Determining PID-resistance based on accelerated tests extrapolated to field stress levels

Scope

- Not on mechanism – more on method!
- Not on quality – more on reliability!

- Business reality
  - Demands a high-degree of comfort with fielding modules in a floating array.
  - Acknowledges risk
    - Being wrong may result in MW-sized replacements in as soon as 1 year.
    - Banks and Independent Engineers are not happy with ambiguity.

- Observations from running nineteen ~2m^2 modules at a negative bias in an elevated temperature and humidity DOE.
  - Leakage current stability is an issue
  - Leakage current variability is not trivial
  - Resulted in a lower activation energy than other works and may support multiple current paths.

- Need - A consensus-driven approach to reliability from accelerated testing.

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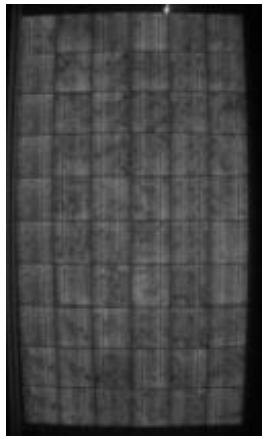
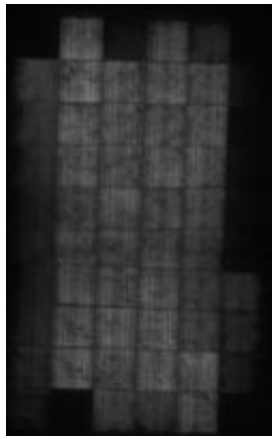
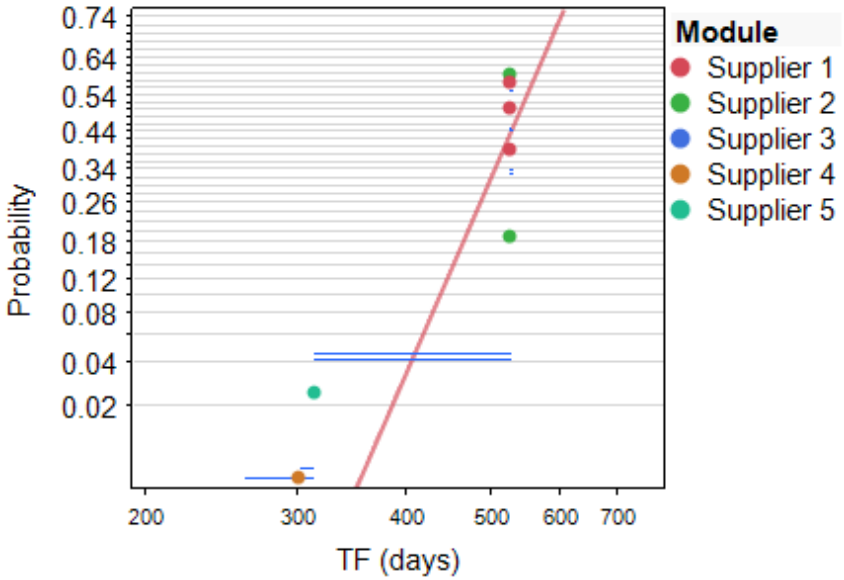
PID Reality

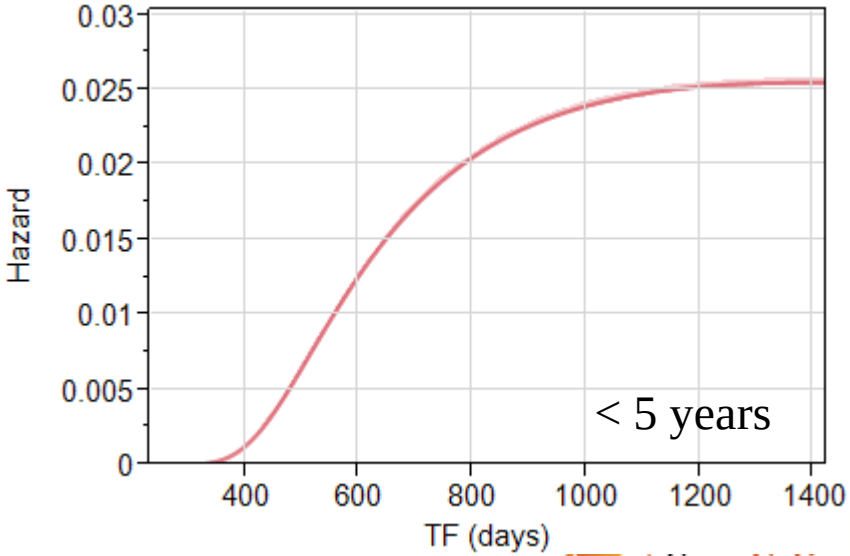
- PID from supplier modules
  - EL indicates cell damage near grounded frame.
  - High probability of occurrence in 2 years – if it is going to occur.

Pattern matters!



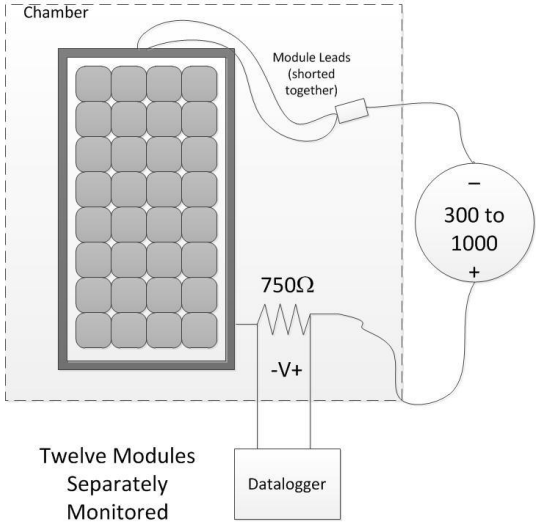






Plan

- "How long do I test the modules to ensure they are not at risk of developing PID?"
  - Characterize similar full-sized modules.
  - Design of Experiments: Vary T, RH, V and measure
    - Coulombs to failure
    - Leakage current
    - Extrapolate leakage current function to field stress levels and accumulate to a 5-year Coulomb value.
    - Run accelerated testing to 5-year Coulomb value and look for degradation levels >5% coincident with tell-tale signs of PID.
  - Answer requires several guesses
    - Issues with comparing Coulombs to fail
    - Accelerated tests affect all cells in the module
    - Implication of leakage current variability



