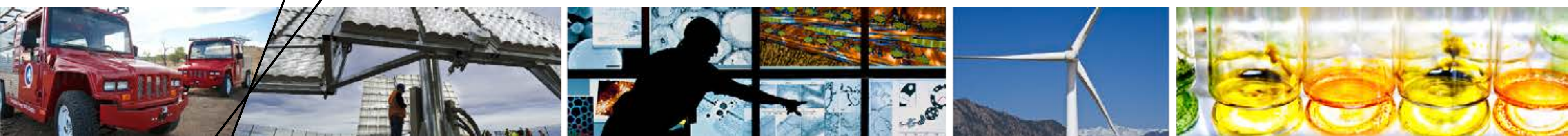
Determining the Acceleration Rates for PV Module Stress Tests



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Atlas/NIST Workshop

Outline of Talk

- **Introduction - What we really want to know about reliability, durability and service life of PV modules.**
- **How we developed the accelerated stress tests we utilize today.**
- **How do we establish the relationships between long term outdoor exposure and accelerated stress tests?**
- **Qualitative versus Quantitative Accelerated Stress tests.**
- **Determining the acceleration factors for Quantitative Accelerated Stress tests.**
- **Using the acceleration factors to predict the service life of PV modules.**

What we want to know

- How reliable are the modules being produced or purchased; what fraction will fail in any given time period?
- How durable are the modules being produced or purchased; what fraction of their initial power will they lose over time?
- What is the service life of the modules being produced or purchased; how many years will they continue producing adequate power in a safe manner?

What we want to know (Continued)

- Is there a set of tests that we could perform on the modules that would predict their long term field performance in terms of reliability, durability or service life?
- The answer is no, such a set of tests does not exist today.
- This was one of the major reasons for the formation of the

International PV Module QA Task Force

What is our overall goal

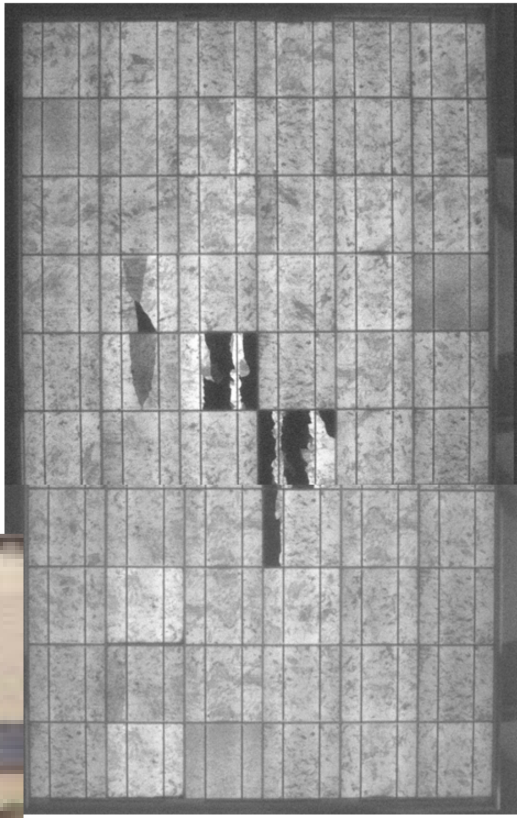
- To evaluate the long term performance of PV modules in a variety of terrestrial climates.
- Really should use outdoor performance data to do this.
- However, none of us wants to wait 25 years to determine if a particular module type is going to have a 25 year lifetime.
- Therefore, we use accelerated 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.
- I will only look at crystalline-Si in this presentation because there is more data and better understanding of the observed failure modes and how the field data compares to the accelerated stress test data.

