Measurement and Reporting Guidelines for Solar Mirror Aging Tests Using Xenon Arc Lamp Exposure (XALE)

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1 National Renewable Energy Laboratory
2 Replicant LLC

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1 XALE Specification and Application

The Xenon Arc Lamp Exposure (XALE) method for accelerated aging of concentrated solar reflectors provides a method for sample preparation, weathering, measurement, and reporting using xenon arc lamp technology. Xenon arc lamps simulate solar ultraviolet (UV) and visible spectrum radiation. Inside a weatherometer, the XALE technique introduces this radiation along with variations in temperature and humidity to accelerate degradation of the reflector samples.

The degradation of the samples can be measured in accordance with a designed test plan. Guidance for developing this test plan is provided herein. The sample degradation is then used to compute a degradation rate and corresponding acceleration factor by comparing the weatherometer degradation against an environmentally degraded sample. The acceleration factor provides a tool for modeling reflector degradation, lifecycle analysis, and performance monitoring.

2 Reference Guidelines and Standards

SolarPACES guideline version 3.0: Parameters and method to evaluate the solar reflectance properties of reflector materials for concentrating solar power technology. (Available online: https://www.solarpaces.org/csp-research-tasks/task-annexes-iea/task-iii-solar-technology-and-advanced-applications/reflectance-measurement-guidelines/)

Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface (Available online: https://compass.astm.org/document/?contentCode=ASTM%7CG0173-03R20%7Cen-US)

3 Sample Preparation

3.1 Sample Cleaning Procedure

- Samples are rinsed with deionized water
- Samples are sprayed with Bilco cleaning solution or reagent-grade isopropyl alcohol
- Samples are lightly scrubbed with non-abrasive cotton swabbing material
- Samples are rinsed thoroughly with deionized water
- Samples are blown dry using compressed nitrogen – samples should not be wiped dry
- If required, samples are cut and rewashed in accordance with above procedure
    - Samples are recommended to be cut to a size of 10-cm x10-cm .

3.2 Sample Pre-Screening

3.2.1 Visual Inspection

Cleaned samples shall be visibly inspected for severe defects such as scratches, chips, abrasions, cracks, or discoloration of primary glass or backing paint. Any sample visibly varying from the sample population shall be determined unsuitable and discarded.

3.2.2 Sample Uniformity Testing

Remaining samples shall be screened using a pre-determined number N (suggest 16 or more) reflectance measurements at regular intervals across the mirror surface. The reflectance measurements shall be solar-weighted hemispherical/specular reflectance.

A. Across a single sample, the N measurements should result in measurement uncertainty less than a pre-determined threshold (0.15% in NREL's prior experience), computed using the equations in Appendix A. This serves to verify surface uniformity across an individual sample. This uncertainty will likely increase as the sample degrades; the listed constraint is for new samples during the pre-screening process only.

B. Across the selected population, a Welch's t-test computed to 95% significance, as in Appendix A, should not result in samples with statistically significant differences in the mean reflectance. Samples statistically differing from the population mean should be discarded.

3.2.3 Photograph and Documentation

Samples deemed suitable for measurement shall be appropriately labeled and photographed prior to measurement or testing. NREL recommends an angled sample stage diffusely lit with a diffuse backdrop to avoid glare. Conditions should be sufficient to show surface condition of the reflector.

Labels shall be printed, etched, or otherwise affixed to the sample and labeled according to the guideline below:

- DDMMYY (Date of initial characterization) + Population ID (Abbreviated manufacturer, or source) Sample # (XX)

- Example:
  - 15 samples received from MIRROR X CORPORATION
  - Prepared and initially characterized on December 15, 2018
  - Sample IDs
    - 15122018MXC01
    - 15122018MXC02
    - 15122018MXC [03-15]

Sample information regarding date of receipt, manufacturer, and sample numbers shall be reported in an initial characterization report. Once test conditions have been developed, samples designated for specific test conditions shall be documented in the test plan.

4 Sample Characterization

A complete characterization of each sample includes visual inspection and measurements of the reflectance properties of each sample. Appendix C outlines useful instrumentation and use cases. The provided list is not exhaustive but may be used to guide operators towards additional suitable instrumentation if the listed equipment is unavailable.