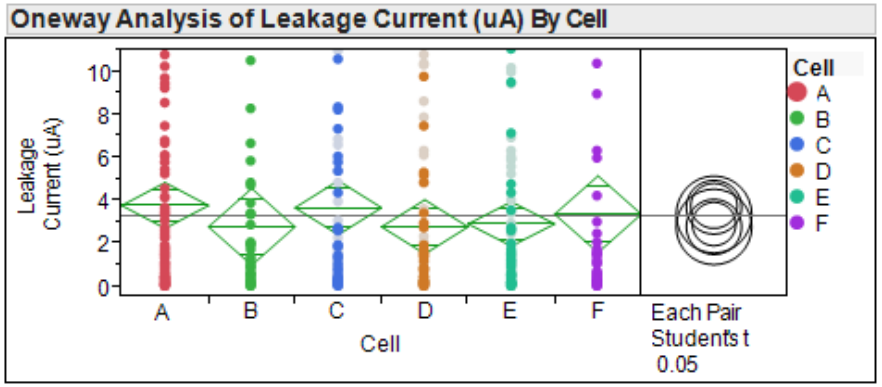
DOE

- 19 samples into a 4x3x3 + 1 + 1 condition study
  - 13→

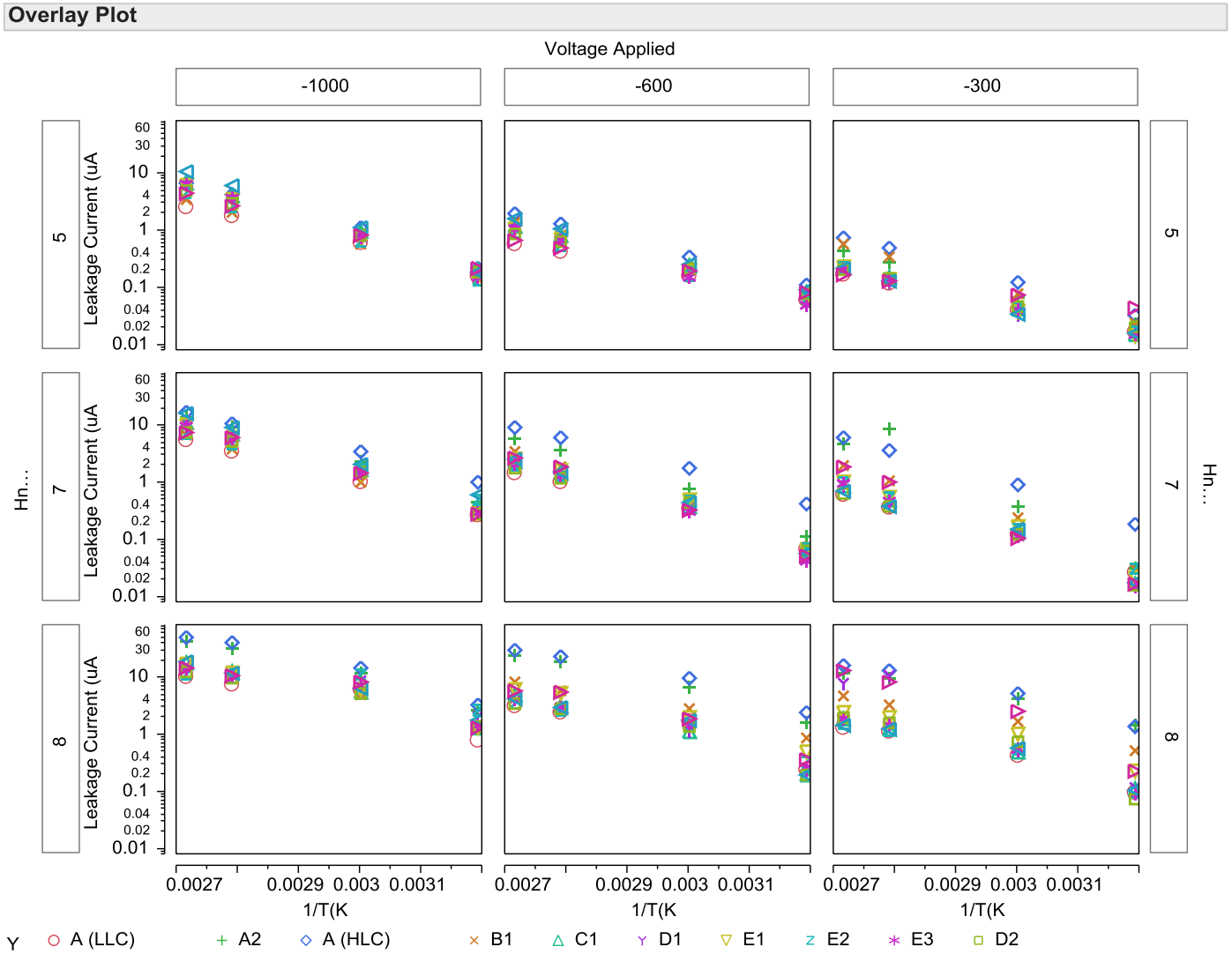
Temp. (°C) & Dwell (hours)	Humidity (%RH)	Voltage Bias (-V)
40 / 2	50	300
60 / 6	70	600
85 / 8	85	1000
95 / 8		

    - Added 90°C, 90%RH, -1000V for 48 hours
  - 6→85°C, 85%RH, -1000V for 1200+hours

- 72-cell monocrystalline Si p-type BSF, 3.2mm tempered ARC glass, EVA encapsulant, TPE backsheet, aluminum frame.
  - Different cells studied, however, leakage current did not correlate to cell and highest and lowest leakage current occurred within the replicates for one cell type.

