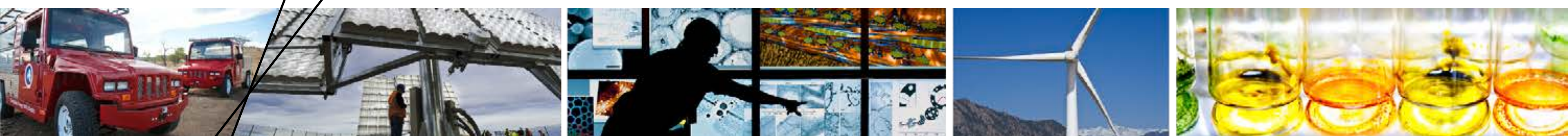
Differences Between Qualification Tests, Comparative Tests and Service Life Predictions and How They Use Accelerated Stress Tests in Different Ways



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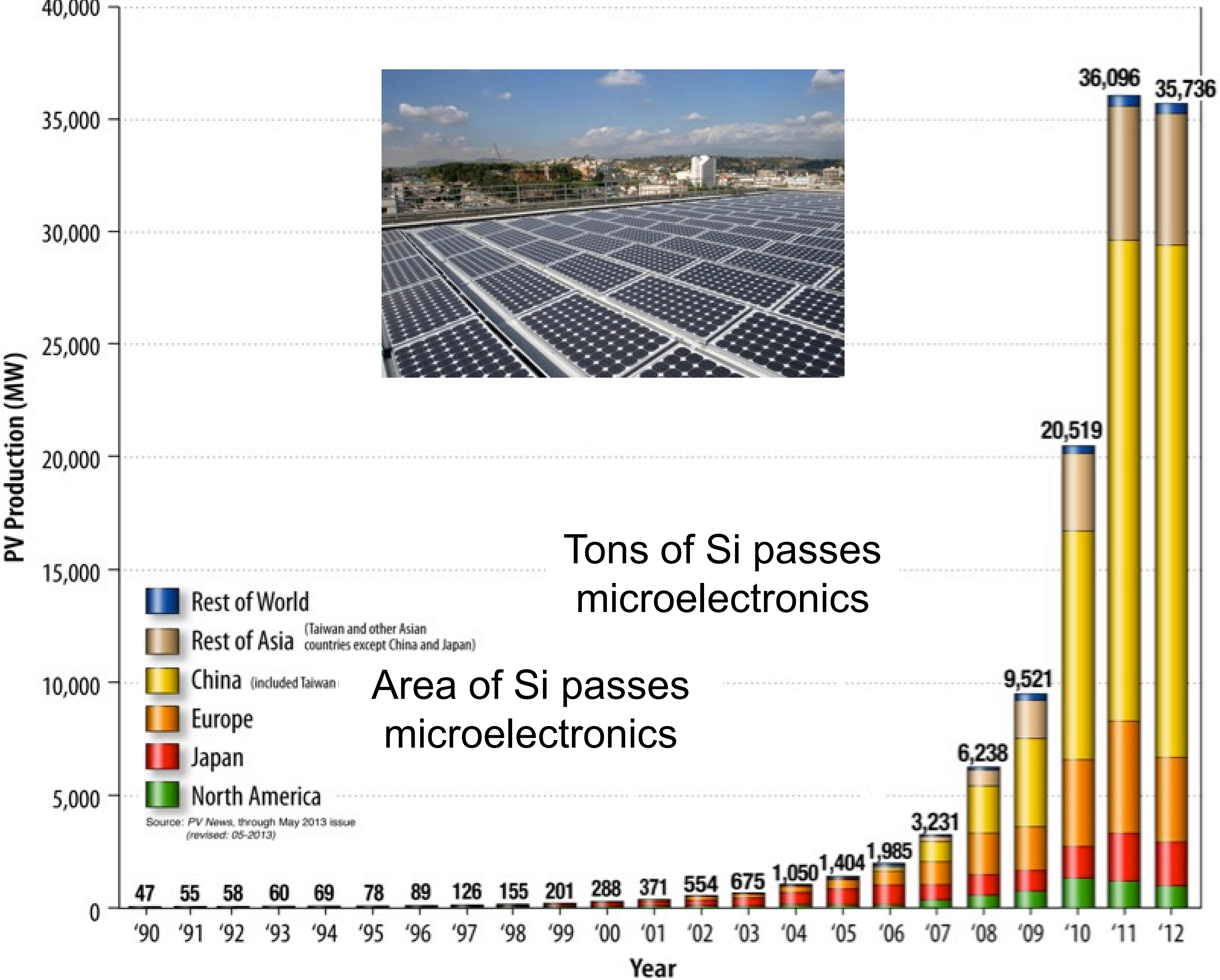
October 10, 2013

