Packaging Requirements for ITO-Hardened CIGS

Dennis Coyle, Holly Blaydes, James Pickett, **Todd Tolliver**, Ri-An Zhao, and J.ames Gardner

GE Global Research
Niskayuna, NY, 12309

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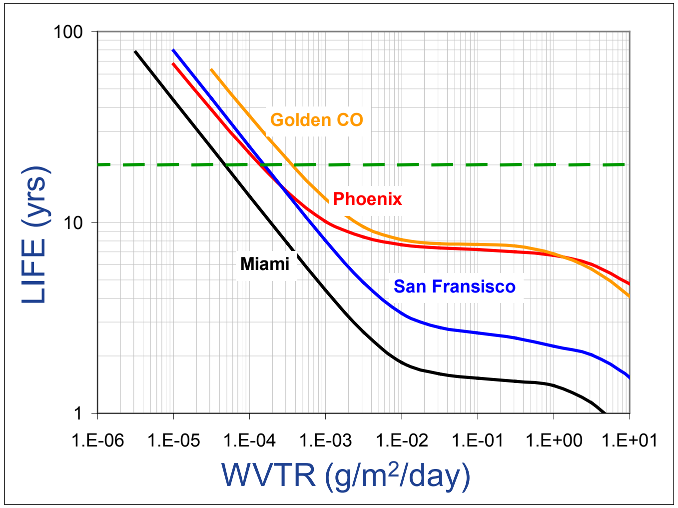
imagination at work

Flexible CIGS Module

Advantages

- Lightweight – no racking, no structural engineering, labor savings
- High efficiency – low-cost manufacturing (potential), high power density

→ ***ideal for commercial rooftop!***



Challenges

- Lifetime – moisture sensitive devices, UV degradation, interconnects
- Cost – low-scale production, expensive packaging materials

→ ***detailed understanding of degradation needed!***

Factors for Lifetime Prediction (CIGS Module)

This study focuses on moisture driven failure modes…

- Cell Construction/Materials
  - ITO vs AZO window layer
  - Type of ECA for interconnect

- Environment/Exposure
  - Accelerated testing (ovens with various temp, RH)
  - Real-world exposure (Miami, Phoenix, …)

- Package Materials
  - Barrier properties of topsheet and backsheet
  - Edge seals

Life Model – Moisture Sensitivity

1. CIGS Degradation Kinetics

- Degradation rate vs. Temp, humidity
- ITO vs AZO
- ECA - Interconnect degradation can play a role

2. Moisture Diffusion into Package

- 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

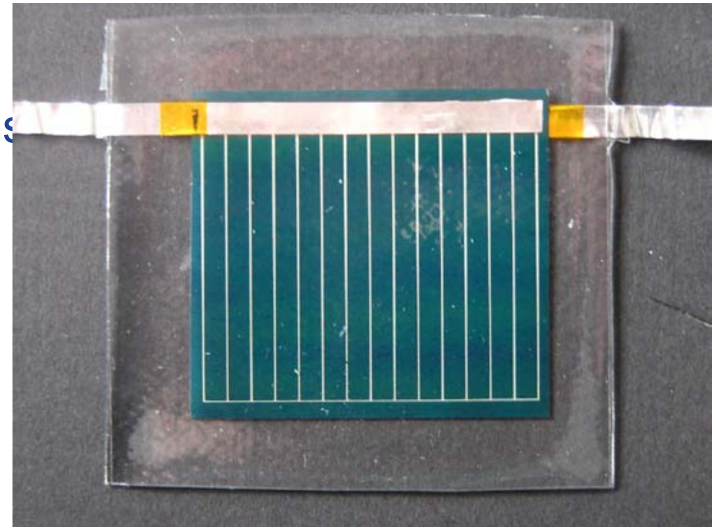
3. Coupled Model

- Cumulative degradation and average life vs. location and package design
- Tradeoffs between CIGS sensitivity and package design/cost
- Interpretation of accelerated tests results

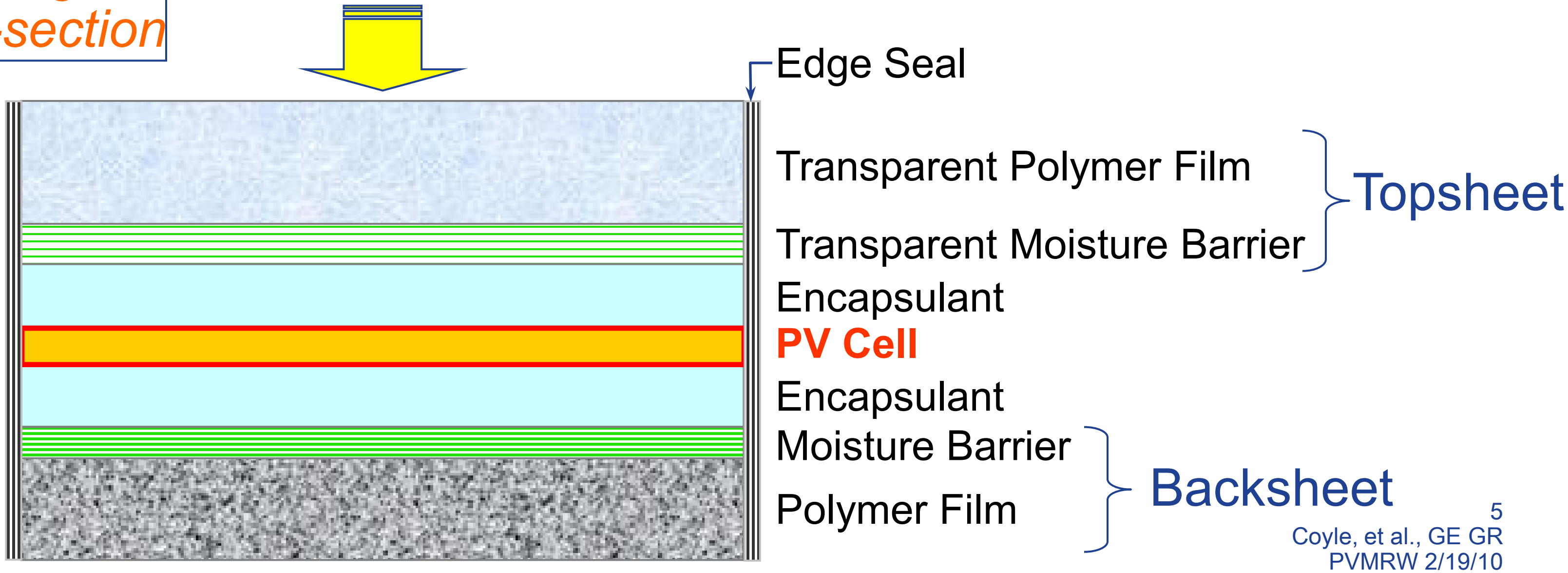
Test Structures

Test Structures/Package Configurations

- Metal foil substrate
- Electrically conductive adhesive (2) + tabs/ribbons
- AZO/ITO window layer
- Nominal cell performance
  - Efficiency ~ 10 – 12.5%
  - Voc ~ 550 - 610 mV, Jsc ~ 28-33 mA/cm2
  - FF ~ 59 - 62%, Area ~ 16.5 cm2



