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

DOE SETP

Photovoltaics (PV)

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-Excitons

Cost Reduction
Remove System and Market Barriers

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

Goal: Grid Parity
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
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.

* 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

National Labs & Academia
- Build & communicate knowledge
- New test development especially for emerging technologies

Industry Partners
- Improved product performance and reliability
- Commercialization

T&E/R on R&D products, Field tests

Test Technology Transfer
- Commercial product and Qual testing
- Commercial testing
- New test capabilities for commercial products

Codes & Standards Development

Commercial Test Houses, Test Labs
Thank You

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New PV Technologies

Direct interactions with industry

New
Methods, Models, etc.

Workshops
Guideline Documents
Codes Standards Certifications
Direct Transfer Of capabilities
Publications
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:
• Logistics:
  – D. Glickson, I. Thornton, S. Moon, S. Padilla
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
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.

Summary points:

- Competing imperatives

PV bankability - a function of durability

- Common calculation of PV costs = (upfront $ – incentives)
  - Durability often overlooked
  - Factoring in 0.5%/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.
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
Significance of Durability & Reliability

The PV “triumvirate”
  – Safety
  – Performance
  – Reliability

Durability impacts all
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

Reliability

- MIL-STD-721C and MIL-HDBK-338 have two definitions of 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
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.
Durability

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

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)
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.
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
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
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.
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.
Reliability & Durability Testing

IEC design type qualification tests

IEC 61215 environmental tests
IEC 61646 environmental tests are similar

Failure Rate $\lambda$

Accumulating damage/declining performance

Lifetime
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”

Hoffman & Ross
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
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.
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
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.
• 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.
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)
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
Testing for Durability & Reliability

• Alternate methods
  – Utilize:
    • FMEA, Experience, Knowledge
    • Cumulative damage models
    • Results may never have better than “good estimates” (defensible)
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.
The $d$FMEA can be a useful tool for deciding which durability test types and specific test conditions are appropriate.
Design for Reliability/Durability
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!
Overview of Failure Mechanisms and PV Qualification Tests

John Wohlgemuth
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 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
- SERI IQT (1990) – modifications for thin films (a-Si)
- IEC 61215 (Ed 1 - 1993, Ed 2- 2005) – Crystalline Si
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

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<th>II</th>
<th>III</th>
<th>IV</th>
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<td>50 -40 to +90</td>
<td>50 -40 to +90</td>
<td>50 -40 to +90</td>
<td>200 -40 to +90</td>
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<tr>
<td>Humidity</td>
<td>70C,90% 68 hrs</td>
<td>5 cycles 40 to 23C 90%</td>
<td>5 cycles 40 to 23C 90%</td>
<td>5 cycles 54 to 23C 90%</td>
<td>10 cycles 85 to -40C 85%</td>
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<tr>
<td>HOT SPOT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 cells 100 hrs</td>
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<tr>
<td>Mechanical Load</td>
<td>100 cycles 2400 Pa</td>
<td>100 cycles 2400 Pa</td>
<td>10000 2400 Pa</td>
<td>10000 2400 Pa</td>
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<tr>
<td>Hail</td>
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<td>9 impacts ¾” –45 mph</td>
<td>10 impacts 1” – 52 mph</td>
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<td>&lt; 50 µA 1500 V</td>
<td>&lt; 50 µA 1500 V</td>
<td>&lt; 50 µA 2*Vs+1000</td>
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</table>
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

- 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
• 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
• 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

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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
Empirical methods vs. Physics of Failure

Diagram showing the comparison between empirical methods and physics of failure in the context of design and failure identification.
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
PoF Reliability Assessment Methodology

1. Design Capture
2. Load Transformation (stress analysis)
3. Life-Cycle Loading Characterization
4. Failure Risk Assessment
5. Ranking of Potential Failures Under Life-Cycle Loads

- Load
- Time to Failure
- Field
- 1, 2, 3
Accelerated Product Qualification

1. Virtual Qualification
   - Hardware configuration
   - Stress analysis
   - Durability assessment (Energy partitioning)
   - Potential failures under life-cycle loads are ranked

2. Accelerated Test Planning and Development
   - Test configuration
     - Test matrix
     - Specimen design
     - Fixture design
     - Test platforms
   - Sensors (Thermocouples)
   - Load controller
   - Failure detection scheme
     - Non-functional: Event detectors
   - Design of expts

3. Test Vehicle Characterization
   - 10x10 mm
     - Experiment
     - Prediction
     - Time to failure (hrs)
   - 5x5 mm
     - Time to failure

4. Accelerated Life Testing
   - 10x10 mm
     - Verify failures and update PoF models
     - Manufacturing variabilities affect life estimates
     - Quality improvements
   - 5x5 mm
     - Time to failure

5. Reliability Assessment
   - Load
     - Field
     - ALT
     - N_{ALT}=14
     - N_{Field}=246
     - Time to failure (hrs)

- Design of expts
- Manufacturing variabilities affect life estimates
- Quality improvements
- Time to failure
- Hardware configuration
- Stress analysis
- Durability assessment (Energy partitioning)
- Potential failures under life-cycle loads are ranked
- Test configuration
  - Test matrix
  - Specimen design
  - Fixture design
  - Test platforms
- Sensors (Thermocouples)
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- Durability assessment (Energy partitioning)
- Potential failures under life-cycle loads are ranked
- Test configuration
  - Test matrix
  - Specimen design
  - Fixture design
  - Test platforms
- Sensors (Thermocouples)
- Load controller
- Failure detection scheme
  - Non-functional: Event detectors
- Design of expts
- 10x10 mm
  - Experiment
  - Prediction
  - Time to failure (hrs)
- 5x5 mm
  - Time to failure
Comprehensive System Reliability Assessment

Overall system

Sub-system1

Sub-system2

Sub-systemn

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

Failure mechanism1

Failure mechanism2

Failure mechanismn

L = L_{r} \left( \frac{V_{r}}{V_{0}} \right) \times 2 \left( \frac{T_{r} - T_{d}}{10} \right)

\varepsilon = \frac{(R - \rho_{r})d\psi}{\rho_{1}\Psi_{i}} \approx \frac{(r - \rho_{r})d\psi}{\rho_{1}\Psi_{i}} = \frac{r(\psi_{i} - \psi_{f})}{\rho_{1}\Psi_{i}}

N_{f} = 0.5 \left( \Delta \gamma / 2\varepsilon_{r} \right)^{c}
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.

Design Capture
Wafer Type Module

T. McMahon and C. Osterwald, NREL
Design Capture
Thin-Film Type Module

T. McMahon and C. Osterwald, NREL
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.
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.

**Diagram:**

1. **Raw Data**
2. **Raw Data**
3. **Binning Software**
4. **Detailed segmented profile**
5. **Accelerated segmented profile**
6. **Applied Test Data**
7. **Reliability Assessment**

- Provided by user
- Add time stamps
- Cycle counting, descriptive statistics and distributions
- Group individual cycles into segments based on parameters
- Virtual and experimental qualification
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.
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
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.
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
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

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

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

## Failure Mechanism Models – PV Module

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

# Failure Mechanism Models - CPV

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

(2) [http://www.nrel.gov/csp/troughnet/pdfs/mahoney_receiver_devel.pdf](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
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.
Comprehensive System Reliability Assessment

Overall system

Sub-system1

Sub-system2

Sub-systemn

Part1

Part2

Partn

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

Failure mechanism1

Failure mechanism2

Failure mechanismn

Nf = 0.5 (Δγ/2εi)c

\[ L = L_r \left( \frac{V_r}{V_0} \right) \times 2 \left( \frac{T_r - T_d}{10} \right) \]

\[ \varepsilon = \frac{(R - \rho_r) d \psi}{\rho_i \Psi_i} \approx \frac{(\bar{r} - \rho_r) d \psi}{\rho_i \Psi_i} = \frac{r(\psi_i - \psi_f)}{\rho_i \Psi_i} \]

PoF mechanism identification

FFOP estimation of the overall system
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
  - Electroluminescence imaging
  - Photoluminescence 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 photovoltaics: 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

---

Imaging Camera (near IR-vis)

Excessive hot carriers or leakage = Light emission

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

\[
\Delta V = I \left( \frac{\delta R}{\delta T} \right) \times \Delta T
\]

AC voltage signal ~ current

Probe of local current
\[I = \Delta V \times (\text{constant})\]

Probe of resistance along line

OBIRCH 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**

$\gg$ 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
  - Sensitive to delamination (Failed encapsulant)
  - Poor contacts (solder bumps)

- Water bath required

- ~10\(\mu\)m resolution
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

Si chip

Soak in Dye

Pry off top

Stain on poor contact

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

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

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)
    - Photoluminescence (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

  ![Passivated poly-xtal Si](image1)

  ![Unpassivated poly-xtal Si](image2)

  **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

Energetic electrons with large reverse bias:
“Avalanche” breakdown or “Zener” breakdown = broadband emission
Correlation to metallic impurities
Correlated to local heating

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

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

- **Photoluminescence**: no bias required
  - Applicable to unpatterned cells

- **Emission Intensity ~ lifetime**
  - Intensity = $G \times \tau$
    - (Generation rate * Carrier lifetime)
  - Fixed generation rate
    - Intensity ~ lifetime

- **Quantitative lifetime**
  - Not an absolute measurement
  - Calibration with known sample required
  - Transient method for calibration

- **High illumination required**

---

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)].

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

- 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 $\rightarrow$ 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

Infrared imaging of cells:
Local shunts / weak diodes

www.movitherm.com

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 = $\Sigma_i [B_i - D_i]$

  - Uses high speed infrared CCD cameras
  - <1mK thermal resolution
  - Spatial resolution =
    - Thermal Diffusion / frequency ~ 3mm

- **Very quantitative (variables scale out)**
  - Shunt current, shunt IV

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

  (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

Thermal reflectance imaging in visible

Silicon with 230nm oxide 800nm nitride

Reflectance change / temperature

$\frac{1E4 \times \Delta R}{\Delta T}$
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**
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)

<table>
<thead>
<tr>
<th>Company Site (Alphabetical order)</th>
<th>State</th>
<th>Scanning Acoustic Imaging</th>
<th>Florescence Dye or Dye and Pry</th>
<th>Emission Microscopy (EL)</th>
<th>Scanning Optical (LBIC/OBRICH)</th>
<th>Photoluminescence</th>
<th>Thermal – Infrared or Liquid Crystal</th>
<th>Thermal – Reflectance</th>
<th>Voltage Contrast</th>
<th>SEM</th>
<th>X-ray imaging, 2-D and 3-D</th>
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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
double crystal material

Sputter profile
Uniform

Sputter profile
broadened by deposition (minor)

Sputter profile
double crystal material

Sputter rate varies with orientation (channeling)

VERY broad sputter profile
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… To make a difference…
1. Efficiency 1. Cost
2. Reliability 2. Reliability
3. Cost 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

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
SiO2 cracking in water  
E* ~ 1.39 eV/bond
Mechanics of Damage Evolution

Damage occurs when...

\[ G \geq G_c \left[ \frac{J}{m^2} \right] \]

- Lower thin-film stresses – driving force for cracking
  \[ G = \frac{Z(\sigma_f)h_f}{E_f} \]
  – 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

\[ G \geq G_c \left[ \frac{J}{m^2} \right] \]

presence of chemical species and photons, damage propagates even if

\[ G < G_c \left[ \frac{J}{m^2} \right] \]

Role of coupled kinetic parameters:

- mechanical stress
- temperature
- environmental species
- photons (photochemical reactions)
Quantitative Adhesion/Cohesion and Debond Kinetics

DTS Delaminator v4.0

Adhesion/Cohesion

Cohesion Energy, G (J/m²)

Solar Cells

1.5
1
0.5
0

10⁻¹¹
10⁻¹⁰
10⁻⁹
10⁻⁸
10⁻⁷

Crack Growth Rate, da/dt (m/s)

0 1 2 3 4 5 6 7

Strain Energy Release Rate, G (J/m²)

UV intensity
1.2 mW/cm²

No UV
0 mW/cm²

Threshold crucial for reliability

0.6 mW/cm²

Degradation Kinetics
(temp/environment/UV effects)

Inherent Solar Cell Thermomechanical Reliability, G_c

Grad students: Vitali Brand, Jeff Yang and Chris Bruner
Adhesion/Cohesion Sample Preparation

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
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

TEM of P3HT:PCBM film
Effect of Thickness of BHJ on Cohesion

\[ G_{\text{total}} = G_o + G_{\text{zone}} \]

interface chemistry

frictional contact
ductile adjacent layer

Kearney, Dauskardt, Acta Mat. 2008

Segregation of PCBM towards bottom PEDOT due to more polar nature of PCBM compared to P3HT
XPS on Top of Spin Coated BHJ Surface

Effect of Composition of BHJ on Cohesion

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

Annealing effects during Al vapor deposition is a possibility

Topography

- $R_a = 20$ nm
- $R_q = 24$ nm
Buckling and Wrinkling in Stressed Films


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

Wrinkling of Stressed Elastic Film on Viscoelastic Layer

Equilibrium amplitude of sinusoidal wrinkle:

\[ A_{eq} = 2\sqrt{1 - \nu^2} \frac{\sigma_0}{E_f} \left\{ \frac{\pi h}{12(1-\nu^2)} \left[ \frac{2(1-\nu)\mu_\infty}{1-2\nu} E_f \frac{1}{E_\psi} \right]^{1/2} \right\} \]

Equilibrium wrinkle wavelength: \( k = 2/L_{eq} \)

- *Layers initially flat - elastic layer with in-plane biaxial compressive stress \( \sigma_0 \).*
- Wrinkling to relax stress in elastic layer – viscoelastic layer deforms to maintain conformality.
- \( \mu_\infty/E_f \) is ratio of rubbery modulus of the viscoelastic layer and the elastic modulus of the elastic layer.
- \( k \) is the wavevector: \( k = 2/L_{eq} \)

Small Molecule Solar Cell Thin Films

\[ G_c = 1.1 \pm 0.4 \, \text{J/m}^2 \]

Molecular Bond Rupture Kinetics (Barrier Films)

Grad student: Fernando Novoa and Monika Kummel

\[ G < G_c \left[ J / m^2 \right] \]
Weathering Test of Polysiloxane Barrier

UV exposure: 28 mW/cm² at 6 mm UV-257nm

120 min…………….15 min……………………5 min

Film Stress Accumulation with UV Exposure

Driving force for damage:

\[ G = \frac{Z\sigma_f^2 h_f}{E_f} \]

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) 
  \( E^* \approx .81 \text{ eV/bond} \)
- \( \text{SiO}_2 \) cracking in water
  \( E^* \approx 1.39 \text{ eV/bond} \)

Assessing UV and Environment on Debonding Kinetics

Debonding Kinetics
- explore role of:
  - UV flux
  - humidity, \( \text{O}_2\), \( \text{OH} \), …
  - temperature
  - mechanical loading
UV Effects on Molecular Bond Rupture

UV Exposure (3.4 eV)

UV intensity
1.2 mW/cm²

$G_{hv} \sim 1.3 \text{ J/m}^2$

No UV
0 mW/cm²

0.6 mW/cm²

$G_{hv} \sim 0.8 \text{ J/m}^2$

Crack Growth Rate, $\frac{da}{dt}$ (m/s)

Strain Energy Release Rate, $G$ (J/m²)

Modeling Bond Rupture Kinetics

- Interaction of moisture with strained debond tip bonds
  
  $nH_2O + B(\text{debond tip}) \rightarrow B'(\text{activated complex})$

- Atomistic bond rupture models:
  
  $rate = f_o \left[ \exp \left( \frac{-U'}{kT} \right) - \exp \left( \frac{-U}{kT} \right) \right]$

- Damage growth rate:
  
  $\frac{da}{dt} = v_o \sinh \left( \frac{G_{ip} + G_{hv} + 2\gamma}{\eta} \right)$

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

Bond Rupture Parameters

- $N$ - bonds per unit area
- $f_o$ - attempt frequency
- $u_o$ - work of rupture
- $u_1$ - energy barrier
- $2\gamma$ - $N$ $u_o$
- $w$ - crack width
- $\eta$ - $2NkT$
UV Sources

- Fluorescent Lamp
- AM1 solar spectrum
- Mercury Lamp (Pen-Ray from uvp)
- 3.4 eV, 4.1 eV, 4.9 eV

Solar spectrum from B. Van Zeghbroeck, U. Colorado

UV Effects on Molecular Bond Rupture

UV exposure 4.9 eV
adhesive failure at 20°C 40%RH

- adhesive
- Growth Rate, \( \frac{da}{dt} \)
  - Simulated UV Exposure
  - Glass Substrate
  - polysiloxane barrier
  - Glass Substrate
  - Simulated UV Exposure

- Debond Growth Rate, \( \frac{da}{dt} \) (m/s)
  - 10^-5
  - 10^-6
  - 10^-7
  - 10^-8
  - 10^-9

- Strain Energy Release Rate, \( G \) (J/m^2)
  - 0
  - 1
  - 2
  - 3
  - 4
  - 5
  - 6

- 6.6 mW/cm^2
- 4.6 mW/cm^2
- 2 mW/cm^2
- No UV
Modeling Bond Rupture Kinetics

- Interaction of moisture with strained debond tip bonds
  \[ nH_2O + B(\text{debond tip}) \rightarrow B^* \text{(activated complex)} \]

- Atomistic bond rupture models:
  \[ \text{rate} = f_b \exp \left( -\frac{U^*}{kT} \right) \exp \left( -\frac{U}{kT} \right) \]

- Damage growth rate:
  \[ \frac{da}{dt} = v_o \sinh \left( \frac{G_{\text{tip}} + G_{\text{barrier}}}{2\gamma} \right) \]

  \[ v_o = \frac{2N w}{N_{\text{w}}} \exp \left( -\frac{u_o}{kT} \right) \]

Bond Rupture Parameters:
- \( N \) - bonds per unit area
- \( f_o \) - attempt frequency
- \( u_o \) - work of rupture
- \( 2\gamma \) - energy barrier
- \( w \) - crack width

\[ \eta = \frac{2N}{N_{\text{w}}} \]

Modeling Bond Rupture Rupture Kinetics

- Crack growth rate vs. strain energy release rate
- Predicted UV rupture kinetics without cross-linking (bonds = \( N \))
- Predicted with cross-linking during UV (bonds = \( 2N \))
UV Effects on Molecular Bond Rupture

No UV exposure
cohesive failure at 20°C

Simulated UV Exposure
Glass Substrate
polysiloxane barrier
Glass Substrate
Simulated UV Exposure

cohesive cracking in polysiloxane exhibits little sensitivity to moisture

Strain Energy Release Rate, G (J/m²)

Crack Growth Rate, da/dt (m/s)

{\text{No UV exposure cohesive failure at 20°C}}

UV Effects on Molecular Bond Rupture

UV exposure 4.9 eV
cohesive failure at 20°C, 50%RH

Simulated UV Exposure
Glass Substrate
polysiloxane barrier
Glass Substrate
Simulated UV Exposure

In-situ UV 7.6mW/cm²

Strain Energy Release Rate, G (J/m²)

{\text{UV exposure 4.9 eV cohesive failure at 20°C, 50%RH}}
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.


- 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.

Delamination of EVA-TPE Lamination

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

![Diagram showing adhesion and time dependant debonding](image)
Examples from Microelectronics

Adhesion of Interfaces in Packages:
Role of Functional Group and Surface Coverage

Adhesion energy corrected for surface coverage.

Adhesion and Debonding in Device Packaging

Anomalous Threshold Behavior

Bisphenol F Underfill/SiNx

25°C

\[ m_1 > 40 \]
\[ m_2 \sim 2 \]

85% RH

60% RH

30% RH

1% RH

Applied Strain Energy Release Rate, \( G \) (J/m²)

Debond Growth Rate, \( \frac{da}{dt} \) (m/s)

85% RH

60% RH

30% RH

1% RH

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

Stress-Dependent Moisture Transport Model

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

Petropolous & Roussis (1978)

\[
\frac{da}{dt} = \frac{c_{\text{H}_2}\text{O}}{\delta n \Sigma} D_0 \exp\left(-\frac{E^* + \alpha \sqrt{G}}{RT}\right)
\]

\( E^* \sim 25 \text{ kJ/mol} \)

Time Dependent Debonding: Cyclic and Static Loading

Cyclic:
\[
da/dN = C(\Delta G)^m
\]

Static:
\[
da/dt = C'(G)^{m'}
\]

Polymer(BCB)/Silica Subcritical Debonding

Subcritical Debonding

Adhesion Energy

Polymer, Silane, Fatigue, Monotonic, Silicon

Cyclic Stress-Dependent Transport Model

\[ \frac{da}{dt} = \frac{cuaH\delta}{\delta n\Sigma} D_{0} \exp \left( \frac{-E_d + \alpha \sqrt{G}}{RT} \right) \]

\[ g(f,t) = f \int_{0}^{t} \exp \left[ \frac{\alpha}{RT} \sqrt{\left( G_{av} + \Delta G \sin(2\pi ft) \right)} \right] dt \]

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.
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

- Product Concept
- "Back of the Envelope" Feasibility Calculations
- Product Design
- Detail Design
- Design Guidance Modeling
- Detailed Modeling
- Reliability Testing, Qualification
- Long term / projected lifetime modeling
- Modeling related to test results and any failures
- Product Release
- Design revisions, Future products
- Modeling in support of future products

PV Module Modeling Overview  February 18, 2010
Material Testing/FEA Flow Diagram

1. Prior Knowledge of Material?
2. Primary Loading Mode?
3. Budget and Time Constraints?
4. Initial Model Selection
5. Specify Tests
6. Sufficient Data Already Available
7. Get Test Data
8. Calibrate Model
9. Confirm Model
10. Run FEA

Credit: John Lawler, GreenMountain Engineering
When to Model?

**PV is growing up!**

Prototype
- Observe failure
- Identify mechanism
- Develop test
- Mitigate problem
- Identify next failure

Mature product
- Failure analysis
- Identify mechanism
- Develop (ALT) test
- Measure acceleration
- Predict performance

When do we move from focus on mitigation to focus on prediction?

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
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.

<table>
<thead>
<tr>
<th>Material</th>
<th>Typical Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>Elastic</td>
</tr>
<tr>
<td>Silicon</td>
<td>Elastic</td>
</tr>
<tr>
<td>Encapsulant</td>
<td>Viscoelastic, or hyperelastic(?) or temperature-dependent elastic</td>
</tr>
<tr>
<td>Backsheet</td>
<td>Elastic or temperature-dependent elastic</td>
</tr>
<tr>
<td>Copper</td>
<td>Elastic-Plastic</td>
</tr>
<tr>
<td>Solder or Adhesive</td>
<td>Elastic-Plastic or viscoelastic</td>
</tr>
</tbody>
</table>
### Material Properties

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

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbols</th>
<th>Typ. Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus (stiffness)</td>
<td>E, G</td>
<td>Pa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>ν</td>
<td>None</td>
</tr>
<tr>
<td>Plastic Deformation</td>
<td>σ_y, E_t</td>
<td>Pa</td>
</tr>
<tr>
<td>Viscoelasticity</td>
<td>T_g, E_s, E_l, E_{1..n}, τ_{1..n}</td>
<td>Pa, s</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>c_{te}, α</td>
<td>ppm/°K</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>K</td>
<td>W/m°K</td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>ρ</td>
<td>Ω-cm</td>
</tr>
</tbody>
</table>
Material Testing

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

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

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.

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)
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
Resistance of a conductor scales linearly with geometric parameters (cross-section, length): \( R = \frac{\rho L}{A} \)
Voltage drop is also linear with resistance and current: \( I R \)
Power loss in a resistance scales with current squared: \( I^2 R \)

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.

SPICE-simulated IV curves

1-sun IV curves: varying Rs in this range has a minor effect

10-sun IV curves: varying Rs has a major effect

Increased Voc with concentration (but ignoring temperature)

Each curve has 2x the Rs of the adjacent curve

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

I-V curve of module with fully shaded cell

I-V curves of each string (one with a shaded cell)

P-V power output curves
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
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)

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

For example, processes like tempering affect a metal’s strength but not its stiffness.
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:
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 54. 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.

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

Source: B. Yang, Stress, Strain, and Structural Dynamics
Scaling Laws, Rules of Thumb

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

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$ (GPa)</th>
<th>$t$ (mm)</th>
<th>$C_{te}$ (ppm)</th>
<th>$E \times t \times C_{te}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>73</td>
<td>4.0</td>
<td>9</td>
<td>~2600</td>
</tr>
<tr>
<td>EVA</td>
<td>0.006</td>
<td>0.4</td>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>Backsheet</td>
<td>2.7</td>
<td>0.35</td>
<td>100</td>
<td>~100</td>
</tr>
</tbody>
</table>

- 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.

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.

[Diagrams showing global and local models]
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.
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 \( \delta \).

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

• Qualitatively, a high value of the loss tangent, \( \tan\delta \), suggests greater material stiffness at high-frequency loading.