4th International PV Module QA Forum

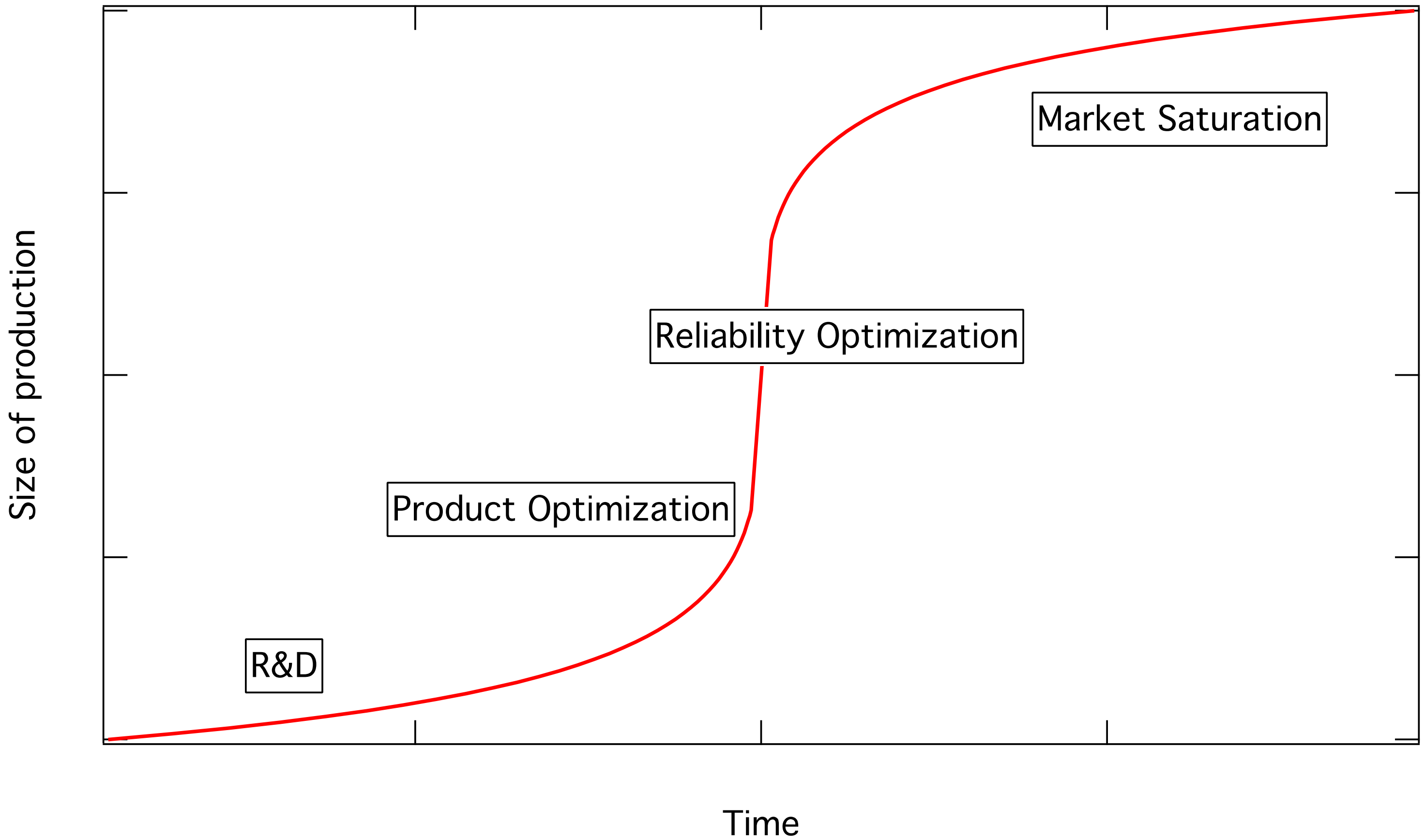
Outline of Talk

- Why reliability is becoming even more important in PV
- Try to describe the relationships between
  - Field test results
  - Accelerated stress tests
- What are Qualification Tests and what are their limits.
