NREL/TP-471-7022 • UC Category: 1300 • DE95000260

State-of-the-Art Low-Cost Solar Reflector Materials

Cheryl Kennedy
Gary Jorgensen
National Renewable Energy Laboratory

*Prepared for the 8th International
Vacuum Web Coating Conference,
Las Vegas, Nevada,
November 6–8, 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

November 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

STATE-OF-THE-ART
LOW-COST SOLAR REFLECTOR MATERIALS

C. Kennedy and G. Jorgensen
National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, CO 80401

ABSTRACT

Solar thermal technologies generate power by concentrating sunlight with large mirrors. The National Renewable Energy Laboratory (NREL) is working with industrial partners to develop the optical reflector materials needed for the successful deployment of this technology. The reflector materials must be low in cost and maintain high specular reflectance for extended lifetimes in severe outdoor environments. Currently, the best candidate materials for solar mirrors are silver-coated low-iron glass and silvered polymer films. Polymer reflectors are lighter in weight, offer greater flexibility in system design, and have the potential for lower cost than glass mirrors. In parallel with collaborative activities, several innovative candidate reflector-material constructions were investigated at NREL. The low-cost material requirement necessitates manufacturing compatible with mass-production techniques. Future cooperative efforts with the web-coating industry offers the promise of exciting new alternative materials and the potential for dramatic cost savings in developing advanced solar reflector materials.

INTRODUCTION

Solar thermal technologies generate power by using large mirrors to concentrate sunlight. Durable, high performance, inexpensive reflector materials are of critical importance to the solar manufacturing industry in the commercialization of these technologies (1). Currently, several dish concentrator programs are being developed jointly by the U.S. Department of Energy (DOE) and industry, and a large central receiver power plant is being activated under the auspices of DOE and a consortium of nine public utility companies. These programs emphasize the importance of the commercial availability of quality reflector materials for all solar concentrator technologies.

The National Renewable Energy Laboratory is responsible for developing optical reflector materials suitable for solar thermal concentrating systems. The present state of the art in reflector materials for solar concentration includes back-silver-coated low-iron glass and silvered polymer films. These materials meet the past programmatic performance goals of maintaining greater than 90% specular reflectance for at least 5 years in outdoor service (2). However, the cost of these products (\$2.00–\$3.00/ft^2)

remains higher than that needed to make solar thermal electric systems economically viable. New goals have emerged for mirrors that maintain high specular reflectance for extended lifetimes (at least 10 years) under outdoor service conditions and whose costs are less than \$1.00/ft^2. This paper will examine some of the materials proposed to meet these challenging conditions.

SOLAR REFLECTOR MATERIALS

Notable progress has been made during the past year in developing advanced reflector materials for solar concentrator applications. Collaborative cost-shared research and development (R&D) with industrial partners has resulted in the following: a commercial silvered-polymer solar reflector, designated ECP-305+ by the 3M Company, which offers increased durability (3); samples of an all-polymeric reflector material prepared by the Dow Chemical Company; and the increased potential of silvered Teflon™ as a candidate mirror material. Research at NREL has also identified several innovative reflector concepts.

Silvered Polymer Reflector Material (ECP-305+)—Collaborative research by NREL and the 3M Company between 1984 and 1991 led to a silvered polymer reflector material (ECP-305) of high optical quality and improved outdoor durability (4). The acrylic polymer is polymethylmethacrylate (PMMA). Silver is used as the reflective layer, because it reflects more than 90% of the terrestrial solar resource.

A commercial run of a highly durable metallized polymer solar reflective material (ECP-305+) was completed under a collaborative cost-shared subcontract between NREL and the 3M Company. Figure 1 shows the construction of ECP-305+, where the major changes from ECP-305 are the addition of the copper back layer and a reformulation of the pressure-sensitive adhesive. Figure 2 demonstrates that compared to other silvered polymer reflectors, ECP-305+ exhibits dramatically improved resistance to corrosion during accelerated exposure testing. Results of accelerated tests also demonstrate the material's improved resistance to delamination. ECP-305+ is undergoing continued accelerated exposure testing and outdoor exposure at NREL's outdoor test sites. Based on results of these tests, NREL believes that ECP-305+ could have an effective lifetime of 10 years or more in good environments.

Based on earlier experience with ECP-305, members of the solar manufacturing industry are very excited about ECP-305+ and are eager to have access to the commercial material for the purpose of prototype demonstration. NREL has provided significant quantities of ECP-305+ to interested solar manufacturers for field deployment and demonstration purposes. ECP-305+ is being used in a parabolic trough as the reflective surface for a commercial solar heat project. The project will deploy about 7000 ft^2 of line-focus concentrators to provide hot water for a Colorado state facility. NREL has also provided 8000 ft^2 of ECP-305+ for field deployment and demonstration purposes associated with the Dish/Stirling Joint Venture Project (D/S JVP). With the intention of commercialization of solar thermal electric systems, these cooperative efforts dramatically demonstrate an effective interaction between NREL, the solar manufacturing community, and the polymer film and metallization industry.

