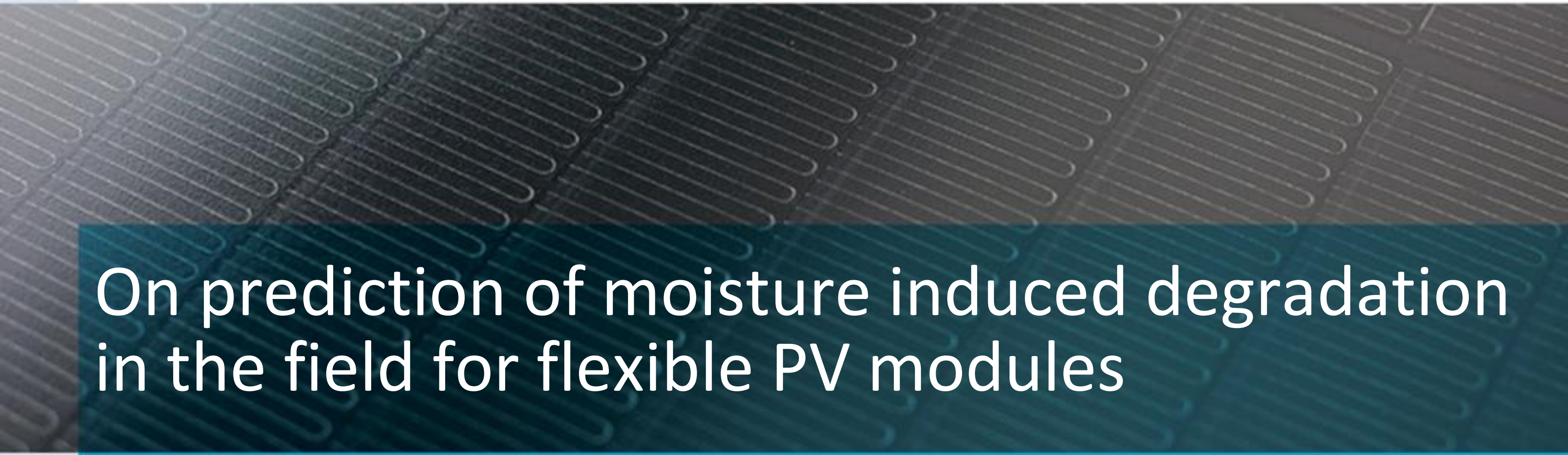

On prediction of moisture induced degradation in the field for flexible PV modules

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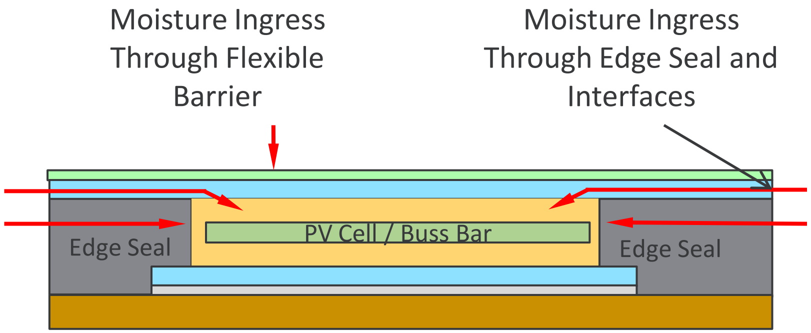
Background

- MiaSolé is a leading manufacturer of high efficiency low cost CIGS thin film solar cells and modules
- MiaSolé has demonstrated a record efficiency of >16.5% for its CIGS thin film flexible solar panels.
- For flexible PV modules using new technology relevant field data is not yet available over extensive periods since the product is recently introduced.
- The design and material choices for the product need to meet stringent reliability criteria to guarantee product performance over the long product life.
- Relating accelerated test results to PV module performance in the field under aggressive environmental conditions is challenging.

A representative MiaSolé flexible panel

Outline

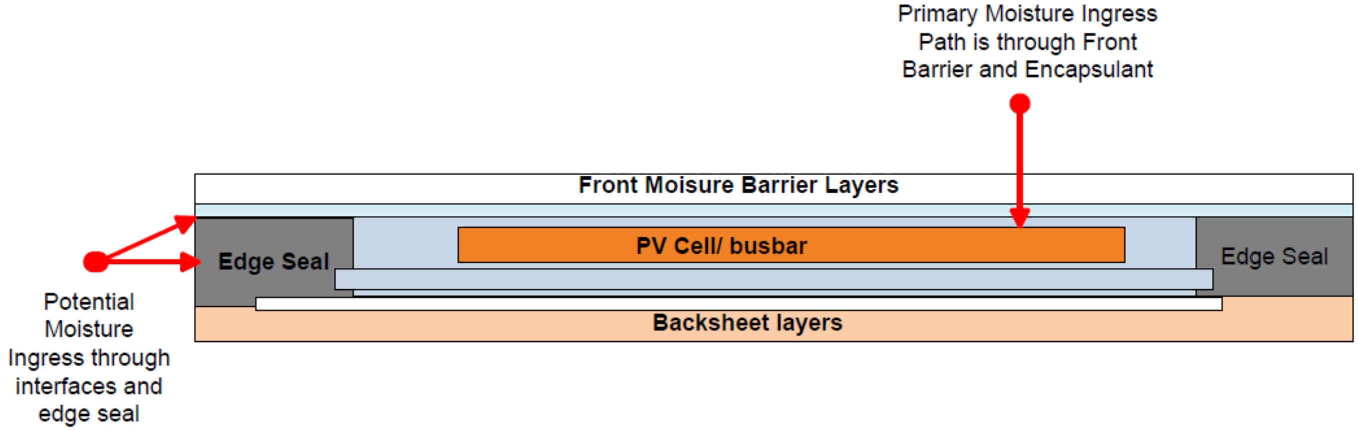
- Semi-Analytical model for accelerated testing and lifetime prediction based on moisture ingress.
- Candidate empirical model for moisture induced degradation.
- Acceleration factor model development and lifetime prediction.
- Module lifetime prediction for moisture induced degradation based on framework for rate processes.
- Conclusions