- What are Comparative Tests and why should we be interested in them.
- What are Service Life Predictions and what we have to do to achieve them.

PV Industry has Grown to be Huge!



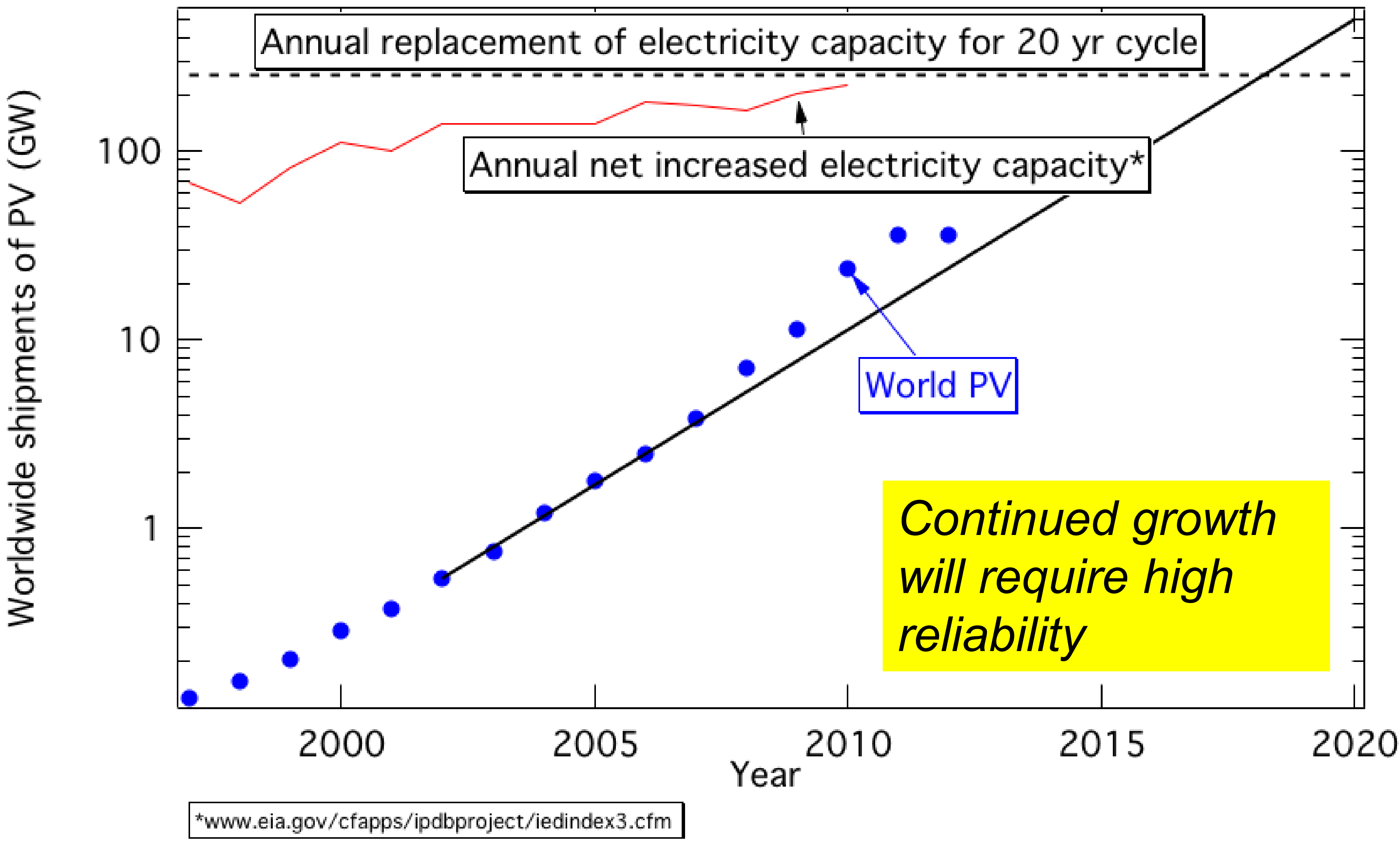
Reliability Optimization is an Important Element of Growth



