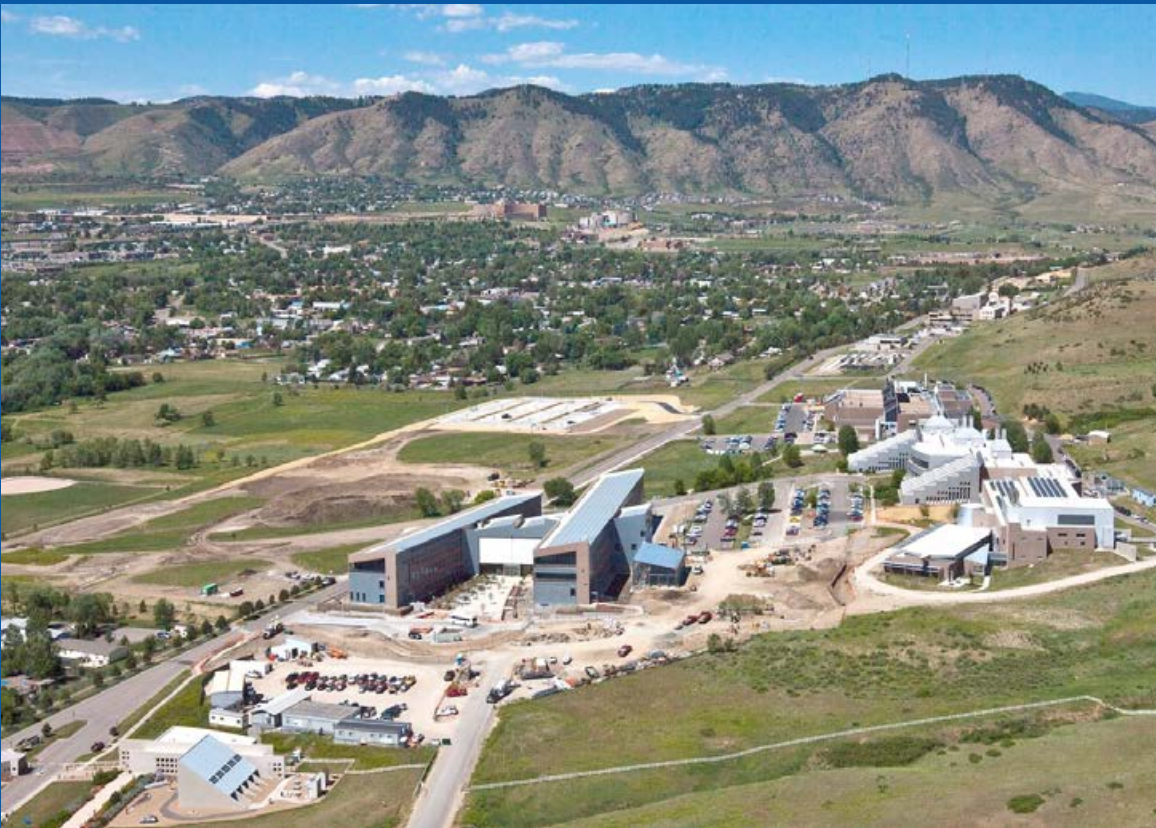


Modeling the Ranges of Stresses for Different Climates/Applications



**International PV Module
QA Forum**

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July 15, 2011

NREL/PR-5200-52312

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

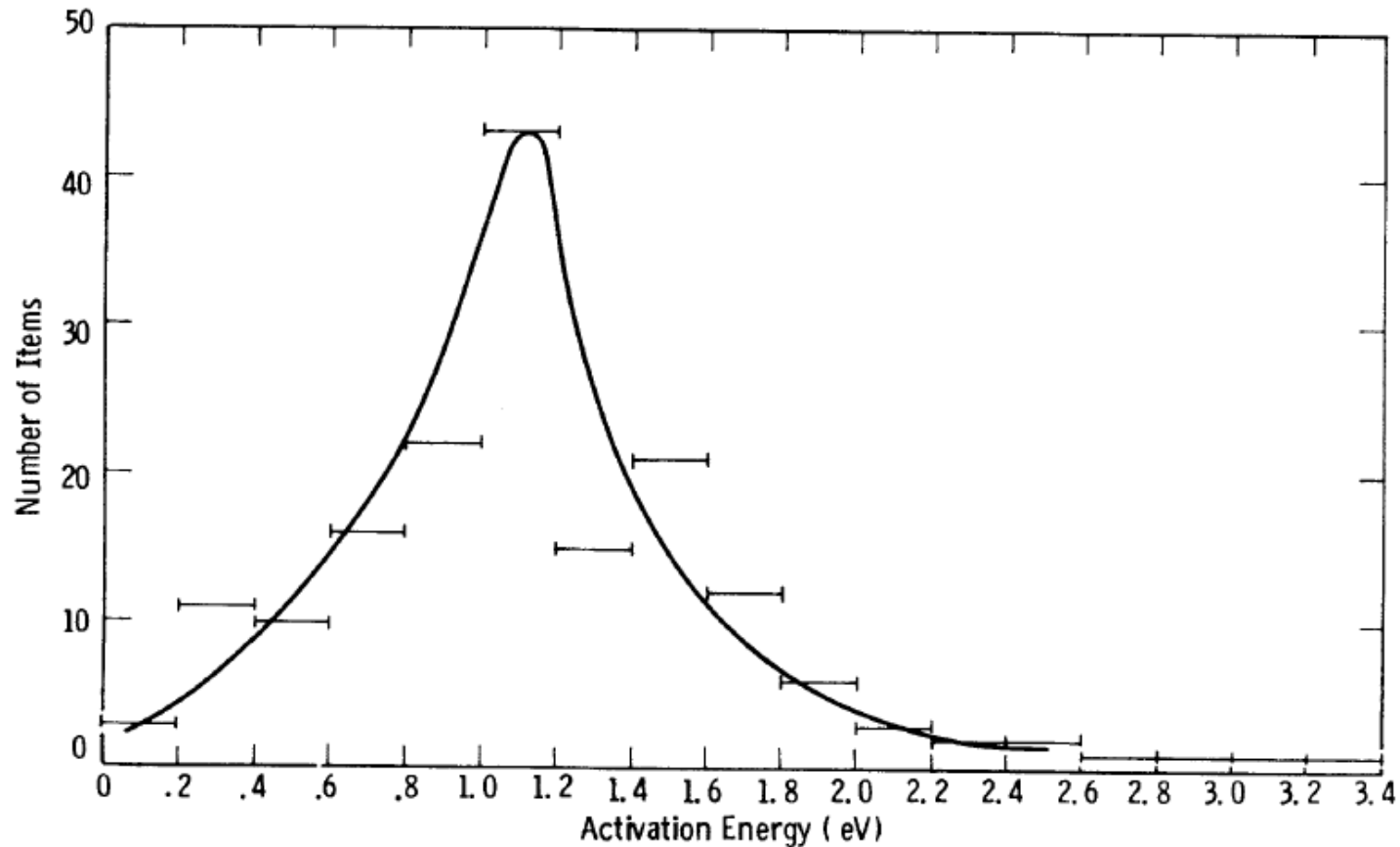


