NATIONAL RENEWABLE ENERGY LABORATORY

Modeling the Ranges of Stresses for Different Climates/Applications

International PV Module QA Forum

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Introduction

Photovoltaic modules must be designed to be installed in a wide variety of environments with variable types of mounting configurations.

The environment influences the amount of UV radiation, the exposure to humidity, and the range of ambient temperatures that will be seen.

Additionally, the mounting configuration influences convective heat transfer creating the potential for significant variability in thermal stresses at the same geographic location.

All these environmental, site specific, attributes must be considered when evaluating the durability of photovoltaic modules.

Outline

- Activation Energy
  - Effect of Environment
  - Effect of Mounting Configuration
- Moisture ingress
  - Edge Seal Modeling
- Generic Corrosion Models
- Conclusions

Degradation Processes Are Thermally Activated

- Photovoltaic modules will degrade because of many different environmental stress factors:
  I. Temperature
  II. Humidity
  III. UV light
  IV. Thermal cycling
  V. Dynamic loading
  VI. Static loading

- Here, we will discuss simple degradation processes dominated by temperature and/or moisture effects

$$Rate \propto e^{\left[\frac{-E_a}{kT}\right]}$$

The Arrhenius equation is one of the most commonly reported models for the temperature dependence of degradation processes.

Definition of Equivalent Temperature

$$e^{\left[\frac{-E_a}{kT_{eq}}\right]} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} e^{\left[\frac{-E_a}{kT(t)}\right]} dt$$

Rate at Constant Temperature = Time Average Degradation Rate

$$T_{eq} = \frac{-E_a}{k \ln\left\{ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} e^{\left[\frac{-E_a}{kT(t)}\right]} dt \right\}}$$

T_{eq} gives a characteristic temperature for an environment that is related to the expected degradation kinetics. However, the Choice of the activation energy is vital.