The dish in the D/S JVP comprises twelve 65-in.-diameter facets. The design uses ECP-305+ laminated to a 4-mil-thick polyethylene terephthalate (PET) substrate. The composite membrane is tensioned and bonded along the periphery to an aluminum ring. To provide edge protection, the edges are bent at 45° into a tuck groove and are caulked. During a severe rain storm, roughly half of the deployed facets experienced some degree of tunneling, in which the top polymer film delaminated from the silver reflective layer in a characteristic tunneling pattern. Examination of the failed facets revealed the start of extensive delamination along the perimeter of the facets, directly above the bond joint and in close proximity to where the edges were bent. The polymer film used in ECP-305+ is a brittle acrylic and is susceptible to cracking when overflexed. The acrylic in the reflective film can swell when it absorbs water. Excessive stress concentrations may build up in the bond between the reflective film and the PET, because of the rigid attachment of the PET substrate onto the ring. Based on these initial findings, we believe that these tunneling problems may be design specific and that solutions may be relatively easy to implement. These results clearly show the importance and necessity of commercial-scale testing of new reflector materials.

Interlayer adhesion failure can limit the performance of the optical components used to convert solar energy into thermal or electric energy. In practice, the bonding between silver and PMMA is weak, particularly in the presence of moisture. Researchers at NREL demonstrated that optically transparent, inorganic interlayers can improve the adhesion between PMMA and silver (5). Calculations of the Lifshitz-van der Waals interaction show that the predicted bonding values are much weaker than the experimental values and cannot explain the strength of silver/PMMA bonding. An alternative model uses Lewis acid-base concepts to explain the observed adhesion. Strongly acidic oxide layers like SiO_2 (and perhaps Cr_2O_3) may be expected to bond well to basic PMMA. Fe_2O_3 is more neutral on a scale of isoelectric points and is predicted not to bond as well to PMMA, while the basic MgO is predicted to bond poorly. Interlayers were deposited between the silver and PMMA to improve adhesion. A thin layer of SiO_2 improved the peel strength significantly without degrading mirror optics. Cr_2O_3 layers also improved peel strength, but these interlayers must be kept thin to maintain optical performance. As predicted oxide layers of Fe_2O_3, being neutral, did not bond as well to PMMA, and MgO interlayers poorly bonded the silver to the PMMA. The MgO layers resulted in weaker bonds than the bonds using Fe_2O_3 interlayers and were much weaker than bonds using SiO_2 or Cr_2O_3. Thus, inorganic interlayers that effectively increase the peel strength were demonstrated, providing some support for the acid-base model for adhesion.

All-Polymeric Solar Reflector Material—A collaborative cost-shared subcontract with the Dow Chemical Company has produced an innovative, all-polymeric solar reflector material. Dow supplied NREL with samples of an innovative, all-polymeric reflector material, specifically designed to match the terrestrial solar spectrum (Figure 3). The samples are 44 mils thick and comprise 4817 alternating coextruded layers of low-cost, commercially available, transparent thermoplastics. A tailored gradation in layer thickness was successfully achieved, resulting in a reflectance of about 80% throughout the visible spectrum (400–1800 nm). We believe that reflectance could be increased above 90% by increasing the number of layers by 5%–30%. Based on economic modeling, the customer cost of this product is estimated to be \$1.50/ft^2. Samples have been optically characterized at NREL and are being subjected to accelerated exposure testing and outdoor exposure at NREL's outdoor test sites. Samples are also being subjected to cyclic delamination testing to investigate interlayer adhesion properties. Figure 4 shows that after 6 months of accelerated exposure testing, the prototype all-polymeric reflectors have maintained their initial reflectance. Results from the final samples are expected to be just as promising. Because of the all-polymeric design, optical performance cannot degrade by the mechanism typical of previously described mirrors—the corrosion of the metallic reflecting layers. Another attractive feature of this all-polymeric design is that the reflector materials can be directly thermoformed into useable structures, thereby reducing costs associated with support elements.

Silvered Teflon™ Solar Reflector Material—In a previous collaborative cost-shared subcontract, a silvered Teflon™ (fluorinated ethylene propylene, FEP) solar reflector material was developed by Industrial Solar Technology (IST) and NREL. Candidate corrosion-resistant constructions (Figure 5) were fabricated that exhibited promising optical durability in accelerated exposure tests but inadequate specularity (Figure 6). Building on the progress demonstrated during the previous collaborative cost-shared subcontract between IST and NREL, a new collaborative cost-shared subcontract is underway. IST will investigate a promising approach to improving the specular reflectance of silvered Teflon™ mirrors by using sol-gel leveling layers deposited prior to metallization of the film. Sol-gel is readily silvered, has excellent flexibility for the thin layers of interest, and could provide improved corrosion resistance by providing an additional barrier layer between the polymer film and the silver layer.

The performance of reflector materials deployed in the field also degrades with dirt retention, independent of corrosion and other failure mechanisms. The reflectors must be cleaned periodically to recover this loss in performance. Economic factors and the rate of soiling determine the frequency of cleaning. Soiling rates are site-specific depending on weather, soil types, and pollution levels (6). Cleaning is the largest cost in maintaining a solar collector field because of the large surface area involved. IST will also explore an innovative cleaning process—a jet-spray technique—that has been demonstrated to be very effective in removing particulates for specialized cleaning tasks within the aerospace and defense industries.

Front-Surface Reflector Materials—One of the most promising ways to reduce the cost of solar mirrors is to metallize an inexpensive substrate material and then overcoat the reflector with a protective top layer (Figure 7). PET is a good choice as a substrate material because it is relatively inexpensive and has good mechanical properties. In some applications, this eliminates the need for the reflector to be laminated to a structural substrate. Silver is the reflective metal of choice, but aluminum could be used. A candidate top layer can be either organic (such as organosilicones, polyurethanes, and acrylics) or inorganic (such as Si_3N_4, diamond-like carbon, SiO_x, Al_2O_3, and other oxides), or a composite of both. To protect the silver, a candidate transparent top coat needs to be dense, abrasion-resistant, adherent to silver, and resistant to cracking. Resistance to soiling by the coating would be a positive feature. Reflectors with organic and inorganic top layers demonstrate promising results in accelerated durability tests at NREL (see Figures 8 and 9), indicating that they may ultimately be capable of achieving the cost and performance goals of the program. Research at NREL and a collaborative cost-shared subcontract are being actively pursued in this area.