Fig. 3: Frequency distribution of activation energies of various components/materials (D. Cain - EPRI information)

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.**

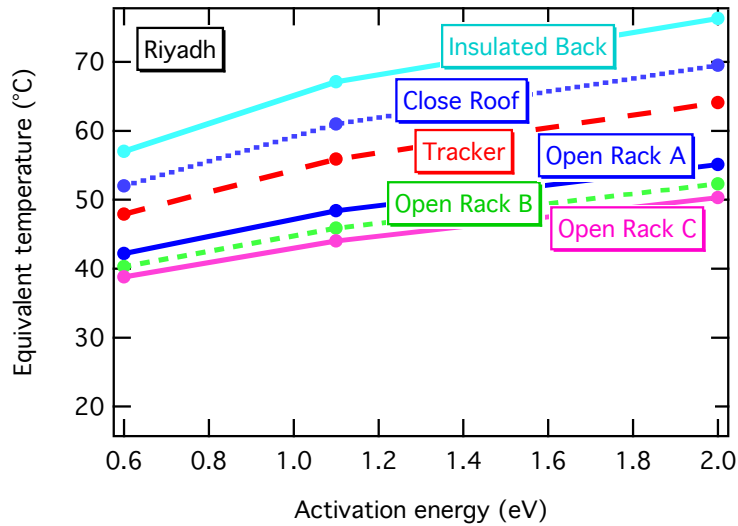
$$T_m = T_{amb} + Irradiance \times \exp[-a - b \times WS] + \Delta T \times Irradiance / 1000$$

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.

