NREL/TP-471-7018 • UC Category: 1233 • DE95000248

Advanced Reflector Materials for Solar Concentrators

Gary Jorgensen
Tom Williams
Tim Wendelin
National Renewable Energy Laboratory

Prepared for the 7th International Symposium on Solar Thermal Concentrating Technologies, Moscow, Russia, September 26–30, 1994

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

A national laboratory of the U.S. Department of Energy
managed by Midwest Research Institute
for the U.S. Department of Energy
under Contract No. DE-AC36-83CH10093

October 1994

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling (615) 576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

Printed on paper containing at least 50% wastepaper and 10% postconsumer waste

ADVANCED REFLECTOR MATERIALS FOR SOLAR CONCENTRATORS

Gary Jorgensen
Tom Williams
Tim Wendelin

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401
USA

ABSTRACT

This paper describes the research and development program at the U.S. National Renewable Energy Laboratory (NREL) in advanced reflector materials for solar concentrators. NREL's research thrust is to develop solar reflector materials that maintain high specular reflectance for extended lifetimes under outdoor service conditions and whose cost is significantly lower than existing products. Much of this work has been in collaboration with private-sector companies that have extensive expertise in vacuum-coating and polymer-film technologies. Significant progress and other promising developments will be discussed. These are expected to lead to additional improvements needed to commercialize solar thermal concentration systems and make them economically attractive to the solar manufacturing industry. To explicitly demonstrate the optical durability of candidate reflector materials in real-world service conditions, a network of instrumented outdoor exposure sites has been activated.

KEYWORDS

Solar thermal optical materials, heliostats, concentrator costs

1.0 INTRODUCTION

Advanced optical materials are one option that show promise for dramatically reducing the life-cycle cost of concentrators for solar thermal power systems. Concentrator costs are a major portion of the total costs of a solar thermal system. For example, the heliostats used in power-tower systems are projected to account for about 40%-50% of the total cost of the power plant. Concentrator costs constitute a similar percentage of dish/engine systems. There is, therefore, a strong incentive to reduce concentrator costs in order to develop more economical solar thermal electric (STE) systems.

One of the most promising ways for reducing concentrator costs involves the use of advanced optical materials in stretched-membrane designs. Properly designed stretched-membrane concentrators have two potential cost advantages over today's concentrators that use glass mirrors. First, stretched-membrane designs can use less material than do glass mirrors mounted on metal frames, which directly lowers material costs. Second, stretched-membrane concentrators can use lighter-weight support structures and sun-tracking mechanisms. Cost projections estimate that stretched-membrane designs can reduce the initial costs of conventional glass-mirror heliostats by one-third or more. For 200-MWe power-tower plants, the initial cost savings represented by using a stretched-membrane heliostat would be approximately $550/kWe. Reflective films made from new optical materials are the central component of high-performance concentrators made from stretched membranes.

Glass mirrors are generally considered to be the baseline reflector material for solar thermal electric applications. Glass mirrors have high specular reflectance (typically 91% at 8 mrad full-acceptance angle), long lifetimes, durability in the field, and (usually) modest degradation of reflectivity over the concentrator lifetime. Drawbacks of glass include weight, fragility, and expense. Relative to glass, polymer mirrors have advantages of being flexible, lightweight, and less expensive, but they have lower durability and shorter lifetimes than glass mirrors.

Recent improvements have been made in the performance and durability of silvered-polymer reflector materials [1,2]. In the past, NREL has worked to achieve the STE program's 5-year goals [3] for these materials' performance, durability, and cost. The current commercially available state-of-the-art silvered-polymer reflector (ECP-305, developed jointly by NREL and the 3M Company) meets these goals.

Members of the solar manufacturing industry have proposed new goals, including mirrors that maintain high specular reflectance for extended lifetimes (typically at least 10 years) under outdoor service conditions and whose cost to concentrator manufacturers may be less than $\$11/m^2$. To achieve these considerably more aggressive targets, effective collaboration with companies in the vacuum-coating and polymer-film industries is emphasized.

