SOLAR PANELS - FROM TESTS TO LIFE PREDICTION

Dr. R.G. Ross Jr
Jet Propulsion Laboratory

Mr. Carl Osterwald
Solar Energy Research Institute

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SOLAR PANELS - FROM TESTS TO LIFE PREDICTION

Agenda

- Reliability Testing in the Module Design Process
  - Introduction to Degradation Mechanisms
  - The Overall Reliability Design Process
  - Characterization Tests for Quantifying Degradation
  - Establishing Mechanism-level Reliability Goals
  - Design Validation Testing Overview

- Practice and Procedures for Module Reliability Testing
  - Reliability Testing and Pass/Fail Criteria
  - Module Performance
  - Other Electrical Tests
  - Environmental Reliability Tests

Ross

Osterwald
## INTRODUCTION TO RELIABILITY TESTING AND LIFE PREDICTION

<table>
<thead>
<tr>
<th>TYPES OF PV MODULE DEGRADATION MECHANISMS</th>
<th>PRINCIPAL PARAMETER DEPENDENCIES</th>
</tr>
</thead>
<tbody>
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<td>• Encapsulant Yellowing &amp; Cracking</td>
<td>• Time</td>
</tr>
<tr>
<td>• Fatigue of Circuit Elements</td>
<td>• Environmental Stress Levels</td>
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<tr>
<td>• Cell Cracking</td>
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<td>• Cell Metallization Corrosion</td>
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<td>• Electrical Insulation Breakdown</td>
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<td>• Construction Geometry</td>
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<tr>
<td>• Structural Damage</td>
<td>• Circuit Design</td>
</tr>
</tbody>
</table>
EXAMPLE DEGRADATION TIME DEPENDENCIES

Fatigue

Soiling

Encap. Yellowing

Wind Damage
EXAMPLE DEGRADATION STRESS-LEVEL DEPENDENCIES

Fatigue

TEMP. CYCLE DEPTH

Soiling

RURAL URBAN

Encap. Yellowing

TEMPERATURE

Wind Damage

PRESSURE LOAD
EXAMPLE DEGRADATION DESIGN DEPENDENCIES

Fatigue

INTERCONNECT THICKNESS

Soiling

SILICONE GLASS

Encap. Yellowing

PVB  EVA

Wind Damage

GLASS THICKNESS
### Module Reliability Design and Test Objective

#### Degradation Mechanisms
- Encapsulant Yellowing & Cracking
- Fatigue of Circuit Elements
- Cell Cracking
- Optical Surface Cracking
- Optical Surface Soiling
- Encapsulant Delamination
- Cell Metallization Corrosion
- Electrical Insulation Breakdown
- Hot-spot Heating
- Structural Damage

#### Principal Parameters
- Time
- Environmental Stress Levels
  - Temperature, Humidity
  - Wind, Hail and Snow
- Operational Stress Levels
  - Applied voltages
- Module Design Parameters
  - Material Properties
  - Construction Geometry
  - Circuit Design

**To Minimize These**

**Given These**

**Pick These**
OVERALL RELIABILITY DESIGN PROCESS

- Establish Overall Reliability Design Requirements
- Determine Environmental and Operational Stress Levels
- Generate Strawman Conceptual Design
- Identify Principal Failure Mechanisms
- Determine Failure Mechanism Parameter Dependencies
  - Reliability Physics
  - Characterization Tests
- Determine Impact of each Failure on System Performance
- Allocate Overall Reliability Among Mechanisms
- Select Detailed Design Attributes of Module
- Fabricate Engineering Prototype
- Conduct Product Verification Tests and Evaluations
  - Qualification Tests
  - Accelerated Life Tests
  - Field Aging Tests
- Analyze Failures and Feed back into Design
EXAMPLE OVERALL RELIABILITY OBJECTIVE

30-Year Operational Life with $\leq 20\%$ Degradation in Life-cycle Value

- Some degradation (Lost revenue)
- Some maintenance (Expenses)
## Module Reliability
### Design and Test Elements

<table>
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<tr>
<th>Degradation Mechanisms</th>
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</table>
TYPICAL ENVIRONMENTAL AND OPERATIONAL STRESS LEVELS FOR 30-year DESIGN LIFE

