Considerations for Estimating Service Life of Polymeric Materials in PV Applications

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David Burns, 3M Weathering Resource Center
A Diverse Portfolio of Weatherable, Durable Products

The leader in many different markets with high outdoor performance needs

3M utilizes *weathering science* to understand *product performance* in different climates, and to develop high durability products
3M Weathering Science
Committed to delivering Product Durability for over 70 years

- Combining experts in photochemistry, materials engineering, degradation kinetics and climatology to conduct fundamental and applied research on materials degradation
- Creating advanced state-of-the-art exposure tests to quantify the effect of solar radiation, heat, moisture, thermal cycling
- 3M Scientists lead or participate in many national and international committees on outdoor durability

Artificial accelerated weathering tests, are conducted in in the WRC and at satellite 3M international laboratories. The WRC at 3M Center is the largest artificial weathering laboratory in the world operating >100 weathering devices 24/7.

Natural outdoor weathering is conducted worldwide in both benchmark climates and a wider range of climates representative of where 3M products are used.
3 Weathering Resource Center

Description:
- The Weathering Resource Center is a 3M facility that provides testing and research services for the study of material failures resulting from exposure to light, heat, and moisture. Controlled outdoor weathering is conducted in a number of global locations. Accelerated weathering devices are operated in the WRC laboratory to provide similar environmental stresses on materials and constructions, but in a shorter time frame.

Value Proposition:
- The WRC’s unique ability to support research of the degradation effects and lifetimes of many product types across many 3M divisions leads to increased product durability and improved product reliability.

Technical Benefits:
- The WRC has developed a number of proprietary laboratory tests that exhibit very good correlation with natural weathering results. Faster tests are achieved through the use of patented light sources that yield higher levels of realistic solar radiation.

Applications:
- Numerous 3M products have durability requirements, whether used in a natural, outdoor environment or in an artificially lit environment, such as an office or a lighted display.
Considerations for Estimating Service Life of Polymeric Materials in PV Applications

Request: “Give a talk that describes how 3M approaches service life prediction and durability”

Goal Set #1:
Establish common concepts and vocabulary
Address common misconceptions
Provide examples of:
  Service life predictions
  Some 3M approaches to product durability
  Compare and contrast those two
Evolve through discussions with thought leaders in the field

Goal Set #2:
Thoughts on market-driven product segmentation
Reliability / Service Life
PV misnomers

• Anything that fails any test is a failure
  – (Think 85/85, blow torch, 10,000 suns)
  – Highly Accelerated Testing (HAT) = Service Life Prediction (SLP)

• 25 years = X suns for Y years... (define X and Y)
  – All UV exposures sources are the same
  – All materials are the same
  – Reciprocity? What’s that?
  – All service lifetimes are the same (Dubai, Chicago, ...)

• Durability = reliability
  – What is system failure?
  – What is component failure?
    • Materials degrade... (e.g. encapsulant yellows, PET embrittles)
Glossary

- At Module level and Component level
  - Degradation rate
  - Definition of failure defined by user
  - Rate of failure
  - Failure mechanism (mechanics of device failure)
  - Degradation mechanism (materials change)

- Device failure v. component failure/component degradation, failure

- Failure mode (environmental stress)
  - “extreme environments” definition: what are they? 85/85, or 90/40

- Universal Acceleration factor (e.g. 2 weeks of any machine = 1 year of outdoor exposure anywhere)
  - The Holy Grail of outdoor durability work.