PV is now approaching ~$100 Billion/y

Reliability is key to continued natural growth

Growth of PV Industry Requires Reliability



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

What is our overall goal

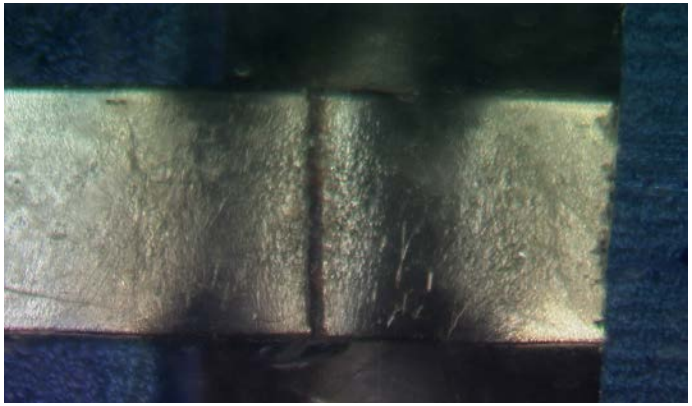
- To evaluate the long term performance of PV modules in a variety of terrestrial climates.
- Really should use outdoor performance data to do this.
- However, none of us wants to wait 25 years to determine if a particular module type is going to have a 25 year lifetime.
- Therefore, we use accelerated 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 Interconnects



Corrosion

From JPL

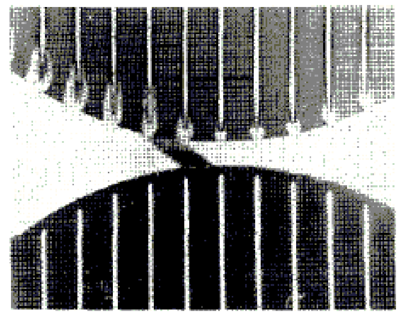
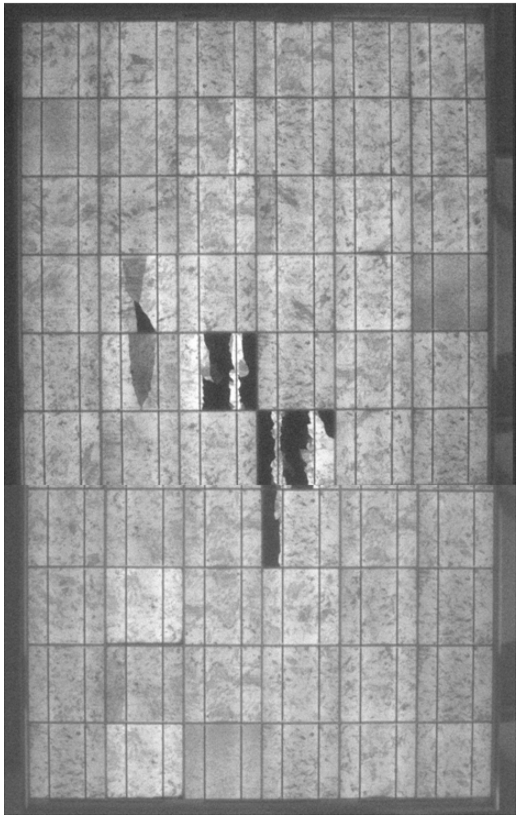