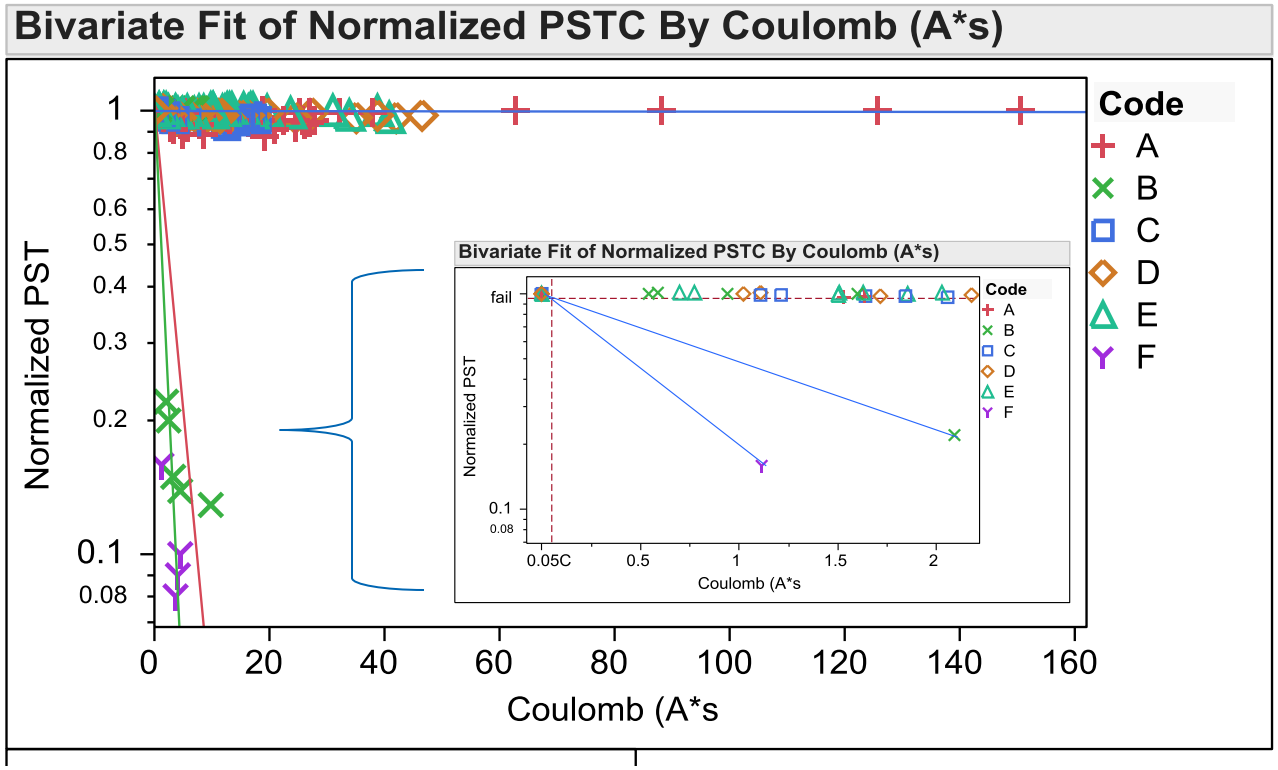


Leakage Current Results

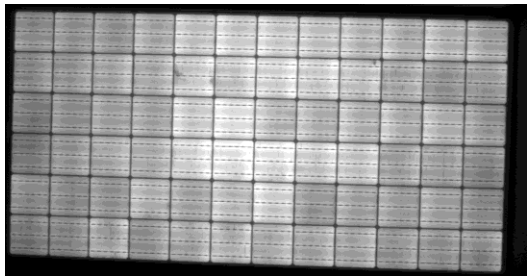


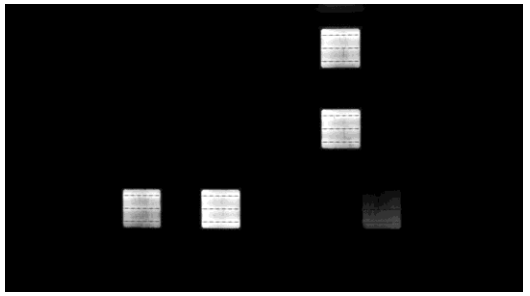
- Reasonable linearity.
- Rational voltage and humidity relationship.
- Large spread of leakage current results.

Coulomb Result



Pattern matters!





- At 85C/85%RH, -1000V failure occurs in a short time in test - consistent with other works.
- Pattern inconsistency with field → Affects Pmax degradation rate!
  - May contribute to Type 1 error; deemed conservative
- What about Coulombs? Data suggests as little as 0.05C for 5% drop.
  - 0.5C taken as a conservative limit.

Hoffmann and Koehl, 2012

What might 0.5C mean in the field?

- 0.2 C in 2 years @ -600V in the Canary Islands
- 0.5 C in ~ 3.3 years

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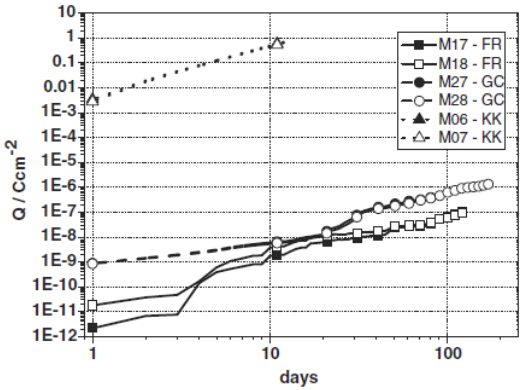
RESEARCH ARTICLE

Effect of humidity and temperature on the potential-induced degradation

Stephan Hoffmann and Michael Koehl*

Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, D-79110 Freiburg, Germany



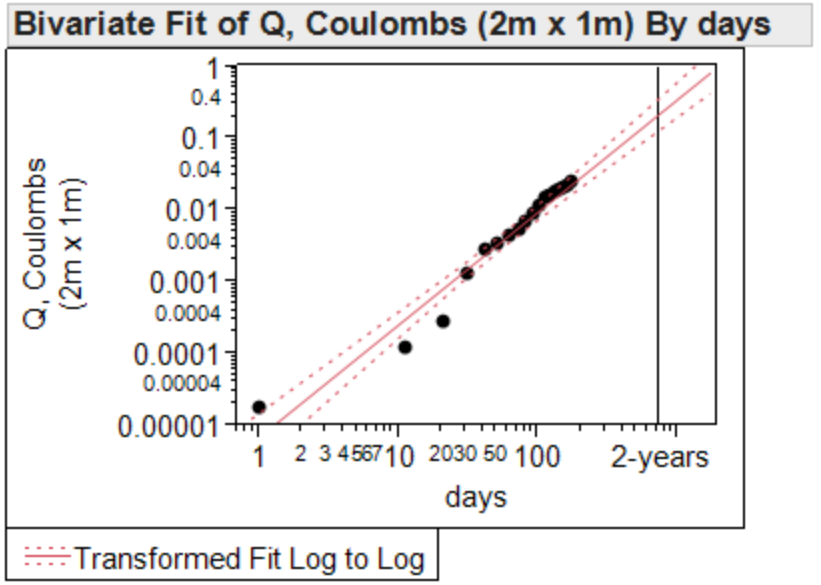


Figure 9. Cumulated leakage current as function of the time for exposure in Canary Island (circles and points), Freiburg (squares and straight line) and during damp-heat testing (85% relative humidity at 85 °C) (triangles and dashed line) for always two modules with different bias voltage of 600 V direct current (solid symbols) and 450 V direct current (open symbols).

