NREL/TP-471-6092 • UC Category: 237 • DE94000264

Progress in the Development of Advanced Solar Reflectors

Cheryl Kennedy
Gary Jorgensen

Prepared for the Seventh International Vacuum Web Coating Conference, Miami, Florida, November 10-12, 1994

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Operated by the Midwest Research Institute
for the U.S. Department of Energy
under Contract No. DE-AC02-83CH10093

January 1994

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A03

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements and Index (GRA and I)*; *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

Printed on recycled paper

PROGRESS IN THE DEVELOPMENT OF ADVANCED SOLAR REFLECTORS

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

ABSTRACT

Solar thermal technologies require large mirrors to provide concentrated sunlight for renewable power generation. Such materials must be inexpensive and maintain high specular reflectance for extended lifetimes in severe outdoor environments. Polymer reflectors are lighter than glass mirrors, offer greater system design flexibility, and have the potential for lower cost. During the past year, collaborative cost-shared research and development between the National Renewable Energy Laboratory (NREL) and industrial partners has identified candidate materials that perform better than the state-of-the-art commercial silvered-polymer reflectors in terms of corrosion degradation and resistance to delamination failure. Additional cooperative efforts will produce new alternative materials with reduced costs due to high speed production line capability. NREL welcomes continued and expanded interest and web coating industry involvement in developing advanced solar reflector materials.

I. INTRODUCTION

A pivotal need exists within the solar manufacturing industry for durable, high performance, inexpensive reflector materials (1). The commercial availability of such materials is important to all solar concentrator technologies and is accentuated by current commercial deployment projections. These include several dish concentrator programs being jointly developed by the U.S. Department of Energy (DOE) and industry, and activation of a large central receiver power plant under the auspices of DOE and a nine-utility consortium.

The need for improved mirrors for solar applications was recognized in the 1980s, and a program was initiated to develop advanced reflector materials (2). At that time the state-of-the-art was low iron glass coated on the back surface with silver. Thick glass mirrors were considered too heavy, fragile, and expensive. Candidate alternatives included metallized polymers, front surface reflectors, and thin glass mirrors. At that time, front surface reflectors (with a metal reflective layer deposited on a substrate followed by a protective coating) suffered from high expense and questionable durability. Also, it was uncertain if these reflectors could be produced economically in a roll form that was sufficiently wide (>1m). Although the performance of thin glass mirrors had been demonstrated, no U.S. manufacturers existed.

Several candidate metallized polymer reflector materials were screened, including acrylic, silicone, fluoropolymer, polyacrylonitrile (PAN), polycarbonate, and polyester films. Silver and aluminum were considered for the reflective layer. Acrylic, specifically polymethylmethacrylate (PMMA), was found to be the most promising candidate. Collaborative research between 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. Figure 1 demonstrates the superiority of ECP-305 over earlier candidate reflector materials in the maintenance of optical durability in terms of both accelerated weathering tests and outdoor tests conducted in Colorado, Arizona, and Florida (3,4).

Additional progress has been made recently in performance and durability of silvered polymer reflectors. With ECP-305 NREL and 3M have achieved the DOE's Solar Thermal Electric (STE) program goals for solar reflector materials, which call for maintenance of greater than 90% specular reflectance into a 4-mrad half acceptance angle and a minimum 5-year lifetime in outdoor service (5).

New goals and more aggressive targets are proposed for mirrors that maintain high specular reflectance for extended lifetimes (typically at least 10 years) under outdoor service conditions and whose manufacturing costs are less than $1.00/ft^2. NREL will continue to develop advanced reflectors by identifying, developing,and testing new advanced candidate materials, and by supporting promising industry-led efforts.

Collaborative ventures with industrial partners have identified silvered Teflon™ as a promising candidate material and demonstrated tangible improvements in ECP-305 in terms of corrosion degradation and delamination resistance. The solar industry is very excited about the enhanced ECP-305 material and is eager to obtain a commercial version for prototype demonstration purposes. In addition to industry collaborations, NREL's independent research has continued with some promising developments. Perhaps the most attractive involves application of dense, optically clear coatings of SiO_x on a silver reflective surface. This technique is compatible with mass production and could result in the most optically durable films yet.

