Overview of Failure Mechanisms and PV Qualification Tests

John Wohlgemuth

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Introduction

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- 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)

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- 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

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- 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

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

Accelerated tests for PV

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

Qualification testing or Certification

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

History of Qualification Testing

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

History of JPL Block Buys

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

JPL Block Qualification Tests

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

Block Field Experience

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

Testing Development

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- 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

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- 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

IEC 61215 Edition 2

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

IEC 61646 Edition 2

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

IEC 61215 Edition 3 – In Preparation

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- 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.