Potential moisture ingress through multiple paths in a flexible module

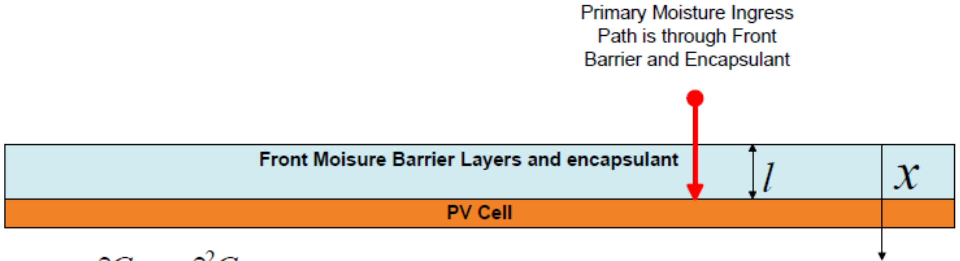
Identifying primary path for moisture ingress

- When the edge seal width is sufficiently large the primary path for moisture ingress in a flexible PV module is through the front barrier.
- It was demonstrated in the past through development of an acceleration factor model and testing of Miasole module construction that 10mm wide edge seal in glass-glass product is sufficient to prevent moisture ingress beyond typical warranty period of ~25 years.
- The study was extended to establish the critical width of edge seal for flexible module to be 14mm or greater.



Diffusion-based model

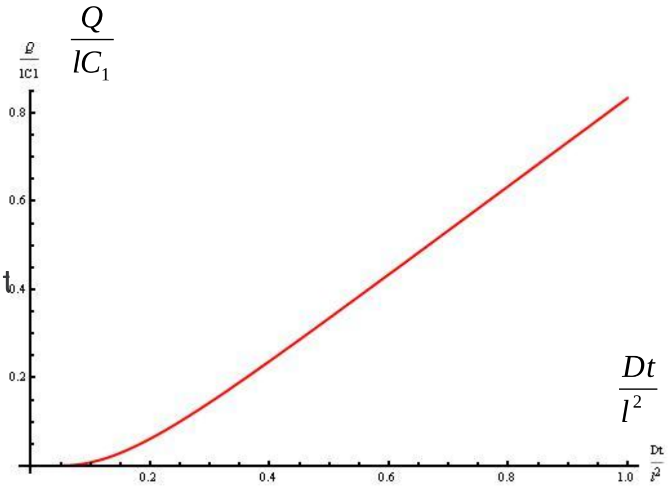
- ► Moisture ingress and associated cell degradation can be modeled using 1-D diffusion equation
- ► Analytical solution is available in literature and can provide insights into expected scaling enabling development of an acceleration factor model.


Primary Moisture Ingress Path is through Front Barrier and Encapsulant

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2};\quad C(x=0,t)=C_1;\quad C(x=l,t)=0;\quad C(x,t=0)=C_0$$

Analytical solution for quantity Q_t of moisture that has arrived at the cell up to time ‘t’

$$\frac{Q}{lC_1} = \frac{Dt}{l^2} - \frac{1}{6} - \frac{2}{\pi^2}\sum_{1}^{\infty}\frac{(-1)^n}{n^2}\exp\left(-\frac{Dn^2\pi^2 t}{l^2}\right)$$



Implications from Diffusion-based model

- If the degradation of cell is assumed to be proportional to the amount of moisture arriving at the cell, the degradation (reduction in module power) is expected to be linear in time

$$\left(\frac{\Delta P}{P}\right) \propto t$$

- Degradation (amount of moisture arriving) is proportional to external concentration C1 and implies that time to failure as defined by critical degradation can be expected to be inversely proportional to RH

$$\left(\frac{\Delta P}{P}\right) \propto (RH)$$

- Combining the above with expected Arrhenius behavior of diffusion coefficient provides a semi-analytical model for time to failure -

$$TTF \propto (RH)^{-1} \exp\left(\frac{\varepsilon_a}{kT}\right)$$

- The exponent for RH can presumably be different depending on the nature of reaction between the moisture and cell

Candidate Empirical Acceleration Factor Model

- In consumer electronics industry Hallberg-Peck model [1] is used to predict performance against moisture induced failures.

$$AF = \frac{TTF(field)}{TTF(test)} = \left(\frac{RH_{field}}{RH_{test}}\right)^{n} \exp\left(\frac{\varepsilon_a}{k}\left[\frac{1}{T_{field}} - \frac{1}{T_{test}}\right]\right)$$

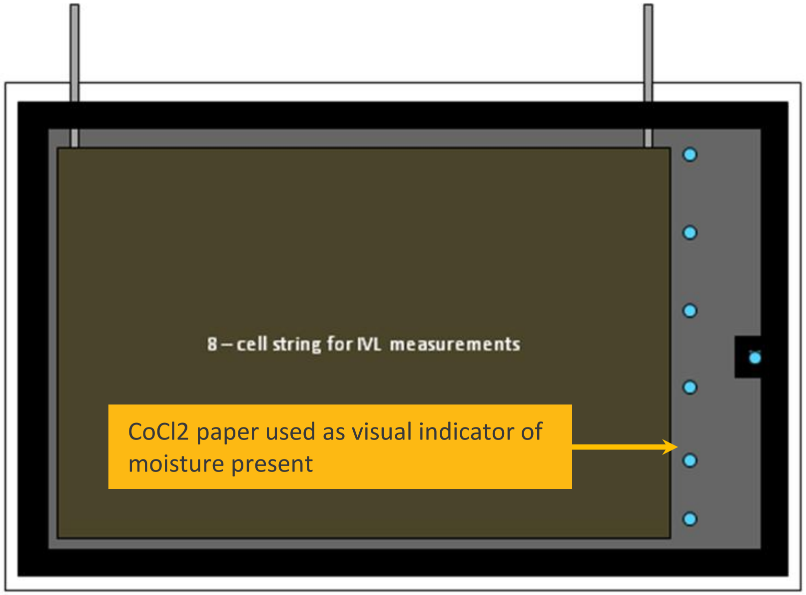
TTF: Time to failure
RH: Relative humidity
ε_a : Activation energy
n: Humidity exponent
AF : Acceleration factor

- This corrosion rate model and its validity is not established for PV applications.
  - Originally proposed for corrosion failures of encapsulated metallization in electronic devices.
- Hallberg-Peck model may be a suitable candidate for prediction of flexible PV module performance for moisture induced degradation but further scrutiny is warranted due to possible differences.
  - Details of mechanism by which CIGS cell degrades due to moisture can be different from corrosion of encapsulated metallization
  - CIGS cells can have temperature dependent degradation significantly different from the degradation of encapsulated metallization