HISTORY OF FIELD FAILURES for Cry-Si

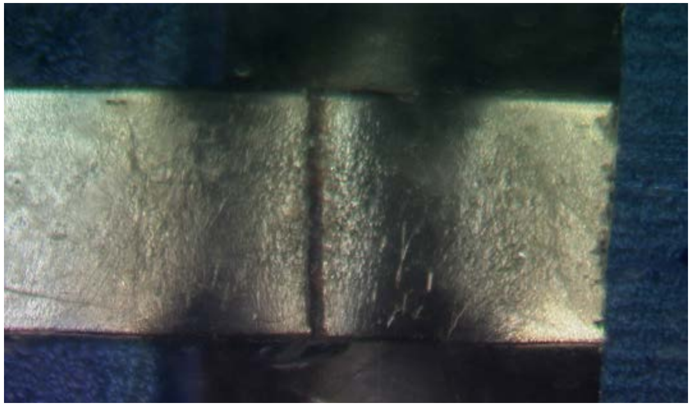
- Broken interconnects
- Broken cells
- Corrosion of cells, metallization and connectors
- Delamination/loss of adhesion between layers
- Loss of elastomeric properties of encapsulant or backsheet
- Encapsulant discoloration
- Solder bond failures
- Broken glass
- Glass corrosion
- Hot Spots
- Ground 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

