REFLECTECH MIRROR FILM: DESIGN FLEXIBILITY AND DURABILITY IN REFLECTING SOLAR APPLICATIONS

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ABSTRACT

ReflecTech® Mirror Film is a highly reflective, flexible polymer film for concentrating solar energy applications. Developed specifically for concentrating solar power applications, this reflective film is used in many solar concentrators that leverage this polymer film's low cost, light weight, and flexible properties. These advantages are illustrated by describing how ReflecTech® Mirror Film is used in SkyFuel's parabolic trough solar collector.

A significant barrier to technical acceptance by solar developers and manufacturers is the question of durability under severe outdoor conditions. This paper presents new results of environmental tests for weatherability in which reflectors are subjected to controlled conditions more extreme than actual outdoor environments. Included are the National Renewable Energy Laboratory's (NREL) testing capabilities for reflectors including the new ultra accelerated weathering system (UAWS), and the third party ACUVEX® outdoor accelerated weathering test.

1. INTRODUCTION

ReflecTech® Mirror Film is like a glass mirror for reflecting and concentrating sunlight, with one major difference. It is made of unbreakable highly-reflective, flexible, polymer-based silver film that comes on a roll. Invented, designed, engineered and tested in collaboration with NREL, it solves two historical problems with solar polymer mirrors, delamination and optical durability.

New concentrating and reflective solar technologies are greatly enabled by the low cost and flexibility of reflective polymer film. With performance at the level of silvered glass mirrors, reflective polymer film technology offers additional benefits and savings through installed cost, design flexibility, lower weight, and resistance to severe environments.

For any outdoor application to achieve product lifetime goals, the reflective technology must be weatherable - stable against ultraviolet (UV) light, resistant to the effects of moisture, and durable under high wind events. Many reflective technologies are available but very few can last outdoors. Thick glass mirrors with high lead backside protective paint installed at large concentrating solar power (CSP) plants during the 1980's have proven reliable in desert CSP environments, although high wind events cause some breakage and efficiency loss. The polymer mirror film discussed in this paper is the only commercially available reflective film technology currently available that has been demonstratively subjected to the accelerated and outdoor weathering tests described herein.

2. PROPERTIES AND DESIGN CONSTRUCTION

This polymer mirror film has a solar-weighted hemispherical reflectance of 94% and a specular reflectance of 94% at a 25-mrad (1.4°) full acceptance angle at 660 nm (Table 1). This performance is comparable to glass mirrors that are made for CSP applications.

TABLE 1. TYPICAL PERFORMANCE, REFLECTECH® MIRROR FILM

Parameter	**Value**
Specular Reflectance[1]	94%
Solar-Weighted Hemispherical Reflectance[2]	94%
Nominal Thickness	0.1 mm (0.004”)

[1] At 1.4° (25 mrad) full acceptance angle measured with D&S Specular Reflectometer at 660nm
[2] DIN 5036-1, 3, ASTM G 173 – 03 Integrated over air mass 1.5 direct normal solar spectrum.

The polymer mirror film consists of a silver reflective layer within multiple layers of polymer films [1, 2] that protect the silver layer from oxidation and UV (ultraviolet) degradation. A pressure sensitive adhesive enables application to smooth, non-porous surfaces such as aluminum sheet. The film also has a peel-off protective mask that protects the mirror surface until the final reflector product is installed. Edge tape is used to protect film edges from long term exposure to wind, moisture and mechanical damage.

The polymer mirror film comes on standard rolls in 1.22 and 1.52 m (4 and 5 ft) widths up to 122 m (400 ft) in length and fits in a single box that weighs less than 36 kg (80 lbs), making it easy to transport in large quantities. A standard full pallet of twenty-five 1.52 m (5 ft) rolls has 2,286 m (7,500 ft) of film which is 3,484 m^2 (37,500 ft^2) of mirror area.

The weight of ReflecTech® Mirror Film laminated to 1.3 mm (0.050 in) aluminum substrate is approximately 3.6 kg/ m^2 (0.74 lb/ft^2) compared to glass mirrors (Flabeg RP2 4 mm) at 10 kg/ m^2 (2 lb/ft^2).

