A framework for characterization and prediction of the edge seal performance in PV module. - Kedar H., Dan V. , Ajay S., Todd K.

Introduction

- Degradation in performance of PV modules due to moisture ingress is a concern.
- Typical testing/prediction hinges on convolution of moisture barrier performance of edge seal and device degradation for a particular architecture.
- Testing method for edge seal performance independent of particular solar cell architecture is desired.
- Relatively cheap test method is developed
- Theoretical framework is developed to analyze data from accelerated tests.
- Theoretical framework enables prediction of edge seal performance in the field from analysis of test data.

Theory: Proposing Appropriate Functional Forms

- Objective: Obtain functional form for breakthrough time using rigorous analysis.
- Analytical solution of 1-D diffusion equation can be used in absence of desiccants.
- Presence of desiccants delays moisture penetration further

Analytical solution to 1D diffusion equation (No desiccant)

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \Rightarrow C(x,t)=C_0\left[1-erf\left(\frac{x}{2\sqrt{Dt}}\right)\right]$$

$$t_f = Ax^2;\ A \propto \frac{1}{D\left[erf^{-1}\left(1-\frac{C^*}{C_0}\right)\right]^2} \approx \frac{1}{D}\left(\alpha_1+\beta_1\frac{C^*}{C_0}\right)$$

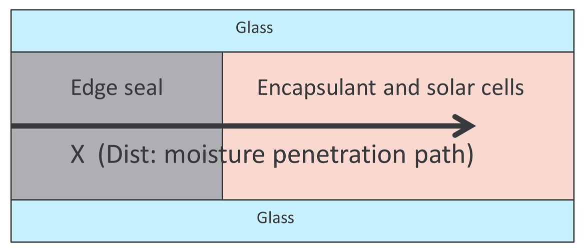
C*: Detection threshold

C_0 – Edge concentration

Functional form in presence of desiccants

$$t_f = Ax^2+Bx;$$

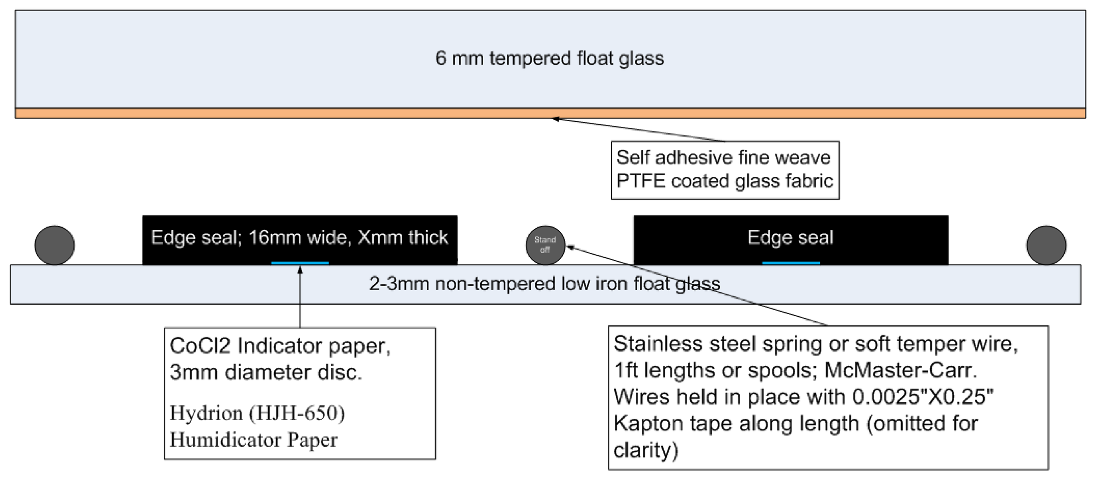
$$A=\left(\alpha+\frac{\beta}{C_0}\right)\exp\left(\frac{\gamma}{T}\right);\quad B=\frac{q}{C_0}$$



