FIELD TESTING FOR RELIABILITY ASSESSMENT OF NEW CPV TECHNOLOGIES

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ABSTRACT

Since early 2007 SolFocus has commissioned up to 25kW concentrator photovoltaic (CPV) generating capacity at several test sites. The goal of these sites is to conduct long-term durability tests in different climate zones to evaluate lifetime and climate acceleration factors. The Arizona site has proven critical to quickly identify material and operational failures difficult to detect in industry standard accelerated stress tests. Identification of the failure modes enabled SolFocus to integrate design changes to improve the product durability and reliability. Continual array level data as well as periodic panel-level data have been gathered to quantify system performance. This field performance data, along with accelerated weathering tests have been used to gain an understanding of the product reliability and expected product lifetime. This field data, analysis and corrective actions to problems found are presented in this paper.

FIELD TEST PROGRAM DESCRIPTION

In 2007 and 2008, SolFocus installed approximately 25kW generating capacity at 5 different sites, 2 in the San Francisco bay area, 2 in the Phoenix region of Arizona and one in Kailua-Kona, Hawaii. The primary goal of these sites is to gain long-term operational experience with prototype and standard production versions of the SolFocus CPV system under various environmental conditions. This includes experience with the CPV panels as well as with the tracker system and the development of the tracker calibration methodology. Because of the extreme thermal and solar conditions common in the Phoenix region, the sites there have proven most effective in stressing the hardware and driving required design changes.

Solfocus established one site at the Arizona Public Service, Solar Test and Research (APS-STAR) center in April of 2007. The field data presented in this paper is from the APS-STAR site. The site consists of five grid-connected 2.5kW arrays mounted on two-axis tracking systems (Fig. 1). Several of the arrays there have been continually functioning for the past 12 months. Three distinct populations of CPV panels have been installed and tested at the site. Early prototype units showed rapid performance deterioration and were replaced with improved models. These updated models have been continually operating for almost a year with no detectable performance deterioration.

Figure 1. Four of the five SolFocus 2.5 kW arrays at the APS-STAR center in Tempe, AZ.

CPV SYSTEM DESCRIPTION

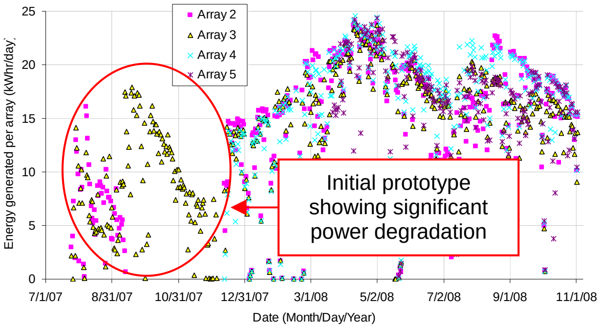
The SolFocus CPV design utilizes non-imaging optical system with four distinct elements: the protective cover glass, a primary mirror, a secondary mirror, and a lightguide. This system has been described in more detail previously [1, 2]. Both the first generation SF1000 panel and it's successor, the SF1100 use the same basic optical system. For both models, light is focused down onto a triple-junction photovoltaic cell.

The SolFocus site at the APS-STAR center is populated with SF1000 panels, which consist of 16 power units (optics set + photovoltaic receiver) connected in series and generate approximately 210 watts at 850W/m^2 of direct normal irradiance (DNI). There is one bypass diode per power unit. The arrays consist of two parallel strings of 6 panels each connected to a commercial grid-tied inverter. The tracker controllers were custom designed by SolFocus and use an epherimis based control algorithm to track the sun to better than 0.5° alignment accuracy.

CPV SYSTEM PERFORMANCE

Array level performance has been monitored over the last 15 months. The energy generated per day is shown in Fig. 2 for arrays 2 through 5. Array #1 was never fully populated and is not included here. Arrays 2 and 3 were installed in mid-July of 2007. After good initial performance, the power output severely degraded within a few weeks. The failure mode, which was attributed to an inadequate coating on the secondary mirror, detailed in the following section, had not been observed in panels that had been already operating in the San Francisco region for 4+ months. This illustrates the difficulty of detecting different failure modes based on standard acceleration factors.

In November of 2007, new panels with more robust secondary mirrors were introduced to the APS arrays 2, 3 and 4. Array #5 was populated with similar modules in March of 2008. These systems have been operating continually since their deployment.



Initial prototype showing significant power degradation

Figure 2. Daily energy generation of SolFocus arrays at the APS-Star center.

