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ABSTRACT

Many applications of solar energy require large mirrors to provide high levels of concentrated sunlight. The success of such conversion systems hinges on the optical durability and economic viability of the reflector materials. A major effort at the National Renewable Energy Laboratory (NREL) has been to improve the existing reflector materials technology and to identify candidates that retain optical performance and durability criteria and offer potential for reduced cost. To attain the goals, it is desirable to maintain and increase the involvement of industrial organizations in reflective materials R&D related to the conversion of solar resources to useful energy. Toward this end, NREL has recently initiated several collaborative efforts with industry to develop advanced reflector materials.

INTRODUCTION

Terrestrial solar radiation can provide a ready source of clean, renewable energy for a variety of residential, commercial, and industrial applications. Many designs for converting this free and abundant resource to usable energy rely on concentrating sunlight using large-scale optical elements. Both reflective and refractive concentrators have been considered for solar energy technologies. Reflectors are generally preferred because they are considerably less expensive on a per area basis and because reflective losses are usually less than transmission losses through refractive elements. Consequently, most designs make use of reflective concentrators. Such concentrators consist of a reflector (mirror) that is bonded to a substrate material that in turn is attached to some type of structural support (Figure 1). Curvature of the reflector surface is typically desired to increase the level of concentration.

Reflector Material
Substrate Material
Structural Support

Figure 1. Typical Construction of Solar Concentrator

SOLAR CONCENTRATOR TECHNOLOGIES

A concentrator is a device that concentrates the sun's radiation onto a given area, thereby increasing the intensity of the collected energy [1]. A number of solar technologies make use of concentrators. These include solar thermal electric (STE), solar thermal industrial, and photovoltaic (PV) concentrators. In addition, secondary concentrators have been proposed for use in tandem with many of these solar technologies.

Solar Thermal Electric Technology

The conversion of solar radiation to thermal energy and subsequently to electricity by means of an engine or power cycle is known as the solar thermal electric (STE) technology. Concentrated sunlight is typically used to produce 300°-700°C heat capable of generating electrical power (in a modular fashion) in the capacity range of 5 kW_e to 200 MW_e. Generally,three concentrator systems comprise this technology, namely, parabolic trough, central receiver (CR), and parabolic dish. A parabolic trough collector is a paraboloidal trough, usually a single-axis tracking concentrator, that focuses radiant energy onto an attached linear-focus receiver. A CR system is an array of dual-axis sun-tracking mirrors (heliostats) that concentrates solar radiation onto a common tower-mounted receiver. A parabolic dish collector is a paraboloidal dish, dual-axis tracking concentrator that focuses radiant energy onto an attached point-focus receiver or engine/receiver unit.

Solar Thermal Industrial Technology

Three segments of the solar thermal industrial technology which make use of concentrated sunlight are process heat, high-flux processes, and detoxification of hazardous waste. Process heat typically uses line-focus concentrators to obtain temperatures somewhat lower than required for STE applications. Consequently, the optical and thermal requirements are less demanding, allowing lower cost components. For industrial processes (e.g., steam used in textile mills, canneries, pasteurization units), temperatures around 300°C are required. Commercial applications (e.g., hot water for recreation centers, hotels, government facilities) make use of temperatures <200°C.

High-flux processes include such applications as materials processing [2], high-temperature photochemistry, and solar pumped lasers. These applications are not associated with power generation and are fairly new in concept and development. They use the concentrated sunlight directly as an energy source for the process.

Another nonpower-generation solar application being developed is detoxification of hazardous waste [3]. Two approaches are being pursued; the first of these relatively new technologies remediates dangerous chemicals in aqueous form, and the second deals with treatment of chemicals in the gas phase. For aqueous detoxification, concentration ratios of 1X-20X are foreseen. Such levels can be obtained by flat-plate (nonconcentrating for 1X) or line-focus (parabolic trough) systems. Gas-phase detoxification may require concentrations of 300X-1000X, achievable with a two-axis, tracking, parabolic dish concentrator. Each of these technologies makes use of near-ultraviolet photons (~300-400 nm). The terrestrial resource within this spectral range is extremely limited, requiring high specular reflectance within this bandwidth to maximize collection efficiency.

