# Durability of Front Surface Solar Reflectors

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## ABSTRACT

Concentrating solar power (CSP) technologies use large mirrors to collect sunlight to convert thermal energy to electricity. The cost of the solar collector technologies needs to be reduced by half to achieve the long-term U.S. Department of Energy (DOE) Solar Program goals of developing parabolic trough power plants, power towers, and dish-Stirling systems capable of competing on a cost-competitive basis with conventional fossil power technologies. For mirrors, this is accomplished through technology advances by moving from heavy glass mirror reflectors to lightweight reflectors such as thin-glass, polymer, and front-surface mirrors that include surface coatings to reduce soiling. Commercialization of CSP technologies requires developing advanced reflector materials that are low cost and maintain high specular reflectance for lifetimes of 10 to 30 years under severe outdoor environments. Front-surface reflectors are a high-performance option for the glass mirrors currently used in CSP applications. The reflectors use a silvered substrate protected by an alumina hardcoat deposited under high vacuum by ion-beam-assisted deposition (IBAD). Samples have been produced on a laboratory roll-coater onto a 30.5-cm-wide chrome-plated carbon-steel web with an alumina deposition rate above 20 nm/s while maintaining high optical performance and durability. Materials undergoing testing have demonstrated high reflectivity after more than 6 years of accelerated and outdoor weathering. The results of the durability testing will be described.

## INTRODUCTION

Concentrating solar power (CSP) systems concentrate the thermal energy of the sun with different mirror configurations to drive a steam turbine or heat engine. The turbine or engine then drives a generator to produce electricity. CSP technologies (i.e., parabolic troughs, power towers, and dish-engine systems) have been dormant since 1993 due to low energy prices, but several new projects are now being developed or constructed. Recent siting studies show that CSP systems deployed at sites in the southwestern United States with high direct-normal solar resource potential and low slope (<1%), excluding environmentally sensitive lands and urban areas, would provide several times the total U.S. electric power generation. Opportunities are emerging for deploying CSP systems in the Southwest United States. More than half the states have adopted green power requirements in the form of renewable portfolio standards (RPS) and renewable energy mandates. These state RPS mandates have successfully jump-started desirable growth in the generation and use of renewable power. In the United States, construction was completed in December 2005 on a 1-MW parabolic trough power plant in Arizona and construction is scheduled to be completed on a 64-MW parabolic trough plant in Nevada in April 2007. Two 20-year power purchase agreements (PPAs) were signed in 2005 to construct 800 MW of solar dish-Stirling projects in Southern California over a 4-year period, with options to expand to 1.75 gigawatts (GW). Realistically, CSP could reach hundreds of GW in the Southwest, or greater than 10% of U.S. electric supply. The Western Governors Association estimates that 4 GW of new CSP plants could be built in the United States by 2015 [1].

Although the potential markets in the United States are large, the developing worldwide markets for CSP could reach hundreds of GW by 2040. Two identical 50-MW parabolic trough plants are being built in Spain (where there are special solar premiums), with at least two more planned. The first commercial 11 MW power tower was completed in Spain; construction of a second 20-MW tower began last year. There are plans to build a 500-MW trough plant in Israel. In Australia, three concentrating photovoltaic (CPV) dish power stations were completed in 2005, with rated output totaling 720 kW, while generating 1,555 MWh/yr. The construction of a new $420 million, 154-MW CPV heliostat power station in northern Australia was announced in October 2006; the project will connect to the national electricity grid and generate 270 GWh per year, enough for more than 45,000 homes. The International Energy Agency (IEA) projects that the installed capacity will more than double because worldwide demand for electrical power is increasing. More than half the capacity will be in developing countries, principally in areas with good solar resources, limited fossil fuel supplies, and lacking a power distribution network. From a current total installed capacity of 355 MW, the annual installation rate is estimated to reach 970 MW/yr by 2015 (with a total installed capacity of 6,454 MW) and 4.6 GW/yr by 2025 [2].

