Global acceleration factors for damp heat tests of PV modules

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Abstract **– Time-to-failure data from PV modules subjected to damp heat tests of different temperature and relative humidity conditions was compiled from SunEdison and literature reports. Analysis of the data led to a power law model of time-to-failure for PV modules in damp heat conditions as follows: TTF = A * e^(Ea/kT) * RH^(n), where TTF is the time in hours to reach 20% module power loss, A = 6.4e-10, Ea = 0.89 ± 0.11 eV, and n = -2.2 ± 0.8. Damp heat acceleration factors were then computed for >2500 global typical meteorological year data sets with reference to the standard 85 ºC and 85% relative humidity test condition. The distribution of damp heat acceleration factors for the United States, Europe, China and India reflect the importance of regional climate on predictions of long-term PV module reliability.**

Index Terms **– accelerated stress testing, acceleration factor, corrosion, damp heat, reliability physics**

I. INTRODUCTION

Accelerated stress testing is a central part of photovoltaic (PV) module qualification and certification. The test sequence IEC 61215 for crystalline silicon (c-Si) PV modules includes exposure to 1000 hours of 85 ºC and 85% relative humidity (RH) and stipulates that modules must retain a specified percentage of their initial maximum power (Pmax) [1]. Despite the prevalence of damp heat testing, a consensus has yet to emerge as to the acceleration factor to be associated between damp heat testing and field conditions.

One method for estimating acceleration factors relies on empirical modeling of the effect of stress conditions on time-to-failure (TTF). For microelectronics failures relating to metal corrosion within polymer packaging, Peck and Hallberg showed good predictive ability of a power law model of time-to-failure [2], [3]. However, when the model has been applied to PV reliability data, estimates of the modeling parameters have varied over a large range, with the activation energy ranging from 0.65 to 1.32 eV and the humidity exponent ranging from -2 to -7.2 [4]–[7]. The large spread in modeling parameters results in significant uncertainty of the acceleration factor, limiting the predictive power of damp heat test results.

This work compiles the results from a series of damp heat tests in which PV modules were subjected to different temperature and humidity conditions. Tests conducted by SunEdison and also several literature reports have been compiled to develop a power law model of time-to-failure as a function of temperature and humidity stress. The optimized power law model was then applied to a global data set of typical meteorological year (TMY) files, yielding estimates of damp heat acceleration factors for PV markets worldwide. Finally, the acceleration factors were used to deliver estimates for several major markets of the amount of stress hours at 85 ºC and 85% RH that is expected to correspond to 25 years of field operation.

II. EXPERIMENTAL

Module performance data was compiled both from internal testing at SunEdison and from literature reports. All of the PV modules included in the survey correspond to a nominal construction of c-Si cells fabricated from p-type wafers, encapsulated in ethylene vinyl acetate (EVA), and packaged with glass front sheet and polymer back sheet. For each study, the observed time-to-failure was computed using the criteria of 5%, 10% and 20% module Pmax loss.

Literature reports including module Pmax data from multiple temperature and relative humidity conditions were compiled for analysis of corrosion stress. Four literature

