Optical Durability of Candidate Solar Reflectors

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Concentrating solar power (CSP) technologies use large mirrors to collect sunlight to convert thermal energy to electricity. The viability of CSP systems requires the development of advanced reflector materials that are low in cost and maintain high specular reflectance for extended lifetimes under severe outdoor environments. The long-standing goals for a solar reflector are specular reflectance above 90% into a 4 mrad half-cone angle for at least 10 years outdoors with a cost of less than $13.8/m² (the 1992 $10.8/m² goal corrected for inflation to 2002 dollars) when manufactured in large volumes. Durability testing of a variety of candidate solar reflector materials at outdoor test sites and in laboratory accelerated weathering chambers is the main activity within the Advanced Materials task of the CSP Program at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. Test results to date for several candidate solar reflector materials will be presented. These include the optical durability of thin glass, thick glass, aluminized reflectors, front-surface mirrors, and silvered polymer mirrors. The development, performance, and durability of these materials will be discussed. Based on accelerated exposure testing the glass, silvered polymer, and front-surface mirrors may meet the 10 year lifetime goals, but at this time because of significant process changes none of the commercially available solar reflectors and advanced solar reflectors have demonstrated the 10 year or more aggressive 20 year lifetime goal. [DOI: 10.1115/1.1861926]

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1 Introduction

CSP technologies are capital intensive and, for the first truly commercial systems, about half of the total capital cost of a power plant will be invested in the solar collectors. This makes reducing the cost of solar collectors critical to achieving energy cost targets compatible with economic viability; it requires cost reductions by a factor of 2–4, depending on the technology. The reflector cost for all three CSP technologies represents about 30% of the collector cost. However, because structural costs are closely related to reflector costs, the potential cost impact of the reflector design can be ~50% of the cost of a dish or heliostat and >75% of the cost of a trough collector. Thus, improved solar reflectors play an important role in achieving the required cost reductions in solar collectors. In addition, CSP systems must operate reliably for decades under extremely harsh environmental conditions that include solar ultraviolet irradiance, wind, rain, blowing sand, soiling, and high and low temperatures. This constitutes a formidable challenge to manufacturing low-cost, highly durable concentrator elements.

The widespread application of CSP generation depends largely on developing a durable, low-cost reflector. NREL, working jointly with Sandia National Laboratories as Sun◆Lab, oversees development of reflectors for the U.S. Department of Energy (DOE) CSP Program. The CSP Program's goals for a solar reflector are specular reflectance above 90% into a 4 mrad half-cone angle that lasts for at least 10 years under outdoor service conditions, and a large-volume manufacturing cost of less than $10.8/m² ($1/ft²) [1]. Unofficially, the more aggressive goals of 95% reflectivity and a 15–30 year lifetime have been pursued.

This cost goal was defined in 1992; correcting for inflation, a $10.8/m² ($1/ft²) mirror in 1992 dollars would be equivalent to $13.8/m² ($1.3/ft²) in 2002 dollars [2].

Currently, the best candidate materials for solar reflectors are silver-coated glass and silvered-polymer films. Polymer reflectors are lighter in weight, offer greater system design flexibility, and have the potential for lower cost than glass reflectors. However, silvered polymer reflectors, deployed on systems during the 1980's, have several limitations, including a lifetime of less than 10 years, poor adhesion between the silver and the polymer upon exposure to water, and higher costs than the cost goal [3]. Silvered thin (1.0 mm thick) glass is durable but is fragile in shipping and handling, durability is dependent on adhesive selection, availability is limited to only a single U.S. manufacturer, and has relatively high cost compared to the cost goal. These materials may meet the current reflector goal, but it is uncertain whether they can meet a longer lifetime goal of 20 years of outdoor service.

The Advanced Material Task directs the development of advanced reflector and absorber materials through collaborative efforts with solar manufacturers and by interacting with the coatings industry. This allows crucial gaps in the technology to be addressed and suggestions by industry experts or from the literature to be explored. This paper provides an update on the status of the top candidate solar reflectors [4].

2 Durabilty

Candidate reflector materials are identified based on their potential for low cost and high optical performance and durability. Samples are supplied by industry, fabricated by NREL subcontractors, or prepared in-house by NREL staff; all constructions are optically characterized prior to exposure testing. These mirrors are then subjected to accelerated or outdoor weathering at a variety of geographically diverse exposure sites.

2.1 Optical Characterization. Optical performance is characterized in terms of specular reflectance: the degree to which a mirror is capable of transferring directed radiation to a target re-

Table 1 OET stress conditions

Site	Stress conditions	Ave daily UV dose (MJ/m^2*d)
Phoenix, AZ	Hot–Dry	0.9131
Miami, FL	Hot–Humid	0.7666
Golden, CO	Cool–Mild	0.9117

ceiver surface. Candidate reflector materials must exhibit very good specular reflectance; microroughness of the mirror surface, crazing of protective topcoats, or both, can result in scattering (loss) of light outside a specified acceptance angle. Depending on the CSP application, the system requirement is typically 90% reflectance into a half-cone angle of 2–4 mrad [1]. The requirement for a 4 mrad half-cone angle is based on the higher specularity requirements of parabolic dishes and heliostats; these specularity requirements are not as restrictive for parabolic trough collectors because linear concentrators have considerably lower concentration ratios. During weathering, loss in specular reflectance has generally been found to be proportional to loss in hemispherical reflectance. Weathering-induced corrosion of the reflective layer usually causes loss of hemispherical reflectance much sooner than specularity is lost due to surface effects (soiling, crazing, etc.) of the superstrate or a variety of other mechanisms. Because spectral hemispherical reflectance is relatively easier to measure than specular reflectance, and because it is the predominant contributor to loss in specular reflectance during weathering, it is the performance parameter that is predominantly monitored. A Field Portable Specular Reflectometer from D&S Instruments was used to measure the specular reflectance of the reflectors at 7, 15, and 25 mrad full-cone angles at 660 nm.

