PV Reliability Development Lessons from JPL's Flat Plate Solar Array Project

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FSA Engineering and Reliability Mngr, 1975-1990

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Topics

- Overview of the FSA Program Approach
  - Closed-loop module development process
  - Program players and roles

- Reliability Management Lessons
  - Closed-loop process
  - Defining reliability requirements
  - Measuring reliability against requirements

- Reliability Development Lessons
  - Large applications for problem identification
  - Computer simulations for life prediction
  - Failure analysis and reliability physics research
  - Qual tests for rapid product assessment

- Summary Observations
DoE / FSA Program Approach to PV Module Development

- **Requirements Research**
  - JPL Lead

- **Module Tech Base Development**

- **Module Design Synthesis**

- **Prototype Production & Qual Test**
  - PV Manufacturer Lead

- **Module Large-scale Production**

- **Accelerated Life & Field Testing**

- **Field Perf. Data Acquisition**
  - Gov't Lead (NASA-GRC, MIT/LL, Sandia)

- **Fielded PV Applications**

- **Balance of System Development**
By the mid 1980s we'd completed some big full-scale systems.
## Evolution of Reliability Issues during FSA Project (1975-1985)

<table>
<thead>
<tr>
<th>Problem Area</th>
<th>Year</th>
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<td>Bond Delamination</td>
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<td>Interconnect Fatigue</td>
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<td>Electrochemical Corrosion</td>
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<td>Photothermal Degradation</td>
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<td>Structural Failure</td>
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<td>Hail Impact Damage</td>
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<td>Glass Breakage</td>
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<td>Cell Cracking</td>
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<td>Voltage Breakdown</td>
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<td>HotSpot Heating</td>
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<td>Excessive Soiling</td>
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<td>Module Arcs and Fires</td>
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<td>High Operating Temperature</td>
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</table>
### Example Reliability Requirements at System & Components Level

#### Type of Degradation

<table>
<thead>
<tr>
<th>Component failures</th>
<th>Power Degradation</th>
<th>Module failures</th>
<th>Life-limiting wearout</th>
</tr>
</thead>
</table>

#### Failure Mechanism

- Open-circuit cracked cells
- Short circuit cells
- Interconnect open circuits
- Cell gradual power loss
- Module optical degradation
- Front surface soiling
- Module glass breakage
- Module open circuits
- Module hot-spot failures
- Bypass diode failures
- Module shorts to ground
- Module delamination
- Encapsulant failure due to loss of stabilizers

#### Units of Degradation

- %/yr
- %/yr²
- %
- years

#### Level for 10% Power Degradation

- Increase
- Allocation for 30-year Life Module
- Economic Penalty

#### Allocation for 30-year Life Module

- Energy
- O&M

#### Normalized Power Output

- Baseline

#### Working Definition

- Years

#### Economic Penalty

- 1 PER 20,000 PER YEAR
- 0.2 % PER YEAR
- 1 PER 1,000 PER YEAR

#### Example Reliability Requirements at System & Components Level

- 1 PER 20,000 PER YEAR
- 0.2 % PER YEAR
- 1 PER 1,000 PER YEAR

#### Working Definition

- Years

#### Notes

- *k=discount rate,
- †Very difficult to measure in module level testing
Reliability Requirements
Ranked by Difficulty

- **System Operating Voltage**
  - Large number of series cells magnifies component failure effects
  - High voltage exacerbates corrosion and safety issues

- **Operating Temperature and Temperature Cycles**
  - Accelerates nearly all failure mechanisms
  - x2 life reduction for each 10°C increase in Temperature

- **Ambient Humidity Level**
  - x2 life reduction for each 10% increase in Relative Humidity

- **Ultraviolet Exposure Level**
  - Encapsulant degradation (highly nonlinear with UV level)

- **Ambient Soiling Level**
  - Much worse in urban environments

- **Maximum Hail Size**
  - Site specific, a problem with early applications in central US

- **Presence of Salt Fog**
  - Very specific to marine locations

- **Maximum Wind & Snow Loads**
  - Site specific, generally not a significant issue
Site Specific Effects of Temperature, Humidity and Voltage

Plots of Temp/Humidity chamber exposure equivalent to 20-year field exposure at indicated sites based on integrating SOLMET hourly weather data

For 24-hour/day Field Exposure

- MIAMI
- BOSTON
- PHOENIX

Factor of 2 per 10 points (T+RH)

85°C + 85% RH

Time, hours

Temp (°C) + RH (%)

100 140 170 200

Bottom Line: 10°C increase in Temp or 10% increase in RH drops life by factor of 2

For daylight-hours/day Field Exposure

- MIAMI
- BOSTON
- PHOENIX

Factor of 2 per 10 points (T+RH)

85°C + 85% RH

Time, hours

Temp (°C) + RH (%)

100 140 170 200

Time, days

360 180 90 45 20 10 5 2 1
Transmission Loss through EVA vs Temperature and UV Level

UV response is very nonlinear and difficult to accelerate

\[
\frac{\tau}{\tau_0} = 1 + a_1 Q + a_2 Q^2 + a_3 Q^3
\]

\[
\frac{Q}{t} = e^{(a_4/T)} + a_5 e^{(a_6/T)} S_{a_7} - a_8 e^{(a_9/T)} S_{a_{10}}
\]
Transmission Loss through EVA Increases Arrheniusly with Temp

