Modeling based on Damp Heat Testing

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Prologue

- Single stress testing *success*:
  - 1978 – 1986 – Large JPL body of work on specific PVB/EVA *Systems*.
- Damp Heat Manifestations
  - 169 hrs at 70C, 90%RH, Block I
  - 720hrs at 40C/93%RH, CEC 501
  - 480hrs at 90C, 95%RH, CEC 502
  - 1989→1000hrs 85/85, JIS C 8917
- Otth and Ross (1984)
  - "Rule-of-Thumb" 10° ~ 2x also
  - 1C≡1%RH
  - 1000-hour Damp Heat ~ 20 years in Miami, Florida (sort of…)
- New *Durability* offerings at 2x + the qualification standards.
- Question: How do we interpret this result in a reliability-relevant way.

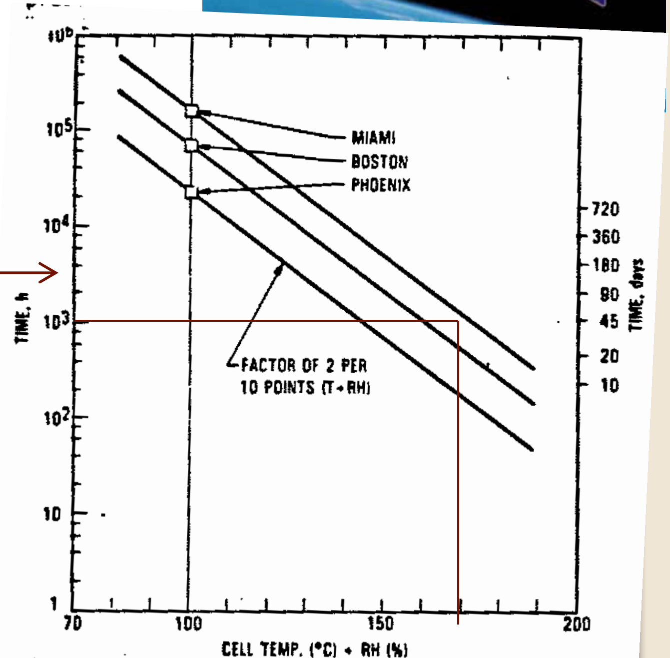
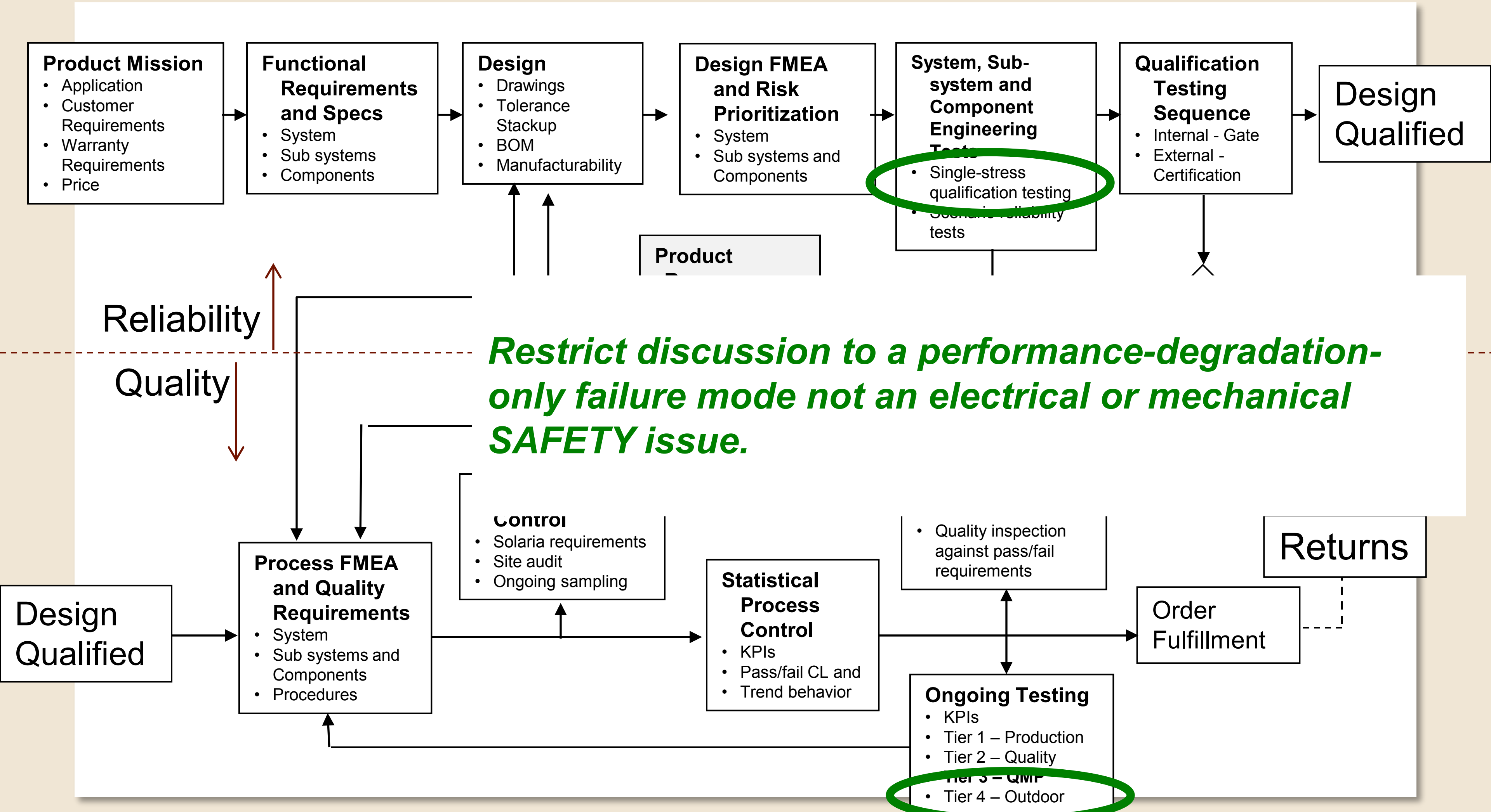


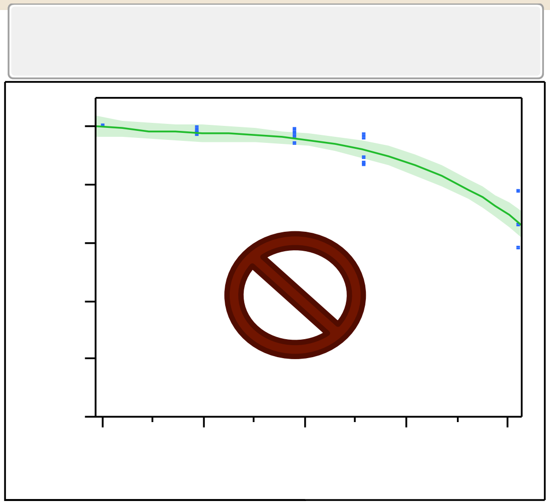
Figure 2. Temperature-humidity test duration equivalent to 20-year field exposure at indicated sites.