Degradation problems with solar reflector materials can prove very expensive, and methods of predicting outdoor service life are seen as critical for commercial deployment of new materials. While accelerated testing is commonly used to screen materials for concentrating solar thermal applications, little work has been done to correlate accelerated test results with actual outdoor weathering patterns. NREL has recently established a program of outdoor testing of reflector materials at a variety of sites [4] to obtain data that can be correlated with accelerated testing results. Current sites are established across the Southwestern United States. Meteorological data are continuously monitored at the sites, and samples are characterized regularly to evaluate the impacts of weathering.

2.0 PROGRAM STRUCTURE

NREL's overall goal in this area is to achieve significant reductions in the cost of solar thermal power by developing advanced optical materials. This goal requires products successful in the laboratory, on the manufacturing shop floor, and in the field where they are deployed. Achieving this goal requires effective collaboration with materials manufacturers, solar concentrator manufacturers, and users/owners of solar technology. NREL's program is structured around the following activities:

- Concept Investigation—Identifying new optical materials and laboratory verification of performance properties and projected life.
- Outdoor Testing—Controlled monitoring and testing of promising materials to develop better predictions of actual service life.
- Manufacturability Investigation—Investigating promising concepts to determine how they could be manufactured and whether the quality of the manufactured version meets or exceeds the laboratory scale materials.
- Commercial Testing—Producing commercial-grade materials and testing at scales and conditions that replicate commercial solar thermal projects.

Activities in each of these areas are discussed below.

3.0 CONCEPT INVESTIGATION

Concept investigation is conducted at laboratory scale. The work is split roughly evenly between activities conducted by NREL researchers and collaborative efforts with industry. By involving industry in the earliest stages of the research and development process, the number of promising candidates can be expanded and practical issues of materials manufacturing can be considered. Efforts in this area typically involve production of small samples of material, testing for optical and mechanical properties, and accelerated weathering testing.

3.1 Protective Top Coats

One of the most promising ways to reduce the cost of solar mirrors is to metallize an appropriate and inexpensive substrate material such as a polyethylene terephthalate (PET) film and then overcoat the reflector with an abrasion-resistant, durable, protective top layer. Some reflectors having this generic construction have demonstrated promising results in accelerated durability tests at NREL, indicating that such materials may ultimately achieve the cost and performance goals of the program. Candidate top layers can be either organic (such as organosilicones, polyurethanes, or acrylics) or inorganic (such as Si_3N_4, diamond-like carbon, SiO_x, Al_2O_3, and other oxides). Organic/inorganic composite coatings have also been suggested.

NREL has explored several top-coat options. Experimental mirrors having Si-O bonds have performed remarkably well in accelerated exposure tests. A number of variations of SiO_x-overcoated silver samples have been tested at NREL. Following sputter deposition of SiO_x over silver, samples have been post-treated in both boiling water and nickel acetate solution in an attempt to densify and/or seal the coating. Optical durability has been poor in accelerated exposure tests by materials prepared at NREL having the following construction:

SiO_x / Ag / PET

The nature of these SiO_x coatings has been quantified by analytical techniques at NREL. X-ray photoelectron spectroscopy (XPS) suggests the stoichiometry of the coating is SiO_2. Scanning electron microscopy (SEM) photographs show that thick films (~10,000 Å) exhibit a highly porous structure which presumably results in poor optical durability. NREL is presently exploring alternate ways of obtaining denser SiO_x coatings to provide greater optical durability. One approach—ion-assisted deposition—will be attempted in collaboration with the Pacific Northwest Laboratory (PNL).

Polyurethane (PUR) has also been evaluated as a protective top coat for silver reflector materials. The hemispherical reflectance of samples comprising silver protected by polyurethane paint having ultraviolet absorber additives has generally degraded during accelerated exposure testing. This has been true for samples on both glass and PET substrates, with and without copper protective layers behind the silver.

