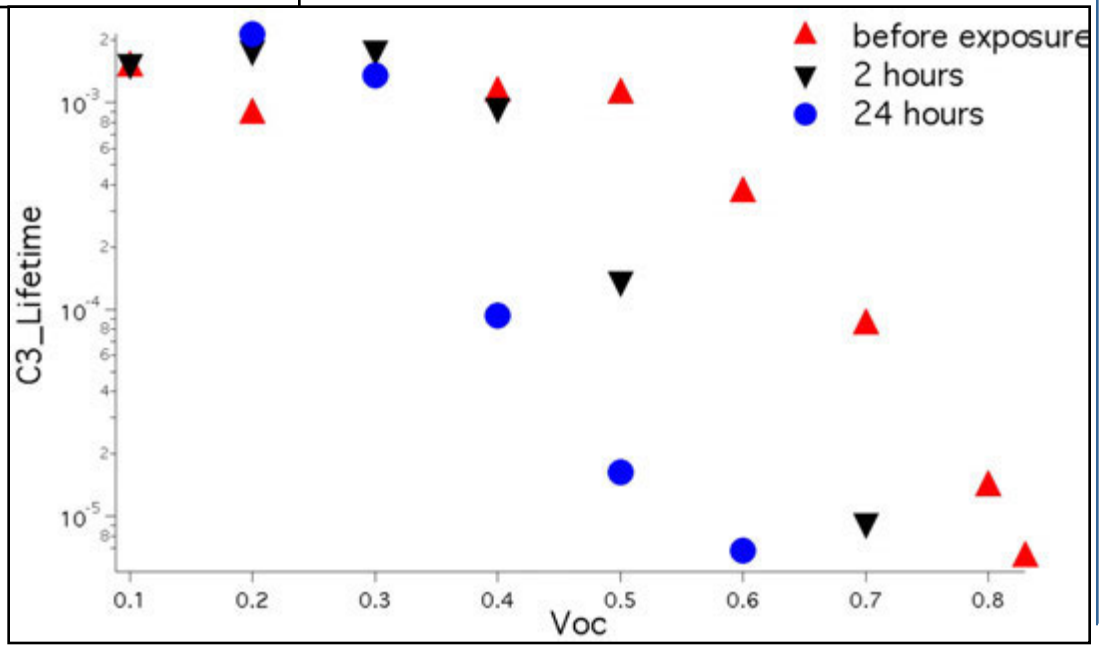


Photo-carrier lifetime decreased by order of magnitude upon Xe stress.



Carrier Lifetime_5409-8

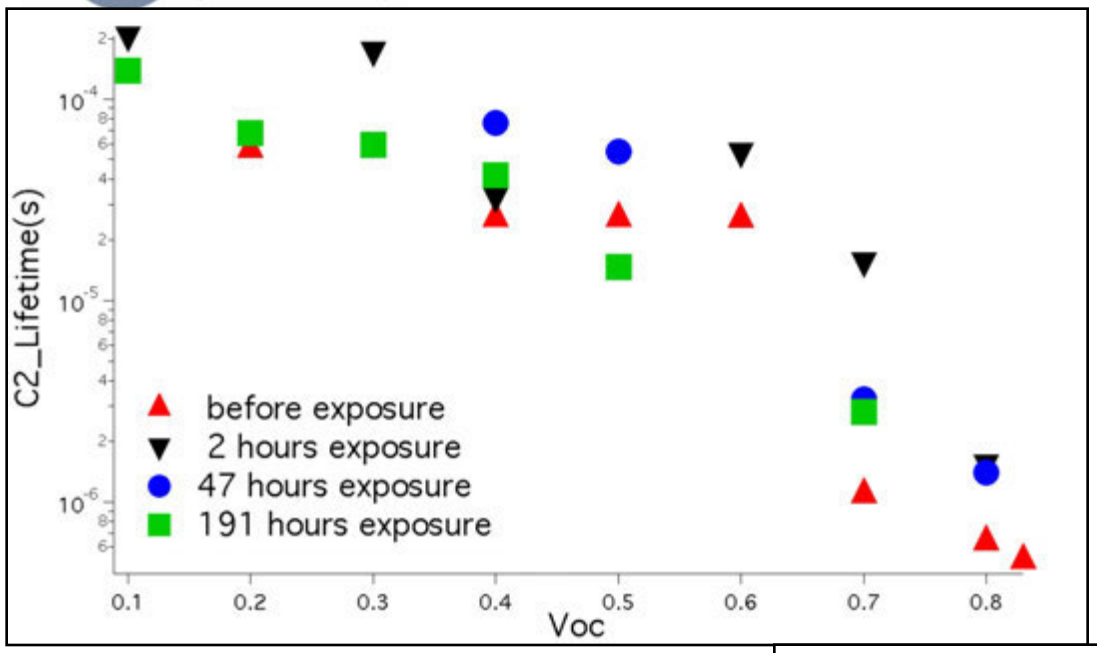
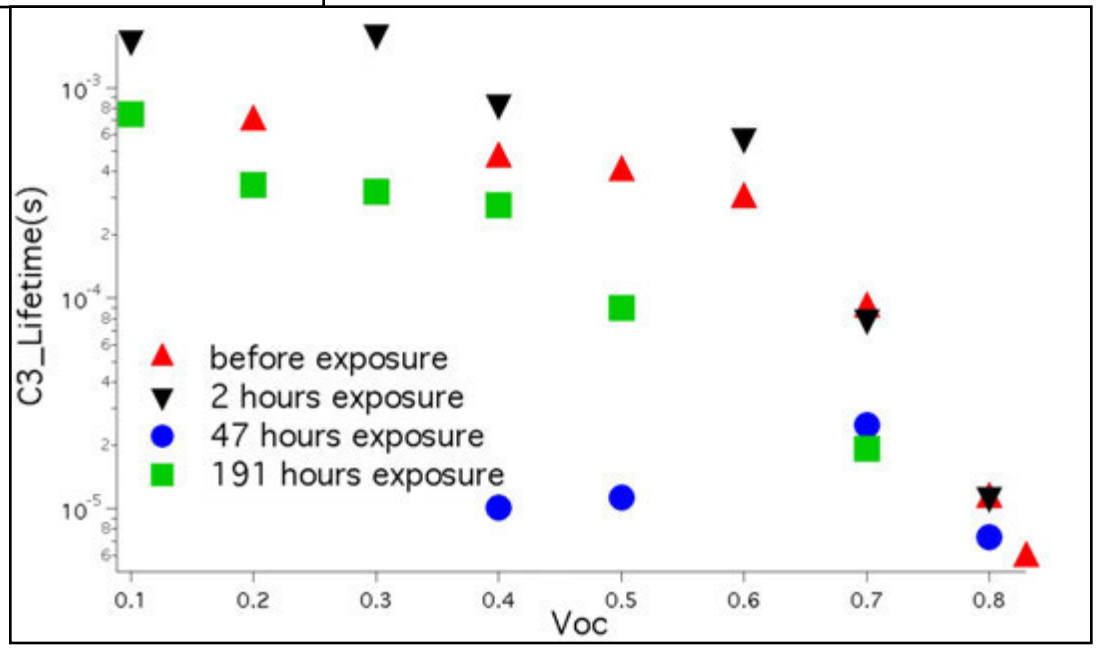


Photo-carrier lifetime was affected much less under sulfur plasma compared to Xe.



Summary

- A three-capacitor model was found to fit our devices over a wide range of bias voltage and active layer thicknesses.
  - C1: geometric of active layer; C2: interfaces with HTL; C3: interface with metal.
  - C-V analysis showed geometric capacitance C1 did not change much with bias voltage.
  - Mott-Schottky analysis yielded build-in voltage and intrinsic dark carrier concentrations for C2 and C3.
- As a function of decreasing active layer thickness:
  - C1: fitted data agreed well with calculated assuming a relative dielectric constant of 3.5.
  - C2 and C3: dark carrier densities appeared to increase; density of state decreased; reasonable carrier lifetime was extracted.
- As devices were stressed under Xe:
  - Photo-carrier lifetime decreased, suggesting photo-chemical degradation of the active layer components;
  - Carrier density increased, consistent with doping from photo-chemical degradation .
- Sulfur plasma caused less damaging than Xe:
  - UV component is likely a large contributor to the degradation.

Impedance measurement and analysis are useful tools to derive equivalent circuit model, study carrier concentration, build-in voltage, carrier lifetime. These parameters in turn can be used to probe degradation mechanisms.

OPV Lifetime Testing

NREL Reliability Workshop

February 18 & 19, 2010

Konarka Technologies Inc

Pathways for Degradation of OPV

- Delamination
- Interdiffusion of Electrode Material
- Morphology Changes
- Interfacial Degradation
- Photo-oxidation of Organic Layers
- Oxidation of Electrodes
- Moisture induced degradation
- Moisture ingress failure of package

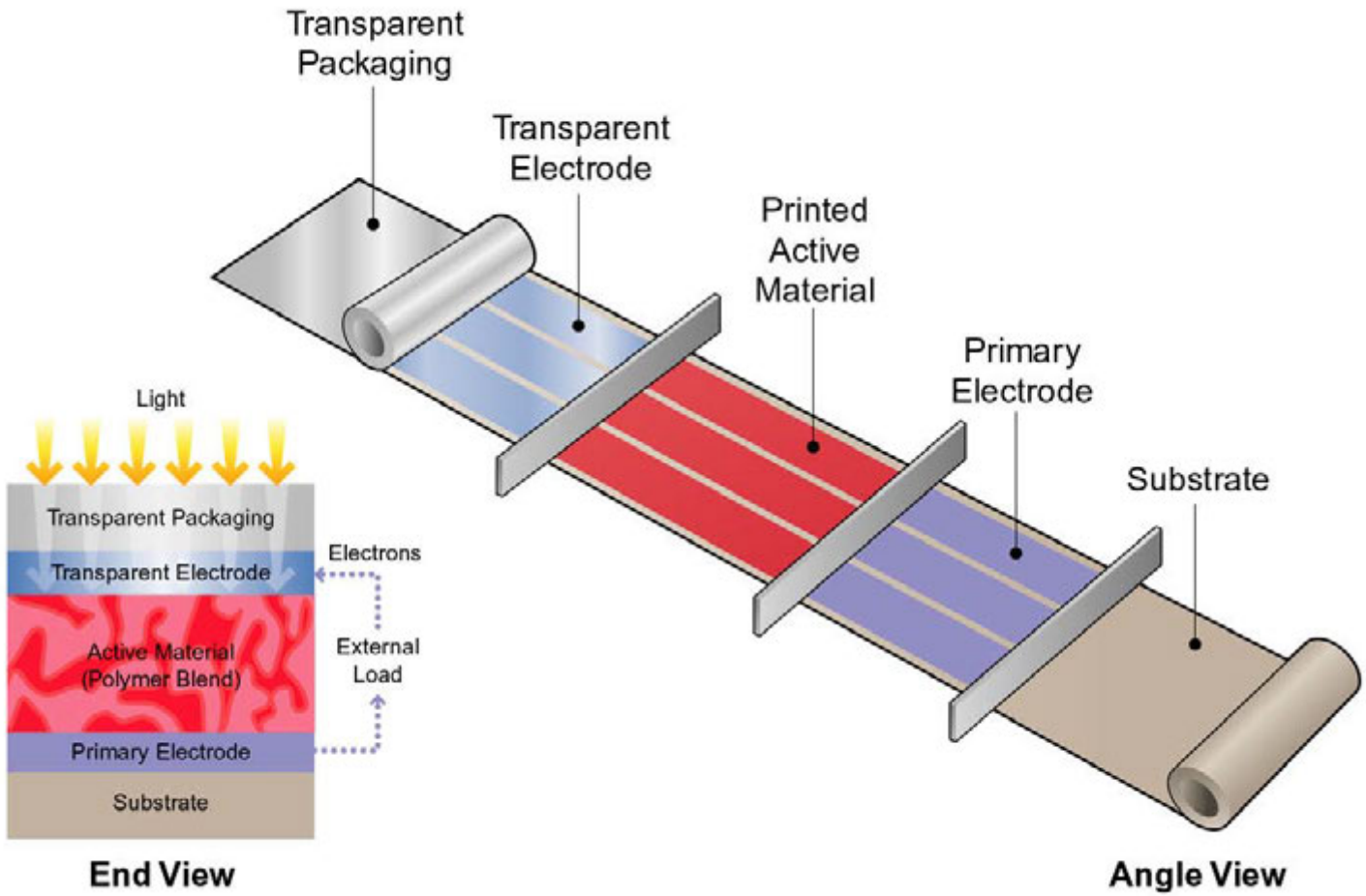
KONARKA®

Indoor Accelerated Tests Performed

- Room temperature (controls)
- 65 c dry oven (open circuit, dark)
- 65 c/85%RH (open circuit, dark)
- Light Soaking @ 1 sun (open circuit, module temp 65 C)
- Thermal Cycling (IEC 61646 10.11)
- Mechanical Testing

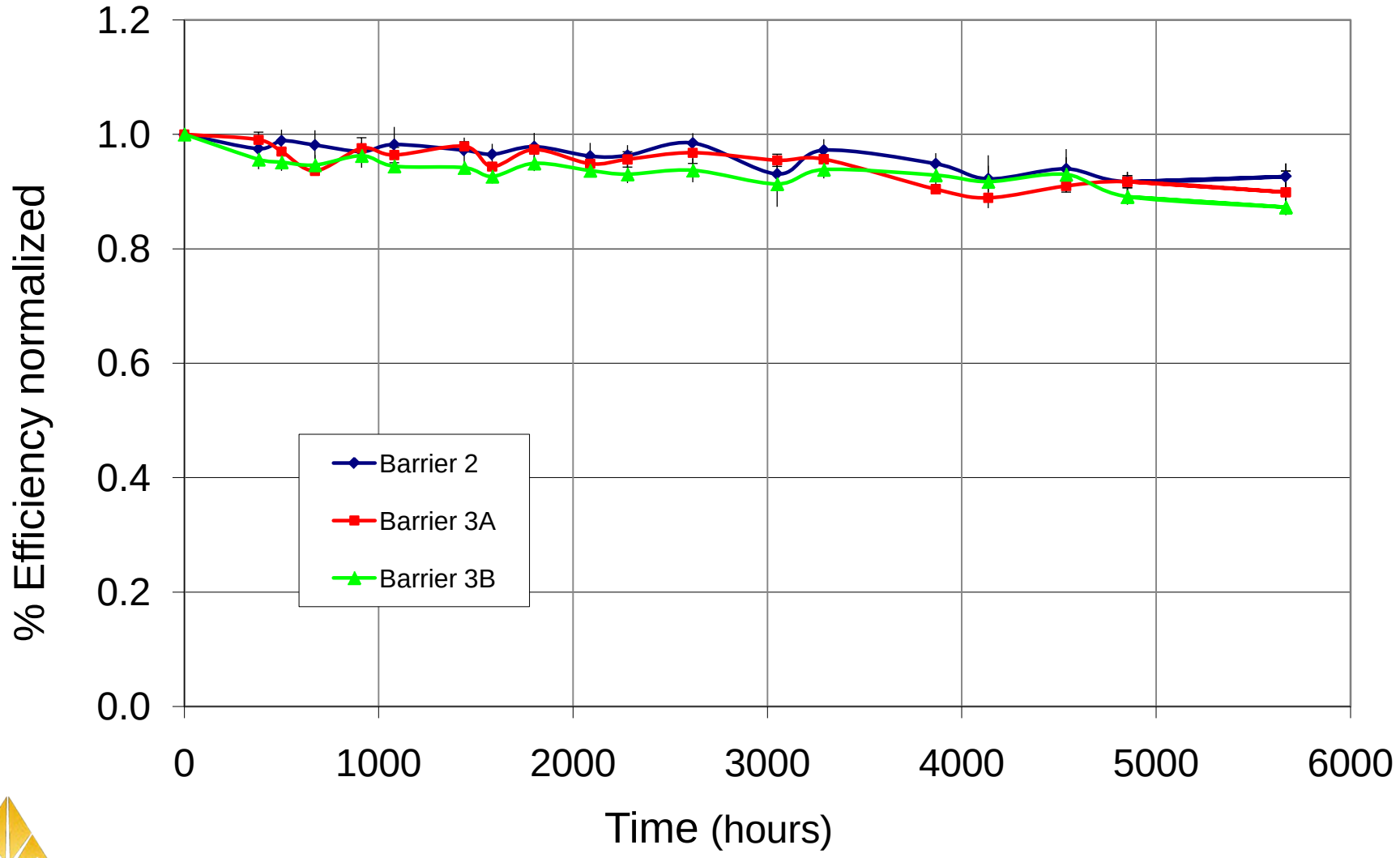
KONARKA®

Flexible OPV Stack



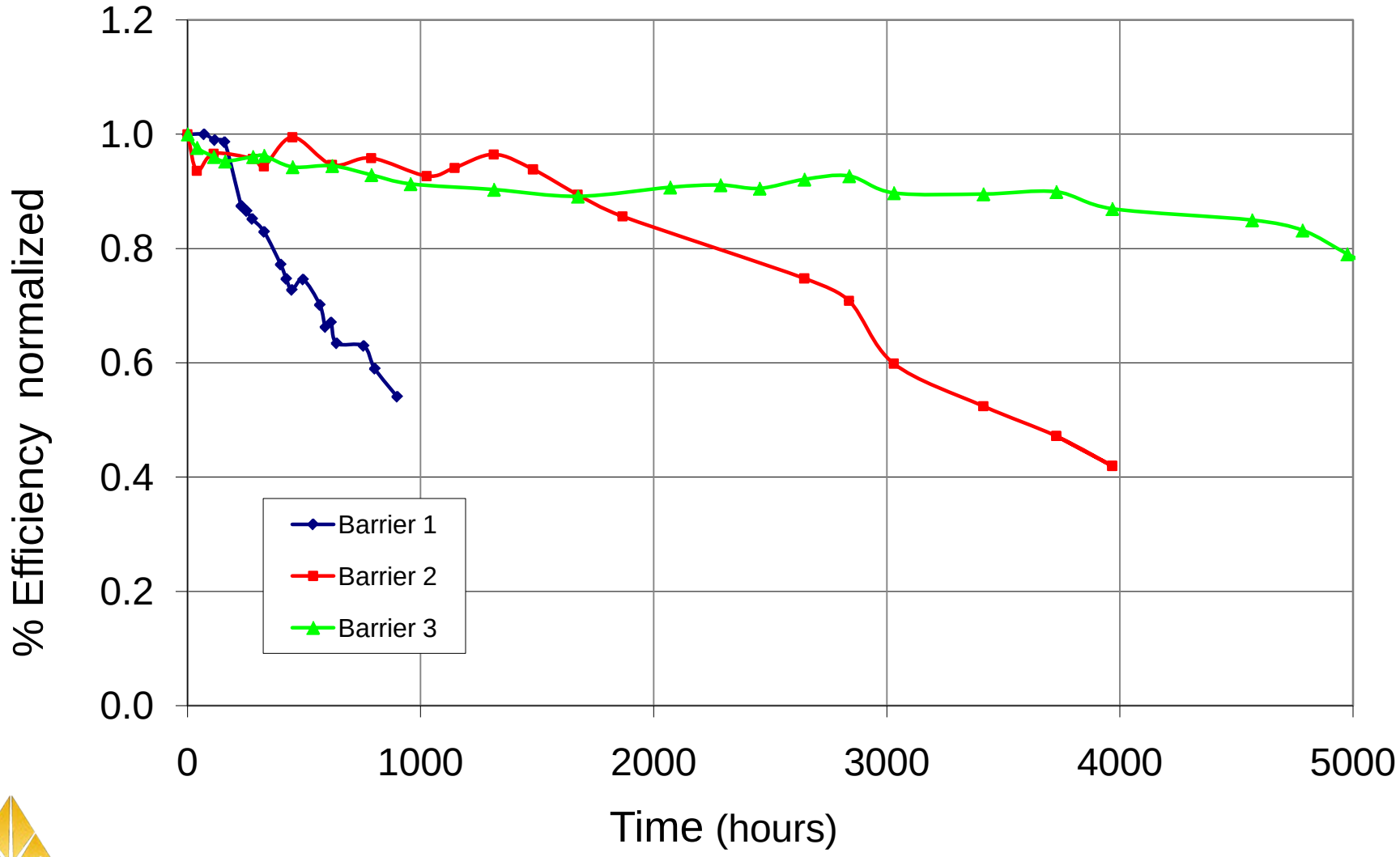
KONARKA®

OPV Modules Results with Various Flexible Barrier Films
65 C dry oven (open circuit, dark)



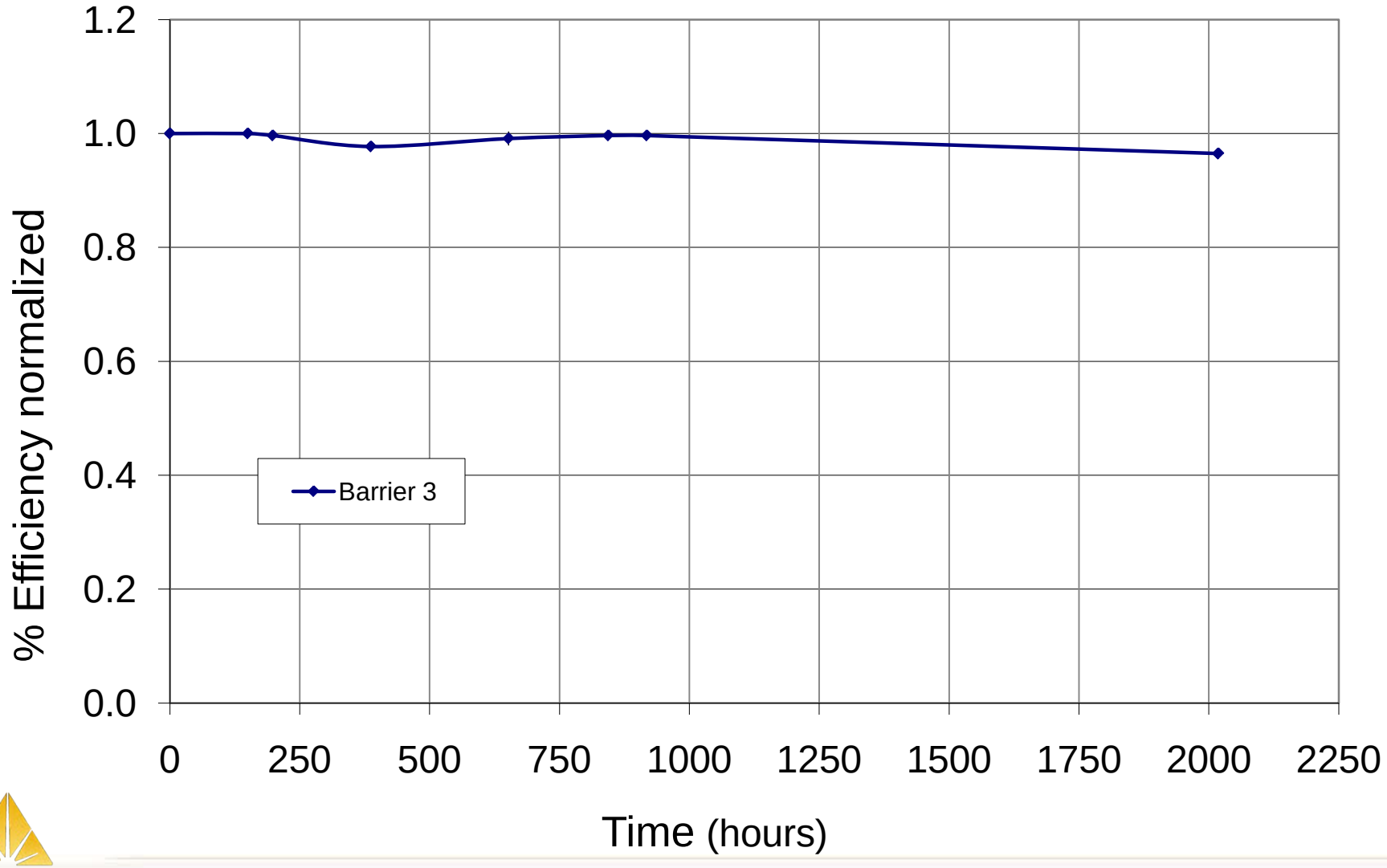
KONARKA®

OPV Modules DH Results with Various Flexible Barrier Films
65 C / 85%RH (open circuit, dark)