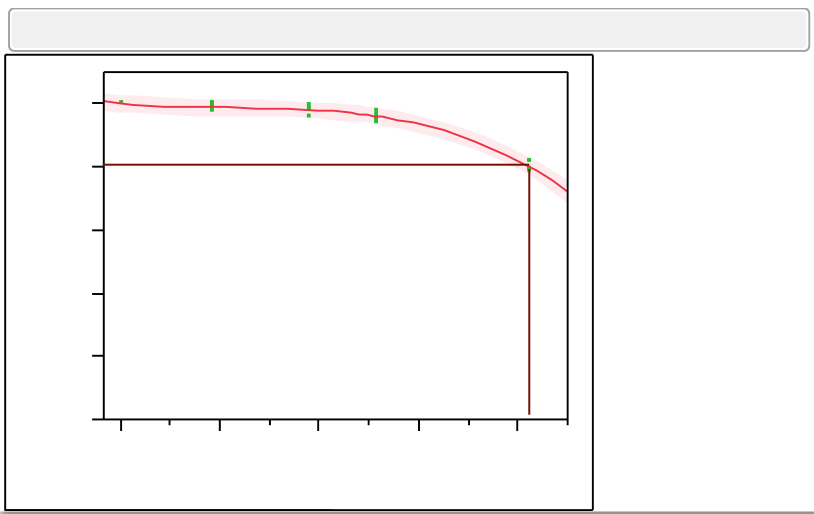
Context – When do we care?



Restrict discussion to a performance-degradation-only failure mode not an electrical or mechanical SAFETY issue.

Restriction – Damp Heat Only



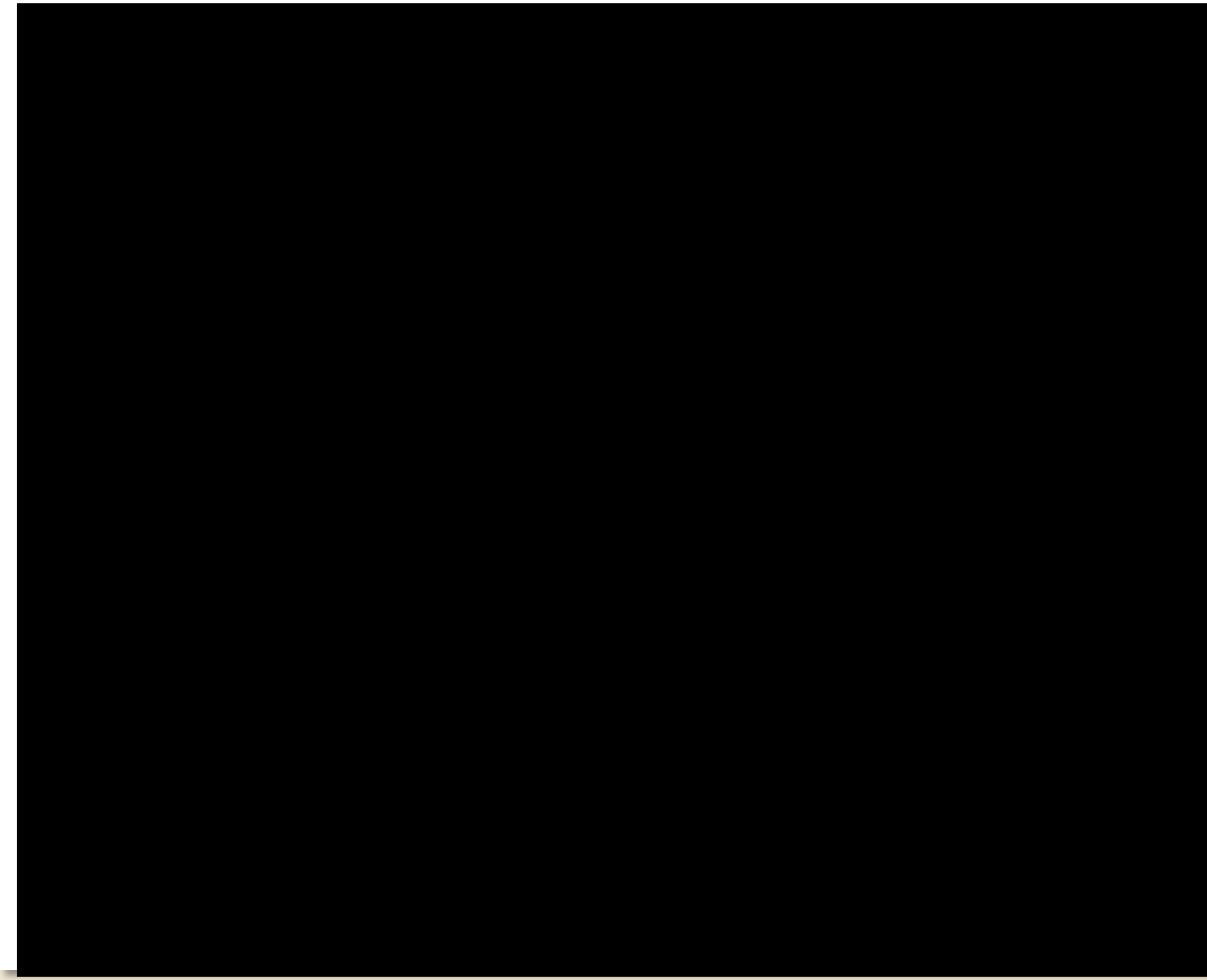


Do not perceive a significant risk of a PID failure (negative bias of p+ cells)

Positive bias work still underway.

HOWEVER – 2000 hours of DH produces ~20% Pmax degradation.

