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Evaluation of a reflective polymer film for heliostats

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Abstract

Commercially available Solar Mirror Film (SMF) 1100 from 3M was evaluated for application in concentrating solar power tower applications, where large arrays of heliostats are used to reflect and concentrate sunlight toward a central receiver at potentially large distances. The reflectance and soiling rate of SMF1100 was compared to silvered glass mirrors during outdoor exposure for over a year. In addition, the reflected beam quality and peak flux resulting from solar reflections from SMF1100 and silvered glass facets at distances up to ~1700 m were compared. Results showed that the impacts of soiling and outdoor exposure on the solar-weighted reflectance of coupons of SMF1100 did not differ significantly from that of silvered glass over a year of testing. However, the initial (clean) specular reflectance (at 660 nm) of SMF1100 was found to be ~2–4% lower than that of silvered glass for acceptance angles ranging from 25 mrad to 15 mrad, which contributed to a lower overall heliostat beam power projected onto the tower ~200 m away when compared to an adjacent heliostat with silvered glass. The peak flux was measured from individual facets with SMF1100 and silvered glass at distances up to ~1700 m. Slight differences existed in the focal length, specular reflectance, and time of testing of the individual facets, but results showed that the mean of the measured peak fluxes (normalized to the direct normal irradiance at the time of testing) of the SMF100 and silvered glass facets were statistically similar.

Keywords: Heliostat; Polymer film; SMF1100; Beam quality

1. Introduction

The cost of the collector field (heliostats) for central receiver systems can comprise up to ~40% of the total levelized cost of electricity for the plant (Kolb et al., 2011). Therefore, efforts are being made to reduce the costs associated with heliostat materials, shipping, production, assembly, and operation. Potential advantages of using reflective metallized polymer films over silvered glass mirrors include lower weight, easier application, larger continuous reflective area, and competitive costs.

Reflective polymer films based on an acrylic substrate, with silver as the reflective layer, have been evaluated in the past. In the 1980s, Alpert et al. (1988) 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 the quality resulting from glass mirror designs. Although Alpert et al. (1988) 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.

Improved versions of reflective polymeric films have been developed since the 1980s and 1990s and have been applied to parabolic troughs (Jorgensen et al., 2010; McMahan et al., 2010). However, unlike the parabolic troughs that have short (~1–2 m) focal lengths, large power tower plants, such as the 110 MW_e Crescent Dunes

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Solar Energy Project being constructed near Tonopah, Nevada, rely on large fields of heliostats, where the furthest heliostat can be nearly 1600 m (~1 mile) away from the tower. The ability to use reflective polymer films, which have been shown in the past to have a lower specular reflectivity (Ho et al., 2011), is uncertain at these longer distances. This paper presents the results of tests that evaluate the reflected flux distribution from facets consisting of SMF1100 and silvered glass at these longer distances. Reflectivity measurements of exposed silvered-glass and SMF1100 coupons were also recorded over a period greater than a year to evaluate the quality and durability of the polymer films.

2. Approach

SMF1100 was tested on heliostat facets 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 (Fig. 1). 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, 14th heliostat position west of center (12W14) (Fig. 1). Each 1.22 m × 1.22 m (48″ × 48″) mirror facet on the heliostat was fairly flat, with only a very slight parabolic circular curvature of approximately 200 m focal length. SMF1100 film had not been optimized for this project and covered only 1.22 m (48″ vertically) and 1.19 m (47″ horizontally) of the old mirror facets with tape used to seal the edges, reducing the total reflective area by 3–4%.

The SMF1100 with an aluminum substrate and pressure-sensitive adhesive was laminated directly onto the original mirrors. 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 2 h. 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 2 h.

Reflectivity and specularity measurements of the SMF1100 facets were taken with both Device & Services 15R and Surface Optics 410 Solar reflectometers. These values were compared with those of silvered glass as a function of time. In addition, the beam quality of the heliostat with SMF1100 was evaluated using a beam characterization tool (Ho and Khalsa, 2012). 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).

3. Results

3.1. Reflectance measurements

The total and specular reflectivity of the SMF1100 was measured using the Surface Optics 410 Solar reflectometer (Surface Optics Corporation, San Diego, CA, USA). The 410 Solar measures the reflectivity in seven spectral bands from 335 to 2500 nm at a 20° 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

Fig. 1. 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.

reflectivity is also calculated from these data using an air mass index of 1.5. In addition, the Devices & Services (D&S) 15R reflectometer (Devices & Services Co., Dallas, TX, USA) 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 D&S 15R (Fig. 2 right).

