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On-Sun Testing of a Heliostat Using Facets with Metallized Polymer Films

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Abstract

The 3M™ Solar Mirror Film 1100 (SMF1100) was installed on a heliostat at the National Solar Thermal Test Facility at Sandia National Laboratories. Reflectivity tests and beam quality tests were performed to evaluate the soiling rate and impact of specularity of the SMF1100 at long focal distances relative to a heliostat with silvered-glass facets. Results showed some differences in the reflective properties between SMF1100 and silvered-glass, but the size and shape of the projected beams were similar. The total power projected from the SMF1100 heliostat was ~8 – 13% less than the adjacent silvered-glass heliostat, and the peak flux from the SMF1100 heliostat was also lower than the peak flux from the silvered glass mirror. Factors that may have contributed to this difference include a lower reflective area of the SMF1100 heliostat (3 – 4%), lower specular reflectivity (~1% for clean samples, an additional ~4 – 6% for soiled samples in the field, possibly due to longer field exposure), and different heliostat locations and aim points. The soiling rate of the SMF1100 was found to be similar to that of silvered glass over the first month of testing.

1. Introduction

The cost of the collector field (heliostats) for central receiver systems can comprise 40-50% of the total levelized cost of electricity for the plant [1]. Therefore, efforts are being made to reduce the costs associated with heliostat materials, shipping, and production. In this paper, a metallized polymer film is investigated as an alternative to traditional silvered glass mirrors for heliostat facets.

Reflective polymer films based on an acrylic substrate, with silver as the reflective layer, have been evaluated in the past. In the 1980's, Alpert et al. [2] performed optical tests of the first prototype stretched-membrane mirror module using 3M™ ECP-300, a silvered-acrylic film. The solar-weighted reflectivity of the ECP 300 film was reported to be 93 – 94%. Results of the on-sun testing of the ECP 300 showed that the quality (size and shape) of the reflected beam was at least as good as from glass mirror designs. Although Alpert et al. [2] reported that the reflective surface was generally in good condition after two years of exposure, the solar-weighted reflectivity had reduced to ~90%, and delamination of the film had begun with progressive deterioration. In this paper, we evaluate a new commercially available silvered acrylic film, SMF1100, which is an improved version of 3M™ ECP-305+ from the early 1990s.

1.1. Description of SMF 1100

The 3M Solar Mirror Film 1100 (SMF1100) is a silver metallized, lead-free, weatherable acrylic film. It has a solar-weighted total hemispherical reflectance of 94%, a specular reflectance of >95% [3] (Devices & Services 15R using 25 mrad at 660 nm), and is designed for use in concentrating solar collectors [4]. A pressure-sensitive adhesive allows application to smooth substrates. Some benefits marketed by the manufacturer include high reflectance, less weight (potentially enabling lower cost sub-structure designs), and improved mechanical properties. An early prototype of SMF1100 (ECP 305+) has been exposed to outdoor testing at the National Renewable Energy Lab (NREL) since 1995 with less than 3% loss in total hemispherical reflectance (Figure 1).

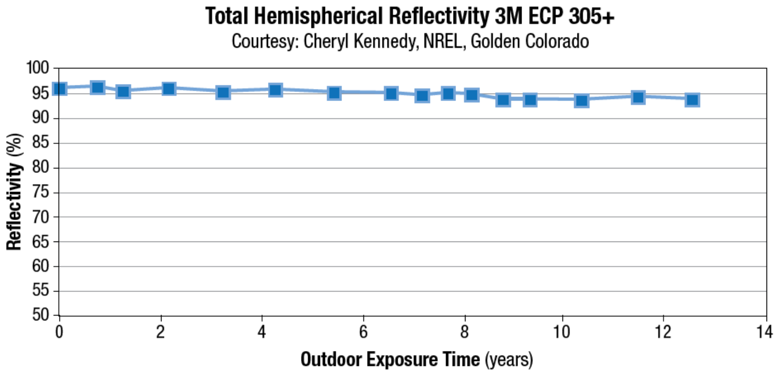

Figure 1. Total hemispherical reflectivity of 3M ECP 305+ film as a function of outdoor exposure time [4].