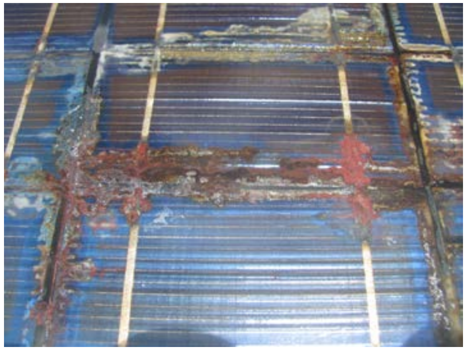
Broken Cells



Broken Interconnects



Corrosion



Delamination

Failed Solder Bond

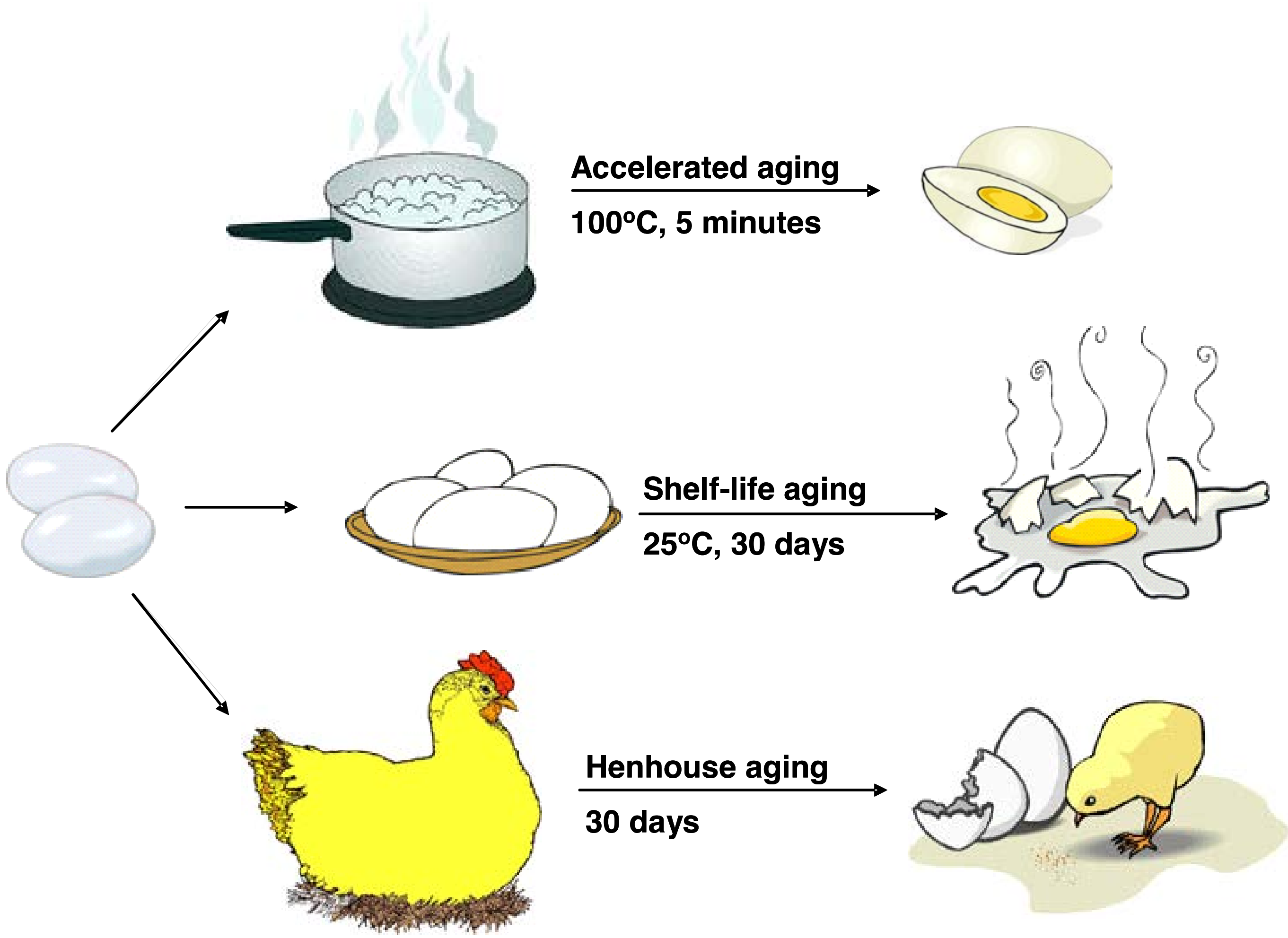
From Peter Hacke, NREL

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
  - A combination of several or all of the above
  - 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
  - Operation at higher temperature
  - Cycle the 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 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.**
- **Two types of ASTs**
  - Qualitative: Torture tests used primarily to reveal probable failure modes in the module.
  - Quantitative: Tests designed to quantify the life of the product and to produce the data required for accelerated life data analysis.
- **Because Quantitative ASTs are causing the same failure as seen in the field there is a chance that if we understand the science behind the degradation mechanism that we can extrapolate the test data to provide a lifetime prediction for this one failure mode.**
- **The 35 years of PV history with field failures and ASTs have given us a good background to build on.**
- **So let's make a list of the ASTs used in PV.**

Accelerated Stress Tests for PV

- Thermal Cycling
- Humidity Freeze
- Damp Heat
- UV and Temperature
- Static Mechanical Load
- Dynamic Mechanical Load
- Hot Spot Test
- Hail Test
- By-pass Diode Thermal Test
- Salt Spray Test
- Ammonia Test

These PV ASTs are Qualitative

- **Humidity Freeze – are interfaces well adhered?**
- **Static Mechanical Load – Can module sustain adequate dead loads to survive?**
- **Hot Spot Test – Are modules adequately diode protected to keep cells from overheating in reverse bias?**
- **Hail Test – Can module survive specific size hail stone at its terminal velocity? You might consider the fact that you can use different ice ball sizes and velocities as quantitative, but these aren't going to help you to determine an acceleration factor or lifetime they only indicate what level of hail the module is likely to survive.**
- **By-pass Diode Thermal Test – Can by-pass diode protect cells without overheating itself?**
- **Salt Spray Test – Is module reasonably resistant to corrosion by salt water? You might consider this test Quantitative if you try using the different exposure levels defined in edition 2 of IEC 61701.**
- **Ammonia Test – Is the module reasonably resistant to corrosion by ammonia (from animal waste)?**