CSP technologies are capital intensive—about half the total capital cost will be invested in the solar collectors for the first commercial power plants. The reflectors represent about 30% of the collector cost. However, the potential impact of reflector cost can be ~50% of the cost of a dish or heliostat and >75% of the cost of a trough collector because structural and reflector costs are closely related. The cost of the solar-collector technologies needs to be reduced by half to achieve the long-term goal of developing CSP plants capable of competing on a cost-competitive basis with conventional fossil power technologies as dispatchable intermediate power generation in the wholesale power market (levelized energy cost [LEC] of \$0.04–\$0.06/kwh). Thus, improved solar reflectors play an important role in achieving the required cost reductions (2–4X) for solar collectors. Optimized designs, volume production, and increased competition should help reduce prices. In the longer term, further cost reduction can be achieved through technology advances. For mirrors, this is accomplished by moving from heavy glass mirror reflectors to lightweight front-surface reflectors that include surface coatings to reduce soiling.

The widespread application of CSP generation depends, in part, on developing a durable, low-cost reflector. The DOE CSP Program's goals are for an advanced solar reflector with specular reflectance above 90% into a 4-mrad half-cone angle that survives for at least 10 years under outdoor service conditions, with a large-volume manufacturing cost of less than \$10.76/$m^2$ (\$1/$ft^2$) [3]. Unofficially, more aggressive goals of 95% reflectivity and a 15–30-year lifetime have been advanced. Adjusting for inflation, the cost goal would be equivalent to \$15.46/$m^2$ (\$1.44/$ft^2$) when corrected from 1992 to 2006 dollars [4]. In addition, CSP systems must operate reliably for decades under extremely harsh environmental conditions, which include solar ultraviolet (UV) irradiance, wind, rain, blowing sand, soiling, and high and low temperatures. This constitutes a formidable challenge in manufacturing low-cost, highly durable front-surface reflectors.

## FRONT-SURFACE MIRRORS

The architecture of a typical front-surface mirror (FSM) is shown schematically in Figure 1. In practice, an FSM requires a dense, protective dielectric layer a thousand times thinner than standard thin-glass mirrors (1 mm thick) that provides corrosion protection and abrasion resistance to survive exposure to the environment. Silver is the preferred reflective layer because it provides the maximum specular reflectance across the solar spectrum (300 - 2500 nm), although aluminum can also be used. Good adhesion between the overcoat, silver layer, and back protective coating or substrate is a necessity. In many cases, the bond between silver and the oxide overcoat is poor, and very thin (1 – 10 nm) adhesion-promoting interlayers can improve the adhesion of the oxide to the silver, which results in improved durability. Silver transmits light around 320 nm; therefore, back layers can provide UV screening or act as adhesion-promoting layers if the substrate requires it. The substrate must be highly specular and suitable for direct deposition with good adhesion by a wide-web roll-to-roll or batch coating process. Candidate substrates considered include polyethylene terephthalate (PET, polyester) film, aluminum, stainless-steel foil, and stainless-steel foil leveled to provide a specular surface. An antisoiling layer (such as $TiO_2$) can be added to the outer surface to prevent soil from adhering to the reflector and could lower the operating and maintenance costs by decreasing the frequency of mirror cleaning.

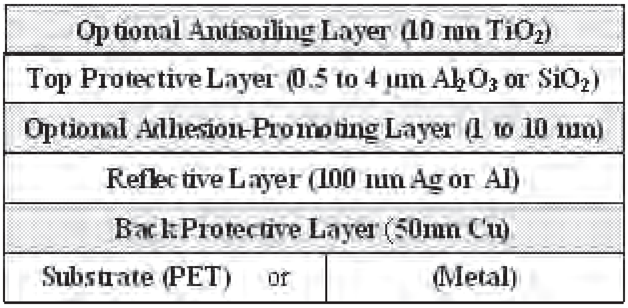
Optional Antisoiling Layer (10 nm $TiO_2$)
Top Protective Layer (0.5 to 4 μm $Al_2O_3$ or $SiO_2$)
Optional Adhesion-Promoting Layer (1 to 10 nm)
Reflective Layer (100 nm Ag or Al)
Back Protective Layer (50nm Cu)
Substrate (PET) or (Metal)