EL Observations



Primary impact ~ *series resistance*

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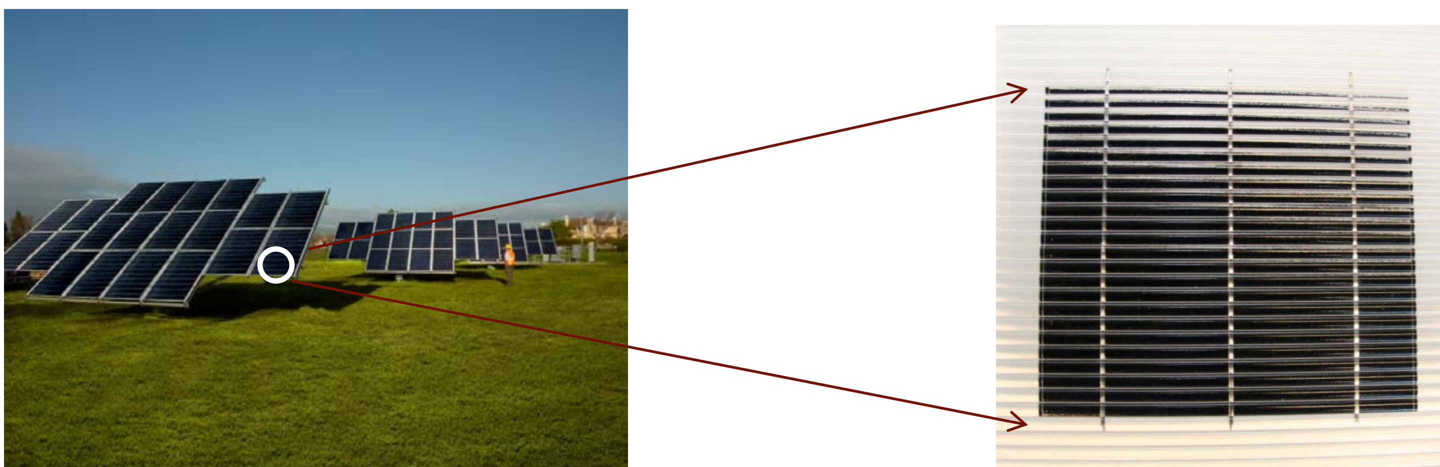
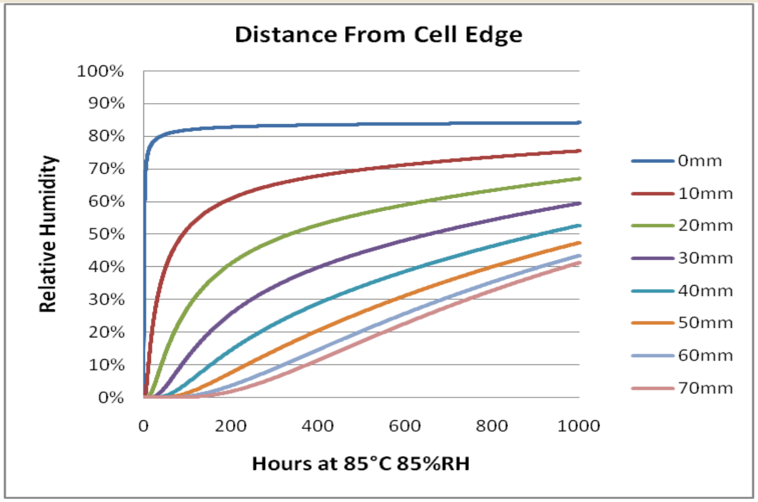
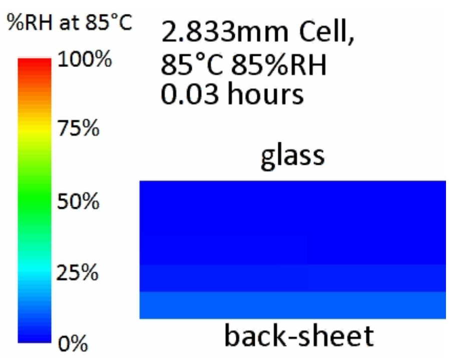
Where to begin

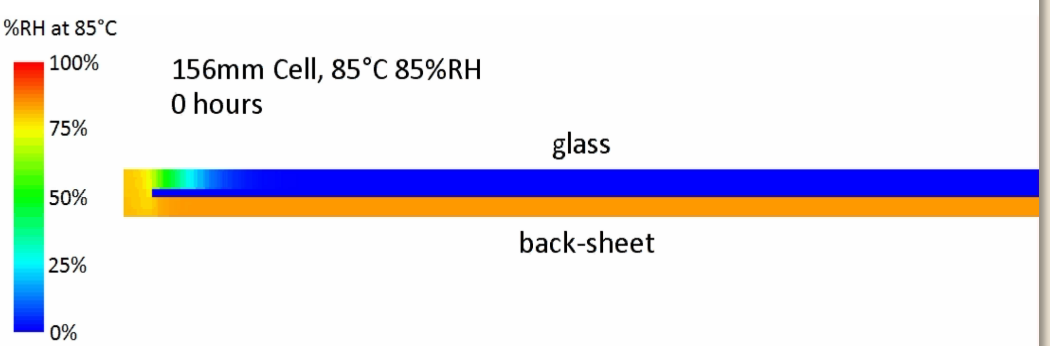
- Must understand consequence of “shortened” time-to-failure in 0V Damp Heat.
  - Modeling
    - Accelerated Modeling – Peck/Power Law and Exponential Corrosion
    - Degradation Modeling – Extrapolation of reaction rates to field conditions
- Start with the Solaria product design…



WVTR as a function of EVA transmission across sunny side of PV cell







Fick's Diffusion: $\vec{J} = -D\nabla C$

2006, Michael Kempe, *Modeling of Rates of Moisture Ingress into Photovoltaic Modules*, Solar Energy Materials & Solar Cells, Vol 90, 2006

Acceleration Model 1 – Peck/Power Law

- 1986, Stewart Peck
  - Survey of all available data on the corrosion of silicon-aluminum systems in plastic packages.
  - Goal was to identify a basic relationship that could be used to accelerate Damp Heat testing (85°C, 85%RH).

