WREF 2012: SERVICE LIFE PREDICTION FOR REFLECTECH® MIRROR FILM

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ABSTRACT

The outdoor lifetime of ReflecTech® mirror film has increased as it has advanced through various commercial versions. Quantifying its lifetime is important, and use in utility-scale power generation requires extensive testing and validation to ensure compliance with the demands of extreme outdoor service environments.

A test matrix was developed and implemented with NREL; a variety of ReflecTech® samples were subjected to many accelerated exposure tests. The tests spanned several years, and include several versions of ReflecTech®, from the early versions through the newest version (ReflecTech®PLUS) that incorporates an abrasion resistant coating. This paper describes the various tests, how they were used to determine reflector degradation rates, and how these tests lead to the quantification of outdoor service lifetimes.

The analysis of accelerated test results permits the prediction of the useful lifetime of ReflecTech® under various conditions that are characteristic of Europe, China, Brazil, India, and the United States. For all these locations, the test results indicate outdoor lifetimes above 35 years.

1. INTRODUCTION

Through accelerated and real time product verification testing, polymer reflector technology has been demonstrated as a viable alternative to glass mirrors in concentrating solar power applications. Polymer film reflectors must be resilient to high ultraviolet (UV) radiation (~300MJ/m^2 per year, λ<400 nm) in combination with temperature from below freezing to peaks approaching 60°C (140°F), also in combination with moisture. Through accelerated and real time testing of products made with successive improvements, a damage function is derived and service lifetime prediction (SLP) methodology developed. This is applied to predict product lifetime for specific locations where concentrating solar thermal plants will be located.

2. APPROACH

This paper describes testing associated with 5 points along a polymer film's history as referenced herein as "stages" (Table 1). Each stage is characterized by advancements in weatherability over previous stages. RT-1 was an early test version of ReflecTech® mirror film (RTMF). RT-2 and RT-3 are successive scale-ups. RT-4 increased UV protection and RT-5 added a protective abrasion resistant hardcoat (ARC). The current commercially available ReflecTech®

PLUS mirror film further improves UV protection over the most advanced construction described here, RT-5.

TABLE 1. VERSIONS, REFLECTECH® MIRROR FILM.

Term	**Stage**
RT-1	Prototype
RT-2	Early/Pilot
RT-3	Commercial
RT-4	RT-3 w/improved UV
RT-5	RT-3 w/improved UV + ARC

Validation testing performed on products from development through commercial scale-up is presented in Table 2 through Table 5. Performance tests were applied to all film lots to verify compliance with reflectance requirements (Table 2). With every development and commercial production run, mechanical tests verify that product and process parameters are met (Table 3). Selective durability tests are applied to prequalify and test any significant design and/or process change (Table 4). Accelerated tests are applied on every new and significant design/process change to ensure weatherability and determine limits (Table 5).

TABLE 2. PERFORMANCE TESTS

Measurement	Standard	Value
Solar-Weighted Hemisp. Reflectance	ASTM E891	93%
Specular Reflectance	25 mrad, 660 nm	94%

(1) At 1.4° acceptance angle measured on D&S Specular Reflectometer.
(2) Integrated over an air mass 1.5 direct normal solar spectrum.

TABLE 3. MECHANICAL TESTS

Test	Standard	Value
Peel Strength on Alum	ASTM D903	Min 10 N/25mm
Cross-cut adhesion	ASTMD3359	5B
Bend Test	ASTM D522	Radius 25mm

TABLE 4. DURABILITY TESTS

Test	Standard	Test
Water Immersion	ASTM D870	30 days in DI water
Freeze Thaw	ASTM D6944	80 cycles: -60°C to 80°C, 0 to 80% RH
Hail test	ASTM E822	25mm ice ball, 30 m/s front & back
Salt Spray	ASTM B117	500 hours
Steel wool (hardcoat)	Supplier	#0000, 10 cycles 1134g weight
Taber Abrasion (hardcoat)	ASTM D4060 modified	250g weight, 30 cycles, pre and post weathering
Scrub Brush Abrasion (hardcoat)	ASTM D2486	53,000 scrub cycles
Sand Drop Abrasion (hardcoat)	ASTM D968	2L of 120 grit sand