3. ATTRIBUTES OF POLYMER MIRROR FILM

This polymer mirror film has demonstrated stability during exposure to UV light, which is needed for the severe outdoor ambient environments that solar applications experience. Unlike some reflective films installed during the 1980's it demonstrates excellent mechanical stability against moisture. Water immersion tests also show no signs of delamination.

The polymer film has an adhesive backing to enable easy application to a rigid substrate material such as aluminum. This enables the use of reflective polymer film for a large variety of reflector shapes and sizes from nearly flat reflectors to curved parabolic shapes and V-shaped reflectors.

The reflectance of ReflecTech® Mirror Film is shown relative to the solar spectrum in Figure 1. The film is highly reflective in the wavelength region where most of the solar resource is available.

When laminated to an aluminum substrate the polymer film reflector exhibits high specular reflectance. At acceptance angles representative of parabolic trough solar concentrators (14 mrad half acceptance angle at the rim as seen in Figure 2) the specular reflectance at 660 nm of the polymer film laminated to standard mill grade aluminum is 94%.

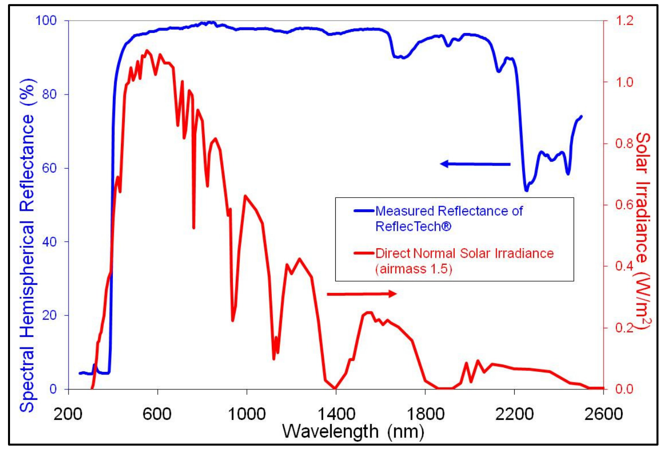

Fig. 1: Spectral Reflectance of ReflecTech® Film and Solar Irradiance.

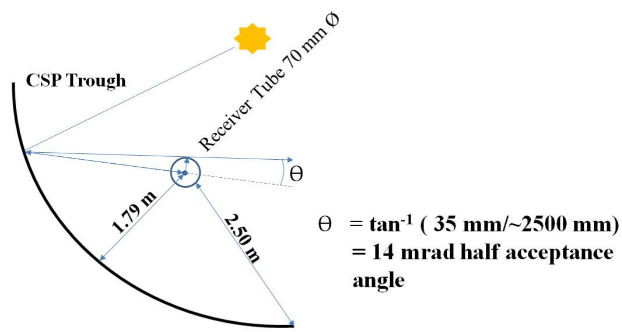

Fig. 2: Specular Reflectance for Parabolic Trough

ReflecTech® film is easily manufactured at high volume in rolls containing up to several hundred meters of material. This allows for greater production efficiency and design flexibility in reflector aperture widths.

The film can be applied to a substrate material using a film laminator equipped with rubber rollers (Figure 3). These machines automatically remove the backside protective liner, unwind the roll of ReflecTech® Mirror Film, and feed in the substrate or sheets, and press the pressure-sensitive adhesive side of the film to the substrate material.

Fig. 3: Lamination of polymer film to aluminum sheet

4. APPLICATIONS

Light weight and durable to high wind events, polymer film reflectors have applications in commercial-scale installations and utility-scale solar thermal and CPV applications. ReflecTech® film laminated to 1.3 mm (0.050 in) aluminum substrate has only 1/3 the weight of comparable 4 mm glass reflectors. In addition there is no safety risk from broken shards of glass, allowing polymer reflectors to be used in rooftop solar concentrators. Flat polymer film mirrors enable greater design flexibility and larger aperture reflectors with relative ease.

An excellent illustration of the attributes that polymer film brings to these and other solar applications is SkyFuel's SkyTrough™ parabolic trough solar collector (Figure 4) [3]. The SkyTrough™ uses polymer film adhered to flat aluminum sheet to make full-aperture reflectors as its key design-driving innovation.