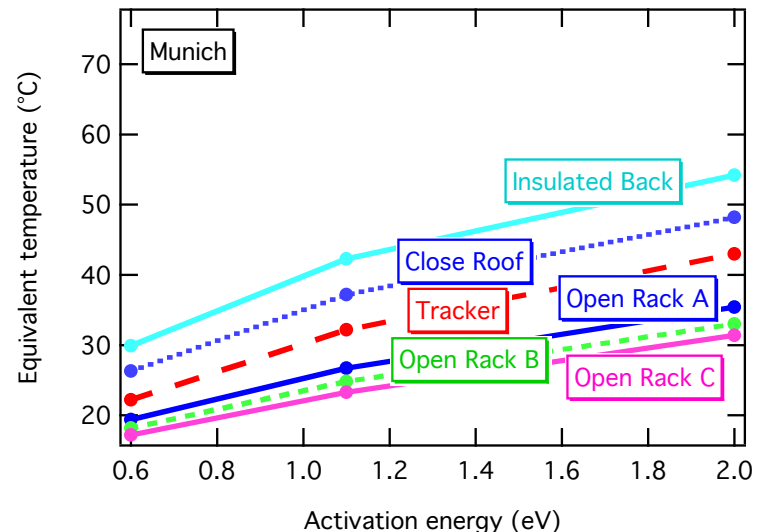
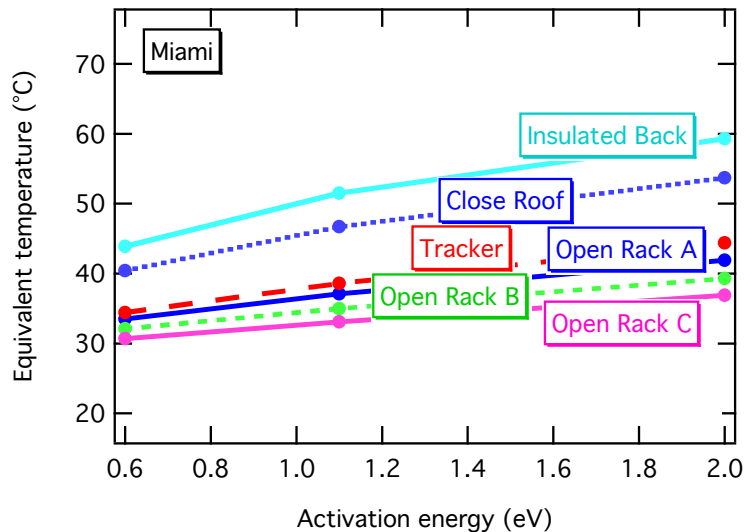
** D.L. King, W.E. Boyson, and J.A. Kratochvil, "Photovoltaic Array Performance Model," Sandia National Laboratories, SAND2004-3535, (2004).

T_{eq} Varies by Location and Mounting Configuration



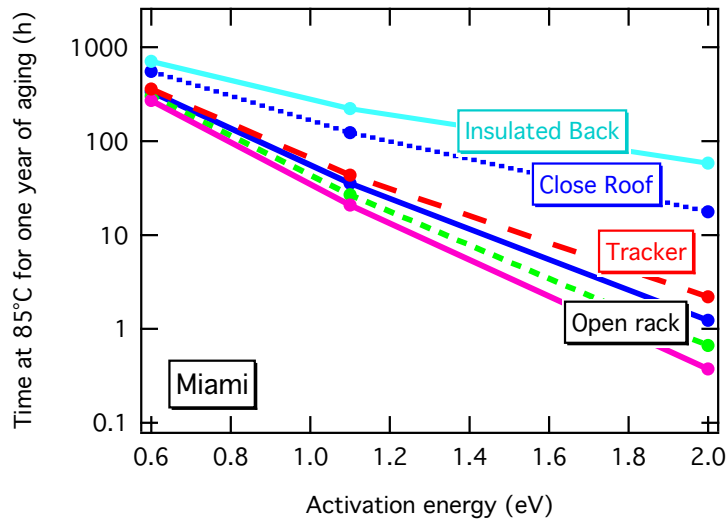
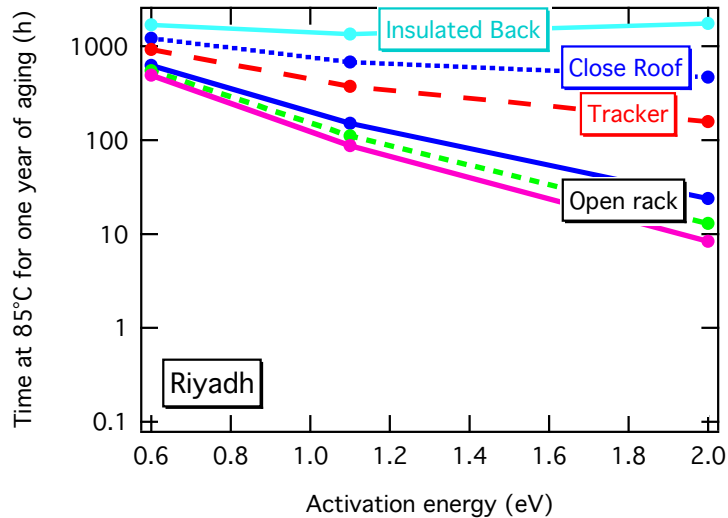
Mounting Configuration: $\pm 10^\circ\text{C}$
 Location: $\pm 15^\circ\text{C}$
 Activation Energy: $\pm 10^\circ\text{C}$

