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STEP-STRESS ACCELERATED DEGRADATION TESTING FOR SOLAR REFLECTORS

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Abstract

To meet the challenge of reducing the cost of electricity generated with concentrating solar power (CSP), new low-cost reflector materials are being developed, including metalized polymer reflectors, and must be tested and validated against appropriate failure mechanisms. We explore the application of testing methods and statistical inference techniques for quantifying estimates and improving service lifetimes of solar reflectors associated with failure mechanisms initiated by exposure to the ultraviolet (UV) part of the solar spectrum. In general, a suite of durability and reliability tests are available for testing a variety of failure mechanisms where the results of a set are required to understand the overall service lifetime of a CSP reflector. We will focus on the use of the Ultra Accelerated Weathering System (UAWS) for assessing various degradation patterns attributable to accelerated UV exposure. Depending on number of samples, test conditions, degradation, and failure patterns, test results may be used to derive insight into failure mechanisms, associated physical parameters, service lifetimes, and uncertainties. In the most complicated case warranting advanced planning and statistical inference, step-stress accelerated degradation testing (SSADT) methods are proposed.

Keywords: step-stress accelerated degradation testing, solar reflectors, ultra accelerated weathering system, service lifetime prediction

1. Introduction

1.1 Concentrating solar power

Commercialization of CSP technologies requires advanced optical materials that are low in cost and maintain high optical performance for lifetimes of 25 to 30 years under severe outdoor environments [1]. This includes maintaining greater than 95% specular reflectance into a small full-cone angle over the life of the reflector in trough, tower, dish, and linear Fresnel systems. The cone angle requirements are dependent on system technology.

1.2 Durability tests for CSP reflectors

NREL uses several durability tests to aid the development and validation of advanced reflectors [2]. Outdoor testing of reflectors in a variety of settings provides the best long-term test; however, these tests are time-prohibitive due to the design goal of 25- to 30-year lifetimes for CSP reflectors. Accelerated testing of known and unknown failure mechanisms is required to decrease testing times such that advanced concepts can be developed and validated under a compressed schedule. Standard accelerated durability testing begins with exposing reflectors to light, heat, and humidity at stress levels that are greater than normally experienced in dry climates. The neutral salt spray (NSS) or copper accelerated acetic acid salt spray (CASS) tests introduce additional stresses [10]. Soiling and cleaning of advanced mirrors is a topic of increasing interest.

1.3 UV as a special case for polymeric reflectors

Polymer materials and silvered-polymer reflectors in particular are known to be especially susceptible to degradation and failure mechanisms associated with exposure to the UV part of the solar spectrum [3]. Specifically, Jorgensen et al. present experimental results of the effects of exposure to such UV light [7].

1.4 UAWS

To rapidly test and validate the performance and durability solar reflectors subject to this degradation path, a unique accelerated testing device, the Ultra Accelerated Weathering System (UAWS), is utilized. The UAWS is an outdoor weathering system that uses Fresnel mirrors to concentrate the UV portion of natural sunlight 50 to 100 times. The UAWS dramatically increases the UV radiant exposure per unit time over what is attainable with current accelerated exposure chambers. The system shows high fidelity to natural solar UV spectral power distributions while attenuating visible and IR wavelengths to maintain acceptable specimen exposure temperatures [3]. The temperature of the samples may be controlled so that two sets of samples are stressed at two different temperatures simultaneously while being exposed.

Fig. 1. UAWS at NREL.

1.5 Accelerated degradation testing and lifetime testing

To validate the failure mechanisms of CSP reflectors, reflector samples are exposed in the UAWS at different temperatures and different intensities of light depending on initial tests. The specular and hemispherical reflectance of the samples is measured at regular intervals to track the degradation of the mirror. The expected outcomes range from no degradation to a complete failure of the mirror with respect to a given threshold of reflectance. Service lifetime prediction depends on the availability of data from the exposure to multiple stress levels. If sudden failure occurs, accelerated lifetime testing (ALT) techniques may be applied. If there is measurable degradation, accelerated degradation testing (ADT) techniques may be applied. ADT relies on degradation data instead of failure data. In general, a multiple constant-stress ADT (MCSADT) and ALT (MCSALT) may be used for life prediction of products, while single constant-stress ADT (e.g., Damp-Heat Test) can be used for qualification testing with a specific durability criteria. When the samples are subject to a specific intensity of light, a constant stress, for the first part of a test, and it is warranted to measure the degradation rate at a second stress by subjecting the sample to a lower (or higher) intensity of light, step-stress accelerated degradation testing (SSADT) and inference may be applied.