- Thermal response is relatively predictable (typically Arrhenius with approx. rate doubling each 10°C)
- Accurate regulation of temperature is critical to successful UV testing
# Hourly Calculation of EVA Yellowing Rate in Phoenix

## Yellowing Rate at each Temperature-UV Level

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<tr>
<th>Cell temperature, °C</th>
<th>UV level in suns</th>
<th>0.05</th>
<th>0.15</th>
<th>0.25</th>
<th>0.35</th>
<th>0.45</th>
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## Annual Hours at each Temperature-UV Level

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<th>UV level in suns</th>
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</table>

## Predicted power loss after 30-years in Phoenix:

- **Ground-mounted array = 3.5%**
- **Roof-mounted array = 7.9%**

*Because roof array operates at higher temperature*
FSA Project Relied on a Variety of Test methods

- **Large Application Experiments** that include all system-level interfaces
  - Extremely valuable for quantifying reliability of mature designs and identifying failures driven by complex interfaces
  - Outdoor Test Racks of minimal value: unaccelerated and lack key system voltage-current interface conditions

- **Laboratory Research and Life Tests**
  - High value for quantifying reliability physics parameter dependencies and resolving reliability problems

- **Qualification (or screening) Tests**
  - High value for screening new designs for known failures
Full-Up System-Level Testing
Objectives and Attributes

OBJECTIVE

• To accurately assess hardware functionality and reliability in big systems with emphasis on system synergisms, interactions, and interfaces

ADVANTAGES

• Complete system interfaces and operating conditions provides reliable assessment of subsystem compatibility issues and degradation mechanisms associated with large numbers of modules with real system interactions and operational stresses
• Inclusion of balance-of-system (BOS) hardware provides data and confidence in complete functional system

LIMITATIONS

• Requires complete system with all important balance-of-system components and interfaces
• Occurs very late in the design cycle; problems at this point are highly visible and expensive
• Added complexity in constructing and testing complete system
Characterization and Accelerated Life Testing Objectives and Attributes

OBJECTIVE

• To understand and quantify the fundamental interdependencies between performance (failure level), environmental and operational stress level, hardware materials and construction features, and time

ADVANTAGES

• Mechanism-level understanding achieved by selecting specialized tests and facilities targeted at specific degradation stress environments and construction material parameters

• Carefully controlled parameters (generally at parametric levels) with acceleration consistent with accurate extrapolation to use conditions

LIMITATIONS

• Expensive and time consuming — requires specialized testing equipment and modestly long test durations (2 weeks to 5 years)

• Requires multiple tests to address the total spectrum of degradation mechanisms and levels

• Number of specimens insufficient to quantify random failures
Key Output of Reliab. Physics Testing was TechBase for Module Design

- **New lamination adhesives**, primers, and stabilizers (PVB, EVA, EMA) for lower cost and improved weathering
- **Circuit redundancy configurations** for controlling cell cracking and broken interconnects
- **Interconnect design and test methods**
- **Cell attachment techniques** to minimize losses due to cell cracking
- **Glass strength** calculation methods
- **Bypass diode design** and hotspot test methods
- **Hail resistance data** and test methods
- **Cell fracture strength** and test methods
- **Voltage breakdown data** and test methods
- **Electrochem corrosion** data and test methods
- **UV-thermal durability data** and test methods
Qualification Testing
Objectives and Attributes

**OBJECTIVE**

- To rapidly and economically screen module designs for prominent failure mechanisms
- To rapidly assess the *relative durability* of alternative designs

**ADVANTAGES**

- Quick turnaround — relatively inexpensive
- Relatively standard procedures allows inter-comparison with historical data
- Separate tests for important environmental and operational stresses aids identification of high-risk mechanisms

**LIMITATIONS**

- Minimal life-prediction capability (a relative measure of robustness, generally does not quantify life attributes)
- Requires multiple tests and specialized facilities to address the total spectrum of stressing environments
- Number of specimens insufficient to quantify random failures
<table>
<thead>
<tr>
<th>QUAL TEST</th>
<th>I</th>
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<th>IV</th>
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<td>10,000</td>
<td>*Excluding shingle modules</td>
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<td>Number Cycles</td>
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<td>*Shingles only</td>
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<td>HAIL IMPACT</td>
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<td>*1500 for resid. modules</td>
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JPL's Role in National PV Program Sunsetted in the Early 1990's
• Overall closed-loop performance measurement process is critical to reliability identification & quantification
  • Full-up systems providing definitive operational feedback
  • Mechanism-level & life testing for root-cause identification
  • Qual tests for quick production screening

• Module Technology Devel. is critical to reliability growth
  • Encapsulation systems development (EVA, Tedlar, primers, etc)
  • Requirements Refinement (natural environments, UL 1703, NEC 690)
  • Engineering Tech Base Development (fatigue, corrosion, glass strength, hail resistance, hot-spot heating, voltage breakdown, electrochemical corrosion, UV-thermal degradation, etc)
  • Improved failure analysis and measurement techniques
Summary Lessons (Con't)

- Rapid open communication between all stakeholders is critical to rapid reliability improvement
  - Rapid Problem Identification and communication
  - Resolution Teamwork across many organizations (JPL FSA project had 131 organizations under contract; Engineering (ES&R, Module Proc, & Encapsulation) had a total of 37 organizations under contract)

- In total, over 380 of the key reports resulting from the Engineering and Reliability activities of the FSA Project are cataloged on the JPL web site:
  http://www2.jpl.nasa.gov/adv_tech/photovol/PV_pubs.htm