Life Prediction for CIGS Solar Modules

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One can use accelerated testing data to predict real-world module failures only if the degradation mechanisms are known and their dependence on environmental factors measured. The moisture-induced degradation rate of flexible CIGS solar cells has been measured as a function of temperature and humidity and fit to a kinetic rate expression. This expression is coupled to a model of moisture diffusion into a package and typical meteorological input data to create a cumulative damage model to predict lifetime of packaged cells versus outdoor exposure and package construction. Estimated acceleration factors for damp heat (85C/85%RH) vs. Miami range from 15X to 50X, depending on the package, since diffusion through the package is accelerated differently than the cell degradation kinetics. The degradation rates are strongly dependent on the transparent conductive oxide used for the window layer and the electrically-conductive adhesive used for the contacts. The dependence of degradation on encapsulant materials is fundamentally different than is often assumed in the literature.
Prototype Flexible CIGS Module
Flexible Thin-Film PV Package

- Top Sheet
  - Transparent
  - UV Stable, UV block
  - Electrical insulation
  - Mechanical (cut, hail)
  - Moisture barrier

- Encapsulant
  - Low $T_g$ compliant “glue”
  - Transparent
  - Adhesion

- Backsheet
  - Electrical insulation
  - Mechanical (cut)
  - Moisture barrier

- Edge Seal
  - Barrier
  - Adhesion
Moisture-induced degradation

- Increased Series Resistance $R_s$
- Decreased Shunt Resistance $R_{sh}$
- Increased Recombination
  1. Quasi-neutral region
  2. Depletion region
- Increased Series Resistance $R_s$

Test Cells:

1. Global Solar Test Cells (ITO)
2. AZO

GSE test cell
tabbed and encapsulated

~ 36 x 46 mm exposed
Stainless steel foil
Mo coating
ECA – Tabs/ribbons

Efficiency ~ 12 – 13.5%
$V_{oc} \sim 600 - 610 \text{ mV}$
$J_{sc} \sim 33-36 \text{ mA/cm}^2$
$FF \sim 60 - 62$
$A \sim 16.5 \text{ cm}^2$
Factors for prediction of lifetime (moisture degradation):

1. Cell construction
   - ITO vs AZO window layer
   - Type of ECA for interconnect
   - Other

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

3. Package
   - Barrier properties of topsheet and backsheet
   - Encapsulant
   - Edge seals
   - other
Life Model – Moisture Sensitivity

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

2. Moisture Diffusion into Package - Model
   - 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 - Predict
   - Cumulative degradation and average life vs. location and package design
   - Tradeoffs between CIGS sensitivity and package design/cost
   - Interpretation of accelerated tests results
Degradation Data - Examples

- High temperature, humidity faster
- Driven by FF loss due to $R_{oc}$ and some shunting
Scaling with partial pressure water

**Interfacial equilibrium (Henry’s Law)**

\[
\frac{C_a}{S_a} = \frac{C_b}{S_b} = RH
\]

**Negative activation energy!**

Need to scale with % saturation (RH)
CIGS Degradation Kinetics  (Global Solar test cells)

- For every Temp & RH, fit data to linear degradation rate (1\textsuperscript{st} 20% of degradation)
- Fit rate of degradation vs Temp, RH to kinetic model

\[ R_{Deg} = k_0 e^{\left(-\frac{E_{a,deg}}{RT}\right)} \left[ \frac{RH_{cell}}{1 - RH_{cell} + \varepsilon} \right] \]

- Strong RH dependence at high RH
- ECA affects temperature dependence

CIGS Degradation - AZO vs ITO

- AZO ~ 25X ITO
- Comparable to published data
Arrhenius Plot

- ECA\textsubscript{0} very low activation energy
Package Diffusion Model

Mass Balance, Interfacial Equilibrium, Fickian Diffusion, $D_{\text{barrier}} \ll D_{\text{encapsulant}}$

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

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

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)

Life vs. Barrier: ITO-ECA$_0$

Need $\sim 4 \times 10^{-5}$ g/m$^2$/day package $\sim$ 20 yr life
Life vs. Barrier: ITO-ECA₁

Need ~ $8 \times 10^{-3}$ g/m²/day package ~ 20 yr life
Life vs Barrier – ITO vs AZO

ITO Life 5-25x AZO Life
Accelerated Testing

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

~10,000 hrs
~4,000 hrs
~2,500 hrs
FL, AZ Testing

Results as expected after 3 months

- ITO/ECA₁ no measurable degradation
- ITO/ECA₀ ~ 5% down as expected
Encapsulant Effect

- Low solubility encapsulants become saturated faster => BAD!!

\[
\begin{align*}
  t_c &= \frac{L_E S_E}{WVTR_{\text{max}}} \\
  \frac{C_E}{S_E} &= RH \left[ 1 - e^{\left(\frac{-t}{t_c}\right)} \right]
\end{align*}
\]
Encapsulant Experimental Plan (85°C, 85%RH)

- **Graph 1:**
  - **Y-axis:** Solubility (g/cm^3)
  - **X-axis:** 1/T (1/K)
  - Lines for Urethane, EVA, Silicone, and Polyolefin
  - Urethane is 10x higher than Silicone

- **Table: Encapsulant Performance**

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Solubility @85°C g/cm³</th>
<th>t½ Hrs @85°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urethane</td>
<td>0.355</td>
<td>3.0E-02</td>
<td>89</td>
</tr>
<tr>
<td>Urethane</td>
<td>1.065</td>
<td>3.0E-02</td>
<td>268</td>
</tr>
<tr>
<td>Silicone</td>
<td>0.480</td>
<td>3.1E-03</td>
<td>12</td>
</tr>
<tr>
<td>Polyolefin</td>
<td>0.400</td>
<td>3.6E-03</td>
<td>12</td>
</tr>
</tbody>
</table>

- **Graph 2:**
  - **X-axis:** WVTR at 85°C (g/m^2/day)
  - **Y-axis:** Hours Life 85°C 85% RH (20% degrade)
  - Plot for Urethane, Silicone, Polyolefin, and Aclar®
  - **Legend:**
    - GSE cells
    - ECA1
    - Polyolefin
    - Silicone
    - Aclar®
    - PET 5.7mil
    - PC 5.7mil

- **Text:**
  - All encapsulants the same
  - Thick, high S_E encapsulants better
Encapsulant Confirmation Experiment

- EVA outlier – unusually fast degradation
- Urethane (TPU), silicone, polyolefin same, latter two even with Aclar®, as expected
- Barrier (Aclar®) makes no difference for silicone & polyolefin, as expected
- Barrier (Aclar®) improves TPU life, especially thicker, as expected
Comparison of Experiment & Model

Saturation

Degradation
Conclusions

1. Life model and accelerated test scaling developed
   - *Relative humidity* and % *saturation* of encapsulant are key

2. Moisture sensitivity of CIGS almost independent of encapsulant type

3. Module lifetime longer for *thick encapsulants* with *high* water solubility

4. AZO vs ITO CIGS degradation kinetics quantified ~25X

5. ECA can also be a strong factor in degradation

6. Diffusion-controlled: Life ~ \((t_c/R_D)^{1/2}\) ~ (diffusion-time*degrade-time)^{1/2}

7. Significant moisture barriers required for 20 yr life – even for ITO

8. Acceleration factor for damp heat smaller than assumed, highly nonlinear!

9. Methodology can predict life for any moisture-sensitive module
   (once kinetic constants are measured)
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