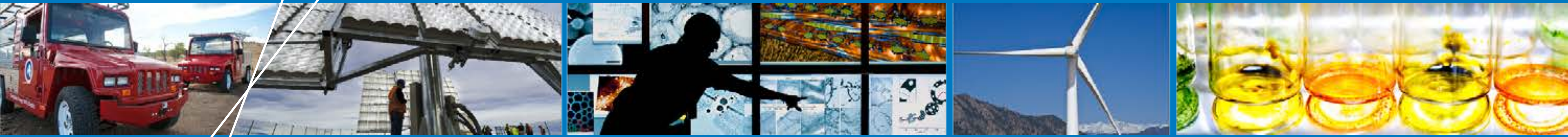
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Predicting the Performance of Edge Seal Materials for PV



National Renewable Energy Laboratory – Photovoltaic Module Reliability Workshop

NREL-PVMRW

Michael Kempe
Dhananjay Panchagade
Arrelaine Dameron
Matthew Reese

March 1, 2012

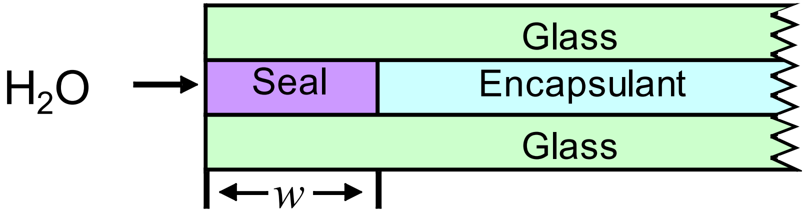
NREL/PR-5200-54582

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.

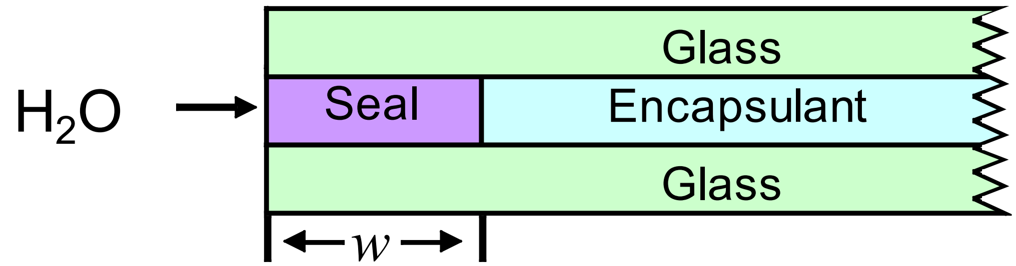


Outline

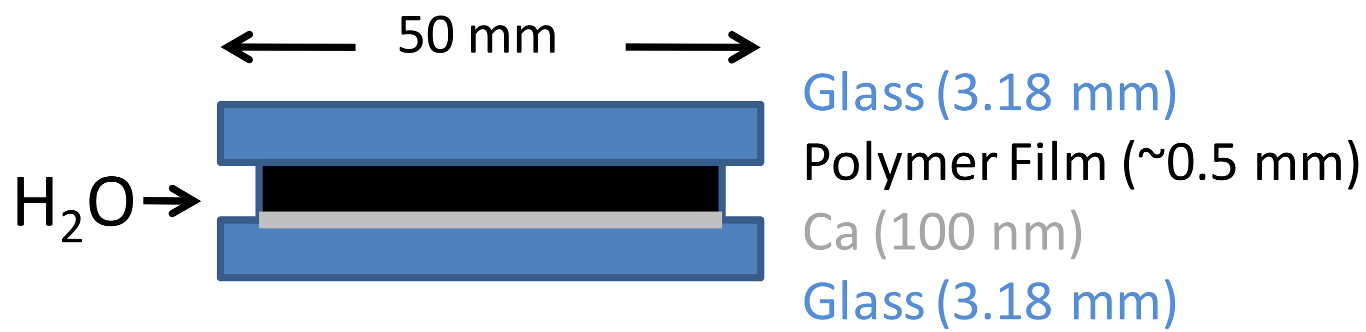
- **Ca film method for moisture ingress determination.**
- **Finite element modeling of moisture ingress.**
- **Investigation of failure modes.**
  - Edge Pinch
  - UV Light
  - Heat and Humidity

Test Sample Designed to Mimic Module Edge

Module Edge



Test Sample

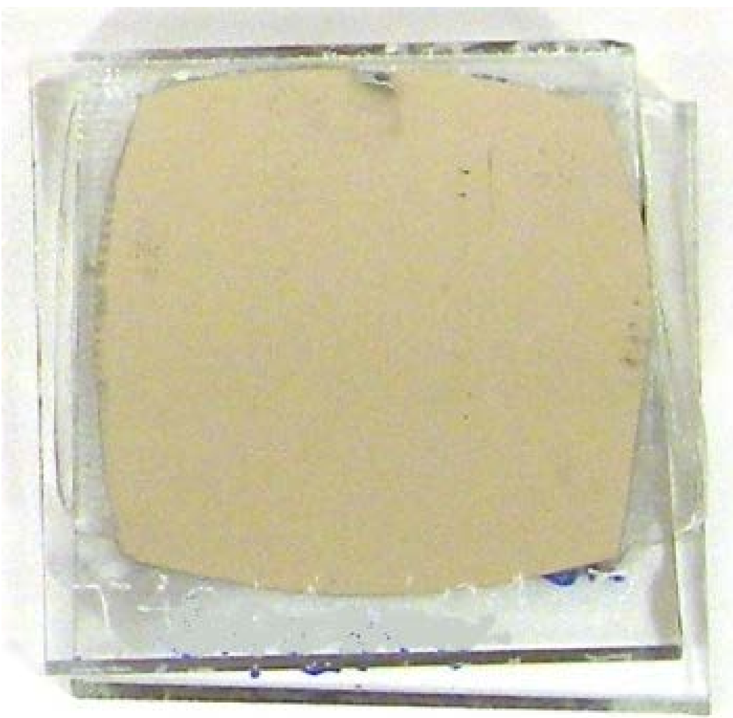


$$Ca + 2\ H_20 \rightarrow Ca(OH)_2 + H_2$$

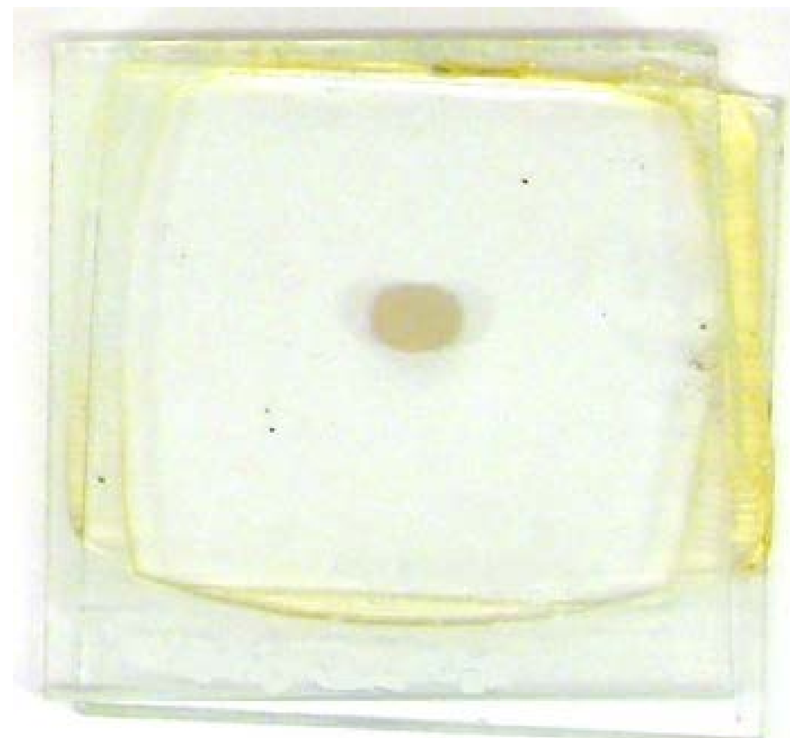
Oxidation of Ca Indicates Moisture Ingress

