NREL
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Understanding Moisture Ingress Rates in PV Modules

Barrier Technologies Workshop

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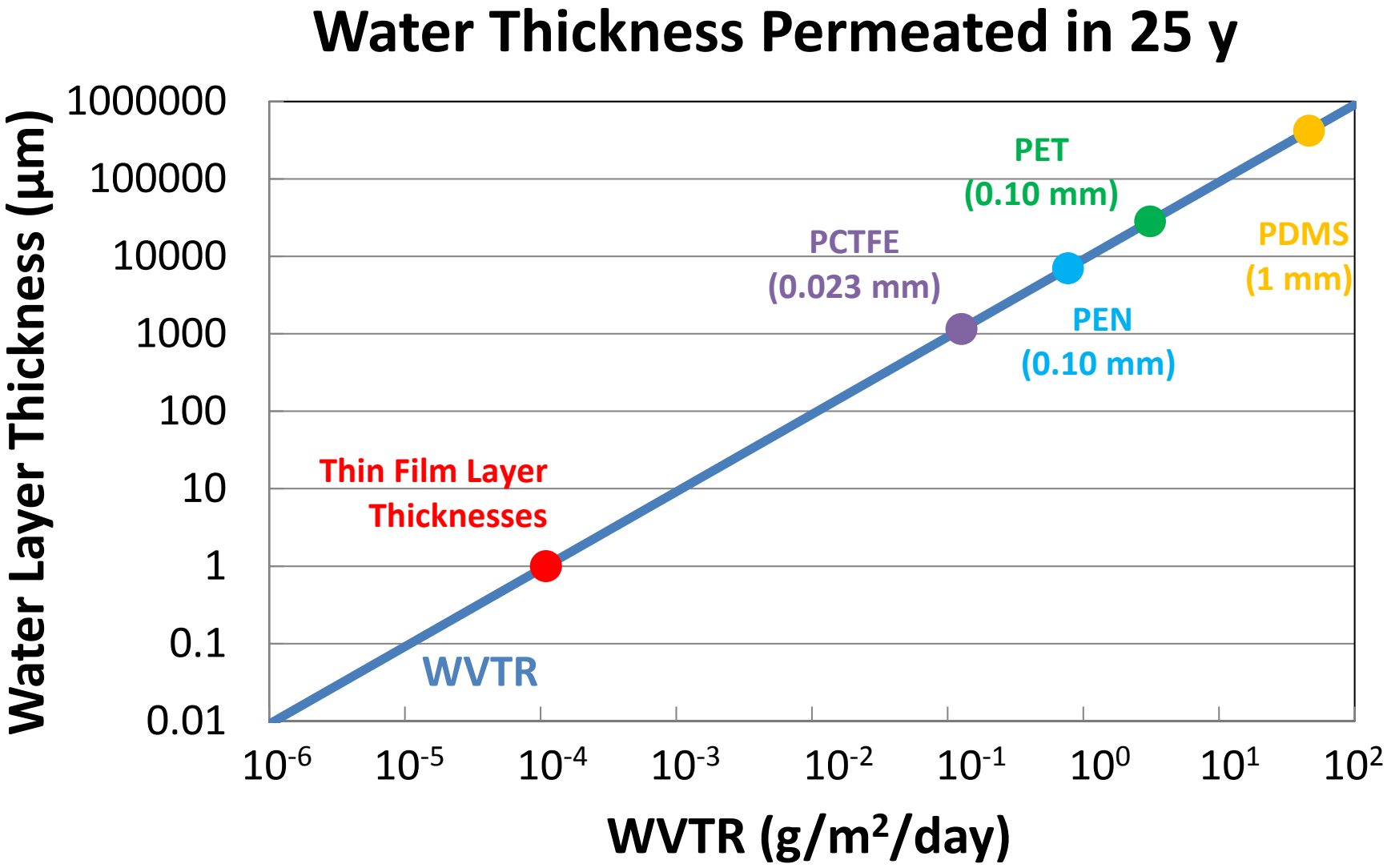
Introduction

- **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.**
  - Ease of application.
  - Weight limits for some structures.
  - Here I will explain the theory behind why such low permeation is necessary and how to prevent moisture ingress.

Outline

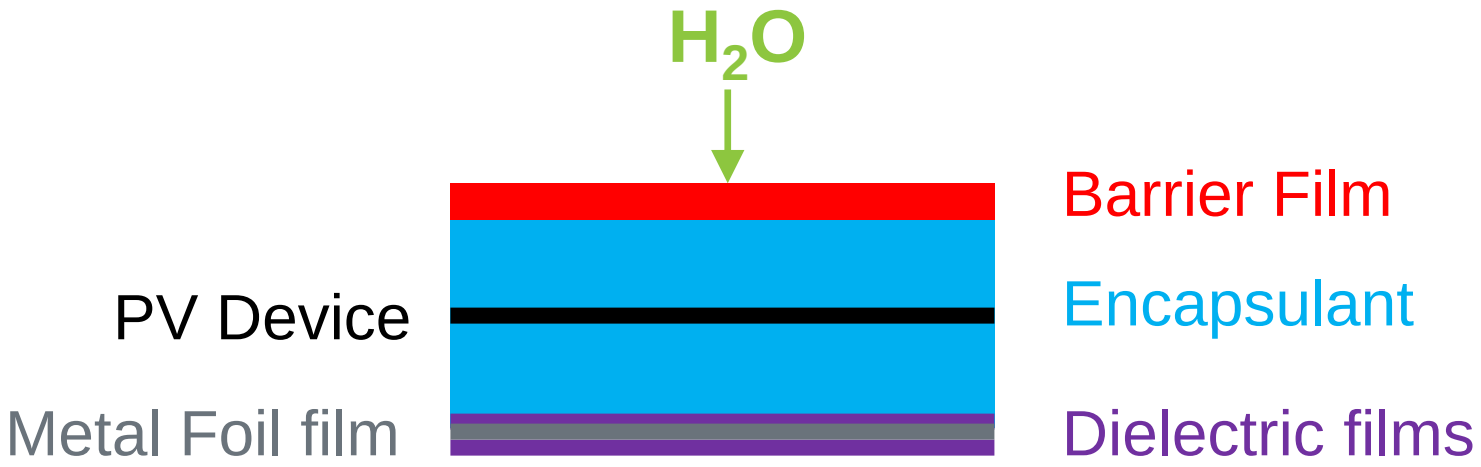
- Permeation through barrier films. 25 y requirements.
- Diffusion from the module edges.
- Edge seals

