Understanding Moisture Ingress Rates in PV Modules

Barrier Technologies Workshop

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Introduction

• Many electronic devices are sensitive to moisture (e.g. OLEDs, OPV, CIGS, CdTe).
• For some applications we would like to have a transparent flexible moisture barrier material.
  o Ease of application.
  o Weight limits for some structures.
  o Here I will explain the theory behind why such low permeation is necessary and how to prevent moisture ingress.
Outline

• Permeation through barrier films. 25 y requirements.
• Diffusion from the module edges.
• Edge seals
How Does WVTR Relate to Total Permeation?

Water Thickness Permeated in 25 y

This depicts how much water would get in if it was consumed immediately.
Moisture in Breathable Front-Sheets

Moisture Permeation Assumptions:

(1) \( C_{EVA} \) not a function of position \( X \)  (i.e. \( D_{EVA} \gg D_B \))

(2) WVTR is proportional to \( \Delta C_B = C(0) - C(l_B) \)

\[
\frac{dC_{EVA}}{dt} = \frac{WVTR_{B, Sat}}{C_{E,Sat.}l_{EVA}} \left[ C_B(0) - C_B(l_B) \right]
\]
Time Constant for Water Ingress

$$\frac{dC_{EVA}}{dt} = \frac{WVTR_{B, Sat}}{C_{E, Sat} \cdot l_{EVA}} \left[ C_B(0) - C_B(l_B) \right] \Rightarrow C(t) = C_0 \left( 1 - e^{-\frac{WVTR_{Sat}}{C_{Sat,EVA} \cdot l_{EVA}}} \right)$$

$$\tau = 0.693 \frac{C_{Sat,EVA} \cdot l_{EVA}}{WVTR_{B, Sat}} = 0.693 \frac{\text{Amout of water EVA can hold}}{\text{Rate of moisture ingress}}$$
Time Constant for Water Ingress

\[ \tau_{1/2} = 0.693 \frac{C_{Sat,EVA} l_{EVA}}{WVTR_B, Sat} \]

- \( l_{EVA} = 0.46 \text{ mm}, T = 27 \, ^\circ\text{C}, C_{Sat,EVA} = 0.0022 \, \text{g/cm}^3 \)
- \( l_{PET} = 0.10 \text{ mm}, l_{PEN} = 0.10 \text{ mm}, l_{PCTFE} = 0.022 \text{ mm} \)

<table>
<thead>
<tr>
<th>Material</th>
<th>( \tau_{1/2} ) (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET</td>
<td>0.22</td>
</tr>
<tr>
<td>PEN</td>
<td>0.91</td>
</tr>
<tr>
<td>PCTFE</td>
<td>5.5</td>
</tr>
</tbody>
</table>

For \( \tau_{1/2} = 25 \text{ years} \) need \( 0.8 \cdot 10^{-4} \, \text{g/m}^2/\text{day} \)

At \( 1 \cdot 10^{-3} \, \text{g/m}^2/\text{day} \), the encapsulant will have a half time of 1.9 y. This short time frame is insignificant compared to a 25 y warranty.
Encapsulant Materials Structures

\[ \tau^{1/2} = 0.693 \frac{C_{Sat,E}l_E}{WVTR_{B,Sat}} \]

R = -CH₃ , -(CH₂)nCH₃, others or multiple "R" groups.

Thermoplastic Polyolefin (TPO)

Thermoplastic Polyurethane (TPU)

Polydimethylsiloxane (PDMS)

Ionomer

Polyvinyl Butyral (PVB)

Ethylene Vinyl Acetate (EVA)

Significantly More Adsorbent Polymers Exist

A 10X more water adsorbent polymer may reduce the barrier requirements by a factor of 10.
EVA Allows Significant Moisture Ingress From Edges

Finite element analysis using meteorological data from Miami Florida 2001

**Graph Description:**
- The graph shows the dissolved water content in g/cm³ as a function of distance X from the edge in cm.
- The x-axis represents the distance X from the edge, ranging from 0 to 20 cm.
- The y-axis represents the dissolved water content in g/cm³, ranging from 0.00000 to 0.0025.
- The graph includes data points for EVA and glass materials.
- The data is color-coded by month, with each month represented by a different color.
- The graph indicates increasing dissolved water content over time, with a peak at X=0 and a decrease as X increases.