$$Ca + 2\ H_20 \rightarrow Ca(OH)_2 + H_2$$

Mirror-Like → Transparent

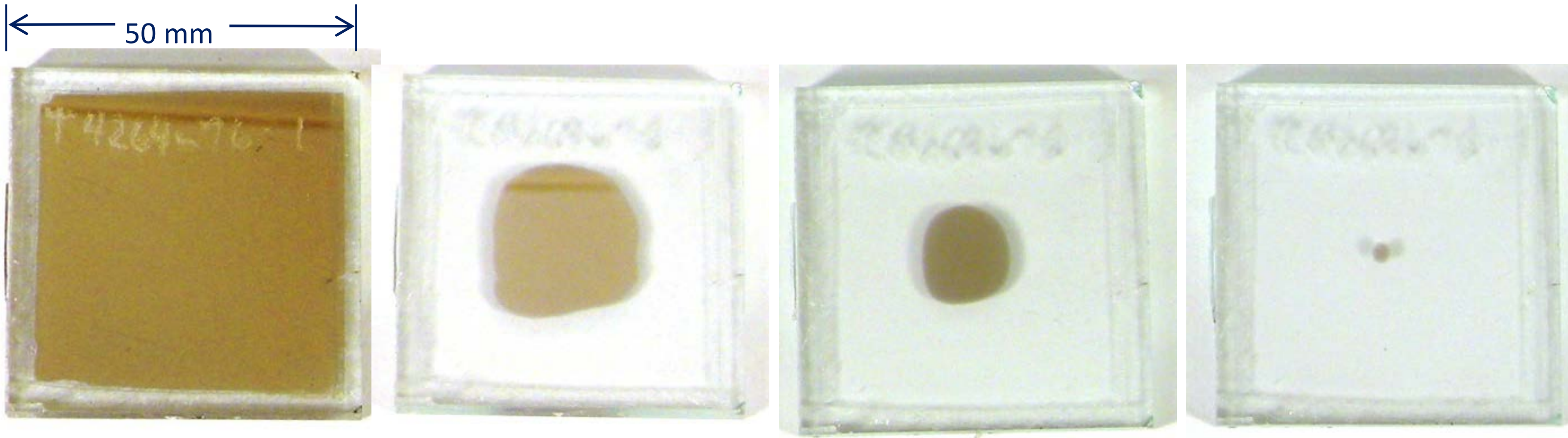


→



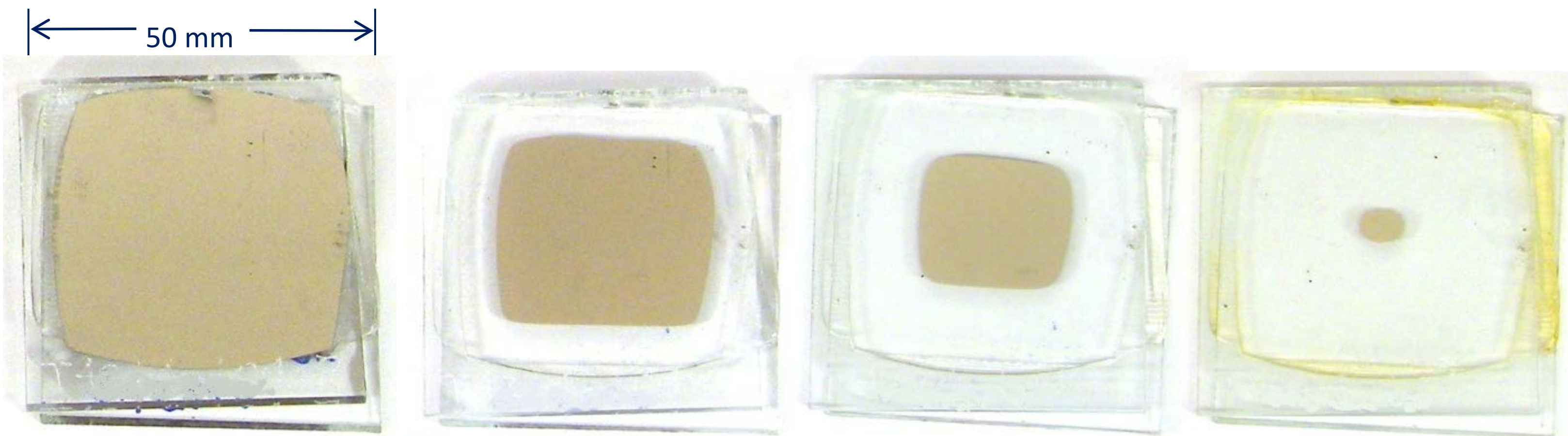
Moisture Ingress Varies Greatly in Encapsulants