Fig. 4: SkyTrough™ Collector using ReflecTech® Film

The use of thin, lightweight, flexible polymer film mirrors provides greater design flexibility in the support frame. Significant cost savings result from a decrease in frame materials, manufacturing, and field-assembly.

With polymer film laminated to flat aluminum substrate, and reflectors that slide into precision guided tracks that require no optical adjustment (Figure 5), the customer reduces installation costs. In contrast, CSP troughs that use thick glass mirrors typically require four mirrors across the arc of the trough with multiple fasteners per panel.

The polymer mirror film combined with aluminum substrate reduces the reflector weight load on the support frame by about 65% compared to other CSP trough designs that use thick glass mirrors. The larger mirror-module aperture area reduces the cost per megawatt of electric capacity due to fewer parts and less materials in modules, pylons, and foundations.

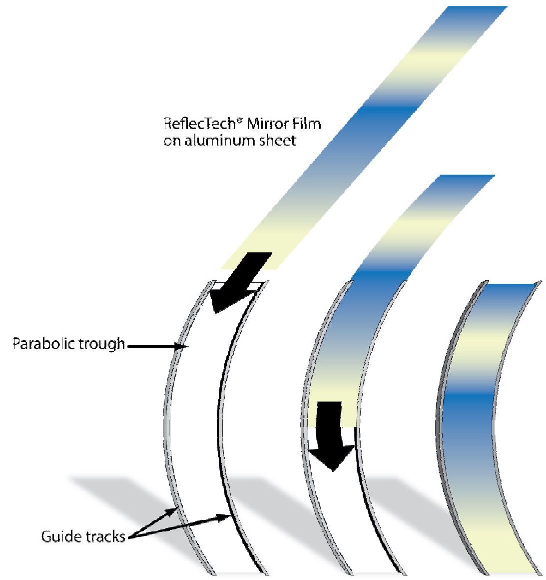

Fig. 5: Flexible mirror panels slide into the SkyTrough™

5. ACCELERATED DURABILITY TESTING

Reflector materials are tested for durability under exposure to outside environments through real time exposure and accelerated testing. Accelerated testing is the only predictive tool available for technologies that have not been installed for the full expected lifetime of reflectors. This pertains to all reflectors except high-lead thick glass mirrors (no longer manufactured) installed at the SEGS system in California which, except for breakage, have lasted for over 25 years.

NREL has an extensive capability to test the durability of candidate solar mirrors. A variety of specialized equipment is used for environmental stress tests to determine the characteristics and longevity of materials that are exposed to accelerated environmental conditions. Failure mechanisms identified by outdoor testing are replicated through accelerated laboratory-controlled testing including the UAWS.

High doses of UV light, high humidity and high temperatures more extreme than actual outdoor environments are used to accelerate failure mechanisms. Material degradation typically seen as corrosion in glass and polymer reflectors is accelerated by UV in combination with humidity and temperature. Tests for humidity include environmental chamber testing and water immersion testing.

UV durability is key for polymer reflectors. Accelerated exposure testing for reflectors includes the methods discussed in [4]. Figure 6 illustrates different UV acceleration methods and relative factors. These test conditions are discussed in the remainder of this document.

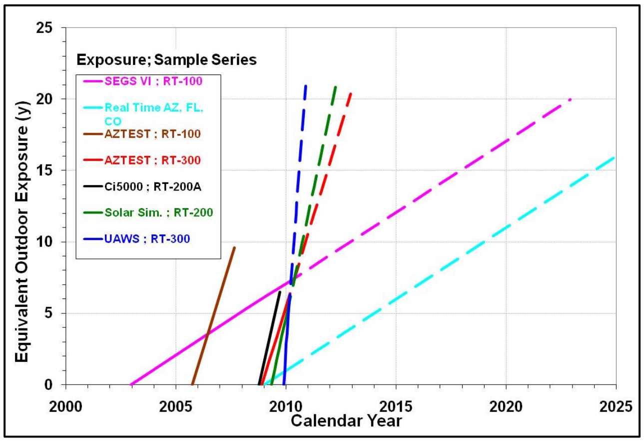

Fig. 6: UV Exposure Testing of ReflecTech® Mirror Film

5.1 Solar Simulator

The Solar Simulator exposure chamber was developed by NREL and provides concurrent testing of up to 8 samples in each of 4 quadrants having various combinations of dry/wet and ambient/hot conditions. This allows 3 stress factors, constant UV light 300-500 nm spectrum (2X), temperature (up to 70°C), and humidity (to 70% RH) to achieve highly accelerated testing of reflector samples.