All candidate solar mirror materials are optically characterized prior to exposure testing. Optical performance is periodically remeasured as a function of exposure time (environmental stresses) to assess optical durability. Initial spectral hemispherical reflectance of samples is measured using dual-beam UV-VIS-NIR spectrophotometers with integrating-sphere attachments using secondary reflectance standards (traceable to the National Institute of Standards and Technology), which allows the absolute reflectance to be measured as per ASTM E903-82 [5]. A meaningful single measure of optical performance is the solar-weighted hemispherical reflectance, $\rho_{2\pi}$, weighted across the entire solar spectrum ($\lambda = 250-2500$ nm). To obtain the solar-weighted average, the spectral measurement can be convolved with, and normalized by, a terrestrial solar spectrum [6]. If the initial performance is below some predefined critical level (typically, for silver reflectors <90% and for aluminum reflectors <80%), the construction will not be subjected to exposure testing.

2.2 Outdoor Exposure Testing. Outdoor exposure testing (OET) is routinely performed at three exposure sites: Phoenix, Arizona (APS); Miami, Florida (FLA); and Golden, Colorado (NREL). Screening is typically done only at NREL. A qualitative description of the average temperature–humidity conditions at the various sites (for example, "Hot–Humid" at Miami, Florida) is provided in Table 1. Outdoor sites are fully instrumented in terms of monitoring meteorological conditions and solar irradiance. The time interval between successive characterizations is typically 1, 3, 6, 9, and 12 months during the first year of exposure and every 3–6 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. Environmental stress factors that cause degradation have been identified from outdoor and accelerated exposure tests [7]. For most solar mirrors, exposure during service to sunlight (particularly ultraviolet wavelengths), temperature, and moisture can lead to loss in reflectance. The relative severity of these stresses is

generally in the order they were mentioned above. Degradation can also result from synergistic effects (e.g., photothermal, photohydrolytic).

2.3 Accelerated Exposure Testing. If the same failure mechanisms identified by outdoor testing are replicated by laboratory-controlled testing; it may be possible to accelerate these failure mechanisms by exposing materials to a combination of higher temperatures, higher relative humidity, and increased UV doses. This allows for early screening of developmental materials. A variety of suitable accelerated weathering chambers are typically used to screen samples by accelerated exposure testing (AET). The accelerated weathering chambers allow control and monitoring of light intensity, relative humidity (RH), and temperature (T). Two exposure chambers have been primarily used, namely, an Atlas Ci65 WeatherOmeter (Ci65) and an Atlas Ci5000 WeatherOmeter (Ci5000). Typical conditions are $T = 60°C$ and RH = 60%. Each chamber can accommodate a large number ($\sim 200–300$) of samples (roughly 67 mm $\times$ 44 mm) at the same time with simulated solar irradiance levels of roughly 1 to 2 times. These units use a xenon-arc light source with filters designed to give a close match to the terrestrial air-mass (AM) 1.5 global solar spectrum [6]. The Ci65 and Ci5000 operate continuously, with light levels about equal to outdoor exposure for the Ci65 and twice that for the Ci5000. As outdoor weather conditions vary continuously, accelerated exposure conditions can also change as well, either purposely (by programming a desired weathering profile) or inadvertently (for example, loss of light intensity due to aging of the bulb). Consequently, all relevant weathering parameters must be known and measured as a function of time. An OL754 spectral radiometer system is used to measure from 250 to 800 nm at a 1 nm resolution the spectral content and spatial uniformity of artificial light sources so that samples can be subjected to accelerated testing in known and controlled laboratory environments.

3 Test Results

Optical durability test results are presented graphically as plots of optical performance (% change in hemispherical reflectance from baseline condition) versus exposure time under specified environmental conditions (for accelerated test chambers) or location (for outdoor sites). The solar-weighted hemispherical reflectance is plotted as a function of total ultraviolet (UV) dose outdoor exposure. The total annual UV dose at FLA is equivalent to 280 MJ/m² per year and 330 MJ/m² per year at APS and NREL. The total annual UV dose for the Ci65 is equivalent to 1030 MJ/m² per year and 2060 MJ/m² per year for the Ci5000. The total annual UV dose is calculated from averages of the solar data and the spectral measurements. The primary gridlines divide the total UV dosage by 330 MJ/m² 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 Ci65 and/or different outdoor sites.

Many such plots exhibit sharp changes in hemispherical reflectance with exposure. These changes are typically caused by measurements taken in different areas of the sample or by discontinuing a degraded sample. The standard practice is to measure roughly the center portion of the sample. However, large areas of corrosion, cracking, or breakage sometimes necessitate measuring in a different region of the sample. Individual curves are typically an average of multiple samples; when a failed sample is discontinued, the average can increase, as the poor performer is no longer included in the average value associated with a particular type of material. The data (symbols) represent average values for
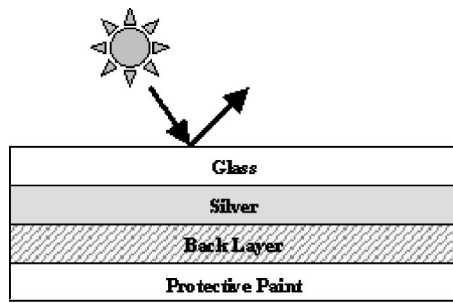
Fig. 1 Glass mirror architecture

whatever numbers of sample replicates are available; error bars are for ± one standard deviation and indicate the variation and non-uniformity of the samples as they weather.