3.2 Directly Deposited Reflector Material

NREL recently completed a collaborative study with Science Applications International Corporation (SAIC) investigating directly deposited solar reflector materials. The basic construction pursued by SAIC was:

Top coat / Reflective layer / Levelizing layer / Substrate

The advantage of such a material is that it eliminates the need for adhesives and lamination during the manufacturing process, the substrate provides back protection, and it has potential low cost. A number of commercial organic-coating materials were tested for use as both a protective top coat and as a levelizing layer. Several materials provided acceptable levelization (in terms of specularity) but none have provided adequate protection of the metal reflective layer. Samples have severely degraded in accelerated exposure testing at NREL. Many candidate top coats yellowed during weathering. Interlayer adhesion was also a problem. Often the levelized reflective layers flaked off upon flexure of the thin metallic substrates. Another approach called transfer coating was attempted but was unsuccessful. This work has demonstrated the limitations of this technology for solar applications.

3.3 Silvered Teflon™ Reflector Material

Industrial Solar Technology Inc., has been working with NREL to develop a silvered Teflon™ solar reflector material. The advantages of such a mirror include the fact that Teflon™ is an inherently weatherable and nonhygroscopic material, has good barrier properties, and exhibits a low surface energy which may reduce soil retention. The specular reflectance of unweathered samples is generally low (typically 80% at 650 nm and 8-12 mrad full-acceptance angle, with >90% being the goal). Significant progress has been made in understanding the problem of wide-angle scattering and in identifying ways to improve specularity. Candidate corrosion-resistant constructions have been fabricated that exhibit promising optical durability in accelerated exposure tests.

3.4 Polymer MultiLayer Reflector Material

Under a subcontract with NREL, the Pacific Northwest Laboratory (PNL) has initiated work on developing a polymer-silver deposition process for fabricating solar reflector materials on flexible plastic substrates [5]. These efforts build on previous developments and capabilities at PNL where researchers will use their Polymer MultiLayer (PML) technology to fabricate samples of the following construction:

$$\mathrm{Si_3N_4} \text{ and-or PML / Ag / PML / Substrate}$$

where Si_3N_4 represents a candidate protective top hard coat. The PML is intended to encapsulate the silver reflective layer to prevent corrosion. Deposition of the PML is accomplished by a vacuum flash-evaporation technique compatible with standard vacuum deposition of the reflective layer (i.e., without breaking vacuum between layers). This process has the potential for extremely high production-line speeds and consequent low production cost.

A number of additional candidate samples are being prepared by PNL. A variety of ion-assisted sputter-deposited hard coats will be applied to silvered PET film. The ion-assisted coatings are intended to result in dense structures for improved (compared to non-assisted) optical durability.

3.5 All Polymeric Reflector Material

Dow Chemical Company is exploring a concept that uses alternating coextruded layers of low-cost commercially available transparent thermoplastics to produce all-polymeric reflector materials. Because this concept is an all-polymeric design, degradation of optical performance caused by corrosion of metallic reflecting layers is not a concern. Another attractive feature of this approach is that such reflector materials can be directly thermoformed into useable structures, thereby reducing costs associated with support elements. Efficient broadband solar reflectors are envisioned that would be fabricated from a high-speed, low-cost technique that has been commercially demonstrated. Concerns regarding this concept include the level of reflectance that may be achievable, the possibility of scattering losses and loss of reflectance with incident angle, and adhesion between the multilayers. Samples have been provided to NREL that are 60 mils thick and comprise 5000 alternating coextruded layers having a tailored gradation in layer thickness designed to result in a reflectance of approximately 90% throughout the visible spectrum (400-1800 nm). Samples have been optically characterized at NREL and are being subjected to accelerated durability testing.

