Understanding the Temperature and Humidity Environment Inside a PV Module

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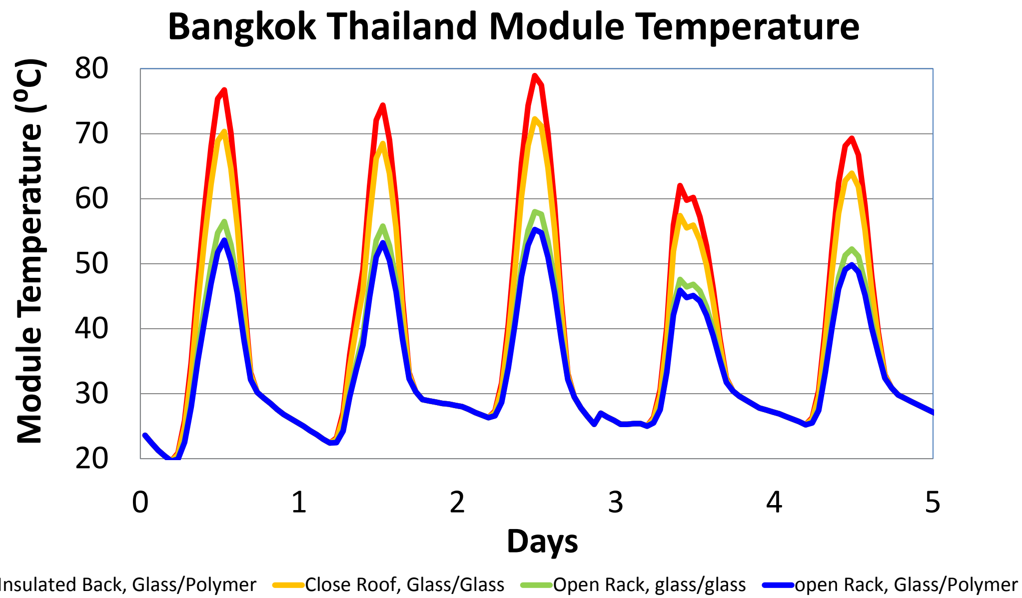
Introduction

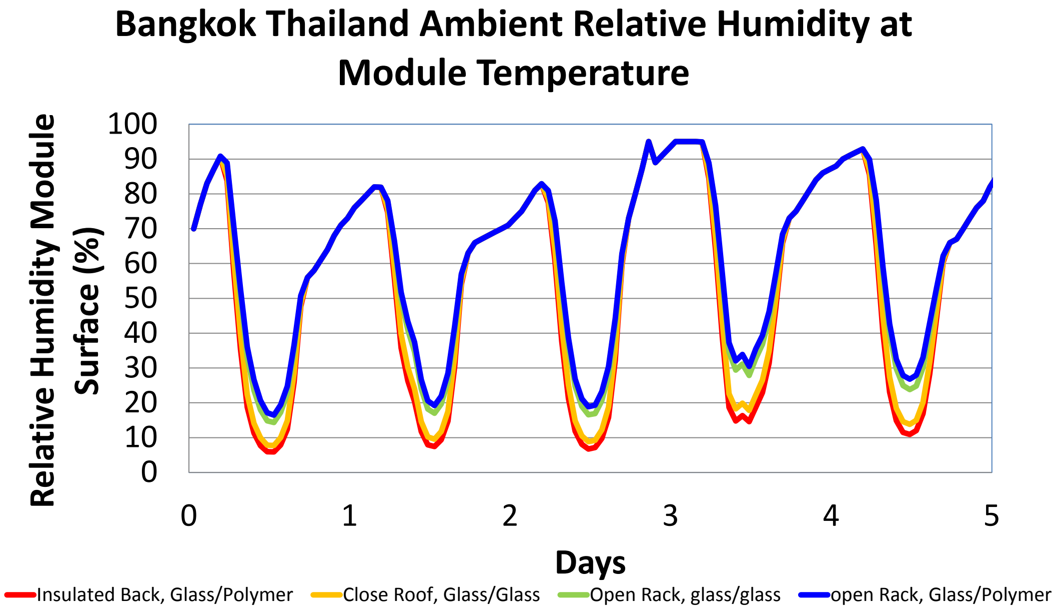
- Many degradation processes within a PV module are driven by moisture.
- The concentration of moisture in a module is a complex function of the use environment and the module construction.
- In accelerated stress testing one must know how water affects degradation to determine what temperature and humidity conditions to use.
- Here we show that by choosing humidity conditions that more closely match the use environment, one can minimize the uncertainty associated with moisture induced degradation modes.

Outline

- Describe moisture on the backside of a module.
- Look at the hydrolysis of a typical back-sheet made of PET as a case study for comparing 85 ^{o}C/85% RH to outdoor exposure.
- Examine the moisture and temperature environment on the front of a module as a worst case scenario.
- Show how good choices for RH testing will minimize uncertainty.

Representative Module Environment





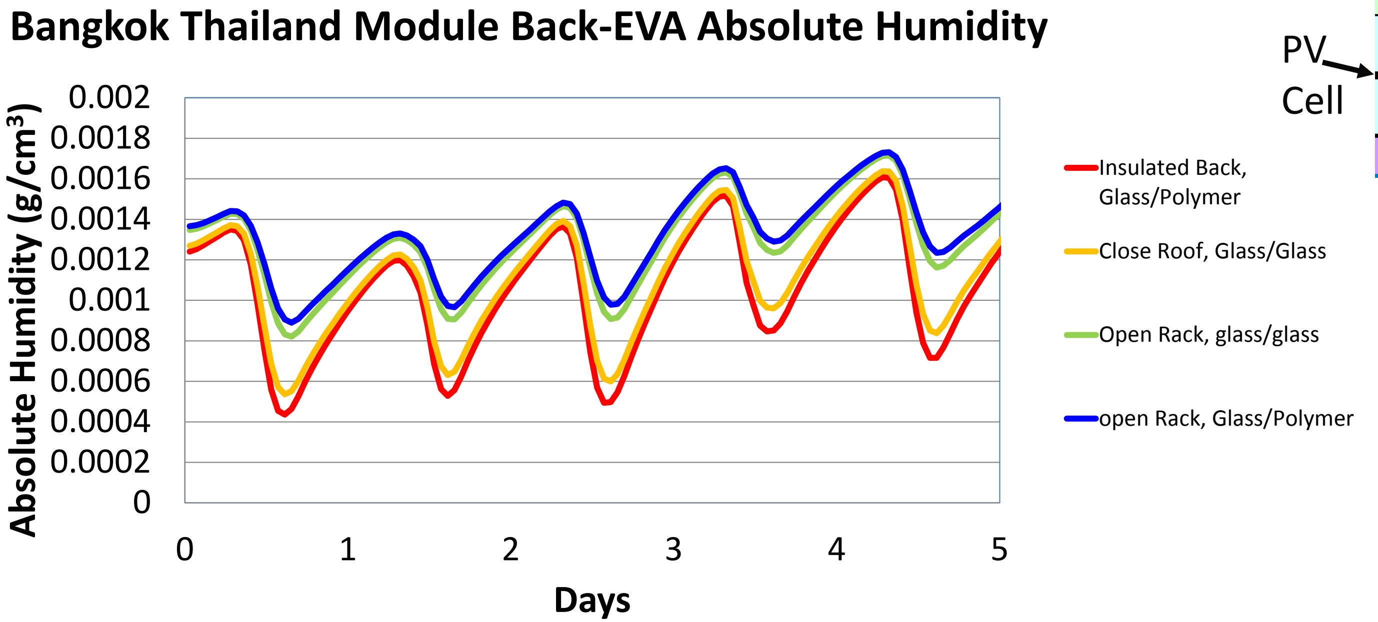
- **Use either IWEC or TMY-3 data for select environments.**
- **Use the model of King et al.* for module temperature.**
- **This produces *"representative"* data intended to generally duplicate a use environment**

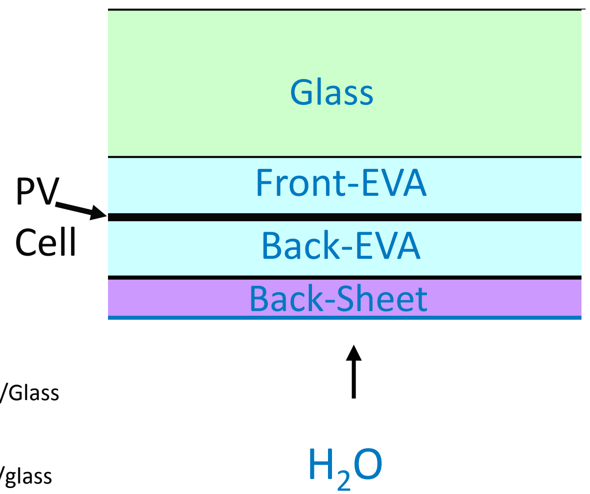
*D. L. King, W. E. Boyson, and J. A. Kratochvil, "Photovoltaic array performance model," SAND2004-3535, Sandia National Laboratories, Albuquerque, NM, 2004.

