Life Prediction for CIGS Solar Modules

D.J. Coyle, H.A. Blaydes, R.S. Northey, J.E. Pickett, K.R. Nagarkar,

R.A. Zhao, and J.O. Gardner

GE Global Research

Niskayuna, NY, 12309

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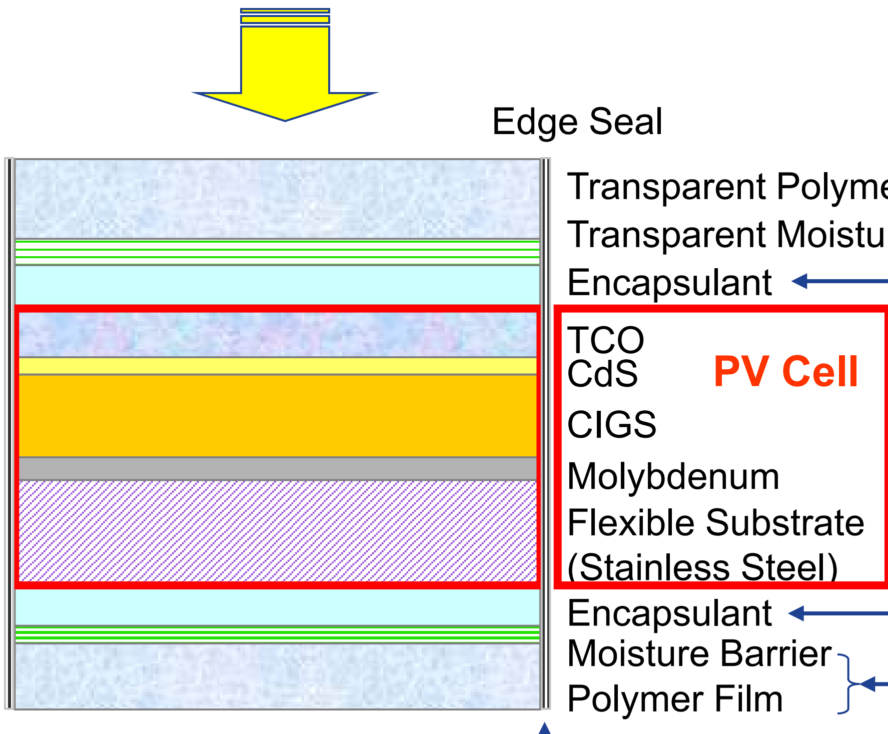
One can use accelerated testing data to predict real-world module failures only if the degradation mechanisms are known and their dependence on environmental factors measured. The moisture-induced degradation rate of flexible CIGS solar cells has been measured as a function of temperature and humidity and fit to a kinetic rate expression. This expression is coupled to a model of moisture diffusion into a package and typical meteorological input data to create a cumulative damage model to predict lifetime of packaged cells versus outdoor exposure and package construction. Estimated acceleration factors for damp heat (85C/85%RH) vs. Miami range from 15X to 50X, depending on the package, since diffusion through the package is accelerated differently than the cell degradation kinetics. The degradation rates are strongly dependent on the transparent conductive oxide used for the window layer and the electrically-conductive adhesive used for the contacts. The dependence of degradation on encapsulant materials is fundamentally different than is often assumed in the literature.

Prototype Flexible CIGS Module

Flexible Thin-Film PV Package



Top Sheet
- Transparent
- UV Stable, UV block
- Electrical insulation
- Mechanical (cut, hail)
- Moisture barrier

Encapsulant
- Low T_g compliant "glue"
- Transparent
- Adhesion

Backsheet
- Electrical insulation
- Mechanical (cut)
- Moisture barrier

Edge Seal
- Barrier
- Adhesion

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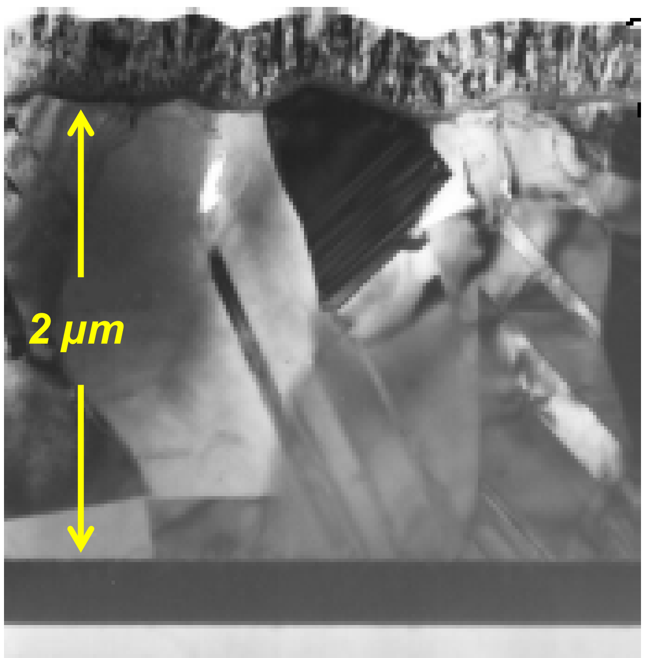
$Cu(InGa)Se_2$ Device Environmental Stability

Moisture-induced degradation



ZnO/ITO ← Increased Series Resistance Rs

CdS ← i-ZnO Buffer Layer

Decreased Shunt Resistance Rsh

$Cu(InGa)Se_2$ ← Increased Recombination

1. Quasi-neutral region
2. Depletion region

Mo ← Increased Series Resistance Rs

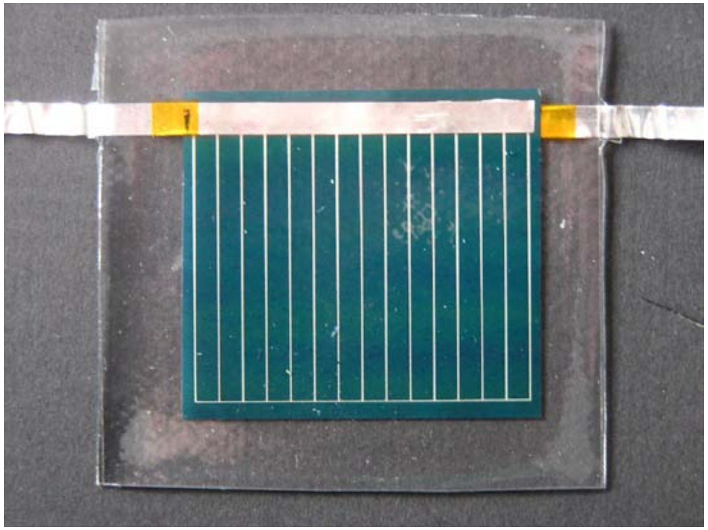
(W. Shafarman & L. Stolt, *Handbook of Photovoltaic Science and Engineering*, Ed. A. Luque & S. Hegedus, Wiley, 2003)

Test Cells:

1. Global Solar Test Cells (ITO)
2. AZO

GSE test cell

tabbed and encapsulated



~ 36 x 46 mm exposed

Stainless steel foil

Mo coating

ECA – Tabs/ribbons

Efficiency ~ 12 – 13.5%

V_{oc} ~ 600 - 610 mV

J_{sc} ~ 33-36 mA/cm^2

FF ~ 60 - 62%

A ~ 16.5 cm^2

Factors for prediction of lifetime (moisture degradation):

1. Cell construction
   - ITO vs AZO window layer
   - Type of ECA for interconnect
   - Other
2. Exposure
   - Accelerated testing (ovens with various temp, RH)
   - Real-world exposure (Miami, Phoenix, …)
3. Package
   - Barrier properties of topsheet and backsheet
   - Encapsulant
   - Edge seals
   - other