Figure 2. Solar-Cell Electrochemical Corrosion

Delamination

Broken Cells



From Peter Hacke, NREL

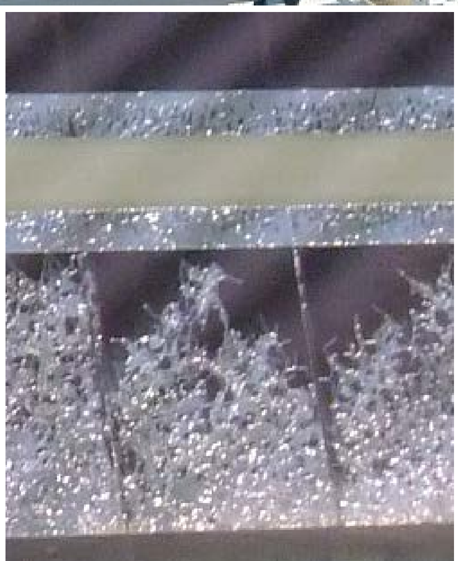
10

Additional Failure Modes for Thin Film Modules

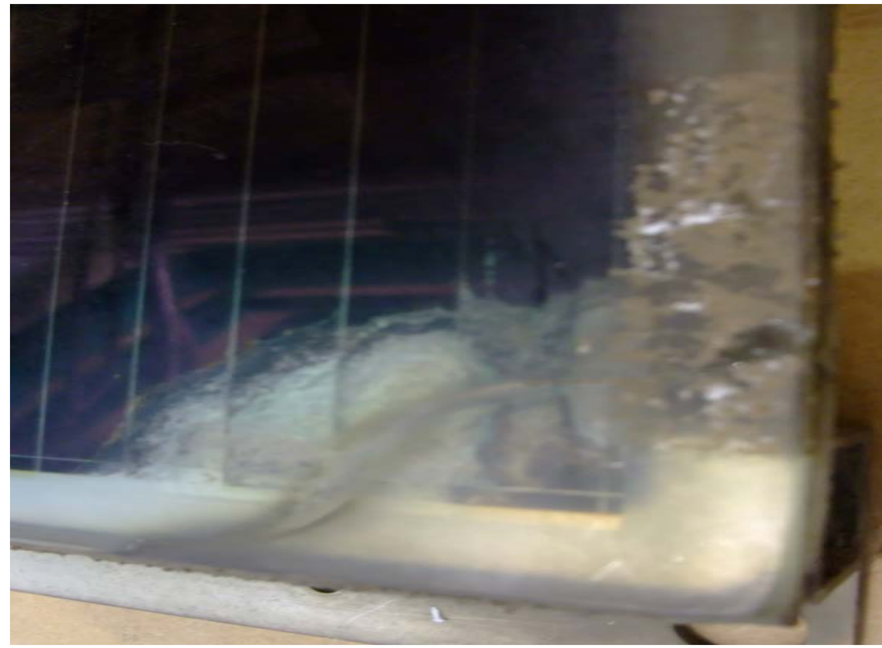
- Electro-chemical corrosion of TCO.
- Light Induced Degradation
- Inadequate Edge Deletion
- Shunts at laser scribes
- Shunts at impurities in films
- Diffusion of metals from contacts through the junction