- SOLAR UV EXPOSURE: 50,000 hours at 1 sun
- TEMPERATURE EXTREMES: -40 to +90 °C
- LONG-TERM TEMPERATURE AGING: 50,000 hours at 50°C
- TEMPERATURE CYCLING: 11,000 cycles at 46°C ΔT
- LONG-TERM HUMIDITY AGING: 100,000 hours at 60°C, 40% RH
- WIND AND SNOW LOADS: 50 lbs/ft²
- HAIL IMPACT: 1" hailstone at 76 ft/sec
- LONG-TERM VOLTAGE STRESS: 50,000 hours at System Voltage Level
- 1 minute VOLTAGE STRESS: 2 x System Voltage + 1000 volts
EQUIVALENT THERMAL AGING TIMES
FOR 20-YEAR-LIFE PV FIELD ENVIRONMENTS

FACTOR OF 2 PER 10°C

20-yr ENVIRONMENT
PHOENIX ROOF
BOSTON ROOF
BOSTON GND

ENCAPSULANT TEMPERATURE, °C

THERMAL AGING TIME, hours

TIME, days

20 30 40 50 60 70 80 90 100 110 120

20 30 40 50 60 70 80 90 100 110 120
EQUIVALENT THERMAL-HUMIDITY AGING TIMES
FOR 20-YEAR-LIFE PV FIELD ENVIRONMENTS

Day and Night Hours

Daylight Hours Only

TIME, hours

TEMPERATURE (°C) + RH (%)

FACTOR OF 2 PER 10 POINTS (T+RH)

FACTOR OF 2 PER 10 POINTS (T+RH)
## Module Reliability
### Design and Test Elements

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</table>

- Module Design Parameters
TYPICAL FLAT-PLATE MODULE DESIGN

INTERCONNECT
SUPERSTRATE

SUBSTRATE
SOLAR CELL

[Diagram of a typical flat-plate module design with labeled components]
## EXAMPLE DESIGN ATTRIBUTES GOVERNING PRINCIPAL FAILURE MECHANISMS

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<thead>
<tr>
<th>FAILURE MECHANISM</th>
<th>DESIGN ATTRIBUTE</th>
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</thead>
<tbody>
<tr>
<td>Encap. Yellowing &amp; Cracking</td>
<td>Encapsulant Photothermal Stability</td>
</tr>
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<td>Encapsulant Glass Transition Temp.</td>
</tr>
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<td>Interconnect Fatigue</td>
<td>Cell/Structure CTE match</td>
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<tr>
<td></td>
<td>Interconnect thickness and loop height</td>
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<tr>
<td>Cell Cracking</td>
<td>Cell/Structure CTE match</td>
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<td></td>
<td>Encapsulant modulus and thickness</td>
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<td>Optical Surface Cracking</td>
<td>Glass thickness, temper, and edge seam</td>
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<td>Optical Surface Soiling</td>
<td>Encapsulant self-cleaning ability</td>
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<td>Encapsulant Delamination</td>
<td>Bonding primers</td>
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<td>Cell Metallization Corrosion</td>
<td>Galvanic compatibility of cell metals</td>
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<td>Ionic conductivity of encapsulants</td>
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<td></td>
<td>Hermeticity of module design</td>
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<td>Electrical Insulation Breakdown</td>
<td>Insulation system design</td>
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<td>Conductor-to-ground separation</td>
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<td>Hot-spot Heating</td>
<td>Bypass diode frequency</td>
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<td>Structural Damage</td>
<td>Temperature stability of encapsulants</td>
</tr>
<tr>
<td></td>
<td>Structural member dimensions</td>
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</table>
### EXAMPLE STRESS DEPENDENCIES GOVERNING PRINCIPAL FAILURE MECHANISMS

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<tr>
<th>FAILURE MECHANISM</th>
<th>GOVERNING STRESS</th>
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<td>Encap. Yellowing &amp; Cracking</td>
<td>Long-term UV and temperature levels</td>
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<tr>
<td></td>
<td>Temperature extremes</td>
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<tr>
<td>Interconnect Fatigue</td>
<td>Number and depth of temperature cycles</td>
</tr>
<tr>
<td></td>
<td>Wind cycling (with large flexible modules)</td>
</tr>
<tr>
<td>Cell Cracking</td>
<td>Temperature extremes and cycling</td>
</tr>
<tr>
<td></td>
<td>Hailstone size and velocity</td>
</tr>
<tr>
<td>Optical Surface Cracking</td>
<td>Hailstone size and velocity</td>
</tr>
<tr>
<td>Optical Surface Soiling</td>
<td>Temperature gradients</td>
</tr>
<tr>
<td>Encapsulant Delamination</td>
<td>Airborne soiling level</td>
</tr>
<tr>
<td>Cell Metallization Corrosion</td>
<td>Temperature/humidity cycling</td>
</tr>
<tr>
<td>Electrical Insulation Breakdown</td>
<td>Long-term humidity exposure</td>
</tr>
<tr>
<td>Hot-spot Heating</td>
<td>Voltage level</td>
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<td></td>
<td>Surface wetness</td>
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<td></td>
<td>Humidity and temperature level</td>
</tr>
<tr>
<td>Structural Damage</td>
<td>Shadowing and temperature extremes</td>
</tr>
<tr>
<td></td>
<td>Temperature stability of encapsulants</td>
</tr>
<tr>
<td></td>
<td>Wind and snow loads</td>
</tr>
</tbody>
</table>
CHARACTERIZATION TESTING