These PV ASTs are Quantitative

- **Thermal Cycling**
  - Using the change in temperature and CTE mismatch between constrained materials to impart strain which results in stress within and between these materials.
  - Tests for broken interconnects, broken cells, solder bond failures, adhesion loss (including j-box and frame)
- **Damp Heat**
  - Using damp heat to evaluate failures due to moisture ingress into the module
  - Tests for corrosion, loss of adhesion especially encapsulant and backsheet, and Potential Induced Degradation.
  - JPL selected 1000 hours at 85 °C and 85% Relative Humidity based on a model of this representing 20 years in Miami, FL for a failure mechanism associated with ion conductivity in PVB encapsulant.
- **UV and Temperature**
  - Using UV and elevated temperature to determine the susceptibility of the materials in PV module to degradation by the UV radiation in sunlight.
  - Tests for loss of adhesion especially encapsulants and backsheets, discoloration of encapsulants and frontsheets, and breakdown of materials that provide the insulation for the package (encapsulants, backsheets, junction boxes, connectors and cables.
  - Level used in the Qualification tests is too short to cause much degradation.
- **Dynamic Mechanical Load – Can be either Quantitative or Qualitative depending on how it is utilized.**
  - At high stress levels it can cause continued damage to interconnect ribbons similar to thermal cycling so could be considered qualitative
  - At low stress levels it typically only breaks those things that are pre-stressed already. The damage plateaus after a number of cycles so could be considered quantitative.

Testing for Acceleration Factors

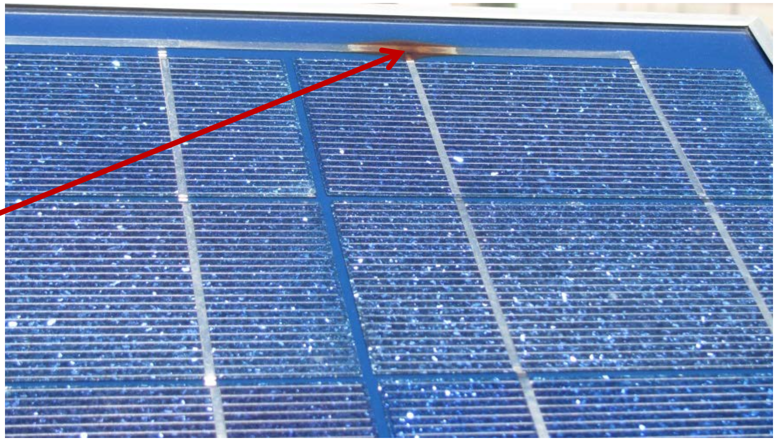
- From this analysis we only have 3 ASTs to worry about determining acceleration factors for.
- This is good because as you will see it is a very complicated process.
- Our last chart gave us a first look at this since none of the 3 Qualitative ASTs causes only one failure mode.
- If we look at thermal cycle and just consider the failure modes that impact fill factor (ignoring j-box and frame adhesive failures for now) we still have three failure modes to consider - broken interconnect, broken cells and solder bond failures.
- To make it even more complicated, it is likely that TC does not break cells, but rather opens up the metal grid lines in cells that were already broken – which is why the sequence of dynamic mechanical loading followed by TC is so effective.
- So for each of the 3 failures there are different mechanisms that cause the failure each with its own acceleration factor.