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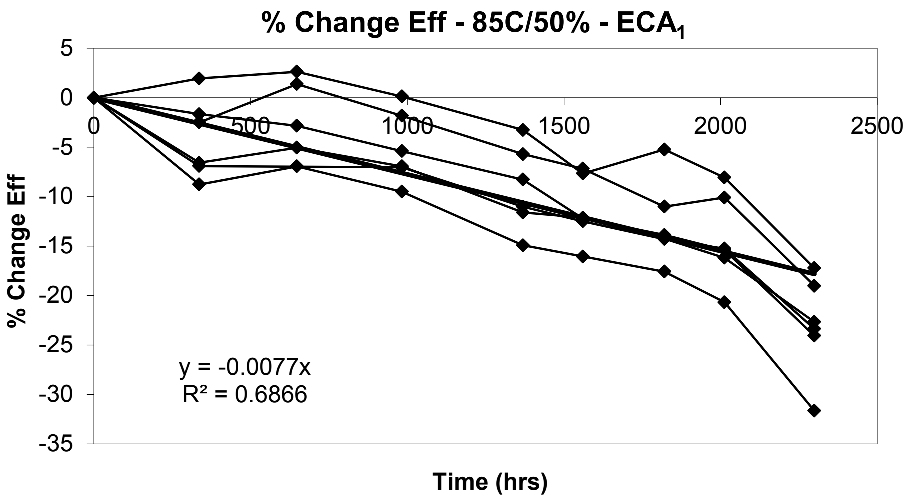
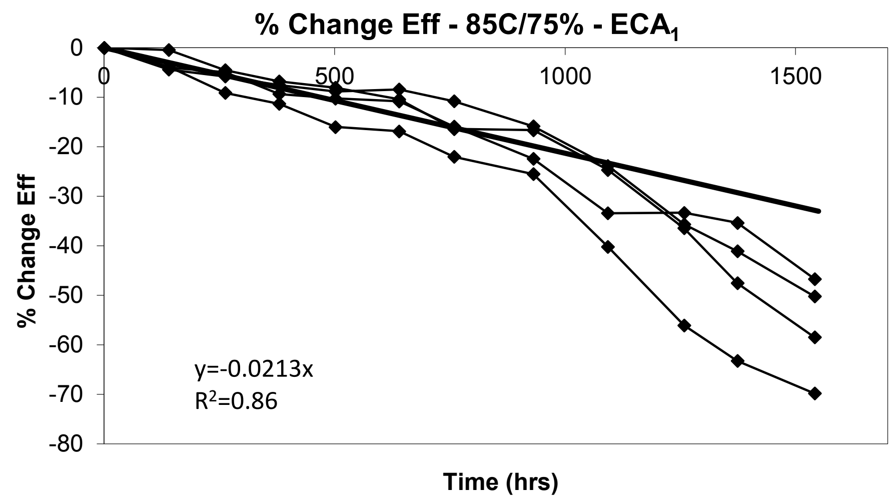
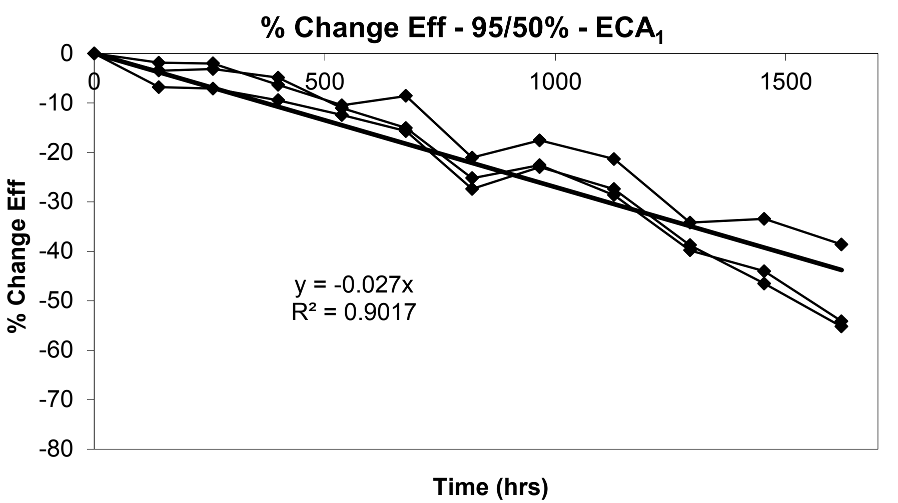
Life Model – Moisture Sensitivity

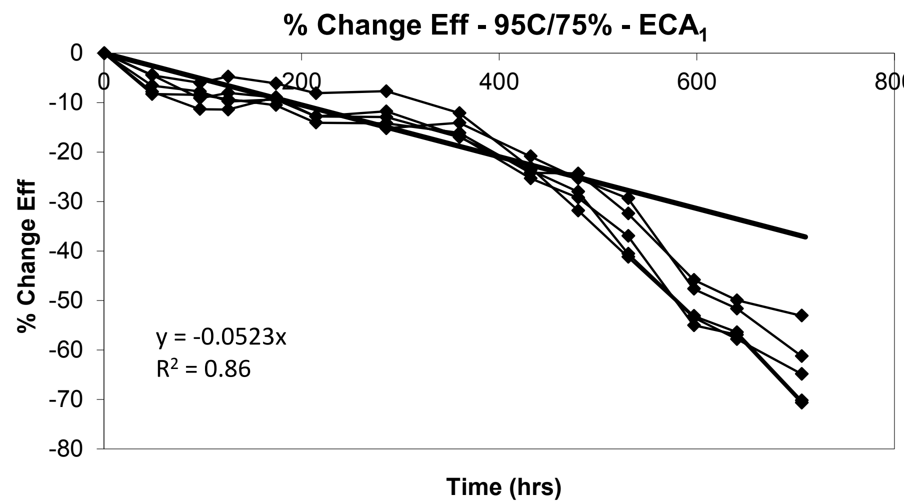
1. CIGS Degradation Kinetics - *Measure*
   - Degradation rate vs. Temp, humidity
   - ITO vs AZO
   - ECA - Interconnect degradation can play a role
2. Moisture Diffusion into Package - *Model*
   - Meteorological data – TMY3 from NSRDB
     - Hourly irradiance, air temp, ground temp, humidity, wind speed
   - Heat transfer model of module
     - Radiation, free & forced convection
   - Diffusion through barrier film, Saturation of encapsulant, no edge effects
3. Coupled Model - *Predict*
   - Cumulative degradation and average life vs. location and package design
   - Tradeoffs between CIGS sensitivity and package design/cost
   - Interpretation of accelerated tests results

Degradation Data - Examples



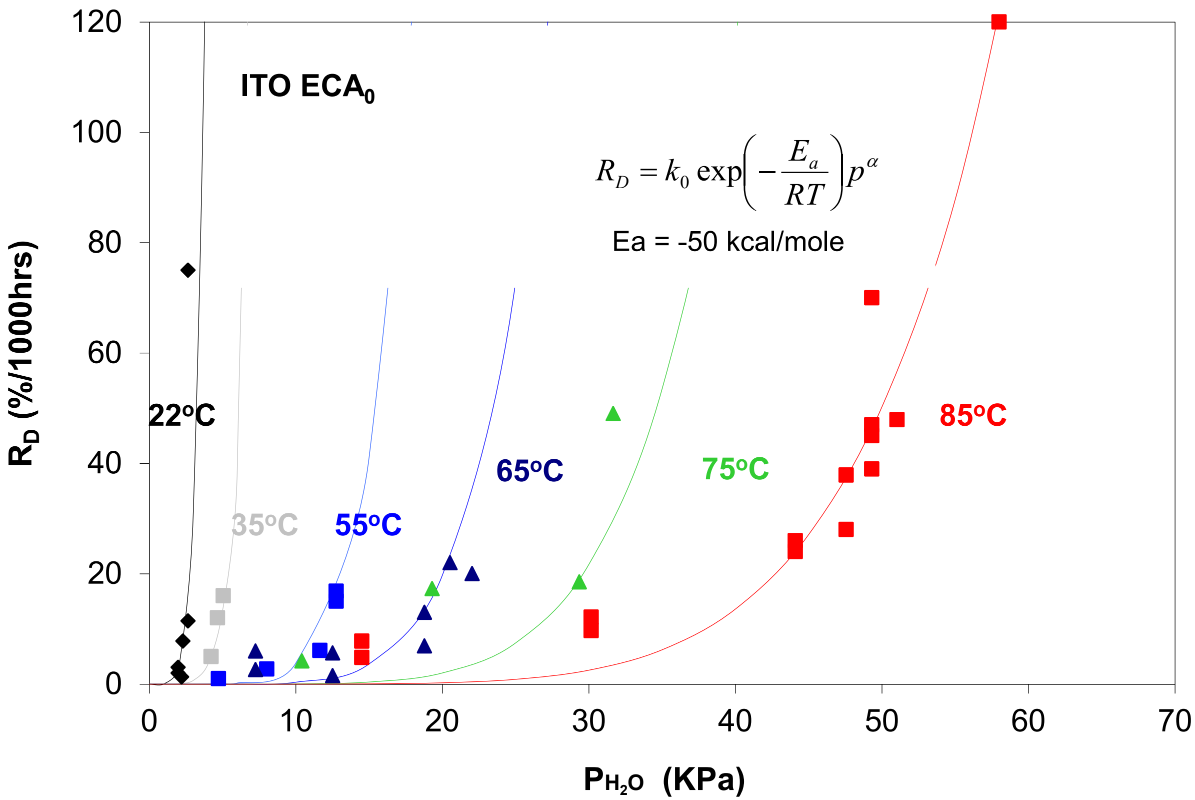






- High temperature, humidity faster
- Driven by FF loss due to R_{oc} and some shunting