One of the challenges of the field data analysis is the removal of the different sources of variability due to the environment. The method chosen here was a characterization of the sensitivity of the system for ambient temperature (*T_{amb}*), wind speed (*W*), DNI and spectrum variation (*S*). For the design analysis, the predicted power in time (*t*) can be expressed by eqn. 1, where P_{norm} is the nominal power of the array. A first order approximation can be expressed by a taylor series of the function $f(x_i)$ around the normalized conditions of T_{amb}=20°C, W=2m/sec, DNI=850W/m^2, and spectrum = AM1.5 (eqn. 2) where the B_i coefficients are the first derivative of the function f with respect to the variable x_i (eqn. 3). These coefficients can be estimated by design, but in this case were evaluated by regression analysis of the field data using power data every 5 minutes. A more complex equation form can be used if the effect of a given external variable on the performance is well known. An example would be the secondary effect of the DNI due to temperature change of the cell.

$$P(t) = P_{norm} \frac{DNI}{850} f(T_{amb}, W, S, DNI, t) \qquad (1)$$

$$\begin{aligned} f &= A + B_T(T_{amb} - 20) + B_W(W - 2) + \ldots \\ &+ B_s(S - AM1.5) + B_{DNI}(DNI - 850) + B_t t \end{aligned} \qquad (2)$$

$$B_T = \frac{\partial f}{\partial T}_{(T=20)} \qquad B_W = \frac{\partial f}{\partial W}_{(W=2)} \qquad \ldots \qquad (3)$$

All external variables can be easily measured except the spectrum which could influence significantly the efficiency of a triple junction cell due to an unbalance of the current in the top and middle junctions. For this external variable, it was found that the efficiency correlated strongly with the elevation of the sun. Therefore, the spectrum sensitivity was converted into an elevation sensitivity. This relation would deviate significantly in case of strong variation of the particle types in the atmosphere such as during periods of poor air quality due to forest fires for example.

Other sources of variation are the misalignment of the array with respect to the sun and variation due to soiling of the glass. Misalignment errors are potentially caused by calibration errors, drift in the parameters of the kinematic equations or structural defects. This source or power error is harder to remove due to the lack of knowledge of the exact state of the tracker during operation. Soiling of the front glass is a function of environmental factors (dust, moisture, rainfall), positioning of the array and also the frequency of panel cleaning.

After subtracting all the quantifiable sources of variability, we can find the intrinsic panel performance in time. An example of the corrected power from external variation is shown in Figure 3 (raw) and Figure 4 (normalized) for array #4 at APS-STAR. The normalization has lowered, but not eliminated variability.

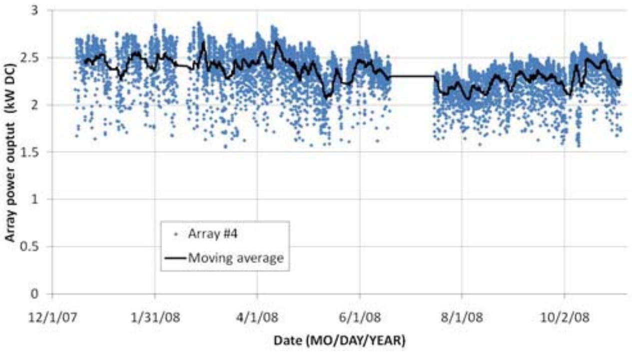


Figure 3. Raw DC power output generation of array #4 (DNI > 600 W/m^2).

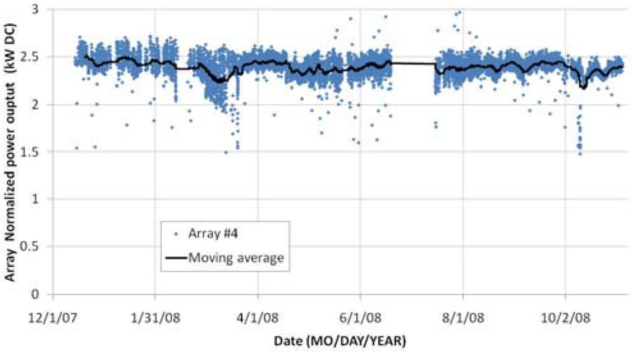


Figure 4. Normalized DC power output for array #4 (DNI > 600 W/m^2).