PDMS



0 h | 1.5 h | 3 h | 4.5 h

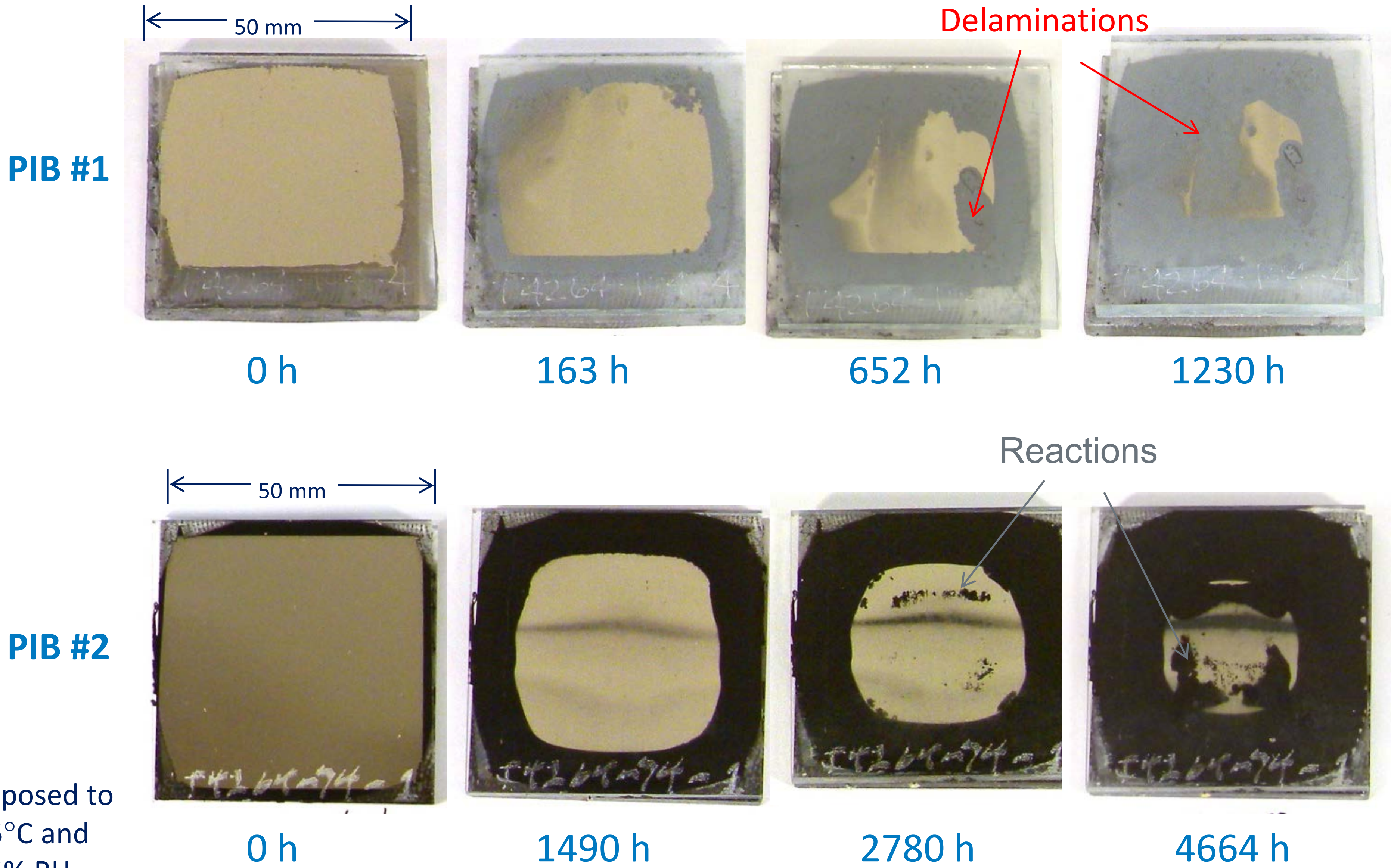
Ionomer #1



0 h | 67 h | 240 h | 652 h

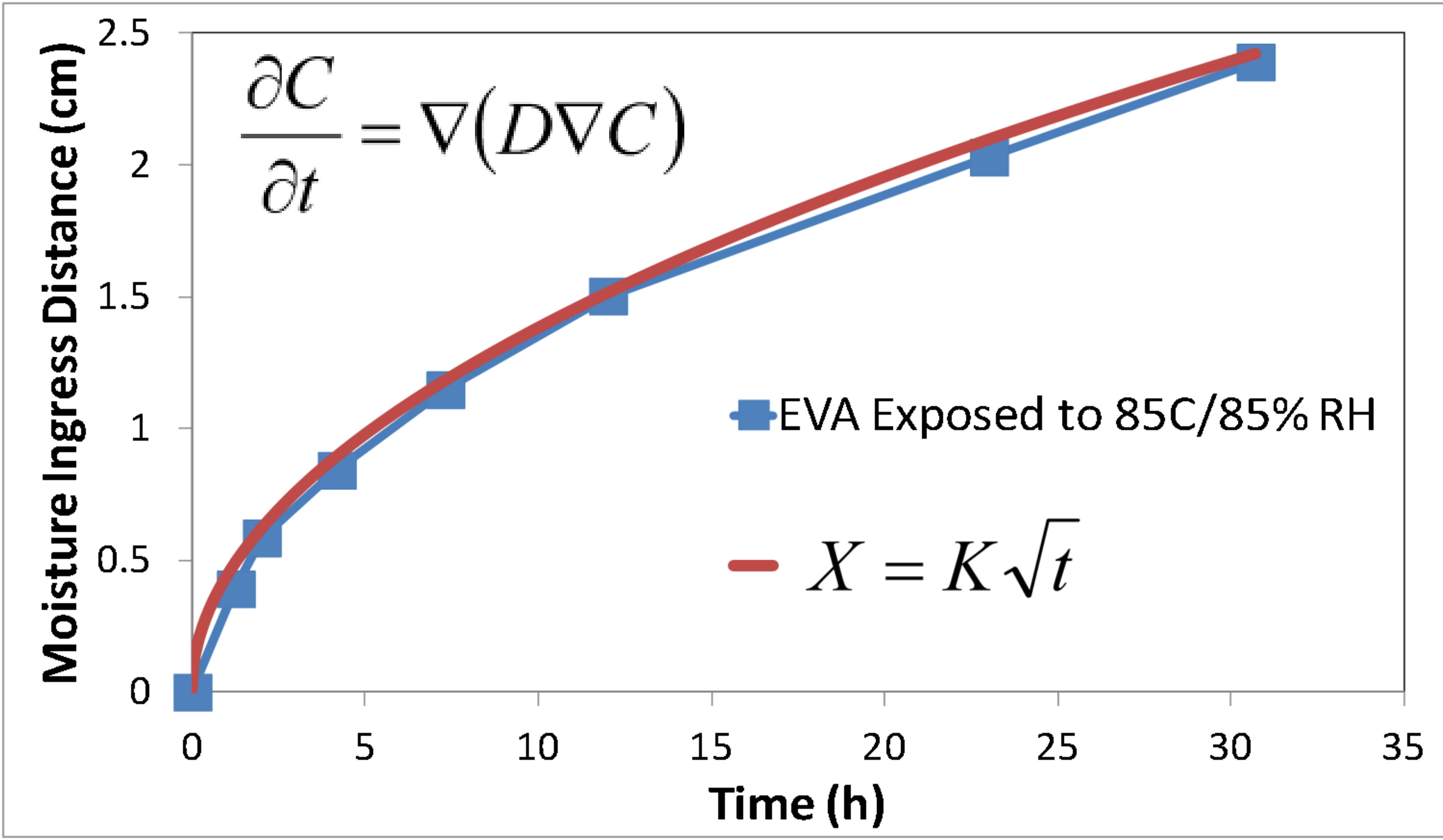
Exposed to 85°C and 85% RH

Polyisobutylene Edge Seals Slow Ingress



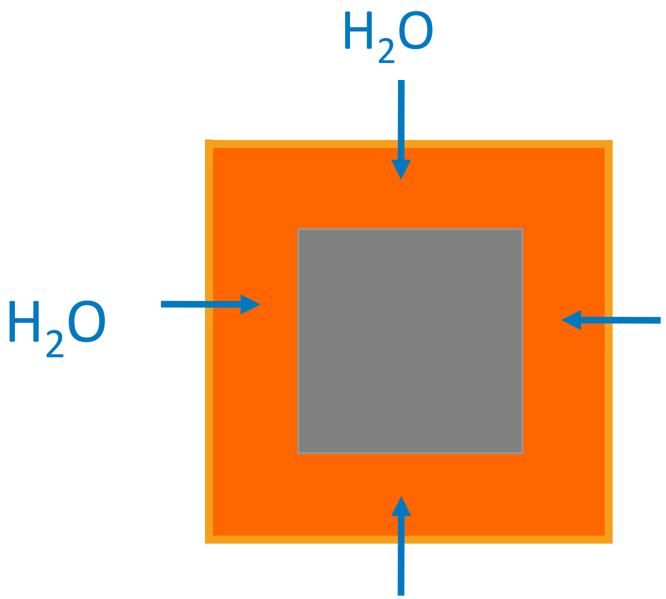
Exposed to 85°C and 85% RH

Moisture Ingress Rate Governed by Diffusion



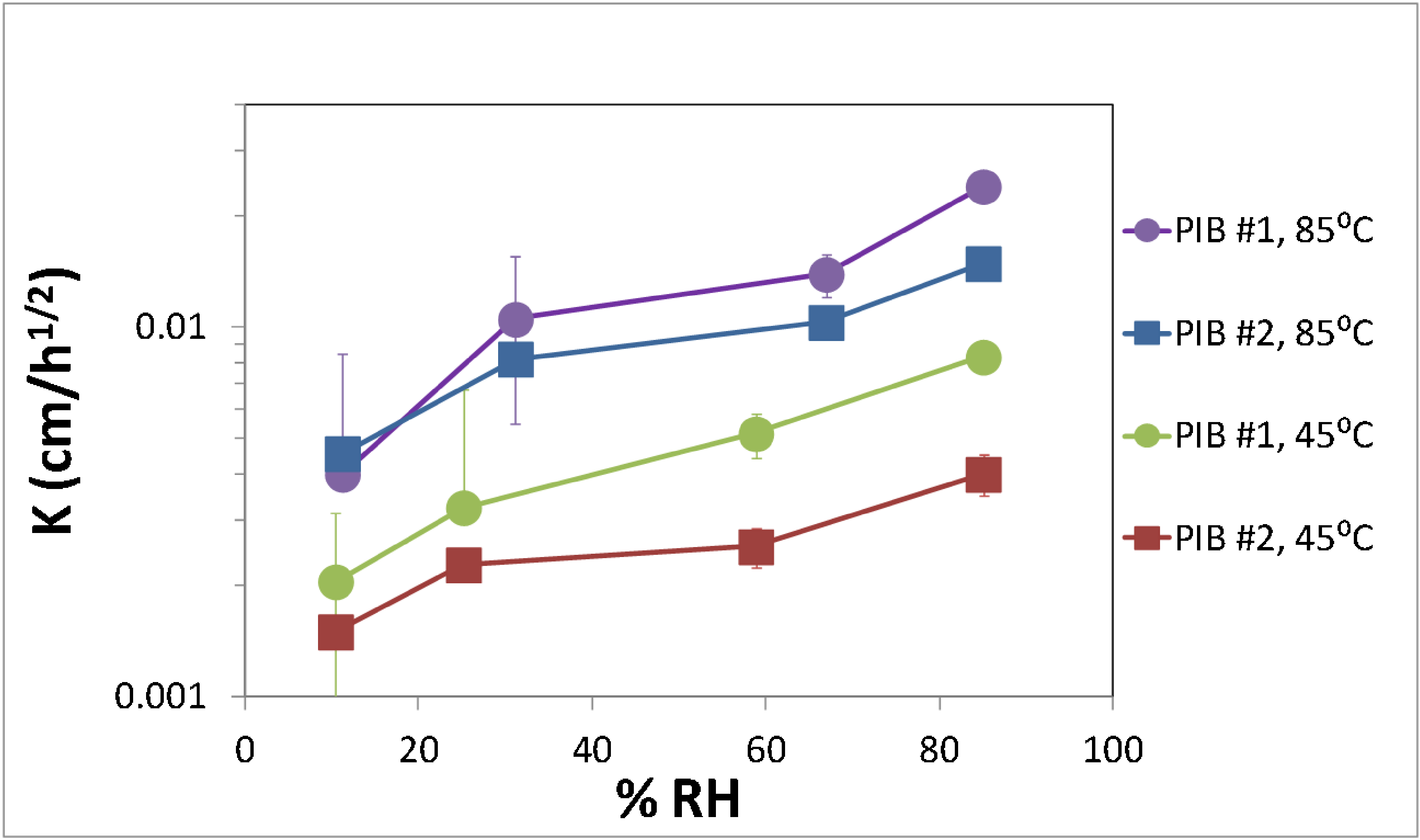
Moisture Ingress Rate Governed by Diffusion

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

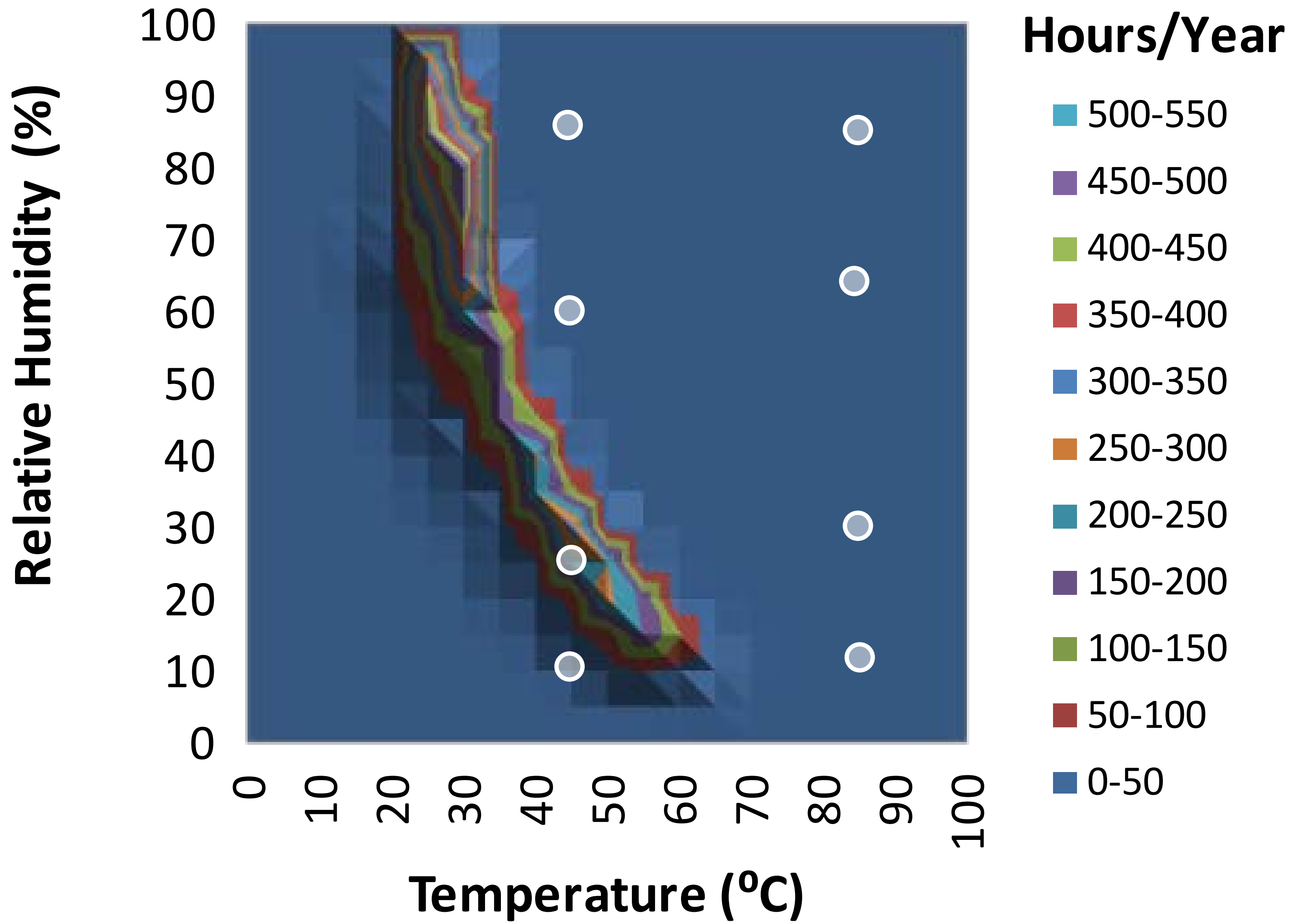


$$C_{m,n}^{P+1} = \frac{D\Delta t}{(\Delta X)^2}\left(C_{m+1,n}^{P} + C_{m-1,n}^{P} + C_{m,n+1}^{P} + C_{m,n-1}^{P}\right) + \left[1 - 4\frac{D\Delta t}{(\Delta X)^2}\right]C_{m,n}^{P} - (Calcium)$$

Permeation Measured at Low RH



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.**

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

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

$$D_{eff} = D_o e^{\left(-\frac{Ea_D}{kT}\right)}$$

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.