Scaling with partial pressure water



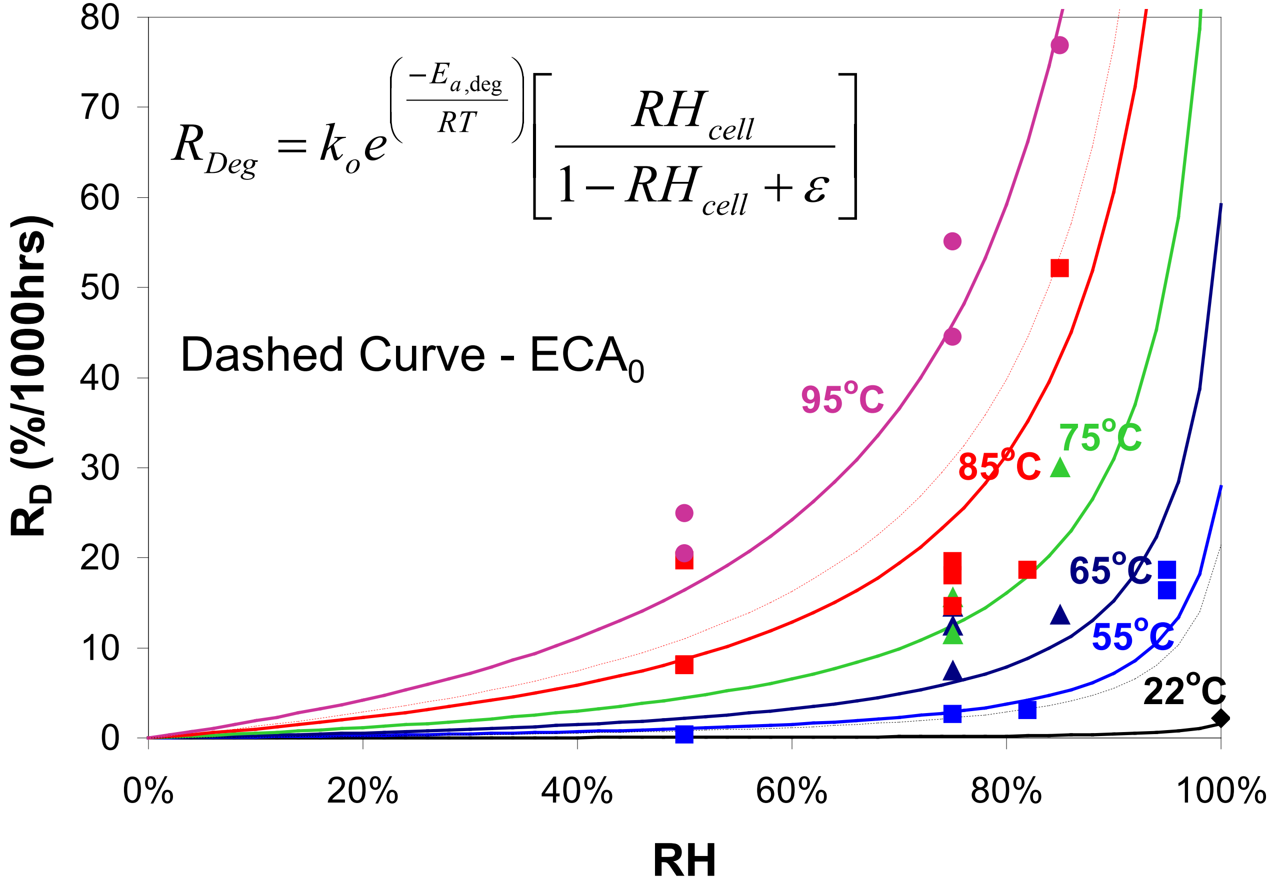
Negative activation energy!

Need to scale with % saturation (RH)

Interfacial equilibrium (Henry's Law) $$\frac{C_a}{S_a} = \frac{C_b}{S_b} = RH$$

CIGS Degradation Kinetics (Global Solar test cells)

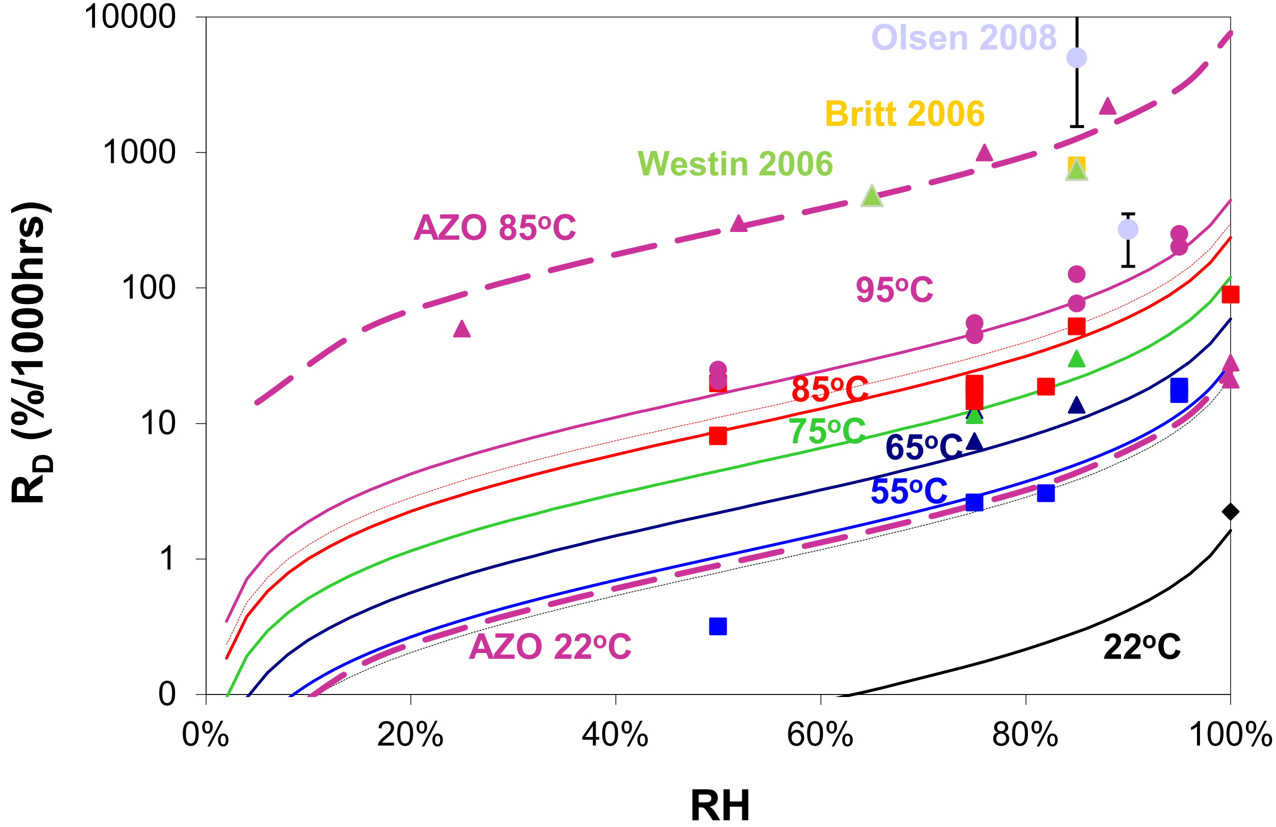
- For every Temp & RH, fit data to linear degradation rate (1st 20% of degradation)
- Fit rate of degradation vs Temp, RH to kinetic model