Schematic: Edge of Glass-Glass PV Module

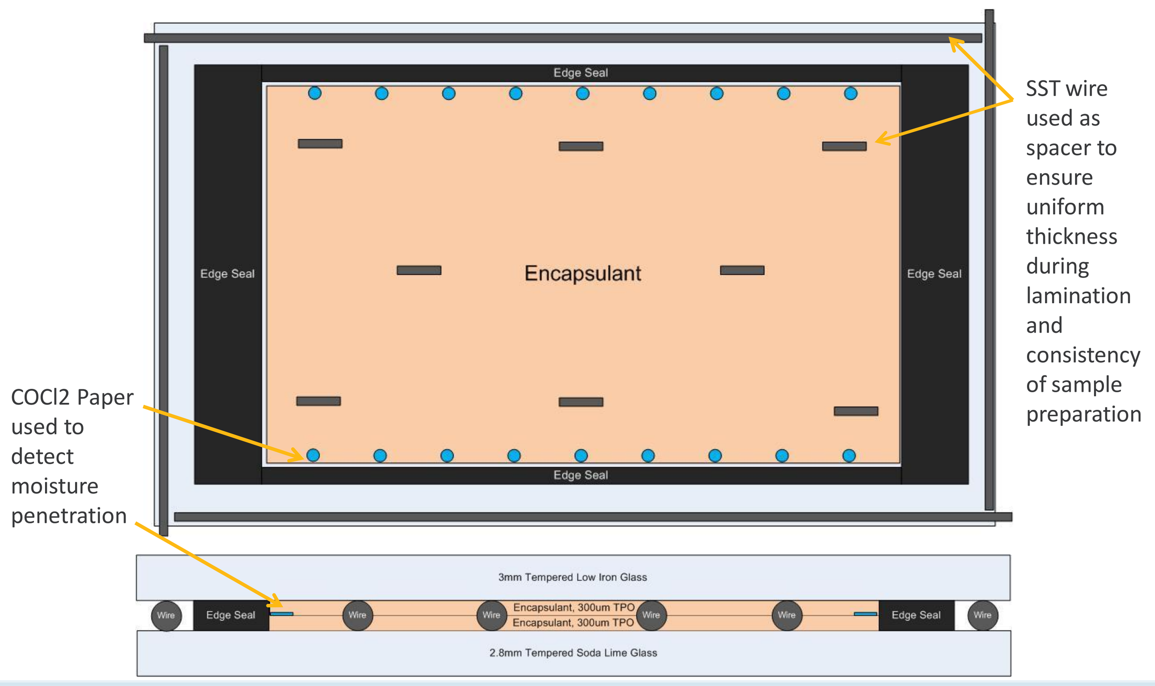
Designing Sample for Fast Data Acquisition

- Objective is to develop a test method to characterize performance of edge seal in its end product form
- Sample type-I provides a short path for moisture penetration reducing test time for initial data by an order of magnitude



