Calcium Based Test Method for Evaluation of Photovoltaic Edge-Seal Materials

Michael Kempe,
Arrelaine Dameron,
Matthew Reese

2011 NREL PV Module Reliability Workshop

February 16, 2011

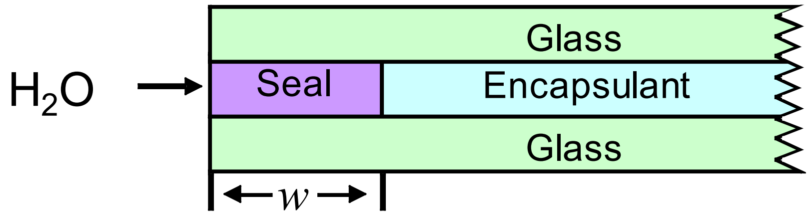
NREL/PR-5200-50839

Experimental Objectives

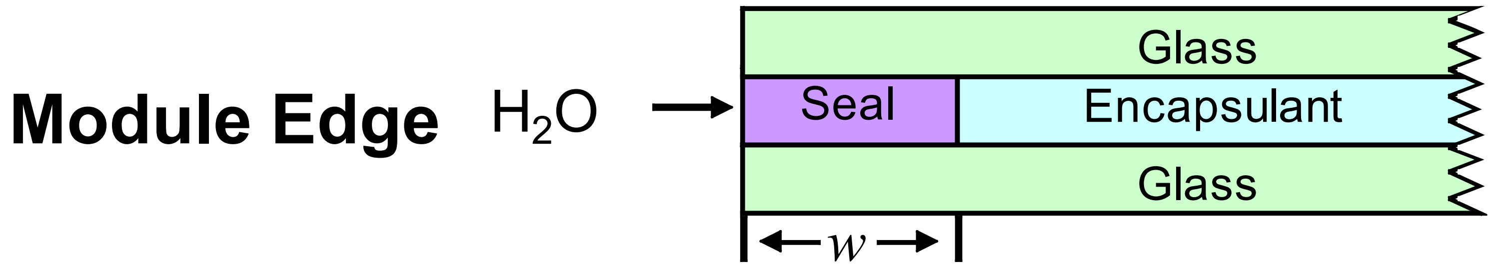
Many PV technologies are sensitive to moisture. Even with impermeable front- and back-sheets, moisture can penetrate from the sides. Edge seals are incorporated around the perimeter to prevent this ingress.

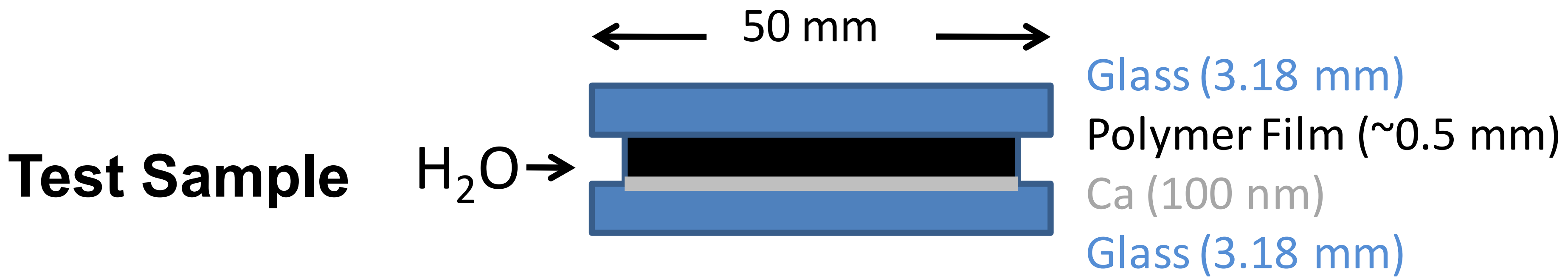
Here we use a Ca-based method to evaluate the moisture ingress time for edge seal materials.

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



Test Sample Designed to Mimic Module Edge





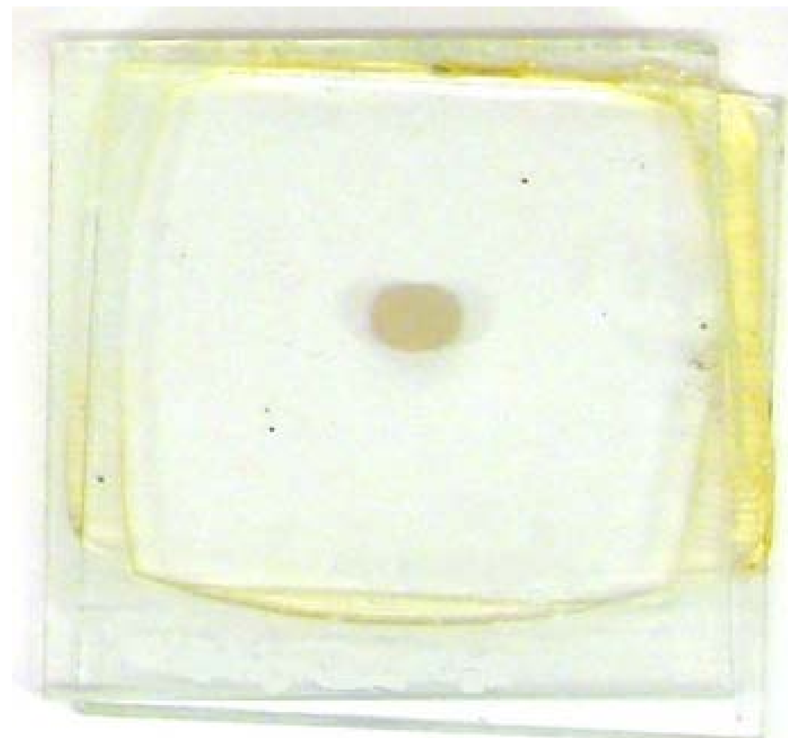
$$Ca + 2\ H_20 \rightarrow Ca(OH)_2 + H_2$$