Researchers at NREL have prepared an experimental reflector construction that has demonstrated outstanding optical durability during accelerated exposure (Figure 10). PET was used as the substrate material because of its satisfactory adhesion to deposited silver reflective layers, low cost, and good mechanical properties. Silver was sputtered onto the PET and coated with a proprietary organized molecular assembly (OMA). To protect the OMA, a thin layer of the dissolved PMMA resin incorporating ultraviolet stabilizers, which is used in ECP-305, was spin-coated onto the OMA. The spin coating is a similar process to the cost-effective industrial flood-coat processes. The purpose of the OMA was to enhance adhesion between the PMMA and silver layers and to provide corrosion protection at that interface. Figure 11 shows that after 8 months of accelerated exposure in an Atlas Weather-Ometer, the solar-weighted hemispherical reflectance of the experimental construction has remained unchanged at 95.4%. In comparison, ECP-305 laminated to a painted aluminum substrate degraded linearly from 93.0% to 89.7% in the same exposure time. A patent for this innovative concept has been filed by NREL (7).

SUMMARY

During the past year, significant progress has been made in developing advanced reflector materials for solar concentrator applications. Research at NREL has identified several new reflector concepts. Collaborative cost-shared R&D with industrial partners has resulted in:

- a commercial silvered-polymer solar reflector, designated ECP-305+ by the 3M Company, which offers increased durability in terms of corrosion degradation and delamination resistance;
- samples of an all-polymeric reflector material prepared for evaluation by the Dow Chemical Company of Midland, Michigan;
- the increased potential of silvered Teflon™ as a candidate mirror material.

The solar industry is very excited about the enhanced ECP-305+ material, and NREL has provided large quantities to industrial partners for evaluation and prototype demonstration purposes. Additional cooperative efforts with industry offer exciting new alternative materials and the potential for dramatic cost savings as a result of the high-speed production line capability of the web-coating industry.

ACKNOWLEDGMENTS

The authors thank D. King and P. Schissel for their numerous contributions to the success of this project. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-83CH10093.

REFERENCES

1. C. Kennedy and G. Jorgensen, "Progress in the Development of Advanced Solar Reflectors," *Proceedings of Seventh International Conference on Vacuum Web Coating*, Miami, FL, November 1993.

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

3. P. Schissel, C. Kennedy, G. Jorgensen, Y. Shinton, and R. Goggin, "Durable Metallized Polymer", U.S. Patent No. 94906711.0

4. P. Schissel, G. Jorgensen, C. Kennedy, and R. Goggin, "Silvered-PMMA Reflectors," *Sol. Energy Mater.* **33**, 183–197 (1994).

5. P. Schissel, C. Kennedy, and R. Goggin, "Role of Inorganic Oxide Interlayers in Improving Adhesion of Sputtered Silver Film on PMMA," *J. Adh. Sci. Tech.*, to be published.

6. Industrial Solar Technology, *Soiling Rates and Cleaning Techniques for ECP-300*, Final Report, Prepared for the National Renewable Energy Laboratory, Contract No. HL-9-189017-1, 1989.

7. D. King, A. Czanderna, and C. Kennedy, "Molecular Assemblies as Protective Barriers and Adhesion Promotion Interlayer," U.S. Patent, applied for June 10, 1994.