The solar-weighted specular reflectivity of the SMF1100 averaged over 10 facets measured on June 06, 2011, after nearly 7 months of outdoor exposure on the heliostat was 0.84 ± 0.069 ($\pm$one standard deviation), while the solar-weighted specular reflectivity of the adjacent 12W13 heliostat using 3-mm silvered glass on July 06, 2011, was 0.90 ± 0.012 after nearly 5 months of exposure. The difference in exposure times was caused by different installation times of the SMF1100 on 12W14 and the new silvered-glass facets being installed on 12W13 (and the rest of the field). The testing and measurements had to work around the installation schedules. Small portions of each SMF1100 facet were cleaned using a damp 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 cleaned.

The specular and total hemispherical reflectivity of the SMF1100 was measured again on July 06, 2011, after there had been some slight rain during the weeks following the initial measurements on June 06, 2011. The specular and total hemispherical solar-weighted reflectivity averaged over three measurements on each of five facets on July 06, 2011, was 0.86 ± 0.026 and 0.93 ± 0.014, respectively. The specular and total hemispherical solar-weighted reflectivity of the adjacent 12W13 heliostat using 3-mm silvered glass on July 06, 2011, were 0.90 ± 0.012 and 0.94 ± 0.0026, respectively.

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. However, the specular reflectivity at 660 nm of cleaned samples was measured to be lower for the SMF1100 using the D&S reflectometer. In addition, reducing the aperture from 25 mrad to 15 mrad on the D&S reflectometer resulted in a reduction of the measured specular reflectivity of the SMF1100 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, particularly within a 15–25 mrad cone angle about the reflected beam.

The rate of soiling of SMF1100 relative to glass mirrors was also evaluated by measuring the specular and total hemispherical reflectivities of different mirror samples affixed to a sawhorse. Fig. 2 (left and middle) shows the reflectance measurements of mirror coupons that were exposed outdoors for nearly a year using the Surface Optics 410 Solar reflectometer. The total and specular reflectivity of the SMF1100 and several silvered-glass coupons was measured on a sawhorse in both face-up and side-facing positions.

Fig. 3 shows the normalized specular reflectivity values of different silvered-glass coupons and the SMF1100 coupon as a function of days exposed for both face up and side facing orientations obtained using the Surface Optics 410 Solar reflectometer. Current results show that the SMF1100 (black dots) has not shown any accelerated degradation relative to the silvered-glass coupons. Significant fluctuations in reflectivity result from dust and particulate soiling, rain, and/or snow, and no coupon type was identifiable as having superior or inferior properties. Side-facing samples maintained significantly higher reflectivity, with no coupon type dropping below a normalized specular reflectivity value of 0.85, whereas all face-up samples reached normalized values as low as 0.70 over the course of the exposure period (Fig. 3). Continued evaluation of each sample may reveal reflectivity trends, averaged over random soiling and cleaning (rain/snow) events during exposure.

3.2. Beam characterization

Fig. 1 shows the heliostat that was used for the beam characterization tests. A beam characterization system was used to evaluate the size, shape, and irradiance of the reflected heliostat beams. The quality of the beam

Fig. 2. Left: mirror samples affixed to sawhorse. Middle: measuring reflectivity of samples on sawhorse. Right: measuring reflectivity of heliostat facets.

