Test-to-Failure Program for Photovoltaic Modules

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Introduction

In order for a solar panel manufacturer to most efficiently manage risk within a product's lifecycle, a system is required to a) provide reasonable assurance of the reliability of said design, and b) to maximize the likelihood of failure mode detection early in the overall life cycle; i.e. during the design /qualification phases. This presentation outlines one such strategy, whereby a suite of evaluations are conducted on an ongoing basis to provide assurance of product reliability. Performance of the systematically-selected samples during these ongoing checks is compared to internal and/or industry criteria and metrics, primarily to ascertain changes that constitute classification as a failure mode, and secondarily to benchmark performance. In the event that a failure is detected, an escalation is initiated to understand the impact of the failure mode on a module in the field, via the Failure Mode Specific procedural flow that is also defined herein. By sharing an overview of MiaSolé's Test-to-Failure (TTF) Program, it is our intent to highlight the need for more consistency across the industry with respect to ongoing test program protocols, the need for custom programs and specialized analysis dependent upon product design, and the value of this type of program in reducing the risk of failure during a product's lifecycle, thereby enhancing the reputation of both the manufacturer and the photovoltaic industry.

TTF Program Sequence

- Program Sequence is assumed to be of the most value when conducted on an ongoing basis, to capture manufacturing process/vendor/other changes or variations that may not have been captured through a specific qualification activity.

1.0 Select stressor of interest
- Starting point: qualification sequences cast a broad net, and will catch presence of many failure modes.
  - UV, particularly for polymeric components
  - TC, fatigue due to thermal expansion / contraction
  - DH, time-at-temperature, particularly for Arrhenius-type relationships and polymers
  - HF, expansion / contraction of frozen water in spaces
- Tailor additional stressors based on the results of an FMEA for the specific module design
  - Corrosive Atmosphere, SO2, or NH3
  - Concentrated sunlight or UV
  - Dynamic loading

2.0 Determine Sampling
- Define both sample size and Frequency
- Sample selection considerations:
  - Difficult to get sufficient quantities for statistical confidence due to Size, Cost, and Test equipment limitations
  - Random selection vs. process window – the TTF Program may define sampling granularity down to lot level or a time interval, presuming that the process window's have been defined separately during individual tool and/or component level qualifications. In other words, TTF Specific area of concern / failure mode to investigate
  - R&D versus production; with respect to effect on the mechanism and failure, signal should be considered. MiaSole's TTF program relies on bi-monthly production sampling to increase likelihood of detecting modes related to production processes and material.

3.0 Test limits
- Confirm that Qualification sequence limits are of relevance for anticipated failure modes or revise limits to account for specific component responses, such as non-linear mechanical or threshold type limits
- Acceleration factors

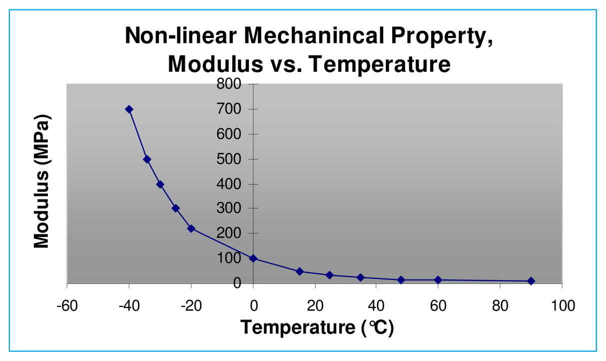

Figure 1. Non-linear responses need to be considered when translating performance data derived from certification or accelerated testing to field predictions. An encapsulant modulus is shown.

4.0 Define evaluation methods and criteria
- Standard characterization methods include:
  - Electrical Performance (I-V)
  - Insulation integrity (dry & wet hypot)
  - Visual Inspection for cosmetic effects
  - Bonding / Grounding Path Integrity
  - Accessibility
- Literature review to capture industry learning on technology specific failure modes
  - Electroluminescence imaging

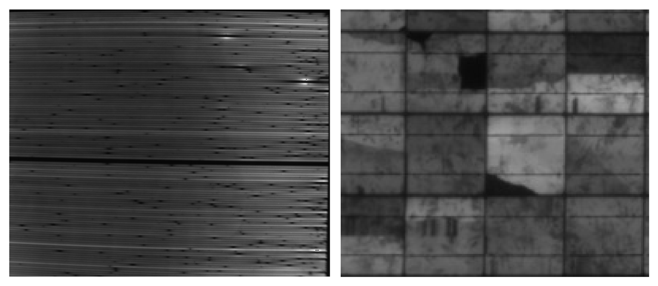

Figure 2. Example of EL signatures after thermal cycle stress from a monolithically integrated sample exhibiting localized shunting effects (left) and c-Si showing a more traditional failure mode; cell-cracking (right).