Package Cross-section



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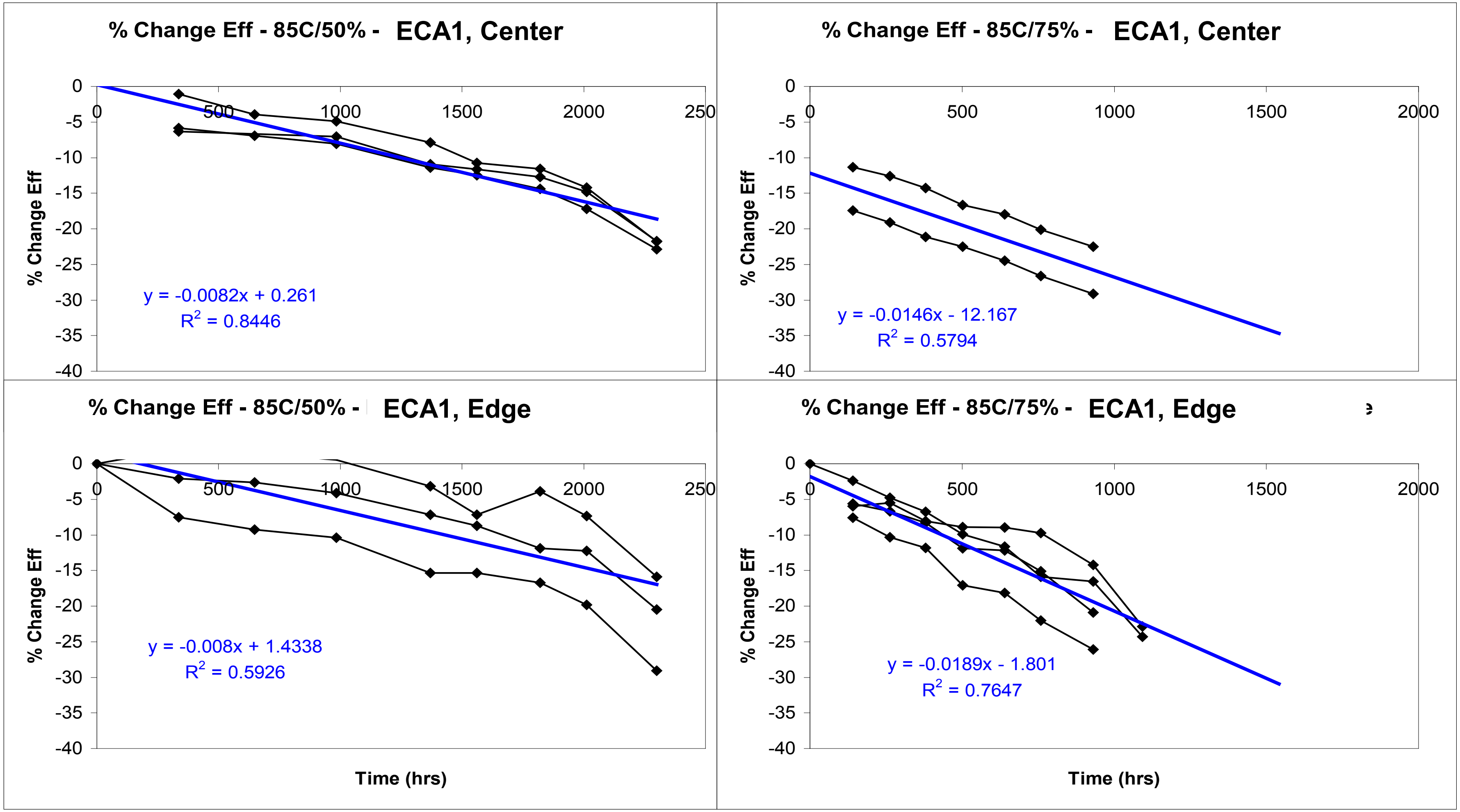
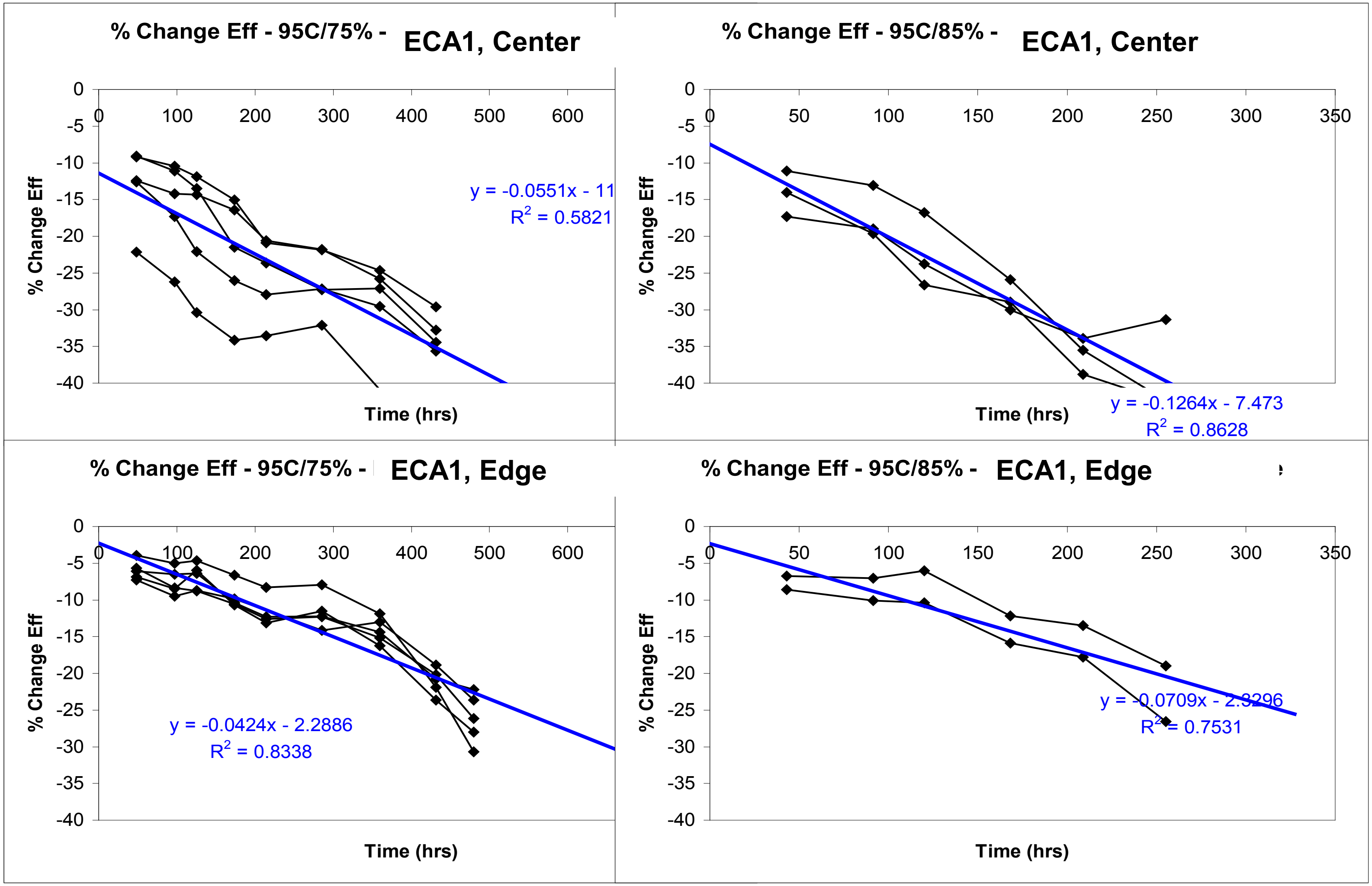
Degradation data – example (humidity)



- High humidity faster
- Center cells rapid initial degradation
- Same long-term rate center vs edge

Degradation data – example (temperature)



- High temperature faster
- Center cells rapid initial degradation
- Same long-term rate center vs edge

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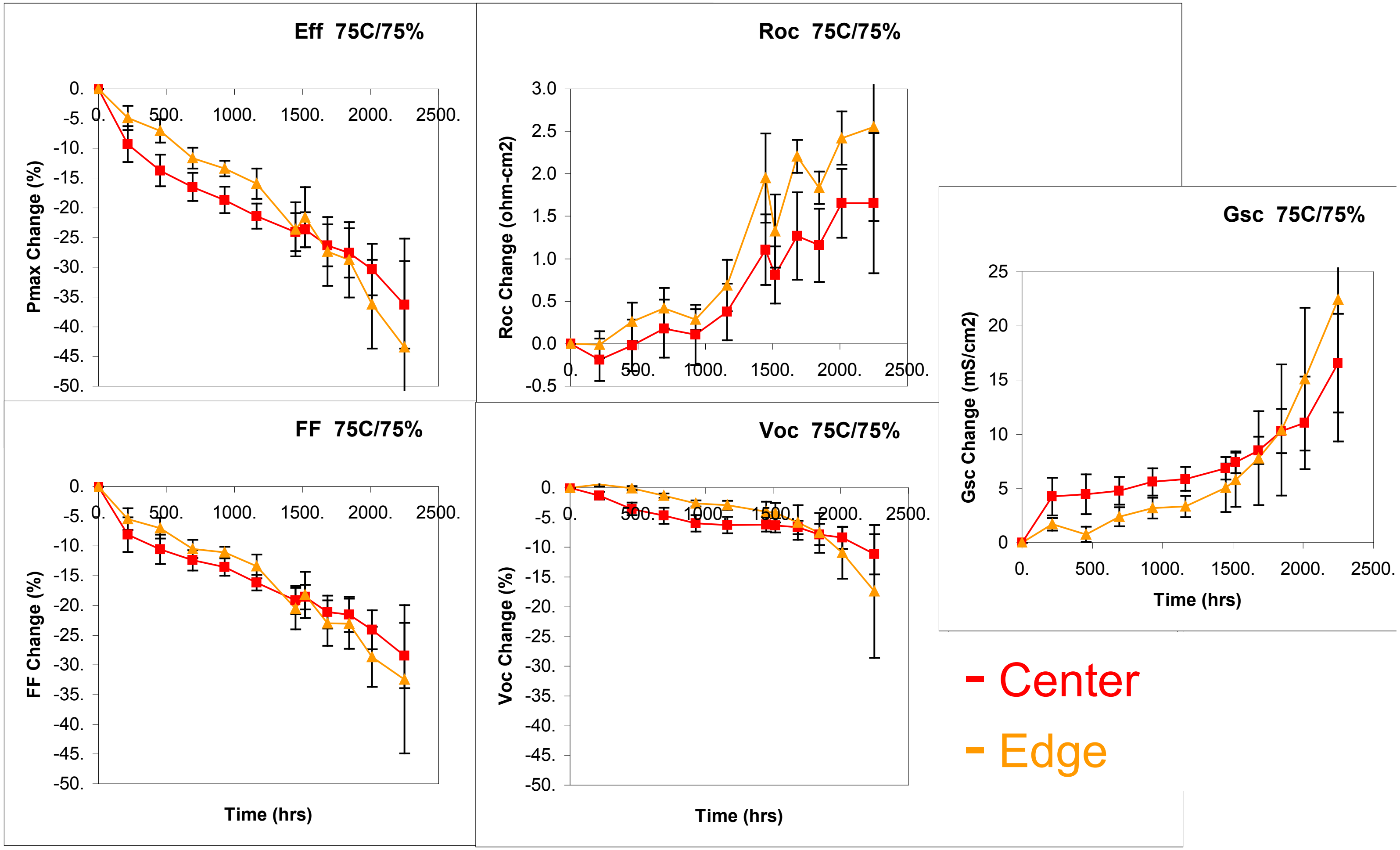
Which JV Parameter is the Driver?