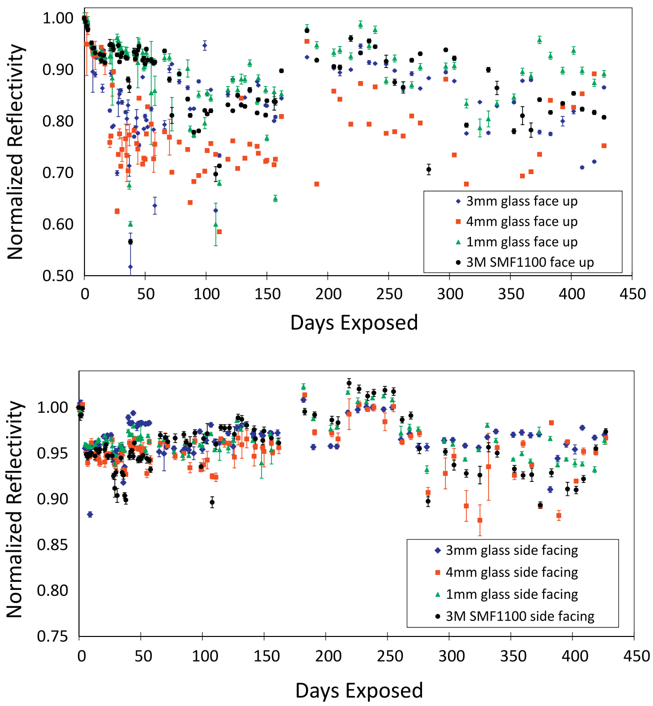

Fig. 3. Normalized specular reflectivity from face-up and side-facing silvered glass and SMF1100 coupons as a function of outdoor exposure time, measured using Surface Optics Corporation 410 Solar reflectometer.

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. Fig. 4 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 June 06, 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 outdoor 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 3–4%. The average solar-weighted specular reflectivity of the SMF1100 at the time of testing (~84–86%) was 5–6% lower than that of the silvered-glass mirrors, which was around 90%, as measured by the 410 Solar reflectometer. Given the testing of both initial total reflectivity and soiling rates showed little difference, this reduction in specular 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 June 30, 2011, and July 01, 2011, 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 1000 Series flux transducer, Vatell Corporation, Christiansburg, VA, USA, 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 likely due to the reduced specular reflectance of the SMF1100 at the time of testing, which may have been caused by longer exposure outdoors and a lower initial specular reflectance (~2%).

Fig. 5 shows additional beam testing that was performed on individual mirror facets taken from the heliostats and placed at distances up to ~1700 m away from a long-range heliostat target (LRHT) at the National Solar Thermal Test Facility (NSTTF) in Albuquerque, New Mexico. Both silvered-glass facets from heliostat 12W13 and 3M SMF1100 facets from heliostat 12W14 were used.

The long-range heliostat target (LRHT) consists of a vertical array of collimated Li-COR Li-200 pyranometers (Li-COR Inc., Lincoln, Nebraska, USA) attached to a portable 15 m tower (Sment et al., 2012). Fig. 6 shows the LRHT and a view of the solar reflection from a single facet ~1700 m away from the target. Each sensor on the LRHT was aimed at the reflected sunlight from the facet before each test. During the test, the beam was swept with a known rate across the LRHT. The resulting irradiance values from each sensor along the vertical tower were then stitched together to create a flux map of the beam. Background irradiance was subtracted from the flux maps of the beam irradiance distribution.

Fig. 7 shows the measured irradiance distribution resulting from single-facet beam tests at ~500 m away from the target. The flux maps from both the silvered glass (left image) and the SMF1100 (right image) show similar irradiance distributions with the peak flux ~80 W/m^2. The height and width of the beams are approximately ~6 m and 8–10 m, respectively. The horizontal sweep rate of the beams was controlled manually, so uncertainties in