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Del Cueto and Rummel, 2010

Degradation of Photovoltaic Modules Under High Voltage Stress in the Field

Preprint

J.A. del Cueto and S.R. Rummel

To be presented at SPIE 2010 Optics and Photonics Conference
San Diego, California
August 1-5, 2010

Generally a lack of individual module leakage current measurements. More under fixed external bias.

0.5 Coulomb (in this work) was accumulated in ~ 1 year, for the portion of study where voltage was varied 10-600V.

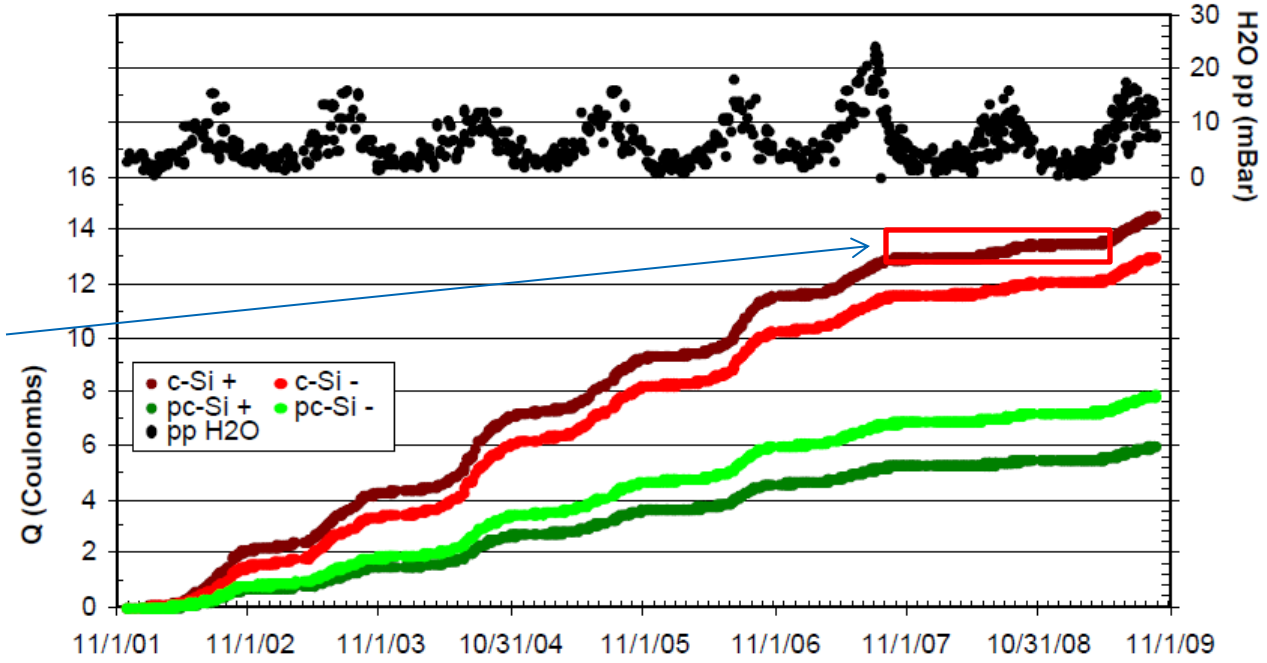

Figure 6. Integrated charge on c-Si and pc-Si modules read along the left-hand abscissae plotted vs. time; and partial pressure of water vapor in the atmosphere, read along the right-hand abscissae, also plotted vs. time.

Results in General

- Leakage current behavior not simple.
  - Suspicions:
    - Nature of leakage current paths through module may change as a function of test conditions. Not new.
    - Surface conductivity of glass strongly suspected to change the effective influence of the grounded frame over the biased cells. Not new.
    - Distances through EVA are NOT constant sample-to-sample. Not aware of this in other works.
- Dwell at test conditions is critical to repeatability.