Moisture in the Back-EVA Layer

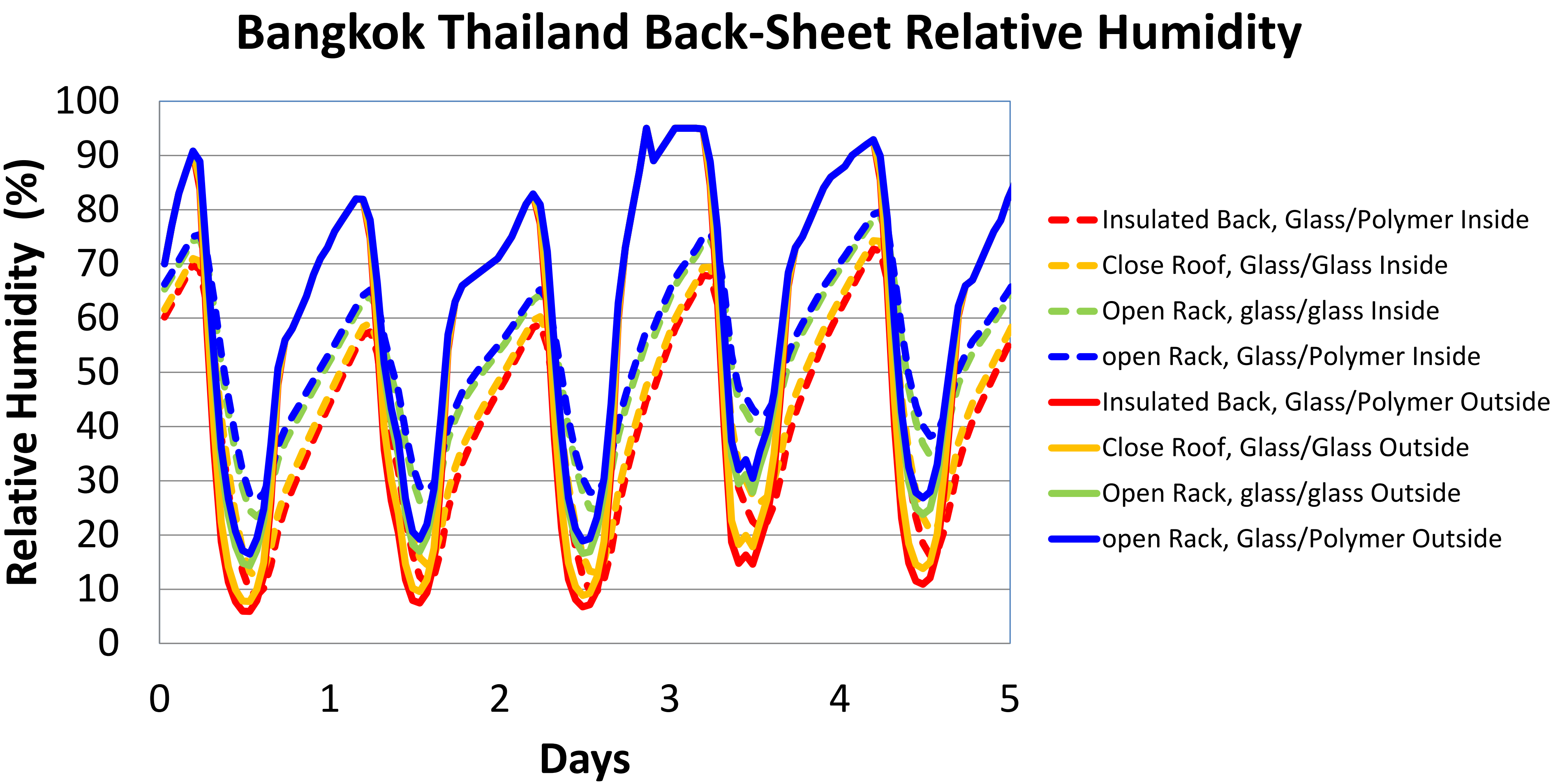
- **Assume diffusivity in EVA is much greater than in the back-sheet.**
- **Also assume transient moisture gradient in the back-sheet is unimportant.**

$$\frac{dC_E}{dt} = \frac{WVTR_{B,Sat}}{C_{E,Sat} l_E} \left(C_{E,Eq} - C_E \right)$$



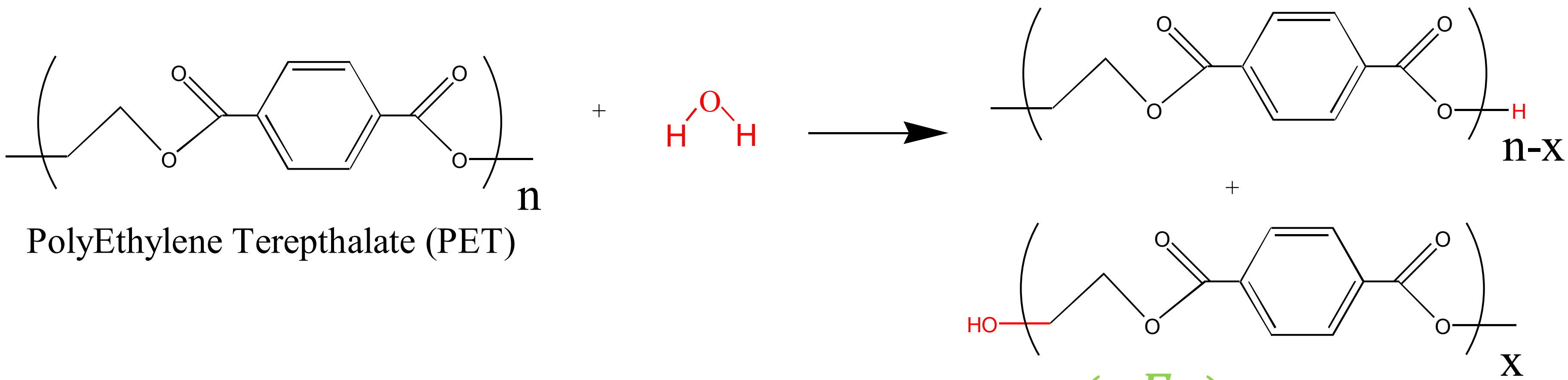


Back-Sheet Exposure



- **A PET based back-sheet will be exposed to humidity between that outside and inside the module.**

Pet Hydrolysis Kinetics



PolyEthylene Terepthalate (PET)

$$log\left(\frac{C}{C-x}\right) = A \cdot t \cdot RH^2 \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

Ea=129.4 kJ/mol (1.340 eV), *A*=$2.84 \cdot 10^{10}$ 1/day, *RH* expressed as a percentage.

*PET becomes brittle (1/3 initial tensile strength) and "failed" when log(C/C-x)=~0.0024, or about 0.55% hydrolysis of ester bonds.

**Pickett et. al saw the activation energy vary between 125 and 151 kJ/mol with an average of 136±13 kJ/mol for four different PET grades.

*W. McMahon, H. A. Birdsall, G. R. Johnson, and C. T. Camilli, "Degradation Studies of Polyethylene Terephthalate," Journal of Chemical & Engineering Data, vol. 4, pp. 57-79, 1959.
**J. E. Pickett and D. J. Coyle, "Hydrolysis Kinetics of Condensation Polymers Under Humidity Aging Conditions," Submitted to the Journal of Polymer Degradation and Stability, 2013.