3.1 Thick Glass. The traditional wet silvered process is used to manufacture glass mirrors (Fig. 1). The silver (Ag) layer is extremely vulnerable to airborne pollutants (specifically acids, ammonia, or hydrogen sulfide) and the moisture or salt particles present in coastal environments and shorelines. To protect the silver, mirror backing systems consisting of a copper (Cu) back layer and a protective paint have been developed that extend the service life of the mirrors significantly [8]. The copper layer has a significant protective role (to retard tarnishing of the silver layer) and provides a surface for the mirror paint to adhere to [9]. The mirror-backing paint layer protects the copper layer from abrasion and corrosion, thus significantly extending the service life of Ag–Cu mirrors.

Thick glass mirrors (>1 mm) have excellent durability in terms of reflective layer corrosion and are readily available, but are heavy and fragile. They have the confidence of the solar manufacturing industry and have been commercially deployed, but curved shapes are difficult and require slumped glass, which is expensive. Trough mirrors (used by the Solar Electric Generating System (SEGS) plants in California), manufactured by Flabeg, use silvered, thick, slumped glass with a proprietary multilayer paint system designed for outdoor exposure; they currently cost $43.2–$64.8/m² ($4–$6/ft²) for large volume purchases. For trough applications, it is desirable for the mirror costs to be reduced to $21.6–$27/m² ($2–$2.5/ft²). Initial hemispherical reflectance is ~93% and the mirrors are durable, as shown in Fig. 2.
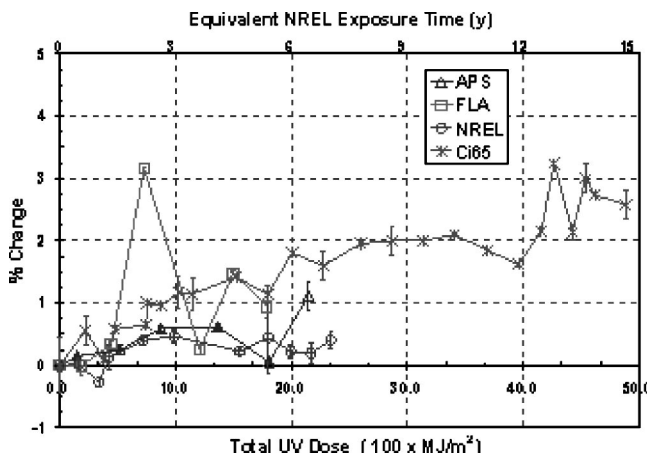

Fig. 2 % change from base-line solar-weighted hemispherical reflectance (93%) of Flabeg silvered thick-glass reflectors with proprietary multilayer paint system as a function of accelerated Ci65 WOM and outdoor exposure at APS, FLA, and NREL
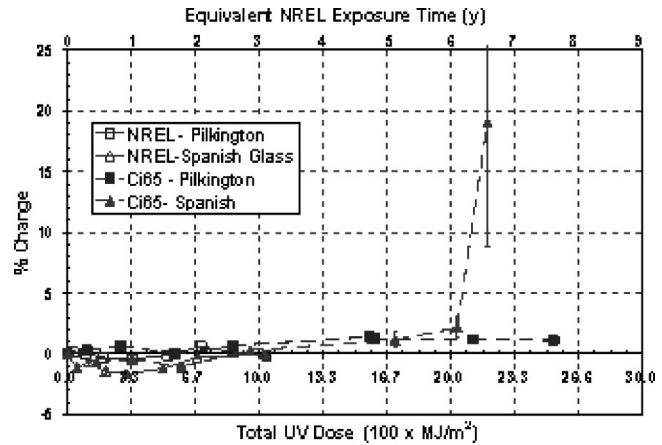

Fig. 3 % change from base-line solar-weighted hemspherical reflectance (93%) of Pilkington and Spanish silvered thick-glass reflectors with Cu-less back layer and Pb-free paint as a function of accelerated Ci65 and NREL outdoor exposure

In the last five years, two significant changes in mirror manufacturing have occurred in the classical wet chemistry process because of environmental concerns. The first is the method of forming a copper-free reflective mirror, and the second is the use of lead-free paints. The copper-free back layer inhibits corrosion of the silver by contacting the silver simultaneously with both a specified cation solution and a specified anion or hydroxyl ion solution that react to form a water-insoluble precipitate on the silver surface [9–12]. The preferred cation solution contains tin (e.g., $SnCl_2$), and the preferred anion solution contains hydroxyl ions (e.g., NaOH). The treated coating is rinsed, and the mirrors are painted with conventional paints or covered with a polymer coating to protect the mirror against corrosion and abrasion of the silver film.

Mirror-backing paints are intended for mirrors produced by traditional technology for domestic use. Of the various paint formulations that could be used for protecting a mirror, those that afford the best protection against corrosion contain lead (Pb) pigments. The pigment is the active corrosion-inhibitor component of typical mirror paint systems. Although these lead paints are robust, for reasons of environmental health, their use is being discontinued. Twenty years ago, for outdoor applications, heavily leaded paints containing 10%–20% lead by weight were used. In the past 3–10 years, the most heavily leaded paints available were 2–4% lead by weight, and 1% was typical. Today, even these low-lead paints have been almost phased out. One of the best-performing Pb-free corrosion inhibitor pigments is a (Ni^{2+} and Co^{2+})-bis-hydrogen cyanamide [9,12,13]. Lead-free paint systems are intended for domestic (interior) conditions. An important benefit to the environment is that the copper-free mirrors can be protected with the lead-free paints.