4.1 Visual Inspection and Documentation

Photographs at each stage of weathering should be taken and recorded. Magnification aids may be used but are not required. Any notable physical deformations during the weathering process should be noted in an interim report in the format specified in Appendix B.

4.2 Measurement of Solar-Weighted Hemispherical/Specular Reflectance

Solar-weighted hemispherical/specular reflectance shall be used as the sample's overall reflective metric. In accordance with SolarPACES guidelines, the solar-weighted hemispherical/specular reflectance is independent of the directionality of the reflection, or the sample's ability to reflect most of the incident light. The solar-weighted reflectance between two bounding wavelengths can be computed using Equation 4 in Appendix A.

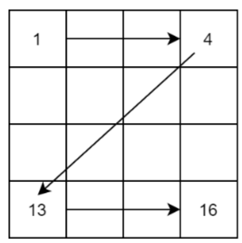


Figure 1. Measurement pattern for hemispherical reflectance measuring surface uniformity

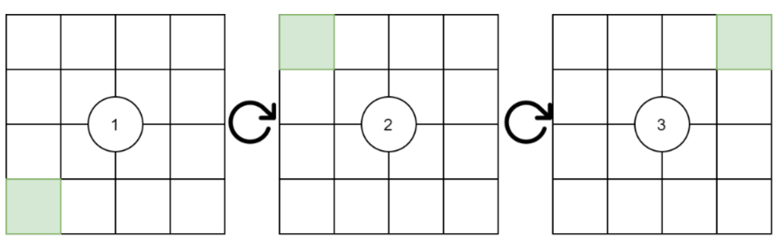


Figure 2. Measurement pattern for using bench-mounted hemispherical reflectometer

Solar-weighted hemispherical reflectance should be measured using one of two methods:

1. At several locations across the surface of the mirror in a regular pattern, totaling 16 measurements for a 10x10 cm sample, seen in Figure 1 above. If larger samples are used, the grid resolution should remain at 2.5x2.5 cm minimum for a representative surface profile.

2. In the center using a bench-mounted, high-resolution reflectometer if possible. Measurements should be taken at the center of the sample, with the sample in 3 different orientations as in Figure 2 above.

4.3 Measurement of Specular Reflectance at One or More Acceptance Angles

The specular reflectance is a function of wavelength, incidence angle and acceptance angle [1]. It will be assumed that reflectance is independent of incidence angle, however the incidence angle of the instrument should be reported. Specular reflectance is often measured at given acceptance angles and its specularity profile can be estimated accordingly. The larger the acceptance angle is, the larger the specular reflectance. How quickly the specular reflectance increases with the increasing acceptance angle can be characterized by the specularity root mean squared (RMS) when a single Gaussian distribution is used to approximate the specularity function.

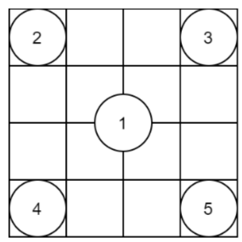


Figure 3. Minimum measurements conducted for analyzing reflector specularity

The sample specular reflectance will be measured directly using a specular reflectometer. Several locations shall be measured. See Figure 3 above as an example of a 5-point measurement plan. Specular reflectance measurements must be taken at the same points during each sample characterization. The locations noted above are easily recreated using a simple alignment jig. Several points must be collected to effectively characterize the sample specularity and ensure measurement robustness. A single point is not sufficient. The specular reflectance with the associated wavelength(s) and the specularity RMS value shall be reported. The specularity RMS value can be computed using the equations in Appendix A.

5 Test Plan Development

The developed test plan should produce a representative data set supported by measurements taken prior to weathering, at regular intervals in the weathering process, and post-weathering. The test plan should address and produce data following the conditions outlined below. If tests are limited or otherwise constrained by the chosen xenon-arc weatherometer, those constraints should be reported.