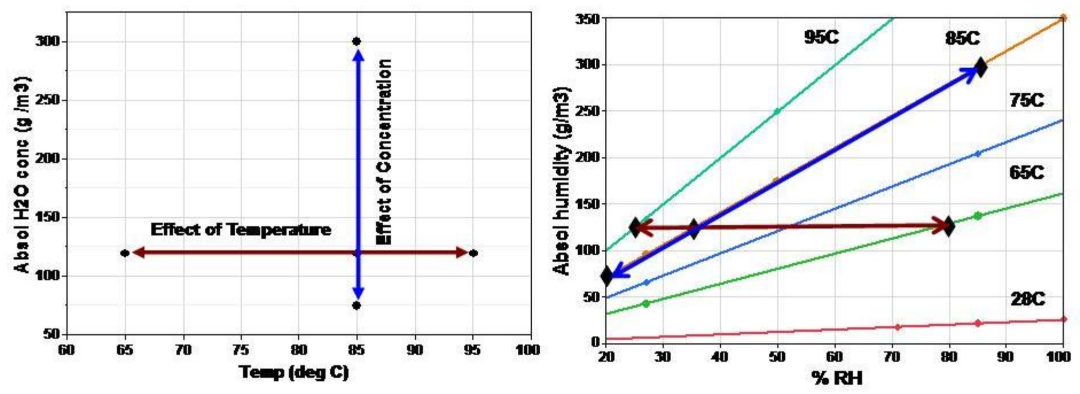
Simulated Module Construction

- Sample type II is representative of module construction



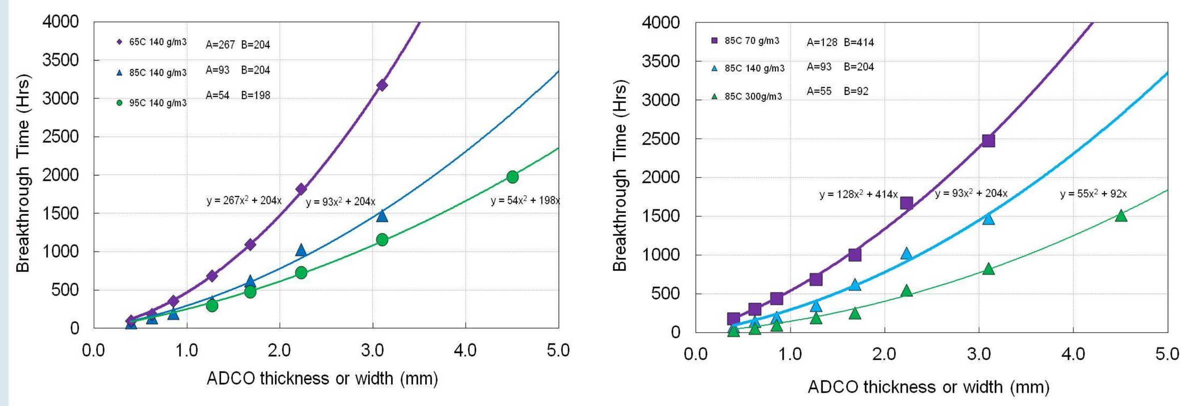
Testing in Environmental Chambers

- Tests carried out in standard temperature-humidity controlled chambers
- Color change of indicator paper was monitored
- Data taken every 24 hrs initially and frequency adjusted later based on estimated breakthrough time (Resolution +/- 12hrs)



Results - I

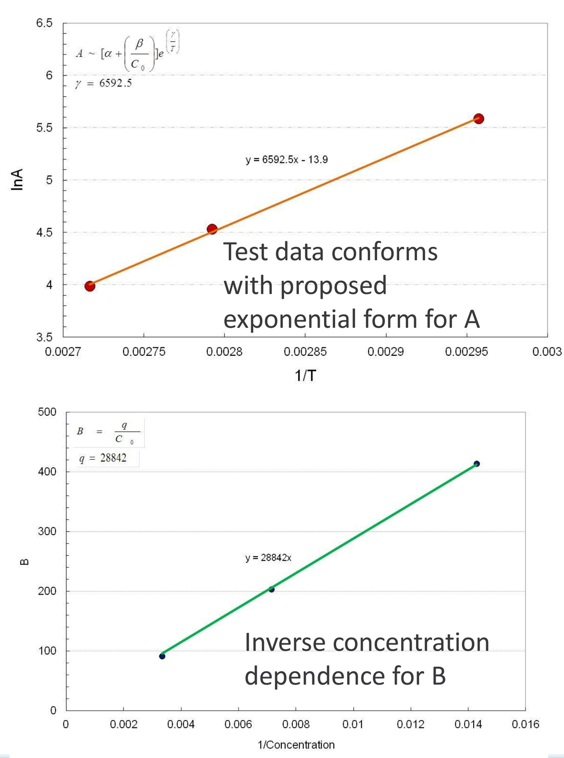
- Test results fit the proposed functional form thereby validating the theoretical framework.
- Extract parameters 'A' and 'B' for different test conditions

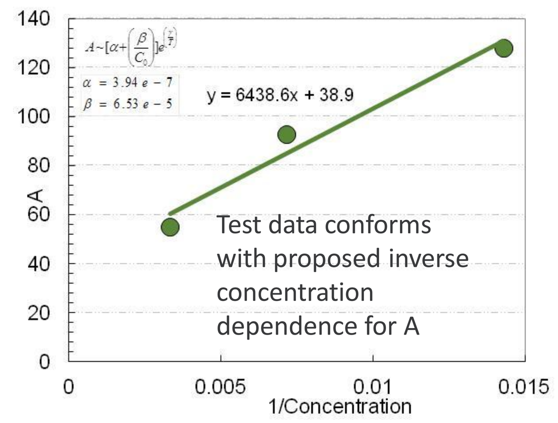


Varying temperature at fixed concentration

Varying concentration at fixed temperature

Results- II





Test data conforms with proposed functional forms providing a validation for theory.