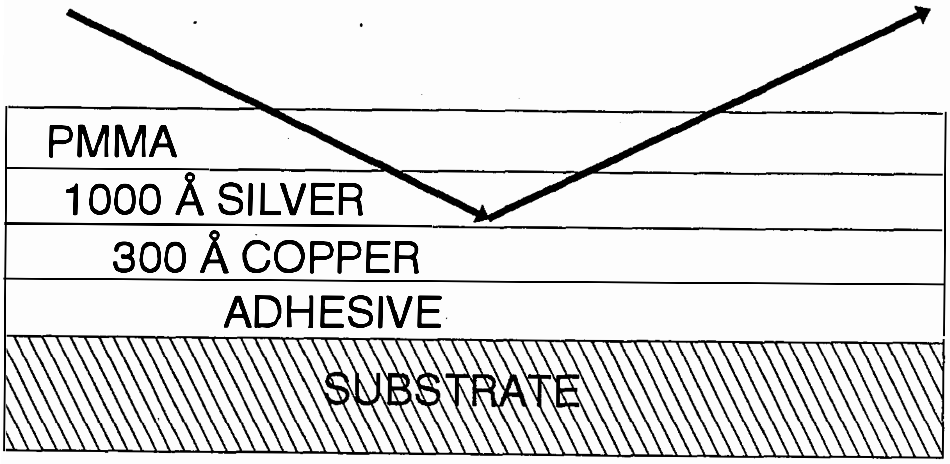

Figure 1. 3M ECP-305+ reflector material construction

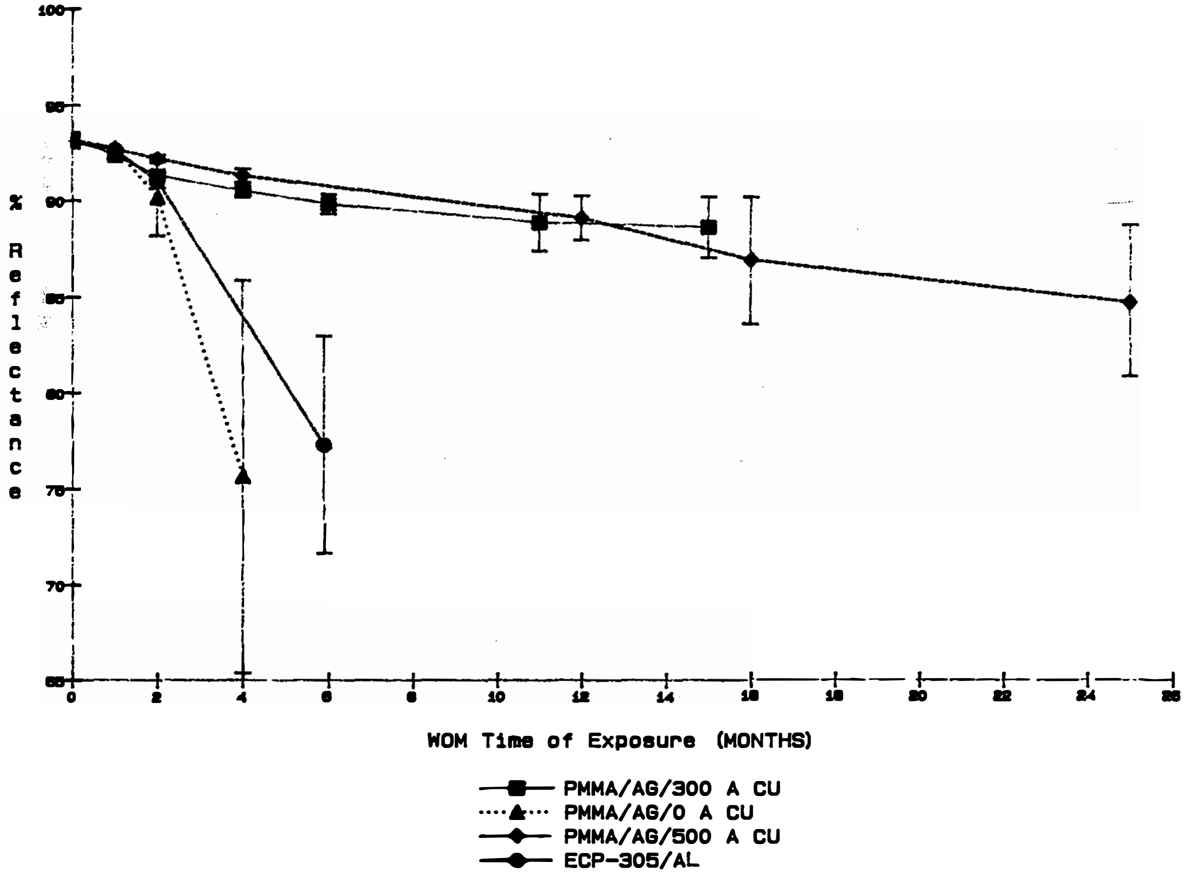

Figure 2. Solar-weighted hemispherical reflectance of silvered PMMA reflectors as a function of exposure in an Atlas Weather-Ometer (60°C, 80% Relative Humidity [RH], 1× light intensity)