  - Basic form

$$TF = A_o \cdot RH^{-n} \cdot e^{\frac{Ea}{kT}}$$

Expanded form

$$TF = A_o \cdot RH^{-n} \cdot f(V) \cdot e^{\frac{Ea}{kT}}$$

According to the present model, acceleration factors over 85/85 results include the following:

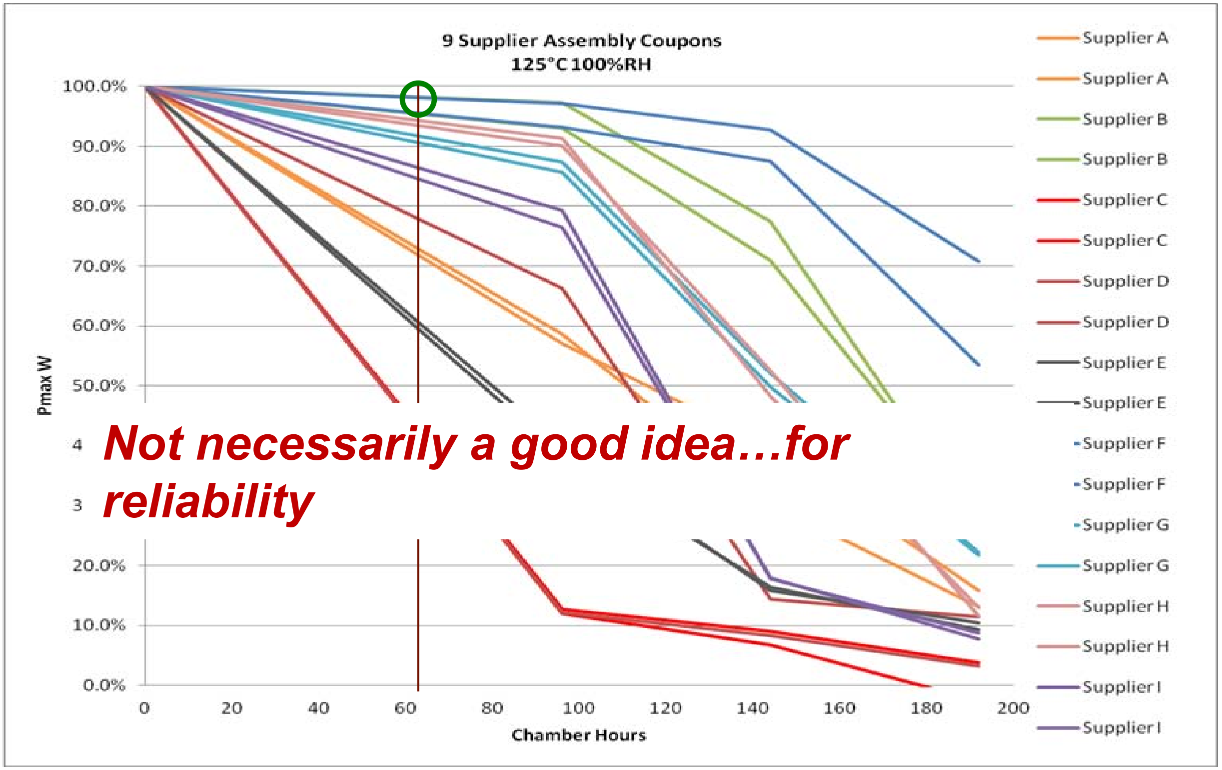
Condition	Acceleration
121/100	16
135/94	30
140/94	40
140/100	50
150/100	77

Jedec Test Method A110-B

~62.5 hours→1k hrs Damp Heat
121 C and 100%RH

Durability Cell Comparison

- Same construction coupons varying only the cell supplier.
- Primary objective, corrosion tolerance in the Damp Heat test.



Not necessarily a good idea…for reliability

Design of Experiments

Power-law humidity model [42]:

$$\mathrm{TF} = A_0(\mathrm{RH})^{-n}\exp\left(\frac{Q}{K_B T}\right)$$

Exponential humidity model [37–44]:

$$\mathrm{TF} = A_0\exp(-a\cdot\mathrm{RH})\exp\left(\frac{Q}{K_B T}\right)$$

Semiconductor corrosion failure models

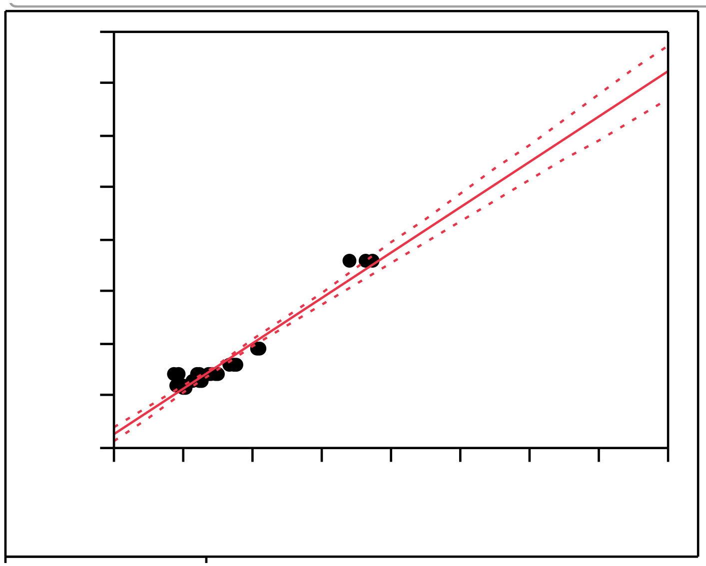
Handbook of Semiconductor Manufacturing Technology, edited by Robert Doering, Yoshio Nishi, CRC Press, 2007.

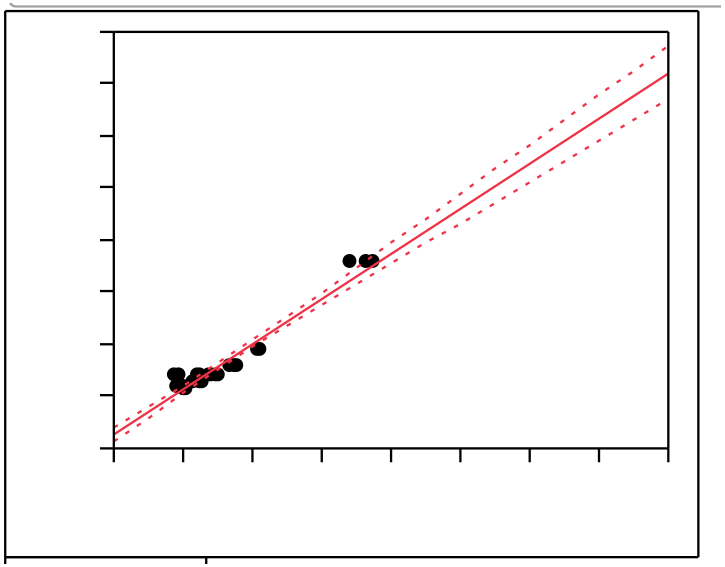
To solve these equations – several factors + time + money!