Additional Field Failures for Thin Films

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



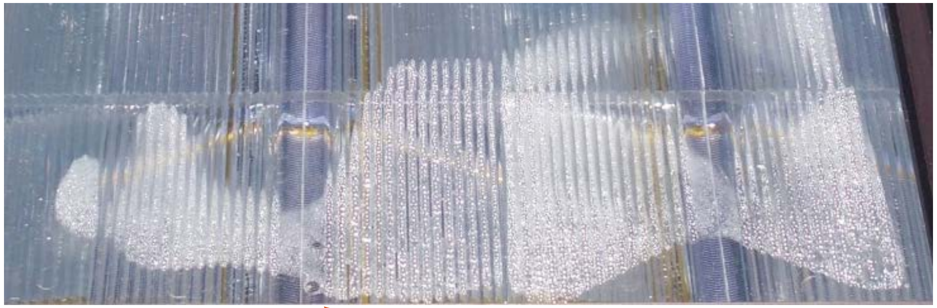
Broken Glass Leading to Corrosion

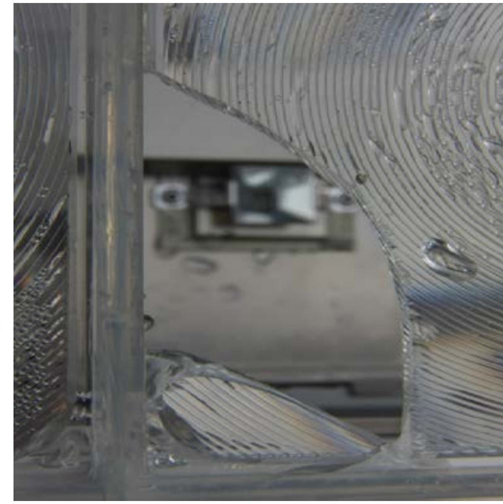


Additional Failure Modes for CPV Modules

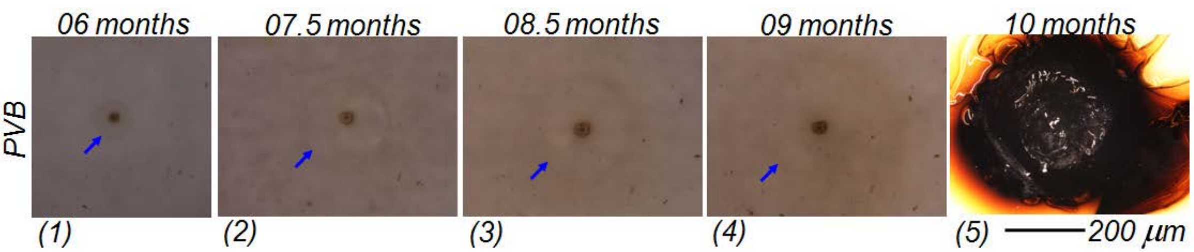
- Tracker misalignment
- Tracker failures
- High current densities leading to overheating
- Rapid and numerous thermal cycles stressing the cell to substrate bond
- UV degradation of optics
- Moisture condensing with optical package
- Overheating of the encapsulant due to UV darkening