2. Approach

SMF1100 is being tested using a heliostat at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories in Albuquerque, NM. In November of 2010, panels of SMF1100 were retrofit onto a heliostat with 30-year-old glass mirrors as a means to restore the reflectance of the mirrors (Figure 2). The SMF1100 mirror film was applied to a 0.508 mm (0.020”) painted aluminum substrate with an acrylic adhesive on the back side of the aluminum substrate. Both laminations were performed under controlled conditions at 3M. This panel could then be more readily laminated to the existing glass mirror facets in the field on site. The panels were shipped to Sandia for installation on a 25-facet heliostat, located in the 12th row, 14^{th} heliostat position west of center (12W14) (Figure 2). Each 1.22 m x 1.22 m (48” x 48”) mirror facet on the heliostat is fairly flat, with only a very slight parabolic circular curvature of approximately 200 m focal length. However, the SMF1100 film covered only 1.22 m (48” vertically) and 1.19 m (47” horizontally) of the old mirror facets and tape was used to seal the edges, reducing the reflective area by 3 – 4%.

The SMF1100 with an aluminum substrate and pressure-sensitive adhesive was laminated directly onto the original mirrors, eliminating the need to remove the original glass substrates and dispose of the original mirrors (which contained lead). The entire support structure of the original heliostat remained intact. After cleaning the original mirrors, the adhesive liner was removed from the top edge of the mirror panel. The SMF1100 panel was aligned to the glass mirror and tacked into place. The remainder of the adhesive liner was removed as hand rollers were used to secure the panel in place. Two people were required per mirror facet installation. For the bottom row, lamination was performed while standing on the ground. A scissor power lift was used for the other four rows of facets. A crew of five (two laminators for bottom row and one lift operator plus two laminators for other rows) completed the lamination of 25 facets in less than two hours. It should be noted that two of the glass mirrors were cracked with some voided surface. These defects did not print through the new panel lamination.

The final two steps of the installation were to remove the protective liner from the SMF1100 surface and to apply 3M™ Weather Resistant Film Tape 838 to the edges of the panels as protection against moisture ingress over the lifetime of the panels. The bottom edge was taped first, followed by the two sides, and finishing with the top edge. This was done so that any moisture would not be trapped under a tape joint in the corners. A crew of three people completed the process in less than two hours.

Reflectivity and specularity measurements of the SMF1100 facets were taken with both Device & Services 15R and Surface Optics 410 Solar reflectometers. These values are compared with those of silvered-mirror facets on nearby heliostats as a function of time. In addition, the beam quality of the heliostat with SMF1100 is evaluated using a beam characterization tool [5]. The beam shape, peak flux, and total power are compared against another adjacent silvered-glass mirror heliostat immediately to the east in the field (12W13).

Figure 2. Left: heliostat 12W14 at the NSTTF in Albuquerque, NM, which was retrofitted with 3M™ Solar Mirror Film 1100. Right: NSTTF heliostat field with location of 12W14 heliostat circled.

3. Results

3.1. Reflectivity

The total and specular reflectivity of the SMF1100 was measured using the Surface Optics 410 Solar reflectometer. The 410 Solar measures the reflectivity in seven spectral bands from 335 – 2500 nm at a 20 degree incidence angle. The beam spot size is 6.35 mm in diameter with a 6° (105 mrad) cone angle for specular measurements. The solar weighted reflectivity is also calculated from these data using an air mass index of 1.5. In addition, the Device & Services (D&S) 15R reflectometer was used to measure the specular reflectivity of the SMF1100 at 660 nm using a 10 mm beam (spot size) with aperture acceptance angles of 15 and 25 mrad (receiver aperture diameters of 0.81 mm and 1.4 mm, respectively). A total of six measurements were taken at different locations (center and corner) on each of 10 facets (top and bottom row of the heliostat) using both the 410 Solar and 15R (Figure 3).