Cell	Temperature	Humidity
A/B/C	85°C	85%
A/B/C	110°C	100%
A/B/C	120°C	100%
A/B/C	125°C	100%
A/B/C	130°C	80%
A/B/C	130°C	90%
A/B/C	130°C	95%

Initial DOE

Cell Type A– 25 year window at 5% significance





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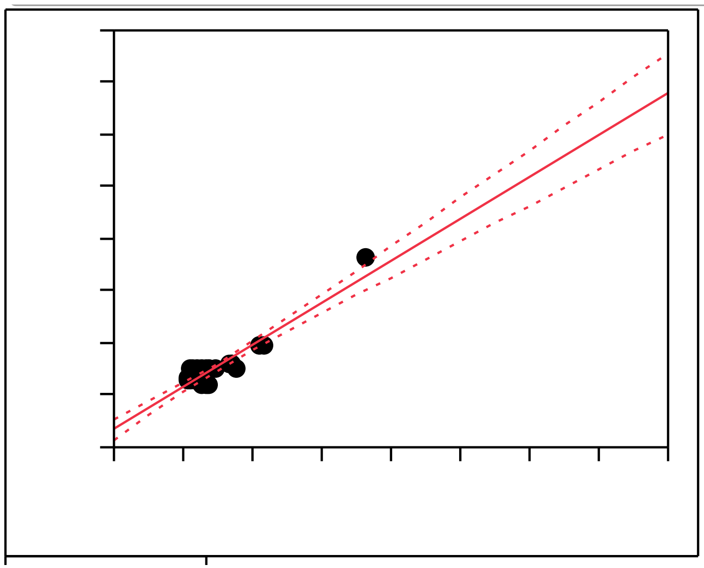
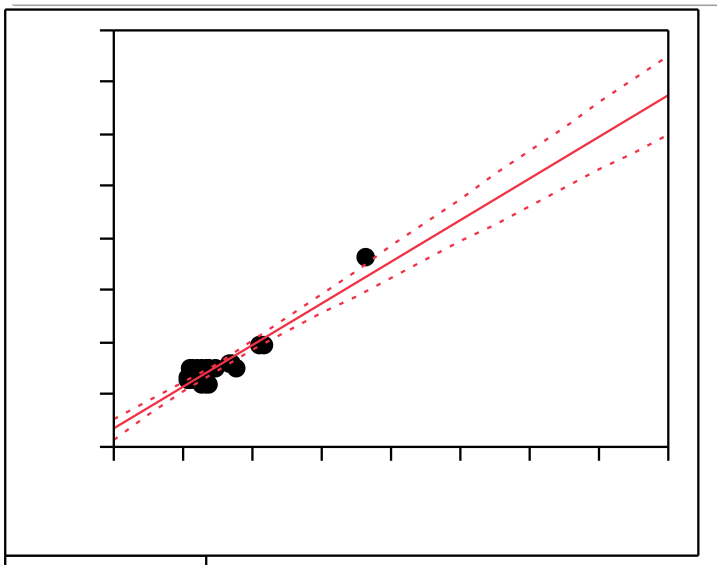
Cell Type B – 25 year window at 5% significance