OBJECTIVE AND ATTRIBUTES

OBJECTIVE

- To understand and quantify the fundamental interdependencies between failure level, environmental stress level and time, and module design parameters

ATTRIBUTES

- Carefully controlled parameters
- Generally parametric parameter selections
  - Materials and construction features
  - Environment combinations
  - Environment stress levels
- Modest acceleration consistent with accurate extrapolation to use conditions
TEMPERATURE-HUMIDITY-UV TEST CHAMBER
FOR PHOTOTHERMAL AGING STUDIES
YELLOWING RATE FOR EVA ENCAPSULANT
vs UV FLUX LEVEL AND TEMPERATURE

UV EXPOSURE, suns

RELATIVE YELLLOWING RATE

85°C
120°C
135°C
CYCLIC FATIGUE TESTING APPARATUS
FOR SOLAR CELL INTERCONNECTS
INTERCONNECT FATIGUE ENDURANCE
vs DEPTH AND NUMBER OF STRAIN CYCLES

(OFHC 1/4-Hard Copper)

\[ \log \Delta \varepsilon = -0.3228 \log N - 1.0148 + 0.9998p \\
- 1.4839p^2 + 0.9019p^3 \]
EFFECT OF CELL PROCESSES ON THE TWIST STRENGTH OF SILICON WAFERS AND CELLS

TWIST STRENGTH, $\tau_s$, MNm$^{-2}$

FRACTURE PROBABILITY

AS-CUT WAFERS
EDGE ROUNDED WAFERS
CHEM. POLISHED WAFERS
TEXTURE ETCHED WAFERS, LOT E
COMPLETE CELLS, LOT E
COMPLETED CELLS, LOT A

TWIST STRENGTH, $\tau_s$, ksi
HAIL TEST APPARATUS USED TO FIRE FROZEN ICE BALLS
HAIL IMPACT RESISTANCE

REF: PHOTOVOLTAIC SOLAR PANEL RESISTANCE TO HAIL
LSA TASK REPORT 5101-62, DOE/JPL-1012-78/6

TOP SURFACE MATERIAL

CLEAR SILICONE POTTING

0.10 in. ACRYLIC SHEET

0.09 in. ANNEALED GLASS
(ALUM SUBSTRATE)

0.12 in. ANNEALED GLASS

0.12 in. TEMPERED GLASS

0.19 in. TEMPERED GLASS

HAILSTONE DIAMETER - in.
ARRAY LOSS DUE TO SOILING

JPL (URBAN)

RTV 615

TEDLAR

GLASS

PERCENT LOSS IN VSC

FIELD EXPOSURE, years

TABLE MOUNTAIN (REMOTE)

RTV 615

TEDLAR

GLASS

FIELD EXPOSURE, years
ELECTRICAL CONDUCTIVITY OF PVB AND EVA

PVB

EVA

RH, %

100°C

85°C

70°C

55°C

40°C

25°C

10°C

0°C

10^{-7}

10^{-8}

10^{-9}

10^{-10}

10^{-11}

10^{-12}

10^{-13}

10^{-14}

10^{-15}

10^{-16}

10^{-17}

10^{-18}

10^{-19}

0

20

40

60

80

100
FIELD CHARACTERIZATION TESTING
OF POLYMER SURFACE CONDUCTIVITY PROPERTIES
SURFACE LEAKAGE CURRENT LEVELS
(Laboratory vs Field Test Results)

2-PLY PVB

4-PLY PVB

2-PLY EVA

4-PLY EVA

RH, %

T = 85°C

LABORATORY

TEST STAND

RAINY 10°C

CLOUDY 15°C

WARM 35°C

DEWY, CLOUDY 25°C
THE PROBLEM OF QUANTIFYING THE IMPACT OF RANDOM COMPONENT FAILURES ON OVERALL PV SYSTEM PERFORMANCE
EXAMPLE POWER LOSS GRAPH