**Legend:**
- Black: Jan
- Dark grey: Feb
- Medium grey: Mar
- Purple: Apr
- Dark blue: May
- Sky blue: Jun
- Teal: Jul
- Pale green: Aug
- Yellow: Sep
- Orange: Oct
- Maroon: Nov
- Red: Dec

**Graph Notes:**
- The graph visually represents the moisture ingress into EVA and glass materials over time.
- The data points are color-coded to distinguish between months and to show the progression of moisture content.
Lower diffusivity can reduce ingress rates from the side by two orders of magnitude.
Determining Moisture Ingress Distance From Edges

Distance from edge which after 25 years will be at 5% of the equilibrium concentration.

\[
\begin{align*}
E_{a_{PDMS}} &= 27 \text{ kJ/mol} \\
E_{a_{EVA}} &= 38 \text{ kJ/mol} \\
E_{a_{TPO}} &= 53 \text{ kJ/mol} \\
E_{a_{Ionomer\#1}} &= 56 \text{ kJ/mol}
\end{align*}
\]

<table>
<thead>
<tr>
<th>Effective Temperature (°C)</th>
<th>Diffusivity Weighted Average Module Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rack Mounted</td>
</tr>
<tr>
<td></td>
<td>PDMS</td>
</tr>
<tr>
<td>Munich, Germany</td>
<td>19.5</td>
</tr>
<tr>
<td>Denver, Colorado</td>
<td>25.8</td>
</tr>
<tr>
<td>Miami, Florida</td>
<td>33.8</td>
</tr>
<tr>
<td>Albuquerque, New Mexico</td>
<td>30.6</td>
</tr>
<tr>
<td>Bangkok, Thiland</td>
<td>38.0</td>
</tr>
<tr>
<td>Phoenix, Arizona</td>
<td>40.6</td>
</tr>
<tr>
<td>Riyadh, Saudi Arabia</td>
<td>42.3</td>
</tr>
</tbody>
</table>

M.D. Kempe, A. A. Dameron, M.O. Reese, to be submitted to Progress in Photovoltaics (2012)
Test Sample Designed to Mimic Module Edge

**Edge Seals**

[Diagram of edge seals with labels: Polyisobutylene, Glass (3.18 mm), Polymer Film (~0.5 mm), Ca (100 nm), Glass (3.18 mm), H2O]

**Module Edge**

\[ \text{H}_2\text{O} \rightarrow \text{Seal} \rightarrow \text{Encapsulant} \rightarrow \text{Glass} \]

**Test Sample**

\[ \text{H}_2\text{O} \rightarrow 50 \text{ mm} \rightarrow \text{Glass (3.18 mm)} \]

\[ \text{Polymer Film (~0.5 mm)} \]

\[ \text{Ca (100 nm)} \]

\[ \text{Glass (3.18 mm)} \]

**Desiccant**

(e.g. CaO or molecular sieves, Preferably type 3A Molecular Steve that does not absorb O\(_2\) and N\(_2\))

**Chemical Reaction**

\[ \text{Ca} + 2 \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 + \text{H}_2 \]
Oxidation of Ca Indicates Moisture Ingress

\[ \text{Ca} + 2 \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 + \text{H}_2 \]

Mirror-Like \rightarrow Transparent

Unexposed 1500 h, 85\(^\circ\)C, 85% RH

\[ \frac{\partial C}{\partial t} = \nabla(D \nabla C) \]

\[ X = K \sqrt{t} \]
Moisture Ingress Rate Governed by Diffusion

\[ \frac{\partial C}{\partial t} = \nabla (D \nabla C) \]

\[ X = K \sqrt{t} \]

Moisture ingress measured at 45°C and 85°C, with RH held at 85%, and at lower levels using saturated salt solutions of LiCl, MgCl, or NaNO₃.