Pilkington (UK) commercially introduced the copper-free process in 2000 for thick (3–6 mm) soda-lime glass for domestic use. Testing of samples of Pilkington and "Spanish" (Cristaleria Espanola S.A—Saint-Gobain Spanish branch) glass mirrors (copper-free and lead-free paint), bonded to steel with four different candidate adhesives, was initiated in 2000 for possible use at Solar Tres. Although the mirrors exposed outdoors do not yet show degradation, the Pilkington mirrors exhibit better optical durability than the Spanish mirrors after 29 months of accelerated Ci65 exposure; on average, the Pilkington mirrors degraded 1%, whereas the Spanish glass mirrors degraded 19% (Fig. 3). As shown in Fig. 4, adhesive-related degradation is more prevalent with Spanish glass mirrors. Depending on the adhesive used to
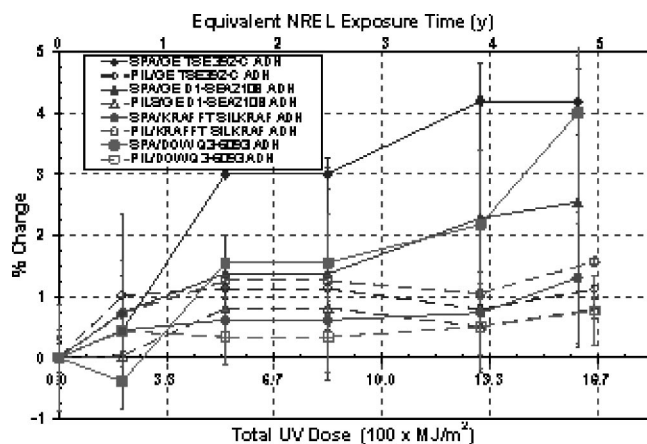
Fig. 4 % change from base-line solar-weighted hemispherical reflectance (93%) of Pilkington and Spanish silvered thick-glass reflectors with Cu-less back layer, Pb-free paint, and four adhesives as a function of accelerated Ci65 exposure
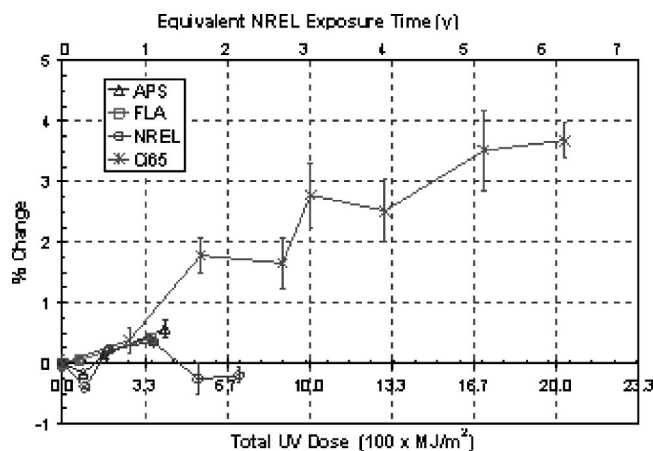

Fig. 5 % change from base-line solar-weighted hemispherical reflectance (92%) of Naugatuck silvered thin-glass reflectors with copper back layer and Pb-free paint system as a function of accelerated Ci65 and outdoor exposure at APS, FLA, and NREL

bond the mirror, Spanish mirrors degraded 1.3%–4.2%, whereas Pilkington mirrors degraded 0.8%–1.6% after 18 months of accelerated Ci65 exposure.

3.2 Thin Glass. CSP companies have deployed thin-glass mirrors that were produced by wet silver processes on ∼1 mm thick, relatively lightweight glass and bonded to metal substrates in commercial installations. Initial hemispherical reflectance is ∼93 to 96%, and the cost is ∼$16.1/m^2 to $43.0/m^2 (∼$1.5/ft^2 to $4.0/ft^2). The mirrors have the confidence of the CSP industry, but are fragile and difficult to handle, which impacts the concentrator labor costs.

Corrosion has been observed in mirror elements deployed outdoors for two years as part of operational solar systems. This is very similar to the corrosion bands and spots observed on small (45 mm×67 mm) thin-glass mirrors laminated with several different types of adhesives and subjected to AET at NREL. These samples exhibited corrosion at the unprotected edges and along cracks, and the choice of adhesive affected the performance of weathered thin glass mirrors.

Thin-glass mirror manufacturers have also switched to the copper- and lead-free process. Glaverbel (Belgium) and Naugatuck (U.S.) are using the copperless lead-free paint systems in their commercial mirror lines. The following thin-glass mirrors are being tested to assess their performance and durability: 1.0-, 1.2-, and 2.0 mm Naugatuck mirrors with and without copper and with low-lead and no-lead paint; the 0.85 mm Glaverbel Mirox (copperless mirror); and silvered thin glass reflectors prepared by German companies and provided by Deutsches Zentrum für Luft-und Raumfahrt (DLR) from Schlaich, Bergermann, und Partner; Steinmüller; and Erie Electroverre [14]. To date, mirrors exposed outdoors show little to no degradation (Fig. 5). After three years of accelerated Ci65 exposure, the Naugatuck mirrors with no-lead paint are exhibiting comparable durability to the mirrors with low-lead paint (Fig. 6), although both show degradation up to 3% depending on the mirror mounting (i.e., substrate and adhesive used to mount mirror).

3.3 Aluminized Reflectors. Front-surface-aluminized reflectors use a polished aluminum substrate, an enhanced aluminum reflective layer, and the formation of a protective oxidized topcoat (alumina) [14,15]. The reflectors initial reflectance is ∼90%. The product was commercially available from Alanod in Germany for <$2/ft^2. Germany is very interested in such aluminized reflectors because of their potential low cost and flexibility

with regard to system design issues; the major concern has been poor durability of such materials in urban and industrialized (polluted) locations.

Candidate front-surface aluminum solar mirrors include anodized aluminum from Regiolux, another anodized aluminum mirror material from Metalloxyd, and physical vacuum deposited (PVD) aluminized aluminum from Alanod. An improved anodized aluminum mirror from Alanod incorporated a protective polymeric overcoat onto PVD aluminized aluminum (''original'' in Fig. 7).