Photovoltaics Technology

The PV technology relies on the direct conversion of sunlight to electricity via the photoelectric effect. Some PV system designs make use of concentrated flux to optimize the cost/performance benefit of generated electricity. This approach is attractive because the conversion efficiency of PV cells increases logarithmically with the level of solar irradiance (up to the point at which resistive losses dominate) and because the cost per area of reflector materials is several orders of magnitude less expensive relative to most PV cells. The concentrated light must provide a uniform flux profile over the area containing the cell array (composed of a number of cells connected in series) to maximize the output current from such a module. Several ranges of applicable concentration levels have recently been suggested for PV concentrator use [4]. These are generally tied to the current state of PV cell technology and include low (10X-30X), intermediate (200X-400X), and high (700X-1000X) concentration.

Secondary Concentrator Technology

Secondary concentrators have been proposed for use with both STE dish systems [5] and PV concentrator systems [6]. Such a device located near the focal plane of a primary concentrator (dish) can be used to redirect the incident flux into a smaller receiver aperture, thereby increasing the level of concentration. The reflective layer of secondary concentrators must withstand substantially higher temperature and insolation levels than those associated with primary concentrators and therefore require optical properties and design constructions beyond the scope of this paper.

MARKET STATUS AND PROJECTIONS

Generation of electricity from solar thermal energy is considered to be the most market-ready of the various concentrator technologies. Projections [7] are that approximately 950 MW_e of such systems will be installed world-wide during the last four years of this century. This translates into the need for roughly 1.9×10^6 m^2/yr (20×10^6 ft^2/yr) of reflector material. After the year 2000 rapid growth is expected to continue, driven primarily by the international market. Currently, parabolic trough systems are considered to be commercially viable, CRs are entering the demonstration stage, and parabolic dish systems are being developed.

Nine plants with a generating capacity of over 350 MW_e have been installed in California and provide power to the utility grid. These are hybrid systems composed of line-focus parabolic troughs with natural gas back-up capacity. The reflector material is silvered glass mirrors, and 2.3×10^6 m^2 (24.9×10^6 ft^2) of reflector area has been installed. Although no new plants are planned for the near future, these plants continue to operate and provide usable energy.

Significant penetration of the CR technology is related to the success of a cooperative effort between DOE and a consortium of nine utilities from the western United States. This project, known as Solar 2, is a 10 MW_e demonstration central receiver plant due to be activated in 1997. It is hoped that this project will significantly reduce the perceived risks associated with this technology and spur utility willingness to undertake construction of commercial-size plants (roughly 100 MW_e capacity).

Another government-sponsored activity is a joint venture project with a solar manufacturer to develop a dish concentrator/Stirling engine system. Early commercialization of this technology is believed to be roughly 2-3 years away. Three phases of 5 kW_e dish/Stirling systems will be installed and field tested in this project.

REQUIREMENTS FOR REFLECTOR MATERIALS

A common requirement of all of these technologies is the need for a low-cost, high-performance, reflector material capable of extended service lifetime in an outdoor environment. The prospect of solar concentrator systems hinges on the service durability and economic viability of such materials. Achieving commercial success in STE will require continued reductions in the energy cost of the technology. One of the more promising avenues for achieving these energy cost reductions is by developing advanced (lower cost/performance ratio) reflector materials.

Concentrators represent roughly half the capital cost of STE power plants, and reflector materials are a significant portion of concentrator costs. Decreased reflector durability would require periodic replacement during the lifetime of the plant and related labor costs. Decreased performance (lower initial reflectance) would increase the installed system cost because larger collector fields would be required to achieve target power levels.

Optical performance is characterized in terms of specular reflectance, the degree to which a mirror is capable of transferring directed radiation to a target receiver surface. Microroughness of a mirror surface can result in scattering (loss) of light outside a specified acceptance angle defined as the half angle (ψ) subtended by the receiver as viewed from the reflector surface (Figure 2). At each wavelength(λ), the level of specular reflectance (ρ_s) is a function of both the hemispherical reflectance ($\rho_{2\pi}$) and the half width (σ) of the (assumed Gaussian) distribution of scattered light, as defined in Equ. 1:

$$\rho_s(\psi,\lambda) = \rho_{2\pi}(\lambda)\,[1 - e^{-\frac{[\psi/\sigma(\lambda)]^2}{2}}] \tag{1}$$