Solar Simulator results for the ReflecTech® polymer film are shown in Figure 7 and compared against another reflective film construction (ECP-300 formerly made by 3M). 3M's ECP-300 was a silvered acrylic film with acceptable optical properties, but limited outdoor weatherability.

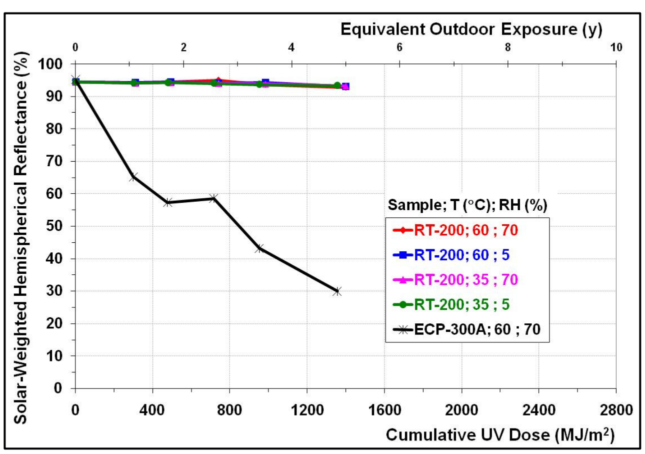

Fig. 7: Solar Simulator 2X UV Exposure of Polymer Films

Previous testing makes this film useful as a reference for showing the effectiveness of this test method for causing UV-induced corrosion of the metalized silver layer. This corrosion limited ECP-300 to a 3 to 5 year outdoor lifetime [5, 6].

5.2 WeatherOmeter®

The Ci5000 WeatherOmeter® chamber made by Atlas Material Testing Technology LLC is used to subject samples to UV, temperature, and humidity [7]. Samples are exposed to UV light intensities between 1X to 2X. Elevated chamber temperature (60ºC) and relative humidity (60%) are also used.

Accelerated testing of ReflecTech® Mirror Film in the Ci5000 chamber shows solar-weighted hemispherical reflectance values above 94% for all wavelengths with significant contributions to the solar spectrum (Figure 8).

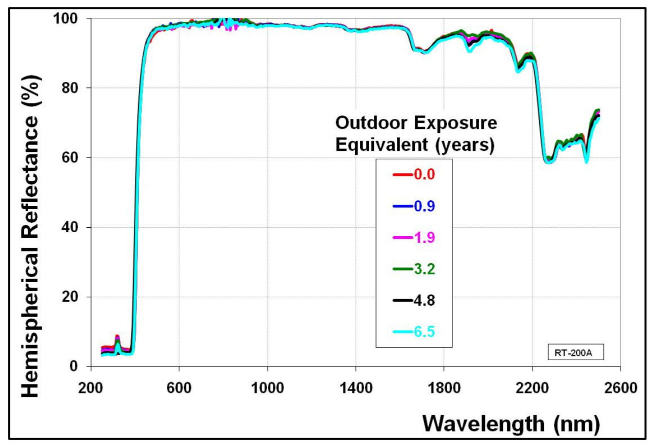

Fig. 8: Spectral Reflectance Retained w Ci5000 Exposure

Samples exposed in the Ci5000 chamber to an equivalent outside cumulative UV dose of 6.5 years show no relative change in spectral hemispherical reflectance (Figure 9).