PET Hydrolysis Results

$$\log\left(\frac{c}{c-x}\right) = A \cdot t \cdot RH^2 \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

	Years to 0.55% degradation (i.e. Hydrolysis Service Life) (y)		1000 Hours 85°C/85% RH Years equivalent (y)		Relative Humidity at 85°C so that 1000 h equals 25 years exposure (%)		Temperature at 85% RH so that 1000 h equals 25 years exposure (°C)	
	Open Rack	Insulated Back	Open Rack	Insulated Back	Open Rack	Insulated Back	Open Rack	Insulated Back
Denver, Colorado	13,000	4,900	6,500	2,400	5.3	8.7	45	49
Munich, Germany	11,000	4,400	5,100	2,100	6.0	9.2	47	50
Albuquerque, New Mexico	9,000	3,200	4,400	1,500	6.4	11	48	52
Riyadh, Saudi Arabia	8,200	3,000	4,000	1,500	6.7	11	48	52
Phoenix, Arizona	3,400	1,300	1,700	630	10	17	54	58
Miami, Florida	1,100	510	530	250	19	27	62	65
Bangkok, Thailand	700	310	320	150	24	34	66	69

PET is predicted to “fail” after 2064 h of 85 °C and 85% RH.

Site Specific Equivalent T and RH

$$R = A \cdot RH^n e^{\left(-\frac{Ea}{kT}\right)}$$

$$RH_{weighted\ average} = RH_{WA} = \left[\frac{\sum RH^n e^{\left(-\frac{Ea}{kT}\right)}}{\sum e^{\left(-\frac{Ea}{kT}\right)}}\right]^{\frac{1}{n}}$$

This tells you what the relative humidity is at the temperatures where the most damage is done.

These terms cancel out

$$(RH_{WA})^n e^{\left(-\frac{Ea}{kT_{eq}}\right)} = \frac{\sum RH^n e^{\left(-\frac{Ea}{kT}\right)}}{N} = \left\{\left[\frac{\sum RH^n e^{\left(-\frac{Ea}{kT}\right)}}{\sum e^{\left(-\frac{Ea}{kT}\right)}}\right]^{\frac{1}{n}}\right\}^n e^{\left(-\frac{Ea}{kT_{eq}}\right)}$$

$$\therefore\ \frac{\sum e^{\left(-\frac{Ea}{kT}\right)}}{N} = e^{\left(-\frac{Ea}{kT_{eq}}\right)} \quad \therefore\ T_{eq} = -\frac{K}{Ea} ln\left[\frac{\sum e^{\left(-\frac{Ea}{kT}\right)}}{N}\right]$$

The equivalent temperature (T_{eq}) gives the temperature at RH_{WA} for which constant conditions will produce a degradation rate equivalent to the yearly average.

PET Hydrolysis Equivalent T and RH

$$log\left(\frac{C}{C-x}\right) = A \cdot t \cdot RH^2 \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

	Years to 0.55% degradation (i.e. Hydrolysis Service Life) (y)		1000 Hours 85^{o}C/85% RH Years equivalent (y)		Teq for Ea=129.3 kJ/mol (^{o}C)		RH, at Teq for 2nd order Kinetics of PET (%)	
	Open Rack	Insulated Back	Open Rack	Insulated Back	Open Rack	Insulated Back	Open Rack	Insulated Back
Denver, Colorado	13,000	4,900	6,500	2,400	33	54	14	4.6
Munich, Germany	11,000	4,400	5,100	2,100	28	46	25	8.4
Albuquerque, New Mexico	9,000	3,200	4,400	1,500	37	58	13	4.2
Riyadh, Saudi Arabia	8,200	3,000	4,000	1,500	48	70	5.6	2.0
Phoenix, Arizona	3,400	1,300	1,700	630	46	68	9.8	3.3
Miami, Florida	1,100	510	530	250	37	54	36	14
Bangkok, Thailand	700	310	320	150	41	59	33	12