The optical durability of a mirror is its ability to resist losing specular reflectance during real-world service

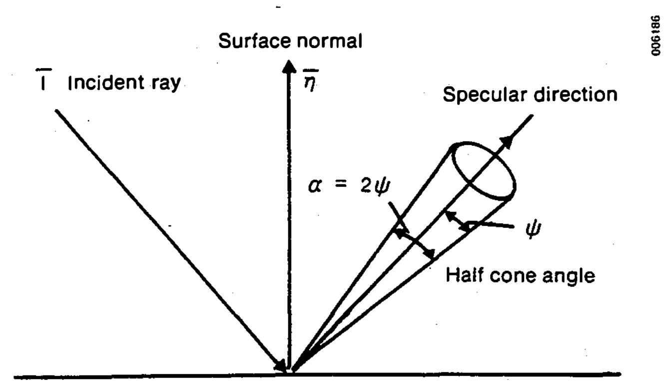

Figure 2. Specular Reflectance

exposure. Such a loss can result from corrosion of the reflective layer and subsequent loss in $\rho_{2\pi}$, or to increased microroughness and widening of the reflected beam (σ) because of soiling or abrasion of the mirror surface or a variety of other mechanisms. Potential deleterious environmental stresses that can cause such degradation include moisture, temperature, ambient pollutants, airborne particulates, hail, and harmful (typically ultraviolet) radiation. To screen candidate reflectors, accelerated weathering chambers are used in which the various stress factors can be isolated and emphasized under controlled laboratory conditions. Real-time outdoor testing is also carried out at a number of instrumented exposure sites throughout the United States.

HISTORICAL PERSPECTIVE

In the mid 1980s, the need for improved mirrors for solar applications was recognized, and a program was initiated to develop such materials. At the time, the state-of-the-art reflector material was back silver-coated low-iron glass [8]. Glass mirrors were generally considered to be too heavy, required special handling because of their fragility, and were too expensive. Candidate alternatives included metallized polymers, front surface reflectors, and thin glass. The performance characteristics of thin glass mirrors for solar applications had been demonstrated [9,10]. However, based on market analysis results at the time, no U.S. manufacturers existed. Front surface reflectors, in which the metal reflective layer is deposited on a substrate material prior to deposition of a thin top protective coating, were considered to have questionable weatherability and were expensive. In addition, it was uncertain whether such a construction could be economically produced in sufficiently wide (>1m) roll form.

Metallized polymeric reflector materials are significantly lighter in weight and potentially much less expensive than conventional glass mirrors. Additionally, they offer greater system design flexibility. In particular, polymer reflectors enable the use of a stretched-membrane concept (an innovative, low-cost concentrator design) for concentrating collectors. The structure of such mirrors is shown in Figure 3. Because metallization with silver provides the highest level of reflectance, the main thrust of recent development efforts has focused on silvered polymer reflector materials.

Figure 4 shows a chronology of how the cost per performance (durability of specular reflectance) ratio of silvered polymer reflector materials has dropped with R&D advances. In the early 1980s, a number of candidate metallized reflector materials were evaluated, including acrylic, silicone, fluoropolymers, polyacrylonitrile (PAN), polycarbonate, and polyester films. Both silver and aluminum reflective layers were considered. Based on screening tests, acrylic (primarily polymethylmethacrylate [PMMA]) was determined to be the most promising polymer candidate from a performance perspective. A collaborative effort was initiated between NREL and the 3M Company (a leading manufacturer of PMMA films) to develop a commercial metallized PMMA film for solar applications.