- Strong RH dependence at high RH
- ECA affects temperature dependence

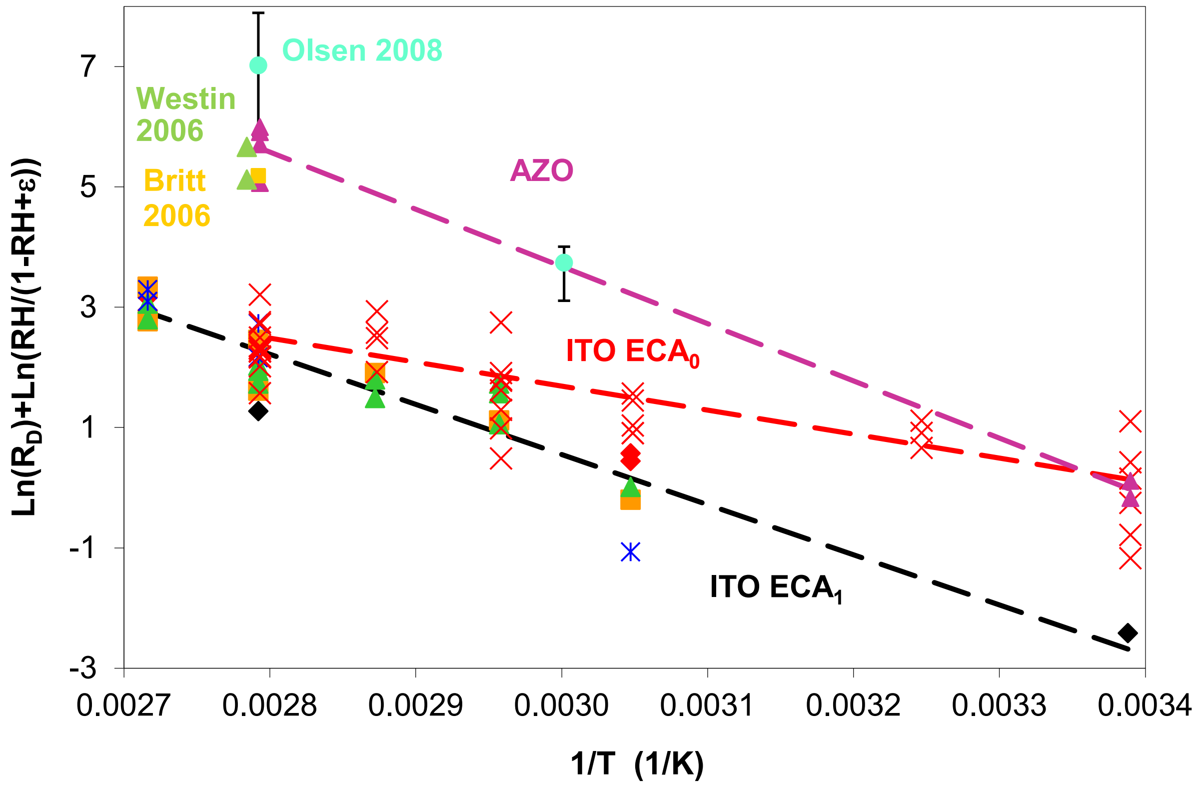
(Klinger, D. J., *"Humidity acceleration factor for plastic packaged electronic devices"*, Quality and Reliability Engineering International. Vol. 7, 965-3711, 1991).

CIGS Degradation - AZO vs ITO



- AZO ~ 25X ITO
- Comparable to published data

Arrhenius Plot



- ECA$_0$ very low activation energy

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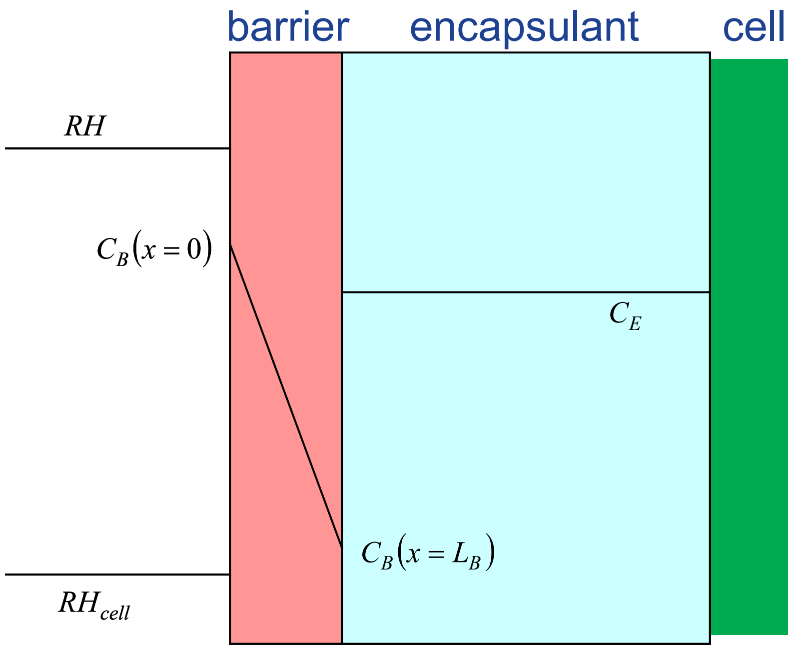
Package Diffusion Model



Mass Balance, Interfacial Equilibrium, Fickian Diffusion, $D_{barrier} << D_{encapsulant}$

$$\frac{\partial C_E}{\partial t} = \frac{S_E RH - C_E}{t_c}$$

$$t_c = \frac{L_E S_E}{WVTR_{\max}}$$

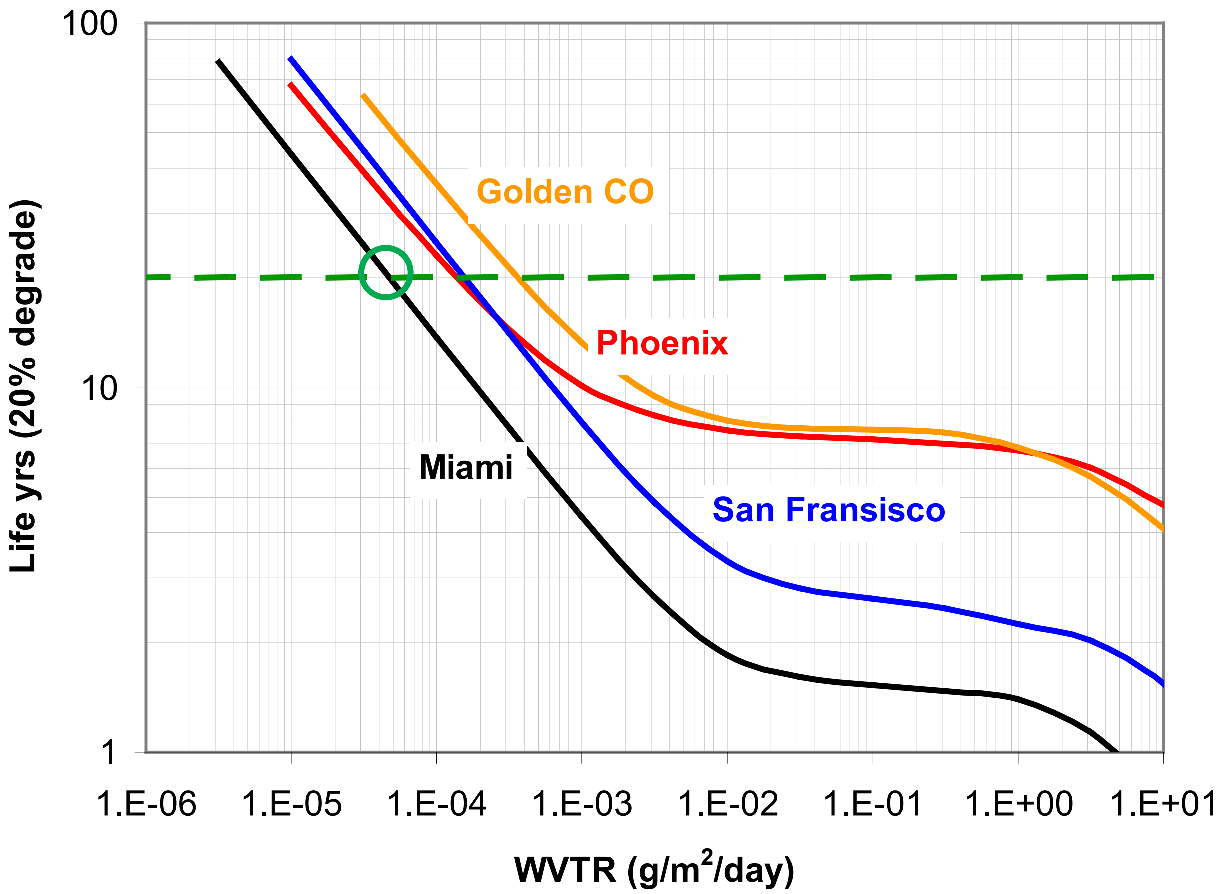
If initially dry:

$$\frac{C_E}{S_E} = RH\left[1 - e^{\left(-t/t_c\right)}\right]$$

Integrate moisture ingress with hourly weather data (TMY3)

(Kempe, M.D., *"Modeling of rates of moisture ingress into photovoltaic modules,"* Solar Energy Materials & Solar Cells, Vol 90 (2006) pp. 2720–2738).

Life vs. Barrier: ITO-ECA_0



Need ~ $4x10^{-5}$ $g/m^2/day$ package ~ 20 yr life

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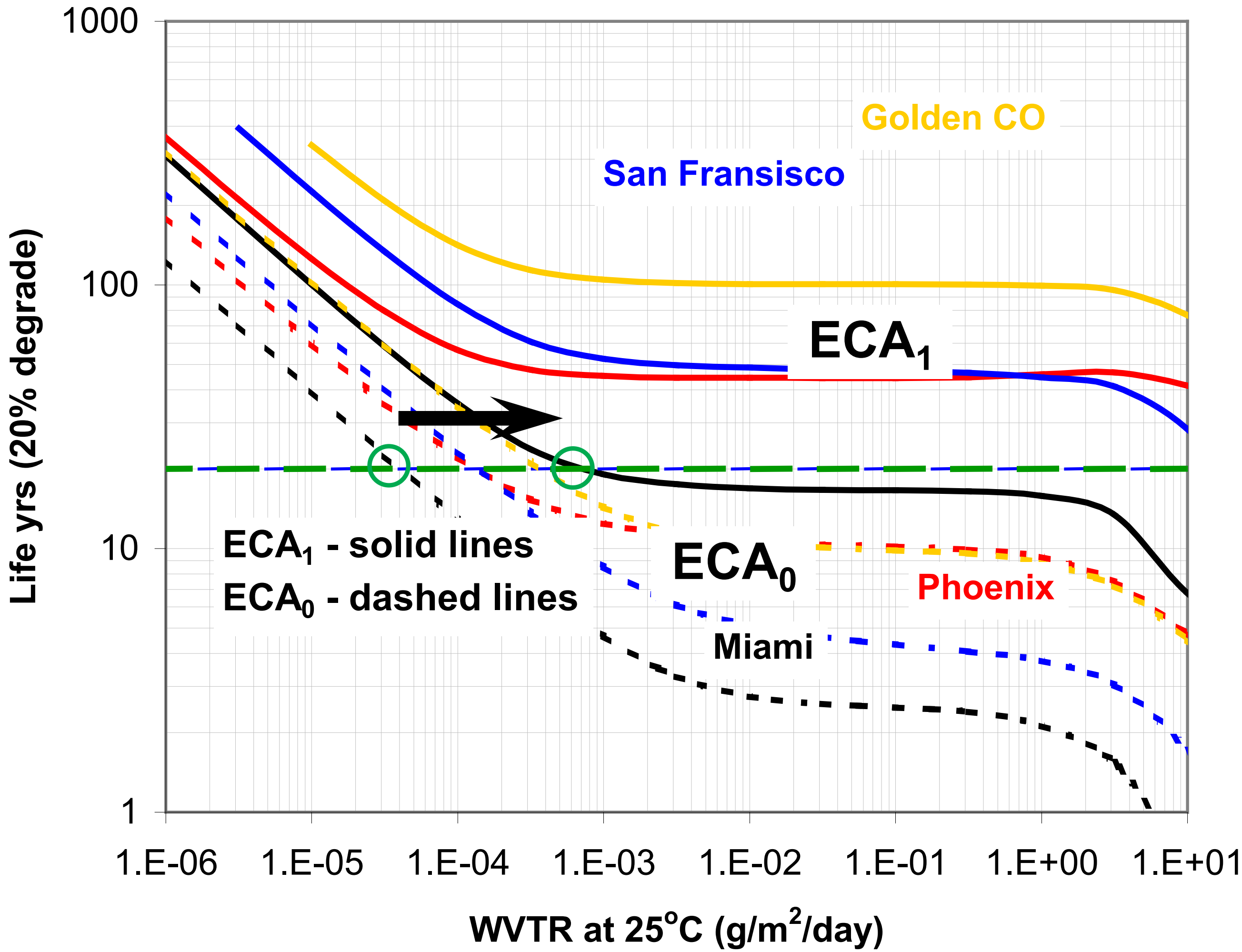
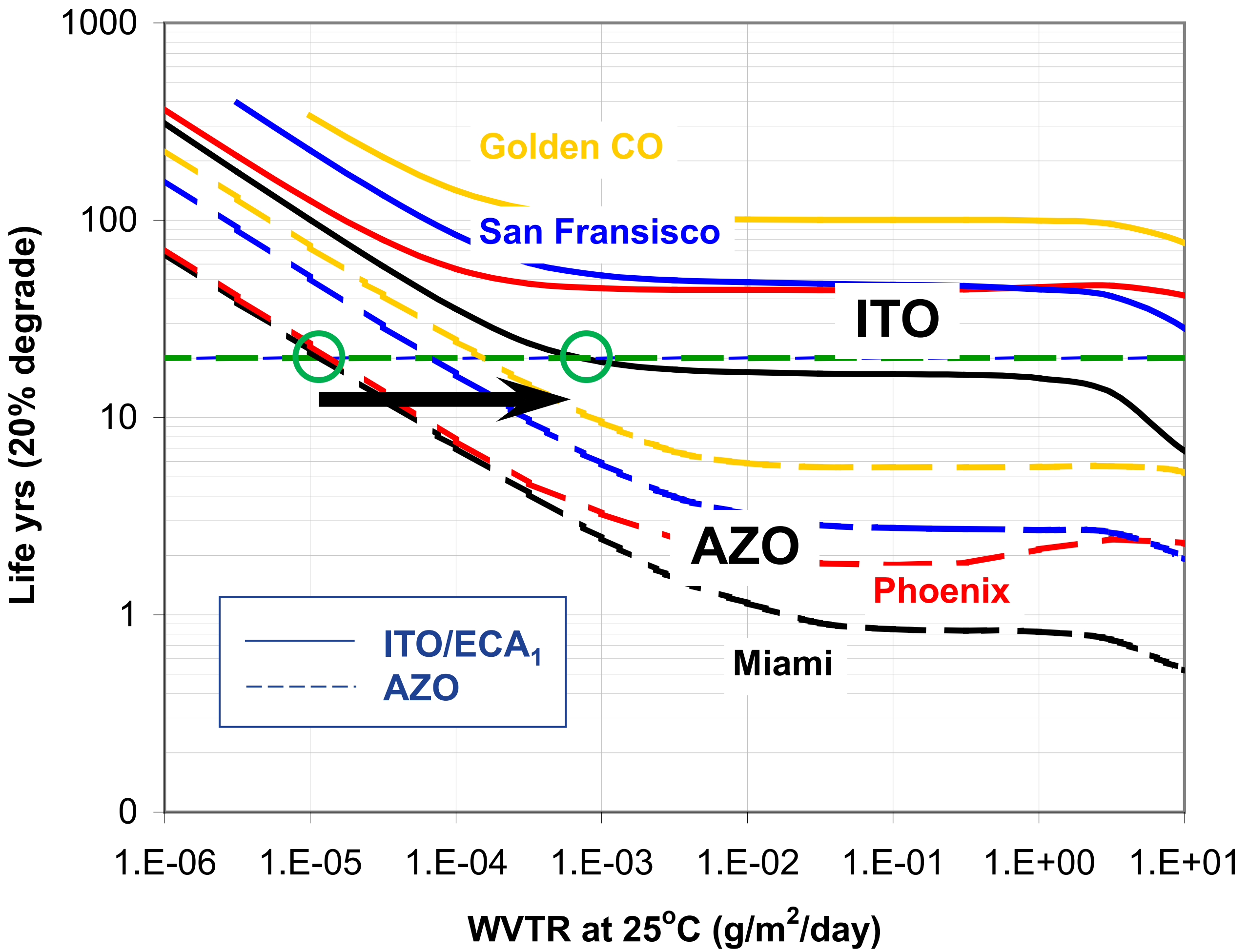
Life vs. Barrier: ITO-ECA_1