Oxidation of Ca Indicates Moisture Ingress

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

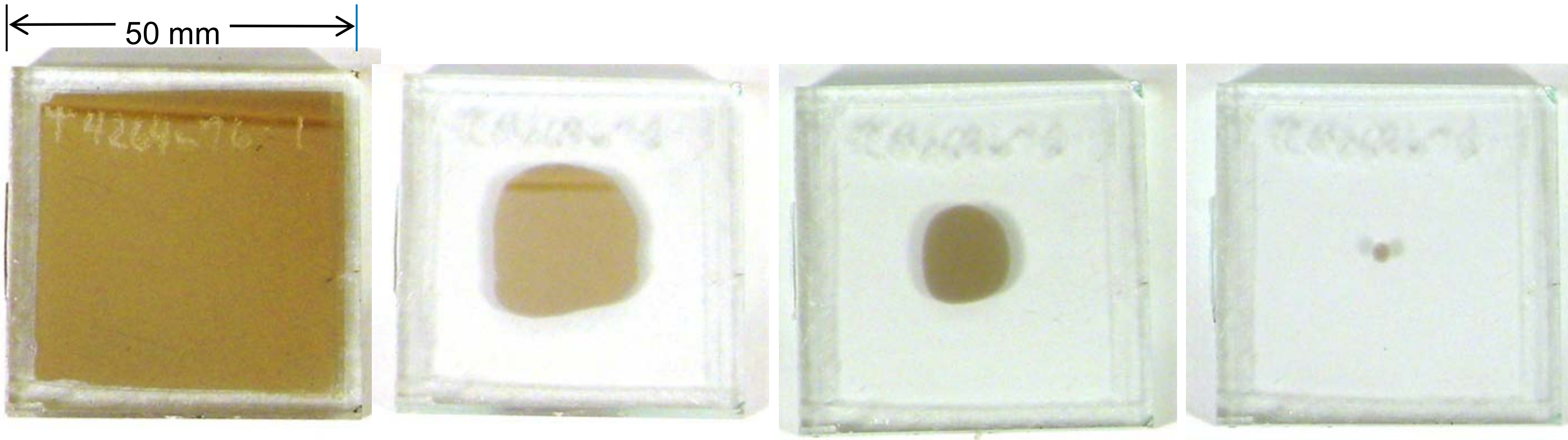
Mirror-Like → Transparent

→



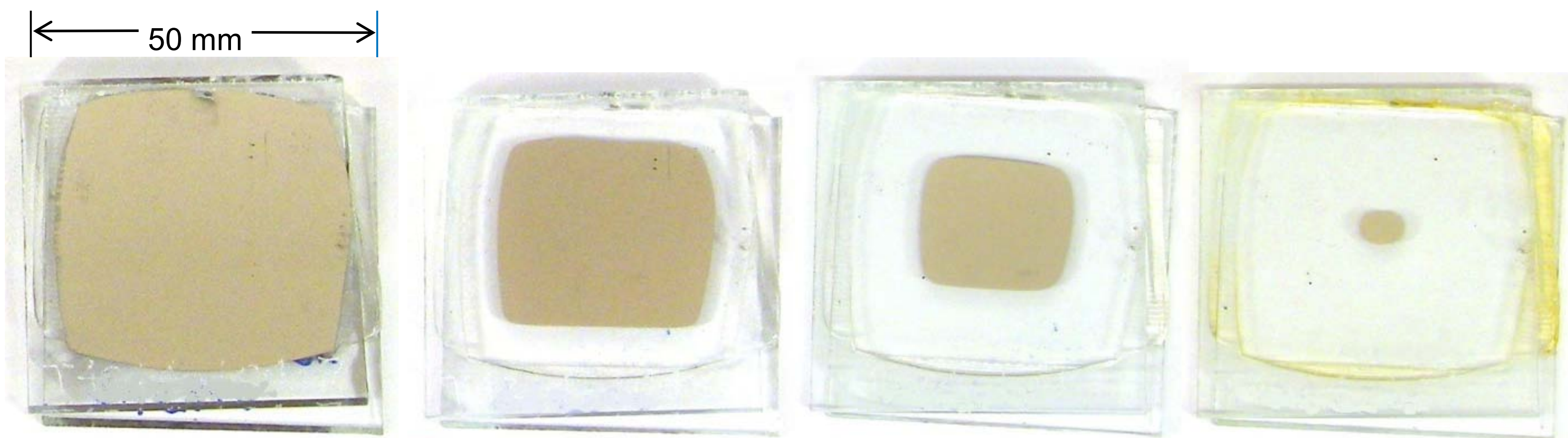
Moisture Ingress Varies Greatly in Encapsulants