Typical Thermal Degradation Activation Energies

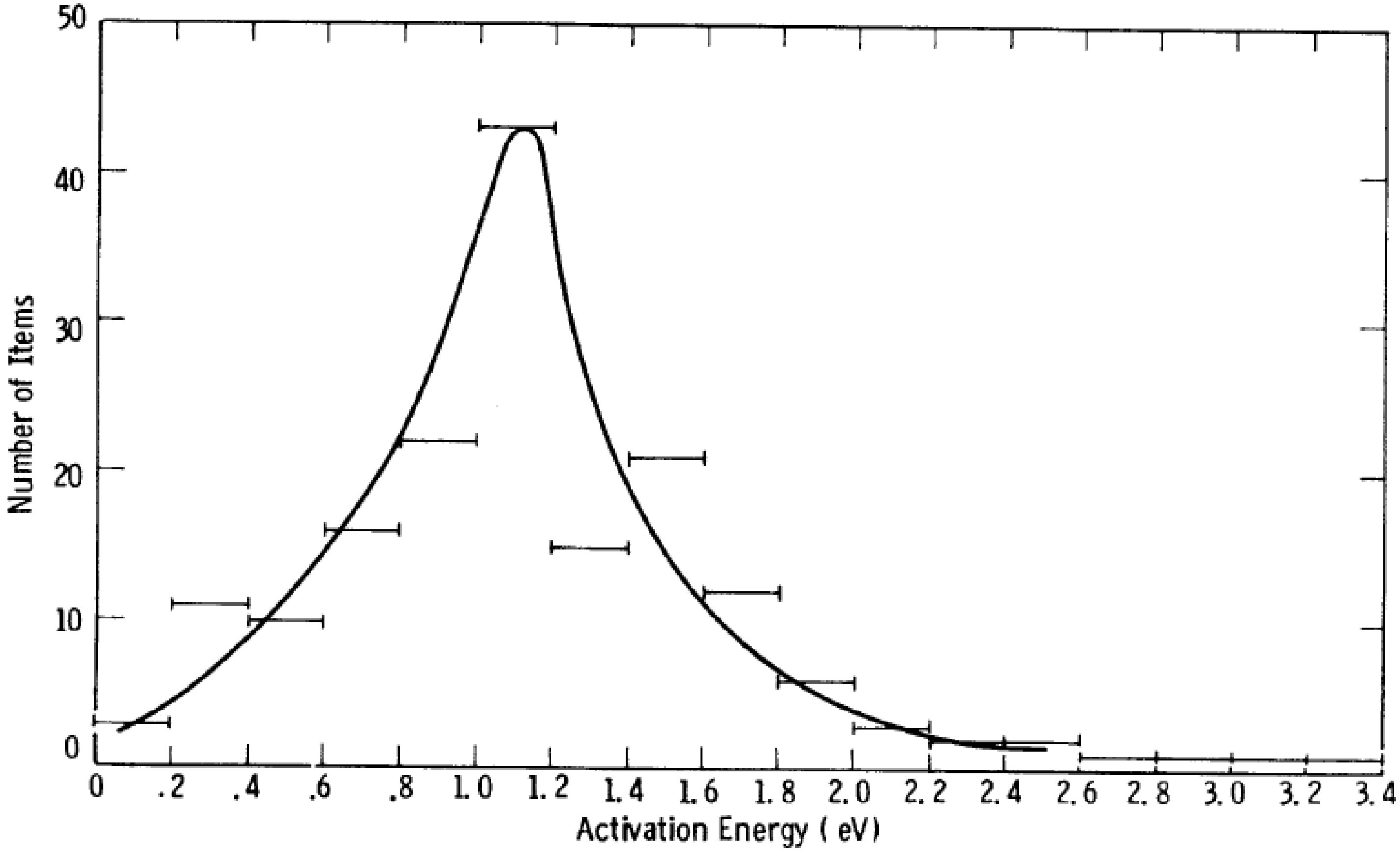


Fig. 3: Frequency distribution of activation energies of various components/materials (D. Cain - EPRI information)

R. R. Dixon, "Thermal Aging Predictions from an Arrhenius Plot with Only One Data Point," *Electrical Insulation, IEEE Transactions on,* vol. EI-15, pp. 331-334, 1980

Modeling Parameters

•Used TMY-3 data from several representative climates.*

•Module temperature approximated according to King et al.**

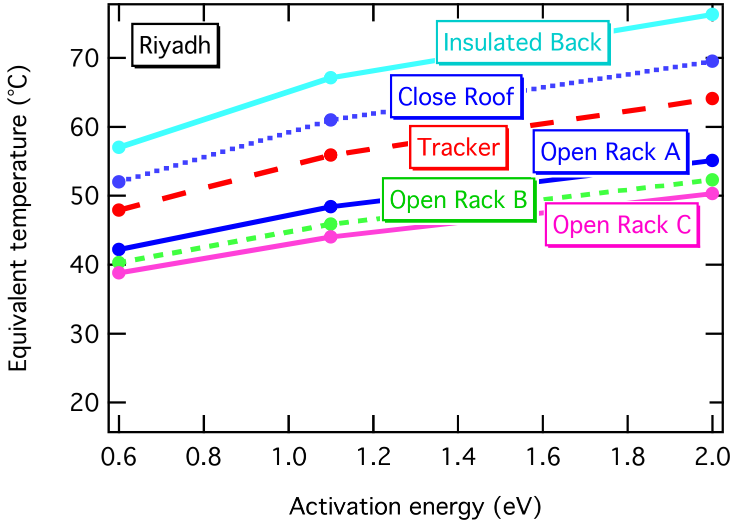
$$T_m = T_{amb} + Irradiance \times \exp[-a - b \times WS] + \Delta T \times Irradiance / 1000$$

Module type	**Mount**	***a***	***b***	***ΔT* (°C)**
Glass/cell/glass	Open rack	-3.47	-0.0594	3
Glass/cell/glass	Close roof	-2.98	-0.0471	1
Glass/cell/polymer sheet	Open rack	-3.56	-0.0750	3
Glass/cell/polymer sheet	Insulated back	-2.81	-0.0455	0
Polymer/thin-film/steel	Open rack	-3.58	-0.113	3
22X Linear concentrator	Tracker	-3.23	-0.130	13

* http://apps1.eere.energy.gov/buildings/energyplus/, as described in: S. Wilcox and W. Marion, "Users Manual for TMY3 Data Sets" *Technical Report* NREL/TP-581-43156, revised May, 2008.

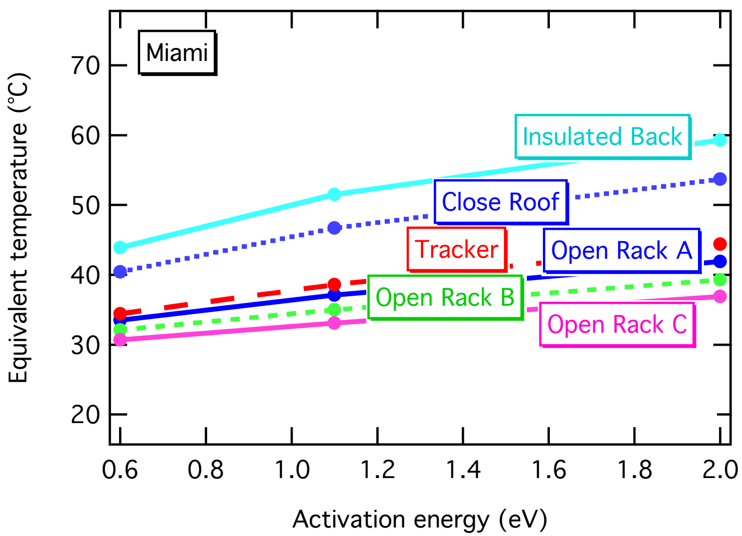
** D.L. King, W.E. Boyson, and J.A. Kratochvil, "Photovoltaic Array Performance Model," Sandia National Laboratories, SAND2004-3535, (2004).