Total Range: $\pm 30^\circ\text{C}$

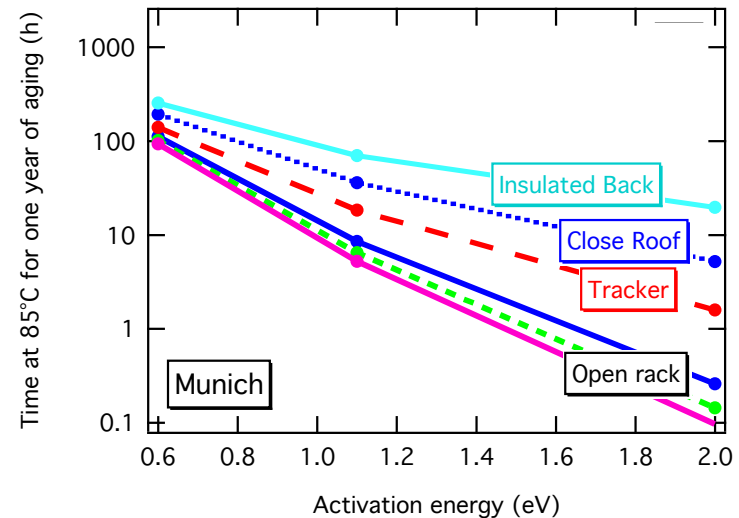


S. Kurtz, K. Whitfield, G. TamizhMani, M. Koehl, D. Miller, J. Joyce, J. Wohlgemuth, N. Bosco, M. Kempe, and T. Zgonena, "Evaluation of high-temperature exposure of photovoltaic modules," *Progress in Photovoltaics: Research and Applications*, DOI: 10.1002.

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.