*Figure 1: Architecture of FSM. Modified ASRM uses adhesion-promoting interlayer and antisoiling top-layer. Original ASRM did not include these additional layers.*

## TECHNICAL APPROACH

All candidate materials were optically characterized prior to exposure testing and as a function of exposure time to assess optical durability. The hemispherical reflectance of the samples from 250 - 2500 nm was measured using a Perkin-Elmer Lambda 9 or 900 UV-VIS-NIR spectrophotometer with a 60-mm, integrating-sphere attachment. The direct-normal air-mass 1.5 (DIRNOR15) solar-weighted hemispherical reflectance was calculated from data collected in the 250 - 2500 nm range [5,6]. The specular reflectance was measured at 7- and 25-mrad cone angle with a Device and Services (D&S) Field Portable Specular Reflectometer at 660 nm.

Outdoor exposure testing (OET) is performed in Golden, Colorado (NREL); Miami, Florida (FLA); and Phoenix, Arizona (APS) at meteorologically monitored sites, but screening is typically only done at NREL. Historically, OET was also performed at Daggett, California (BAR); Sacramento, California (SMUD); and Ft. Davis, Texas (TX) until the sites were taken out of service. The time interval between successive characterizations was typically 1, 3, 6, 9, and 12 months during the first year of exposure and every 36 months thereafter. Field-weathered samples can be measured both before and after appropriate cleaning to provide information about soiling and ease-of-cleaning properties of candidate materials.

Accelerated exposure testing (AET) was performed in Golden, Colorado, in an Atlas Ci65A (Ci65) and Ci5000 (Ci5000) Weather-Ometer (WOM), and a 1.0-kW solar simulator (1.0kW-SS), which allow the control of exposure temperature and ambient humidity. The Ci65 uses a xenon-arc light source with filters designed to closely match the terrestrial air-mass 1.5 solar spectrum and operates continuously at 60°C and

60% relative humidity (RH), with light levels about equal to outdoor exposure. A single day (24 hours) of testing is roughly equivalent to three times the outdoor exposure in terms of light intensity. The Ci5000 operates continuously at 60°C and 60% RH, with light levels about twice that of outdoor exposure. A single day (24 hours) of testing is roughly equivalent to six times the outdoor exposure in terms of light intensity. The 1.0kW-SS uses filtered xenon-arc light sources and can achieve intensities of about five times the outdoor exposure with wavelengths between 300 and 500 nm, and it operates at 80°C and 80% RH.

Optical durability test results are presented graphically as plots of optical performance versus exposure time under specified environmental conditions (for accelerated test chambers) or location (for outdoor sites). The solar-weighted hemispherical reflectance (SWV) is plotted as a function of total UV dose outdoor exposure. The total annual UV dose is calculated from averages of the solar data and the spectral measurements. The total annual UV dose is equivalent to 280 MJ/m$^2$ per year at FLA, 330 MJ/m$^2$ per year at APS and NREL, 1030 MJ/m$^2$ per year for the Ci65, and 2060 MJ/m$^2$ per year for the Ci5000. The primary gridlines divide the total UV dosage by 330 MJ/m$^2$ per year (or multiples of 330), and a secondary x-axis above the graph shows the corresponding equivalent NREL exposure time in years. “NREL exposure year” is used for the label when the exposure is only outdoors at NREL, and “equivalent NREL exposure year” is used when the samples are exposed at a combination of the WOMs and/or different outdoor sites.

## FRONT-SURFACE MIRROR DURABILTY

The basic design of isolating the silver between impervious dielectric layers to prevent silver corrosion from water and other corrosion initiators was recognized in the early 1980s as having high potential, but the difficulty has been to find a durable top-coating. Optical durability tests of candidate FSMs obtained from industry, fabricated through subcontracts, and prepared in-house refined the desired properties for an oxide protective layer and provided confidence that this construction could meet the CSP optical durability requirements. Protective inorganic oxide overcoat materials such as alumina ($Al_2O_3$) and silica ($SiO_2$) films deposited by IBAD and pulsed D.C. sputtering have shown a high probability of success.

