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P. Schissel
G. Jorgensen
R. Pitts

National Renewable Energy Laboratory
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Golden, Colorado 80401-3393
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APPLICATION EXPERIENCE AND FIELD PERFORMANCE OF SILVERED POLYMER REFLECTORS*

Paul Schissel, Gary Jorgensen, and Roland Pitts
National Renewable Energy Laboratory**
1617 Cole Blvd.
Golden, CO 80401

ABSTRACT

The solar-weighted hemispheric reflectance of unweathered silvered acrylic mirrors exceeds 92%, and specular reflectance into a 4-milliradian, full-cone acceptance angle is greater than 90%. Comparison of outdoor and accelerated tests suggests that the protected silver can resist corrosion for the five-year life that is the current goal. An installation of parabolic troughs has been cleaned monthly for two years, and reflectance is regularly returned to within a few percent of the initial reflectance values. In the presence of moisture, the silver/acrylic bond can delaminate to form a maze of tunnels and destroy specular reflectance. Proper edge preparation and protection delay the initiation of tunnels.

KEYWORDS

Silvered polymer mirrors, weathering, durability.

INTRODUCTION

For most applications, silver is the reflective material of choice. The hemispheric reflectance of freshly deposited silver weighted over the solar spectrum (0.3–3.0 μm) is greater than 97%. A transparent layer is required to protect the silver from abrasion, soiling, and corrosion. An acrylic polymer with ultraviolet (UV) absorbers (to inhibit UV-photon-activated degradation) can be used. The solar-weighted hemispheric reflectance of new, unweathered, silvered acrylic material exceeds 92%.

The composite mirror is shown schematically in cross section in Fig. 1. The performance goals for silvered polymer films are a five-year life with a specular reflectance greater than 90% into a 4-mrad, full-cone acceptance angle. The optical goals for unweathered mirrors have been met, and current emphasis is on durability in the environment (Susemihl and Schissel, 1987).

Experimental mirrors are tested in accelerated weathering tests. Laboratory results have led to a series of production materials called ECP 300 followed by ECP 300A and ECP 305 from the 3M Company. The production materials also are undergoing accelerated weathering tests and outdoor tests near Denver, Albuquerque, Miami, Phoenix, and other sites.

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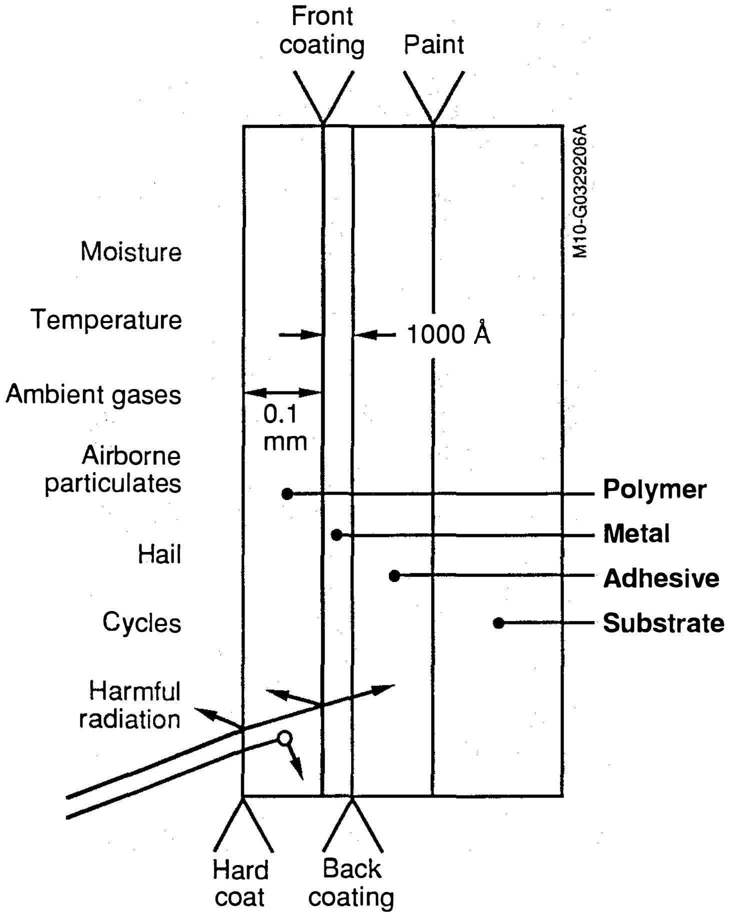

Figure 1. Metallized polymer reflector construction

Silvered acrylic mirrors lose reflectance principally in the following ways: (1) trace impurities in the mirror materials and/or the atmosphere can cause corrosion of the silver, (2) soil coats the mirror surface, and (3) delamination at the polymer/silver interface can decrease specular reflectance.