SINGLE STRING
FF = .70
ONE SERIES BLOCK PER DIODE

ARRAY POWER LOSS FRACTION

1.0
0.1
0.01
0.001
0.0001
120 - 2400

F_{SS}' SUBSTRING FAILURE DENSITY

1

SERIES BLOCKS PER SOURCE CIRCUIT
4
8
15
30
60
# Mechanism-Level Degradation Allocations Based on Life-Cycle System Cost Impacts

<table>
<thead>
<tr>
<th>Type of Degradation</th>
<th>Failure Mechanism</th>
<th>Units of Degrad.</th>
<th>Level for 10% Energy Cost Increase*</th>
<th>Allocation for 30-Year-Life Module</th>
<th>Economic Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component failures</td>
<td>Open-circuit cracked cells</td>
<td>%/yr</td>
<td>k = 0: 0.08 k = 10: 0.13</td>
<td>0.005</td>
<td>Energy</td>
</tr>
<tr>
<td></td>
<td>Short-circuit cells</td>
<td>%/yr</td>
<td>k = 0: 0.24 k = 10: 0.40</td>
<td>0.050</td>
<td>Energy</td>
</tr>
<tr>
<td></td>
<td>Interconnect open circuits</td>
<td>%/yr^2</td>
<td>k = 0: 0.05 k = 10: 0.25</td>
<td>0.001</td>
<td>Energy</td>
</tr>
<tr>
<td>Power degradation</td>
<td>Cell gradual power loss</td>
<td>%/yr</td>
<td>k = 0: 0.67 k = 10: 1.15</td>
<td>0.20</td>
<td>Energy</td>
</tr>
<tr>
<td></td>
<td>Module optical degradation</td>
<td>%/yr</td>
<td>k = 0: 0.67 k = 10: 1.15</td>
<td>0.20</td>
<td>Energy</td>
</tr>
<tr>
<td></td>
<td>Front surface soiling</td>
<td>%</td>
<td>k = 0: 10 k = 10: 3</td>
<td></td>
<td>Energy</td>
</tr>
<tr>
<td>Module failures</td>
<td>Module glass breakage</td>
<td>%/yr</td>
<td>k = 0: 0.33 k = 10: 1.18</td>
<td>0.1</td>
<td>O&amp;M</td>
</tr>
<tr>
<td></td>
<td>Module open circuits</td>
<td>%/yr</td>
<td>k = 0: 0.33 k = 10: 1.18</td>
<td>0.1</td>
<td>O&amp;M</td>
</tr>
<tr>
<td></td>
<td>Module hot-spot failures</td>
<td>%/yr</td>
<td>k = 0: 0.33 k = 10: 1.18</td>
<td>0.1</td>
<td>O&amp;M</td>
</tr>
<tr>
<td></td>
<td>Bypass diode failures</td>
<td>%/yr</td>
<td>k = 0: 0.70 k = 10: 2.40</td>
<td>0.05</td>
<td>O&amp;M</td>
</tr>
<tr>
<td></td>
<td>Module shorts to ground</td>
<td>%/yr^2</td>
<td>k = 0: 0.022 k = 10: 0.122</td>
<td>0.01</td>
<td>O&amp;M</td>
</tr>
<tr>
<td></td>
<td>Module delamination</td>
<td>%/yr^2</td>
<td>k = 0: 0.022 k = 10: 0.122</td>
<td>0.01</td>
<td>O&amp;M</td>
</tr>
<tr>
<td>Life-limiting wearout</td>
<td>Encapsulant failure due to loss of stabilizers</td>
<td>Years of life</td>
<td>k = 0: 27 k = 10: 20</td>
<td>0.01</td>
<td>End of life</td>
</tr>
</tbody>
</table>

*k = Discount rate
DETAILED MODULE DESIGN AND MATERIAL SELECTION

- **Optical Surface**
  - Transparency
  - Anti-soiling properties
  - Impact resistance
  - Abrasion/scratch resistance

- **Encapsulant**
  - Photodegradation stability
  - Low ionic conductivity
  - Low modulus
  - Good bonding properties

- **Electrical Circuit**
  - Redundant against open circuits
  - Fatigue resistant
  - Hot-spot mitigation (diodes)

- **Structural system**
  - Consistent with wind and snow loads
  - CTE matched to cells

- **Electrical Insulation System**
  - Compatible with surface moisture
  - Abrasion/scratch resistant
## TYPES OF DESIGN VALIDATION TESTS