How Does WVTR Relate to Total Permeation?



This depicts how much water would get in if it was consumed immediately.

Moisture in Breathable Front-Sheets



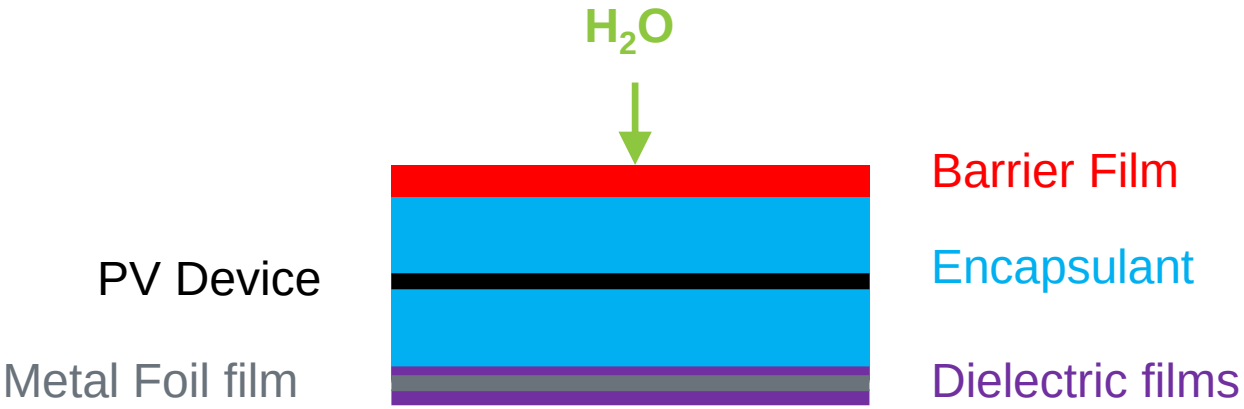
Moisture Permation Assumptions:

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

(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



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

$$\tau_{1/2} = 0.693\frac{C_{Sat,EVA}l_{EVA}}{WVTR_{B,Sat}} = 0.693\frac{Amout\,of\ water\ EVA\ can\ hold}{Rate\,of\ moisture\,ingress}$$

Time Constant for Water Ingress

$$\tau_{1/2} = 0.693 \frac{C_{Sat,EVA} l_{EVA}}{WVTR_{B,Sat}}$$

l_{EVA} =0.46 mm, T=27 °C, $C_{Sat,EVA}$=0.0022 g/cm^3
l_{PET}=0.10 mm, l_{PEN}=0.10 mm, l_{PCTFE}=0.022 mm

	PET	PEN	PCTFE	
$\tau_{1/2}$ =	0.22	0.91	5.5	(day)

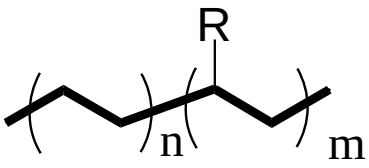
For $\tau_{1/2}$=25 years need 0.8·10^{-4} g/m^2/day

At 1·10^{-3} g/m^2/day, the encapsulant will have a half time of 1.9 y. This short time frame is insignificant compared to a 25 y warranty.

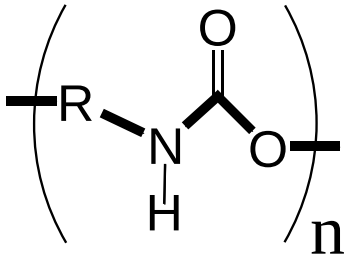
Encapsulant Materials Structures

$$\tau_{1/2} = 0.693 \frac{C_{Sat,E} l_E}{WVTR_{B,Sat}}$$

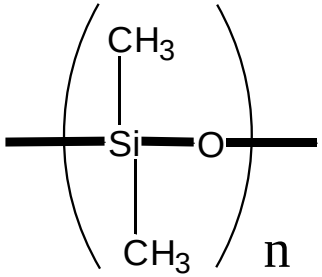
R= $-CH_3$,$-(CH_2)nCH_3$, others or multiple "R" groups.