- Criteria
  - Standard based (IEC, UL) criteria limits
  - Design based criteria limits such as relative degradation from initial value or standard limit:

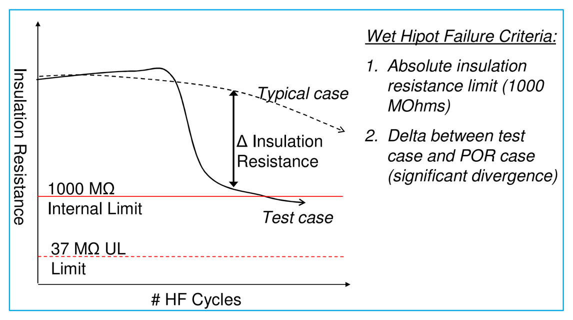

Figure 3. Illustration of wet insulation resistance criteria for evaluation of a junction box design modification. Both absolute and relative change limits are defined.

- Evaluation Intervals
  - Multipliers of standard intervals, or
  - Subsets of standard intervals

5.0 Conduct testing once program scoped

6.0 Detect new failures by comparing monitoring data relative to pre-defined criteria and/or observation of atypical findings.

7.0 Determine if immediate response is needed to contain issue. For example: catastrophic failures, such as complete loss in power production, or severe hazard such as shock or fire

8.0 Initiate failure mode specific investigation -> requires failure mode specific scoping and project activity

Failure Mode Specific Investigation

- Though an offshoot of the ongoing TTF activity, the failure-mode specific investigation provides the requisite feedback for implementing specific mitigation once a product has moved into the manufacturing phase. As such, additional schedule constraints may apply, requiring that these sub-activities, outlined serially herein, be executed in parallel.

8.1 Scope the failure
- Root cause investigation
  - Fish-bone diagram

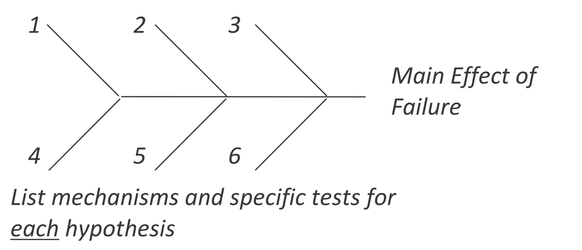

Figure 4. Example of a Fishbone diagram.

- Define the condition that resulted in failure
  - Capture the stressor, test parameters, sample size, and time of failure
  - Construction details; differences between good and failed components
- Define the characteristics of failure versus baseline
  - Non-destructive evaluation
    - Performance readings
    - Visual inspections
    - EL and IR imaging
    - Ultrasonic imaging
    - XRay
  - Destructive evaluations
    - Peel-apart, excavation, or cross-section followed by:
      - optical evaluation,
      - FTIR
      - EDXRF

8.2 Isolate the cause(s)
- Design limits exceeded
  - Manufacturing and supplier process variation
- Single stressor
  - Time at temperature
  - Low temperature excursions
  - Water freezing and expanding at J-box seal
  - Thermal expansion / contraction of interconnects
- multiple stressor / combined effect
  - UV plus heat
  - Temperature plus humidity affecting leakage current
  - Temperature and operating voltage
  - Deflection during snow loading at low temperature

8.3 Attempt to replicate
- Confirm mechanism / root-cause; partition causes where multiple leading causes remain
- Generate statistical data
  - Larger sample size
  - Continue additional samples to failure
  - Fit appropriate distribution
    - Exponential
    - Log-normal
    - Weibull
  - Determine if it is an early, normal use, or end-of-life failure; systematic or random failure
- Revisit the Fish-bone diagram and identify the likely root cause based on learning