1. Environmental variables (include ranges)
   - A. Temperature with specified range (degrees C)
   - B. Humidity with specified range (percent humidity)
   - C. Solar irradiance with specified range ($W/m^2/nm$ at a given wavelength along with a specified solar spectrum, and equivalent number of suns with 1 sun = 950 W/m^2)
2. Test conditions
   - A. A complete test consists of 2 values for each environmental variable where the other, untested variables are fixed.
     - i. For example – Temperature will be tested at 50 and 75 degrees C. Relative humidity will be held constant at 70% and solar irradiance at 950 W/m^2 (1 Sun). This is equivalent to 0.70 $W/m^2/nm$ at 340 nm, which is required for setting the weatherometer according to ASTM G137. This is repeated for all environmental variables – requiring a minimum of 6 distinct test conditions.
     - ii. If the sample is to undergo destructive testing, 3 values should be used for each environmental value, requiring 9 test conditions.
3. Interim measurements
   - A. The test plan should outline interim measurement plans to track the degradation. Interim measurements should be taken at regular intervals, in accordance with the expected rate of degradation. Time elapsed between measurements may be as close as 2 weeks, or as distant as 10 weeks and beyond depending on test conditions.
   - B. Interim measurements should consist of at least, but are not limited to, wide-aperture or full hemispherical reflectance and specular reflectance measurements to monitor degradation. A single reflectometer such as the SOC 410-Solar is appropriate and sufficient. A full characterization as in Section 4 may be completed at each interval but is not required.
4. Optional tests
   - A. If available, the data computed during the XALE accelerated aging procedure may be compared to a suitable outdoor, natural degradation condition. If conducted, an acceleration factor may be computed as the ratio between the computed degradation rates as in Equation 2. Section 6 below contains information on calculating degradation rates and acceleration factors if applicable.

6 Analysis and Reporting

The XALE test procedure is designed to induce and monitor accelerated weather-related aging and degradation in reflectors. The section below outlines the major components of a characterization report relative to the stage in the test plan. A report checklist is given in Appendix B for interim and final reports.

6.1 General Characterization Report

6.1.1 Sample Identification

This section shall include all information regarding the samples to be characterized. The information should include the:

- Source
- Date and quantity received
- Condition upon receipt
- Identifier and label information with appropriate photographs

6.1.2 Sample Pre-Screening (Initial Report Only)

This section includes the pre-screening results for samples deemed suitable for testing. The report should indicate if any samples were rejected during the prescreening process and the reason for rejection, but the data need not be included for these samples.

6.1.3 Instruments Used for Measurement

This section includes the relevant specifications for the instrumentation used during characterization and the measurements received by the listed instruments. See Appendix C, Table 4 for example instrument table.

6.1.4 Measurements and Data

This section includes the raw measurement results in accordance with the proposed test plan. The following data should be presented for each sample, at each stage of the test plan (Initial, Interim, and Final):

- Raw measurement data
- Surface uniformity if applicable
- Degradation rate (Interim and Final reports only)
- Appropriate R^2 value for the computed degradation rate.

Degradation rates shall be computed using one or more of the following metrics:

- Solar-weighted hemispherical reflectance
- Solar-weighted total specular reflectance
- Solar specularity RMS.

Calculation of the degradation rate should be consistent throughout the test condition. Calculations should be clearly displayed with the appropriate inputs and be accompanied by appropriate graphics.

6.1.5 Discussion

The status and test stage should be summarized in a discussion section. This section should also clearly present notable findings, results, or deviations from expectations.

6.2 Analysis

The degradation rate can be assumed to be linear as a function of months of exposure time. For both conditions, the degradation rate, β, can be computed as a function of the change in reflectance between two measurements of the same sample, Δρ, and the exposure time between measurements, t, in Equation 1 below:

$$\Delta\rho = \beta \cdot t$$

Equation 1

The degradation rate above can be computed using either solar-weight hemispherical or solar-weighted total specular reflectance data. Shown in Figure 4, the degradation data should be fitted with a regression line to verify that the degradation can be modeled with a linear degradation rate. The R^2 statistic should be reported, accompanied by the fitted regression line graphically displayed as in Figure 4 below.