What Are Relevant Activation Energies

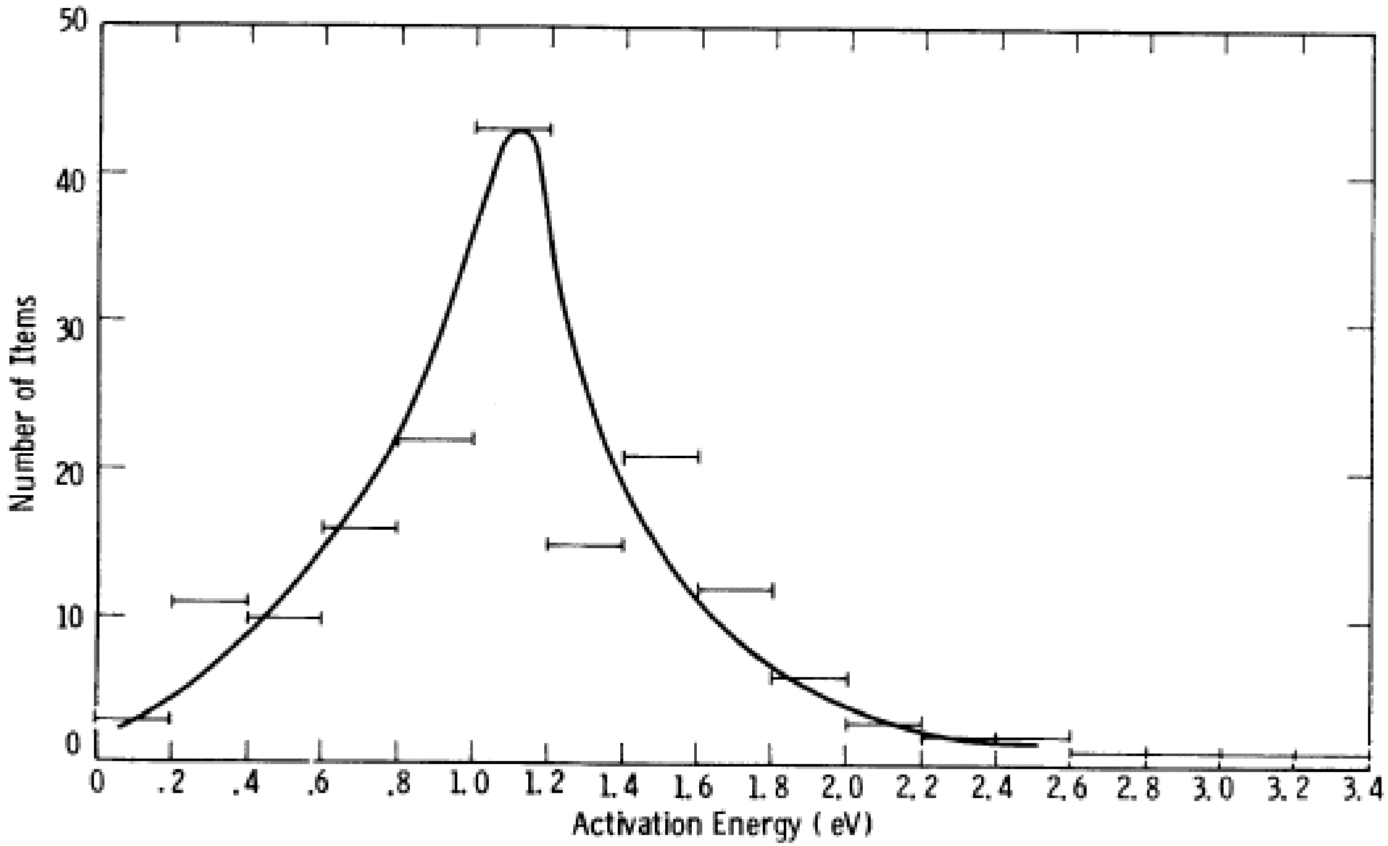


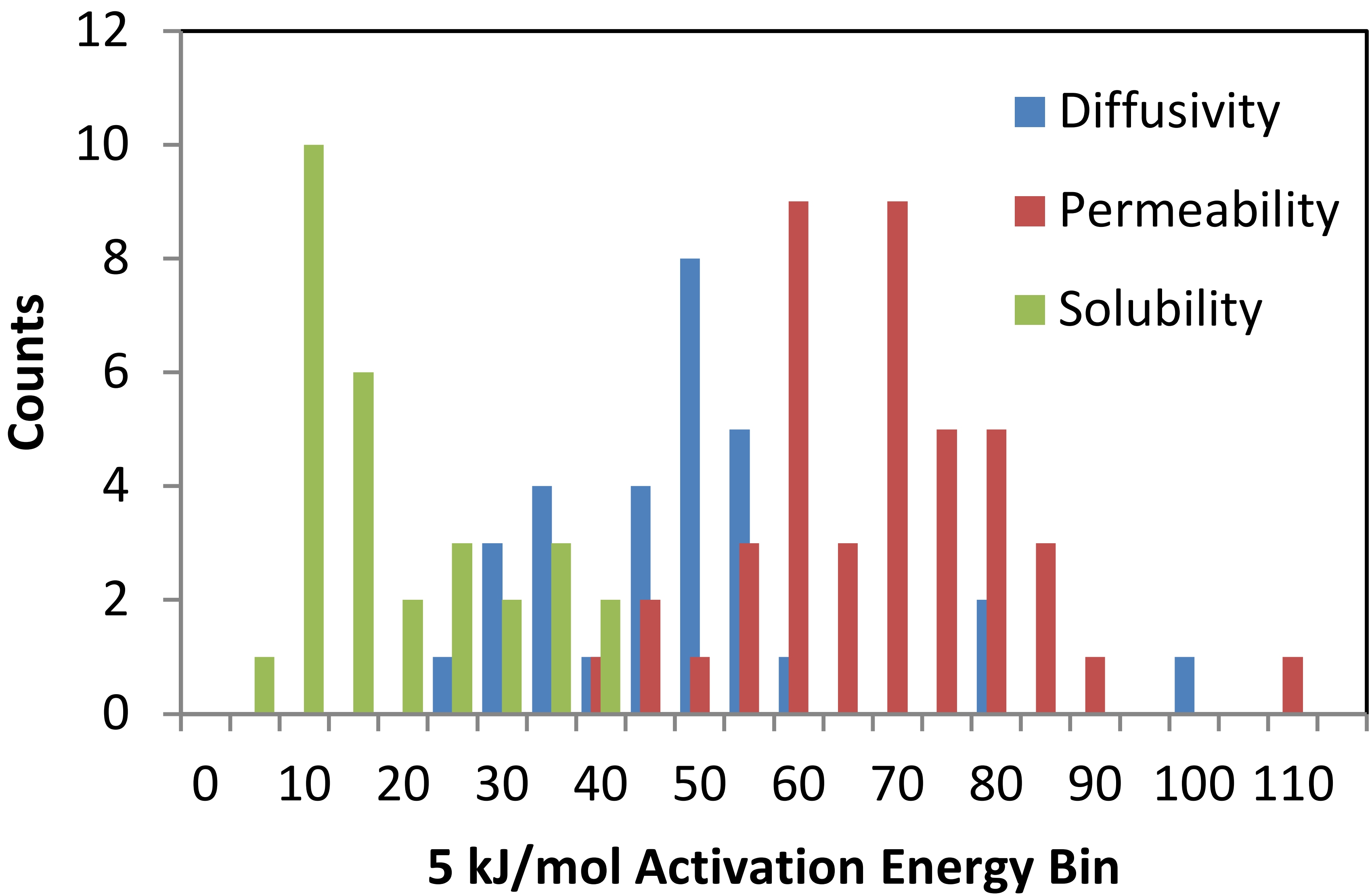
Fig. 3: Frequency distribution of activation energies of various components/materials (D. Cain - EPRI information)

Degradation activation energy from Dixon*. Based on RTI testing for properties such as:

Elongation at Break
Flexural strength
Tensile Strength
Shear Strength
Burst Strength
Weight Loss
Dielectric Strength
Imp. Strength

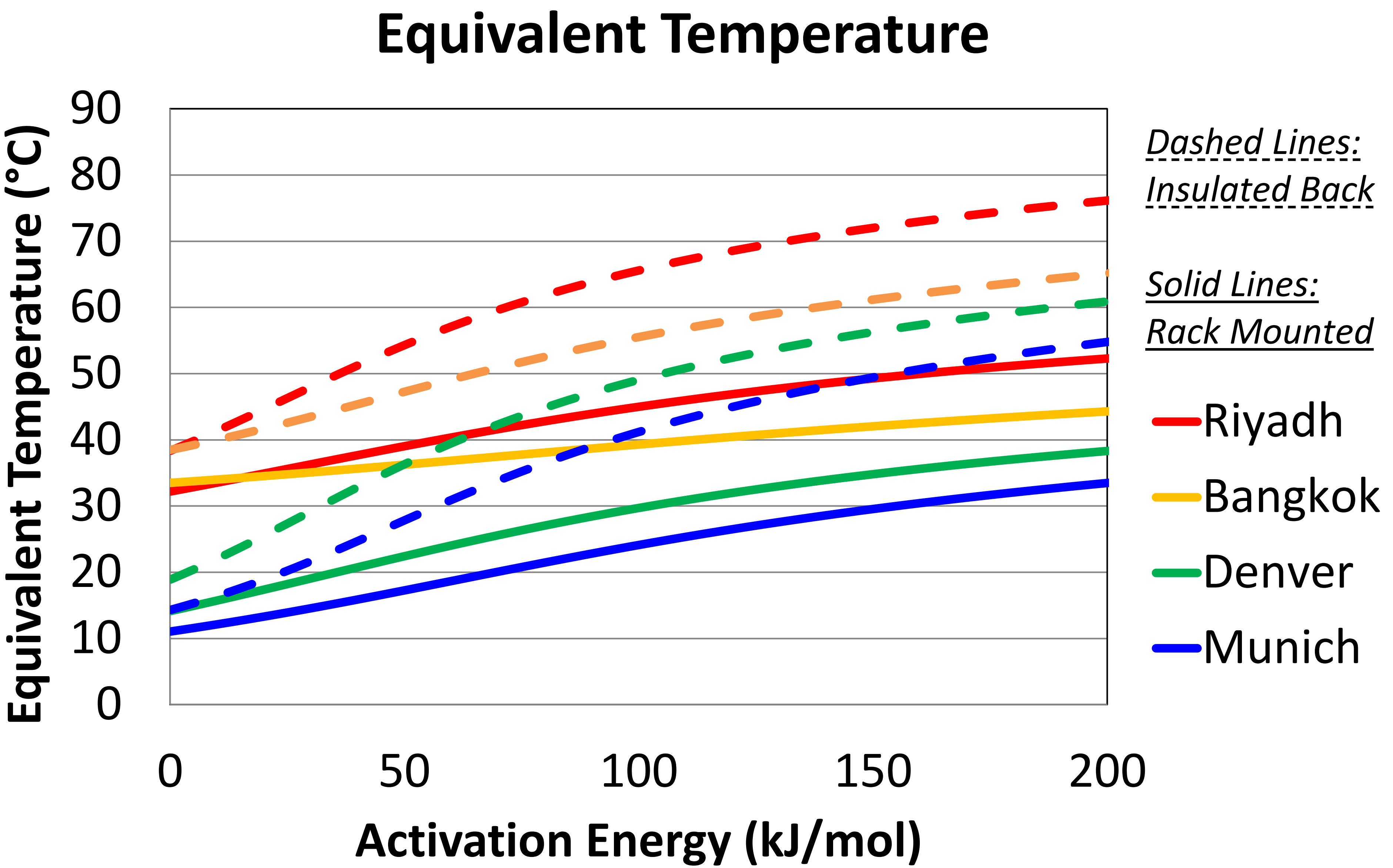
*R. R. Dixon, "Thermal Aging Predictions from an Arrhenus Plot with Only One Data Point," *Electrical Insulation, IEEE Transactions on,* vol. EI-15, pp. 331-334, 1980.