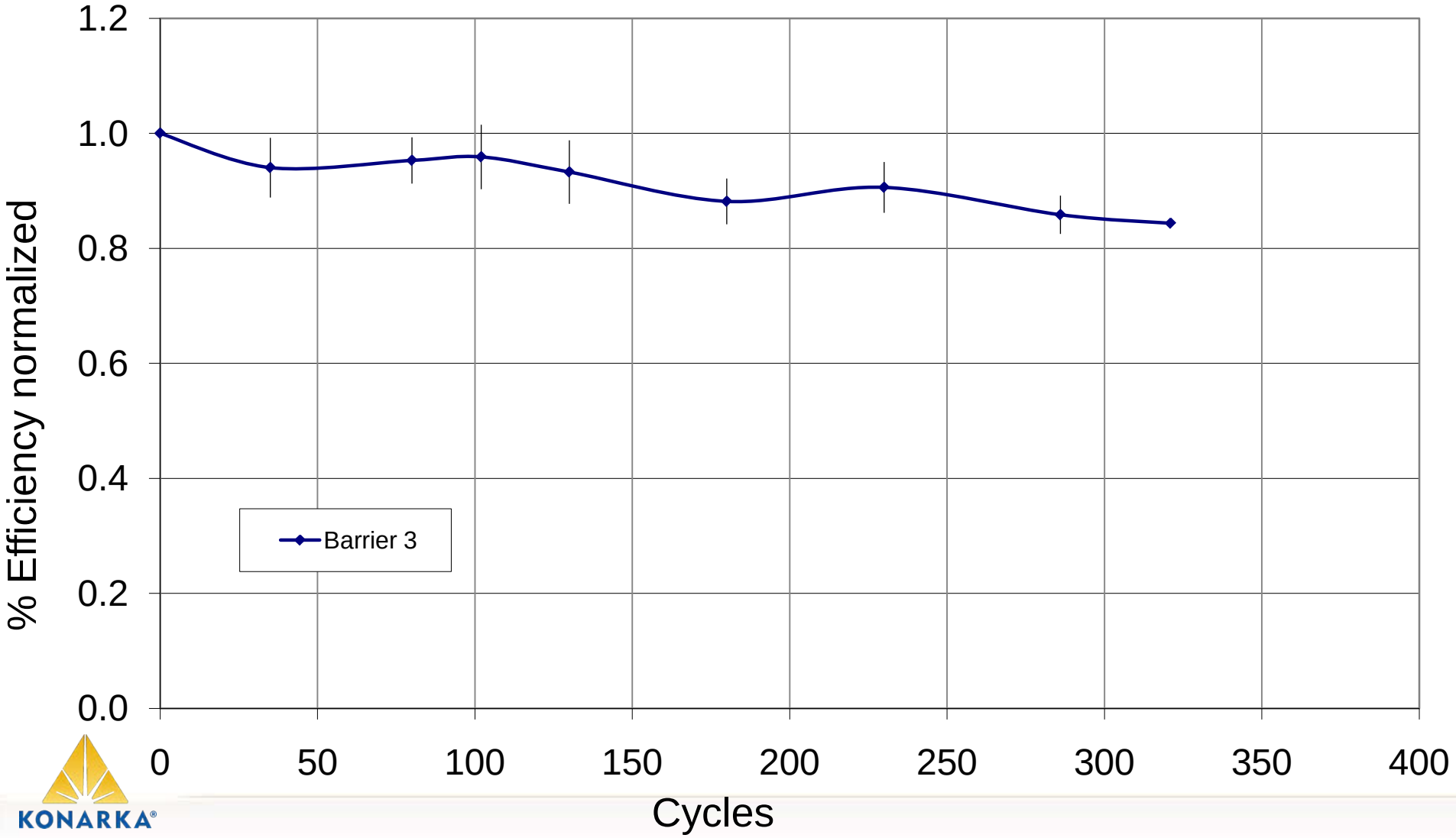
KONARKA®

OPV Modules Light Stability@ 1 sun, 65 C



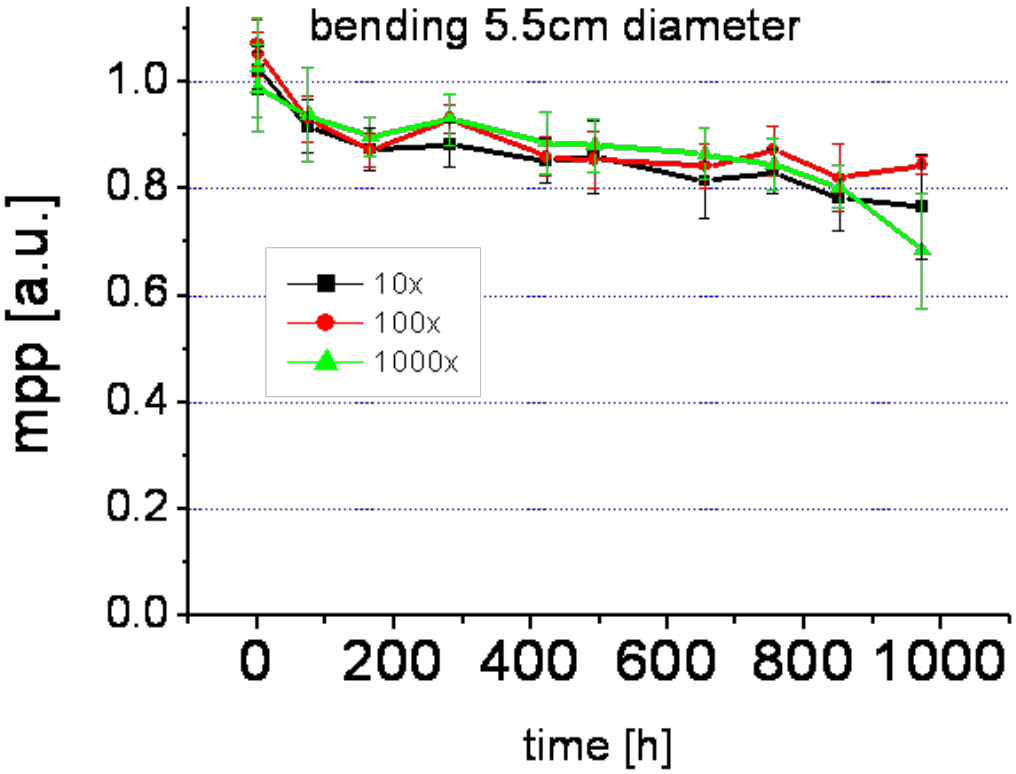
KONARKA®

OPV Thermal Cycling IEC 61646 10.11



KONARKA®

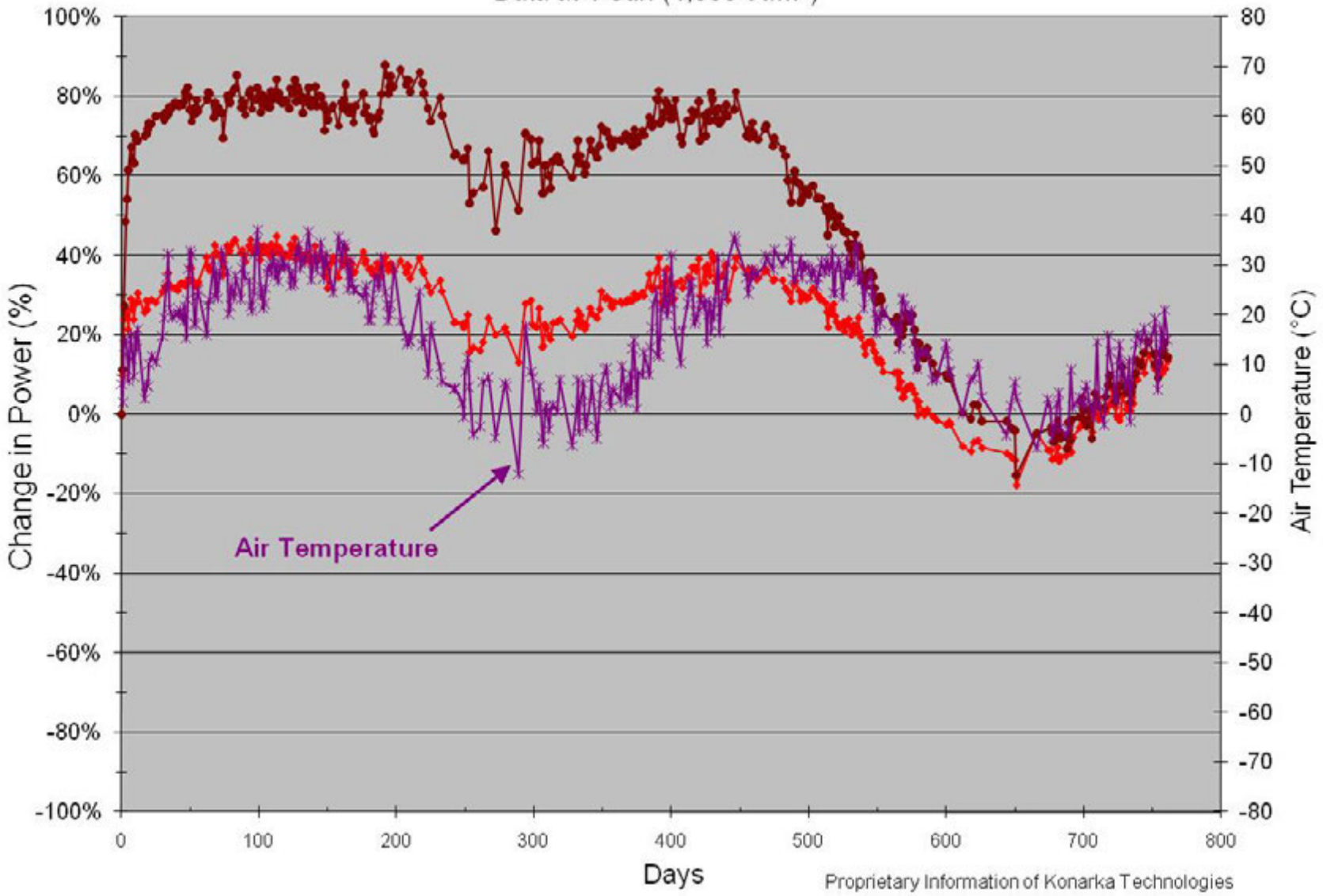
OPV Modules mechanical testing + 65 C/85%RH



The applied mechanical stress (bending of the substrates with a diameter of 5.5cm) does not show any influence on the LT performance under 65 C/85% RH for the first 1000 hours.

KONARKA®

OPV Cells: Aging on Rooftop Test Station - under Load



KONARKA®



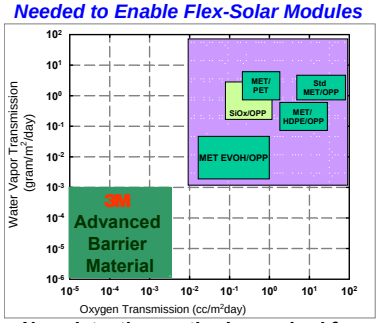
Pulsed Valve Mass Spectrometry Film Permeation Tool

Dana Reed, Mark Roehrig, Alan Nachtigal, Mark Weigel, and Robert Messner

Corporate Research Laboratory and Renewable Energy Division, 3M Company, St. Paul Minnesota

Ultra-low Flexible Barriers

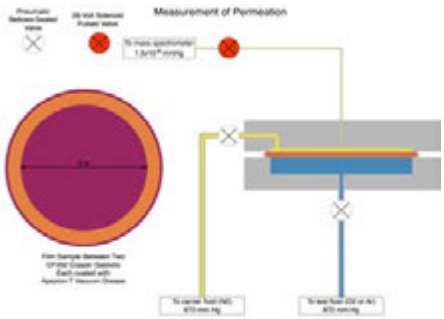
Needed to Enable Flex-Solar Modules



New detection methods required for permeation performance verification

Approach: Pulsed valve sample introduction from atmospheric pressure test cell, permeation detection by mass spectrometry

Instrument Schematic

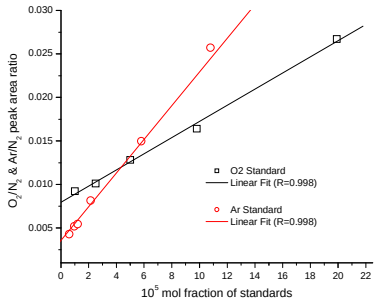


Key Features

- ➔ **Atmospheric pressure test conditions**
- ➔ **Measurements up to 100°C**
- ➔ **Multiple species detection**
- ➔ **Integration of permeation signal⟶ high sensitivity**
- ➔ **Proprietary method & apparatus**

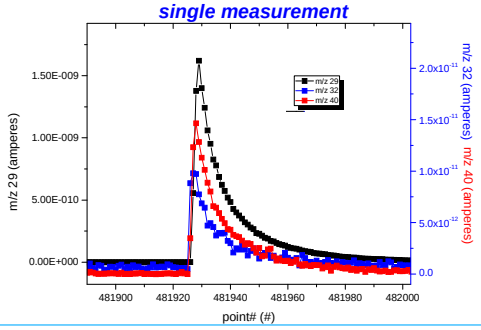
Calibration, Pulsed Signal Response, Certification Film

Calibration Plots for Ar & O2 Gas Standards



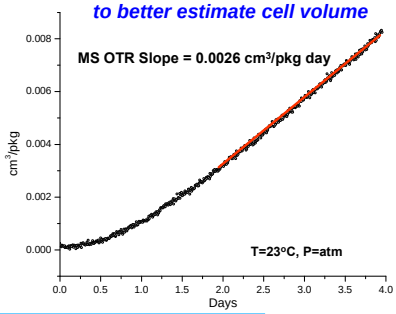
MS Signal/Valve-pulse

Multiple permeant detection in a single measurement



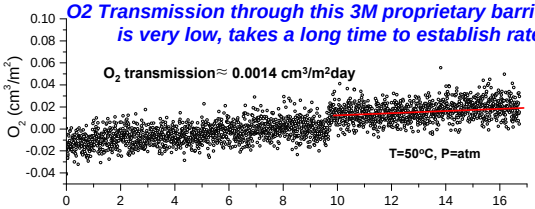
OTR Certification Film Measurement

Certification film (0.0026 cm³/pkgday) used to better estimate cell volume

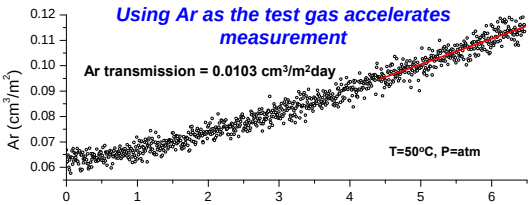


Measurements on 3M Proprietary Barrier Film

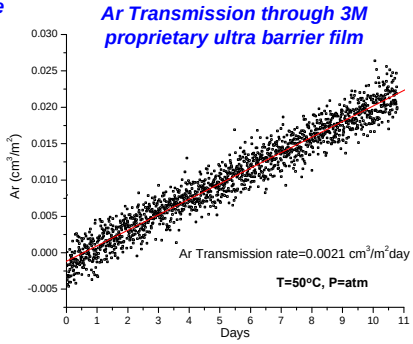
O2 Transmission through this 3M proprietary barrier film is very low, takes a long time to establish rate



Using Ar as the test gas accelerates measurement



Ar Transmission through 3M proprietary ultra barrier film



Summary

3M is developing proprietary barrier films with engineered performance for solar and display applications

This mass spec based permeation tool allows for high sensitivity, fast determination of barrier performance

Tool can detect below limits of other commercial instruments

Development is underway for a water MS permeation tool

© 3M 2009. All Rights Reserved.

PV Module Reliability and Durability Studies at the FSEC PV Materials Lab

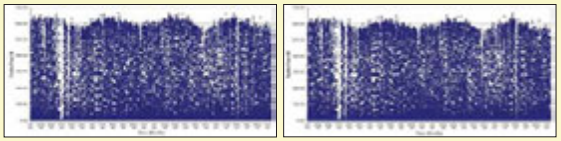
Neelkanth G. Dhere, Shirish A. Pethe, Ashwani Kaul
Florida Solar Energy Center, University of Central Florida, 1679 Clearlake Road, Cocoa, Fl, USA 32922
dhere@fsec.ucf.edu

Introduction

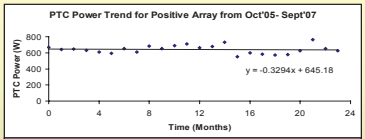
- Limitations of accelerated testing to predict all possible degradation modes and mechanisms for the PV modules necessitate actual outdoor monitoring and testing of PV modules to be carried out for extended period.
- Several parameters must be taken into consideration in order to characterize the performance of a PV device.
- These parameters include current and voltage generated by the PV device, solar irradiance, back of module temperature, relative humidity, wind speed, UV irradiance, and ambient temperature.
- It is essential to test PV modules under real time meteorological as well as electrical conditions and is advisable to carry out the testing in harsh climates such as the hot and humid climate of Florida and under high electrical stress conditions.

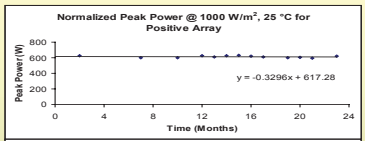
Outdoor Monitoring of PV Modules

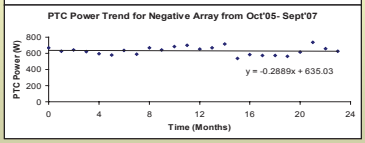
- PV modules are connected in two arrays that builds up to a maximum voltage of +600 V or -600 V. Each array is maintained near the maximum power point condition. Output parameters namely current, voltage, along with the meteorological parameters are monitored and recorded continuously using a data acquisition system (DAS).
- As the module array is maintained at near maximum power point condition the annual energy yield estimation can be carried out.
- The data collected over prolonged period can be analyzed using the PVUSA type regression and the annual degradation rates can be estimated.
- The periodic current-voltage measurements carried out on the arrays provides another approach for estimating the annual degradation rates. The two methods used for estimating the degradation rates complement each other.

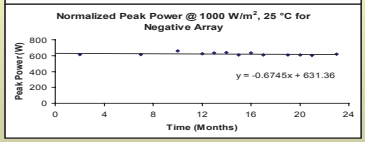


- Raw Data for positive and negative array
- Avg. annual energy yield estimated is 1385 kWhr/kWp/Yr.





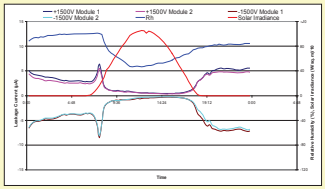


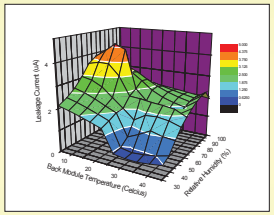


- The annual degradation rate calculated from the above graphs for positive and negative array is 0.6%/yr and 0.5 %/yr respectively with uncertainty of 1.5% using the PTC power trends over a two year period.

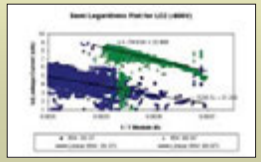
High Voltage Bias Testing of PV Modules

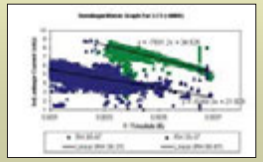
- In grid connected PV systems the PV cells may be at voltage as much as ±600 volts with respect to ground in USA and as high as ±1000 volts with respect to ground in Europe.
- Individual modules are generally biased from +150 V and -150 V up to +1500 V and -1500 V at the FSEC high voltage test bed.
- Such an outdoor high voltage bias test is more a realistic accelerated test as compared to damp heat test since it is exposed to solar irradiance, humidity and temperature cycling. PV modules are under bias even at night. Therefore, the high voltage bias testing acts as an accelerated test under near-real time conditions that the PV module would encounter in the field.
- The leakage current along with the relative humidity and ambient temperature is continuously recorded.





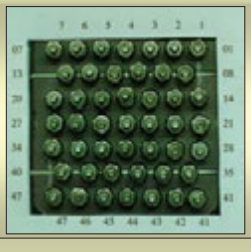
- It is essential to model the leakage current pathways in order to determine the possible degradation mechanisms. The photovoltaic module leakage conductance is thermally stimulated with a characteristic activation energy that depends on relative humidity that can be calculated by plotting the Arrhenius graphs.



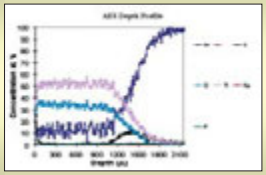


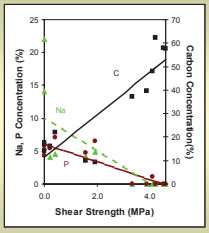
Module Bias	Activation Energy (eV)	
	RH 35-37%	RH 95-97%
+600 V	0.445	0.683
-600 V	0.456	0.639

PV Module Diagnostic Testing



- Materials characterization and adhesional strength measurement is carried out after coring samples in PV modules. This destructive sample extraction process was developed at Sandia and further improved at FSEC.
- Adhesional strength can be measured in two ways- (1) Torque test (2) Peel test, however the torque test better simulates the actual shear type of stress conditions of the PV module.
- Chemical analysis of the extracted samples using techniques such as AES, XPS is carried out to determine the underlying cause behind an observed degradation and/ or loss in adhesional strength.





Conclusion

- Over the years, FSEC has gathered wealth of data and experience in outdoor testing and high voltage bias testing of PV modules. Such study of PV modules of various technologies is essential to estimate the module lifetimes and for improving the fabrication technology.
- Annual degradation, seasonal variation and energy yield estimation are successfully determined for various PV Technologies.
- Over time, the sample extraction process has been modified and optimized with corresponding reduction in loss of samples. This enables to carry out adhesional strength testing as well as correlating the relationship between impurities migration and loss of adhesional strength.

The Atlas 25PLUS Testing Process

Module A

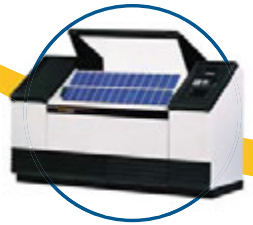
One PV module is run through the Atlas 25PLUS testing sequence over the course of 12 months.

ATLAS 25 Comprehen ive PV Dura ility Tes ing

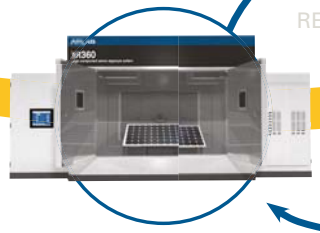
1 UV Conditioning



2 Salt Spray Corrosion



3 Condensing Humidity



4 Solar/Thermal/ Humidity Cycle

REPEATING CYCLE

5 Solar/Thermal/ Humidity/Freeze Cycle

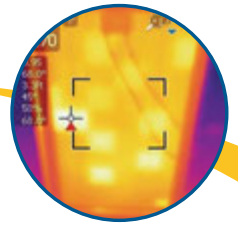


6 Arizona Solar Tracking including peak summer



7 Initial, final and multiple interval measurements

Visual inspections, IV curves, infrared thermographs and digital photography included.



8 Results and data

Completion of the Atlas 25PLUS program provides test data that would be otherwise unattainable with current test methods.

A report details all data, images and analyses at the end of the one year test sequence.





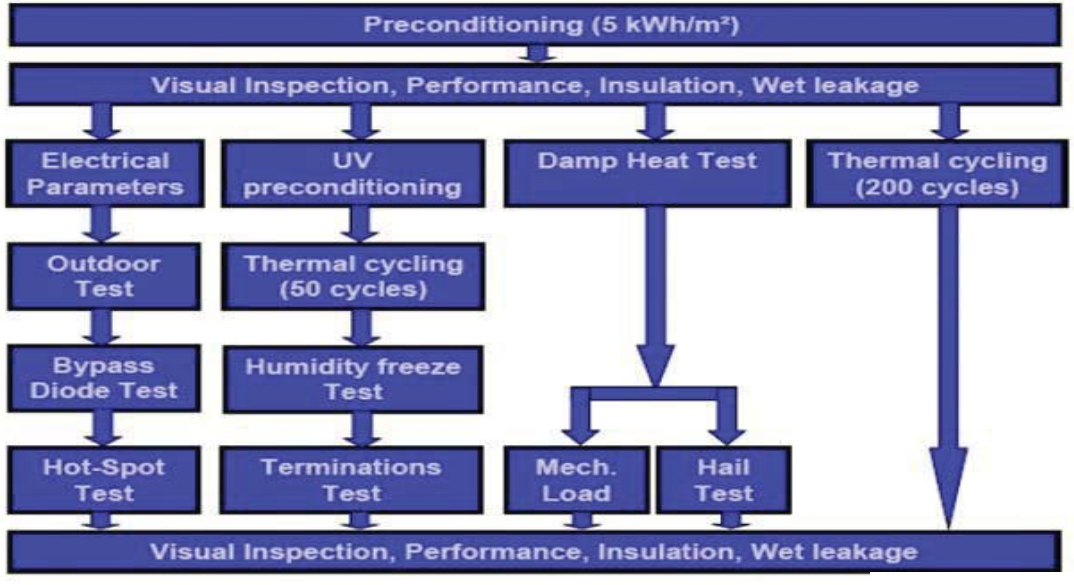
Modules B & C

Two modules provide baseline data using outdoor solar tracking in subtropical South Florida and the arid Arizona Sonoran desert for one year.