PDMS



0 h | 1.5 h | 3 h | 4.5 h

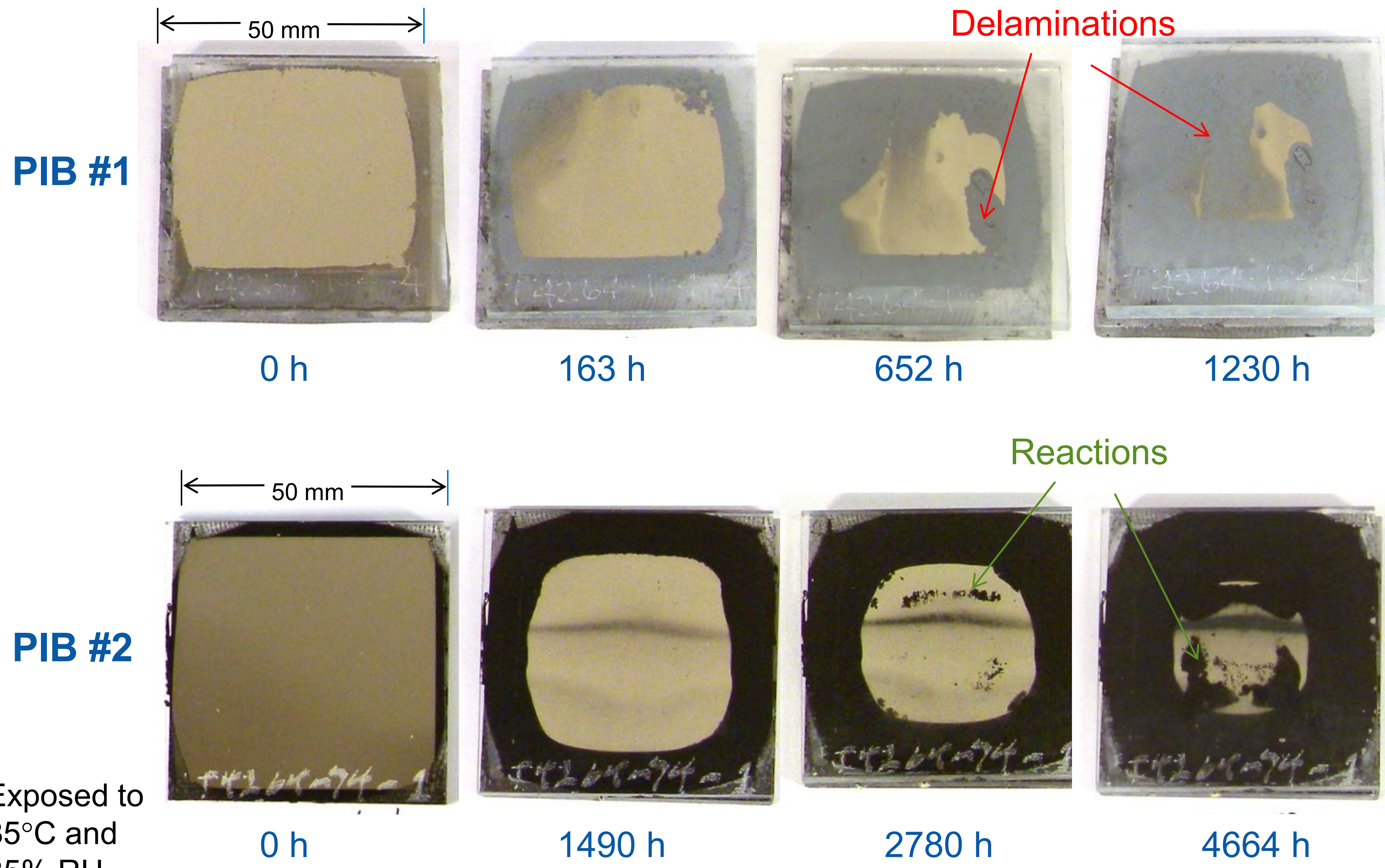
Ionomer #1



0 h | 67 h | 240 h | 652 h

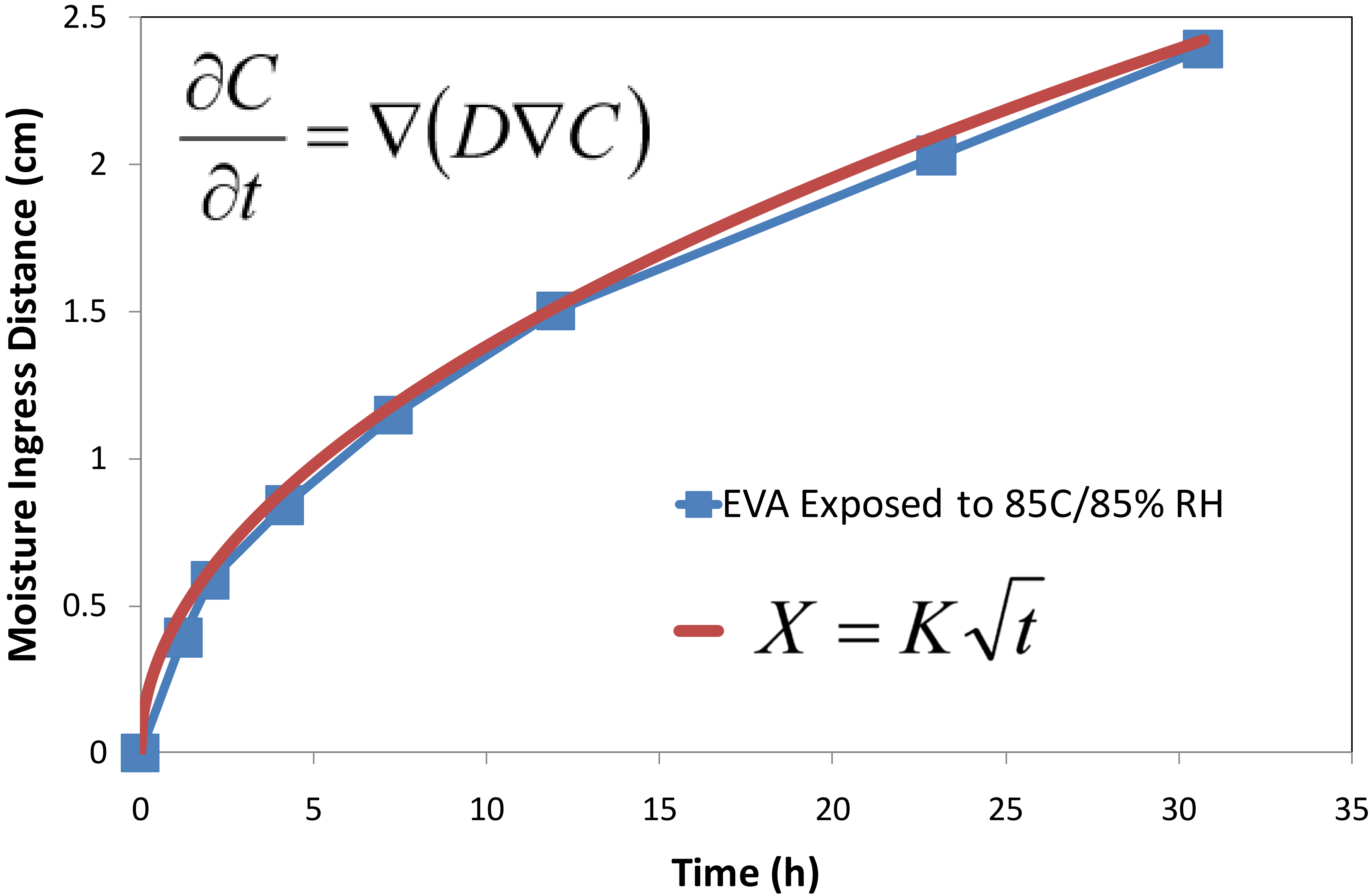
Exposed to 85°C and 85% RH