- Acceleration factor: specific to material and environment

- Acceleration factor range

- Reciprocity

- Reliability: failure to perform desired function

- Durability: wear out

- Screening tests: a product development test, useful to assess and screen set of options
  - HAT: 85/85, HALT, HAST: PCT

- Failure mode analysis (modeling the rates of degradation/failure under particular environmental stresses)

- Service life: length of time from installation until the critical property reaches failure as defined by the user (will depend on geographic location)

- Activation energy; Arrhenius model: rule of thumb that occasionally models actual behavior; needs correct mechanism

- Standards Durability Test Protocol (concept)
  - should be essentially fitness-for-use test; some thought to be given to where the bar is set.
  - High bar-
  - Low bar – promotes competition and cost reduction
  - Arbitrary(e.g. 85/85)

- Standards Qualification Test (e.g. IEC 61215)
  - Sets due diligence in nominal safety (legal protection)

- Manufacturer Qualification Test
  - Internal test procedures for acceptance of components for use in specific modules by a specific manufacturer
Durability issues and service lifetime prediction of electrochromic windows for buildings applications

A.W. Czanderna\textsuperscript{a}, D.K. Benson\textsuperscript{b}, G.J. Jorgensen\textsuperscript{a}, J.-G. Zhang\textsuperscript{b}, C.E. Tracy\textsuperscript{b}, S.K. Deb\textsuperscript{b} (NREL)

**SLP element 1.** The “final” (or prototype) design and materials selections are needed for the multilayer stack.

**SLP element 2.** The “stresses” imposed on the device in real-time use and the same types of stresses for ALT need to be identified and quantified.

**SLP element 3.** The complete devices are subjected to ALT and RTT to determine their durability and the most sensitive measurement(s) of the performance loss (or of a parameter that can be correlated to the performance) is measured periodically as a function of exposure time.

**SLP element 4.** The mechanisms of degradation of bulk materials and/or reactions at interfaces must be identified and understood. The degradation mechanism must result in a loss in performance of the device, or compromise the materials function, or both, to be of concern.

**SLP element 5.** Models need to be developed for correlating ALT data and RTT data taken at several geographic sites with diverse stresses.

**SLP element 6.** Data bases of stresses and materials response must be established that include data from different outdoor sites.

**SLP element 7.** Predictive service lifetime models are then developed from the data obtained in elements 2–6 by using statistical approaches and life distribution models.
# SLP Steps

<table>
<thead>
<tr>
<th>Phase</th>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td><strong>Screening</strong> - failure mode identification (which environmental stresses cause degradation at an appreciable rate)</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td><strong>chemical degradation rate</strong> study (bond scission) (include reciprocity demonstration)</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td><strong>Physical property degradation rate</strong> study (e.g. T&amp;E) (include reciprocity demonstration)</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td><strong>Failure definition</strong> (relationship of physical property degradation to device failure)</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td><strong>Multi-mode analysis</strong>&lt;br&gt;Define the mechanisms&lt;br&gt;Model the degradation rates&lt;br&gt;Estimate lifetimes in extreme environments</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td><strong>Global Service Life Prediction</strong> (includes target local climatic input)</td>
</tr>
</tbody>
</table>
SLP Phases

1. HAT (Highly Accelerated Test)
2. FM analysis
3. SLP
**HAT** -> FM analysis -> SLP

- **HAT**: how it *can* break (not necessarily how it *will* break)
  - ALT, HALT, HAST, 85/85, PCT, UVB13,
  - **OUTPUTS**:
    - *Screening* results: pass/fail
    - *Failure mode(s)* (environmental stress)
    - Possibly, a rate of failure for probably non-relevant stresses
    - *False positives* and *false negatives* possible
      - False negatives: problematic for cost optimization programs
    - May or may not relate to reality; materials dependent
    - Data is not useful for service life prediction
HAT -> **FM analysis** -> SLP

- **FM analysis:**
  - Map HAT failures to real world (RW) failures
    - Environment: **RW extreme conditions**
      - Expert area:
        » Specific applications knowledge
        » E.g. hot/humid (FL or Singapore), hot (AZ or Saudi Arabia), cyclic
    - Materials: **“engineering judgement”** as to appropriate range of artificial stress conditions
      - Expert areas – need the correct disciplines involved
      - Be careful with Lore versus data-based Knowledge
        » Polymer science (Tg, Tm, hygroscopic behavior, CTE, diffusion rate)
          • Need to show good example
        » “Stress” physics modeling (photons/frequency, real world humidity for modules vs. module and ambient conditions)
      - Would rule out 85/85 if it changes the behavior of a polymer because of plasticization, Tg, melting points.
    - **OUTPUT:** Range of artificial stress conditions appropriate for a given material in given application
      » Which are “allowed” (relevant, and model-able)
      » Which should not be allowed (likely not relevant, due to too many structural changes to the material)

