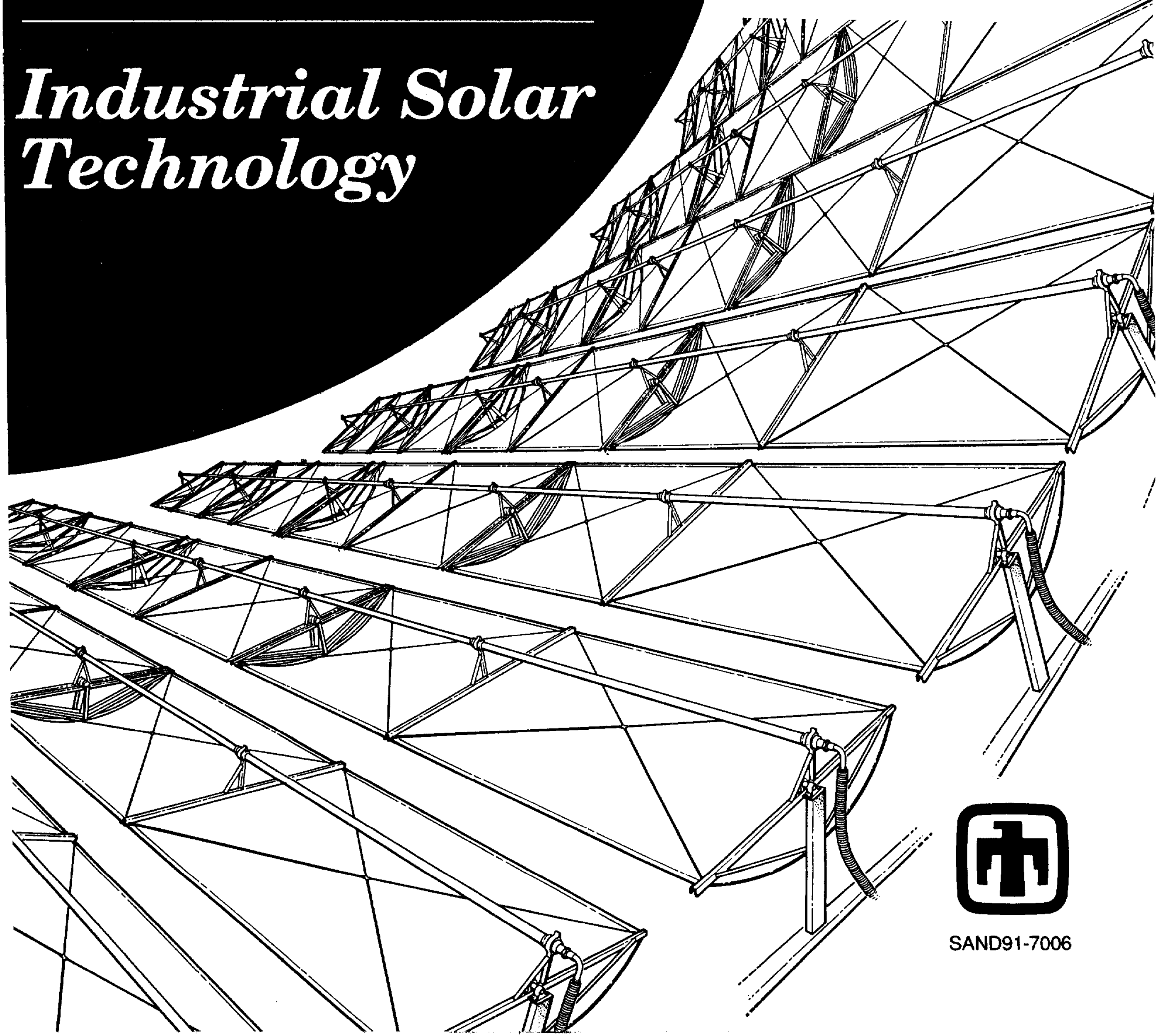
A Replaceable Reflective Film for Solar Concentrators