3.6 Adhesively Bonded Reflector Material

New solar reflector samples have been jointly prepared by NREL and a potential large-scale solar manufacturing company, Cummins Power Generation (CPG). In support of the Dish/Stirling Joint Venture Project, a matrix of Tefzel™ / silvered PET laminated samples was fabricated. 1000-Å silver was sputter deposited at NREL onto three different candidate PET film substrate materials provided by CPG. Two thicknesses of Tefzel™ top film were then laminated to the silvered PET using two different types of adhesives. The various combinations of samples were bonded by CPG to tension frames prior to initial optical characterization. This general material construction is of interest because it is a potentially low-cost reflector. In addition, problems with poor specular reflectance associated with metallizing fluoropolymer films could be avoided with this approach. The main performance concern is the durability of the adhesive layer during weathering. Samples subjected to accelerated exposure testing at NREL generally have not weathered well; the adhesive layer tends to blacken fairly readily.

4.0 OUTDOOR TESTING

Because the optical durability of new candidate materials remains uncertain, the demonstration of their longevity during real-world exposure is critical to reducing perceived risks associated with solar thermal technologies. Consequently, it is important to demonstrate to potential investors and manufacturers the optical durability of candidate reflector materials in outdoor environments that are representative of prospective sites for solar system installation. Outdoor testing in a variety of environments also provides data that can hopefully lead to better correlations between accelerated testing results and actual experience in commercial applications.

NREL's outdoor exposure testing network provides a diverse set of environmental conditions for materials exposure. To determine the most useful locations, a set of criteria was used to evaluate candidate sites. The utility industry and the solar power manufacturing industry were involved to generate interest and support for solar thermal technologies and to identify sites deemed suitable for future solar thermal energy production. Thus, initial industry contacts were directed primarily at utilities and companies that already have shown interest in solar thermal technology as a possible renewable energy source.

Five sites are currently operational across the Southwestern United States. Other sites, including a coastal location representative of third-world applications, are being considered. NREL is also exploring international cooperative efforts.

5.0 MANUFACTURABILITY INVESTIGATION

Materials that offer promise from accelerated and outdoor screening test results are considered candidates for pilot-scale manufacturing. This scaleup is very important in assessing the real value of the materials, because the requirements of mass production can affect the desirable properties of a material. These types of studies are typically conducted by a cost-shared subcontract to a materials producer, and they result in moderate quantities of material produced in pilot-scale manufacturing levels.

An example of this process is the development, under a collaborative cost-shared subcontract between NREL and the 3M Company, of a commercial solar reflector designated ECP-305+. 3M incorporated an NREL innovation [6] in which a protective back-coating (behind the silver reflective layer) of copper is deposited during the production process. In accelerated exposure testing, ECP-305+ has demonstrated dramatically improved resistance to corrosion and delamination failures compared to other silvered polymer reflectors. Based on results of these tests, NREL believes the ECP-305+ could have an effective lifetime of 10 years or more in good environments. In addition, cost projections indicate that high-volume production of such a product could reduce the price to solar manufacturers to almost \$11-/m^2, meeting goals suggested by the industry. Solar manufacturers are eager to begin deploying this material in field installations.

6.0 COMMERCIAL TESTING

Materials that appear promising following pilot-scale production are tested in environments that simulate a commercial deployment of the material. Experience over the last decade has taught us that there is, unfortunately, no substitute for this real-world testing. The variation of concentrator designs, manufacturing processes, and environments introduces more uncertainty in predicting lifetime and failure mechanisms than can be accommodated by either accelerated testing or outdoor testing. In addition, the commercial testing directly involves the concentrator supplier, giving them firsthand experience with all aspects of working with the new material.