SILVER CORROSION

Outdoor performance is site-dependent. Denver's climate is relatively mild, and test samples continue to maintain reflectance after years of exposure (Fig. 2). In Fig. 2, we have plotted hemispherical rather than specular reflectance because it is more convenient to measure, and results show that the two types of reflectance degrade similarly because of corrosion near the polymer/silver interface. Approximately 700 m^2 of ECP 300A were installed four years ago by Industrial Solar Technology (IST) on parabolic troughs near Denver. The film has resisted corrosion of the silver

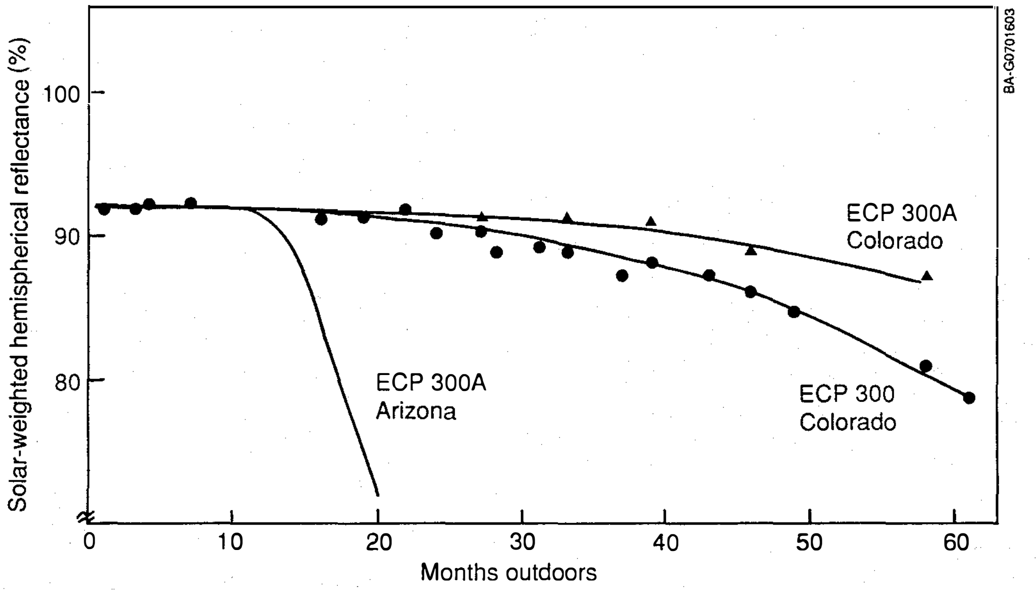

Figure 2. Solar-weighted hemispheric reflectance vs. months of outdoor exposure, silvered polymer mounted on aluminum