The solar-weighted specular reflectivity of the SMF1100 averaged over 10 facets measured on 6/6/11 after nearly seven months of outdoor exposure on the heliostat was 0.84 ± 0.069 (± one standard deviation), while the solar-weighted specular reflectivity of the adjacent 12W13 heliostat using 3-mm silvered glass on 7/6/11 was 0.90 ± 0.012 after nearly five months of exposure.[1] Small portions of each SMF1100 facet were cleaned using a liquid glass cleaner and a cloth wipe. The solar-weighted specular reflectivity of the cleaned spots increased to 0.91 ± 0.02. It should be noted that small scratches on the SMF1100 were observed where the spots were wiped clean.

The total hemispherical solar-weighted reflectivity of the SMF1100 averaged over the 10 facets before and after cleaning was 0.92 ± 0.01 and 0.93 ± 0.01, respectively. This indicates that the specular reflectivity of the SMF1100 can be significantly lower than the total hemispherical reflectivity, especially when soiled. Measurements of the reflectivity of clean samples of both SMF1100 and silvered glass revealed that the total hemispherical reflectivity at 660 nm was higher for the SMF1100 (Figure 4). The specular reflectivity at 660 nm of cleaned samples was measured to be lower for the SMF1100 using the D&S reflectometer. In addition, when the aperture setting was reduced from 25 mrad to 15 mrad on the D&S reflectometer, the measured specular reflectivity of the SMF1100 was reduced by 3.4% (from 95.1% to 91.9%) while the specular reflectivity of the glass samples was reduced by only 1.1% (from 97% to 95.9%). Thus, more scattering occurs from the SMF1100 within a 15 – 25 mrad cone angle about the reflected beam.

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[1] The specular and total hemispherical reflectivity of the SMF1100 was measured a month later after there had been some slight rain during the weeks following the initial measurements. The specular and total hemispherical solar-weighted reflectivity averaged over three measurements on each of five facets on 7/6/11 was 0.86 ± 0.026 and 0.93 ± 0.014, respectively, similar to the measurements taken on 6/6/11. The specular and total hemispherical solar-weighted reflectivity of the adjacent 12W13 heliostat using 3-mm silvered glass on 7/6/11 were 0.90 ± 0.012 and 0.94 ± 0.0026, respectively.

Figure 3. Reflectivity measurements of the SMF1100 facets on the 12W14 heliostat using the 410 Solar (left) and D&S 15R reflectometers.

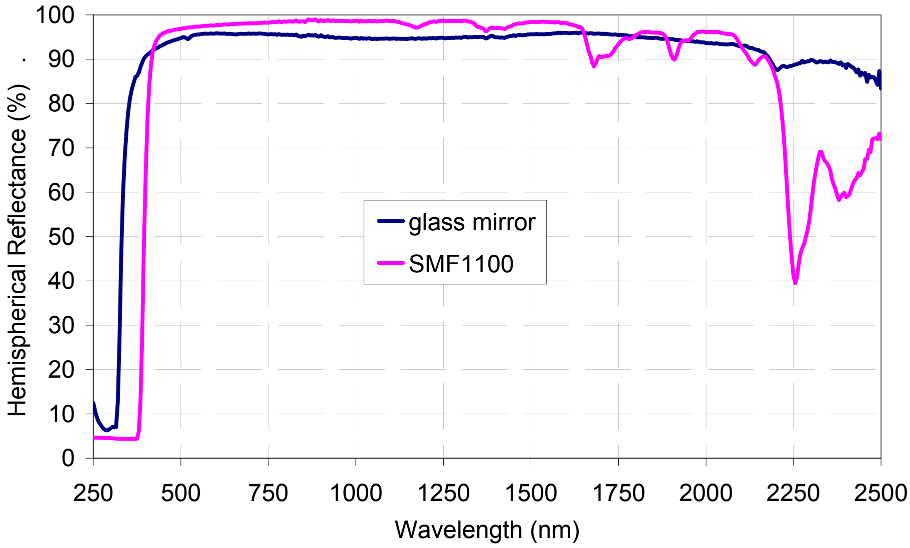

Figure 4. Total hemispherical reflectance of SMF1100 and silvered glass mirror using Perkin Elmer Lambda 1050 with 6" integrating sphere.