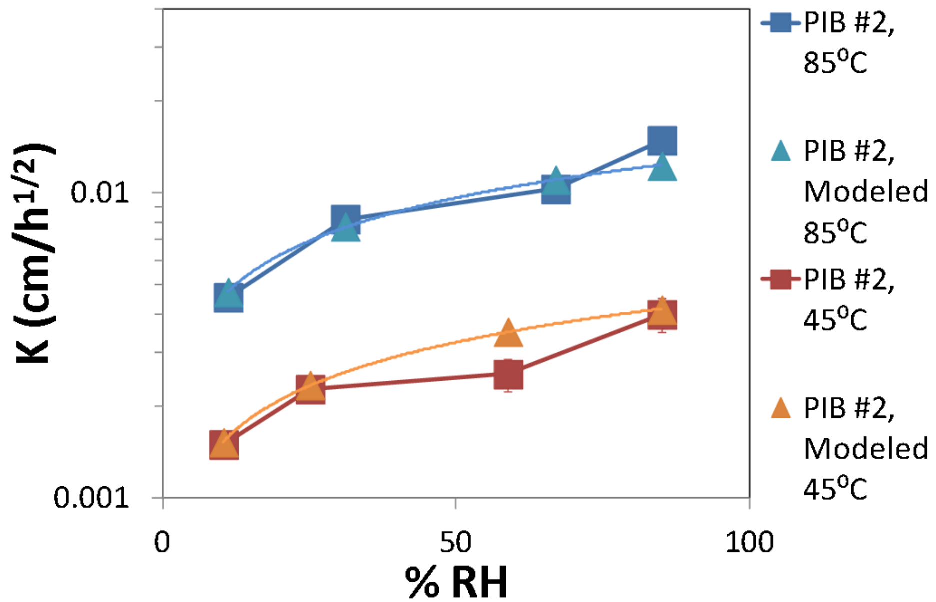
$S_o\ ,\ Ea_S$

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

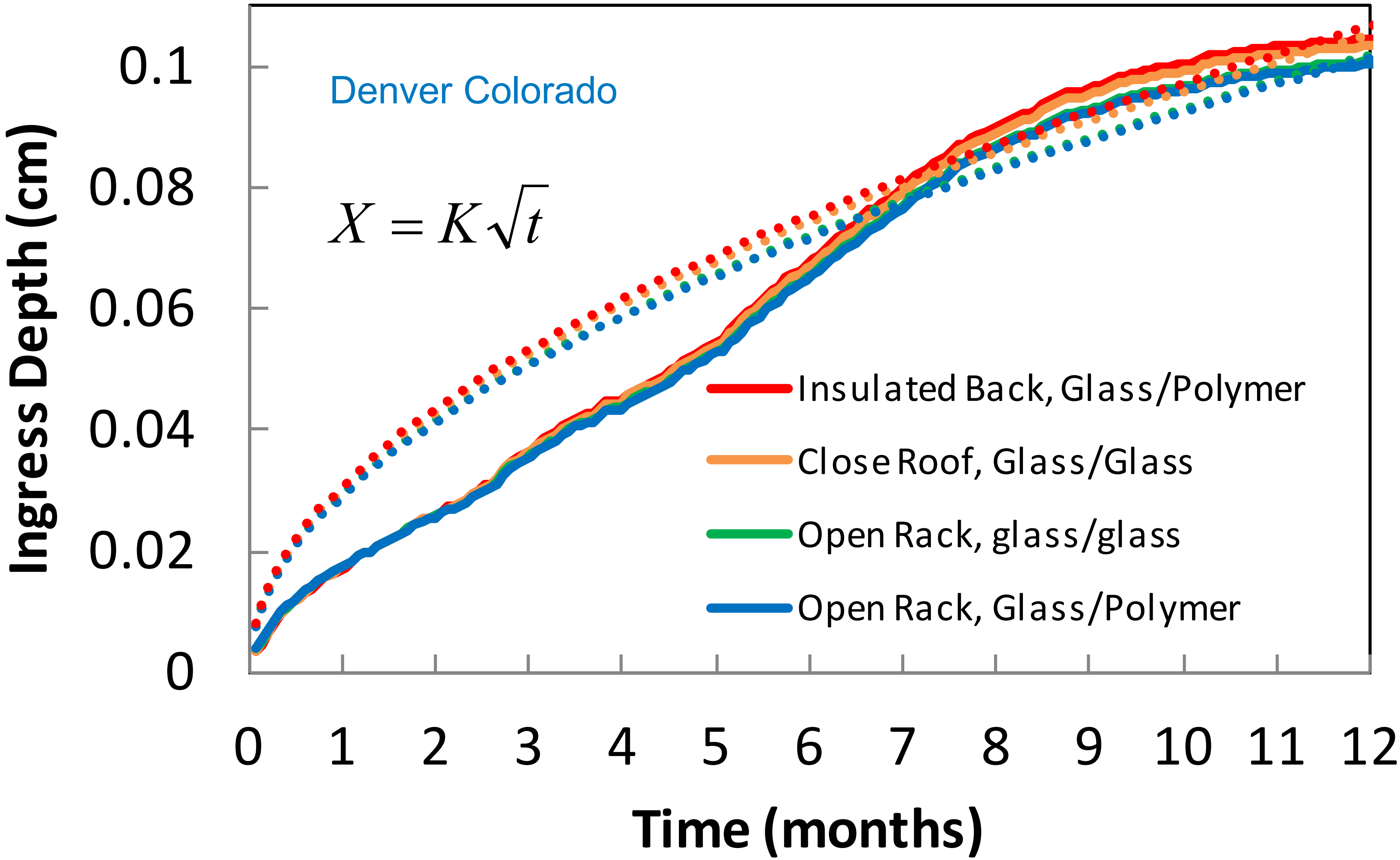
Curvature of K vs %RH is determined by the ratio of S to R_{H2O}

$D_o\ ,\ Ea_D$

Estimate from other parameters and fit to Ca data. Specifically the difference between 45 and 85^{o}C curves.