CASE STUDY: SECONDARY MIRROR COATING DEGRADATION

The secondary mirror in the SolFocus SF1000 CPV panel is a first surface protected silver coating applied to a glass substrate. Due to its exposure to concentrated solar irradiation (approx 30x) and the resultant high operating temperatures (70 to 100°C), this is a very challenging application. Even before the initial failure of the mirror coating observed during the summer of 2007 at the APS-STAR center, SolFocus was conducting an intense development effort for a robust first surface mirror coating. While many coatings were investigated, the three distinct coatings which were used for the SF1000 panels at APS-STAR are as follows:

- Coating #1: Initial poor coating that failed rapidly. Failure shown in Figure 5.
- Coating #2: Optimization of coating #1 using same vendor and same basic process.
- Coating #3: New vendor and process. Current coating used for commercial products.

With the aggressive operating conditions of the secondary mirror, the accelerated weathering test conditions commonly used for photovoltaics (85°C/85%RH Damp Heat, Humidity Freeze, etc.) were not effective to reproduce the failure observed in the field or to rapidly screen potential coating designs. During failure analysis of the deteriorated mirror coatings, it was determined that the failure was caused by silver migration through the protective dielectric coating while at elevated operating temperatures. Figure 6 is an SEM image of the deteriorated region of a mirror. When this residue was removed from the mirror surface onto carbon tape, SEM/EDX measured the presence only of Silver, Oxygen and Carbon.

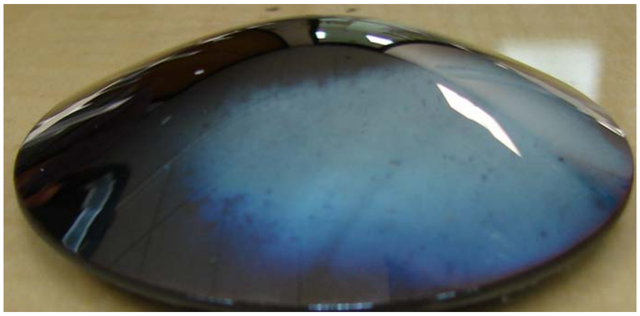


Figure 5. Secondary mirror coating #1, failure after operation in the field.

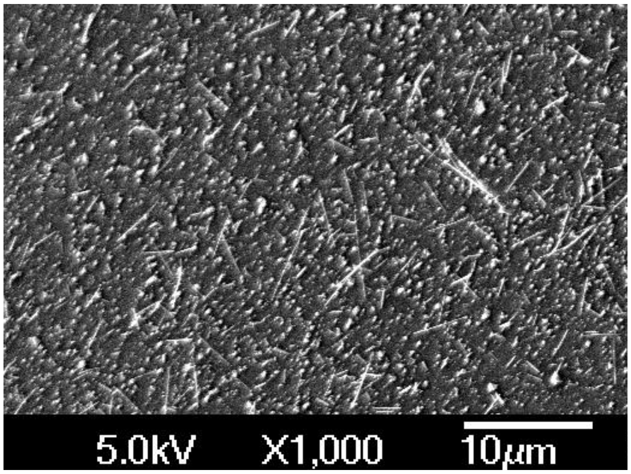


Figure 6. SEM image of degraded region of secondary mirror coating #1.

The dominant factor with this reaction is temperature. The failure accelerated in the field when, the silver transferred to the surface and increased absorption, causing increased temperatures. It was possible to conduct high temperature exposure tests to effectively reproduce the failures seen in the field (fig. 7).

A component level (secondary mirror only) 250°C high temperature storage exposure test was developed to screen prospective secondary mirror coatings. Many coatings went through this screening process. Results from this test along with a rough estimation of field life for the three coatings in panels at APS-STAR are as follows:

- Coating #1: Fail after 20 hours at 250°C, estimated field life of 1 to 4 months.
- Coating #2: Fail after 500 hours at 250°C, estimated field life of 1 to 3 years.
- Coating #3: Not yet failed after 4000 hours at 250°C, estimated field life of 20+ years.

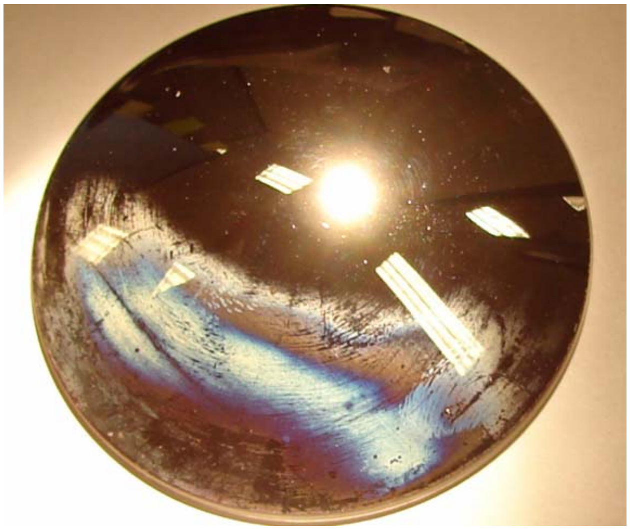


Figure 7. Secondary mirror coating #1, failure after 20 hours high temperature storage at 250°C.