II. DEVELOPMENT OF SOLAR REFLECTOR MATERIALS

NREL's in-house research and joint efforts with industry helps bridge crucial technological gaps and opens dialogue between industry experts. As requisite fundamental studies are coordinated and the results centrally disseminated, enhancements of promising materials can be more easily investigated. During the past year, three cost-shared subcontracts were completed. These included efforts at increasing the durability of 3M's baseline ECP-305 material, development of the silvered Teflon™ reflector, and exploration of a directly deposited solar reflector concept. The first two of these projects involved metallized polymers; the third was a front surface reflector. Two additional collaborations were initiated during this time. The first is another front surface reflector design which uses polymer multilayers to encapsulate the silver reflective layer. The second involves an innovative all-polymeric solar reflector design. Both of these concepts have potential for extremely high line speeds and low production costs.

A. Metallized Polymer Reflectors

Metallized polymer reflectors generally have the following construction:

- A front polymer film that protects the metal from the environment.
- An optional adhesion-promoting interlayer between the polymer and the metal.
- Silver reflective layers that reflect greater than 90% of the terrestrial solar resource.
- Protective back coatings to improve corrosion protection.
- Bonding between the metal layer and the substrate by means of an optically smooth pressure-sensitive adhesive.

A program has been pursued with the 3M Company to improve ECP-305 reflective film. Previous accelerated exposure tests at NREL demonstrated that silvered PMMA with thick (500 and 1500 Å) protective back coatings of copper increased corrosion resistance (Figure 2). Thinner layers of copper were also investigated because the economic viability of such a construction is a function of the back layer thickness. Samples with 0, 100, 300, 500, and 1000 Å copper back coatings were prepared and tested in accelerated exposure chambers and in the outdoors. After 2000 hours of solar simulator exposure (Xenon Arc lamp 50x light intensity, 80°C, 80% relative humidity), all samples with protective layers have maintained good optical performance, as indicated in Figure 3. In sharp contrast are those samples with no copper backcoatings that severely degraded in 300 hours. A renewed collaborative effort has resulted in pilot plant versions incorporating the ECP-305 with the copper backing that benefits from improved optical durability and increased resistance to delamination failure. The new versions should significantly allay concerns of solar manufacturers regarding the use of this material in solar concentrator systems. In addition, cost projections indicate that high volume production of such a product could reduce the price for solar manufacturers to almost $\$1/ft^2$.

Industrial Solar Technology (IST), an installer of commercial solar trough systems, has developed a silvered Teflon™ solar reflector material. Teflon™, a fluorinated ethylene propylene (FEP) copolymer film with outstanding outdoor weathering properties, provides the front surface protective layer. The metal reflective layer is silver. Although initial specularity of candidate samples was less than expected, significant progress has been made in understanding the specularity problem and identifying ways to improve it. Candidate corrosion resistant constructions were fabricated which exhibited promising optical durability in accelerated exposure tests (Figure 4). The silvered Teflon™ solar reflector material has the potential for low cost with high volume production if the performance goals can be met.

B. Front Surface Reflectors

Front surface reflectors generally have the following construction:

- A substrate material providing mechanical stability such as thin stainless steel or polyethylene terephthalate (PET, a thermoplastic copolyester).
- A levelizing layer that smooths the substrate surface in order to enhance specular reflectance.
- A metal reflective layer, typically silver or aluminum.
- A thin, optically clear protective top coating.

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 PET film, and then overcoat the reflector with an abrasion resistant top layer. Some reflectors with this generic construction have demonstrated promising results in accelerated durability tests at NREL, indicating that they may ultimately be capable of achieving the cost and performance goals of the program. Candidate top layers can be either organic (such as organosilicones, polyurethanes, acrylics, etc.) or inorganic (such as Si_3N_4, diamond-like carbon, SiO_x, Al_2O_3, and other oxides). Organic/inorganic composite coatings also have been suggested.