The addition of an acrylic polymeric overcoat to protect alumina improved the durability and samples survived more than five years of outdoor exposure in Golden, Colorado (''improved Miro2'' in Fig. 7), and Phoenix, Arizona, and more than three years of outdoor exposure in Miami, Florida, and Köln, Germany. However, the acrylic overcoated material failed in accelerated testing. The acrylic overcoat was replaced (''Miro/4270kk''in Fig. 7), and the new formulation shows improved hemispherical durability as shown in Fig. 7. However, specularity has degraded with outdoor exposure at Arizona, Florida, and NREL, and with accelerated exposure in the Ci65 (Fig 8). The longer time scale for the degradation in the Ci65, indicates the AET does not replicate the
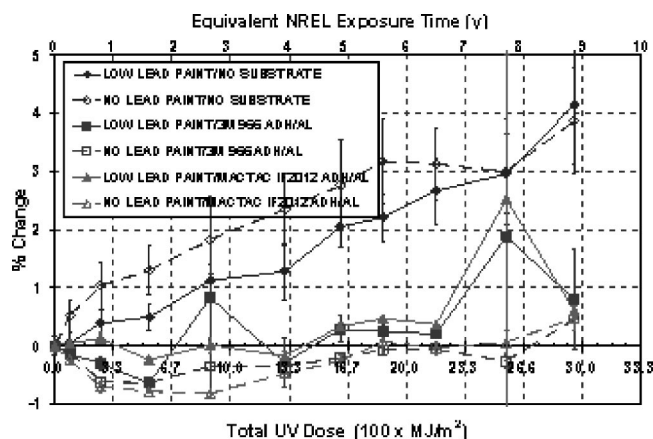

Fig. 6 % change from base-line solar-weighted hemispherical reflectance (92%) of Naugatuck silvered 1 mm thin-glass reflectors with low-Pb and no-Pb paint and with no substrate vs laminated to aluminum substrate with Mactac IF2012 and 3M 966 pressure sensitive adhesive as a function of accelerated Ci65 exposure
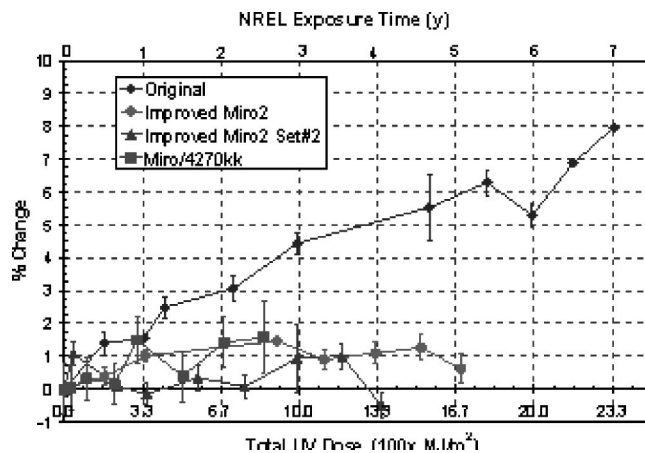
Fig. 7 % change from base-line solar-weighted hemispherical reflectance (92%) of Naugatuck silvered 1 mm thin-glass reflectors with low-Pb and no-Pb paint and with no substrate vs. laminated to aluminum substrate with Mactac IF2012 and 3M 966 pressure sensitive adhesive as a function of accelerated Ci65 exposure

Fig. 9 % change from base-line solar-weighted hemispherical reflectance of 3M ECP-305+ (94.5%) and 3M SS-95 (96%) as a function of NREL outdoor exposure

OET failure mechanisms. Aluminized reflectors from other manufacturers exhibit similar performance. Recently, Alanod has stopped selling this material for outdoor use because of problems with delamination of the overcoat. The company is working to find a solution to this delamination problem and associated specularity decrease and to improve the abrasion resistance of the reflector [16,17].

3.4 Silvered Polymer Reflectors. An alternate mirror construction for solar mirrors uses silvered polymers to make lightweight, flexible, solar mirrors. A silvered acrylic reflector developed jointly by 3M Company Energy Control Products (ECP) with NREL, ECP-305+, consisted of 0.1 mm UV-stabilized polymethylmethacrylate (PMMA) film with an evaporated reflective Ag layer, a protective Cu layer, and a pressure-sensitive adhesive layer for application to a rigid support structure. For optical purposes, the PMMA layer is thick; this provides integrity to the stack and serves as a superstrate. Acrylic demonstrates the following characteristics: Excellent stability in the environment, excellent optical properties, the ability to protect silver, and the ability to be extruded into a thin, flexible film. However, it is brittle and
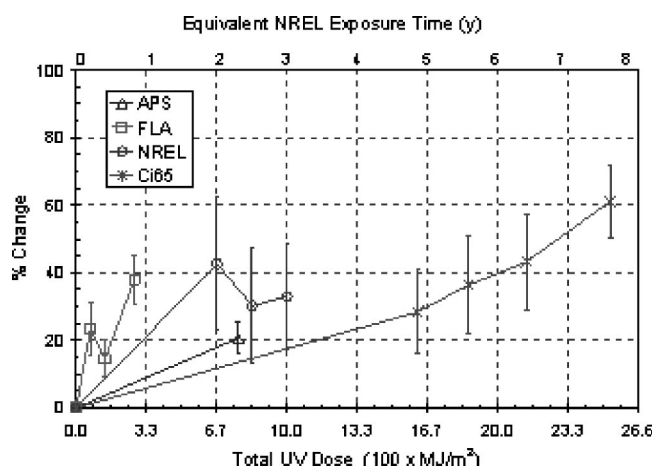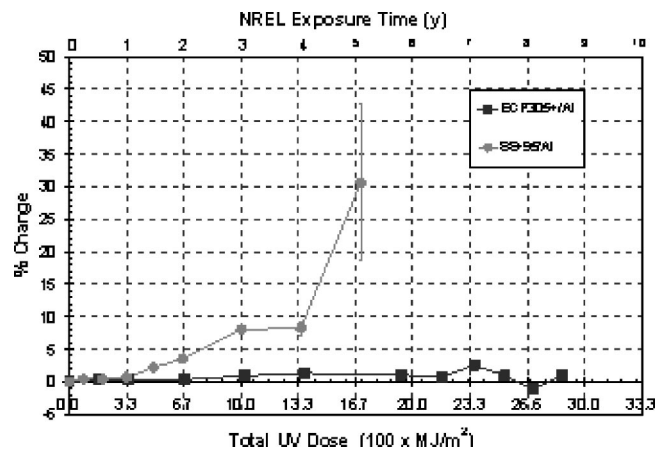