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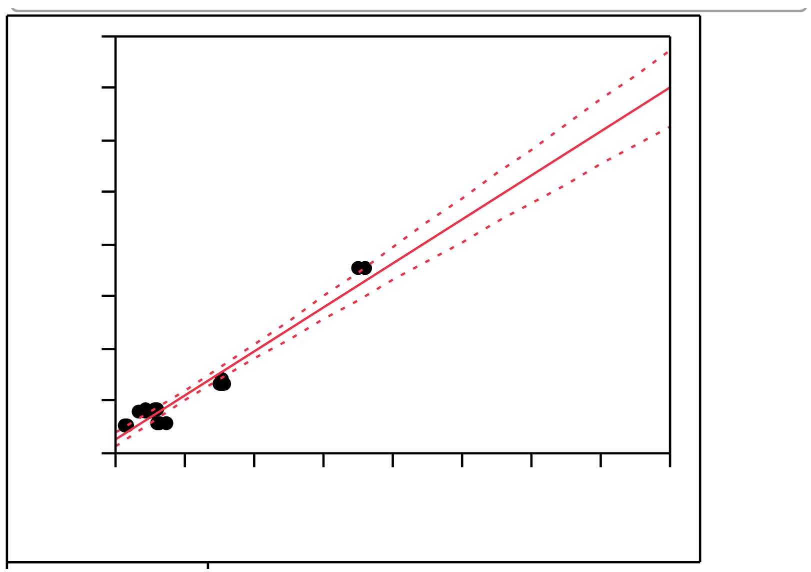
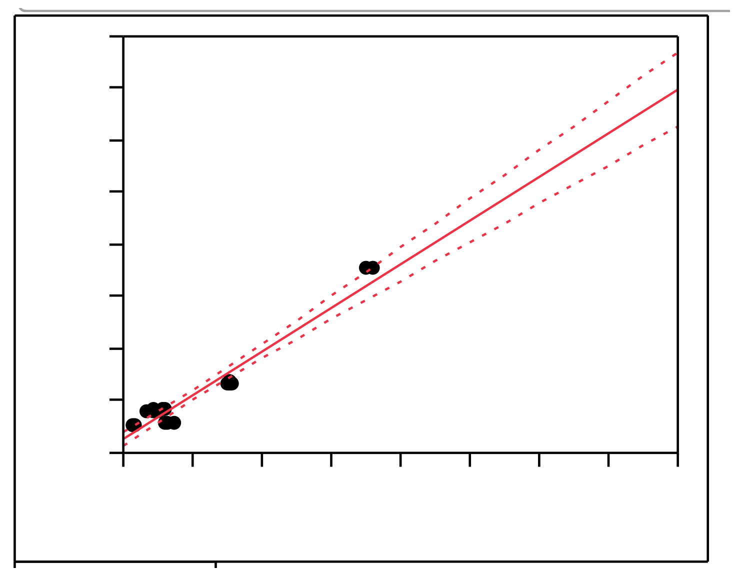
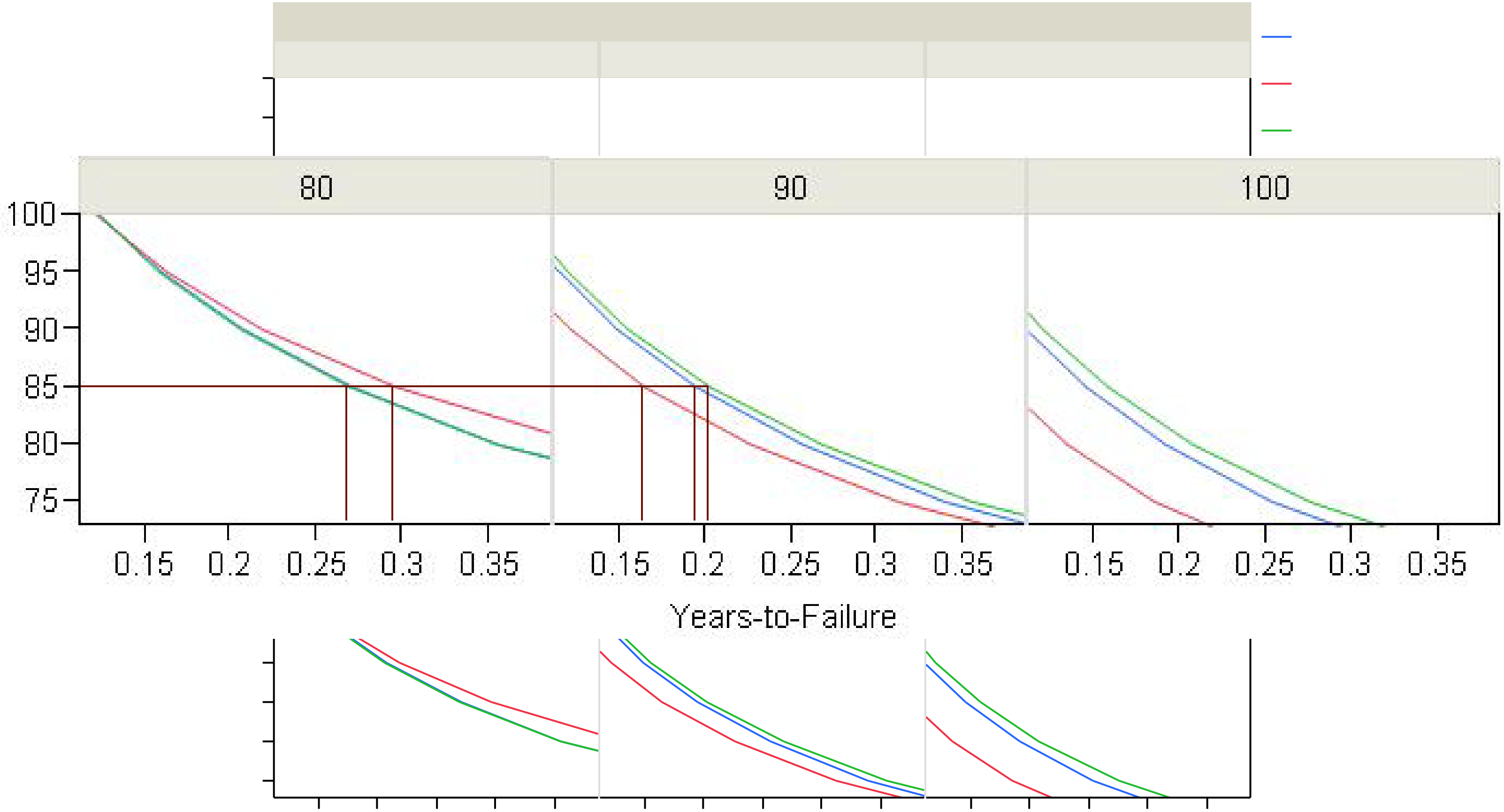
Cell Type C – 25 year window at 5% significance

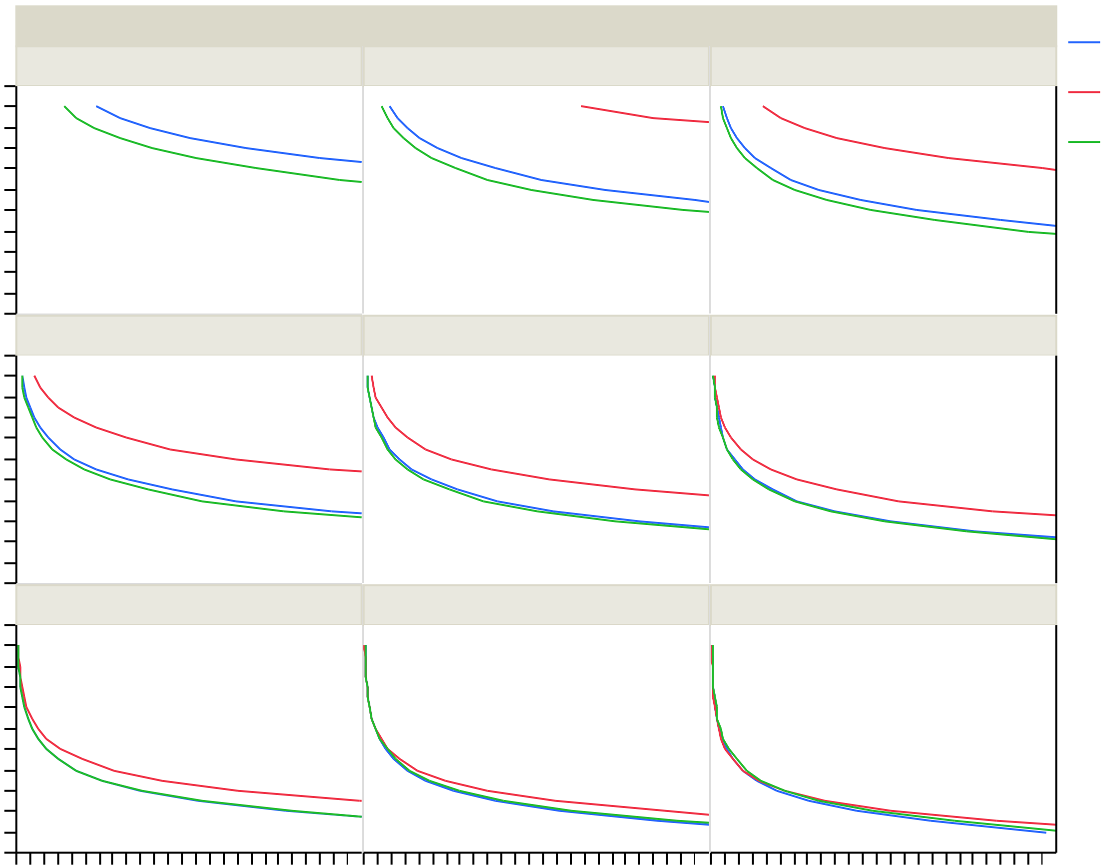




Acceleration Model Significance



Divergence at Low Humidity - Expected



Poor Agreement

Good Agreement

How to Reconcile?