### IBAD $Al_2O_3$ Protective Layer

NREL funded Science Applications International Corporation (SAIC) to develop a low-cost reflector material. This advanced solar reflective mirror (ASRM) has a silvered specular substrate protected by an alumina ($Al_2O_3$) coating several microns thick deposited by IBAD. Samples of the ASRM were produced by batch and continuous roll-coating processes on PET, PET laminated to stainless-steel foil, and chrome-plated carbon-steel substrates. The steel substrate has the advantage that it can withstand higher deposition temperatures and potentially has lower collector installation costs. Crucial to the ASRM durability is that alumina coatings deposited with the proprietary reactive-ion gas did not crack, unlike alumina coatings produced by oxygen-ion bombardment that did crack. The initial alumina deposition rate was 1 nm/s, and four 15.2-cm$^2$ samples were produced in a single batch [7]. Many samples batch-deposited have maintained a high (95%) hemispherical reflectance after 77 months of outdoor and accelerated exposure testing.

The ASRM (original and with an adhesion-promoting layer) was deposited by roll coating with alumina deposition rates as high as 20 nm/s in a SAIC-built, laboratory-scale roll-coater. Deposition of the alumina is the slowest and most difficult step in the ASRM production, and the durability was previously found to be extremely dependent on the IBAD deposition conditions [8]. Consequently, the IBAD process parameters were varied during most of the roll-coated runs to explore a wider parameter space. Six deposition runs were performed using the roll coater with an alumina deposition rate of 10 nm/s, and 16 deposition runs were performed where the alumina deposition rate was increased to 20 nm/s. Four of the 16 deposition runs with a deposition rate of 20 nm/s included a proprietary adhesion layer, and one run replaced the copper back-layer with titanium. It was considerably more difficult than expected to increase the deposition rate from 10 to 20 nm/s on the laboratory-scale roll coater, requiring additional technical challenges to be surmounted [8].

The roll-coating samples have been undergoing OET for 36 to 52 months at NREL and AET for 38 to 49 months in the WOMs. ASRM samples exposed outdoors produced at 20 nm/s by roll coating were equivalent to samples produced at 1 nm/s by batch coating (Figure 2). IBAD conditions [i.e., high (+), medium (0), and low (-) voltage (V), current (I), stress (S), and temperature (T)] were found at 20 nm/s that produced samples with good durability (Figure 3). Adding the adhesion-promoting interlayer and substituting the copper back-layer with titanium further improved durability (Figure 2). The ASRM performs better in accelerated exposure testing and is less dependent on optimization of the IBAD deposition conditions than when the ASRM is exposed outdoors. To date, ASRM samples exposed in the accelerated WOM and 1.0kW-SS show little degradation of the hemispherical reflectance—for the most part, being independent of the alumina thickness, deposition rate, IBAD conditions, proprietary adhesion layer, or back coating. This is in contrast with samples exposed outdoors, where all of these conditions affect the durability. Previously, it was observed that compared to other solar reflectors, the durability of front-surface mirrors is more dependent on differing weather conditions (i.e., rain, snow, freeze/thaw) and less dependent on UV exposure [8]. For FSMs in order of exposure-site severity, from best to worst, is: 1 kW-SS, Ci65, Ci5000, TX, BAR, APS, NREL, SMUD, and FLA. This is quite unusual compared to polymer and glass reflectors. Typically, accelerated exposure is more severe than outdoor exposure [i.e., 1 kW-SS (~5xNREL), Ci5000 (~6xNREL), and Ci65 (~3xNREL)]. Normally, the most severe outdoor sites are FLA, BAR, and APS; TX is intermediate, and SMUD and NREL are the least-severe sites [8].