<table>
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<tr>
<th>TYPES OF TEST</th>
<th>PRINCIPAL FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Qualification</strong></td>
<td>• Short duration (&lt; 2 weeks)</td>
</tr>
<tr>
<td><strong>Accelerated Life Testing</strong></td>
<td>• Modest duration (up to 2 years)</td>
</tr>
<tr>
<td><strong>Field Weathering</strong></td>
<td>• Long Duration (1 to 10 years)</td>
</tr>
<tr>
<td><strong>Demonstration System</strong></td>
<td>• Long duration (1 to 10 years)</td>
</tr>
<tr>
<td></td>
<td>• Unaccelerated</td>
</tr>
<tr>
<td></td>
<td>• Design independent</td>
</tr>
<tr>
<td></td>
<td>• Combined weathering environments</td>
</tr>
<tr>
<td></td>
<td>• Full operational environment including system interfaces &amp; voltages</td>
</tr>
</tbody>
</table>
QUALIFICATION TESTING

OBJECTIVE

- To rapidly and economically screen module designs for unacceptable life-limiting failure mechanisms
- To rapidly assess the relative durability of alternative designs

ADVANTAGES

- Separate tests for important environmental and operational stresses aids identification of failure causes
- Quick Turnaround
- Broadly recognized standard procedures available
- Relatively inexpensive

LIMITATIONS

- Limited life-prediction accuracy
  - High accelerations
  - Lack of combined environments
  - Some missing environments (e.g. soiling and UV aging)
  - Number of modules insufficient to quantify random failures
- Requires multiple tests and specialized facilities to cover broad spectrum of environments
LARGE TEMPERATURE-HUMIDITY CHAMBER USED FOR MODULE QUALIFICATION TESTING
ACCELERATED LIFE TESTING

OBJECTIVE
- To accurately quantify specific degradation mechanisms with known stress dependencies

ADVANTAGES
- Improved accuracy over Qual testing achieved by selecting specialized tests and facilities targeted at specific degradation mechanisms and module construction materials
- Much faster than field or demonstration system testing

LIMITATIONS
- Expensive and time consuming -- requires specialized testing equipment and modestly long test durations (2 weeks to 2 years)
- Requires multiple tests to address the total spectrum of degradation mechanisms
- Number of modules insufficient to quantify random failures
EXAMPLE OF ACCELERATED LIFE TESTING

(Dark Oven Aging of Amorphous Silicon Modules)
MODULE FIELD TESTING

OBJECTIVE
- To accurately assess module weatherability in the field
- To uncover generic degradation mechanisms under real-world combined weathering environments

ADVANTAGES
- Relatively inexpensive
- Real-world combined environments

LIMITATIONS
- Unaccelerated environment requires multi-year test times
- Number of modules insufficient to quantify random failures
- Often does no spot important failures caused by system interface stresses such as voltage breakdown and hot-spot heating
TYPICAL OUTDOOR FIELD TEST SITE
(Jet Propulsion Laboratory, Pasadena, California)
EXAMPLE FIELD AGING RESULTS
(Amorphous Silicon Light Induced Effects)
MODULE LEAKAGE CURRENTS DURING OUTDOOR FIELD EXPOSURE

TIME OF DAY, hours

LEAKAGE CURRENT, mA

0.1 1.0 10.0

4/30/80 5/1/80 5/5/80
DEMONSTRATION SYSTEM TESTING

OBJECTIVE

- To accurately assess module functionality including weatherability and system interface compatibility

ADVANTAGES

- System interfaces and operating conditions allow accurate assessment of interface compatibility issues and degradation mechanisms associated with operational stresses
- Large number of modules allows accurate quantification of statistically random failures
- Inclusion of balance-of-system hardware provides data and confidence in complete functional PV system

LIMITATIONS

- Unaccelerated environment requires multi-year test time
- Very expensive
  - Significant added complexity in constructing complete system
  - Significant upkeep required for balance-of-system components
TYPICAL DEMONSTRATION SYSTEM TEST SITE
(New Mexico State University Southwest Region Experiment Station)
EXAMPLE EXTREME ENVIRONMENT DEMONSTRATION SYSTEM
SUMMARY

- PV modules contain a broad variety of degradation mechanisms that have complex dependencies on a diverse number of parameters
  - Time
  - Environmental Stresses
  - Operational Stresses
  - Module Design Parameters

- Achieving long-life requires that these functional dependencies be characterized and quantified, and thoroughly addressed in the module design process -- This is the function of characterization testing

- Once a module has been designed and fabricated there are a variety of design validation tests that are extremely useful in identifying any design deficiencies that potentially limit the suitability of the module for field service
  - Qualification Tests
  - Accelerated Life Tests
  - Outdoor Field Weathering Tests
  - Demonstration System Tests