Theoretical Framework for Prediction

- Variation in ambient conditions amounts to
  - –Variation in edge concentration $C_0(t)$
  - –Variation in diffusivity D(T)~ D(t)
- Use effective diffusivity
- External variations decay within ~1mm

Addressing Variation of Diffusivity

$$\frac{\partial C}{\partial t}=D(t)\frac{\partial^2 C}{\partial x^2}\Rightarrow$$

$$C(x,t)=C_0\left[1-erf\left(\frac{x}{2\sqrt{D_{eff}t}}\right)\right]$$

$$D_{eff}=\frac{1}{t}\int_0^t D(t)dt$$

Addressing varying edge concentration

$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial x^2};\ C(0,t)=C_0\sin\omega t;\ C(x\to\infty,t)=0\Rightarrow$$

$$C(x,t)=C_0\exp\left(-x\sqrt{\frac{\omega}{2D}}\right)\sin\left[\omega t - x\sqrt{\frac{\omega}{2D}}\right]\Rightarrow l_{decay}\propto\sqrt{\frac{2D}{\omega}}$$

Use of effective diffusivity and averaging enables mapping test results to field conditions

Method for predicting field performance

- Obtain breakthrough time for various conditions using test technique developed
- Determine fit parameters using functional forms suggested by theory.
- Determine average absolute humidity for a given location using TMY data.
- Determine equivalent temperature T_{eq} using TMY data

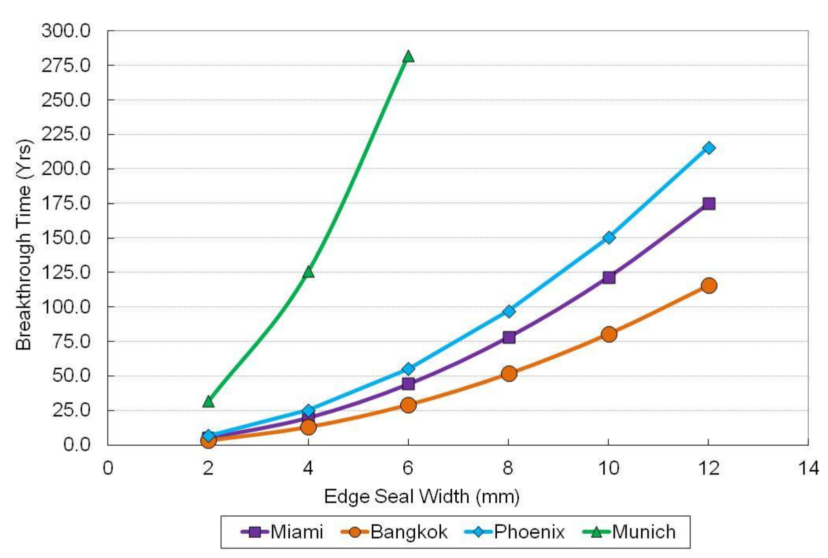
$$\exp\left(-\frac{\gamma}{T_{eq}}\right)=\frac{1}{t_{1yr}}\int_0^{t_{1yr}}\exp\left(-\frac{\gamma}{T(t)}\right)dt$$

- Calculate constants 'A' and 'B' for field conditions at T_{eq}.
- Substitute and obtain time for moisture breakthrough

$$t_f = Ax^2+Bx$$

Estimated moisture ingress time in the field

- Analysis suggests that in the particular case of the edge seal tested on certain MiaSole glass-glass modules, moisture ingress can be prevented well beyond the intended service life



Conclusions

- A relatively cheap test technique was developed to test moisture barrier performance of the edge seal in a manner decoupled from other components of PV module.
- A theoretical framework was developed to analyze test data from accelerated tests and predict field performance of the edge seal.
- Theoretical model was validated by experimental results.
- In particular case of the edge seal tested on certain MiaSole glass-glass modules it is predicted that moisture ingress can be prevented well beyond the intended service life.

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Corresponding Author
Kedar Hardikar, Ph.D.
E-mail: khardikar@miasole.com
Tel: 408-919-5702