Need ~ $8x10^{-3}$ $g/m^2/day$ package ~ 20 yr life

Life vs Barrier – ITO vs AZO



ITO Life 5-25x AZO Life

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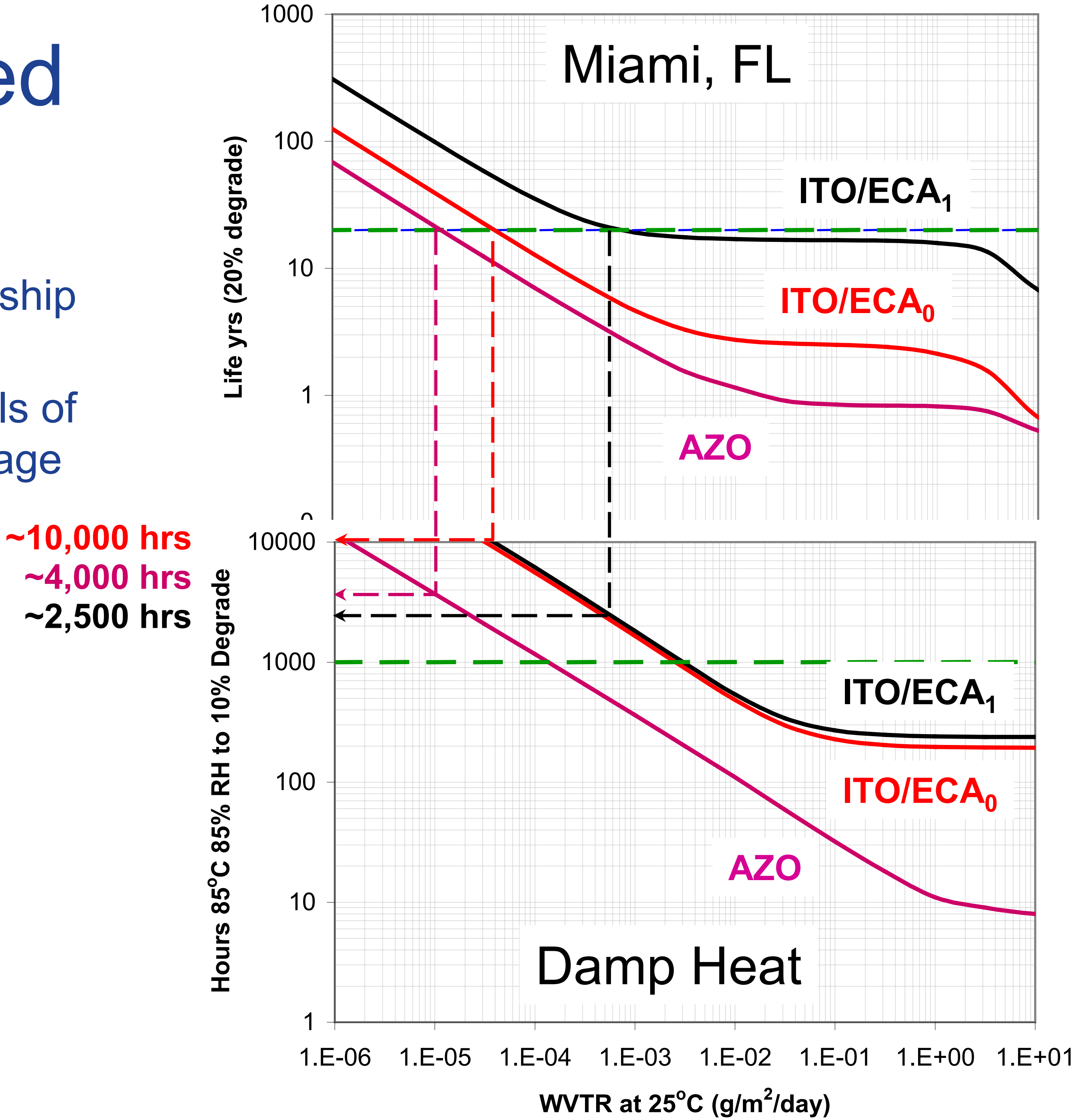
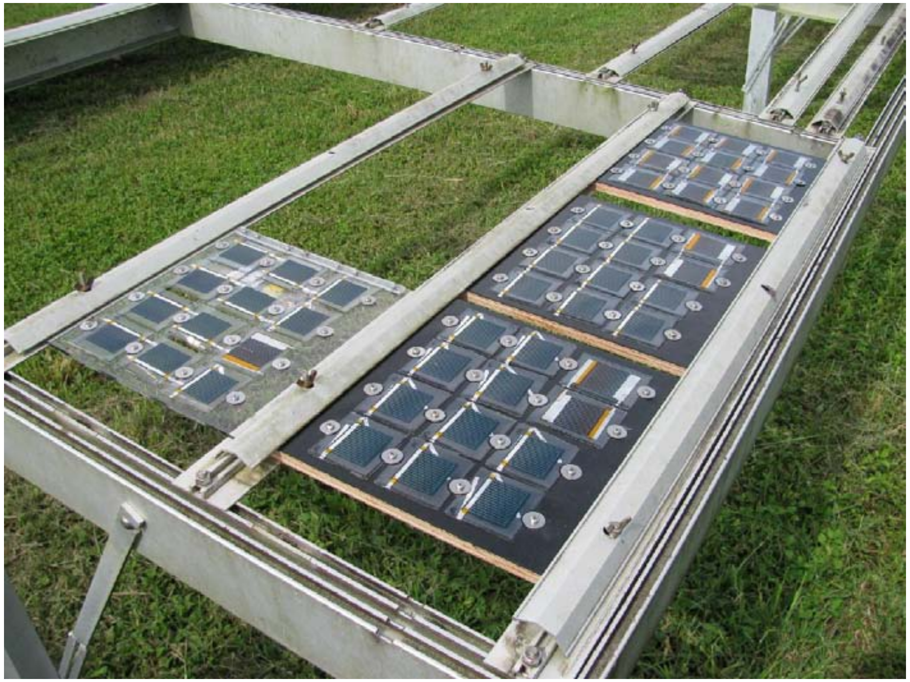
Accelerated Testing

- Nonlinear relationship
- No simple scaling
- Depends on details of kinetics and package