The rate of soiling of SMF1100 relative to second-surface glass mirrors was also evaluated by measuring the specular and total hemispherical reflectivities of different mirror samples affixed to a sawhorse. The mirror samples consisted of the SMF1100 film and three different thicknesses of 2^{nd}-surface glass mirrors (1 mm, 3 mm, and 4 mm). Samples of each mirror type were affixed to the sawhorse in both the face-up and side-facing position (pointing south). Daily measurements (except on weekends) were taken using both the 410 Solar and D&S 15R reflectometers, and the normalized reflectivities (fraction of clean reflectivity) were reported (Figure 6 and Figure 7). Results showed that during the first 30 days of exposure, the SMF1100 did not show significant differences in soiling rates relative to the glass mirrors. The total hemispherical reflectivity for all samples remained above ~97% of the clean total reflectivity for the side-facing samples, and above ~95% of the clean total reflectivity for the face-up samples. The measured specular reflectivity of the samples was more variable, ranging from ~90 – 97% of the clean specular reflectivity for the side-facing samples, and from ~70 – 95% for the face-up samples (~92 – 95% for the SMF1100 face-up sample). As shown in the left photo of Figure 5, distinct spots of soiling were evident following episodes of light rain, which caused significant variability in the measured specular reflectivities. Additional measurements are ongoing and will be evaluated to determine if distinctive trends can be observed among the glass-mirror samples and SMF1100 film.

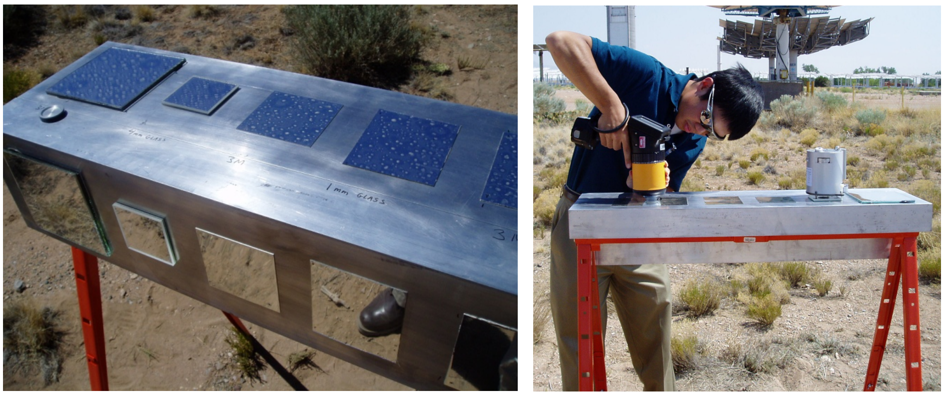

Figure 5. Left: mirror samples affixed to sawhorse. Right: measuring reflectivity of samples.