- **Model** the expected behavior
  - Accelerated testing to identify effect of key variables
    - Needs to be multipoint (temperature and time)
      » May need include different wavelength for UV
    - “Reciprocity” (does 5 suns = 5 x 1 sun?)
    - Cannot expect Arrhenius behavior – need to weather to failure to establish the model

- **Outputs:**
  - **Model of degradation behavior** needs validation by RW results)
  - **Rate(s) of degradation** for material under relevant environmental stresses
  - **Activation energy(s)** for degradation mechanism(s)
    - Different degradation mechanisms can occur for both different materials AND different environmental stresses
      » EACH degradation mechanism needs to be approached separately
SLP (Service Life Prediction)
- Define failure mode(s) (end of life)
- Relate degradation rates to failure rates (time to failure)
- Model the expected behavior and verify w/ accelerated testing ---TEST TO FAILURE
  - Utilize multistress environments
- OUTPUT 1: a quantified rates of failure for relevant environmental stresses

Combine failure rates with known climatic information
- OUTPUT 2: projected service life wrt a particular failure, at a particular terrestrial location and application specific orientation
  - Often used for extreme conditions, e.g. AZ, FL, MN
- OUTPUT 3: projected service life for a given location, all different failures mechanisms included
SLP Examples

• **Specific mechanisms for one component**
  – Color in a dyed film
  – PET hydrolysis
  – EVA yellowing
  – PET photolysis
Hydrolysis kinetics of condensation polymers under humidity aging conditions

James E. Pickett*, Dennis J. Coyle
GE Global Research

From Jim:
• Below 40C, PET is more hydrolytically stable than PC.
• Above 40C, PC is more hydrolytically stable than PET.
• PET Photolysis is another mechanism
• “Hydrolytically Stable PET = Photolytically less stable
Combining Failure Mechanisms:

From Roger French:

Figure 1: Some Example PV Module Performance Degradation Pathways
SLP Examples

- **Specific mechanisms for one component**
  - Color in a dyed film
  - PET hydrolysis
  - PET photolysis
  - EVA yellowing

- **Multilayer bond strength degradation**
  - Cohesive or adhesive failure?
  - Too much mechanical stress on the bond
    - Change in stress
      » (CTE mismatch, freeze/thaw cycles, water/humidity update cycles)
    - Change in materials
      » PET surface degradation

- **Combination of mechanisms for a multicomponent system**
  - ???
How do I develop a product that will perform its function for X years?

• In 3M, we do a lot of this.
• In PV, we are doing a lot less of this than I would like. (Too much focus on HAT tests).
• Depends on whether it’s a new-new product, or a product improvement
  – New product for new application:
    • Front sheet for flexible CIGS
  – Improved product for a mature application:
    • New backsheet for China market
Considerations for product development

• One global application = one product?
• Evolving to a Portfolio of products
  – Market segments, Applications
    • Performance levels (masking tape)
    • OEM customers (automotive tape)
    • Weathering Performance (secondary attribute)
      – reflective road signs
      – Fleet graphics
    • Geographic regions (local source of supply)
    • Value Story (price points)

• Climate zones?
  – Road Markings
Masking Tape

- DIY (Home Depot)
- Contractors
- Automotive OEMs
- Automotive Aftermarket
Acrylic Foam Tapes
Automotive Attachment