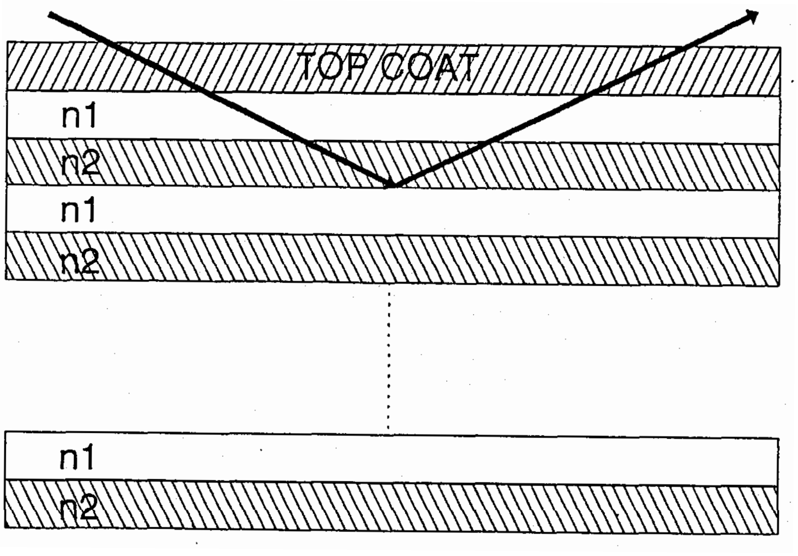

Figure 3. Dow all-polymeric reflector material construction

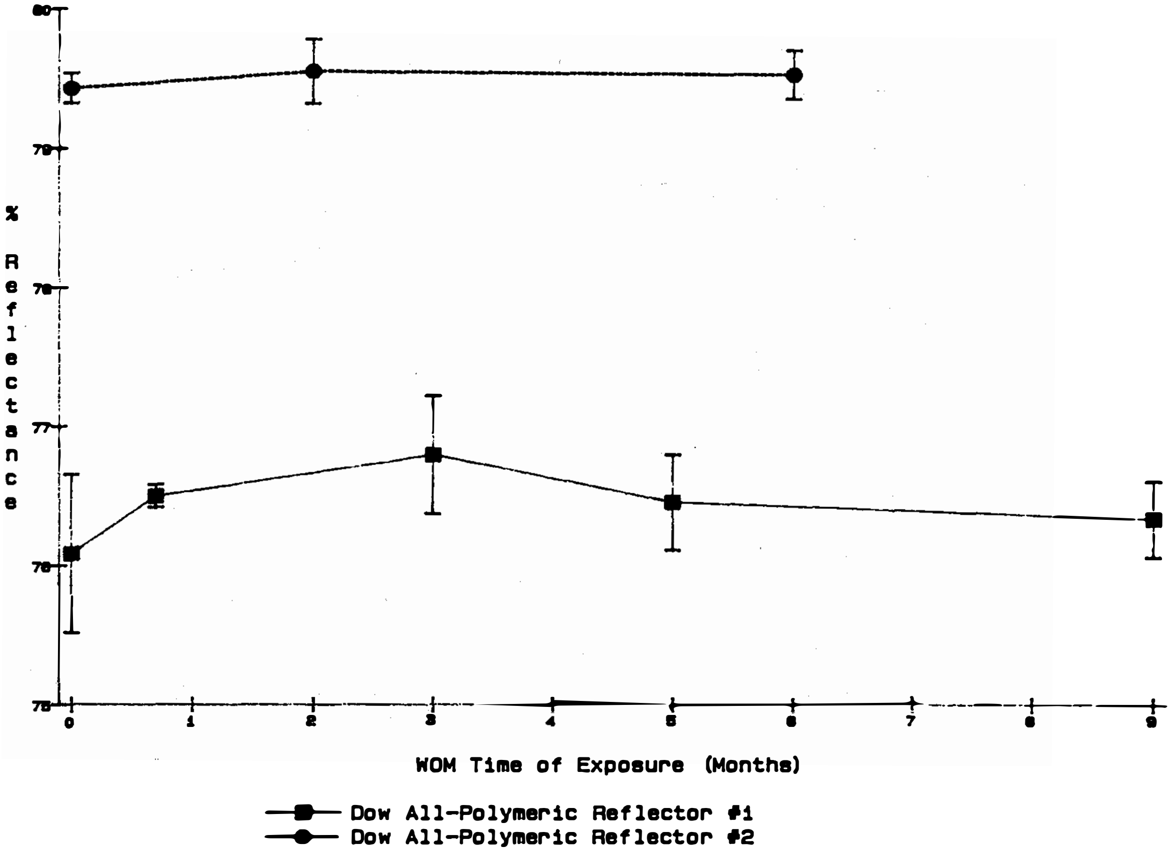

Figure 4. Solar-weighted hemispherical reflectance of Dow all-polymeric reflectors as a function of exposure in an Atlas Weather-Ometer (60°C, 80% RH, 1× light intensity)