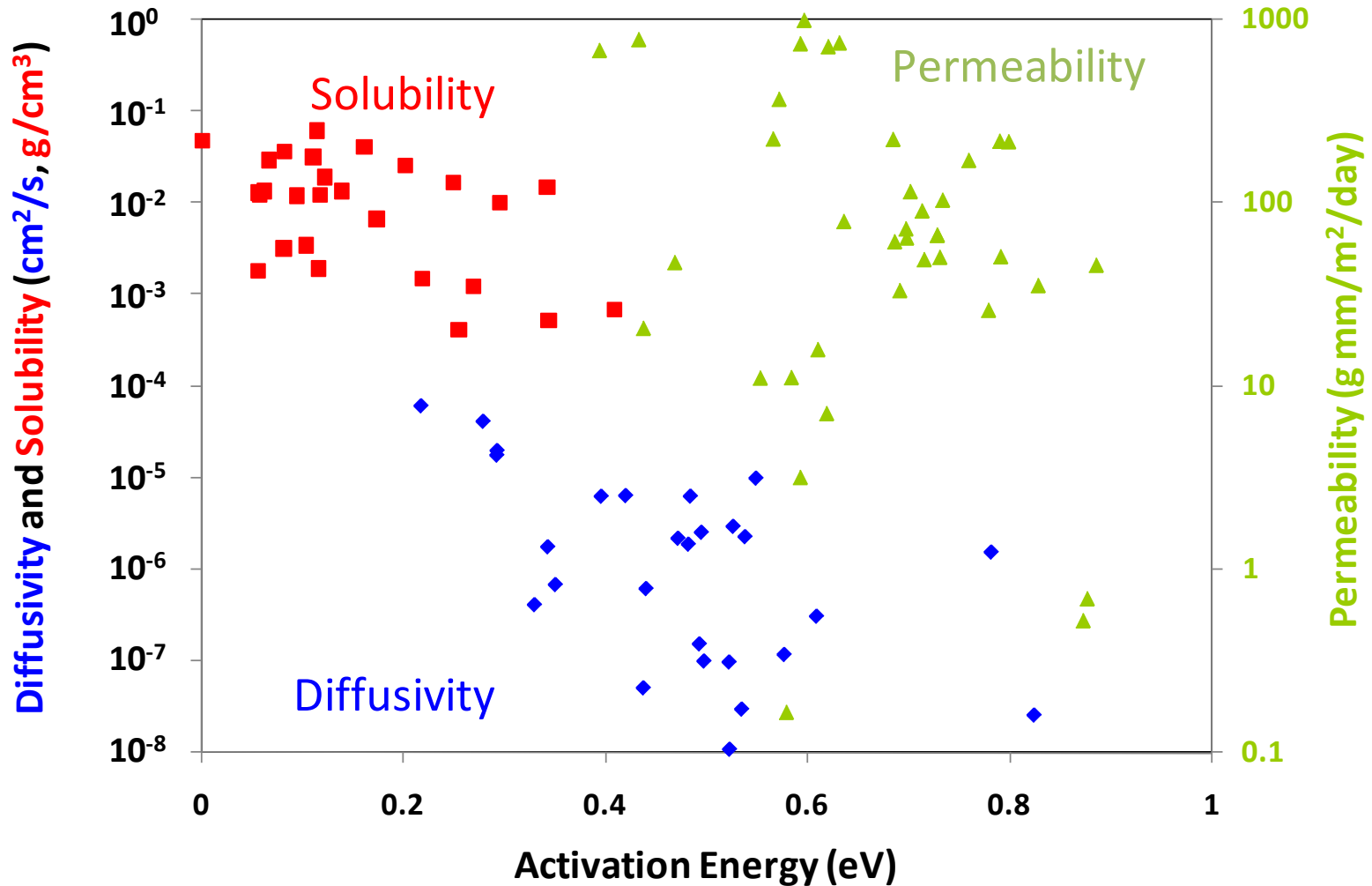


S. Kurtz, K. Whitfield, G. TamizhMani, M. Koehl, D. Miller, J. Joyce, J. Wohlgemuth, N. Bosco, M. Kempe, and T. Zgonena, "Evaluation of high-temperature exposure of photovoltaic modules," *Progress in Photovoltaics: Research and Applications*, DOI: 10.1002.

Do all Processes Have the Same Activation?

Mass Transport Phenomena Have Low Activation Energies.

H₂O Transport Properties at 85°C



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

Edge Seal Modeling

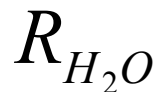
The use of fillers, pigments, and desiccants makes the determination of modeling parameters much more difficult.