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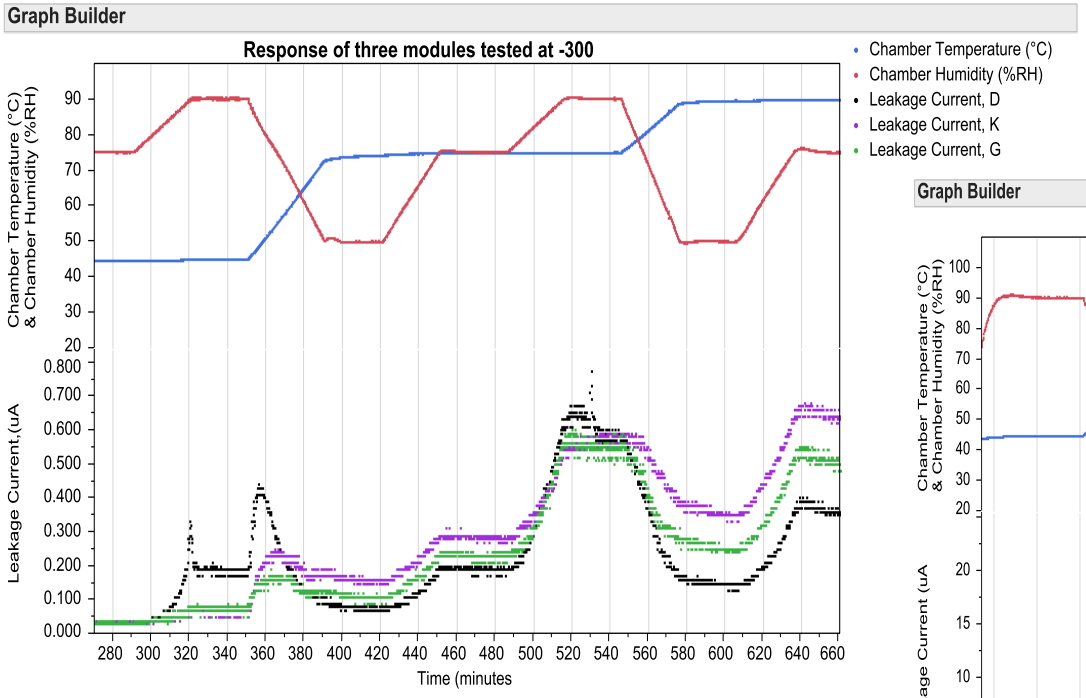
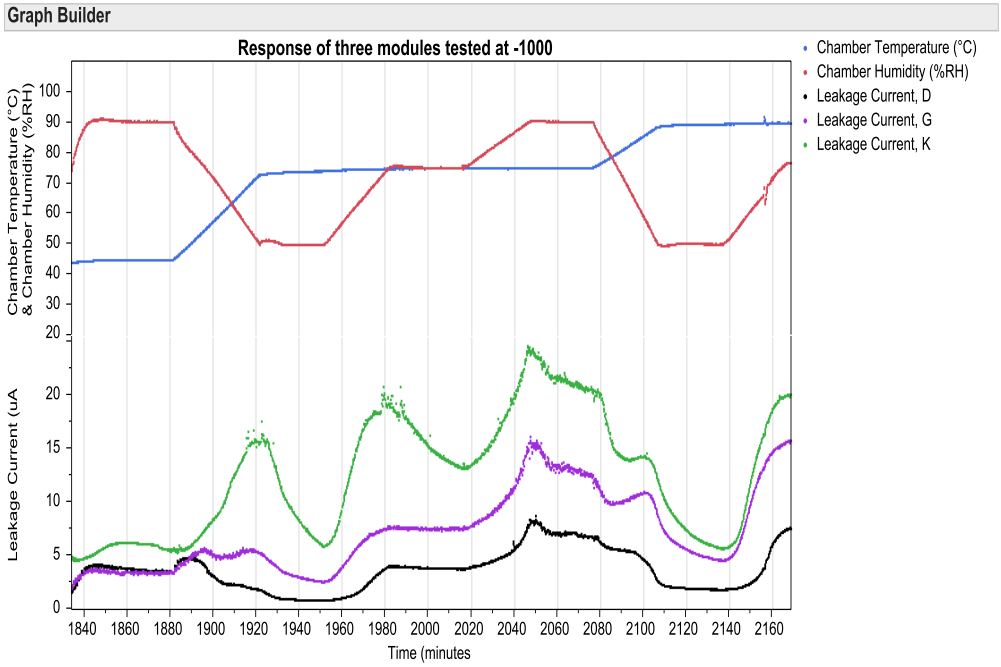
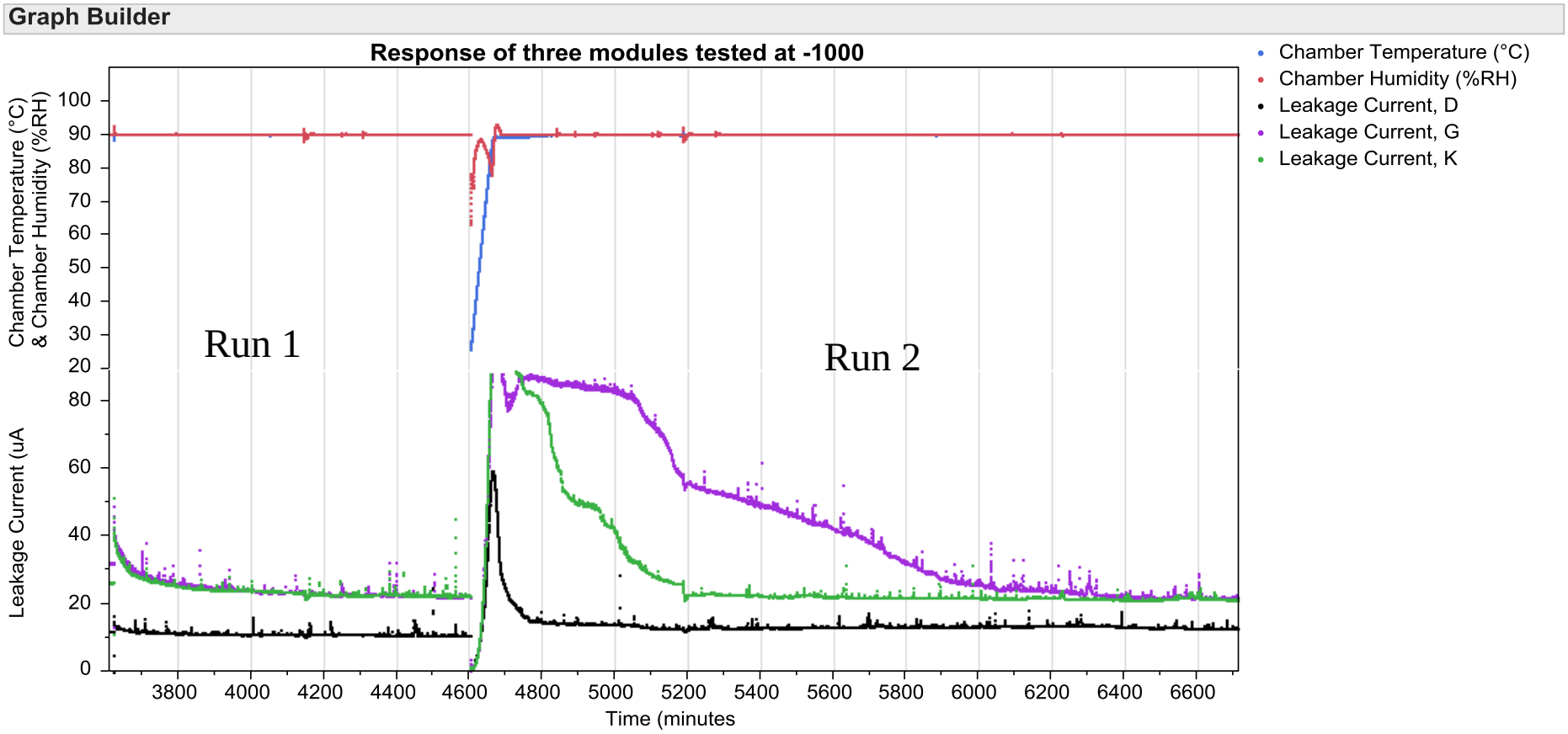
Leakage Current Stability