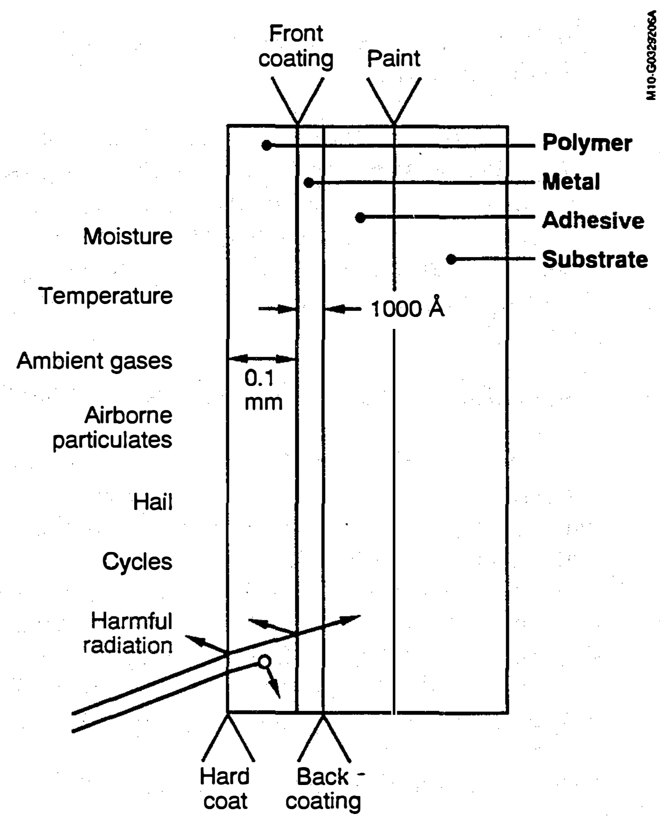

Figure 3. Metallized Polymer Reflector Construction

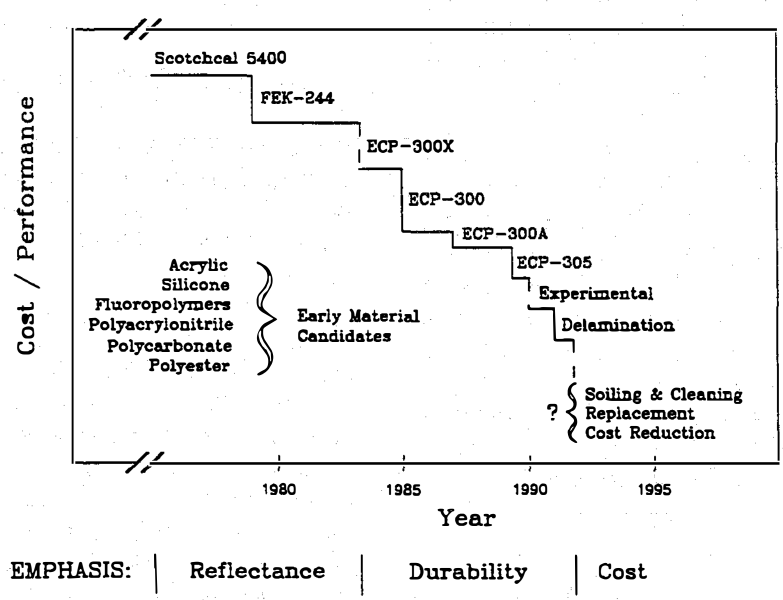

Figure 4. Improvement in Cost Per Performance Ratio with Time/R&D for Various Metallized Polymer Reflectors

Prior to 1984, improvements in specular reflectance were emphasized. Between 1984 and 1991, improvements in optical durability were stressed. Through the development of a series of improved products, substantially enhanced optical durability has been demonstrated in accelerated weathering tests. Data for samples of 3M's latest commercial product (ECP-305) weathered for 2 years at outdoor test sites in Arizona (Figure 5) and Florida indicate maintenance of real world optical durability as well. An experimental enhancement of ECP-305 has been developed at NREL. Based upon accelerated testing of this material, even further improvement in optical durability is expected.

As the optical durability problems have been addressed, the principal way to further reduce the cost-per-performance ratio of such solar reflector materials is to decrease cost. In response to this realization and to feedback from the solar manufacturing industry that cost is a driving issue, the development of low-cost reflector materials has emerged a key thrust of NREL's reflector material program.

REFLECTOR MATERIAL GOALS

Performance of silvered polymer films has been evaluated at NREL by accelerated testing methods as well as outdoors. These materials are likely to meet the DOE STE programmatic performance goals set in 1986 of maintaining greater than 90% specular reflectance for at least 5 years in outdoor service. However, the cost of these products (~\$22/m^2; \$2/ft^2) remains too high for solar thermal electric applications.

