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Quantifying the Thermal Fatigue of CPV Modules

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Abstract: A method is presented to quantify thermal fatigue in the CPV die-attach from meteorological data. A comparative study between cities demonstrates a significant difference in the accumulated damage. These differences are most sensitive to the number of larger (ΔT) thermal cycles experienced for a location. High frequency data (<1/min) may be required to most accurately employ this method.

Keywords: Accelerated Lifetime Testing, Thermal Fatigue, Die-Attach, Rainflow.
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INTRODUCTION

Fatigue is the progressive damage that occurs when a material is subject to cyclic loading. Thermal fatigue suggests loading is manifest from a temperature change of constrained materials that have a mismatch in coefficients of thermal expansion (CTE). This condition exists in multiple locations within a CPV module, but nowhere is it so acute as the PV cell/ substrate connection. At this location the resulting differential strain between the PV cell and its substrate must be accommodated by a die-attach material. For each loading cycle (temperature change) work is done to the die-attach, the accumulation of which leads to voiding, cracking and ultimately failure.

The time to failure is predicated on both module design (cell-assembly material properties and geometry) and the weather. While the first of these factors is defined and easily quantified even before the module is built, the second, weather, is not so straightforward. It is the weather that will dictate the driving force for damage (loading cycle magnitude) and the rate at which it will accumulate (the frequency of those cycles). In this paper a method is presented for quantifying CPV die-attach thermal fatigue damage from meteorological data. First, a time history of the CPV cell temperature is modeled and the significant temperature changes identified. Those changes are then quantified and input into a thermal fatigue model that weights each as the relative damage imparted to the die-attach material. By considering meteorological data collected at several locations around the world, a relative comparison of assembly lifetime vs. deployment location is presented.

METHODS

A steady state temperature model developed by King et al. is employed to calculate CPV cell temperature from ambient temperature, T_{amb}, direct normal irradiance, E, and wind speed, WS [1]:

$$T_{cell} = T_{amb} + E\exp\left(a + bWS\right) + \frac{E}{E_o}T_o \qquad (1)$$

The coefficients a and b were empirically determined for a 22x linear concentrator to be -3.23 and -0.13, respectively [1]. E_o is the reference solar irradiance of 1000 W/m^2 and T_o represents the temperature difference between the cell and module at this reference irradiance. For the 22x system T_o was determined to be 13 °C; however this offset temperature will be very sensitive to the method of die-attach. For the current model, the cell temperature is elevated from ambient by ~ 52 °C at high irradiance and low wind speeds.

Once cell temperature is modeled from meteorological data, it is distilled into segments of temperature change (or half-cycles) that relate to loading of the die-attach. Several cycle-counting methods can conveniently summarize lengthy and irregular load vs. time histories [2]. For the current work, the three-parameter Rainflow counting algorithm is chosen for its ability to only quantify cycles significant for a die-attach type fatigue damage analysis [3]. Additionally, the three parameters output for each cycle (temperature change ΔT, maximum temperature T_{max}, and transitions time t_t) are those required for the thermal fatigue model employed in

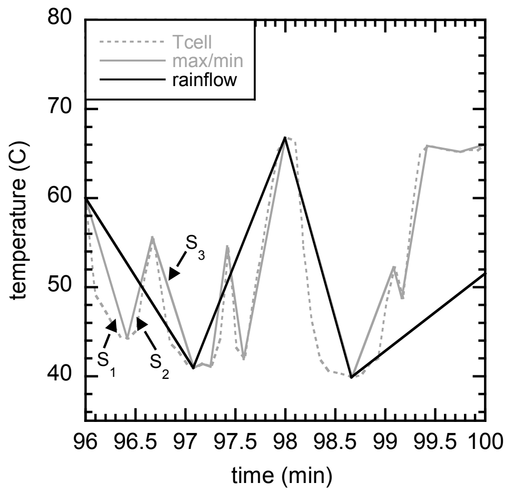

FIGURE 1. Illustration of the Rainflow count algorithm.