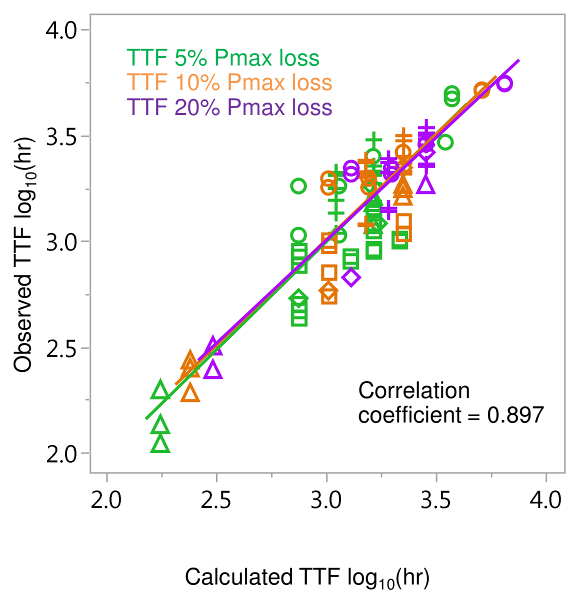

Figure 1: Observed and calculated time-to-failure (TTF) data under damp heat conditions for c-Si solar cells in a glass-polymer package with EVA encapsulant. The marker shape represents the data source as follows: ◊ [7], + [8], Δ [9], ○ [10], □ this paper. The time to failure data is fit to the power law relation, $t_{TTF} = A * e^{(E_a/kT)} * RH^{(n)}$, where E_a = 0.89 eV, and n = -2.2.

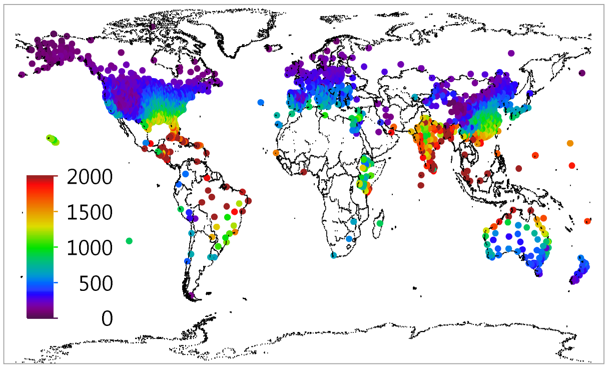

Figure 2. Global map of acceleration factors, with a color scale to represent the test duration in hours at 85 °C/85% RH that is expected to correspond to 25 years of operation in the field. Each data point represents a TMY data set that is interpreted using the stress model (1).

studies were incorporated which included a range of temperatures from 75 ºC to 110 ºC and a range of humidity conditions from 50% RH to 100% RH [7]–[10]. To this data set, the results of a SunEdison study were added which included a range of temperatures from 75 ºC to 95 ºC and a range of humidity conditions from 75% RH to 95% RH. The summarized multi-stress data set consists of 107 data points measured from 63 modules.

Calculated time-to-failure was then assessed using the following power law model of humidity and temperature:

$$t_{TTF} = A * e^{\frac{E_a}{kT}} * RH^n \quad (1)$$

where t_{TTF} is the TTF in hours, T is the temperature in K, RH is the relative humidity in percent, k is the Boltzmann constant in eV/K, E_a is the activation energy in eV, n is the humidity exponent, and A is a prefactor. The prefactor A was modeled as a function of the TTF threshold percentage:

$$A = b * log_{10}(P_{threshold}) + c \quad (2)$$

where $P_{threshold}$ is the threshold for percent power loss defining the time to failure, and b and c are constants. The logarithmic form of (2) provides a reasonable fit to the degradation curve of module Pmax versus damp heat stress hours. Non-linear curve fitting was performed of the measured t_{TTF} data, using an analytic Gauss-Newton approach to optimize E_a, n, b, and c.

Typical meteorological year (TMY) data sets were retrieved from EnergyPlus, an energy simulation program funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO). The data sets contain hourly weather data from a typical year for each of the 2590 locations in the global database. Module temperature was estimated based on the global horizontal irradiance, wind speed and ambient temperature using an empirical model for ground mounted, glass-polymer PV modules [11]. Module internal humidity was estimated using a 96-hour rolling average of the ambient relative humidity data, reflecting the moisture equilibration expected during field exposure.