Additional Failures for CPV

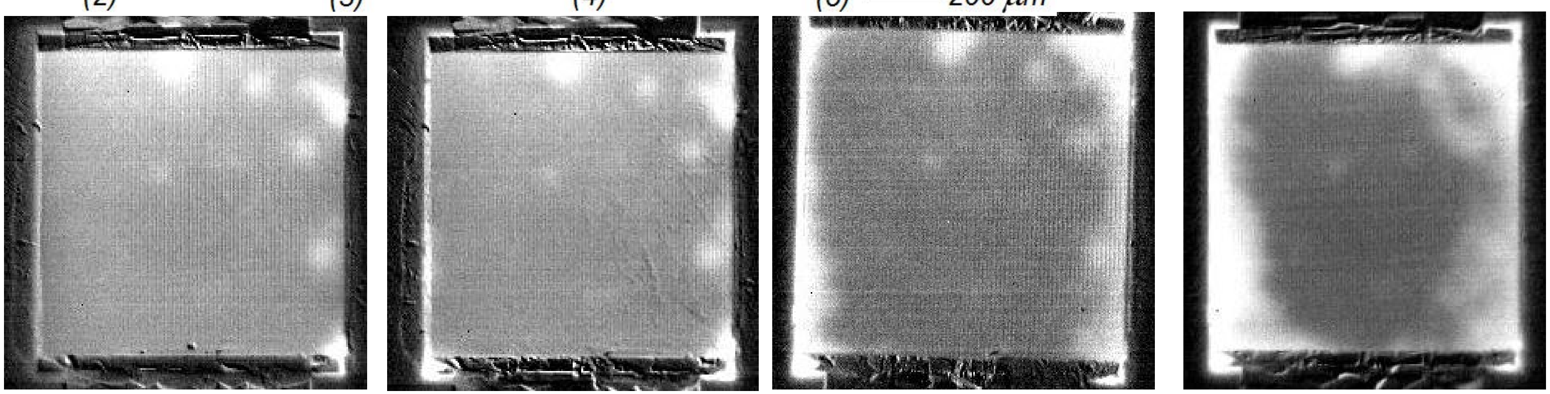




From Matt Muller, NREL



From Dave Miller, NREL



initial 500 cycles 1000 cycles 1500 cycles

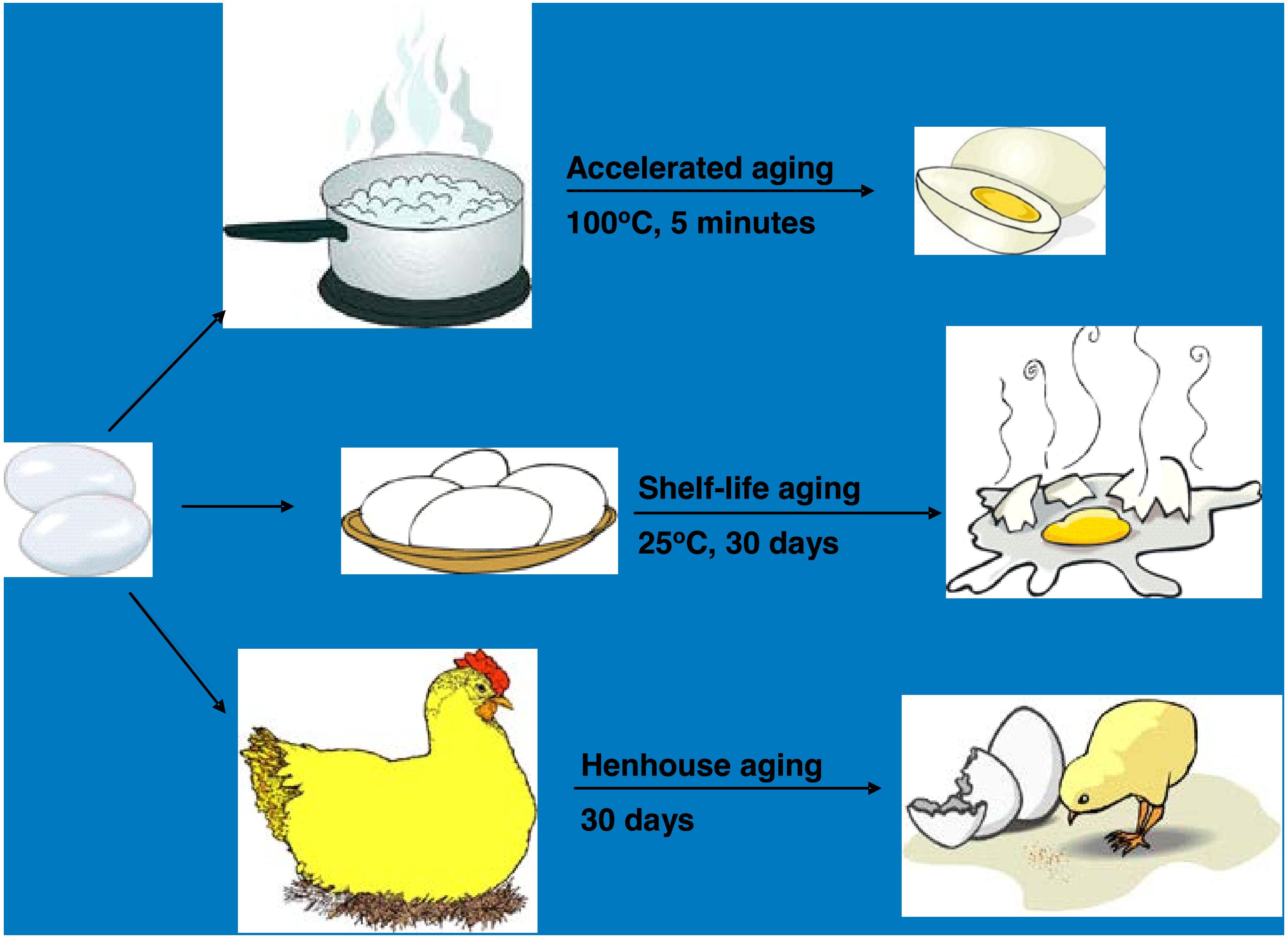
Progression of IR images illustrating die-attach cracking through thermal cycling from Nick Bosco, NREL