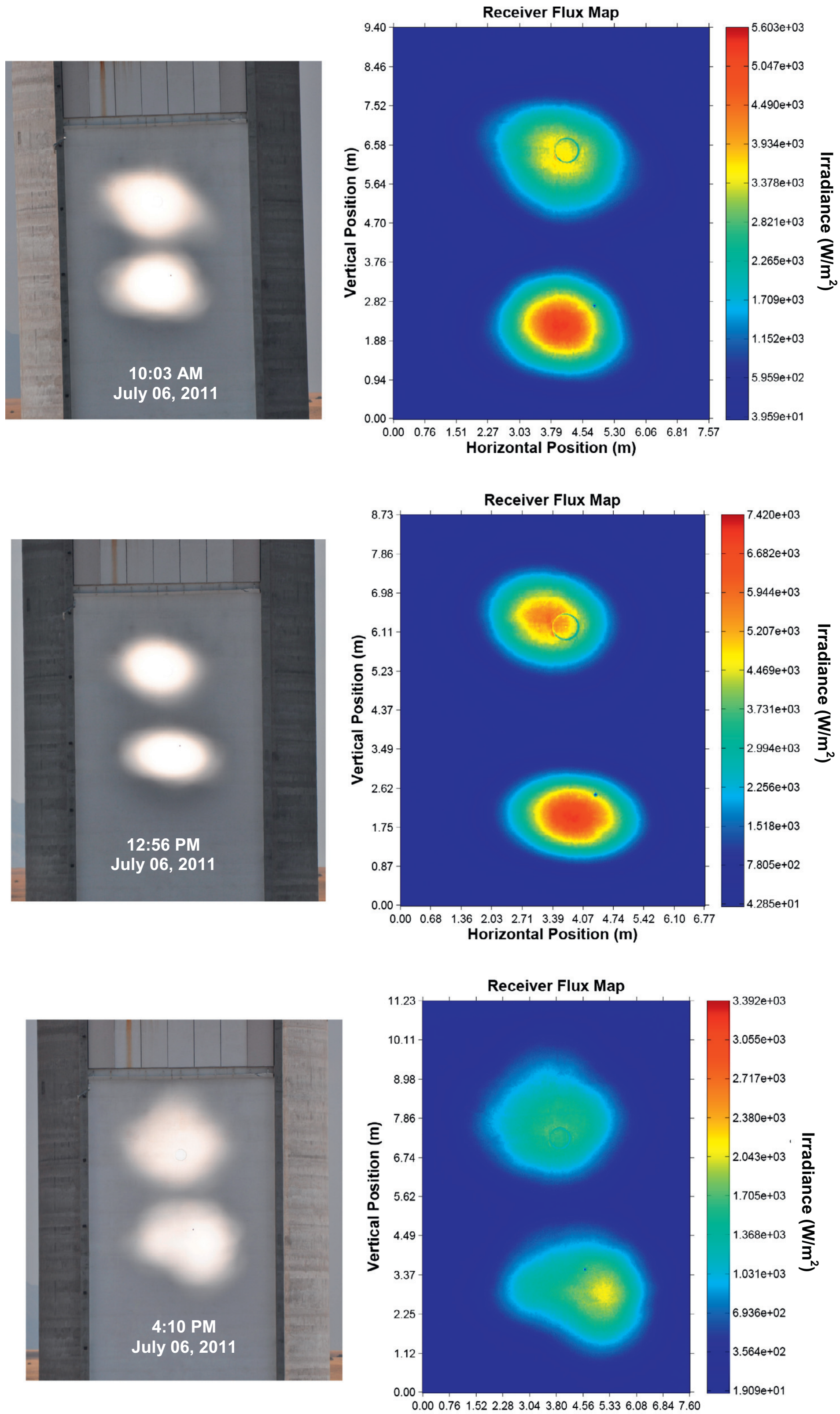

Fig. 4. Photographs and flux maps of heliostat-reflected beams on the face of the tower on July 6, 2011, at 10:03 AM (top), 12:56 PM (middle), and 4:10 PM (bottom) (Mountain Daylight Time). The beam on top is from heliostat 12W14 (3M SMF1100), and the beam on the bottom is from heliostat 12W13 (3 mm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

the width of the beam exist. Ray-tracing simulations using the commercial code ASAP (Breault Research Organization, Tucson, AZ, USA) of the silvered glass and SMF1100 facets were performed for the ~500 m test.

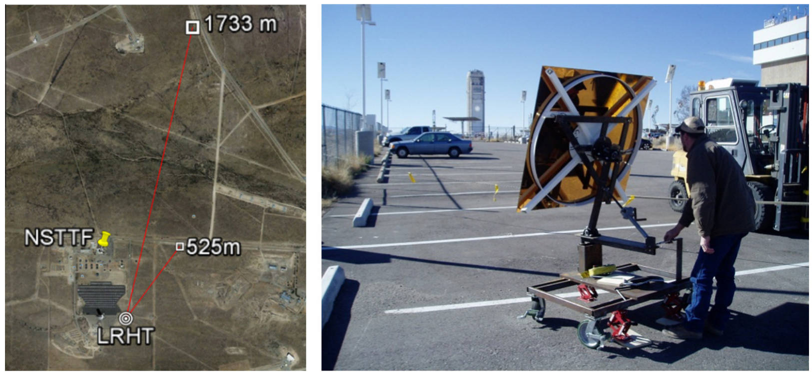

Fig. 5. Left: Map showing the locations of the single-facet beam tests at 525 m and 1733 m away from the long-range heliostat target (LRHT). Right: Rig used to hold and track the facets.

Fig. 6. Left: Long-range heliostat target (LRHT) Sment et al., 2012. Right: View from the (LRHT) looking at the solar reflection from a single facet ~1700 m away.