TABLE 5. ACCELERATED TESTS

Test	Standard	Test (UV,Temp,RH)
Accelerated Weathering (Ci5000)	ASTM G155	2X UV, 60°C, 60%RH
Accelerated Weathering (Solar Simulator)	ASTM G155	2X UV, 30°&60°C, 5% & 65% RH
Accelerated UV (ACUVEX®)	ASTM G90	5X UV, Ambient, water spray
Accelerated UV (UAWS)		50X UV, 30°&60°C
Moisture condensation (QUV)	ASTM D4587	1X UV, 30°&60°C, 100%RH

ReflecTech® mirror film is an organic-based metalized reflector. As with other organic-based products degradation occurs from stresses associated with outdoor weathering including UV, moisture and temperature. An experience-based methodology based on macroscopic response to environmental stresses is used to analyze results from a variety of accelerated exposure test methods. The intent is to show that data sets of these accelerated exposure tests are complimentary and can be used together to allow reliable service lifetime predictions.

Based on test data from RT-2 and RT-3 a service life prediction is calculated for the R-4 and RT-5 for site specific conditions. This model is applied to predict useful lifetime at several operating CSP thermal sites.

3. SERVICE LIFE PREDICTION

The first step in implementing SLP is to obtain a suitable material-specific damage function model that accurately relates changes in an appropriate response variable to relevant applied environmental stresses. A methodology outlined in [1] and further developed in [2] has proven useful for characterizing metalized polymer solar reflectors. In this approach the change in optical performance (reflectance) with exposure to in-service time-dependent weather conditions can be expressed as:

$$\frac{\Delta\rho}{\Delta t} = A\, I^n\, D(t)\, e^{-E/[R*T(t)]}\, e^{B*RH(t)} \qquad 1$$

where:

$\Delta\rho$ = change in solar-weighted hemisph reflectance
Δt = change of time/dose
I = intensity acceleration factor
D = cumulative UV dose (MJ/m^2 UV)
T = sample exposure temperature (°C)
RH = relative humidity (%)

n = intensity power law exponent
E = activation energy (kJ/mole/K)
B = relative humidity coefficient
R = gas constant (8.3145 J/mol/K)

For accelerated weathering chambers in which exposure conditions are held constant. Equation 1 can be simplified.

$$\frac{\Delta\rho}{\Delta t} = A\, I^{n}\, D\, e^{-E/[R*T]}\, e^{B*RH} \qquad 2$$

Samples can be exposed at different elevated levels of stress factors and the response variable can be measured periodically until some specified critical value is reached. A nonlinear regression can then be used to fit these data to Equation 2 to obtain the coefficients A, E, B, and n. Once these coefficients are known, they can be used in the time-dependent Equation 1 to estimate service lifetime under real-world meteorological and radiometric conditions.

4. RESULTS OF EXPOSURE TESTING

UV durability is especially important for polymer reflectors. The UV portion of terrestrial sunlight is particularly deleterious to organic bonds in polymeric materials. Metalized polymer reflectors generally exhibit a piecewise-linear durability profile (degradation curve) as shown in Figure 1. After some period of time/dose, reflectance drops to a critical value (ρ_{crit}) corresponding to an unacceptable loss of reflectance. We use ρ_{crit}=90%.

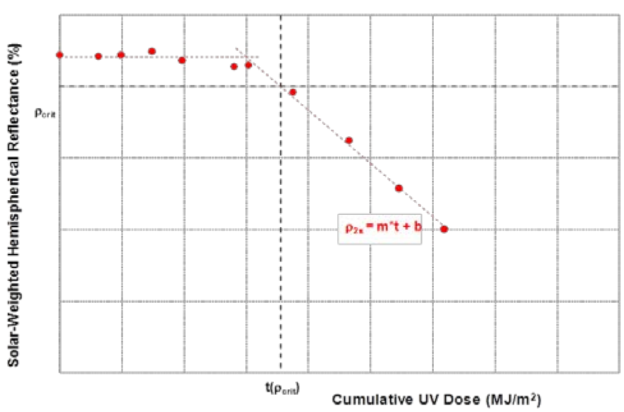

Fig. 1: Typical response of a generic metalized polymer reflector to UV exposure.

Such materials resist degradation for some time while the polymer and polymer/metal interface are protected from damage (by a UV screening layer). Once the combined stresses experienced by the mirror exceed some threshold, the protective layers/components lose their damage-resisting functionality and (usually) linear degradation (loss in reflectance) begins. The slope of the post-induction degradation curve is a function of the severity of the weathering conditions. It is useful to use the cumulative UV dosage at which optical performance decreases to an unsatisfactory level (for example ρ_{crit} = 90%).

