DEMONSTRATING RELIABILITY IN HCPV SYSTEMS

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ABSTRACT

High Concentration Photovoltaic (HCPV) power sources must compete with established energy sources such as fossil fuel or nuclear power, and must be as reliable and cost effective as other energy sources. HCPV manufacturers must address issues of technology viability, unique design requirements, immature manufacturing processes, quality control, and the impact these have on the reliability over a 25 year life. SolFocus is investing in proving the lifetime of its HCPV product and developing reliability assessment methods. This approach allows the company to provide an industry standard warranty with good knowledge of the financial risks involved and to set a cornerstone for product and company acceptance in the maturing solar industry. The SolFocus Reliability Program is divided into two major areas; panel and tracker reliability. This paper outlines the processes behind each program and summarizes current results.

INTRODUCTION

Competing with established energy sources such as fossil fuel or nuclear power is a difficult proposition for this new technology, especially as the fast-paced solar market has established high expectations for quality, lifetime, and overall corporate bankability. SolFocus is facing this competition head on by setting rigorous reliability goals and demonstrating reliability through extensive test programs.

Panel reliability is demonstrated by minimal power output degradation and few functional failures over 25 years. Reliability challenges to the HCPV panel include ‘standard’ stresses associated with outdoor operating conditions and the unique stresses associated with concentrated solar energy. Many components of the CPV panel must be resistant to high density, full spectrum solar irradiation, extreme thermal non-uniformities and rapid thermal cycles. Since it is almost impossible to reproduce these stresses in the lab, the panel reliability program must run accelerated field tests in addition to temperature and humidity stress tests that exceed current IEC standards.

HCPV trackers necessary to move the panels can have a significant impact on performance. Fatigue, structural failure, pointing errors and mechanical wear-out must be quantified and addressed to meet lifetime goals. This quantification must be developed through carefully designed accelerated tests that will indicate the product’s expected longevity and performance degradation.

PANEL RELIABILITY PROGRAMS

The SolFocus CPV panel reliability program consists of component level up to full system level accelerated test programs. These accelerated test programs complement a monitoring program tracking the long-term performance of representative panel populations operating non-accelerated in the field.

At the lowest level, the individual components that have been identified as critical to reliability are tested as independent parts. The test conditions include IEC 62108 requirements as well as specialized tests derived from operating conditions and known failure modes specific to each component type. All components must exceed defined ‘qualification’ limits based upon power output degradation after a defined amount of time. This guarantees a minimum expected component life. These tests are then extended until the components have failed in order to fully quantify the expected life. All component variations, including new designs and vendors and processes, must pass the qualification limits before incorporation into commercial production.

The effects of several conditions cannot be observed by component level tests, so tests must be run at the panel or full system level (array of panels, tracker, controller, and inverter). These effects result from specific conditions that arise when sunlight is being concentrated by the mirrors. Two different panel level tests are performed to investigate failure modes associated with the stresses from solar concentration. A traditional temperature/humidity step-stress test examines interactions and failures that may occur due to weathering stresses. A field test under accelerated conditions is necessary to learn about failure modes associated with operation under concentrated HCPV conditions.

Temperature/Humidity Tests

A temperature/humidity step-stress test provides a partial answer to the basic question: What does 1000 hours at 85°C/85%RH mean? The test process is outlined in Figure 1. The step-stress test is conducted using smaller ‘mini-panels’ that are composed of individual, fully functional power units (a full panel consist of 20 power units). This allows the test program to include many different temperature and humidity levels at a reasonable expense. These tests are run until the mini-panels fail or until fail times can be extrapolated based upon partial degradation. From this a temperature/humidity relationship is created. This relationship is then input into a use-condition model that determines the conditions inside the panel based upon the specific geographic location of that panel. The expected panel life is then determined as a function of the specific site location (i.e., desert or tropical locations). The resultant life estimation is only viable for mechanisms triggered by variations in temperature and humidity.