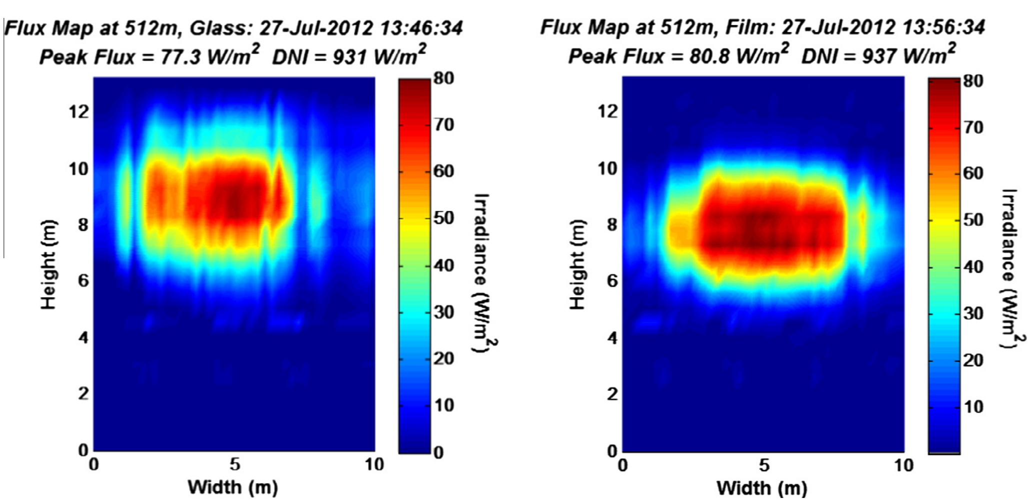

Fig. 7. Measured irradiance distribution at ~500 m from the silvered glass facet (left) and the SMF1100 facet (right). The peak flux in both cases is ~80 W/m^2.

Horizontal and vertical focal lengths and slope errors were obtained using SOFAST (Andraka et al., 2009). Solar-weighted reflectivities were measured using the 410 Solar reflectometer. A summary of the optical properties of the individual facets used in the ray-tracing simulations is shown in Table 1.

Results show that the simulated peak fluxes for both the silvered glass and SMF1100 beams were ~70 W/m^2. The size of the simulated beams was ~6 m in the vertical direction and 7–8 m in the horizontal direction. Slight differences in the simulated irradiance distributions were caused by differences in the measured facet reflectivities, slope errors, and focal lengths of the SMF1100 and silvered glass facets, but the results are similar (see Fig. 8).

Fig. 9 shows the measured irradiance distribution resulting from single-facet beam tests at ~1700 m away from the

Table 1
Measured optical properties of the silvered glass and SMF1100 facets used in the single-facet beam tests.

	Silvered glass	SMF1100
Solar-weighted reflectivity	0.92	0.88
RMS slope error	0.78	0.87
Horizontal focal length (m)	286	516
Vertical focal length (m)	2.02E+04	1300

target. The flux maps from the silvered glass (left image) and the SMF1100 (right image) show irradiance distributions with peak flux values ranging from ~7 and 8 W/m^2. The height of the beam is difficult to ascertain since the height of the target was only 15 m. However, the height of the beams appear to be ~20 m and the width of the beams are approximately ~30–40 m, respectively. Ray-tracing simulations of the silvered glass and SMF1100 facets for the ~1700 m test show that the simulated peak fluxes for both the silvered glass and SMF1100 beams were ~6 W/m^2. The size of the simulated beams was ~6 m in the vertical direction and ~20–30 m in the horizontal direction (see Fig. 10).

Fig. 11 shows the measured mean peak flux values normalized by the measured DNI during each test at 512 m and 1733 m. The error bars represent one standard deviation. A two-sample *t*-test was performed and the resulting data are shown in Table 2. Since the absolute value of the test statistic (T) is less than the absolute value of the