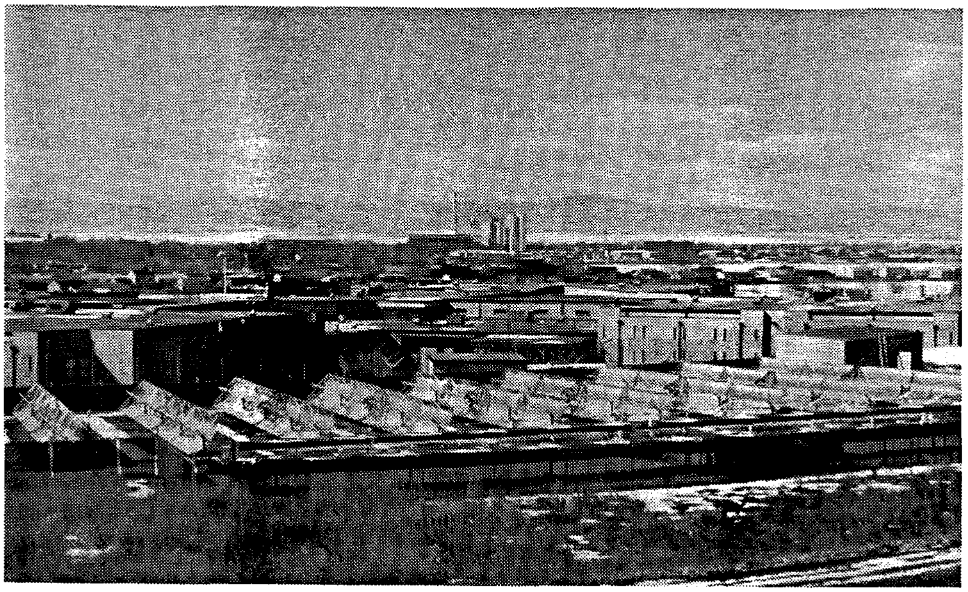

Figure 3. Parabolic troughs, Industrial Solar Technology, Denver

and has withstood monthly noncontact spray cleaning that regularly recovers reflectance above 90% (Fig. 3). Other sites like Phoenix are harsher (Fig. 2).

We have investigated improved silvered acrylic materials (Fig. 2), including high-purity polymers, more effective UV stabilizers, and coated polymers better able to resist scratches and to reject soil. Inter-layers in front of and behind the silver and paint layers on aluminum or stainless steel substrates can retard corrosion. We evaluate new materials in accelerated laboratory tests in our Weather-Ometer (Atlas Electric Co.). In the process, samples are illuminated with a xenon arc lamp, with filters to match the solar spectrum, and are maintained at 60°C in air at 80% relative humidity (Schissel and Neidlinger, 1987). Figure 4 compares the durability of reflectance in the Weather-Ometer for three sample types. ECP 300A, an earlier production material from the 3M Company, is now superseded by ECP 305. An experimental mirror fabricated at the National Renewable Energy Laboratory (NREL) is also shown in Fig. 4.

The experimental mirrors are now so stable that we also use a more accelerated test. The collimated beam from a solar simulator concentrates the near-UV radiation to more than ten suns while the samples are maintained at 80°C in air at 75% relative humidity. Figure 5 again compares the three types of mirrors and demonstrates the better performance of the newer materials. In Fig. 5, the corrosion of ECP 300A and ECP 305 has been slowed because the mirrors are mounted on painted aluminum substrates, which are known to provide better durability than unpainted aluminum for these mirror types. The data of Figs. 2, 4, and 5 suggest that the newer films can resist corrosion of the silver to meet the durability goal of five years.

SOILING AND CLEANING

Noncontact cleaning using only a medium-pressure spray of deionized water is effective, according to tests at Industrial Solar Technology (1989) (Fig. 3). The tests, conducted in Brighton, Colorado, cleaned 560 m^2 of parabolic troughs that use the silvered-polymer-mirror-type ECP 300A. The specular reflectance was measured periodically, including immediately before and after noncontact cleaning, using a Devices and Services Model 14R portable reflectometer. Figure 6 shows the specular reflectance immediately after washing at 650-nm wavelength and at a larger full-cone acceptance angle (25 mrad) because of the