1.6 Advanced physics-based statistical inference

Estimates of service lifetime focus on identifying physical mechanisms of degradation and defining a durability test that will have an associated acceleration factor for similar samples such that a product's service lifetime may be estimated or ensured to last for some defined amount of time. For example, if a sample is exposed to twice as much light during a test as it would be exposed to in a natural use condition, its life is expected to be half as much. When degradation patterns are identified, they are fit by equations that are motivated by physical phenomena. Alternatively, the dependence of the rate at which degradation occurs on natural stressors may also be investigated. An example is the common assumption that Arrhenius' equation applies for temperature dependence.

To build on the success of such techniques, advanced ALT and ADT methods explicitly include the patterns of degradation and the physically motivated dependence on natural stressors. In addition, they include a probability distribution on the lifetime data so that estimates of uncertainty may be included in the mathematical representation of a set of samples. In general, to make predictions about natural conditions that vary requires at least two experiments at two different stress levels so that predications can be interpolated or extrapolated to the natural use condition. Step-stress methods are special methods that include two or more stress levels in a single test.

In this paper, we discuss the expected reflector failures associated with exposure in the UAWS. We define failure and then categorize several primary degradation patterns in Section 2. Test plans for physics-of-failure and failure distribution tests are described in Section 3. In Section 4, we describe potential test result outcomes in the context of the primary degradation patterns and tests in Section 4. Finally, we propose and describe the use of the step-stress statistical inference method in Section 5.

2. Degradation/failure test components

2.1 Reflector failure

When the measured performance of a reflector passes a pre-defined threshold, typically 10% loss in reflectance from the initial value, the reflector under test has failed. The goal of the U.S. Department of Energy's (DOE) CSP program associated with the DOE SunShot Initiative is for a reflector to maintain 95% specular reflectance over the 30-year lifetime of the reflector. Thresholds associated with the hemispherical reflectance may also be used to define failure and will be used in our discussions below.

2.2 Primary degradation/failure patterns

For failure mechanisms associated with exposure to the UV part of the solar spectrum, four primary degradation patterns are expected: no failure, sudden failure, gradual degradation failure, and break-in patterns. These patterns are depicted in Figure 1 and explained in the subsequent paragraphs.

No failure: A reflector may not experience "measurable" degradation during the accelerated test. This pattern is represented as the blue line in Figure 2. In particular, a mature or production-quality reflector is not likely to exhibit "measurable" degradation or failure during a test. If the accumulated solar radiation is greater than 30 years equivalent at elevated temperatures, this is an indication that the reflector has been designed to address failure mechanisms associated with exposure to UV solar radiation.

Sudden failure: The reflector shows little to no degradation followed by rapid degradation in performance past the pre-determined threshold value (denoted by the green line in Figure 2). In this scenario, the materials that form the reflector's structure may be slowly degrading over time without affecting hemispherical reflectance. At some point, the structural materials degrade beyond a critical point, and the degradation is manifest in the reflector's hemispherical or specular reflectance. The period where the failure rate is increasing is known as the wearout failure period. In general, one of the main goals of reliability testing is to assure that the onset of the wearout period occurs far enough away in time as not to be a concern during the useful life of the product [5].

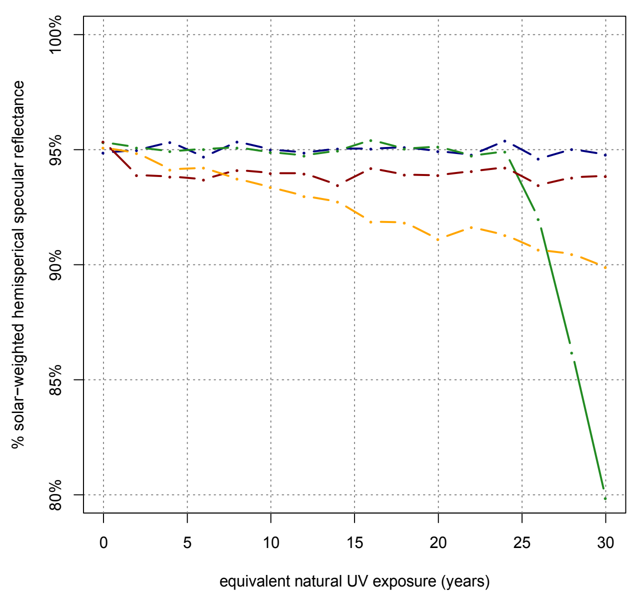

Fig. 2. The four primary degradation/failure patterns are shown: no failure (blue), sudden failure (green), gradual degradation (yellow), and break-in (red).