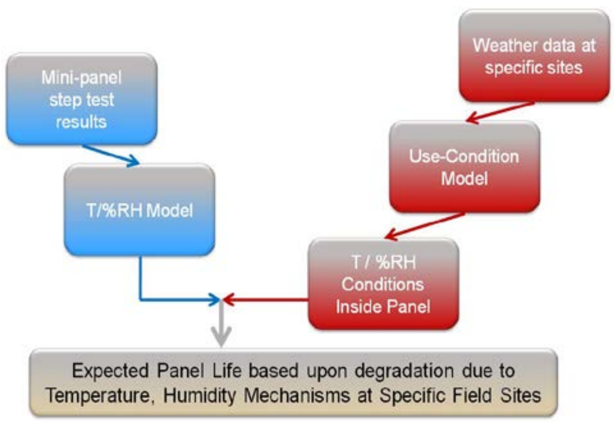

Figure 1 Process to determine life based upon temperature and humidity driven mechanisms at specific field sites

Solar Irradiance Tests

For mechanisms associated with concentration solar irradiation, special panels are built and deployed at target field sites. These special panels are configured to cause specific parts that are exposed to concentrated solar irradiation to run at higher temperature levels. Thus, any degradation that is at least partially driven by temperature can be quantified with an Arrhenius-type model. For example, SolFocus has conducted accelerated field tests on receivers by disabling the conductive heat removal pathway from the CPV cell. Panels are run at nominally 20°C and 40°C levels above non-accelerated panels. Figure 2 shows the temperature rise, which is a function of both energy in and the conductive heat path out, over 1 year for non accelerated and accelerated panels. As of 1.3 years of accelerated operation, there is no measurable degradation of the accelerated panels (see Figure 3). Since there has not yet been a failure of the accelerated panels, it is impossible to calculate the expected life of non-accelerated panels, but applying the basic '2x every 10°C' rule-of-thumb indicates that receiver life may be >21 years. The test will be ongoing until at least the 2 year point has been reached.

There are other valuable methods to accelerate the aging of HCPV panels in the field. SolFocus also runs a power cycle where a full array of panels is cycled on and off axis. This cycling initiates a thermal cycle on the components receiving concentrated sunlight which happens in HCPV operation every time the sun rises/sets or the sun is shadowed by a cloud. Figure 3 shows that after 1.3 years of power cycling (approx 10,000 cycles total), the power cycle accelerated panels have not deteriorated. Another way of accelerating field operation is to modify the optical system to input more energy into the accelerated components.

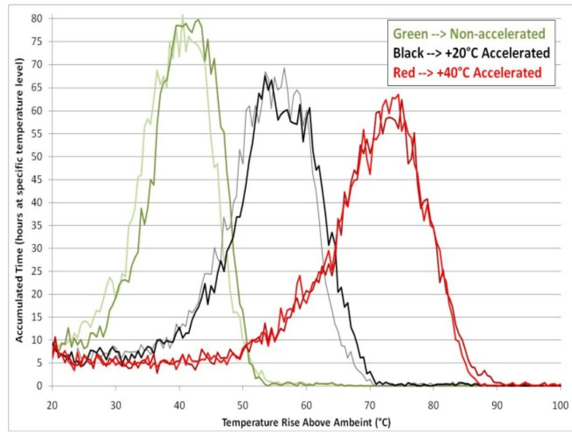

Figure 2 Temperature rise distribution for receivers from Oct 2009 to Oct 2010 for thermally accelerated panels

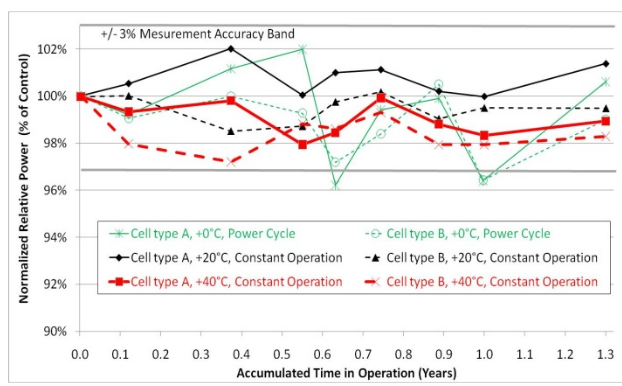

Figure 3 Power outputs of accelerated panels normalized to non-accelerated 'control' panels

TRACKER RELIABILITY PROGRAM

Tracking the sun is critical to the overall performance of a HCPV array. Reliability tests focus on both the electronics for control and the mechanical structures for motion. The controller and tracker have been tested together to create the most representative environment possible for an accelerated test. Twelve production ready trackers and controllers are set up at our supplier in China. Another one is in Palo Alto, California. In a few months we will bring on line an additional twelve full trackers at a test site in Michigan and another 12 in Southwestern USA.