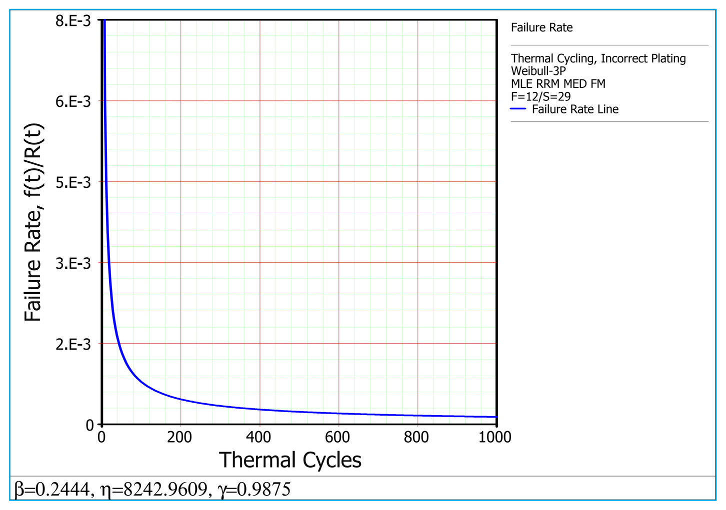

Figure 5. Thermal cycle data gathered from replicate samples with the incorrect plating, showing early failure mode (β<1), using a Weibull 3-parameter distribution.

8.4 Model the failure
- Computer modeling, for example Finite Element Analysis (FEA) Modeling. Input geometries and material properties:
  - Coefficient of thermal expansion (CTE)
  - Elemental composition (from specifications, manufacturer data, EDXRF, FTIR, Auger, etc.)
  - Tensile strength
  - Modulus of elasticity
  - Durometer
  - Melt-point
  - Glass-Transition Temperatures
  - Adhesion

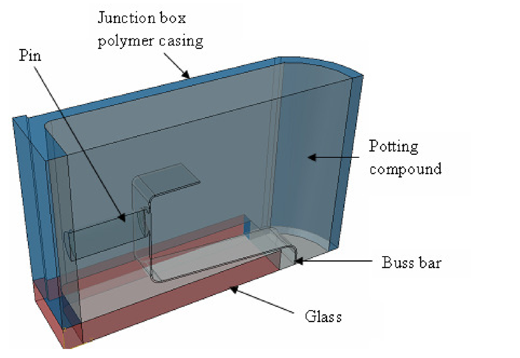

Figure 6. Illustration of MiaSolé's J-box system, as defined in the FEM model.

8.5 Compare test stresses with end-use environment
- Define end-use environment(s) in terms of stressor causing failure
- Consider importance of various factors:
  - Temperature extremes
  - Ambient humidity
  - Sunlight or UV hours

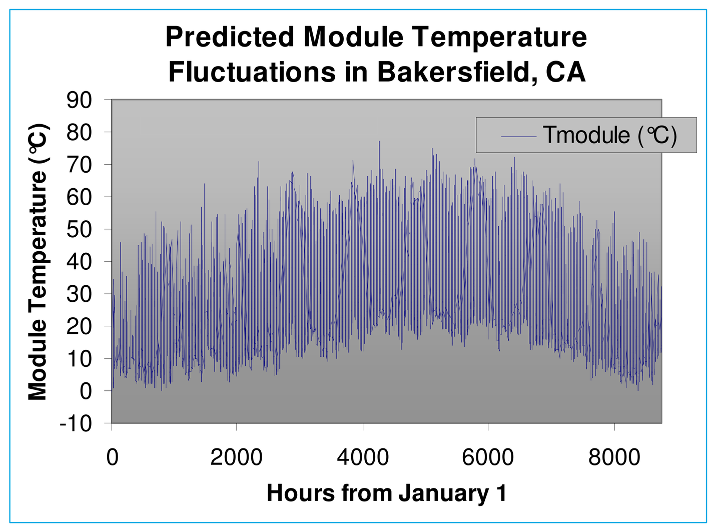

Figure 7. Typical Meteorological Year (TMY) data, converted to module operating temperature, to define dynamic range of temperature excursions at a select location.