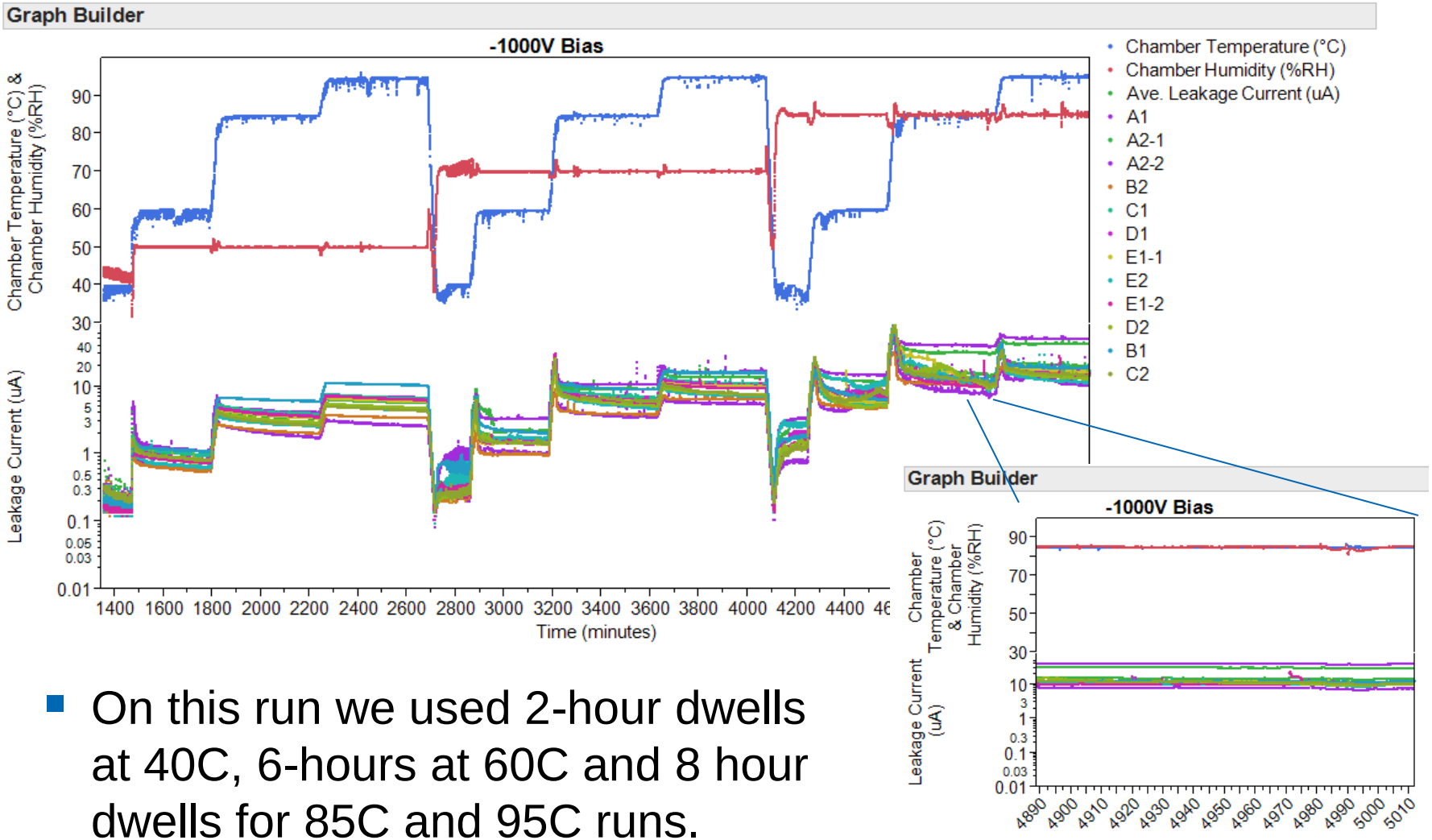
- Voltage has a strong impact on LC settling time.

Leakage Current Stability



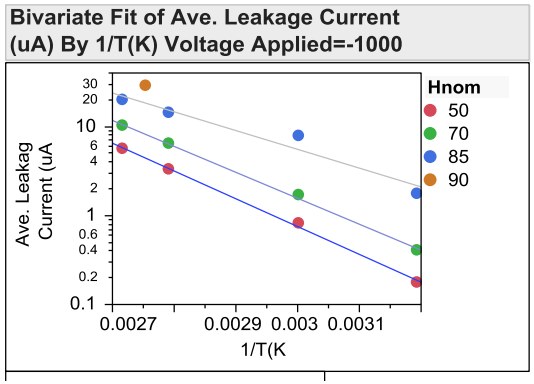
- Humidity at higher temperatures has a SIGNIFICANT effect on stability. Very pronounced at 85% and above.

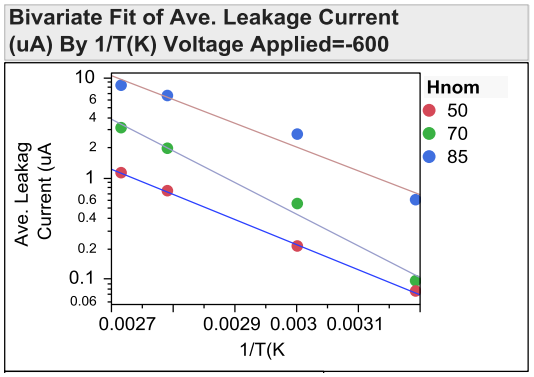
General Approach for Data Collection

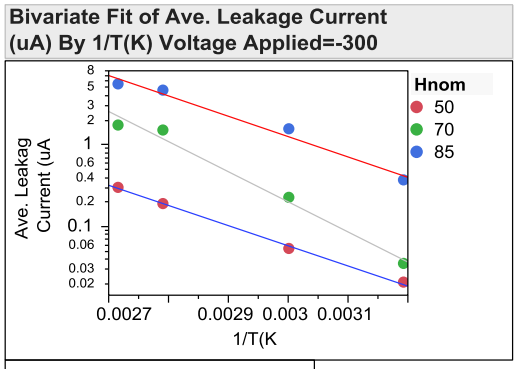


- On this run we used 2-hour dwells at 40C, 6-hours at 60C and 8 hour dwells for 85C and 95C runs.