Most of the test systems use dummy weights specifically designed to preserve the loads, forces, and moments created by the solar panels. We 'accelerate' their movement by removing dead-time between tracker motions (see figure 4). The acceleration, speed, number of movements and direction of movement the tracker makes in a calendar day remain unchanged so the mechanical inertia, static and dynamic friction, and wear tendencies in the accelerated movement are the same as the standard (unaccelerated) movement. Thus, a tracker can experience 17-18 days of operation in a single calendar day.

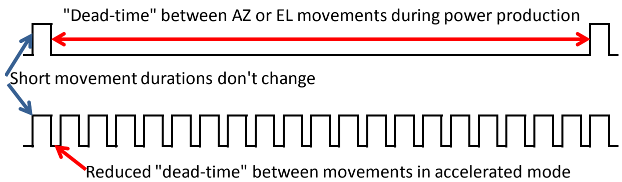

Figure 4 Accelerated life test by way of dead-time reduction

To date, in over 20 years of accelerated time, there have been a low number of mechanical problems, and so far, we have demonstrated surviving our 10 year warranty with 93% probability (Figure 5). Even with only 2 failures, the characteristic signatures provide insight as to wear rates and expected life.

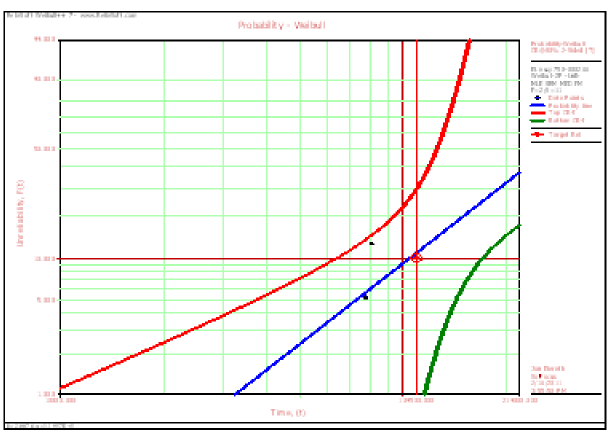

Figure 5 Maximum Likelihood Estimate (MLE) of probability of failure over the 10 year warranty

Eventually, all signatures will be combined, reviewed for 'tracers' that can be used in the current or future tracker designs to estimate life expectance to a statistical significance. We will run these tests until all trackers have experienced a mechanical failure.

At the beginning of the reliability test, every tracker is characterized, measuring motor current and vibration levels (accelerations) at 16 locations [1]. These are used to infer wear and, ultimately, life. Voltage and temperature are also measured but more as insurance that the electronics are working properly and that the motors and the field effect transistors in the control box are not being overheated by the characterization.

After approximately one year of accelerated usage, each tracker is stopped and re-characterized. So, over the life of the test there are approximately 20-30 characterizations depending on their life. Additional details of the SolFocus test process can be found in [1].

Current as an Indicator of Wear

The amount of current required to move the tracker elevator assembly or slew (for the azimuth movement) is an indicator of mechanical tightness and wear [2]. If the current decreases over time, the mechanism is "wearing in" and becoming looser. If the current increases over time, there is increased friction or worn bearings, requiring more power to move them. Figure 6 shows a decrease in current from initial characterization (jagged red line) to usage equivalent to approximately 20 years (smoother blue line. The variation from, say, 1 amp to 2 amps in milliseconds is a result of our pulse width modulated power source and is not related to wear or friction. This decrease in absolute current, smoothing of the maximum current, and shortening of the time required to travel the same arc indicates wear-in resulting from usage.