Stress rates for field conditions were computed using hourly data of estimated module temperature and module internal humidity by the following relations:

$$\sigma_F = t_{TTF} * \overline{\left(\frac{d\sigma}{dt}\right)} \quad (3)$$

$$\frac{d\sigma}{dt}(T, RH) = 1 \,/\, \left(A * e^{\frac{E_a}{kT}} * RH^n\right) \quad (4)$$

where σ is a unitless measure of stress, σ_F is the stress required for failure, and $\overline{(d\sigma/dt)}$ is the mean stress per hour. When σ is normalized such that $\sigma_F = 1$, stress rate can be calculated by (3). The average stress rate across a year of TMY data was then compared to the stress rate at 85 ºC and 85% RH to yield an acceleration factor for each location:

$$AF = \frac{\frac{d\sigma}{dt}(85\,°C, 85\%)}{\frac{1}{h} * \sum_{t=0}^{h} \frac{d\sigma}{dt}\left(T_{mod}(t), RH_{mod}(t)\right)} \quad (5)$$

where AF is the acceleration factor, h is the number of hours per year, $T_{mod}(t)$ is hourly module temperature, and $RH_{mod}(t)$ is hourly internal humidity. The resulting acceleration factors were then scaled to represent the number of hours of exposure to 85 ºC and 85% RH condition expected to correspond to 25 years of field operation.

Literature reports focusing on the 85 ºC and 85% RH stress condition were also compiled to evaluate the variability in module Pmax data for the same nominal construction [12]–[15]. Module Pmax data corresponding to alternate encapsulant and back sheet materials were excluded. The data set consisted of 44 modules and 124 TTF data points. The distribution of data for the 10% TTF threshold were fit by a lognormal distribution, using right-censored values for the 3 out of 44 modules that had not reached 10% Pmax loss by the end of testing.

III. DATA AND RESULTS

Figure 1 shows the observed and calculated time-to-failure data for the acceleration study at SunEdison and three additional literature studies. The TTF data was compiled for each PV module using three thresholds for Pmax loss: 5%, 10% and 20%. All of the TTF data was fit using the same values for the activation energy and the humidity exponent, but the prefactor, A, was allowed to vary for each time to failure threshold. Estimated values and 95% confidence intervals of E_a = 0.89 ± 0.11 eV, n = -2.2 ± 0.8 were found by non-linear curve fitting. Prefactor values of 3.7e-10 for 5% Pmax loss, 5.0e-10 for 10% Pmax loss, and 6.4e-10 for 20% Pmax loss were derived from non-linear curve fitting of b and c from (2). The correlation coefficient between observed and calculated time to failure values was found to be 0.90 for the data set.

Figure 2 shows the global acceleration factor map derived from the power law model demonstrated in Fig. 1. The map is scaled to represent the estimated hours of damp heat testing at

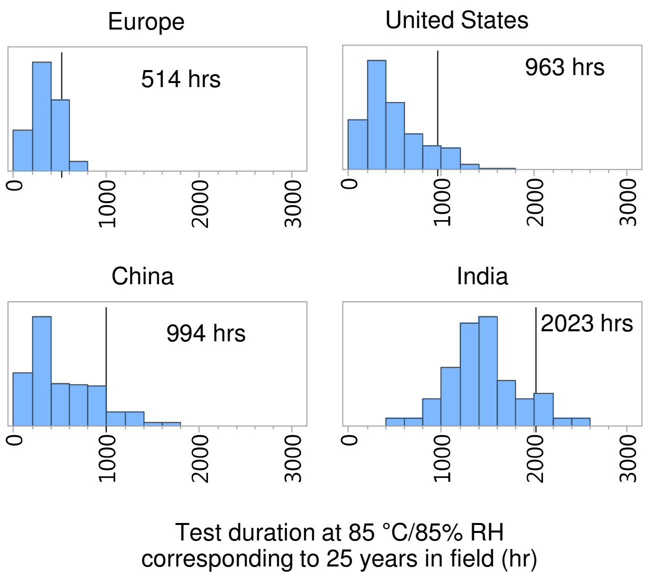

Fig. 3: Histograms representing the test duration in hours at 85 °C/85% RH that is expected to correspond to 25 years of operation in the field. The vertical lines designate the location at the 90th percentile stress amount.

85 ºC and 85% relative humidity that are expected to be equivalent to 25 years of operation in the field. More than 80% of the TMY files are for locations in Europe, the United States, China and India.

Figure 3 shows histograms of estimated hours of damp heat testing at 85 ºC and 85% relative humidity that are expected to be equivalent to 25 years of operation in the field. The histograms for the United States, Europe, China and India are shown and the 90th percentile of estimated damp heat hours is marked on each histogram.