• This behavior is specifically described by decomposing the elastic modulus into real and imaginary components:
• $E_S$ (also called $E'$), the *storage modulus*, and $E_L$ (also called $E''$), the *loss modulus*, can also be expressed as

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

• 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
STATISTICAL LIFETIME PREDICTION FOR PHOTOVOLTAIC MODULES

Joseph M. Kuitche

Arizona State University & TUV Rheinland PTL
Arizona, United States
OUTLINE

➢ Introduction & Scope

➢ Conventional Approach: Time-To-Failure Analysis

➢ Degradation Analysis with non-constant model parameters
INTRODUCTION & SCOPE
Our approach to lifetime prediction

- Field data analysis from different climates
- Accelerated test data analysis
- Correlation between field and accelerated data
The purpose of this presentation is to provide our statistical approach to predicting lifetime 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.
TIME-TO-FAILURE ANALYSIS
• Sample Power output data for modules installed on a two-axis tracker
• Data are shown as fraction of measured initial power output

<table>
<thead>
<tr>
<th>Test Date</th>
<th>S70L45</th>
<th>S72L46</th>
<th>S73L47</th>
<th>S71L48</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/24/1998</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3/29/2000</td>
<td>98.56707</td>
<td>98.30695</td>
<td>98.13213</td>
<td>99.64207</td>
</tr>
<tr>
<td>3/30/2001</td>
<td>96.17613</td>
<td>95.50743</td>
<td>99.06003</td>
<td>92.65495</td>
</tr>
<tr>
<td>4/18/2002</td>
<td>95.99587</td>
<td>93.96017</td>
<td>97.29334</td>
<td>91.41772</td>
</tr>
<tr>
<td>5/7/2003</td>
<td>94.70425</td>
<td>91.75761</td>
<td>97.08592</td>
<td>87.15466</td>
</tr>
<tr>
<td>3/16/2004</td>
<td>92.98966</td>
<td>88.53482</td>
<td>95.50054</td>
<td>84.47388</td>
</tr>
<tr>
<td>7/14/2005</td>
<td>86.65919</td>
<td>88.54046</td>
<td>93.44639</td>
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</tr>
<tr>
<td>5/25/2006</td>
<td>76.14737</td>
<td>77.13774</td>
<td>88.38811</td>
<td>75.11946</td>
</tr>
<tr>
<td>5/29/2007</td>
<td>69.60249</td>
<td>71.62216</td>
<td>82.89079</td>
<td>68.44898</td>
</tr>
<tr>
<td>4/23/2008</td>
<td>69.07595</td>
<td>72.03201</td>
<td>83.63877</td>
<td>64.46939</td>
</tr>
<tr>
<td>11/20/2009</td>
<td>58.31153</td>
<td>63.49378</td>
<td>76.61548</td>
<td>65.06237</td>
</tr>
</tbody>
</table>
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
## Extrapolated TTF at 80% degradation

<table>
<thead>
<tr>
<th>Samples at Latitude tilt</th>
<th>Samples on the Tracker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>Failure time (years)</td>
</tr>
<tr>
<td>3801</td>
<td>33.41386</td>
</tr>
<tr>
<td>4821</td>
<td>26.93645</td>
</tr>
<tr>
<td>DG22</td>
<td>25.60665</td>
</tr>
<tr>
<td>DG822</td>
<td>20.84669</td>
</tr>
<tr>
<td>RA240</td>
<td>32.01457</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
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</tr>
</tbody>
</table>
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**
  \[ f(t) = \frac{1}{\sigma t \sqrt{2\pi}} e^{-\frac{(\ln t - \ln T_0)^2}{2\sigma^2}} \]

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

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta (m)</td>
<td>5.3759</td>
<td>3.3</td>
<td>8.7484</td>
</tr>
<tr>
<td>Eta (c)</td>
<td>32.0597</td>
<td>28.5706</td>
<td>35.975</td>
</tr>
<tr>
<td>Mean Life</td>
<td>29.5591</td>
<td>25.2656</td>
<td>34.5821</td>
</tr>
<tr>
<td>Failure Rate</td>
<td>24.3424</td>
<td>0.2683</td>
<td>2208.7097</td>
</tr>
</tbody>
</table>

- 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
DEGRADATION ANALYSIS WITH NON-CONSTANT MODEL PARAMETERS
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%
  
  $$R = \Pr \left[ \text{fraction of initial } P_{\text{max}} > 0.5 \right]$$
- We make the following assumptions:

  
  $$R = \begin{cases} 
  \text{fraction of initial power if } > 0.5; \\
  0 \text{ otherwise} 
  \end{cases}$$
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
  
  $a, b = f(\text{Insolation, Tambient, RH, WS, etc.})$;

  $(\text{insolation, Tambient, RH, WS, etc.})_i = \text{environmental cell i}$

- From the weather data, define a “typical day” of a month as a series of $x$ hours period.
## Non-Constant parameters approach

<table>
<thead>
<tr>
<th>Date</th>
<th>Parameter 1</th>
<th>Parameter 2</th>
<th>Parameter 3</th>
<th>Parameter 4</th>
<th>Days</th>
<th>Average R</th>
<th>ln (1/R)</th>
<th>Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/9/2004</td>
<td>0.840257667</td>
<td>0.83049</td>
<td>0.73012</td>
<td>0.75569</td>
<td>359</td>
<td>0.789139</td>
<td>0.23681</td>
<td>A</td>
</tr>
<tr>
<td>4/12/2006</td>
<td>0.78911445</td>
<td>0.78723</td>
<td>0.68367</td>
<td>0.71686</td>
<td>1092</td>
<td>0.74422</td>
<td>0.29542</td>
<td>A</td>
</tr>
<tr>
<td>4/11/2007</td>
<td>0.806853207</td>
<td>0.79791</td>
<td>0.69166</td>
<td>0.72138</td>
<td>1456</td>
<td>0.754453</td>
<td>0.28176</td>
<td>A</td>
</tr>
<tr>
<td>4/17/2008</td>
<td>0.810279984</td>
<td>0.78122</td>
<td>0.68636</td>
<td>0.71219</td>
<td>1828</td>
<td>0.747514</td>
<td>0.291</td>
<td>A</td>
</tr>
<tr>
<td>12/23/2004</td>
<td>0.829707377</td>
<td>0.81488</td>
<td>0.70536</td>
<td>0.74428</td>
<td>617</td>
<td>0.773555</td>
<td>0.25676</td>
<td>D</td>
</tr>
<tr>
<td>12/29/2005</td>
<td>0.826896293</td>
<td>0.80344</td>
<td>0.70281</td>
<td>0.73692</td>
<td>988</td>
<td>0.767515</td>
<td>0.2646</td>
<td>D</td>
</tr>
<tr>
<td>12/21/2006</td>
<td>0.829814596</td>
<td>0.81501</td>
<td>0.68434</td>
<td>0.72719</td>
<td>1345</td>
<td>0.764091</td>
<td>0.26907</td>
<td>D</td>
</tr>
<tr>
<td>12/30/2008</td>
<td>0.799022942</td>
<td>0.78191</td>
<td>0.66973</td>
<td>0.7096</td>
<td>2085</td>
<td>0.740065</td>
<td>0.30102</td>
<td>D</td>
</tr>
<tr>
<td>6/24/2003</td>
<td>0.873406436</td>
<td>0.85342</td>
<td>0.79745</td>
<td>0.82749</td>
<td>69</td>
<td>0.837942</td>
<td>0.17681</td>
<td>J</td>
</tr>
<tr>
<td>6/21/2004</td>
<td>0.825861406</td>
<td>0.82025</td>
<td>0.73449</td>
<td>0.76658</td>
<td>432</td>
<td>0.786798</td>
<td>0.23978</td>
<td>J</td>
</tr>
<tr>
<td>6/16/2005</td>
<td>0.840483675</td>
<td>0.83395</td>
<td>0.75017</td>
<td>0.78105</td>
<td>792</td>
<td>0.801412</td>
<td>0.22138</td>
<td>J</td>
</tr>
<tr>
<td>6/21/2006</td>
<td>0.824962664</td>
<td>0.8139</td>
<td>0.73793</td>
<td>0.75718</td>
<td>1162</td>
<td>0.783494</td>
<td>0.24399</td>
<td>J</td>
</tr>
<tr>
<td>6/13/2007</td>
<td>0.832947475</td>
<td>0.81657</td>
<td>0.75642</td>
<td>0.75829</td>
<td>1519</td>
<td>0.791058</td>
<td>0.23438</td>
<td>J</td>
</tr>
</tbody>
</table>
Non-Constant parameters approach

- The data were found to best fit a Weibull
- Thus, \( \ln(1/R) \) can be defined by a power function
  \[
  \ln(1/R) = b \cdot t^a
  \]
- The fit yields the parameters \((a, b)\) showed in table

<table>
<thead>
<tr>
<th>Test Month</th>
<th>Parameter a</th>
<th>Parameter b</th>
<th>Avge Max Tamb</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.1298</td>
<td>0.112</td>
<td>35.03</td>
</tr>
<tr>
<td>D</td>
<td>0.12</td>
<td>0.113</td>
<td>24.95</td>
</tr>
<tr>
<td>J</td>
<td>0.095</td>
<td>0.122</td>
<td>43.02</td>
</tr>
<tr>
<td>S</td>
<td>0.114</td>
<td>0.113</td>
<td>41.03</td>
</tr>
</tbody>
</table>

- 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:
  \[
  (a, b) = C_1 + \frac{C_2}{T}
  \]
Non-Constant parameters approach

- The data were found to best fit a Weibull
- If $a$ is constant, we have for a day:
  \[
  \ln(1/R) = [b_{7-9}(1/a)(2/24) + b_{9-11}(1/a)(2/24) + \ldots]a
  \]
- We can now predict over a given time frame.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$C_2$</th>
<th>$C_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>126.94</td>
<td>-0.295</td>
</tr>
<tr>
<td>$b$</td>
<td>-31.8</td>
<td>0.218</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Typical Day</th>
<th>7a - 9a</th>
<th>9a - 11a</th>
<th>11a - 1p</th>
<th>1 - 3 p</th>
<th>3 - 5p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avge Max Temp</td>
<td>20.87</td>
<td>39.37</td>
<td>50.65</td>
<td>50.12</td>
<td>43.7</td>
</tr>
<tr>
<td>$b = C_1+C_2/T$</td>
<td>0.109842813</td>
<td>0.11626</td>
<td>0.11981</td>
<td>0.11965</td>
<td>0.11766</td>
</tr>
<tr>
<td>$b_i^{(1/a)}$</td>
<td>5.39131E-09</td>
<td>8.8E-09</td>
<td>1.1E-08</td>
<td>1.1E-08</td>
<td>9.7E-09</td>
</tr>
</tbody>
</table>

\[
\ln(1/R) = [\text{Sum(...)}]^a \cdot (kt)^a
\]
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
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
Weathering test tools

All photos courtesy NREL
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
## IEC and weathering methods

<table>
<thead>
<tr>
<th><strong>Design Qualification environmental tests</strong></th>
<th><strong>Atlas module weathering tests</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intent:</strong> Accelerated tests to screen for major materials design and manufacturing flaws which result in premature (infant mortality) failures.</td>
<td><strong>Intent:</strong> 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.</td>
</tr>
<tr>
<td><strong>Climate Stresses:</strong> E.g. Temperature-only cycling; UV-only exposure; Humidity-Freeze cycling; Damp-Heat. Most tests delivered to separate modules.</td>
<td><strong>Climate Stresses (comprehensive):</strong> 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.</td>
</tr>
<tr>
<td>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.</td>
<td>Stress levels based on climate-derived conditions: Multiple simultaneous stresses delivered in short and long term cycles and at levels more representative of nature.</td>
</tr>
<tr>
<td>“Global Composite” climate condition standard; alternative Hot Arid Desert, Tropical/Subtropical or Northern Temperate climate conditions available.</td>
<td>Optional test modifiers: Coastal/Marine; Alpine/Snow Load; Urban Industrial; Agricultural Chemicals, Dust-Dirt, Acid Rain, Mildew effects.</td>
</tr>
</tbody>
</table>
### IEC and weathering methods

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

**Max module temperature typically < 90°C**
Atlas 25PLUS™ comprehensive weathering program

Atlas 25Plus “global composite” environmental test cycle
(other climates available)

1-module system

UV conditioning
Salt spray corrosion
Condensing humidity

Solar – Thermal – Humidity Cycle
Solar – Thermal – Humidity/Freeze Cycle

Arizona solar tracking including peak summer

1-year solar tracking South Florida & Arizona

Total test program duration: 12 months
## UV/Corrosion/Moisture Stress

<table>
<thead>
<tr>
<th></th>
<th><strong>Arid Desert</strong></th>
<th><strong>Tropical / Subtropical</strong></th>
<th><strong>Northern Temperate</strong></th>
<th><strong>“Global”</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Corrosion</strong></td>
<td>N/A (optional)</td>
<td>ISO 9227, ASTM B117 200 hours; 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour &quot;Neutral Salt Spray Test&quot;</td>
<td>ISO 9227, ASTM B117 400 hours; 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour &quot;Neutral Salt Spray Test&quot;</td>
<td>ISO 9227, ASTM B117 400 hours; 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour &quot;Neutral Salt Spray Test&quot;</td>
</tr>
<tr>
<td><strong>Condensing Humidity</strong></td>
<td>ASTM D2247, 125 hours @38°C or ISO 6270 40 °C</td>
<td>ASTM D2247, 125 hours @38°C or ISO 6270 40 °C</td>
<td>ASTM D2247, 125 hours @38°C or ISO 6270 40 °C</td>
<td>ASTM D2247, 125 hours @38°C or ISO 6270 40 °C</td>
</tr>
<tr>
<td><strong>UV Preconditioning</strong></td>
<td>IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB</td>
<td>IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB</td>
<td>IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB</td>
<td>IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB</td>
</tr>
</tbody>
</table>
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
PV and service environment
# Solar/Environment chamber

<table>
<thead>
<tr>
<th>Solar/Environment Chamber w/Solar SC 2000 or Environmental Chamber w/Solar</th>
<th>Temperatue-Humidity Cycle with simultaneous Solar</th>
<th>Tropical / Subtropical</th>
<th>Northern Temperate</th>
<th>“Global”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arid Desert</strong></td>
<td>30% 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 9.5 days (158 cycles)</td>
<td>55% RH (turn RH% control off at 40°C) and 65°C → 15 °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)</td>
<td>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)</td>
<td>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)</td>
</tr>
<tr>
<td><strong>Temperature-Humidity Freeze Cycle with Solar</strong></td>
<td>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]</td>
<td>N/A</td>
<td>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]</td>
<td>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]</td>
</tr>
</tbody>
</table>
Cyclic Weathering Stresses

Solar-Temperature-Humidity Cycle

- Dark
- Light 1,000 W/m²

deg C or RH%

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
<th>55</th>
<th>60</th>
<th>65</th>
<th>70</th>
<th>75</th>
<th>80</th>
<th>85</th>
<th>86</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHT deg C</td>
<td>86</td>
<td>66</td>
<td>54</td>
<td>41</td>
<td>27</td>
<td>16</td>
<td>10</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>26</td>
<td>44</td>
<td>58</td>
<td>69</td>
<td>73</td>
<td>77</td>
<td>83</td>
<td>86</td>
</tr>
<tr>
<td>RH%</td>
<td>55</td>
<td>47</td>
<td>54</td>
<td>41</td>
<td>27</td>
<td>16</td>
<td>10</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>26</td>
<td>44</td>
<td>58</td>
<td>69</td>
<td>73</td>
<td>77</td>
<td>83</td>
<td>86</td>
</tr>
<tr>
<td>Panel deg C</td>
<td>86</td>
<td>66</td>
<td>54</td>
<td>41</td>
<td>27</td>
<td>16</td>
<td>10</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>26</td>
<td>44</td>
<td>58</td>
<td>69</td>
<td>73</td>
<td>77</td>
<td>83</td>
<td>86</td>
</tr>
</tbody>
</table>

Time (minutes)
Module temperature tracking

Solar-Temperature-Humidity-Freeze Cycle

<table>
<thead>
<tr>
<th>Time (minutes)</th>
<th>CHT deg C</th>
<th>RH%</th>
<th>Module deg C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>65</td>
<td>55</td>
<td>86</td>
</tr>
<tr>
<td>5</td>
<td>42</td>
<td>17</td>
<td>64</td>
</tr>
<tr>
<td>10</td>
<td>23</td>
<td>20</td>
<td>43</td>
</tr>
<tr>
<td>15</td>
<td>12</td>
<td>34</td>
<td>27</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>41</td>
<td>21</td>
</tr>
<tr>
<td>25</td>
<td>4</td>
<td>49</td>
<td>16</td>
</tr>
<tr>
<td>30</td>
<td>-3</td>
<td>60</td>
<td>6</td>
</tr>
<tr>
<td>35</td>
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</tr>
<tr>
<td>105</td>
<td>68</td>
<td></td>
<td>87</td>
</tr>
</tbody>
</table>
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

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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.
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• 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


Tell us about the module

*Module Manufacturer

*Module Model

Module Serial Number

Module Manufacture Date

Month January Year 2010

*When Was Module Installed

Tell us how it failed

First click on a category, then select the failure type.

Physical Damage (Cracks, Distortions)

- Visual Changes (Color), or corrosion
- Peeling/delamination
- Electrical Damage (Shorts, Burns)
- Performance Degradation
- Unknown/Other

Physical Damage (Cracks, Distortions)

- junction box - cracking
- frame - corrosion
- area between or around cells or active light absorbing film
- backsheet or backing material
- wire leads - cracking insulation
- cells/ light absorbing region
- junction box - separating from module
- mounting bracket
- frame - bending/breaking
- front window
- connector - break/crack
- cells/ metallization
- wire leads - pulling out, weakly held in junction box
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

Terrestrial Photovoltaic Module Accelerated Test-to-Failure Protocol

C.R. Osterwald
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

Qualification Testing of c-Si PV Modules at ASU-PTL

Failure Rate

<table>
<thead>
<tr>
<th>Initial dry highpot</th>
<th>Initial wet resistance</th>
<th>Thermal cycling (200 cycles)</th>
<th>UV test</th>
<th>Thermal cycling (50 cycles)</th>
<th>Humidity Freeze (10 cycles)</th>
<th>Damp heat (1000 hours)</th>
<th>Outdoor</th>
<th>Termination</th>
<th>Hail impact</th>
<th>Static load</th>
<th>Diode</th>
<th>Hotspot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

Courtesy G. TamizhMani et al. TUV-PTL
Distribution of major defects of commercial modules provoked per Qualification Tests performed between 1990 and 2006

<table>
<thead>
<tr>
<th>Type of module failure</th>
<th>Tests type</th>
<th>OE</th>
<th>HSP</th>
<th>UVE</th>
<th>Total irradi. tests</th>
<th>TC50</th>
<th>HUF</th>
<th>TC200</th>
<th>DAH</th>
<th>Total envir. tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules which failed the IEC 61215</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Visual defect</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>3</td>
<td>16</td>
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<tr>
<td>Power loss</td>
<td></td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>7</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Visual defect and power loss</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>5</td>
<td>1</td>
<td>8</td>
</tr>
</tbody>
</table>
Effects of Damp Heat with System Bias

- 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 ingress
- temperature
- Na content in glass
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.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>A. Control</th>
<th>B. Damp Heat with Bias 85°C/85%RH</th>
<th>C. Thermal Cycling with load -40°C/85°C</th>
<th>D. Alternating Seq. B/C DH/TC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
<td>B1</td>
<td>C1</td>
<td>D1</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>B2</td>
<td>C2</td>
<td>D2</td>
</tr>
</tbody>
</table>

**5 kW hrs/m² 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
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

<table>
<thead>
<tr>
<th>Modul e model</th>
<th>Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>– 4 rounds</td>
</tr>
<tr>
<td>2</td>
<td>– 1 round</td>
</tr>
<tr>
<td>3</td>
<td>– 1 round</td>
</tr>
<tr>
<td>4</td>
<td>– 1 round</td>
</tr>
</tbody>
</table>
Performance Results

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

<table>
<thead>
<tr>
<th>Module</th>
<th>Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4 rounds</td>
</tr>
<tr>
<td>2</td>
<td>1 round</td>
</tr>
<tr>
<td>3</td>
<td>1 round</td>
</tr>
<tr>
<td>4</td>
<td>1 round</td>
</tr>
</tbody>
</table>
### Performance Results

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

<table>
<thead>
<tr>
<th>Module</th>
<th>Completed</th>
<th>Model</th>
<th>Rounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 CTRL</td>
<td></td>
<td>1</td>
<td>4 rounds</td>
</tr>
<tr>
<td>A2 CTRL</td>
<td></td>
<td>1</td>
<td>1 round</td>
</tr>
<tr>
<td>B1 DH (+)</td>
<td></td>
<td>1</td>
<td>1 round</td>
</tr>
<tr>
<td>B2 DH (-)</td>
<td></td>
<td>1</td>
<td>1 round</td>
</tr>
<tr>
<td>C1 TC</td>
<td></td>
<td>1</td>
<td>1 round</td>
</tr>
<tr>
<td>C2 TC</td>
<td></td>
<td>1</td>
<td>1 round</td>
</tr>
<tr>
<td>D1 Alt DH (+)</td>
<td></td>
<td>1</td>
<td>1 round</td>
</tr>
<tr>
<td>D2 Alt DH (-)</td>
<td></td>
<td>1</td>
<td>1 round</td>
</tr>
</tbody>
</table>
Performance Results

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

![Graph showing fraction module power remaining for different test sequences and module models. The graph includes data for module sequences 1-4, with completed cycles indicated for each.]
Ag gridline corrosion visible
Series resistance increase according to dark I-V curve fitting

<table>
<thead>
<tr>
<th>$r_s (\Omega \text{ cm}^2)$</th>
<th>0 hrs</th>
<th>1000 Hrs</th>
<th>2000 Hrs</th>
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<tbody>
<tr>
<td></td>
<td>0.83</td>
<td>1.02</td>
<td>1.22</td>
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</table>
Failure analysis, DH (-)

- 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

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

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)
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.

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
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
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
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.

Design for Reliability Process

1. Define Requirements and Use Environment
2. Identify High Risk Areas in Design
3. Analyze Reliability of Proposed Design
4. Test Quantify & Improve Reliability
5. Validate Reliability
6. Control Reliability

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

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

**Life vs Stress**

**Weibull _Shape_ Parameter = \( \beta = 3.4 \)**

**Slope = 5589 = \( \frac{E_a}{k} \)**

**\( E_a = 0.48eV \)**

**Example for Non-Encapsulated Thin Film Cells**

**Time to Failure = Time to 50% Degradation in \( P_{max} \)**
Phase 2 Example: Life vs Humidity Profile

Life vs Stress

T(R=10%)

T(R=90%)

η

Weibull Shape Parameter = β = 3.4
Slope = 21
Equivalent $E_a = 0.0183eV$

Example for Non-Encapsulated Thin Film Cells
Time to Failure = Time to 50% Degradation in Pmax
Phase 2 Example: Unreliability vs Time

Unreliability vs Time

Unreliability Curve Generated for Use
Stress Estimated at Temp = 30C, RH = 50%

Ryan Gaston
The Dow Chemical Company
2/18/2010
12:16:59 AM
Acknowledgements

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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.
Quantifying the Weather: an analysis for thermal fatigue

Nick Bosco and Sarah Kurtz
NREL PV Module Reliability Workshop
February 18-19, 2010
Golden, CO
Problem:

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

- 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?
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?
What is the cell/ module temperature while in service?

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

**Steady State Models**

\[
T_{cell} = T_{amb} + E \exp(a + bW) + ER
\]

\[
T_{cell} = T_{amb} + E \exp(a + bW) + \frac{E}{E_o} \Delta T
\]


**Non-Steady State Model**

\[
T_{cell}(t+1) = T_{cell}(t) + \frac{dT_{cell}}{dt}
\]

\[
\frac{dT_{cell}}{dt} = f(E, A, \varepsilon, T_{amb}, T_{cell}, h, C_m)
\]

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 the less frequent data.
quantifying the weather: rainflow

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

1. Peak and Valley

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

2. Rainflow count

- 1. maximum temperature $T_{\text{max}}$
- 2. temperature change $\Delta T$
- 3. transition time $t_t$

$S_1 > S_2 \leq S_3$
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

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

\[ c = -0.422 - 6 \cdot 10^{-4} T_{\text{mean}} + 1.74 \cdot 10^{-2} \ln \left( 1 + \frac{360}{t_d} \right) \]

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.
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 were deployed in Golden, CO.
Temperature range output from the rainflow count illustrates the higher number of large temperature ranges experienced in Golden, CO.
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.
If known, can we relate this damage to that incurred during accelerated testing?