ATLAS 25 TESTED

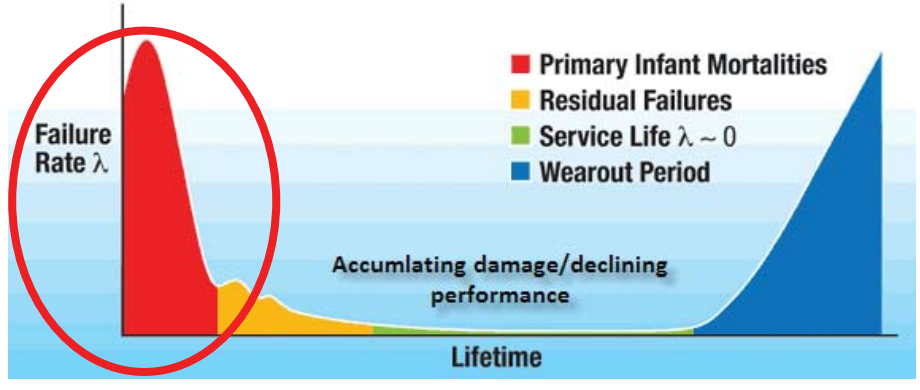
To learn more about the Atlas 25PLUS Program, contact your local Atlas Sales Representative or visit us online at **www.solardurability.com**

IEC design type qualification tests



IEC 61215 environmental tests

IEC 61646 environmental tests are similar



IEC and weathering methods

Design Qualification environmental tests	Atlas module weathering tests
Intent: Accelerated tests to screen for major materials design and manufacturing flaws which result in premature (infant mortality) failures.	**Intent: Accelerated environmental durability tests to reproduce likely field failures and estimate service life. Tests target failures resulting for the accumulated damage of long term outdoor exposure.**
Climate Stresses: E.g. Temperature-only cycling; UV-only exposure; Humidity-Freeze cycling; Damp-Heat. Most tests delivered to separate modules.	**Climate Stresses (comprehensive): Alternating cycles of SolarSim-Temperature-Humidity and SolarSim-Temperature-Humidity-Freeze; additional UV, salt spray, condensing humidity and outdoor solar tracking (AZ,FL). Modules under solar operate at max power point.**
Stress levels and delivery not representative of end-use: No module goes through all tests; limited to 1 or 2 stresses, e.g., thermal cycling, damp heat, humidity-freeze.	**Stress levels based on climate-derived conditions: Multiple simultaneous stresses delivered in short and long term cycles and at levels more representative of nature. "Global Composite" climate condition standard; alternative Hot Arid Desert, Tropical/Subtropical or Northern Temperate climate conditions available. Optional test modifiers: Coastal/Marine; Alpine/Snow Load; Urban Industrial; Agricultural Chemicals, Dust-Dirt, Acid Rain, Mildew effects.**

ATLAS
MATERIAL TESTING SOLUTIONS

IEC and weathering methods

Design Qualification environmental tests	Atlas module weathering tests
Corrosion Testing: **Limited to Damp-Heat test**	**Salt Spray and Condensing Humidity tests and outdoor exposures included.**
No long term outdoor exposure. **IEC cautions about shortness of test; most tests are chamber-based with limited stresses.**	**Uses combination of lab accelerated and outdoor solar tracking exposures with additional outdoor reference modules on one-year exposure in Arizona and Florida.**
Few cycles but under harsh conditions: **Designed to stress for infant mortality failures; may induce failures which will not occur in service**	**Higher number of cycles (diurnal >1500) under climate derived conditions designed to stress to longer term environmental effects.**
Modules exposed non-operational **Only short outdoor test is electrically active under load.**	**Modules exposed during solar load (lab and outdoor) operated under resistive load at maximum power point.**
Solar Load: **No solar load in chamber tests – modules at chamber temperature**	**Modules primarily under full spectrum solar load (natural or SolarSim) for differential heating and solar load effects.** **Max module temperature typically < 90°C**

ATLAS
MATERIAL TESTING SOLUTIONS

Weathering cycle

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

1 module

UV conditioning

Salt spray corrosion

Condensing humidity

Solar – Thermal – Humidity Cycle

Solar – Thermal – Humidity/Freeze Cycle

Arizona solar tracking including peak summer

1 module FL

1 module AZ

1-year solar tracking South Florida & Arizona

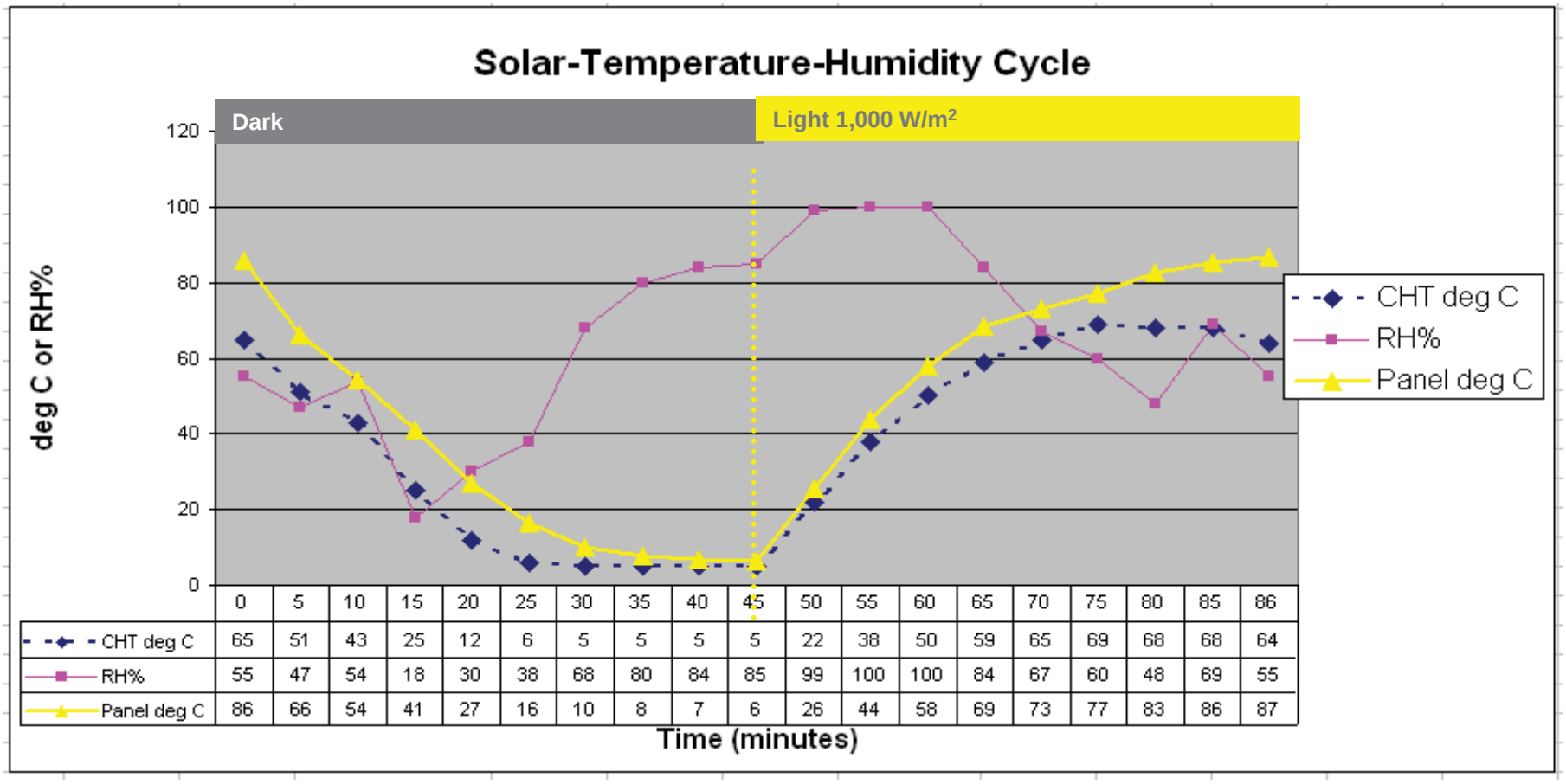


Total test program duration: 12 months

ATLAS
MATERIAL TESTING SOLUTIONS

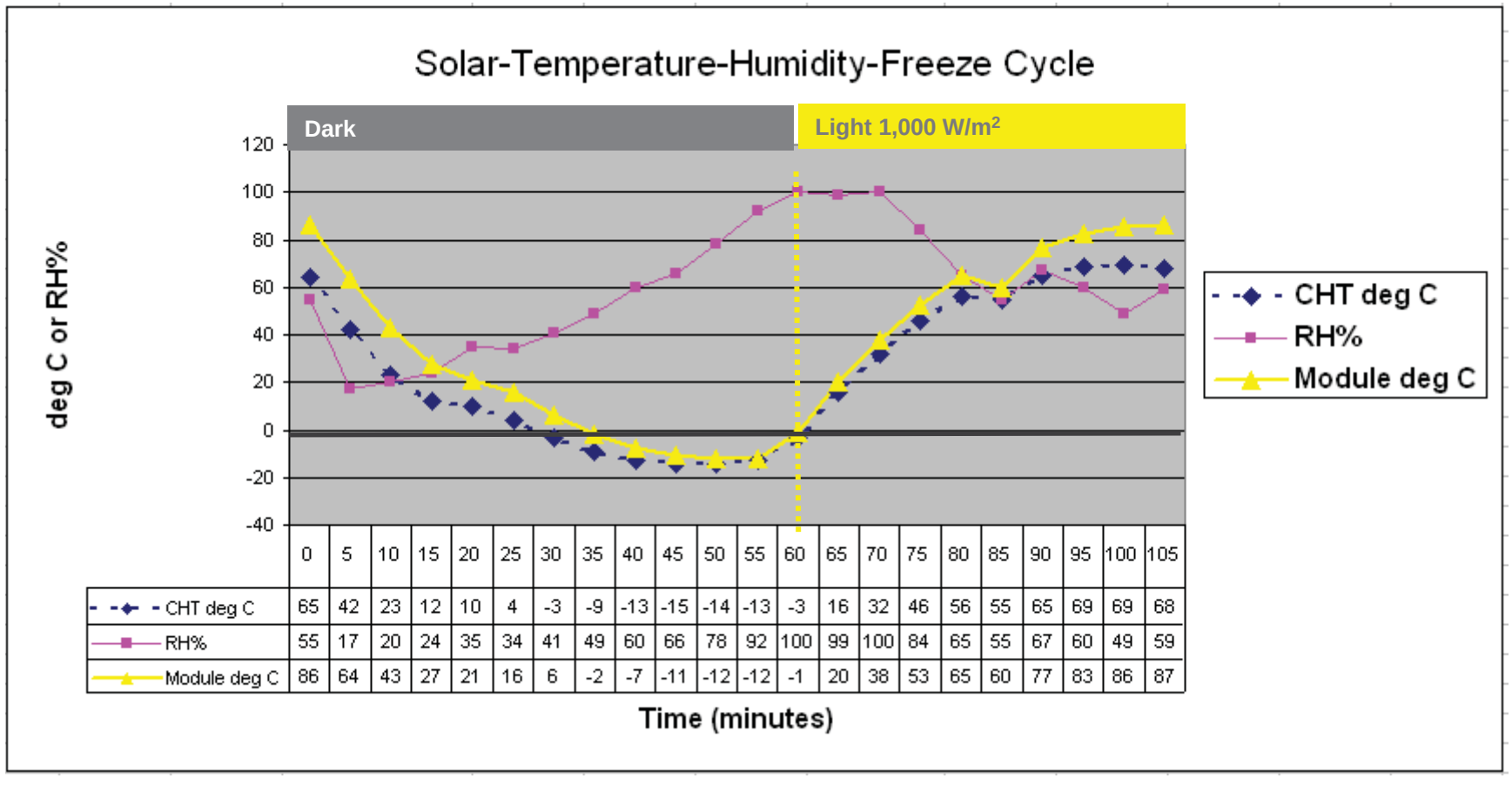
	Arid Desert	*Tropical / Subtropical*	*Northern Temperate*	*"Global"*
Corrosion	N/A (optional)	ISO 9227, ASTM B117 200 hours; 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour "Neutral Salt Spray Test"	ISO 9227, ASTM B117 400 hours; 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour "Neutral Salt Spray Test"	ISO 9227, ASTM B117 400 hours; 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour "Neutral Salt Spray Test"
Condensing Humidity	ASTM D2247, 125 hours @38°C or ISO 6270 40 °C	ASTM D2247, 125 hours @38°C or ISO 6270 40 °C	ASTM D2247, 125 hours @38°C or ISO 6270 40 °C	ASTM D2247, 125 hours @38°C or ISO 6270 40 °C
UV preconditioning	IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB	IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB	IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB	IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB
Humidity Cycle with simultaneous Solar SC 2000 or Enviromental Chamber w/Solar	control off at 40°C) and 65°C →5 °C (dark) in 25 min, hold 20 min, ramp up (light 1100 W/m²) 21 minutes, hold 20 min; repeat Cycle time 86 minutes 16.7cycles per day repeat 9.5 days (158 cycles)	control off at 40°C) and 65°C →15 °C (dark) in 25 min, hold 20 min, ramp up (light 1100 W/m²) 21 minutes, hold 20 min; repeat Cycle time 86 minutes 16.7cycles per day repeat 7 days (117 cycles	control off at 40°C) and 65°C →5 °C (dark) in 25 min, hold 20 min, ramp up (light 1100 W/m²) 21 minutes, hold 20 min; repeat Cycle time 86 minutes 16.7cycles per day repeat 7 days (117 cycles	control off at 40°C) and 65°C →5 °C (dark) in 25 min, hold 20 min, ramp up (light 1100 W/m²) 21 minutes, hold 20 min; repeat Cycle time 86 minutes 16.7cycles per day repeat 7 days (117 cycles)
Temperature-Humidity Freeze Cycle with Solar	55% RH (turn RH% control off at 40°C) and 65°C →-10 °C (dark) in 40 min), hold 20 min, ramp up (light 1100 W/m²) 25 minutes, hold 20 min; 105 minute cycle, 13.7 cycles/day, repeat 0.5 day (7 cycles) [4% of total 10 day cycles are freeze]	N/A 55% RH (turn RH% control off at 40°C) and 65°C →-+5 °C (dark) in 40 min), hold 20 min, ramp up (light 1100 W/m²) 25 minutes, hold 20 min; 105 minute cycle, 13.7 cycles/day, repeat 3 days (44 cycles) *No freeze in tropics*	55% RH (turn RH% control off at 40°C) and 65°C →-10 °C (dark) in 40 min), hold 20 min, ramp up (light 1100 W/m²) 25 minutes, hold 20 min; 105 minute cycle, 13.7 cycles/day, repeat 3 days (44 cycles) [27% of total 10 day cycles are freeze]	55% RH (turn RH% control off at 40°C) and 65°C →-10 °C (dark) in 40 min), hold 20 min, ramp up (light 1100 W/m²) 25 minutes, hold 20 min; 105 minute cycle, 13.7 cycles/day, repeat 3 days (44 cycles) [27% of total 10 day cycles are freeze]

Module temperature tracking



	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	86
CHT deg C	65	51	43	25	12	6	5	5	5	5	22	38	50	59	65	69	68	68	64
RH%	55	47	54	18	30	38	68	80	84	85	99	100	100	84	67	60	48	69	55
Panel deg C	86	66	54	41	27	16	10	8	7	6	26	44	58	69	73	77	83	86	87

Module temperature tracking



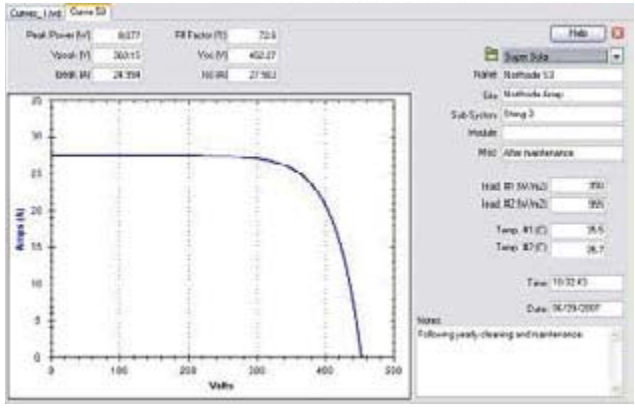
	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105
CHT deg C	65	42	23	12	10	4	-3	-9	-13	-15	-14	-13	-3	16	32	46	56	55	65	69	69	68
RH%	55	17	20	24	35	34	41	49	60	66	78	92	100	99	100	84	65	55	67	60	49	59
Module deg C	86	64	43	27	21	16	6	-2	-7	-11	-12	-12	-1	20	38	53	65	60	77	83	86	87

Monitoring








Help
Volts


Area
Max. 170
°F
ε 0.95
Refl. T 68.0°
Dist 3.3ft
FOV 45°
Rel. H 50%
Atm. T 68.0°
172
11.9
FLIR
08/24/09
14:37



Sunset Technology, Inc.

PV Standards. What does the IEC have for you?

By Howard O. Barikmo, Sunset Technology, Inc.
hbarikmo@aol.com
February 18, 2010

Technical Committee 82 and its Working Groups

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

TC 82 Standards

blue indicates standard is either new work item or is being revised

WG 1. GLOSSARY

IEC 61836: 2007 Ed 2, Solar photovoltaic energy systems - Terms, definitions and symbols. Ed 3 in process; publish 3Q 2011

WG2. MODULES

IEC 60891: 2009 Ed 2, Procedures for temperature and irradiance corrections to measured I-V characteristics of crystalline silicon photovoltaic (PV) devices.

IEC 60904-1: 2006 Ed 2, Photovoltaic devices-Part 1: Measurements of PV current-voltage characteristics

IEC 60904-2: 2007 Ed 2, Photovoltaic devices – Part 2: Requirements for reference solar devices

IEC 60904-3: 2008 Ed 2, Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data

IEC 60904-4: 2009 Ed 1, Photovoltaic devices - Part 4: Reference solar devices - Procedures for establishing calibration traceability

IEC 60904-5: 1993 Ed 1, Photovoltaic devices – Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method. Being revised; publish about 1Q 2011

IEC 60904-7: 2008 Ed 3, Photovoltaic devices - Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices

IEC 60904-8: 1998 Ed 2, Photovoltaic devices – Part 8: Measurement of spectral response of a photovoltaic (PV) device

TC 82 Standards (Cont'd)

IEC 60904-9: 2007 Ed 2, Photovoltaic devices – Part 9: Solar simulator performance requirements

IEC 60904-10: 2009 Ed 2, Photovoltaic devices – Part 10: Methods of linearity measurement

IEC 61215: 2005 Ed 2, Crystalline silicon terrestrial PV modules – Design qualification and type approval. Ed 3 in process; publish 1Q 2011

IEC 61345: 1998 Ed 1, UV test for photovoltaic (PV) modules

IEC 61646: 2008 Ed 2, Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval

IEC 61701: 1995 Ed 1, Salt mist corrosion testing of photovoltaic (PV) modules. Ed 2 in process; publish 4Q 2010

IEC 61730-1: 2004 Ed 1, Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction Amendment 1 in process; publish 4Q 2010

IEC 61730-2: 2004 Ed 1, Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing Amendment 1 in process; publish 3Q 2010

IEC 61829: 1995 Ed 1, Crystalline silicon photovoltaic (PV) array - On-site measurement of I-V characteristics. Ed 2 in process; publish 1Q 2011

IEC 61853-1: Ed 1, Photovoltaic (PV) module performance testing and energy rating - Part 1: Irradiance and temperature performance measurements and power rating; publish 1Q 2011

IEC 61853-2: Ed 1, Photovoltaic (PV) module performance testing and energy rating - Part 2: Spectral response, incidence angle and module operating temperature measurements; publish 4Q2010

TC 82 Standards (Cont.)

WG3 SYSTEMS

IEC 61194: 1992 Ed 1, Characteristic parameters of stand-alone photovoltaic (PV) systems

IEC 61683: 1999 Ed 1 Photovoltaic systems - Power conditioners - Procedure for measuring efficiency Revision to Ed 2 is underway; expect publication in 3Q 2011

IEC 61702: 1995 Ed 1, Rating of direct coupled photovoltaic pumping systems

IEC 61724: 1998 Ed 1, Photovoltaic system performance monitoring – guidelines for measurement, data exchange and analysis

IEC 61725: 1997 Ed 1, Analytical expression for daily solar profiles

IEC 61727: 2004 Ed 2, Photovoltaic (PV) systems – Characteristics of the utility interface

IEC 62124: 2004 Ed 1, Photovoltaic (PV) stand alone systems - Design verification

IEC 62446: 2009 Ed 1 Grid connected photovoltaic systems - Minimum requirements for system documentation, commissioning tests and inspection

IEC 62253: Ed 1 Equipment and safety specifications for direct coupled photovoltaic (PV) – pumping systems; publish 2Q 2010

IEC 62548: Ed 1 Installation and Safety Requirements for Photovoltaic (PV) Generators; publish 2Q 2010

TC 82 Standards (Cont.)

WG6 BALANCE OF SYSTEMS

IEC 61683: 1999 Ed 2, PV systems – Power conditioners – Procedure for measuring efficiency

IEC 62093: 2005 Ed 1, Balance-of-system components for photovoltaic systems - Design qualification natural environments

IEC 62109-1 Ed. 1.0 Safety of power converters for use in photovoltaic power systems -- Part 1. General requirements. Publish 2Q 2010

IEC 62109-2 Ed. 1.0 Safety of power converters for use in photovoltaic power systems -- Part 2. Particular requirements for inverters. Publish 4Q 2010

IEC 62109-3 Ed. 1.0 Safety of power converters for use in photovoltaic power systems -- Part 3. Controllers. New Work Item Proposal

IEC 62116: 2008 Ed 1, Test procedure of islanding prevention measures for utility-interconnected photovoltaic inverters

IEC 62509 Ed. 1.0 Performance and functioning of photovoltaic battery charge controllers. Publish 4Q 2010

TC 82 Standards (Cont.)

WG7 CONCENTRATOR PHOTOVOLTAICS

IEC 62108: 2007 Ed 1, Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval Amendment or revision is underway

Concentrator Photovoltaic (CPV) Module and Assembly Performance Testing and Energy Rating: Part 1: Performance Measurements and Power Rating - Irradiance and Temperature

CPV safety standard. New Work Item Proposal.

Tracker specification. New Work Item Proposal.

JWG TC21/TC82, PV BATTERIES

IEC 61427: 2005 Ed 3, Secondary cells and batteries for photovoltaic energy systems (PVES) - General requirements and methods of test Revision to include latest battery technology is underway

TC 82 Standards (Cont.)

JCWGTC82/TC21/TC88/TC105

IEC/TS 62257-1: 2003 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 1: General introduction to rural electrification

IEC/TS 62257-2: 2004 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 2: From requirements to a range of electrification systems

IEC/TS 62257-3: 2004 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 3: Project development and management

IEC/TS 62257-4: 2005 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 4: System selection and design

IEC/TS 62257-5: 2005 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 5: Protection against electrical hazards

IEC/TS 62257-6: 2005 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 6: Acceptance, operation, maintenance and replacement

IEC/TS 62257-7: 2008 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 7: Generators

TC 82 Standards (Cont.)

IEC/TS 62257-7-1: 2006 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 7-1: Generators - Photovoltaic arrays

IEC/TS 62257-7-3: 2008 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 7-3: Generator set - Selection of generator sets for rural electrification systems

IEC/TS 62257-8-1: 2007 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 8-1: Selection of batteries and battery management systems for stand-alone electrification systems - Specific case of automotive flooded lead-acid batteries available in developing countries

IEC/TS 62257-9-1: 2008-09 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 9-1: Micropower systems

IEC/TS 62257-9-2: 2006 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 9-2: Microgrids

IEC/TS 62257-9-3: 2006 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 9-3: Integrated system - User interface

IEC/TS 62257-9-4: 2006 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 9-4: Integrated system – User installation

TC 82 Standards (Cont.)

IEC/TS 62257-9-5: 2007 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 9-5: Integrated system - Selection of portable PV lanterns for rural electrification projects

IEC/TS 62257-9-6: 2008 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 9-6: Integrated system - Selection of Photovoltaic Individual Electrification Systems (PV-IES)

IEC/TS 62257-12-1: 2007 Ed 1 Recommendations for small renewable energy and hybrid systems for rural electrification - Part 12-1: Selection of self-ballasted lamps (CFL) for rural electrification systems and recommendations for household lighting equipment

Recommended Protocol for Accelerated Aging Testing: A Literature Review for Protocol Development

Mani G. Tamizh-Mani
Arizona State University

ACCELERATED AGING TESTS OF PV MODULES			
	ACCELERATED QUALIFICATION TESTING	**ACCELERATED COMPARATIVE TESTING**	**ACCELERATED LIFETIME TESTING**
Design Quality and Confidence	Minimum*	Medium**	High***
Objective	Minimum testing for reliability/durability of **specific** module **design**	Extended qualification testing to compare relative reliability/durability of **multiple designs**	Site (and configuration) specific testing or worst case site (s) testing of any **specific** module **design**
Cost and Time	Low	Medium	High
Goal	**Introduce** the specific design in the market	**Compare** (to improve/purchase/invest) multiple designs	**Predict** lifetime and/or protect warranty
Testing Protocol	Test **standards exist**	Tester defined protocols exist but a **uniform protocol is needed**	None publicly exists, if any. **Needs a comprehensive understanding on failure mechanisms, failure modes and mathematical models to develop an appropriate testing protocol**
Test requirement	**Pass/Fail** (>5% Pmax drop = Fail)	**Relative** power loss for a specific stress time or relative stress time for a specific power loss	Identify ultimate failure mode and/or **to determine/substantiate warranty period**
User	Manufacturers/ Consumers/Investors	Manufacturers/ Consumers/Investors	Manufacturers

CURRENT STUDY

Literature search and review on **failure mechanisms**	Literature search on **failure modes**	Literature search and review on **mathematical models**	Literature search and review on **potential accelerated testing protocols to simulate the failure mechanisms and ultimate failure modes**

FUTURE WORK NEEDED

- Develop an appropriate accelerated lifetime testing protocol
- Design and execution of preliminary experiments
- Develop initial mathematical models
- Validate and improve mathematical models through detailed experiments
- Develop "Recommended Protocol for Accelerated Lifetime Testing"

ASU ARIZONA STATE UNIVERSITY



Sandia's PV Reliability Program*

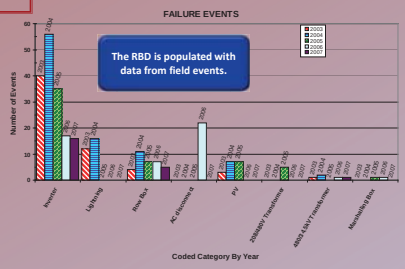
Rob Sorensen, Michael Quintana, Jennifer Granata, Mike Mundt, Jeff Mahn, Elmer Collins, Chad Staiger, Enrico Quintana
Sandia National Laboratories

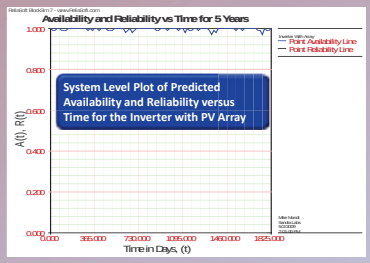
*Sandia & NREL work collaboratively on the DOE Solar Energy Technologies Program PV Reliability Project

Reliability Model (PVRAM & PVROM)

PVRAM Goal: Predict for any component and any level of the system - *degradation* versus time; *reliability* versus time; *availability* versus time

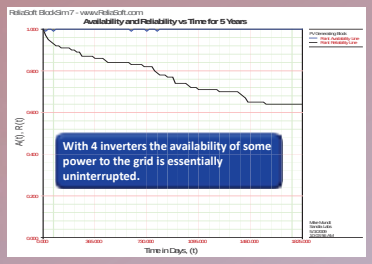


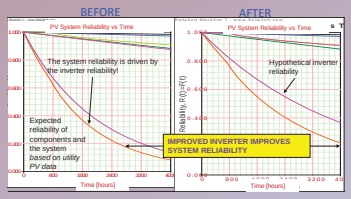




PVROM Goal: Compile failure event data into a web-based database for use with PVRAM







The system reliability would improve drastically!