- Double sided foam tape – VHB
- Automotive OEMs
  - Same general attributes:
    - adhesive strength
      - Green strength
      - Low angle peel
      - 90 degree peel
    - high temperature shear performance
    - Low temperature shock performance
  - Different specification sets for each OEM
  - Different products for each OEM
Acrylic Foam Tapes
Automotive Attachment

Durability of 3M™ VHB™ Tapes

Summary
This bulletin addresses the long-term durability of VHB™ Acrylic Foam and Adhesive Transfer Tape products and their ability to perform in certain types of demanding environments. This will be addressed from a variety of viewpoints including chemical composition, resistance to harsh environments, 3M and independent tests for product durability, and certain applications where VHB™ Tape products have demonstrated excellent ability to perform in demanding applications. Test results on moisture resistance, UL durability, accelerated weathering, outdoor weathering, thermal cycling and fatigue resistance will be discussed.

- Resists all of the following:
  - High temperature
  - Cold
  - Temperature cycling
  - UV light
  - Moisture and solvents
- Seal against environmental conditions
- Prevent bi-metallic corrosion
- Damp vibration to prevent metal fatigue
- Compensate for differential of thermal expansion

Replace rivets in bonding truck side panels to steel frames for a much smoother, cleaner appearance and a strong bond. VHB tape can also reduce vibration in the boxes.

Signs that resist cold winds in Denmark (installed 1985)

Individual OEM specifications
Reflective Sheeting
(for Road Signs)

Table C – Minimum Percent Retained of Table B Initial $R_a$ for applicable Warranty Period for Ordinary Colors (white, yellow, red, green, blue and brown)

<table>
<thead>
<tr>
<th>Warranty Period</th>
<th>Minimum Percentage $R_a$ Retained</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-7 Years</td>
<td>80%</td>
</tr>
<tr>
<td>8-12 Years</td>
<td>70%</td>
</tr>
</tbody>
</table>

Table D – Warranty Period for Fluorescent Colors.

<table>
<thead>
<tr>
<th>Color</th>
<th>Warranty Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescent Yellow</td>
<td>10/7 Years</td>
</tr>
<tr>
<td>Fluorescent Yellow Green</td>
<td>10/7 Years</td>
</tr>
<tr>
<td>Fluorescent Orange</td>
<td>3 Years</td>
</tr>
</tbody>
</table>

5 States south 35° latitude
Graphic Film
# Graphic Film (Fleet Graphics)

## Warranty Period for Finished Graphics, in Years

<table>
<thead>
<tr>
<th>SOLVENT PRINTERS and INKS</th>
<th>ERI™ VUTEk® 150, 2360/3360, 3300, 3300/5300, 3000/5000 Printers</th>
<th>HP Scitex XL 1200, XL 1500 Printers</th>
<th>HP Scitex TJ8300 and TJ8350 Industrial Printers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphic Protection</td>
<td>3M Ink Series 1500v2</td>
<td>3M Ink Series 4400</td>
<td>3M Ink Series 4800</td>
</tr>
<tr>
<td>8518, 8519, 8520, 8915</td>
<td>VEH 4 OUT 2 WATER 8</td>
<td>VEH 4 OUT 2 WATER 8</td>
<td>VEH 4 OUT 2 WATER 8</td>
</tr>
<tr>
<td>8528, 8548G</td>
<td>7/2 4 OUT 2 WATER 8</td>
<td>7/2 4 OUT 2 WATER 8</td>
<td>7/2 4 OUT 2 WATER 8</td>
</tr>
<tr>
<td>8908, 8909</td>
<td>3 1 OUT 3 WATER 8</td>
<td>3 1 OUT 3 WATER 8</td>
<td>3 1 OUT 3 WATER 8</td>
</tr>
<tr>
<td>1920DR</td>
<td>3 3 OUT 2 WATER 5</td>
<td>3 3 OUT 2 WATER 5</td>
<td>3 3 OUT 2 WATER 5</td>
</tr>
<tr>
<td>9740i</td>
<td>5 4 OUT 2 WATER 8</td>
<td>5 4 OUT 2 WATER 8</td>
<td>5 4 OUT 2 WATER 8</td>
</tr>
<tr>
<td>8530</td>
<td>2 2 OUT 3 WATER 3</td>
<td>2 2 OUT 3 WATER 3</td>
<td>2 2 OUT 3 WATER 3</td>
</tr>
<tr>
<td>none</td>
<td>2 2 OUT 2 WATER 2</td>
<td>2 2 OUT 2 WATER 2</td>
<td>2 2 OUT 2 WATER 2</td>
</tr>
</tbody>
</table>