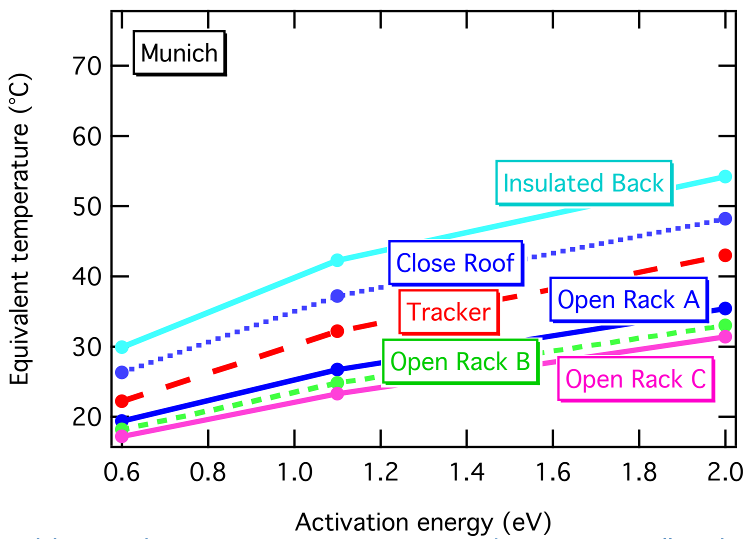
T_{eq} Varies by Location and Mounting Configuration



Mounting Configuration: ±10ºC
Location: ±15ºC
Activation Energy: ±10ºC

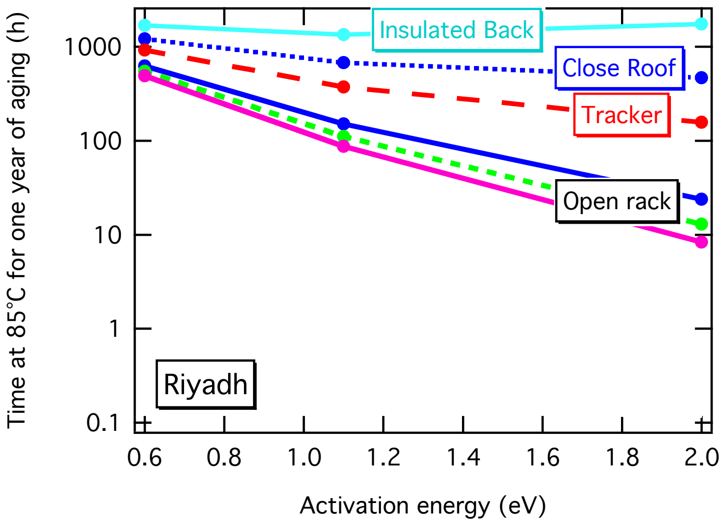
Total Range: ±30ºC





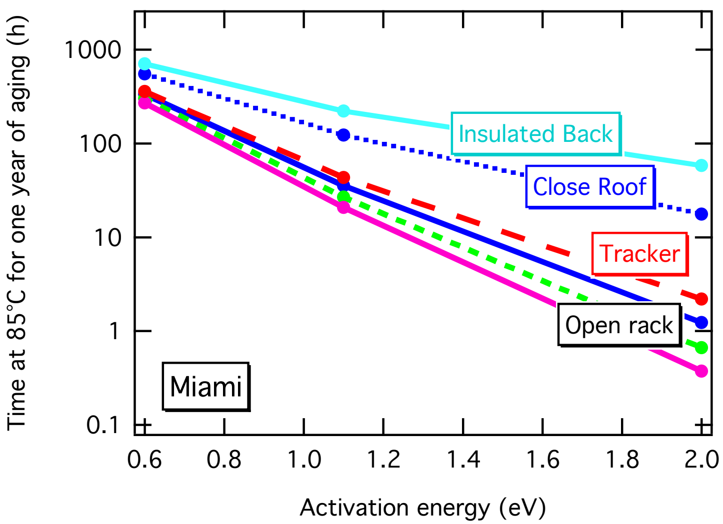
S. Kurtz, K. Whitfield, G. TamizhMani, M. Koehl, D. Miller, J. Joyce, J. Wohlgemuth, N. Bosco, M. Kempe, and T. Zgonena, "Evaluation of high-temperature exposure of photovoltaic modules," *Progress in Photovoltaics: Research and Applications,* DOI: 10.1002.

