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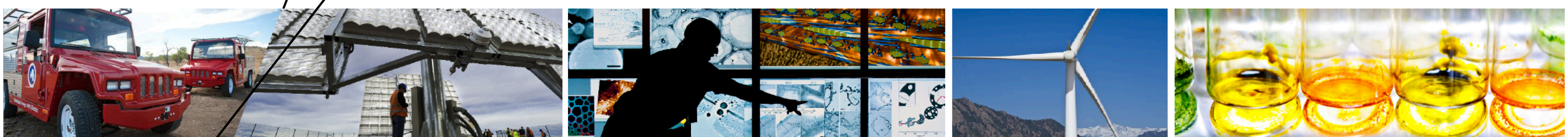
Accelerated Stress Testing, Qualification Testing, HAST, Field Experience – what do they all mean?



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Introduction

- The commercial success of PV is based on long term reliability and safety of the deployed PV modules.
- Today most PV modules are warranted for 25 years with a maximum allowable degradation rate of 0.8%/year.
- These modules are typically qualified/certified to:
  - IEC 61215 for Crystalline Silicon Modules
  - IEC 61646 for Thin Film Modules
  - IEC 62108 for CPV Modules
- These qualification tests do an excellent job of identifying design, materials and process flaws that could lead to premature field failures.

Introduction (Continued)

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

International PV QA Task Force

Goals of Talk

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

What is our overall goal

- To evaluate the long term performance of PV modules in a variety of terrestrial climates.
- Really should use outdoor performance data to do this.
- However, none of us wants to wait 25 years to determine if a particular module type is going to have a 25 year lifetime.
- Therefore, we use accelerated stress tests to try to predict what is going to happen outdoors.
- These accelerated stress tests are based on duplicating the failure modes observed in the field.
- The first step in this process is to identify the various field failures that have been observed for different types of PV modules.

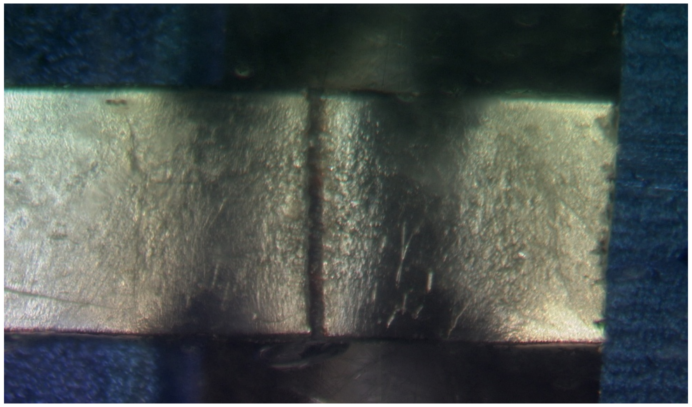
HISTORY OF FIELD FAILURES for Cry-Si

- Broken interconnects
- Broken cells
- Corrosion of cells, metals and connectors
- Delamination/loss of adhesion between layers
- Loss of elastomeric properties of encapsulant or backsheet
- Encapsulant discoloration
- Solder bond failures
- Broken glass
- Glass corrosion
- Hot Spots
- Ground faults due to breakdown of insulation package
- Junction box and module connection failures
- Structural failures
- Bypass Diode failures
- Open circuiting leading to arcing
- Potential Induced Degradation