<table>
<thead>
<tr>
<th>Standard</th>
<th>Option</th>
<th>$T_{\text{max}}$ °C</th>
<th>$T_{\text{min}}$ °C</th>
<th>$T_d$ min</th>
<th>n</th>
<th>$t_{eq}$ SRRL years</th>
<th>$t_{eq}$ Sanary years</th>
<th>observed years</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC 62108</td>
<td>TCA-1</td>
<td>110</td>
<td>-40</td>
<td>10</td>
<td>500</td>
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<tr>
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<tr>
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<td>TCA-3</td>
<td>65</td>
<td>-40</td>
<td>10</td>
<td>2000</td>
<td>21.8</td>
<td>44.6</td>
<td></td>
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<tr>
<td>IEC 61215</td>
<td></td>
<td>85</td>
<td>-40</td>
<td>10</td>
<td>200</td>
<td>11</td>
<td>10*</td>
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</tr>
</tbody>
</table>

future work

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

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.
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.
• 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”

**Concept / Design**
- Get samples
- Graphics
- Sketches

**Prototype**
- Drawings
- Material bids
- Eng. Build
- Test

**Pre-release**
- Establish BOM’s and Drawings
- Make small runs or lots
- Test, send samples to Labs for Certification

**Production**
- Formal release all drawings, parts, etc.
- Make changes as required
- Achieve certs.
- Qualification / Performance
- Safety
- Sell the stuff
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”
“Consensus Guidelines For Quality Assurance and Their Role as a Foundation for Lifetime Prediction”

&

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
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 materially differ 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.
Big Picture

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

- Focus today is on Manufacturing Quality
- Simple model:

Design $\rightarrow$ Inputs $\rightarrow$ Process $\rightarrow$ Outputs

Supplier Quality Control $\rightarrow$ Statistical Process Control $\rightarrow$ Out-of-box Audit $\rightarrow$ Ongoing Reliability Testing

Manufacturing Quality
**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

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**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

**LEVEL 1 WHAT to CONTROL**

- Identify key variables that have a major impact on the performance of the product, process, or equipment
- Risk/Time-to-Info assessment

**LEVEL 2 HOW to CONTROL**

- Ensure sampling plan adequately monitors risk areas
- Sampling plan that effectively monitors the key variables and thus reduces the risk

**LEVEL 3 ESTABLISH CONTROL**

- Online SPC Charts
- Satisfies capability and capacity requirements

**LEVEL 4 VERIFY CONTROL**

- Charts effectively ID OOC’s / Implement OCAP
- Regular chart review/ Achieve Performance Goals

**LEVEL 5 OWNERSHIP**

- Active RCCA
- Tool Matching

**LEVEL 6 CONTINUOUS IMPROVEMENT**

- Team Full Ownership
- Improvement Targets

*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*
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.
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
SPC Example: getting a process under control

Line 1 Mechanical Yield Loss
(does not include Electrical yield loss)
SunPower Manufacturing Process

>22% Efficiency Solar Cell

Lightly doped front diffusion
- Reduces recombination loss

Texture + ARC

N-TYPE HIGH LIFETIME SILICON
- REDUCES BULK RECOMBINATION

Backside Mirror
- Reduces back light absorption & causes light trapping

Localized Contacts
- Reduces contact recombination loss

Passivating SiO$_2$ layer
- Reduces surface recombination loss

Backside Gridlines
- Eliminates shadowing
- High-coverage metal reduces resistance loss

High-level process flow:

1. Cleaning and Etching
2. Doping and Passivation
3. Metalizing
4. Soldering
5. Laminating and Framing

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SPC Examples: major tests at each step

Cleaning and Etching
Doping and Passivation
Metalizing
Soldering
Laminating and Framing

- Thickness
- Metal contaminants
- Thickness
- Surface recombination velocity
- Bulk Recombination Rate
- Sheet resistance
- All process parameters
- Refractive Index
- $J_0$ (emitter saturation current density)
- Bulk Recombination Rate
- Sheet resistance
- Deposition uniformity and profile
- Breakage and alignment
- All process parameters
- Metal thickness
- All process parameters
SPC Examples: major tests at each step

- Cleaning and Etching
- Doping and Passivation
- Metalizing
- Soldering
- Laminating and Framing

- Visual inspection (cracks, cosmetic criteria)
- Cell efficiency, fill factor, $I_{sc}$, $V_{oc}$, $R_{series}$, $R_{shunt}$
SPC Examples: major tests at each step

- Cleaning and Etching
- Doping and Passivation
- Metalizing
- Soldering
- Laminating and Framing

• Chips and shape
• Substring voltage
• All process parameters
SPC Examples: major tests at each step

- Cleaning and etching
- Doping and Passivation
- Metalizing
- Soldering
- Laminating and Framing

- 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
**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)
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).
Ongoing Reliability Testing

- Autoclave
- Damp Heat, Temp cycle, Humidity-Freeze
- UV Tester

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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
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?
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
• 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.
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])


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

• c-Si: Temperature test – 140 modules (2006-2009)
Qualification Testing of 3169 c-Si Modules at TÜV Rheinland PTL (1997-2009)

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

  - Thermal cycling failure rates: 2007/2005 = increased; 2009/2007 = increased

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

Qualification Testing: c-Si

- Thermal cycling failure rates: 2007/2005 = increased; 2009/2007 = increased

Qualification Testing: Thin-Films

- Static load failure rates: 2007/2005 = decreased; 2009/2007 = increased

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

- $T_{avg-norm-Voc}$: 84°C
- $T_{max-norm-Voc}$: 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 criteria?
  • A: IEC tests performance at STC required there, not full qual test
Degradation Rates ($R_d$) most often reported
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 $\rightarrow$ limited by numbers of degree of freedom $\rightarrow$ need more data points $\rightarrow$ 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 ARIMA 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

Annual Percentage Power Loss of 70 1986 Mobil Solar 30W Modules
(Field Measurements Translated to Equivalent 2010 STC Ratings
Using Recalibrated EKO MP-170 I-V, Irradiance & Temperature Data)

6 catastrophic failures

New Energy Options, Inc.
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: **Microinverter 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
- 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.
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 on 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
• 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 2\textsuperscript{nd} 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 (i.e., glass), substrate (i.e., 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.
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 supposed to have high resistance standoff 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)
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.
Experience with Qualification and Safety Testing of Photovoltaic Modules

Mani G. Tamizh

TUV Rheinland PTL

www.tuvptl.com
Qualification Test Results of PV Modules (IEC 61215/61646)
(3636 modules [87% c-Si]; 20 different countries; 1997-2009 [13 years of data])


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

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])

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

• 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%
Qualification Testing of 1225 c-Si Modules at TÜV Rheinland PTL
Distribution of Failure Criteria (2007-2009)

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%)
Qualification Testing of 467 Thin-Film Modules at TUV Rheinland PTL (1997-2009)

- **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%)
Qualification Testing of 467 Thin-Film Modules at TUV Rheinland PTL (1997-2009)

**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
Qualification Testing of 467 Thin-Film Modules at TÜV Rheinland PTL (1997-2009)

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

  • 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)

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 > \((T_{\text{norm}} + 20°C)\)

\[ T_{\text{norm}} = \left( T_{\text{max}} - \text{Mean } T_{\text{amb}} \right) \times \frac{1000}{\text{Mean Irradiance}} + 40 \]

Where
\( T_{\text{norm}} \) is the normalized temperature, \( T_{\text{max}} \) is the maximum component temperature during the test, and \( T_{\text{amb}} \) is the ambient temperature during the test.
Temperature test - ~140 modules (2006-2009) - Open circuited

Cell Tmax-Normalized (open circuit)

Average = 87°C

Temperature test - ~ 140 modules (2006-2009) - Short circuited

Cell Tmax-Normalized (short circuit)

Average = 89°C
### Summary

#### Qualification Testing: c-Si

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Damp heat failure rates</td>
<td>increased</td>
<td>decreased</td>
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<tr>
<td>Thermal cycling failure rates</td>
<td>increased</td>
<td>increased</td>
</tr>
<tr>
<td>Humidity freeze failure rates</td>
<td>increased</td>
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<tr>
<td>Diode failure rates</td>
<td>increased</td>
<td>decreased</td>
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#### Qualification Testing: Thin-Films

<table>
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<tr>
<td>Static load failure rates</td>
<td>decreased</td>
<td>increased</td>
</tr>
</tbody>
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#### Safety - Temperature Testing: Polymeric Substrate (c-Si)

- \( T_{avg-norm-Voc} \): 84°C
- \( T_{max-norm-Voc} \): 97°C
Degradation Rates

This presentation does not contain any proprietary or confidential information.
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

- Median: 0.6 %/year
- Average: 0.8 %/year
- $N = 370$

Ref

- Perfor & Reliability_Adelstein_NREL_PVSC_2005
- Outdoor testing at ASU_Mani_ASEU_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
- CIS Degradation Rate__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_ASEU_2006
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- 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 year old 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
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- 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 ratingpd_Kimber_PVSC_2009
Historical Degradation Rates

Degradation Rates ($R_d$) most often reported

- Median: 0.6 %/year
- Average: 0.8 %/year
- $N = 370$

Installation
- Pre: before 2000
- Post: after 2000

All technologies show some degradation rates around 0 %/year for modules installed after 2000.
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 $\rightarrow R_d$ looks believable

Uncertainty for Data set(2) large $\rightarrow 2$ different slopes

$Deg.\ Rate(2) = 1.0 \pm 0.2\% / year$

$Deg.\ Rate(1) = 1.0 \pm 1.3\% / year$
Degradation Rate Uncertainty Impact

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

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

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

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%\(\pm\)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

1. PVUSA equation

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

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

2. Sandia Model

3. BEW Model

2. Step
Time series + Linear Fit, Standard Least Squares

\[ P = b + m \cdot t \]

\[ m = \frac{n(\sum P \cdot t) - (\sum P)(\sum t)}{n(\sum t^2) - (\sum t)^2} \]

\[ b = \frac{(\sum P \cdot t^2) - (\sum P)(\sum t)}{n(\sum t^2) - (\sum t)^2} \]

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

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

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

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

Linear Fit using Standard Least Square → Method 1

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
Performance Energy Rating Testbed = PERT

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

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

---

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

\[ P_i = T_i + S_i + E_i \]  Additive Model

Original Data

Seasonality
Average of each month for all years of observation

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

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

\[
(P_t - P_{t-1}) = a_0 P_t + c + e_t
\]

Discrete difference equation

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

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

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

• Regression of it’s lagged self → auto-regression

• Because only 1 time lag is included → AR(1)

• AR(1) subset of larger class of AutoRegressive Integrated Moving Average (ARIMA)
ARIMA + Decomposition

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

Traditional: 1 outlier $\rightarrow R_d$ changed significantly

Class. Decomposition: 1 outlier $\rightarrow R_d$ does not change significantly, 2 outliers $\rightarrow$ significant change

ARIMA+Decomposition: Least sensitive to outliers $\rightarrow$ 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

- Original Data
- c-12-month MA

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

- Original Data
- c-12-month MA
- corrected c-12-Month MA
Data Shift – blind test

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

![Graph showing data set with marked hump in the c-12-Month Moving Average](image1)

- Original Data
- c-12-month MA

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

![Graph showing c-12-Month Moving Average after shift correction](image2)

- Original Data
- c-12-month MA
- corrected c-12-Month MA

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

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

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Degradation Rate (%/year)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLS, all data</td>
<td>0.14</td>
<td>0.13</td>
</tr>
<tr>
<td>SLS, all data Shift-corrected</td>
<td>0.14</td>
<td>0.07</td>
</tr>
<tr>
<td>Class.Decomp. Shift-corrected</td>
<td>0.13</td>
<td>0.07</td>
</tr>
<tr>
<td>ARIMA+Class.Decomp Shift-corrected</td>
<td>0.15</td>
<td>0.04</td>
</tr>
</tbody>
</table>

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

Correction procedure enables to determine degradation rate with small enough uncertainty
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

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 $\rightarrow$ limited by numbers of degree of freedom $\rightarrow$ need more data points $\rightarrow$ 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

New Energy Options, Inc.
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/ft²
- Temp Coefficient of Current $\Delta I / \Delta T = 0.46 mA/ ^\circ C$
- Temp Coefficient of Voltage $\Delta V / \Delta T = -78 mV/ ^\circ C$
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

New Energy Options, Inc.
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)

New Energy Options, Inc.
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

New Energy Options, Inc.
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

New Energy Options, Inc.
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.

New Energy Options, Inc.
Beverly, Massachusetts 100kW PV Array
1980 to 2010

New Energy Options, Inc.
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/m² or greater
- Gardner retested with measurements confirmed with secondary data logger:
  - POA, Tc, Ta, Voc, Isc

New Energy Options, Inc.
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

New Energy Options, Inc.
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

Common anomalous feature
Beverly Massachusetts 30 Year Module History
Annual Percentage Power Loss of 84 Solar Power Corporation G12-361CT Modules

New Energy Options, Inc.
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%

New Energy Options, Inc.
Percentage Power Loss Per Year
Mobil Solar Ra-30-12H Modules

Annual Percentage Power Loss of 70 1986 Mobil Solar 30W Modules
(Field Measurements Translated to Equivalent 2010 STC Ratings
Using EKO MP-170 I-V, Irradiance & Temperature Data)

Negative values indicate an increase in power over original STC rating

6 cases of catastrophic failure

0  2  4  6  8  10  12  14

Number of Modules

-1  0.8  0.6  0.4  0.2  0  0.2  0.4  0.6  0.8  1  More

Annual % Power Loss

New Energy Options, Inc.
Mobil Solar Ra-30-12H Retest
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

EKO measures a nominal 100W/m² below CSI/Licor

New Energy Options, Inc.
Comparison of Cell Temperature: EKO I-V Curve Tracer vs. Campbell/K Thermocouple

EKO measures a nominal 8 °C above CSI/thermocouple
Comparison of Short Circuit Current: EKO I-V Curve Tracer vs. Fluke 83 III

Correlation: 0.899
Comparison of Open Circuit Voltage: EKO I-V Curve Tracer vs. Fluke 83 III

Measured Open Circuit Voltage

Correlation: 0.992
Annual Percentage Power Loss of 70 1986 Mobil Solar 30W Modules
(Field Measurements Translated to Equivalent 2010 STC Ratings
Using Recalibrated EKO MP-170 I-V, Irradiance & Temperature Data)

6 catastrophic failures

New Energy Options, Inc.
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

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President
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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

- 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/m² 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?
Aepy - 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/cm² 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/cm² 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
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
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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

NREL’s Spectral Solar Radiation Data Base

The Solar Energy Research Institute (SEERI)*, Electric Power Research Institute (EPRI), Florida Solar Energy Center (FSEC), and Pacific Gas and Electric Company (PG&E) cooperated to produce a spectral solar radiation data base representing a range of atmospheric conditions (or climates) that is applicable to several different types of solar collectors. Data that are included in the data base were collected at FSEC from October 1986 to April 1988, and at PG&E from April 1987 to April 1988. FSEC operated one SEIRI and one SEIRI spectroradiometer almost daily at Cape Canaveral, which contributed nearly 2000 spectra to the data base. PG&E operated one BERSI spectroradiometer at San Ramon, Calif., as resources permitted contributing nearly 300 spectra to the data base. SEIRI collected about 200 spectra in the Desert/Golden, Colo., area from November 1987 to February 1988 as part of a research project to study urban spectral solar radiation, and added these data to the data base.

*In September 1991 the Solar Energy Research Institute became the National Renewable Energy Laboratory

Spectral Solar Radiation Data Base Documentation, Vol. I

Spectral Solar Radiation Data Base Documentation, Vol. II

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

179,000 Circumsolar profile scans
0.025° steps
11 locations

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

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DIRECT BEAM SOLAR RADIATION FOR CONCENTRATING COLLECTORS (kWh/m²/day), Percentage Uncertainty = 8

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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 |

GNI to DNI Ratio (FP to CX)

Diffuse on Track FP (GNI-DN)
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

DNI/GNI
0.874

DNI/GNI
0.836

GNI model from
NSRDB
Glo, Beam, Diff
with Perez
Anisotropic
model
Example DNI Vs GNI > 800 Wm$^{-2}$

DNI/GNI
0.874

DNI/GNI
0.836
Averages 36 Sites, 30 yr hourly GNI> 800 Wm$^{-2}$

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<td>933.04</td>
<td>72.03</td>
<td>813.77</td>
<td>109.71</td>
<td>1.16</td>
<td>0.13</td>
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<td>-121.5</td>
<td>929.26</td>
<td>69.07</td>
<td>804.46</td>
<td>86.51</td>
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<tr>
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<td>832.80</td>
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<td>0.13</td>
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<tr>
<td>Bakersfield_CA</td>
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<td>-119</td>
<td>935.99</td>
<td>71.93</td>
<td>808.45</td>
<td>90.80</td>
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<td>0.10</td>
<td>47259</td>
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<tr>
<td>Fresno_CA</td>
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<td>-119.8</td>
<td>935.14</td>
<td>71.08</td>
<td>807.41</td>
<td>92.30</td>
<td>1.17</td>
<td>0.12</td>
<td>46850</td>
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<tr>
<td>Kahului_HI</td>
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<td>-156.5</td>
<td>910.09</td>
<td>62.11</td>
<td>802.94</td>
<td>95.05</td>
<td>1.14</td>
<td>0.10</td>
<td>44970</td>
</tr>
<tr>
<td>Wichita_Falls_TX</td>
<td>33.9</td>
<td>-98.5</td>
<td>922.91</td>
<td>68.56</td>
<td>801.22</td>
<td>107.14</td>
<td>1.17</td>
<td>0.13</td>
<td>41522</td>
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<td>Honolulu_HI</td>
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<td>-157.9</td>
<td>905.50</td>
<td>63.44</td>
<td>758.18</td>
<td>105.06</td>
<td>1.21</td>
<td>0.15</td>
<td>36966</td>
</tr>
<tr>
<td>Fort_Worth_TX</td>
<td>32.8</td>
<td>-97.1</td>
<td>926.24</td>
<td>69.38</td>
<td>789.85</td>
<td>120.03</td>
<td>1.20</td>
<td>0.17</td>
<td>39765</td>
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<td>Cheyenne_WY</td>
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<td>-104.8</td>
<td>927.11</td>
<td>71.68</td>
<td>837.23</td>
<td>101.14</td>
<td>1.12</td>
<td>0.10</td>
<td>38131</td>
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<tr>
<td>San_Antonio_TX</td>
<td>29.5</td>
<td>-98.5</td>
<td>926.76</td>
<td>70.33</td>
<td>776.17</td>
<td>127.49</td>
<td>1.22</td>
<td>0.19</td>
<td>37249</td>
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<tr>
<td>Bismarck_ND</td>
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<td>-100.8</td>
<td>914.89</td>
<td>65.22</td>
<td>806.72</td>
<td>96.15</td>
<td>1.15</td>
<td>0.12</td>
<td>31778</td>
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<tr>
<td>Austin_TX</td>
<td>30.3</td>
<td>-97.7</td>
<td>923.59</td>
<td>69.85</td>
<td>786.33</td>
<td>117.60</td>
<td>1.19</td>
<td>0.15</td>
<td>37194</td>
</tr>
<tr>
<td>Lewiston_MT</td>
<td>47</td>
<td>-109.5</td>
<td>911.32</td>
<td>66.28</td>
<td>818.68</td>
<td>93.57</td>
<td>1.12</td>
<td>0.09</td>
<td>27507</td>
</tr>
</tbody>
</table>

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

Mean GNI 939.6 ± 70
Mean DNI 830.6 ± 100
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\(^{-2}\)
### MEASUREMENTS

<table>
<thead>
<tr>
<th>$U_{\text{meas}}$ ($\pm$%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

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

### MODELS

<table>
<thead>
<tr>
<th>Model</th>
<th>$U_{\text{mod}}$ (Glo/Dif RMS)</th>
<th>$U_{\text{bias}}$ (Glo/Dif MBE)</th>
<th>$U_{\text{mod}}$ (Dir RMS)</th>
<th>$U_{\text{bias}}$ (Dir MBE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>METSTAT</td>
<td>8</td>
<td>2</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>SUNY</td>
<td>5</td>
<td>0</td>
<td>14</td>
<td>1</td>
</tr>
</tbody>
</table>

### Uncertainty

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

### U_{\text{add METSTAT}} ($\pm\%$)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Additional Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time shifting</td>
<td>2</td>
</tr>
<tr>
<td>Ground snow cover</td>
<td>5</td>
</tr>
<tr>
<td>High latitude</td>
<td>10</td>
</tr>
</tbody>
</table>

### U_{\text{add Satellite}} ($\pm\%$)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Additional Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short- and med-term filling</td>
<td>4</td>
</tr>
<tr>
<td>Long-term filling</td>
<td>14</td>
</tr>
<tr>
<td>Cloud probability derivation</td>
<td>4</td>
</tr>
<tr>
<td>Cloud probability nearby site</td>
<td>4</td>
</tr>
<tr>
<td>ASOS-only</td>
<td>22</td>
</tr>
</tbody>
</table>
Sanity Check: Other Methods; Meteonorm

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 $\pm 7.2\%$ error margin, and in 19 locations (3.5% of all stations) the uncertainty is higher than $\pm 10\%$. 
### PV system monitoring vs satellite based solar maps


<table>
<thead>
<tr>
<th>Location</th>
<th>Modeled yield (kWh/kW)</th>
<th>Measured yield (kWh/kW)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borna</td>
<td>928</td>
<td>998</td>
<td>-7.0</td>
</tr>
<tr>
<td>Seifenzersdorf</td>
<td>926</td>
<td>930</td>
<td>-0.4</td>
</tr>
<tr>
<td>Starbach</td>
<td>942</td>
<td>930</td>
<td>1.3</td>
</tr>
<tr>
<td>Hartha</td>
<td>976</td>
<td>957</td>
<td>1.9</td>
</tr>
<tr>
<td>Zwickau</td>
<td>906</td>
<td>957</td>
<td>-5.3</td>
</tr>
<tr>
<td>Plauen</td>
<td>921</td>
<td>850</td>
<td>8.4</td>
</tr>
<tr>
<td>Berzdorf</td>
<td>1040</td>
<td>964</td>
<td>7.9</td>
</tr>
<tr>
<td>Freiberg</td>
<td>906</td>
<td>977</td>
<td>-7.3</td>
</tr>
<tr>
<td>Mittweida</td>
<td>912</td>
<td>958</td>
<td>-4.7</td>
</tr>
<tr>
<td>Dresden</td>
<td>966</td>
<td>989</td>
<td>-2.3</td>
</tr>
</tbody>
</table>

-5 to +8 %
Sample Results: European Benchmarking Satellite vs Ground (IEA Task 36)

<table>
<thead>
<tr>
<th>Station</th>
<th>GHI av [W/m²]</th>
<th>nov</th>
<th>R²</th>
<th>Bias%</th>
<th>RMSD%</th>
<th>KSI%</th>
<th>DNI av [W/m²]</th>
<th>nov</th>
<th>R²</th>
<th>Bias%</th>
<th>RMSD%</th>
<th>KSI%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camborne (BSRN, 2001-2003)</td>
<td>238.5</td>
<td>10815</td>
<td>0.95</td>
<td>-1.01%</td>
<td>29.77%</td>
<td></td>
<td>262.5</td>
<td>7655</td>
<td>0.83</td>
<td>-0.52%</td>
<td>60.98%</td>
<td>0</td>
</tr>
<tr>
<td>Carpentras (BSRN, 2000)</td>
<td>345.8</td>
<td>5618</td>
<td>0.98</td>
<td>2.82%</td>
<td>18.55%</td>
<td></td>
<td>482.4</td>
<td>4779</td>
<td>0.9</td>
<td>2.66%</td>
<td>31.41%</td>
<td>0</td>
</tr>
<tr>
<td>DeAar (BSRN, 2001-2003)</td>
<td>501.5</td>
<td>9168</td>
<td>0.97</td>
<td>3.44%</td>
<td>16.76%</td>
<td></td>
<td>673.9</td>
<td>8469</td>
<td>0.9</td>
<td>0.89%</td>
<td>23.80%</td>
<td>0</td>
</tr>
<tr>
<td>Geneva (IDMP, 2002-2003)</td>
<td>309.9</td>
<td>6560</td>
<td>0.95</td>
<td>7.74%</td>
<td>29.37%</td>
<td></td>
<td>372.9</td>
<td>5384</td>
<td>0.84</td>
<td>7.52%</td>
<td>52.58%</td>
<td>0</td>
</tr>
<tr>
<td>Lerwick (BSRN, 2001-2003)</td>
<td>174.1</td>
<td>12112</td>
<td>0.93</td>
<td>-1.72%</td>
<td>38.64%</td>
<td></td>
<td>187.2</td>
<td>7082</td>
<td>0.68</td>
<td>-9.43%</td>
<td>92.72%</td>
<td>0</td>
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<tr>
<td>Payerne (BSRN, 2000-2003)</td>
<td>383.6</td>
<td>11139</td>
<td>0.96</td>
<td>0.66%</td>
<td>18.84%</td>
<td></td>
<td>428.3</td>
<td>9886</td>
<td>0.87</td>
<td>-3.33%</td>
<td>36.88%</td>
<td>0</td>
</tr>
<tr>
<td>SedeBoqer (BSRN, 2003 - 2005)</td>
<td>561.5</td>
<td>10048</td>
<td>0.98</td>
<td>4.64%</td>
<td>12.96%</td>
<td></td>
<td>607.2</td>
<td>9934</td>
<td>0.78</td>
<td>-2.50%</td>
<td>30.37%</td>
<td>0</td>
</tr>
<tr>
<td>SolarVillage (BSRN, 2000 - 2002)</td>
<td>574</td>
<td>11640</td>
<td>0.98</td>
<td>-0.02%</td>
<td>10.84%</td>
<td></td>
<td>578.1</td>
<td>11418</td>
<td>0.81</td>
<td>-0.37%</td>
<td>31.09%</td>
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</tr>
<tr>
<td>all</td>
<td>387.3</td>
<td>77100</td>
<td>0.97</td>
<td>1.93%</td>
<td>18.79%</td>
<td></td>
<td>467.8</td>
<td>64607</td>
<td>0.87</td>
<td>-0.73%</td>
<td>36.83%</td>
<td>0</td>
</tr>
</tbody>
</table>

### Time scale

<table>
<thead>
<tr>
<th>Time scale</th>
<th>RMSD GHI %</th>
<th>R²</th>
<th>RMSD DNI %</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>hour</td>
<td>18.79%</td>
<td>0.97</td>
<td>36.83%</td>
<td>0.87</td>
</tr>
<tr>
<td>day</td>
<td>11.08%</td>
<td>0.99</td>
<td>23.58%</td>
<td>0.95</td>
</tr>
<tr>
<td>month</td>
<td>4.95%</td>
<td>0.99</td>
<td>9.69%</td>
<td>0.99</td>
</tr>
<tr>
<td>year</td>
<td>3.66%</td>
<td>0.99</td>
<td>4.92%</td>
<td>0.99</td>
</tr>
</tbody>
</table>
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 !!


