Modeling Thermal Fatigue in CPV Cell Assemblies

NREL PV Module
Reliability Workshop

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quantifying thermal fatigue

- Thermal fatigue will cause die-attach failure.
- How can we model this failure?
- Will this model result in a lifetime prediction?
review: rainflow counting

1: CPV cell temperature modeling

\[
T_{\text{mod}} = T_{\text{amb}} + E \exp(a + bW) \\
T_{\text{cell}} = \bar{T}_{\text{mod}} + \frac{E}{E_o} \Delta T
\]

3: damage calculation

\[
N_f = \frac{1}{2} \left( \frac{\Delta \gamma_p}{2 \varepsilon_f} \right)^{\frac{1}{c}}
\]

\[
c = -0.422 - 6 \cdot 10^{-4} T_{\text{mean}} + 1.74 \cdot 10^{-2} \ln\left(1 + \frac{360}{t_d}\right)
\]

\[
\Delta \gamma_p = \frac{\sqrt{2FL}}{2h} \Delta \alpha \Delta T
\]

\[
D = \sum_i \frac{n_i}{N_i}
\]

2: rainflow cycle counting

- Method can quickly analyze long time histories
- Several sources of error exist
- Not capable of differentiating between materials and designs*
review: rainflow counting

- Algorithm distills time history of temperature into discrete segments.
- Attempts to count only the “significant” segments.
- Damage is exponential with temperature change.
finite element modeling

FEM: CPV Cell Assembly

¼ model
1 cm² x 100 μm Ge die
50 μm eutectic Pb-Sn solder
650 μm DBC

simulation: IEC 62108 thermal cycles

![Graph showing temperature over time](image)
finite element modeling

FEM output:

inelastic strain

hot dwell
cold dwell

stress-strain hysteresis
ergy density

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inelastic strain

hot dwell
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stress-strain hysteresis
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damage calculation

\[ N_o = K_1 \Delta W_{ave}^{\alpha} \]

\[ \frac{da}{dN} = K_2 \Delta W_{ave}^{\beta} \]

\[ D = \frac{\Delta W_{acc}}{\Delta W_f} \]
finite element modeling

simulation: clear and partly cloudy days

FEM output: energy density
finite element modeling

Analysis:

Comparison of energy accumulated through thermal cycling and outdoor exposure provides for the calculation of equivalent times (acceleration factors)

\[ t_{eq} = \frac{nD_{TCA}}{365D_{day}} \]

<table>
<thead>
<tr>
<th>Standard</th>
<th>Option</th>
<th>n</th>
<th>( t_{eq}) clear</th>
<th>( t_{eq}) cloudy</th>
<th>( N_{25}) clear</th>
<th>( N_{25}) cloudy</th>
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</thead>
<tbody>
<tr>
<td>IEC 62108</td>
<td>TCA-1</td>
<td>1000</td>
<td>33</td>
<td>6.5</td>
<td>750</td>
<td>3800</td>
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<tr>
<td></td>
<td>TCA-2</td>
<td>500</td>
<td>26</td>
<td>5</td>
<td>480</td>
<td>2400</td>
</tr>
<tr>
<td></td>
<td>TCA-3</td>
<td>2000</td>
<td>27</td>
<td>5.5</td>
<td>1800</td>
<td>9000</td>
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</tbody>
</table>

**FEM**

**RFC**

<table>
<thead>
<tr>
<th>( t_{eq})</th>
<th>Golden years</th>
<th>( t_{eq})</th>
<th>Phoenix years</th>
<th>( t_{eq})</th>
<th>Miami Years</th>
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</thead>
<tbody>
<tr>
<td>TCA-1</td>
<td>13.2</td>
<td>48</td>
<td>24</td>
<td></td>
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</tr>
<tr>
<td>TCA-2</td>
<td>8.3</td>
<td>30</td>
<td>15</td>
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<tr>
<td>TCA-3</td>
<td>20.3</td>
<td>74</td>
<td>37</td>
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</tr>
</tbody>
</table>
FEM vs. RFC

- All damage normalized with respect to the most damaging day.
- Only a 10% difference exists in the relative measurement.
- Bubble size: relative damage
- Bubble color: climate zone
thoughts and future work

- RFC method shows promise for comparative studies between locations.
- Algorithm is convenient to quickly handle long time histories.

- FEM is capable of accurately quantifying the damage that causes failure.
- Accuracy should not be dependent on stress level.
- Models can differentiate between materials and geometries.
- Simulations are slow and expensive.

- Use FEM as a tool to refine algorithm and damage analysis
- Understand sources and magnitudes of error
- Goal: a more accurate RFC method with life prediction capabilities.