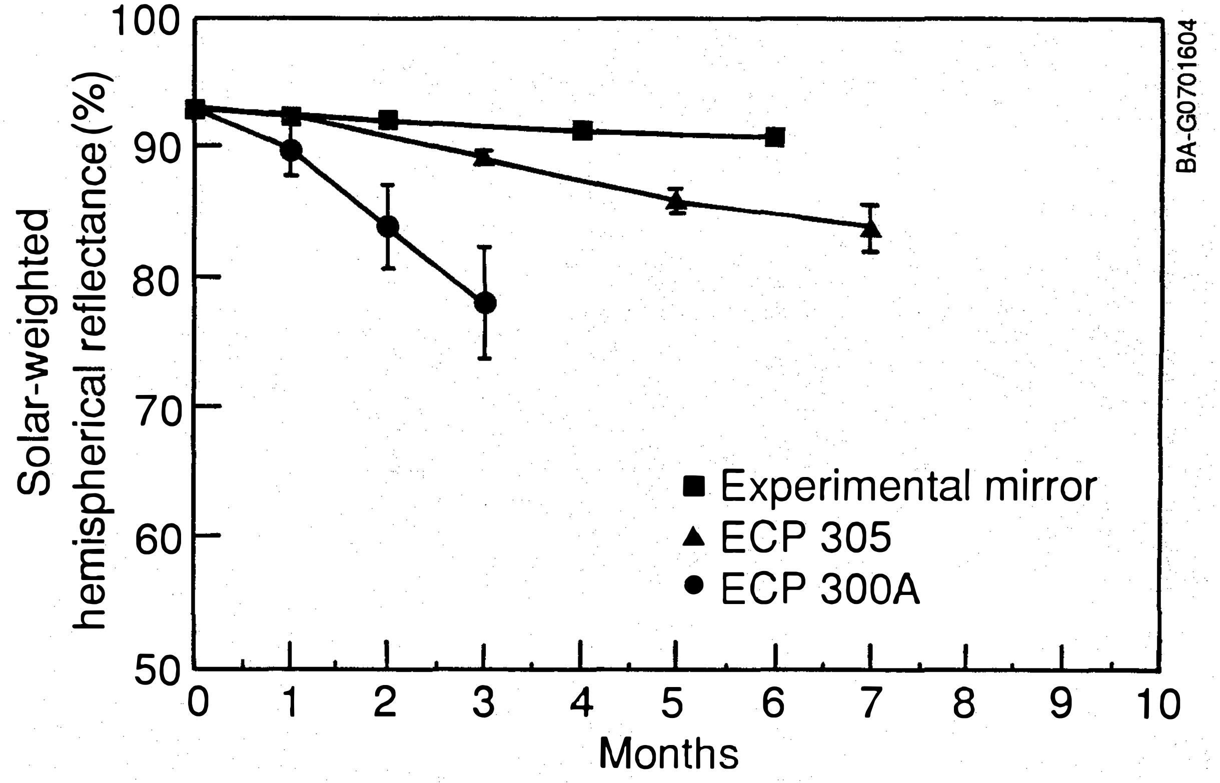

Figure 4. **Solar-weighted hemispheric reflectance vs. months in the Weather-Ometer accelerated weathering chamber**