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 processes can be accelerated more easily than others

Accelerating 25 y into 3 months is like hatching a chick in 6 hours!



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 a chance that we can extrapolate the test date to provide a 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.

Testing Beyond Qualification

- If qualification tests do not test for wear-out, how can we use the accelerated stress tests to evaluate module wear-out.
- The first step is to identify failure modes for modules that pass the qualification tests.
- 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?

Testing Beyond Qualification

- Perform experiments or use published data to determine the reaction rate(s) 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.

Comparative Testing

- Once we reach the "Use model to predict" bullet on the previous page we should be able to design an accelerated stress that that is comparative (see below). This can be done well before lifetime tests can be determined.
- Comparative means that the results of the test can be used to compare the performance of several products but not to determine absolute performance.
- If module a does better in the comarative test than module b, it will survive longer in the field in the relevant climate.

	Qualification	Comparative	Lifetime
Purpose	Minimum design requirement	Comparison of products	Substantiation of warranty
Quantification?	Pass/fail	Relative	Absolute
Mechanisms studied	Infant mortality	Wear out	Wear out
Climate or application	No differentiation	Differentiated	Differentiated

Comparative Testing

- **How can Comparative Testing be Useful?**
  - To determine how changes in module design, processing or materials impact the reliability and lifetime.
  - To select a module type for a particular project.
  - Provide data for setting insurance rates.
- **How Comparative Testing Shouldn't be used.**
  - To validate warranty or lifetime.

Service Life Predictions

- **Once we have worked our way through the entire sequence on pages 26 and 27 we should be define lifetime tests for specified climates.**
- **The problem here is that the relationships between accelerated tests and field results are likely to be product specific.**
  - There will be a different response to UV for each encapsulation system.
  - Thee may be a different response to thermal cycling for each geometry and each interconnect ribbon.

So how do we do Service Life Predictions

- Because of the specifics of construction and climates it is likely that we will not be able to specify a one to one relationship between a test result on all modules and their field performance.
- We may not be able to say that 4000 hours of a specific UV exposure equates to 25 years of field service in Arizona.
- What we may have to do is write a standard that provides a methodology for determining the field equivalency for each of our tests.
- Then the PV module manufacturer would follow the procedure to determine the relationship (Acceleration factor) for their product in a particular climate.
- The data and method used for this calculation would be part of the manufacturing Quality Assurance Plan that could be audited to validate their claims and warranty.

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.
- The effort now underway as part of the PV Module QA Task Force, will lead to Comparative Tests.
- Taking the step to Service Life Predictions will take a longer time and will likely involve each manufacturer determining their product's lifetime based on their own data using a standard methodology.