Industrial Solar Technology



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A REPLACEABLE REFLECTIVE FILM FOR SOLAR CONCENTRATORS

Industrial Solar Technology
Denver, Colorado

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ABSTRACT

The 3M Company manufactures a silvered acrylic film called ECP-305 that is regarded as the preferred reflective film for use on stretched-membrane heliostats. However, ECP-305 will degrade in time, due to both corrosion of the silver layer and delamination at the film's silver-to-acrylic interface, and will eventually need to be replaced. 3M uses a very aggressive adhesive on this film, and once it is laminated, replacement is very difficult. The purpose of this investigation was the development of a replaceable reflector, a reflective film that can be easily removed and replaced. A replaceable reflector was successfully configured by laminating ECP-305 to the top surface of a smooth, dimensionally stable polymer film, with a removable adhesive applied to the underside of the polymer film. Several stages of screening and testing led to the selection of a 0.010-inch thick polycarbonate (GE 8030) as the best polymer film and a medium tack tape (3M Y-9425) was selected as the best removable adhesive. To demonstrate the feasibility of the replaceable reflector concept and to provide a real-time field test, the chosen construction was successfully applied to the 50-m^2 SKI heliostat at the Central Receiver Test Facility at Sandia National Laboratories in Albuquerque.

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1. INTRODUCTION

The U.S. Department of Energy has pioneered the development of stretched-membrane heliostats for central receiver power plants. The stretched-membrane design concept uses thin metal membranes that are stretched over both sides of a large-diameter metal ring. A reflective polymer film is adhesively bonded to the front membrane. A slight vacuum in the space between the two membranes stretches the front membrane to produce a concave focused mirror. This simple and lightweight design allows stretched-membrane heliostats to have manufactured costs that are potentially lower than designs that used glass mirrors.

Under contract to Sandia National Laboratories, two 50-m^2 prototype stretched-membrane mirror modules were built and installed at Sandia's Central Receiver Test Facility during 1986 for evaluation. A 3M silvered-acrylic film, called ECP-300, was used as the reflective film on both prototype heliostats. The film has a solar-weighted reflectance of about 93%. ECP-300 was developed by 3M as an outgrowth of the aluminized acrylic film called ECP-244 (formerly FEK-244) that 3M had manufactured for several years for solar applications. ECP-244 and ECP-300 are of similar construction, except that the metallized layer for ECP-244 is aluminum, compared to silver for ECP-300. The front surface of the films is 0.004-inch thick extruded acrylic. The bottom surface of the metallized reflector is coated with approximately 0.001 inch of an aggressive acrylic-based pressure-sensitive adhesive. A clear polyester release liner is used to protect the adhesive prior to application.

In actual outdoor tests, both ECP-244 and ECP-300 have degraded over time due both to corrosion of the metallized layer and to delamination at the metal-to-acrylic interface. ECP-244 was first used on a solar installation in 1976. The first well-documented instance of ECP-244 delamination, a separation of the acrylic from the aluminum metallizing layer, is described in a Sandia report [1]. In the spring of 1981, Coilzak reflectors on 23,040 ft^2 of Acurex collectors at the Coolidge solar irrigation system were replaced with ECP-244. In July 1981, a rain storm accompanied by strong winds caused delaminations on 10 to 15% of the panels comprising the collector field. This occurred even with the collectors in the face-down stow position. About half the affected panels were replaced, and the rest of the delaminations were repaired. Delaminations and their repair continued to be a maintenance problem at the site. In July 1982, the collectors were deliberately washed in a gentle rain. This wetting caused delaminations in 10% of the panels. Half of the delaminations occurred in panels previously unaffected. Delaminations of ECP-244 have also occurred at other solar installations, such as the parabolic trough systems at the U.S. Army Proving Ground in Yuma, Arizona,and the Indian Health Service in Whiteriver, Arizona.