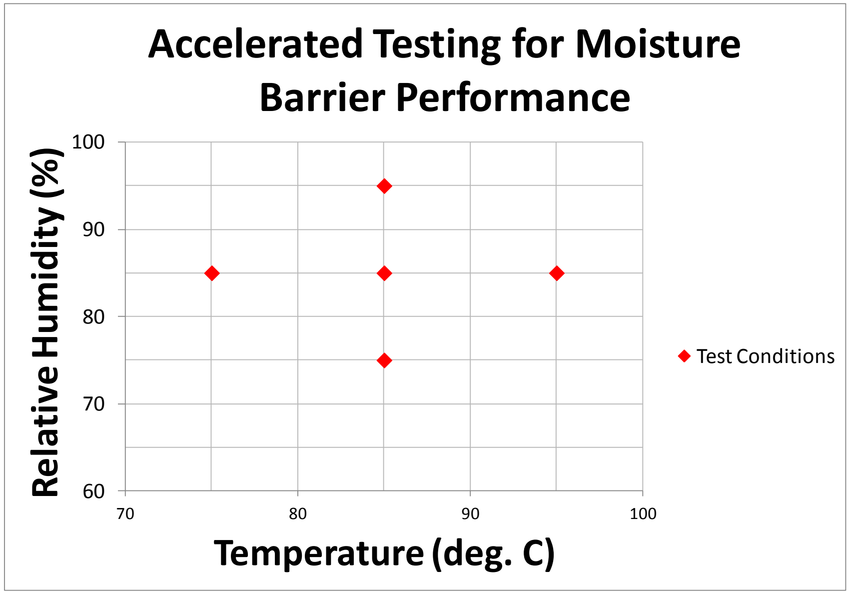
Accelerated testing plan

- Barrier materials independently characterized by Mocon testing for diffusivity at different temperatures.
- Module-level testing carried out at different temperature and RH conditions with 5 samples per barrier type.
- Test conditions chosen include conditions beyond typical 85C/85% RH based on desire to highly accelerate certain failures. Results require scrutiny in case of unrealistic failures.

Name	WVTR
Barrier-1	0.0071 g/sq.m/d @37C/100%RH
Barrier-2	<0.0022 g/sq.m/d @37C/100% RH
Barrier -3	<5e-4 g/sq.m/d @50C/100%RH (Not amenable to MOCON testing)