FL, AZ Testing

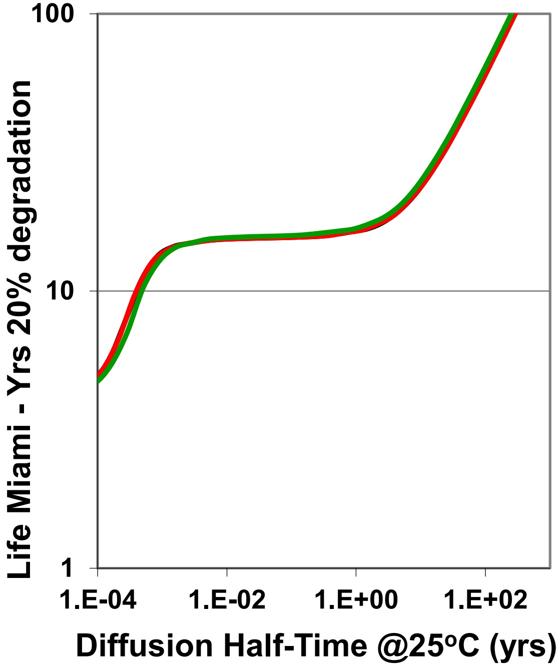
	Calc P_{max} change	Measured P_{max} change
Phoenix ECA_1	-0.1%	-1% +-2%
Miami ECA_1	-0.5%	-1% +-2%
Miami ECA_0	-4.1%	-5% +-2%

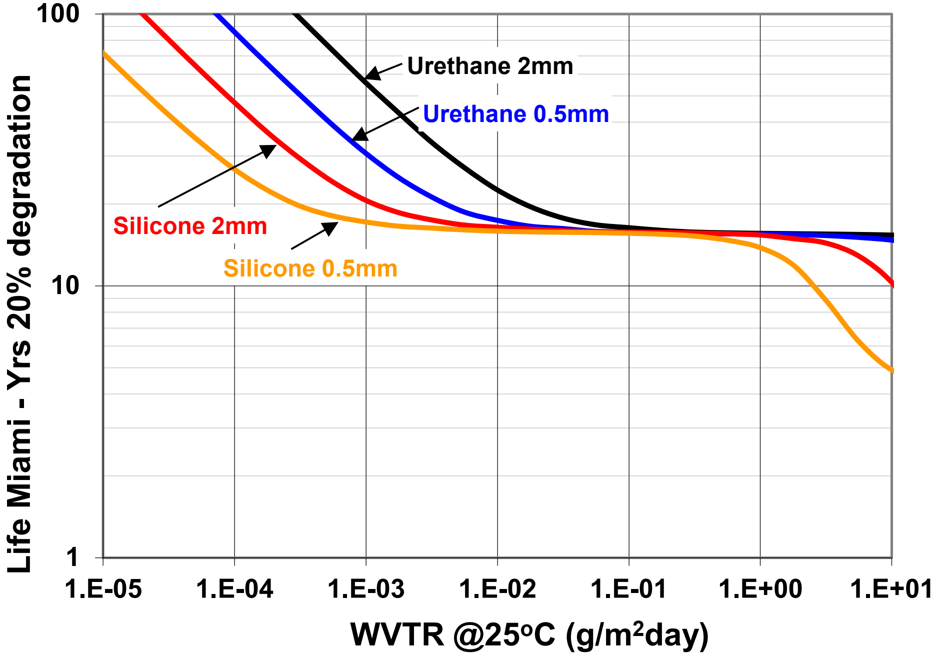


Results as expected after 3 months

- ITO/ECA_1 no measureable degradation
- ITO/ECA_0 ~ 5% down as expected

Encapsulant Effect





$$t_c = \frac{L_E S_E}{WVTR_{\max}}$$

$$\frac{C_E}{S_E} = RH\left[1 - e^{\left(-t/t_c\right)}\right]$$

- Low solubility encapsulants become saturated faster => BAD!!

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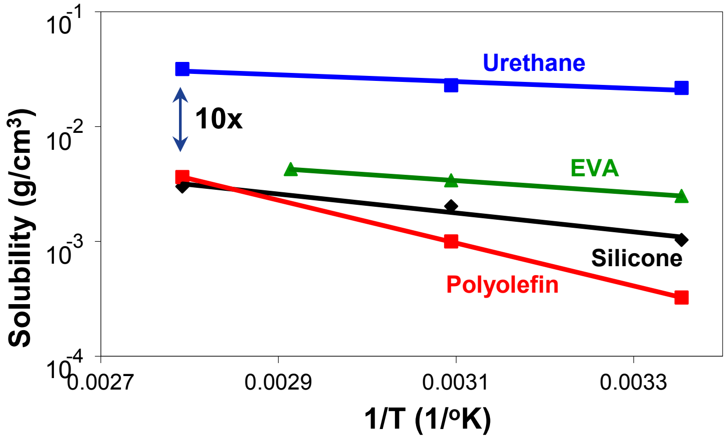
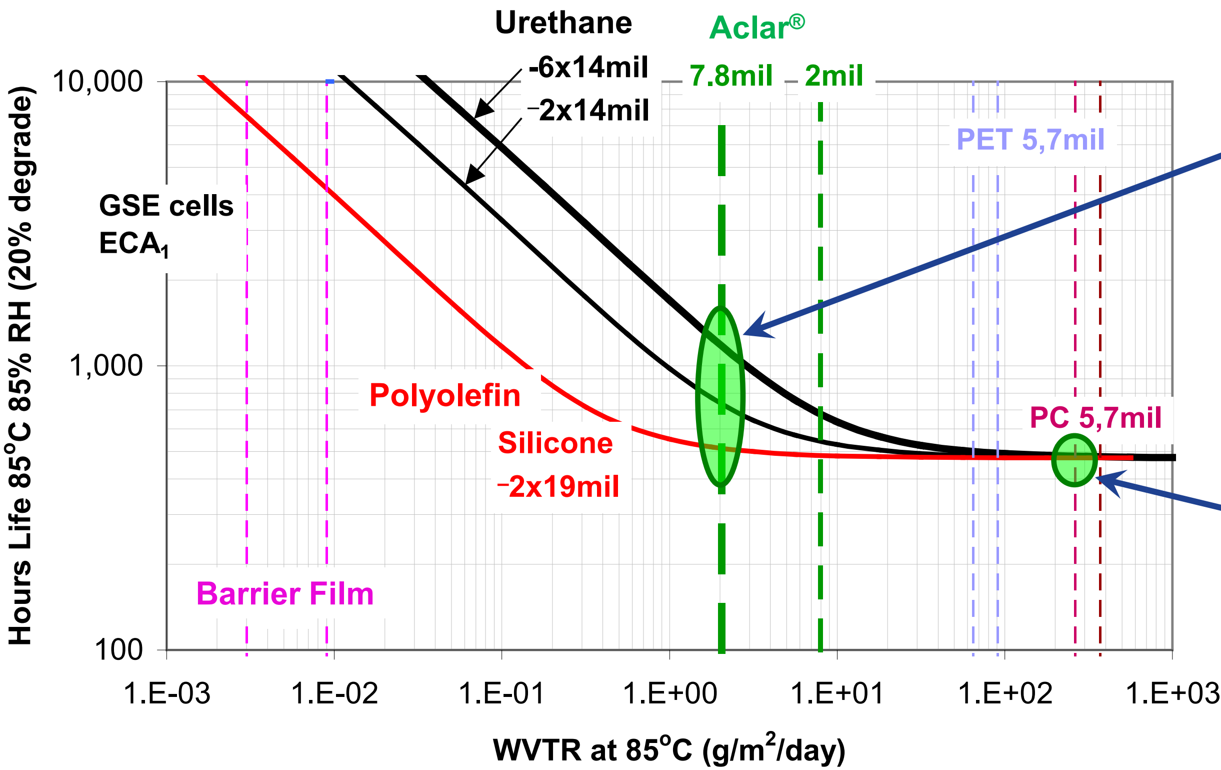
Encapsulant Experimental Plan (85°C, 85%RH)



Material		Thickness (mm)	Solubility @85C g/cm^3	$t_{1/2}$ Hrs @85C
Encapsulant	Urethane	0.355	3.0E-02	89
	Urethane	1.065	3.0E-02	268
	Silicone	0.480	3.1E-03	12
	Polyolefin	0.400	3.6E-03	12
Barrier			WVTR @85C g/m^{2}day	
	Aclar®	0.307	2.0	