The useful longevity of the UV screening functionality depends on the photostability of the UVAs [3]. Figure 2 shows the UV transmittance of an early prototype UV screening film as a function of exposure to cumulative UV dose. As can be seen, initially the film has a transmittance cut-off at about 390 nm. After continued exposure to UV irradiance, the cut-off wavelength moves to lower wavelengths. After ~2000 MJ/m^2 UV the cut-off wavelength decreased to ~380 nm. Further exposure further reduces effectiveness at blocking UV of lower wavelengths.

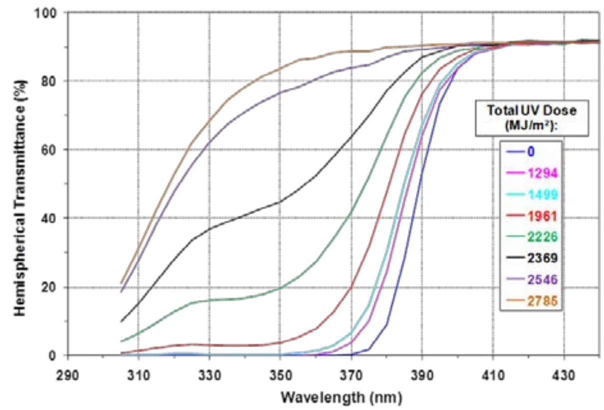

Fig. 2: Spectral transmittance of prototype UV screening film as a function of total UV dose (Ci5000).

Improved UV screening films having UVA additives with greater photopermanence have now been incorporated into the RTMF construction. Corresponding increased durability of the mirror stack has been demonstrated.

A variety of UV exposure tests of RTMF have been conducted in combination with other stress factors such as exposure temperature and relative humidity, and are summarized in Table 5.

- Samples at the outdoor sites and in NREL's Ci5000 have not experienced sufficient exposure to result in measureable degradation upon this writing.
- NREL's Solar Simulator exposure chamber provides concurrent testing of up to 8 samples in each of 4 quadrants having various combinations of dry/wet and ambient/hot conditions.
- The ACUVEX® outdoor weathering test is a commercial 10-mirror Fresnel-reflector tracking array that delivers an accelerated dose of about 5X natural sunlight to exposed samples [4].
- NREL's ultra-accelerated weathering system (UAWS) concentrates terrestrial natural sunlight 100X with a 50X acceleration factor of direct normal UV at two controlled levels of temperature, 30° and 60°C [5].

4.1 Results of RT-2 Exposure Testing

Samples of RT-2 have been exposed in the solar simulator chamber, the UAWS, and at the ACUVEX® facility. The temperature, humidity, and intensity levels experienced during each of these tests are shown in Table 6. Conditions for the solar simulator and UAWS were controlled as specified in Table 6. Samples are also being exposed with the UAWS at 30°C but these have not yet degraded to $\rho_{2\pi}$ = 90% so an estimate for the corresponding critical cumulative dose are not available. Samples exposed with the ACUVEX® experience unmonitored variations in temperature and humidity that depend upon ambient weather conditions. Samples are sprayed with water every 8 minutes so the average relative humidly likely varies between 15-25%; a value of 20% is used in Table 6. Sample temperature is a function of ambient temperature, the incident concentrated thermal load, and the amount of sunlight absorbed by the samples. RTMF is highly reflective throughout the solar spectrum except for the UV region (300-380 nm) where light is absorbed.

The total thermal load on a sample is:

$$L_{th} = I * \frac{\int [\rho_{conc}(\lambda) * \Phi(\lambda)]\left[1 - \rho_{samp}(\lambda)\right] d\lambda}{\int\left[1 - \rho_{samp}(\lambda)\right] d\lambda} \qquad 3$$

where:

$\rho_{conc}(\lambda)$ = the spectral reflectance of the concentrating mirrors
$\Phi(\lambda)$ = the spectral intensity of the terrestrial solar spectrum [6]
$\rho_{samp}(\lambda)$ = spectral reflectance of the sample being exposed

From Equation 3, the thermal load experienced by samples of RTMF exposed with the ACUVEX® concentrator is ~7.5 less than experienced with the UAWS. The UAWS concentrator is able to maintain a sample exposure temperature of 30°C by conductive cooling. The ACUVEX® system uses convective cooling. Based on this and the substantially lower thermal load the average ACUVEX® sample exposure temperature is estimated as 35-40°C; a value of 38°C is used in Table 6.