- 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/m² appropriate compromise with GNI, Flat Plate ~ 1000, and DNI Reference spectrum
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 0.4 cm PWV decreases radiation by 10% while an increase from 0.4 to 4 cm 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:

\[
\text{Rated Efficiency} = a|AM - b|
\]

\[ a = \text{rate efficiency changes with AM, } b = \text{AM at which the efficiency peaks} \]

Example AM correction

<table>
<thead>
<tr>
<th>Module</th>
<th>PVUSA Efficiency</th>
<th>AM Peak</th>
<th>Rate of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.5</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>2.8</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>22.4</td>
<td>2.5</td>
<td>0.95</td>
</tr>
</tbody>
</table>
## PVUSA Ratings for 3 Modules

<table>
<thead>
<tr>
<th>Module #</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power (W)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>69.5</td>
<td>68.2</td>
<td>69.5</td>
<td>71.3</td>
<td>72</td>
<td>72.5</td>
<td>72</td>
<td>69.9</td>
<td>68.7</td>
<td>70.9</td>
<td>67.9</td>
<td><strong>70.2</strong></td>
</tr>
<tr>
<td>%S.E. *</td>
<td>1.90%</td>
<td>3.50%</td>
<td>2.10%</td>
<td>2.40%</td>
<td>2%</td>
<td>1.00%</td>
<td>1.70%</td>
<td>2.80%</td>
<td>4.20%</td>
<td>3.70%</td>
<td>2.20%</td>
<td></td>
</tr>
<tr>
<td># of data</td>
<td>111</td>
<td>339</td>
<td>227</td>
<td>734</td>
<td>466</td>
<td>499</td>
<td>176</td>
<td>932</td>
<td>1156</td>
<td>172</td>
<td>88</td>
<td></td>
</tr>
</tbody>
</table>

| Power (W) |       |       |     |      |      |     |      |     |     |     |     |      |
| 2        |       |       |     |      |      |     |      |     |     |     |     |      |
| %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  |      |     |       |

| Power (W) |       |       |     |      |      |     |      |     |     |     |     |      |
| 3        |       |       |     |      |      |     |      |     |     |     |     |      |
| %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 Module 1
~2.2% difference in energy produced between Module 1 and Module 3
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
Failure Modes of CPV Modules and How to Test for Them

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 $1.25 \times I_{SC}$ 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
Definitions

- Bare Cell or Device
- Receiver (Rx)
- Receiver Assembly
Rx Cross Section

- Ribbon Bonds
- Coverglass
- Silicone
- Cell
- Copper
- Ceramic
- Copper
- Heat Sink
## CPV Module Reliability Issue Matrix

<table>
<thead>
<tr>
<th>Condition</th>
<th>Cell Issue</th>
<th>Receiver Issue</th>
<th>Subassembly Issue</th>
<th>Module Issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damp heat</td>
<td>Cell Corrosion</td>
<td>Electrolytic corrosion</td>
<td>Acrylic Lens Warp</td>
<td></td>
</tr>
<tr>
<td>Wet insulation</td>
<td></td>
<td>Must pass at Rx level for non-hermetic modules</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry Insulation</td>
<td></td>
<td>Melting coverglass</td>
<td>Yellowing of encapsulants</td>
<td>Hard Shorts</td>
</tr>
<tr>
<td>Outdoor Exposure</td>
<td></td>
<td></td>
<td>Rx attach failures</td>
<td></td>
</tr>
<tr>
<td>Damp Freeze</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Thermal Cycle</td>
<td>Thermal Runaway</td>
<td>DBC Conchoidal Fracture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESD</td>
<td>Bare cells vulnerable</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
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.
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
- 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.
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.
HBM ESD Stress Test DIV Curves

- Forward Voltage (V)
- Measured Current Density (A/cm²)

- PRE
- 500V
- 250V
HBM ESD Stress Test DIV Curves

Measured Current Density (A/cm²)

Forward Voltage (V)

- PRE
- 1000V
- 500V
- 250V

1 kV
Typical In-process Pass/Fail Requirement

HBM ESD Stress Test DIV Curves

Measured Current Density (A/cm²)

Forward Voltage (V)

- PRE
- 8000V
- 4000V
- 2000V
- 1000V
- 500V
- 250V
Thermal Runaway
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
The previous slide shows a pair of photographs of the FLIR Thermography setup 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
Power Thermal Cycling
IEC 62108 section 10.6 calls for a periodic forward bias current of $1.25 \times I_{sc}$ 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 $120^\circ C$ above ambient (heat sink).
Coverglass Melting
Coverglass Failures
Cartoon Cross Section of Melted Coverglass

Coverglass
Silicone
Cell
Cartoon Cross Section of Melted Coverglass

Coverglass

Silicone

Cell
Closer Examination of Failures

**Visual**

No apparent damage to cell

**TC EL**

**Xray**

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?
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
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.
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
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

<table>
<thead>
<tr>
<th>Option</th>
<th>Maximum cell temperature °C</th>
<th>Total cycles</th>
<th>Applied current</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCA-1</td>
<td>85</td>
<td>1 000</td>
<td>Apply 1,25xI_{sc} when T&gt;25 °C, Cycle speed is 10 electrical/thermal</td>
</tr>
<tr>
<td>TCA-2</td>
<td>110</td>
<td>500</td>
<td>Apply 1,25xI_{sc} when T&gt;25 °C, Cycle speed is 10 electrical/thermal</td>
</tr>
<tr>
<td>TCA-3</td>
<td>65</td>
<td>2 000</td>
<td>Apply 1,25xI_{sc} when T&gt;25 °C, Cycle speed is 10 electrical/thermal</td>
</tr>
</tbody>
</table>

From text
“A dwell time of at least 10 min within ±3 °C of the high and low temperatures is required. The cycling frequency should be 10 to 18 cycles per day.”
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.
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,
A rainflow count applied to the modeled temperature resulting from current cycling demonstrates no additional damage due to the extra fluctuations in temperature.
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

\[ T_{\text{min}} = -40 \degree C \]
\[ T_{\text{max}} = 110 \degree C \]
\[ t_d = 5 \text{ min} \]
\[ f = 48/\text{day} \]

- Samples consist of ~ 1\( \text{cm}^2 \) multi-junction cell on ~2 x 2 \( \text{cm} \) substrate
- Cell assembly heating is via the application of forward bias current, \( I_{\text{max}} = 3\text{A} \)

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
Additional samples demonstrate increased cracking with cycling, though survive the 4A current ramp.
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/cm² 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 planned

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 presented

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
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
Capture the Power of 3M

Andy Hartzell
3M Renewable Energy Division

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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 Optical Products for the Solar Market
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.
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.
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
Testing Lens Transmission

Typical Application

Diffuse Transmission

Nearly all light that gets through the lens is included in measurement
3M Products for Solar Power Manufacturing

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

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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
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.
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
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.
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?
Definition of Failure – Mechanical Concerns

- Visual Inspection is still needed for anomalies that may lead to failure
  - Crazing
  - Bubbles
  - Warping
  - Delamination

- 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
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.
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 Marriott
2010/02/19  1:20 PM

This presentation does not contain any proprietary or confidential information.
Overview

• Introduction/scope/terminology

• Experiment (@ NREL) vs. literature

• Failure modes
  • Optical durability
  • Mechanical durability
  • Soiling

• Failure mechanisms
  • Photodegradation
  • Thermal decomposition

• Summary
Scope

• Focus: Fresnel lens component in refractive CPV system
• Opto-mechanical component expected to last 30 years
• Direct solar resource (for reference)
  solar disc: $\pm 4.65$ mrad ($\pm 0.27^\circ$)
  circumsolar region: $\pm 50$ mrad ($\pm 2.9^\circ$)
  reference spectrum: ASTM G173 direct

Schematic of representative CPV systems in cross-section
Terminology

Fabrication methods:
- hot-embossing (*low σ*)
- casting
- extruding
- laminating
- compression-molding (*low $\sigma$*)

**Figures of merit**

Not perfectly sharp!

Materials implementation (monolithic vs. composite)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>REPRESENTATIVE VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_f$</td>
<td>0.1-0.5 mm</td>
</tr>
<tr>
<td>$t_s$</td>
<td>2.0-5.4 mm</td>
</tr>
<tr>
<td>$t_t$</td>
<td>2.5-5.5 mm</td>
</tr>
<tr>
<td>$R_p$</td>
<td>2-30 µm</td>
</tr>
<tr>
<td>$R_v$</td>
<td>1-30 µm</td>
</tr>
<tr>
<td>$\theta_f$</td>
<td>1.0-1.6 rad</td>
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<tr>
<td>$\theta_d$</td>
<td>35-52 mrad</td>
</tr>
<tr>
<td>$w_p$</td>
<td>0.01-1.0 mm</td>
</tr>
<tr>
<td>$w_l$</td>
<td>2-30 cm</td>
</tr>
<tr>
<td>$\theta$</td>
<td>±5-150 mrad</td>
</tr>
<tr>
<td>$C$</td>
<td>5-1000</td>
</tr>
<tr>
<td>$f/$</td>
<td>0.5-1.5</td>
</tr>
<tr>
<td>$\eta$</td>
<td>78-86%</td>
</tr>
</tbody>
</table>

Schematic of lens in cross-section

PMMA
- AR, hardcoat

PMMA or PDMS
- anti-reflective (AR) coating

Glass superstrate
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

Test instrument: ATLAS Ci4000 Weather-ometer
(Xenon-arc lamp @ 2.5x UV suns. Chamber @ 60°C/60%RH)

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>SPECIMEN TYPES</th>
</tr>
</thead>
<tbody>
<tr>
<td>stock sheet</td>
<td>11</td>
</tr>
<tr>
<td>linear lens</td>
<td>1</td>
</tr>
<tr>
<td>spot lens</td>
<td>8</td>
</tr>
<tr>
<td>veteran lens</td>
<td>3</td>
</tr>
</tbody>
</table>
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
  - $\geq 8$ acceleration factor
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
Mechanical Durability (Fracture/Toughness)

Unstable crack propagation ($\sigma_f$) 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 = $f[H,E]$); $H = f[\sigma_y]$; $\sigma_y = f[M_w]$

\[ G = \frac{K_{IC}^2}{E} = \frac{\pi a_o Y^2 \sigma_f^2}{E} = 2(\gamma_s + \gamma_p) \]

Fracture mechanics: Griffith representation

Mechanical Durability (Fatigue)

\[ \frac{\partial a}{\partial N} = f[M_w] \]


\[ \frac{\partial a}{\partial N} = C \Delta K^m \]

"Paris law" for crack growth rate

- Steady-state crack propagation modeled by log-linear relationship
- Hysteric heating above ~5 Hz
- Like unstable fracture, M_w & H_2O absorption can be influential
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) $\theta$: 66 $\rightarrow$ 58 $\rightarrow$ 43°

Comparison of transmittance as-received and after cleaning for 19, 8 year old Fresnel lens specimens
### Soiling (Literature Summary)

- Issue of soiling is significant (could compromise $\eta_{\text{module}}$)!
- Data from: Baja Mexico (*ocean & desert*), Europe (Spain & Italy), North & South Africa, Australia, West China might add perspective

<table>
<thead>
<tr>
<th>YEAR</th>
<th>REFERENCE</th>
<th>LOCATION</th>
<th>ENVIRONMENT</th>
<th>SPECIMEN(S) (FIRST SURFACE)</th>
<th>SPECIMEN TYPE</th>
<th>DURATION</th>
<th>↓T, typical (%)</th>
<th>↓T, max (%)</th>
<th>RECOMMENDED CLEANING</th>
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<td>1971</td>
<td>Hamberg []</td>
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<td>glass</td>
<td>mirror</td>
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<td>urban</td>
<td>glass, PV module</td>
<td>mirror</td>
<td>5 years</td>
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<td>Hammond [], []</td>
<td>Phoenix, AZ, USA</td>
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<td>glass, PV module</td>
<td>mirror</td>
<td>3 years</td>
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<td>mirror</td>
<td>3 years</td>
<td>10</td>
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<td>Haebelin []</td>
<td>Burgdorf, Switzerland</td>
<td>urban</td>
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<td>mirror</td>
<td>90</td>
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<td>glass, sheet</td>
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<td>2003</td>
<td>Al-Nashar []</td>
<td>Abu Dhabi, UAE</td>
<td>urban, desert</td>
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<td>mirror</td>
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<td>15</td>
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<tr>
<td>2005</td>
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<td>PMMA</td>
<td>sheet</td>
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<td>11</td>
<td>24</td>
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<td>2006</td>
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<td>mirror</td>
<td>1 year</td>
<td>6</td>
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<td>sheet</td>
<td>20 years</td>
<td>4.5</td>
<td>14</td>
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<td>2008</td>
<td>Vivar []</td>
<td>Madrid, Spain</td>
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<td>CPV module</td>
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<td>PMMA</td>
<td>sheet</td>
<td>1 month</td>
<td>10</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

**Soiling Statistics**

- ↓T, AVG %: 9
- ↓T, ST DEV %: 7
- ↓T, MAX %: 35
- ↓T, AVG %: 34
- ↓T, ST DEV %: 26
- ↓T, MAX %: 100
Soiling (Over Time)

- Asymptotic degradation w/ time
  \[
  \left( \frac{1 - T}{T_{clean}} \right) = d \cdot \text{erf} \left[ d \cdot \omega^3 \right]
  \]
  (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
- Scrapping effect from snow

Subject to tilt angle:
- Horizontal inclination $\Rightarrow$ most soiling; vertical $\Rightarrow$ least soiling
- Relates to accumulation and natural cleaning processes
- Trackers: store them face down overnight
- Uniformity... accumulation at the bottom $\Rightarrow$ partial shading

Soiling (Mechanisms)

CPV environment:
- Great insolation, little precipitation \(\Rightarrow\) more prone to soiling
- Alkaline (desert) vs. acidic (temperate) soils


C: large \(\varnothing\) (<50\(\mu\)m); inert; easily removed by rain
B: fine \(\varnothing\) sediment; scrub to remove
A: ‘cementing’ matter; tenacious (abrasives)

Energetic gradients:
- coarse \(\varnothing\), non-polar organics, low \(\gamma\)
- fine \(\varnothing\), polar inorganics, high \(\gamma\)

Carbonates, sulfates (calcite, gypsum, halite, sylvite)
Salts (external or from glass)
Montmorillonoid clay

Mica, quartz, feldspar
"Cementing" matter; tenacious (abrasives)
Photodegradation

- Random main chain scission by UV (photolysis) \( \Rightarrow M_w \) therefore \( T_g \) reduced
- \( T_g \) reduced \( \downarrow \sim 5^\circ C \) after 18 years outdoors
  
- Likewise affects mechanical durability: \( K_{IC} \downarrow \Rightarrow \sigma_f \downarrow \cdots \partial a/\partial N \uparrow \)

- Many classic studies of quantum yield vs. \( \lambda \), atmosphere
- 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
Thermal Decomposition

- Occurs readily for $T > 200^\circ C$
- Synergistic effect with irradiation (UV) occurs at $T < 200^\circ C$
- Many classic studies of $E_a$ vs. heating rate, atmosphere
  - $O_2$ suppresses decomposition

- Unzipping of main chain in methyl methacrylate (monomer)
- Autocatalytic process (zip length on order of 1000)
- Significant weight loss (vs. minimal in chain scission)

Chain unzipping after Aboulezz and Waters, “Studies on the Photodegradation of Poly(Methyl Methacrylate)”, 1978
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 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
Acknowledgements

- NREL: Daryl Myers, Marc Oddo, Robert Tirawat, Bryan Price, Matt Beach, Christa Loux, Kent Terwilliger


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

• Some useful additional figures...


Particle size for natural cleaning; day only (152) vs. day & night (396 hr)
Roth and Anaya, Trans. ASME, 1980.

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
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.
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
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
Two of Many Designs

Two Fundamental Approaches

- **Refractive:** with lenses
- **Reflective:** with mirrors

Amonix, California

Solar Systems, Australia
Thermal Cycle Test

- Section 10: current cycling in the hi-T parts of thermal cycle test using one of:
  a) Driving the cell to $1.25 \times I_{sc}$ forward current using an external DC source
  b) Illuminating with full intensity light to generate $1.25 \times I_{sc}$
  c) Partial illumination combined with an external drive to generate $1.25 \times I_{sc}$

- 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 $1.25 \times I_{sc}$ 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
Driven $1.25 \cdot I_{sc}$ 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**
- $V_{oc} = \sim 1\text{V}$
- $I_{sc} = 6\text{A (150cm}^2\text{ cell)}$
- $J_{sc} = 40\text{mA/cm}^2$
- $P = 40\text{mW/cm}^2$
- $P = 6\text{W}$
- $1.25 \cdot J_{sc} = 50\text{mA/cm}^2$
- Monolithic

**III-V HCPV Cell**
- $V_{oc} = \sim 3\text{V}$
- $I_{sc} = 6\text{A (1cm}^2\text{ cell)}$
- $J_{sc} = 6\text{A/cm}^2$
- $P = 17\text{W/cm}^2$
- $P = 17\text{W}$
- $1.25 \cdot J_{sc} = 7.6\text{A/cm}^2$
- Epitaxial Construction
DIV vs LIV Stress

- Any small defects under the buss bar concentrate forward current
- Thermal run-away results
Currents as low as...

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 ...
### 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.
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
Other Possible Revisions

- Thermal Cycling:
  - Probably cycles too slowly
  - 18 cycles/day => ~5°C/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
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
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.
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

[Images showing EL Image, Metallic corrosion (in this case yellowing), and Edge seal de-adhesion]
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…

![Image of EL after 2500 hrs Damp Heat Exposure]

No edge-seal

![Graph of Damp Heat - No Edge Seal]

![Graph showing Relative Efficiency vs Hours Exposure]

Whitfield summary
Life vs. Barrier: ITO-ECA$_0$

Need ~ $4 \times 10^{-5}$ g/m$^2$/day package ~ 20 yr life

WVTR (g/m$^2$/day)

Life yrs (20% degrade)

- Miami
- San Francisco
- Golden CO
- Phoenix
Conclusions, Plans & Acknowledgements

Conclusions
• AZO vs ITO CIGS degradation kinetics quantified – 25X
• Life model and accelerated test scaling developed
• Diffusion-controlled: Life \( \sim (t_c/R_D)^{1/2} \) or \( \sim (\text{diffusion-time}\times\text{degrade-time})^{1/2} \)
• 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.
■ 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
Common Failure Modes for Thin-Film Modules and Considerations Toward Hardening CIGS Cells to Moisture

A “Suggested” Topic

Kent Whitfield, Dir. Reliability
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
- Do I have a bias?
- How objective can I really be?
- How current is my information?
- Am I aiming at a particular manufacturer?
- Am I interested in casting a dark shadow on the thin-film industry?

#### RISK/EVIDENCE
- **High/Obvious**
  - Have participated in all sides on this issue.
- **Medium**
  - Have participated in all sides on this issue.
- **Fairly Low Risk**
  - Attempt to stay on top of voluminous data on the subject.
- **Low**
  - No manufacturer has zero failure modes. The outcome is dictated 100% by their response to a finding.
- **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
### 2002

<table>
<thead>
<tr>
<th></th>
<th>Thin-Film (Glass Substrate)</th>
<th>Crystalline Technologies</th>
<th>Approx. Sys. Cost Impact to Thin-Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Module Power (to Edge)</td>
<td>4 to 7.5 W/Ft²</td>
<td>10 to 15 W/Ft²</td>
<td>$0.30/W - $1.25/W</td>
</tr>
<tr>
<td>2 Mechanical Strength</td>
<td>Annealed/Heat Strengthened</td>
<td>Tempered (5 to 10X stronger)</td>
<td>$0.06/W - $0.30/W</td>
</tr>
<tr>
<td>3 Lamination QA/QC</td>
<td>Poor</td>
<td>Good</td>
<td>Included in #2</td>
</tr>
<tr>
<td>4 Module O.C. Voltage</td>
<td>45V to 100V typ.</td>
<td>20V to 50V typ.</td>
<td>$0.03/W - $0.33/W</td>
</tr>
<tr>
<td>5 Typical ‘String’ Power</td>
<td>200W to 750W</td>
<td>1500W to 3000W</td>
<td>Included in #4</td>
</tr>
<tr>
<td>6 Stability</td>
<td>Poor</td>
<td>Good (Not Great)</td>
<td>$0.30/W - $0.60/W</td>
</tr>
<tr>
<td>7 Voltage Isolation</td>
<td>Intermittent</td>
<td>Excellent</td>
<td>Included in #6</td>
</tr>
<tr>
<td>8 Module Design Flex.</td>
<td>Poor</td>
<td>Excellent</td>
<td>Not quantified</td>
</tr>
<tr>
<td>9 Blocking Diode Req’d</td>
<td>Yes</td>
<td>No</td>
<td>$0.02/W - $0.05/W</td>
</tr>
<tr>
<td>10 Opaque to UV?</td>
<td>No</td>
<td>Yes</td>
<td>$0.00/W - $0.10/W</td>
</tr>
<tr>
<td>11 End of Life Recycle?</td>
<td>Some</td>
<td>No</td>
<td>$0.00/W - $0.20/W</td>
</tr>
</tbody>
</table>

**Avg cost impact:** $1.77/W  **TOTAL:** $0.71/W - $2.83/W


**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

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.

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.

McMahon, 2004

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?

Failure analysis of design qualification testing: 2007 vs. 2005

G. Tamez-Mani, B. Li, T. Arends, J. Knüche, 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.

Crystalline Si - Courtesy of Werner Herrmann

#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.
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.
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

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 85°C and 0% RH.

M. Kempe, K Terwilliger, D Tarrant 2008

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…

![Image of EL after 2500 hrs Damp Heat Exposure]

![Graph of Damp Heat - No Edge Seal]

No edge-seal
References

Packaging Requirements for ITO-Hardened CIGS

Dennis Coyle, Holly Blaydes, James Pickett, Todd Tolliver, Ri-An Zhao, and James Gardner

GE Global Research
Niskayuna, NY, 12309

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

\[ R_{\text{Deg}} = k_0 e^{-\left(\frac{-E_{a,\text{deg}}}{RT}\right)} \left[ \frac{RH_{\text{cell}}}{1 - RH_{\text{cell}} + \varepsilon} \right] \]

CIGS Degradation - AZO vs ITO

- AZO ~ 25X ITO
- Comparable to published data
Arrhenius Plot
Package Diffusion Model

Mass Balance, Interfacial Equilibrium, Fickian Diffusion, $D_{\text{barrier}} \ll D_{\text{encapsulant}}$

\[
\frac{\partial C_E}{\partial t} = \frac{S_E RH - C_E}{t_c}
\]

\[
t_c = \frac{L_E S_E}{WVTR_{\text{max}}}
\]

If initially dry:

\[
\frac{C_E}{S_E} = RH \left[ 1 - e^{-t/t_c} \right]
\]

→ Integrate moisture ingress with hourly weather data (TMY3)

Plastic Package (No Barrier)  \( \text{WVTR} = 10^0 \text{ g/m}^2/\text{day} \)

- Package equilibrates \( \sim t_{1/2} = 0.7 \) days
- PV degrades \( \sim 1 \) year
Barrier Package

WVTR = $10^{-4}$ g/m²/day

- Package equilibrates ~ $t_{1/2} = 20$ yrs
- Module Degrades < 13 yrs
Life vs. Barrier: ITO-ECA$_0$

Need $\sim 4 \times 10^{-5}$ g/m$^2$/day package $\sim 20$ 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

<table>
<thead>
<tr>
<th></th>
<th>Calc $P_{\text{max}}$ change</th>
<th>Measured $P_{\text{max}}$ change</th>
<th>Roc change</th>
<th>$P_{\text{max}}$ change shunted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phoenix ECA$_1$</td>
<td>-0.1%</td>
<td>-1% + -2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miami ECA$_1$</td>
<td>-0.5%</td>
<td>-1% + -2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miami ECA$_0$</td>
<td>-4.1%</td>
<td>-5% + -2%</td>
<td>29% + -7%</td>
<td>-30% + -5%</td>
</tr>
</tbody>
</table>

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

Damage after damp heat stress

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

Shunting

No Shunting

400x
Conclusions

• AZO vs ITO CIGS degradation kinetics quantified – 25X
• Life model and accelerated test scaling developed
• Diffusion-controlled: Life $\sim (t_c/R_D)^{1/2}$ or $\sim (\text{diffusion-time} \times \text{degrade-time})^{1/2}$
• Significant moisture barriers required for 20 yr life – even for ITO
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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
Methods for Measuring Moisture Ingress

Arrelaine Dameron, Mathew Reese, Thomas Moricone, & Michael Kempe

This presentation does not contain any proprietary or confidential information.
Moisture Barrier Requirements

Next generation PV will require barriers with WVTR $< 1 \times 10^{-6}$ g/m$^2$/day using materials with low defect density; Diffusivity $< 1 \times 10^{-18}$ 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

How much water?