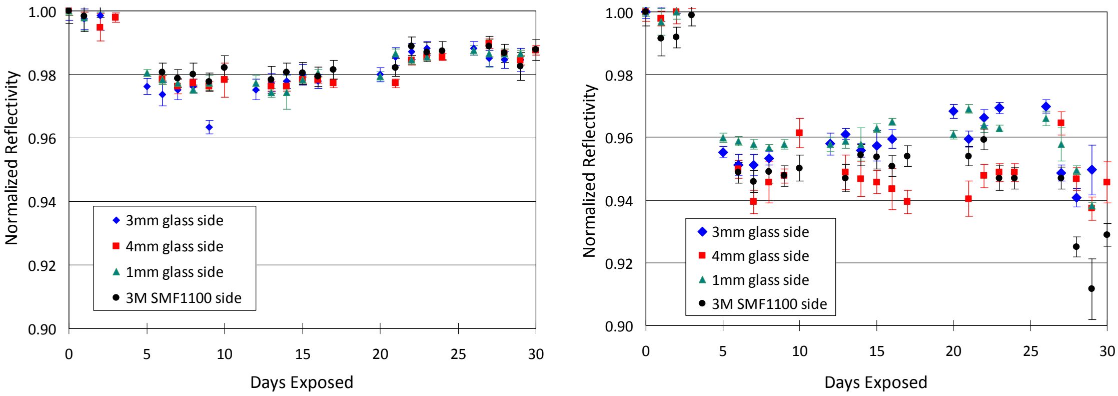

Figure 6. Normalized reflectivities (fraction of clean reflectivity) measured with the 410 Solar as a function of exposure time for <u>side-facing</u> samples. Left: total hemispherical solar-weighted reflectivity. Right: specular solar-weighted reflectivity.

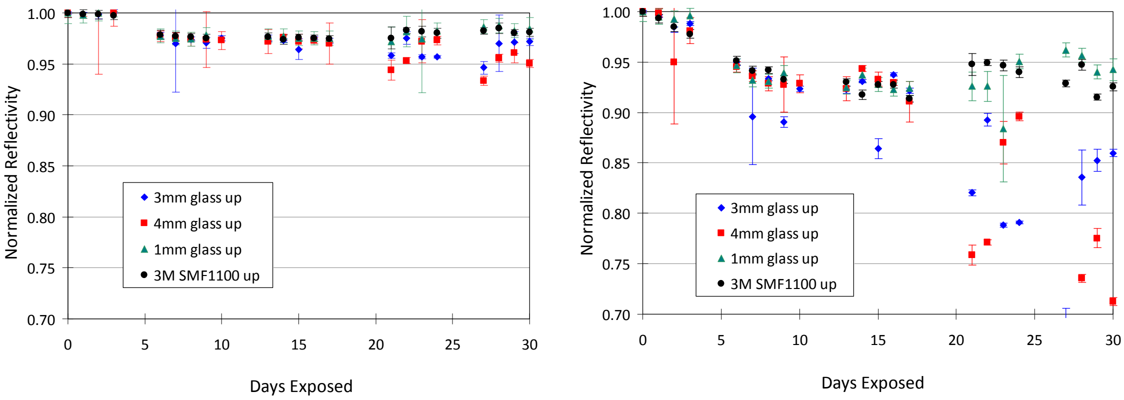

Figure 7. Normalized reflectivities (fraction of clean reflectivity) measured with the 410 Solar as a function of exposure time for <u>face-up</u> samples. Left: total hemispherical solar-weighted reflectivity. Right: specular solar-weighted reflectivity.

3.2. Beam Characterization

The quality of the beam produced by heliostat 12W14 with SMF1100 was evaluated by projecting the beam onto the face of the tower, which was nearly 200 m away. The adjacent heliostat, 12W13, which used silvered-glass mirrors (3 mm 2nd surface), was also used to project a beam to the tower for comparison. Figure 8 shows photographs and flux maps of the projected beams from 12W14 (top beam) and 12W13 (bottom beam) at three different times during the day on July 6, 2011. Results show that the shape and size of the beam projected by SMF1100 are similar to those of the beam produced from silvered glass (the facets from both heliostats were canted and focused to the same location on the tower).