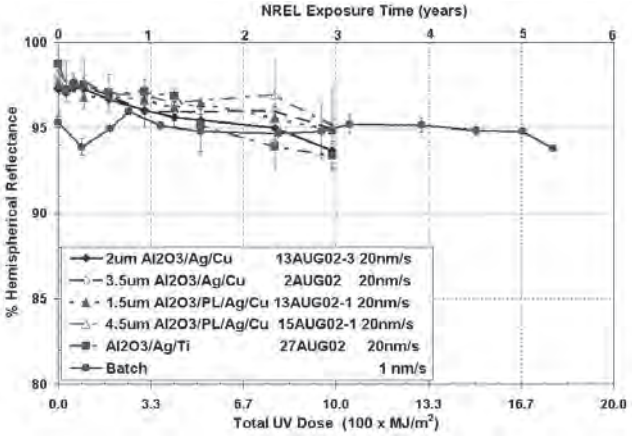

*Figure 2: SWV of SAIC ASRM constructions with alumina deposition rate of 20 nm/s for roll-coated versus 1 nm/s for batch-coated as a function of outdoor exposure at NREL.*

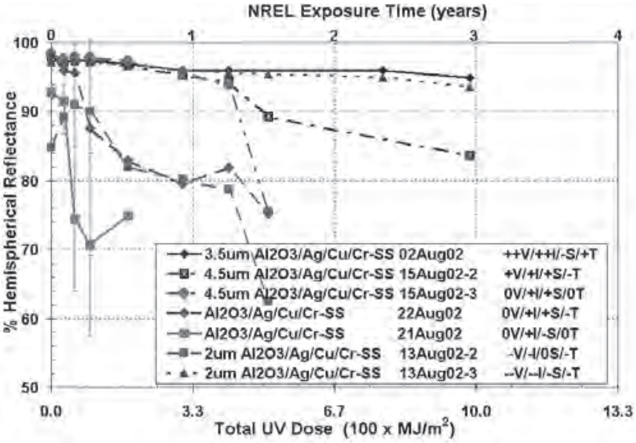

*Figure 3: SWV of SAIC roll-coated ASRM constructions where alumina IBAD conditions are varied as a function of outdoor exposure at NREL.*

A rigorous cost analysis was performed that showed that the ASRM has the potential for a manufacturing cost lower than \$10.76/m$^2$ depending on the substrate, but the alumina deposition rate and substrate are critical drivers for the cost of the ASRM. The cost analysis showed that a commercial roll-coating company (\$200/h machine burden) can attain the \$10.76/m$^2$ cost goal for deposition rates above 40 nm/s using a 1200-mm-wide web deposition system with two or three zones, a PET substrate, high-purity alumina, and an alumina thickness of 1 μm [9]. Durability testing is ongoing and the lifetime of the ASRM still must be determined. However, the ASRM needs additional improvement. The chrome-plated substrate must be replaced because it rusts at cut edges and pinholes in the chrome plating; this disrupts the alumina coating, causing samples to degrade at unprotected edges and at pinholes. For long-term durability, edge protection will be necessary and durability appears to be improved by the addition of an adhesion-promoting layer between the silver and alumina.

### IBAD $SiO_2$ Protective Layer

For a FSM to be cost effective, a high deposition rate is critical. As a complementary effort, IBAD of silica could produce an equally promising solar mirror, with the advantage that silica can be deposited at an increased deposition rate because it has a lower melting point than alumina (1710ºC vs. 2045ºC). Vacuum deposition of silica at 100 nm/s is commonly used to provide low-cost barrier coatings on polymeric substrates for the packaging industry.

Ion-beam-assisted e-beam evaporation was used to fabricate the $SiO_2$/adhesion-promoting layer/Ag/PET construction; the metal layers were not ion-assisted. Transparent dense $SiO_2$ coatings can be deposited by IBAD from $SiO_2$ e-beam starting materials, but the adhesion to silver is poor and adhesion-promoting interlayers are needed. $Al_2O_3$ is potentially a good adhesion-promoting interlayer. Thin interlayers of chromium (Cr), titanium (Ti), titanium dioxide ($TiO_2$), and niobium (Nb) are reputed to provide excellent adhesion to silicon and its oxides and nitrides. However, experience has shown that chromium significantly degrades the durability of silver mirrors. Other adhesion-promoting interlayer schemes use thin layers of Cr/Ti+Si+N/Cr, Ti/Ti+Si+N/Ti, or a zinc sulfide interlayer to stabilize the silver prior to depositing an $Al_2O_3$ adhesion-promoting interlayer. Using the hard-acid-soft-base (HSAB) principle of adhesion by Pearson [10], which uses the strong reaction of hard acids and hard bases with soft acids and soft bases, and correlating adhesion with oxide free-energy could point toward other adhesion-promoting interlayers.