Figure 4 shows histograms of the time-to-failure data in hours of modules subjected to the 85 ºC and 85% relative humidity stress condition. Histograms were compiled for the 5%, 10% and 20% Pmax loss thresholds. The distributions are quite broad with the mean value for 20% Pmax loss occurring at 3220 ± 780 hours.

Figure 5 shows the cumulative probability density function fit to the 10% Pmax loss TTF data from Figure 4b using a lognormal distribution. The plot shows that about 10% of the reported modules in the literature review showed >10% Pmax loss when subjected to the 85 ºC and 85% relative humidity stress condition for 2000 hours.

IV. DISCUSSION

The activation energy, E_a, and humidity exponent, n, found in this study are consistent with the values previously reported for microelectronic devices. In the initial review [2] and later update [3], values of E_a ranged from 0.77 to 0.9 eV and values of n ranged from -2.4 to -3.0. Both PV modules and epoxy-

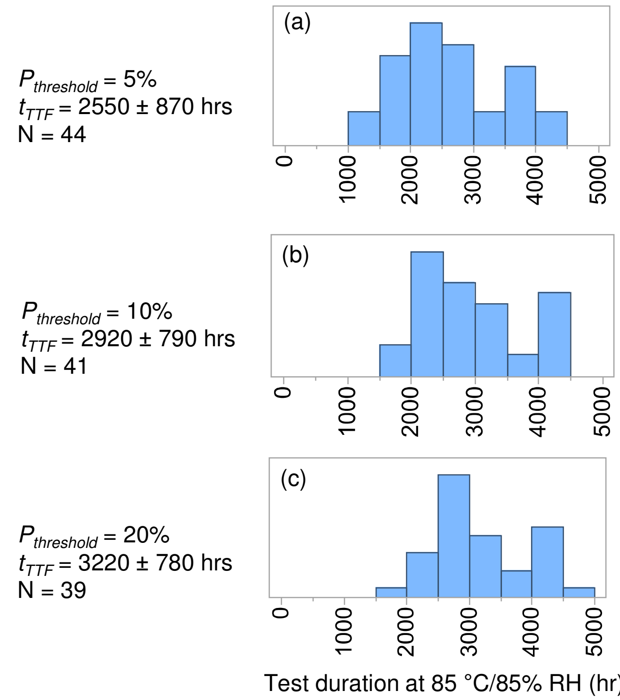

Figure 4: Histograms representing the time-to-failure in hours at 85 °C/85% RH corresponding to 5%, 10% and 20% module Pmax loss. Mean, standard deviation and module count is compiled for each time-to-failure threshold.

encapsulated microelectronic devices exhibit degradation due to diffusion of moisture through polymer encapsulant and corrosion of metals at internal junctions, so it is not surprising that similar acceleration factors might describe both processes.

The 95% confidence intervals for the terms E_a = 0.89 ± 0.11 eV and n = -2.2 ± 0.8 repr esent significant uncertainty in the estimated acceleration factors. To evaluate this effect, a large number of E_a and n values were generated assuming normal distributions with σ_{Ea} = 0.05 eV and σ_n = 0.4. Acceleration factors were computed for each of the generated E_a and n values, and the distribution of the resulting acceleration factors was used to supply estimates with of the 90th and 95th percentile. Table I shows the results from four locations with the test hour equivalent for the expected value, the 90% confidence value, and the 95% confidence value.

The distribution of module performance shown in Figure 4 and Figure 5 only represents a sample of the c-Si modules reported in the literature. The width of the distribution likely relates to variability in the quality of the c-Si cells, encapsulant, and backsheet. The distribution of TTF values for any batch of photovoltaic modules is likely to show different values for mean and standard deviation than those reported in Figure 4. However, the literature review provides insight into the range of TTF behavior that has been observed. Most modules reach 10% Pmax loss between 2000 and 4000 hours exposure to 85 °C/85% RH stress.