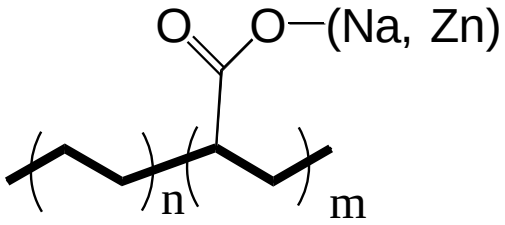
Thermoplastic Polyolefin (TPO)



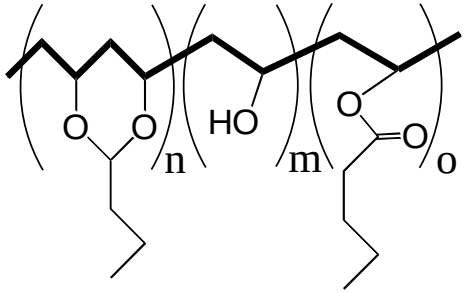
Thermoplastic Polyurethane (TPU)



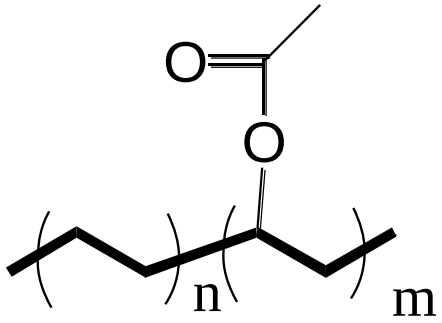
Polydimethylsiloxane (PDMS)



Ionomer



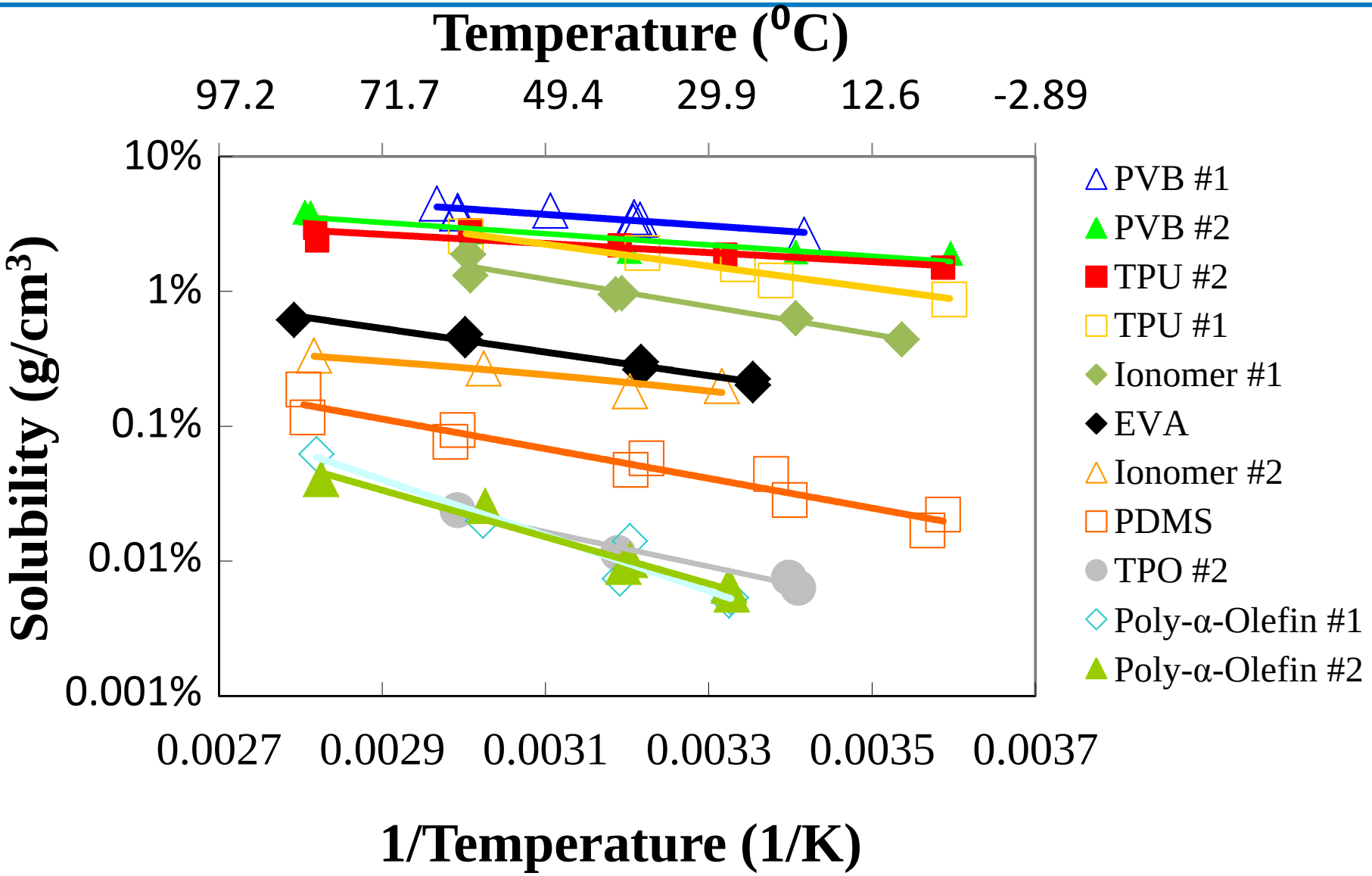
Polyvinyl Butyral (PVB)



Ethylene Vinyl Acetate (EVA)