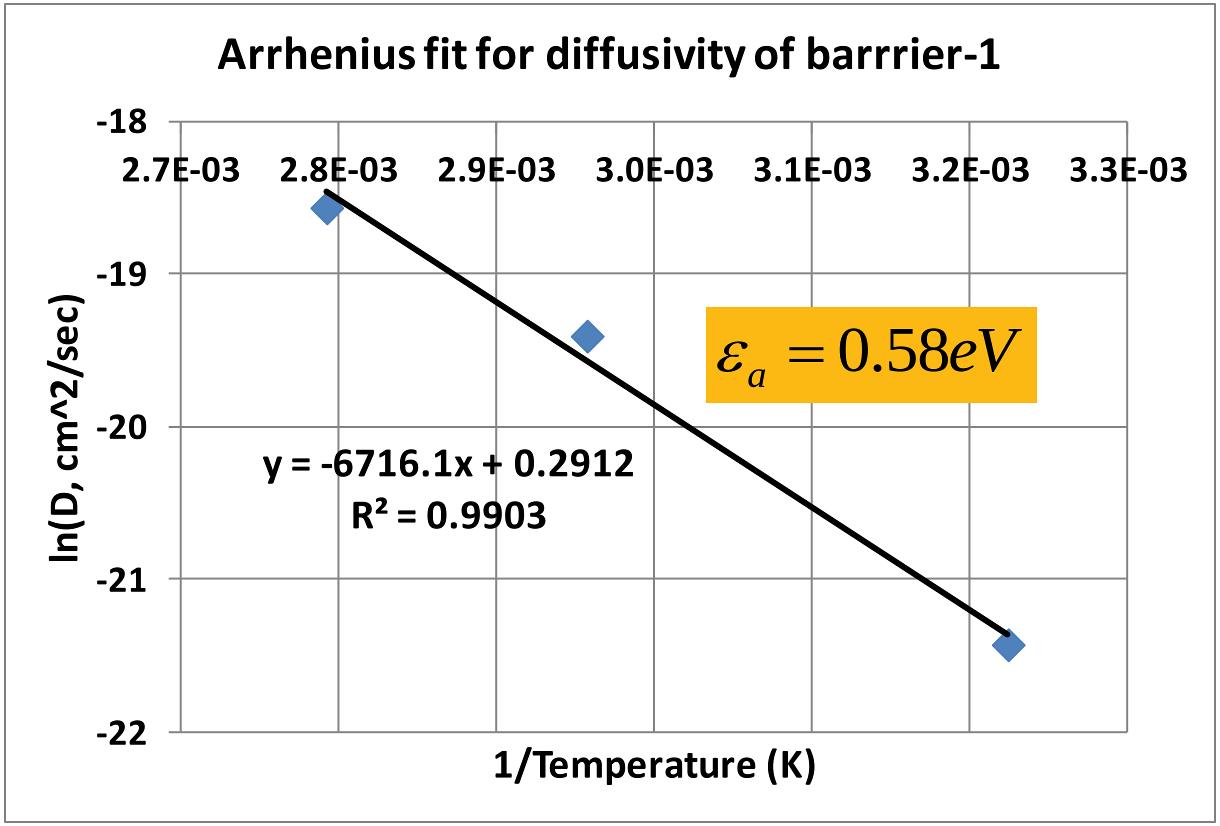


CoCl2 paper used as visual indicator of moisture present


Accelerated Testing for Moisture Barrier Performance

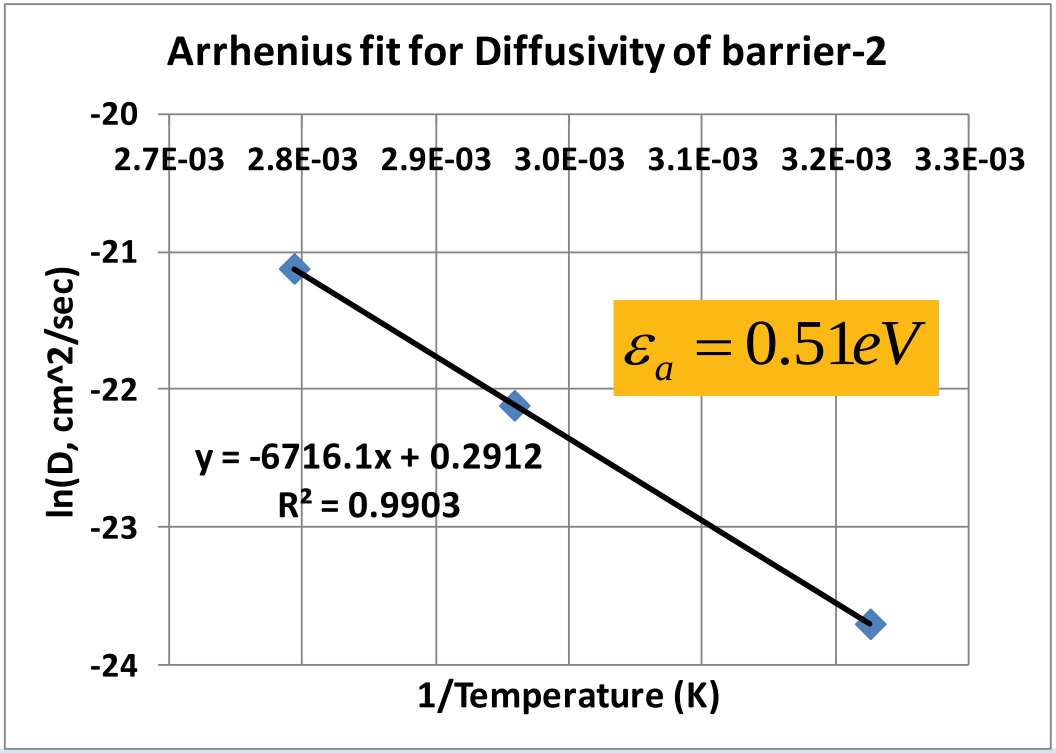
Mocon Testing - 1

- Diffusivity for baarier-1 and barrier -2 were measured by Mocon testing services at 37C, 65C and 85C.
- Measuerments exhibit Arrhenius behavior with activation energy of 0.58eV



Mocon Testing -2

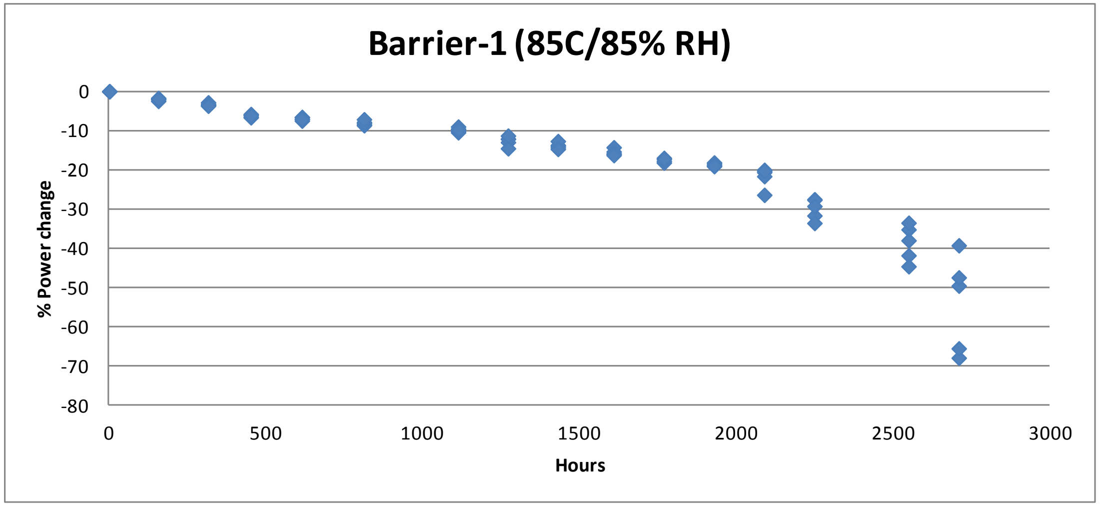
- Barrier 2 testing at low temperature was terminated due to excessive test times. Arrhenius behavior was seen for WVTR and values extrapolated. Activation energy for diffusivity was 0.51 eV.
- Barrier-3 was not amenable to Mocon testing due to apparatus limitation for high barrier systems

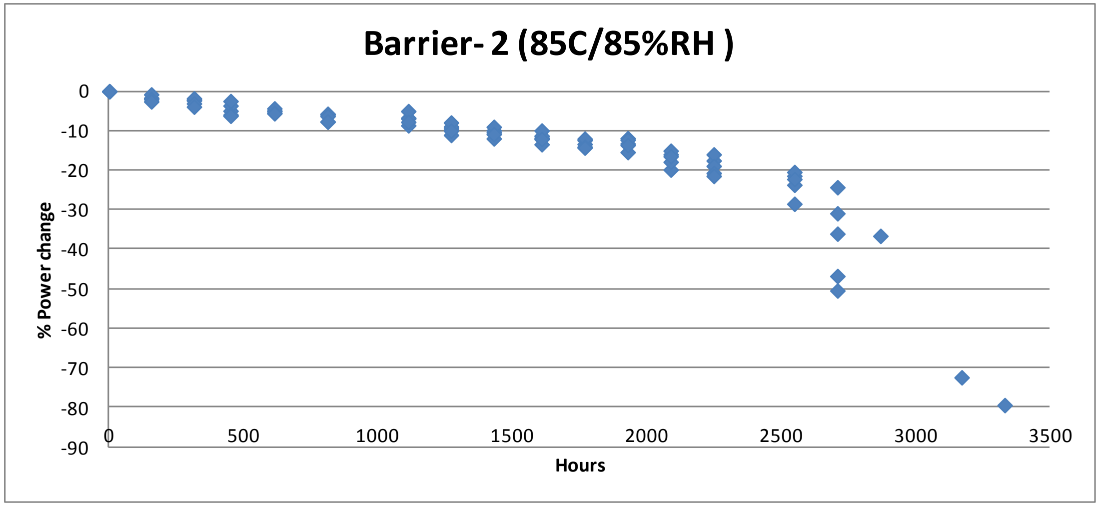


Arrhenius fit for Diffusivity of barrier-2

Representative results for degradation

- Data exhibits two different regimes in degradation.
- Approximate linear degradation is seen up to ~20% drop in Pmax beyond which a "crash behavior" is seen.
- Two regimes are seen to be different even on log-log scale.
- Scatter in data is higher in post-crash behavior.
- Barrier-3 samples did not exhibit dP<-20% after ~7000 hrs at 85C/85% RH