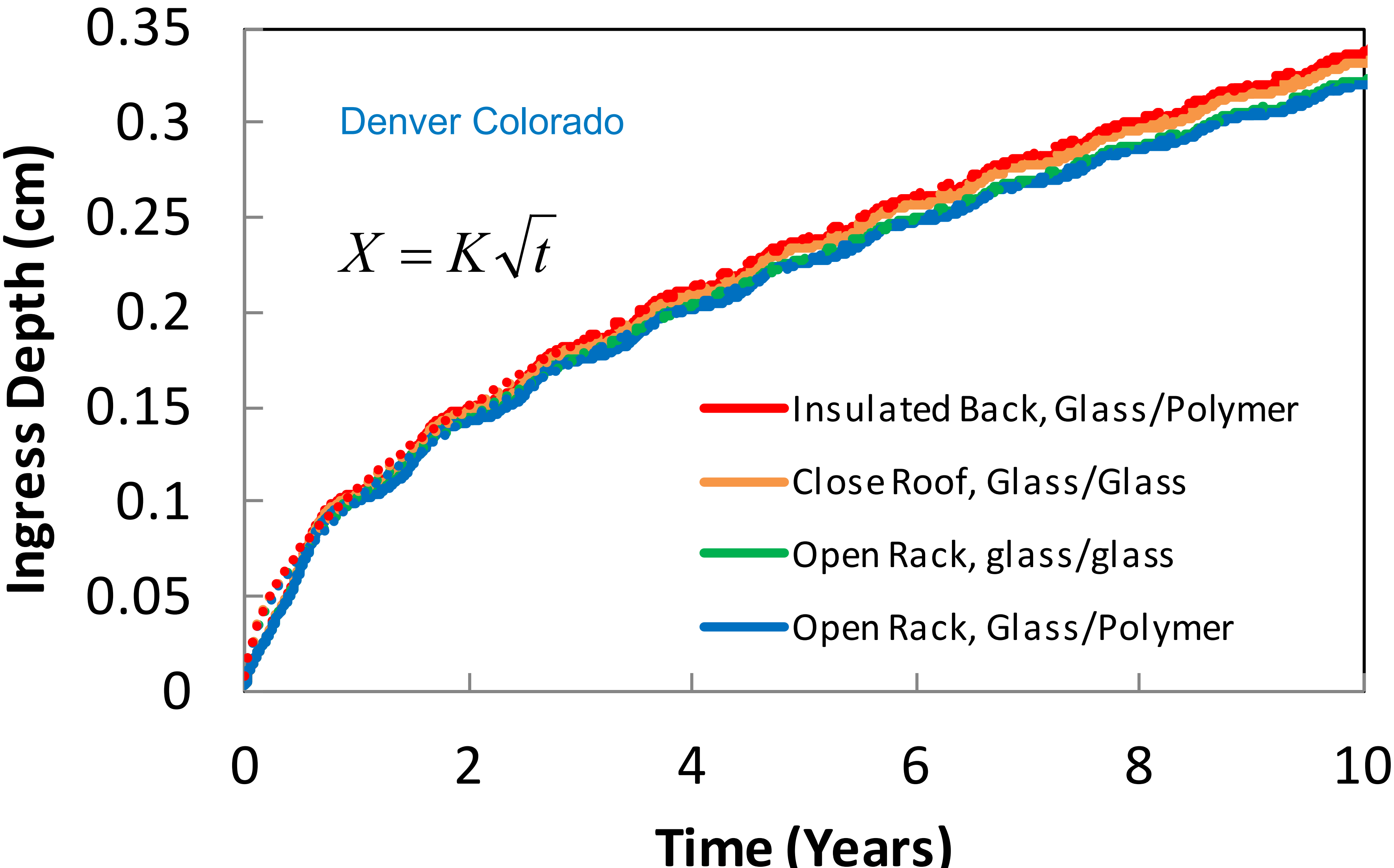


Ingress Estimated Using Finite Element Analysis



Used TMY3 Data and Temperature estimates similar to King et al, and Kurtz et al.

Square Root Relation Works to Longer Times



Used TMY3 Data and Temperature estimates similar to King et al, and Kurtz et al.

Preliminary Results for Different Climates

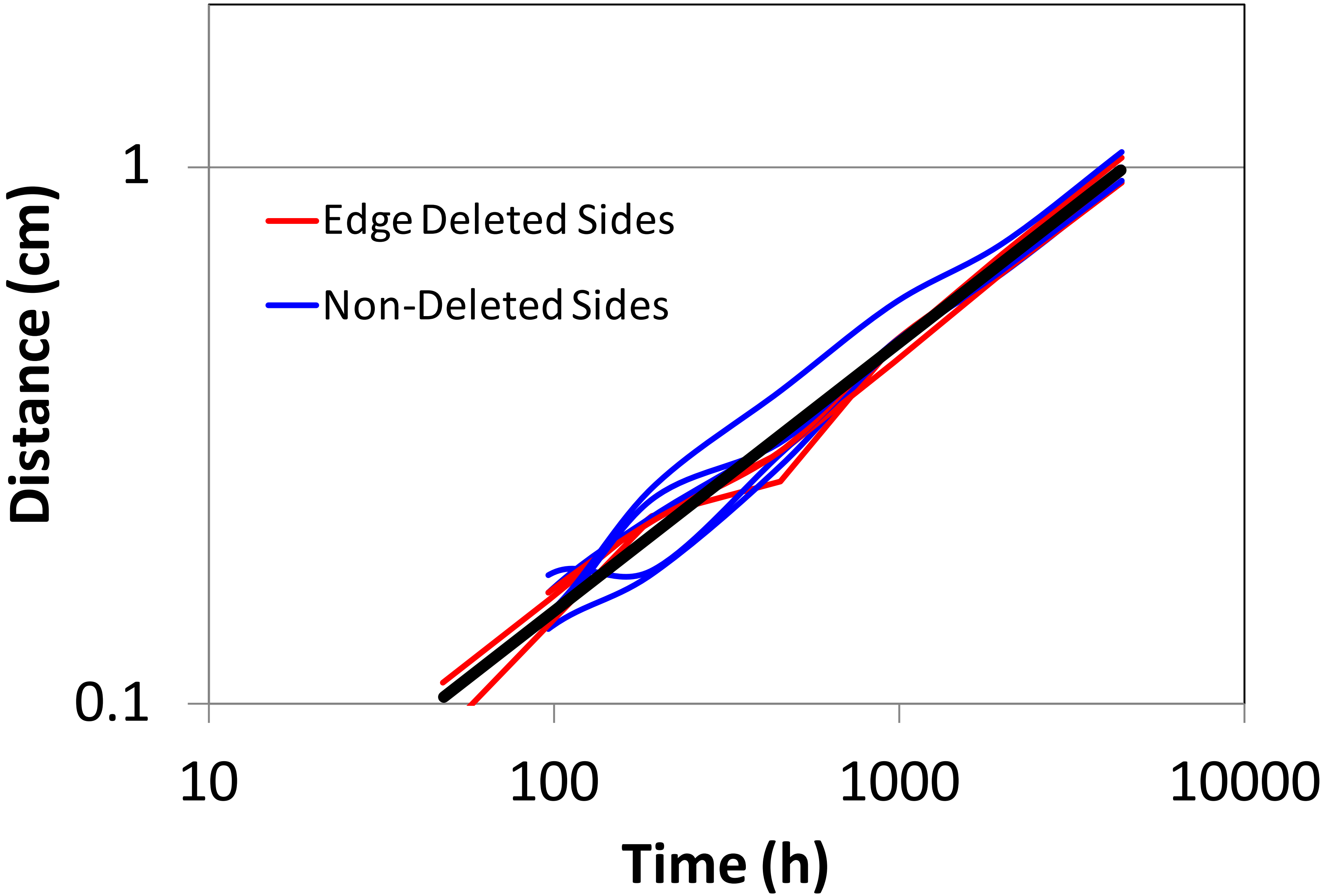
D_o (cm²/s)=		0.33	K	20 y required width	20 yr equivalent at 85°C/85% RH	20 yr equivalent at 45°C/85% RH
Ea_D (kJ/mol)=		47				
S_o (g/cm³)=		0.16				
Ea_S (kJ/mol)=		5				
Reactive Ca absorption (g/cm³)=		0.047	(cm/h$^{1/2}$)	(cm)	(h)	(years)
DENVER/CENTENNIAL [GOLDEN - NREL]	Open Rack, Glass/Polymer		0.00087	0.45	623	1.4
	Open Rack, glass/glass		0.00089	0.45	630	1.5
	Close Roof, Glass/Glass		0.00098	0.46	661	1.5
	Insulated Back, Glass/Polymer		0.00103	0.47	676	1.6
RIYADH	Open Rack, Glass/Polymer		0.00102	0.48	712	1.6
	Open Rack, glass/glass		0.00104	0.48	721	1.7
	Close Roof, Glass/Glass		0.00117	0.50	765	1.8
	Insulated Back, Glass/Polymer		0.00124	0.50	787	1.8
MUNICH	Open Rack, Glass/Polymer		0.00096	0.50	761	1.8
	Open Rack, glass/glass		0.00097	0.50	767	1.8
	Close Roof, Glass/Glass		0.00103	0.51	795	1.8
	Insulated Back, Glass/Polymer		0.00107	0.51	808	1.9
PHOENIX SKY HARBOR INTL AP	Open Rack, Glass/Polymer		0.00128	0.58	1035	2.4
	Open Rack, glass/glass		0.00131	0.58	1048	2.4
	Close Roof, Glass/Glass		0.00145	0.60	1113	2.6
	Insulated Back, Glass/Polymer		0.00153	0.61	1145	2.6
MIAMI INTL AP	Open Rack, Glass/Polymer		0.00199	0.87	2332	5.4
	Open Rack, glass/glass		0.00202	0.87	2361	5.5
	Close Roof, Glass/Glass		0.00218	0.90	2490	5.8
	Insulated Back, Glass/Polymer		0.00225	0.91	2555	5.9
BANGKOK	Open Rack, Glass/Polymer		0.00228	0.98	2980	6.9
	Open Rack, glass/glass		0.00232	0.99	3015	7.0
	Close Roof, Glass/Glass		0.00249	1.02	3182	7.4
	Insulated Back, Glass/Polymer		0.00258	1.03	3261	7.5