Gradual Degradation: A reflector that degrades according to a pattern (possibly according to a physical model for extrapolation) until the performance falls below a threshold [6]. This pattern is shown as the yellow line in Figure 2.

Break-in patterns: Some reflectors may experience initial degradation, increase, or fluctuation, and then follow one of the three patterns discussed above; this is denoted by the red line in Figure 2. Early life behavior is not necessarily indicative of the long-term behavior of the reflector.

3. Physically based statistical models

In general, physics-based statistical models of each relevant failure mechanism may be formulated and integrated into a greater understanding of failure of a device. The UAWS is capable of running at multiple temperatures and intensities of light and thus may be used to understand the dependence of failure on those two stressors.

For metalized polymer reflector materials, the degradation is expected to be proportional to $(I_{UV})^n$ where n has been found to be approximately one and proportional to $exp(-E_a /kT)$, an Arrhenius physical relationship [7]. I_{UV} is the intensity of the UV part of the solar spectrum, n is a material dependent constant, E_a is the material dependent activation energy, and k is the Boltzmann's constant. There is evidence in glazed materials that n may be less than 1 [2].

In the event that a degradation curve is measurable, insight into the fundamental mechanisms of degradation may be ascertained dependent on the shape of the observed curve [8]. Understanding of the physical mechanism or underlying physical processes may be used to justify greater extrapolation than can otherwise be achieved. Reliability studies and cases [8] have discussed and various statistical models for the shape of the observed curve presented in Figure 2. For example, basic patterns such as linear, exponential, power, and logarithmic are commonly modified and applied to specific products that have these unique degradation patterns.

In the event that mirrors are susceptible to a failure mechanism initiated by a specific test, and the reliability of a product needs to be estimated, more than three samples should be subjected to the stress test such that the failure distribution may be ascertained. In this case, a likelihood function may be combined with a physical model of degradation. SSADT, MSCADT, or MCSALT may be used.

4. Approach

4.1 Test plans

Two primary types of tests can be run: a physics-of-failure test and a failure distribution test. The UAWS has space for a limited number of samples, so the test can depend to some extent on the question being investigated. The physics-of-failure test uses fewer samples per type of sample so that multiple types of samples can be tested simultaneously. The failure distribution test is run after a sample has been tested and characterized and is understood well enough to warrant the entire UAWS capacity for several months on a single sample type.

For the physics-of-failure test, two sets of three 2.25-cm square samples of each reflector sample type to be tested are prepared, including initial specular and hemispherical reflectance measurements. Samples are exposed to the UV portion of the solar spectrum at 100 times the normal solar intensity using natural sunlight. Specular and hemispherical reflectance of the reflectors is measured periodically, approximately equivalent to 1 to 2 years of solar light exposure. Thirty years of equivalent exposure requires approximately 4 months, depending on weather and time of year.

Many of the physical phenomena involved in the reliability of a device are highly dependent on temperature. Each of the UAWS' two plates hosts a set of three samples for a given sample type and is cooled to a different temperature, usually 30°C and 60°C. This is an MCSADT and MCSALT testing plan.

If there is measurable degradation, the light concentration of the UAWS can be lowered during the test to 50 times, such that data can be collected concerning the dependence of degradation on the solar radiation intensity. This is an

SSADT testing plan, and testing time is still measured in months and equivalent exposure in years. For the failure distribution test, a single type of sample is run, occupying the entire capacity of the UAWS, and may be run with one or two different temperatures depending on the result of the physics-of-failure run.

4.2 Test analysis and statistical inference

There are four distinct expected outcomes from the test that are related to the primary degradation/failure patterns. As the explanation of the failures associated with this exposure is integrated into a larger understanding of the failure of the reflector in general, a different set of methods is applied to the different outcomes.

In the case of no failure, the failure mechanisms associated with exposure to UV light are likely to have been addressed in the reflector design, and the reflector is considered to have been tested and validated for this failure mechanism. The encompassing model of failure would take this into account.

If the samples experience short-term performance variation at the beginning of the sample life (break-in behavior patterns), those patterns can be taken into consideration before classifying the failure according to the latter part of the degradation pattern. If those patterns are significant, they may be investigated in their own right.

The test result associated with a sudden failure pattern may occur. In some cases, we will simply compare this test result with another test result to identify the reflector that should be further investigated. Inspection of the results of spectrum associated with the hemispherical reflectance may reveal specific parts of the spectrum that degrade. MCSALT methods may be applied because samples are tested at two different temperatures, including fitting a physical model, as described above, to estimate the activation energy. Consideration of optical measurement and activation energy estimates in conjunction with macro and microscopic inspection of the sample may be used to identify the root cause and possible mitigating processes.