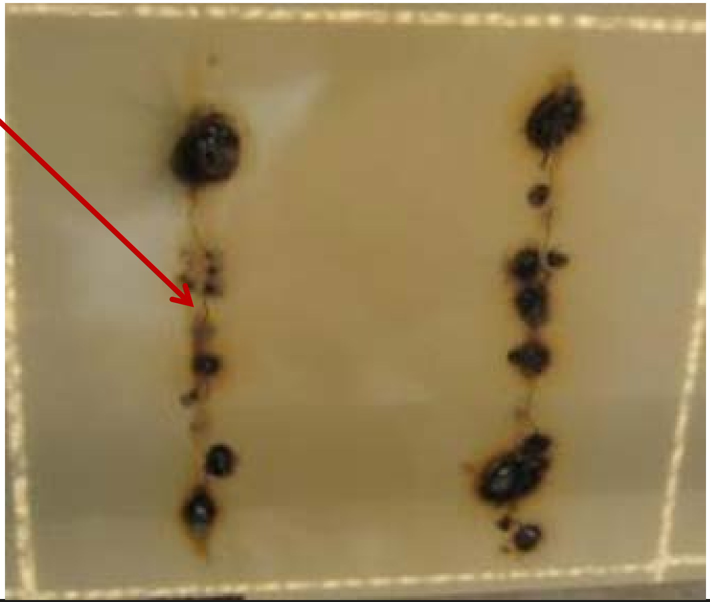
Tools for Studying Acceleration Factors

- **To study acceleration factors it is useful to perform the accelerated stress tests different levels.**
- **Outdoor exposure**
  - o Degradation rates
  - o Observed types of failures
  - o Failure rates
- **Modeling**
  - o How the weather stresses the module.
  - o How the weather induced stress degrades the module.

Design versus Workmanship Failures

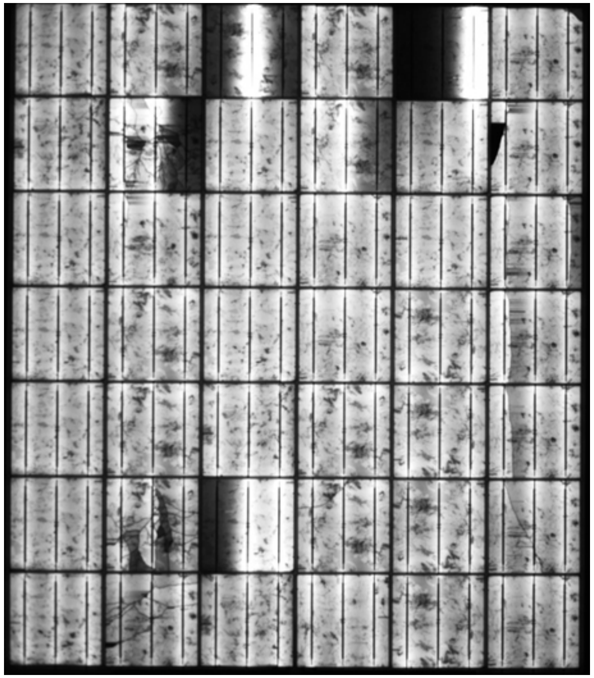
- When field failures are observed we must determine whether they are due to design flaws or workmanship problems.
- For example when you see one bad solder bond on a bus bar it is probably a workmanship problem.
- When you see multiple bad solder bonds in the same module it is likely a design issue (solder bonds too small) or a process issue (production equipment not in control).
- We are interested in the latter.
- However this does mean that the acceleration rates we measure are ignoring the manufacturing issues.
- This is why a robust QA system for PV module manufacturing is so important.