Science Applications International Corporation (SAIC) has completed their investigation of directly deposited solar reflector materials. Direct deposition of a reflective layer onto a substrate material eliminates problems and costs associated with adhesives and substrate lamination. If the number of layers and passes through the deposition process line can be minimized, the cost of such a material could be very low. The basic construction pursued by SAIC was:

Top coat / Reflective layer / Levelizing layer / Substrate.

A number of commercial organic top coating materials were tested for use as both the protective top coating and as a levelizing layer. A few materials provided acceptable levelization in terms of specularity, but none to date have provided adequate protection of the metal reflective layer. The samples severely degraded in accelerated exposure testing at NREL. Interlayer adhesion was also a problem.

The Battelle Memorial Institute Pacific Northwest Laboratory (PNL) initiated work using their Polymer MultiLayer (PML) technology to fabricate samples of the following construction:

Si_3N_4 and/or PML / Ag / PML / Substrate

where Si_3N_4 is intended as a 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 line speeds and consequent low production costs.

Other industry contacts have provided five candidate organic top coated reflectors for testing at NREL. The samples are 7-mil PET sputtered with an aluminum reflective layer. The five protective top coatings are a proprietary scratch resistant coating (SRC), a ultraviolet (UV) cured acrylic, a low emissivity coating, a thermal-cured organosilicone, and a UV-cured organosilicone. The SRC and organosilcones coatings have maintained their initial hemispherical reflectance, as shown in Figure 5. However, all five materials exhibit a hazy, nonspecular appearance after a short period of accelerated exposure.

NREL has explored several additional top coat options. Compared to other protective coatings having Si-O bonds, one of the proprietary experimental mirrors supplied by industry has performed remarkably well in accelerated Weather-Ometer (WOM, Atlas Electric Co.) exposure (see Figure 6) by maintaining the initial hemispherical reflectance for 36 months. A number of variations of SiO_x overcoated silver have been tested at NREL. Following sputter deposition of SiO_x over silver, samples have been post-treated in an attempt to densify and/or seal the coating. To date, poor optical durability in WOM testing has been exhibited by materials prepared at NREL with the following construction:

SiO_x / Ag / PET.

Analytical techniques at NREL quantified the nature of these SiO_x coatings. X-ray photoelectron spectroscopy (XPS) suggests that the stoichiometry of the coating is very near SiO_2. Scanning electron microscopy (SEM) photographs show that thick films (~10,000 Å) exhibit a highly porous structure which results in poor optical durability. NREL is presently exploring alternate ways of obtaining denser SiO_x coatings to improve durability. One approach, ion assisted deposition, is to be researched in conjunction with PNL. A variety of ion assisted sputter deposited hard coats will be applied to silvered PET. The ion assisted coatings are intended to densify the structures for improved optical durability.

Polyurethane (PUR) was also evaluated as a protective top coat for silver reflector materials. Such painted mirrors (mirrors with organic coatings applied in a painted fashion, such as solution casting, dip coating, etc.) are adaptable to current production techniques and can be inexpensive, but have not demonstrated their optical durability. Several experiments with a two-part DuPont PUR demonstrated that PUR is stable, but does not protect the silver interface. A one-part PUR from Minwax was coated onto silver and immediately reduced reflectance. Two other one-part PURs from Minwax and Helmsman remained clear for just a few days as the mirror samples aged in the lab. Silver protected by polyurethane paint containing UV absorber additives has generally failed to maintain hemispherical reflectance in accelerated WOM testing. This has been true for samples on glass or PET substrates and also with copper protective layers behind the silver.

C. Other Reflectors

Dow Chemical Company has initiated work on an in-house concept that uses alternating coextruded layers of inexpensive, commercially available, transparent thermoplastics to produce all-polymeric reflector materials. The concept is shown schematically in Figure 7. Abrasion resistant top coatings that incorporate UV protection will be evaluated. Degradation of optical performance caused by corrosion of metallic reflecting layers is not a concern, because this concept is an all-polymeric design. Another attractive feature of this approach is that such reflector materials can be directly thermoformed into useable structures, thereby reducing the costs associated with concentrator support elements. Efficient broadband solar reflectors are envisioned that would be fabricated from a high speed, low cost technique which has been commercially demonstrated. NREL will evaluate the material performance of this concept.