20% reliability point nearly doubles

Predictions Made using RBD

Component	Actual Number of Failures 5 yr Cum	Expected Number of Failures 5 yr Cum	Expected Number of Failures 10 yr Cum	Expected Number of Failures 20 yr Cum
PV 150 Inverter (26 cSi arrays)	125	132	231*	429*
PV Module	29	26	31	38
AC Disconnect	22	17	23	31
Lightning	16	10	20	41
208/480 Transformer	4	3	3	3
Row Box	34	25	35	50
Marshalling Box 480VAC/34.5KV Xformer	2	4	7	11
	5	4	5	9

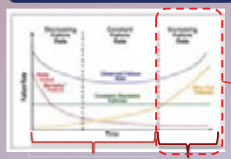
Without ALT data, predictions beyond the five years of field data are increasingly uncertain.

Selected a database tool to be used as a repository for field data: XFRACAS (Failure Reporting, Analysis, and Corrective Action System)

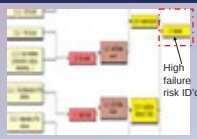
- Supports acquisition, management and analysis of system quality and reliability data from multiple sources
- Creates a standardized method for collecting and maintaining O&M data
- Web-based: easy access for all users
- Security:
  - Password-protected
  - Single administrator determines individual user's access to every area of the database
  - Customer-specific data will be made available to data owner only
  - Aggregate data analysis will be made available through Public Reports
- Supports both real-time and legacy failure/suspension data acquisition
  - Legacy data imported into database via Excel template
  - Real-time incident records created via Incident Wizard and incident Tracking Utility
- Supports incident record searches and report generation
- Data can be directly exported to predictive model tools for analysis

Accelerated and Diagnostic Testing

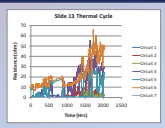
Field data do not provide wear out (end-of-life) information



Failure Modes and Effects Analysis Identifies Reliability Concerns (Metal Foil Tape)

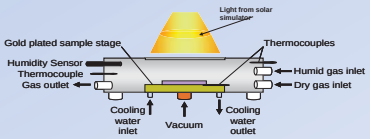


ALT Data Generated in Lab Tests



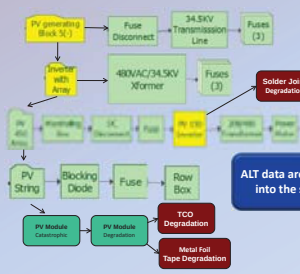
FMEA for CIGS: TCO is high level reliability concern



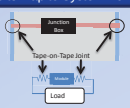


Possible Materials Failure Issues

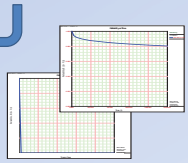
- Metal foil tape joints
- Na diffusion into EVA (Voltage breakdown – arcing)
- Connector Degradation
- Conductive epoxy
- Inverter materials reliability (capacitors)
- …



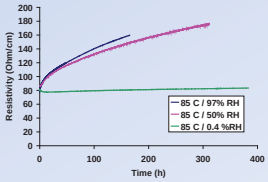
ALT Results Map to System Performance



ALT data are incorporated into the system RBD







Humidity (%RH)	Temperatures (°C)	Irradiation (Suns)	TCO
85	85, 50, 30	0,1	AZO[1], *i*-ZO/AZO[2]
50	85, 50, 30	0,1	AZO, *i*-ZO/AZO
25	85, 50, 30	0,1	AZO, *i*-ZO/AZO
0	85, 50, 30	0,1	AZO, *i*-ZO/AZO

Real Time Reliability Studies

System-Level Real Time Reliability Studies

- System Long-term Exposure of 13, 1-kW grid-tied systems in 3 environments (5 manufacturers)
- Controlled study includes baseline testing(Dark IV, IR, outdoor electrical performance)
- Hot/Dry, Hot/Humid, and Cold environments
- Performance monitoring; Quarterly and Semi-annual testing
- At ~5 years use field degradation rates and failure modes to correlate/validate ALT results, feedback to stakeholders, and input to predictive model development

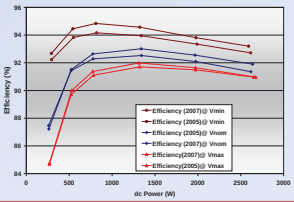
GSA System Reliability Monitoring and O&M Data Collection

- Monitor systems to collect reliability data: failure modes, O&M, and performance
- Mostly roof mount, many in diffuse climates, variable size systems, some will use emerging technologies

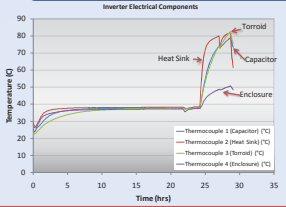
Inverter Long-Term Exposure

- Hot/dry and Hot/humid long term degradation studies
- Inverter high-risk component temperature monitoring studies in hot/dry and hot/humid climates
- Temperature data will be used to develop ALT's for high risk components
- emerging technologies

Inverter Characterization (2005 vs. 2007)



Thermal Profile for Inverter Electronics

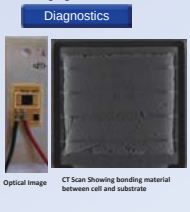


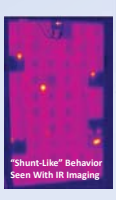
Industry Outreach and Standards Support

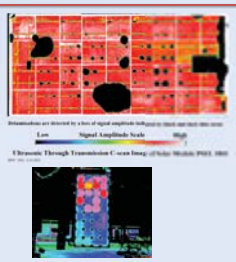
Integrator Reliability Workshop

- March 31- April 1, 2010 San Jose, CA
- Focus on reliability issues specific to integrators
- The goal of this workshop is to examine the roles of the PV integrator portion of the supply chain, understand the reliability implications for installed systems, and define opportunities to enhance how reliability is addressed by integrators. Ultimately, this understanding can advance the industry-wide goal of making photovoltaics a significant part of the U.S. electricity generation portfolio.

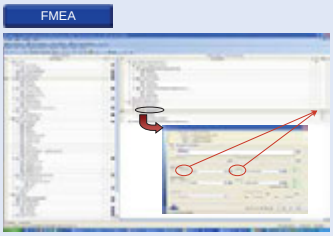
Diagnostics







FMEA



Publications

Granata et al., Long-Term Performance and Reliability Assessment of 8 PV Arrays at Sandia National Laboratories, 34th IEEE PVSC
Mundt et al., Reliability and Availability Analysis of a Fielded Photovoltaic System, presented at June 2009 International Applied Reliability Symposium
Collins et al., Reliability and Availability Analysis of a Fielded Photovoltaic System, 34th IEEE PVSC
Sorensen et al., The Effect of Metal Foil Tape Degradation on the Long Term Reliability of PV Modules, 34th IEEE PVSC and 2009 SPIE
Quintana et al., Exploring Diagnostic Capabilities for Applications to New Photovoltaic Technologies, 34th IEEE PVSC
Granata, et al., "Approaches to Photovoltaic Systems Reliability," International Symposium on Testing and Failure Analysis 2009

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
Sandia acknowledges the support of the DOE Solar Energy Technologies Program in particular for the work presented here.
Sandia would like to thank Abound Solar for providing test samples and critical discussion relative to this work.

Sandia National Laboratories

Spi-Sun Simulator™

- SPECTRAL
- SPATIAL
- TEMPORAL



Automation options available to efficiently manage throughput

Short- and long-term spectral stability over the life of the tool

Extraordinary stability resulting in more than 100,000 module tests without a lamp change

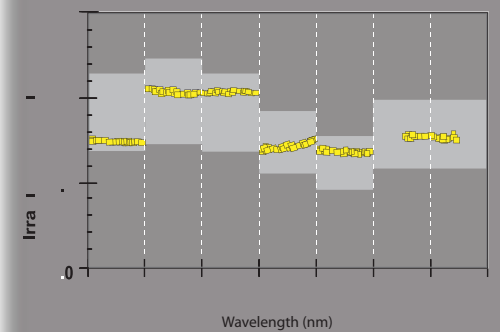
Spire measures 96 spatial points across the test plane to validate intensity and spectral spacial uniformity

Up to 3 user-selectable irradiance levels (200-1,100 mW/m²) in a single flash on SLP (single long-pulse) models

Every SLP flash lasts up to 80 ms resulting in:
- Up to 4,800 datapoints
- 3 I-V curves (compliant with IEC standard 60891 for series resistance measurement)

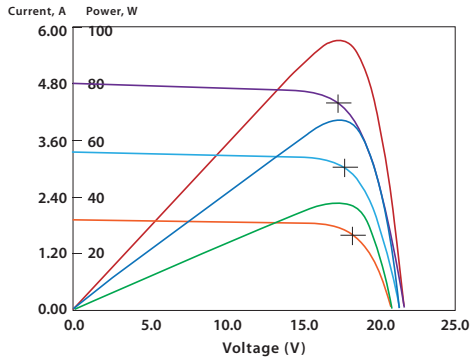
CLASS A SPECTRUM IN ALL LOCATIONS

Although Class A requires only one measurement point, Spire measures 96



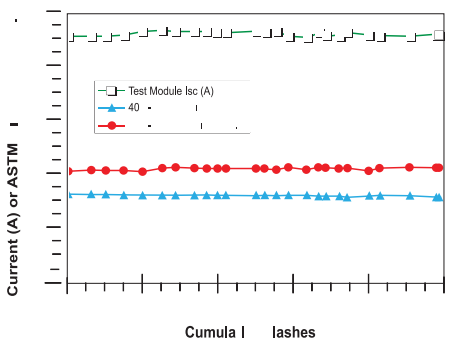
IEC - COMPLIANT R_S MEASUREMENT

Three-level R_S measurement performed in a single flash



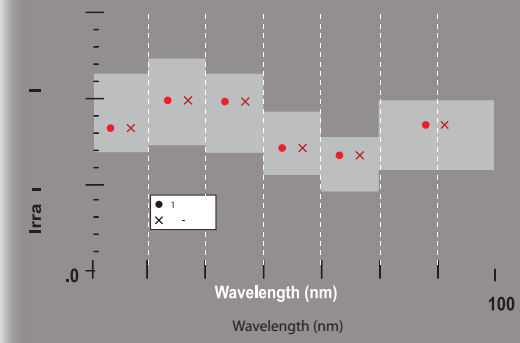
LONG-TERM SPECTRAL STABILITY

Simulator produces consistent testing results over at least 100,000 flashes



SHORT-TERM SPECTRAL STABILITY

Spectrum remains unchanged during flash



Simulator Models	Spi-Sun Simulator 4600	Spi-Sun Simulator 3500	Spi-Sun Simulator 4600SLP	Spi-Sun Simulator 3500SLP
Maximum Module Dimensions (mm)	2,000 x 1,370	1,620 x 1,020	2,000 x 1,370	1,620 x 1,020
Light Source				
Number of Lamps	2	1	2	1
Lamp Type	Multi-Pulse filtered xenon tube		Single Long Pulse filtered xenon tube	
Pulse Width	1ms		20 to 80 ms at 1,000 W/m²	
Spectrum	+/-25%, AM1.5G (Class A)		+/-25%, AM1.5G (Class A)	
Irradiance Temporal Stability	+/-1% (Class A)		+/-0.2% (Class A)	
Irradiance Spatial Uniformity	+/-2% (Class A)		+/-2% (Class A)	
Lamp Life	> 10,000,000 flashes		> 100,000 flashes	
Measurement Range				
Range of Light Intensity	700-1,100 W/m²		**Standard** 400-1,100 W/m²; **Optional** 200-1,100 W/m²	
Measurement Duration	30-45 seconds		< 1 second	
Power/Module (max)	500 W		600 W	
Voltage Ranges	3 ranges (2, 25, 150 V full-scale)		5 ranges (2.5, 10, 25, 100, 250 V full-scale)	
Current Ranges	3 ranges (0.2, 2, 20 A full-scale)		4 ranges (3, 6, 12, 25 A full-scale)	
I/V Resolution	0.003%		0.003%	
Throughput				
Peak Time (manual)	15 seconds		15 seconds	
Continuous Typical Minimum Cycle Time	45 seconds		30 seconds	
System Specifications (not including control cabinet)				
Length x Width x Height (mm)	2,980 x 2,010 x 910	2,290 x 1,980 x 910	2,980 x 2,010 x 910	2,290 x 1,980 x 910
Net Weight	1,230 kg (2,700 lbs)	955 kg (2,100 lbs)	1,230 kg (2,700 lbs)	955 kg (2,100 lbs)
Control Cabinet Specifications				
Length x Width x Height (mm)	1,549 x 432 x 1,194		1,549 x 432 x 1,194	
Net Weight	1,606 kg (730 lbs)		1,606 kg (730 lbs)	
Utility Requirements				
Electricity	220 V, +/-10%, 15 A, 50/60 Hz, 1 Ph		220 V, +/-10%, 20 A, 50/60 Hz, 1 Ph	
Compressed Air	550-700 kPa (80-100psi), 28 lpm (1 scfm)		550-700 kPa (80-100 psi), 28 lpm (1 scfm)	
Options				
Module QA Test System	High voltage isolation and ground continuity testing, automated load and unload of modules, optional automatic labeling of modules			
Length x Width x Height (mm)	2,010 x 7,140 x 2,590	1,980 x 6,550 x 2,590	2,010 x 7,140 x 2,590	1,980 x 6,550 x 2,590
Net Weight	1,910 kg (4,210 lbs)	1,635 kg (3,604 lbs)	1,910 kg (4,210 lbs)	1,635 kg (3,604 lbs)
All simulators are CE compliant				

WESTPAK, INC.

SOLAR LOGISTICS TESTING

NOW



WHAT'S MISSING ?



WHY ?

- THE HIGHEST LEVEL OF MECHANICAL STRESS OCCURS DURING TRANSPORTATION
- IMPACT AND VIBRATION STRESS SHOULD BE INCORPORATED INTO RELIABILITY TEST SPECS
- LOGISTIC TEST SPECS AND PROCEDURES ARE WIDELY KNOWN AND USED (ISO 11607)

- OTHER INDUSTRIES UTILIZE "PACKAGE PERFORMANCE" TESTING (ASTM D-4169)
- LOGISTICS IS THE SINGLE BIGGEST COST COMPONENT OF A DELIVERED SOLAR SYSTEM (40%)
- OPTIMIZING LOGISTICS DELIVERS BEST ECONOMIC VALUE

THIS PRESENTATION DOES NOT CONTAIN ANY PROPRIETARY OR CONFIDENTIAL INFORMATION

HERB SCHUENEMAN, CEO, WESTPAK, INC.

Split-Plot Design: *Characterizing 10 factors in "12" runs*

- Rob (Qing Yuan) Ong
SOLEXEL Powering the Grid™
PV Module Reliability Workshop, February 18–19, 2010, Denver West Marriott, Golden, Colorado. Contact info: rob.ong@gmail.com

1. Introduction: Why Characterize?

→ **Increase process knowledge and improve robustness.**
- Main effects: Number of factors + range tested.
- Interactions: Combination of factors changed simultaneously.

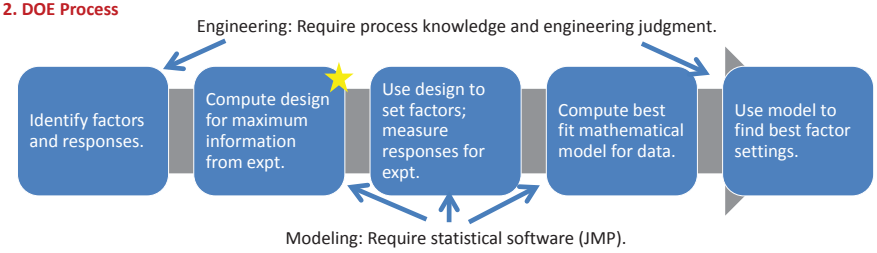
→ **Use knowledge to continually improve process during product lifecycle.**

Why use Design of Experiments (DOE)?

→ **Move from costly and time-consuming trial-and-error searches to elegant and cost-effective statistical methods.**

→ **DOE can characterize, predict, and then improve performance.**

2. DOE Process



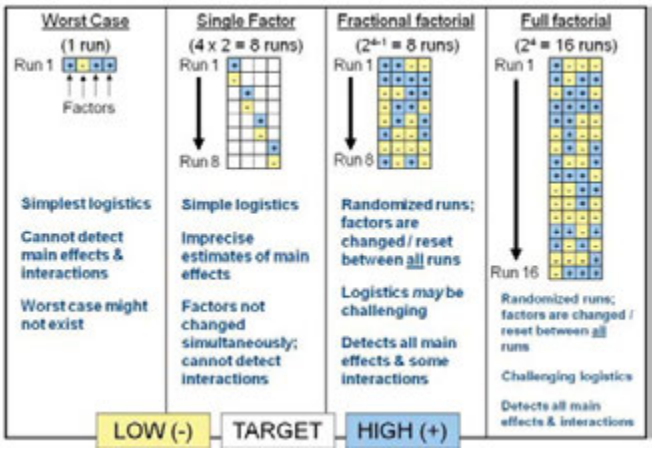
★ 3. Challenge: How do we simultaneously change and test many process factors without logistical difficulties?

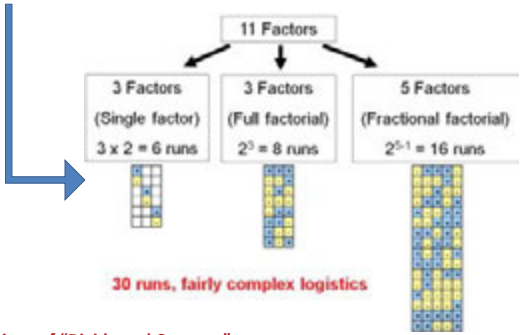
4. "Traditional" Divide and Conquer Approach

→ Leverage scientific knowledge and experience with other similar processes and materials.

→ Maximize process knowledge and validate the process by testing predicted uncertainties.

→ Divide factors into smaller separate experiments using "traditional" designs.





Limitations of "Divide and Conquer"

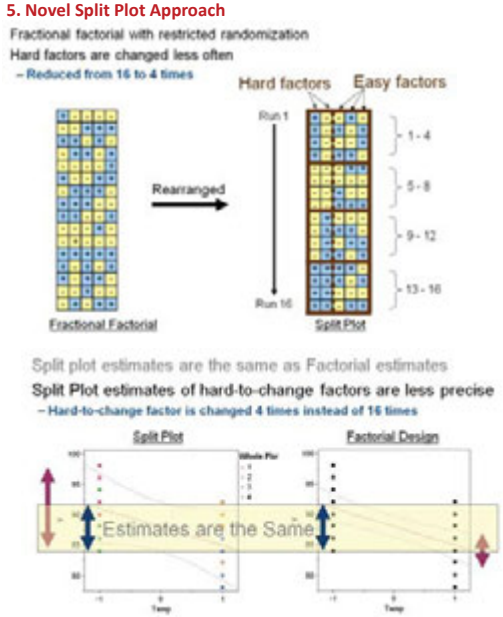
→ **Not suitable for novel materials and processes.**

→ **Observations from similar processes may not translate exactly to the process being characterized.**
- May not detect unpredicted effects and interactions.

→ **Few replicates at the high and low factor levels.**
- Detected "effects" may be imprecise and inconclusive.

→ **Separate experiments result in small and disjointed design spaces.**
- No knowledge of process performance when all factors are changed simultaneously.

5. Novel Split Plot Approach



Factors are categorized by ease of change.
- Easy: Programmable / Automated.
- Hard: Manual.

Hard factors used to create whole plots.
- Easy factors changed b/w all runs.
- Hard factors changed b/w whole plots.

2 sources of variations.
- Run-to-run.
- Whole plot-to-whole plot.

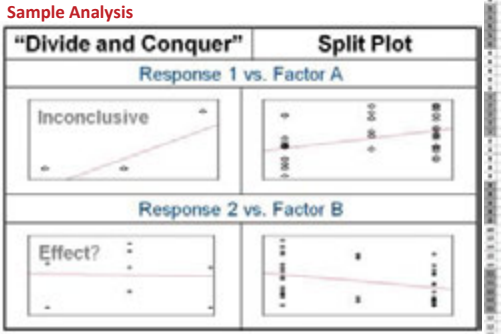
Statistical analysis is more involved.
- Fractional factorial: Standard least squares.
- Split plot: Mixed effect models.

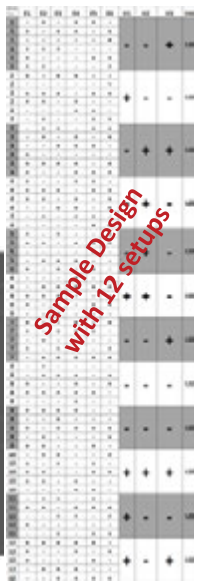
Ignoring the split plot nature and analyzing as a factorial design will lead to erroneous conclusions.
- Hard factors labeled as significant too often.
- Easy factors and interactions labeled as significant not often enough.

6. Application to PV Characterization – Tabbing/Stringing

Easy	Hard
Lamp Power	Base-plate Temperature
Heating Time	Flux
Cool-down Time	Cu Thickness
Cool-down Air Flow-rate	Solder Thickness
Preheat Power	
Preheat Time	

Sample Analysis





7. Conclusions

1. Characterize process over a wide range of conditions.
   – Increase process knowledge.
   – Contribute to process robustness.

2. Testing all factors simultaneously maximizes process knowledge.
   – Does not require prior experience with similar processes.
   – Can detect unpredicted effects.

3. Split plot is an excellent characterization tool.
   – Gained process knowledge
   – Simplified logistics.

Thermalreflectance Imaging: High Resolution Defect Inspection Through Glass

Glenn B. Alers, Dustin Kending and Ali Shakouri
Department of Physics and Basking School of Engineering
University of California, Santa Cruz, CA

Abstract

Thermalreflectance Imaging is used for the simultaneous acquisition of thermal, electroluminescent and bright field images of fully packaged solar modules. Thermal images are obtained with the lock-in detection of small changes in reflectivity associated with temperature changes in the PV absorber layer . Reflectivity changes are measured with visible illumination using a conventional high-resolution Si camera. Temperature changes less than 100mK have been imaged with a spatial resolution of <1μm. Images with no illumination are sensitive to electroluminescent emission from of the PV absorber layer and can be combined with the AC thermal images and the steady state bright field images to obtain a combined optical, thermal and EL image of defects in the solar cells and modules

Advantages of Thermal-reflectance Images

1) **Insensitive to thermal emission from glass** with imaging in the visible. Standard IR imaging and lock-in thermography can only image the glass surface.

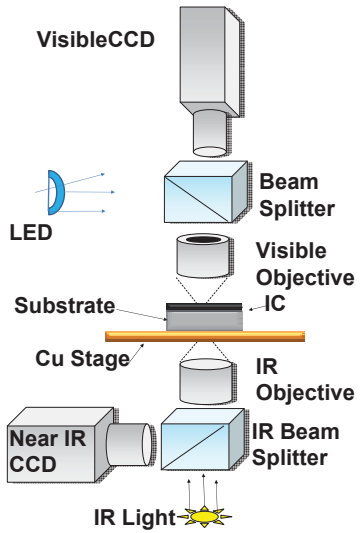
2) **Sub-micron resolution** with monochromatic visible illumination.

3) **Transient response and reduced thermal spreading** with pulsed current and lock-in detection, ns resolution.

4) **Combined EL imaging** for direct correlation of thermal/EL to prebreadown sites.

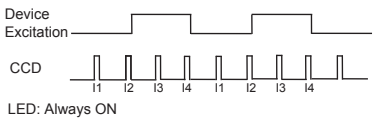
5) **Combined optical imaging** for direct correlation to visual defects.

Apparatus



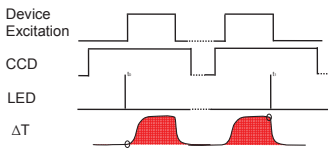
Imaging Technique

I. Four Bucket
Four images used to extract the phase and magnitude of the signal



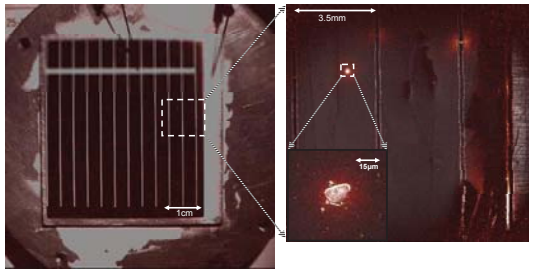
II. Transient Differencing Method

I. Shutter is open the full acquisition period
II. Illumination is pulsed

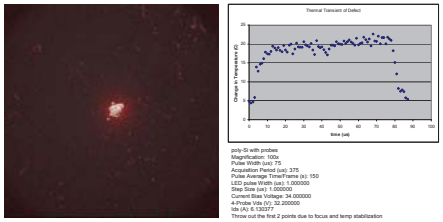


Examples

Combined Thermal/optical Images: Defects in a poly-Si solar cell

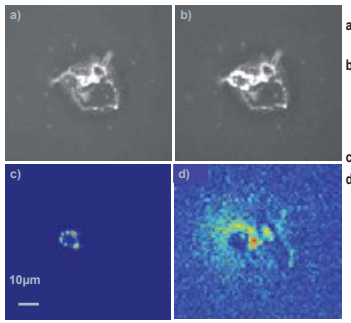


Transient Thermal Response of Defect

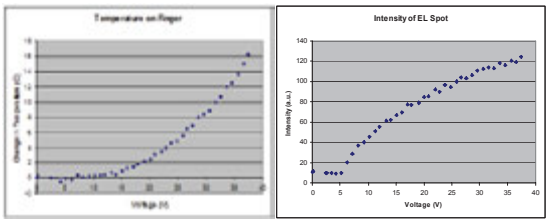


This shows the thermal image 75 us after the rising edge of a voltage pulse in reverse bias. The graph shows the transient response of the silicon around the defect. The defect reaches thermal equilibrium after ~10 us, while the response of the bulk material is on the order of seconds. We can adjust the pulse width and duty cycle to control the maximum temperature of the device.