The peak flux from the SMF1100 heliostat was lower than the peak flux from the silvered glass mirror. Factors that may have contributed to this difference include the smaller reflective area, lower specularity, increased soiling with longer ourdoor exposure, and different heliostat locations and aim points. The total reflective area of the SMF1100 heliostat was less than the silvered-glass heliostat because of the reduced horizontal dimension of each facet (1.19 m vs. 1.22 m) and the tape that was used to seal the edges, but the difference in total area is estimated to be 2-4%. The average solar-weighted specular reflectivity of the SMF1100 at the time of testing (~84-86%) was about 5-6% lower than that of the silvered-glass mirrors, which was around 90%, as measured by the 410 Solar reflectometer. Given testing of both initial total reflectivity and soiling rates showed little difference, this reduction in total reflectivity may be related to additional field exposure of SMF1100. Additional scattering (within the 105 mrad cone angle of the 410 Solar reflectometer) may also reduce the peak flux of the SMF1100 beam. The different locations and aim points of the two heliostats can alter the peak flux significantly (10% or more according to ray-tracing simulations). Finally, it should be noted that although the direct normal irradiance (DNI) was approximately between 800 and 900 W/m^2 during the test, the presence of high clouds may have reduced the DNI (and hence peak flux) during the time the photos were taken.

Tests were also conducted on 6/30/11 and 7/1/11 in which the beams from both the SMF1100 (12W14) heliostat and the silvered-glass heliostat (12W13) were pointed at the same location on the tower (toward a Vatell Thermogage flux tranducer with an accuracy of ±3%) in succession. The total power was calculated based on the measured flux and the scaled pixel values in the camera image. Results showed that the total power projected from the SMF1100 heliostat (~20 – 30 kW) was ~8 – 13% lower than the total power projected from the silvered-glass heliostat, depending on the time of day. Because the reflective area of the SMF1100 heliostat is estimated to be 3 – 4% less than that of the silvered-glass heliostat, the remaining difference in projected power is attributed to the reduced specular reflectance of the SMF1100.

3.3. *Cost*

SMF1100 is a thin, lightweight mirror film originally designed for CSP trough applications. A film based mirror can provide a large aperture trough with a continuous mirror surface, eliminating the segmentation of the mirror. SMF1100 mirrors have been demonstrated in very large aperture (10 meter) parabolic trough configurations, providing high intercept factors [6]. The combination of large, continuous mirrors can result in a 14% reduction in the cost of a solar mirror film, based on the Andasol-1 50MW power plant near Aldiere, Spain [7].

In heliostat applications, the same design flexibility of SMF1100 that is advantageous for parabolic trough applications may also be relevant:

1) Lower weight and high stiffness panels to reduce cost and drive requirements
2) Continuous mirror surfaces to minimize edge effects
3) New reflector configurations amenable to high volume stamping processes

At Sandia National Laboratories' National Solar Thermal Test Facility, the cost was limited to the SFM1100 mirror panel cost and the installation. Since the original glass mirrors remained in place, the cost of removal and disposal of the lead-containing mirrors was avoided.