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 (85C/85% RH).**
- **Adhesion to edge delete region.**
- **UV Light.**
- **Edge Pinch**

Laser Edge Delete Did Not Increase Ingress



Edge-Seals May Have Edge Pinch

Schematic side views of module edge

Idea Edge Profile

(no bend in glass at the module perimeter)

Edge Pinch

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

Edge Seal Test Specimen

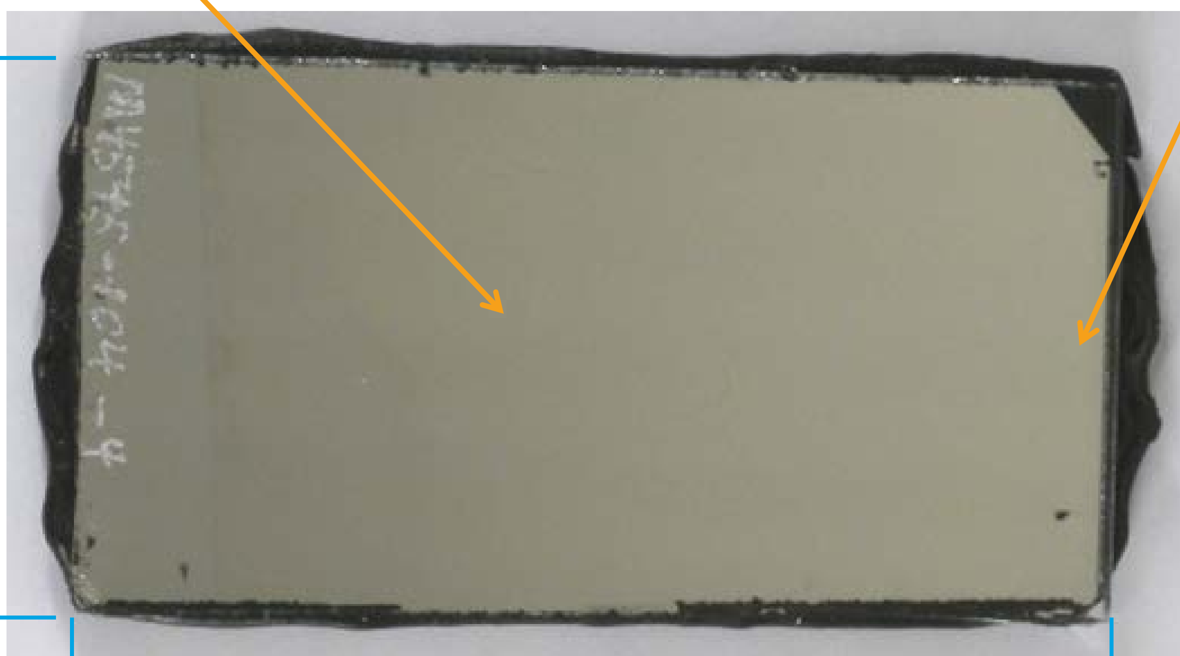
Schematic side view of test sample

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

0.5 mm thick polymer

0.2 mm thick polymer

Photographic top view

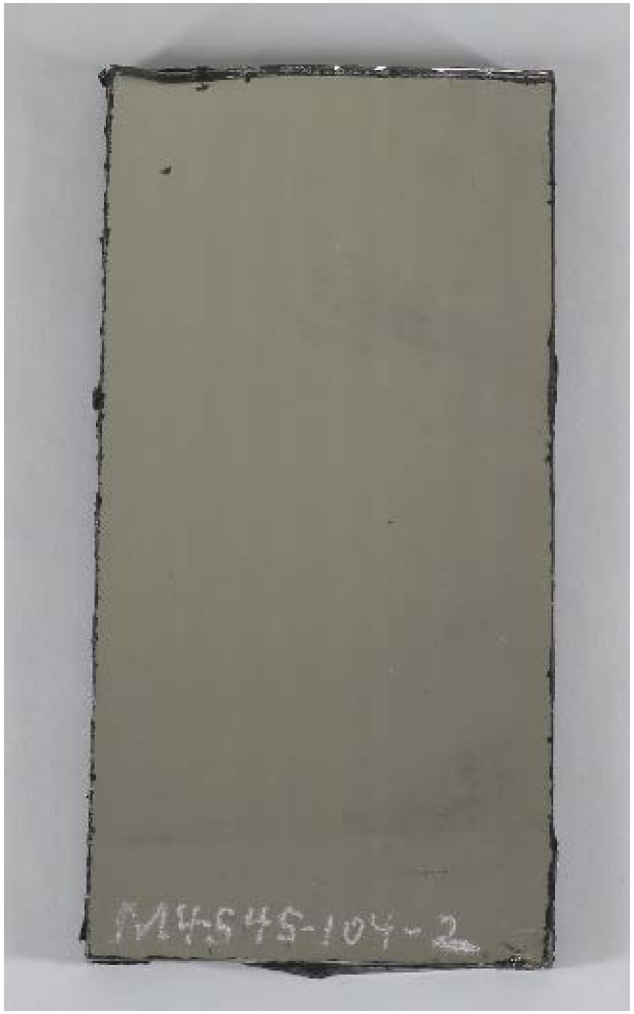


50 mm

100 mm

0.30 mm of edge pinch

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



No Exposure

170 h 85°C/85% RH

674 h 85°C/85% RH

Only small signs of minor delamination on ends exposed to tensile stress.

Edge pinch is 0.31±0.01 mm for all exposures.