this study. The process of the three-parameter Rainflow count is summarized in Fig. 1. First, the time history of temperature is reduced into temperature segments by recording the points at which *dT/dt* changes sign. Second, three at a time the magnitude of temperature change, *S*, for these max/min segments are considered with the Rainflow condition:

$$S_1 > S_2 \leq S_3 \tag{2}$$

If this condition is true, segment S_2 is discarded, segments S_1 and S_3 combined, and the next three segments considered. If the condition is false, segment S_1 is regarded significant, its values of ΔT, T_{max}, and t_t recorded, and the next three segments considered. This process is continued until all segments in the time history are considered and results in an array of half-cycles, each characterized by a unique set of ΔT, T_{max}, and t_t values.

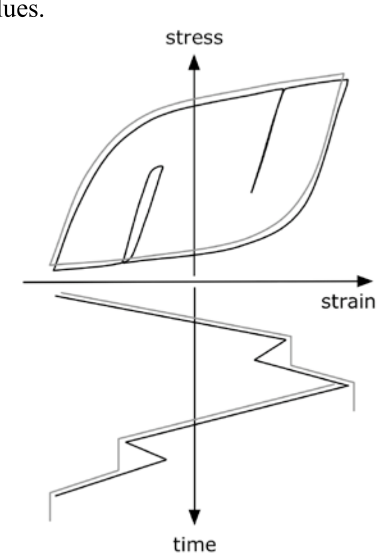

FIGURE 2. Schematic of the Rainflow count identifying a significant cycle.

The concept of a "significant" half-cycle originates from the material forming a closed stress-strain hysteresis loop through the loading excursion, Fig. 2. Small load reversals (black curve) within the larger cycle that form the hysteresis loop do not significantly contribute to the work (damage) imparted to the material and may therefore be ignored (grey curve). The algorithm of the Rainflow count is designed to remove these smaller, insignificant cycles.

The Engelmaier thermal fatigue model, developed for leadless surface-mount solder attachments, is used to calculate the damage imparted to the die-attach with each cycle distilled from the meteorological data. The Engelmaier equation calculates a fatigue life, N_f (number of cycles to failure), for a specific set of stress conditions[4]:

$$N_f = \frac{1}{2}\left(\frac{\Delta\gamma_p}{2\varepsilon_f}\right)^{\frac{1}{c}} \tag{3}$$

where ε_f is the fatigue ductility coefficient and varies with die-attach material. The cyclic plastic strain range, $\Delta\gamma_p$, reduces to:

$$\Delta\gamma_p = \frac{\sqrt{2}FL}{h}\Delta\alpha\Delta T \tag{4}$$

when symmetry of a typical CPV cell assembly is assumed, and where *F* is a calibration constant, *h* and *L* geometrical factors and $\Delta\alpha$ and ΔT the differential CTE between cell and substrate the and magnitude of temperature change, respectively. The fatigue ductility exponent, *c*, is a function of the mean cycle temperature, T_m, and dwell time, t_D, according to:

$$c = -0.422 - 6\cdot 10^{-4}T_m + 1.74\cdot 10^{-2}\ln\left(1+\frac{360}{t_D}\right) \tag{5}$$

In the current treatment, t_D is taken as half the transition time, t_t, computed from the Rainflow count. The coefficients for equation (4) are appropriate for eutectic Sn/Pb solder however do not vary significantly from these values for most solders.

Die-attach damage is considered to be linearly proportional to the ratio of the number of cycles completed at a specific set of stress conditions, n_i, to the total number of cycles that would result in failure for those same conditions, N_i:

$$D_i = \frac{n_i}{N_i} \tag{6}$$

This relation is known as the Palmgren-Miner hypothesis. If die-attach damage is assumed to accumulate at the same rate for a given stress level without regard to past history, the total damage accumulated is the sum of the damage for each specific stress level. Considering every half-cycle of the Rainflow count is a unique stress condition, therefore $n=1$, equations (3), (4) and (6) may be combined to compute the damage accumulated through the temperature history of interest:

$$D = \sum_i \Delta T_i^{-\frac{1}{c}} \qquad (7)$$

To allow a direct comparison between deployment locations, all material and geometrical factors are considered constant and therefore are omitted from equation (7).