M. Kempe, "Overview of Scientific Issues Involved in Selection of Polymers for PV Applications", 37th IEEE PVSC (2011).

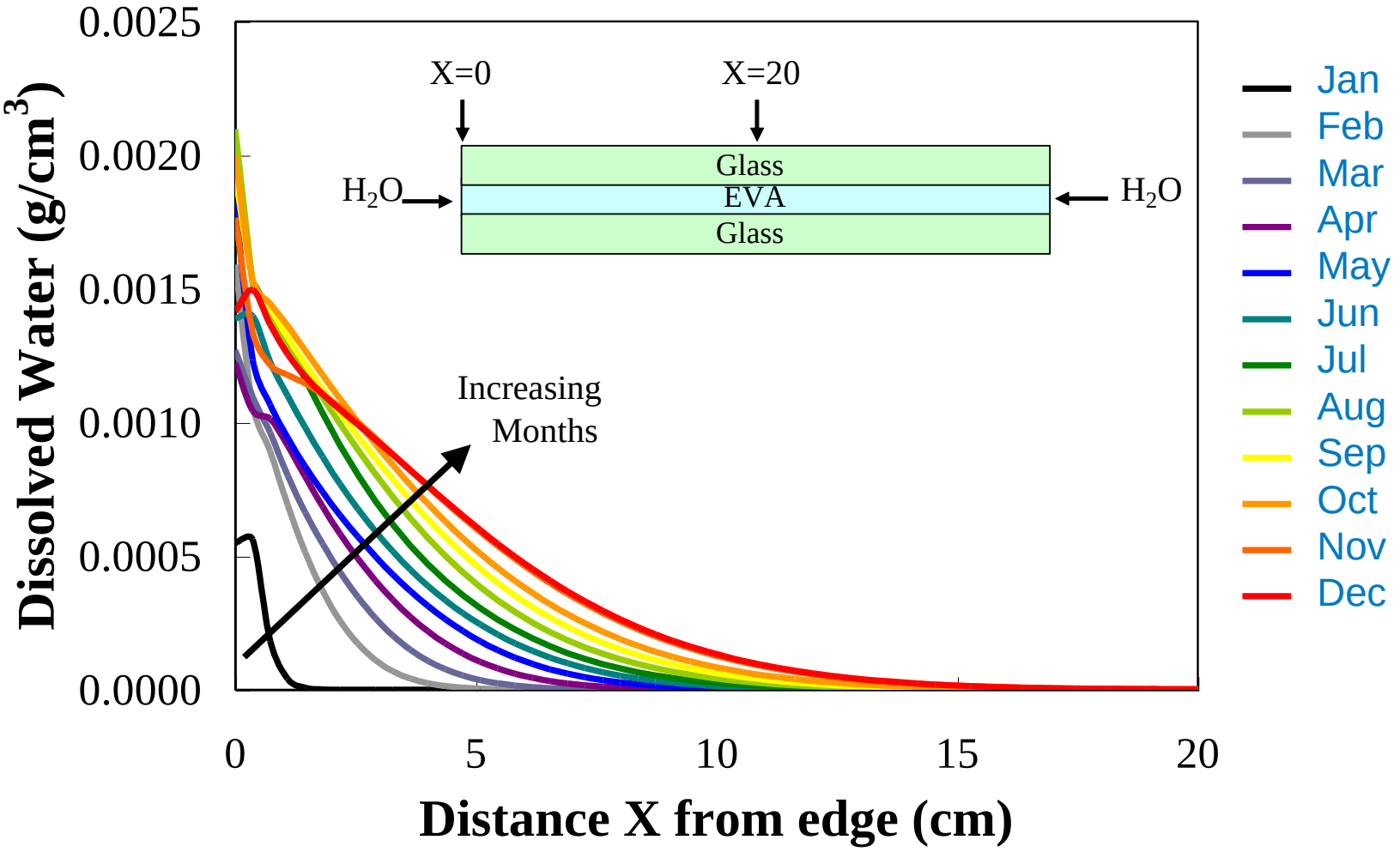
Significantly More Adsorbent Polymers Exist