ECP-300 has delaminated in the field to an even greater extent. In December 1985, Industrial Solar Technology (IST) installed a parabolic trough system consisting of 2,400 ft^2 of solar collectors using ECP-300. This film had recently become available from 3M, and laboratory testing had shown good durability. To produce the reflectors for this system, IST dry-laminated the ECP-300 to an aluminum sheet metal substrate. The outside edges of the ECP-300 were hand cut with a razor in order to be the proper width for the parabolic concentrator. All the edges were sealed with aluminized acrylic edge tape. No holes were drilled through the film, and all stress concentration points were avoided. During a rainy period in the spring of 1986, a considerable number of delaminations occurred throughout the field. From discussions with personnel at 3M, a repair procedure was devised, and in accordance with this procedure, the delaminations were repaired and edges of the film were re-taped. Such repair work is very tedious and labor intensive. The repairs were partially successful in that the repairs have reduced the incidence of delaminations.

In December 1986, IST installed another commercial solar system comprising 6,000 ft^2 of collectors. Reflectance data on ECP-300 still showed good durability in the Colorado environment. The economic incentive to use ECP-300 still existed, and it was hoped that 3M's revised lamination procedure would greatly reduce the possibility of delaminations. This hope was realized, and delaminations have been less frequent at the second system compared to the first.

The two 50-m^2 prototype stretched-membrane heliostats installed in 1986 also experienced delamination problems. In 1988, Sandia summarized the delamination problems in a memo [2]. The ECP-300 began to delaminate on one of the heliostats almost immediately after it was installed. The delamination became progressively worse with each occurrence of precipitation and eventually resulted in gross delamination of the acrylic. The second heliostat did not experience any delamination until after 23 months, but efforts to repair the damaged areas were largely unsuccessful.

During 1989, 3M began production of an improved film, called ECP-305, which is expected to have significantly improved corrosion resistance compared to ECP-300. Based on accelerated weathering tests, ECP-305's silver corrosion rate is anticipated to be from three to five times better than ECP-300. Outdoor testing of ECP-305 has been initiated, but it will be a number of years before sufficient field-exposure data have been collected to verify the extended life.

Even if ECP-305 is shown to have improved corrosion resistance in outdoor testing, it will be necessary to occasionally replace the film in the course of a heliostat's anticipated 30-year lifetime. Additionally, delamination of the film may govern the replacement interval, rather than silver corrosion rates.

Finding a solution to the delamination problem was not a major goal of this research project, even though much consideration was given to the delamination problem and testing was performed to evaluate the resistance of the replaceable reflector to delamination. Rather, the primary focus of this research effort was the development of a reflector that is replaceable. Other research efforts are underway, primarily at SERI, to investigate and solve the delamination problem.

Until long-term durability of the film against both corrosion and delamination has been demonstrated, it is essential that the film be easily replaceable. 3M uses a very aggressive adhesive on its ECP films, and once the film is laminated, replacement of the film is difficult and time consuming. Research conducted to develop and demonstrate a replaceable reflector, a reflective film that can be easily removed and replaced, is presented in this report.

2 REPLACEABLE REFLECTOR DESIGN

Acrylic is the polymer of choice for reflective films because of its excellent clarity and good weathering resistance. Unfortunately, acrylic is hygroscopic. Under high humidity conditions (the film does not actually have to be wet) the acrylic tends to expand. It is postulated that this produces considerable stress at the metal/acrylic interface, since the metal itself does not expand. Further, water absorbed by the acrylic appears to weaken the strength of the acrylic-to-silver interface. Delamination seems to occur with the entry of water into micropores at edges of the film, or wherever a break in the acrylic occurs. (Capillary action may pull more water into the pores and act as a wedge to pry open a space between the acrylic and metal layer.) Once underway the process will continue, as the film draws a continuous supply of moisture from the air. Because aluminum bonds more strongly to acrylic than to silver, ECP-244 is more resistant to delamination than ECP-300. In the case of ECP-300, the bond between the silver and the acrylic can be so weakened, that the entire acrylic front surface of the film can be peeled off in a single piece across the entire two-foot width of the film.