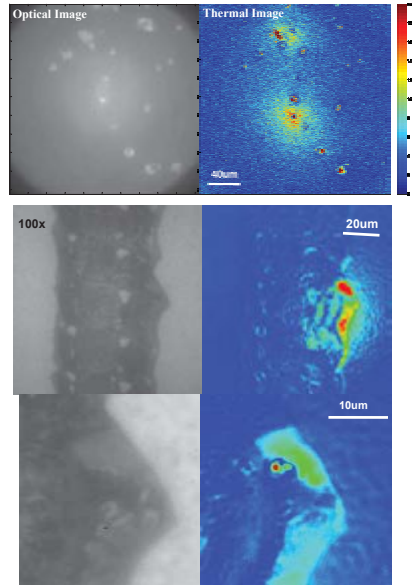
Electroluminescence and Thermal images



a) Optical image of defect in poly-Si
b) Combined optical and electroluminescence (EL) image to show the location of the EL with respect to the defect
c) EL image
d) Thermal image after 300 s of averaging



High Resolution Thermal images



Conclusions

- Thermal reflectance imaging of defects offers many advantages over conventional lock-in and IR thermography including higher resolution, combined optical / EL / Thermal images and transient response
- For further information: Glenn Alers (galers@ucsc.edu) , Ali Shakouri (ali@soe.ucsc.edu)

A Single Layer Thin-Film Moisture Barrier for CIGS Solar Cells

Peter F. Carcia*, R. Scott McLean* and Steven Hegedus#

*DuPont Central R&D, Experimental Station, Wilmington, DE 19880, # Institute of Energy Conversion, University of Delaware, Newark, DE, 19716

Introduction

•CIGS cells have very high demonstrated efficiency: ~20% for 1 cm² size.

•Flexible CIGS cells with module efficiency > 10% are attractive for building integrated application.

•But CIGS cells are moisture sensitive. Modeling studies [1,2] deduce that encapsulation with water vapor transmission rate (WVTR) of 10^{-4} to 10^{-6} g-H_2O/m²-day is needed for long lifetime (> 20 years).

Approach

• Develop ALD barriers and evaluate using Ca test

• Fabricate baseline 1 cm2 CIGS devices on glass at IEC by multisource evaporation

• Encapsulate using various barrier layers

• subject to damp heat (85°C, 85% RH) stress for 1000 hrs under ~ 1 sun illumination, Voc.

Atomic Layer Deposition (ALD)

• layer-by-layer growth process

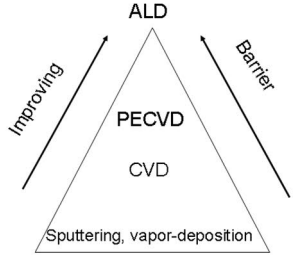
• self-limiting, sequential, saturating surface reactions

• produces pin-hole free inorganic films with ultra-barrier properties [3]

• this work, ALD process for growth of Al_2O_3 films from trimethyl aluminum and water.

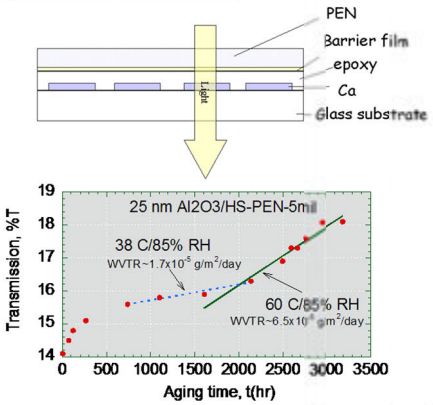
• ALD is a superior process for producing thin-films with ultra-barrier (WVTR~10^{-6} g-H_2O/m²-day) properties-

• **Significantly better than other processes.**



Moisture Barrier Properties of ALD thin-film Al_2O_3

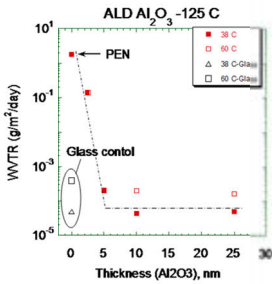
Fig. 2. Ca-test for ultra-barriers



WVTR= $\rho(Ca(OH)_2) \times D(Ca(OH)_2)/t \times 2 \times m(H_2O)/m(Ca(OH)_2)$

(g-H_2O/m²-day) [Ref. 4]; $D(Ca(OH)_2)$ from optical modeling.

Fig. 3 Dependence of WVTR on Al_2O_3 thickness. Substrate is polyethylene naphthalate (PEN).



Temperature-dependent WVTR

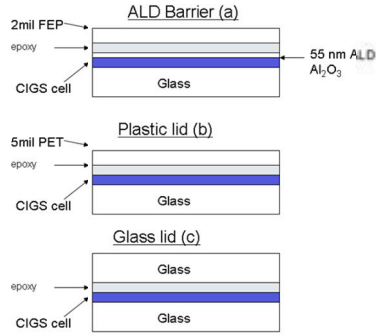
Temperature (°C)	WVTR (g/m²-day)
60	6.5×10^{-5}
38	1.7×10^{-5}
23*	**6.0×10^{-6}**

*Value at 23°C based on apparent activation energy of Ea= 52 kJ/mole

Three Encapsulants on CIGS Test Structures

(a) 55 nm thick ALD Al_2O_3
(b) a PET plastic lid
(c) a glass lid

Fig. 4 Test structures with glass/CIGS devices.



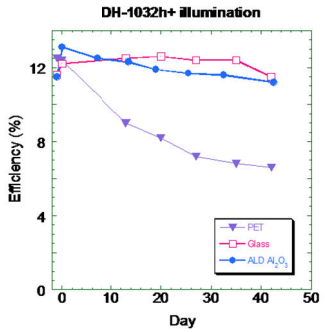
Efficiency of CIGS structures:

1000 hrs@ 85° C/85% RH+light at open circuit

•Cells protected with a single ALD Al_2O_3 barrier layer or a glass lid change little (<3%) after aging > 1000 hr. in "damp heat" (85°C/85% RH) with illumination

•Cells protected only with a plastic lid degrade significantly.

Fig. 5 Dependence of CIGS cell efficiency on encapsulation with damp heat +illumination.



Comparison of Voc, FF, and Jsc for CIGS with ALD layer (solid symbols) and glass lid (open symbols).

• With ALD barrier (solid)

-no change in Voc and FF

-decrease in Jsc attributed to "yellowing" of the epoxy, solved by a more robust encapsulant

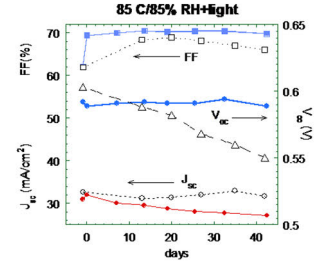
• With glass lid (open)

-Voc decreased 50 mV

• With PET lid (not shown)

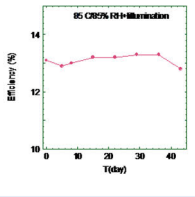
-all parameters decreased significantly, consistent with the ~50% decrease in efficiency

Fig.6 Comparison of PV cell parameters.



Flexible (PET) front sheet with ALD Barrier

Fig. 7. Damp heat test of CIGS cell with flexible ALD barrier front sheet



A flexible PET lid coated with a thin ALD barrier also provides excellent protection for a CIGS cell, exposed to damp heat with simultaneous illumination



Conclusions and References

From damp heat testing with simulated solar illumination, a single layer ALD Al_2O_3 thin-film ultra-barrier has been shown to provide superior moisture protection for CIGS cells, either by direct ALD deposition on the cell or with an ALD-coated plastic lid.

References

[1] M. D. Kempe, Modeling of rates of moisture ingress into photovoltaic modules, Solar Energy Mater. & Solar Cell 90 (2006) 2720-2738.

[2] D. J. Coyle, H.A. Blaydes, J. E. Pickett, R. S. Northey, and J. O. Gardner, Degradation kinetics of CIGS solar cells, in Proceedings of the 35th IEEE Photovoltaics Specialists Conference (2009).

[3] P. F. Carcia, R. S. McLean, M. H. Reilly, M. D. Groner, and S. M. George, Ca-test of gas diffusion barriers grown by atomic layer deposition on polymers, Appl. Phys. Lett. 89 (2006) 031915-1-3.

[4] P. F. Carcia, R. S. McLean, M. D. Groner, A. A. Dameron, and S. M. George, Gas diffusion ultrabarriers on polymer substrates using Al2O3 atomic layer deposition and SiN plasma-enhanced chemical vapor deposition, J. Appl. Phys. 106 (2009) 023533-1-6.

CIGS Cell-Level Reliability Task and Studies at NREL

National Renewable Energy Laboratory

Task Participants: John Pern, Raji Sundaramoorthy, Clay DeHart, Steve Glynn, Xiaonan Li, Ingrid Repins, Lorelle Mansfield, Miguel Contreras, Rommel Noufi, Tim Gessert

Contributors: Steve Glick, Bobby To, Tom Gennett, Jian Li

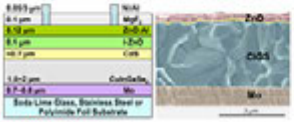
Acknowledgement: This work was performed at the National Center for Photovoltaics under DOE contract number DE-AC36-08GO28308 with the National Renewable Energy Laboratory

Task Objectives

Long-Term: To achieve high long-term performance reliability for thin-film CIGS PV modules with more stable materials, device structure designs, and moisture-resistant encapsulation materials and schemes.

Short-/Near-Term:
- To establish systematic experimental procedures and test designs.
- To identify degradation mechanisms & quantify degradation rates.
- To seek chemical / physical mitigation methods.
- To identify stable new materials or device designs.
- To develop/evaluate new encapsulation materials and schemes, especially for flexible CIGS.

Typical CIGS Device Structure



Performance Reliability Issues:
- Moisture Sensitivity of All Component Materials
- Glass/Glass Encapsulation with Desiccant Edge Sealant
- Damp Heat-Resistant, Light-Weight, Flexible Packaging

Main Subjects & Direction

Component-Level Materials and Reliability
- Mo, CIGS, ZnO, Alternative TCOs (Al:$Zn_{1-x}Mg_xO$, ITO, InZnO)
- Primary test conditions: Damp Heat (85°C, 85%RH, IEC61215, IEC61646), Dry Heat (<10%RH), and in Weathrometer (WOM).

Device Level Reliability
- Bare and Encapsulated CIGS solar cells

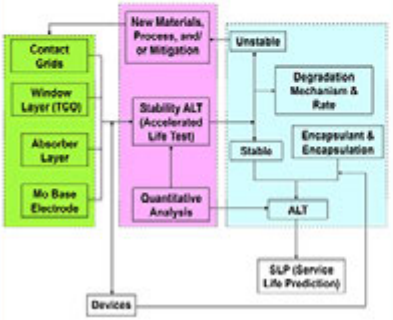
Chemical and Physical Mitigations
- Chemical formulations & application methods
- Moisture barrier oxides

Interconnect Technologies and Reliability
- Conductive adhesives for flexible interleafing connects
- All-Laser Scribing for P1, P2, and P3

Development of Quantitative Analysis
- Non-invasive, non-destructive moisture ingress sensors
- Degradation rate vs. Moisture ingress rate/quantity
- New analytical method(s) and/or test structure design(s) for in-situ, on-device measurements.

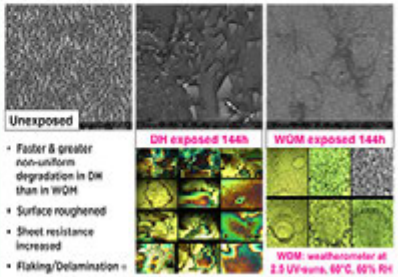
Industrial Collaborations

Work Flowchart



CIGS Component Reliability – 1

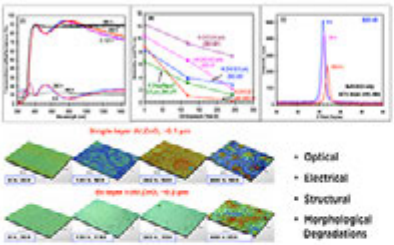
Degradation of Mo on SLG



- Faster & greater non-uniform degradation in DH than in WOM
- Surface roughened
- Sheet resistance increased
- Flaking/Delamination

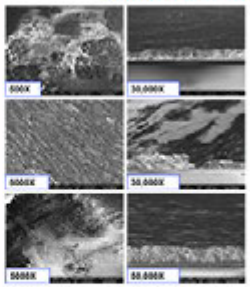
CIGS Component Reliability – 2a

Degradation of ZnO in DH



- Optical
- Electrical
- Structural
- Morphological Degradations

DH=480h ZnO Films Became Porous & 10-20X Thicker



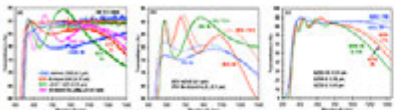
Al:ZnO (AZO) 0.12 μm => ~1.5 μm, porous, ring-like features

i-ZnO 0.1 μm => ~2 μm, porous, segregated (ditched)

i-/Al:ZnO (BZO) 0.22 μm => ~2 μm, porous, two layers

CIGS Component Reliability – 2b

Degradation of TCOs in DH

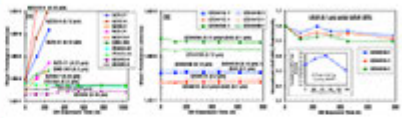


ZnO Films:
- Increased Transmittance due to Loss of Free Carrier Absorption
- Formation of $Zn(OH)_2$ and insulating ZnO (cubic)
- Thicker ZnO:Al (AZO) > Thinner AZO

DH Stability of TCOs: SnO_2:F > In_2O_3:Sn (ITO) ~ InZnO >> ZnO ~ ZnMgO

CIGS Component Reliability – 2c

Degradation of TCOs in DH



DH-Induced Electrical Degradation:
- In_2O_3:Sn (ITO) < InZnO (IZO) << ZnO ~ ZnMgO
- Observed Variation in AZO and BZO degradation rates

InZnO (IZO) offers protection of i-ZnO underneath.

CIGS Component Reliability – 3a

Humidity Susceptibility of CIGS Absorber

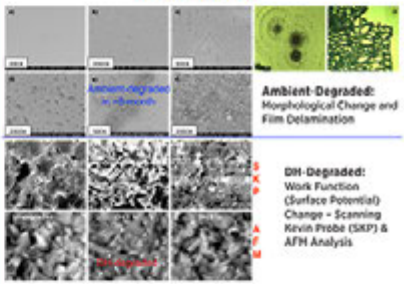
Typical Approach to Study:



Approach in This Work:



Humidity Susceptibility of CIGS Absorber



Ambient-Degraded: Morphological Change and Film Delamination

DH-Degraded: Work Function (Surface Potential) Change – Scanning Kevin Probe (SKP) & AFM Analysis

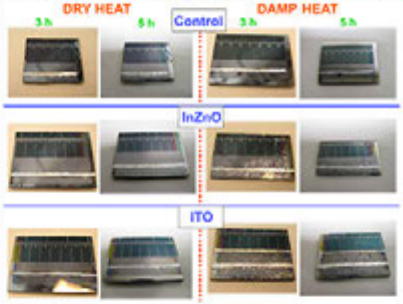
Performance of Devices made with Moisture-Degraded CIGS Absorbers

Table 3. Cell Parameters for CIGS Samples with or without Exposure to Ambient or Damp Heat

Sample ID	Exposure	Device No.	Voc (V)	Jsc (mA/cm²)	FF (%)	Eff (%)	Rs (ohm-cm²)	Rsh (ohm-cm²)
A	ambient	1	0.410	10.20	34.3	1.5	10.8	30
		3	0.436	8.44	31.6	0.9	33.5	78
B	ambient	1	0.411	22.89	43.5	3.8	6.9	66
		4	0.385	25.67	44.9	4.4	4.5	55
C-1A	DH 15 min	2	0.544	30.84	65.6	11.0	2.5	413
		4	0.560	32.84	66.8	11.8	2.4	428
C-1B	DH 30 min	1	0.512	30.20	64.4	10.0	2.8	556
		3	0.510	30.91	63.7	10.1	2.8	376
C-2A	No (N2 dry box)	5	0.656	30.28	71.1	14.1	1.7	6331
		7	0.650	31.30	70.3	13.7	1.6	14128
C-2B	No (N2 dry box)	5	0.668	29.78	71.2	14.1	2.1	4228
		8	0.672	31.10	77.2	16.1	1.6	20136

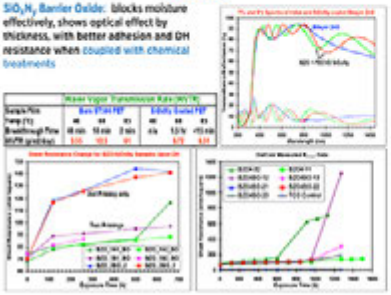
- Prolonged ambient exposure resulted in very poor devices due to substantial compositional and morphological degradations on the absorber films. The devices' high series resistance (Rs) and low shunting resistance (Rsh) suggest that shorting and shunting had occurred.
- Brief exposures in DH for 15 min and 30 min readily induced significant efficiency losses.

DH-Induced Delamination of Bare CIGS Devices



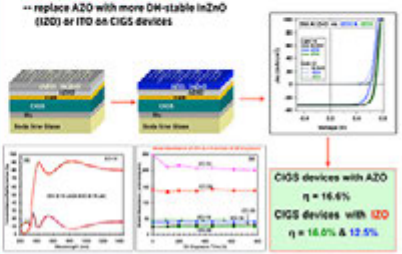
Chemical/Physical Mitigation for BZO

SiO_xN_y Barrier Oxide: blocks moisture effectively, shows optical effect by thickness, with better adhesion and DH resistance when coupled with chemical treatments



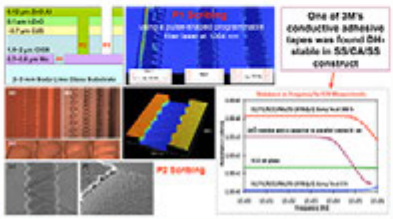
Mitigate DH-Degradation of CIGS Devices – Approach 2

Alternative TCO window layer
-- replace AZO with more DH-stable InZnO (IZO) or ITO on CIGS devices



Interconnects and Reliability

1. Developing "all laser-scribing" capability in collaboration with PyroPhotonics.
   - To investigate performance and reliability of scribe lines and mini-modules
2. Investigated the DH stability of "shingling" (interleafing) interconnection using conductive tape on stainless steel substrates



Industrial Collaborations / Task Publications 2009

- Thin-Film CIGS Glass/Glass Mini-Module and Edge Sealing: (JLN Solar, WFO)
- Conductive adhesives for interleafing connects: (3M)
- Laser Scribing: (PyroPhotonics)
- CIGS Encapsulation and Reliability Testing: (Optony)
- Flexible CIGS Packaging: (Sandia Solar)

1. "Module Encapsulation Materials, Processing, and Testing," John Pern, APP International PV Reliability Workshop (PVRW'8), Dec. 4-5, 2008, SJTU, Shanghai, China.
2. "Stability Issues of Transparent Conducting Oxides for Thin-Film Photovoltaics," John Pern, APP International PV Reliability Workshop (PVRW'8), Dec. 4-5, 2008, SJTU, Shanghai, China.
3. "Investigation of the Stability Issues of TCO Barrier Layers for CIGS Devices upon Damp Heat and Dry Heat Exposures," Raj Sundaramoorthy, Ingrid Repins, David Albin, Tom Gennett, Jian Li, John Pern, and Tim Gessert, APS, March, 2009.
4. "Preliminary Evaluation of Conductive Adhesive Tapes as Potential Interleafing Connects for Flexible Thin-Film PV Applications," F. J. Pern, R. A. Jones, L. M. Gedvilas, and T. A. Gessert, MRS Spring, San Francisco, CA, April 2009.
5. "A Study on the Humidity Susceptibility of Thin-Film CIGS Absorbers" F. J. Pern, B. Egaas, B. To, C.-S. Jiang, Jian Li, S. S. Glynn, and C. DeHart, 34th IEEE PVSC, 6/7-12/2009, Philadelphia, PA.
6. "Comparison of Amorphous In2O3 and Polycrystalline ZnO:Al as A Conductive Layer for CIGS PV Solar Cells," R. Sundaramoorthy, J. L. Repins, T. Gennett, Jian Li, D. Albin, F. J. Pern, C. Eberspacher, S. Glynn, J. Perkins, D. Ginley, and T. Gessert, 34th IEEE PVSC, 6/7-12/2009, Philadelphia, PA.
7. "Humidity-Resistant High-Conductivity Amorphous-In2O3 Transparent Conductors," T. Gennett, D. T. Grayson, M. O. Reese, L. J. Simpson, F. J. Pern, J. D. Perkins, and David S. Ginley, 34th IEEE PVSC, 6/7-12/2009, Philadelphia, PA.
8. "Stability of TCO Window Layers for Thin-Film CIGS Solar Cells upon Damp Heat Exposures – Part I," R. Sundaramoorthy, F. J. Pern, C. DeHart, T. Gennett, F.Y. Peng, M. Contreras, and T. Gessert, SPIE PV Reliability, 8/2-6/2009, San Diego, CA.
9. "Stability of TCO Window Layers for Thin-Film CIGS Solar Cells upon Damp Heat Exposures – Part II," F. J. Pern, S. H. Glick, B. To, C. DeHart, T. Gennett, M. Contreras, and T. Gessert, SPIE PV Reliability, 8/2-6/2009, San Diego, CA.

Cohesion and Phase Separation in Organic PV Heterojunction Layers

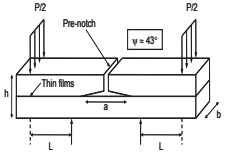
Vitali Brand, Reinhold H. Dauskardt
Department of Material Science & Engineering, Stanford, CA 94305

Objectives for OPV Reliability Thrust

- The objective of our research is to establish a well-defined relationship between the durability of the solar cell and the environmental factors effecting it
- Develop quantitative methods to characterize basic thermomechanical properties (e.g. adhesion, cohesion)
  - Effect of composition of the heterojunction layer
  - Effect of heterojunction layer thickness
  - Effect of annealing
- Are degradation processes coupled and how?
- Leverage from more mature area of reliability physics in microelectronics
  - mechanisms, kinetic models, accelerated testing and life prediction

Quantitative Adhesion/Cohesion and Debond Kinetics





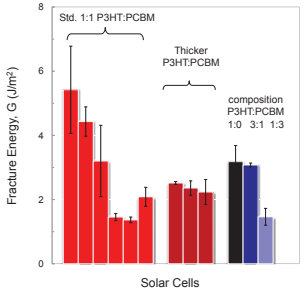
FPB adhesion

$$G \geq G_c \left[J/m^2\right]$$

crack driving "force" | cracking "resistance"

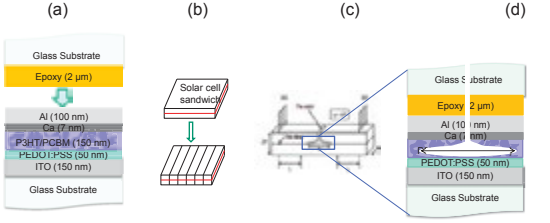
$$G = \frac{Z\,\sigma_f^2\,h_f}{\bar{E}_f}$$

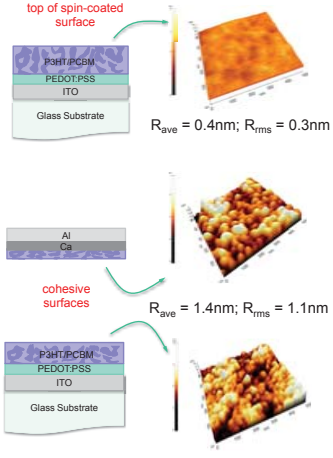
The DTS delaminator is used to measure fracture energy using the 4-point bending (FPB) technique by applying a crack driving "force" that is higher than the cracking "resistance" of the weakest layer in the thin film stack that makes up the solar cell



Preliminary measurements showing the range in cohesive fracture energy values for P3HT:PCBM organic photovoltaics

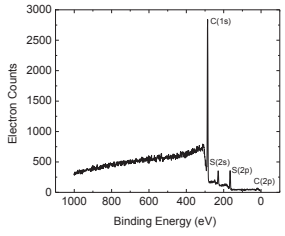
Adhesion/Cohesion Sample Preparation and testing



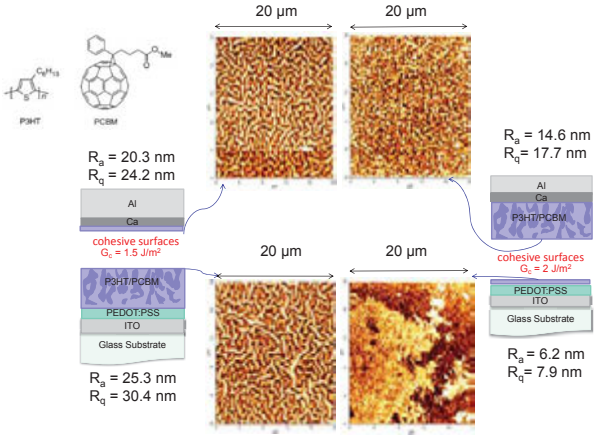


Adhesion specimens are fabricated by *a)* bonding a glass substrate to the solar cell with epoxy to produce a *b)* "solar cell sandwich" which is diced into beams that *c)* form the four point bend (FPB) specimens used to measure the fracture energy G_c by *d)* delaminating the solar cell inside the weakest layer.

