Global acceleration factors for damp heat tests of PV modules

Gregory M. Kimball, Shuying Yang, Ajay Saproo
SunEdison, Belmont, California 94002, United States.

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Global acceleration factors for damp heat tests of PV modules

1. Literature review and time-to-failure model

2. Global maps of damp heat acceleration factors

3. Effect of uncertainty on acceleration factor
1. Method for determining acceleration factors

Damp heat testing at 85 °C and 85% relative humidity (RH) is commonly used to evaluate the reliability of PV modules.

With extended testing, most c-Si PV modules* show severe Pmax loss after 2000 – 4000 hours.

How do we relate chamber test data to performance in the field?

* glass-polymer package, EVA encapulant, c-Si p-type diffused homojunction with Ag metallization

Relating chamber to field conditions

Compiled chamber testing and field conditions

Multi-stress studies can be used to extrapolate to field conditions, which typically have average module temperatures of 15 to 35 °C and 50 to 80% RH.

We have compiled multi-stress studies from the literature to study the damp heat acceleration factor for PV modules.
Empirical model of time-to-failure

Observed time-to-failure (TTF) data can be fit using a Hallberg-Peck model of TTF based on the temperature and humidity condition:

\[ t_{TTF} = A \left( \frac{E_a}{e^{kT}} \right) RH^n \]

where \( T \) is the temperature in K, \( RH \) is the relative humidity in percent, \( E_a \) is the activation energy in eV, and \( n \) is the humidity exponent.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimated value</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_a )</td>
<td>0.89 eV</td>
<td>± 0.11 eV</td>
</tr>
<tr>
<td>( n )</td>
<td>-2.2</td>
<td>± 0.8</td>
</tr>
</tbody>
</table>

Estimating module stresses in the field

The failure stress ($\sigma_F$) is the time-to-failure ($t_{TTF}$) times the stress rate ($d\sigma/dt$), for scale-accelerated failure time models.

$$\sigma_F = t_{TTF} \left( \frac{d\sigma}{dt} \right)$$

Stress rate is a function of the temperature and relative humidity.

$$\frac{d\sigma}{dt}(T, RH) = 1 / (A \times e^{\frac{E_a}{kT}} \times RH^n)$$

Acceleration factor ($AF$) is the ratio of the stress rate at 85 °C/85% RH and the average stress rate under field conditions.

$$AF = \frac{\frac{d\sigma}{dt}(85 \degree C, 85\%)}{\left( \frac{1}{\sum_{t=0}^{h} \frac{d\sigma}{dt}(T_{mod}(t), RH_{mod}(t))} \right)}$$
2. Global maps of damp heat acceleration factors

Global weather data is available at EnergyPlus.net

Hourly ambient temperature and relative humidity data is available for 2590 sites worldwide.

Module temperature was estimated using a “King” model. Module internal humidity was taken as the 96-hour rolling average of relative humidity.

Map of available Typical Meteorological Year (TMY) data files


https://energyplus.net/weather
Hours at 85C/85RH equivalent to 25 years

\[ t_{\text{chamber\_equivalent}} = \frac{25 \times 365}{AF} \]
Hours at 85C/85RH equivalent to 25 years by region

For Europe, about 500 hours at 85 °C/85% RH is expected to correspond to 25 years in the field.

For the United States and China, about 1000 hours at 85 °C/85% RH is expected to correspond to 25 years in the field.

For India, about 2000 hours at 85 °C/85% RH is expected to correspond to 25 years in the field.
3. Uncertainty in acceleration factors

Uncertainty in the values of $E_a$ and $n$ has a significant effect on the confidence interval of the predicted time-to-failure.

$$t_{TTF} = A \frac{E_a}{ekT} RH^n$$

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<td>± 0.8</td>
</tr>
</tbody>
</table>

For tropical environments, $E_a$ uncertainty affects TTF estimates by about ±40%, whereas $n$ uncertainty affects TTF estimates by <2%.
Damp heat testing hours required for confidence in module lifetime

<table>
<thead>
<tr>
<th>Location</th>
<th>Expected value</th>
<th>80% confidence</th>
<th>90% confidence</th>
<th>95% confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chennai, India</td>
<td>2060</td>
<td>&lt;2480</td>
<td>&lt;2690</td>
<td>&lt;2910</td>
</tr>
<tr>
<td>Ji-an, Jiangxi, China</td>
<td>1000</td>
<td>&lt;1230</td>
<td>&lt;1370</td>
<td>&lt;1480</td>
</tr>
<tr>
<td>Mayport, FL, USA</td>
<td>960</td>
<td>&lt;1200</td>
<td>&lt;1350</td>
<td>&lt;1470</td>
</tr>
<tr>
<td>Barcelona, Spain</td>
<td>520</td>
<td>&lt;650</td>
<td>&lt;740</td>
<td>&lt;830</td>
</tr>
</tbody>
</table>

For tropical regions such as Chennai, 2000 hours at 85 °C/85% RH is expected to correspond to 25 years.