Acrylic can have a moisture content of up to 1.5% of its weight. The moisture level in acrylic will depend on the relative humidity of the environment. When the relative humidity of the air changes from a lower value to a higher one, acrylics will absorb moisture, which in turn tends to cause dimensional growth. This dimensional change can occur very rapidly. For example, a dry sunny day with low humidity (perhaps 20%) can quickly change to a rainy day with high humidity (up to 100%). This change can induce relatively rapid dimensional growth of up 0.25% in an acrylic film such as ECP-300. This compares to only a 0.04% elongation when the membrane of a stretched-membrane heliostat is tensioned. Temperature-induced differential growth between ECP-300 and the metal membrane can be as large as 0.10% during a peak temperature swing of 30°F over a day. Peak temperature swings over a year can be even larger, but this variation occurs gradually, allowing for creep of the polymer reflector under this gradual temperature-induced stress. Hence, the largest and most abrupt dimensional growth or mechanical stress occurs due to moisture absorption by the acrylic reflector.

When strongly bonded to a solid substrate, such as metal, hygroscopic growth is constrained by the substrate. The adhesive used by 3M on ECP-300 is a relatively high-strength pressure-sensitive adhesive and provides an aggressive bond to the metal substrate. For this reason, ECP-300 is difficult to remove should it need to be replaced. Hence, while a relatively high-strength adhesive is needed to resist hygroscopic growth of ECP-300, this high-strength bond is not consistent with easy replacement of the reflective film.

Use of a low-tack adhesive on ECP-300, instead of the high-strength adhesive presently used by 3M, will produce a reflective film that is easy to remove. In fact, 3M had some experimental samples made during 1988 using a removable, low-tack 3M adhesive called Y-9415. Y-9415 is actually a polyester film coated on one side with a high-tack ("permanent") adhesive and on the other side with a low-tack ("removable") adhesive.

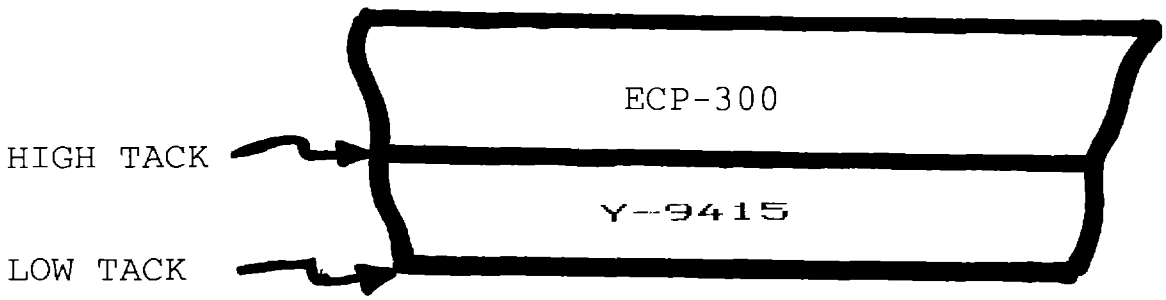

Figure 1: 3M low-tack adhesive samples

A cross-section of the reflective samples that were made by 3M is shown in Figure 1. Several laminate samples were applied to operating IST parabolic trough collectors in Colorado during 1988. Some of the samples were small (less than 1 foot square) and other samples were large (2 x 12 feet). Some of the small samples were placed over an existing layer of ECP-300, which was aggressively bonded to an aluminum substrate. The other samples were placed directly onto an aluminum substrate. Application was easily accomplished by smoothing out the samples by hand. The low-tack adhesive also allowed the reflector to be repositioned by pulling it back from the substrate and laying it down again. The samples have withstood high winds and high-pressure washing. However, all but the small samples developed wrinkles or "puckers" due to the release of the low-tack adhesive from the underlying substrate. These samples have been subjected to the naturally occurring changes in relative humidity. During periods when relative humidity increased greatly in a short period of time, the "puckers" developed. Hence, while the ECP-300/Y-9415 laminate was easy to apply and allowed for easy film replacement, it does not yield a stable reflective surface.