Fig. 8 % change from base-line 7 mm Specular reflectance at 660 nm (78%) of Alanod Miro/4270kk aluminized reflectors as a function of APS, FLA, and NREL outdoor exposure and accelerated Ci65 exposure

has intrinsically weak adhesion between the polymer and the silver reflective layer, which lead to delamination problems during field application, especially after extremely rainy conditions. The reflectivity of the ECP-305+ was excellent at 94.5%, and the durability of test samples reached 10 years for some locations, as shown in Fig. 9. The cost of ECP-305+ in 1995 was $2.25 /ft². 3M discontinued production of ECP-305+ in 1997. Several factors influenced this decision. In the past, 3M had been able to accommodate low-quantity orders by making small runs. The belief that suitable market opportunity did not exist led to internal redirection of resources (funding, manpower, etc.) to other business areas. Ironically, worldwide orders increased to necessitate scale-up, but were not large enough to warrant the financial investment required to meet the volume. Additionally, despite positive progress in solving the delamination problem, there was widespread negative publicity surrounding the delamination problem during field service. Finally, additional technical problems were identified with scaling up the manufacturing process.

The 3M SS-95 reflector, an indoor lighting product, has silver evaporated onto a polyethylene terephthalate (PET, a polyester) film substrate with a thin layer of a weatherable acrylic, PMMA, flood-coated over the silver. The reflectivity of SS-95 was excellent at 96% but the optical durability, as shown in Fig. 9, was poor. The SS-95 reflector is also no longer commercially available.

A new polymeric solar reflective material has been developed through collaborative research with ReflecTech that combines experience gained from the development of ECP-305 and SS-95. This material possesses unique and desirable properties for solar concentrators. It incorporates a unique ultraviolet screening construction as part of the silvered reflective film. The ReflecTech silvered film has an initial solar-weighted hemispherical reflectance of 94% and a specular reflectance of 94% at 25 mrad (1.4°) acceptance angle. The ReflechTech film can be supplied in roll widths up to 1.2 m for less than $14/m², with a removable cover sheet to protect the film until final usage, and a pressure sensitive adhesive protected by a release liner for application to smooth nonporous surfaces.

A very small pilot run was made by ReflecTech on standard commercial equipment; it demonstrated that all production steps for the reflective film could be achieved using standard commercial film converter equipment in widths up to 1.2 m. Real-time outdoor weathering tests (Fig. 10) show that the pilot-run samples have no significant loss in solar-weighted reflectance, although the outdoor weathering period has spanned only 2.5 years at present. Additionally, accelerated ACUVEX® outdoor weathering tests are near an 10 year equivalent time period, and they also show no
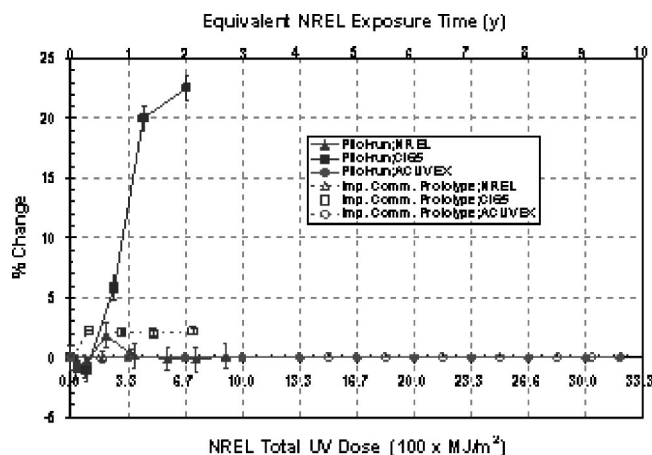
Fig. 10 % change from base-line solar-weighted hemispherical reflectance (93.5%) of ReflecTech Pilot-run and of Improved Commercial Prototype as a function of NREL and ACUVEX® outdoor exposure and accelerated Ci65 exposure

Fig. 12 % change from base-line solar-weighted hemispherical reflectance (96%) of SAIC ASRM construction with alumina batch process deposition rate from 1 to 22.5 nm/s as a function of outdoor exposure at NREL

significant loss in solar-weighted reflectance. The Arizona Desert Testing ACUVEX® uses reflected natural sunlight in Phoenix, Arizona concentrated 7 to 8 times with a Fresnel-reflector accelerated outdoor weathering test machine where the samples are cooled to near ambient conditions with a fan and are sprayed with deionized water 8 min per natural sun hour per ASTM G90-98 [18]. However, Ci65 results (Fig. 10) show significant reflectance loss earlier than had been anticipated. Historically, the degradation mechanisms observed for polymeric reflectors by OET have been replicated in the Ci65. The difference in performance between the samples exposed in the Ci65 and the ACUVEX® may indicate that the Ci65 accelerates degradation mechanisms not observed in the ACUVEX® or the field. Improvements in the baseline construction have been explored, using the pilot-line coating equipment in 40 cm wide×9 m long rolls, and tested. Also, shown in Fig. 10, is the comparison between the early pilot-run version of the ReflecTech film and the prototype of the improved commercial ReflecTech film. The more recent version appears to have further improved the durability of the reflective film. A pilot run of this improved commercial version is scheduled for July 2004. Although the 10 year reflectance goal currently seems achievable, the accelerated and real-time outdoor tests will be continued to allow determination of the durability of this reflective material.