Characterization of Cohesive Surfaces



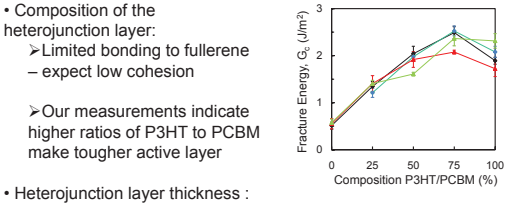
- XPS reveals similar debond path for DCB and 4-pt bend samples
- C ~ 93%, S ~ 7%
- Suggests cohesive failure in PCBM:P3HT layer

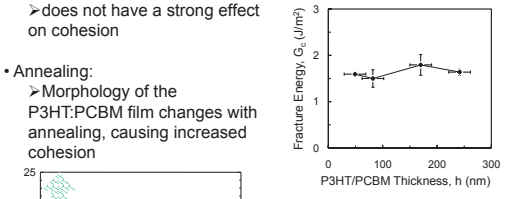


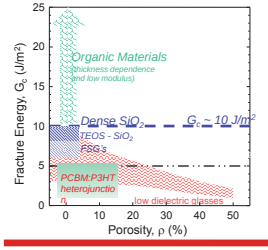
The P3HT:PCBM OPVs generally delaminate at two different locations in the BHJ layer. These locations, as shown above, have a characteristic cohesive fracture energy associated with them, where the top of the BHJ film is generally weaker than the bottom. The presence of ripples on the cohesive surface revealed by the AFM scan provides evidence of compressive stresses.

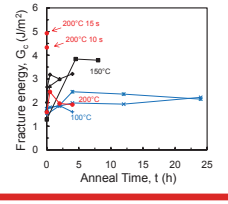
Factors Effecting Cohesion of P3HT/PCBM Layers

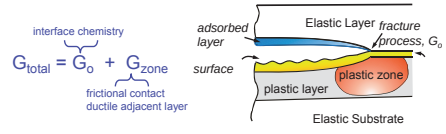
- Composition of the heterojunction layer:
  - Limited bonding to fullerene – expect low cohesion
  - Our measurements indicate higher ratios of P3HT to PCBM make tougher active layer
- Heterojunction layer thickness :
  - does not have a strong effect on cohesion
- Annealing:
  - Morphology of the P3HT:PCBM film changes with annealing, causing increased cohesion

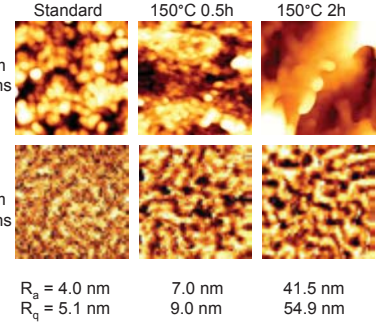












	Standard	150°C 0.5h	150°C 2h
R_a	4.0 nm	7.0 nm	41.5 nm
R_q	5.1 nm	9.0 nm	54.9 nm

5 micron AFM scans reveal the effects of annealing. The rougher morphology corresponds to higher cohesion fracture energy.

Note: All devices were cured at 90°C for 1h prior to subsequent anneals

Acknowledgements

This publication was based on work supported by the Center for Advanced Molecular Photovoltaics (Award No KUS-C1-015-21), made by King Abdullah University of Science and Technology (KAUST).



Effects of Various Module Preconditioning Procedures on CdTe Pmax Measurements

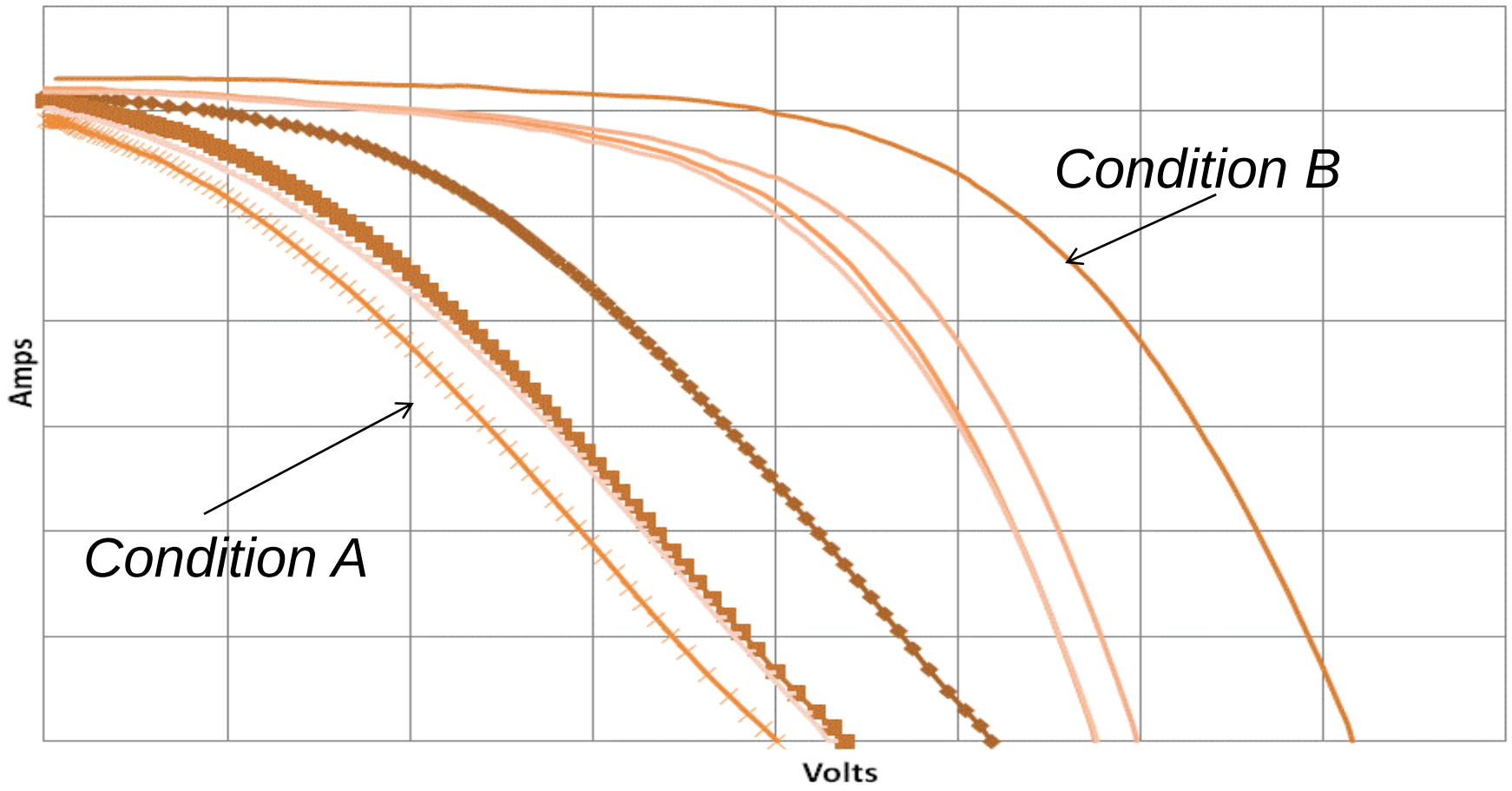
Michelle Propst, Keith Goshia, & Jason Hevelone

NREL PV Reliability Workshop, February 18-19, 2010

Introduction

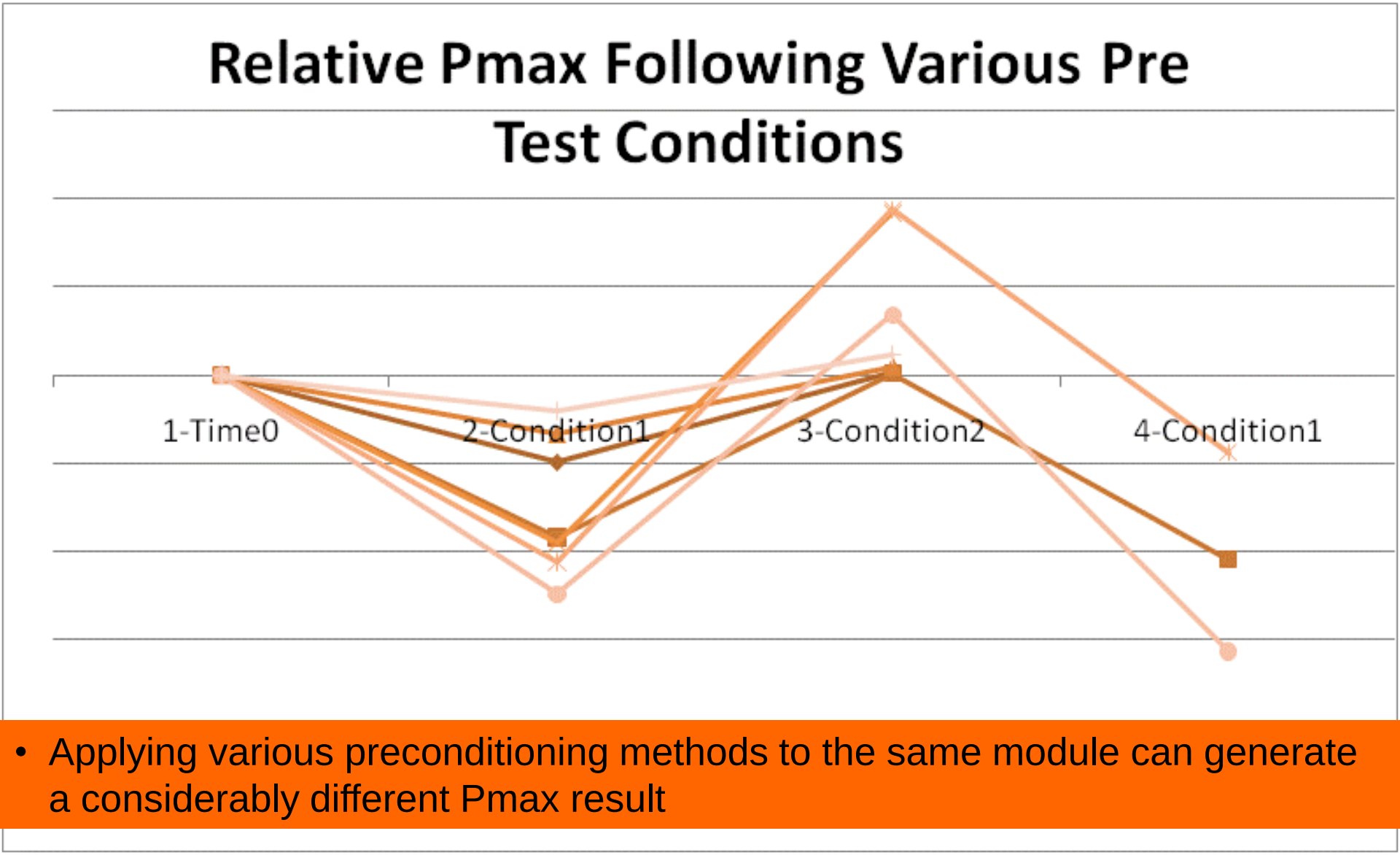
- The repeatability and accuracy of CdTe PV module Pmax measurements is significantly impacted by the condition of the module immediately prior to test
- This can create uncertainty in the results of accelerated life testing by creating unrelated drops or gains in Pmax.
- It is important to understand and characterize the impacts of preconditioning modules prior to Pmax measurements so that actual reliability trends can be identified.

Module JV Post Temp Cycling with Varying Pre-Test Conditions



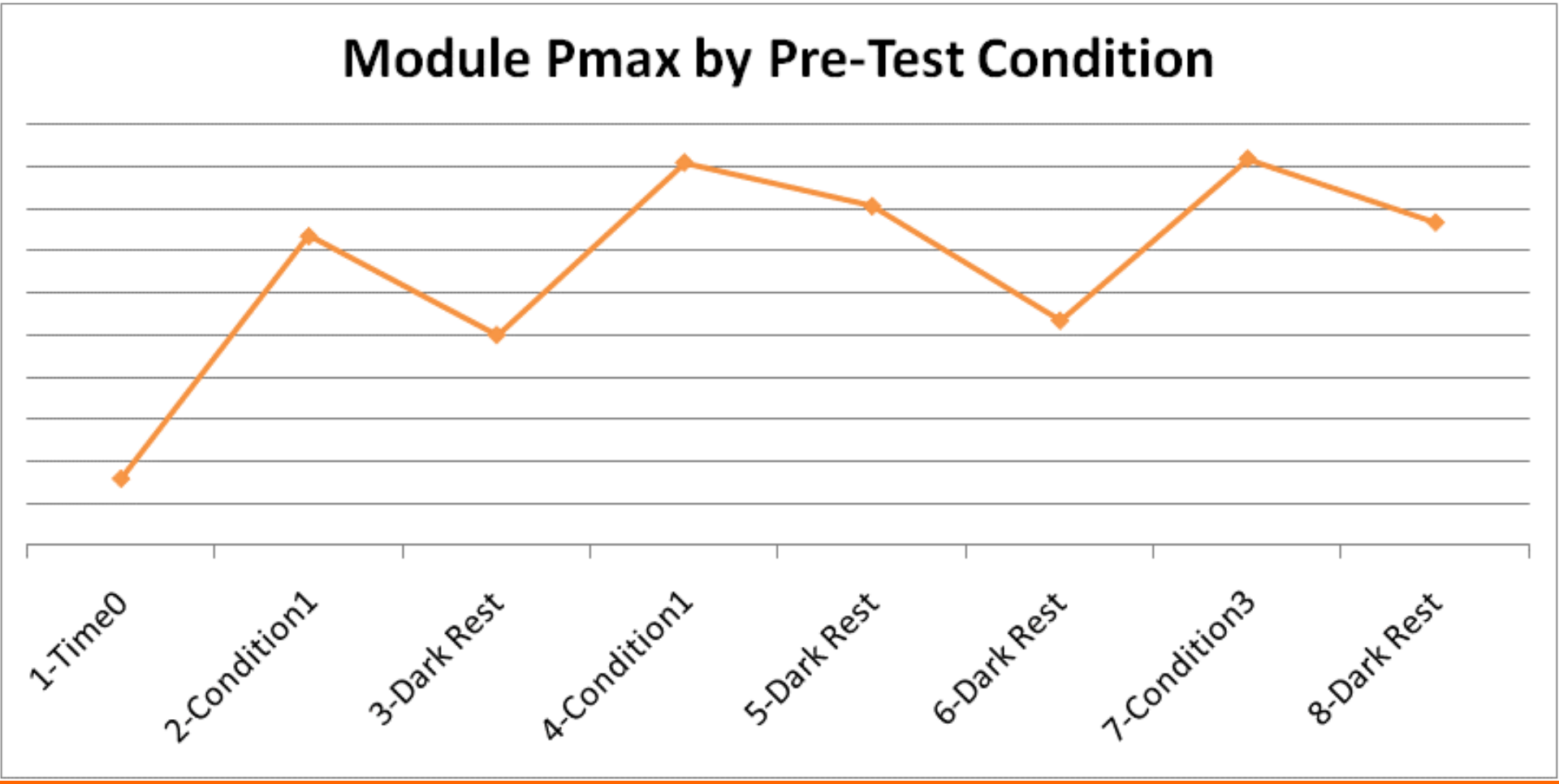
- Degradation seems to suggest a serious problem in Temperature Cycling
- However, module Pmax measurements are actually modulated by the Pre-Test Conditioning method used
- Goal is to find a Preconditioning method to match real world outdoor measurements

Pre-Test Condition vs Pmax Readout



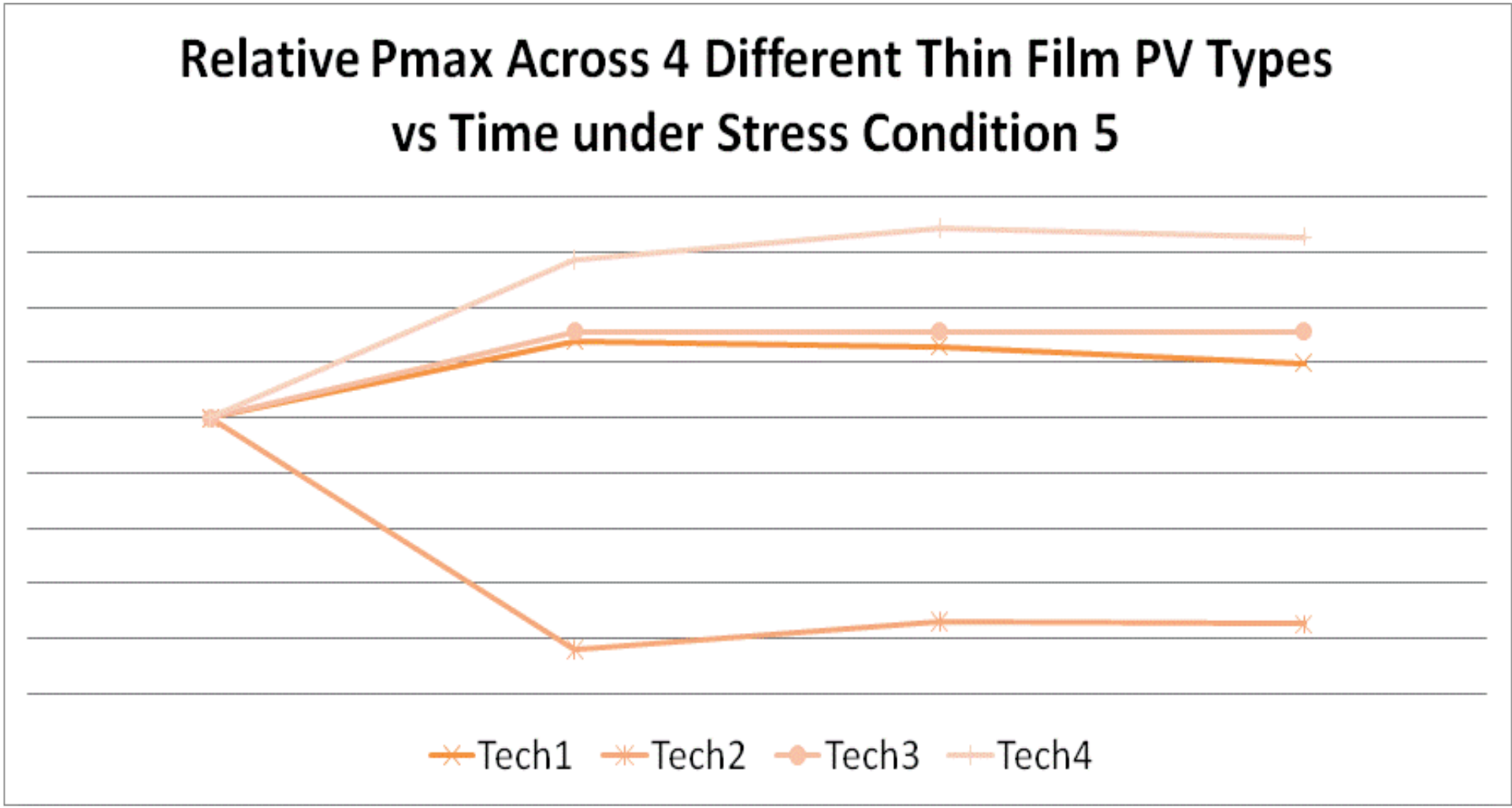
- Applying various preconditioning methods to the same module can generate a considerably different Pmax result

Pre-Test Dark Rest Impact on Pmax Readout



- Dark Rest, of varying duration, results in a dramatic decrease in the Pmax measurement

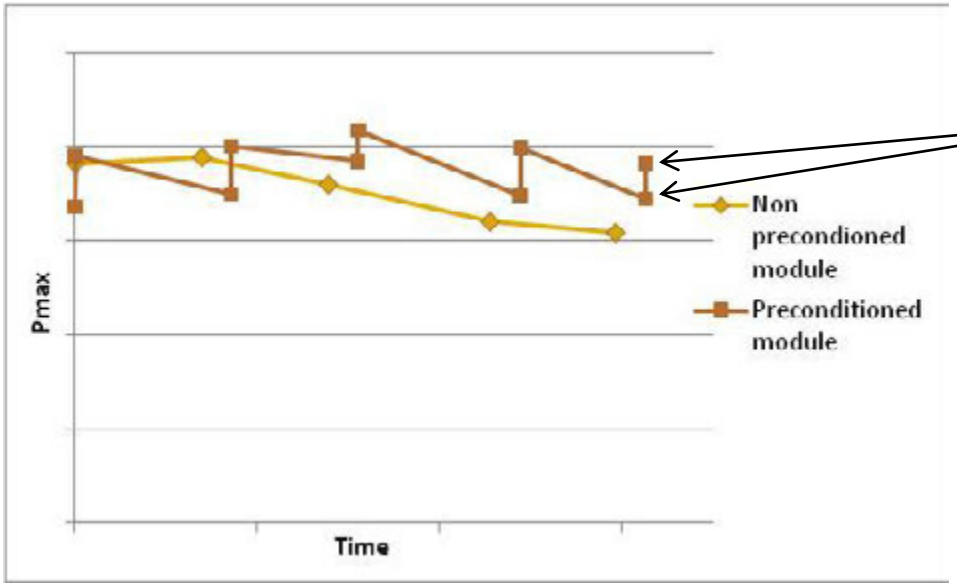
Results vary by Technology



- Even subtle changes in PV technology can generate varying responses to the precondition method applied to the module prior to test.

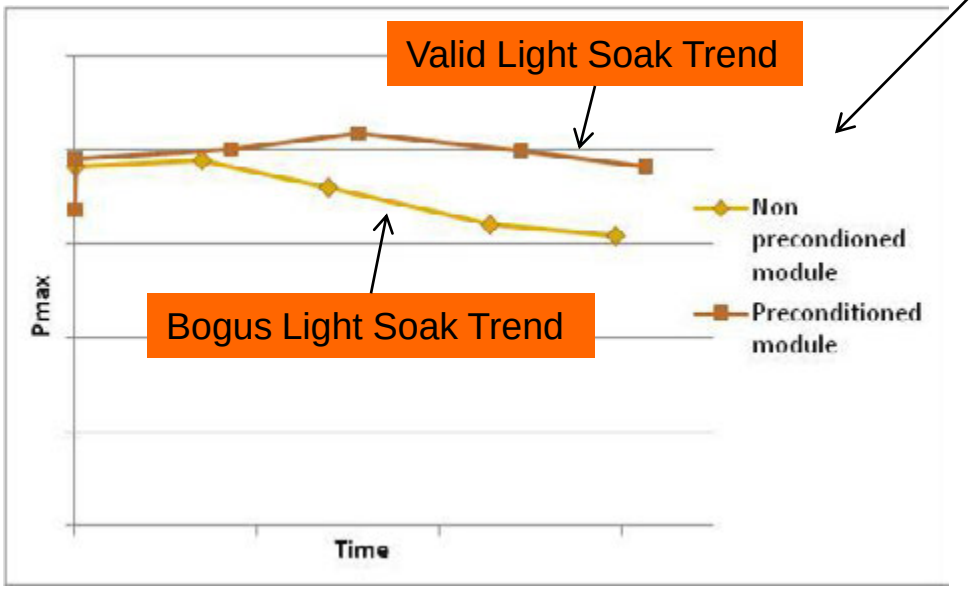
Open Circuit Indoor Light Soak Stability

With and without Module Preconditioning



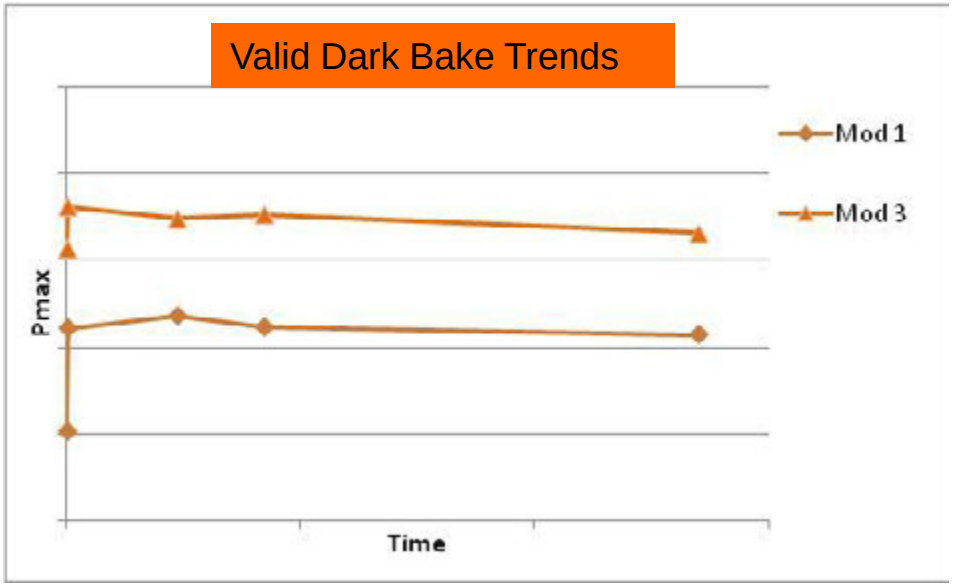
Before (lower Pmax) and After (higher Pmax) Module Preconditioning