Fill in the Blanks!!

Data are being collected at 120°C and 9%RH

- Prediction Peck A = 20.6 years
- Prediction Exponential A = 3600 hrs

- Prediction Peck B = 8.96 years
- Prediction Exponential B = 2700 hrs

- C-type cells are predicted to last over 1-year with the Exponential model…

Also gathering data at 95°C and 80%RH to Refine Crossover Behavior

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Modeling Product Temperature in the Field

Methodology and approach from:

+

SNL Coefficients for Solaria (2June2011):

a=-3.53, b=-0.077, $\Delta T=3$

Comparison to New Mexico Test Site

Conclusion: Method provides an ability to predict Tm to ±5°C at 95%confidence

Could also use David Faiman's approach

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RESEARCH ARTICLE

Evaluation of high-temperature exposure of photovoltaic modules

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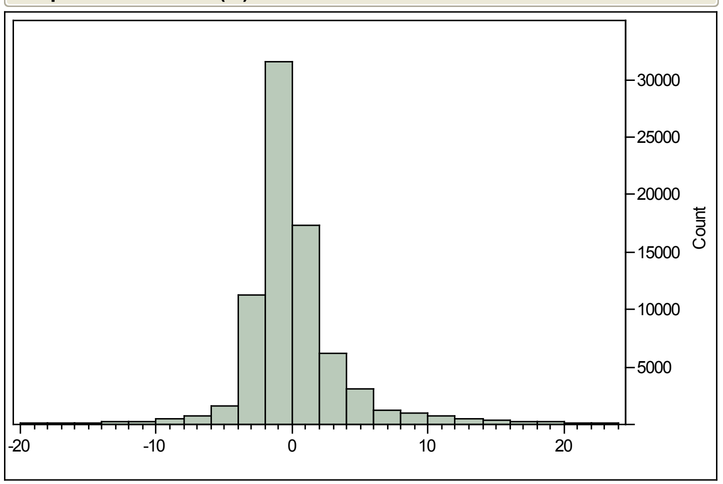
[4] Fraunhofer ISE, Freiburg, Germany
[5] Underwriters Laboratories Inc., Northbrook, IL, USA

Compensated Difference (°C)

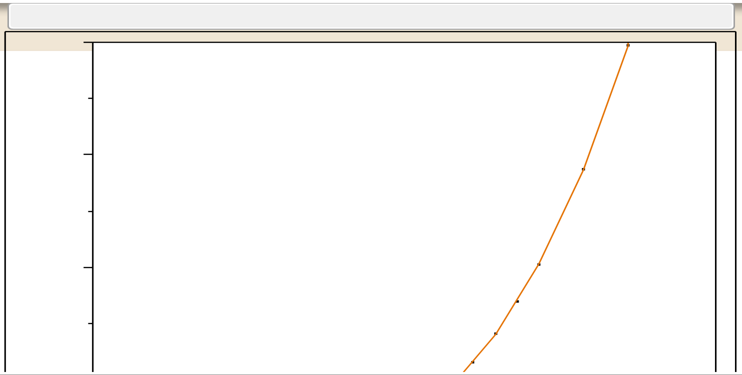


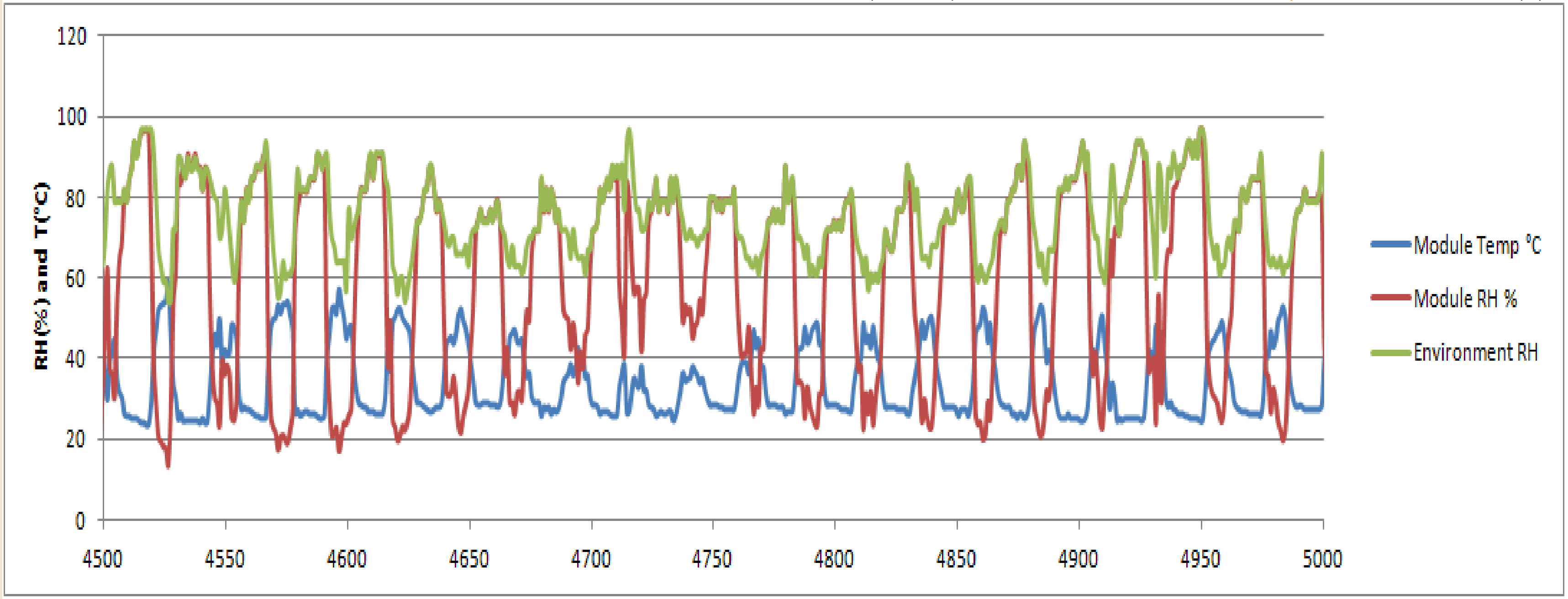
Tolerance Intervals

Proportion	Lower TI	Upper TI	1-Alpha
0.900	-5.27479	5.314319	0.950

Isobaric Heating – Module RH from Ambient

During the day, module is typically 20 to 30 C above ambient. At night, re-radiation may make module slightly cooler than ambient.