3.5 Advanced Solar Reflective Mirror. Another promising low-cost reflector material for CSP generation has a silvered specular substrate protected by an alumina (Al_2O_3) coating several microns thick (Fig. 11). The alumina hard coat of these front-surface mirrors is deposited under high vacuum by ion-beam-assisted-deposition (IBAD). Samples of this advanced solar
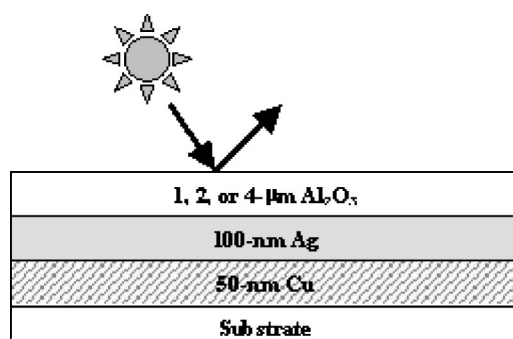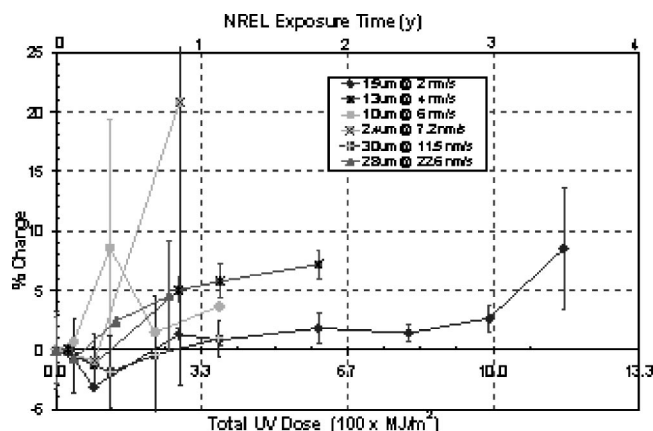
reflective mirror (ASRM) have been produced both by batch and continuous roll-coating processes. The substrate materials investigated were PET, PET laminated to stainless-steel foil, and chrome-plated carbon steel strip. The advantage of steel strip compared to PET is that it withstands a higher process temperature and potentially lowers the collector installation costs. Nine years ago, the alumina deposition rate was 1 nm/s, and four 15.2 cm² samples could be produced in a single batch. The details of the sample production and testing have been reported previously [19]. An important aspect is the reactive gas used in the ion source. Alumina coatings crack when produced with oxygen, but alumina coatings produced with a proprietary reactive gas do not crack. Many samples prepared have maintained a high (95%) hemispherical reflectance, even after 3600 h of accelerated exposure testing in a 1 kW solar simulator exposure chamber and 64 months of outdoor and accelerated Ci65 exposure testing.

Two goals have guided the technical work: (1) To increase the alumina deposition rate to 30 nm/s, and (2) to transition the IBAD process to a roll-coating format. The alumina deposition rate was increased for batch samples from 1 to 22.5 nm/s. Samples prepared with properly optimized deposition parameters have maintained high hemispherical reflectance for 42 months of outdoor exposure at NREL. Funding constraints prevented optimization of the deposition parameters at each incremental deposition rate. Consequently, some of the samples had insufficient ion assist, and the outdoor reflector durability was poor for about half of the samples (Fig. 12). For example, in the 7 nm/s deposition rate case, the samples had insufficient ion assist and the durability was unsatisfactory. The alumina in the 11.5 nm/s and 22.5 nm/s samples was not completely oxidized, as indicated by the slightly brown color, the lower hemispherical reflectance, and tensile cracks formed because of excessive residual tensile stress. The alumina reflectors deposited at high deposition rates replicated the durability demonstrated when the alumina was deposited at 1 nm/s, but durability was found to be extremely dependent on deposition conditions.

Samples were inadvertently exposed outdoors without edge protection, a condition known to be extremely harsh. As a result the samples with insufficient ion assist began to fail due to flaking around the edges. The flaking was particularly severe for the outdoor samples after snowstorms. The failure to provide edge protection was fortuitous, because comparisons between accelerated and outdoor exposure tests indicate that this ASRM is more susceptible to weather conditions not simulated by NREL's standard accelerated test protocols (e.g., rain, sleet, and snow) (Fig. 13). In general, the performance of samples in accelerated exposure testing is better than those exposed outdoors and is less dependent on
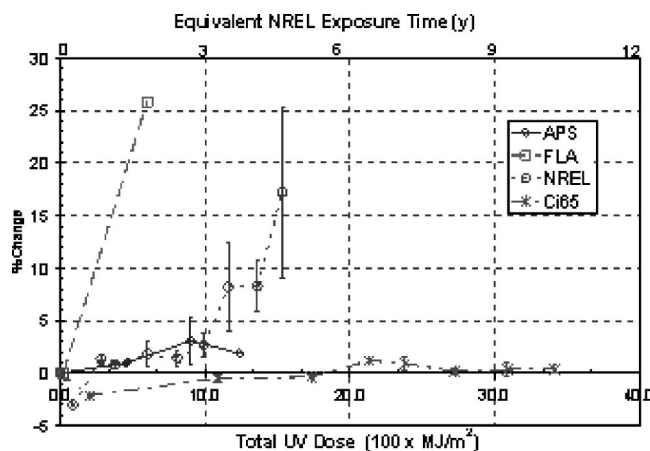

Fig. 11 SAIC ASRM architecture

Fig. 13 % change from base-line solar-weighted hemispherical reflectance (96%) of SAIC ASRM construction with 1.5 μm alumina deposited at 2 nm/s by batch process as a function of APS, FLA, and NREL outdoor exposure and accelerated Ci65 exposure

the optimization of deposition conditions. Compared to other solar reflectors, the ASRM's performance with exposure is less dependent on UV exposure and more dependent on the differing weather conditions.