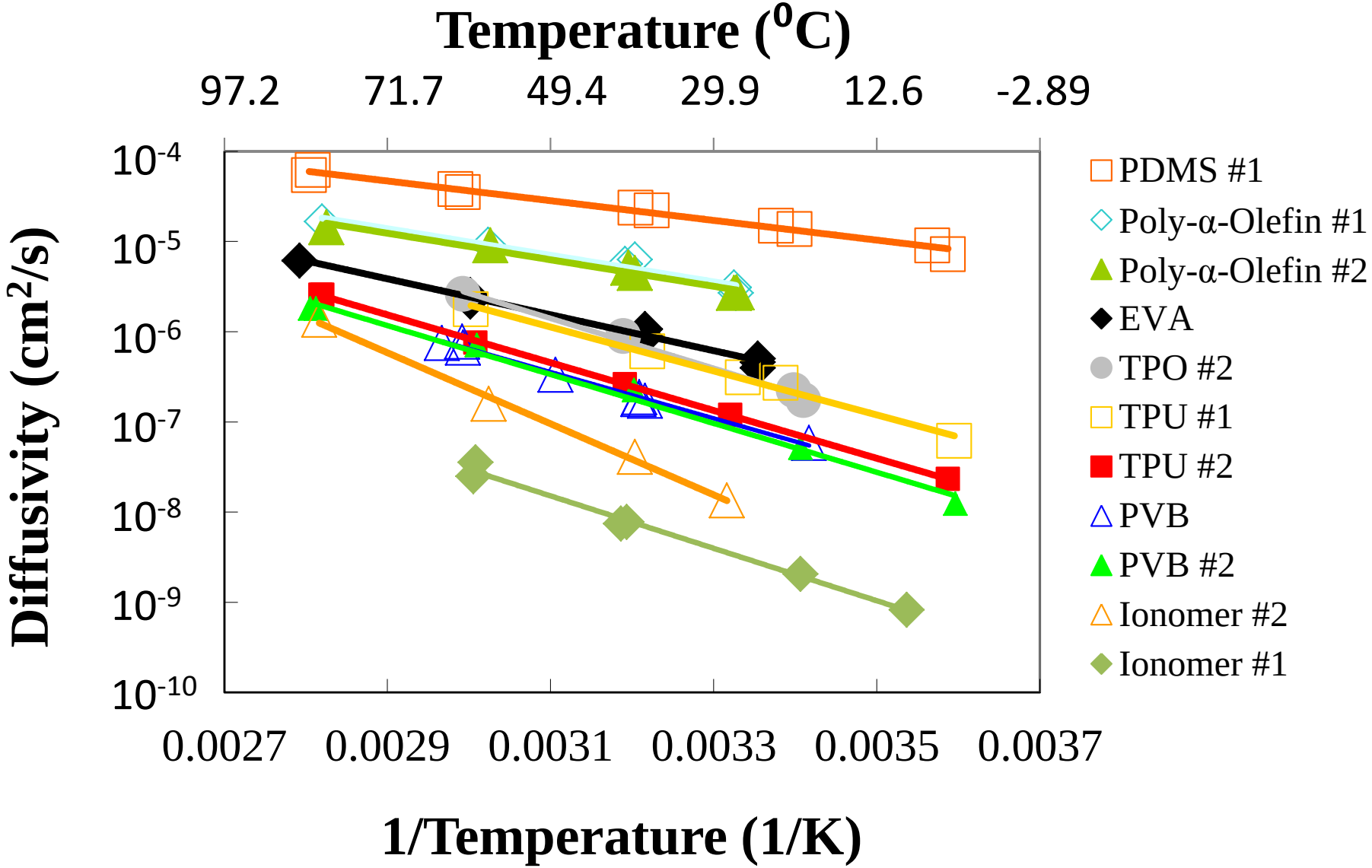
A 10X more water adsorbent polymer may reduce the barrier requirements by a factor of 10.

EVA Allows Significant Moisture Ingress From Edges

Finite element analysis using meteorological data from Miami Florida 2001



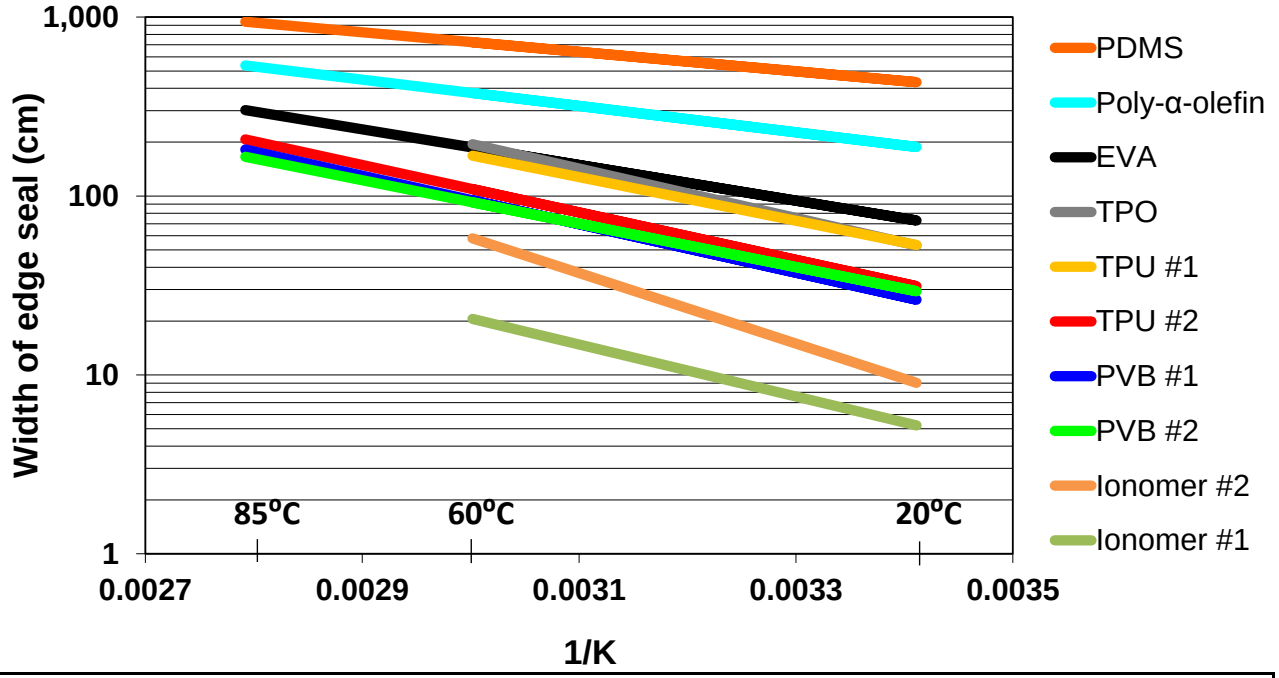
Alternative Encapsulants Slow Down Moisture Ingress



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.