For Diffusion Controlled Processes

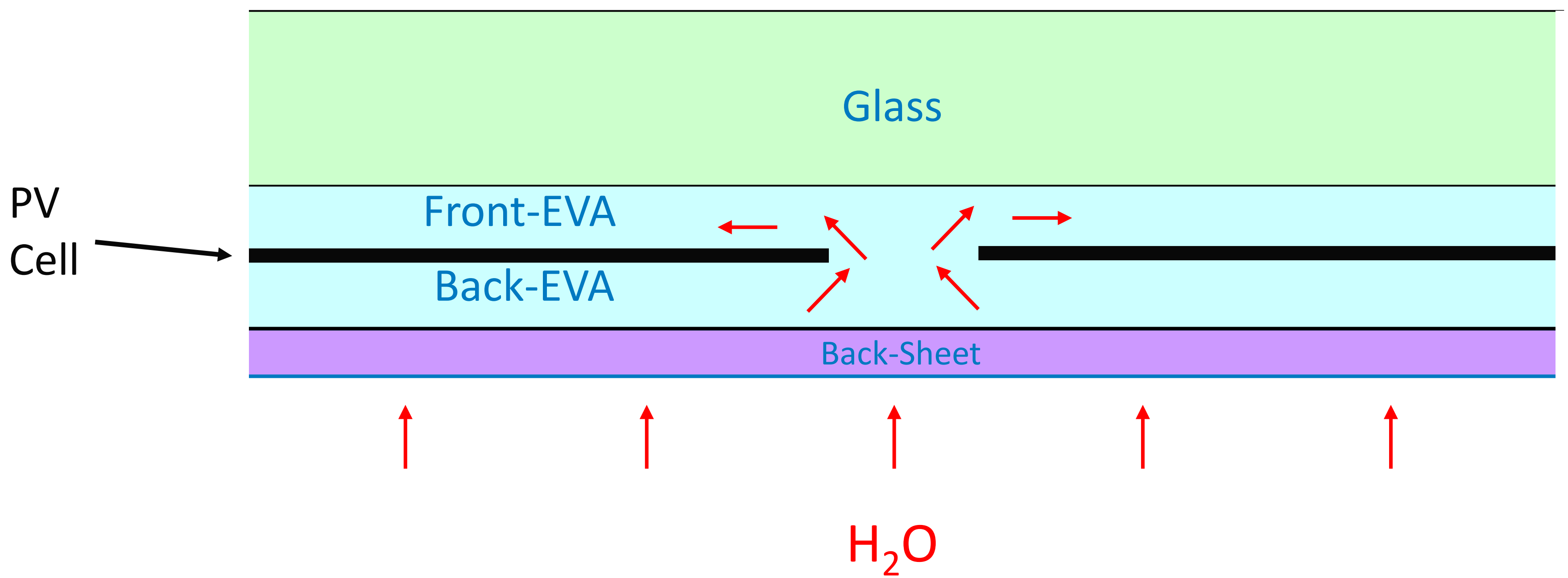


Histogram for moisture ingress activation energy for PV polymeric materials.

Thermal Stress by Location and Mounting



Modeling Moisture in the Front-EVA



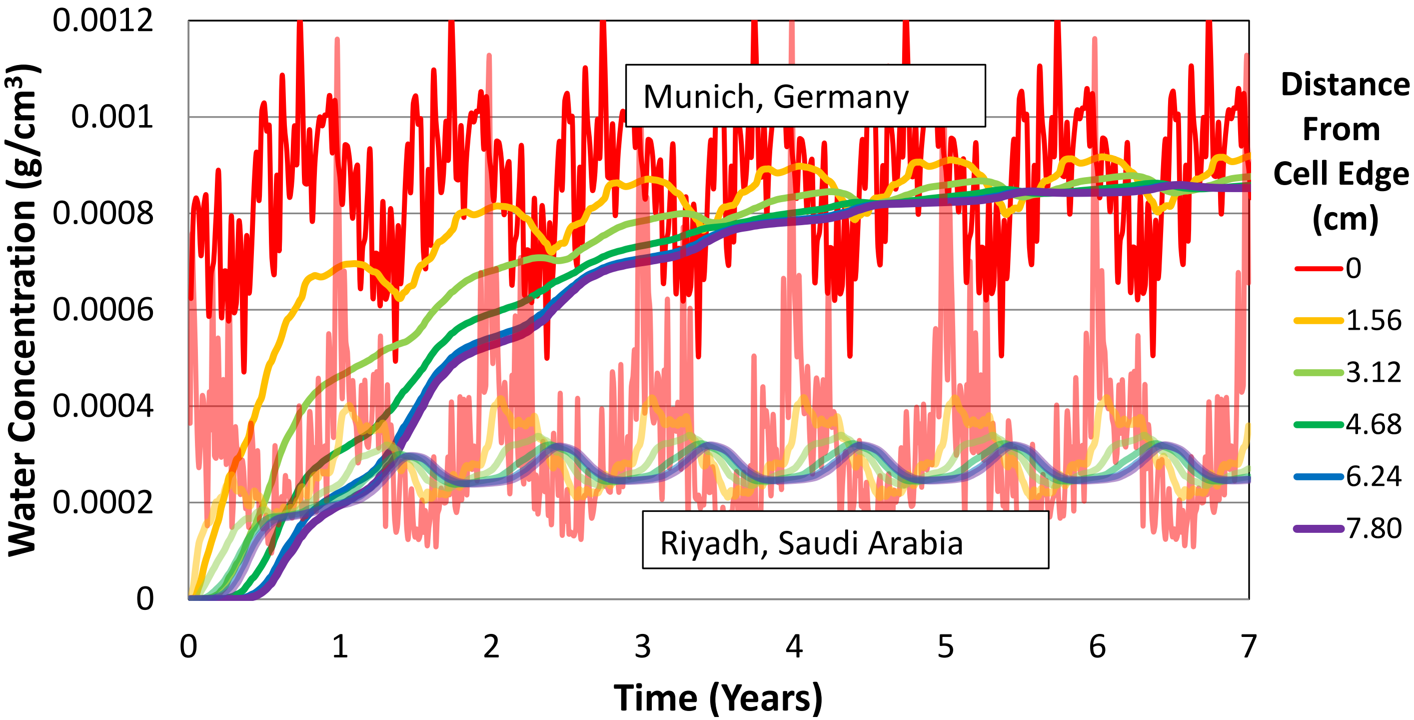
The Back-EVA equilibrates with a characteristic time of about a day.

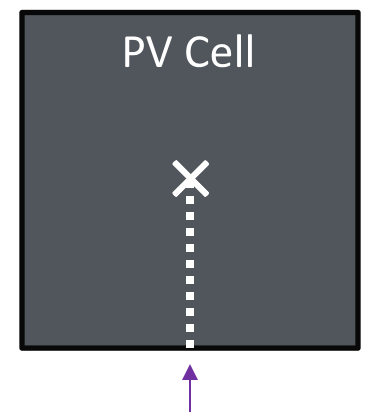
The Front-EVA equilibrates with halftimes of between a day and several years depending on the mounting configuration, location, and the position in front of the cell.

Uses the backside water concentration at the perimeter in a 2-D diffusion finite element algorithm. The cell size is 156+2 mm to account for water diffusing from the back to the front.

Front Encapsulant Water Content

Rack mounted, Glass/Polymer modules



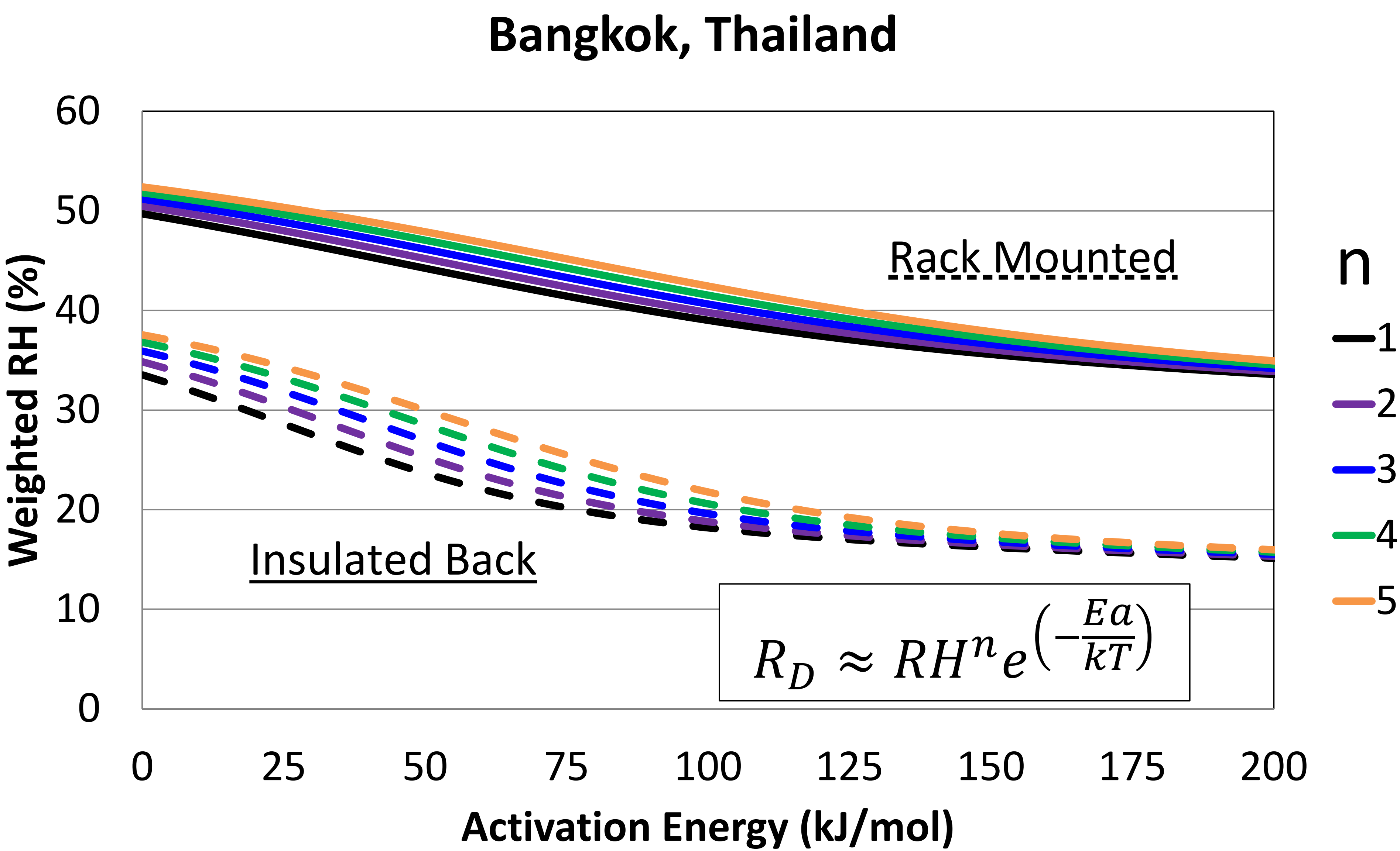


Profiles along this line are plotted.