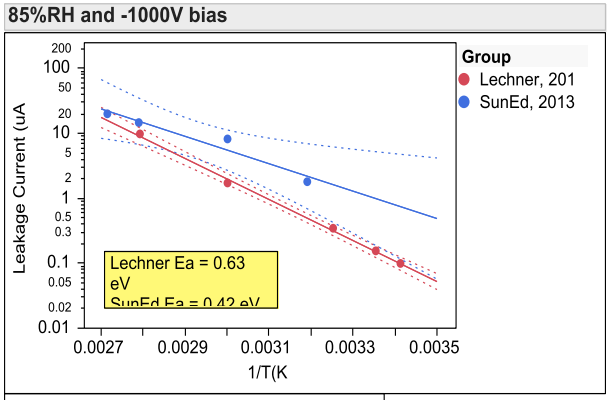
Runs Analyzed Individually

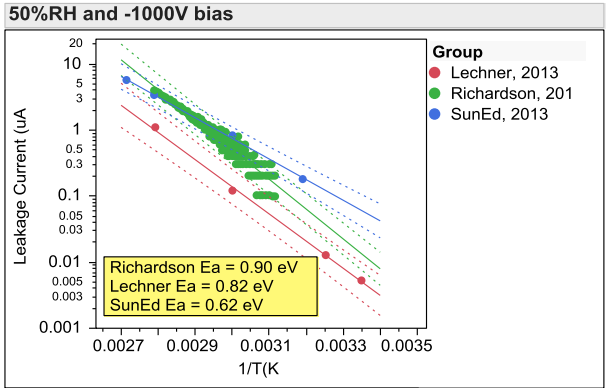






As compared to others, outcome was lower Ea





- Considerable variability, so remaining focus on best fit to highest LC dataset

		Average Leakage Current-Derived		Highest Leakage Current Sample	
Humidity (%RH)	Voltage (V)	Prefactor (A)	Ea (eV)	Prefactor (A)	Ea (eV)
50	-1000	1765	0.620	2238	0.620
50	-600	6.567	0.494	34.50	0.529
50	-300	1.416	0.488	58.34	0.575
70	-1000	875.7	0.579	149.0	0.507
70	-600	1165	0.623	337.3	0.551
70	-300	21340	0.729	2039	0.622
85	-1000	11.85	0.419	284.7	0.489
85	-600	24.69	0.468	54.32	0.454
85	-300	35.42	0.493	22.61	0.445

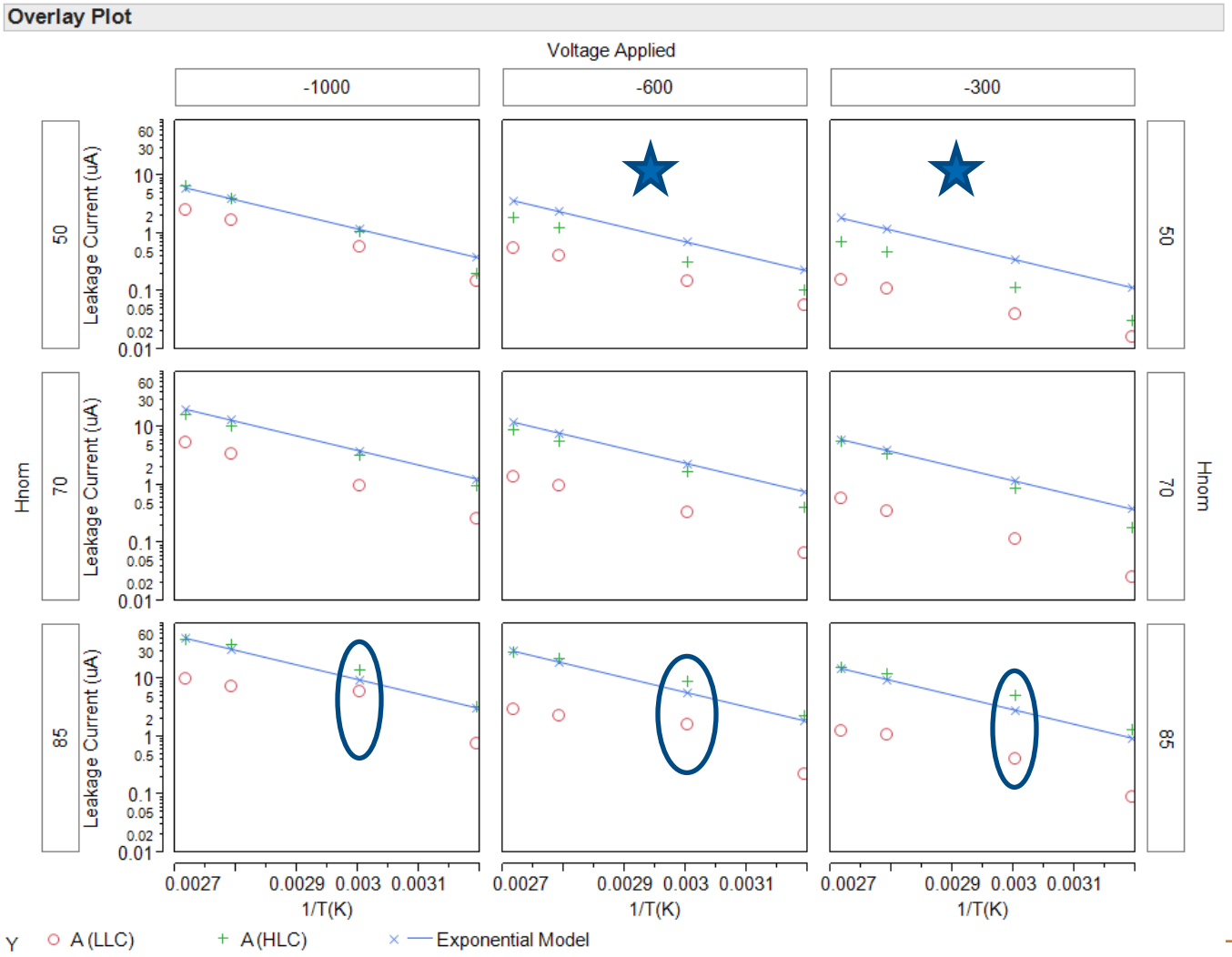
Nonlinear Regression to a Standard Model

- Already have an indication that thermal rate of change of Coulombs is not constant.
  - Presume that there exists a relationship between the significant independent variables that allows us to separately estimate apparent contributions to rate (i.e., LC) due to voltage, relative humidity and temperature.
  - Results are then interpreted as *apparent* activation energy.