Examples of Field Failures

Broken Cells

Broken Interconnects



Corrosion

From JPL

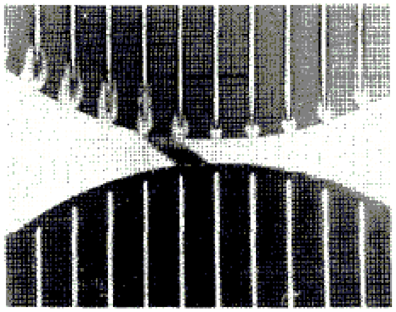
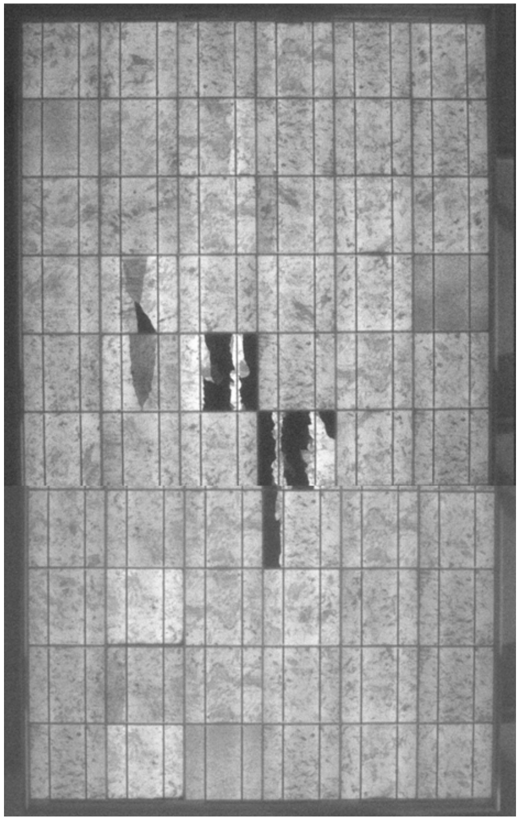


Figure 2. Solar-Cell Electrochemical Corrosion



From Peter Hacke, NREL

Delamination

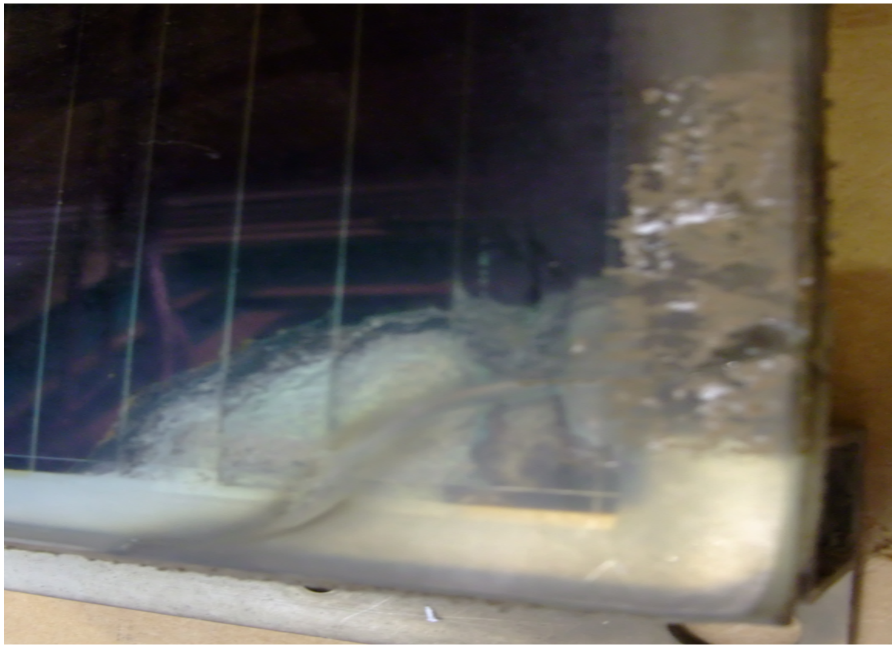
Additional Failure Modes for Thin Film Modules