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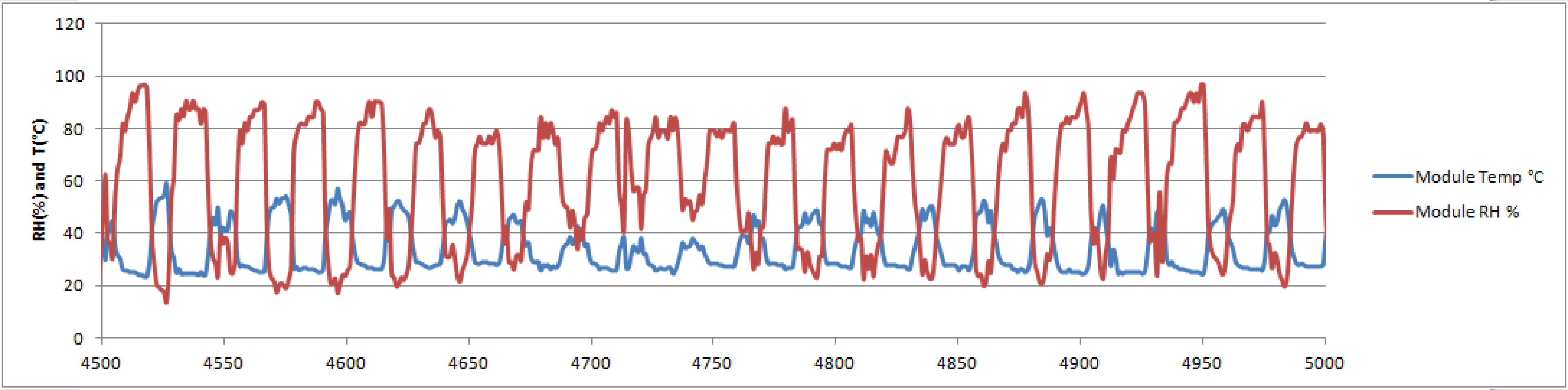
Module Temperature and Humidity



Miami, FL TMY3 Simulation

- Would not properly account for the out-of-phase nature of the relationship between the two.
- Recall that design does not have significant phase-lag, so we are assuming that it is irrelevant for now.

- Need a numerical integration method.

Degradation Model

- Assume a power law or an exponential corrosion model *will* enable us to predict a time-to-failure, TF, based on varying module temperature $T_m(t)$ and effective module humidity $RH_m(t)$.
- Furthermore, define a extent-of-reaction variable X, such that

$$X = \begin{matrix} 0 : P\max = 100\%, t = 0 \\ 1 : P\max = 80\%, t = TF \end{matrix}$$

- Where $TF = TF(RH_m, T_m)$ from the earlier acceleration models.
- If we define X=t/TF (or R*t) we also see that

$$\int_0^{X'} dX = \int_0^{t'} \frac{1}{TF(RH_m(t), T_m(t))} dt$$

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Making a Field Connection

- We consider, one *typical* year, where, using the exponential corrosion accelerated model,

$$TF(Tm_t, RHm_t) = A * e^{-b \cdot RHm(t)} * e^{Ea / k \cdot Tm(t)}$$

$$X' = \int_0^{t'} \frac{1}{A * e^{-b \cdot RHm(t)} * e^{Ea / k \cdot Tm(t)}} dt = \int_0^{1\,year} \frac{1}{A} * e^{b \cdot RHm(t)} * e^{-Ea / k \cdot Tm(t)} dt$$

- As all *typical* years are the same, the integrand becomes a constant reaction rate such that

$$X' = R * (1 year)$$

and at failure, $1 = R * TF(years)$

or $TF = \frac{1}{R} = \frac{1}{X'}$

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Finally

- Numerical integration method over a one-year weather file and presume that this weather pattern repeats itself indefinitely.

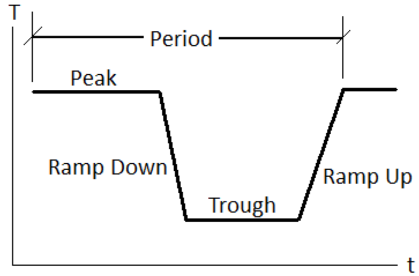
12839 Miami, FL -5						
	A-Power	B-Power	C-Power	A-Exponential	B-Exponential	C-Exponential
Reaction Extent after One Year	4.69%	4.88%	2.22%	6.26%	6.61%	2.70%
Time to Failure (Years)	21	20	45	16	15	37

725090 Boston, MA -5						
	A-Power	B-Power	C-Power	A-Exponential	B-Exponential	C-Exponential
Reaction Extent after One Year	1.78%	1.83%	0.82%	2.46%	2.60%	0.99%
Time to Failure (Years)	56	55	122	41	38	101

722780 Phoenix, AZ -7						
	A-Power	B-Power	C-Power	A-Exponential	B-Exponential	C-Exponential
Reaction Extent after One Year	0.64%	0.78%	0.16%	3.50%	4.45%	0.59%
Time to Failure (Years)	156	127	622	29	22	169

- Divergence between Power Law and Exponential Models extreme for dry climates!

More Work Needed

- Longer duration data at lower stress levels mandatory because at highly accelerated conditions:
  - Effect of measurement uncertainty exaggerated
  - Effect of testing perturbations exaggerated.
- Real effort – Validation
  - Must corroborate predictions against a test!
  - 

- Starting with 125°C, 100%RH to a 85°C, 85%RH trough

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Conclusions

- Damp Heat has been the standard corrosion test for well over 30 years.
  - Remains an important milestone for certification and will always have a place in my heart.
  - Cannot alone enable reliability prediction.
    - Must perform multiple-stress tests to understand risk.
    - Interpretation requires a modeling approach. Shown here:
      - Acceleration Models (Peck/Power Law or Exponential Corrosion)
      - Degradation Modeling (Linear extrapolation based on a constant reaction rate calculated over a typical meteorological year)
        - » Presumes knowledge of module temperature and "module" humidity
        - » Shown here was an isobaric approximation for "module" humidity based on an assumption of infinitely fast mass transfer ~clear approximation
- Running a 2000-3000 hour Damp Heat test will not guarantee a 25-year life!

Select References

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