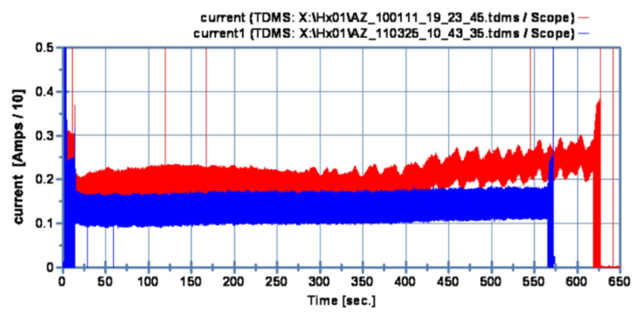

Figure 6 Plot of AZ current as a function of use (age)

Changes in current can also indicate onset of wear-out. Figure 7 shows two elevator currents for the same elevation drive assembly. The red shows the current at time zero while the blue shows the current at approximately twenty years. The upper plot shows current over the entire range of characterization while the lower plot is a blow-up of the upper, covering only time 150 sec. to 300 sec. The "jaggedness" of the original characterization (red) shows the effect of a tight tooth in the elevator screw-drive. As the elevator is used, the jaggedness disappears as a result of "wear-in". However, as evidence by the blue curve (at 20 years) the current required to move the elevator is noticeably greater than the original measurements (look at the 50 sec. mark) at the starting position. It then decreases until the 230 sec. point, at which time it again begins to increase to about 3 amps, approximately the same as the original characterization. In general, the "V-shape" of the current is expected because of the change in current requirements over the entire range of travel due to the changes in mechanical advantage. Important findings from this activity were the high value up until 150 sec., and the rise at 335 sec. These indicate increased friction at specific points in the elevator travel. This reliability testing has hence provided important information that SolFocus is able to use to optimize the product to minimize any performance issues associated with this.

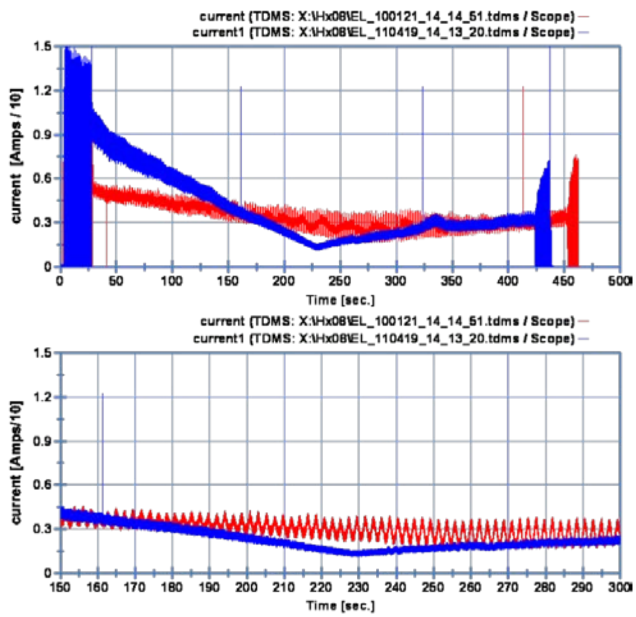

Figure 7 Comparative elevator current plots at 0 and 20 years

Vibration as an Indicator of Wear

Vibration is the second indicator of wear in the tracker reliability test plan. Every moving mechanism has a "vibration signature" [3] that changes as a function of use. Changes in vibration frequency, amplitude and power distributions, measured by accelerations, indicate wear in the gears, bearings and sliding surfaces based on position, direction of movement, and usage (age). A good discussion of this use of vibration measurement is in [4], and is not presented further here.

Positional Indication

Accelerations are measured during each characterization. Since the characterizations are performed over the exact same physical distance or arc, unusual vibrations can be correlated to physical positions. For example, in the test system Hx06, shown in Figure 8, high vibrations are observed in the first 50 seconds and the last 25 seconds of the characterization. These times correspond to the physical positions that have the highest load and forces and appeared when the mechanism had accumulated approximately 18 years of equivalent use. The four accelerometers that register these high accelerations are located on the worm-gear block, which has four bearings in it, and were identified from previous testing as being potential failure points. Again, this analysis allows SolFocus to have a very solid understanding of failure modes and hence to address them and ensure the highest reliability of the product.