Table 6 also lists the cumulative dosages at which the solar-weighted hemispherical reflectance values dropped to 90% for each of the exposure conditions listed. Results for the four test conditions used in the solar simulator are shown in Figure 3. Results for samples exposed in the ACUVEX® and UAWS exposure chambers are also shown in Figures 4 and 5 respectively. The slope of the degraded part of each curve is used to determine the cumulative dose at which SWHR drops to 90%, $D(\rho_{2\pi}=90)$.

TABLE 6. ACCELERATED EXPOSURE CONDITIONS AND TEST RESULTS FOR RT-2 SAMPLES.

Type of Exposure	T (°C)	RH (%)	I	D ($\rho_{2\pi}$ = 90) (MJ/m^2 UV)	$D_{calc}(\rho_{2\pi}$ = 90) (MJ/m^2 UV)	$t_{equiv}(\rho_{2\pi}$ = 90) (y)*
SolSim	60	65	2	1742	1793	5.8
SolSim	60	0	2	2360	2317	7.4
SolSim	35	65	2	2364	2333	7.5
SolSim	35	0	2	2973	3015	9.7
ACUVEX®	38	20	5	2853	2830	8.6
UAWS	60	0	50	2750	2757	7.4

*t_{equiv} based on 300 MJ/m^2/y

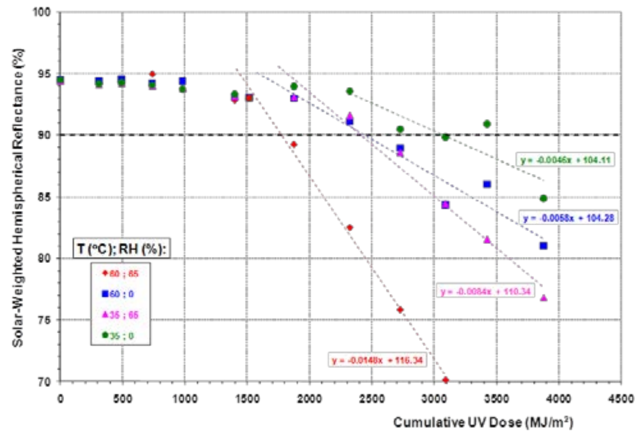

Fig. 3: Solar Simulator exposure of RT-2 samples with varying temperature and relative humidity.

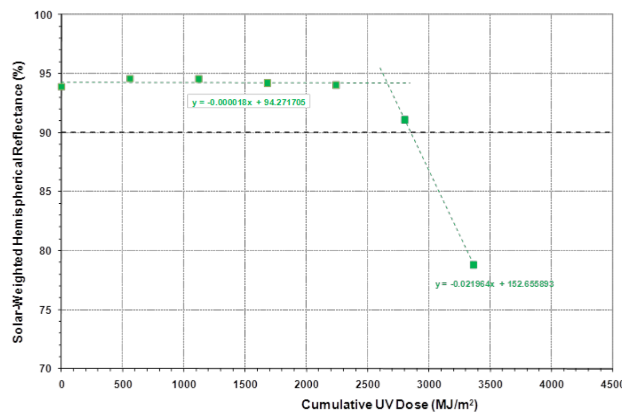

Fig. 4: ACUVEX® exposure of RT-2 samples under time varying environmental conditions.

The $D(\rho_{2\pi}$ = 90) data from the various exposure tests of RT-2 film were fit to Equation 2 using Excel's Solver feature. This allowed the coefficients of the damage function to be obtained. Resultant values for A, B, E, and n are provided in Table 7. The calculated cumulative dosages, $D_{calc}(\rho_{2\pi}$ = 90), in Table 6 are based on these coefficients. A comparison between the measured and calculated dosages is shown in Figure 6. These results span over three weathering systems that operate over a wide range of exposure intensities with light sources that include natural sunlight (both full spectrum and UV only) and artificial xenon arc lamps. The effects of other important weathering variables (temperature and humidity) are also taken into account. The data all follow very close to a straight line having a nearly ideal slope of unity. This excellent agreement demonstrates a very powerful and robust approach to accelerated weathering data analysis and SLP.