WVTR = 1 g/m²/day
  In a day:
    \( X = \sim 1 \text{ µm} \)
  In 20 years:
    \( X = \sim 7.3 \text{ mm} \)
    \( \sim 7.3 \text{ L collected} \)

WVTR = \( 1 \times 10^{-4} \text{ g/m²/day} \)
  In 20 years:
    \( X = \sim 1 \text{ µm} \)
    \( \sim 7.3 \text{ mL collected} \)

WVTR = \( 1 \times 10^{-6} \text{ g/m²/day} \)
  In 20 years:
    \( X = \sim 10 \text{ nm} \)
    \( \sim 7.3 \text{ µL collected} \)
Entry Points

Transparent Top Layer (Environmental Protection)

Encapsulant

Photovoltaics

Back Sheet (Environmental Protection/Mechanical Support)

Edge Seal

Glass

Dessicant

Filled Polyisobutylene

H₂O

EVA

Glass/Metal

J-box

How?
Diffusion

\[ \frac{\partial C}{\partial t} = -\nabla J = \nabla (D \nabla C) \]

Assume Fickian: material has no dependence on concentration

\[ J = -D \nabla C \]

Concentration Gradient

Diffusivity

Permeate Flux
WVTR, Permeability, Diffusivity and Solubility

\[ WVTR(t) = \frac{DC_s}{l} \left[ 1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp \left( -\frac{Dn^2 \pi^2 t}{l^2} \right) \right] \]

\[ Q(t) = \int_0^t WVTR(t) \, dt = \frac{DC_s}{l} t - \frac{lC_s}{6} - \frac{2lC_s}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \exp \left( -\frac{Dn^2 \pi^2 t}{l^2} \right) \]

\[ P = \frac{|Q|}{At \Delta p} = DS \]

**Key Terms**
- WVTR: Water Vapour Transmission Rate
- Permeability
- Diffusivity
- Solubility
- Thickness
- Area
- Partial Pressure
- Damation
WVTR and Q

EVA Transient Permeation (85°C, 2.84 mm thick)

- \( t_{b(5\%)} = \frac{l^2}{18.3D} \) (12 min)
- \( t_{lag} = \frac{l^2}{6D} \) (37 min)
# Barrier Testing Method Types

## Scavenger Methods
A material that reacts with or absorbs water is used for quantification.

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium Test</td>
<td>Water is directly quantified as Q(t)</td>
</tr>
<tr>
<td>Radioactive Tracer Test</td>
<td></td>
</tr>
<tr>
<td>Gravimetric Cup test</td>
<td></td>
</tr>
</tbody>
</table>

## Diffusion Cell Methods
Water is directly quantified as WVTR(t).

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isostatic Test (MOCON)</td>
<td></td>
</tr>
<tr>
<td>Radioactive Tracer Test</td>
<td></td>
</tr>
<tr>
<td>Mass Spectrometry</td>
<td></td>
</tr>
</tbody>
</table>
Gravimetric Cup Test

Standard: ASTM E96

Measurement:

\[ \frac{\partial m}{\partial t} \Rightarrow WVTR(t) \]

(assuming constant WVTR for \(\Delta t\))

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:
\[
A_{\lambda}(t) \Rightarrow [H_2O]_{test}(t)
\]

\[
\frac{[H_2O]_{test}(t)}{[H_2O]_{standard}(t)} \Rightarrow WVTR_{test}(t)
\]

Coulometric:

\[
\Delta R(t) \Rightarrow \Delta molH_2O(t) \Rightarrow WVTR(t)
\]

Sensitivity Limits:
100 g/m²/day – 5×10⁻⁴ g/m²/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:

\[ A_\lambda(t) \rightarrow molCa(t) \]
\[ molH_2O(t) \rightarrow WVTR(t) \]

Sensitivity Limits:

1×10^{-2} \text{ g/m}^2\text{/day} – 1×10^{-6} \text{ g/m}^2\text{/day}

Pros: sensitivity; visual evaluation

Cons: cost

Electrical Ca Test

Standard: None

Measurement:

\[ R(t) \Rightarrow \text{molCa}(t) \Rightarrow \text{molH}_2\text{O}(t) \Rightarrow \text{WVTR}(t) \]

Sensitivity Limits:

1 g/m²/day – 1×10⁻⁶ g/m²/day

Pros: sensitivity; throughput; controlled temp/humidity

Cons: cost

Ca + H₂O \rightarrow \text{CaO} + H₂
Ca + 2H₂O \rightarrow \text{Ca(OH)}₂ + H₂

Mass Spectrometry

Standard: None

Measurement:

$$\frac{\partial P_{H_2O}}{\partial t} \Rightarrow molH_2O(t) \Rightarrow WVTR(t)$$

Sensitivity Limits:

$$1 \text{ g/m}^2/\text{day} - 1 \times 10^{-7} \text{ g/m}^2/\text{day}$$

Pros: sensitivity

Cons: cost; throughput; limited temp/humidity

Mass Spectrometry

Standard: None

Measurement:

\[ \frac{\partial P_{H_2O}}{\partial t} \Rightarrow molH_2O(t) \Rightarrow WVTR \]

Sensitivity Limits:
1 g/m²/day – 1×10⁻⁷ g/m²/day

Pros: sensitivity, multiple permeates simultaneously

Cons: cost; throughput; limited temp/humidity
Radioactive Tracer

Standard: None
Measurement:
Ionization: \( i(t) \Rightarrow molT(t) \Rightarrow molH_2O(t) \Rightarrow WVTR \)
Scintillation: \( I(t) \Rightarrow molT(t) \Rightarrow molH_2O(t) \Rightarrow WVTR \)

Sensitivity Limits:
1 g/m²/day – 1\( \times \)10⁻⁶ g/m²/day

Pros: sensitivity; throughput
Cons: radioactivity; 100% RH

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:
\(~1 \times 10^{-7} \text{ g/m}^2\text{/day}\)
Current Experimental:
\(~1 \times 10^{-5} \text{ g/m}^2\text{/day}\)

Can measure WVTR @
\(~1 \times 10^{-5} \text{ g/m}^2\text{/day}\) 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
Example: 70 nm IZO on PEN 40C/85%RH

<table>
<thead>
<tr>
<th></th>
<th>Lag (hr)</th>
<th>WVTR (g/m2/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin Line</td>
<td>3.84</td>
<td>6.958e-02</td>
</tr>
<tr>
<td>Thick Line</td>
<td>4.29</td>
<td>7.330e-02</td>
</tr>
<tr>
<td>Medium Line</td>
<td>4.15</td>
<td>7.410e-02</td>
</tr>
<tr>
<td>Average</td>
<td>4.09</td>
<td>7.233e-02</td>
</tr>
</tbody>
</table>
**Edge Seal Testing**

Using the Ca Test concept as an effective means of evaluating edge seal materials similar to applied environment.

\[ X = K \sqrt{t} \]

- Glass
- 100nm Ca
- Edge Seal
- Glass

Ca turns transparent appearing to shrink toward center.

- PDMS
- 85°C/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

Glass

100nm Ca

Edge Seal

Glass

A. A. Dameron

National Renewable Energy Laboratory

Innovation for Our Energy Future
Ionomer

3 h

162 h

652 h

Glass

100nm Ca

Edge Seal

Glass

A. A. Dameron
Relative Comparison of Materials

- PDMS #2 (0.60)
- EVA (0.33)
- PVB (0.25)
- TPU (0.23)
- Ionomer (0.067)
- PIB #1 (0.024)
- PIB #2 (0.018)

Typical Edge Seal Width

85°C/85% RH Exposure Time (h)
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.
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
Motivation for Thin Film Barrier Development

- Displays
- Solid State Lighting
- 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
Encapsulaiton Performance Needs

OTR [cm³/m²/day/atm] vs. WVTR [g/m²/day]

- Commercial polymer (PET, PEN)
- Food / Pharmaceutical packaging
- Inorganic/metal coated polymers
- Ultra high Barrier Films
- Single Layer and Multilayer Films
- Polymer films
- Food packaging
- Organic electronics

Encapsulation Structures

+ : 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

Critical thickness

Voids

Grain boundary

Channel
High Quality Single Layer Encapsulation: Al$_2$O$_3$

High density, pinhole free, conformal deposition

Permeation governed by nanoscale defects vs macrodefects.

Structure: PEN/ Al$_2$O$_3$

Deposition: ALD

WVTR \([\text{g/m}^2/\text{day}]\): \(1.7 \times 10^{-5}\)

Test condition: 38°C and 85% R.H.


### Multilayer Encapsulation

<table>
<thead>
<tr>
<th>Structure</th>
<th>Al₂O₃/ Polyacrylate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition</td>
<td>DC Sputtering, Evaporation/ UV curing</td>
</tr>
<tr>
<td>WVTR [g/m²/day]</td>
<td>Maximum: 2.1x10⁻⁶</td>
</tr>
<tr>
<td>Test condition</td>
<td>20°C, 50% R.H.</td>
</tr>
</tbody>
</table>


**Thin Film Encapsulation Methods**

**Graded organic and inorganic layer (GE, Shaepkens, et al., JVST 2004)**

- Structure: SiOxNy/ SiOxCy
- Deposition: PECVD
- WVTR [g/m²/day]: \(5 \times 10^{-5} \sim 5 \times 10^{-6}\)
- Test condition: 23°C, 50% R.H. for 20 days


- Structure: 3 pairs SiOx/SiNx/ + Parylene + 3 pairs SiOx/ SiNx
- Deposition: PECVD, PVD
- WVTR [g/m²/day]: Maximum: \(2.5 \times 10^{-7}\)
- Test condition: 23°C and 40% R.H. for 75 days
Processing of Barrier Films

Materials Used

PECVD: SiO\textsubscript{x}, SiN\textsubscript{x}
PVD: Parylene
ALD: Al\textsubscript{2}O\textsubscript{3}

Measured by Ca Corrosion Method at 50 % R.H. and 20 °C
Ca Corrosion Tests

\[
WVTR \left[ \frac{g}{m^2 / day} \right] = 2\delta_{Ca} \times \rho_{Ca} \times \frac{dG_s}{dt} \times \frac{M(H_2O)}{M(Ca)} \times \frac{Ca\_Area}{Window\_Area}
\]

\[
\begin{align*}
\rho_{Ca} & = 1.55 \text{ g/cm}^3 \\
\delta_{Ca} & = 3.4 \times 10^{-6} \text{ cm } \Omega
\end{align*}
\]

G_s = \frac{1}{R_s} = (W/L) \times (1/R)

L : Length of Ca  \\
W : Width of Ca

M(H_2O) 18 \text{ amu}  \\
M(Ca) 40.1 \text{ amu}

**Multilayer Results**

![Graph showing WVTR vs Number of layer (pair)]

### Requirement for 10,000 h lifetime of OLED

<table>
<thead>
<tr>
<th>No. of Layers [pairs]</th>
<th>WVTR [g/m²/day] Before annealing</th>
<th>WVTR [g/m²/day] After annealing</th>
<th>Decrease in WVTR [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$4.3 \times 10^{-3}$</td>
<td>$2.4 \times 10^{-3}$</td>
<td>44</td>
</tr>
<tr>
<td>2</td>
<td>$4.4 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-4}$</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$7.3 \times 10^{-6}$</td>
<td>94</td>
</tr>
<tr>
<td>4</td>
<td>$4.4 \times 10^{-5}$</td>
<td>$6.6 \times 10^{-6}$</td>
<td>85</td>
</tr>
</tbody>
</table>

SiOx/ Parylene (3 pairs)

$8.4 \times 10^{-4}$ $\rightarrow$ $6.6 \times 10^{-5}$ (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 the film

Driving force

\[ J = -D \left( \frac{\partial c}{\partial x} \right) \quad \text{Fick's first Law} \]
\[ \rightarrow c = Sp \quad \text{Henry's Law} \]

\[ J = DS \frac{\Delta p}{l} \]

- \( J \): Flux of permeant
- \( \partial c / \partial x \): concentration gradient
- \( p \): Partial pressure of permeant
Mass Transport in Barrier Films

Diffusion in multilayer structure

For inorganic layers, use effective permeability

WVTR calculation

Lag time calculation

\[ L = \left( \sum_{i=1}^{n} \frac{L_i}{D_i} \prod_{j=1}^{i-1} k_j \right)^{-1} \sum_{i=1}^{n} \left\{ \frac{L_i^2}{2D_i} \sum_{j=1}^{i-1} \frac{L_m^2}{D_m} \prod_{j=1}^{i-1} k_j \right\} - \frac{L_i^3}{3D_i^2} \prod_{j=1}^{i-1} k_j + \sum_{i=1}^{n} \left( \prod_{j=1}^{i-1} k_j \sum_{\beta=i+1}^{n} \frac{L_\beta}{D_\beta} \sum_{m=\beta}^{n} \left( \prod_{j=1}^{m-1} k_j \right) \frac{L_m^{m-1}}{D_m} \prod_{j=1}^{m-1} k_j \right) - \frac{L_\beta^2}{2D_\beta} \prod_{j=1}^{m-1} k_j \]

where, \( k_j = \frac{k_j}{k_{j+1}} \)
We have seen lag times greater than 1000 hours in our films. Impacts the WVTR measured.

Lag Time: 1300 hours

Transient WVTR: $8 \times 10^{-6}$ g/m$^2$/day

Steady State: $2 \times 10^{-3}$ g/m$^2$/day

(Data not obtained from graph on left)
\[ \frac{M_t}{M_\infty} = \frac{2}{L} \left( \frac{D t}{\pi} \right)^{1/2} \]

- **M**: Mass uptake
- **D**: Diffusion coefficient
- **L**: Thickness of film

Solution to Fick’s 2\textsuperscript{nd} law for short times (Valid only \(M_t/M_\infty < 0.6\))
Diffusion Coefficient and Solubility

**Diffusion Coefficient (cm²/s )**

<table>
<thead>
<tr>
<th>Test #</th>
<th>Before Anneal</th>
<th>After Anneal for 10 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>3.27 × 10⁻⁹</td>
<td>2.06 × 10⁻⁹</td>
</tr>
<tr>
<td>STDV</td>
<td>4.29 × 10⁻⁹</td>
<td>1.01 × 10⁻¹⁰</td>
</tr>
</tbody>
</table>

**Solubility coefficient measurement**

\[
S = \frac{M_\infty}{M_0} \cdot \rho_{\text{polymer}} \times \frac{22,414}{p} \quad \text{where} \quad M_\infty : \text{Equilibrium mass uptake} \\
M_0 : \text{Mass of the water –free polymer} \\
MW_{\text{penetrant}} : \text{molecular weight (g/mole)} \\
p : \text{Vapor pressure [atm]} \\
22,241 : \text{Conversion from moles to cm}^3(\text{STP})
\]

**Solubility (g/cm³atm)**

<table>
<thead>
<tr>
<th>Test #</th>
<th>Before Anneal</th>
<th>After Anneal for 10 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.286</td>
<td>0.140</td>
</tr>
<tr>
<td>STDV</td>
<td>0.054</td>
<td>0.044</td>
</tr>
</tbody>
</table>

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.
### Comparison of Results

<table>
<thead>
<tr>
<th>Multilayer Film</th>
<th>WVTR (g/m²/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 dyads of SiOx/Parylene</td>
<td>6 ± 2 x 10⁻⁵</td>
</tr>
<tr>
<td>3 dyads of SiNx/Parylene</td>
<td>7 ± 2 x 10⁻⁶</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hybrid Architecture</th>
<th>WVTR (g/m²/day)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiOx/Al₂O₃/Parylene</td>
<td>2 ± 1 x 10⁻⁵</td>
</tr>
<tr>
<td>SiNx/Al₂O₃/Parylene</td>
<td>3 ± 2 x 10⁻⁵</td>
</tr>
</tbody>
</table>

*Films contain 50 nm of Al₂O₃
**Al₂O₃ layer 3 x 10⁻⁴ g/m²/day

### Reducing ALD thickness: minimal impact!!!

Al₂O₃ thickness: 10 nm
SiOₓ/Al₂O₃/Parylene: 4 ± 0.5 x 10⁻⁵ g/m²/day

### Coated PET Substrate

Al₂O₃ thickness: 50 nm
SiOₓ/Al₂O₃/Parylene: 2.5 ± 1.5 x 10⁻⁵ g/m²/day
Integration with OPVs

Device fabrication and encapsulation

ITO/ Pentacene (50 nm)/ C$_{60}$ (45nm)/ BCP (8 nm)/ Al


Encapsulation (1~4 pairs of SiNx/ Parylene)

Measurement procedure

Performance measurement → OPVs encapsulation → Performance measurement → Keep in environmental chamber
Process Impact on OPVs

![Graph showing current density vs voltage before and after process impact.]  

<table>
<thead>
<tr>
<th></th>
<th>( V_{oc} ) (V)</th>
<th>( J_{sc} ) (mA/cm²)</th>
<th>FF</th>
<th>( \eta ) (%)</th>
<th>Average (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0.39</td>
<td>12.19</td>
<td>0.54</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>After</td>
<td>0.41</td>
<td>11.40</td>
<td>0.54</td>
<td>3.3</td>
<td>3.3</td>
</tr>
</tbody>
</table>

- Average is based on 12 devices
- Light source: 175W Xenon Lamp
Device Performance Vs. Time

Overall device efficiency (Oriel 91160, AM 1.5G)

- Unencapsulated
- 1 pair SiN/Par.
- 2 pairs SiN/Par.
- 3 pairs SiN/Par.

- Normalized overall efficiency
- Time (h)

- (7.3x10^-6 [g/m²/day])
- (1.3x10^-4 [g/m²/day])
- (2.4x10^-3 [g/m²/day])
Hybrid Encapsulation Architecture

Overall device efficiency (Oriel 91160, AM 1.5G)

Excellent performance for simple architecture. \((\text{WVTR} \approx 10^{-5})\).

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.

Barrier Performance under Bending

Results

WVTR (g/m²/day)

Radius of Curvature (mm)

SiOx/parylene
SINx/parylene

Non-uniform oxidation

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.

\[ \varepsilon_z = \left( \frac{Z - Z_n}{R} \right) \]

\[ Y_1d_1^2 = Y_2d_2^2 \]
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.

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)
Technology Specific Issues
Packaging Session
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 have 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: [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.
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)
- Fractographies 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.
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.
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

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**
- **Benzotriazole (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**


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.

### EVA Has Good Optical Transmittance

<table>
<thead>
<tr>
<th>Encapsulant</th>
<th>Transmission to Cells through 3.18 mm glass and 0.45 mm Encapsulant</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentive RTV615</td>
<td>94.5 ± 0.3</td>
<td>PDMS, Addition Cure</td>
</tr>
<tr>
<td>Dow Corning Sylgard 184</td>
<td>94.4 ± 0.3</td>
<td>PDMS, Addition Cure</td>
</tr>
<tr>
<td>Dow Corning 527</td>
<td>94.4 ± 0.3</td>
<td>PDMS, Addition Cure</td>
</tr>
<tr>
<td>Polyvinyl Butyral</td>
<td>93.9 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>EVA</td>
<td>93.9 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>NREL Experimental</td>
<td>93.4 ± 0.4</td>
<td>Poly-α-olefin</td>
</tr>
<tr>
<td>Thermoplastic Polyurethane</td>
<td>93.3 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>Thermoplastic Ionomer #1</td>
<td>92.3 ± 0.4</td>
<td>Copolymer of Ethylene and Methacrylic acid</td>
</tr>
<tr>
<td>Dow Corning 700</td>
<td>91.7 ± 0.3</td>
<td>PDMS, Acetic Acid Condensation Cure</td>
</tr>
<tr>
<td>Thermoplastic Ionomer #2</td>
<td>88.4 ± 0.4</td>
<td>Copolymer of Ethylene and Methacrylic acid</td>
</tr>
</tbody>
</table>

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 Conductivity Varies Greatly

Polymer Resistivity

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

Leakage Current Correlates With Performance loss

Figure 8. Power Output Reductions Versus Accumulated Unit Charge Transfer for α-Si Cells

**Backsheets Protect Against Electrical Shock**

![Diagram of a Framed Silicon Wafer Module](image)

- **Cells**
- **Al Frame**

**Materials:**
- **PET**
  - PolyEthylene Terephthalate
  - Provides Electrical insulation.
- **PVF**
  - Poly Vinyl Floride
  - Provides UV stability
**Time Constant for Water Ingress**

$$C(t) = C_0 \left(1 - e^{-\frac{WVTR_{B,Sat} t}{C_{Sat,EVA} l_{EVA}}}ight)$$

$$\tau_{1/2} = 0.693 \frac{C_{Sat,EVA} l_{EVA}}{WVTR_{B,Sat}} = 0.693 \frac{\text{Amount of water EVA can hold}}{\text{Rate of moisture ingress}}$$

- $l_{EVA} = 18$ mil, $T = 27$ °C, $C_{Sat,EVA} = 0.0022$ g/cm³

<table>
<thead>
<tr>
<th>Material</th>
<th>$\tau_{1/2}$ (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVF</td>
<td>0.0741</td>
</tr>
<tr>
<td>ETFE</td>
<td>0.223</td>
</tr>
<tr>
<td>PVF/PET</td>
<td>0.457</td>
</tr>
<tr>
<td>PET</td>
<td>1.78</td>
</tr>
<tr>
<td>PCTFE</td>
<td>6.87</td>
</tr>
</tbody>
</table>

For $\tau_{1/2} = 20$ years need $10^{-4}$ g/m²/day

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

H₂O → Glass → Seal → Encapsulant → Glass

Schematic of Test sample

H₂O → 50 mm → Butyl Rubber (0.3 mm) → Ca (100 nm) → Glass (3.18 mm)

PIB test sample after 3500 h
85°C and 85% RH
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.
Safety Concerns with New PV Polymeric Materials

Tim Zgonena
Underwriters Laboratories Inc (UL)

February 19, 2010
Connector Materials

This passed qualification test.
This is after 8 years operation in AZ
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 cause these ribbons to open or short circuit.
Terrible Tabbing Tether!!!
J-Box Arcing Problems
• 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
<table>
<thead>
<tr>
<th>Hazard</th>
<th>Failure Mechanism</th>
<th>Test</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Shock</td>
<td>Electric strength – dielectric breakdown due to degradation of insulating material</td>
<td>Dielectric Strength</td>
<td>IEC 60243, IEC 60216-5 (thermal aging)</td>
</tr>
<tr>
<td></td>
<td>Voltage tracking – voltage causing a permanent electrically conductive carbon path after application of wet contaminants.</td>
<td>CTI</td>
<td>IEC 60112</td>
</tr>
<tr>
<td></td>
<td>Material electrically conductive</td>
<td>Volume Resistivity</td>
<td>IEC 60167</td>
</tr>
<tr>
<td></td>
<td>Insulation thickness consistency</td>
<td>Partial discharge</td>
<td>IEC 61730-2</td>
</tr>
<tr>
<td></td>
<td>Mechanical protection from tearing</td>
<td>Tensile Strength, Tear Resistance, Cut Test</td>
<td>ISO 527-3, ASTM D1004, IEC 61730-2</td>
</tr>
<tr>
<td></td>
<td>Mechanical protection from punctures due to installation tools</td>
<td>Puncture Properties</td>
<td>ASTM D7192</td>
</tr>
<tr>
<td></td>
<td>Mechanical support of junction box due to movement or stretching of backsheet</td>
<td>Tensile Creep</td>
<td>ISO 899</td>
</tr>
<tr>
<td></td>
<td>Superstrate / Glass movement/creep</td>
<td>Creep/flow test, Dynamic Mechanical Analysis (DMA)</td>
<td>D6382</td>
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<tr>
<td></td>
<td>Substrate / Encapsulant movement from J-box and cable weight</td>
<td></td>
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<tr>
<td></td>
<td>Interfacial Delamination/adhesion</td>
<td>Bond strength, Peel strength, Intra-layer adhesion</td>
<td>SAE Automotive or IEC 60950-1 (2.10.11)</td>
</tr>
<tr>
<td></td>
<td>Common failures include crazing (micro scale) that grow to cracking and mechanical failures.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SEM or TEM optical microscope to view</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water ingress from delamination</td>
<td>Water Absorption</td>
<td>ISO 62</td>
</tr>
<tr>
<td>Flammability</td>
<td>Additional fuel for the fire</td>
<td>Flammability test, Radiant Heat Ignitability (Cone Calorimeter test)</td>
<td>IEC 60695-11-10, ISO 5657</td>
</tr>
<tr>
<td></td>
<td>Insulated or uninsulated wire attaining red heat during a fault causing possible ignition</td>
<td>HWI or Glow Wire</td>
<td>IEC 60695-2-20</td>
</tr>
<tr>
<td></td>
<td>Loose connections and broken leads in the vicinity of the polymer material causing arcing</td>
<td>HAI</td>
<td>IEC 60695-1-1</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Mechanical failure due to degradation of insulating material</td>
<td>Tensile Strength and Tensile Elongation</td>
<td>ISO 527-3, IEC 60216-5 (thermal aging)</td>
</tr>
<tr>
<td></td>
<td>Thermal stress due to material expansion</td>
<td>Thermal Expansion (CTE)</td>
<td>ISO 11359-2</td>
</tr>
<tr>
<td></td>
<td>Adhesion to glass and backsheet</td>
<td>Bond strength, Peel strength</td>
<td>SAE Automotive or IEC 60950-1 (2.10.11)</td>
</tr>
<tr>
<td></td>
<td>Inter-layer adhesion of backsheet</td>
<td>Bond strength, Intra-layer adhesion</td>
<td>SAE Automotive or IEC 60950-1 (2.10.11)</td>
</tr>
<tr>
<td></td>
<td>Surface treatment, chemical, corona treatment</td>
<td>Surface finish rating scale for machined metals?</td>
<td>??</td>
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</tr>
</tbody>
</table>
Certification and Performance Certification and the Product Development Cycle

### Performance Certification
- **Pre-design**
- **Design**
- **Prototype**
- **Production**
- **Distribution**
- **Field Products**

- **One time 61215 or 61646 evaluation**
- **Follow Up Not Required**

### Safety Certification
- **Consulting**
- **Preliminary Investigation**
- **Certification**
- **Manufacturing Follow Up Inspection & Testing**
- **Product failure Investigation Field Reports**

Without Follow Up modules, component and materials can change and invalidate performance certification.
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)
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

Compression

Tension
Wallner Lines in 19 mm Glass edge
Surface in Tension
Surface in Compression
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 $\pm \Delta$Pressure in sealed air space.

Max. stress near corners for uniform load
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
Classic Thermal Stress fracture origin. Break typically starts in the central $\frac{3}{4}$ of the edge length and not at a corner.
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.
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 developing 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

<p>| | |</p>
<table>
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</tr>
</tbody>
</table>
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

Hertzian cone formation from tensile zone under contact point
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.
2. Solarization

Some glass compositions show slight yellowing when exposed to strong UV light for extended periods of time.
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:
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?
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.
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
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°C±5°C.

**CV profiling:**
Changes in depletion width and hysteresis with light or thermal anneal. Quantifying 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 preconditioning before measurements recommended.