New goals have evolved based on the aspirations and recommendations of the solar industry. These more aggressive goals call for mirrors that maintain high specular reflectance for extended lifetimes (typically at least 10 years) under outdoor service conditions and whose cost to concentrator manufacturers is likely to be less than ~\$11/m^2 (\$1/ft^2).

Compatibility with low-cost concentrator designs is an important criterion for advanced reflector materials. Low weight, shape flexibility, and formability offer optimum potential in this regard. Manufacturability in terms of web width, lamination, and other such characteristics is also critical. Mirrors that exhibit abrasion resistance, cleanability, and replaceability are desirable as well.

CANDIDATE REFLECTOR MATERIALS

Several classes of candidate advanced materials have been identified. These include, but are not limited to, protected front surface reflectors, improved metallized polymer films, and thin glass mirrors. The state of the art in front surface reflector technology has progressed to where durability problems can potentially be solved. Whether production scale-up is economically possible remains a concern. A number of candidate alternative polymer films have been suggested for use as

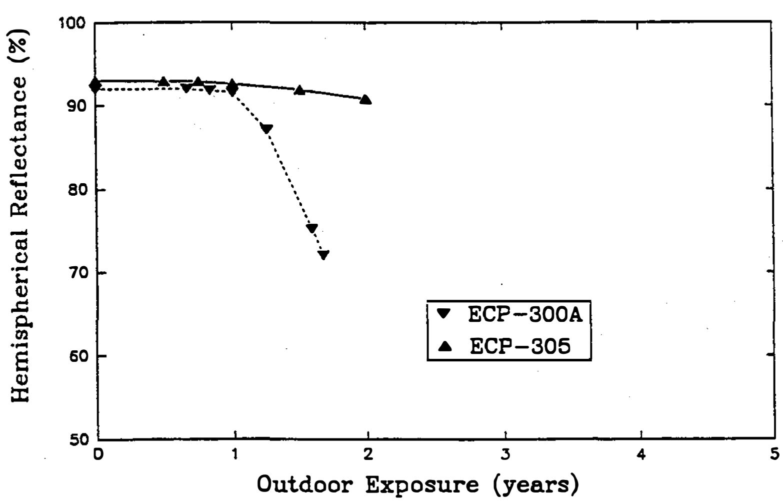

Figure 5. Solar-weighted hemispherical reflectance of silvered polymer reflectors as a function of outdoor exposure in Phoenix, AZ

reflector superstrates and are being considered. Recent interest in thin glass has been expressed by several U.S. manufacturers as well as by companies in Europe and Japan.

Candidate materials are identified based on their likelihood of being able to maintain performance and durability and offer the potential for lower cost. Promising sample constructions are either provided by industry partners or fabricated in house. In addition, extensive optical characterization and durability testing is carried out at NREL for candidate materials in support of industry.

A number of collaborative cost-shared R&D efforts have been initiated with industrial partners. These include a directly deposited reflective surface, a metal/polymer multilayer stack construction, an enhanced version of ECP-305, a metallized fluoropolymer reflector, and an all-polymeric solar reflector material.

Front Surface Reflectors

Front surface reflectors generally have the following construction:

- A substrate material that can provide some degree of mechanical integrity (such as thin or sheet stainless steel or aluminum or a polymer film such as polyethylene terephthalate, PET)
- A levelizing layer to provide a smooth surface to enhance specular reflectance
- A metal reflective layer (typically silver or aluminum)
- A thin, optically clear protective top coating.

Both organic and inorganic candidate top coat materials are being evaluated. Organic layers of organosilicone, polyurethane (PUR), and acrylic are being considered. Inorganic coatings such as Si_3N_4, diamond like carbon (DLC), SiO_x, Al_2O_3, and other oxides are under test. Organic/inorganic composite coatings have also been suggested.

Science Applications International Corporation (SAIC) has assembled a team that is interacting with NREL in a project to develop a directly deposited reflector material. The proposed construction is shown in Figure 6. This approach uses a commercial coating

Abrasion-Resistant Hardcoat
Primer
Reflective Layer
Adhesion Layer
Levelizing Layer
Primer
Substrate (Stainless Steel, Al)

Figure 6. SAIC Sample Construction

material, which has demonstrated outdoor weatherability, as a levelizing undercoat and a protective top layer. This coating is applied to thin metal substrates suitable as structural membranes for solar concentrators. A reflective metal layer is applied prior to the final top protective coating.