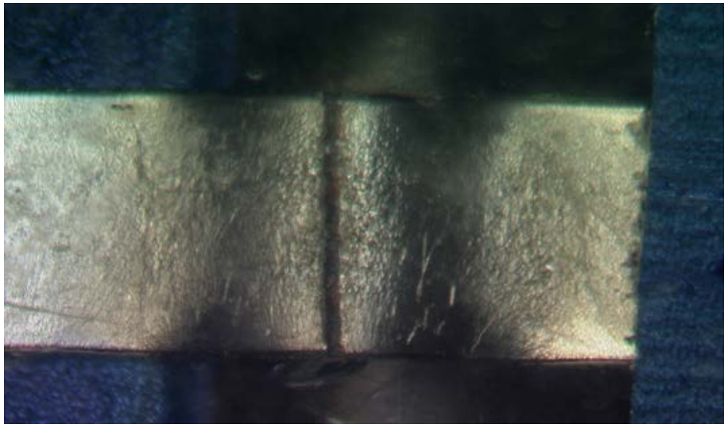




Evaluating Field Data for TC related issues

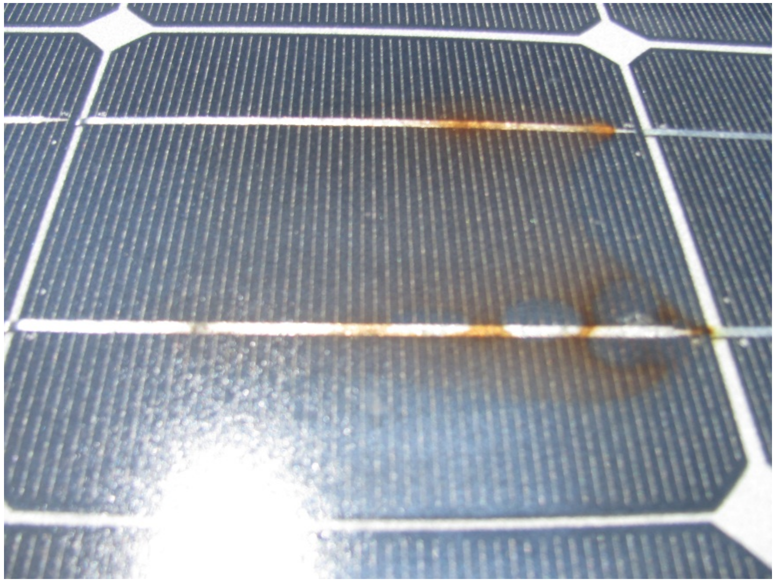
- **Broken interconnects**
  - Observe in EL as dark area where that interconnect should be collecting.
  - Can actually see the cracks in some interconnect ribbons.
  - Usually takes longer time period (at least > 5 years) to have a major impact on performance even if poorly designed. (So they pass Qualification test).
  - If design issue you often see multiple interconnect breaks in each module.





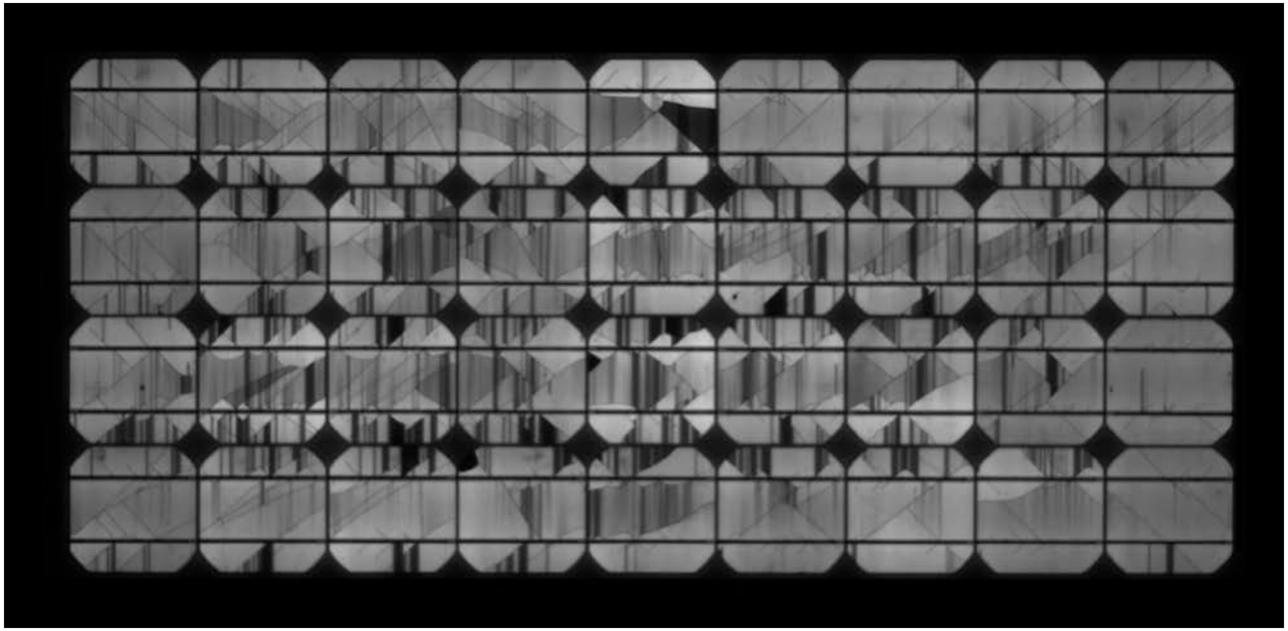
Evaluating Field Data for TC related issues