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

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

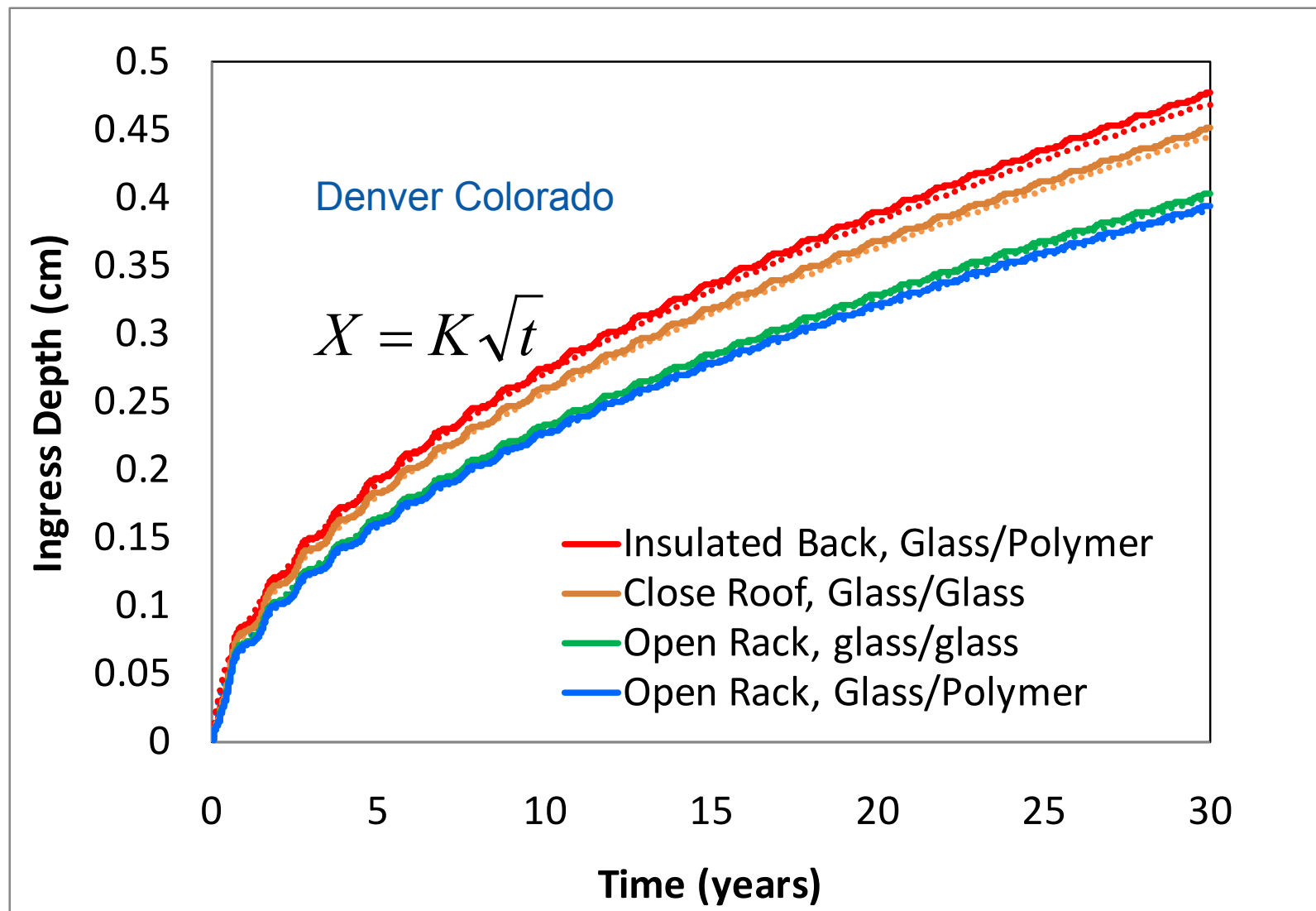
$$D_{eff} = D_o e^{\left(-\frac{Ea_D}{kT}\right)}$$

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



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

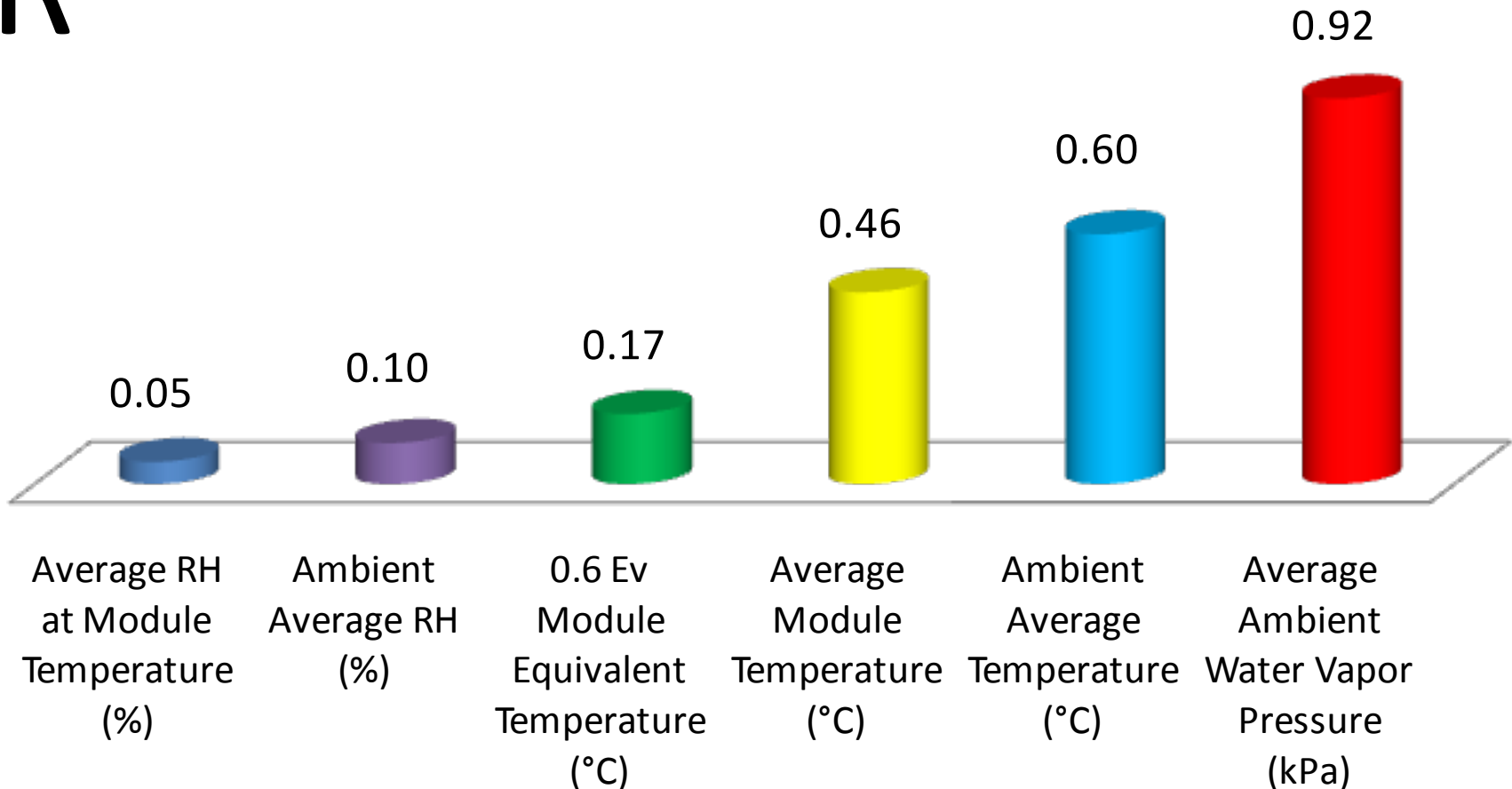
D_o (cm ² /s)=		9.22	20 y required width (cm)	20 yr equivalent at 85°C/85% RH (h)
Ea_D (kJ/mol)=		56		
S_o (g/cm ³)=		7.77		
Ea_S (kJ/mol)=		16		
Reactive Ca absorption (g/cm ³)=		0.0327		
DENVER/CENTENNIAL [GOLDEN - NREL]	Open Rack, Glass/Polymer	0.32	316	
	Open Rack, glass/glass	0.33	330	
	Close Roof, 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 $\pm 15\%$ on K and Width, and $\pm 30\%$ on 20 yr equivalent time.