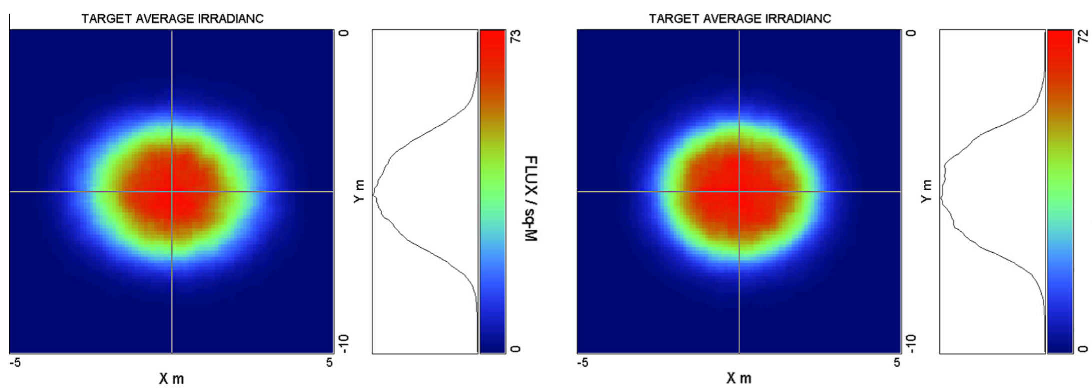

Fig. 8. Simulated irradiance distribution at ~500 m from the silvered glass facet (left) and the SMF1100 facet (right).

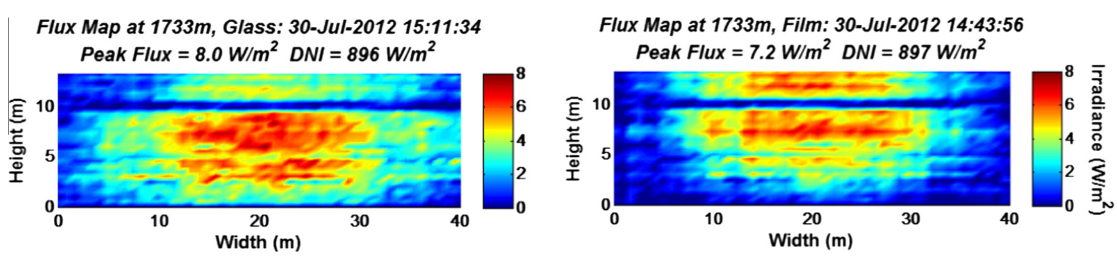

Fig. 9. Measured irradiance distribution at ~1700 m from the silvered glass facet (left) and the SMF1100 facet (right). The peak flux in both cases is ~7–8 W/m^2.

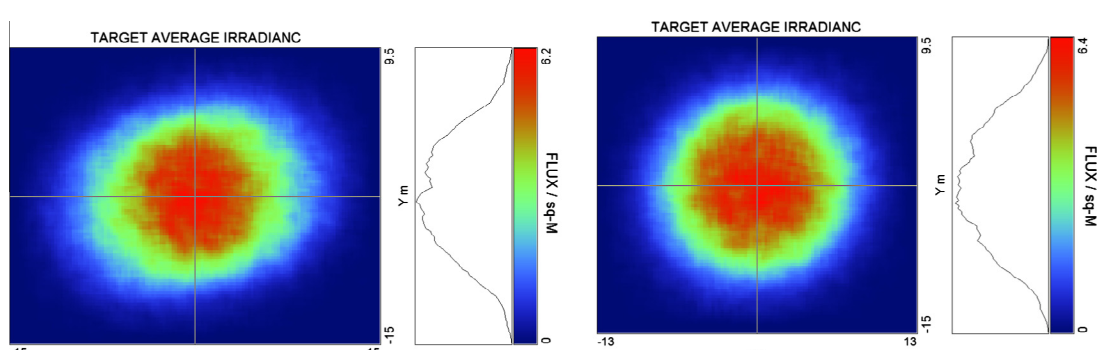

Fig. 10. Simulated irradiance distribution at ~1700 m from the silvered glass facet (left) and the SMF1100 facet (right).

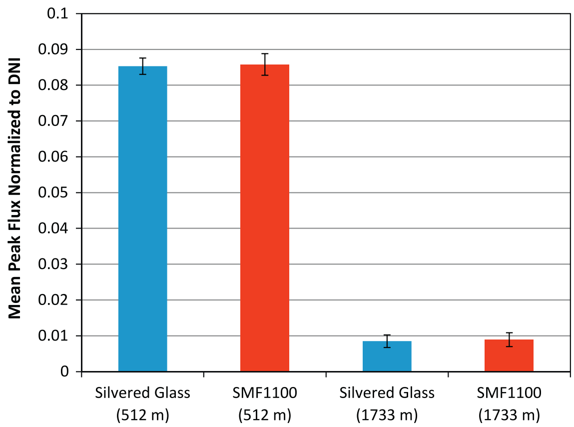

Fig. 11. Measured peak flux normalized by DNI for silvered glass and SMF1100 facets at 512 m and 1733 m.