- Steady degradation driven resistance - FF and Roc
- Initial drop driven by shunting - Gsc

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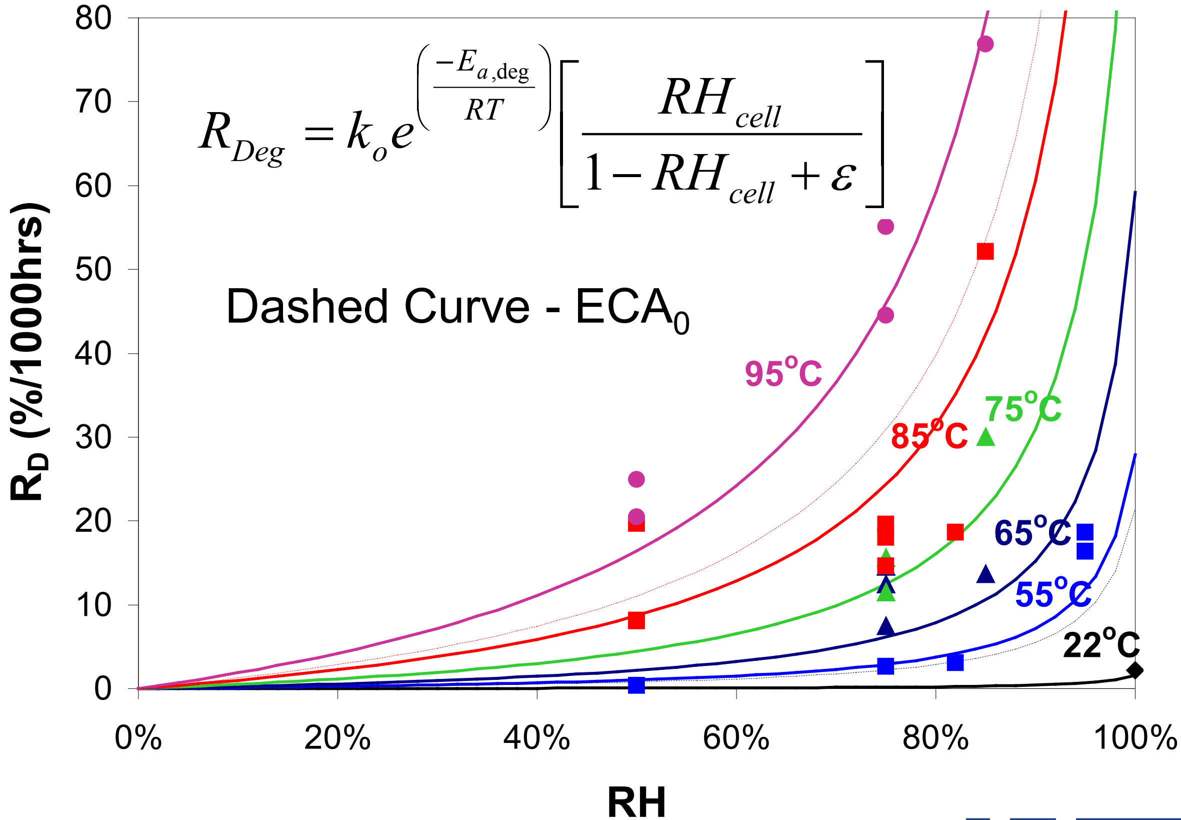
CIGS Degradation Kinetics

(ITO-based test structures)

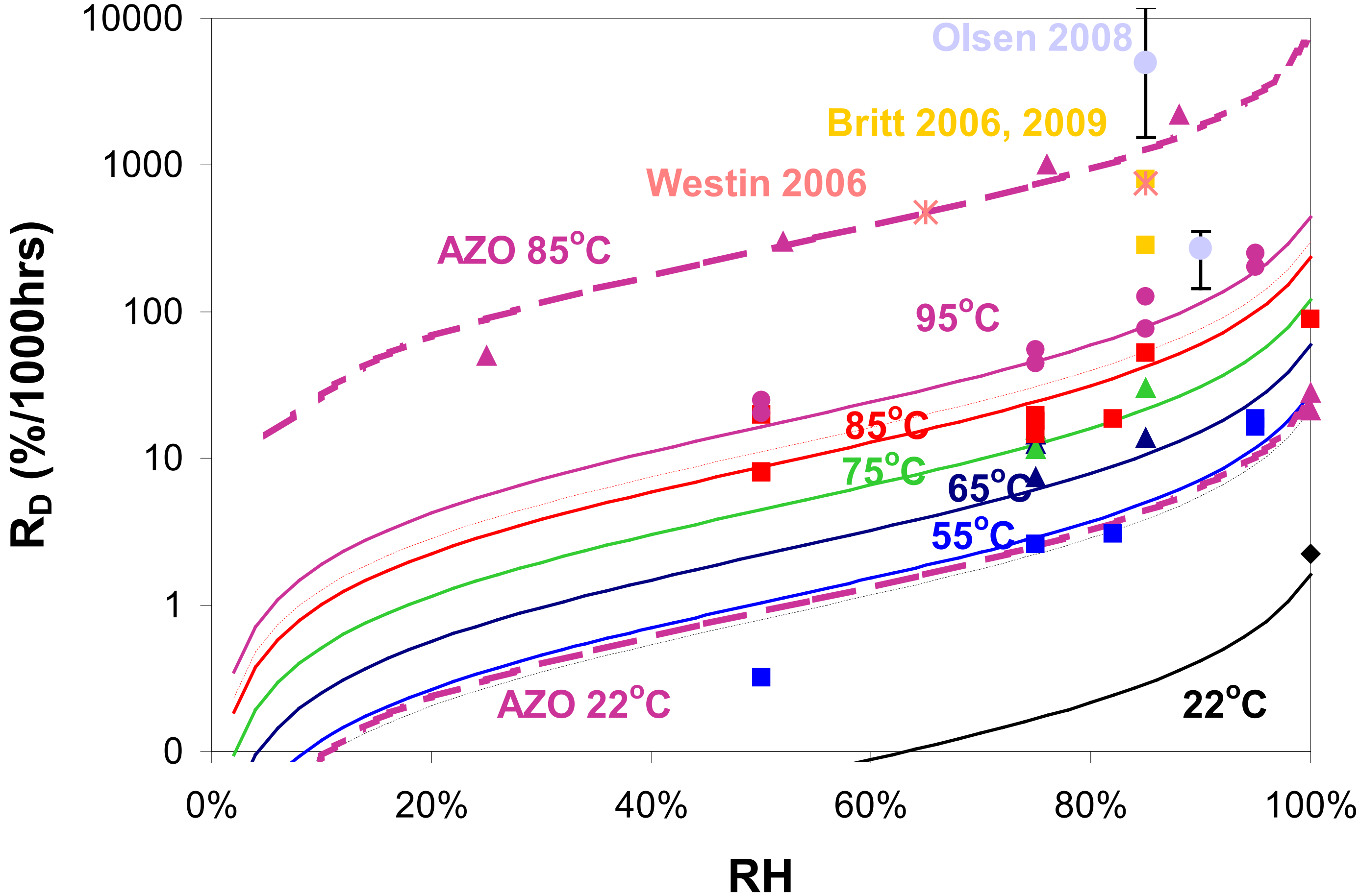


- For every Temp & RH, fit data to linear degradation rate (1st 20% of degradation)
- Fit rate of degradation vs Temp, RH to kinetic model
- Strong RH dependence at high RH
- ECA affects temperature dependence