In the case where the reflector fails, but the failure time is long enough to be acceptable for production, MCSALT-derived estimates of mean time to failure can be made. In this case, a failure distribution test on production samples would be recommended, so that the failure distribution of the production reflector can be estimated, in addition to the uncertainty and reliability of the mirror.

The test result associated with a gradual degradation pattern may occur similarly to the simulated example given in Figure 3. Again, the spectrum may be inspected, MCSADT methods applied, and the activation energies determined. In addition, information associated with the degradation pattern may be utilized. The character of the degradation pattern may be used to derive hypotheses concerning physical mechanisms causing the degradation. The slope or parameter associated with how rapidly the degradation occurs is associated with activation energy. The service lifetime may be estimated by determining where the degradation crosses the threshold of failure via interpolation or extrapolation.

If a step down to 50 times the normal intensity of light were warranted, SSADT methods may be applied, and a model that includes both activation energy and dependence on intensity of light can be fit. This is especially important if *n,* the exponent of the power law associated with the intensity of light in the physical model, is less than 1. A failure distribution test

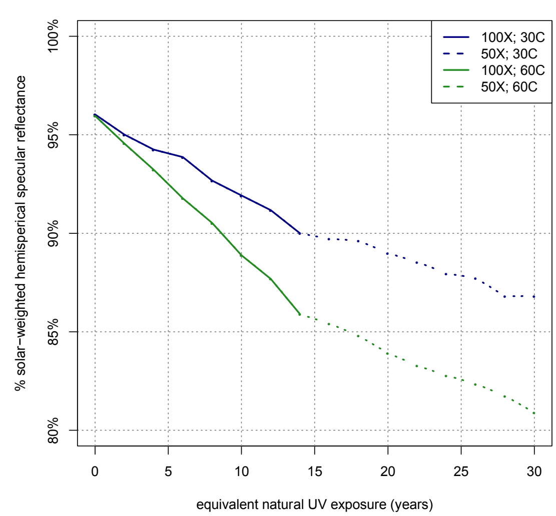

Fig. 3. Hypothetical degradation pattern of solar-weighted hemispherical reflectance for a two-temperature design and a step in UV intensity near 15 equivalent years.

and application of SSADT methods may also be useful in the case that the service lifetimes need to be quantified including uncertainty.

5. Step-stress statistical inference

In the most complicated—and possibly most important—scenario for production-quality manufactured products, a failure distribution test will be warranted, a degradation failure will have occurred in the previous test, and the resulting rate of degradation will have been affected by both temperature and intensity of light. The data might look something like the data in Figure 3, except that there might be 36 tracks instead of two. In this scenario, service lifetime is expected to be important, as is quantifying the response due to random non-normal variation in the samples of the same type. We will work within the context of assuming one primary failure mechanism.

We propose two different models and discuss their characteristics. The first stage in constructing either model is to identify the physical relationship of stress for degradation rate. Because the experiment is only carried out at two different temperatures and at two different intensities of light, the physical relationship is assumed known from previous work and can only depend on temperature and intensity of light [9]. All other factors are assumed to be constant. Previous work on silvered polymer reflectors has found the following relationship:

$$b = c \cdot I_{UV}^{n} \cdot \exp\left(-\frac{E_a}{kT}\right) \tag{1}$$

where other stressors like relative humidity are including in the constant, *c*. The exponent of the intensity of light may be close to 1, and the use of the step-stress method will either validate this or provide a better estimate. Since we are working at 50 to 100 times acceleration, it may be important to derive small variations from $n = 1$.

The second stage is to identify the degradation pattern. As a comparison, corrosion processes might be exponential, and kinetic processes might follow a power law. Previous work for silvered polymer reflectors assumes a linear degradation pattern [8]. The data taken from the physics-of-failure and a failure distribution test will allow us to validate this assumption or identify a different functional form. The third stage is to combine the physical relationship for stress with the degradation pattern. We expect to assume the following degradation model:

$$d(t) = A \cdot I_{UV}^{n} \cdot \exp\left(-\frac{E_a}{kT}\right) \cdot t \tag{2}$$

Least squares estimation: The most common approach to estimation of a product's service lifetime, activation energy, E_a, the exponent of the intensity, *n*, and the other constants in the degradation model, is to use the method of least squares (LS) on appropriately transformed variables. Because we have two temperatures and a step down in intensity, the degradation path, *d*, is written as

$$d(t) = \begin{cases} d(t \mid s_1) & if\, 0 \le t < \tau_1 \\ d(t + w_1 - \tau_1 \mid s_2) & if\, \tau_1 \le t < \tau_2 \end{cases} \tag{3}$$

where τ_1 is the time when the stress is changed from 100 times to 50 times and τ_2 is the end of the experiment. *w* is the time at which the observed degradation under the first stress level would have occurred for the second stress level, had the second stress level been applied from the beginning of the experiment. In the development of this approach, the cumulative damage is taken into account when stepping to the next intensity. Thus, the product's entire exposure history is properly built in to the final degradation model.