III. TESTING OF CANDIDATE MATERIALS

The optical durability of candidate reflector materials is evaluated based upon results from both real time exposure at outdoor test sites and from accelerated weathering in controlled laboratory environments. Outdoor testing is important because the durability of optical materials in field environments is crucial to success. Accelerated testing is used to screen new candidate materials on the basis of their optical durability. In addition, as new advanced reflector materials demonstrate ever increasing lifetimes, correlations between outdoor and accelerated exposures will become necessary in order to predict service lifetimes without extensive delays for testing.

During the past year, NREL has expanded its outdoor testing program through the activation of three test sites. The objective of this activity is to provide data on material durability and lifetimes at a number of locations that are attractive to utilities with an interest in solar thermal electric power generation. The sites provide a way for utilities to gain direct experience with materials that may be used in early commercial power plants. Additionally, the program will provide meteorological data that will augment the correlation between outdoor testing and accelerated test results. Eventually this should enable quantitative predictions of material lifetimes at various sites.

As new advanced reflector material candidates are identified, their development is typically an iterative process. Samples initially subjected to exposure testing may not exhibit the desired level of optical durability. Mechanistic studies of failure modes of candidate materials are performed so improvements can be incorporated to increase service lifetimes.

IV. SUMMARY

Although solar thermal technologies are economically viable in some markets today, expansion into broader markets will require low cost mirrors that maintain high specular reflectance for extended lifetimes under outdoor service conditions. Several categories of candidate advanced materials have been identified and are under test at NREL. Additional cooperative efforts with industry offer new alternative materials and the potential for cost savings due to high speed production line capability. NREL works closely with the solar manufacturers to develop these materials, and welcomes suggestions and proposals from the vacuum coating and polymer industry to reach these goals.

6. References

1. P. J. Call, "Overview of Solar Energy Conversion Technologies: Quantum Processes and Thermal Processes," *Basic Research Needs and Opportunities on Interfaces in Solar Materials*, A. W. Czanderna and R. J. Gottschall, editors, DOE/CONF-8006156, April 1981.

2. C. Kennedy, G. Jorgensen, and P. Schissel, "Requirements and Potential for Low-cost Solar Reflector Materials," *Proceedings of Sixth International Conference on Vacuum Web Coating*, Reno, NV, October 1992.

3. G. Jorgensen and P. Schissel, "Optical Performance and Durability of Silvered Polymer Mirrors," *Metallized Plastics 1: Fundamentals and Applied Aspects*, K.L. Mittal and J.R. Susko, Editors, Plenum Press, New York, 1989, pp. 79-92.

4. P. Schissel, G. Jorgensen, and R. Pitts, "Application Experience and Field Performance of Silvered Polymer Reflectors," *1991 Solar World Congress, Vol. 2, Part II*, M.E. Arden, S.M.A. Burley, and M. Coleman, Editors, Pergamon Press, Oxford, England, 1991, pp. 2076-2081.