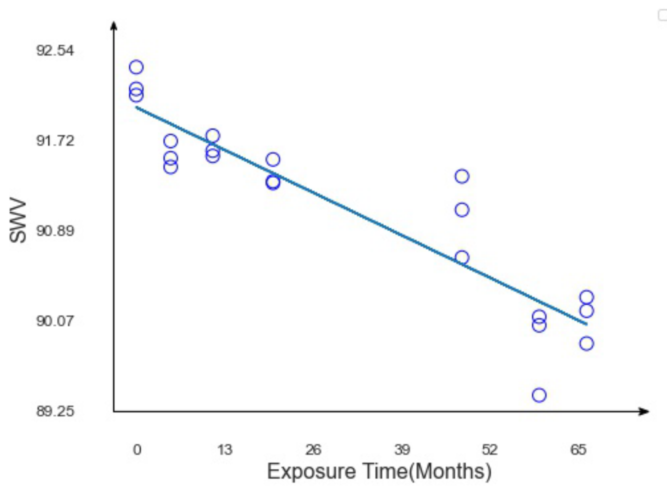


Figure 4. Example degradation rate and R2 linear fitness test – R^2 = 0.838

The acceleration factor (AF) for a given degradation rate for an accelerated test condition (β_{ac}) and a reference outdoor condition (β_{od}) can be calculated using Equation 2 if applicable:

$$\mathrm{AF} = \frac{\beta_{ac}}{\beta_{od}} \qquad \text{Equation 2}$$

The XALE methodology subjects selected samples to accelerated weather conditions to promote degradation. Other environmental factors such as wind, debris, natural disasters, or impacts can subject mirror surfaces to erratic and unpredictable degradation patterns and impacts to optical quality. Therefore, if desired, the acceleration factor can be associated with the appropriate R^2 value from the sample degradation rate. Clear correlations yielding high R^2 values result in confidence in the calculated degradation rates, while lower R^2 values result in lower confidence in the fitness of the linear regression.

Appendix A. Measurements and Calculations

A.1 Solar Reflectance Measurements and Derivations

Solar-weighted Value

The solar-weighted value (SWV) calculation presented in Equation 3 can be found in the SolarPACES guideline for reflective measurements in Section 7.2. Reflectors will be measured across the solar spectrum over the guideline-specified range of 320-2500 nm.

$$\rho_{Ss,h}([\lambda_a, \lambda_b], \theta_i, h) = \frac{\sum_{\lambda_{\min}}^{\lambda_{\max}} \rho_{\lambda,h}(\lambda, \theta_i, h) \cdot G_b(\lambda) \cdot \Delta\lambda}{\sum_{\lambda_{\min}}^{\lambda_{\max}} G_b(\lambda) \cdot \Delta\lambda} \text{for} \lambda = \{\lambda_{\min}, \lambda_{\min} + 5, \ldots \lambda_{\max}\}$$

Equation 3

Above, ρ is the measured reflectance and G_b is the corresponding weight assigned to the wavelength at which that measurement was collected.

Mirror Specularity

Specularity is a measurement of how efficiently incident light is reflected in accordance with the law of reflection. A perfectly specular mirror reflects 100% of the incident beam in the specular direction. The RMS value of each individual sample can be found by formulating the specular reflectance as a Gaussian function of the aperture, ϕ, using Equation 4 [1] below:

$$\rho_{spec}(\phi) = \rho_{spec,tot}\left(1 - e^{-\left(\frac{\phi}{\sqrt{2}\sigma_s}\right)^2}\right)$$

Equation 4

If the measurement taken is assumed to be $\rho_{spec,tot}$, and ϕ is the array of maximum acceptance angles (3.5 mrad, 12.5 mrad, and 23 mrad for each aperture used herein, or half of the aperture's total width) with respect to the specular direction, we can find the RMS, σ_s, by minimizing the residuals from Equation 4. The residuals are defined by Equation 5 below:

$$residual = \left\|\rho_{gauss} - \rho_{meas}\right\|$$

Equation 5

The reported RMS is then as follows in Equation 6:

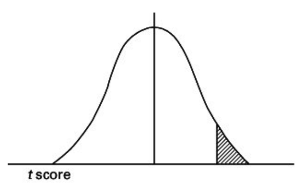
$$\sigma_s = \sqrt{\sum_{i=1}^{n} \sigma_i^2} \qquad \text{Equation 6}$$