Polyisobutylene Edge Seals Slow Ingress

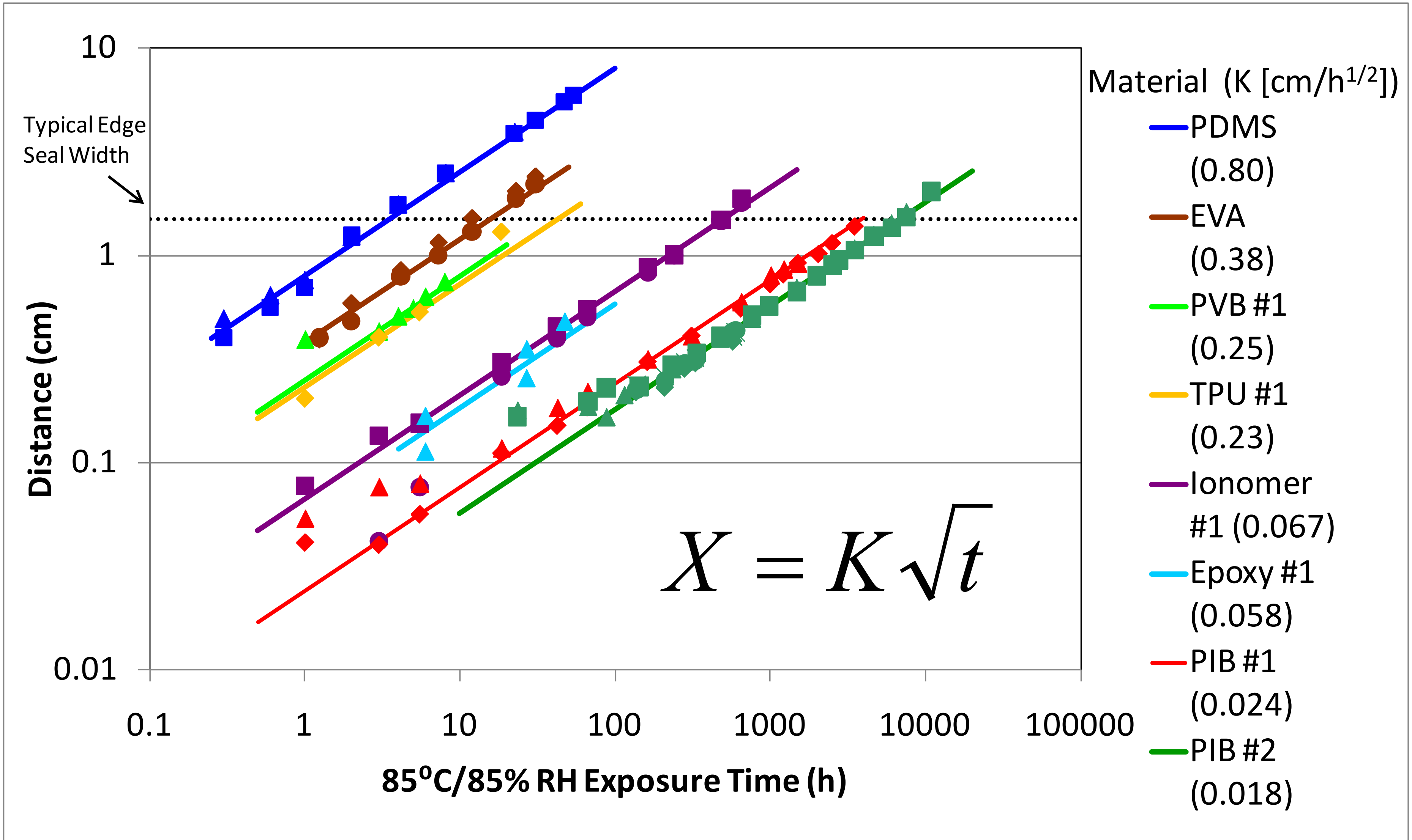


Exposed to 85°C and 85% RH

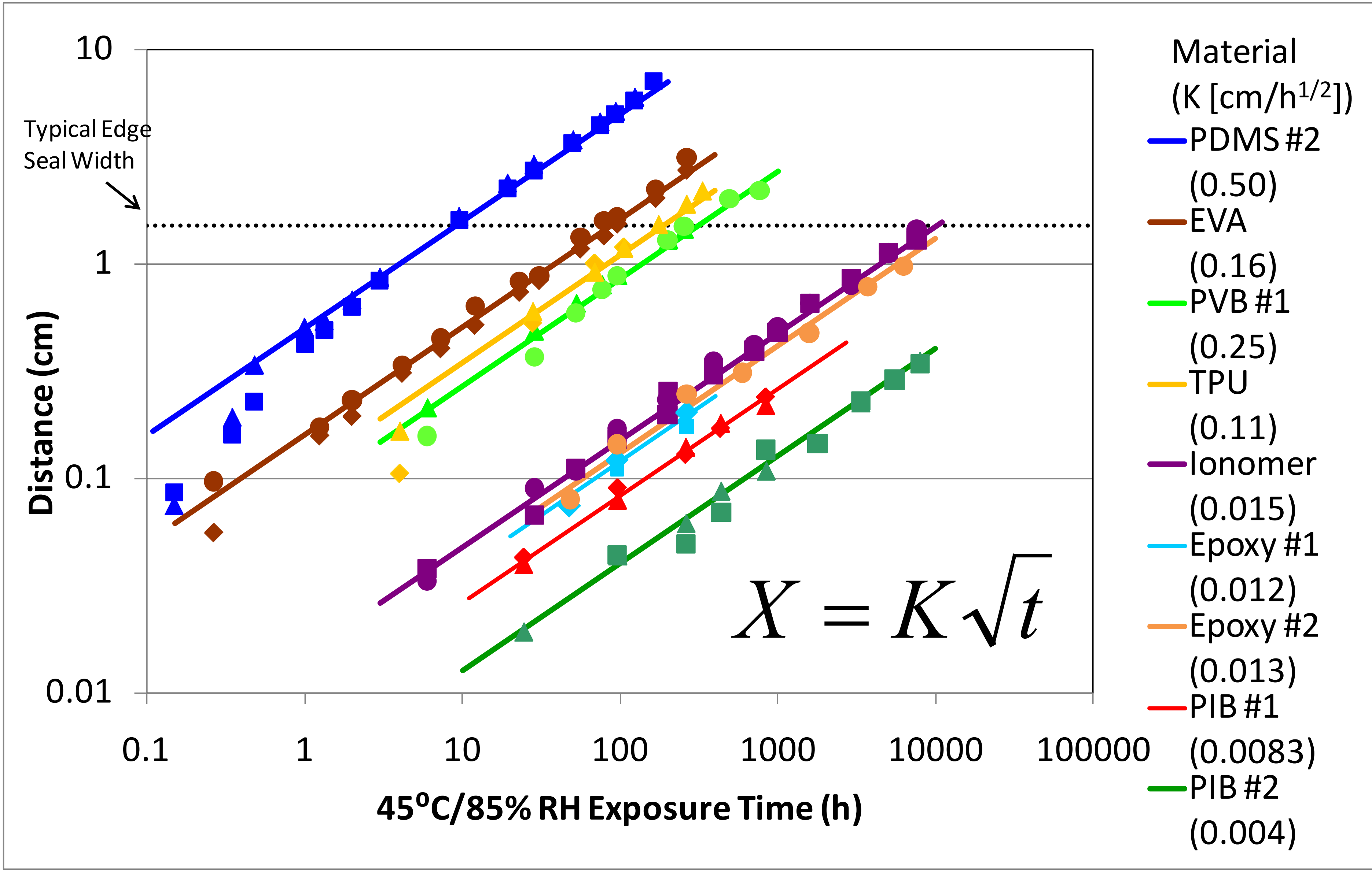
Moisture Ingress Rate Governed by Diffusion