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

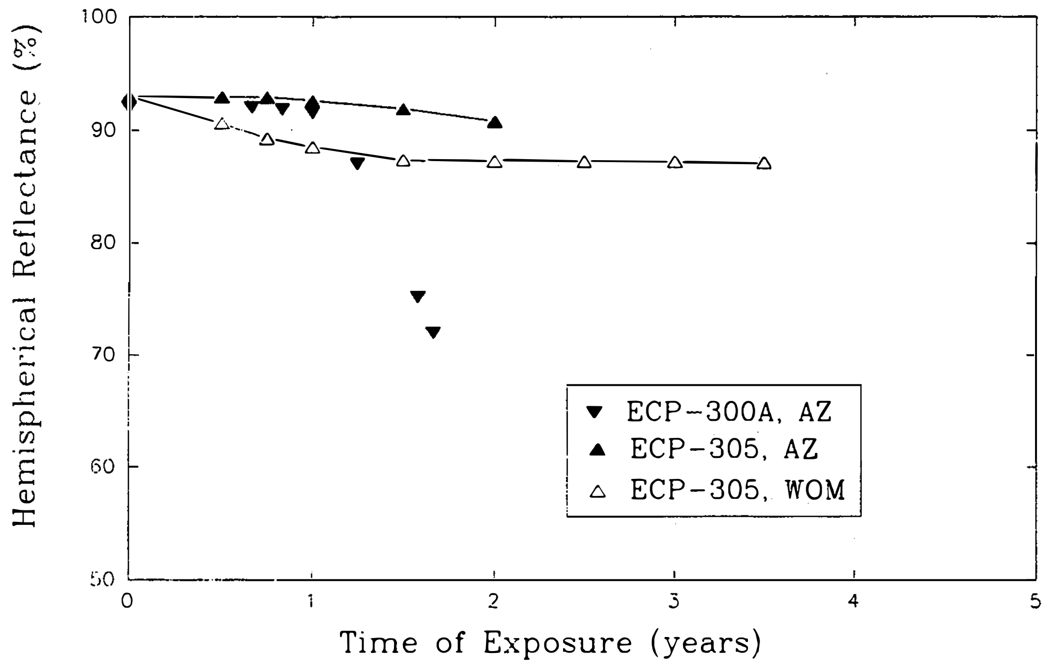

Figure 1. Solar-weighted hemispherical reflectance of silvered PMMA reflectors on painted aluminum substrates as a function of outdoor exposure in Phoenix, AZ and in an Atlas Weather-Ometer (60°C, 80% RH, 1X light intensity)

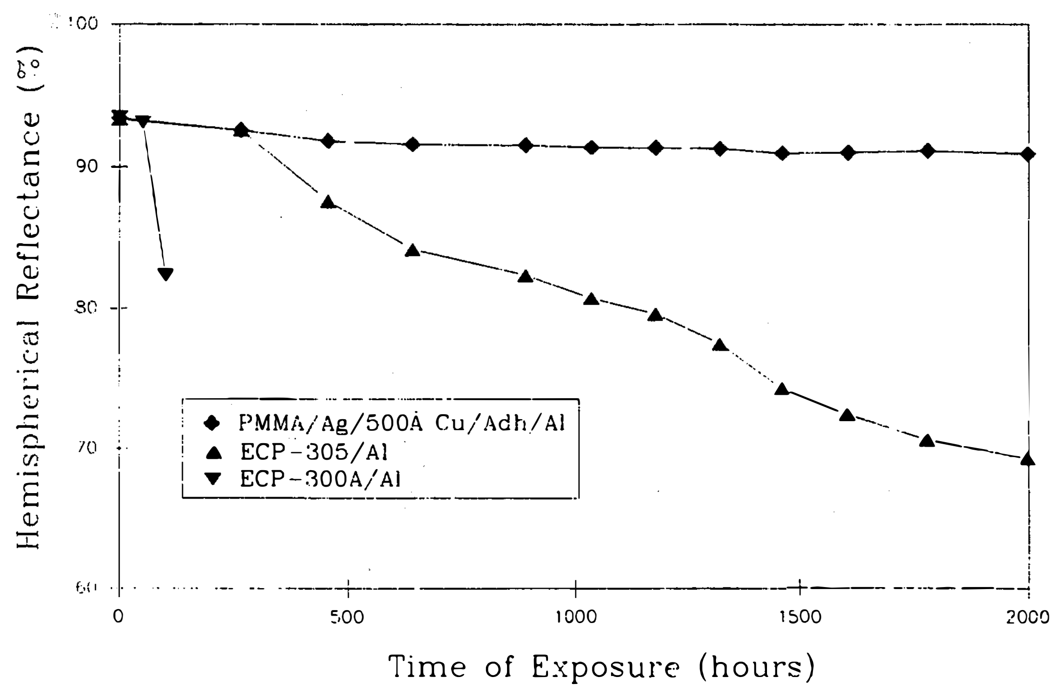

Figure 2. Solar-weighted hemispherical reflectance of silvered PMMA reflectors as a function of exposure in a solar simulator chamber (80°C, 75% RH, 50X light intensity)