- Overlaminates 8528 and 8548G: first number represents the vertical warranty and the second number represents the horizontal warranty.

## Desert Southwest Region - Defined

The following portions of the hot, and desert areas of Southwestern U.S., which carry reduced warranted durabilities as specified in the 3M Product Bulletins are defined to be:

### Southern Counties:
- Clark (Las Vegas), Lincoln, Nye, Esmeralda, Mineral

### Western Counties:
- El Paso, Hudspeth, Culberson, Loving, Ward, Reeves, Ward, Presidio, Brewster

### Northern Counties:
- Mcintosh, San Benardino, Riverside, Imperial

![Desert Southwest Map]
Market Focused PV segments

• Customers
  – Finance
  – Utilities
  – Homeowners
  – Residential Contractors
  – Commercial Building – Maintenance
  – Insurance Companies (Residential, Commercial, Utility)

• Differing Interests
  – Service Life
  – Total cost: service life and confidence level
  – Warranty
  – Fire hazard
  – Aesthetics
  – Voltage: total system voltage, grounding plan
Varied climate – generalized approach

• Understand failure modes, and relevant environmental stresses
• Estimate/calculate service life times for extreme locations
• Utilize technical knowledge to make business decisions
• Tell the customer what 3M warranties
• The market understands
  – Warranties can differ differently
    • road signs
      – Saudi Arabia (5 years)
      – Ireland, Minnesota, Florida and Arizona all 12 years
      – Traffic Engineers in MN and FL view sign lifetime differently
    • commercial graphics
      – Florida versus Arizona 7, 5

• Always an opening for alternative products with a better value story
Evolution of testing for durability as an application/product matures

1. Start
   - No benchmark materials
   - Junkyard: any HAT is just as good for screening purposes

2. How long will it last in the application:
   a) Rational development of environmental stress tests
   b) In service durability assessment
   c) Validated environmental stress tests are developed
      • Conformance Test: defined test with pass/fail criterion

3. Domain of Rightly Engineered Materials
   - Benchmark materials are established
   - Failure mechanisms for benchmarks are known
   - Improvements can be made
   - Target market segments are sorted out
   - Rightly engineered products are targeted toward the appropriate market segments, at the right value.
      • HAT testing will eliminate good candidates
Suggestion for an initial goal

• Define extreme environments
  – Include system voltage, module operating temperatures

• Understand service lifetimes there
  – “This module and its components have gone through rigorous environmental testing. and are estimated to have the following service lifetimes (<1% efficiency loss/year)”

<table>
<thead>
<tr>
<th>Climate</th>
<th>Mounting</th>
<th>Service Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot/Dry</td>
<td>Backed</td>
<td>A years</td>
</tr>
<tr>
<td>Hot/Wet</td>
<td>Backed</td>
<td>B years</td>
</tr>
<tr>
<td>Freeze/Thaw</td>
<td>Backed</td>
<td>C years</td>
</tr>
<tr>
<td>Frozen</td>
<td></td>
<td>D years</td>
</tr>
<tr>
<td>Temperate</td>
<td>Open, Tracking</td>
<td>E years</td>
</tr>
</tbody>
</table>

• Build capabilities toward:
  • “Estimated Service Lifetimes at other geographic locations are available upon request”
Improving the Safety of the Roadway through Specifications

Timeline of Road Construction Specifications

Public Roads 2002