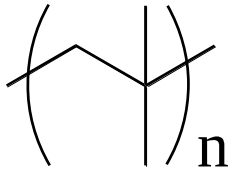


Ea_{PDMS}=27 kJ/mol Ea_{EVA}=38 kJ/mol Ea_{TPO}=53 kJ/mol $Ea_{Ionomer\#1}$=56 kJ/mol	Effective Temperature (°C)							
	Diffusivity Weighted Average Module Temperature							
	Rack Mounted				Insulated Back			
	PDMS	EVA	TPO	Ionomer #1	PDMS	EVA	TPO	Ionomer #1
Munich, Germany	19.5	23.3	28.3	29.2	30.3	38.2	47.7	49.2
Denver, Colorado	25.8	30.1	35.3	36.2	40.2	48.4	56.7	57.9
Miami, Florida	33.8	35.6	37.9	38.3	44.4	48.9	54.3	55.2
Albuquerque, New Mexico	30.6	34.6	39.4	40.1	46.4	54.0	61.3	62.4
Bangkok, Thialand	38.0	39.7	42.0	42.4	48.9	53.4	58.9	59.8
Phoenix, Arizona	40.6	40.6	48.7	44.3	56.6	63.8	71.1	72.1
Riyadh, Saudi Arabia	42.3	45.8	50.1	50.8	58.0	65.0	72.2	73.3

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



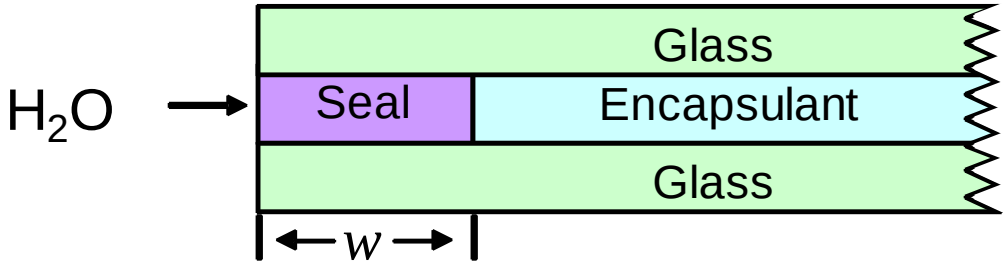
Polyisobutylene

+

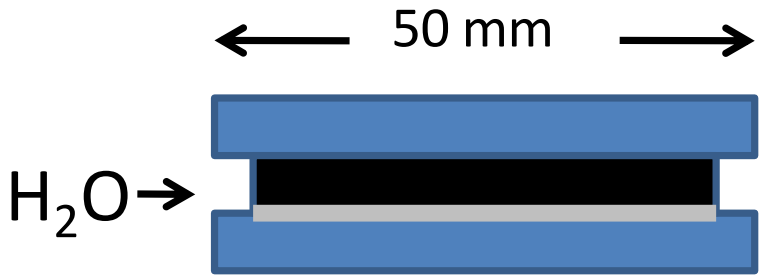
Desiccant

(e.g. CaO or molecular sieves, Preferably type 3A Molecular Steve that does not absorb O_2 and N_2)

Module Edge



Test Sample



Glass (3.18 mm)

Polymer Film (~0.5 mm)

Ca (100 nm)

Glass (3.18 mm)

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

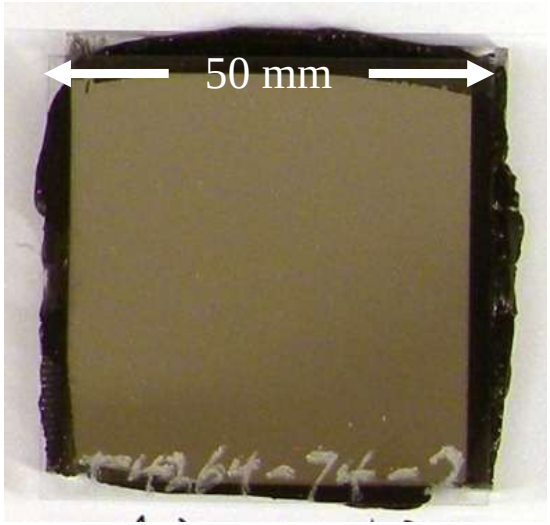
Oxidation of Ca Indicates Moisture Ingress

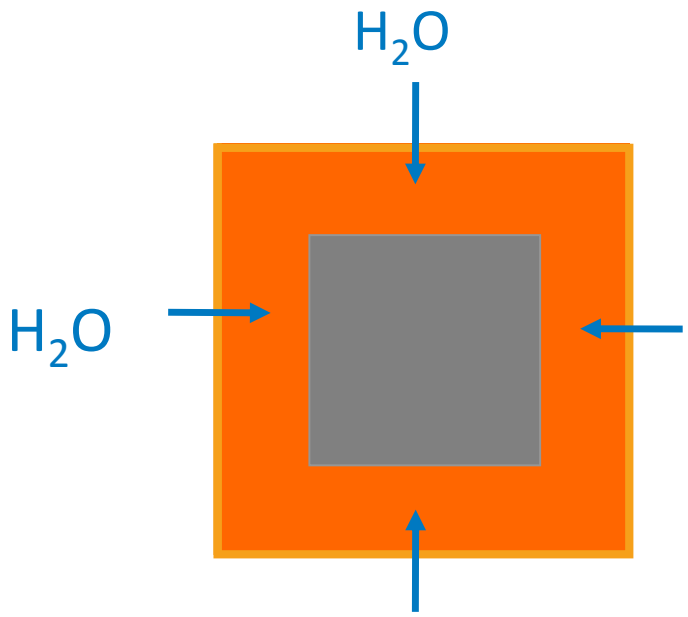
$$Ca + 2\,H_2O \rightarrow Ca(OH)_2 + H_2$$