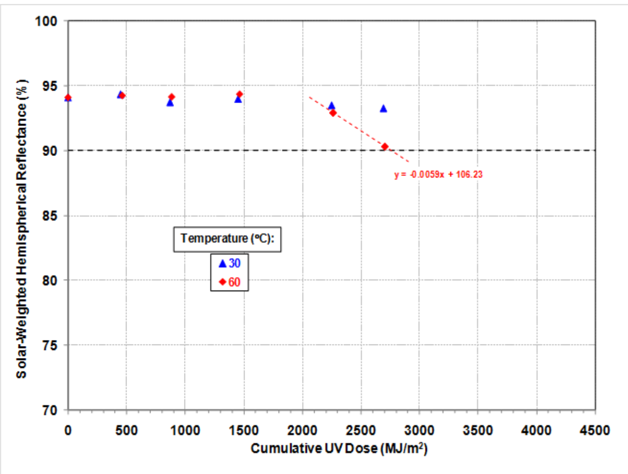

Fig. 5: UAWS exposure of RT-2 samples at 30 and 60°C.

TABLE 7. RT-2 DAMAGE FUNCTION COEFFICIENTS

Coefficient	Value	Units
A	86.87	
B	0.0039	
E	8.99	kJ/mol
N	0.95	

The various exposure systems attempt to accelerate weathering by increasing the intensity of the light source to levels greater than natural exposure (1X). An important question is whether the degradation rates experienced by samples being tested increase in direct proportion to the dosage rate being applied (D). This effect is accounted for in Equations 1 and 2 by the term I^n. When n = 1 exact proportionality is achieved and linear reciprocity holds. If n < 1 the rate of degradation is less than expected from increased light intensity. This means that the full effect of the increased light intensity is not experienced. The equivalent lifetime (in years) is then related to the cumulative dose as:

$$t_{equiv} = \frac{D}{K} * I^{n-1} \qquad 4$$

K is the yearly UV dose of direct normal irradiance at a particular geographic location where the solar mirror is deployed. Typically, K ≈ 300 MJ/m^2/y. Values of t_{equiv} (in years) calculated from Equation 4 are tabulated in the last column of Table 6.

Equation 2 and the coefficients from Table 7 are used to estimate that RT-2 samples exposed in the UAWS chamber will degrade to 90% reflectance at a cumulative dose of ~3800 MJ/m^2. This analysis also predicts that RT-2 film used in a solar concentrator installed at a location where the relative humidity is low and the ambient temperature averages about 30°C, then the solar-weighted hemispherical reflectance would remain above 90% for 10.3 years.

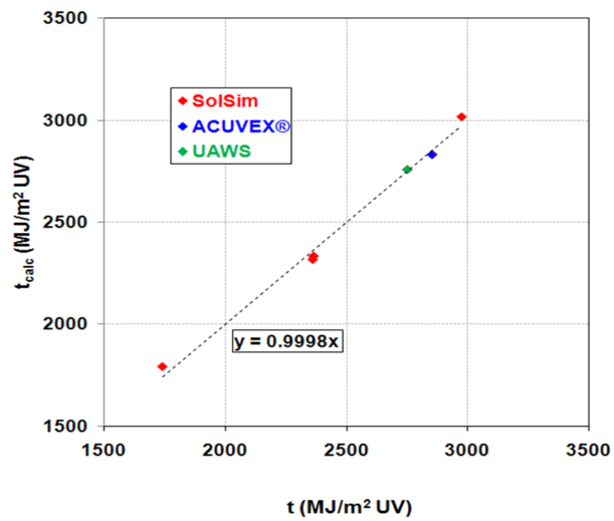

Fig. 6: Actual vs. calculated cumulative dose at $\rho_{2\pi}$ = 90% for RT-2 RTMF

4.2 Results of RT-3 Exposure Testing

The RT-3 version used a new and improved UV screening layer than that used by RT-2 RTMF. Less data is available for RT-3 with the exception of very long term UAWS results (Figure 7) that enable estimates of the longevity of this material. Because the UAWS does not control moisture during sample exposures, the damage function will not exhibit any relative humidity dependence and the calculated dose at which the SWHR drops to 90% will be:

$$D_{calc}(\rho_{2\pi} = 90) = \frac{A}{I^{n-1}} e^{E/[R*T]} \qquad 5$$

Notice that the two temperature curves in Fig. 7 exhibit self-similarity. An important prerequisite for the applicability of this approach is the fulfillment of the self-similarity criterion (i.e., the shape of the characteristic aging curves is similar for different temperatures). A superposition of data generated for various aging temperatures is obtained by shifting the various aging curves horizontally along the time axes so that a single master curve is obtained. The time-temperature acceleration shift factor that relates data at 30°C exposure to data at 60°C exposure is