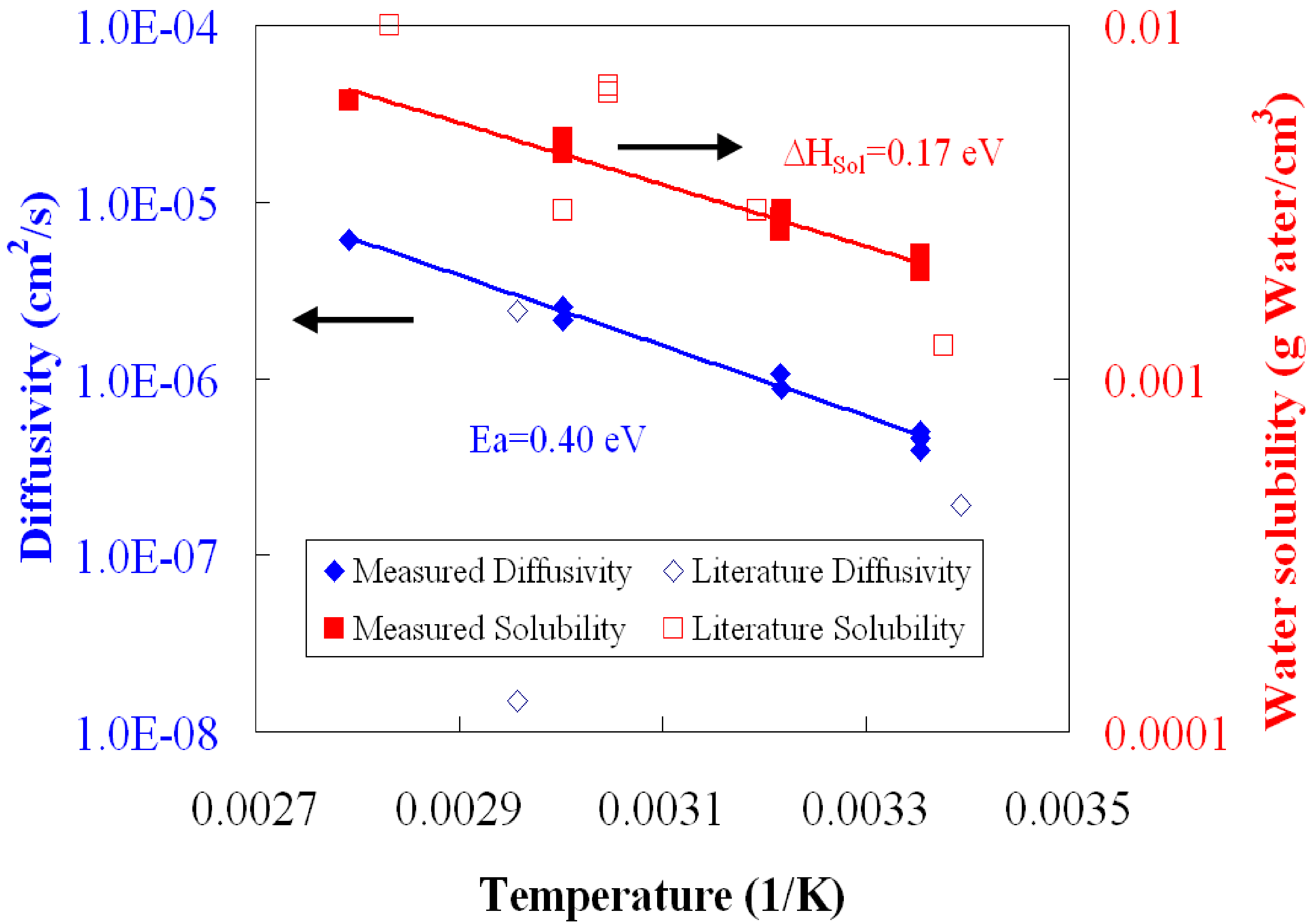
Ingress Rates Vary Greatly (85ºC)



Ingress Rates Vary Greatly (45ºC)



EVA Water Permeation Parameters

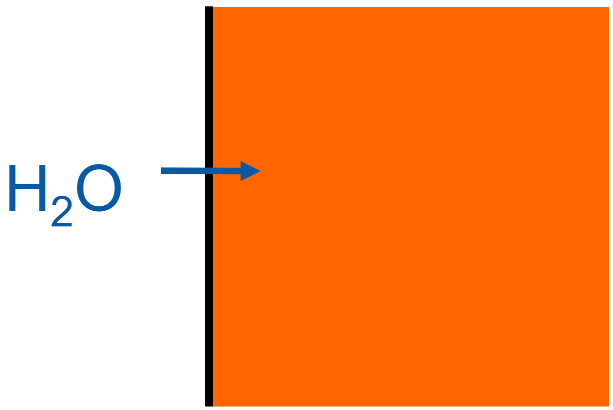


Moisture Ingress Rate Governed by Diffusion

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

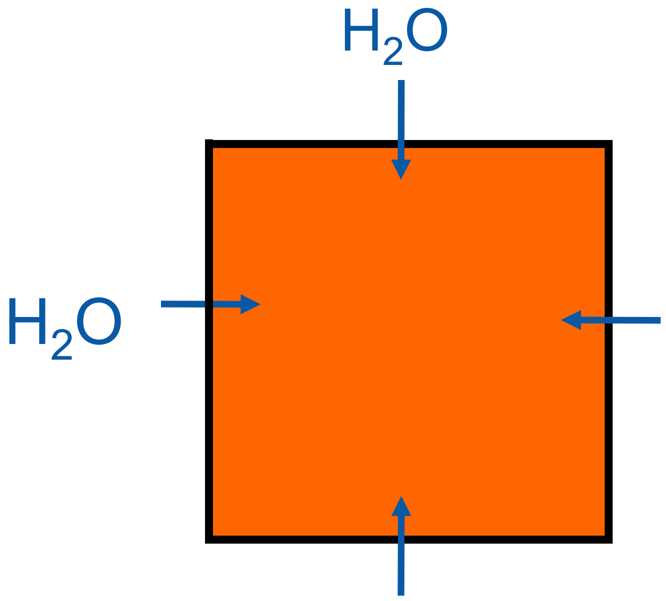
1-D Semi-Infinite Solid

$$C\left(x,t\right) = C_{eq}\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right]$$



Moisture Ingress Rate Governed by Diffusion

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



1-D Semi-Infinite Solid

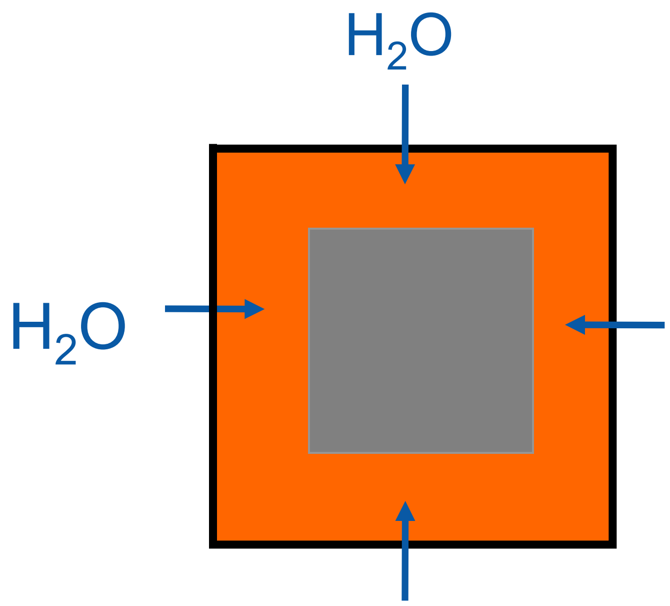
$$C\left(x,t\right) = C_{eq}\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right]$$

2-D Ingress, Infinite rectangular bar

$$\frac{C_{eq} - C\left(X,Y,t\right)}{C_{eq}} = \frac{16}{\pi^2}\sum_{m=0}^{\infty}\frac{1}{2m+1}\sin\left[\frac{\left(2m+1\right)\pi X}{l_x}\right]e^{\left[-\frac{D\left(2m+1\right)^2\pi^2 t}{l_x{}^2}\right]}\sum_{n=0}^{\infty}\frac{1}{2n+1}\sin\left[\frac{\left(2n+1\right)\pi Y}{l_y}\right]e^{\left[-\frac{D\left(2n+1\right)^2\pi^2 t}{l_y{}^2}\right]}$$