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

Additional Field Failures for Thin Films

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

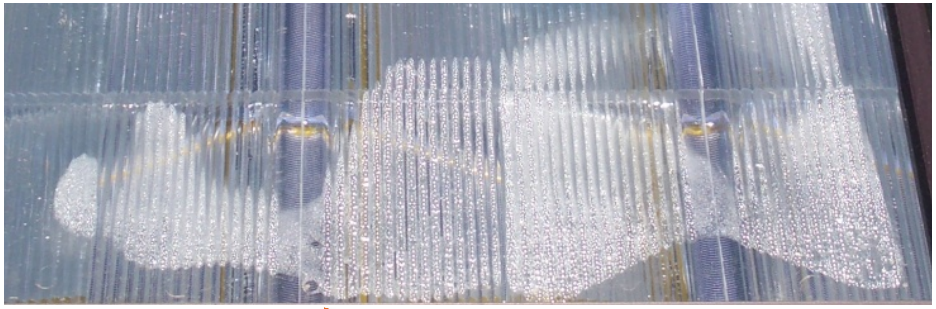
Broken Glass Leading to Corrosion

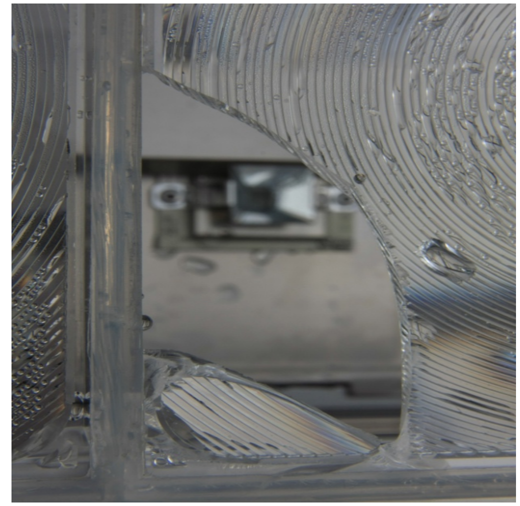


Additional Failure Modes for CPV Modules

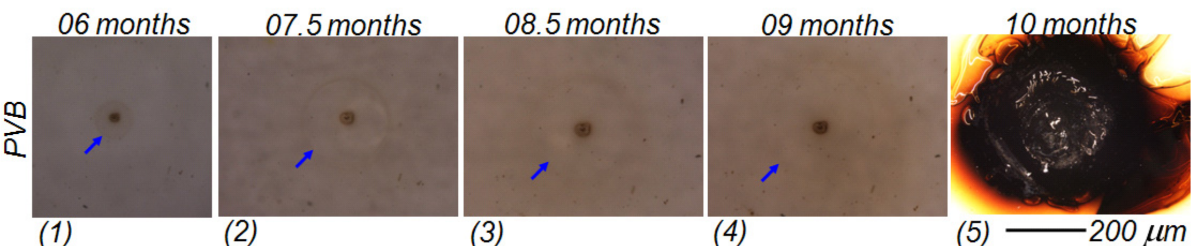
- Tracker misalignment
- Tracker failures
- High current densities leading to overheating
- Rapid and numerous thermal cycles stressing the cell to substrate bond
- UV degradation of optics
- Moisture condensing with optical package
- Overheating of the encapsulant due to UV darkening