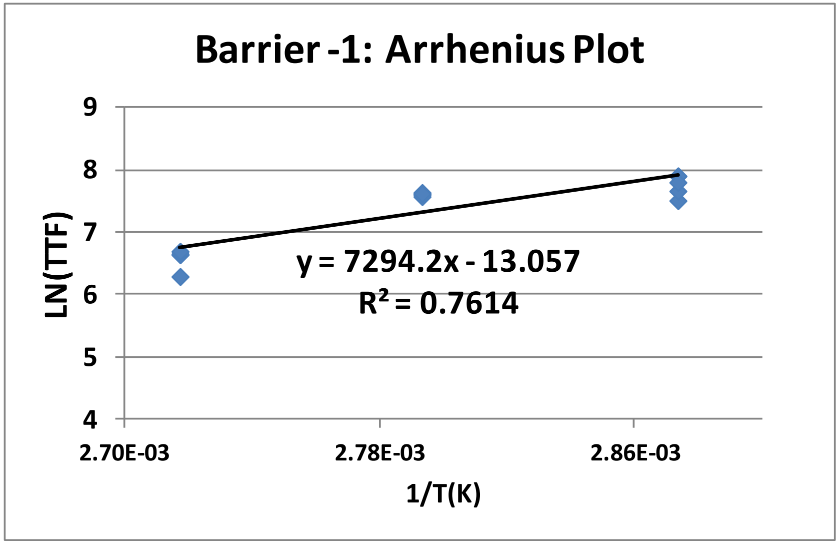




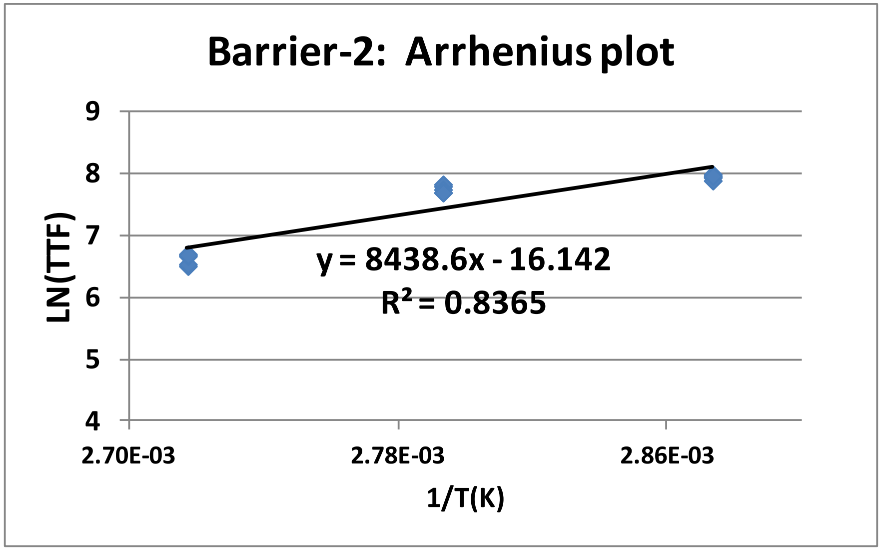
H-P Fit for Module Tests (ΔP=-20%)

Barrier - 1 $\varepsilon_a = 0.63eV;\ n = -3.41$

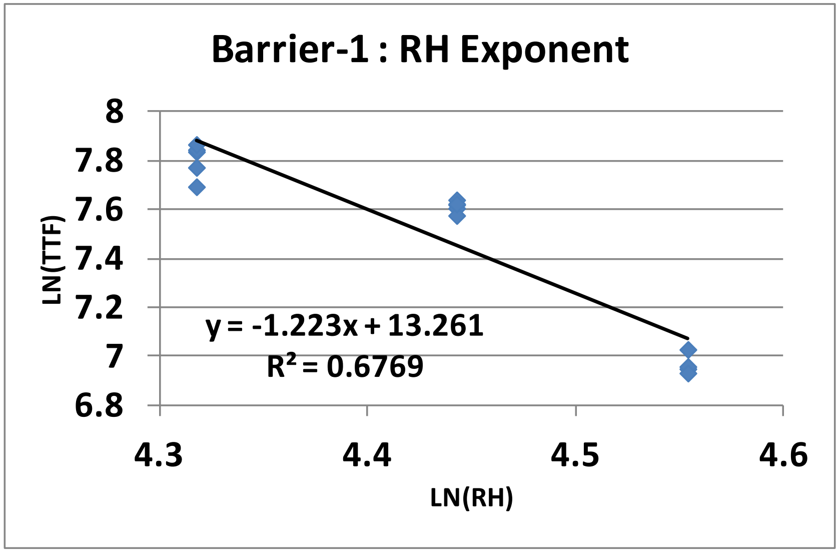
Barrier-2 $\varepsilon_a = 0.73eV;\ n = -1.21$