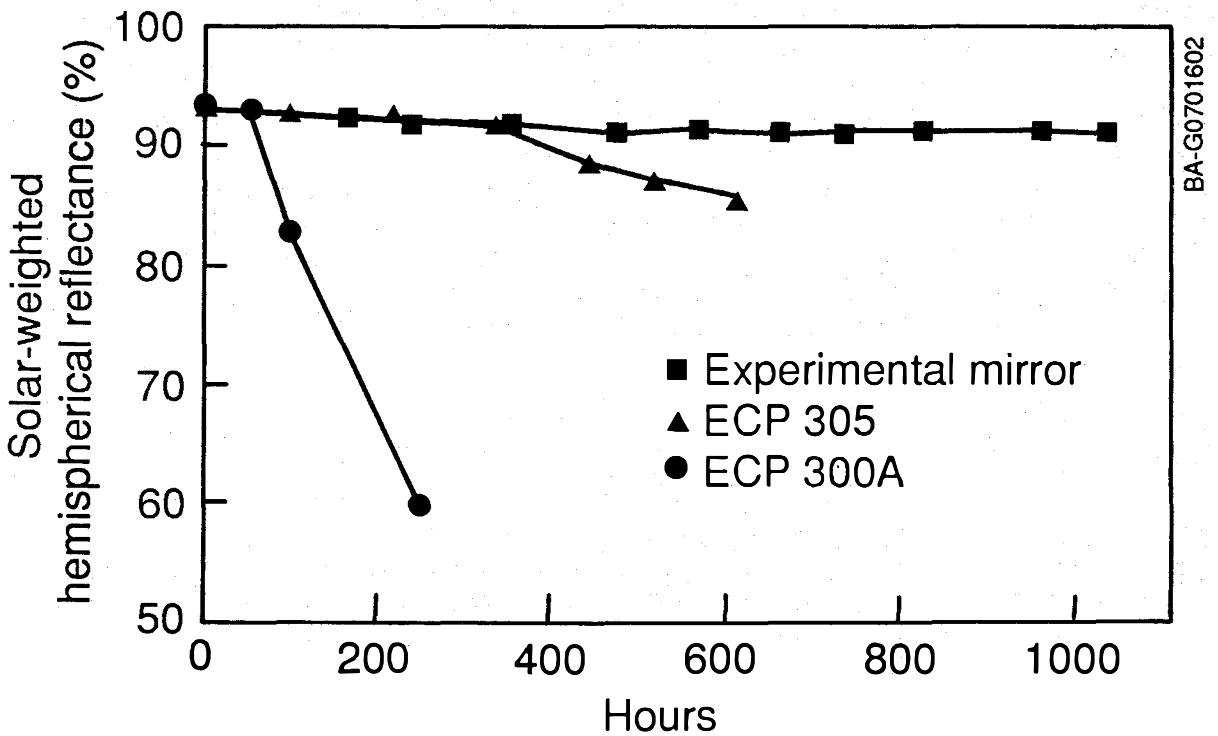

Figure 5. **Solar-weighted hemispheric reflectance vs. hours in the solar-simulator accelerated weathering chamber**

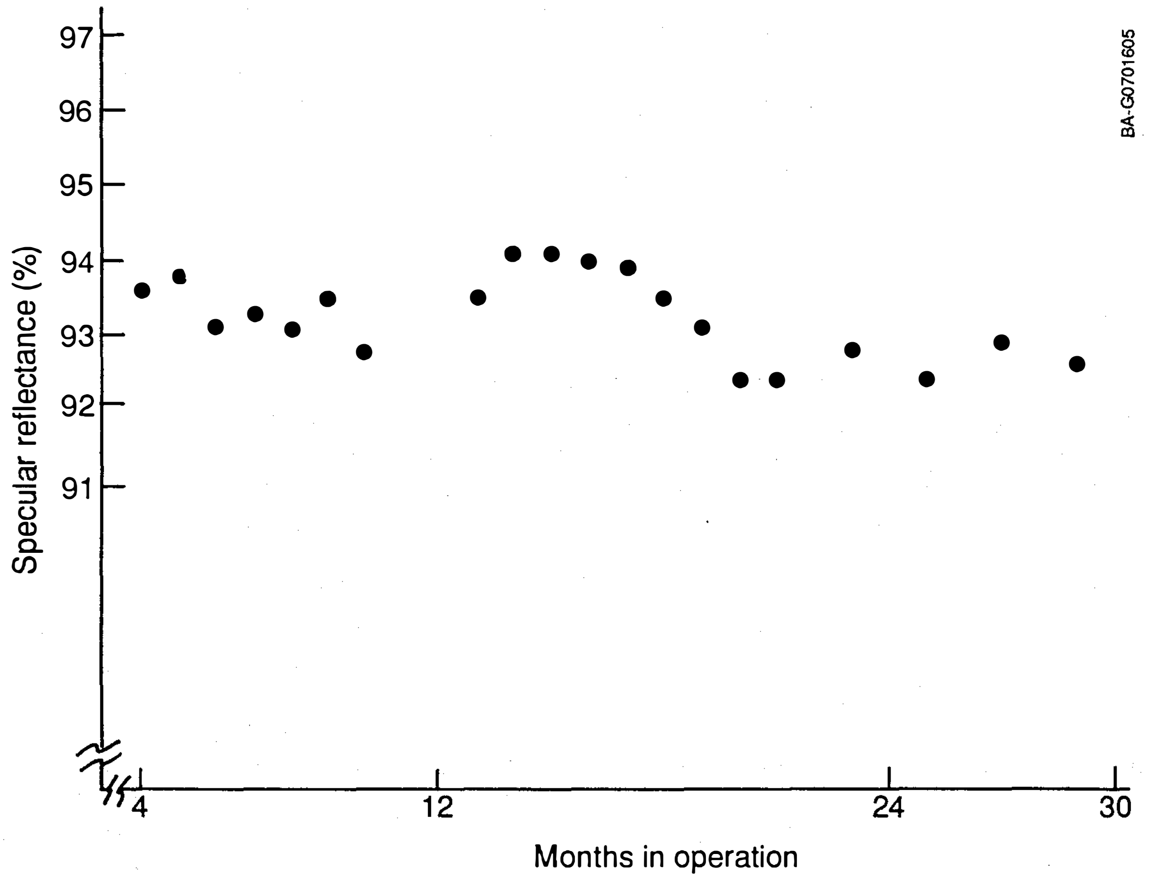

Figure 6. **Average specular reflectance at 650-nm wavelength and 25-milliradian acceptance angle immediately after noncontact spray cleaning of a 560-m^2 installation of parabolic troughs successively over a two-year period. Reflective film ECP 300A.**

curvature of the troughs. The troughs had been operating for about four months when the monthly cleaning test began. As Fig. 6 shows, the specular reflectance is regularly returned to about 93% after cleaning.