Moisture Ingress Rate Governed by Diffusion

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



1-D Semi-Infinite Solid

$$C(x,t) = C_{eq}\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right]$$

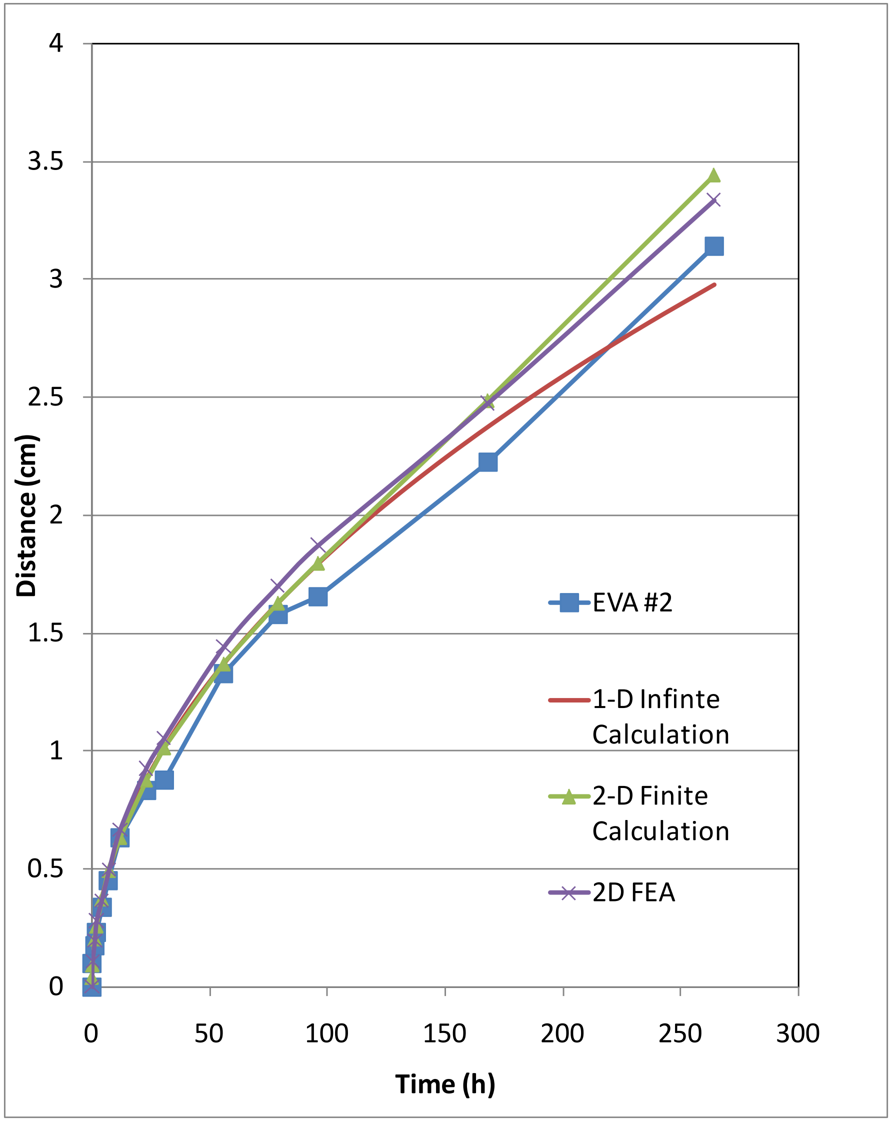
2-D Ingress, Infinite rectangular bar

$$\frac{C_{eq} - C(X,Y,t)}{C_{eq}} = \frac{16}{\pi^2}\sum_{m=0}^{\infty}\frac{1}{2m+1}\sin\left[\frac{(2m+1)\pi X}{l_x}\right]e^{\left[-\frac{D(2m+1)^2\pi^2 t}{l_x^2}\right]}\sum_{n=0}^{\infty}\frac{1}{2n+1}\sin\left[\frac{(2n+1)\pi Y}{l_y}\right]e^{\left[-\frac{D(2n+1)^2\pi^2 t}{l_y^2}\right]}$$

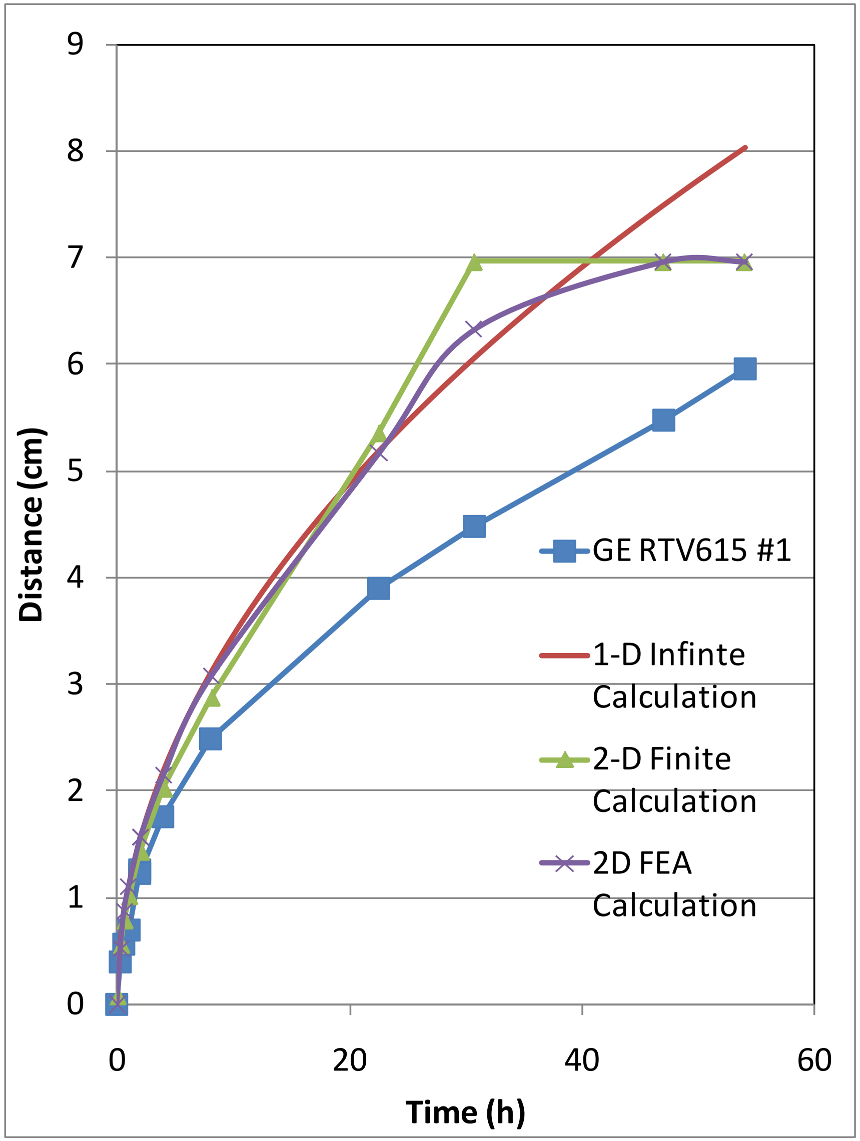
2-D Finite Element Analysis with Ca-H_20 Reaction

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

D and S allow for Modeling of Performance



EVA



Silicone

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.