Figure 8. Secondary mirror coating #3 after 1000 hours at 250°C. No indications of failure.

In order to improve the life estimates and gather kinetic reaction rates for this mechanism, the high temperature storage tests were expanded to multiple levels for coatings #2 and #3. The temperature levels used for these tests were 200°C, 250°C and 300°C. In this test program, the end of life is defined as a 5% reduction in the light throughput across the secondary mirror. The collimated flash solar simulator described by Askins, et.al. [3] is used to conduct these measurements. The secondary mirrors under test are placed in a common reference SF1000 power unit. Thus we are able to get the relative performance of the individual component within the overall SF1000 optical path. Due to the relative robustness of Coating #3, these tests are still in progress. Preliminary results for Coating #3 are shown in Figure 9.

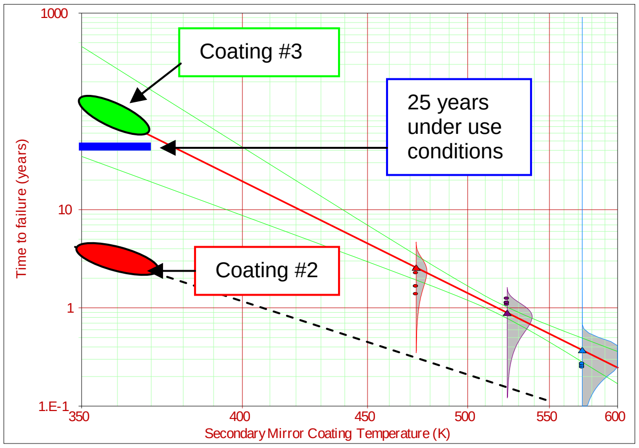


Figure 9. Secondary mirror coating life test results (preliminary) – extrapolating to standard operating temperatures (350 to 375K).

Coating #3 was identified as the preferred mirror coating for large scale production of the SF1000 and SF1100 panels. All panels at customer sites, such as the 200kW and 300kW ISFOC installations [4], use secondary mirrors with this coating. While life tests are not complete, SolFocus has a high confidence in 20+ year lifetime from the rigorous test program and acceleration model. The majority of panels at the APS-STAR site use this coating and have not shown any degradation after a year of operation. Half of the panels on Array #3 at APS-STAR have the inferior Coating #2. These panels were kept operating in order to verify the life model developed during the accelerated high temperature exposure test program. Figure 10 shows that the coating #2 panels on array #3 are performing at a statistically significant lower level after approximately 1.2 years at the site.

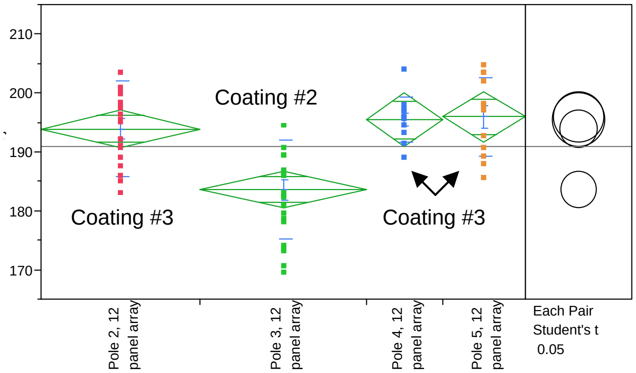


Figure 10. Comparison of the individual panel power distribution after 15 months (Array #3), 10 months (Arrays #2, 4) and 6 months (Array #5) of operation.

Accurately predicting the degradation correlation between the lab testing and the field data requires 3 different areas of understanding. First is the knowledge of the acceleration factor of the main failure mechanism. Second, a good understanding of the use condition (or level of stress) of the component in the field is required. Finally, an understanding of the relation between the degradation amplitude of the component and the system degradation is needed. The secondary mirror failure mechanism is used to illustrate this process.

The failure mechanism considered here is the degradation of the reflectivity fo the secondary mirror coating due to high temperature exposure. The acceleration factor (AF) has been evaluated in the lab and was found to follow an Arrhenius function (eqn. 4) with an activation energy E_a of 0.5 for coating #3.

$$AF(T_1 \rightarrow T_2) = e^{\frac{E_a}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)} \qquad (4)$$

where k is the Bolzsman constant equal to 8.617E-5 eV/K and the temperatures are expressed in Kelvin.