Compare to AZO

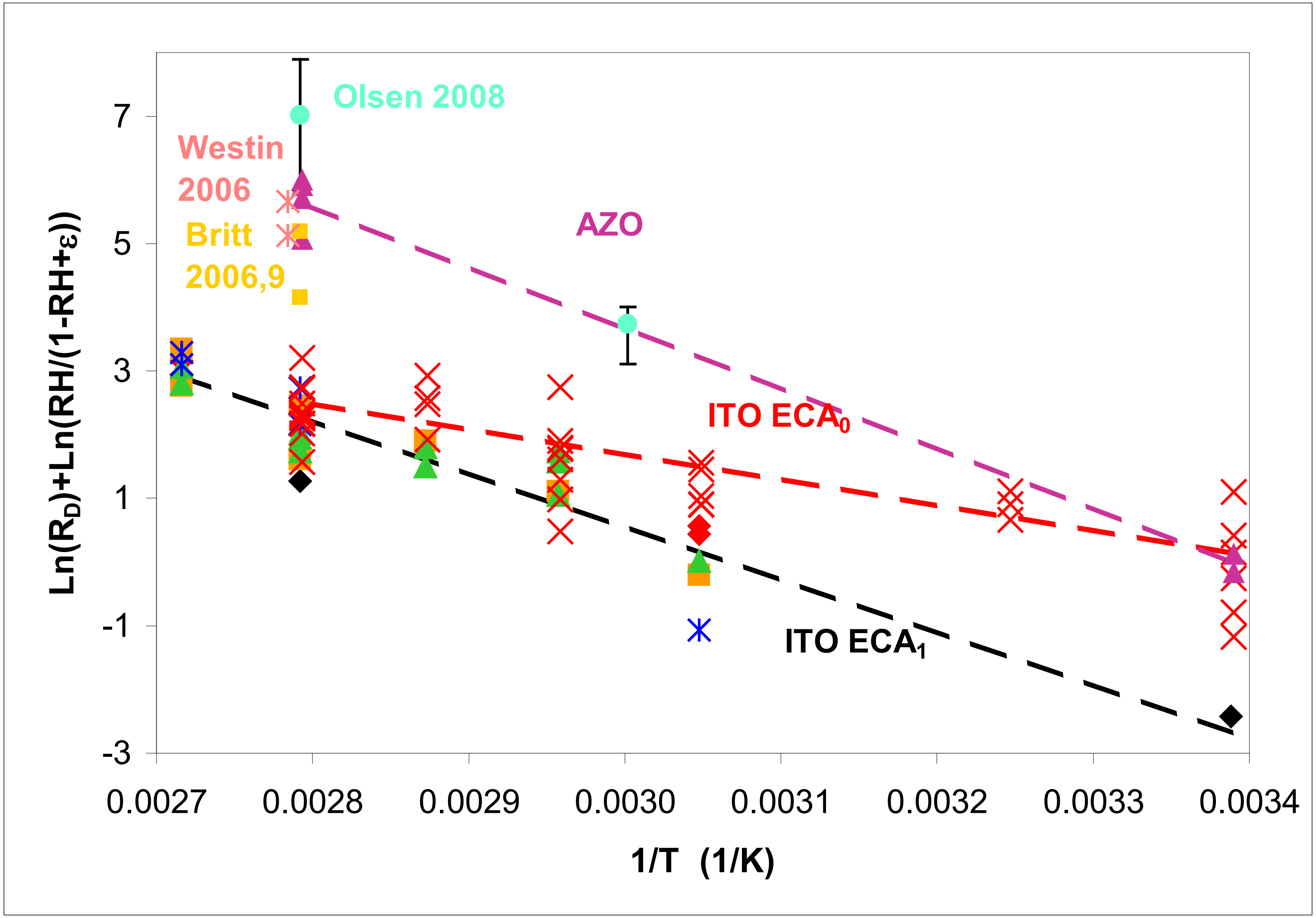
(Klinger, D. J., "Humidity acceleration factor for plastic packaged electronic devices", Quality and Reliability Engineering International. Vol. 7, 965-3711, 1991).

CIGS Degradation - AZO vs ITO



- AZO ~ 25X ITO
- Comparable to published data

Arrhenius Plot



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Package Diffusion Model

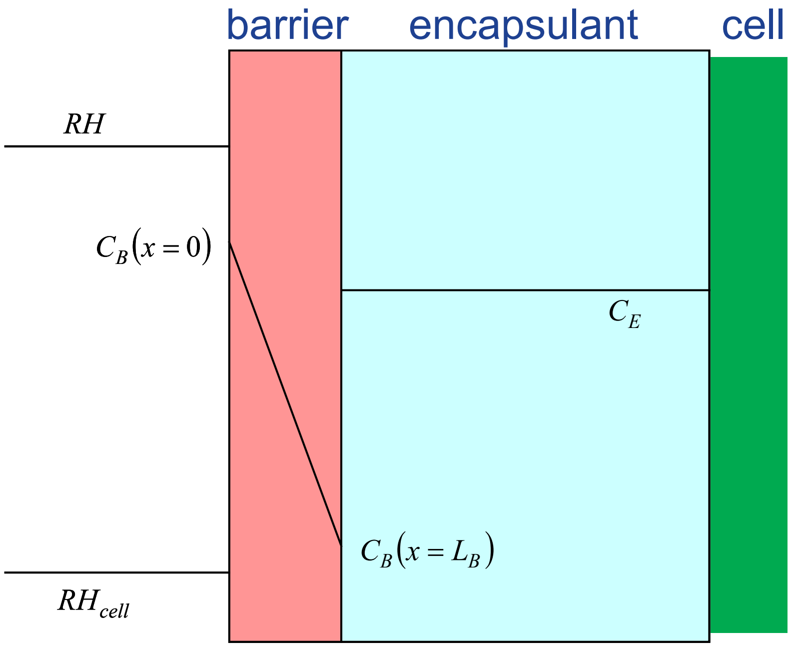
Mass Balance, Interfacial Equilibrium, Fickian Diffusion, $D_{barrier} << D_{encapsulant}$

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

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

If initially dry:

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

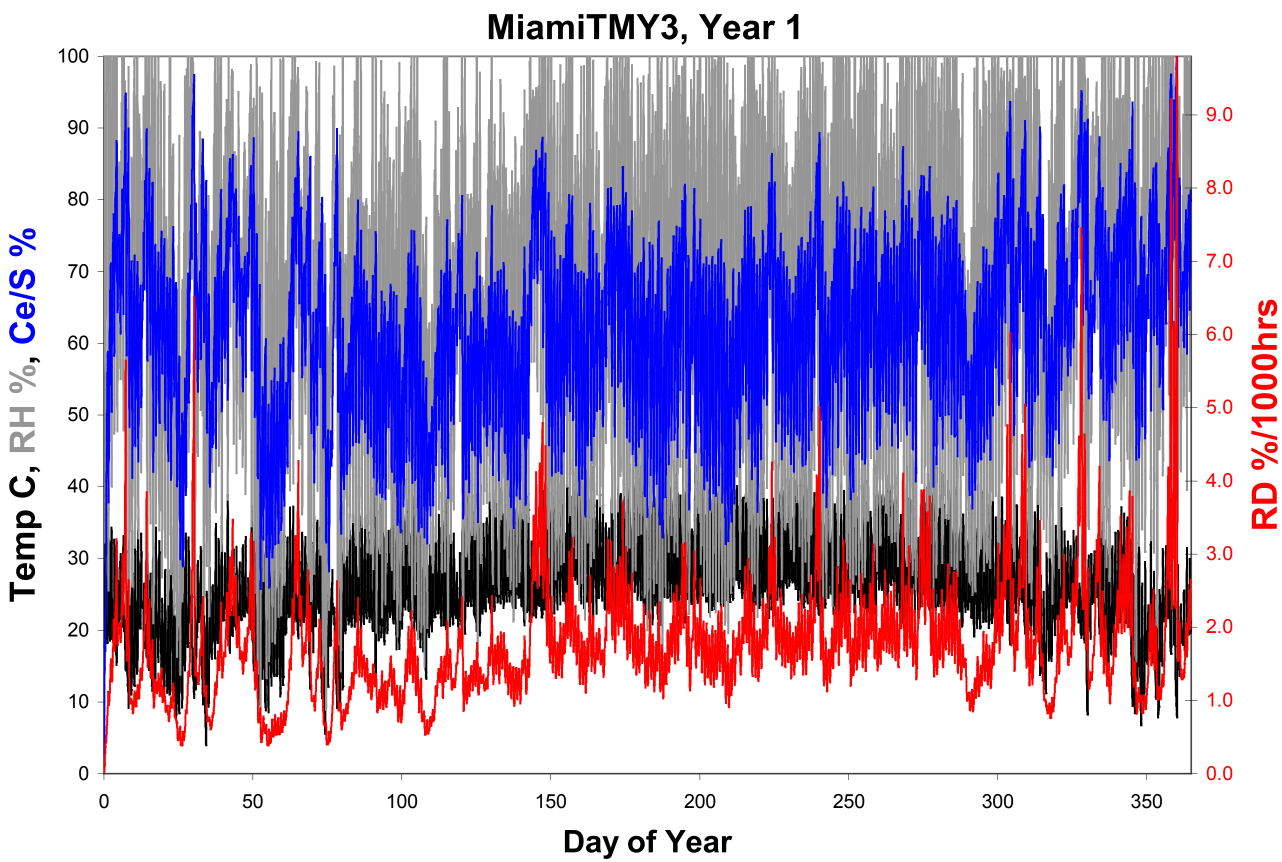


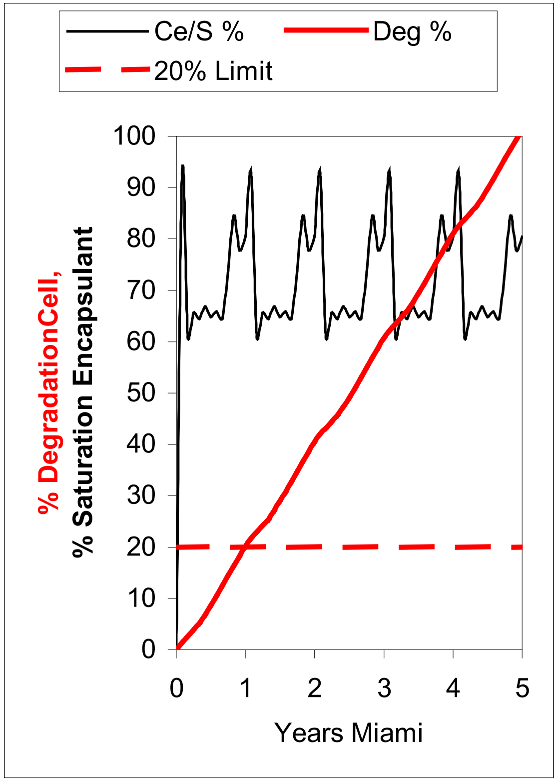
→ Integrate moisture ingress with hourly weather data (TMY3)

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

Plastic Package (No Barrier)

WVTR = 10^0 g/m^2/day





- Package equilibrates ~ $t_{1/2}$=0.7 days
- PV degrades ~ 1 year

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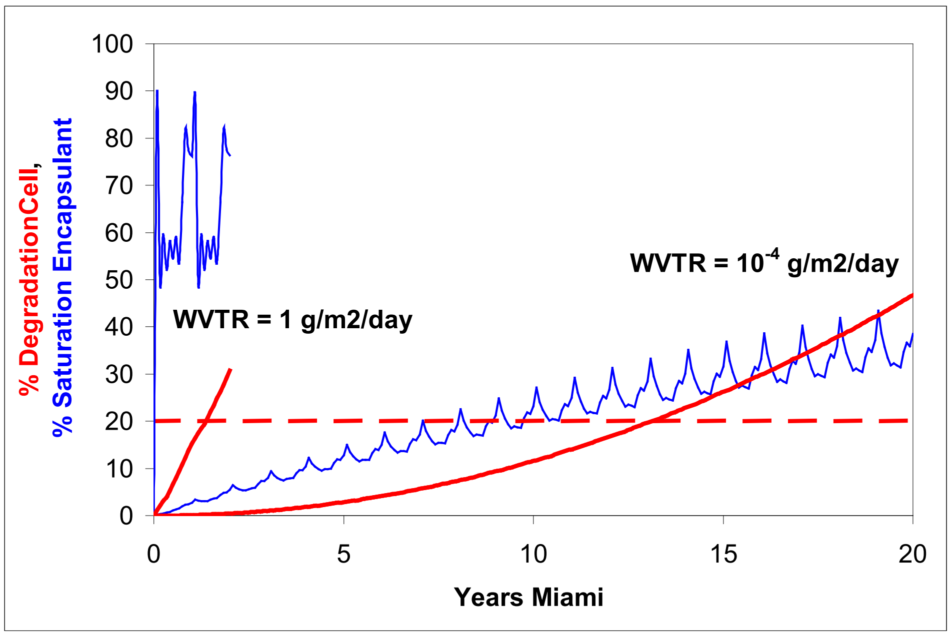
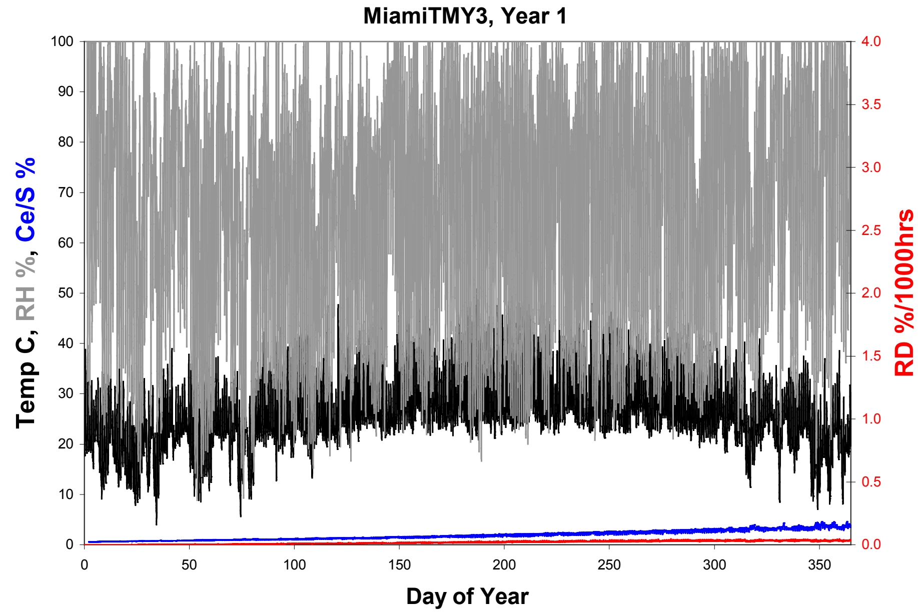
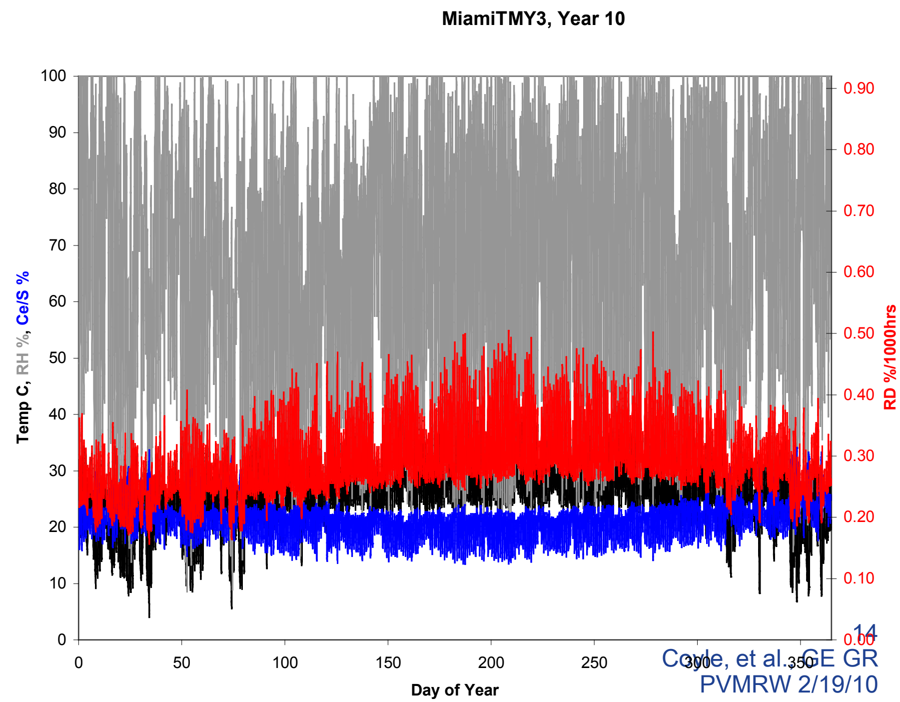
Barrier Package