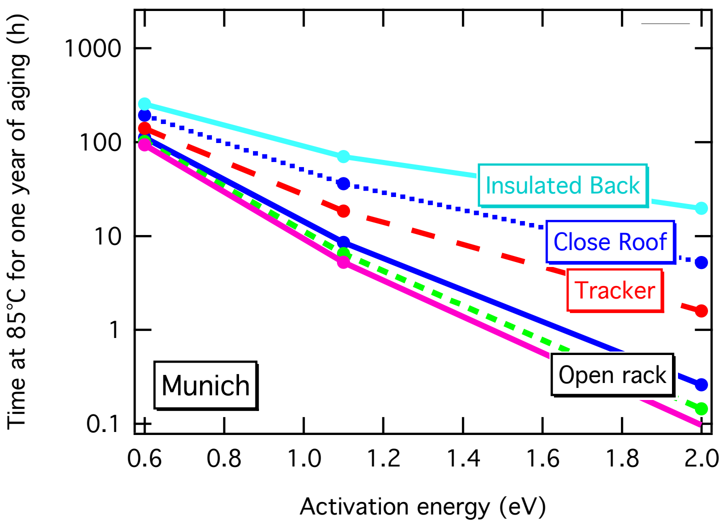
Thermal Acceleration Depends on Mounting and Environment



- Environment : 10X to 100X
- Mounting: 10X to 100X
- Activation Energy: 10 X to 1000X

- Overall there is a 10,000X variability in degradation rates.





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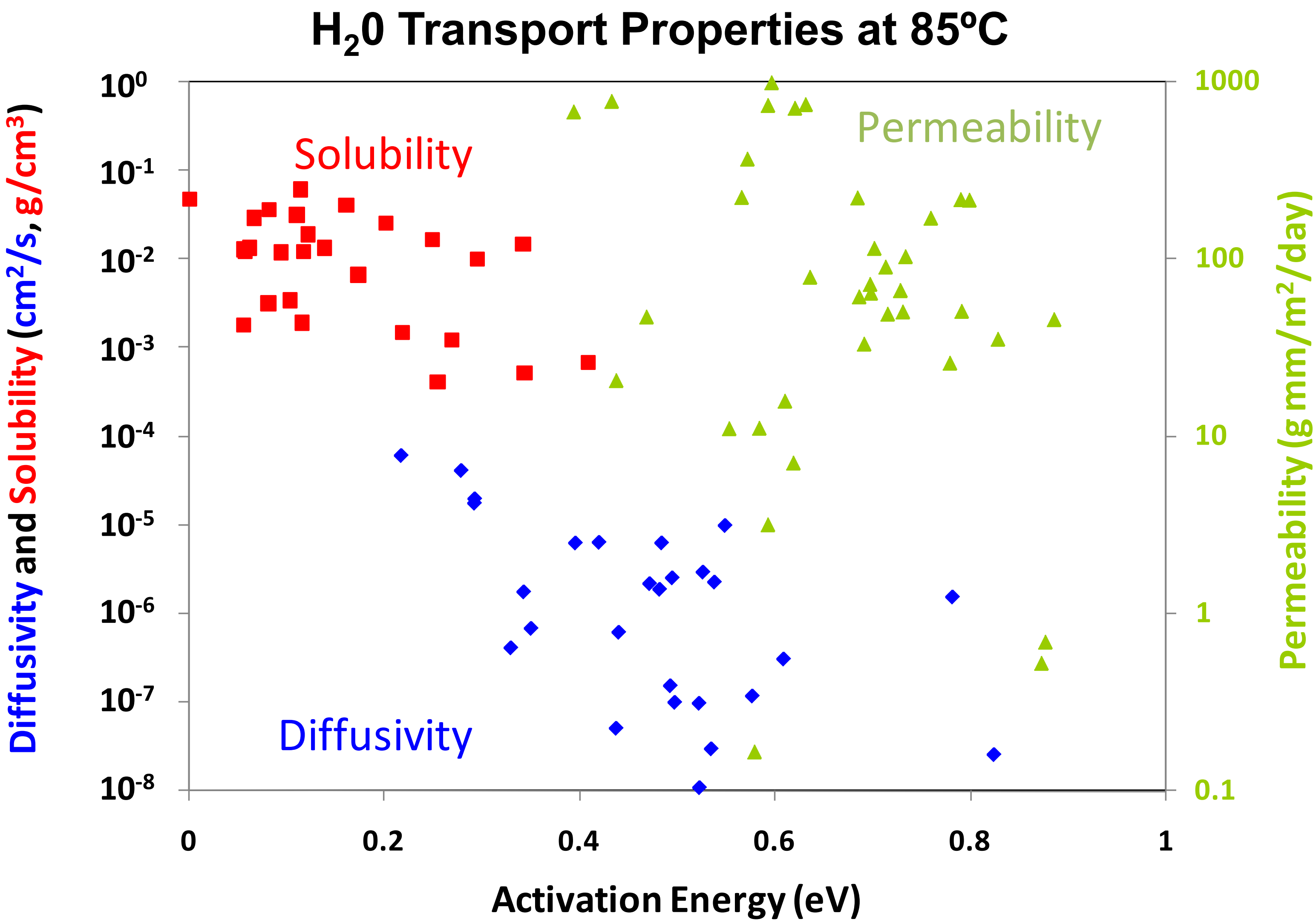
Do all Processes Have the Same Activation?