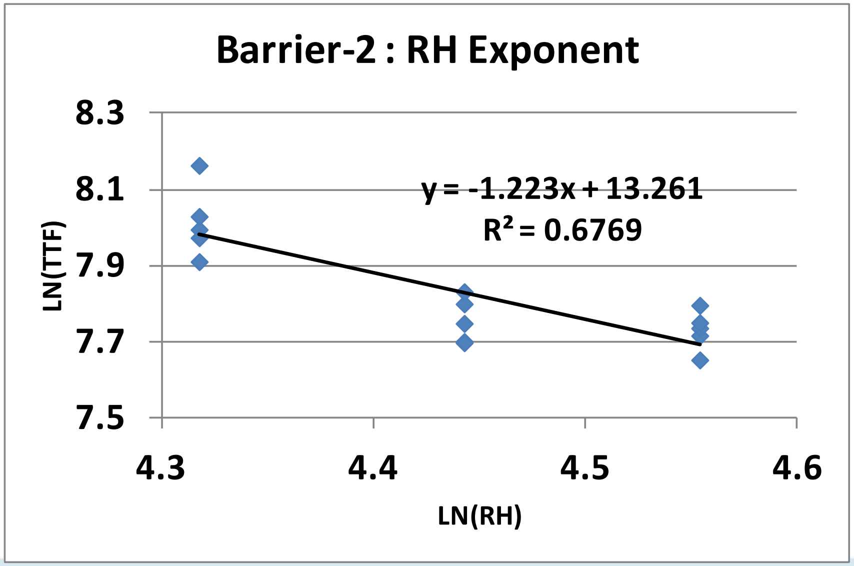
Barrier -1: Arrhenius Plot



Barrier-2: Arrhenius plot



Barrier-1 : RH Exponent



Barrier-2 : RH Exponent

Data Summary

Barrier	Activation energy from Mocon (barrier only)	Activation Energy from module level test (includes cell degradation)	RH Exponent from module level tests
Barrier-1	0.58 eV	0.63 eV	-3.41
Barrier-2	0.51 eV	0.73 eV	-1.22
Hallberg-Peck Recommendation (for encapsulated metallization)	NA	0.7 eV	-2.66

- Activation energy obtained by module level tests is not entirely consistent with the activation energy obtained from Mocon tests.
- Scatter in the data could be addressed with the following –
  - Increasing the sample size.
  - Using larger modules in test to account for potential variations in the cells and localized non-uniformities of barrier surface.
  - Improving consistency of electrical contacts through the test.

Method for assessment of field performance

- Acceleration factor for a given location can be found using hourly TMY data and Hallberg-Peck relation

$$< AF_{1yr} >= \frac{1}{t_{1yr}} \int_{0}^{t_{1yr}} \left(\frac{RH_{field}(t)}{RH_{test}} \right)^{n} \exp\left(\frac{\varepsilon_{a}}{k} \left[\frac{1}{T_{field}(t)} - \frac{1}{T_{test}} \right] \right) dt$$

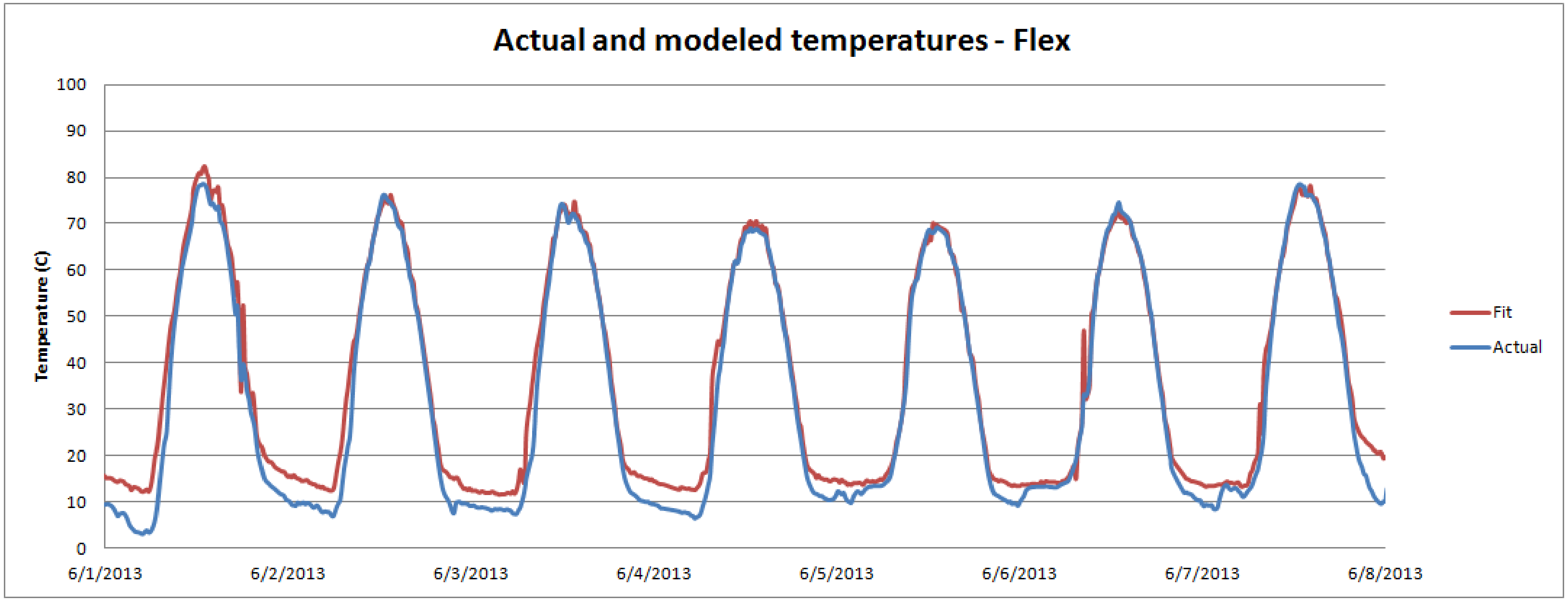
- For a good prediction, ability to predict module temperature in the field is critical.
- Relative humidity used for these calculations is the ambient relative humidity and is believed to provide a conservative estimate.
- This approach assumes that the conditions can be assumed approximately constant over a period of one hour in the field (the interval used for TMY data)

Module Temperature prediction for flexible module

- Module temperature can be predicted using Sandia model with constants obtained for flex module from field locations.

$$T_{\mathrm{mod}}(\mathrm{deg}.C) = T_{amb}(\mathrm{deg}.C) + (DNI\ W/m^2) * \exp(-2.96 - 0.0178\ V_{wind}(m/s))$$

- Constants were obtained from field data at Santa Clara CA. Data acquisition from AZ installation is in progress and will lead to refinement.
- Actual module temperature measured at Santa Clara vs fit shows good agreement during daytime. Largest discrepancy is during evenings/night time.