- **Solder bonds**
  - Some show overheating when they fail.
  - EL image usually shows discontinuous collection pattern.
  - Too small a solder bond leads to overheating and failure of the bond in the field, but not just from thermal cycling.



Broken Cells

- Can lead to major power loss.
- Module in picture is down in power by 9%.
- There may be other stresses that contribute to the cell breakage, particularly mechanical stresses.
- Hard to separate the causes from field results.
- Maybe an elephant jumped on this module before it was deployed.



What have accelerated thermal cycle tests taught us

200 Thermal Cycles are not enough to duplicate many of the failures seen in fielded modules.

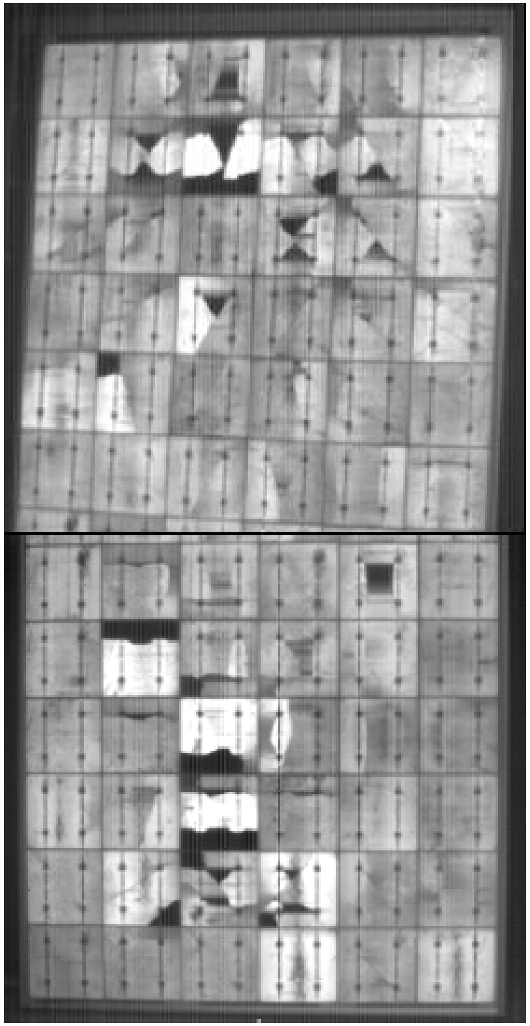
- **Causes for interconnect ribbon failures**
  - Not enough free interconnect between solder bonds on adjacent cells
  - Ribbon too stiff (too high a yield strength) and/or too thick a cross section.
- **Causes for solder bond failures**
  - Interaction with ribbon properties – If ribbon is too stiff it puts too much strain on solder bonds and they break.
  - Too small a solder bond can pass just TC but not if you use current flow during the thermal cycling.

What have accelerated thermal cycle tests taught us

- **Causes for Cell Breakage**
  - A combination of Dynamic Mechanical Loading, Thermal Cycling and Humidity Freeze is a good sequence to observe broken cells.