The use condition of the secondary mirror is the temperature under operation. As a first approximation, the temperature of the mirror can be expressed as eqn. 5 where A_{DNI} is the effect of the heating effect of the sun on the mirror due to absorption and concentration factor. From the historical data of the local weather, we can evaluate the acceleration factor under operation compared to a reference temperature T_{ref}. The acceleration factor between the use condition and the reference temperature is expressed by the integration of the acceleration factor over a long period of time representing a standard weather pattern (eqn. 6).

$$T_{use} \approx T_{amb} + A_{DNI} DNI \tag{5}$$

$$AF(T_{ref} \to use\ condition) = \frac{\int_{t_1}^{t_2} e^{\frac{E_a}{k}\left(\frac{1}{T_{ref}} - \frac{1}{T_{use}(t)}\right)} dt}{t_2 - t_1} \tag{6}$$

This methodology can be used to understand the acceleration factor of failure modes depending on the local climate. This explained why the deficient secondary mirror coating was not discovered until it was operating during the summer at the APS-STAR site in Phoenix.

The final information required is the relation of degradation mechanism to the overall performance of the system. This relation can be quite complex due to the string effect of the different power units in series. The degradation of the reflectivity to the secondary mirror will be proportional to the efficiency of the power unit assuming no significant spectral change of the reflection. If all mirrors are degrading similarly, the overall performance will be scaled by the degradation factor of the mirror reflection. However, if there is a significant variation of the degradation between secondary mirrors, the overall impact on array power loss will depend on the mean of the degradation as well as the standard deviation.

Array #3 is a good vehicle to use to start to understand the relationship between distributed failures of components within a system and the overall performance of the system. Figure 11 shows the normalized power output for Array #3 which has 7 of the 12 panels with the inferior coating #2 on the secondary mirrors. Figure 10 also shows the individual power output distribution of the modules on this array. Once the degradation of these panels gets to a predetermined level, they will be removed from the system and tested in detail to quantify degradation of each power unit. This information will be used for sytem performance model validation.

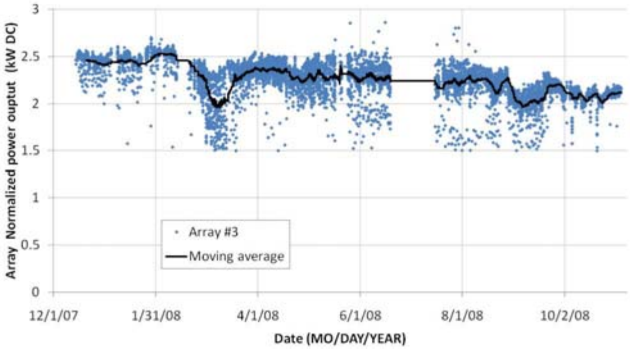


Figure 11. Normalized DC power output for array #3 (DNI > 600 W/m^2).

CONCLUSIONS

Since early 2007, SolFocus has been engaged in a field reliability program testing several different CPV product designs, materials, and vendor variations in different climate conditons. This has been critical in identifying failure modes which were not identified by the standard weathering tests such as damp heat, humidity freeze, or thermal cycle. All components in CPV systems which are exposed to concentrated sunlight are subject to failure modes of this type. In order to prove product reliability, CPV companies must combine lessons learned from carefully monitored field tests along with an accelerated component test program that is tailored to detect specific failure modes. The failure with the secondary mirror coating is a good case study.

The secondary mirror is exposed to concentrated sunlight (30x) and operates at high temperatures (70 to 100°C). Early prototypes had secondary mirrors with a coating that could not survive these stresses. This failure was only discovered after on-sun operation during extreme ambient temperature and DNI conditions. Screening tests specific for this failure mode were then implemented in the coating development process and led to a coating that is very robust, with an estimated 20+ year lifespan. Intensive life tests are still in process to fully quantify the expected life of this component under various stresses.

SolFocus has been running long term durability tests at the APS-STAR site for over 15 months. Intial prototypes showed unsatisfactory degradation rates. Through an iterative process of detecting failures, fully quantifying the use conditions, and understanding the failure modes, effective solutions can be quickly implemented. The SF1000 panel has benefited from this process and has proven to be a robust product with almost a year of continuous operation at ATP-STAR in addition to an extensive component accelerated test program.

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