Based on uncertainty in the stress modeling parameters, we estimate with 80% confidence that the 25-year equivalent stress is <2500 hours, and with 95% confidence that the 25-year equivalent stress is <3000 hours.
Global acceleration factors for damp heat tests of PV modules

1. Method for determining acceleration factors

   Derived empirical equation to represent damp heat stress based on compiled reliability data.

2. Global maps of damp heat acceleration factors

   Damp heat stress on PV modules expected to be ~2x higher in USA and China compared to Europe, and ~4x higher in India compared to Europe.

3. Effect of uncertainty on acceleration factor

   For most locations in Europe, USA and China we estimate with 95% confidence that the 25-year equivalent stress is <1500 hours of 85 °C/85% RH exposure.

   For tropical locations we estimate with 95% confidence that the 25-year equivalent stress is <3000 hours of 85 °C/85% RH exposure.
Map of acceleration factors representing the test duration in hours at 85 °C/85% RH expected to correspond to 25 years in the field.

Each data point represents a TMY data set that is interpreted using the following stress model:

$$t_{TTF} = A \cdot \frac{E_a}{e^{kT}} \cdot RH^n$$
Acceleration factor map: United States

Map of acceleration factors representing the test duration in hours at 85 °C/85% RH expected to correspond to 25 years in the field.

Each data point represents a TMY data set that is interpreted using the following stress model:

\[ t_{TTF} = A \frac{E_a}{ekT} RH^n \]
Acceleration factor map: China

Map of acceleration factors representing the test duration in hours at 85 °C/85% RH expected to correspond to 25 years in the field.

Each data point represents a TMY data set that is interpreted using the following stress model:

\[ t_{TTF} = A \frac{E_a}{e^{kT}} RH^n \]
Acceleration factor map: India

Map of acceleration factors representing the test duration in hours at 85 °C/85% RH expected to correspond to 25 years in the field.

Each data point represents a TMY data set that is interpreted using the following stress model:

\[ t_{TTF} = A \cdot \frac{E_a}{e^{kT}} \cdot RH^n \]
Estimating module stresses in the field

Module temperature is higher than ambient temperature based on the amount of incident irradiance.

Also, module internal humidity is closer to the average humidity than the instantaneously humidity. 96-hour rolling average was used to approximate module internal humidity.

The yearly stress in the field can then be compared to the 85 °C/85% RH standard condition.

TMY data for Odessa, Ukraine obtained from EnergyPlus.net
Uncertainty in module population

Damp heat TTF data was compiled from literature reports with PV modules fabricated from p-type wafers, encapsulated in ethylene vinyl acetate (EVA), and packaged with glass front sheet and polymer back sheet.

- \( P_{\text{threshold}} = 5\% \)
  - \( t_{\text{TTF}} = 2550 \pm 870 \text{ hrs} \)
  - \( N = 44 \)

- \( P_{\text{threshold}} = 10\% \)
  - \( t_{\text{TTF}} = 2920 \pm 790 \text{ hrs} \)
  - \( N = 41 \)

- \( P_{\text{threshold}} = 20\% \)
  - \( t_{\text{TTF}} = 3220 \pm 780 \text{ hrs} \)
  - \( N = 39 \)

Test duration at 85 °C/85% RH (hr)
## Effect of uncertainty on acceleration factor

<table>
<thead>
<tr>
<th>Error source</th>
<th>Value ± 95% confidence interval</th>
<th>Location</th>
<th>Estimated value</th>
<th>Upper 95%</th>
<th>Lower 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_a$</td>
<td>0.89 ± 0.11 eV</td>
<td>Chennai, India</td>
<td>2058</td>
<td>3092</td>
<td>1391</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Barcelona, Spain</td>
<td>514</td>
<td>893</td>
<td>301</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Riyadh, Saudi Arabia</td>
<td>135</td>
<td>176</td>
<td>110</td>
</tr>
<tr>
<td>$n$</td>
<td>-2.2 ± 0.8</td>
<td>Chennai, India</td>
<td>2058</td>
<td>2073</td>
<td>2051</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Barcelona, Spain</td>
<td>514</td>
<td>549</td>
<td>484</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Riyadh, Saudi Arabia</td>
<td>135</td>
<td>63</td>
<td>347</td>
</tr>
</tbody>
</table>

$E_a$ uncertainty has a large effect of acceleration factor of about +50% to -30%.

$n$ uncertainty has very little effect on acceleration factor in humid climates.