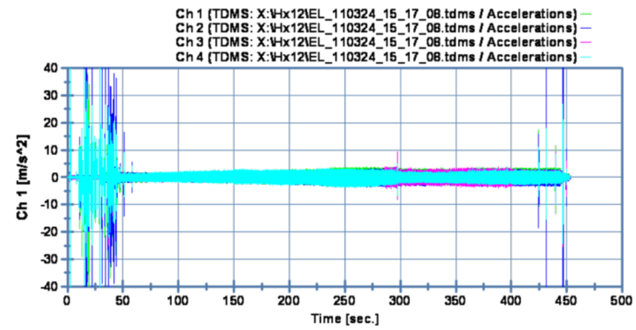

Figure 8 High accelerations can be seen at times of high loads, the endpoints of the elevator's travel

Directional Indication

A worm gear sees different loads and directions for thrust when turned clockwise versus counter-clockwise. In one direction, the mechanism is "pushing" while in the other direction it is "pulling". Thus, as the mechanism wears, different amounts of vibration are seen in the two different directions. In Figure 9, the red and blue plots show vibration as a function of characterization time for the same elevator mechanism at the same age, just opposite directions of motion.

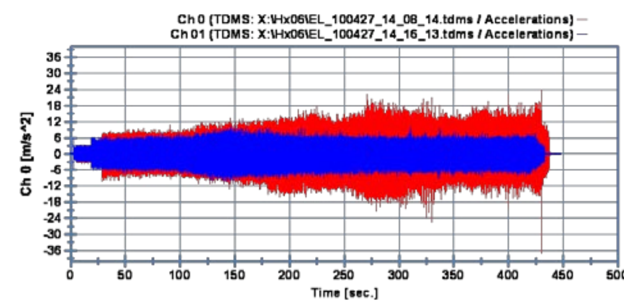

Figure 9 Vibrations for the same elevator drive at the same age, but opposite directions of motion

The power spectral densities for the vibrations in Figure 9 are shown in Figure 10 (top) and the total (integrated) power generated by the vibrations are shown in the bottom plot in Figure 10. Red and blue indicate different directions of travel. The integration accounts for both the amplitude and duration of the vibration and are presented in a cumulative form as a function of the frequency. Each spike in the upper plot results in an increase in the total power in the lower plot. The increase in the total power is an indicator that the vibration is imparting greater energy to the mechanics, in this case, as a result of greater friction and wear.

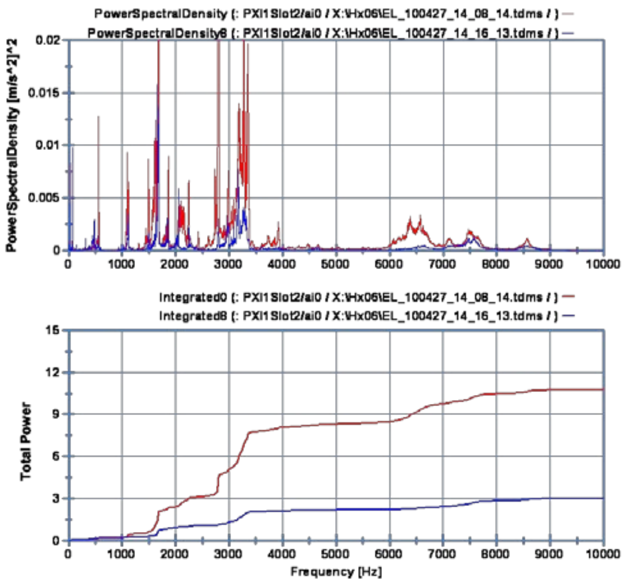

Figure 10 Spectral density (top) and total power plots (bottom) for vibrations in Figure 9

Usage Indication of Wear

Wear from normal usage can be seen in the analysis of the vibrations as well as from the currents. Figure 11 shows the time-domain accelerations at the start of the test in red and after approximately 8 years in blue. Often, for high speed machinery, a change in the amplitude by a factor of three is considered failure. In a low speed tracker, it indicates significant wear and possibly audible noise, but the systems continue to operate.