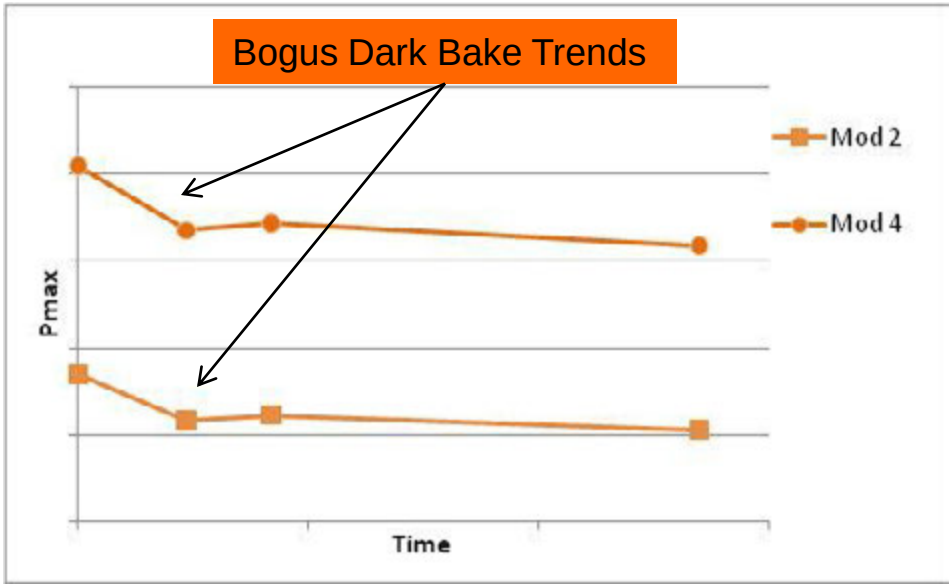
Same chart with only the post-Preconditioned Pmax measurements



- Without module Preconditioning, indoor light soak wrongly suggests module is degrading
- In reality, module is **perfectly stable**

85°C Unbiased Dark Bake Stability
with and without Module Preconditioning





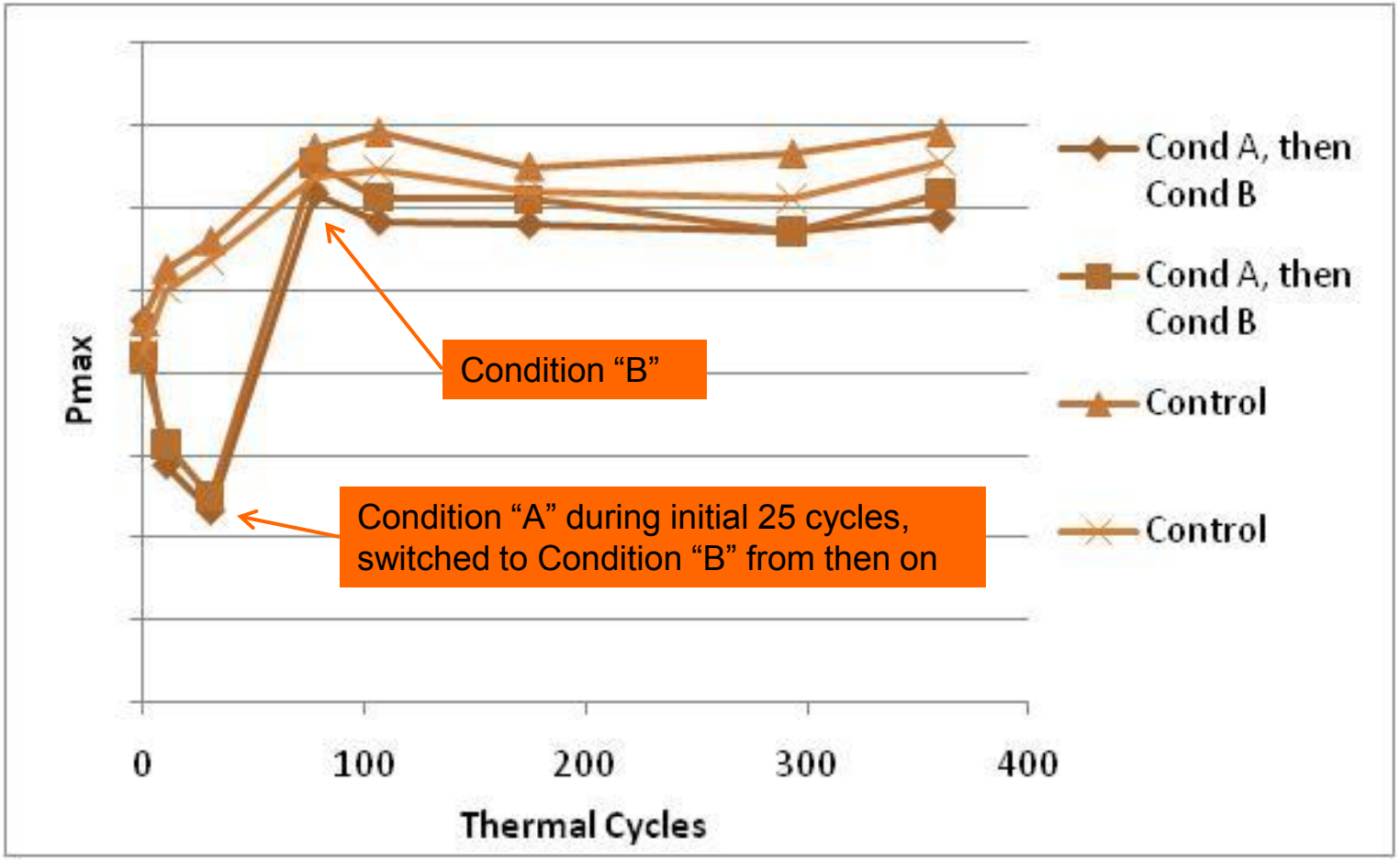
Module Preconditioning performed prior to all Pmax measurements

Module Preconditioning performed only at time zero measurement

- Without module Preconditioning at each Pmax measurement, the 85°C Dark Bake wrongly suggests modules degraded from Time Zero
- In reality, modules are **perfectly stable**

Temperature Cycle Stability

Effects with and without different module conditioning in TC



- Use of condition method "A" while in thermal cycle leads to bogus module degradation that is completely reversible with Condition method "B"
- Similar behavior seen in 85°C Dark Bake

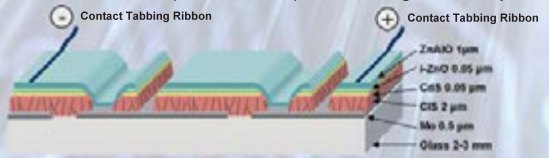
Conclusions

- Dark storage effects on CdTe modules can be reversed through various forms of Preconditioning
- Proper Preconditioning leads to more accurate Pmax determination
- Module Preconditioning leads to more accurate reliability assessments
- There appears to be no consistent methodology used for Preconditioning PV modules in the industry
- Preconditioning effectiveness appears to vary by PV technology and must be characterized by each manufacturer

Electrically Conductive Adhesive Reliability in Thin Film Photovoltaic Modules

Thin Film Solar Modules - Back End

- Thin Film Solar Cells require conductive adhesives to eliminate stress of fragile substrates during electrical interconnection
- Bonding of Sn or SnAg coated Cu tab to the front contact (TCO) with conductive adhesive (CE 3103 WLV)
- Placement of EVA foil and glass
- EVA lamination + cure of adhesive (15 min at 150°C) → cure during lamination process



Electrically Conductive Adhesive CE 3103 WLV

Adhesive Advantages:



- CE 3103 WLV is a fast cure electrically conductive adhesive
- Excellent and stable contact resistance
  - Under thermocycling and humidity testing
- Good mechanical strength on non-Ag bearing tabbing ribbons
  - Can replace solders, conductive tapes and ultrasonic welding for electrical interconnection of thin film solar cells
- Co-curable during standard EVA lamination process (+/- 20 minutes @ 150°C)
- Application method: needle-dispensing

* Electrically Conductive Adhesives tested under the requirements of Thin Film Solar Interconnects

Tabbing Ribbon

CE 3103 WLV

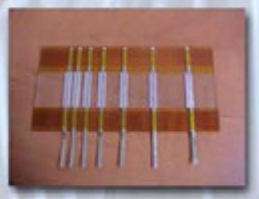
CE 3103 WLV Reliabilility Testing

Contact Resistance Measurements Sn tabs on ITO

Test method on ITO: TLM

Contacting area = 40 mm² (2 x 20 mm²)

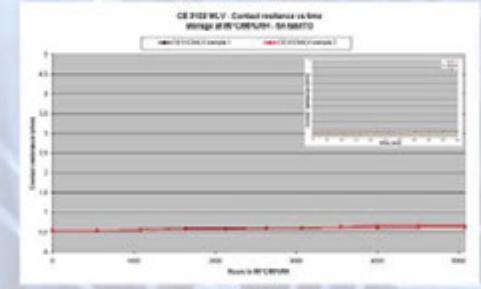
Material is stencil printed on ITO substrate with 100 micron thick stencil



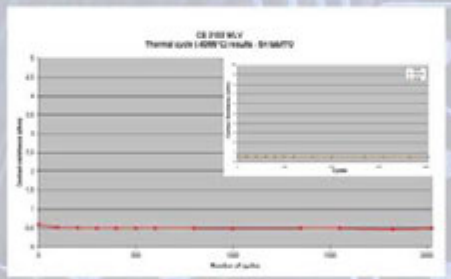
- Resistance measured at increasing distances
- Resistance plotted vs distance
- Rc determined from intercept

* TLM Test Method for Contact Resistance Reliability Measurements

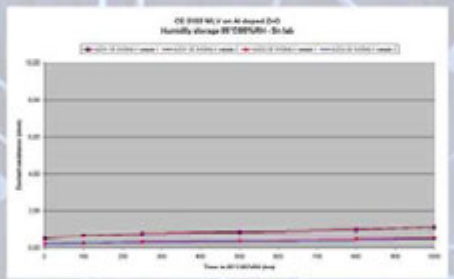
CE 3103 WLV Reliability Testing (85°C/85%RH, Sn-ITO)



CE 3103 WLV Reliability Testing (TC -40°C/+85°C, Sn-ITO)



CE 3103 WLV Reliability Testing Sn – Al:ZnO on glass



CE 3103 WLV Flexibilized

	CE 3103 WLV	XCE 80239
Description	Semi Rigid	Semi Flexible
Viscosity (Pa s)	20	40
Cure time 150°C (min)	5	5
Volume resistivity (Ohm cm)	$1 \cdot 10^{-3}$	$1 \cdot 10^{-3}$
E-modulus (MPa)	5500	1700
TLSS (Al/Al)	10 N	10 N

XCE 80239

Improve bend test performance of CE 3103 WLV modifications with similar reliability for use of flexible metal substrates

Conclusions

- CE 3103 WLV is a fast cure electrically conductive adhesive, 5 min. @ 150°C
- Recommended product for thin film solar assemblies with "Semi-flexible / rigid" substrates
- Excellent contact resistance stability under thermocycling and humidity testing
- CE 3103 WLV outperforms solder regarding cure temperature, flexibility and contact resistance stability
- CE 3103 WLV outperforms ultrasonic welding with regards to process yield and investment requirements; no additional Al deposition required
- If extreme flexibility is required, XCE 80239 may be considered
- Recommended product for **Thin Film Solar Modules**

* Electrically Conductive Adhesives meet the requirements of Thin Film Solar Interconnects

A. Henckens, H. Goossens, G. Dreezen, Henkel Electronic Materials, Westerlo, BE

L. Rector, S. Ruatta, Henkel Electronic Materials, Irvine, CA

Frozen Light Soak Test: "Simulating the Dawn Effect"

Authors: Delphine Bayon, Lei Chen

nanosolar

Purpose

Based on customer experience and input from Beck Energy, Nanosolar sought to simulate the effect of freezing temperatures combined with rapidly-increasing sunlight on panel performance.

Nanosolar's Frozen Light Soak Test combines a baseline of freezing cold temperature with concurrent light exposure to simulate the real-world, outdoor conditions of a frozen yet sunny dawn, such as a solar panel might experience in Germany or Canada.

The combination of thermal and light stress in a panel that is actively producing power causes panel temperature to increase far more rapidly than in the IEC 61646 Humidity Freeze test, while also providing insight into a panel's long-term durability and performance.



Image of Frozen Modules at Dawn



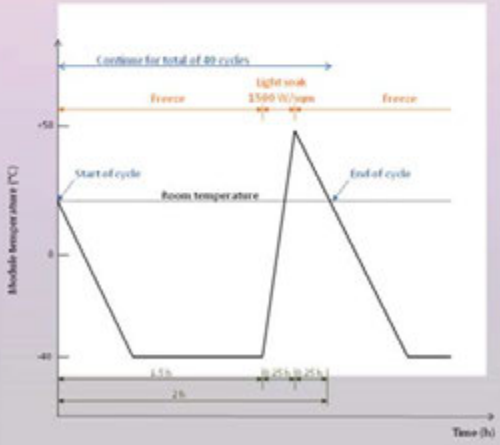
The Nanosolar Utility Panel

Test Process

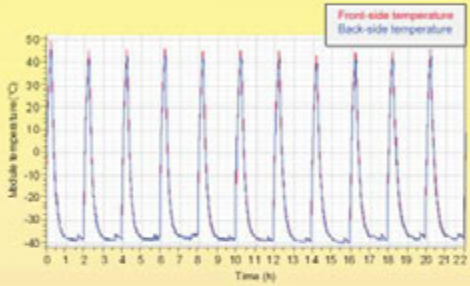
Highly Accelerated Lifetime Test Process

- Freeze the module to -40°C
- Light soak the module at 1500W/sqm for 15 minutes with lamps placed directly on top of the module
- Run the module at maximum power point with an electrical variable load
- Measure module temperature with two thermocouples (one placed on the front side of the module in the middle and the other on the back side of the module in the middle)
- Run this cycle 40x or until failure

Schematic of Test Process



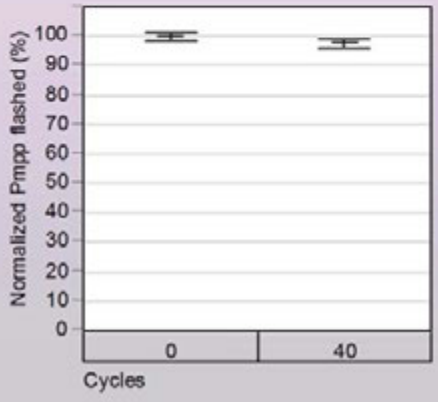
Measured Temperature



Results

After 40 cycles:

- 3% Pmax decrease at the end of the test, as measured from the start of the test
- No visual degradation, such as delamination, edge seal bubbles, edge seal or encapsulant color change
- Wet leakage current test: passed



This presentation does not contain any proprietary or confidential information.

Reliability of CIGS Modules

Deepak Nayak, Norbert Staud, Burak Metin, Eric Lee, and Mustafa Pinarbasi

SoloPower Inc.
San Jose, California, USA

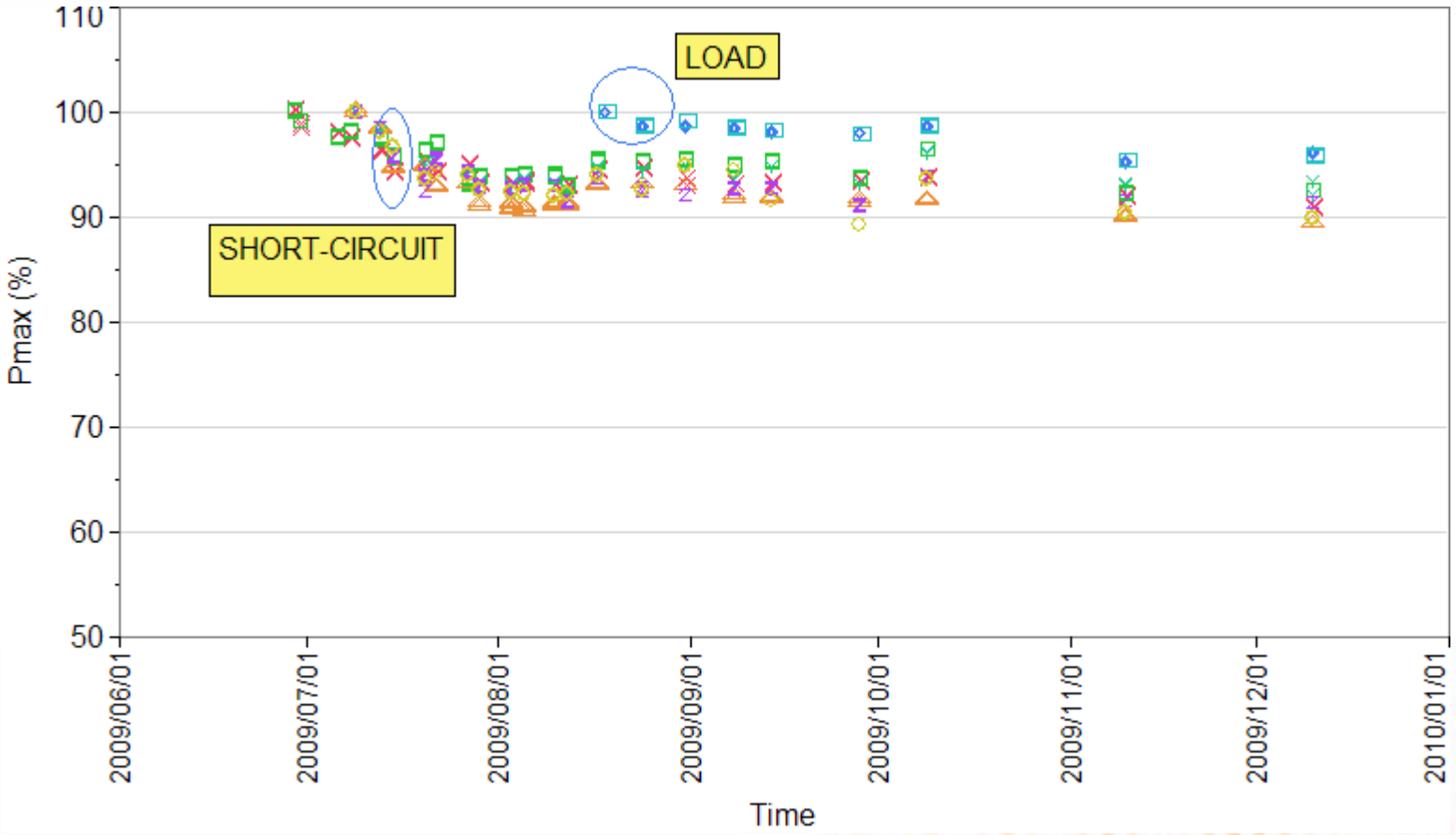
2009 SoloPower, Inc. Confidential

Long-term module performance

- Accelerated outdoor test: Short circuit test
- Short-circuit test: 20-25% higher current than Ipm
- Outdoor load test: Resistive load at Pmax