$$a_T = \frac{t_{T=30}}{t_{T=60}} \qquad 6$$

From Fig. 7, $t_{T=30}(\rho_{2\pi}=90)$ = 7314 MJ/m^2 UV and $t_{T=60}(\rho_{2\pi}=90)$ = 4308 MJ/m^2 UV, from which we obtain a_T = 1.697 for RT-3. The shift factor is related to the thermal activation energy by:

$$a_T = exp\left[\frac{E}{R}\left(\frac{1}{T_{30}} - \frac{1}{T_{60}}\right)\right] \qquad 7$$

or E = 14.82 kJ/mol. Assuming a reciprocity relationship similar to that of RT-2 RTMF (n=0.95) we can fit Equation 5 to determine A = 16.84. This analysis then predicts that if RT-3 were used in a solar concentrator installed at a location where the relative humidity is low and the ambient temperature averages about 30°C then the solar-weighted hemispherical reflectance would remain above 90% for 20.0 years, which is a factor of 2 improvement compared with RT-2 RTMF.

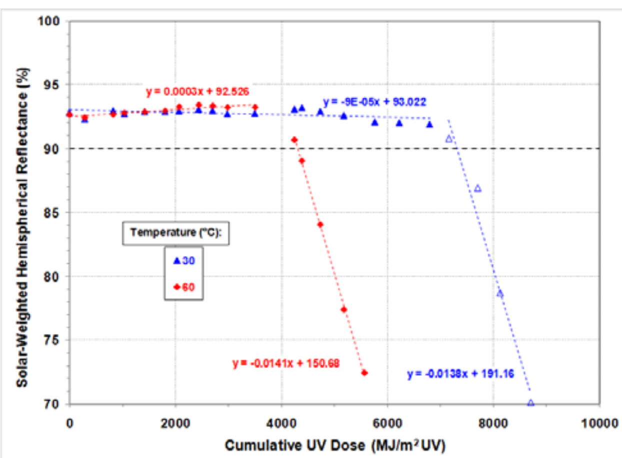

Fig. 7: UAWS exposure of RT-3 samples at 30 and 60°C. Slope of degraded part of curve is used to determine cumulative dose at which $\rho_{2\pi}$=90.

4.3 <u>Results of RT-4 Exposure Testing</u>

The RT-4 commercial version of the polymer film RTMF , was improved with an abrasion resistant hardcoat resulting in RT-5. As seen in Figure 8, samples have experienced over 9000 MJ/m^2 UV at exposure temperatures of both 30 and 60°C in NREL's UAWS. Importantly, these samples have not yet degraded enough to allow the expected cumulative dose at failure to be calculated from Equation 5. Based simply on a typical yearly outdoor UV dose of 300 MJ/m^2/y, RT-5 (ReflecTech® PLUS mirror film) has experienced an equivalent of 30 years service exposure without loss in reflectance. Samples are also being exposed with the solar simulator and ACUVEX® systems but the cumulative dosages are considerably less and no degradation in SWHR has occurred.

A better lower-bound estimate of lifetime can be made based on the 9000 MJ/m^2 UV experienced to date. By assuming the same reciprocity relationship exhibited by RT-2 RTMF (n=0.95 in Equation 4), this cumulative dose is equivalent to ~25 years at an exposure temperature of 60°C. If RT-5 (ARC RTMF) has the same thermal shift factor as RT-3 (a_T = 1.697), then the expected lifetime at 30°C would be ~42 years. The assumption that the damage function coefficients are the same for RT-4 as they are for RT-2 and RT-3 are being confirmed with ongoing further testing, but the basic construction of RTMF and the types of materials used are quite similar.

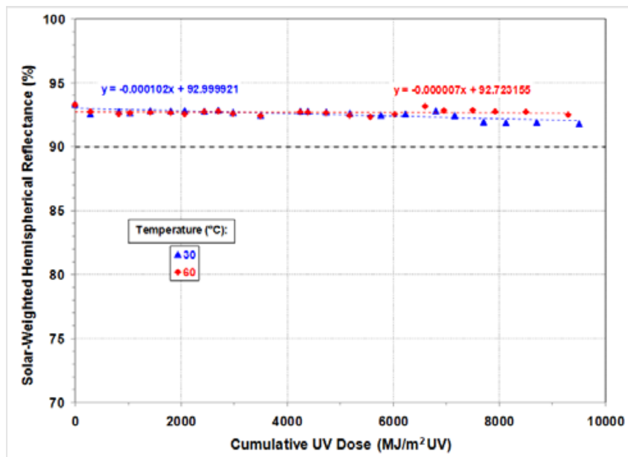

Fig. 8: UAWS exposure of RT-4 samples at 30 and 60°C. Neither SWHR data set dropped below 90%.