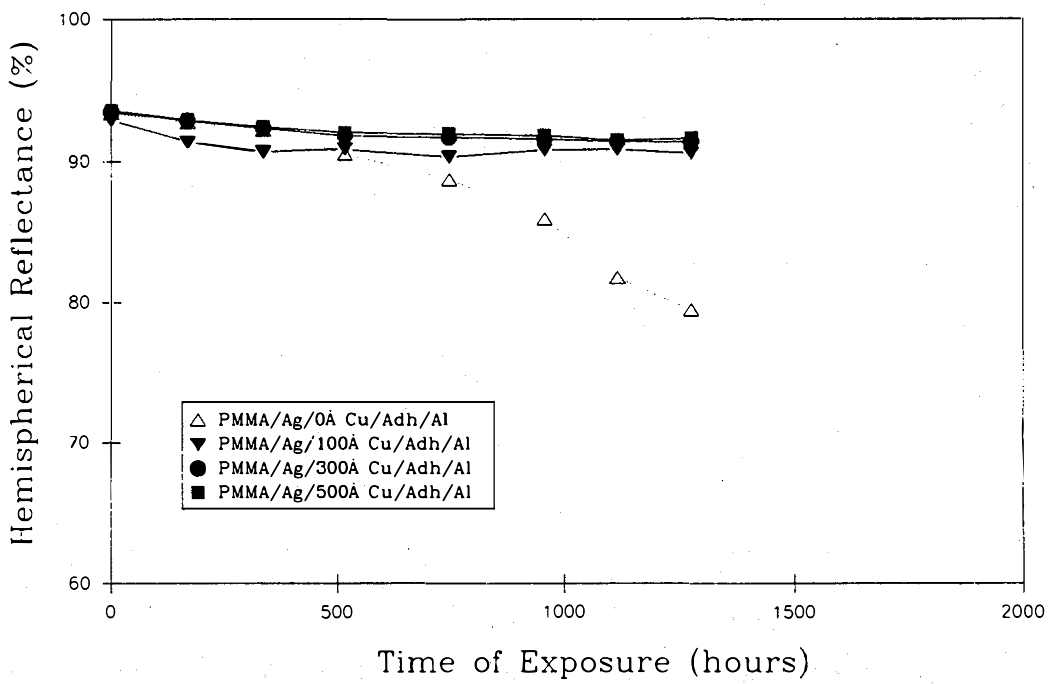

Figure 3. Solar-weighted hemispherical reflectance of silvered PMMA reflectors as a function of copper backing thickness and exposure in a solar simulator chamber (80°C, 75% RH, 50X light intensity)