These observations suggested an alternate, more stable configuration for a replaceable reflector, as shown in Figure 2. ECP-305 reflective film is shown laminated to a smooth, non-hygroscopic polymer backing sheet. The polymer backing sheet can be adhesively bonded to the membrane of a heliostat with a low-tack adhesive so that the reflective sheet can be easily replaced.

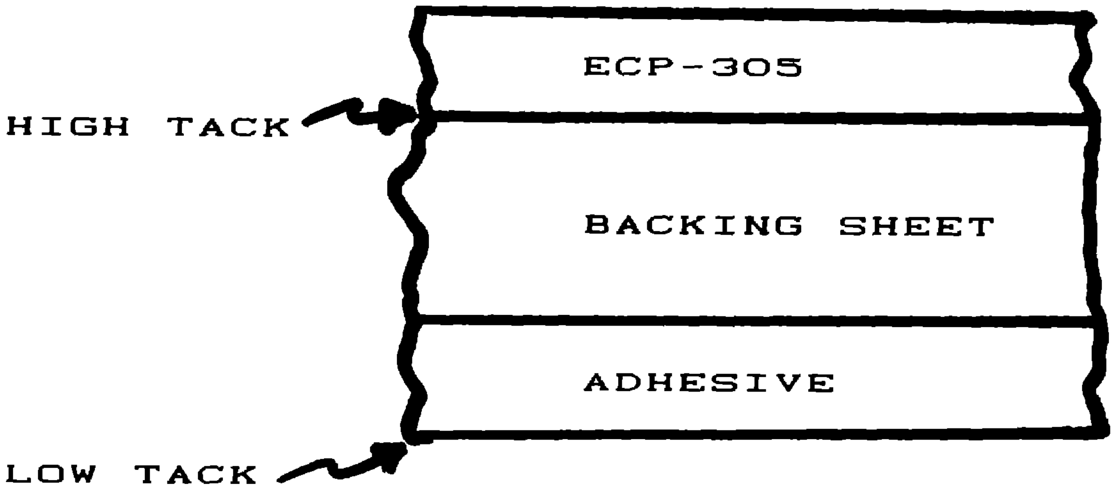

Figure 2: Replaceable reflector construction

The polymer backing sheet must be non-hygroscopic so that dimensional stability of the reflective sheet is improved in order to prevent wrinkling or "puckering" of the reflective sheet. When humidity levels increase and the acrylic absorbs moisture, the acrylic will tend to grow. However, the non-hygroscopic backing sheet will be largely unaffected by humidity and will tend to resist the hygroscopic growth of the acrylic. The adhesive bond between the acrylic and the backing sheet will be high strength (using the pressure-sensitive adhesive that 3M supplies with ECP-305) so that the two layers will stay bonded together. The degree to which the acrylic layer is constrained in growth will depend on the elastic modulus of both the acrylic and the non-hygroscopic backing sheet, and their thicknesses. With the proper choices, the acrylic and non-hygroscopic backing sheet will have enough dimensional stability to allow the use of a low-tack adhesive between the composite and the metal membrane, without developing wrinkles or "puckers."

2.1 Suitable Polymers for Backing Sheet

The choice of material for the polymer backing sheet will depend on a number of physical and mechanical properties. The ideal candidate would have:

- low water absorption, so that hygroscopic growth is minimized,
- high elastic modulus, so that the acrylic layer is highly constrained,
- smooth surface finish, so that specularity of the ECP-305 is maintained,
- low cost, so that overall reflective surface cost is minimized,
- easily bonded surface, so that adhesives can be easily applied,
- high tensile strength, so that the composite does not fail mechanically,
- UV stability, so that properties are maintained outdoors, and
- high tear resistance, to eliminate tearing of the reflective film during installation or removal.