Table 2
Summary of two-sample t-test statistics for peak flux measurements of SMF1100 and silvered glass facets at 512 m and 1733 m (Devore et al., 1982).

	Silvered glass (512 m)	SMF1100 (512 m)	Silvered glass (1733 m)	SMF1100 (1733 m)
Mean peak flux normalized to DNI	0.0853	0.0858	0.00851	0.00893
Variance	5.14E−06	9.12E−06	3.07E−06	3.65E−06
Observations	6	6	5	5
Degrees of freedom	10		8	
Test statistic (T)	0.616		1.22	
Critical t-value (two-sided, $\alpha = 0.025$)	2.23		2.31	

critical *t-value* ($\alpha = 0.05$), the null hypothesis cannot be rejected for either distance. Therefore, the normalized mean peak flux values from the silvered glass and SMF1100 can be considered statistically similar for the tests evaluated in this study (Table 2).

4. Conclusions

A commercial metallized polymer film was evaluated for use in concentrating solar power applications. 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. Reflectance measurements showed that there was no discernible difference in soiling rates between silvered glass and SMF1100 samples when exposed to outdoor conditions for over a year. However, the clean specular reflectance (at 660 nm) of SMF1100 was ~2–4% lower than that of silvered glass for subtended angles ranging from 25 to 15 mrad, respectively. Because the sizes of the reflected beam images on the targets indicated that the subtended angles of the reflected beams were close to ~15 mrad (spot size divided by distance) for the different facets and tests considered, an up to 4% reduction in beam power may be expected from the SMF1100 when compared to silvered glass.

Because the heliostats, although adjacent, were not located in the same position, peak fluxes were not quantitatively compared since optical aberrations caused by the different positions and orientations of the heliostats were different at any given time. To address this issue, flux tests using individual facets with SMF100 and silvered glass were conducted at identical locations at distances up to ~1700 m. Although slight differences existed in the focal length, specular reflectance, and time of testing of the different facets, results showed that the peak flux values resulting from solar reflections from silvered-glass and SMF1100 facets were statistically similar.

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References

Alpert, D.J., Johnson, D.K., Houser, R.M., Yellowhorse, L., VanDer-Geest, J., 1988. Optical Performance of the First Prototype Stretched-Membrane Mirror Modules, Sandia National Laboratories, SAND88-2620.

Andraka, C.E., Sadlon, S., Myer, B., Trapeznikov, K., Liebner, C., 2009. Rapid reflective facet characterization using fringe reflection techniques. In: Proceedings of ASME 2009 International Conference on Energy Sustainability ES2009-90163, San Francisco, CA, July 19–23, 2009.

Devore, J.L., 1982, Probability and Statistics for Engineering and the Sciences, Brooks/Cole Pub. Co., Monterey, Calif., xii, 640 p.

Ho, C.K., Khalsa, S.S., 2012. A photographic flux mapping method for concentrating solar collectors and receivers. Journal of Solar Energy Engineering – Transactions of the ASME 134 (4).

Ho, C.K., Ghanbari, C.M., O'Neill, M.B., Yuan, J., 2011, On-sun testing of a heliostat using facets with metallized polymer films. In: Proceedings of SolarPACES 2011, Granada, Spain, September 20–23, 2011.

Jorgensen, G., Gee, R., DiGrazia, M., 2010. Development and testing of abrasion resistant hard coats for polymer film reflectors. In: SolarPACES 2010, Perpignan, France, September 21–24, 2010.

Kolb, G.J., Ho, C.K., Mancini, T.R., Gary, J.A., 2011. Power Tower Technology Roadmap and Cost Reduction Plan, SAND2011-2419. Sandia National Laboratories, Albuquerque, NM.

McMahan, A., White, D., Gee, R., Viljoen, N., 2010. Field performance validation of an advanced utility scale parabolic trough concentrator. In: SolarPACES 2010, Perpignan, France, September 21–24, 2010.

Sment, J., Ho, C.K., Moya, A.C., Ghanbari, C.M., 2012. Flux characterization system for long-distance heliostats. In: Proceedings of SolarPACES 2012, Marrakech, Morocco, September 11–14, 2012.