RESULTS AND ANALYSIS

An example of the steady state temperature model fit is presented in Fig. 3. The result of the model computed at a one-minute averaged time interval is compared to the measured cell temperature of a module taken every five seconds during the same period. The temperature changes are well represented by the model; however, due to the lower frequency at which the model was computed some significant temperature cycles may be missed.

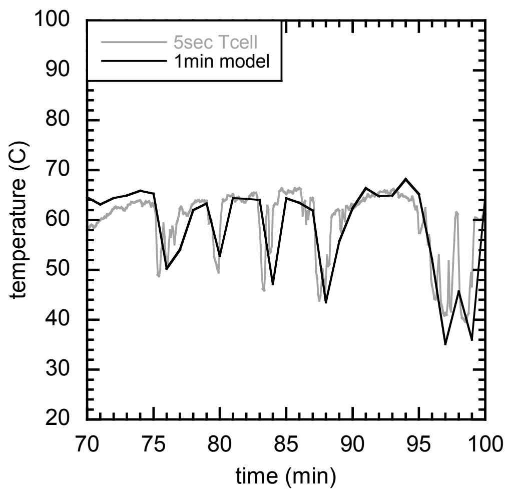

FIGURE 3. Fit of the steady state cell temperature model.

Three years of meteorological data (averaged one-minute intervals) obtained from the Solar Radiation Research Laboratory (SRRL) in Golden, Colorado is examined with the current method, Fig. 4. Five curves are produced by limiting the damage calculation to those cycles containing at least the minimum temperature change (mr) noted and the data normalized with respect to the most damaging case, mr=0 where all cycles are considered. By eliminating cycles of smaller temperature changes, the dependence of relative damage on those cycles is illustrated. For instance, ignoring cycles with $\Delta T \leq 15$ °C, only reduces the total damage by 10 %. The relative damage only significantly decreases when cycles of $\Delta T \leq 30$ °C are ignored. One year of meteorological data (averaged

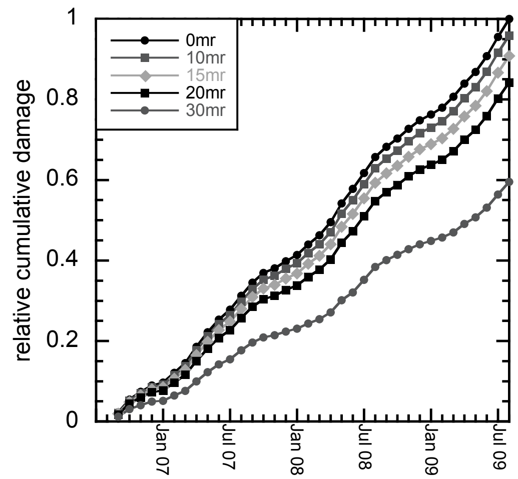

FIGURE 4. Accumulated die-attach thermal fatigue damage for three years in Golden, CO.

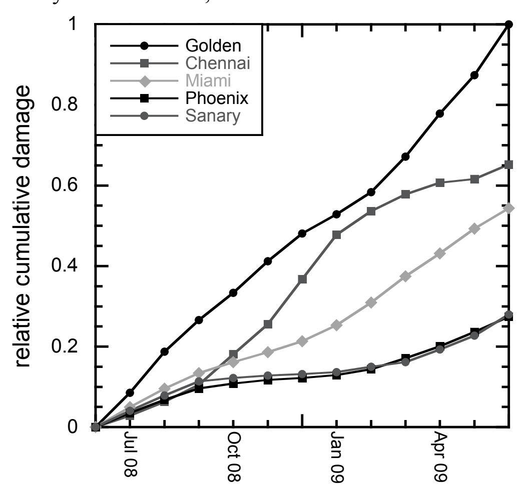

FIGURE 5. Accumulated die-attach thermal fatigue damage for one year in five locations.