2.1.1 Commercially Available Polymer Films

Table 1 lists suppliers, available sizes, and estimated costs on a per square meter basis of polymers that are potentially suitable for use in the backing sheet of the proposed replaceable reflector. This list includes all major classes of polymers that are reasonable candidates for the backing sheet and are available commercially in the form of rolls of film that can be laminated to make the proposed replaceable reflector. Since a key element of the backing sheet is a low coefficient of hygroscopic expansion, only polymers that have low water absorption values have been included. This eliminates a large number of commercially available polymer films such as nylons, cellulosic plastics, ABS, polimides, polyurethanes, polysulfones, as well as acrylic itself. Fluoropolymers have also been excluded from the list because, although they are generally non-hygroscopic, they are very expensive and are very difficult to adhesively bond. Since low cost and bondability are desirable characteristics of the backing sheet, fluoropolymers have not been considered. Some polymers have low water absorption rates but are not commercially available in film (or thin sheet) form. An example is polybutylene, which although it can be produced as film, is difficult to produce. For this reason, polybutylene is not commercially available except for special orders.

The remaining polymer film candidates include polycarbonate, polyester, polyethylene, polypropylene, polystyrene, and polyvinyl chloride. The list is based on plastic supply references and conversations with dozens of plastic suppliers including resin manufacturers, film and sheet processors, and film and sheet distributors. A very large number of copolymers are available commercially, especially polyolefin copolymers, but they have not been included in Table 1. These copolymers are blends of the major polymer groups and hence have properties that are defined by their major constituents. In the packaging industry, these copolymers find widespread use since bulk costs can often be reduced with a blend of materials, while still maintaining the acceptable mechanical properties for a specific application. However for the current effort, an evaluation of the major groups of homopolymers covers the full range of mechanical properties and characteristics.

Pricing has been determined for low-quantity purchases, usually a minimum order of 500 - 1000 pounds. For a 5 mil thickness of film, 1000 pounds will cover 25,000 - 40,000 ft^2.

TABLE 1 - LIST OF LOW OR NON-HYGROSCOPIC POLYMER FILMS

POLYCARBONATE

Product Name or designation: DL1900
Supplier: General Electric
Available in 2,3,4,5 mil thicknesses, up to 48" widths
Cost: \$5.30/lb, 5 mil thickness = \$1.40/m²

Product Name or designation: 8030
Supplier: General Electric
Available in 7,10,15 mil thicknesses, up to 48" widths
Cost: \$4.86/lb, 7 mil thickness = \$1.80/m²

POLYESTER

Product Name or designation: Mylar
Supplier: Dupont
Available in 2,3,5, 7.5, 9 mil thicknesses, up to 72" widths
Cost: \$3.20/lb, 5 mil thickness = \$1.22/m²

Product Name or designation: 4500 Series
Supplier: Hoechst Celanese
Available in 2,3,4,5,7 mil thicknesses, up to 48" widths
Cost: \$3.00/lb, 5 mil thickness = \$1.14/m²

Product Name or designation: 947
Supplier: ICI Americas
Available in 3 mil thickness, up to 62" widths
Cost: \$3.00/lb, 3 mil thickness = \$.68/m²

Product Name or designation: Llumar window film
Supplier: Martin Processing
Available in 3 and 4 mil thicknesses, up to 60" widths
Cost: 3 mil thickness = \$3.44/m²

Product Name or designation: Llumar weatherized film
Supplier: Chemplast/Martin Processing
Available in 5 and 7 mil, up to 48" widths (7 mil) and 60" (5 mil)
Cost: 5 mil thickness = \$6.87/m²

POLYETHYLENE

Product Name or designation: polyethylene film
Supplier: Visqueen
Available in 4 and 6 mil thicknesses, up to 8' widths
Cost: 6 mil thickness = \$.36/m²

Product Name or designation: low-density, blown polyethylene
Supplier: Exxon
Available up to 4 mil thicknesses, up to 85" widths
Cost: \$1.00/lb, 4 mil thickness = \$.16/m²

