Predicting the Performance of Edge Seal Materials for PV

National Renewable Energy Laboratory – Photovoltaic Module Reliability Workshop

NREL-PVMRW

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Edge Seals - Introduction

• Many PV technologies are sensitive to moisture. Even with impermeable front- and back-sheets, moisture can penetrate from the sides. Edge seals are incorporated around the perimeter to prevent this ingress.

• Here we use a Ca-based method to evaluate the moisture ingress time for edge seal materials.

• Then we use this data to model the performance when deployed outdoors.
Outline

• Ca film method for moisture ingress determination.
• Finite element modeling of moisture ingress.
• Investigation of failure modes.
  – Edge Pinch
  – UV Light
  – Heat and Humidity
Test Sample Designed to Mimic Module Edge

Module Edge

H₂O → Glass

Seal

Encapsulant

Glass

Test Sample

H₂O → Glass (3.18 mm)

Polymer Film (~0.5 mm)

Ca (100 nm)

Glass (3.18 mm)

Ca + 2 H₂O → Ca(OH)₂ + H₂
Oxidation of Ca Indicates Moisture Ingress

Ca + 2 H₂O → Ca(OH)₂ + H₂

Mirror-Like → Transparent
Moisture Ingress Varies Greatly in Encapsulants

PDMS

Exposed to 85°C and 85% RH

0 h | 1.5 h | 3 h | 4.5 h

Ionomer #1

50 mm

0 h | 67 h | 240 h | 652 h

Exposed to 85°C and 85% RH
Polyisobutylene Edge Seals Slow Ingress

PIB #1

Exposed to 85°C and 85% RH

0 h 163 h 652 h 1230 h

PIB #2

0 h 1490 h 2780 h 4664 h

Delaminations

Reactions
Moisture Ingress Rate Governed by Diffusion

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

\( X = K \sqrt{t} \)
Moisture Ingress Rate Governed by Diffusion

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

\[ C_{m,n}^{P+1} = \frac{D \Delta t}{(\Delta X)^2} \left( C_{m+1,n}^P + C_{m-1,n}^P + C_{m,n+1}^P + C_{m,n-1}^P \right) + \left[ 1 - 4 \frac{D \Delta t}{(\Delta X)^2} \right] C_{m,n}^P - \text{(Calcium)} \]
Permeation Measured at Low RH

![Graph showing permeation measured at low RH](image)
Low RH Measurements Reduce Extrapolation Errors

Bangkok Thailand RH and Temperature for outside of a Glass/Glass Rack Mounted Module
Edge Seal Modeling

- The use of fillers, pigments, and desiccants makes the determination of modeling parameters much more difficult.

$$S_m = S_o e^{\left( -\frac{E_a_s}{kT} \right) \frac{RH\%}{100\%}}$$

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.
Getting the Modeling Parameters

\( R_{H_2O} \)

Measured by weighing samples before humidity exposure, after humidity exposure, and after drying.

\( S_o, E_{aS} \)

Measured by exposing to controlled humidity then drying in a TGA to determine moisture loss.

Curvature of K vs %RH is determined by the ratio of S to \( R_{H_2O} \).

\( D_o, E_{aD} \)

Estimate from other parameters and fit to Ca data. Specifically the difference between 45 and 85°C curves.
Ingress Estimated Using Finite Element Analysis

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

Denver Colorado

Used TMY3 Data and Temperature estimates similar to King et al, and Kurtz et al.
Square Root Relation Works to Longer Times

Ingress Depth (cm)

Time (Years)

Denver Colorado

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

Used TMY3 Data and Temperature estimates similar to King et al, and Kurtz et al.
### Preliminary Results for Different Climates

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>K (cm/h^{1/2})</th>
<th>20 y required width (cm)</th>
<th>20 yr equivalent at 85°C/85% RH (h)</th>
<th>20 yr equivalent at 45°C/85% RH (years)</th>
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<tbody>
<tr>
<td>$D_0$ (cm²/s)</td>
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<td>$E_a_D$ (kJ/mol)</td>
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</tbody>
</table>

A sensitivity analysis gave about ±15% on K and Width, and ±30% on 20 yr equivalent time.
Edge Seal Failure Modes and Stresses

- Heat.
- Humidity (85°C/85% RH).
- Adhesion to edge delete region.
- UV Light.
- Edge Pinch
Laser Edge Delete Did Not Increase Ingress

![Graph showing distance vs. time with 'Edge Deleted Sides' and 'Non-Deleted Sides' categories.]
Edge-Seals May Have Edge Pinch

Idea Edge Profile
(no bend in glass at the module perimeter)

Edge Pinch
(lamination pressure cause the glass to bend around the perimeter)

Schematic side views of module edge

Very little stress in polymer

Large tensile stress in polymer
Edge Seal Test Specimen

Schematic side view of test sample

Photographic top view

Glass (3.18 mm)
Ca film (100 nm)
Edge Seal
Glass (3.18 mm)

0.5 mm thick polymer

0.2 mm thick polymer

0.30 mm of edge pinch

50 mm

100 mm
Edge Seals With Pinch Resist 85°C and 85% RH

No Exposure
Only small signs of minor delamination on ends exposed to tensile stress.
Edge pinch is 0.31±0.01 mm for all exposures.
UV Light Can Delaminate Edge Seals With Pinch

No Exposure
0.32±0.01 mm pinch

165 h
60°C/60% RH/ 2.5 UV Suns
0.02±0.01 mm pinch

621 h
60°C/60% RH/2.5 UV Suns
0.02±0.01 mm pinch
UV Light Can Delaminate Edge Seals With Pinch

No Exposure
0.32±0.01 mm pinch

Light exposure on non-Ca film backside.
Very significant delamination on ends exposed to tensile stress.

165 h
60°C/60% RH/ 2.5 UV Suns
0.02±0.01 mm pinch

Intact Ca Film

621 h
60°C/60% RH/ 2.5 UV Suns
0.02±0.01 mm pinch

Polymer pulled away from edge
Delamination on front side
UV Light Alone is Much Less Damaging

Unexposed 1962 h 60°C/60%RH/2.5 UV suns

PIB #1

PIB #2
• Under IEC TC82 WG2 a group has formed to work on developing standard test methods for testing PV packaging materials.
  – Encapsulants
  – Back Sheets and Front Sheets
  – Adhesives
  – Edge Seals/Pottants

• If you would like to help with the edge seal standards development, please contact me.
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 edge seal width of 1 cm can be capable of keeping moisture out for 20 years in almost any climate.

• Delamination is the main concern for edge seal performance.

• Edge Seals should be assembled without edge pinch to ensure good adhesion.
Acknowledgements

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David Miller
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