4.4 <u>Results of RT-5 Exposure Testing</u>

The surface of polymer reflectors can be scratched if they are cleaned using contact methods such as brushing, a common technique for cleaning glass reflectors. Pressure washing with demineralized water (without contact brushing) does not cause surface scratching and is the recommended method for cleaning polymer reflectors. But where contact cleaning methods are used, an abrasion resistant coating (ARC) has been developed for RTMF.

As with the uncoated RTMF products, the RT-5 (ARC/RTMF) materials have also been subjected to accelerated exposure testing. ACUVEX® was initiated relatively recently and only ~500 MJ/m^2 UV dose has been accumulated. Test results from solar simulator exposure are shown in Figure 9. Instrumental problems caused samples exposed at elevated humidity to fail unrealistically early in the test. Samples exposed at low humidity have experienced almost 4000 MJ/m^2 UV without SWHR degrading to 90%. Companion samples have been exposed in the UAWS to over 9000 MJ/m^2 UV at exposure temperatures of both 30 and 60°C. As with the uncoated RT-3 samples discussed in the previous section, these samples have not yet degraded enough to allow the expected cumulative dose at failure to be calculated from Equation 5. A lower-bound estimate of lifetime can again be made based on 9000 MJ/m^2 UV experienced to date, which corresponds to an equivalent of 30 years service exposure without loss in reflectance based on K=300 $MJ/m^2/y$ UV. By assuming the same reciprocity relationship exhibited by the RT-2 RTMF (n=0.95 in Equation 4), this cumulative dose is equivalent to ~25 years at an exposure temperature of 60°C. If RT-5 has the same thermal shift factor as RT-4 (a_T = 1.697), then the expected lifetime at 30°C would be ~42 years. As before, the validity of the assumptions about the similarity of the damage function coefficients needs to be verified because the addition of another layer to the reflector construction changes the materials system. With no degradation in the performance of the ARC this strongly suggests that the addition of the ARC to the RTMF stack will add to the weatherability of the new reflector and result service lifetimes even longer than those computed above. The lower bound estimate of lifetime is 30 years, while the 42 year estimate is based on the damage function coefficients derived for the previous-generations of RTMF.

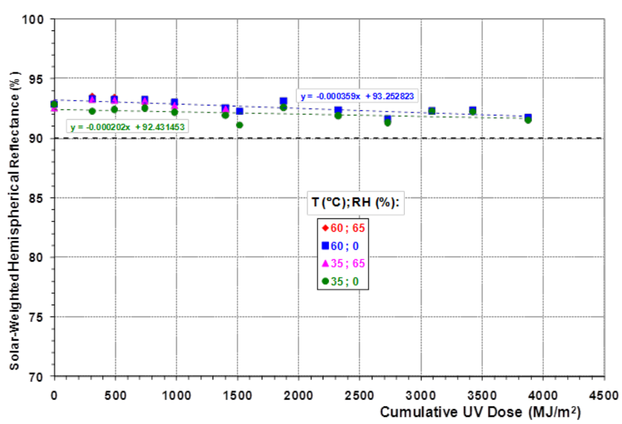

Fig. 9: Solar Simulator exposure of RT-5 samples with varying temperature and relative humidity conditions. SWHR has not yet dropped below 90%.

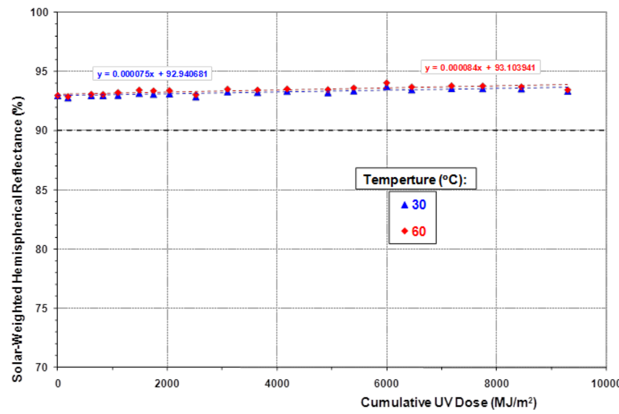

Fig. 10: UAWS exposure of RT-5 samples at 30 and 60°C. The SWHR of neither data set has dropped below 90%.