A web-handling machine was incorporated into a high-vacuum chamber, and the ASRM was deposited by roll coating with alumina deposition rates as high as 20 nm/s. Deposition of the alumina is the most difficult step in the ASRM production and the durability was previously found to be extremely dependent on the IBAD deposition conditions. Consequently, the 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. Most recently, the alumina deposition rate was increased to 20 nm/s on 16 roll-coated samples. It was considerably more difficult than expected to increase the deposition rate from 10 to 20 nm/s on the laboratory-scale roll coater, and new technical challenges were encountered [20]. To date, the hemispherical reflectance durability of some samples produced by roll coating is equivalent to samples produced by batch coating (Fig. 14). These results are preliminary, and durability testing is ongoing. However, the reflector needs
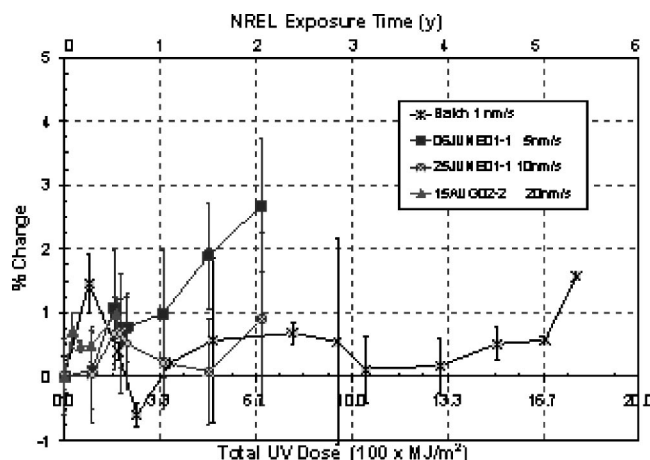

Fig. 14 % change from base-line solar-weighted hemispherical reflectance (96%) of SAIC ASRM construction with alumina roll-coated deposition rate of 5, 10, and 20 nm/s and batch-coated deposition rate of 1 nm/s as a function of outdoor exposure at NREL

additional improvement because the samples degrade at unprotected edges and at pinholes. For long-term durability, edge protection will be necessary and durability could be improved by the addition of an adhesion-promoting layer between the silver and alumina. The ASRM under development has the potential to deliver high performance for long lifetimes at a manufacturing cost lower than $10.76 /m^2, but the deposition rate must be increased to 30–50 nm/s [21,22]. Although thin oxide coatings are routinely deposited at deposition rates greater than 100 nm/s, increasing the deposition rate while maintaining the optimized IBAD deposition conditions could be difficult.

4 Summary

Recently, environmental concerns have dictated two changes in the traditional wet chemistry manufacturing process of glass mirrors, resulting in copper-free reflective mirrors and the use of lead-free paints. Although some mirrors exposed outdoors do not yet show degradation, other thick and thin glass mirrors exhibit degradation (depending on their construction) after 29 months of accelerated Ci65 exposure. The Pilkington thick glass copper- and lead-free mirrors exhibit better optical durability than the Spanish mirrors, and the Naugatuck thin-glass mirrors with no-lead paint exhibit comparable durability to the mirrors with low-lead paint. In addition, we have observed that the AET failure mechanisms for glass mirrors replicate those observed in OET. Testing of these glass mirrors will continue. Although glass mirrors with copper back layers and heavily leaded paints have historically been considered robust outdoors, it cannot be assumed that the new copper- and lead-free silvered glass mirrors have same durability.

The currently available alternative solar mirrors include aluminized, polymeric, and front surface reflectors. The aluminized reflectors require an overcoat to prevent degradation in industrial and urban environments. Delamination of the protective overcoat and resulting loss in specularity has lead Alanod to remove its solar reflector from the market. In addition, for aluminized reflectors the OET failure mechanisms are not replicated nor accelerated by NREL's standard accelerated test protocols. Improvements are ongoing and further durability testing will continue. The new silvered polymeric reflector developed jointly by NREL and ReflecTech has demonstrated extended durability and UV stability in both real-time and accelerated testing. For polymeric reflectors in general, the typical AET degradation mechanisms replicate those observed by OET. The ReflecTech material is commercially ready, and is nearing the equivalent of 10 years of outdoor exposure by ACUVEX, another few months of ACUVEX will indicate whether the 10 year durability goal might be achieved. However, the actual OET is only at 2.5 years and further testing will be needed to determine its actual lifetime. The ASRM deposited with optimized ion assist conditions has also demonstrated extended accelerated and outdoor durability with more than five years of real-time exposure. The durability of some of the ASRM samples produced by roll coating at 20 nm/s is equivalent to samples produced by batch coating. However, like the aluminized reflectors, accelerated tests do not seem to replicate or accelerate the degradation mechanisms seen in outdoor exposure tests for the ASRM. The ASRM, although promising to meet the long-term goals, needs additional improvements because the samples can degrade at unprotected edges and pinholes, and the deposition rate must be increased to meet the cost goals. Improvements are planned and durability testing is ongoing.

Positive progress has been made to develop an advanced solar reflector, but work has been severely limited due to a lack of funding during the last few years. Durability testing of the reflectors supplied by industry is ongoing. An accelerated test that simulates a greater number of relevant outdoor conditions must be developed, particularly for the front-surface reflectors (i.e., aluminized reflector and ASRM). The glass mirrors, ReflecTech, and ASRM may meet the 10 year lifetime goals based on accelerated exposure testing. However, predicting an outdoor lifetime based

on accelerated exposure testing is risky and can only be attempted if the test accelerates the same failure mechanisms identified by outdoor testing. At this time, because the production of all solar reflectors has recently changed considerably, none of the solar reflectors available have been tested long enough to demonstrate the 10 year or more aggressive 20 year lifetime goal, outdoors in real-time.

Acknowledgments

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