Battelle Pacific Northwest Laboratory (PNL) will use a polymer multilayer (PML) technology to fabricate samples having the construction shown in Figure 7. The PML is intended to encapsulate the silver reflective layer to prevent corrosion. The PML is deposited by a vacuum flash evaporation technique compatible with standard vacuum deposition of the reflective layer. This process has the potential for extremely high line speeds and consequent low production cost.

A number of variations of SiO_x overcoated silver have been tried at NREL. Following sputter deposition of SiO_x over silvered PET, samples have been post-treated in both boiling water and nickel acetate solution to try to densify the coating. To date, no material

Top Hard Coat (None or Si_3N_4)
Polymer MultiLayer (PML or None)
Reflective Layer (Sputtered Ag)
Polymer Multilayer (PML)
Substrate (Al, PET)

Figure 7. PNL Sample Construction

prepared in house has exhibited optical durability in accelerated Atlas Weather-Ometer (WOM) exposure. Recent analytical techniques have been used to quantify the nature of the SiO_x coating. X-ray photoelectron spectroscopy (XPS) suggests that the stoichiometry of the coating is SiO_2. Scanning electron microscopy (SEM) photographs of these coatings display a highly porous structure (Figure 8) which presumably results in poor optical durability. NREL is now exploring alternate ways of obtaining denser SiO_x coatings such as ion-assisted deposition to provide greater optical durability. Whether such a process is compatible with production scale-up must be addressed [11].

A series of five candidate organic top coated reflector materials provided by industry have recently been tested at NREL. These are all 7-mil PET substrates having a sputter coated aluminum reflective layer.

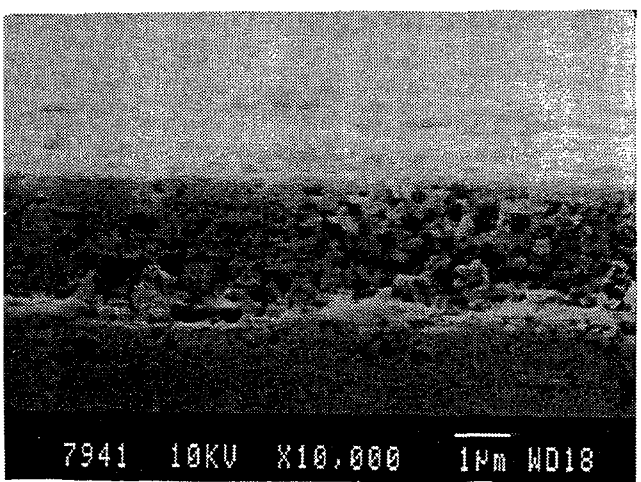

Figure 8. Porous SiO_2 coating (1μ)

The five protective top coatings are a proprietary scratch-resistant coating (SRC), a UV-cured acrylic, a low emissivity coating, a thermal-cured organosilicone, and a UV-cured organosilicone. The organosilicone-coated materials and the SRC overcoated samples have maintained their initial solar-weighted, hemispherical reflectance (H_s) values. Both the UV-cured acrylic and the low emissivity overcoated materials, however, have exhibited a loss in H_s. After 3 months exposure, all five materials exhibited a hazy, nonspecular appearance.

Improved Metallized Polymer Reflectors

A program to improve ECP-305 specular silver reflective film has been pursued with the 3M Company. Previous accelerated exposure tests at NREL have demonstrated increased corrosion resistance of silvered PMMA film reflectors having thick protective back coatings of copper. A new collaborative effort with the 3M Company is intended to incorporate the NREL innovation into a pilot-plant version of this material. Because the economic viability of incorporating back protective layers into the 3M production process is a strong function of the thickness of the coating, thinner layers of copper have been suggested.