Mirror-Like → Transparent

Unexposed

1500 h, 85°C, 85% RH





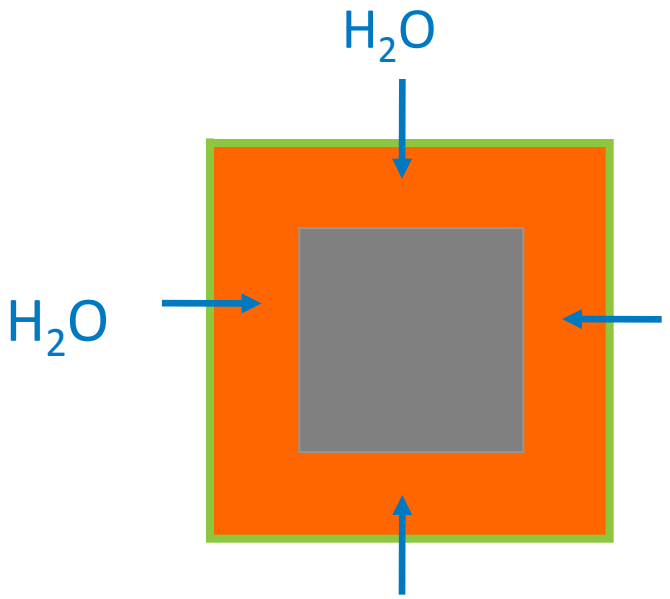
$$\frac{\partial C}{\partial t} = \nabla(D\nabla C)$$

$$X = K\sqrt{t}$$

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 $NaNO_3$.

RH (%)	45 (°C)	85 (°C)
$NaNO_3$	67%	59%
MgCl	31%	25%
LiCl	11%	10%

Edge Seal Modeling

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

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

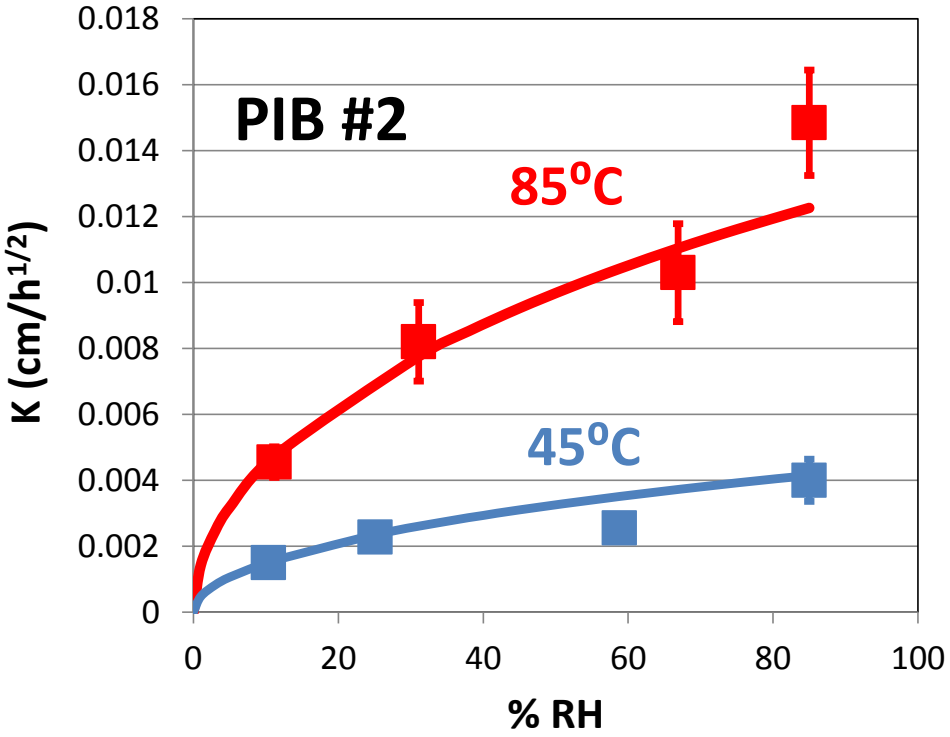
$$D_{eff} = D_o e^{\left(-\frac{Ea_D}{kT}\right)}$$