Prospective solar manufacturers have expressed keen interest in test deployments of ECP-305+. NREL has provided significant quantities of ECP-305+ to interested solar manufacturers for field deployment/demonstration purposes. Industrial Solar Technology has begun a commercial solar heat project using ECP-305+ as the reflective surface for a parabolic trough. The commercial system will deploy approximately 7000 ft^2 of troughs to provide hot water at a Colorado state facility. NREL has also provided roughly 8000 ft^2 of ECP-305+ to Cummins Power Generation for field deployment / demonstration purposes associated with their Dish/Stirling Joint Venture Project. Delamination failures of the reflector material have occurred on a number of dish facets used in CPG's two prototype installations which simulate commercial systems. Initial failure analyses indicate that such problems may be design specific, and solutions may be relatively easy to implement. These results clearly show the importance and necessity of commercial-scale testing of new reflector materials.

7.0 FUTURE DIRECTIONS

Development of a reflector material that can provide a high level of specular reflectance outdoors for more than 10 years is not an easy problem. The outdoor environment is particularly severe, and long-term weatherability under service conditions is difficult to achieve. For example, in the automotive industry, clearcoats are considered to be very durable (in terms of protecting paint undercoats) if they last 5 years [7]. Protection of metal reflective layers is considerably more difficult. Although progress with solar reflectors has occurred, additional work is needed. Unexpected catastrophic failures (such as delamination) can occur, obviating the need for commercial field testing. In addition, several gaps exist in program activities that are important to the successful commercialization of advanced reflector materials. These include anti-soiling strategies and better service-life prediction capabilities.

As improvements in optical durability of silvered-polymer reflectors are demonstrated, samples will experience longer-term exposure. This, coupled with the evolution of candidate front-surface reflectors, will make the need for greater abrasion resistance and better cleaning techniques more critical. Thus, anti-soiling mechanisms and innovative cleaning strategies must be addressed. Some scoping studies in this area have been carried out, but the efforts have not been commensurate with needs. New areas for investigation include low-surface-energy surfaces and renewable surface treatments.

Because emerging advanced reflector materials are expected to demonstrate increased lifetimes, new approaches to service-life prediction are necessary. The use of real-time weathering will become less viable for such long-lived materials. Industry simply cannot afford to wait 10 years to find out if materials will be capable of such lifetimes. Thus, the importance of accelerated test methods will increase. Recent attempts to predict material performance in exterior environments from results obtained in accelerated aging tests have proven to be frustrating and inconclusive. Significant resources and a multidisciplined approach is necessary to address this complex problem.

8.0 ACKNOWLEDGEMENTS

This work was sponsored by the U.S. Department of Energy under contract DE-AC02-83CH10093.

9.0 REFERENCES

1. Kennedy, C., and Jorgensen, G., "Progress in the Development of Advanced Solar Reflectors," *Proceedings of the Seventh International Conference on Vacuum Web Coating, Miami, FL, November 10-12, 1993*, Bakish, R., ed., Bakish Materials Corp., Englewood, NJ.

2. Schissel, P., Jorgensen, G., Kennedy, C., and Goggin, R., "Silvered-PMMA Reflectors," *J. Solar Energy Materials and Solar Cells*, to be published.

3. *U.S. Department of Energy, National Solar Thermal Technology Program, Five Year Research and Development Plan 1986-1990*, DOE/CE-0160, September 1986.

4. Wendelin, T., and Jorgensen, G., "An Outdoor Exposure Testing Program for Optical Materials Used in Solar Thermal Electric Technologies," ASME International Solar Energy Conference, San Francisco, CA, March 1994.

5. Affinito, J., et al, "Vacuum Deposited Polymer/Silver Reflector Material," International Society for Optical Engineering (SPIE) meeting in San Diego, CA, July 27, 1994.

6. Schissel, P., et al, "Durable Metallized Polymer Mirror," U.S. Patent granted, issuance pending, 1994.

7. Bauer, D.R., "Chemical Methods for Predicting Automotive Coating Weatherability," *Proceedings of the American Chemical Society Division of Polymeric Materials: Science and Engineering*, Vol. 68, Spring Meeting 1993, Denver, CO, April 1993, pp. 62-63.