• Any merit to using biases significantly above $V_{\text{MP}}$ 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
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

Annealing time (minutes)

Normalized efficiency (a.u.)

a-Si:H/a-SiGe:H/a-SiGe:H triple-junction

Annealing temperature: 100 °C
Thick a-Si layer causes more degradation
Approaches for Improving a-Si cells

- 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

<table>
<thead>
<tr>
<th>Hydrogen dilution</th>
<th>$J_{sc}$ (mA/cm²)</th>
<th>$V_{oc}$ (V)</th>
<th>FF</th>
<th>Eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near-optimum</td>
<td>10.04</td>
<td>1.018</td>
<td>0.732</td>
<td>7.48</td>
</tr>
<tr>
<td><strong>Optimum</strong></td>
<td>9.88</td>
<td>1.028</td>
<td>0.761</td>
<td>7.73</td>
</tr>
<tr>
<td>On-the-edge</td>
<td>9.82</td>
<td>0.624</td>
<td>0.426</td>
<td>2.61</td>
</tr>
<tr>
<td>Over-the-edge</td>
<td>8.95</td>
<td>0.459</td>
<td>0.562</td>
<td>2.31</td>
</tr>
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</table>
# Effect of Hydrogen Dilution

<table>
<thead>
<tr>
<th>Description</th>
<th>State</th>
<th>$J_{sc}$ (mA/cm²)</th>
<th>$V_{oc}$ (V)</th>
<th>FF</th>
<th>Eff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-Si, low dilution, 300 °C</td>
<td>Initial</td>
<td>12.3</td>
<td>0.94</td>
<td>0.65</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>11.6</td>
<td>0.91</td>
<td>0.55</td>
<td>5.8</td>
</tr>
<tr>
<td>a-Si, high dilution, 300 °C</td>
<td>Initial</td>
<td>11.6</td>
<td>0.96</td>
<td>0.68</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>11.2</td>
<td>0.94</td>
<td>0.61</td>
<td>6.4</td>
</tr>
<tr>
<td>a-Si, low dilution, 175 °C</td>
<td>Initial</td>
<td>11.4</td>
<td>0.96</td>
<td>0.64</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>9.5</td>
<td>0.91</td>
<td>0.46</td>
<td>4.0</td>
</tr>
<tr>
<td>a-Si, high dilution, 175 °C</td>
<td>Initial</td>
<td>10.9</td>
<td>1.00</td>
<td>0.69</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>10.5</td>
<td>0.97</td>
<td>0.60</td>
<td>6.1</td>
</tr>
<tr>
<td>a-SiGe, low dilution</td>
<td>Initial</td>
<td>17.6</td>
<td>0.72</td>
<td>0.55</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>14.9</td>
<td>0.64</td>
<td>0.41</td>
<td>3.9</td>
</tr>
<tr>
<td>a-SiGe, high dilution</td>
<td>Initial</td>
<td>18.0</td>
<td>0.74</td>
<td>0.59</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>Degraded</td>
<td>16.3</td>
<td>0.69</td>
<td>0.45</td>
<td>5.1</td>
</tr>
</tbody>
</table>
Light Trapping

INCIDENT LIGHT

CELL

BACK REFLECTOR

STAINLESS STEEL
Light Trapping Effect

a-SiGe:H cell on ss, Al/ZnO, & Ag/ZnO

- a-SiGe:H cell on ss, Al/ZnO, & Ag/ZnO
- Light Trapping Effect

![Graph showing QE vs Wavelength (nm) for a-SiGe:H cells on different substrates.](image)

- on SS
- on Al/ZnO
- on Ag/ZnO

- 16.65 mA/cm² on ss
- 19.91 mA/cm² on Al/ZnO
- 21.65 mA/cm² on Ag/ZnO
Multi-junction cells using a-Si:H & a-SiGe:H
Ge profiling in a-SiGe:H cells

(a) (b)

(c) (d)
ROLL-TO-ROLL DEPOSITION PROCESS

Roll-to-Roll Machine

Moving Stainless Steel Web

Triple-Junction Solar Cell

TCO
P3
I3
N3
P2
I2
N2
P1
I1
N1
Al/ ZnO
Stainless Steel
UNI-SOLAR Laminates are Unique

Conventional Solar Cells

UNI-SOLAR® Laminates
Historical indoor light-soak data

Light-Soak Stabilization Data for Uni-Solar a-Si Triple-Junction

Product shipped at 15% above stable value

- S-cell (5MW#1155, May '01)
- L-cell (AA0180, May '02)
- US-32 module (AA091.2, Jan '03)
- L-cell (AA2255, Aug '04)
- L-cell (AA3239, Feb '06)
- L-cell (AA3238, Feb '06)
- L-cell (AA4042, Apr 2007)
- L-cell (BA0289, Apr '07)
- L-cell (AA4324, Sep '07)
- L-cell (AA4327, Sep '07)
- L-cell (AA4560, Mar '08)
- L-cell (CB0814, Sep '08)

Fitted data

Normalized P_mp

Exposure Time (Hrs)
A DIFFERENTIATED PRODUCT

Rome, Italy
Rome Trade Fair
A DIFFERENTIATED PRODUCT

Commune St. Georges de Montaigu
A DIFFERENTIATED PRODUCT

Coca-Cola Plant
Los Angeles, California
A DIFFERENTIATED PRODUCT

New 25MW Project with Enel Green Power

Buildings owned by CIS-Interporto di Nola in Italy
A DIFFERENTIATED PRODUCT

The World’s Largest Rooftop Installation
12MW - Zaragoza, Spain
Uni-Solar

PRODUCT FEATURES
Higher Energy Yield (kWh/kW)

Site: Tucson, Arizona, USA
Source: Tucson Electric Power, Arizona, USA

Average Annual Yield (2004-2007)

- a-Si TJ: 1757 kWh/kWp
- avg. mono-Si: 1588 kWh/kWp
- avg. poly-Si: 1491 kWh/kWp
- CIS/CIGS: 1419 kWh/kWp
- avg. a-Si DJ: 1243 kWh/kWp

Average yearly yield (in kWh/kWp) 2004-2007

USO Surplus versus:
- Avg. mono-Si: +11%
- Avg. poly-Si: +18%
- CIS/CIGS: +24%
- Avg. a-Si: +41%
Higher Energy Yield (kWh/kW)

Site: Santa Cruz, California, USA
Source: Solarquest Report

2004 - 2006 Average Annual Yield

<table>
<thead>
<tr>
<th>Tilt</th>
<th>Average Annual Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNI-SOLAR 30°</td>
<td>1654</td>
</tr>
<tr>
<td>UNI-SOLAR 3°</td>
<td>1294</td>
</tr>
<tr>
<td>Crystalline 30°</td>
<td>1268</td>
</tr>
</tbody>
</table>

USO 30° Tilt Surplus versus:
USO 3° Tilt: +28%
Crystalline 30° Tilt: 31%
Higher Energy Yield (kWh/kW)

Santa Cruz Test Site
Energy Production Performance Summary

Cumulative Power Production
November 2003 - March 2007
USO Surplus versus Crystalline: +31%

- UNI-SOLAR PANEL ARRAY (30°)
- CRYSRTALLINE PANEL ARRAY (30°)

Kilowatt Hour

Date

UNI-SOLAR
30° tilt
13.7 MWh

Crystalline
30° tilt
10.4 MWh
Higher Energy Yield (kWh/kW)

Annual Energy Yield of different Technologies, Bolzano, Italy

- Competitor A – Crystalline Silicon
- Competitor B – Crystalline Silicon
- UNI-SOLAR® Thin Film Amorphous Silicon

More kWh/kW

Courtesy of the Energy Conservation Office of the province of Bolzano
Long Term Behavior (single vs. triple junction)
Annealing effect improves summer performance

Results in Switzerland

**Conversion efficiency [%]**


- **Summer period**: Arrows indicating the summer period

**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 annealing effect of a-Si, which gradually improves the conversion efficiency in the warm period of the year.

\[ y = -0.0003x + 42.725 \]

Degradation Rate: 0.35% per Year
Test Period: 8.4 years
Long Term Degradation Studies

3rd party studies on Triple Junction installations

<table>
<thead>
<tr>
<th>Location</th>
<th>Climate</th>
<th>Test Institute</th>
<th>Size</th>
<th>First Year</th>
<th>Data Range</th>
<th>Annual Degr. (%/Yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden, CO, USA</td>
<td>Hot &amp; Dry</td>
<td>NREL</td>
<td>0.032 kWp</td>
<td>1997</td>
<td>1997-2006</td>
<td>0.39</td>
</tr>
<tr>
<td>Juelich, Germany</td>
<td>Temperate</td>
<td>KfZ-Juelich</td>
<td>0.032 kWp</td>
<td>1998</td>
<td>1998-2004</td>
<td>0.14</td>
</tr>
<tr>
<td>Lugano, Switzerland</td>
<td>Temperate</td>
<td>TISO-ISSAC</td>
<td>0.5 kWp</td>
<td>1998</td>
<td>1998-2007</td>
<td>0.33</td>
</tr>
<tr>
<td>Freiburg, Germany</td>
<td>Temperate</td>
<td>ISE-Freiburg</td>
<td>2 kWp</td>
<td>2001</td>
<td>2002-2007</td>
<td>0.10</td>
</tr>
<tr>
<td>Cocoa, FL, USA</td>
<td>Hot &amp; Humid</td>
<td>FSEC</td>
<td>1.2 kWp</td>
<td>2003</td>
<td>2005-2007</td>
<td>0.58</td>
</tr>
<tr>
<td>Golden, CO, USA</td>
<td>Hot &amp; Dry</td>
<td>NREL</td>
<td>1.2 kWp</td>
<td>1998</td>
<td>1998-2004</td>
<td>0.98</td>
</tr>
</tbody>
</table>

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
What causes the 0.3% -- 1% annual degradation?

- EVA yellowing?
- Dirt?
- Contacts?
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%/ °C
Chevron Solarmine, California

Chevron Solarmine
Fellows, CA (near Bakersfield)
614 kWp
Real Life Data

Chevron Solarmine
Monthly Energy Yields for January to December 2008
Annual Energy Yield = 1653 kWh/kWp

Measured Energy Yield (kWh/kWp)

<table>
<thead>
<tr>
<th>Month</th>
<th>Energy Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-08</td>
<td>71.3</td>
</tr>
<tr>
<td>Feb-08</td>
<td>109.5</td>
</tr>
<tr>
<td>Mar-08</td>
<td>153.0</td>
</tr>
<tr>
<td>Apr-08</td>
<td>176.4</td>
</tr>
<tr>
<td>May-08</td>
<td>174.5</td>
</tr>
<tr>
<td>Jun-08</td>
<td>188.9</td>
</tr>
<tr>
<td>Jul-08</td>
<td>183.9</td>
</tr>
<tr>
<td>Aug-08</td>
<td>179.7</td>
</tr>
<tr>
<td>Sep-08</td>
<td>153.6</td>
</tr>
<tr>
<td>Oct-08</td>
<td>123.6</td>
</tr>
<tr>
<td>Nov-08</td>
<td>87.8</td>
</tr>
<tr>
<td>Dec-08</td>
<td>51.0</td>
</tr>
</tbody>
</table>
## Models

<table>
<thead>
<tr>
<th>Tilt: 20°</th>
<th>PVWATTS Energy Yield (kWh/kW_p)</th>
<th>PV*SOL Energy Yield (kWh/kW_p)</th>
<th>PVSYST Energy Yield (kWh/kW_p)</th>
<th>Measured Energy Yield Chevron Solarmine Jan. 2008 to Dec. 2008 (kWh/kW_p)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1457</td>
<td>1669</td>
<td>1629</td>
<td>1653</td>
</tr>
</tbody>
</table>

**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

- 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
Metastable Effects in Polycrystalline Thin Film Cells and Correlations with Performance and Durability

This presentation does not contain any proprietary or confidential information.
Cell durability fundamental to module durability

Systems

Modules

Series-connected cells

Laminate (EVA)

J-box

Backsheet

Glass Front Sheet

Edge Seal
Cell durability is a function of cell fabrication.
Past Cell Durability Studies


“Film thickness and chemical processing effects on the stability of cadmium telluride solar cells”, Albin et al., Thin Solid Films, 2659-2666 (2006)


Cell Accelerated Lifetime Testing (ALT)

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

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 $\pm 1 \, ^\circ C$
- Irradiance can affect $T_{sample}$
SPIE 2009 Study – Performance of CTO/ZTO vs nSnO₂/iSnO₂

- SnO₂
- CTO/ZTO

FF increases about 1 to 1.5 % pts.
No difference in $V_{oc}$
$\sim 1.0 - 1.5$ mA/cm² increase in $J_{sc}$
SPIE 2009 Study – Durability of CTO/ZTO vs nSnO₂/iSnO₂

Cells fabricated identically except for TCO

Stressed identically (100 °C, $V_{oc}$, 1-Sun)

*Differences in degradation due to different TCO layers*
C-V hysteresis (metastability) during ALT

- Charge Density (cm\(^{-3}\))
- Depletion Width, um
- Reverse Bias Voltage, V

CdTe cell with no Cu in contact
  - rev scan
  - fwd scan
CdTe cell with Cu in contact
  - rev scan
  - fwd scan

- “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

\[ \tau_{em} \sim \exp \left( \frac{E_t - E_v}{kT} \right) \]

- **A**  \( v = 0 \)
- **B**  \( v = -1.5 \text{ V; } t = 0^+ \)
- **C**  \( v = -1.5 \text{ V; } t > 0 \)

Depletion Width, um

Reverse Bias Voltage, V

CdTe cell with Cu in contact
- **rev scan**
- **fwd scan**
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 ($\tau_a$)

Perform “fwd” scan
- Measure SCR with Cu$_i^+$ removed from SCR

Perform A $\rightarrow$ B

A $\rightarrow$ B

B $\rightarrow$ C

CdTe cell with Cu in contact
- rev scan
- fwd scan

W$_d$,rev – W$_d$,fwd

Reverse Bias Voltage, V

Depletion Width, um

- $W_d,rev - W_d,fwd$

- $\tau_f$

- $\tau_a$
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 °C; cell stability is determined by changes in FF and $V_{oc}$ (SPIE-2008)

\[
\begin{align*}
W_d (\text{hysteresis}) & \quad 0.58 < R^2 < 0.99 \\
V_{oc} & \quad 0.46 < R^2 < 0.98
\end{align*}
\]
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 $\Delta\text{Eff}$ vs $\Delta V_{oc}$, $\Delta J_{sc}$, and $\Delta\text{FF}$

- Strong correlations between $\Delta\text{Eff}$ and $(V_{oc}, \text{FF})$

- Cell and mini-module reliability good at 65-80 ºC

- Higher stress temperatures (125 ºC) see “outliers” in $\text{Eff}$ 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 °C 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.
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)
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 $\leq 2\%$ 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 85°C/85% RH, 1000h certification test
  - consists of two branches: light exposure & biased dark exposure, both ~65°C±5°C
  - Biased dark exposure is advantageous if successful because of ease and lower cost
  - Swap light/dark-soak modules in Φ–Ι ⇔ dark/light-soak modules Φ–ΙΙ, no dark anneal

- **Phase I**
  - **t=0**
  - Dark thermal anneal 90°C, 40% RH, 48-h, Measure IV, CV
  - light / dark-soak question
    - a) light-soak
    - b) dark-soak
    - light-soak on 1 CIS B module in Phase Ι
      - performed outdoors
  - Measuring IV, CV
  - dark, Vbias ~Vmax-Voc, Tmod ~65°C±5°C, time increment: 24-48 h
  - load ~Vmax, time increment: 24-48 h
  - *Note: light-soak on 1 CIS B module in Phase Ι performed outdoors

- **Phase II**
  - Swap modules
    - a) light soak -> dark soak
    - b) dark soak -> light soak
  - **t=0**
  - Dark storage
  - Phase I or II?
  - **exposure t>120 h?**
    - Yes
    - Measure IV, CV
    - Phase III: Expose outdoors ~6-10 weeks; test IV, CV
    - Evaluate
  - No
  - Measure IV, CV
  - *Note: light-soak on 1 CIS B module in Phase Ι performed outdoors

- **Phase III**
  - Expose outdoors ~6-10 weeks; test IV, CV
  - Evaluate

- **Performance > Minimum?**
  - Yes, Main Phase I
  - t=0
  - No
  - Discard
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

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Quantity</th>
<th>Configuration</th>
<th>Pre-existing exposure conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdTe A</td>
<td>2</td>
<td>Glass-superstrate-glass laminate, monolithically interconnected</td>
<td>Yes, outdoors 3 years</td>
</tr>
<tr>
<td>CdTe B</td>
<td>2</td>
<td>Glass-superstrate-glass laminate, monolithically interconnected</td>
<td>No, nascent</td>
</tr>
<tr>
<td>CdTe C</td>
<td>1</td>
<td>Glass-superstrate-glass laminate, monolithically interconnected</td>
<td>Yes, indoor light-soak, 1130 kW-h in 2002</td>
</tr>
<tr>
<td>CIGS A</td>
<td>3</td>
<td>Glass-substrate-glass laminate, monolithically interconnected</td>
<td>Nascent: 3 controls from 2003</td>
</tr>
<tr>
<td>CIGS B</td>
<td>2</td>
<td>Glass-flexsubstrate-glass laminate, solder bond interconnect</td>
<td>No, nascent</td>
</tr>
</tbody>
</table>
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 \(\Leftrightarrow\) signature to potential metastability

- 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 \(\Rightarrow\) little hysteresis in C-V profile, lower carrier densities
  - Cu in back contact \(\Rightarrow\) 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, $N \sim 1-3 \times 10^{16}$
  - outdoor precondition 27 kW-h/m², slight shift of $W_d$ upwards from baseline
  - dark anneal: drops $N \sim 2-7 \times 10^{15}$, large shift up of $W_d$, large hysteresis $\sim 50\%$ at $v=0$
  - End of 3 dark soak steps (24h, 48h & 48 h)
    - restores $N$ & $W_d$ profiles closer to data after outdoor precondition, partway between precondition & anneal

- **Dark storage $\sim$ 3-4 months**

- **Phase II** (indoor light soak)
  - Begin light soak after dark storage
    - $N$, $W_d$ 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 $\Rightarrow$ phase II light soak

Carrier Concentration $N_{\text{top}}$, depletion width $W_d_{\text{bottom}}$

- **Phase I** (indoor dark soak)
  - Baseline, (valley) $N \sim 7 \times 10^{13}$-$1 \times 10^{14}$
  - Outdoor precondition 27 kW-h/m²: some change in $W_d$ upwards in forward bias, $\Delta N$ small
  - Dark anneal: raises $N \sim 1$-$5 \times 10^{14}$, large shift down of $W_d$, small hysteresis $\leq 5\%$ 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
    - $N$, $W_d$ profiles relax close to state at baseline
  - End 3 light soak steps (48h, 30h & 48 h)
    - returns $N$, $W_d$ 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 $\Delta$, some pre-existing higher
- Outdoor precondition 1 & 26 kW-h/m²
  - CIGS A, CdTe A & B improve
  - CIGS B, CdTe C drop
- Dark thermal anneal
  - All CIGS + CdTe B drop,
  - CdTe A & C improve to pre-existing performance

### Phase I (cont)
- Exposures: 4 light / 3 dark soak steps
  - CIGS seem to stabilize ($\Delta \eta \leq 2\%$) 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 ($\Delta \eta \leq 2\%$)
    - 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 $V_{max}$ & $V_{oc}$
  - $I_{bias} < 20\% I_{max}$
  - might have stifled stabilization

- **Biased dark soak phase II**
  - $V_{bias}$ closer to $V_{oc}$ than phase I
  - $I_{bias} \sim I_{max}$
  - probably accelerated stabilization or changes in performance
Summary

- Polycrystalline CIGS & CdTe PV show metastable behavior in performance

- Implemented stabilization/preconditioning procedures using two types of 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 $I_{\text{bias}} \sim I_{\text{max}}$ 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
  - Quantifying 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
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2 CIGS Cell-Level Reliability Task and Studies at NREL
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Characterization of an Aggregated Total Internal Reflection Optic

Kevin Fine; David Schultz

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.

MEASURING OPTICAL EFFICIENCY – Jsc METHOD:
Short circuit current (Jsc) is proportional to exposed cell area and the intensity of incident light. Optical Efficiency (OE) is measured by comparing the Jsc of a bare cell to that of a cell coupled with an optic and controlling for the area and source intensity.

\[ OE = \frac{J_{sc,\text{bare cell}} - J_{sc,\text{cell coupled}}}{J_{sc,\text{bare cell}}} \]

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.

ATIR SPECIFIC RELIABILITY 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?

PREDICTED RESULTS: 84.2%

MEASURED RESULTS: 84.7%

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.
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 Berkeley 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.
Design Verification Testing

NREL PV Module Reliability Workshop

Entech Solar, Inc.

Clay Stevenson
Doug Williams

2-18-10
DVT Testing Sequence

1.) Pre-Stress Performance Tests

- Sample Build
- Sun Simulator (IV data)
- Dark IV and Dry Hi-Pot
- Visual Inspection
- Wet Hi-Pot (Wet Insulation Test)

- Control Units
  - 1 Full Size Module
  - 1 Sub Scale
  - 1 FHE (60 Cell)

- Off Axis Beam & Walk Off Test
- Ground Path Continuity Test
- Water Spray Test
- Temperature Data Collection
- Electrical Performance Data Collection (IV data logging)
- Open Circuit Preconditioning (5KWh/m²)

2.) Stress Tests

- Sequence A
  - 1 Manifold (360 cells)
  - 2 FHE (60 cells ea.)
  - Thermal Cycling (-40 to 110°C, 200 cycles)
- Sequence B
  - 2 Full Size Modules
  - 7 Sub Scale Modules
  - Thermal Cycling (-40 to 110°C, 400 cycles)
- Sequence C
  - Same samples as Seq B
  - Hail & Impact Test
  - Mechanical Load & Terminations Test
  - Fire Resistance
- Sequence E
  - 2 Full Size Modules
  - 7 Sub Scale Modules
  - Humidity Freeze (65°C / 85% RH, 20 cycles)
  - Outdoor Testing (Sequence E)
  - 1 Full Size Module
  - 1 Sub Scale Module
  - 1 FHE (60 Cell)
  - Humidity Freeze (65°C / 85% RH, 250hrs)

- Sequence F
  - 1 FHE (60 Cell w/ Insulation)
  - Bypass Diode Temperature Test

3.) Post-Stress Performance Tests

- Sun Simulator (IV data)
- Dark IV and Dry Hi-Pot
- Wet Hi-Pot (Wet Insulation Test)
- Visual Inspection
- End
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 ÷ 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.
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 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.
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 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

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
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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
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
**Typical CPV Receiver - Material Stack-Up**

**Material Comments**

- Fresnel Lens, Cassegrain Mirror, Parabolic Mirror
- III-V, 10 x 10 x 0.2 mm, Metalized Backside
- E/T Conductive Die Attach Epoxy
- 24x24 x0.38 mm: Alumina, BEO, ALN, Cu Ni Au Both Sides
- Non Conductive Adhesive
- Heat Spreader
- Non Conductive Adhesive

**Design Comments**

- 200 to 1000+ Suns
- Tj,max <100°C to Meet 25 Year Life and Efficiency
- Better Thermal Conductivity Can Improve Efficiency
- Good CTE Match to Die
- OK Thermal Conductivity Electrical Insulator – High Pot Test
- Absorb CTE Mismatch
  - Al₂O₃ / Cu or Al
- Good Thermal Conductor
- Thermal Path to Baseplate

**Receiver Module**

- Concentrated SUN 200 to 1000+
- Triple Junction PV Die
- TIM 0
- Ceramic
- TIM 1
- Cu / Al: Heat Sink / Rail
- TIM 2
- Aluminum Heat Sink (Back Panel / Rail)
## Typical CPV Receiver - Thermal View

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<tr>
<th>Thermal Conductivity</th>
<th>CTE</th>
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<tr>
<td>(W/mK)</td>
<td>(ppm/K)</td>
</tr>
<tr>
<td>50 / 60</td>
<td>5.0 / 6.0</td>
</tr>
<tr>
<td>4.0 / 7.0</td>
<td>5.5</td>
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<td>46</td>
<td></td>
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<tr>
<td>1.0 / 4.0</td>
<td>16 / 24</td>
</tr>
<tr>
<td>210 / 360</td>
<td></td>
</tr>
<tr>
<td>1.0 / 4.0</td>
<td></td>
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</table>

**Receiver Module**

- **Concentrated SUN**: 200 to 1000+
- **Triple Junction PV Die**
- **TIM 0**
- **Ceramic**
- **TIM 1**
- **Cu / Al: Heat Sink / Rail**
- **TIM 2**
- **Aluminum Heat Sink (Back Panel / Rail)**

**TC**: -40°C to 110°C
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 28°C
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.
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
Solder vs. Adhesive Thermal FEA Model – 30W Heat Flow

- $T_{\text{max}} = 38\,^\circ\text{C}$
- BLT=250um
- $K=25\,\text{W/Km}$

- $T_{\text{max}} = 46\,^\circ\text{C}$
- BLT=50um
- $K=1\,\text{W/Km}$
NanoBond® Solder Bond

- Cu Heat Sink and Receiver Module
- >1000 cycles completed, no degradation
- -25 to +125°C (8.5°C per minute ramp)
## Laser Flash Analysis

<table>
<thead>
<tr>
<th>Bonding Method</th>
<th>Bondline Thickness (µm)</th>
<th>Original Bond</th>
<th>After 540 cycles</th>
<th>After 940 cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>*Thermal Cond. (W/Km)</td>
<td>*Thermal Resist. (Kmm²/W)</td>
<td>*Thermal Cond. (W/Km)</td>
<td>*Thermal Resist. (Kmm²/W)</td>
</tr>
<tr>
<td>NanoBond Screen printed DBC</td>
<td>447</td>
<td>42.2</td>
<td>10.6</td>
<td>42.3</td>
</tr>
<tr>
<td>NanoBond Spray coated DBC</td>
<td>467</td>
<td>30.7</td>
<td>15.2</td>
<td>32.4</td>
</tr>
<tr>
<td>Epoxy1 (3M)</td>
<td>50</td>
<td>0.85</td>
<td>58.96</td>
<td>0.81</td>
</tr>
<tr>
<td>Epoxy 2 (Epo-Tek)</td>
<td>50</td>
<td>2.83</td>
<td>17.6</td>
<td>-</td>
</tr>
</tbody>
</table>

- Bond size 24 mm x 24 mm
- DBC material properties have been corrected using laser flash
- Copper thickness 1.6 mm
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
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.
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.
## 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
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
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
Mechanically Induced Microfractures

If a failure occurs due to high cycle wearout or to localized heating that the temperature is above the limit set, it can be controlled with the help of the following process:

1. Identify the cause of the failure.
2. Ensure that the temperature is within the specified range.
3. Adjust the process parameters to maintain the temperature within the safe limits.

By doing this, the reliability of the product can be improved to meet the required specifications.
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 \((3.3 \text{ TW} \times 1 \text{ year})\)

>90% from fossil fuels

Projected world annual power consumption by 2030:
1 zettajoule \((10^{21} \text{ joules})\)

1,000,000,000,000,000,000,000,000,000 JOULES

Replace carbon based energy with clean renewable energy
Total energy potential

Solar
31,000,000 GW

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:

**The Problem**
What material is abundant enough to cover the surface area needed to supply all U.S. electricity?

125 miles

125 miles
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.