Incorporating an $Al_2O_3$ adhesion-promoting interlayer improved the adhesion between the $SiO_2$ top layer and the silvered PET. The samples were clear without cracks, and the initial hemispherical reflectance was 97.1%. However, scanning electron microscopy (SEM) of the IBAD silica/alumina/silver construction showed that at medium ion-assist, the silica coating is dense but still adheres very loosely to the silver. An alumina adhesion-promoting interlayer improved the silica adhesion to silver, but could not overcome the adhesion problems. Silicon monoxide was used as the e-beam starting material with reactive gases, oxygen and nitrogen, to produce SiO, $SiO_X$, and $SiO_XN_Y$ adhesion-promoting interlayers and protective layers. Combinations of IBAD SiO, $SiO_X$, and $SiO_2$ coatings were used to protect silvered PET. SiO had a dark yellow color, excellent adhesion to silver, and high scratch-resistance. Slightly non-stoichiometric $SiO_X$ and $SiO_XN_Y$ coatings were light yellow, had good hardness and adhesion to PET, and neutral stress. SiO used as an adhesion-promoting interlayer for $SiO_X$ coatings produced mirrors that were very light yellow with excellent adhesion and neutral stress. Thin layers of SiO and $SiO_X$ used as adhesion promoting interlayers between $SiO_2$ and silver were clear with good adhesion, hardness, scratch resistance, and compressive stress. SiO, $SiO_X$, and $SiO_XN_Y$ have the potential to make good protective coatings, as well as good adhesion-promoting layers for $SiO_2$. If the dark color is not an issue, SiO could make an excellent protective coating in another application.

IBAD silica solar mirror constructions may potentially meet the CSP requirements. However, use of a silica top-coat depends on incorporating an adhesion-promoting layer, controlling the thermal load generated during deposition by the ion gun, and optimizing the ion-assist conditions. The durability of these IBAD silica reflectors was not examined. But lessons learned from durability studies of industry-supplied silica front-surface mirrors give confidence that if a transparent, thick (>1 µm), dense, adherent silica reflector is made; it has the potential to meet the long-term goals. Positive progress was made to develop an IBAD silica solar mirror, but further work will be needed to make this a viable solar mirror. The main issue to resolve in the future is the poor adhesion of silica to silver.

### Pulsed DC Sputtering

Pulsed D.C. reactive sputtering has the potential to be a faster lower-cost method for the FSM protective layer. Pulsed D.C. reactive sputtering was used to deposit the oxide for the following advanced reflector constructions: a) $Al_2O_3$/Ag/PET, b) $Al_2O_3$/Ag/Cu/PET, c) $SiO_2$/$Al_2O_3$/Ag/PET, d) $Al_2O_3$/Ag/$Al_2O_3$/PET, and e) $Al_2O_3$/Ag/Cu/$Al_2O_3$/PET. In these constructions, the silver reflective layer was deposited by e-beam evaporation; all of the reactively sputtered oxides were stoichiometric within experimental uncertainty, and the initial interlayer adhesion of these materials did not appear to be a problem. Several of the more-promising constructions were subjected to AET. Measurements show that these constructions exhibit initial hemispherical reflectance values greater than 98%. However, after AET, several samples did not have the optical durability necessary to meet the program goals; the oxide delaminated from the silver layer after a relatively short exposure time. SEM characterization of similar unexposed samples showed a columnar morphology in the protective oxide overcoat that allowed water vapor to ingress the surface of the oxide and attack the silver, resulting in changes to the adhesion properties of the oxide to the silver. Positive progress was made to develop a pulsed D.C. sputtered solar mirror, but the density of the oxide layer was insufficient and further work is needed to make this a viable solar mirror.