Getting the Modeling Parameters

R_{H_2O}

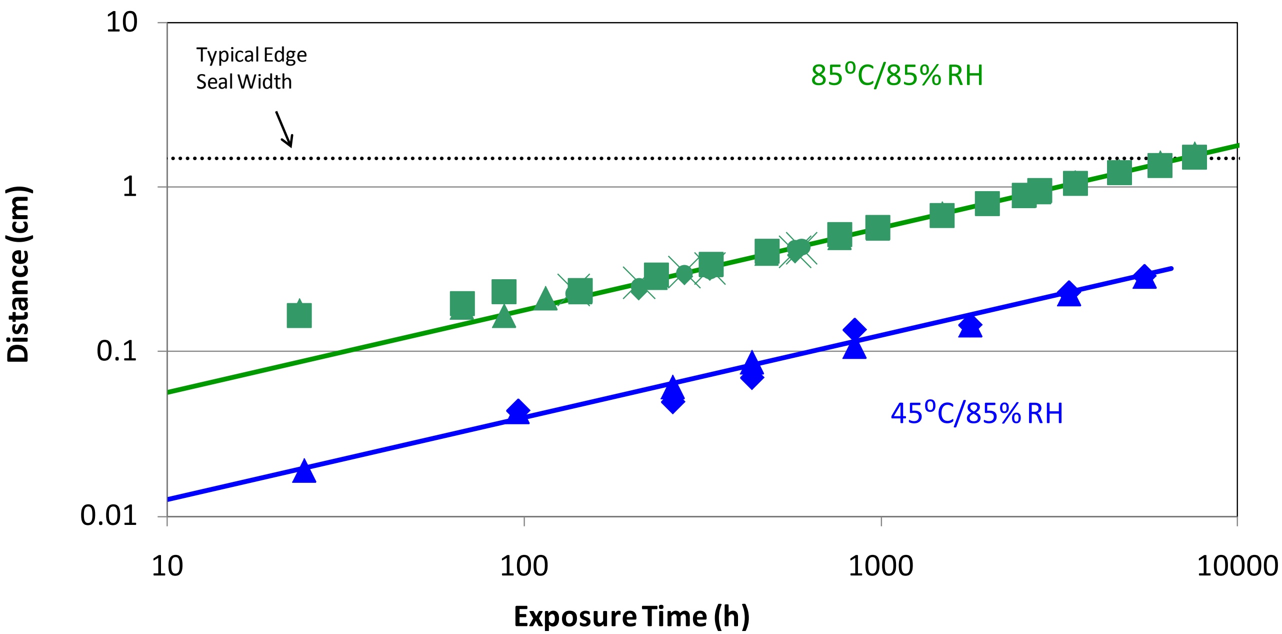
Measured by weighing samples before humidity exposure, after humidity exposure, and after drying.

$S_o\ ,\ Ea_S$

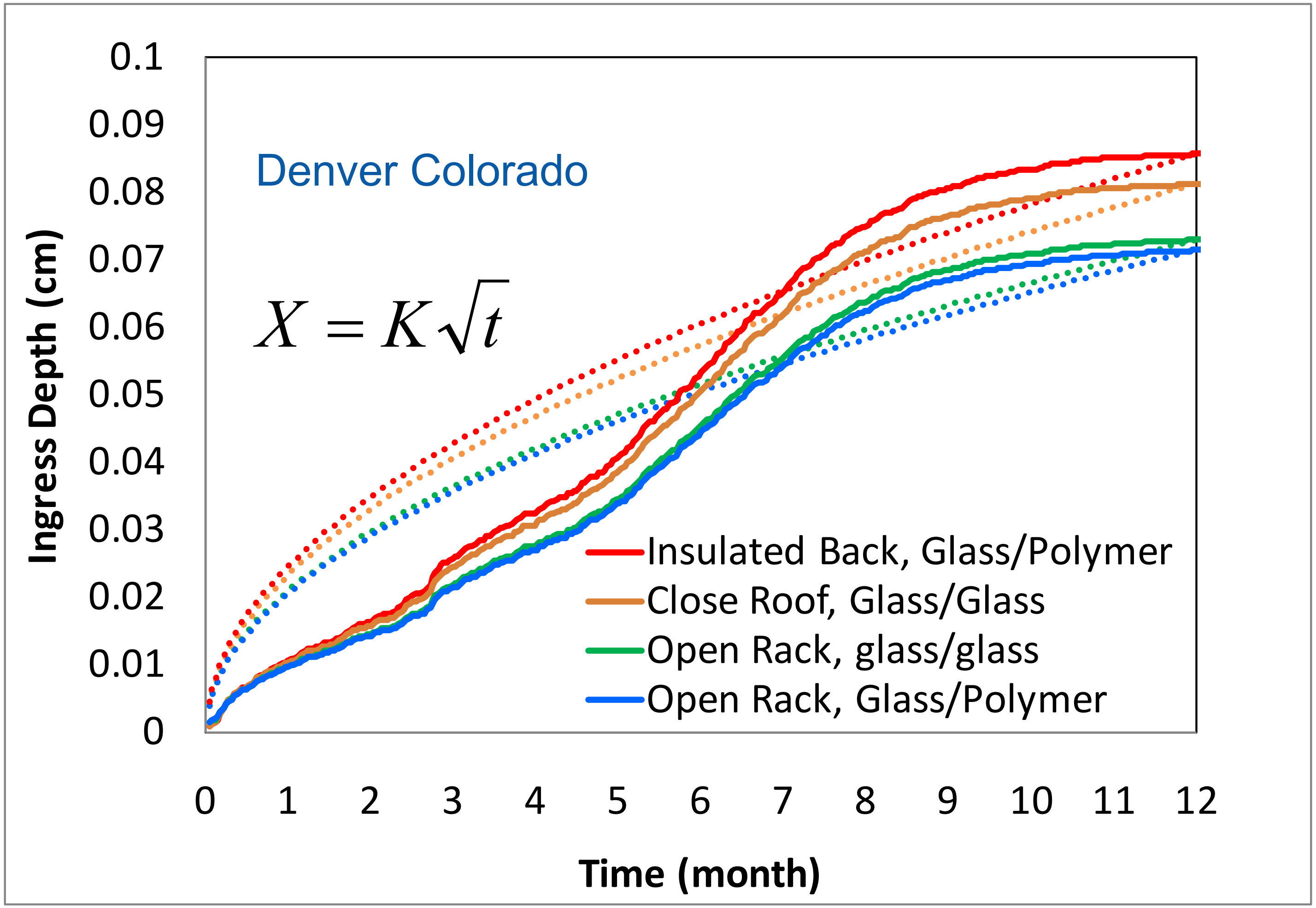
In progress: Measured by exposing to controlled humidity then drying in a TGA to determine moisture loss. Currently assuming Ea_S of 16 KJ/mol.