Table 1. Power loss from accelerated testing of modules with thin cells

Module	Test	Power Loss
A	500 Thermal Cycles	-1.4%
B	500 Thermal Cycles	-0.8%
C	1250 Hrs Damp Heat	+0.8%
D	1250 Hrs Damp Heat	+1.3%
E	1000 DMLC	-1.6%
E	1000 DMLC/50 TC	-1.9%
E	1000 DMLC/50TC/10HF	-3.0%
F	1000 DMLC	-1.4%
F	1000 DMLC/50TC	-5.2%
F	1000 DMLC/50TC/10HF	-21.6%



Modeling to connect field exposure to ASTs

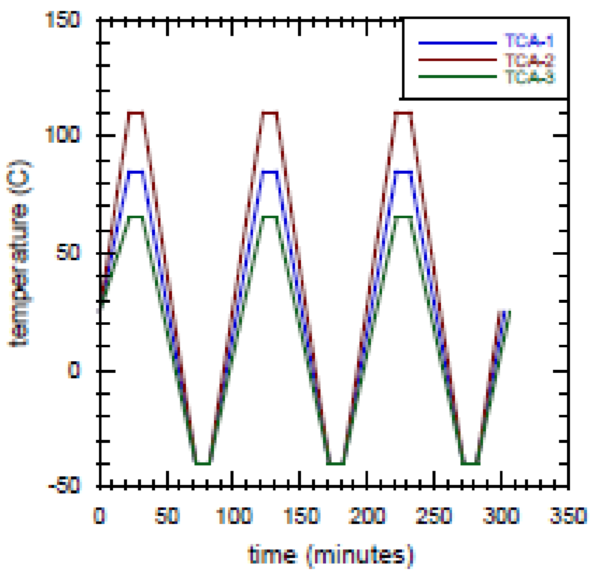
- The first thing to model is how we turn the weather data into a stress level for the module.
- For example yesterday Mike Kempe talked about modeling the moisture ingress into the module during outdoor exposure at various locations around the world.
- For thermal cycling we have a similar task of determining how the module thermal cycles in the outdoor environment.
- Nick Bosco has shown how you can use historical weather data (ambient temperature, irradiance and wind speed) for a particular site to calculate the thermal fatigue expected for the module over time.

Modeling to connect field exposure to ACT

- The second thing to model is how the change in the parameter effects the module.
- For thermal cycling this means finding a relationship between temperature change and stress on the module.
- We can use FEM to determine the relationship between change in temperature and the strain on the ribbon.
- This has been done empirically by both Bosco from 2012 NREL PVMRW and Meier from 35 IEEE PVSC.
- Empirical equations can be used to estimate relative acceleration factors among different cycling sequences.
- For TC Bosco proposed using different Tmax while keeping the Tmin at – 40 °C for this purpose.
- The absolute acceleration factors are calculated from finite element analysis.
- For Thermal Cycling testing of modules, Bosco recommends a fixed cycle between – 40 °C and + 85 °C .

simulation

	TCA-1	TCA-2	TCA-3
T_{max} C	85	110	65
T_{min} C	-40	-40	-40
t_c (min)	100	100	100
t_d (min)	10	10	10



Some lessons learned about thermal cycling

- **Use of extended thermal cycling from -40 °C to + 85 °C has been successfully used to improve the field performance of PV modules and to understand the failure modes observed in the field.**
- **After applying lessons learned, modules survived 2000 thermal cycles – without really adding to cost of the module.**
- **Estimates from field data:**
    - 200 TCs equivalent to approximately 10 years in an average climate.
    - Preliminary analysis from modeling that 200 TCs equivalent to 10 to 12 years in an average climate.

Testing For Acceleration Factors

- Perform experiments and/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 the model to predict results at some different stress levels.
- Perform experiments to validate model.
- Propose test for wear-out based on selected climates around the world.

Service Life Predictions

- **Once we have worked our way through the entire sequence of testing for acceleration factors we should be able to 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.
  - There may be a different response to thermal cycles for different interconnect ribbons and different geometries.

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 500 thermal cycles between -40 °C and + 85 °C equates to 25 years of field service in Golden for all PV modules.
- 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 factors) for their product in a particular climate, using field data to validate the results.
- The data and method used for this calculation would be part of the manufacturer's Quality Assurance Plan that would 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.
- Using this methodology the PV module manufacturers will be able to make an educated trade-off between service life and cost.