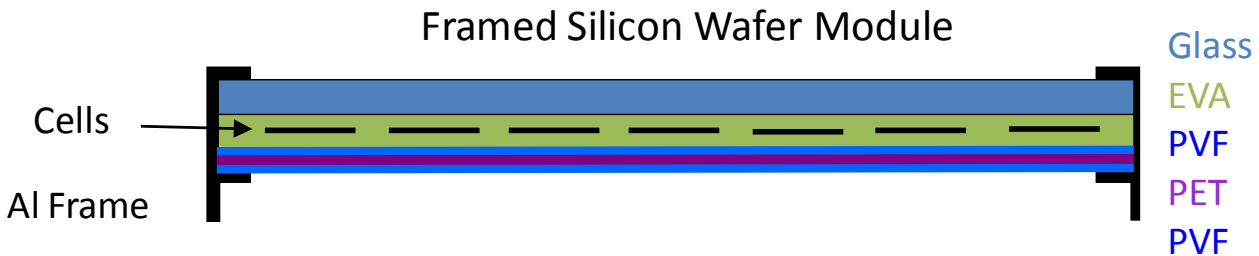
Absolute Humidity Correlates to Water Ingress

R^2

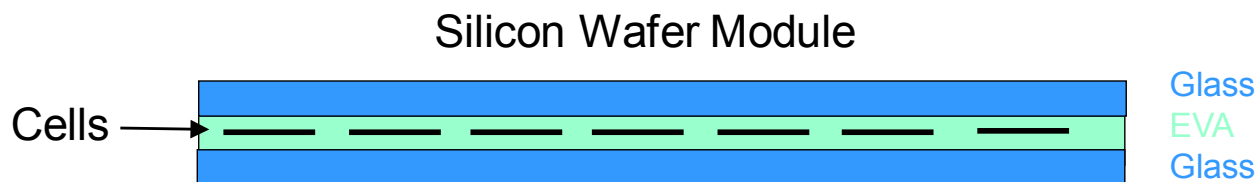
Linear Regression Correlation Coefficient
for Edge Seal Moisture Ingress Distance



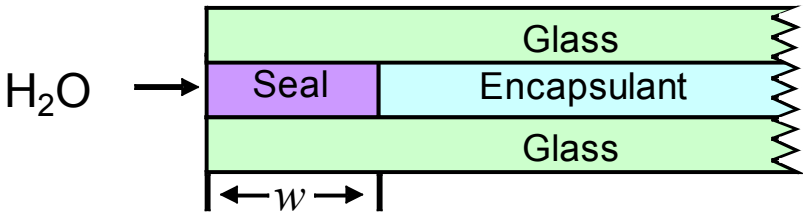
Life Prediction Must Account For Sample Geometry



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, $\alpha=1$.**

*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.