one-minute intervals) collected for an additional four locations by Atlas Testing Services (Sanary, France; Chennai, India; Phoenix, Arizona; Miami, Florida) is compared to the Golden data in Fig. 5. In the same year, the same CPV module deployed in Miami, FL would only accumulate ~55 % of the damage if deployed in Golden. Phoenix and Sanary are the least damaging of the locations studied, accumulating less than 30 % of the damage in Golden.Examining the change in relative damage accumulation with minimum temperature range for Phoenix, similar to Fig. 4 for Golden, gives an insight to this behavior, Fig. 6. Note the relative spread between the curves in Fig. 6 for Phoenix vs. Fig. 4 for Golden. The larger drops in accumulated damage with increasing

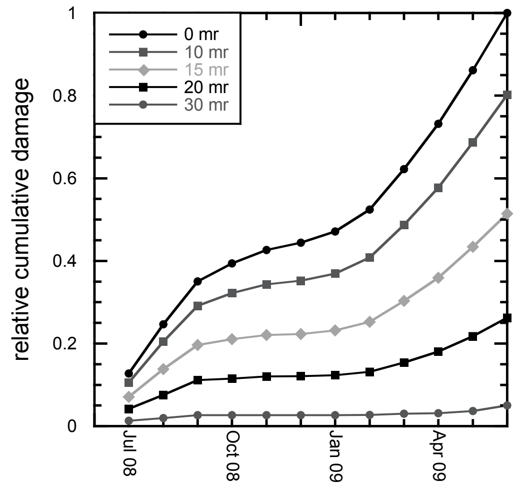

FIGURE 6. Accumulated die-attach thermal fatigue damage for three years in Phoenix, Arizona.

minimum range suggest that fewer of the larger, more damaging cycles exist in Phoenix. In fact, the zero slope for the 30mr curve encountered between September and February reveals that no cycles of *ΔT*>30 °C occur during that period.

The particularly similar damage accumulated in Phoenix and Sanary, and their discrepancy with that accumulated in Golden is explained by examining the distribution of the contributing cycles' *ΔT,* Fig. 7. While the distributions for Phoenix and Sanary are very similar, Golden demonstrates a significant number of larger, more damaging, cycles.

CONCLUSIONS

A method is presented to quantify thermal fatigue in the CPV die-attach from meteorological data. A comparative study between cities demonstrates a significant difference in the accumulated damage. These differences are most sensitive to the number of larger (*ΔT*) thermal cycles experienced for a location. The presented results are based on a generic temperature model where the temperature difference between the cell and ambient, under high irradiance, is ~ 52 °C. Therefore any system that exhibits a lower temperature drop under similar conditions would accumulate less damage and have a corresponding longer lifetime. Due to the short thermal time constant of the CPV cell, high frequency meteorological data must be used for this analysis.

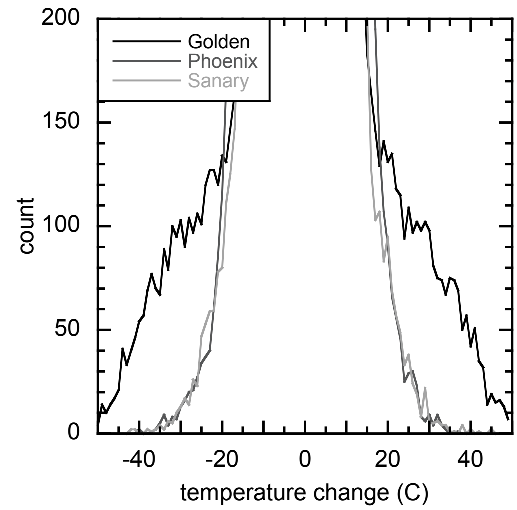

FIGURE 8. Distribution of cycle temperature change.

In the current work, one-minute averaged data is employed; however, as demonstrated in the temperature model fit (Fig. 3), even at this high frequency significant thermal cycles that would contribute to fatigue damage may be missed. Future work includes understanding the magnitude of this effect, developing a statistical model to compensate for lower frequency data, and validating this work with on-sun experiments.

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