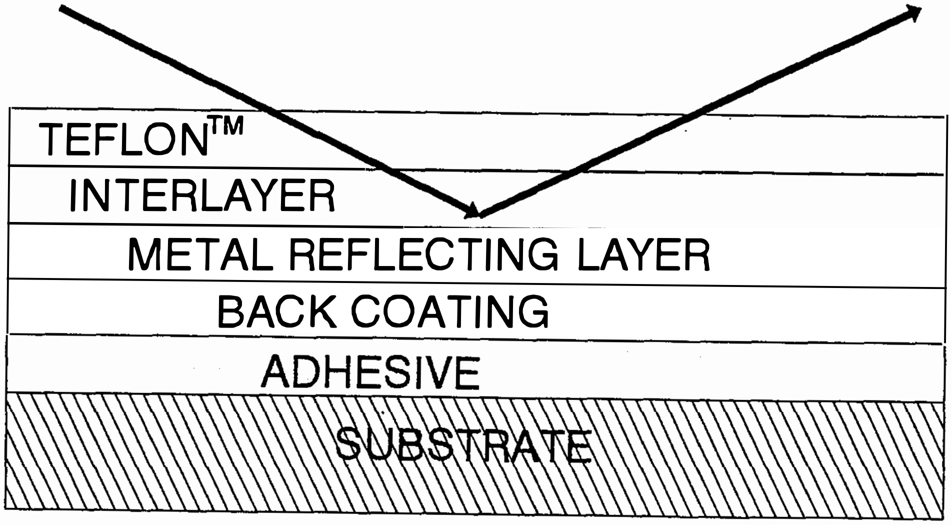

Figure 5. IST silvered Teflon™ reflector construction

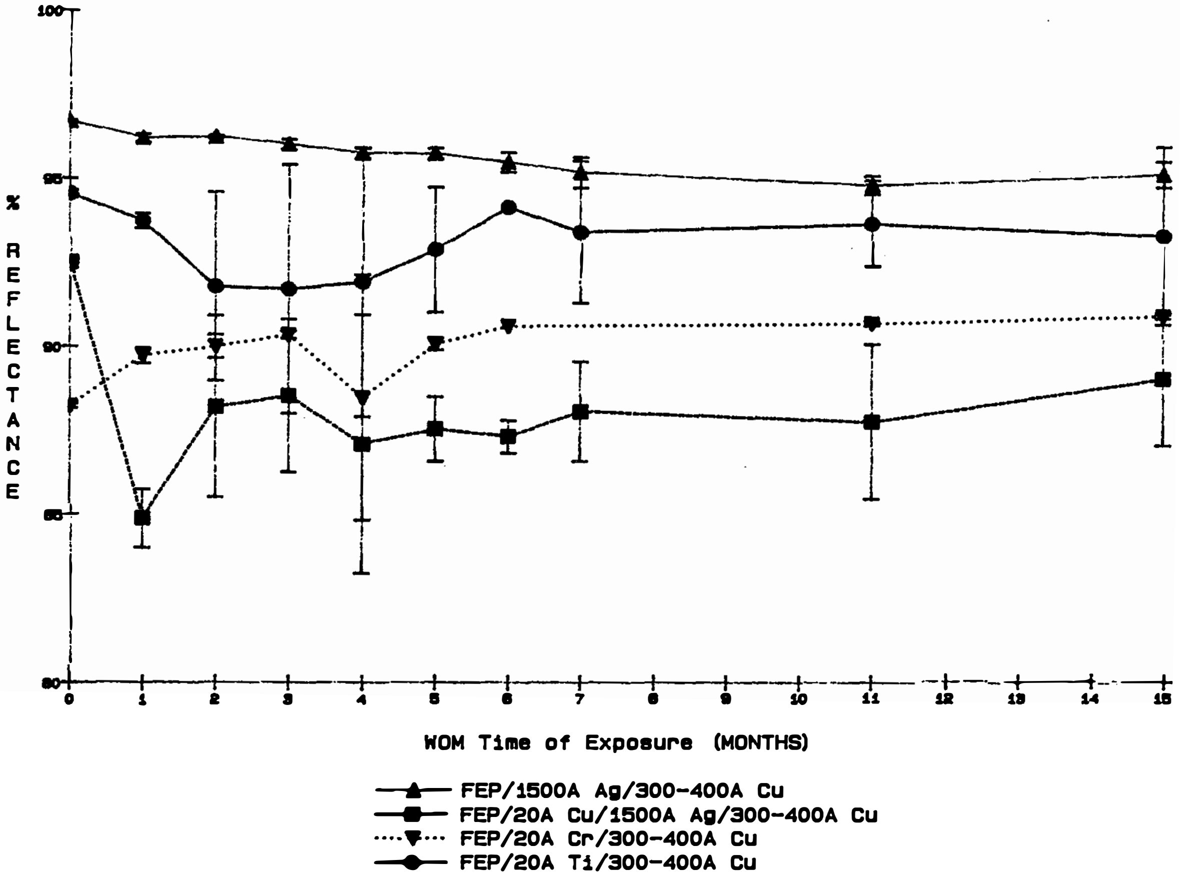

Figure 6. Solar-weighted hemispherical reflectance of IST silvered Teflon™ reflectors as a function of exposure in an Atlas Weather-Ometer (60°C, 80% RH, 1× light intensity)

