Introduction

- Many degradation processes within a PV module are driven by moisture.
- The concentration of moisture in a module is a complex function of the use environment and the module construction.
- In accelerated stress testing one must know how water affects degradation to determine what temperature and humidity conditions to use.
- Here we show that by choosing humidity conditions that more closely match the use environment, one can minimize the uncertainty associated with moisture induced degradation modes.
Outline

• Describe moisture on the backside of a module.

• Look at the hydrolysis of a typical back-sheet made of PET as a case study for comparing 85 °C/85% RH to outdoor exposure.

• Examine the moisture and temperature environment on the front of a module as a worst case scenario.

• Show how good choices for RH testing will minimize uncertainty.
Representative Module Environment

- Use either IWEC or TMY-3 data for select environments.
- Use the model of King et al.* for module temperature.
- This produces “representative” data intended to generally duplicate a use environment.

Moisture in the Back-EVA Layer

- Assume diffusivity in EVA is much greater than in the back-sheet.
- Also assume transient moisture gradient in the back-sheet is unimportant.

\[
\frac{dC_E}{dt} = \frac{WVTR_{B, Sat}}{C_{E, Sat} l_E} \left( C_{E, Eq} - C_E \right)
\]

Bangkok Thailand Module Back-EVA Absolute Humidity

- Insulated Back, Glass/Polymer
- Close Roof, Glass/Glass
- Open Rack, Glass/Polymer
- Open Rack, glass/glass

Diagram showing layers of a solar module with water vapor exchange.
• A PET based back-sheet will be exposed to humidity between that outside and inside the module.
**Pet Hydrolysis Kinetics**

\[
\log \left( \frac{C}{C-x} \right) = A \cdot t \cdot RH^2 \cdot e^{\left( \frac{-E_a}{kT} \right)}
\]

\(E_a=129.4 \text{ kJ/mol (1.340 eV)}, A=2.84 \cdot 10^{10} \text{ 1/day}, RH \text{ expressed as a percentage.}\)

*PET becomes brittle (1/3 initial tensile strength) and “failed” when log(C/C-x)=~0.0024, or about 0.55% hydrolysis of ester bonds.*

**Pickett et. al saw the activation energy vary between 125 and 151 kJ/mol with an average of 136±13 kJ/mol for four different PET grades.*

---


PET Hydrolysis Results

\[
\log \left( \frac{C}{C-x} \right) = A \cdot t \cdot RH^2 \cdot e^{\left( \frac{-Ea}{kT} \right)}
\]

<table>
<thead>
<tr>
<th></th>
<th>Years to 0.55% degradation (i.e. Hydrolysis Service Life) (y)</th>
<th>1000 Hours 85°C/85% RH Years equivalent (y)</th>
<th>Relative Humidity at 85°C so that 1000 h equals 25 years exposure (%)</th>
<th>Temperature at 85% RH so that 1000 h equals 25 years exposure (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open Rack</td>
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<tr>
<td>Denver, Colorado</td>
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PET is predicted to “fail” after 2064 h of 85 °C and 85% RH.
Site Specific Equivalent T and RH

\[ R = A \cdot RH^n e\left(-\frac{Ea}{kT}\right) \]

\[ RH_{weighted\ average} = RH_{WA} = \left[ \frac{\sum RH^n e\left(-\frac{Ea}{kT}\right)}{\sum e\left(-\frac{Ea}{kT}\right)} \right]^{\frac{1}{n}} \]

This tells you what the relative humidity is at the temperatures where the most damage is done.

These terms cancel out

\[ (RH_{WA})^n e\left(-\frac{Ea}{kT_{eq}}\right) = \frac{\sum RH^n e\left(-\frac{Ea}{kT}\right)}{N} = \left\{ \frac{\sum RH^n e\left(-\frac{Ea}{kT}\right)}{\sum e\left(-\frac{Ea}{kT}\right)} \right\}^{\frac{1}{n}} e\left(-\frac{Ea}{kT_{eq}}\right) \]

\[ \therefore \frac{\sum e\left(-\frac{Ea}{kT}\right)}{N} = e\left(-\frac{Ea}{kT_{eq}}\right) \quad \therefore \quad T_{eq} = -\frac{K}{Ea} \ln\left[ \frac{\sum e\left(-\frac{Ea}{kT}\right)}{N} \right] \]