Additional Failures for CPV

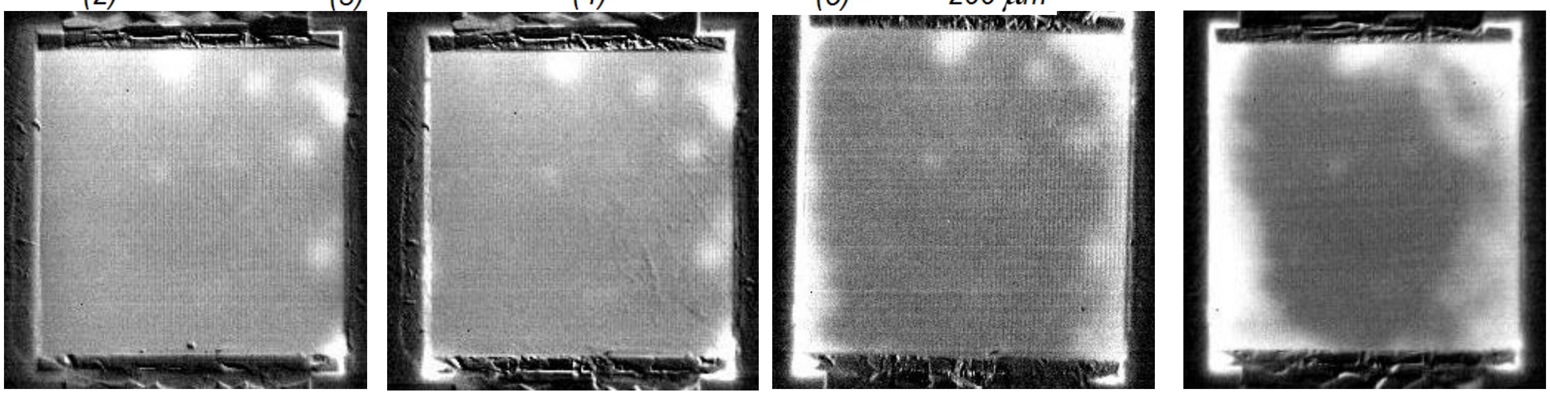




From Matt Muller, NREL



From Dave Miller, NREL



initial   500 cycles   1000 cycles   1500 cycles

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

Developing Accelerated Stress Tests

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

Some Rules Governing our ASTs

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

Accelerated Stress Tests

Accelerated Stress Test	Failure Mode	Technology
Thermal Cycles	Broken interconnect Broken cells Electrical bond failure Junction box adhesion Module open circuit – potential for arcing	Cry-Si & CPV Cry-Si & CPV All All All
Damp Heat	Corrosion Delamination Encapsulant loss of adhesion & elasticity Junction box adhesion Electrochemical corrosion of TCO Inadequate edge deletion Potential Induced Degradation	All All All All TF TF Cry-Si & TF
Humidity Freeze	Delamination Junction box adhesion Inadequate edge deletion Insufficiently cured encapsulant	All All TF All

Accelerated Stress Tests for PV (cont)

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

Accelerated Stress Tests for PV (cont)

Accelerated Stress Test	Failure Mode	
Hot spot test	Hot spots Shunts in cells or at scribe lines Inadequate by-pass diode protection	All All & TF All
Hail Test	Broken glass Broken cells Broken Optics	Cry-Si & TF Cry-Si CPV
By-pass Diode Thermal Test	By-pass diode failures Overheating of diode causing degradation of encapsulant, backsheet or junction box	All All
Salt Spray	Corrosion due to salt water & salt mist Corrosion due to salt used for snow and ice removal	All All

Qualification tests

- Qualification tests are a set of well defined accelerated stress tests developed out of a reliability program.
- They utilize accelerated stress tests to duplicate failure modes observed in the field.
- They incorporate strict pass/fail criteria.
- The stress levels and durations are limited so the tests can be completed within a reasonable amount of time and cost.
- The goal for Qualification testing is that a significant number of commercial modules will pass.

(If not there will be no commercial market.)

- Qualifies the design and helps to eliminate infant mortality

Passing IEC 61215, IEC 61646 or IEC 62108

- **So what does it mean if a module type is qualified to IEC 61215, IEC 61646 or IEC 62108?**
- **Passing the qualification test means the product has met a specific set of requirements.**
- **Those that have passed the qualification test are much more likely to survive in the field and not have design flaws that lead to infant mortality.**
- **Most of today's commercial modules pass the qualification sequence with minimum change, meaning the qualification tests do not provide a means of rankings within the group that has passed the requirements.**

How Successful are the Qualification Tests?

- They must be fairly successful because the PV industry has been growing rapidly.
- Reports of Field Failures/ Warranty Returns:
  - ✓ Whipple reported on 10 years of field results in 1993 (using data from Rosenthal, Thomas and Durand) that
    - Pre-Block V modules suffered from 45% field failure rate
    - Post- Block V modules suffered from < 0.1% field failure rate
  - ✓ Hibberd from 2011 PVMRW – 125,000 modules from 11 different module manufacturers deployed for up to 5 years with only 6 module failures. (0.005%)
  - ✓ Wohlgemuth et. al. from 20th EU PVSEC – Solarex/BP Solar multi-crystalline Si modules deployed from 1994-2005 with 0.13% warranty return rate (1 failure every 4200 module years of operation)
  - ✓ Wohlgemuth et. al. from 23rd EU PVSEC – Solarex/BP Solar multi-crystalline Si modules from 2005 onward with an annual return rate of 0.01%

Limitations of Qualification Tests

By design the qualification tests have limitations.

They were designed to identify early infant mortality problems, but not to:

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

HAST Tests

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

So what tests do we use in PV?

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

International PV Module QA Task Force

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

International PV Module QA Task Force

Goals of International PV QA Task Force:

1. *To develop a QA rating system that provides comparative information about the relative durability of PV modules to a variety of stresses as a useful tool to PV customers and as a starting point for improving the accuracy of quantitative PV lifetime predictions.*
   1) Compare module designs
   2) Provide a basis for manufacturers' warranties
   3) Provide investors with confidence in their investments
   4) Provide data for setting insurance rates
2. Create a guideline for factory inspections of the QA system used during manufacturing.

PV QA Task Force

Task Group 1: Guideline for Manufacturing Consistency

Task Group 2: Thermal and mechanical fatigue including vibration

Task Group 3: Humidity, temperature, and voltage

Task Group 4: Diodes, shading and reverse bias

Task Group 5: UV, temperature and humidity

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

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

Task Group 8: Thin Film PV (New group)

Task Group 9: CPV (New group)

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

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

Summary

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