TABLE 1 CONTINUED - LIST OF LOW OR NON-HYGROSCOPIC POLYMER FILMS

POLYETHYLENE (CONTINUED)
Product Name or designation: high-density polyethylene #190
Supplier: James River Corp.
Available in up to 3 mil thicknesses, up to 85" widths
Cost: $1.10/lb, 3 mil thickness = $.18/m^2

ETHYLENE-VINYL ACETATE
Product Name or designation: EVA #703
Supplier: Consolidated Thermoplastics
Available in 4 and 6 mil thicknesses, up to 24' widths
Cost: 6 mil thickness = $.66/m^2

POLYPROPYLENE
Product Name or designation: EX-12
Supplier: Exxon
Available in 4 to 22 mil thicknesses, up to 30" widths
Cost: $1.38/lb, 5 mil thickness = $.36/m^2

Product Name or designation: T-503
Supplier: Hercules
Available in 1 and 2 mil thicknesses, up to 66" widths
Cost: $2.11/lb, 2 mil thickness = $.21/m^2

Product Name or designation: 175 ASPX, coated with acrylic and PVDC
Supplier: Mobil
Available in 1.7 mil thicknesses, up to 55" widths
Cost: $2.65/lb, 1.7 mil thickness = $.24/m^2

Product Name or designation: JR 1391
Supplier: James River Corp.
Available in 3 mil thickness, up to 100" widths
Cost: $1.40/lb, 3 mil thickness = $.18/m^2

POLYSTYRENE
Product Name or designation: polystyrene film, oriented
Supplier: Tensilwrap
Available in 3,5,7,10 mil thicknesses, up to 42" widths
Cost: $1.95/lb, 5 mil thickness = $.30/m^2

POLYVINYL CHLORIDE
Product Name or designation: C-107
Supplier: VCF Packaging
Available in 1 and 2 mil thicknesses, up to 55" widths
Cost: $3.05/lb, 2 mil thickness = $.47/m^2

Product Name or designation: PVC, roller-polished
Supplier: Kings Specialties
Available in 3 and 5 mil thicknesses, up to 42" widths
Cost: 5 mil thickness = $1.44/m^2

2.1.2 Physical and Mechanical Properties of Polymer Films

The choice of material for the polymer backing sheet will depend on a number of physical and mechanical properties. Appendix A provides an analytical treatment of some of these important properties. In order to select which of the materials listed in Table 1 were worthy of small-scale testing (see Section 3), a list of polymer selection criteria was developed. These selection criteria are described below, with the most important criteria listed first, followed by the less important criteria. Following this description of the major criteria, the properties and characteristics of the commercially-available polymers of interest are shown in Table 2.

<u>Important Physical and Mechanical Properties</u>

Water Absorption - Since the polymer backing sheet is ideally non-hygroscopic in order to constrain the hygroscopic growth of the acrylic, a low water absorption percentage is a critical property. Water absorption is measured by ASTM Test D-570, as a percentage of weight after 24 hours of water immersion. For polymers that absorb moisture, the hygroscopic coefficient of expansion is often measured in units of in/in/%RH. This coefficient provides very useful information regarding the expected behavior of the replaceable reflector (see Appendix A). Unfortunately, this property has been found to be available from the manufacturers in only limited cases.

Elastic Modulus - The elastic modulus of the polymer backing sheet should be high in order to better constrain the hygroscopic growth of the acrylic. A high elastic modulus will minimize the thickness requirement of the backing sheet, and reduce the cost of the reflector laminate. Elastic moduli can vary widely between different polymers.

UV Stability - The polymer must have some stability to moderate levels of UV light. The UV-exposure criterion is not as critical as most solar applications because the polymer backing sheet will be protected from UV light by the metallized acrylic top layer. However, some UV light will be transmitted to the backing sheet, at low levels directly through the silver and acrylic, or through pinholes in the metallized acrylic.

Bondability - The polymer backing sheet must be bondable to adhesives so that the proposed reflector laminate can be constructed. Some polymers are very difficult to bond to. These less bondable polymers are sometimes available with surface treatments so that satisfactory adhesion can be obtained.