Between the monthly washings, reflectance fell at rates between 0.1% and 0.5% per day, depending on weather conditions, with an average rate of 0.25% per day. Unweathered mirrors have a specular reflectance of about 97% at 650 nm, so that a reflectance loss of about 4% occurs that is caused by tenaciously held soil and is not retrievable by noncontact cleaning. Contact (abrasive) cleaning returns reflectance nearly to initial values, but soiling rates increase so that the average reflectance is not improved much during longer-term tests.

The study by IST also indicated the following preliminary conclusions regarding soiling and cleaning: (1) Detergents or higher-pressure sprays do not improve cleaning. (2) Stowing troughs face down minimizes soil accumulation. Soiling depends upon collector position; test samples that are held in a fixed position are of little value for predicting performance of operating systems. (3) The 560-m^2 field could be washed in two hours using 120 gallons of water.

Laboratory and outdoor studies have identified factors such as hardness, smoothness, hydrophobicity, and low surface energy that may influence soiling (Cuddihy and Willis, 1984). Hardcoats do make silvered polymer mirrors more resistant to scratching. Temperature-cured hardcoats also weather well, but low curing temperatures that are limited by the polymer slow the curing and may increase costs. UV-cured hardcoats are equally scratch-resistant. They cure rapidly, but they have not weathered well.

Studies have also indicated that detergents or surface coatings (e.g., fluorine-containing layers) improved the performance of photovoltaic modules (Cuddihy and Willis, 1984). Fluorine-containing molecular monolayers can be stable and can alter the performance of mirrors (Shutt and others, 1989). Other research (Baum, Cross, and Hilyard, 1990) also finds that surface coatings can improve the performance of mirrors, but the effects are lost after continued cleaning cycles. An acceptable coating that resists soiling or allows better maintenance of reflectance during cleaning cycles has not yet been identified.

TUNNELING

ECP 305 mirrors can have a sporadic failure mode termed "tunneling," which usually occurs when the mirror is exposed to high humidity. During tunneling, the polymer separates from the silver in a characteristic pattern. The tunnels are usually about 1-in. wide and are separated by about 3 in. A maze of tunnels can meander over the complete mirror surface if the tunnels are not repaired as they initiate. If water is allowed to puddle on a mirror, the mirror might fail within a few days. However, a parabolic trough installation in Denver by IST has not had any tunneling problems after more than one year of operation. Tunneling is believed to begin when stresses induced at the silver/polymer interface by differential thermal and hygroscopic expansion overcome the weak adhesion between the polymer and silver. The adhesion between the polymer and silver is weak initially and is further weakened upon exposure to moisture.

We use two laboratory tests to evaluate tunneling. The first exposes mirrors to moisture by immersing them in a bath of tap water at room temperature. The second procedure is a cyclic test that alternates the mirrors from a tap-water bath (23°C) to a dry oven (60°C). The water bath tests have identified the following variables that influence tunneling.

Substrates

Experiments show that tunneling occurs more readily when ECP 305 is mounted on aluminum or stainless steel substrates rather than on painted aluminum or glass substrates.

Edge Preparation and Protection

Tunneling virtually always initiates at edges. How the edges are cut affects tunneling. Microscopic examination of edges reveals cut-induced flaws in the brittle polymer that depend on the cutting method. Razor cuts visually are poor, and they perform poorly in the water bath. A heated knife or a laser beam that melts through the polymer yields better edges, probably because local melting anneals the flaws. After cutting, the edges are protected. The standard procedure recommended by the 3M Company is to tape the edges with an aluminized polymer tape. We are investigating other more effective edge protection methods such as Tedlar tapes.

Adhesion

If the adhesion between the polymer and silver can significantly be increased, tunneling could be avoided not only from edges that are formed during fabrication but also from damage (hail, vandalism) that occurs internal to edges. We are investigating optically clear adhesive layers, which, preliminary experiments show, delay tunneling when the mirrors are exposed to the water baths.