- 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

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
Technology Summary

1,000 W/m² 
× 7 m²

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/m²
Average irradiance per cell: 350kW/m²
Technology Summary

Single cell detail:

- Cold Rolled Copper Plate: 500um
- Electroless Nickel Plating ~15um
- Water Impingement Cooling
- Ceramic Filled Polymer Dielectric ~35um
- Electroplated Copper “4oz” ~140um
- Epenieg Plating
- PbSn Solder ~120um
- “Reverse” Wirebond
- CPV Die ~120um
- Silcone Gel (if required)
- Silcone Conformal Coating (~100um)
- Glass TIR Optic Element
- Width of Cell, Active Area: ~3,000um
- Silicone Gel

Electrolytic Nickel Plating ~15um
Water Impingement Cooling
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

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

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
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

Neither Wind…

…Nor Ice…

…Nor Earthquake…

…Nor Rainstorm…

…Nor Lightning…
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
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
Measured Solar Spectrum

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Power (Arb. Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>0</td>
</tr>
<tr>
<td>450</td>
<td>0</td>
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<td>550</td>
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<td>650</td>
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<tr>
<td>750</td>
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<tr>
<td>850</td>
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</tr>
<tr>
<td>950</td>
<td>0</td>
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</table>

Sept. 9th, 1:00 pm

<table>
<thead>
<tr>
<th></th>
<th>Direct</th>
<th>Through Optics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top</td>
<td>Middle</td>
</tr>
<tr>
<td>AM1.5</td>
<td>6.110183</td>
<td>6.326033</td>
</tr>
<tr>
<td>Measured</td>
<td>9.770425</td>
<td>10.81377</td>
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</table>

Output Correction Factor 1.03
Measured Solar Spectrum

Sept. 9th, 9:30 am

<table>
<thead>
<tr>
<th>Direct</th>
<th>Top</th>
<th>Middle</th>
<th>Ratio</th>
<th>Through Optics</th>
<th>Top</th>
<th>Middle</th>
<th>Ratio</th>
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</thead>
<tbody>
<tr>
<td>AM1.5</td>
<td>6.110183</td>
<td>6.326033</td>
<td>0.982643</td>
<td>AM1.5</td>
<td>5.4470991</td>
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<tr>
<td>Measured</td>
<td>5.536455</td>
<td>7.361426</td>
<td>0.858506</td>
<td>Measured</td>
<td>5.0085128</td>
<td>6.61561</td>
<td>0.861744643</td>
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</tbody>
</table>

Output Correction Factor 1.14
Modeled Spectrum on 9/9
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 isotope cell current generation under Soliant Energy optics
Isotype module current production

Spectral mismatch over time

Soliant
Energizing commercial rooftops
Current Production vs. Isotype current ratio

Current generation vs spectrum

Normalized Module Current Generation

Spectral mismatch factor (TC/MC-1)

1/28/2010
2/10/2010
2/13/2010
2/14/2010
2/15/2010
2/16/2010
Spectral mismatch vs. Incoming DNI
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
Reliability and Qualification of Amonix Solar Power Plants
Field testing: Amonix technology in over 70% of world’s installed CPV

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>LOCATION</th>
<th>CAPACITY</th>
<th>DEVELOPERS</th>
<th>COMMISSIONED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guascor Fotón Navarra CPV Plant - Phase II &amp; III</td>
<td>Spain</td>
<td>5.8 MW</td>
<td>Guascor Fotón (Amonix)</td>
<td>2008</td>
</tr>
<tr>
<td>Abengoa Casagrande CPV Project</td>
<td>Spain</td>
<td>2.0 MW</td>
<td>Solucar Energia</td>
<td>2008</td>
</tr>
<tr>
<td>Guascor Fotón Navarra CPV Plant - Phase I</td>
<td>Spain</td>
<td>2.0 MW</td>
<td>Guascor Fotón (Amonix)</td>
<td>2007</td>
</tr>
<tr>
<td>GuascorFotón Murcia CPV Plant</td>
<td>Spain</td>
<td>2.0 MW</td>
<td>Guascor Fotón (Amonix)</td>
<td>2009(b)</td>
</tr>
<tr>
<td>Guascor Fotón Tecnohuertas CPV Plant</td>
<td>Spain</td>
<td>1.5 MW</td>
<td>Guascor Fotón (Amonix)</td>
<td>2006</td>
</tr>
<tr>
<td>Alsanbo Santa Pola Solar CPV Plant</td>
<td>Spain</td>
<td>1.0 MW</td>
<td>Electricidad Alsanbo</td>
<td>2007</td>
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<tr>
<td>Guascor Fotón Energias del Tietar</td>
<td>Spain</td>
<td>1.0 MW</td>
<td>Guascor Fotón (Amonix)</td>
<td>2008</td>
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<tr>
<td>Flix Solar Ramon Escriche Solar CPV Plant</td>
<td>Spain</td>
<td>0.8 MW</td>
<td>Flix Solar</td>
<td>2008</td>
</tr>
<tr>
<td>SolFocus and ISFOC Almoguera CPV Project</td>
<td>Spain</td>
<td>0.3 MW</td>
<td>ISFOC, SolFocus</td>
<td>2008</td>
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<tr>
<td>Concentrix and ISFOC Puertollano CPV Project</td>
<td>Spain</td>
<td>0.2 MW</td>
<td>Concentrix Solar</td>
<td>2008</td>
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<tr>
<td>SolFocus and ISFOC Puertollano CPV Project</td>
<td>Spain</td>
<td>0.2 MW</td>
<td>SolFocus</td>
<td>2008</td>
</tr>
<tr>
<td>Yitai Ordo grid-connected CPV power Project</td>
<td>China</td>
<td>0.2 MW</td>
<td>Inner Mongolia Yitai Group</td>
<td>2007</td>
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<tr>
<td>Amonix Solar CPV Plant (APS STAR Center - West) - Demonstration</td>
<td>United States</td>
<td>0.2 MW</td>
<td>Amonix</td>
<td>2003</td>
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<tr>
<td>Amonix Prescott CPV Plant - Demonstration</td>
<td>United States</td>
<td>0.2 MW</td>
<td>Amonix</td>
<td>2003</td>
</tr>
<tr>
<td>Amonix Solar CPV Plant (APS STAR Center - East) - Demonstration</td>
<td>United States</td>
<td>0.1 MW</td>
<td>Amonix</td>
<td>2002</td>
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<tr>
<td>Amonix Glendale CPV Plant - Demonstration</td>
<td>United States</td>
<td>0.1 MW</td>
<td>Amonix</td>
<td>2001</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>17.6 MW</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 center for energy research (las vegas, nv)
one 7500, one 7700
91 kw

river mountain water treatment facility (henderson, nv)
six 7500s
228 kw
Reliability and qualification program: areas of focus

Reliability and Qualification

Qualification
- IPC 6701, IEC 62108
- TC/HF, IEC 62108
- 85/85, IEC hail impact, IPC Drop Test, etc.

Accelerated Lifetime Testing
- Extended TC and HF, 85°C/85% RH, high temp soak, UV soak, lens weathering, etc.

Field Testing
- Field systems
- Single-module testing (3rd party)
Assumes exponential degradation with temperature

Only the (intentionally) under-built design shows measurable degradation as yet

Tests are ongoing, including additional temperatures and designs
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

A. Transfer printing stamp

B. Target engineered substrate

C. Release of an array of InGaP/GaAs cells

D. Populated target engineered substrate
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/cm² 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
On-Sun Failures

Cell at 1000-Suns Failed Within Hours On-Sun

Focused at top metal

Focused at bottom interposer
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.
Finite Element Analysis

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.

>1 MA/cm² current density
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.
100 A/cm² Forward Bias
Electroluminescence of top cell

- Cells with poor thermal attach failed under forward bias at ~1A/cm² current density.

- After corrective action, >100 A/cm² 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™

3. Free Water Vapor Permeation Into PV Module
   Without desiccant, water penetrates the edge seal quickly.
   In a desiccated edge seal, water diffusion is delayed.

4. Delayed Water Vapor Permeation Into PV Module
   Water captured and not allowed to move freely through the seal.

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.

6. Path Length Effect on Lag Time
   Lag time depends on the 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 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.
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

Critical Backsheet Properties Tested

Backsheet Adhesion to Encapsulant After Damp Heat

- Loss of EVA adhesion for PET and other fluoropolymer based backsheets
- EVA peel from glass indicating strong EVA backsheet adhesion

Backsheet Elongation After Damp Heat

- Embrittlement of PVDF based backsheet

Color Change in Glass/EVA/Backsheet Laminate

- Degradation - Glass/EVA/backsheet laminate after UV Exposure (ASTM G155) at 1190h
- 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)

- 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.

Summary

NREL PV RELIABILITY WORKSHOP, 2/18/2010
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

Exposure to moisture, chemically active environmental species, thermal cycling and UV radiation leads to device failure.

Assessing UV & Environment on Debonding Kinetics

- 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

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
- 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.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shipping/Packaging</td>
<td>Out of the box damage including glass breakage from transport</td>
</tr>
<tr>
<td>Installation and Handling</td>
<td>Glass breakage and cracks as a result of incorrect handling or installation</td>
</tr>
<tr>
<td>Diminished Module Output</td>
<td>Module output power is low</td>
</tr>
<tr>
<td>Intrinsic Module Damage After Deployment</td>
<td>Module has defective wires, glass breakage or cracks or no power output.</td>
</tr>
<tr>
<td>Externally Caused Module Damage After Deployment</td>
<td>Module has been damaged by external source.</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Manufacturer Failure Mode Designations After Technical Assessment</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect/Damage Covered by Warranty Replacement</td>
<td></td>
</tr>
<tr>
<td>Damage due to Handling or Installation:</td>
<td></td>
</tr>
<tr>
<td>Damage through mounting system (glass scratches)</td>
<td></td>
</tr>
<tr>
<td>Damage due to bad module clip position</td>
<td></td>
</tr>
<tr>
<td>Glass Crack due to Thermal Cycling</td>
<td></td>
</tr>
<tr>
<td>Damage Due to External Source</td>
<td></td>
</tr>
</tbody>
</table>

Of the 1310 Return Requests filed, 1073 have been accepted and reviewed technically by the manufacturer.

<table>
<thead>
<tr>
<th>Company Failure Mode Designations for Installed Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic Module Damage After Deployment</td>
</tr>
<tr>
<td>Externally Caused Module Damage After Deployment</td>
</tr>
<tr>
<td>Diminished Module Output</td>
</tr>
<tr>
<td>Installation and Handling</td>
</tr>
<tr>
<td>Shipping/Packaging</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manufacturer Failure Mode Designations Based Upon Technical Assessment of Returns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage Due to Thermal Cycling</td>
</tr>
<tr>
<td>Damage Due to External Source</td>
</tr>
<tr>
<td>Defect/Damage Covered by Warranty Replacement</td>
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</tbody>
</table>

<table>
<thead>
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<th>Installation Company Module Failure Mode Classification</th>
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<td>Externally Caused Module Damage After Deployment</td>
<td>Module has been damaged by external source.</td>
</tr>
</tbody>
</table>

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
Introduction

- **Wet Leakage Resistance (WLR)**
  - An important module safety measure

- **Criteria of Certification Standard**
  - IEC 61646 ed. 2.0 10.15
    - > 40 MΩm² under 1000 V bias if module area > 0.1 m²
  - UL 1703
    - > 40 MΩ m² under 500 V bias if module area > 0.1 m²

- **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.
Equivalent Circuit and Resistance

- Measurement Set-up
- Equivalent Circuit

\[ R_{\text{parallel}} = \frac{1}{\left( \frac{1}{R_{\text{top}}} + \frac{1}{R_{\text{bottom}}} + \frac{1}{R_{\text{positive}}} + \frac{1}{R_{\text{negative}}} \right)} \]

\[ R_{\text{FG}} = \frac{1}{\left( \frac{1}{R_{\text{dry back}}} - \frac{1}{R_{\text{parallel}}} \right)} \]

\[ R_{\text{BS}} = \frac{1}{\left( \frac{1}{R_{\text{module}}} - \frac{1}{R_{\text{dry back}}} \right)} \]
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
Segmentation of Initial Resistance

- For Initial Leakage Resistance:
  \[ R_{BS} > R_{parallel} \gg R_{FG} \]

- Front Glass $\rightarrow$ dominant **leakage path** of initial WLRs

**Initial leakage resistance of each part of a module**
**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*
Dependence on FG Resistivity (cont’d)

• Front glass bulk resistivity can be the dominant term controlling WLR

• Requirement to front glass (FG)
  • High resistivity: >1e11 Ohm·m recommended
  • Validated tight run-to-run quality control
    • Requires composition control and resistivity monitoring
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

\[\text{Glass resistivity vs. temperature}\]

\(^1\)E. Guyer, Electrical Glass, Proceedings of the IRE, December 1944, p. 743-750
FG Resistivity Spec Considerations

- **IEC spec mandates all components meet 40 MOhm.m² 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** $10^{(10.1 + 0.5 + 0.2 + 0.2)} = 10^{11±0.2}$
Degradation post HF Stress Test

Correlation of WLR pre and post HF

Higher initial WLR correlated to higher post stress WLR
Degradation post DH Stress Test

WLRs of the modules (front glass bulk resistivity = 10.7 log(MOhm.m)) post DH
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.
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**
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

FICKIAN 1-D DIFFUSION MODEL

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

MOCON

PVS 101

Competitor

PVS 101: all CF

CF = Cohesive Failure

Conclusions

PVST 101 has been designed to exhibit a superior MVTR as characterized using MOCON and DSC
PVST 101 binds chemically with glass and the bonding strength increases with time
PVST 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.

~42% reduction in width will theoretically match performance of competition assuming a linear relationship in temperature. We recommend 25% as a conservative buffer.
Silicone properties make them ideal candidates as encapsulants for photovoltaic modules

Silicones encapsulant has better reliability and durability over EVA

IEC 61215 Certification
- Passed UV Exposure/Temperature Cycling 500/1000 hours in TUV-PTL.
- Passed Damp Heat (85C/85%) 1000 hours in TUV-PTL.
- Passed Mechanical load after 901000 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 16000 cycle UV exposures even up to 5000 Thermal Cycles.
- The Silicone encapsulant has been approved under “Fast Thermal cycling (180°C - -60°C) test up to 2000 cycles on 2 modules during IEC 61215 certification.
- Silicone encapsulated PV modules have been passed up to 4000 hours damp heat (85°C/85%) on 3 cells coupons and passed 1600 hours on full size modules.
- Two Silicone encapsulated PV systems are operation in California,10years aging and 20 years aging are planned on other regions.

Comparison of alpha before and after damp heat aging
- Both EVA and silicone encapsulant are approved and certified by IEC 61215.
- Silicone encapsulant has no significant changes on optical properties after damp heat aging.
- EVA has significant changes on optical properties after damp heat aging.

Alpha Response to 30X roof top concentrator @ ANU
- Silicones encapsulant shows no visible changes in IRT.
- EVA ch Are damaged after 60 days on 30X tracker.
Accelerated electro-chemical delamination test for the durability of transparent conductive oxide (TCO) glass

Yu Wang1, Satoshi Tanaka2, and David Strickler1
NG Group, Building Products R&D, On-Line Coating Technology
1Pilkington, Northwood, OH, USA; 2NSG, 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. [3] [4] 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. [5] 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.

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 ºC and a 100 V positive bias voltage is applied to the non-coated side for 15 min;
- The schematic diagram of ECDL test equipment is given in Fig. 2. (a) Schematics of ECDL test instrument. (b) Photographs of the ECDL setup and the test procedure. 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.

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.

Results

- Analysis of delaminated samples reveals the weak interface:
  - Under positive bias, alkaline ions in glass and F- in SnO2:F were driven towards TCO/glass interface:
  - When compression stress in the TCO coating becomes larger than the interfacial adhesion, coating delaminates; [5]
  - Mismatch strain: $\varepsilon = \sigma / E$ Mismatch stress is ~0.8 GPa $\sigma_{\text{stress}} = E : (1 / (1 - \nu))$

- 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 in [4] after ECDL test (Fig. 4).

- 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 in [4] after ECDL test (Fig. 4).

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.

Literature cited

Acknowledgments
The authors thank Dr. K. Jansen for his suggestions on optimizing test procedure, Dr. N. McSparran 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.)

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

Examples of two "normal" Fresnel lenses and one "bad" Fresnel lens in a 3x5 module size parquet.

<table>
<thead>
<tr>
<th>LENS</th>
<th>Transmission @ Center (%)</th>
<th>Transmission Grand Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic Design</td>
<td>90.9</td>
<td>87.4</td>
</tr>
<tr>
<td>SoG Design</td>
<td>91.6</td>
<td>86.4</td>
</tr>
</tbody>
</table>

Detector/Receiver Assemblies (used in validating optical models & designs)
An Approach Towards Light and Heat Management in PV Modules

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

Motivation – Quantification of Optical and Temperature Losses

- A significant portion of light does not enter cells
- Most modules have nominal operating cell temperatures (NOCT) in the region 50 to 60 °C
- Result is a significant loss in energy yield

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.
- Optical losses are highly dependant on angle of incidence
- Greatest thermal resistance is at module surface

Experiments - One Approach to Addressing Optical and Temperature Losses – Structured Glass

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

Assumptions: Incident sunlight, No ARC on glass, Anti-Reflection Coating, 3.9mm EVA encapsulant, Si ARC on textured cells, 7.5% of cell area is metallization, 63% cell packing factor in module. Excludes frame and edges.
- Actual transmission to cell = 65% to >90% depending upon technology, architecture and orientation

Adsorber Type | Typical Temperature Coefficient % Pmax/°C
--- | ---
m-cSi | -0.47
-aSi | -0.31
-CIGS | -0.60
c-Fe | -0.20
-aSi (triple junction) | -0.32

References:
Characterization and Reliability of Polymeric Components in PV Modules

Shuying Yang
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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**

— 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 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
Sample Backsheet Reflection Curves

Selection of material is based on higher reflectivity of a backsheet
Aging / Reliability Study

— **Thermal Aging**
  - 95 °C – 105 °C. Long Term Bake of ~ 1000 hrs.
  - Used to differentiate quality of materials.

— **Damp Heat (DH)**
  - 85 °C / 85 % RH for >1000 hrs

— **UV aging**
  - 0.72W/m² for 1000 hrs @ 60 °C

— **Temperature Cycling**
  - -40 °C – 85 °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

Machine Direction
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

Nicoleta Sorloaica-Hickman, Kris Davis, Albert Leyte-Vidal, Florida Solar Energy Center
Sarah Kurtz, Dirk Jordan, National Renewable Energy Laboratory

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.

PVUSA power rating analysis (AC, DC)

\[ P = I_{PQ} \left( a + b \frac{I_{PQ}}{P_{AC}} + CT_{cool} + dW \right) \]

Collect data: Irradiance, DC and AC Power on all PV Systems one-month blocks of 15-minute intervals

Calculate the regression coefficients and the Power Rate (W) at illumination of 1000 W/m² and temperature of 20°C

Estimating Energy Output
The energy output of each system 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

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.

\[ \text{PR} = \frac{Y_t}{Y_s} \]

Linear Fit of Performance Ratio

Conclusion
- The analysis of data from 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)

Acknowledgements
- NREL for funding this project
- Kevin Lynn, William Wilson, Steve Barkasi, 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
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
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
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
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
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
Creep under high load (~7X glass weight)

Encapsulant A

Encapsulant B

Thermoplastic encapsulants will creep under some temperature/stress loading conditions.
Effect of Test Temperature on creep
(High load – 7X glass weight)

Performance depends critically on test temperature
Effect of Test Temperature on creep
(Normal load – 1X glass weight)

Performance depends critically on test temperature
Module Test Result

Method:
Mount module vertically supporting only back glass
Measure displacement of front glass after 500 hours at 92°C

Result:
No displacement observed
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
    - $T_{\text{max}}$ (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.
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
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

- **Reliability monitoring**
  - Program panels post-end point tests

- **Multiple cycles of**
  - One of the following three stress conditions

  - **Humidity Freeze**
    - -40°C/+85°C

  - **Damp Heat 85°C/85%RH**

  - **Thermal cycling**
    - 40°C/+90°C
    - Mix of non-energized and energized at current = Isc

- **Power performance and I-V characteristics at**
  - Intermediate and end point

- **Electroluminescence imaging at**
  - Intermediate and end point

- **Feedback to concerned teams on design and process margins**

- **Data and failure analysis**

- **Visual inspection**

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Evergreen Solar Confidential
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

Samples Thermal cycles -40°C to 90°C, 25 data points

Samples Damp heat hours 85°C/85% RH, 51 data points

Samples Humidity Freeze cycles -40°C to 90°C, 50 data points
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

\[ I = \frac{W_i}{4\pi L} \int_0^L \frac{1}{x^2 + (y-y_0)^2} \, dy \]

Where \( W_i \) is the radiant flux of the lamp in terms of radiant energy of joules per unit time

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%

Determine the Sample Surface Temperature

**Theoretical consideration**

\[
\begin{align*}
J_{\text{source}} &= a_{\text{source}}(\lambda) E_{\text{source}}(\lambda) \, d\lambda \\
J_{\text{convection}} &= a_{\text{convection}} (\tau_{\text{ambient}} - T_{\text{sample}}) \\
J_{\text{conduction}} &= \frac{\tau_{\text{sample}} - T_{\text{ambient}}}{d}
\end{align*}
\]

A customized interior instrument design on 12kW xenon lamp for high-flux stress test of encapsulants for medium-concentration concentrating photovoltaic (CPV) system at National Renewable Energy Laboratory (NREL)

**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)

NIST-traceable irradiance calibration and measurement capability

High Volume Light Soaking and UV Testing of Photovoltaic Modules

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*Atonometrics, Inc., 8900 Shoal Creek Blvd., Suite 116A, Austin, TX 78757

Atonometrics Light Soaking System with in situ I-V

Atonometrics UV Exposure System

Capable of simultaneous testing of 4 to 6 standard size PV modules

Light Soaking results from Literature

CIGS¹
ZMO/CdS/CIGS (CBO: 0.24 eV)

B-Doped Cz C-Si³

a-Si and CdTe²

AM 1.5, 24-hr Average

Lamp Type A
Lamp Type B


²"Advanced Indoor Light-Soaking Facility", J. A. del Cueto, et. al., Presented at the 2004 DOE Solar Energy Technologies Program Review Meeting

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

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Analysis</th>
<th>What is Learned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance under dark vs. bias voltage</td>
<td>Nyquist plot: Im(Z) vs. Re(Z)</td>
<td>• Number of capacitances in the device becomes apparent.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Extract fitted values of C, R.</td>
</tr>
<tr>
<td></td>
<td>C vs. bias voltage (C-V)</td>
<td>• Origin of capacitance (e.g. geometric vs. chemical) is revealed by bias dependence.</td>
</tr>
<tr>
<td></td>
<td>Mott-Schottky plot: 1/C^2 vs. bias voltage</td>
<td>• Build-in potential.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Concentration of intrinsic dark carriers.</td>
</tr>
<tr>
<td>Impedance vs. light</td>
<td>C vs. Voc</td>
<td>• Chemical capacitance, derived from the photo-carriers, is probed.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Carrier lifetime.</td>
</tr>
</tbody>
</table>

Not included in this study but possible: impedance vs. temperature.
Mott-Schottky Analysis*

\[ \frac{1}{C_D^2} = \frac{2}{q \varepsilon N_A} \left( \Psi_{bi} - V - \frac{q}{kT} \right) \]

- \( W_D \): depletion width
- \( \Psi_{bi} \): built-in potential of the barrier
- \( C_D \): depletion layer capacitance per unit area
- \( N_A \): charge carrier density in the barrier

\[ N_A = \frac{2}{q \varepsilon} \left[ -\frac{1}{\frac{1}{C_D^2} / dV} \right] \]

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.

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

Nyquist Plots and Fitting

Bias Voltage: 0.7V

Bias Voltage: 0.6V

Bias Voltage: 0.5V

Bias Voltage: 0 V

PV Reliability Workshop, Feb. 18-19, 2010
C-V and Mott-Schottky Plots

![Graph of C-V and Mott-Schottky Plots]

PV Reliability Workshop, Feb. 18-19, 2010
Thickness Dependence_C1

Geometric capacitance did not change much with bias voltage.