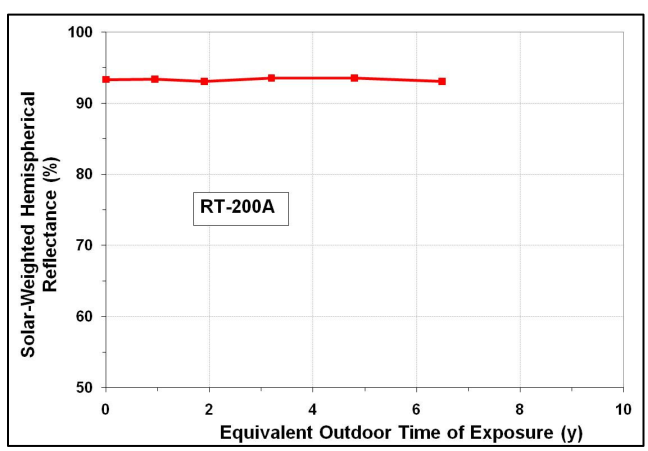

Fig. 9: Exposure of ReflecTech® Mirror Film in Ci5000

5.3 Water Immersion

Samples of ReflecTech® film were immersed in water to test for delamination and "tunneling," defined here as the separation of the top polymer layer from the silvered layer. The immersion test was also applied to ECP-305+ film. The 3M film was well characterized in the laboratory through accelerated tests and is therefore useful as a reference for gauging the weatherability of ReflecTech® Mirror Film.

Delamination and tunneling occurred in 3M's ECP 305+ film after only 4 days of water immersion; no delamination occurred for the ReflecTech® material after 60 days. The immersion test validated the resistance of ReflecTech® film to excessive moisture.

6. ACCELERATED OUTDOOR TESTING

Two highly advanced tests are employed in the outdoor testing of ReflecTech® film, the ACUVEX® Accelerated Weathering test and NREL's UAWS.

6.1 ACUVEX® Outdoor Weathering Test

The ACUVEX® outdoor weathering test is a 10-mirror tracking array that concentrates natural sunlight 7 to 8 times using a Fresnel-reflector where temperatures are maintained by convective air-cooling and sprayed with deionized water [8].

After a near 10-year equivalent time period previous testing showed no significant loss in solar-weighted reflectance [4].

ACUVEX® tests of new samples continue toward a 20 year equivalent outdoor exposure. Testing to 5600 MJ/m^2 will take approximately 4 years, as shown in Figure 6. Samples measured every 560 MJ/m^2 UV (about every 4 to 5 months) indicate no loss in solar-weighted hemispherical reflectance after a 5 year equivalent period (Figure 10).

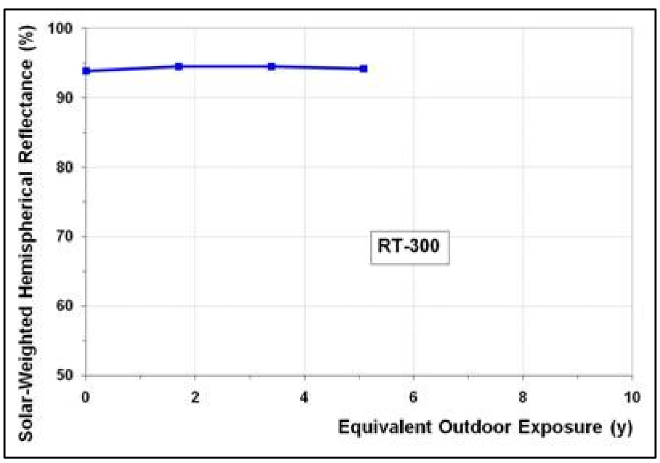

Fig. 10: ACUVEX® Accelerated Outdoor Test Results, UV and Moisture

6.2 NREL's Ultra Accelerated Weathering System

Polymer film samples are being tested on NREL's Ultra Accelerated Weathering System (UAWS) where natural sunlight is concentrated 100X for a 50X-60X UV exposure dose [9, 10]. Samples are typically exposed at two different temperatures, e.g., 30º and 60º C (Figure 11).

Fig. 11: NREL's Ultra Accelerated Weathering System

The ultraviolet solar concentrator was developed in 2009 to speed up the exposure of coatings, paints, and other materials 12 times faster than other accelerated weathering systems to determine their durability and resistance to weathering. After a 5 year equivalent UV dose, samples show no loss in solar-weighted hemispherical reflectance (Figure 12).