4.5 Adding the Effect of Relative Humidity: RT-4 and RT-5

As an extension of the previous two sections, if we assume that the reciprocity and relative humidity coefficients from the RT-2 RTMF exposure test results approximate those associated with RT-4 and RT-5, and that the activation energy and shift factor derived for RT-4 can also be used to characterize RT-4 and RT-5, we can obtain lower bound estimates that apply to both of these materials as a function of temperature and relative humidity. Adding the relative humidity term to Equation 5 gives a value of A = 35.18. The resulting estimated equivalent outdoor lifetime as a function of temperature and relative humidity is shown in Figure 11. We previously found that for an arid climate where the ambient temperature during operation is approximately 30°C, t_{equiv}(T=30°C, RH=0%) ≈ 42 years. For a location where the relative humidity during service is 50%, t_{equiv}(T=30C, RH=50%) ≈ 34 years.

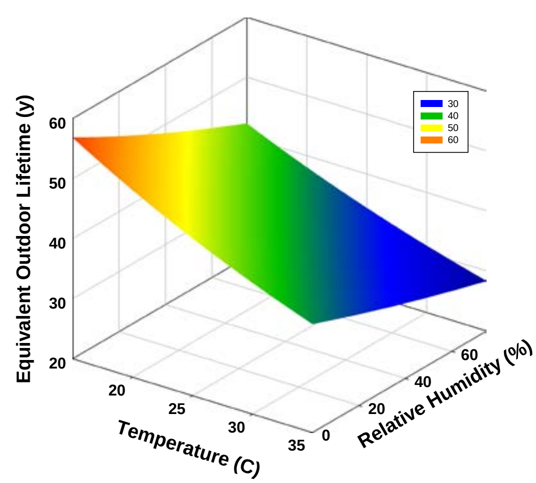

Fig. 11. Outdoor lifetime vs. temperature and relative humidity, based on 300 MJ/m2/y UV irradiance.

Other site-specific estimates for the equivalent outdoor lifetime as a function of temperature and relative humidity can be calculated using Equations 4 and 5 or approximated from Figure 11. For example, Table 8 provides minimum lifetime estimates for RTMF based on average daily temperature and relative humidity conditions at various worldwide locations suitable for CSP plant installation. These values are calculated from Equation 2 using the annual daily average values of ambient temperature and relative humidity. Ideally, the time dependent variations of the various weather parameters should be used in Equation 1. However, such detailed information is not generally available. A better approximation would be obtained by using the average daytime temperature and relative humidity because temperature and humidity do not contribute to degradation in Equations 1 and 2 when the intensity is zero (no sunlight). For example, at Daggett, CA the average daytime temperature is 23.1°C and the average daytime relative humidity is 28.2% as calculated from the TMY2s database for selected US locations [7]. This results in a lifetime estimate of 35.8 years, slightly lower than the value shown for Daggett in Table 8.

TABLE 8. ESTIMATED LIFETIME OF RTMF AT VARIOUS LOCATIONS SUITABLE FOR CSP.

Location	**Average Daily Temp. (°C)**	**Average Daily Relative Humidity (%)**	**Cumulative Annual UV Dose (MJ/m²/y)**	**$t_{calc-equiv}$ (y)**
Daggett, CA	20	33	360	38
Granada, Spain	15	60	278	48
Rajasthan, India	25	47	264	44
Brasilia, Brazil	22	68	254	45
Hohhot, China	6	48	259	66

5. CONCLUSIONS

To accurately assess the outdoor lifetime of ReflecTech® mirror film, a variety of ReflecTech® samples have been subjected to many accelerated exposure tests. The tests spanned several years, and include several versions of ReflecTech®, from the early versions through the newest version that incorporates an abrasion resistant coating.

A service lifetime prediction (SLP) methodology was used in combination with detailed analysis of accelerated and real time testing of these reflector samples, to derive a damage function for ReflecTech® mirror film. This SLP methodology has been applied to predict product lifetime for a wide variety of locations where concentrating solar thermal plants will be located: Europe, China, Brazil, India, and the United States. For all these locations, the test results indicate outdoor lifetimes of ReflecTech® mirror film above 35 years.

6. REFERENCES

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