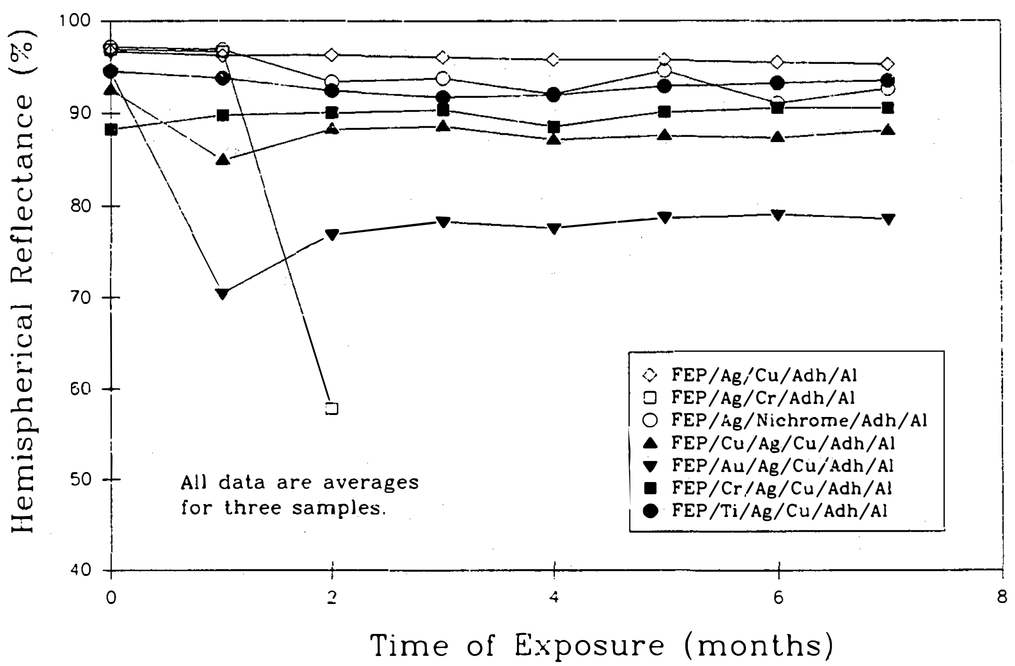

Figure 4. Solar-weighted hemispherical reflectance of silvered Teflon™ FEP reflectors with various metallic interlayers and back coatings as a function of exposure in an Atlas Weather-Ometer (60°C, 80% RH, 1X light intensity)

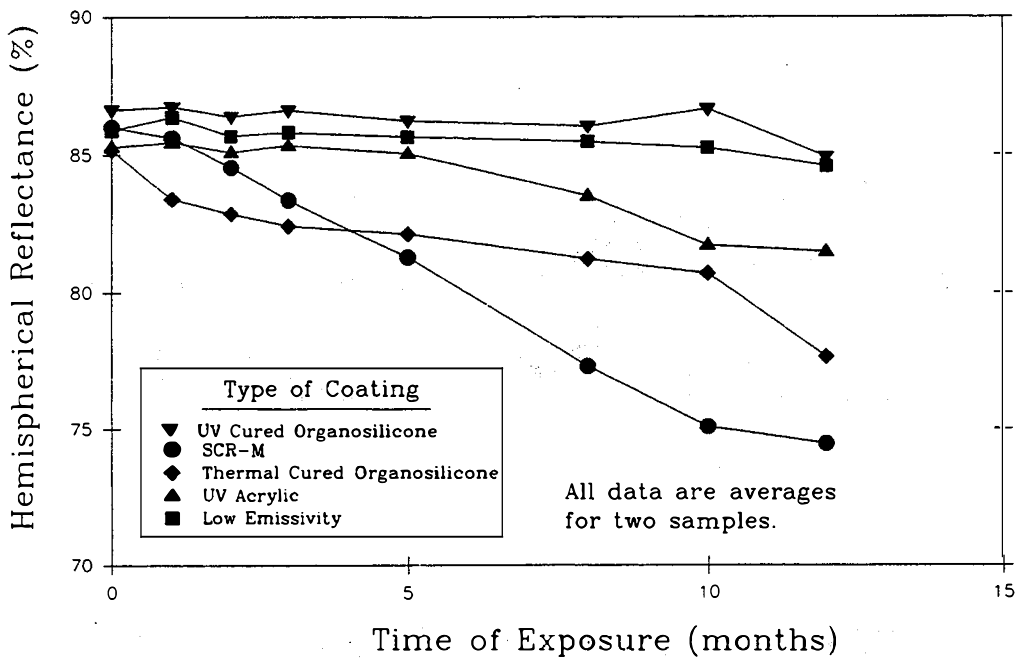

Figure 5. Solar-weighted hemispherical reflectance of aluminized PET reflectors with various metallic interlayers and back coatings as a function of exposure in an Atlas Weather-Ometer (60°C, 80% RH, 1X light intensity)