WVTR = 10^{-4} $g/m^2/day$

- Package equilibrates ~ $t_{1/2}$=20yrs
- Module Degrades < 13 yrs







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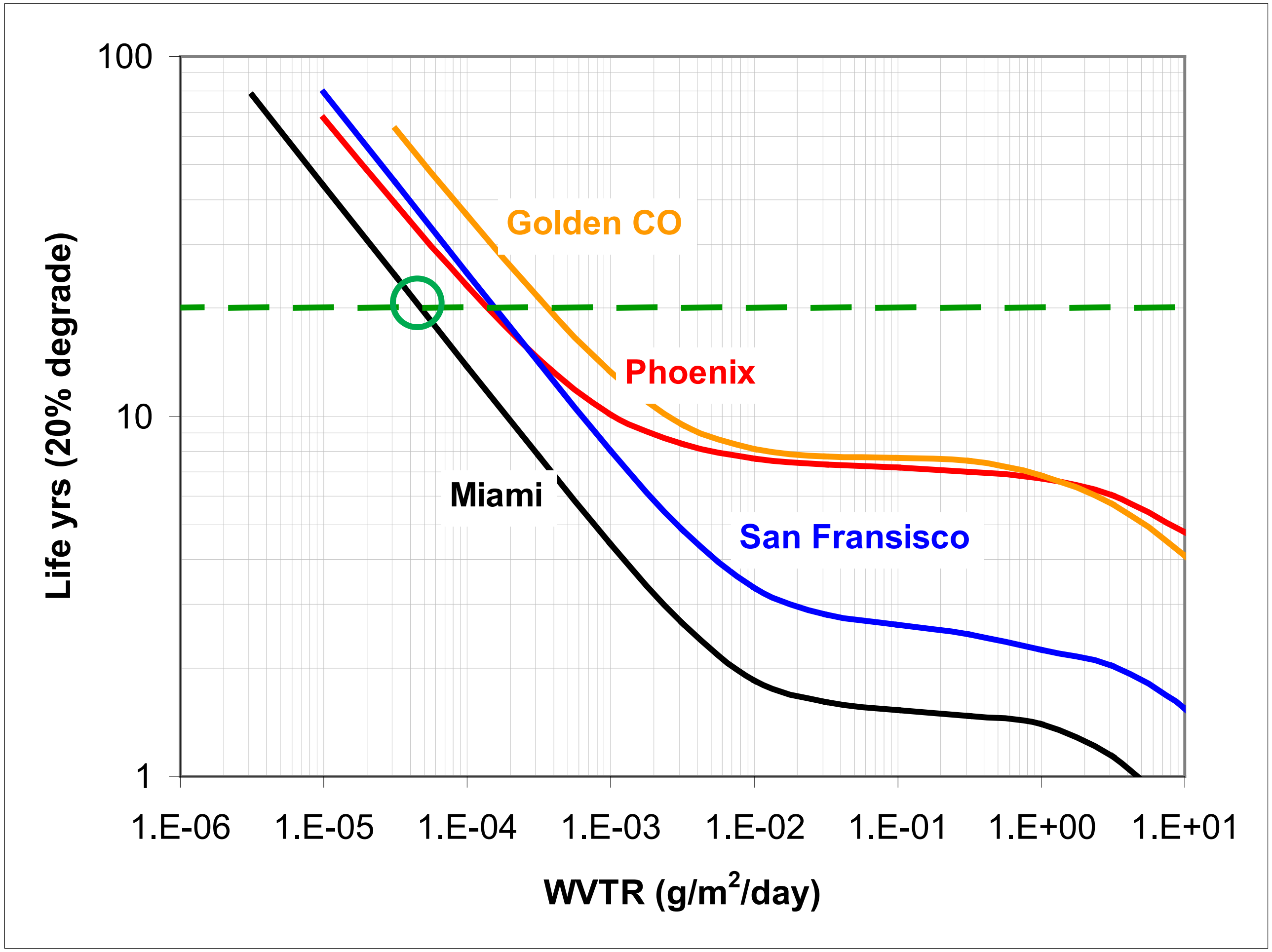
Life vs. Barrier: ITO-ECA$_0$



Need ~ 4×10^{-5} g/m^2/day package ~ 20 yr life

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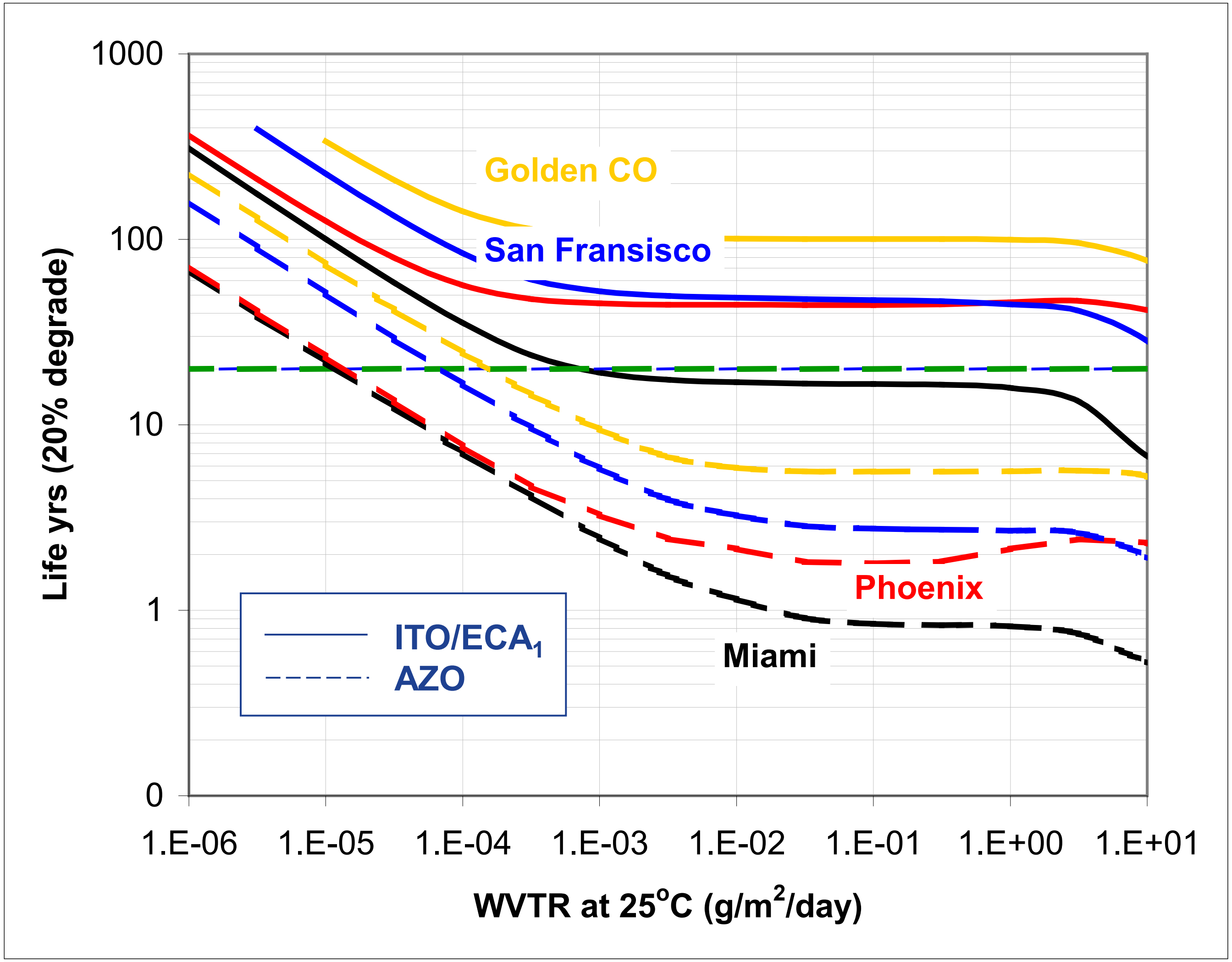
Life vs Barrier – ITO vs AZO