- Many models exist (ref JEDEC JEP122C, also Hoffmann and Koehl)
  - Selected exponential corrosion model
    - Rate basis→ $R \propto LC = A \cdot e^{n \cdot RH} \cdot e^{\frac{-Ea}{k \cdot T}} \cdot f(V)$ and $f(V) \propto V$
  - Use nonlinear regression to seek unknowns using the highest leakage current (HLC) data set.

Model Result

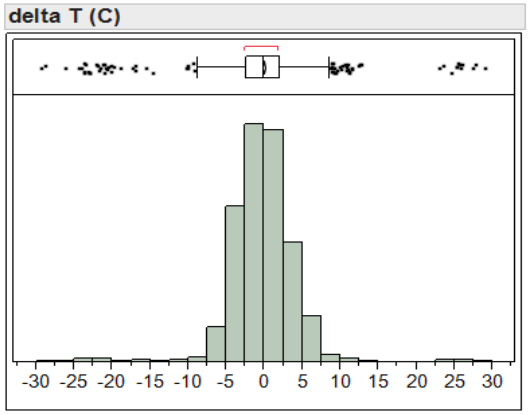
$$HLC(\mu A) = 2200(\mu A/V)\cdot V(V)\cdot e^{0.06/\%\cdot RH_{\text{module}}(\%)}\cdot e^{\frac{-0.5eV}{k\cdot T_{\text{module}}}}$$



Model is considerably conservative to the data

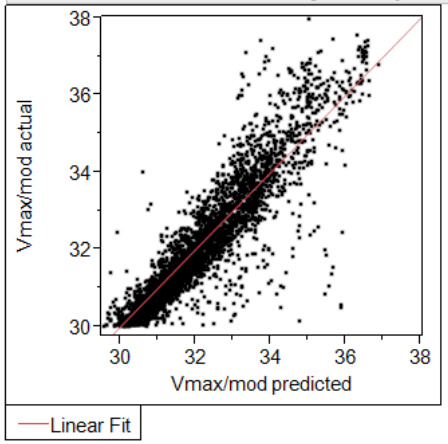
Model under predicts at 60C for the 85%RH condition.

5-year Coulomb Modeling using TMY Input



Summary Statistics

Mean	-0.128375
Std Dev	4.1199455
Std Err Mean	0.0709492
Upper 95% Mean	0.0107324
Lower 95% Mean	-0.267483
N	3372



Nonlinear Fit

Prediction Model

POA Irrad * Exp(a + b * WS)

+ Tambient

Response: Tmodule, Predictor: Model

Control Panel

Converged in Gradient

Criterion	Current	Stop Limit
Iteration	10	60
Obj Change	8.770905e-13	1e-15
Relative Gradient	8.5053269e-7	0.000001
Gradient	0.0000365869	0.000001

Parameter	Current Value	Lock
a	-3.262535366	☐
b	-0.073205032	☐

SSE 57274.761173
N 3372

Edit Alpha	0.050
Convergence Criterion	0.00001
Goal SSE for CL	.

Nonlinear Fit

Prediction Model

(b0 * Tmodule
+ b1 * Tmodule * Log(POA Irrad))
+ b2 * Log(POA Irrad)

Response: Vmax/mod, Predictor: Vmax predicted

Control Panel

Converged in Gradient

Criterion	Current	Stop Limit
Iteration	1	60
Obj Change	3888420.9008	1e-15
Relative Gradient	1.1430988e-9	0.000001
Gradient	7.54943e-9	0.000001

Parameter	Current Value	Lock
b0	0.6377882383	☐
b1	-0.114189087	☐
b2	5.7443317286	☐

SSE 1823.282725
N 3372

Edit Alpha	0.050
Convergence Criterion	0.00001
Goal SSE for CL	.

1. Estimate module temperature from irradiance, ambient temperature and wind speed.
2. Estimate maximum module voltage based on module temperature and irradiance. *Needs to be translated to a system voltage.*
3. Assume an isobaric heating approximation for module effective humidity.

$$RH_{\text{module}} = \frac{RH_{ambient} \cdot P_{sat}(T_{ambient})}{P_{sat}(T_{\text{module}})}$$

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Results

DONE: Determines 5-Year Coulombs in a specific location. Can also estimate how long the test runs for a high-leakage current sample.

$$HLC(\mu A) = 2200(\mu A/V)\cdot V_{sys}(V)/2\cdot e^{0.06/\%\cdot RH_{\text{module}}(\%)}\cdot e^{\frac{-0.5eV}{k\cdot T_{\text{module}}}}$$

Re-running the model with the lowest leakage current data helps establish how long the test might take.

$$LLC(\mu A) = 1319(\mu A/V)\cdot V_{sys}(V)/2\cdot e^{0.046/\%\cdot RH_{\text{module}}(\%)}\cdot e^{\frac{-0.5eV}{k\cdot T_{\text{module}}}}$$

- Basic forward stepping numerical integration over the course of a typical year.

	Five-Year Coulombs (Target Value to Complete Test)	HLC Estimated Testing Time at 85°C, 85%RH, -1000V	LLC Estimated Testing Time at 85°C, 85%RH, -1000V
Bangkok, Thailand	8.6	72	399
Miami, FL	8	67	371
Boston, MA	4.6	38	213
Munich, Germany	4.3	36	199
Denver, CO	2	17	93
Phoenix, AZ	1.8	15	83
Riyadh, Saudi Arabia	1.5	13	70

Conclusions

- Field data of PID failures have occurred in less that two years.
  - Definition of failure selected to be >5% degradation with EL indicating PID within a five-year service time in the field.
- Data from modules tested
  - Indicate PID failure in < 0.5C with others showing stability to > 50C.
    - 1 to 3.3 field years based on others' works consistent with our failure definition
  - Generally conforms to an expanded exponential corrosion model that can be extrapolated to field conditions.
    - Allows for an accelerated test that is terminated based on accumulated charge related to time in the field.
      - 5-year Bangkok estimate 8.6C
      - Likely would take less than two-weeks of -1000V Damp Heat testing to achieve
    - Process believed conservative, however:
      - Variability of leakage current data at a fixed testing condition not well understood.
      - General lack of individual module leakage current data from actual floating arrays in the field to validate results.
- General process of extrapolating accelerated test results to use conditions is an area requiring consensus-driven procedures for PV modules.
  - Well developed in the semiconductor industry.
  - New effort underway for inverters.

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