Table 1. Test hours at 85 °C/85% RH equivalent to 25 yr field exposure for 4 locations. The value in hours represents the 50th, 90th and 95th percentiles the distribution of probable E_a and n values.

	Test hours at 85 °C/85% RH equivalent to 25 yr field exposure		
Location	Expected value	90% confidence	95% confidence
Chennai, India	2060	<2690	<2910
Ji-an, Jiangxi, China	1000	<1370	<1480
Mayport, FL, USA	960	<1350	<1470
Barcelona, Spain	520	<740	<830

The data collected in this study represents a range of damp heat behavior for c-Si solar cells in a glass-tedlar package with EVA encapsulant. The expected module lifetime is likely to change as a function of cell type and module materials, as shown in the variability in TTF for a given stress condition. However, the kinetics of acceleration appear to be consistent with a shared damp heat acceleration factor for the same nominal module type. Significantly different cell types, such as Si heterojunctions, or module types, such as glass-glass, may show different acceleration factors.

The wide variety of climate conditions around the world present significantly different stress environments for installed PV modules. The location-specific acceleration factors presented in this work suggest that PV modules may experience corrosion effects at twice the rate in the United States and China as compared to Europe, and at four times the rate in India as compared to Europe. Based on the acceleration factors distributions in Figure 3 and the module performance distribution shown in Figure 4, an estimate can be made of the extent of the population at risk from corrosion failure in the most extreme environments of each region. In the Europe, United States, and China regions, <1% of the module population is expected to be at risk for >10% Pmax degradation in 25 years. Modules that pass 3000 hours of damp heat are not expected to show failure due to moisture corrosion, even in the most aggressive environments.

Global testing standards and requirements have yet to show differentiation based on the climate of the proposed PV project site. However, improved understanding of the acceleration factors for relevant stress conditions helps enable improved recommendations for testing standards and requirements.

V. SUMMARY

Damp heat acceleration factors for c-Si photovoltaic modules have been estimated using the compiled results of multi-stress accelerated tests and global weather data. Accelerated stress tests conducted by SunEdison and compiled from the literature were used to generate an empirical model of time to failure as a function of temperature and humidity. The empirical model was then applied to module temperature and internal humidity estimated from a global dataset of 2590 weather files to estimate damp heat acceleration factors for Europe, the United States, China and India. Based on the uncertainty in empirical modeling parameters, estimates were provided for the 95% confidence limit for the expected hours at 85 °C/85% RH equivalent to 25 years in the field.

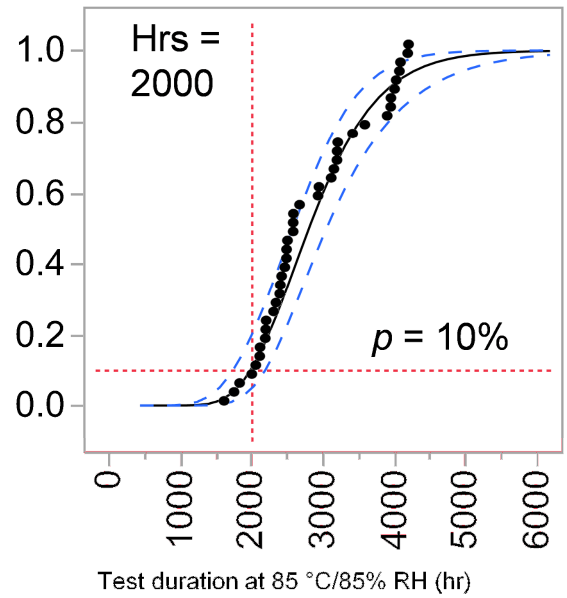

Figure 5: Cumulative probability of modules reaching 10% Pmax loss as a function of test duration at 85 °C/85% RH. Each point represents one module time-to-failure observation, the black line represents the estimated lognormal cumulative distribution and the blue lines represent the 95% confidence interval. At 2000 hours of testing at 85 °C/85% RH, the lower 10th percentile of modules included in the literature review showed >10% Pmax drop.

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