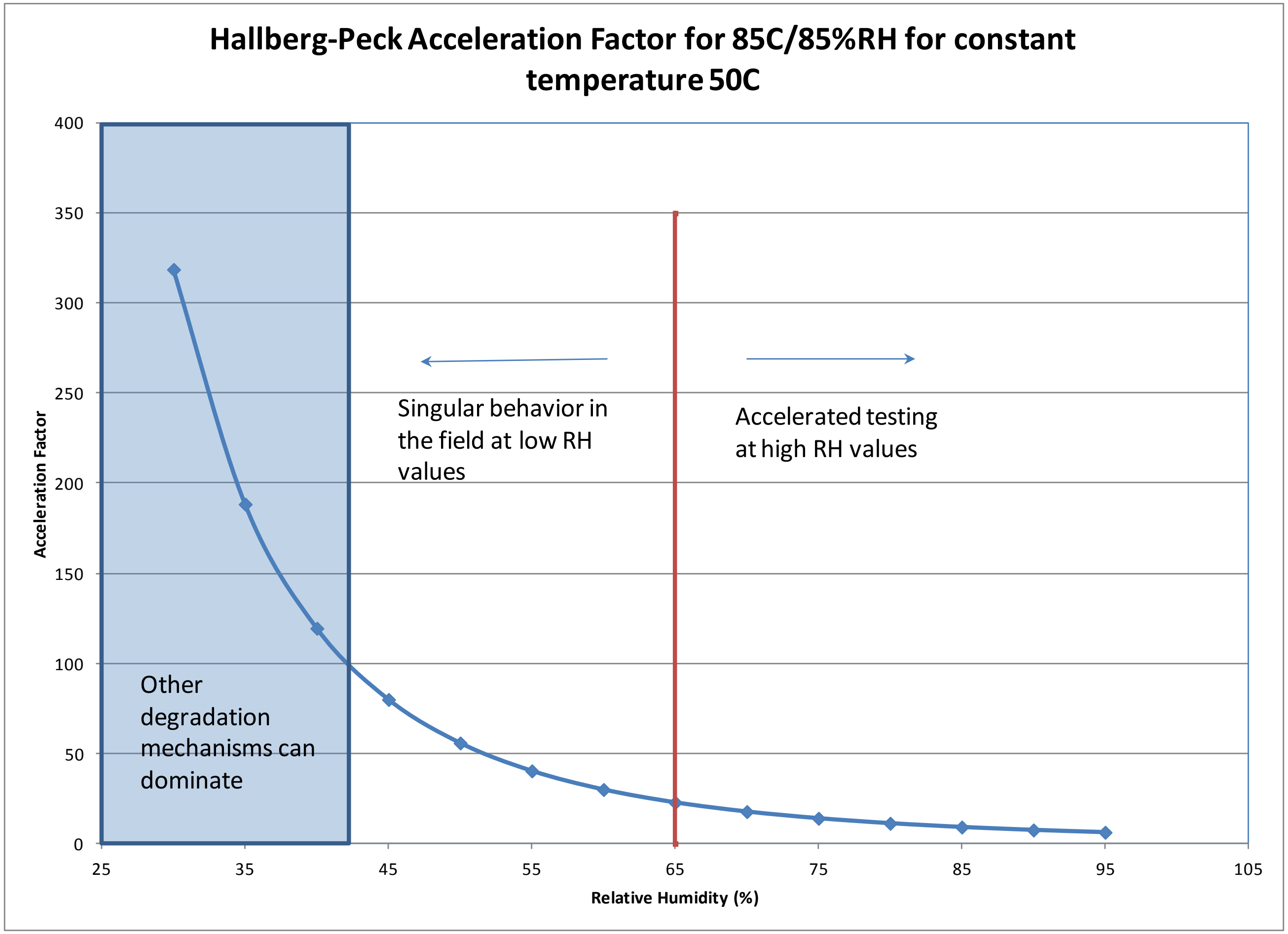
Initial Assessment for Moisture Induced failures

Time to failure (yrs) for barriers based on H-P model and accelerated testing results considering moisture induced degradation only

Location	Criteria	Barrier-2 (n=-3.41)	Barrier -2 (n=-1)	Barrier-1 (n=-3.41)	Barrier-1 (n=-1)
Bangkok	dP=-20%	26.9 yrs	21.1 yrs	13.1 yrs	10.1 yrs
San Jose, CA	dP=-20%	175.4 yrs	84.8 yrs	71.5 yrs	33.1 yrs

- Predictions are based on TTF obtained at 85C/85%RH and Pmax change of 20% as failure criteria.
- In using this method for prediction of field performance additional considerations are necessary.
  - Singular behavior of RH term in H-P model dominates predictions at locations with dry environments.
  - Other mechanisms can dominate in dry conditions. The model merely indicates *unavailability* of moisture over typical warranty period to drive degradation

Singular behavior of H-P model (n=-3.41)



Revisiting Acceleration Factor models for singular behavior

- H-P model is used based on diffusion and reaction considerations as outlined earlier and was originally proposed using purely an empirical approach.
  - In later research justifications have been provided for H-P model using fundamental considerations for diffusion and reaction rates
- Acceleration factor models based on reaction rate kinetics are considered better candidates than purely empirical models.
  - Arrhenius model for temperature dependent accelerations is widely used and successful.
  - Eyring (1941) has provided enhancements to the Arrhenius form for rate processes and provided justification to why the Arrhenius model works
- Eyring model (Theory of Rate Processes, 1941) provides a basis for general functional form of acceleration factor for rate processes accounting for the effect of thermal and non-thermal stresses accelerating reaction rates
  - Based on statistical mechanics and quantum mechanics considerations for reaction rates

Generalized Eyring Model (1941)

- Appropriate functional form for rate processes (rate R) including thermal (T) and non-thermal (S) effects is

$$R = \gamma_0 T^m \exp\left(-\frac{\varepsilon_a}{kT}\right) \exp\left(\gamma_2 S + \frac{\gamma_3 S}{kT}\right)$$