8.6 Establish correlation between TTF test levels and field conditions
- Non-trivial
  - Various end-use locations
  - Variable conditions at each location
- Determine lifetime in end-use environment, by assessing failure rate, while varying stress amplitude and duration

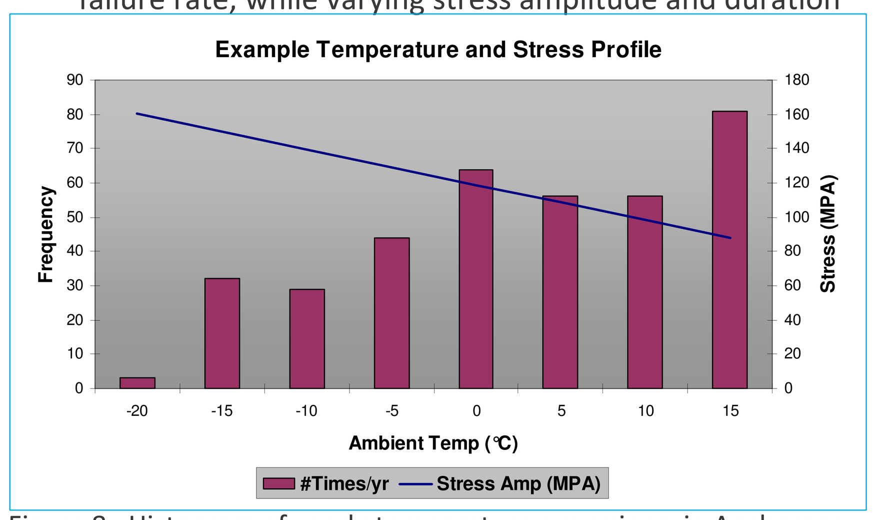

Figure 8. Histogram of yearly temperature excursions, in Anchorage AK, and resultant stress of an interconnect sub-component generated for a fatigue based failure mode – subsequent calculation based on available stress model allowed order-of-magnitude service life prediction.

8.7 Evaluate whether failure mode is likely to manifest itself in the field
- Examine existing field samples for onset of the failure mode

8.8 Develop accelerated test for specific failure mode, which allows:
- Larger sample size
- Component-specific / failure-mode specific test
- Faster turn-around time / larger acceleration factor
- Multiple test stress levels
- Flexibility in acceleration factor(s)
- Confirm correlation with original TTF testing
  - Repeat testing as needed to obtain confidence in results
- Scale to field conditions to replicate field stress
- Evaluate potential solutions and future changes using new test method

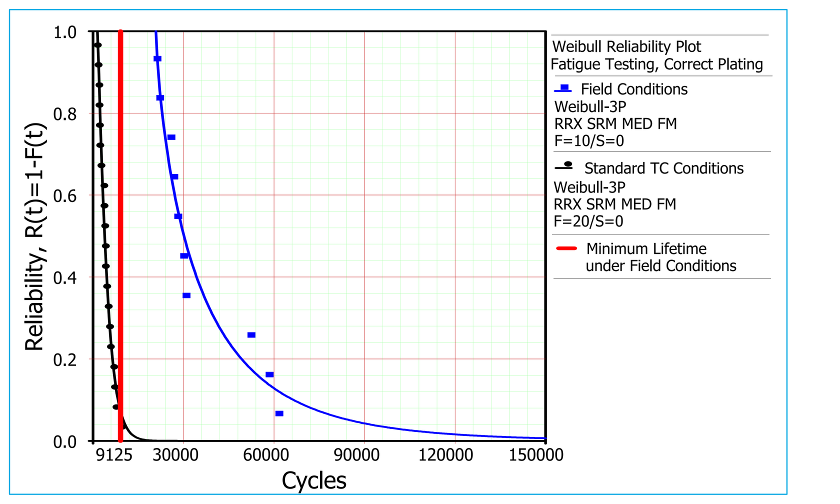

Figure 9. Results of mechanical fatigue testing at MiaSolé, showing that a solution to the incorrect plating meets a 25-year life-time under simulated field conditions (blue line).

8.9 Identify solutions to failure modes
- Design change
- Process Mitigation: Manufacturer changes and/or customer/installation changes and/or supplier/specification changes
- Repeat the TTF Program, mode-specific accelerated testing, and computer modeling to ensure failure mode is addressed, with no unanticipated new failure modes

8.10 Implement mitigation strategy for failure modes
- Modify components and/or manufacturing process

8.11 Identify new pass/fail criteria based on test results
- Modify specifications
- Update Quality procedures and specifications
- Update qualification methods
- Update FMEA with new failure mode