The equivalent temperature \((T_{eq})\) gives the temperature at \(RH_{WA}\) for which constant conditions will produce a degradation rate equivalent to the yearly average.
PET Hydrolysis Equivalent T and RH

\[
\log \left( \frac{C}{C-x} \right) = A \cdot t \cdot RH^2 \cdot e\left( \frac{-Ea}{kT} \right)
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<th>Teq for Ea=129.3 kJ/mol (°C)</th>
<th>RH, at Teq for 2nd order Kinetics of PET (%)</th>
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What Are Relevant Activation Energies

Degradation activation energy from Dixon*. Based on RTI testing for properties such as:

- Elongation at Break
- Flexural strength
- Tensile Strength
- Shear Strength
- Burst Strength
- Weight Loss
- Dielectric Strength
- Imp. Strength

For Diffusion Controlled Processes

Histogram for moisture ingress activation energy for PV polymeric materials.
Thermal Stress by Location and Mounting

Equivalent Temperature

Equivalent Temperature (°C) vs. Activation Energy (kJ/mol)

- **Dashed Lines:** Insulated Back
- **Solid Lines:** Rack Mounted

Locations:
- Riyadh
- Bangkok
- Denver
- Munich

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Modeling Moisture in the Front-EVA

The Back-EVA equilibrates with a characteristic time of about a day.

The Front-EVA equilibrates with halftimes of between a day and several years depending on the mounting configuration, location, and the position in front of the cell.

Uses the backside water concentration at the perimeter in a 2-D diffusion finite element algorithm. The cell size is 156+2 mm to account for water diffusing from the back to the front.
Front Encapsulant Water Content

The front encapsulant traps in moisture seasonally making the center of the cell front the most hydrolytically damaging area.

The remainder of this presentation focuses on the center of the front side to evaluate the most stressful position in the module.
RH Not Very Dependent Kinetics or Ea

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Weighted RH (%) vs. Activation Energy (kJ/mol)

Rack Mounted

Insulated Back

\[ R_D \approx RH^n e^{-\frac{Ea}{kT}} \]
Small RH Dependence in All Climates

\[ R_D \approx RH^n e^{\left( \frac{E_a}{kT} \right)} \]

Solid Lines: Rack Mounted
Dashed Lines: Insulated Back
Darker Line: \( n=2 \)
Lighter Line: \( n=1 \)

Weighted RH (%)

Activation Energy (kJ/mol and eV)

Bangkok
Munich
Denver
Riyadh
$R_D \approx RH^n e\left(-\frac{E_a}{kT}\right)$

85% RH

Solid Lines:
Rack Mounted

Dashed Lines:
Insulated Back

- Rack, $n=2$
- Rack, $n=1$
- Rack, $n=0$
- Insulated, $n=2$
- Insulated, $n=1$
- Insulated, $n=0$
The unknown humidity dependence results in a 1000× uncertainty in the acceleration.
Testing using a chamber humidity of 5% vs. 85% significantly reduces the variability in the acceleration factor.
The Highest RH You Might Want is ~25%

$$R_D \approx R H^n e \left( - \frac{E_a}{kT} \right)$$

Solid Lines:
- Rack Mounted
- Rack, n=2
- Rack, n=1
- Rack, n=0

Dashed Lines:
- Insulated, n=2
- Insulated, n=1
- Insulated, n=0

1000 h, 85 °C, 25% RH, Outdoor Equivalent (Y)

Bangkok, Thailand

Activation Energy (kJ/mol)
Without knowing the moisture induced degradation kinetics, it is better to use a low RH and accelerate processes principally by thermal acceleration.
Conclusions

• With respect to PET hydrolysis, 85 °C/85% RH, may be equivalent to hundreds or thousands of years.
• For thermal and/or moisture induced failure, the mounting configuration can be as important as the location.
• Care must be taken in accelerated stress testing to account for the variable relative acceleration of the different degradation modes.
• Choosing the right humidity level for accelerated stress testing can dramatically decrease the uncertainty in the results.
Acknowledgements

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