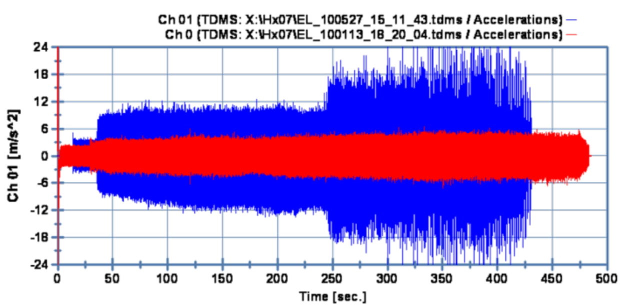

Figure 11 Time domain accelerations for a worn elevator motor

An increase in the total power is sometimes a better indicator of wear than vibration amplitudes from an FFT analysis. The top plot in Figure 12 shows the power spectral density for time-domain vibration plot in Figure 11, and the bottom plot shows the total power. In these plots the elevator is traveling the same direction both times, but at 0 years and 10 years of use, so this is not the result of "directional" vibrations.

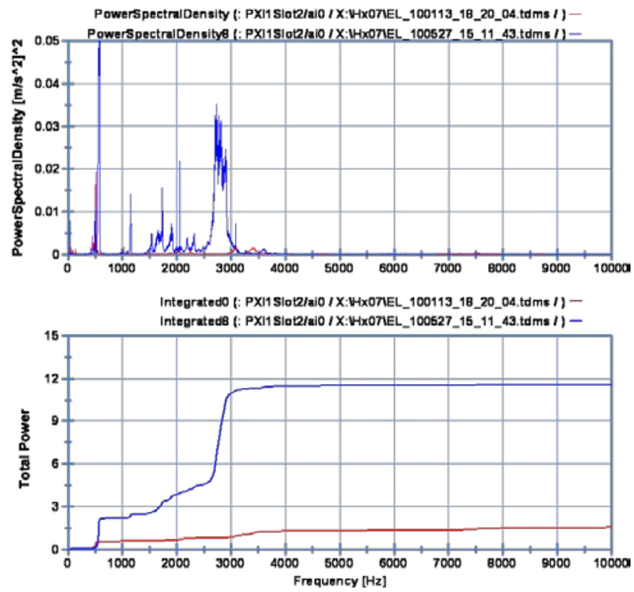

Figure 12 Spectral density and total power for a worn elevator mechanism

Future Work

The data presented here shows acceleration amplitudes and frequencies in the time and frequency domains. As stated earlier, the general "factor of three" rule of thumb used in some industries is not as useful here. Trackers are much more forgiving in terms of vibration because they move at very slow speeds. The same level of change in an automobile wheel bearing would be very noisy and affect handling at freeway speeds. For slow moving machinery it is necessary to monitor currents and/or vibrations as they increase until complete failure occurs. Then distributions can be created to predict operational life.

SolFocus has recently begun using both current and vibration signatures in the manufacturing assembly process as a method of screening. The levels of vibration seen in the reliability life tests form the basis for screening at final assembly. Motors with high currents and elevator assemblies with high vibration levels are being segregated and adjusted for compliance or simply returned to the original manufacturer. This eliminates questionable products from being fielded and enhances the overall reliability of the tracker population in the field.

As design improvements are introduced and new suppliers developed, their current and vibration signatures will be used to confirm low wear rates, high initial quality and long lives.

CONCLUSIONS

SolFocus is in a leadership position for demonstrating reliability of HCPV systems over the 25 year design life. SolFocus has developed and executed sophisticated reliability programs directed at assessing and improving reliability of panels and trackers. Using accelerated life test concepts, product is already demonstrating excellent life-time properties. These tests will continue and more tests are planned.

REFERENCES

[1] J. G. Elerath, "Reliability Assessment of High-Concentration Photovoltaic Trackers," *Proc. Annual Reliability & Maintainability Symp.*, 2011, pp. tbd

[2] H. Haynes, D. Cox, J. Hansen and D. Welch, "Second Test of a C-141 Pitch Trim Actuator (PTA) Using Electrical Signature Analysis (ESA)," Oak Ridge National Laboratory, May 16, 2003.

[3] A. D. Dimarogonas and S. Haddad, Vibration for Engineers, Prentice Hall, 1992, pp. 675-705.

[4] T. A. Duncan, 1999, "An Introduction to Time Waveform Analysis," Universal Technologies, Inc., Last retrieved June 6, 2011. http://www.unitechinc.com/pdf/IntroductiontoTimeWaveformAnalysis.pdf