### Aluminized Front Surface Reflectors

Commercial aluminized reflectors use a polished aluminum substrate, enhanced aluminum reflective layer, and protective oxidized top-coat. The major concern has been the poor durability of such materials in urban and industrialized (polluted) locations. An improved anodized aluminum mirror incorporated a protective polymeric overcoat onto aluminized aluminum. However, the specularity degraded with outdoor exposure at Arizona, Florida, and Colorado (NREL) and with accelerated exposure in the Ci65. Alanod stopped selling this material for outdoor use in 2004 because of problems with the delamination of the overcoat and the associated loss of specularity. Alanod worked to improve the reflector durability and their in-house testing capability. The fluoropolymer overcoat was replaced with a nanocomposite oxide protective layer. New samples received in 2005 are undergoing testing. Alanod reintroduced the product in 2006 for sale as Miro-Sun (4270 KKSP and 4270 KO are related solar mirror products tuned for PV applications). The material is commercially available from Alanod in Germany for ~\$2.50/ft$^2$. The initial SWV is ~91.8%; initial specular reflectance at 25 mrads is ~83.7% and at 7 mrads is ~63.9%. Preliminary exposure-testing results appear encouraging and testing is ongoing (Figure 4). Alanod is now working to develop a silvered solar reflector likely to be called Miro-Silver. Prototype versions are expected to be ready for durability testing in late 2007.

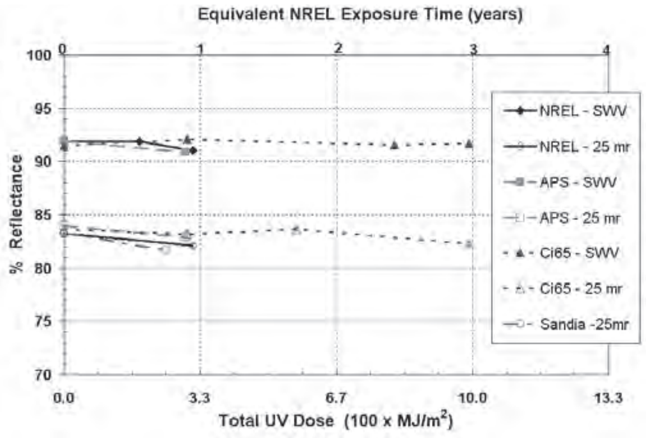

*Figure 4: SWV and 25-mrad specular reflectance at 660 nm for Alanod MiroSun aluminized reflectors as a function of APS, NREL, Sandia, and Ci65 exposure.*

## CONCLUSION

DOE, the Western Governors Association, and state RPS mandates have successfully jump-started desirable growth in the CSP technologies that would require 7 to 10 million square meters of reflector over the next 5 years. The ASRM has the potential to deliver high performance for long lifetimes at a manufacturing cost lower than standard thick-glass solar mirrors that cost \$43.20–\$64.80/m$^2$ (\$4–\$6/ft$^2$) for large production. To date, the durability of some ASRM samples produced by roll-coating at 20 nm/s is equivalent to samples produced by batch-coating at 1 nm/s. The cost analysis showed that the ASRM has the potential for a manufacturing cost lower than \$10.76/m$^2$ depending on the substrate, but the deposition rate must be doubled. Demonstration of further increases will need to be subcontracted to roll-coating companies. An investigation, prior to transitioning to industry, is warranted of different web materials, adhesion-promoting and antisoiling layers, and a lower-purity alumina. The ASRM is nearly ready to be transitioned to a commercial roll-coating company, with SAIC's consultation, if NREL establishes the relationship. Therefore, NREL would like to identify roll-coating partners interested in helping commercialize the ASRM in the future.

Positive progress was made to develop an IBAD silica solar mirror or a sputtered alumina or silica front-surface mirror, but further work is needed to make these a viable solar mirror. Durability testing of advanced solar reflectors supplied by industry is ongoing. Although groups have reported deposition at 100 nm/s by reactive pulsed DC sputtering of several microns of alumina and silica that should also meet the cost goal, it would be a major leap from past work with new risks. The Alanod mirrors are commercially available and, based on accelerated exposure testing, should meet the 10-year lifetime goals. However, predicting an outdoor lifetime based on accelerated exposure testing is risky because all failure mechanisms must be able to be replicated.

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