ITO Life 5-25X AZO Life

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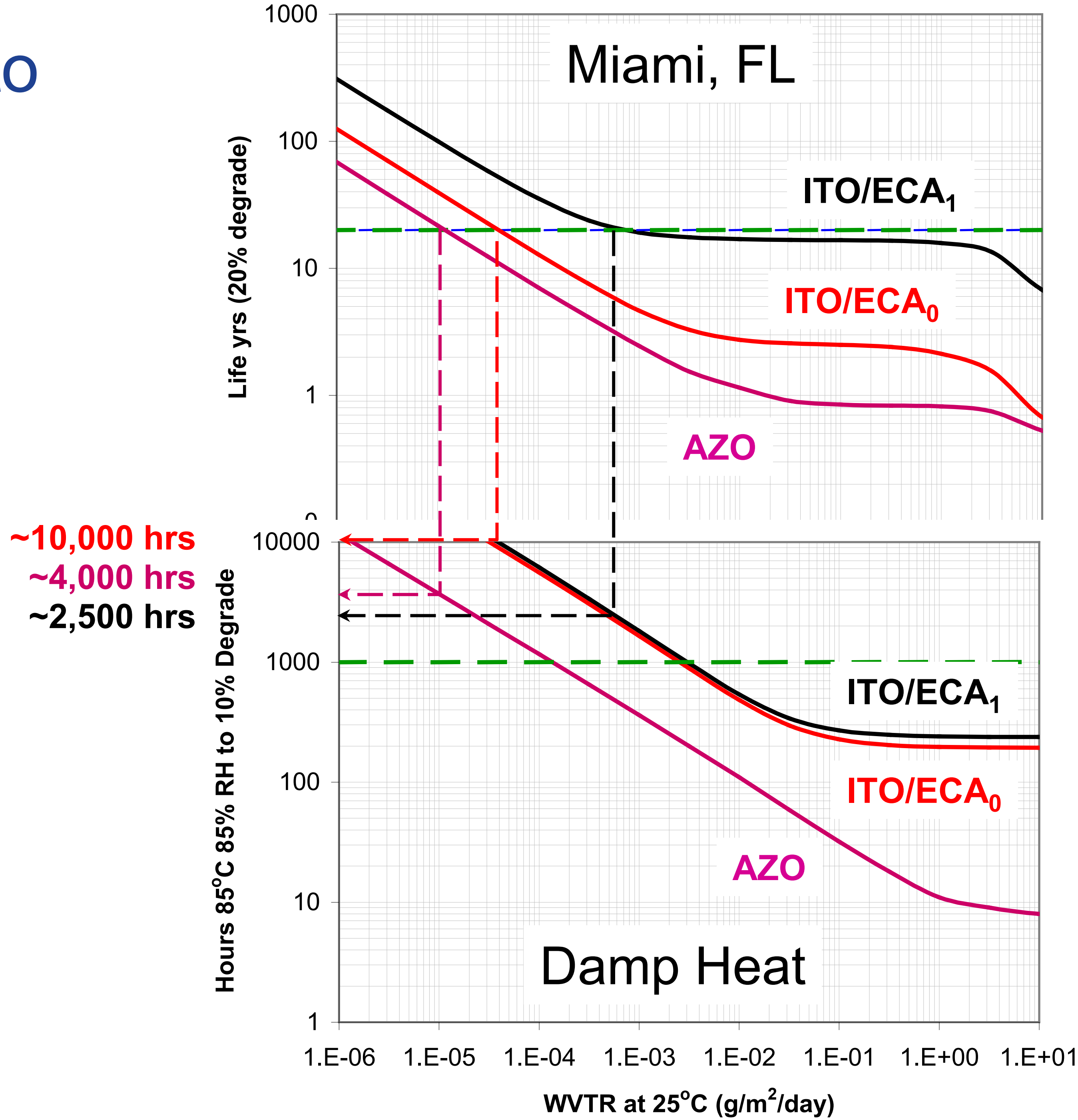
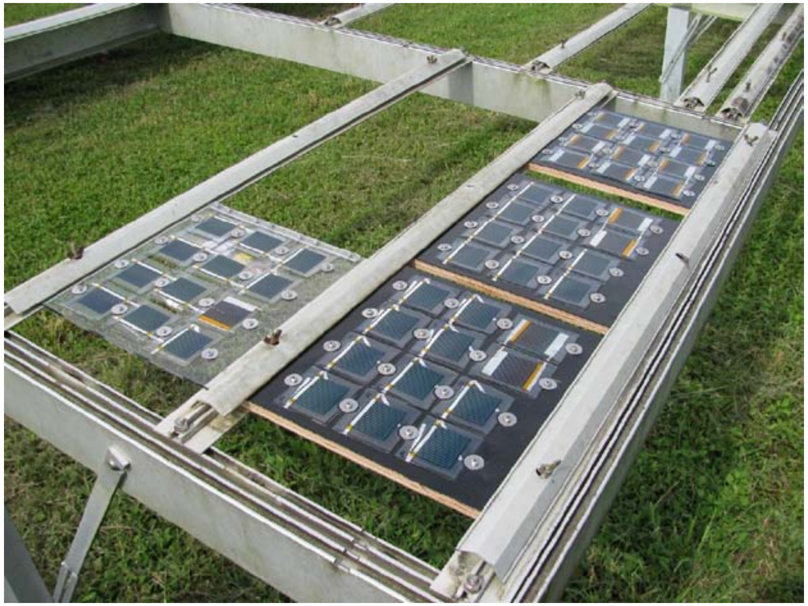
Connection to Accelerated Testing

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



Outdoor Testing

- Generate real time degradation data to compare to life model
- Samples placed in Miami, FL and Phoenix, AZ



	Calc P_{max} change	Measured P_{max} change	Roc change	P_{max} change shunted
Phoenix ECA_1	-0.1%	-1% +-2%		
Miami ECA_1	-0.5%	-1% +-2%		
Miami ECA_0	-4.1%	-5% +-2%	29% +-7%	-30% +-5%

Results as expected after 3 months

- ITO/ECA_1 not measureable yet – will continue
- ITO/ECA_0 ~ 5% down as expected