Mass Transport Phenomena Have Low Activation Energies.



Data obtained from Fickian fit to transient water vapor permeation through films of a variety of PV polymeric materials. Calculated at 85ºC.

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.

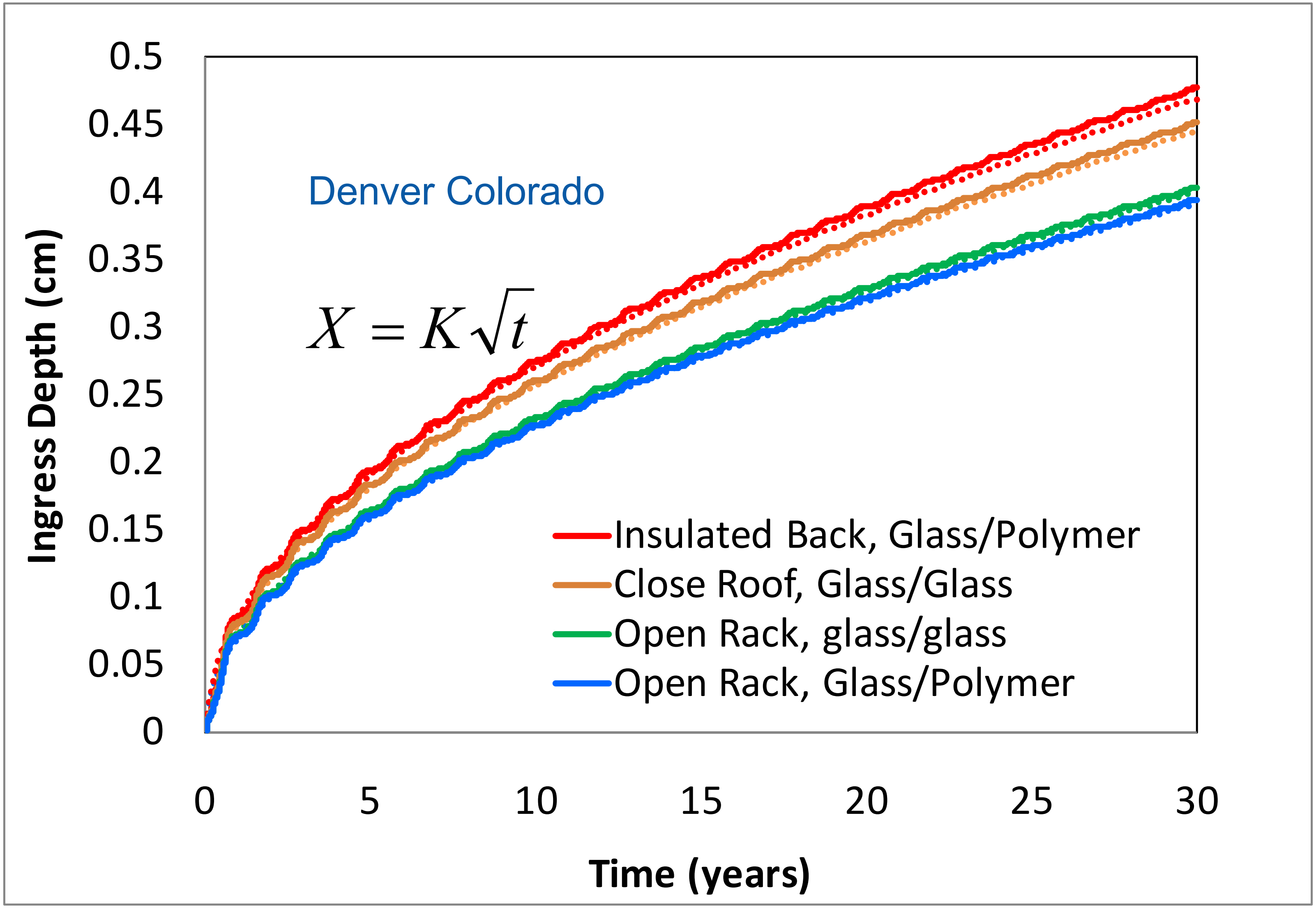
$$D_{eff} = D_o e^{\left(-\frac{Ea_D}{kT}\right)}$$

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.