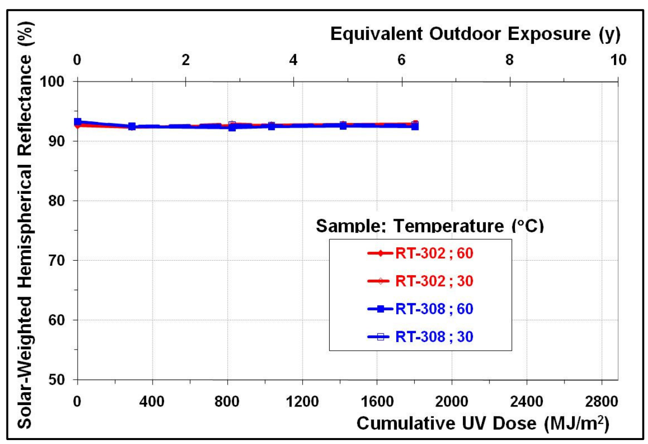

Fig. 12: UAWS 50X UV Exposure of ReflecTech® Mirror Film

7. INSTALLED SERVICE

Polymer film reflectors installed at SEGS VI at Kramer Junction in the Mojave Desert have been in service for 7 years. CSP facilities like the SEGS plants are typically located in the harshest desert environments where high UV, extreme ambient temperatures, and severe winds are experienced. In addition to this harsh environment, the frequent contact cleaning methods used on the glass reflectors installed throughout most of the facility is also used on the polymer film reflectors.

For ReflecTech® mirror film, unlike many silvered polymer products in the past, the silver reflective layer has not corroded/degraded in this timeframe. The polymer film exhibits excellent optical durability and maintains high hemispherical reflectance with less than 1% loss in solar-weighted hemispherical reflectance after 7 years of outdoor exposure at SEGS VI (Figure 13).

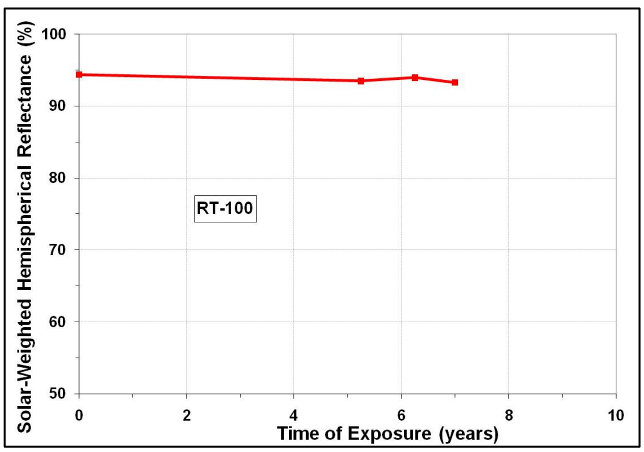

Fig 13: Exposure of ReflecTech® Polymer Film at SEGS VI

The contact cleaning methods (mechanical scrubbing) developed for the glass reflectors at the SEGS systems will scratch the surface of polymers. Over time, the surface scratching reduces the specularity of the film, and indeed the specularity of ReflecTech has dropped due to scrubbing. With non-contact pressure wash methods there would be no loss in reflectance due to surface scratching associated with cleaning methods, and specular reflectance would be higher.

8. CONCLUSIONS

Light weight, lower cost and durable solar reflectors made with polymer mirror film are an attractive alternative to other types of solar reflectors. Lamination to aluminum sheet enables different geometries and flexibility in design. The use of non-glass polymer film reflectors enables a larger concentrator aperture width and a cascade of material reductions and cost savings in the CSP trough design including: reduced collector part count, reduced space frame weight, reduced number of other required components (e.g. support pylons, drilled pier foundations, drives), and reduced installation time.

The durability of ReflecTech® mirror film has been demonstrated by installation in a desert environment for 7 years and accelerated methods more extreme than outdoor conditions. Film reflectance has not dropped during natural sunlight exposure with the ACUVEX® test after nearly 10 years and the UAWS after 6.5 years equivalent. These tests are ongoing with a target of 20 years.

9. NOMENCLATURE

mrad – milliradian (approximately 0.057°)
RH – relative humidity
SEGS - Solar Energy Generating Systems
Solar weighted hemispherical reflectance – Total amount of light reflected from a mirror surface averaged over all wavelengths representative of a terrestrial solar spectrum
Specular reflectance – Amount of light reflected from a mirror surface into a prescribed acceptance angle

10. ACKNOWLEDGMENTS

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