$D_o\ ,\ Ea_D$

Estimate from other parameters and fit to Ca data.

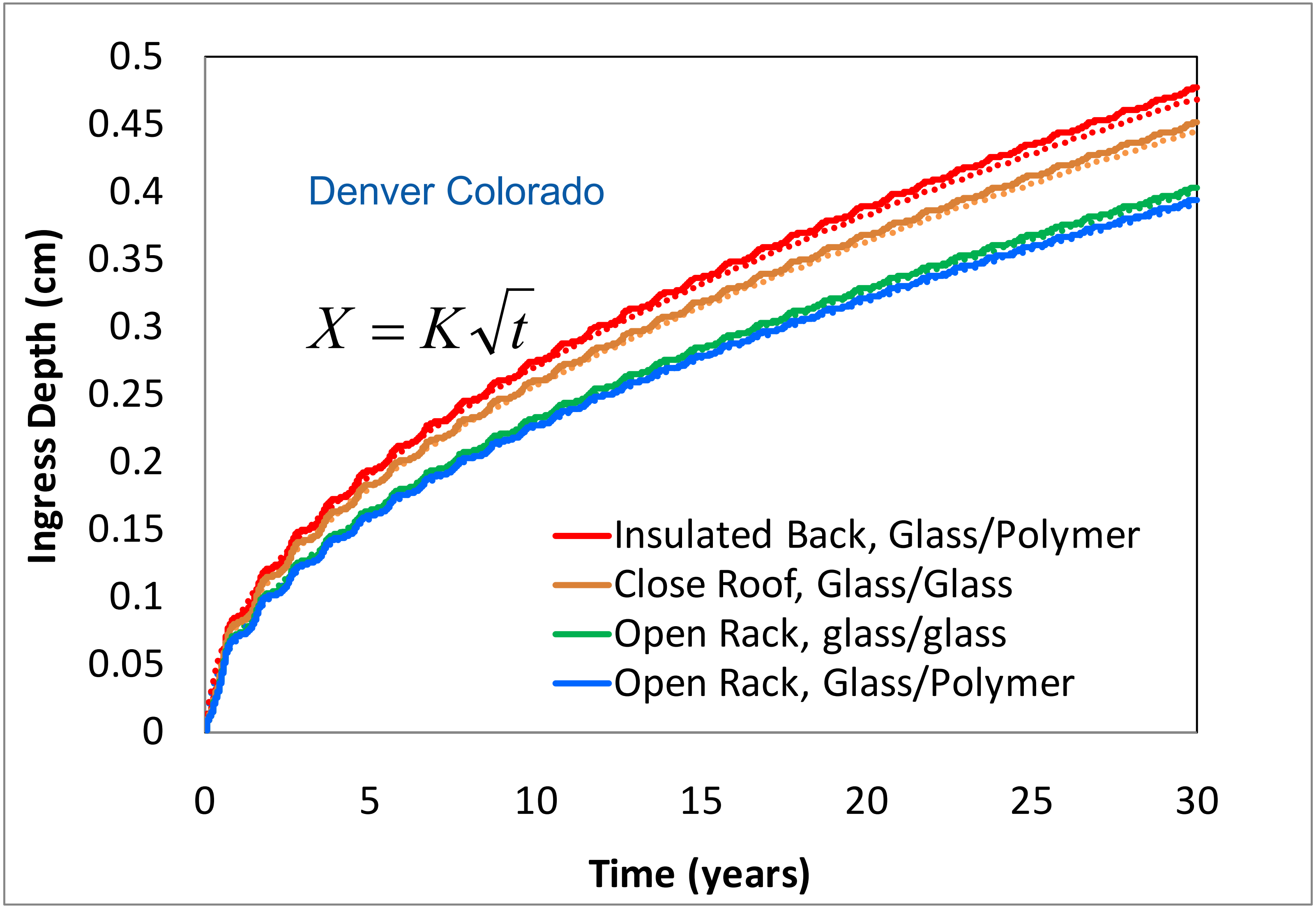


Ingress Estimated Using Finite Element Analysis



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 (cm^2/s)=	9.22
Ea_D (kJ/mol)=	56
S_o (g/cm^3)=	7.77
Ea_S (kJ/mol)=	16
Reactive Ca absorption (g/cm^3)=	0.0327

		K ($cm/h^{1/2}$)	20 y required width (cm)	20 yr equivalent at 85°C/85% RH (h)	20 yr equivalent at 45°C/85% RH (years)
DENVER/CENTENNIAL [GOLDEN - NREL]	Open Rack, Glass/Polymer	0.00076	0.32	**316**	0.7
	Open Rack, glass/glass	0.00078	0.33	330	0.8
	Close Roof, Glass/Glass	0.00087	0.36	408	0.9
	Insulated Back, Glass/Polymer	0.00092	0.38	454	1.0
MUNICH	Open Rack, Glass/Polymer	0.00081	0.34	353	0.8
	Open Rack, glass/glass	0.00082	0.34	364	0.8
	Close Roof, Glass/Glass	0.00089	0.37	432	1.0
	Insulated Back, Glass/Polymer	0.00093	0.39	471	1.1
RIYADH	Open Rack, Glass/Polymer	0.00099	0.41	525	1.2
	Open Rack, glass/glass	0.00101	0.42	551	1.3
	Close Roof, Glass/Glass	0.00114	0.48	705	1.6
	Insulated Back, Glass/Polymer	0.00121	0.51	795	1.8
PHOENIX SKY HARBOR INTL AP	Open Rack, Glass/Polymer	0.00119	0.50	767	1.8
	Open Rack, glass/glass	0.00122	0.51	805	1.9
	Close Roof, Glass/Glass	0.00138	0.58	1,029	2.4
	Insulated Back, Glass/Polymer	0.00146	0.61	1,161	2.7
MIAMI INTL AP	Open Rack, Glass/Polymer	0.00168	0.70	1,520	3.5
	Open Rack, glass/glass	0.00171	0.72	1,580	3.7
	Close Roof, Glass/Glass	0.00187	0.78	1,889	4.4
	Insulated Back, Glass/Polymer	0.00195	0.82	2,062	4.8
BANGKOK	Open Rack, Glass/Polymer	0.00198	0.83	2,115	4.9
	Open Rack, glass/glass	0.00201	0.84	2,192	5.1
	Close Roof, Glass/Glass	0.00220	0.92	2,625	6.1
	Insulated Back, Glass/Polymer	0.00230	0.96	**2,867**	6.6

A sensitivity analysis gave about ±15% on K and Width, and ±30% on 20 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 may 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:

1. An edge seal width of 1 cm can be capable of keeping moisture out for 20 years in almost any climate.
2. The mounting configuration is not a significant factor for determining the diffusion based lifetime of an edge seal.
3. The climate a module is deployed in very significantly impacts edge seal performance.
4. Exposure to between 500 h and 3000 h of 85C and 85% RH will equate to about 20 years of moisture ingress through an edge seal.