Thick, high S_E encapsulants better

All encapsulants the same

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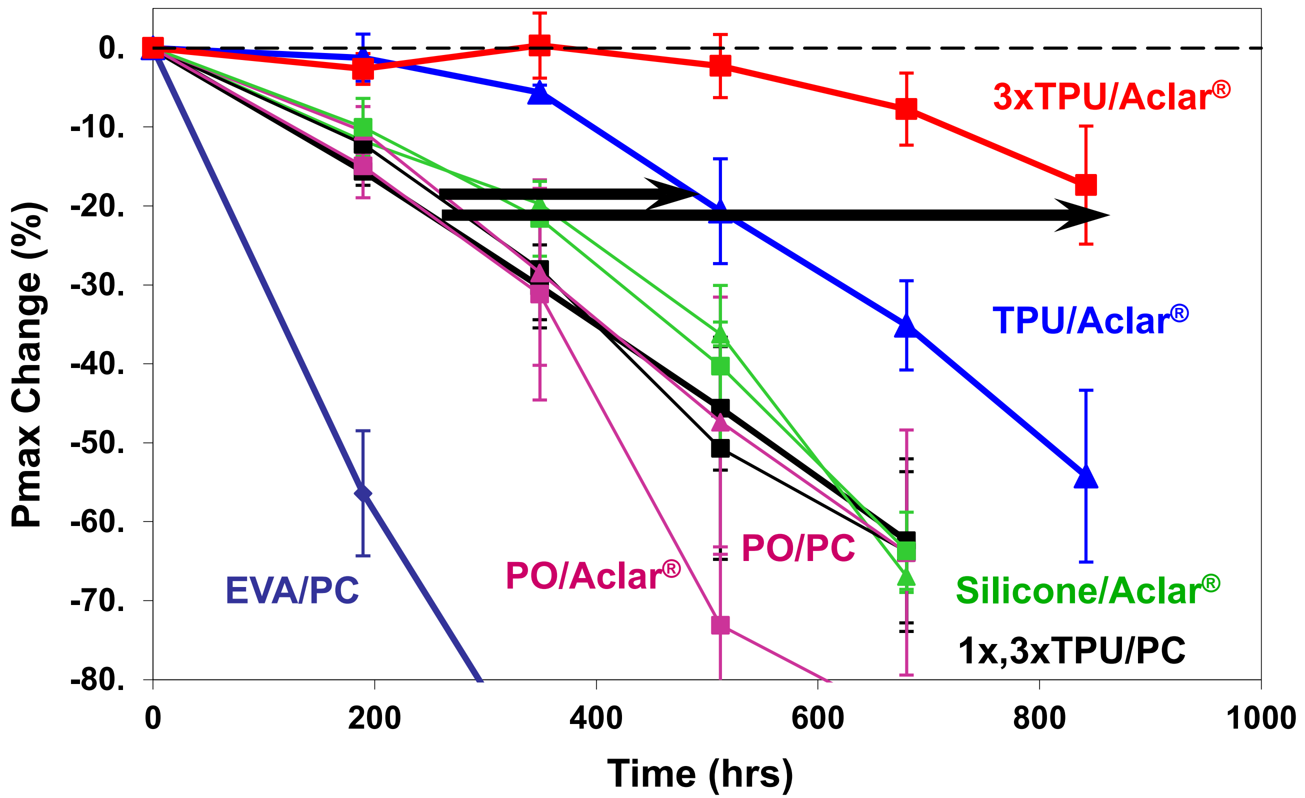
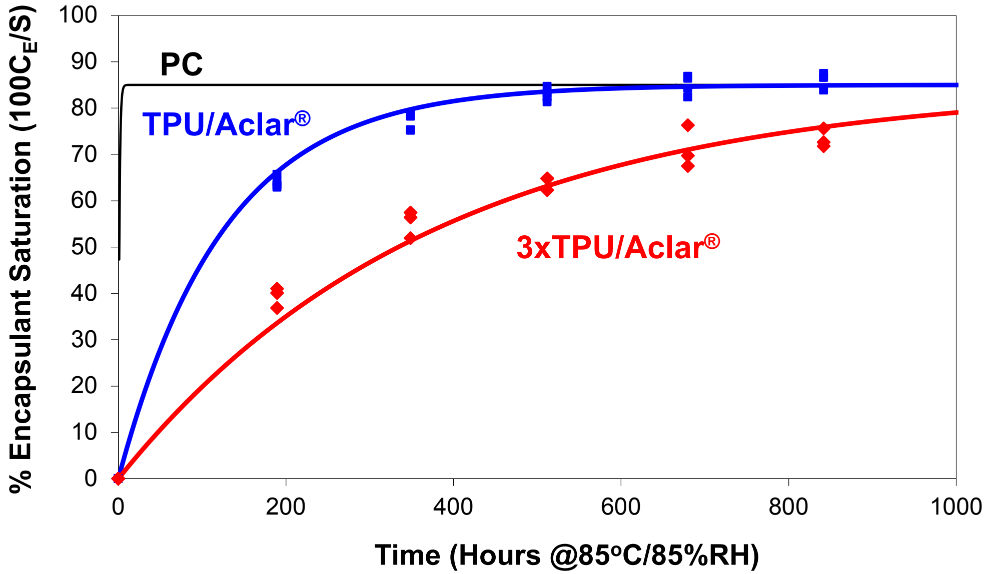
Encapsulant Confirmation Experiment



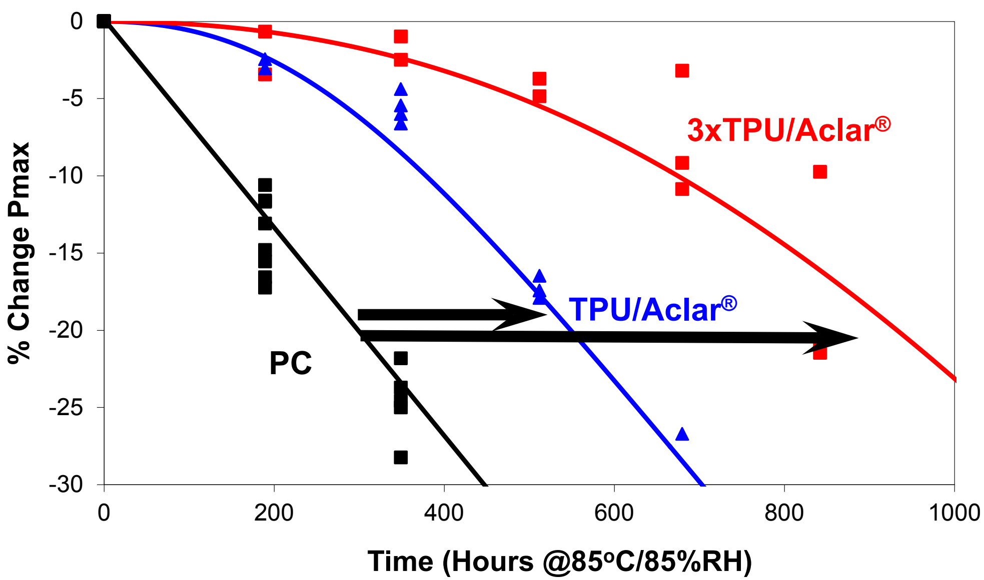
- EVA outlier – unusually fast degradation
- Urethane (TPU), silicone, polyolefin same, latter two even with Aclar®, as expected
- Barrier (Aclar®) makes no difference for silicone & polyolefin, as expected
- Barrier (Aclar®) improves TPU life, especially thicker, as expected

Comparison of Experiment & Model

Saturation



Degradation



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Conclusions

1. Life model and accelerated test scaling developed
   - ***Relative humidity*** and ***% saturation*** of encapsulant are key
2. Moisture sensitivity of CIGS almost independent of encapsulant type
3. Module lifetime longer for ***thick encapsulants*** with ***high*** water solubility
4. AZO vs ITO CIGS degradation kinetics quantified ~25X
5. ECA can also be a strong factor in degradation
6. Diffusion-controlled: Life ~ $(t_c/R_D)^{1/2}$ ~ $(\text{diffusion-time*degrade-time})^{1/2}$
7. Significant moisture barriers required for 20 yr life – even for ITO
8. Acceleration factor for damp heat smaller than assumed, highly nonlinear!
9. Methodology can predict life for any moisture-sensitive module (once kinetic constants are measured)

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