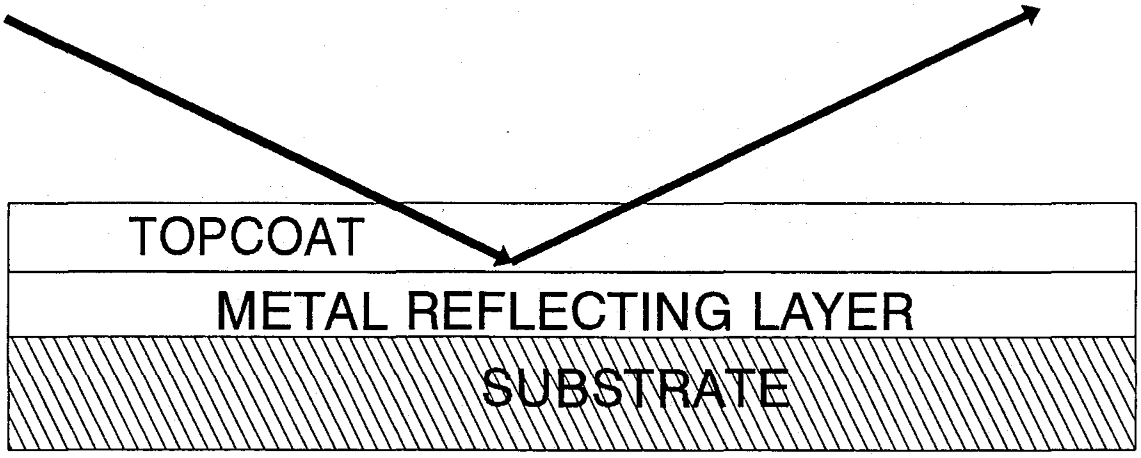

Figure 7. Front-surface reflector construction

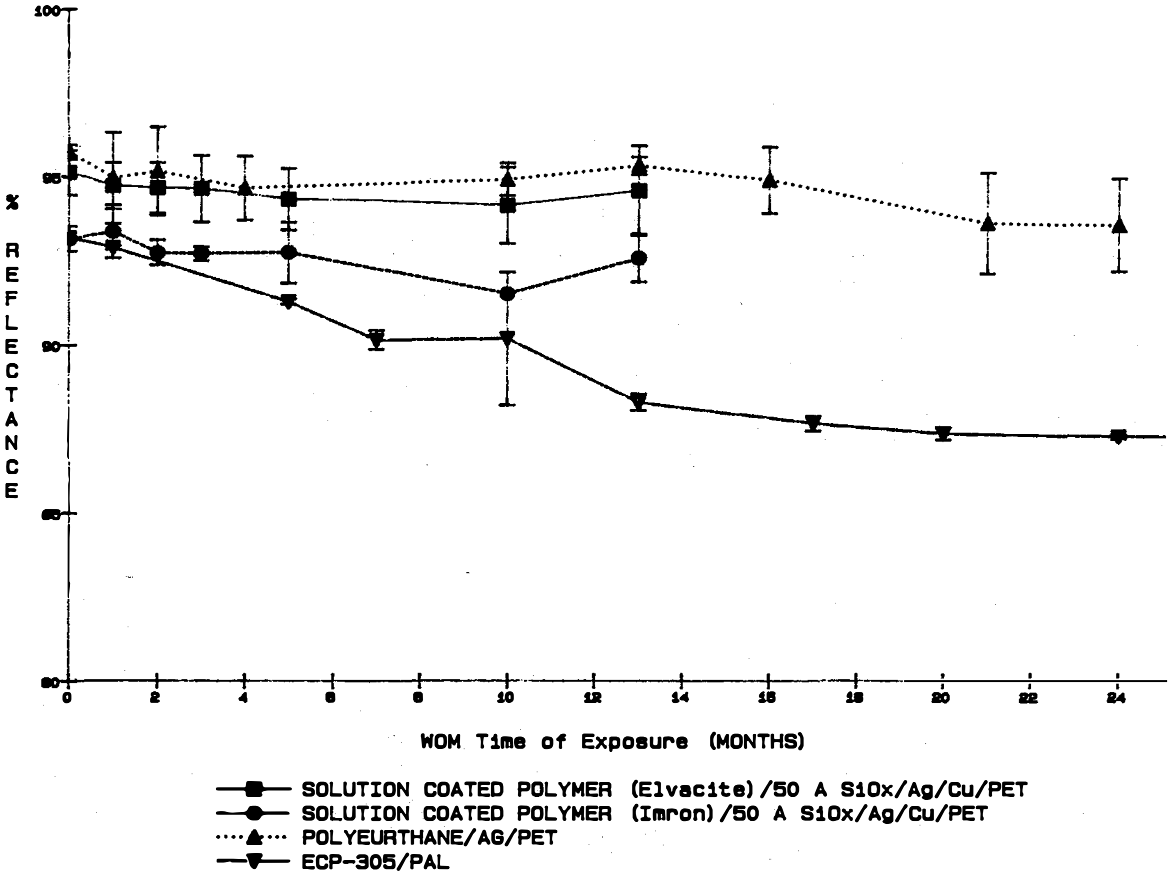

Figure 8. Solar-weighted hemispherical reflectance of organic top coat front-surface reflectors as a function of exposure in an Atlas Weather-Ometer (60°C, 80% RH, 1× light intensity)

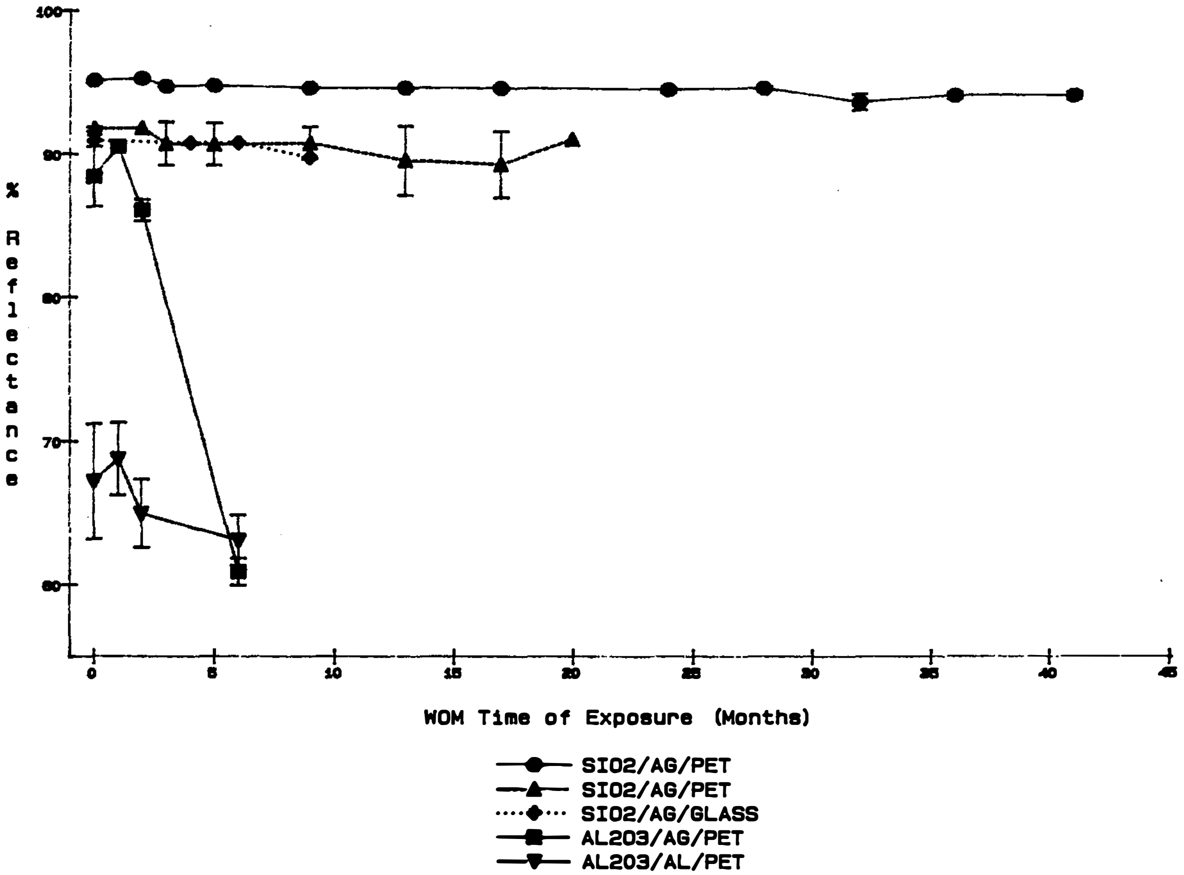

Figure 9. Solar-weighted hemispherical reflectance of inorganic top coat front-surface reflectors as a function of exposure in an Atlas Weather-Ometer (60°C, 80% RH, 1× light intensity)