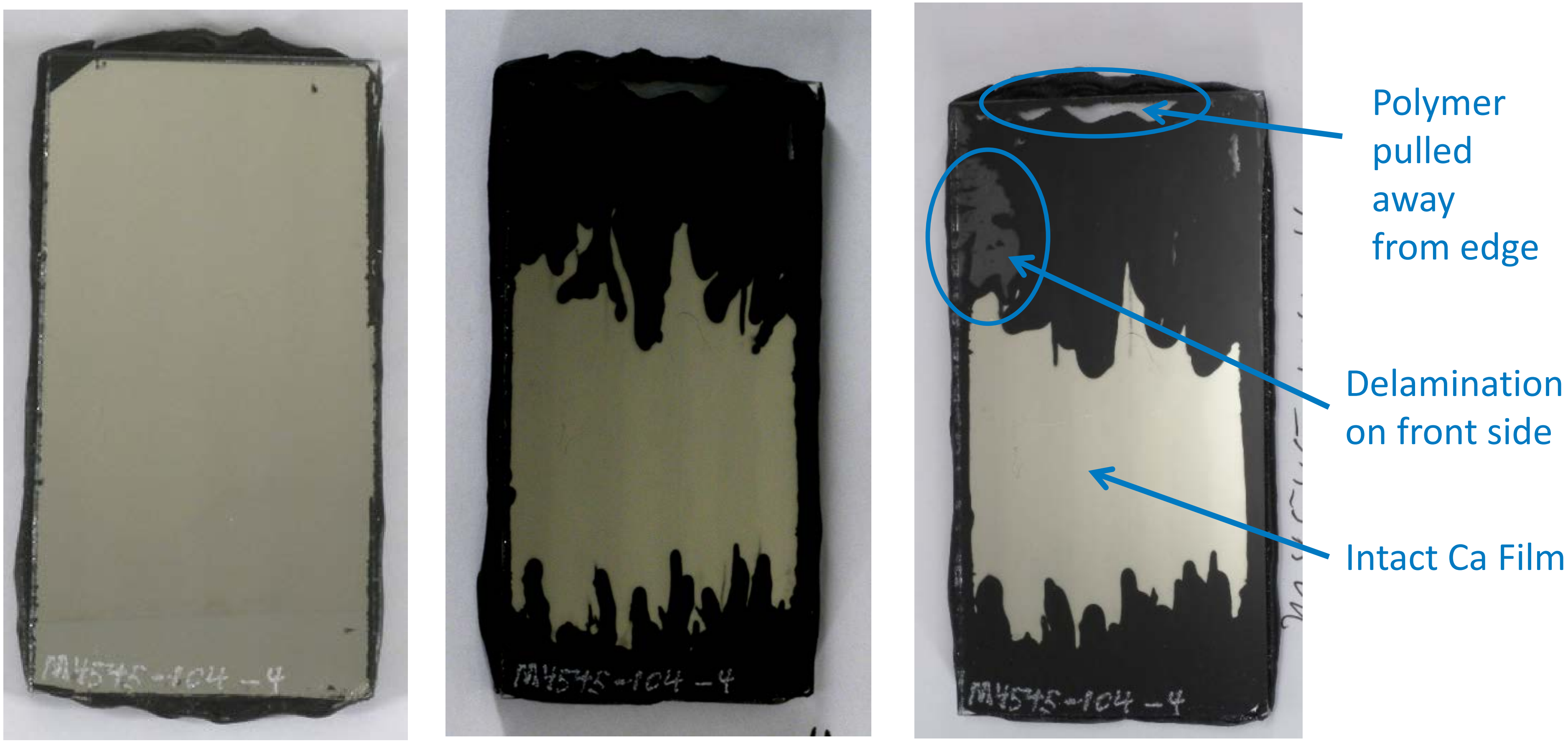
UV Light Can Delaminate Edge Seals With Pinch

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



165 h
621 h

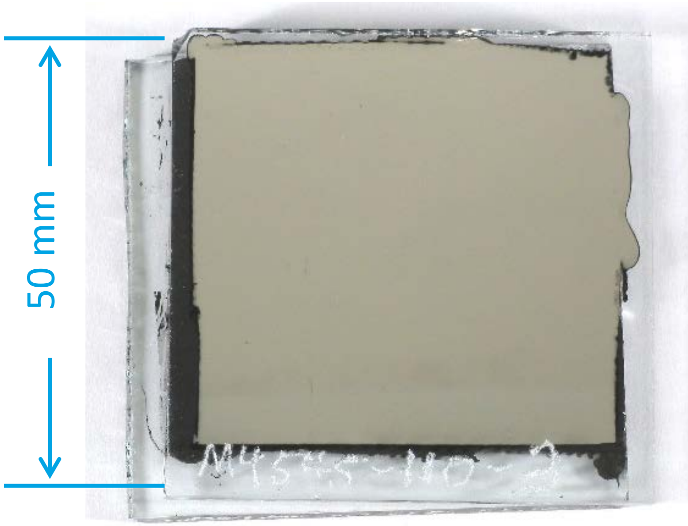
No Exposure
0.32±0.01 mm pinch

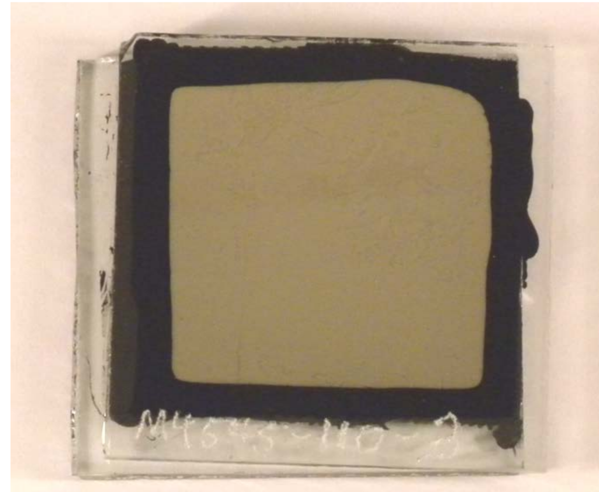
60°C/60% RH/ 2.5 UV Suns
0.02±0.01 mm pinch

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

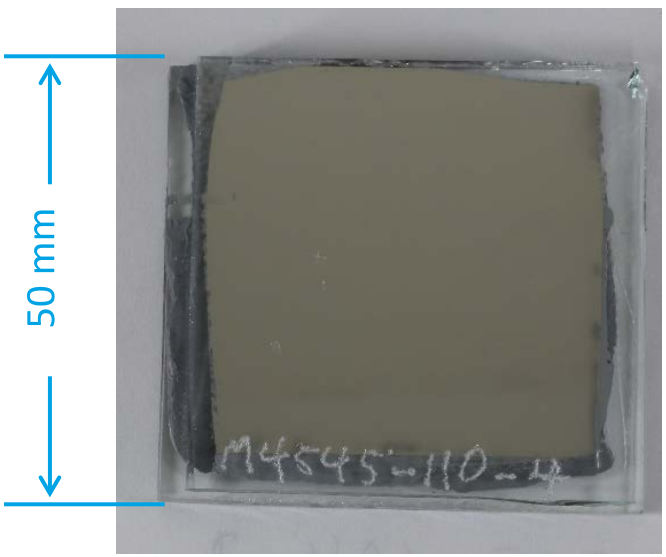
Light exposure on non-Ca film backside.
Very significant delamination on ends exposed to tensile stress.

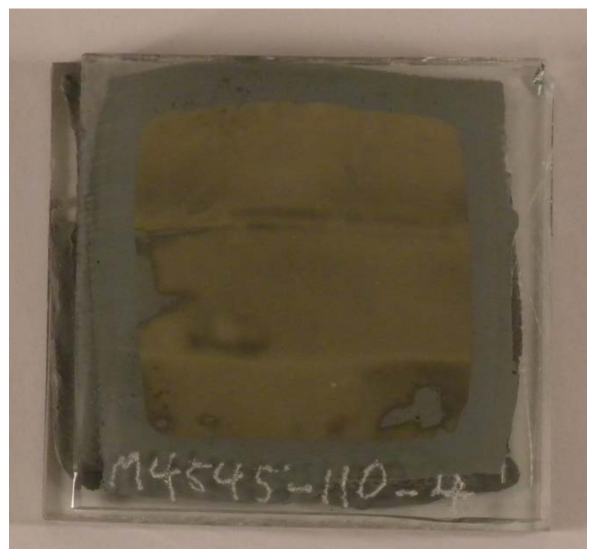
UV Light Alone is Much Less Damaging





PIB #2





PIB #1

Unexposed

1962 h 60°C/60%RH/2.5 UV suns

IEC TC82 WG2 Edge Seal Standards Development

- **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

Sarah Kurtz

John Wohlgemuth

David Miller

Joshua Martin

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.