The effects of some of these variables are shown in Fig. 7. In Fig. 7, the percent of surviving samples is plotted versus days in the water bath for three constructions. Razor-cut samples that are not protected by edge tape tunnel very quickly. Samples cut with a heated knife and not edge-taped resist

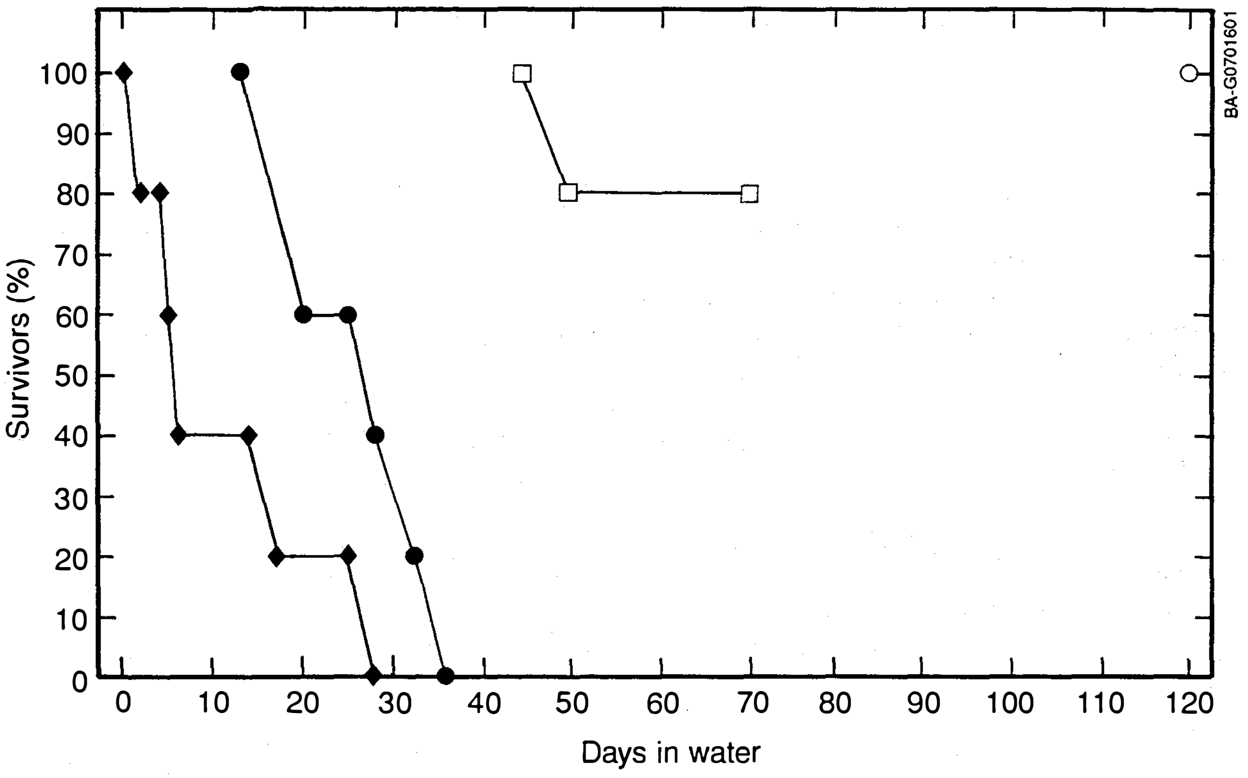

Figure 7. **Percent of intact samples vs. days in a water bath for razor-cut samples with no edge tape (♦), for samples cut with a heated knife and without edge tape (●), and for razor-cut samples that are edge- taped with Tedlar tape (□). Samples (○) cut with a heated knife and edge-taped with Tedlar tape are all intact after 120 days in water.**

tunneling longer but finally fail. When razor-cut samples are edge-taped with a Tedlar tape, there is significant improvement. Other samples were cut with a heated knife and edge-taped with Tedlar tape and are totally intact after 120 days in water.

CONCLUSIONS

Silvered acrylic mirrors such as ECP 305 can have a high specular reflectance and, based upon accelerated laboratory tests, can plausibly be expected to maintain optical performance by resisting silver corrosion for the five-year life that is the current goal. Silvered acrylic mirrors that have been cleaned monthly for two years have maintained reflectance within a few percent of initial values. In the presence of moisture, the silver/acrylic bond is weak and can delaminate. Delamination is delayed or prevented when the edges are properly formed and protected or when interlayer adhesion is enhanced as exhibited by some new laboratory samples.

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