Mounting Configuration Is Not a Large Factor



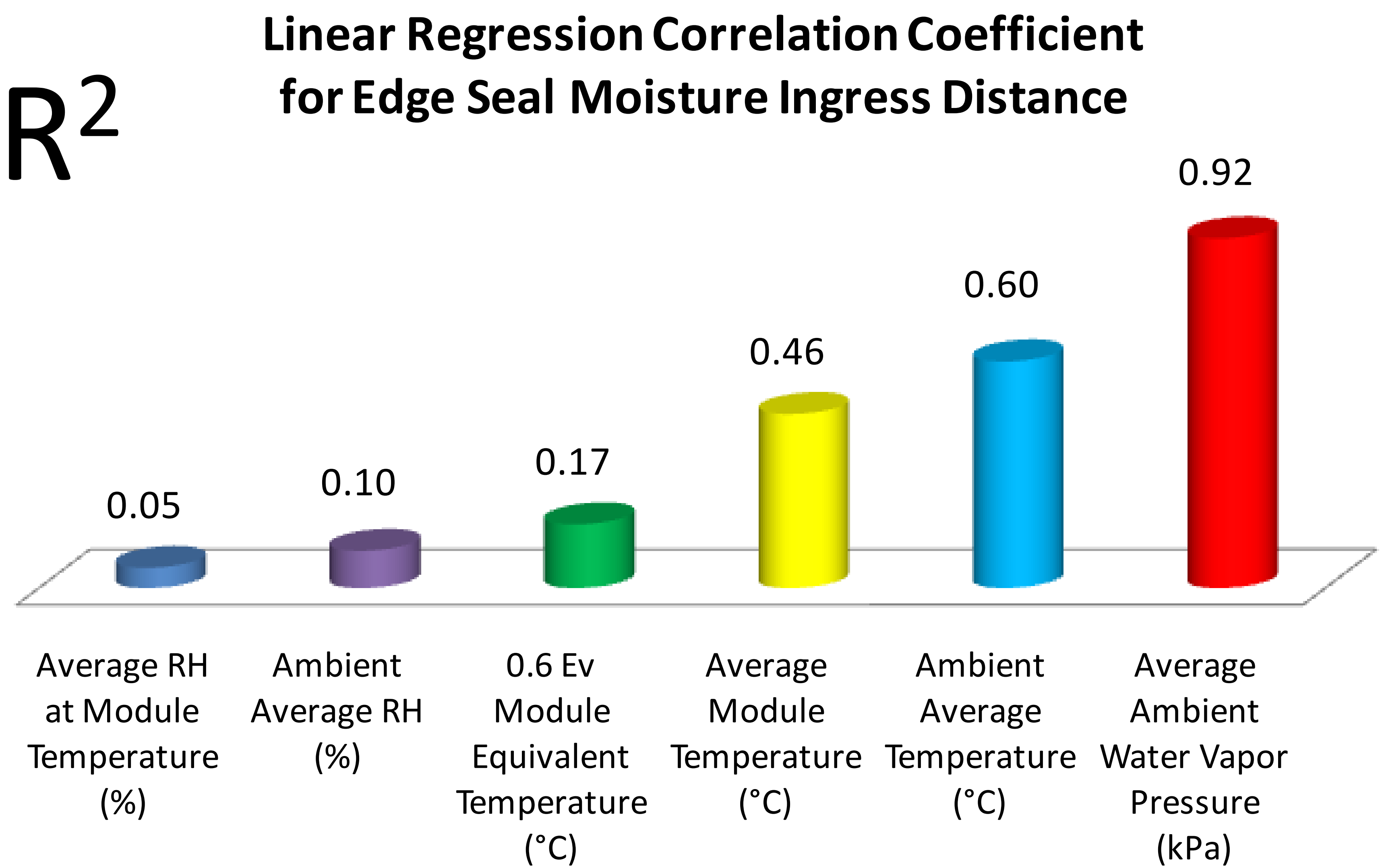
Used TMY3 Data and Temperature estimates similar to King et al, and Kurtz et al.