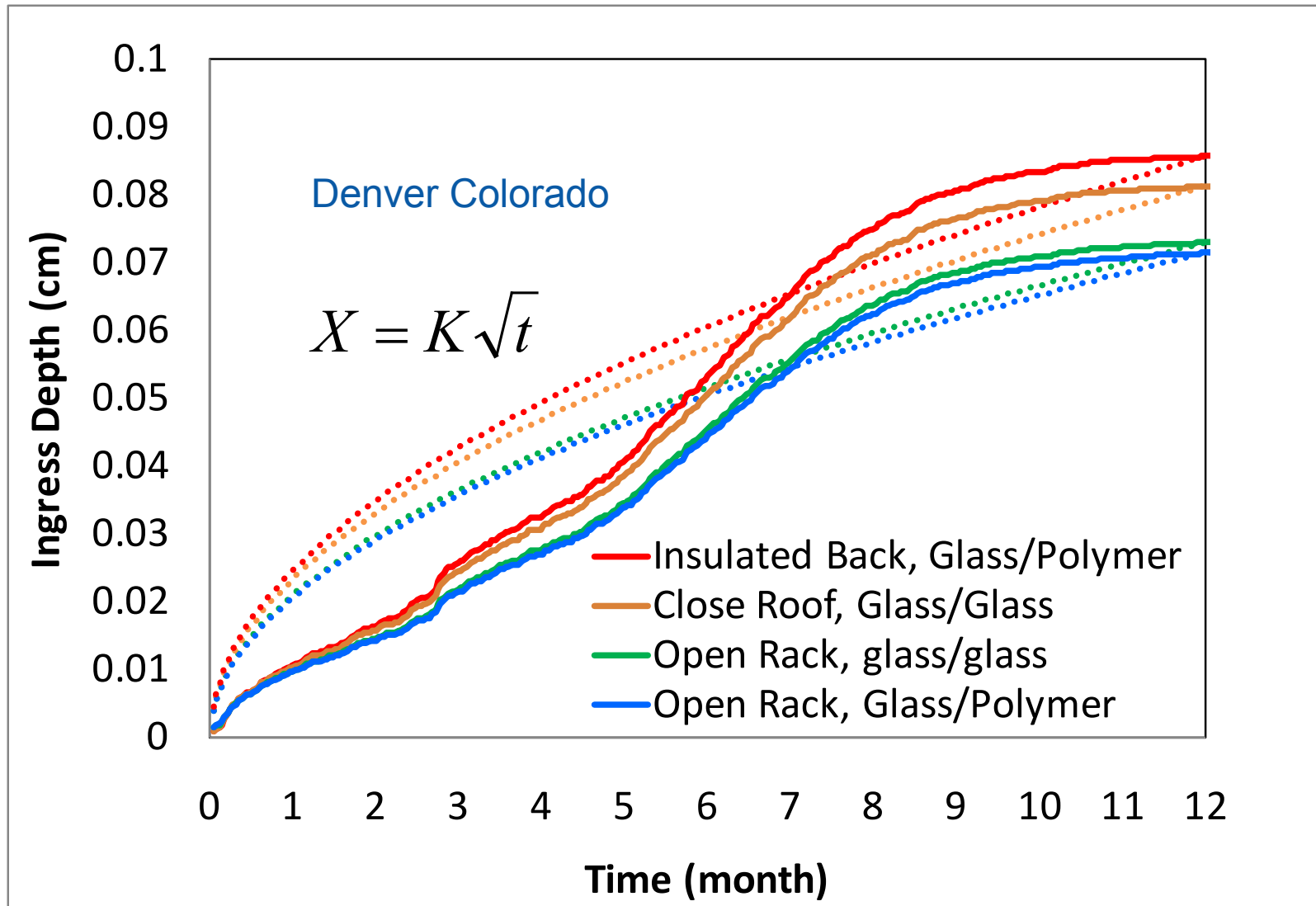
Conclusions

1. The amount of thermal degradation is dependent on both the geographic location and on the mounting configuration.
2. Qualification testing (1000 h 85°C/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

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

Ingress Estimated Using Finite Element Analysis



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

Absolute Humidity Correlates to Water Ingress

Factors Affecting Edge Seal Performance