Maximum likelihood estimation: Alternatively, we use the method of maximum likelihood (ML) to estimate the parameters defined in the physical model (i.e., E_a, *n*, and *c*) and derive the associated quantities of interest, including the point estimate and confidence interval of service lifetime. The major advantage ML estimation exhibits over LS estimation is that you can quantify the uncertainty surrounding your point ML point estimates in the form of confidence intervals. See [11] for a theoretical overview of ML techniques.

In order to use maximum likelihood estimation (MLE) techniques, we need to assume a probability distribution on the lifetime of each sample. It is therefore necessary to transform the degradation data into failure data (e.g., via extrapolation) so that we can examine the failure-time distribution using standard goodness-of-fit statistics (e.g., chi-square test, Kolmogorov-Smirnov test, and Anderson-Darling test) [12]. For explanatory purposes, we assume that the sample lifetimes follow an exponential distribution; additional candidates include, but are not limited to, the Weibull and log-normal distributions.

Coupling the failure distribution with the degradation model, we can construct a likelihood function as the basis for estimation/inference [13], e.g.,

$$L(t\,|\,\lambda) \propto \prod_{C=30C\&60C}\left[\prod_{i_C=100X\&50X}\left(\prod_{j_C=\left(\sum_{p=1}^{i} r_{p-1}\right)+1}^{\sum_{p=1}^{i_C} r_p} \lambda_{i_C}\exp(-\lambda_{i_C} t_{j_C})\right)\left(\exp(-\lambda_{50X,C}\, t_{50X.C})\right)^{m-r}\right] \tag{4}$$

where we have assumed an exponential model with failure rate, λ, defined by the log-linear life stress function [13],

$$\log(\lambda_i) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \tag{5}$$

where βs are unknown parameters (to be estimated), x_1 is a stress of temperature, and x_2 is a stress of UV intensity. This likelihood includes both *r* failed and *m-r* survival samples at the end of testing (see [13-14] for a more detailed discussion). The likelihood function is built with two segments of UV intensity where the segments of each sample are based on the memoryless property of the exponential distribution. The method of maximum likelihood estimation is based on the optimization (maximization) of Equation (4) with respect to the defining parameters. The resulting estimates can be used to estimate the key quantities of interest: mean time to failure, warranty time, etc.

Finally, we would like to stress that the failure distribution test and the inclusion of a non-normal failure distribution is not simply to try to minimize the error in the estimate by having a large number of samples. Indeed, the point is to capture the stochastic nature of the distribution of failure times and, hence, to estimate the uncertainty surrounding the estimates of the key parameters of interest. For example, we can estimate the mean time to failure of CSP reflectors in a low-humidity environment and provide a confidence interval for this quantity. Capturing the nature of the failure distribution is similar to capturing the nature of the dependence of the degradation rate on temperature, by discussing it in the context of the Arrhenius equation and activation energy.

6. Summary

Solar reflectors may be susceptible to a number of failure mechanisms. Metalized polymer reflectors are known to be particularly susceptible to failure mechanisms associated with exposure to the UV part of the solar spectrum. The UAWS is a system that enables the rapid application of this stress to samples in order to test and validate these samples. We have described expected failure signatures, test plans, and hypothetical results for physics-of-failure and failure distribution tests. Expected failures are primarily categorized as sudden failure or gradual degradation failures. When production samples are subject to these failure mechanisms and require better estimates of service lifetime, including warranty time and uncertainty, a failure distribution test will be required. In the most complicated case warranting advanced planning and statistical inference, step-stress accelerated degradation methods may be applied. We propose the use of maximum likelihood estimation methods with integrated physical models. UV solar radiation represents only one type of stress, so results and inferences from the tests will need to be integrated with results for other tests to obtain a greater understanding of service lifetime and potential failure mechanisms. Next steps include application of step-stress and multiple constant-stress accelerated testing statistical methods and models for newly developed and commercial silvered polymer reflectors, for which testing has begun. We also plan to expand the methods to other systems and other reflectors, including silvered glass, anodized aluminum, and front surface reflectors.

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