To evaluate the effectiveness of such coatings, NREL prepared samples having protective back coatings of 0, 100, 300, and 500 Å; these have been subjected to accelerated exposure testing in both the solar simulator chamber and the WOM. Figure 9 presents H_s as a function of exposure time in the solar simulator chamber for samples having each of the coating thicknesses being tested. After roughly 300 hours, the

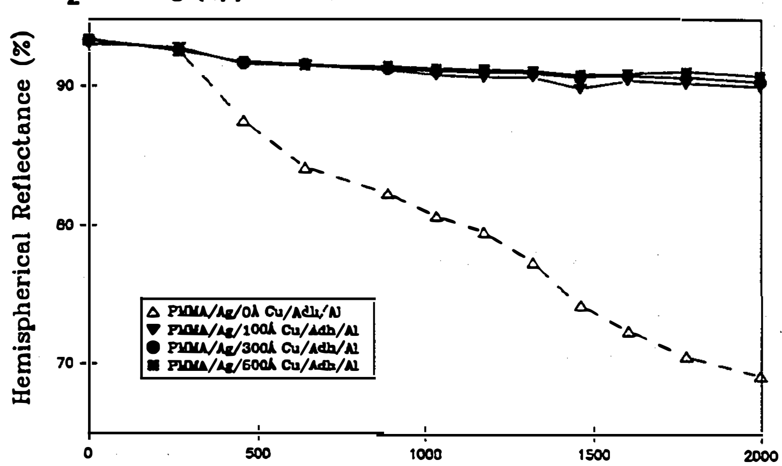

Figure 9. Solar weighted hemispherical reflectance of silvered PMMA reflectors, having back protective copper layers of various thicknesses, as a function of accelerated exposure in NREL's solar simulator chamber

sample without any protective backing exhibited significant optical degradation. After 2000 hours exposure, all samples having protective coatings (even as thin as 100 Å) maintained good optical performance.

Industrial Solar Technology (IST) has teamed with members of the polymer film and metallization industries to develop a reflective Teflon™ film for solar applications. IST's proposed construction is shown in Figure 10. Teflon™, a fluorinated ethylene propylene (FEP) copolymer film with outstanding outdoor weathering properties, provides the front surface protective layer. A nominal thickness of 2 mils has been chosen to minimize handling difficulties associated with thinner films, while still maintaining excellent optical clarity and low cost. To minimize corrosion problems, the silver reflective layer is encapsulated between a transparent, adhesion-promoting barrier interlayer and an opaque back coating.

Top Protective Film (2 mil Teflon™)
Metal Interlayer (Au, Cu, Cr, Ti)
Reflective Layer (Ag)
Back Protective Layer (Inconel, Cu, Cr, Nichrome)

Figure 10. IST Sample Construction

A number of candidate samples designed to have improved corrosion resistance have been fabricated and subjected to accelerated exposure testing in the WOM. The interlayers were generally thin (20Å) metallic layers. The back coatings were also metallic layers of greater thickness (300-400Å). Samples having gold and copper interlayers significantly degraded after only 1 month exposure in the WOM. Visually, the samples with chromium and nichrome back layers had also degraded. Samples having both chromium interlayers and copper back layers have H_s below 90% (even prior to exposure). Samples with copper back protection and either no interlayer or a titanium interlayer have exhibited the best optical durability.

Other Reflectors

Dow Chemical Company is developing an all-polymeric solar reflector material. This approach uses alternating coextruded layers of low-cost commercially available transparent thermoplastics. This concept is shown schematically in Figure 11. Abrasion-resistant top coatings that incorporate UV protection will be evaluated.

Preliminary results associated with a number of candidate front-surface aluminum mirrors for UV reflectance applications have been previously reported [12]. These mirrors have very dense protective top coats deposited via a low-voltage, ion-plating process. These materials demonstrate a high degree of optical durability. As with ion-assisted deposition, the question of process scale-up has to be considered.

SUMMARY

To make a number of solar concentrator technologies economically viable, a clear need exists for inexpensive, optically durable reflector materials. Such mirrors must meet fairly severe performance and lifetime criteria while maintaining low cost. A wide range of candidate advanced solar reflector materials have been identified and are being tested. NREL works closely with solar manufacturers in developing such materials and would welcome suggestions and innovative proposals from the vacuum coating and polymer film industries for alternative approaches to achieving these goals.

Abrasion-Resistant Hardcoat
Polymer A (N_1)
Polymer B (N_2)
Polymer A (N_1)
Polymer B (N_2)
• • •
Polymer A (N_1)
Polymer B (N_2)

Figure 11. Dow Sample Construction

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