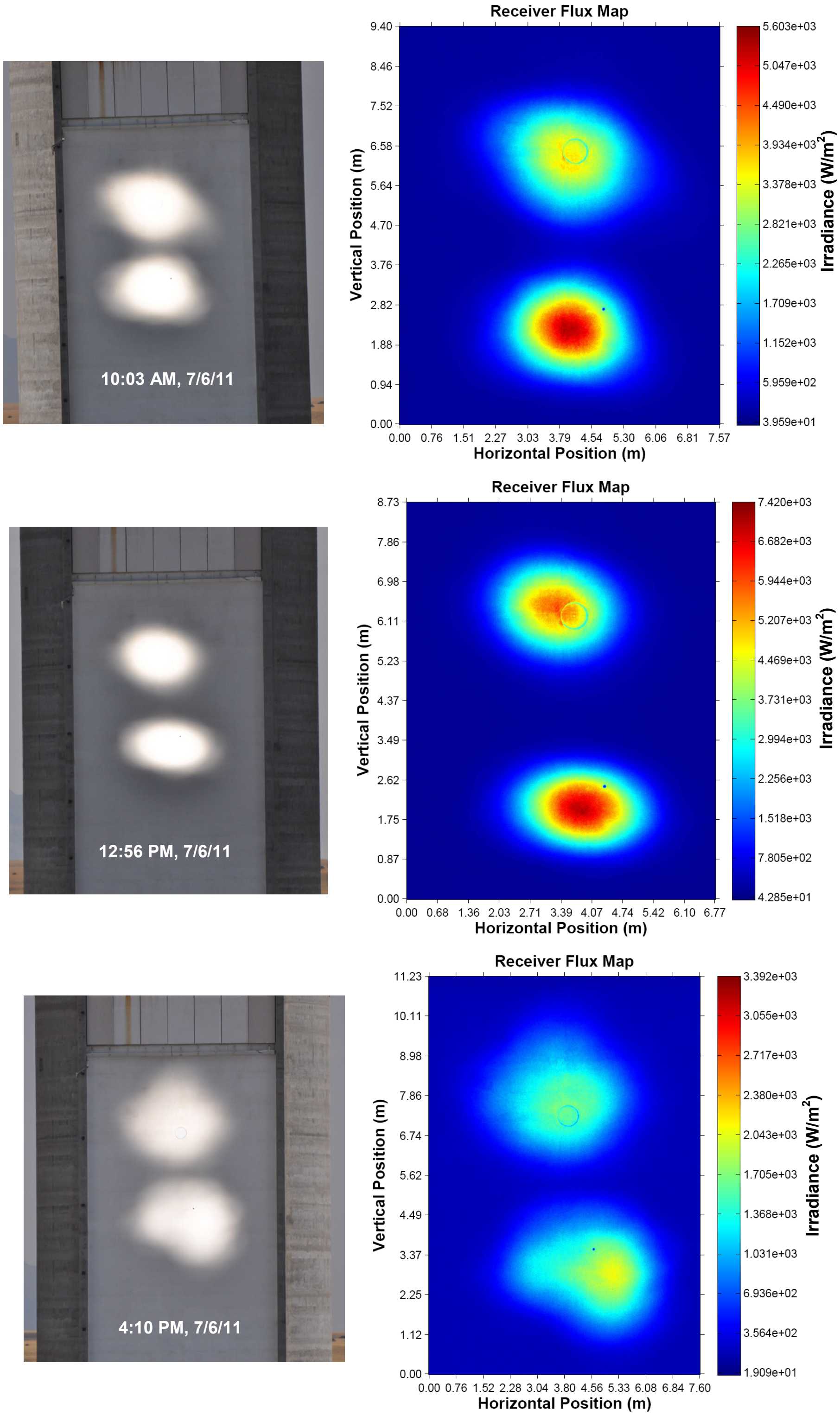

Figure 8. Photographs and flux maps of heliostat-reflected beams on the face of the tower on July 6, 2011, at 10:03 AM (top), 12:56 PM (middle), and 4:10 PM (bottom) (Mountain Daylight Time). The beam on top is from heliostat 12W14 (3M SMF1100), and the beam on the bottom is from heliostat 12W13 (3 mm silvered glass).

4. Conclusions

The 3M Solar Mirror Film 1100 (SMF1100) was installed on a heliostat at the National Solar Thermal Test Facility at Sandia National Laboratories. Reflectivity tests and beam quality tests were performed to evaluate the soiling rate and impact of specularity of the SMF1100 at long focal distances relative to a silvered-glass heliostat. The soiling rate of SMF1100 was found to be similar to that of silvered glass over the first month of testing, but the specularity of SMF1100 was lower than the silvered-glass mirror, possibly due to longer field exposure. In the beam tests, the size and shape of the projected beams were qualitatively similar. However, the total power projected from the SMF1100 heliostat was ~8 – 13% less than the adjacent silvered-glass heliostat, and the peak flux from the SMF1100 heliostat was also lower than the peak flux from the silvered glass mirror. Factors that may have contributed to this difference include a lower reflective area (3 – 4%), lower specular reflectivity (~1% for clean samples, an additional ~4 – 6% for soiled samples in the field), and different heliostat locations and aim points.

Acknowledgments

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