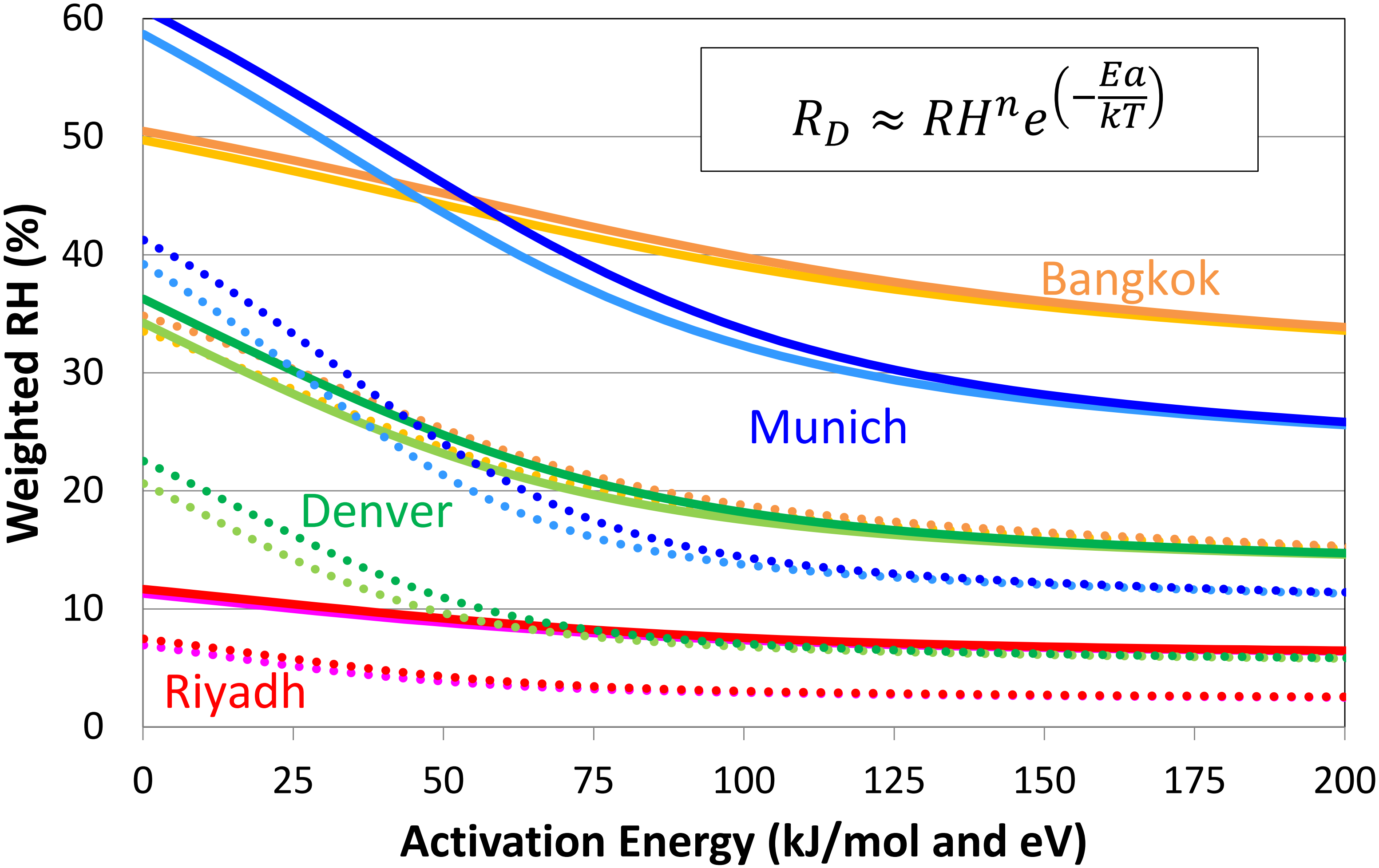
The front encapsulant traps in moisture seasonally making the center of the cell front the most hydrolytically damaging area.

The remainder of this presentation focuses on the center of the front side to evaluate the most stressful position in the module.