A.2 Uncertainty

Uncertainty for this report is computed using a level of significance of 95%. For each set of sample measurements, we compute a sample mean and the resulting standard error, *SE*. The uncertainty is calculated using a t-score via Equation 7:

$$uncertainty = t\,\frac{\sigma}{\sqrt{N}} \qquad \text{Equation 7}$$

Where *t* is found using a two-tailed significance value of $\alpha = .025$, corresponding to a 95% confidence interval and *N-1* degrees of freedom. This uncertainty calculation is used for all sets of measurements using their appropriate degrees of freedom. An example critical value t-table is shown below.



df \ p	0.1	0.05	0.025	0.01	0.005
1	3.078	6.314	12.706	31.821	63.657
2	1.886	2.920	4.303	6.965	9.925
3	1.683	2.353	3.182	4.541	5.841
4	1.533	2.132	2.776	3.747	4.604
5	1.476	2.015	2.571	3.365	4.032
10	1.372	1.812	2.228	2.764	3.169
11	1.363	1.796	2.201	2.718	3.106
12	1.356	1.782	2.160	2.650	3.055
13	1.350	1.771	2.160	2.650	3.012
14	1.345	1.761	2.145	2.624	2.977
15	1.341	1.753	2.131	2.602	2.947
24	1.318	1.711	2.064	2.492	2.797

Figure 5. Critical t-values as a function of significance and degrees of freedom

Appendix B. Reporting Checklist

B.1 Initial Characterization Report

- ☐ Number of reflector samples
- ☐ Sample sources, types, received size, and condition
- ☐ Photographs of received samples
- ☐ Instrumentation used for prescreening
- ☐ Prescreening results including sample reflectance means, uncertainty values, and population consistency (t-test results)
- ☐ Appropriate plots and graphics of the sample reflectance results
- ☐ Suitability of samples
- ☐ Discussion of results
- ☐ Weathering test plan in accordance with section 5 above

B.2 Interim and Measurement Report Checklist

- ☐ Appropriately titled report referencing initially characterized samples
- ☐ Reflector sample IDs corresponding to the appropriate initial characterization report
- ☐ Weathering interval and conditions in accordance with the established test plan
- ☐ Photographs of samples in current state – front and back
- ☐ Instrumentation used for measurement
- ☐ Measurement data in accordance with section 6.1.4 above
- ☐ Computed degradation values and projected degradation rate for the interval
- ☐ Appropriate plots and graphics of the sample solar-weighted hemispherical and specular reflectance

B.3 Final Report and Analysis Checklist

- ☐ Appropriately titled report referencing initially characterized samples
- ☐ Reflector sample IDs corresponding to the appropriate initial characterization report
- ☐ A summary of the test condition and environmental variables from the original test plan
- ☐ Photographs of samples in final state – front and back
- ☐ Instrumentation used for measurement
- ☐ Measurement data in accordance with section 6.1.4 above
- ☐ Computed degradation values and final degradation rate for test condition
- ☐ The acceleration factor AF and any correlation analysis conducted
- ☐ Appropriate plots and graphics of the sample solar-weighted hemispherical and specular reflectance
- ☐ Appropriate plots and graphics of the sample acceleration factor correlation and data fitting

Appendix C. Instrumentation

NREL makes use of the instruments listed below in Table 1 when characterizing reflectance properties. This appendix includes information on the measurement instruments and weatherometers as well as calibration and use recommendations. The information may be followed directly or used to guide operators in selecting appropriate equipment to obtain the measurements listed herein. Additional instrumentation guidelines are available in Section 5 of the SolarPACES Official Reflectance Guidelines.