<table>
<thead>
<tr>
<th>RH (%)</th>
<th>45</th>
<th>85</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(°C)</td>
<td>(°C)</td>
</tr>
<tr>
<td>NaNO₃</td>
<td>67%</td>
<td>59%</td>
</tr>
<tr>
<td>MgCl</td>
<td>31%</td>
<td>25%</td>
</tr>
<tr>
<td>LiCl</td>
<td>11%</td>
<td>10%</td>
</tr>
</tbody>
</table>
Edge Seal Modeling

\[ S_m = S_o e \left( \frac{-E_{a_S}}{kT} \right) \frac{RH \%}{100\%} \]

Mobile phase water absorption is split between the polymer matrix and the mineral components. Assume linearity with relative humidity.

\[ D_{eff} = D_o e \left( \frac{-E_{a_D}}{kT} \right) \]

Mobile phase water diffusivity is an effective diffusivity. This accounts for a rapid equilibration between adsorbed and dissolved water.

\[ R_{H_2O} \]

A non-reversible reaction with water that immobilizes the water.

Values for the 5 constants were found from absorption measurements and a fit to the data.
Square Root Relation Works to Longer Times

Denver Colorado

\[ X = K \sqrt{t} \]

Used TMY3 Data and Temperature estimate methods from King et al.
## Results for Different Climates

<table>
<thead>
<tr>
<th></th>
<th>Modeled K</th>
<th>Modeled 25 yr required width</th>
<th>Modeled 25 yr equivalent time at 85°C/85% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>D₀ (cm²/s)</strong></td>
<td>0.33</td>
<td>(cm/h₁/²)</td>
<td></td>
</tr>
<tr>
<td><strong>Ea_D (kJ/mol)</strong></td>
<td>47</td>
<td>(cm)</td>
<td></td>
</tr>
<tr>
<td><strong>S₀ (g/cm³)</strong></td>
<td>0.16</td>
<td>(h)</td>
<td></td>
</tr>
<tr>
<td><strong>Ea_S (kJ/mol)</strong></td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Reactive Ca absorption (g/cm³)</strong></td>
<td>0.047</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Modeled K</th>
<th>Modeled 25 yr equivalent time at 85°C/85% RH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Denver, Colorado</strong></td>
<td>Open Rack</td>
<td>0.00087</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Insulated Back</td>
<td>0.00103</td>
<td>0.47</td>
</tr>
<tr>
<td><strong>Munich, Germany</strong></td>
<td>Open Rack</td>
<td>0.00096</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Insulated Back</td>
<td>0.00107</td>
<td>0.51</td>
</tr>
<tr>
<td><strong>Riyadh, Saudi Arabia</strong></td>
<td>Open Rack</td>
<td>0.00102</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Insulated Back</td>
<td>0.00124</td>
<td>0.53</td>
</tr>
<tr>
<td><strong>Phoenix, Arizona</strong></td>
<td>Open Rack</td>
<td>0.00128</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Insulated Back</td>
<td>0.00153</td>
<td>0.63</td>
</tr>
<tr>
<td><strong>Miami, Flordia</strong></td>
<td>Open Rack</td>
<td>0.00199</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>Insulated Back</td>
<td>0.00225</td>
<td>0.95</td>
</tr>
<tr>
<td><strong>Bangkok, Thailand</strong></td>
<td>Open Rack</td>
<td>0.00228</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>Insulated Back</td>
<td>0.00258</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Glass/Polymer Modules.
A sensitivity analysis gave about ±15% on K and Width, and ±30% on 25 yr equivalent time.
What edge seal parameters are important?

1. **Adhesion is the most important parameter.**
   a) Must be maintained after environmental exposure.
   b) Residual stress in glass will affect adhesion.
   c) Material may expand as it absorbs water.
   d) Good surface preparation is necessary.

2. **Breakthrough time is the next most important.**
   a) The 12 mm edge delete perimeter should be wide enough to keep moisture out.

3. **Module mounting configuration is not important.**
   a) Hotter installations tend to dry out the module partially countering the effects of increased diffusivity.

4. **The steady state transmission is less important.**
   a) The amount of permeate is very low.
   b) Ideally one will not reach steady state.

Conclusions

• An ingress half time of 25 years is needed. For typical barriers and encapsulants, a WVTR of less than $0.8 \cdot 10^{-4} \text{ g/m}^2/\text{day}$ or better is needed.

• High solubility encapsulants may decrease the barrier needs to as low as $1 \cdot 10^{-3} \text{ g/m}^2/\text{day}$ or better.

• With impermeable front and backsheets, very low diffusivity polymers can limit moisture ingress to a few cm from the edges.

• A PIB based edge seal width of 1 cm should be able to prevent moisture ingress.
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