<table>
<thead>
<tr>
<th>Geometric Capacitor C1</th>
<th>5409-2 (239 nm)</th>
<th>5409-6 (138 nm)</th>
<th>5409-8 (74 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated</td>
<td>1.17E-8</td>
<td>2.03E-8</td>
<td>3.77E-8</td>
</tr>
<tr>
<td>Fitting data</td>
<td>1.13E-8</td>
<td>2.3E-8</td>
<td>3.8E-8</td>
</tr>
</tbody>
</table>

- HTL is considered part of the electrode.
- Calculated values assume relative dielectric constant of 3.5.
Thicknes Dependence C2, C3

<table>
<thead>
<tr>
<th></th>
<th>C2_{N_A} (cm^{-3})</th>
<th>C2_{V_{bi}} (V)</th>
<th>C3_{N_A} (cm^{-3})</th>
<th>C3_{V_{bi}} (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5409-2</td>
<td>1.34E+15</td>
<td>0.462</td>
<td>8.68E+15</td>
<td>0.606</td>
</tr>
<tr>
<td>5409-6</td>
<td>1.45E+15</td>
<td>0.595</td>
<td>1.78E+16</td>
<td>0.697</td>
</tr>
<tr>
<td>5409-8</td>
<td>2.71E+15</td>
<td>0.604</td>
<td>1.51E+16</td>
<td>0.776</td>
</tr>
</tbody>
</table>

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?
Reasonable carrier lifetimes are extracted from the light-induced capacitance.
## Apply to Device Degradation

<table>
<thead>
<tr>
<th>Cause of Degradation</th>
<th>Impact on the Device</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delamination / dark spots</td>
<td>Active area effectively lowered. Jsc ↓.</td>
<td></td>
</tr>
<tr>
<td>Electrode oxidation</td>
<td>Rs ↑. Change in depletion capacitance or Vbi possible. An extra capacitor could potentially form if oxidation is severe.</td>
<td>Nyquist dark, Mott-Schottky</td>
</tr>
<tr>
<td>Active layer chemical decomposition or morphology changes</td>
<td>Recombination ↑. Carrier lifetime ↓. Voc, Jsc, and FF ↓.</td>
<td>Nyquist light</td>
</tr>
<tr>
<td>Active layer doping. Source of dopants can be either extrinsic (i.e. oxygen ingress) or intrinsic (diffusion from electrodes)</td>
<td>Rs ↓. Depletion capacitance ↑. Voc, Jsc and FF could go ↑ or ↓.</td>
<td>Nyquist dark, Mott-Schottky</td>
</tr>
<tr>
<td>Shunting of device due to electromigration of metal</td>
<td>Rp ↓. Voc, Jsc, and FF ↓.</td>
<td>Nyquist dark</td>
</tr>
</tbody>
</table>
## J-V Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Voc (V)</th>
<th>Jsc (mA/cm²)</th>
<th>FF</th>
<th>PCE</th>
<th>R@Voc (Ω)</th>
<th>R@Jsc (Ω)</th>
<th>Rs (Ω) Spice</th>
<th>Rp (Ω) Spice</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>5409-2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before exposure</td>
<td>0.8076</td>
<td>10.01</td>
<td>64.9%</td>
<td>5.25%</td>
<td>124</td>
<td>9.85E3</td>
<td>40</td>
<td>12.5E3</td>
</tr>
<tr>
<td>2 hours</td>
<td>0.8102</td>
<td>11.20</td>
<td>61.6%</td>
<td>5.59%</td>
<td>135</td>
<td>8.06E3</td>
<td>56</td>
<td>11.2E3</td>
</tr>
<tr>
<td>24 hours</td>
<td>0.7066</td>
<td>9.891</td>
<td>55.7%</td>
<td>3.89%</td>
<td>182</td>
<td>5.85E3</td>
<td>116</td>
<td>8.35E3</td>
</tr>
<tr>
<td>96 hours</td>
<td>0.6345</td>
<td>8.640</td>
<td>51.8%</td>
<td>2.84%</td>
<td>238</td>
<td>3.91E3</td>
<td>116</td>
<td>6.15E3</td>
</tr>
<tr>
<td><strong>5409-6</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before exposure</td>
<td>0.8188</td>
<td>5.401</td>
<td>59.4%</td>
<td>2.63%</td>
<td>231</td>
<td>9.07E3</td>
<td>55</td>
<td>12E3</td>
</tr>
<tr>
<td>2 hours</td>
<td>0.7084</td>
<td>5.943</td>
<td>56.4%</td>
<td>2.37%</td>
<td>240</td>
<td>7.09E3</td>
<td>79</td>
<td>11.8E3</td>
</tr>
<tr>
<td>24 hours</td>
<td>0.5950</td>
<td>5.598</td>
<td>54.9%</td>
<td>1.83%</td>
<td>238</td>
<td>7.31E3</td>
<td>64</td>
<td>11.2E3</td>
</tr>
<tr>
<td><strong>5409-8</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before exposure</td>
<td>0.8499</td>
<td>5.176</td>
<td>58.0%</td>
<td>2.55%</td>
<td>230</td>
<td>6.84E3</td>
<td>64</td>
<td>9E3</td>
</tr>
<tr>
<td>2 hours</td>
<td>0.8557</td>
<td>5.158</td>
<td>58.1%</td>
<td>2.56%</td>
<td>228</td>
<td>7.56E3</td>
<td>72</td>
<td>9.65E3</td>
</tr>
<tr>
<td>47 hours</td>
<td>0.8315</td>
<td>5.635</td>
<td>50.2%</td>
<td>2.35%</td>
<td>313</td>
<td>5.40E3</td>
<td>152</td>
<td>6.25E3</td>
</tr>
<tr>
<td>191 hours</td>
<td>0.7748</td>
<td>5.391</td>
<td>55.2%</td>
<td>2.31%</td>
<td>291</td>
<td>6.32e3</td>
<td>140</td>
<td>7.45E3</td>
</tr>
</tbody>
</table>
Mott-Schottky Plots

1/C^2 vs. Bias Voltage

- Red triangles: before exposure
- Black triangles: 2 hours exposure
- Blue circles: 24 hours exposure
- Green squares: 96 hours exposure

1/C^3 vs. Bias Voltage

- Red triangles: before exposure
- Black triangles: 2 hours exposure
- Blue circles: 24 hours exposure
- Green squares: 96 hours exposure
### Mott-Schottky Analysis

<table>
<thead>
<tr>
<th></th>
<th>C2_NA (Carrier Density)</th>
<th>C2_Vbi (Built-in Voltage)</th>
<th>C3_NA</th>
<th>C3_Vbi</th>
</tr>
</thead>
<tbody>
<tr>
<td>5409-2</td>
<td>before stress</td>
<td>1.34E+15</td>
<td>0.462</td>
<td>8.68E+15</td>
</tr>
<tr>
<td></td>
<td>2 hours</td>
<td>3.45E+15</td>
<td>0.463</td>
<td>2.69E+16</td>
</tr>
<tr>
<td></td>
<td>24 hours</td>
<td>4.20E+15</td>
<td>0.6</td>
<td>3.52E+16</td>
</tr>
<tr>
<td></td>
<td>96 hours</td>
<td>2.08E+15</td>
<td>0.193</td>
<td>2.84E+16</td>
</tr>
<tr>
<td>5409-6</td>
<td>before stress</td>
<td>1.45E+15</td>
<td>0.595</td>
<td>1.78E+16</td>
</tr>
<tr>
<td></td>
<td>2 hours</td>
<td>6.88E+15</td>
<td>0.721</td>
<td>1.17E+17</td>
</tr>
<tr>
<td></td>
<td>24 hours</td>
<td>7.16E+15</td>
<td>0.506</td>
<td>1.07E+17</td>
</tr>
<tr>
<td>5409-8</td>
<td>before stress</td>
<td>2.71E+15</td>
<td>0.604</td>
<td>1.51E+16</td>
</tr>
<tr>
<td></td>
<td>2 hours</td>
<td>1.09E+16</td>
<td>0.682</td>
<td>5.27E+16</td>
</tr>
<tr>
<td></td>
<td>24 hours</td>
<td>1.17E+16</td>
<td>0.657</td>
<td>9.95E+17</td>
</tr>
<tr>
<td></td>
<td>191 hours</td>
<td>2.69E+16</td>
<td>0.806</td>
<td>4.39E+17</td>
</tr>
</tbody>
</table>

Carrier density increased after initial stress, suggesting doping.
Photo-carrier lifetime decreased by order of magnitude upon Xe stress.
Photo-carrier lifetime decreased by order of magnitude upon Xe stress.
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.*

PV Reliability Workshop, Feb. 18-19, 2010
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
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
OPV Modules Results with Various Flexible Barrier Films
65 C dry oven (open circuit, dark)
OPV Modules Light Stability @ 1 sun, 65 C

% Efficiency normalized vs Time (hours) for Barrier 3.
OPV Thermal Cycling IEC 61646 10.11

% Efficiency normalized

Cycles

Barrier 3
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.
OPV Cells: Aging on Rooftop Test Station - under Load

Data at 1 Sun (1,000 W/m²)

Change in Power (%) vs. Days

Air Temperature

Proprietary Information of Konarka Technologies
Ultra-low Flexible Barriers
Needed to Enable Flex-Solar Modules

Approach: Pulsed valve sample introduction from atmospheric pressure test cell, permeation detection by mass spectrometry

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 permanent detection in a single measurement

OTR Certification Film Measurement Certification film (0.0026 cm³/pkg day) used to better estimate cell volume

Measurements on 3M Proprietary 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
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.
- 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.

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.
Comprehensive PV Durability Testing

The Atlas 25PLUS Testing Process

1. UV Conditioning
2. Salt Spray Corrosion
3. Condensing Humidity
4. Solar/Thermal/Humidity 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.

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

<table>
<thead>
<tr>
<th>Design Qualification environmental tests</th>
<th>Atlas module weathering tests</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intent:</strong> Accelerated tests to screen for major materials design and manufacturing flaws which result in premature (infant mortality) failures.</td>
<td><strong>Intent:</strong> 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.</td>
</tr>
<tr>
<td><strong>Climate Stresses:</strong>&lt;br&gt; E.g. Temperature-only cycling; UV-only exposure; Humidity-Freeze cycling; Damp-Heat. Most tests delivered to separate modules.</td>
<td><strong>Climate Stresses (comprehensive):</strong>&lt;br&gt; 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.</td>
</tr>
<tr>
<td>Stress levels and delivery not representative of end-use:&lt;br&gt; No module goes through all tests; limited to 1 or 2 stresses, e.g., thermal cycling, damp heat, humidity-freeze.</td>
<td>Stress levels based on climate-derived conditions:&lt;br&gt; Multiple simultaneous stresses delivered in short and long term cycles and at levels more representative of nature.</td>
</tr>
<tr>
<td>“Global Composite” climate condition standard;&lt;br&gt; alternative Hot Arid Desert, Tropical/Subtropical or Northern Temperate climate conditions available.</td>
<td>“Global Composite” climate condition standard; alternative Hot Arid Desert, Tropical/Subtropical or Northern Temperate climate conditions available.</td>
</tr>
<tr>
<td>Optional test modifiers: Coastal/Marine; Alpine/Snow Load; Urban Industrial; Agricultural Chemicals, Dust-Dirt, Acid Rain, Mildew effects.</td>
<td>Optional test modifiers: Coastal/Marine; Alpine/Snow Load; Urban Industrial; Agricultural Chemicals, Dust-Dirt, Acid Rain, Mildew effects.</td>
</tr>
</tbody>
</table>
# IEC and weathering methods

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

Atlas 25Plus "global composite" environmental test cycle (other climates available)

- UV conditioning
- Salt spray corrosion
- Condensing humidity

- Solar – Thermal – Humidity Cycle
- Solar – Thermal – Humidity/Freeze Cycle

Arizona solar tracking including peak summer

Total test program duration: 12 months
<table>
<thead>
<tr>
<th></th>
<th>Arid Desert</th>
<th>Tropical / Subtropical</th>
<th>Northern Temperate</th>
<th>“Global”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion</td>
<td>N/A (optional)</td>
<td>ISO 9227, ASTM B117 200 hours, 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour &quot;Neutral Salt Spray Test&quot;</td>
<td>ISO 9227, ASTM B117 400 hours, 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour &quot;Neutral Salt Spray Test&quot;</td>
<td>ISO 9227, ASTM B117 400 hours, 5% NaCl pH 6.5-7.2, 35°C, 1.0 to 2.5ml/80cm²/hour &quot;Neutral Salt Spray Test&quot;</td>
</tr>
<tr>
<td>Condensing Humidity</td>
<td>ASTM D2247, 125 hours @35°C or ISO 6270 40 °C</td>
<td>ASTM D2247, 125 hours @35°C or ISO 6270 40 °C</td>
<td>ASTM D2247, 125 hours @35°C or ISO 6270 40 °C</td>
<td>ASTM D2247, 125 hours @35°C or ISO 6270 40 °C</td>
</tr>
<tr>
<td>UV pre-conditioning</td>
<td>IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB</td>
<td>IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB</td>
<td>IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB</td>
<td>IEC 61215 to 30 kWh/m² (~28 days) UVA/UVB</td>
</tr>
<tr>
<td>Humidity Cycle with simultaneous Solar SC 2000 or Environmental Chamber w/Solar</td>
<td>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 16.7 cycles per day repeat 9.5 days (158 cycles)</td>
<td>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 16.7 cycles per day repeat 7 days (117 cycles)</td>
<td>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 16.7 cycles per day repeat 7 days (117 cycles)</td>
<td>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 16.7 cycles per day repeat 7 days (117 cycles)</td>
</tr>
<tr>
<td>Temperature-Humidity Freeze Cycle with Solar</td>
<td>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]</td>
<td>N/A</td>
<td>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) [27% of total 10 day cycles are freeze]</td>
<td>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]</td>
</tr>
</tbody>
</table>
Module temperature tracking

**Solar-Temperature-Humidity Cycle**

<table>
<thead>
<tr>
<th>Time (minutes)</th>
<th>CHT deg C</th>
<th>RH%</th>
<th>Panel deg C</th>
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<tbody>
<tr>
<td>0</td>
<td>65</td>
<td>55</td>
<td>86</td>
</tr>
<tr>
<td>5</td>
<td>51</td>
<td>47</td>
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<tr>
<td>10</td>
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<td>15</td>
<td>25</td>
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</tr>
<tr>
<td>86</td>
<td>64</td>
<td>69</td>
<td>87</td>
</tr>
</tbody>
</table>

*Dark* | *Light 1,000 W/m²*
Module temperature tracking

Solar-Temperature-Humidity-Freeze Cycle

deg C or RH% vs. Time (minutes)

Dark to Light 1,000 W/m² transition

- ▲ - CHT deg C
- ℹ️ - RH%
- ▲ - Module deg C

Table:

<table>
<thead>
<tr>
<th>Time (minutes)</th>
<th>CHT deg C</th>
<th>RH%</th>
<th>Module deg C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>64</td>
<td>55</td>
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<tr>
<td>100</td>
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<td>49</td>
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</tr>
<tr>
<td>105</td>
<td></td>
<td>59</td>
<td></td>
</tr>
</tbody>
</table>
Monitoring
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 crystalline & thin-film modules.

• **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.

• **JCGWG 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 60904-1: 2006 Ed 2, Photovoltaic devices-Part 1: Measurements of PV current-voltage characteristics
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
TC 82 Standards (Cont’d)

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 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
WG7 CONCENTRATOR PHOTOVOLTAICS
IEC 62108: 2007 Ed 1, Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval Amendment or revision is underway
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.)

JCGWGTC82/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


TC 82 Standards (Cont.)


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

<table>
<thead>
<tr>
<th>Design Quality and Confidence</th>
<th>Accelerated Qualification Testing</th>
<th>Accelerated Comparative Testing</th>
<th>Accelerated Lifetime Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum*</td>
<td>Medium**</td>
<td>High***</td>
<td></td>
</tr>
</tbody>
</table>

## Objective
- **Design Quality and Confidence**: Minimum testing for reliability/durability of specific module design  
- **Cost and Time**: Low  
- **Goal**: Introduce the specific design in the market
- **Testing Protocol**: Test standards exist  
- **Test Requirement**: Pass/Fail (>5% Power drop = Fail)
- **User**: Manufacturers/Consumers/Investors

## Current Study

<table>
<thead>
<tr>
<th>Literature search and review on failure mechanisms</th>
<th>Literature search and review on failure modes</th>
<th>Literature search and review on mathematical models</th>
</tr>
</thead>
</table>

## 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 Logo]

[Solar America Board for Codes and Standards]
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 (PV RAM & PVROM)  

**PV RAM Goal:** Predict for any component and any level of the system - versus time, versus time, versus time

![System-Level Reliability Diagram](image)

**PVROM Goal:** Compile failure event data into a web-based database for use with PVRAM

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 Joints)**
- **ALT Data Generated in Lab Tests**
- **ALT Data are incorporated into the system RBD**

Real Time Reliability Studies  

**At 5 years use field degradation rates and failure modes to correlate/validate ALT results, feedback to stakeholders, and input to predictive model development**

Industry Outreach and Standards Support  

**Integrator Reliability Workshop**
- March 31 - April 2, 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.

---

Sandia is a multiprogram laboratory operated by Sandia Corporation, a subsidiary of Lockheed Martin Corporation, 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 Alfred Stier for providing test samples and critical discussion relative to this work.
 Spi-Sun Simulator™

• SPECTRAL
• SPATIAL
• TEMPORAL

CLASS A SPECTRUM IN ALL LOCATIONS
Although Class A requires only one measurement point, Spire measures 96

IEC - COMPLIANT $R_s$ MEASUREMENT
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All simulators are compliant
WESTPAK, INC.

SOLAR LOGISTICS TESTING

NOW

R & D → MFG → CERT TEST → 25-YEAR LIFE

WHAT'S MISSING?

R & D → MFG → CERT & LOGISTICS TEST → 25-YEAR LIFE

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
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.
- Use Design of Experiments (DOE)?
- DOE can characterize, predict, and then improve performance.

2. DOE Process
- Engineering: Require process knowledge and engineering judgment.
- Identify factors and responses.
- Compute design for maximum information from exp't.
- Use design to set factors; measure responses for exp't.
- Compute best fit mathematical model for data.
- Use model to find best factor settings.
- Modeling: Require statistical software (JMP).

3. Challenge: How do we simultaneously change and test many process factors without logistical difficulties?
- “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.

4. Novel Split Plot Approach
- Factors are categorized by ease of change.
  - Easy: Programmable / Automated.
- 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.

5. Application to PV Characterization – Tabbing/Stringing
- Factors are categorized by ease of change.
  - Hard: Base-plate Temperature, Flux, Cu Thickness, Solder Thickness.
- 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. Conclusions
- Characterize process over a wide range of conditions.
  - Increase process knowledge.
  - Contribute to process robustness.
- Testing all factors simultaneously maximizes process knowledge.
  - Does not require prior experience with similar processes.
  - Can detect unpredicted effects.
- 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) In sensitive 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 prebreakdown sites.
5) Combined optical imaging for direct correlation to visual defects.

Imaging Technique
I. Four Bucket
Four images used to extract the phase and magnitude of the signal
Device Excitation
CCD
LED: Always ON

II. Transient Differencing Method
I. Shutter is open the full acquisition period
II. Illumination is pulsed
Device Excitation
CCD
LED
ΔT

Apparatus
VisibleCCD
Beam Splitter
LED
Substrate
Visible Objective
IR Objective
IR Beam Splitter
Near IR
CCD
IR Light

Examples
Combined Thermal/optical Images:
Defects in a poly-Si solar cell
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

Runaway Thermal images
a-Si
Reverse bias stressed
Encapsulated
OOS Scribe line
After thermal stress
Encapsulated
OOS Scribe line
After thermal stress
Encapsulated

Conclusions
1. 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.
2. For further information: Glenn Alers (galers@ucsc.edu), Ali Shakouri (all@soe.ucsc.edu)
A Single Layer Thin-Film Moisture Barrier for CIGS Solar Cells

Peter F. Garcia*, 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 applications.
- But CIGS cells are moisture sensitive. Modeling studies [1,2] deduce that encapsulation with water vapor transmission rate (WVTR) of 10⁶ to 10⁷ g·H₂O/100 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 Al₂O₃ films from trimethylaluminium and water.
- ALD is a superior process for producing thin-films with ultra-barrier (WVTR ~ 10⁻⁷ g·H₂O/100 m²·day) properties.
- Significantly better than other processes.

Moisture Barrier Properties of ALD Thin-film Al₂O₃

Three Encapsulants on CIGS Test Structures

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 ~ 50% decrease in efficiency.

Flexible (PET) film and PET/ALD barrier:

Efficiency of CIGS structures:

1000 hrs at 85°C, 85% RH light at open circuit

- Cells protected with a single ALD Al₂O₃ 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.

Conclusion and References

From damp heat testing with simulated solar illumination, a single layer ALD Al₂O₃ 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:
CIGS Cell-Level Reliability Task and Studies at NREL

Task Objectives:
- Long term: 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 term: Establish systematic experimental procedures and test designs.
- Identify degradation mechanisms and quantify degradation rates.
- Seeks chemical/physical mitigation methods.
- Develop reliable new encapsulation materials and schemes.

Main Subjects & Direction:
- CIGS, ZnO, Alternate TCOs (Al2O3, MgO, In2O3, SnO2).
- Fundamental material and device studies.
- Characterization and modeling.
- Device reliability.
- Prevent degradation of CIGS solar cells.

Chemical and Physical Mitigations:
- Chemical characterization techniques.
- Physical characterization techniques.

Interconnect Technologies and Reliability:
- Conductive adhesives for flexible interconnecting interconnects.
- Thin film deposition techniques for ITO, Al, and Pb.

Development of Quantitative Analysis:
- Nondestructive, noninvasive, in-situ and ex-situ characterization tools.
- New analytical methods and/or test structure design for in-situ and ex-situ measurements.

Industrial Collaborations

Performance Reliability Issues:
- Moisture Sensitivity of All Component Materials
- Gas/vacuum Encapsulation with Desiccant Desiccant
- Copper
- Rest

CIGS Component Reliability - 1a
Degradation of Mo on CIGS

DH=480h ZnO Films Became Porous & 10-20X Thicker

CIGS Component Reliability - 1b
Degradation of TCOs in DH

ZnO Films:
- Increased Transmission due to loss of Free-Carrier Absorption
- Formation of ZnOx, and Insulating ZnO (inside)
- Xerogel: Reacting with ITO, Pb, and F3

CIGS Component Reliability - 1c
Degradation of TCOs in DH

DH Induced Electrical Degradation:
- InP + In2O3 + SnO2 + ZnO + ZnO
- Decreased TCO Conductivity
- Slow degradation of In2O3

Humidity Susceptibility of CIGS Absorber

CIGS Component Reliability - 2a
Humidity Susceptibility of CIGS Absorber

Performance of Devices made with Moisture-Degraded CIGS Absorbers

Table 1. Cell Parameters for BIPV samples with and without Exposure to Humidity

DH Induced Delamination of Bare CIGS Devices

Chemical/Physical Mitigation for O2O

Mitigate DH-Degradation of CIGS Devices – Approach 2

Industrial Collaborations

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.
Characterization of Cohesive Surfaces

- XPS reveals similar debond path for DCB and 4-pt bend samples
- \( C \approx 93\%, S \approx 7\% \)
- 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

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 \( G_0 \) by d) delaminating the solar cell inside the weakest layer.

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.
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
• Applying various preconditioning methods to the same module can generate a considerably different Pmax result
Pre-Test Dark Rest Impact on Pmax Readout

Module Pmax by Pre-Test Condition

- 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

- 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.

**Valid Dark Bake Trends**

**Bogus Dark Bake Trends**

Module Preconditioning performed prior to all Pmax measurements

Module Preconditioning performed only at time zero measurement
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 ribs
  - 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

CE 3103 WLV Reliability 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
- R⁰ determined from intercept

* TLM Test Method for Contact Resistance Reliability Measurements

CE 3103 WLV Reliability Testing (TC -40°C/85°C, Sn-ITO)

CE 3103 WLV Reliability Testing (85°C/85%RH, Sn-ITO)

CE 3103 WLV Reliability Testing Sn – Al:ZnO on glass

CE 3103 WLV Flexibilized

<table>
<thead>
<tr>
<th>CE 3103 WLV</th>
<th>XCE 80239</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Semi-rigid</td>
</tr>
<tr>
<td>Velocity (µm)</td>
<td>20</td>
</tr>
<tr>
<td>Diameter (µm)</td>
<td>5</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>1.5G</td>
</tr>
<tr>
<td>Tensile stress (MPa)</td>
<td>100</td>
</tr>
<tr>
<td>True (µm)</td>
<td>15</td>
</tr>
</tbody>
</table>

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. @ 160°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

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 61215 Humidity Freeze test, while also providing insight into a panel’s long-term durability and performance.

Test Process
Highly Accelerated Lifetime Test Process
- Freeze the module to -40°C
- Light soak the module at 1500W/sq.m 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
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
Modules in outdoor test
Modules in outdoor test
Modules in outdoor test
SoloPower CIGS Product

Current Product

UL and IEC Certified

Next Generation

Flexible and light weight
SoloPower Product Line

SoloPower SFX1 Module
- Advanced polymer packaging
- Light weight (~1 lbs/sq.feet)

CIGS Cells
- 0.48 cm², 13.76%
- 102 cm², 12.25%

Flat Plate Modules
- 1.07 m² module
- 107.5 W output
- 10% Module

Flexible Modules
- UL and IEC Certified

**SoloPower SFX1 Module**

Device Area: 102.0 cm²
Irradiance: 1000.0 W/m²

**Parameters**
- $V_{oc} = 0.5411 \text{ V}$
- $I_{sc} = 3.5153 \text{ A}$
- $J_{sc} = 34.449 \text{ mA/cm}^2$
- Fill Factor = 65.72 %
- Efficiency = 12.25 %

**Device Area:** 10720.0 cm²
Irradiance: 1002.1 W/m²

**Parameters**
- $V_{oc} = 54.04 \text{ V}$
- $I_{sc} = 3.350 \text{ A}$
- Fill Factor = 59.4%
- Efficiency = 10.0 %

**UL and IEC Certified**
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
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
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
Glass strength can be affected by statistics and time

<table>
<thead>
<tr>
<th>Probability Factor</th>
<th>$F_P = \left[ \ln \left( \frac{1}{R} \right) \right]^{\frac{1}{m}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area Factor</td>
<td>$F_A = \left( \frac{A_{test}}{A_{product}} \right)^{\frac{1}{m}}$</td>
</tr>
<tr>
<td>Fatigue Factor</td>
<td>$F_F = \left( \frac{1}{\tau} \right)^{\frac{1}{n}}$</td>
</tr>
</tbody>
</table>

- $n = \text{fatigue exponent}$
- $\tau = \text{stress duration}$
- $R = \text{reliability}$
- $A = \text{area}$
- $S_0 = \text{Weibull characteristic strength}$
- $m = \text{Weibull modulus}$

Allowable Stress = \( (F_P \times F_A \times F_F) \times S_0 \)

Surface imperfections and fatigue determine strength over time.
Not all glasses are created equal; Different glasses have different fatigue resistances

<table>
<thead>
<tr>
<th>Glass</th>
<th>Fatigue Exponent</th>
<th>Relative Strength (30 Year Life)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soda-lime</td>
<td>~15</td>
<td>1.0</td>
</tr>
<tr>
<td>Corning PV glass</td>
<td>~20-23</td>
<td>1.4 – 1.6</td>
</tr>
<tr>
<td>Fused Silica (space shuttle windows)</td>
<td>~33</td>
<td>2.0</td>
</tr>
<tr>
<td>TiO$_2$ doped Silica (telescope mirrors)</td>
<td>~45</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Resistance to fatigue is quantified by fatigue exponent
large exponent is better
Thin glass passed hail impact testing

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

Heat strengthened 3.2 mm soda-lime
0.76 mm PVB
0.7 – 3.2 mm thin specialty glass

Pneumatic hail cannon
- ~1,800 25 mm ice ball impacts
- 25 - 44 mm ice ball testing capability

simply supported
- 600 mm
- 5 7 9
- 4 3 8
- 1 2 6

cantilevered
- 600 mm
- 8 9 10 3
- 7 5 2
- 6 4 1

Photovoltaic Glass Technologies © 2010 Corning Incorporated
Ice ball generates lower stresses than steel ball at equivalent impact energy

Steel ball (223g)  
Ice ball (25mm) (23m/s)  

1 meter

600 mm

Ice Ball Impact Location 1  
Steel Ball Impact Location 1

0.0 0.5 1.0
Time, milliseconds

0 20 40 60 80 100 120 140
Stress, MPa

0.0000 0.0005 0.0010 0.0015 0.0020
Time, seconds

Photovoltaic Glass Technologies © 2010 Corning Incorporated
Modeling of mounting configurations indicate that mounting is more important than glass thickness.
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

<table>
<thead>
<tr>
<th>Support Configuration</th>
<th>Glass thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>3 Rails</td>
<td>![Diagram]</td>
</tr>
<tr>
<td>Framed edge</td>
<td>![Diagram]</td>
</tr>
<tr>
<td>2 rails</td>
<td>![Diagram]</td>
</tr>
<tr>
<td>2 edge rails</td>
<td>![Diagram]</td>
</tr>
</tbody>
</table>
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