Preliminary Results for Different Climates

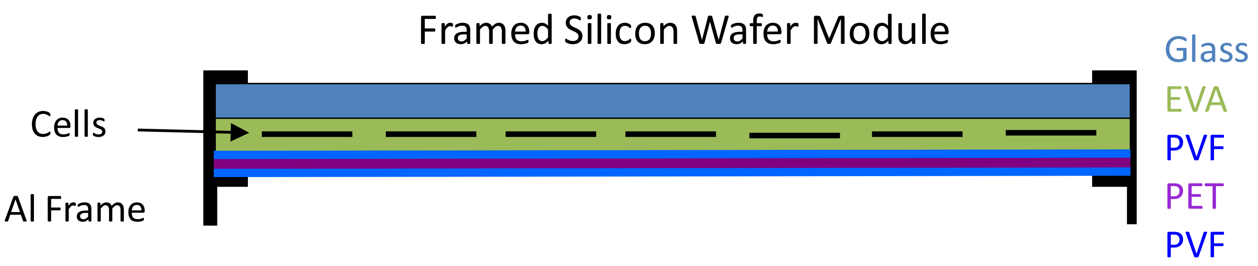
			20 y required width	20 yr equivalent at 85°C/85% RH
D_o (cm^2/s)=		9.22		
Ea_D (kJ/mol)=		56		
S_o (g/cm^3)=		7.77		
Ea_S (kJ/mol)=		16		
Reactive Ca absorption (g/cm^3)=		0.0327	(cm)	(h)
DENVER/CENTENNIAL [GOLDEN - NREL]	Open Rack, Glass/Polymer		0.32	**316**
	Open Rack, glass/glass		0.33	330
	Close Roof, Glass/Glass		0.36	408
	Insulated Back, Glass/Polymer		0.38	454
MUNICH	Open Rack, Glass/Polymer		0.34	353
	Open Rack, glass/glass		0.34	364
	Close Roof, Glass/Glass		0.37	432
	Insulated Back, Glass/Polymer		0.39	471
RIYADH	Open Rack, Glass/Polymer		0.41	525
	Open Rack, glass/glass		0.42	551
	Close Roof, Glass/Glass		0.48	705
	Insulated Back, Glass/Polymer		0.51	795
PHOENIX SKY HARBOR INTL AP	Open Rack, Glass/Polymer		0.50	767
	Open Rack, glass/glass		0.51	805
	Close Roof, Glass/Glass		0.58	1,029
	Insulated Back, Glass/Polymer		0.61	1,161
MIAMI INTL AP	Open Rack, Glass/Polymer		0.70	1,520
	Open Rack, glass/glass		0.72	1,580
	Close Roof, Glass/Glass		0.78	1,889
	Insulated Back, Glass/Polymer		0.82	2,062
BANGKOK	Open Rack, Glass/Polymer		0.83	2,115
	Open Rack, glass/glass		0.84	2,192
	Close Roof, Glass/Glass		0.92	2,625
	Insulated Back, Glass/Polymer		0.96	**2,867**

A sensitivity analysis gave about ±15% on K and Width, and ±30% on 20 yr equivalent time.

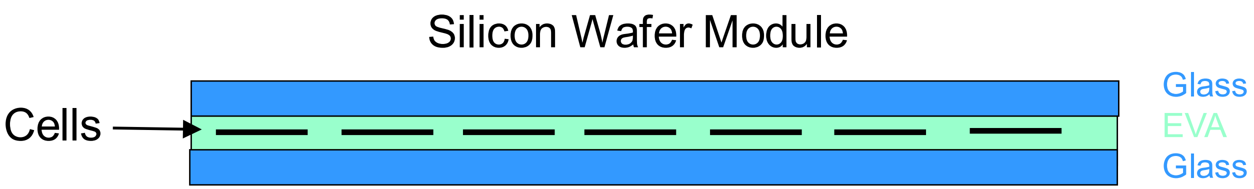
Absolute Humidity Correlates to Water Ingress



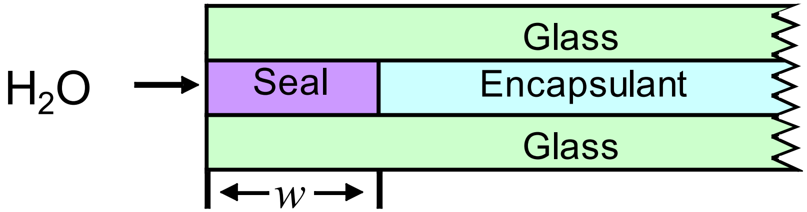
Life Prediction Must Account For Sample Geometry



Backside of cells equilibrates in days. Front Side of cells exposed to moisture within weeks.



It may take several years for most of the module to be exposed to moisture.



Active materials may not be exposed to any moisture for decades.

Typical Microelectronics Degradation Models

Typically, the effects of temperature and humidity are convoluted making the application of appropriate accelerated stress tests extremely difficult even if all the degradation kinetics were known. *

$$R_D = k_o e^{\left(\frac{-Ea}{RT}\right)} \left[\frac{RH}{1 - RH + \varepsilon} \right]^{\alpha}$$

e.g. CIGS Degradation Model by Coyle et al. Ea=0.38 eV, α=1.**

*D. J. Klinger, "Humidity acceleration factor for plastic packaged electronic devices," *Quality and Reliability Engineering International,* vol. 7, pp. 365-370, 1991.
**D. J. Coyle, H. A. Blaydes, J. E. Pickett, R. S. Northey, and J. O. Gardner, "Degradation kinetics of CIGS solar cells," *Proceedings of the 2009 34th IEEE Photovoltaic Specialists Conference (PVSC 2009),* pp. 001943-7, 2009.