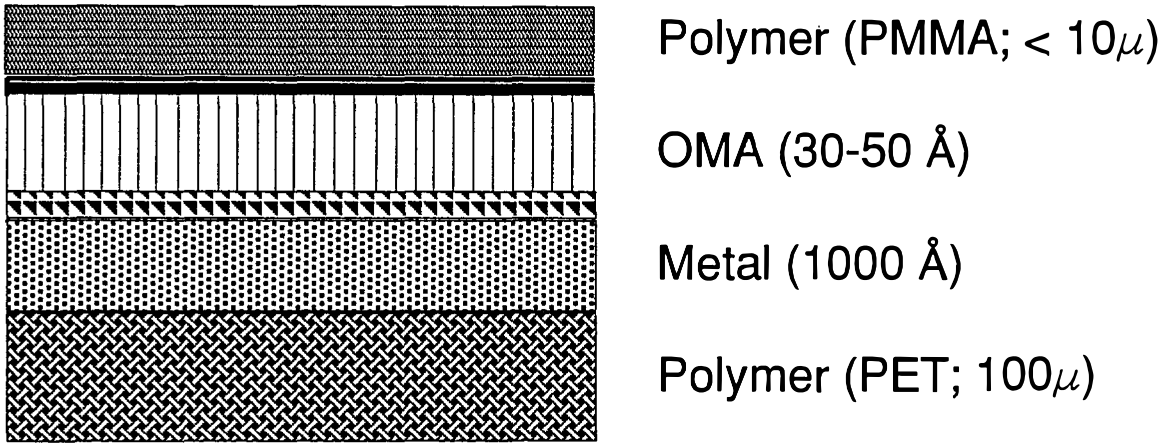

Figure 10. Experimental reflector construction where OMA is used as an adhesion/passivation layer

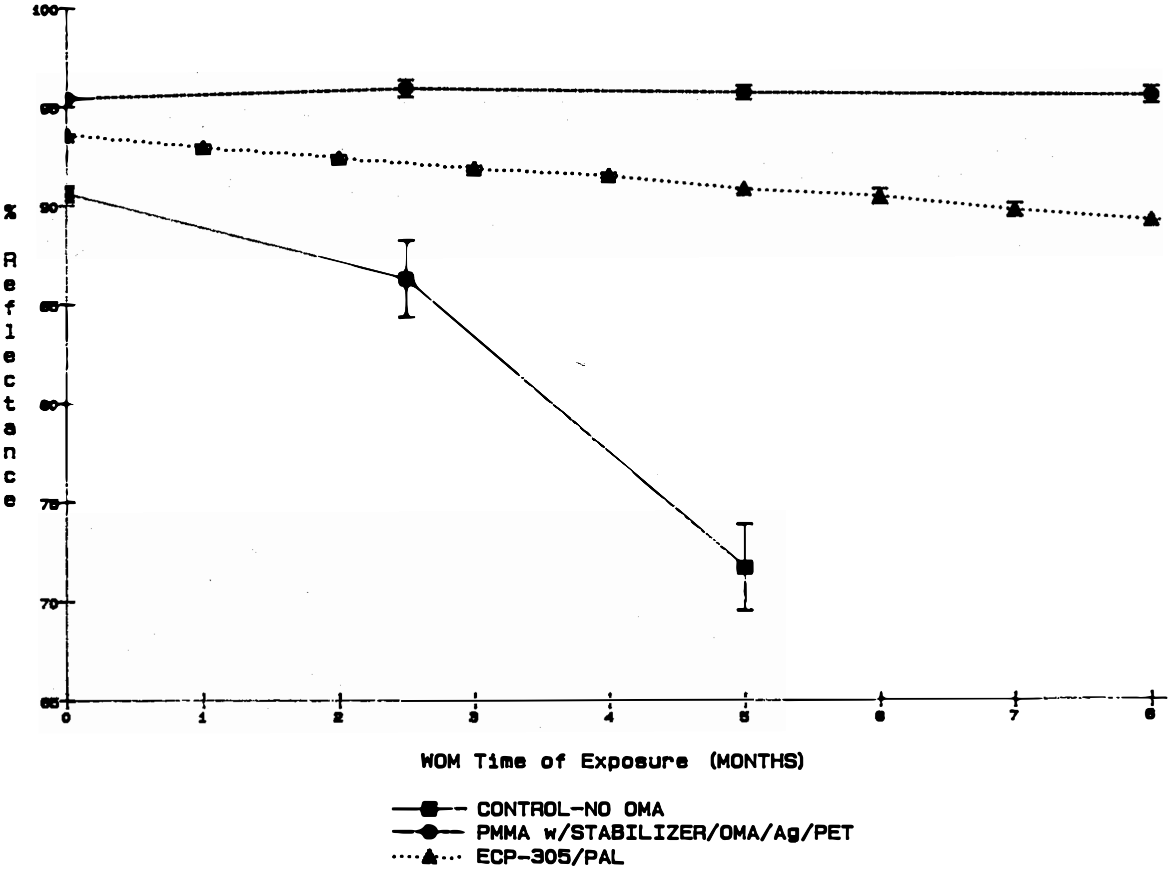

Figure 11. Solar-weighted hemispherical reflectance of experimental OMA reflectors as a function of exposure in an Atlas Weather-Ometer (60°C, 80% RH, 1× light intensity)