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

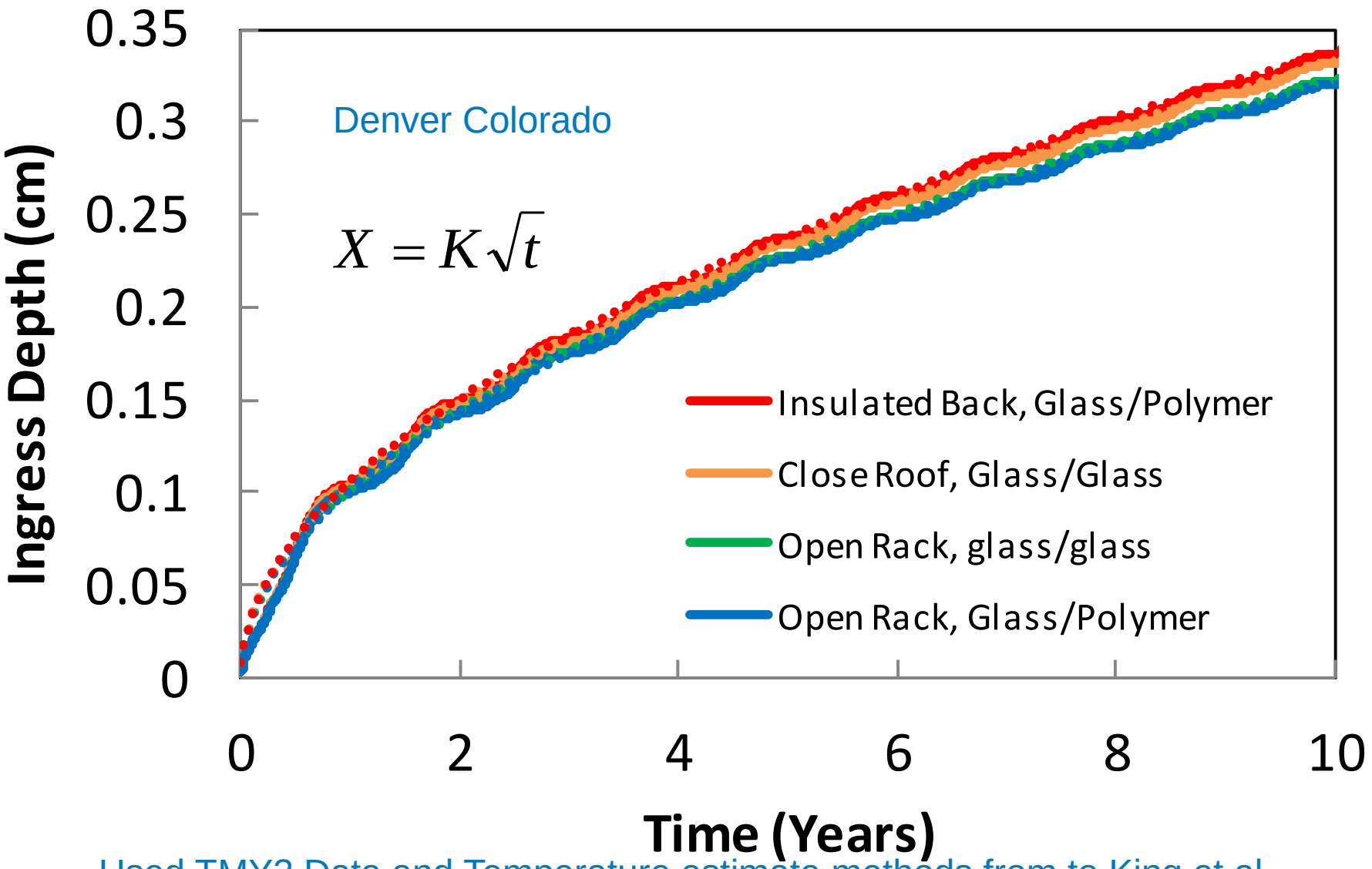
$$R_{H_2O}$$

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

Values for the 5 constants were found from absorption measurements and a fit to the data.



Square Root Relation Works to Longer Times



Used TMY3 Data and Temperature estimate methods from to King et al.

Results for Different Climates

D_o (cm^2/s)=		0.33	Modeled K	Modeled 25 y required width	Modeled 25 y equivalent time at 85°C/85% RH
Ea_D (kJ/mol)=		47			
S_o (g/cm^3)=		0.16			
Ea_S (kJ/mol)=		5			
Reactive Ca absorption (g/cm^3)=		0.047	($cm/h^{1/2}$)	(cm)	(h)
Denver, Colorado	Open Rack		0.00087	0.45	1,100
	Insulated Back		0.00103	0.47	1,300
Munich, Germany	Open Rack		0.00096	0.50	1,400
	Insulated Back		0.00107	0.51	1,500
Riyadh, Saudi Arabia	Open Rack		0.00102	0.50	1,400
	Insulated Back		0.00124	0.53	1,600
Phoenix, Arizona	Open Rack		0.00128	0.60	2,000
	Insulated Back		0.00153	0.63	2,300
Miami, Flordia	Open Rack		0.00199	0.90	4,700
	Insulated Back		0.00225	0.95	5,200
Bangkok, Thailand	Open Rack		0.00228	1.02	6,000
	Insulated Back		0.00258	1.07	6,700

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.

M. D. Kempe, A. A. Dameron, T. J. Moricone, M.O. Reese, "Evaluation and Modeling of Edge-Seal Materials for Photovoltaic Appilcations, 35th IEEE PVSC, Honolulu, HI (2010).

Conclusions

- An ingress half time of 25 years is needed. For typical barriers and encapsulants, a WVTR of less than $0.8 \cdot 10^{-4}$ g/m^2/day or better is needed.
- High solubility encapsulants may decrease the barrier needs to as low as $1 \cdot 10^{-3}$ g/m^2/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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