- For most practical applications where the temperature range (on absolute scale) is small Generalized Eyring Model can be used as a basis for acceleration factor calculations

$$m = 0, \gamma_3 = 0 \; \textit{as it is absorbed in Arrhenius term}$$

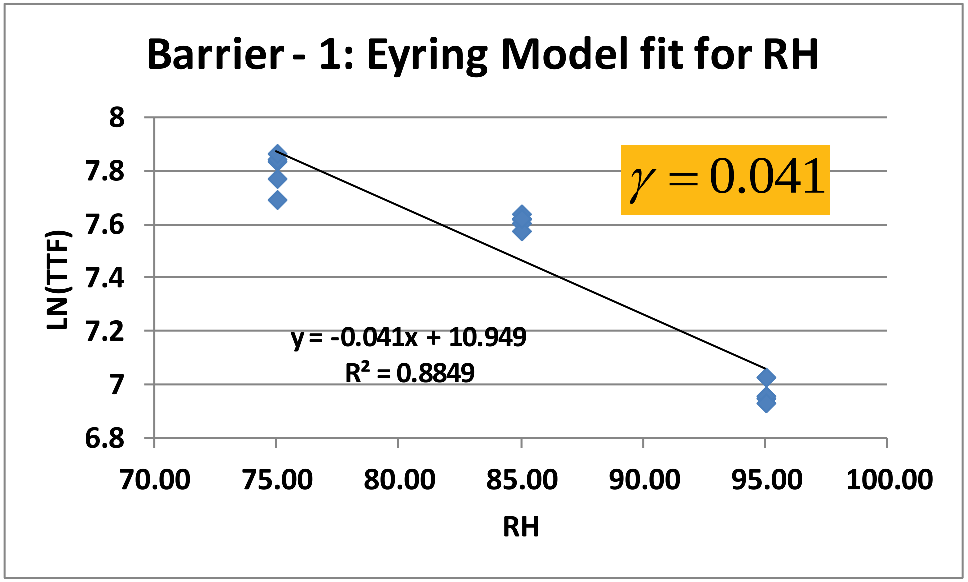
- For degradation driven by temperature and humidity, RH can be taken as a non-thermal stress driving degradation and thus leading to

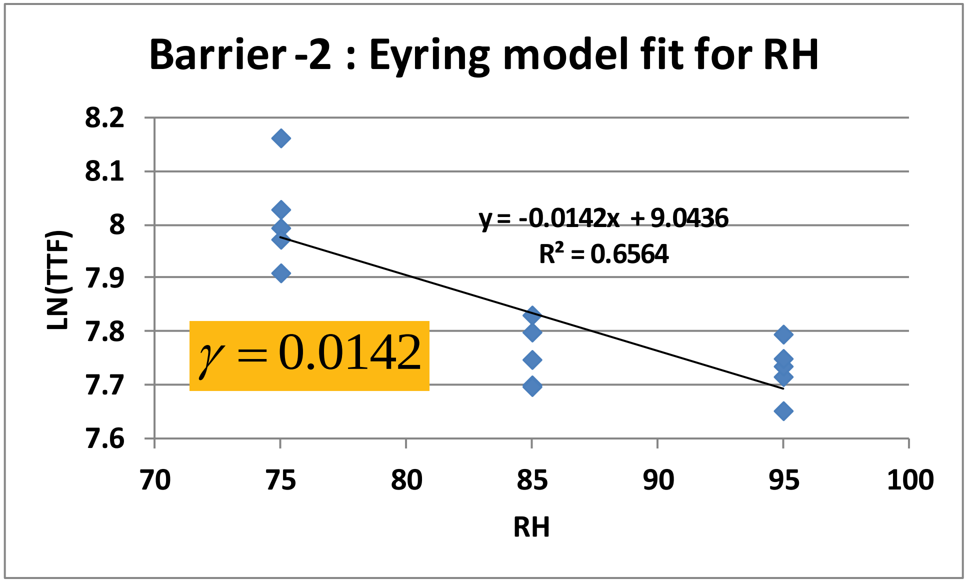
$$TTF \propto \exp\left(\frac{\varepsilon_a}{kT}\right) \exp\left(-\gamma_2 RH\right)$$

- As RH (non thermal) stress goes to zero, the Arrhenius behavior is recovered. This model does not have the singular behavior of H-P model and is seen to provide a bounding estimate for dry environments.

Eyring model for RH

- Eyring model captures RH dependence and eliminated singular behavior in H-P model.
- Improving the quality of fit will require
  - larger sample sizes
  - larger modules as test samples
  - testing with wider range of conditions including at low RH.
  - The associated test times can be prohibitive





Revised Lifetime predictions (Eyring Model)

- Singular behavior of H-P model and analytical model are eliminated using Eyring Model.
- These estimates address degradation driven by temperature and humidity only.
- Due to limited data available, these estimates should be taken as best estimates dictated by available data.
  - The quality of prediction can be improved by obtaining more test data over larger range of conditions.

Estimated Field performance (yrs) for moisture induced degradation only

Location:	Power change:	Barrier-2 (n = -3.41)	Barrier-2 (n = -1)	Barrier-1 (n = -3.41)	Barrier-1 (n = -1)	Barrier-2 (Eyring model, gamma=-0.0142)	Barrier-1 (Eyring Model, gamma=-0.041)
Denver	20%	45664	487	16489	163	363	455
Arizona	20%	3332	86	1649	36	69	100
Bangkok	20%	27	21	13	10	**21**	**12**
San Jose	20%	175	85	72	33	84	48

Singular behavior of H-P model dominates predictions in dry environments

Barrier-1 and Barrier-2 are found to be inadequate for aggressive environments like that in Bangkok

Testing Barrier-3 samples

- Barrier-3 was found to be not amenable to Mocon testing due to limitation of the apparatus for high barrier.
- Barrier- 3 samples have significantly out performed Barrier-1 and Barrier -2 at 85C/85%RH (dP_max >-20% after 7000hrs).
- Some anomalies were encountered in Barrrier-3 samples which were not resolved in a timely manner
  - Leading hypothesis on some of the samples is handling damage.
- Best approach available to date for assessment of Barrier-3 performance is to scale results from test at 85C/85% RH using results for Barrier- 1 and Barrier-2. This suggests field life of Barrier-3 product (for moisture induced damage) far exceeding the warranty requirements.
- Alternate approaches to investigate performance of Barrier-3 samples are being explored due to prohibitive test times.

Conclusions

- Hallberg-Peck model was shown to be a candidate empirical model for assessment of field performance of flexible PV modules with regard to moisture induced degradation in high humidity conditions. H-P model was shown to give a singular behavior in dry environments, which is not desirable.
- Eyring Model was shown to be a better candidate for predicting moisture induced degradation in the field for flexible modules and does not have singular behavior in dry environments.
- Based on accelerated testing and subsequent analysis Barrier-1 and Barrier-2 are shown to not likely meet typical warranty requirements of 25 years in aggressive environments like Bangkok while Barrier-3 is considered adequate.
- Refinement of the analysis and prediction will require testing at low RH values, larger temperature ranges and with larger sample sizes and larger modules. Test times can become prohibitive at low RH values for high barrier systems, particularly for Barrier-3.

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