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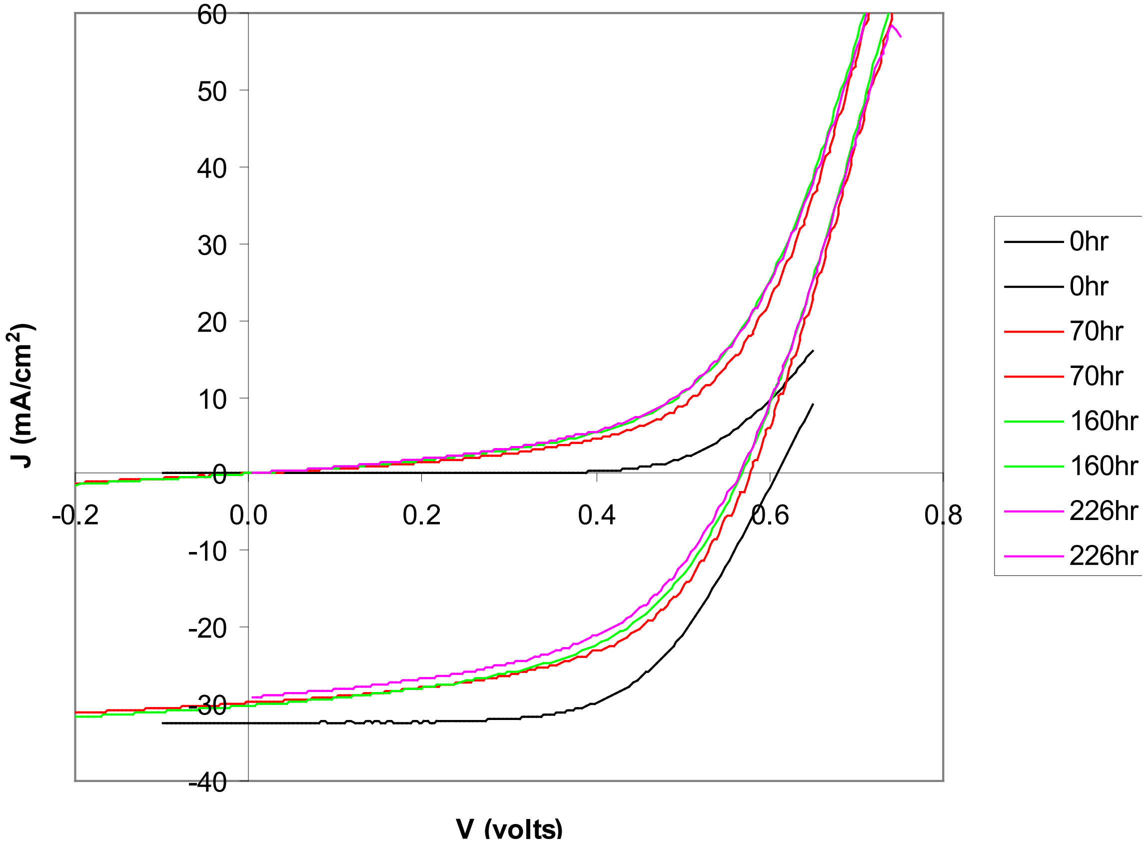
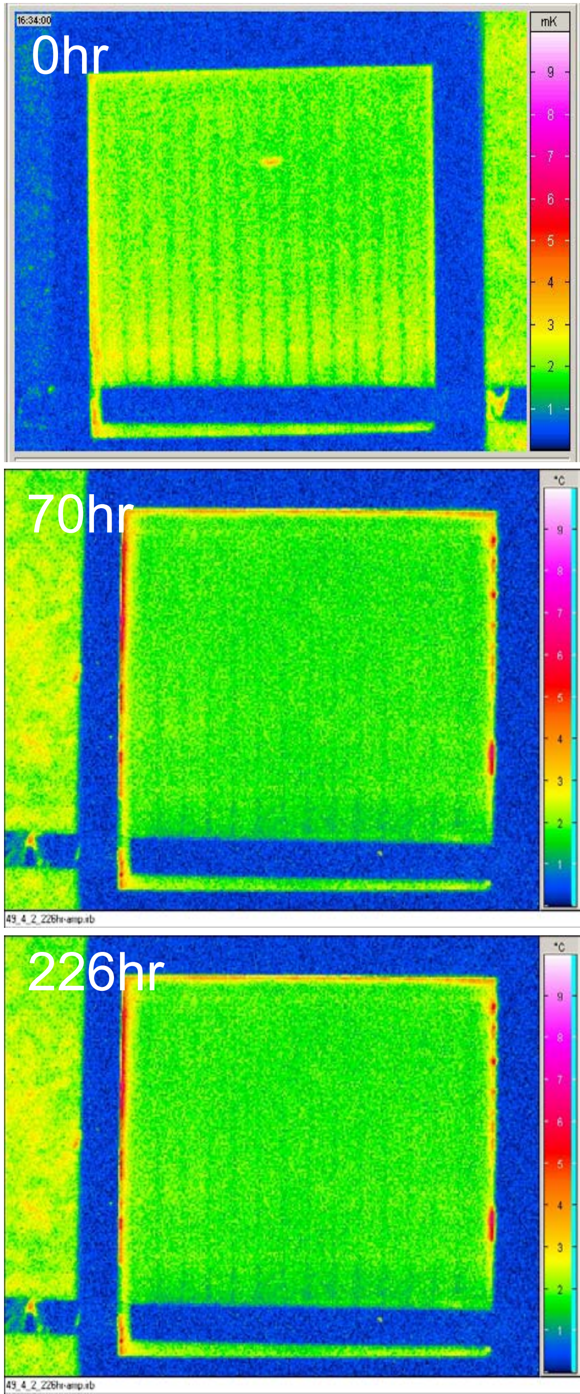
Root Cause Analysis: Shunting

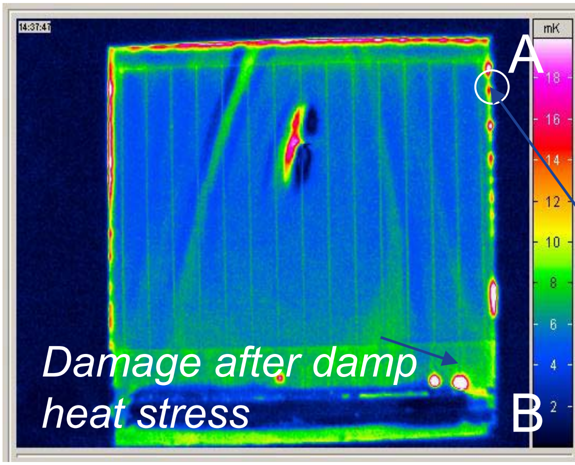




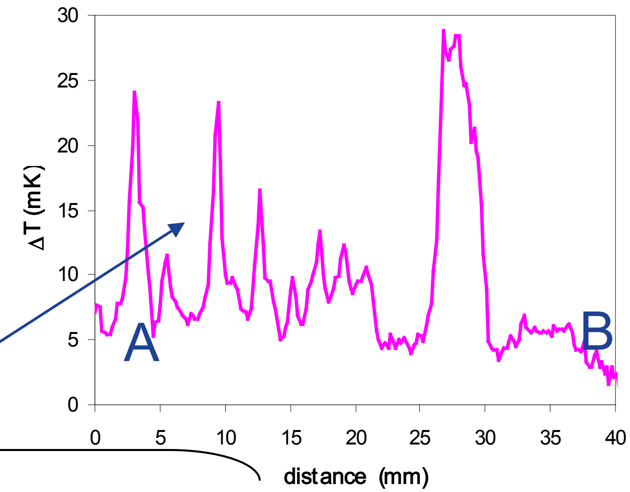
- Use lock-in thermography (LIT) to image shunting behavior
- Image at various stages of damp heat stress
- Initial degradation is dominated by edge shunting

Shunting Failure Analysis Deep Dive

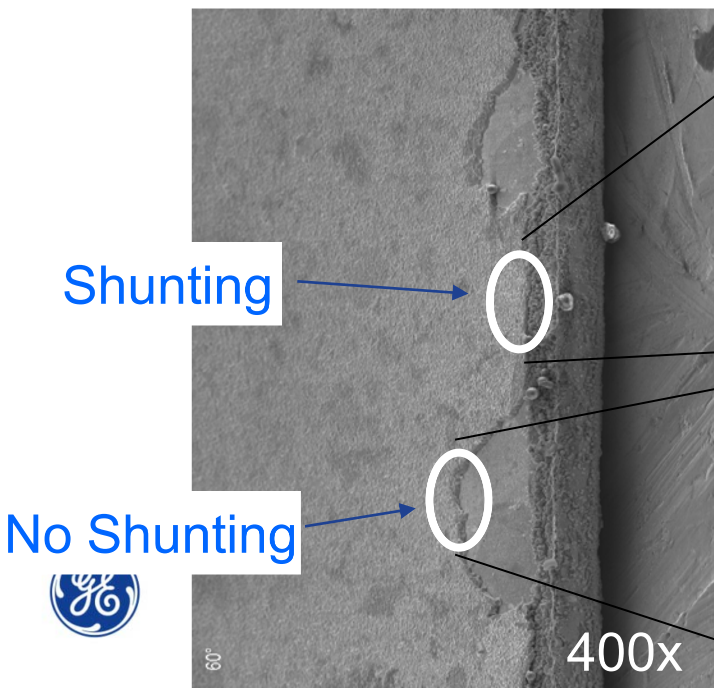
LIT Full Cell Image

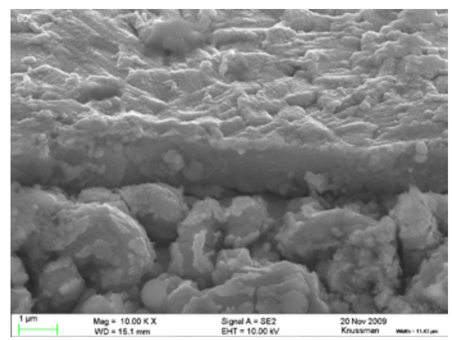


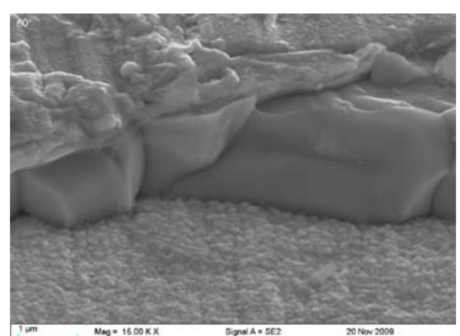
LIT Line Scan of Cell Edge



SEM







- LIT line scan shows distinct localized shunt paths
- image with SEM to look at μ-structure
- Shunting caused by small CIGS edge clearance.

Conclusions, Plans & Acknowledgements

Conclusions

- AZO vs ITO CIGS degradation kinetics quantified – 25X
- Life model and accelerated test scaling developed
- Diffusion-controlled: Life $\sim(t_c/R_D)^{1/2}$ or $\sim(\text{diffusion-time*degrade-time})^{1/2}$
- Significant moisture barriers required for 20 yr life – even for ITO
- Acceleration factor for damp heat smaller than assumed, highly nonlinear!
- Methodology can predict life for any moisture-sensitive module (once kinetic constants are measured)

Future Plans

1. Critical experiments to test model predictions
2. Experimental validation – Miami, FL & Arizona

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imagination at work