C.1 Measurement Instrumentation

Table 1. Summary of the Instruments and Settings Used For Measurements

Instrument	Measurement Type	Wavelength Ranges	Incidence Angle	Measured Spot Size	Acceptance Aperture
L1050	Hemispherical	250-2500nm, 5nm increments	8°	0.50cm^2	hemispherical
D&S	Specular	660nm peak irradiance	15°	5.07*10^{-4} cm^2	3.5 mrad, 12.5 mrad, 23 mrad[1,2]
SOC	Hemispherical/Diffuse/Specular	Bands from 335-2500nm	Near normal	0.18cm^2	106 mrad and hemispherical

Reflectance is a measurement of the light reflected with respect to several factors as shown in Equation 8:

$$\rho = \rho(\lambda, \theta, S(\Omega)) \qquad \text{Equation 8}$$

Where ρ is reflectance, λ is wavelength of light (typically in nm), θ is incidence angle of the light to the reflective surface, and $S(\Omega)$ is the reflecting light acceptance surface size, with Ω denoting the angle of the acceptance surface. Typically, acceptance angles of $\pi/2$ are used for hemispherical reflectance, while smaller acceptance angles are specular, usually between 7-150mrad.

C.2 Instrument calibration and setup

Surface Optics Portable Reflectometer

1. The instrument is powered on and warms up for 30 minutes
2. User follows the calibration procedure prompted by the instrument:
   A. Collect a reading on a diffuse coupon

[1] In the instrument specifications, full aperture angle is typically used, twice to the aperture acceptance angles, which are 7 mrad, 25 mrad, and 46 mrad.
[2] 7.5 mrad and 15 mrad are available to some other D&S 15R model.

B. Collect a reading on a calibration mirror coupon – this coupon should accurately represent the samples to be tested (i.e., secondary surface or primary surface, glass thickness, etc)

C. Collect a reading of ambient light conditions

3. User collects a measurement of the calibration coupon post-calibration to verify reflectance values are within 0.2% of the value prescribed on the coupon

Devices & Services Specular Reflectometer

1. The instrument is powered on and warmed up for 30 minutes
2. The device is set to the 25 mrad aperture
3. Ensure the calibration coupon is properly seated over the aperture
4. Adjust the gain on the device until the reading reads the value prescribed by the instrument for the supplied calibration coupon.
5. Cycle to the largest (46 mrad) aperture – ensure the device reading does not change by more than 1.5% when switching between the 25 and 46 mrad aperture.
   A. If the device reading changes by more than 1.5%, the device will need to be aligned in accordance with the Devices and Services manual.

Perkin-Elmer Lamda-1050 Spectrometer

High-performance spectrophotometers may often be programmed to automatically calculate baseline corrections and apply corrections to the raw data. See specific spectrophotometer manuals for detailed setup of internal corrections files. If corrections files are to be collected manually, follow the procedure below as written.

1. The instrument is powered on and warmed up for 30 minutes
2. Load an appropriate measurement profile. PerkinElmer UV Winlab contains a wizard for designing measurement methods, which can specify outputs, reference materials, integration times, lamp switching, and known baseline corrections.
   - NREL recommends 5 nm resolution, covering wavelengths from 250-2500 nm
3. User inserts the control into the sample port and reference into the reference port locations on the L1050
4. Calibrated standard and reference materials should be representative of the samples being tested – specular materials require specular standards, highly reflective samples require highly reflective standards.
5. The user collects a control scan with the calibrated standard and the reference.
6. Remove the calibrated standard from the sample port and install a light cone or other appropriate light-trapping mechanism.
7. Collect a “blank” scan to record the conditions inside the machine in the absence of a sample.
8. The user should inspect the output for anomalies and inconsistencies across the spectrum

9. Prior to measuring samples, the user inputs a witness module into the machine.
    - Replace the calibrated standard into the reflectance sample port
    - Place a known witness material into the transmission sample port
    - NREL uses a well-characterized Holmium witness sample
10. Run a scan of the witness material
11. The user should compare this witness reading against the known characterization properties. If the witness reading raises concerns, the calibration should be repeated
12. The witness reading should be periodically repeated if testing large numbers of samples

Calibrations should be performed intermittently on all instruments to detect unexpected measurement drift.

References

[1] G. Zhu, D. Kearney, and M. Mehos, "On characterization and measurement of average solar field mirror reflectance in utility-scale concentrating solar power plants," *Solar Energy*, no. 99, pp. 185–202, Dec. 2013.