Conclusions

1. The amount of thermal degradation is dependent on both the geographic location and on the mounting configuration.
2. Qualification testing (1000 h 85ºC/85%RH) may be either over- or under-stressing a module relative to its expected lifetime. (over-stressing for cold environment and high activation energy, under-stressing for hot and low activation energy).
3. For packaging that limits moisture ingress, the mounting configuration is less important and the average environmental absolute humidity correlates to the severity of moisture in the climate.
4. Many degradation mechanisms are accelerated by both moisture and temperature making proper design of generically applicable accelerated stress tests difficult.

Acknowledgements

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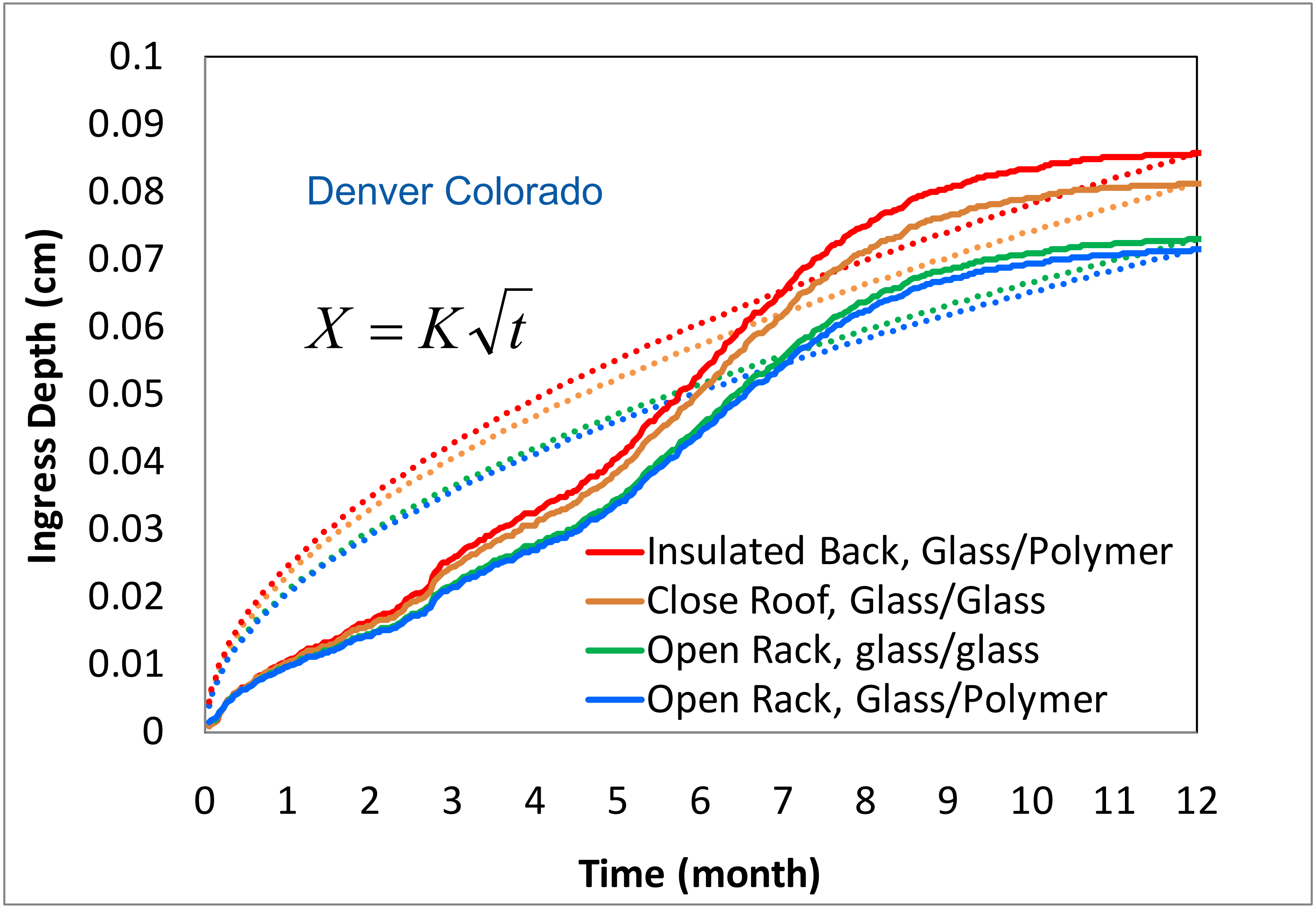
Ingress Estimated Using Finite Element Analysis



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Absolute Humidity Correlates to Water Ingress