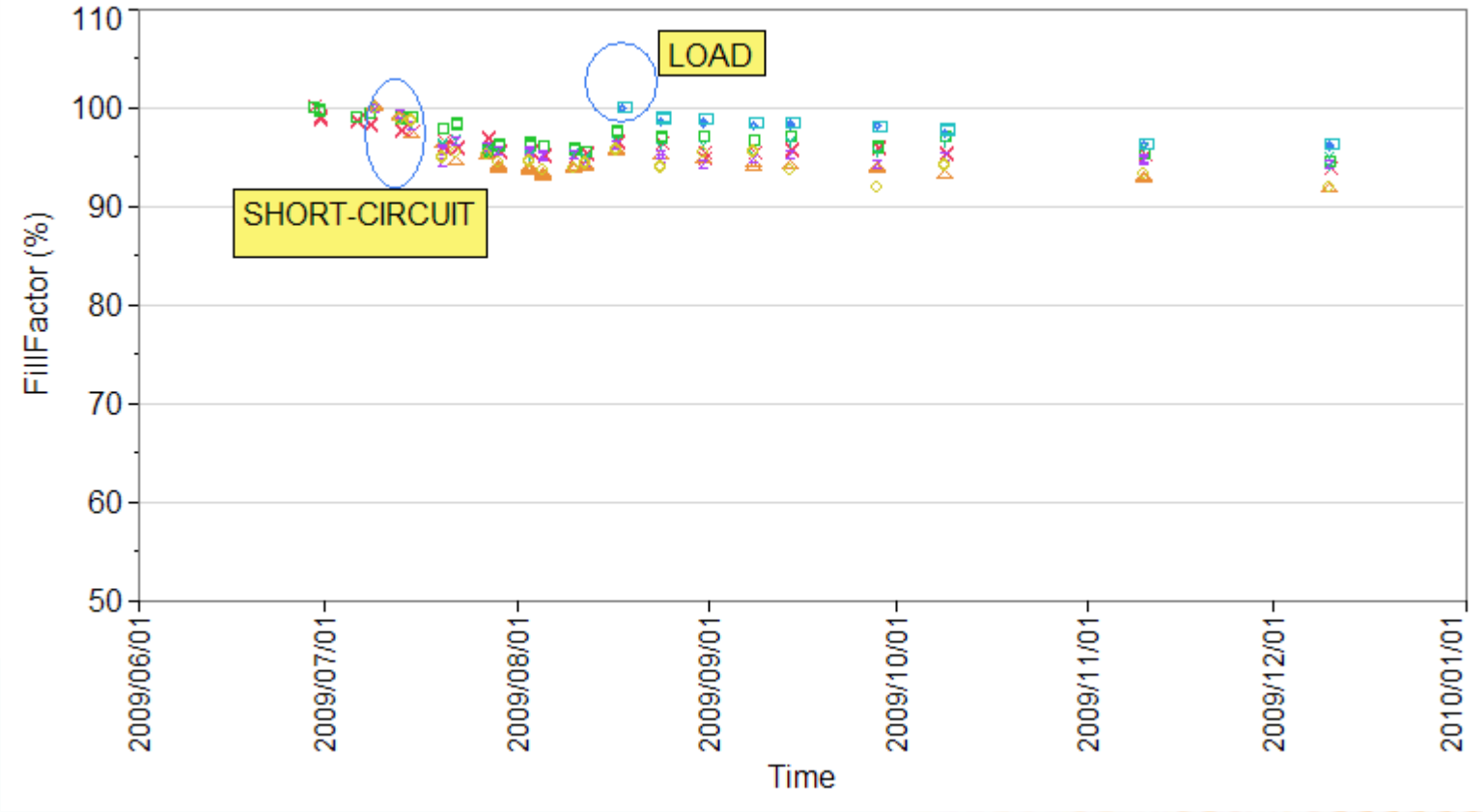
2009 SoloPower, Inc. Confidential

Modules in outdoor test



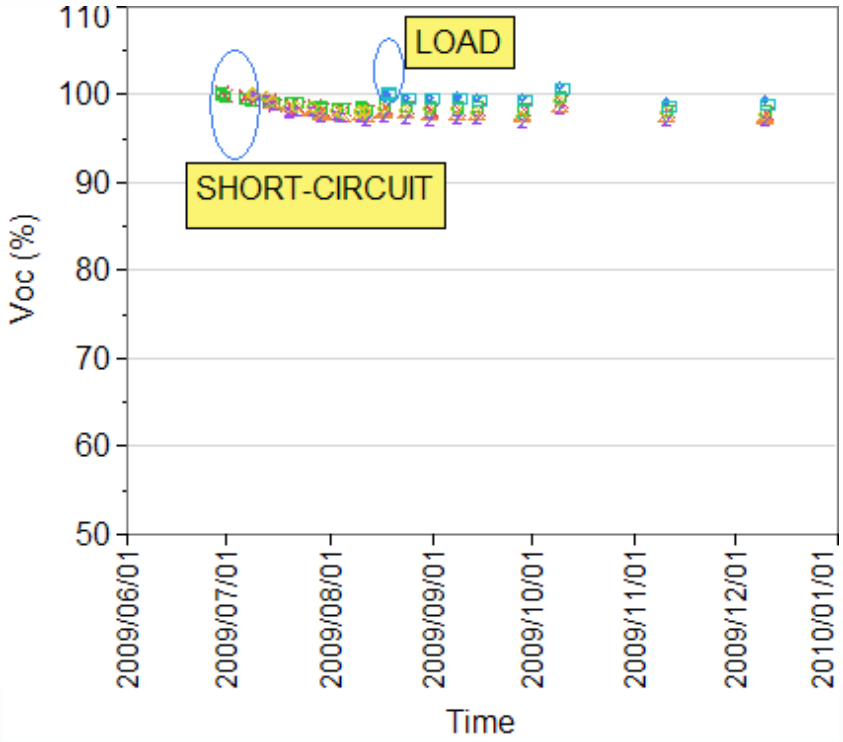
2009 SoloPower, Inc. Confidential

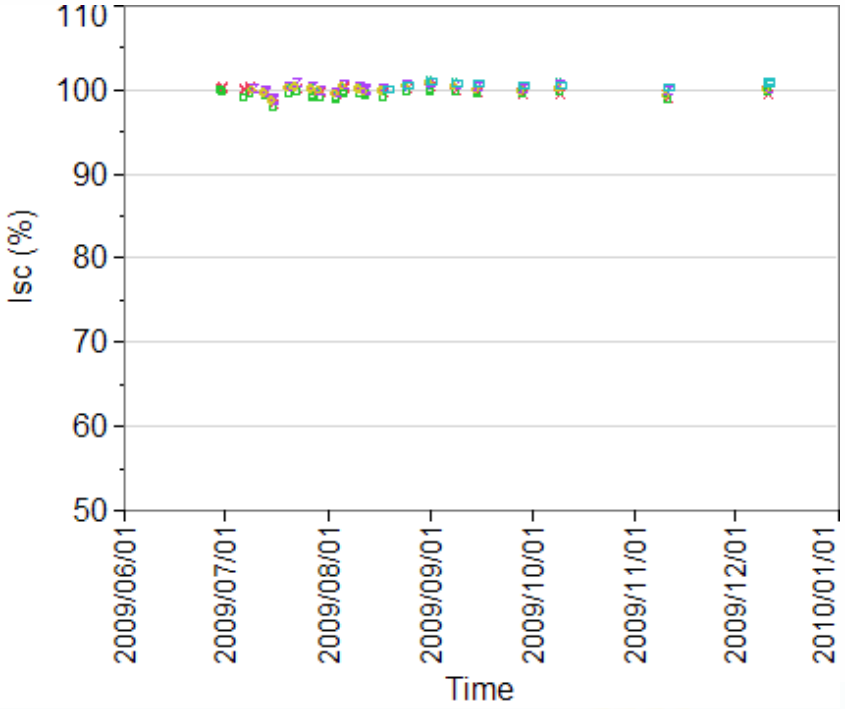
Modules in outdoor test



2009 SoloPower, Inc. Confidential

Modules in outdoor test



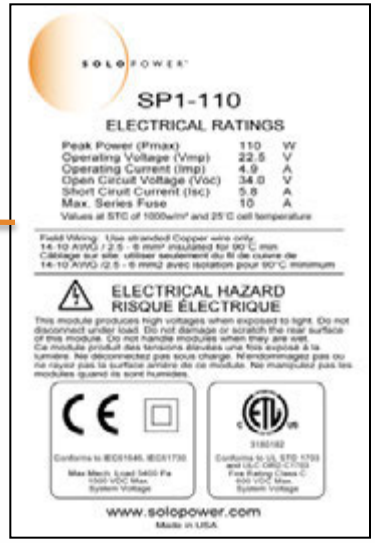


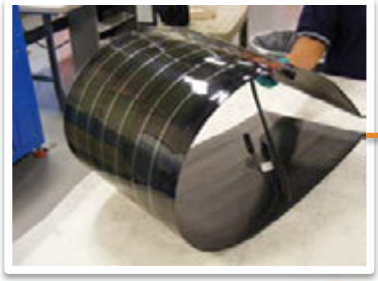
2009 SoloPower, Inc. Confidential

SoloPower CIGS Product

Current Product







Next Generation



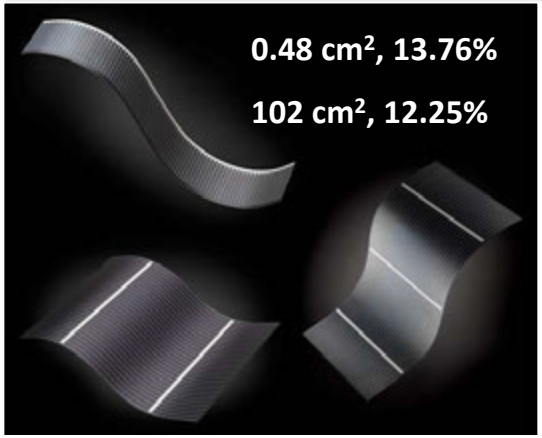
DRAFT COPY

UL and IEC Certified

Flexible and light weight

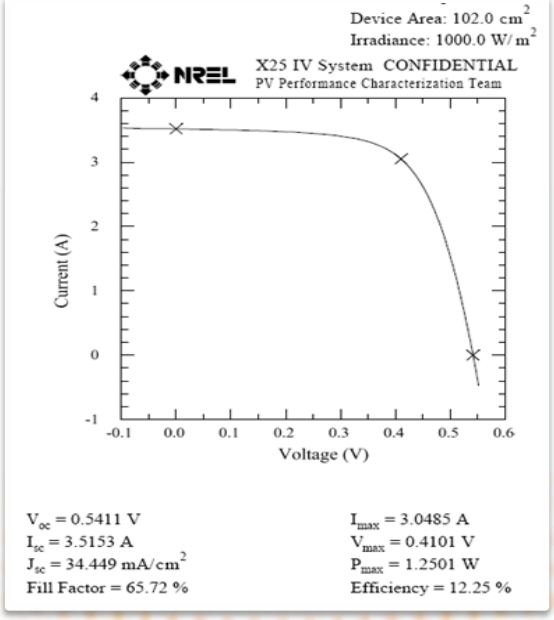
SoloPower Product Line

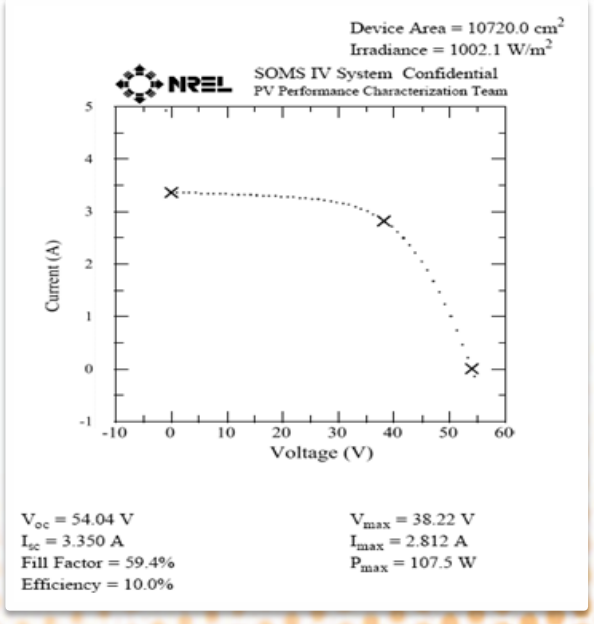
CIGS Cells → Flat Plate Modules → Flexible Modules





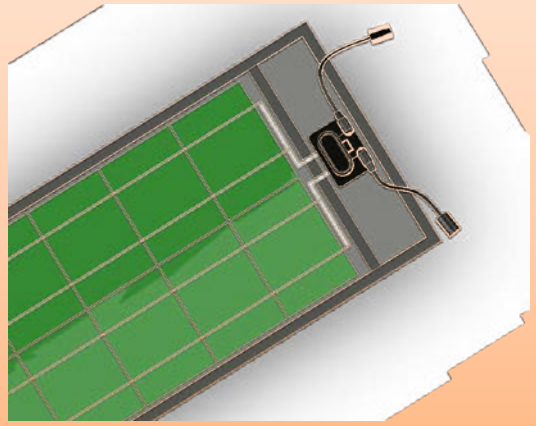






SoloPower SFX1 Module

- Advanced polymer packaging
- Light weight (~1 lbs/sq.feet)



Summary - Module Performance

- Module power stabilizes after few weeks
- Stable power up to 6 months under accelerated test
- No change to Isc
- UL and IEC certified

2009 SoloPower, Inc. Confidential

CORNING

Photovoltaic Glass Technologies

Thin Specialty Glass for Reliable Thin Film PV Modules

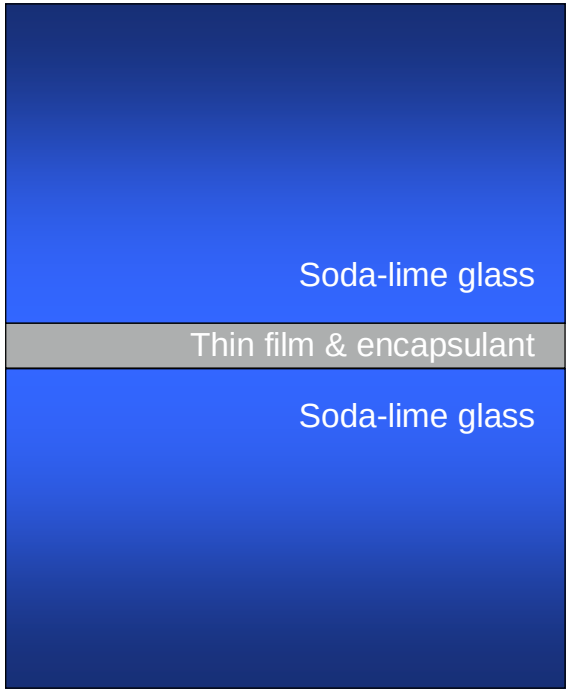
James E. Webb, David I. Wilcox, Kevin L. Wasson, and Suresh T. Gulati

February 18, 2010
NREL PV Reliability Workshop

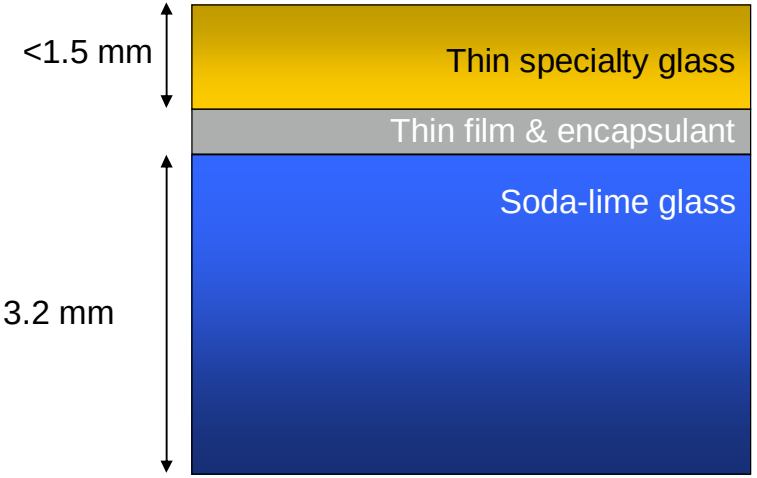
Thin specialty glass enables increased conversion efficiency

- Enables increased conversion efficiency
  - Higher transmission
  - Higher processing temperature
- Lowers manufacturing and BOS costs
  - Shorter heating times
  - Shorter cooling times
  - Reduced weight

Typical PV module cross section



Cross section with thin glass



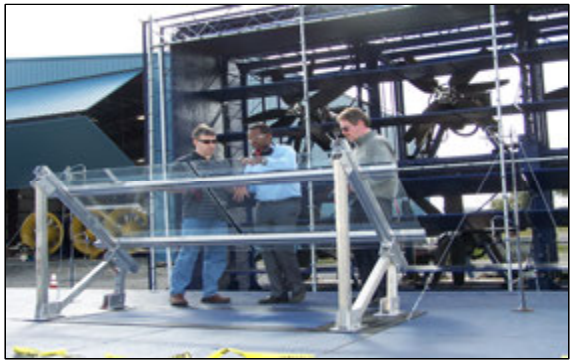
© 2010 Corning Incorporated

Thin glass must meet reliability requirements

- 25 to 30 years - no glass breakage
  - Wind, rain, hail, snow, blowing sand
- IEC 61646
  - Hail Impact
    - 25mm ice ball at 23 m/s
  - Wind load test
    - Uniform 2,400 Pa pressure to both sides
    - Total 6 hour duration
  - Heavy snow load test
    - Uniform 5,400 Pa pressure

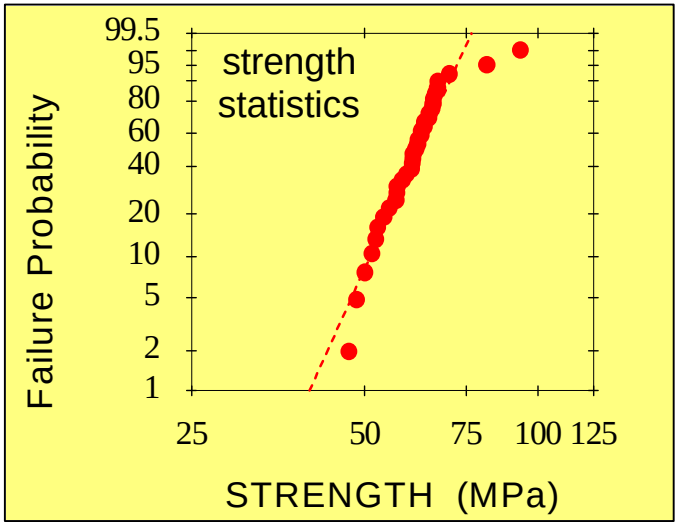


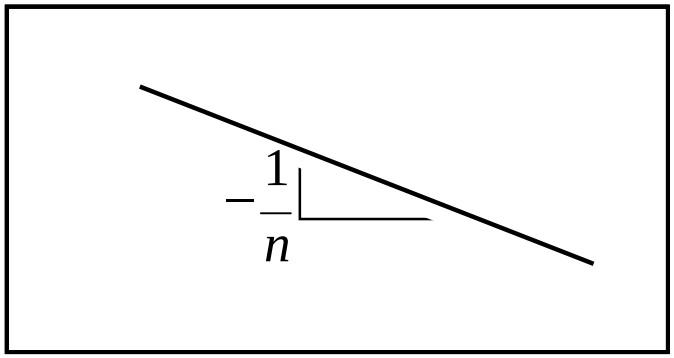




© 2010 Corning Incorporated

Glass strength can be affected by statistics and time





Probability Factor $F_P = \left[\ln\left(\frac{1}{R}\right) \right]^{\frac{1}{m}}$

Area Factor $F_A = \left(\frac{A_{test}}{A_{product}} \right)^{\frac{1}{m}}$

Fatigue Factor $F_F = \left(\frac{1}{\tau} \right)^{\frac{1}{n}}$

n = fatigue exponent τ = stress duration

R = reliability A = area

S_0 = Weibull characteristic strength

m = Weibull modulus

Allowable Stress = (F_P x F_A x F_F) S_o

Surface imperfections and fatigue determine strength over time

© 2010 Corning Incorporated

Not all glasses are created equal; Different glasses have different fatigue resistances

Glass	Fatigue Exponent	Relative Strength (30 Year Life)
Soda-lime	~15	1.0
Corning PV glass	~20-23	1.4 – 1.6
Fused Silica (space shuttle windows)	~33	2.0
TiO_2 doped Silica (telescope mirrors)	~45	2.4

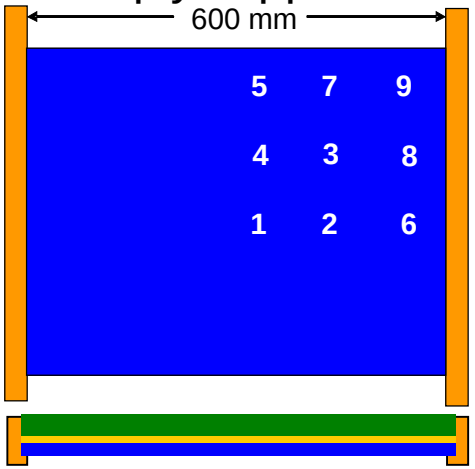
Resistance to fatigue is quantified by fatigue exponent
large exponent is better

© 2010 Corning Incorporated

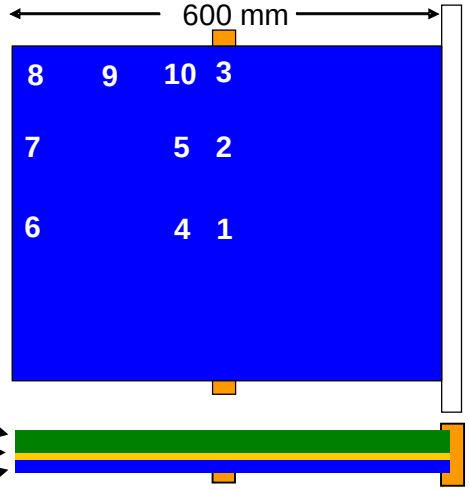
Thin glass passed hail impact testing



simply supported



cantilevered

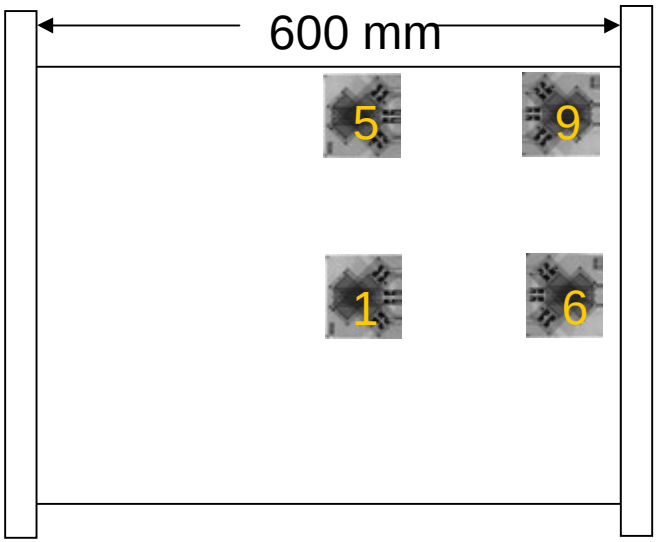


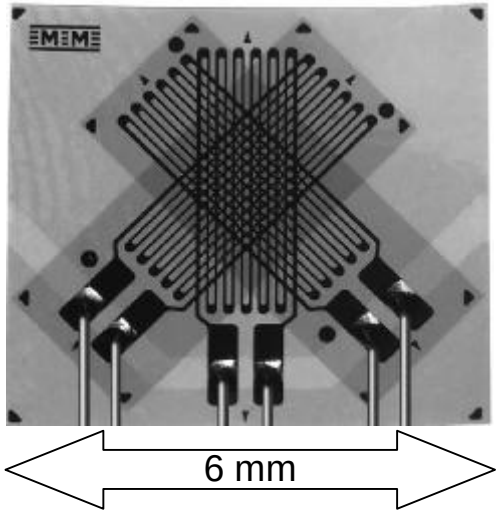
Experiment details
95- 500 X 600 sub-modules
25 mm diameter ice ball
23 m/s velocity
18 to 20 impacts each

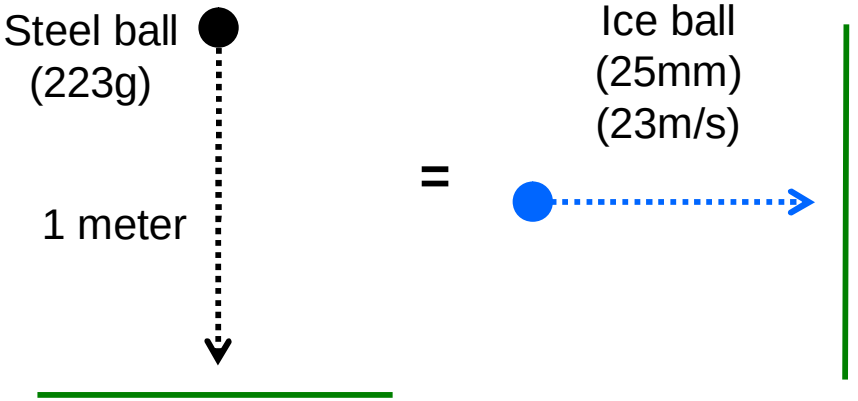
Thin glass
5 thicknesses 0.7 to 3.2 mm
400 grit bullnose edges

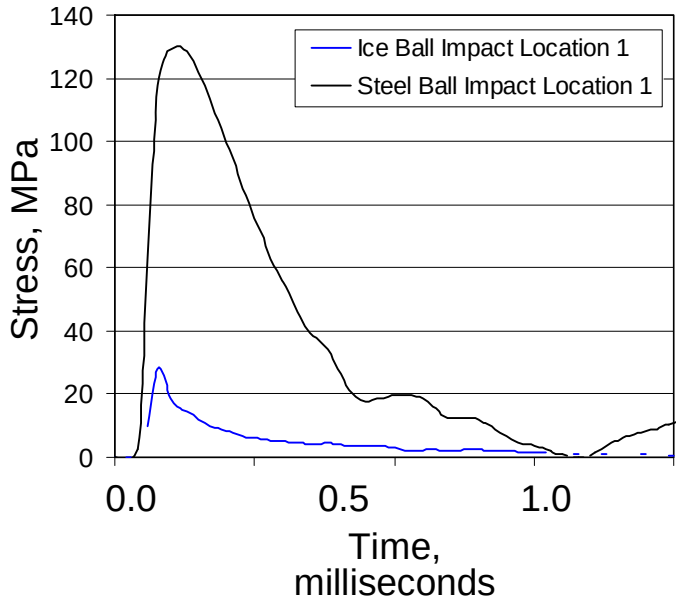
© 2010 Corning Incorporated

Ice ball generates lower stresses than steel ball at equivalent impact energy



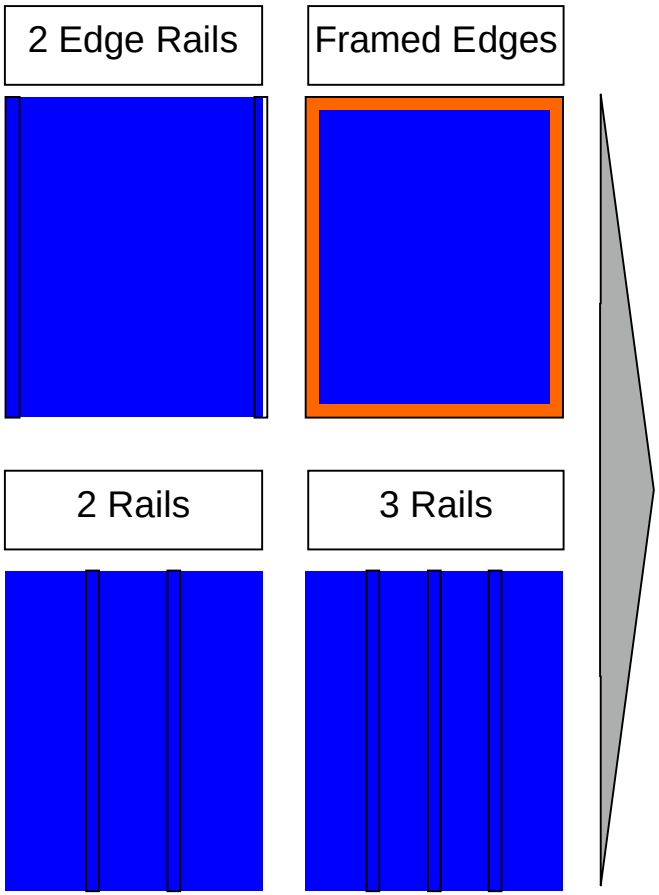


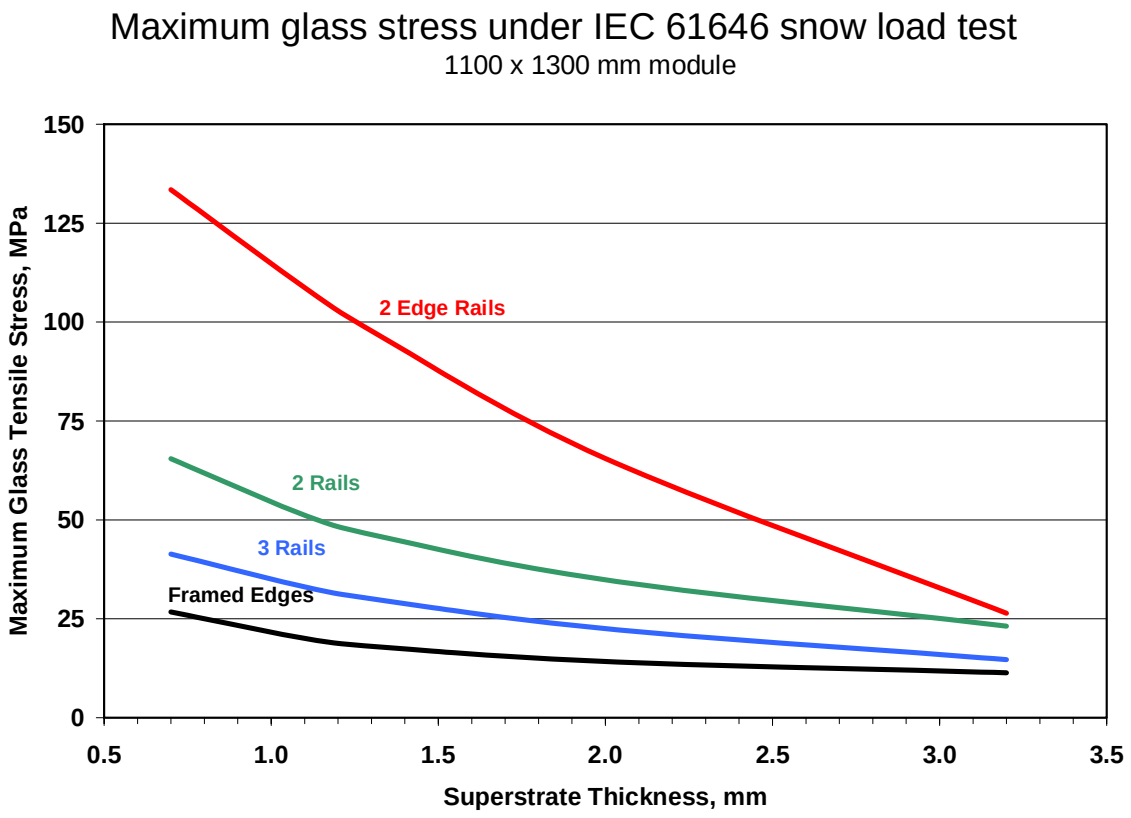




© 2010 Corning Incorporated

Modeling of mounting configurations indicate that mounting is more important than glass thickness



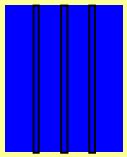
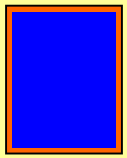
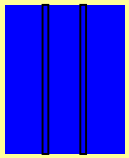
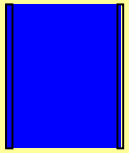


© 2010 Corning Incorporated

Model predicts thin specialty glass to pass heavy snow load test

Model results of IEC 61646 wind and snow load test

1100 x 1300 mm module

Support Configuration	Glass thickness (mm) 0.7	1.1	1.3	1.5	3.2
3 Rails 	●	●	●	●	●
Framed edge 	●	●	●	●	●
2 rails 	●	●	●	●	●
2 edge rails 	●	●	●	●	●

© 2010 Corning Incorporated

In summary, thin specialty glass is reliable and recommended for thin-film PV applications

- Glass strength is determined by surface imperfections and fatigue over time
- Not all glasses are created equal. Glass composition affects long term strength
- Thin specialty glass withstands severe testing
  - Ice ball impact
  - Heavy snow loads
- Wind and snow load stresses depend primarily on mounting design
  - Optimal and more cost efficient mounting configuration must be considered

© 2010 Corning Incorporated