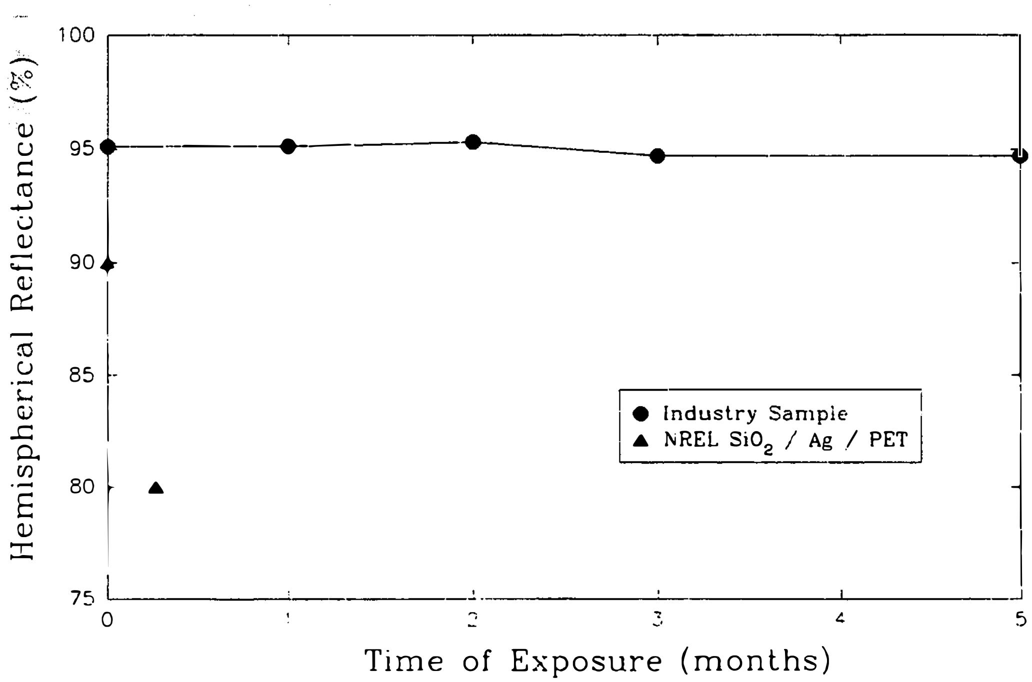

Figure 6. Solar-weighted hemispherical reflectance of front surface silvered PET reflectors as a function of exposure in an Atlas Weather-Ometer (60°C, 80% RH, 1X light intensity)

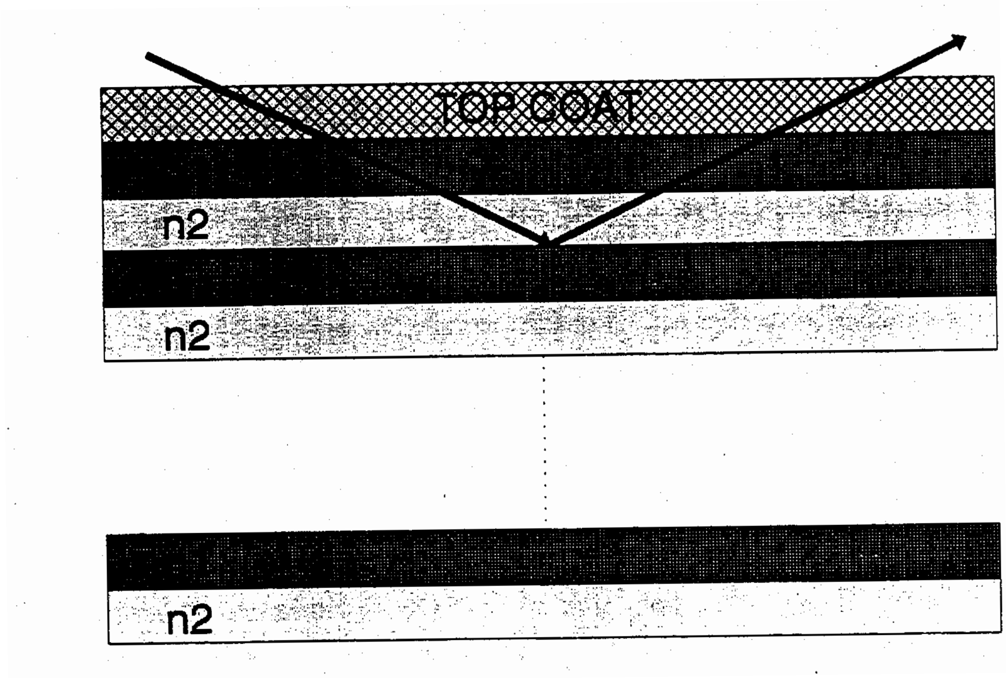

Figure 7. Dow all-polymeric reflector construction