RH Not Very Dependent Kinetics or Ea



Small RH Dependence in All Climates



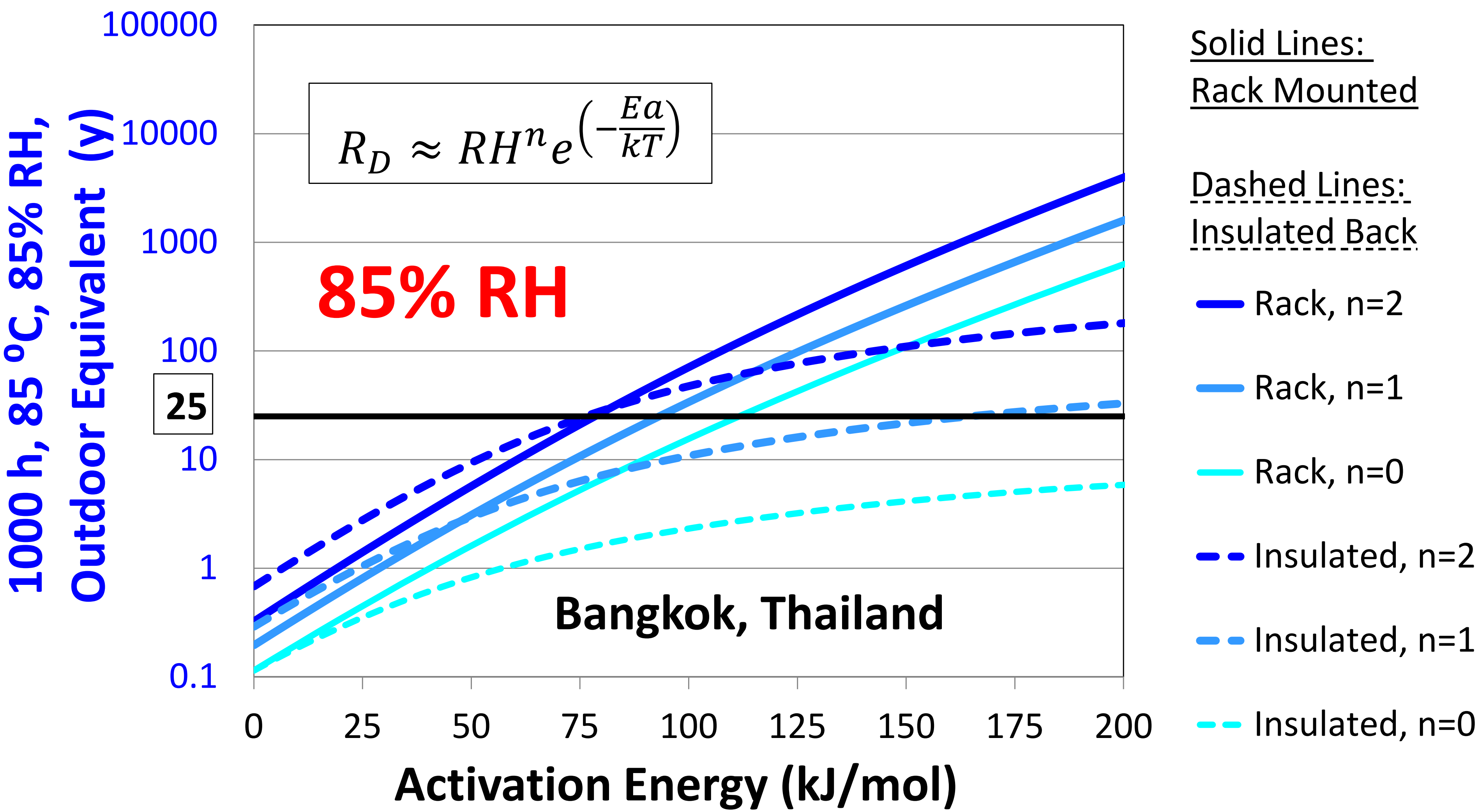
Solid Lines: Rack Mounted

Dashed Lines: Insulated Back

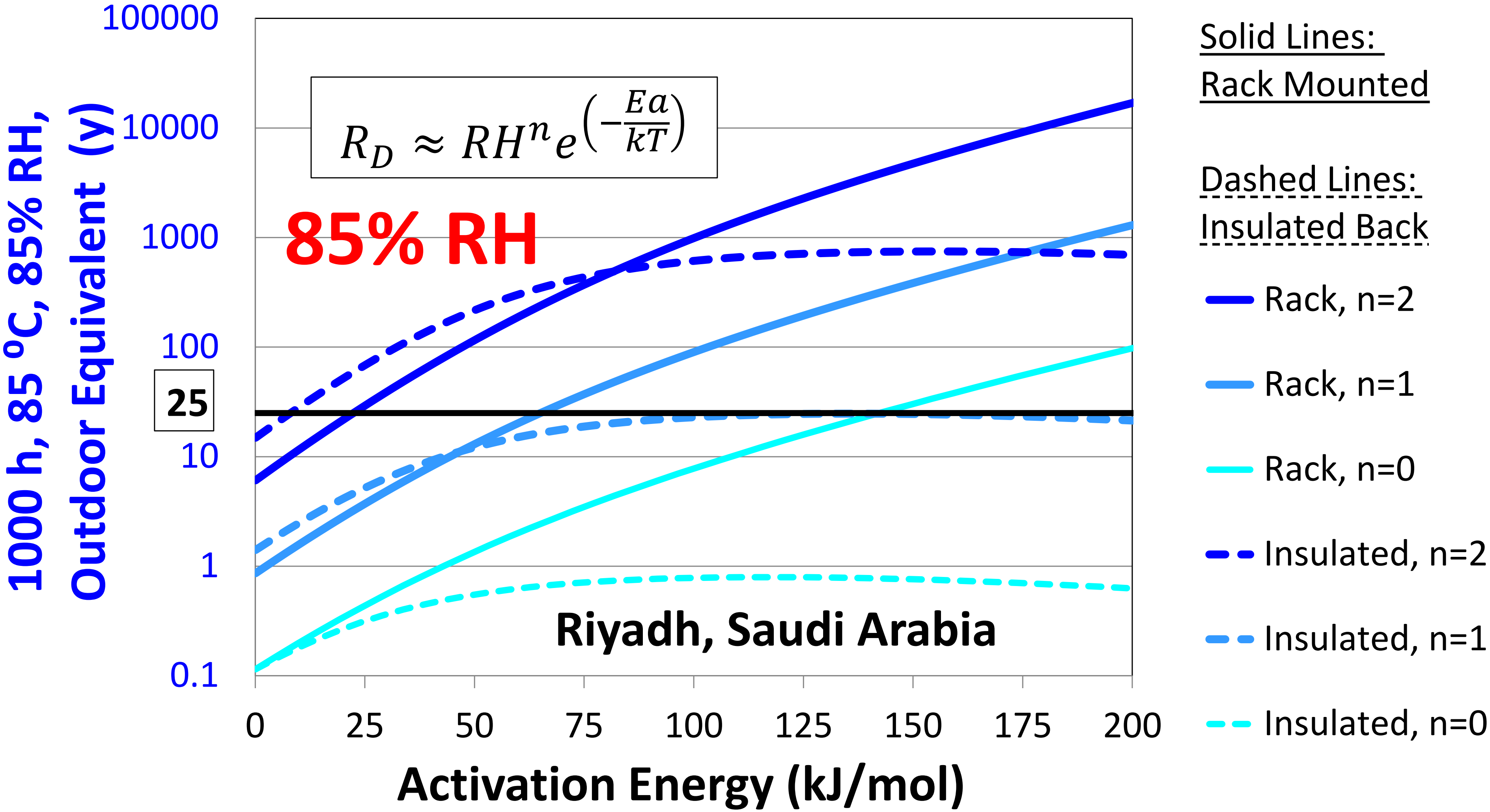
Darker Line: n=2

Lighter Line: n=1

85 ^{o}C/85% RH Equivalent Time-Bangkok

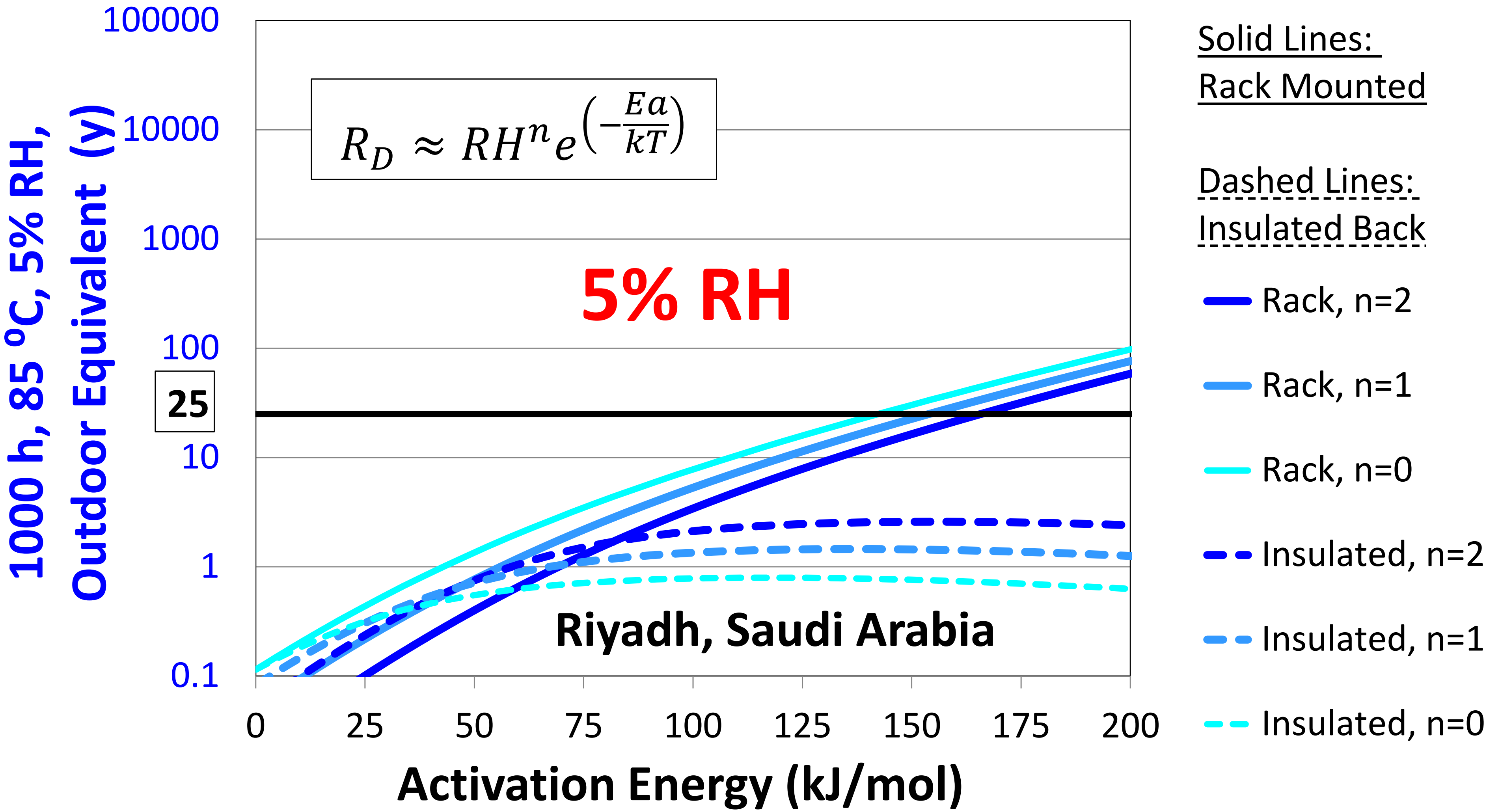


85 ^{o}C/85% RH Equivalent Time-Riyadh



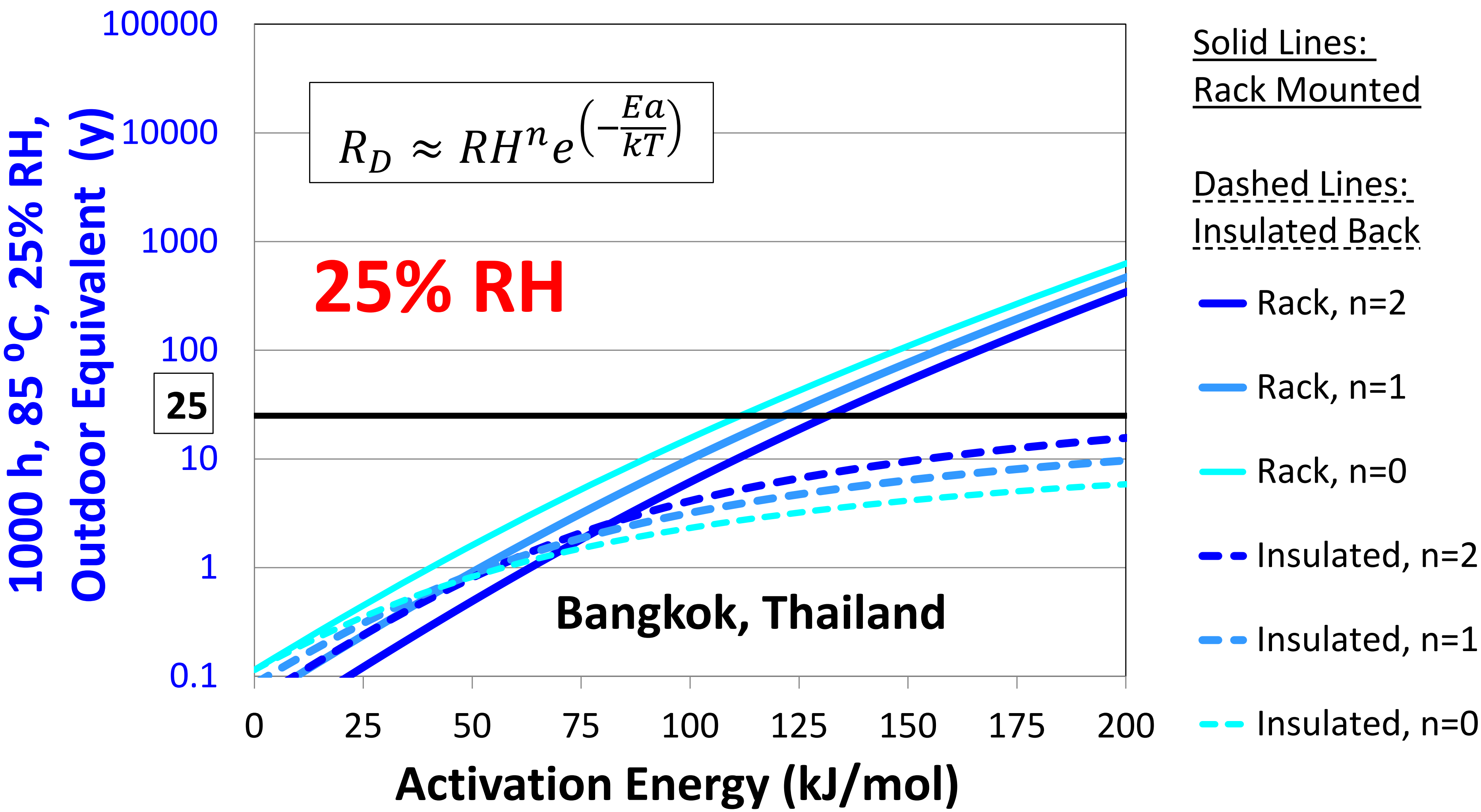
The unknown humidity dependence results in a 1000× uncertainty in the acceleration

Good RH Choice Reduces Uncertainty

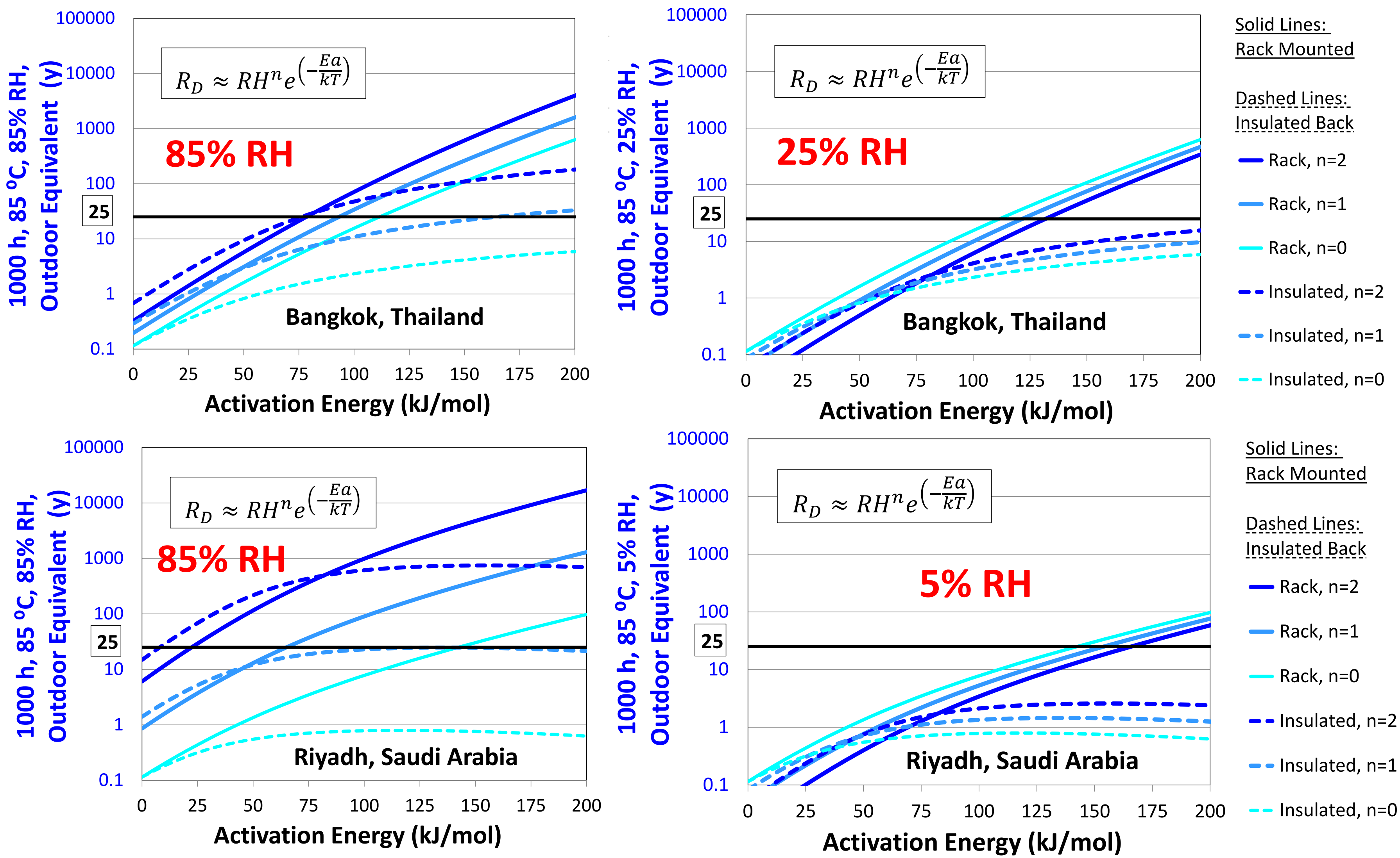


Testing using a chamber humidity of 5% vs. 85% significantly reduces the variability in the acceleration factor.

The Highest RH You Might Want is ~25%



Damp Heat vs. Low RH Stress Test



Without knowing the moisture induced degradation kinetics, it is better to use a low RH and accelerate processes principally by thermal acceleration.

Conclusions

- With respect to PET hydrolysis, 85 ^{o}C/85% RH, may be equivalent to hundreds or thousands of years.
- For thermal and/or moisture induced failure, the mounting configuration can be as important as the location.
- Care must be taken in accelerated stress testing to account for the variable relative acceleration of the different degradation modes.
- Choosing the right humidity level for accelerated stress testing can dramatically decrease the uncertainty in the results.

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