Surface Finish - The polymer backing sheet should have a smooth surface in order to preserve the optical properties of the acrylic reflective layer. Poor surface finish could result in decreased specular reflectance. Polymer film products without surface treatments are preferred since these treatments can roughen the surface of the film.

Thermal Expansion - Although moisture is thought to be the primary driver in the expansion of acrylic, thermal expansion also plays a significant role. Since the thermal expansion coefficient of acrylic is over three times as large as the thermal expansion coefficient of the aluminum heliostat membrane, the polymer backing sheet can also help constrain the thermal expansion of the acrylic in the same way it constrains hygroscopic growth of the acrylic. For this reason, a low thermal expansion coefficient is preferred for the polymer backing sheet.

Tear Strength - High tear strength will ensure that the replaceable reflector will resist tearing during installation and removal. Acrylic is a rather brittle polymer and by itself is difficult to work with. Tears initiate and propagate easily. Two ASTM tests define tearing strength: ASTM D1922 tests for propagating tear strength and ASTM D1004 tests for initial tear strength. Both measures are useful to this research effort.

Tensile Strength - The polymer backing sheet must have sufficient strength to carry the stress that develops during hygroscopic expansion of the acrylic (see Appendix A). Although these stress levels are expected to be low, strength will be considered in selecting candidates for the backing sheet. The glass transition temperature will also be considered, especially for polymers that are amorphous in structure. Some polymers have high creep rates under normal ambient temperatures because of their structure and their low glass transition temperatures.

Cost - Cost of course is an important element in the evaluation of the replaceable reflector. However, the cost of the polymer backing sheet will be small compared to the cost of the silvered acrylic film, even for the more expensive polymers listed in Table 1.

Physical and Mechanical Property Tabulation

The important physical and mechanical properties of the commercially-available polymer films listed in Table 1 are shown in Table 2. As a comparison, the properties and characteristics of the acrylic used in ECP-305 are given below.

Properties and Characteristics of Acrylic in ECP-305

Water Absorption, ASTM D570	1.4%
Elastic Modulus, psi	320,000
UV Stability	Excellent
Bondability	Good
Surface Finish	Smooth
Thermal Expansion, in/in/°F	4.6x10-5
Tear Strength	
initial, D1004, g/mil	770
propagating, D1922, g/mil	6
Tensile Strength, psi	9,000

TABLE 2 - PROPERTIES AND CHARACTERISTICS OF NON-HYGROSCOPIC POLYMER FILMS

POLYMER	WATER ABSORPTION ASTM D570 % by wt.	ELASTIC MODULUS psi	UV STABILITY	BOND-ABILITY	SURFACE FINISH	THERMAL EXPANSION in/in/°F	TEAR STRENGTH init./prop gm./mil	TENSILE STRENGTH psi	COST $/lb
Polycarbonate									
·DL1900	.2	300,000	Fair	Good	Polish	3.8×10^{-5}	726/80	8,500	5.30
·8030	.2	300,000	Good	Good	Smooth/ Matte	3.8×10^{-5}	726/80	8,500	4.86
Polyester									
·Mylar	.7	520,000	Fair	Good	Smooth	0.9×10^{-5}	800/20	26,000	3.20
·HC 4500	.7	600,000	Fair	Good	Smooth	0.8×10^{-5}	1226/20	30,000	3.00
·ICI 947	.6	620,000	Good	Good	Smooth	1.0×10^{-5}	-/38	27,000	3.00
·Llumar	.6	520,000	Good	Good	Smooth	0.9×10^{-5}	20/-	25,000	18.00
Polyethylene									
·JR #190	<.01	150,000	Poor	Poor	Smooth	6.0×10^{-5}	-/100	6,000	1.10
·Exxon LDPE	<.01	40,000	Poor	Poor	Smooth	$11. \times 10^{-5}$	550/250	3,000	1.00
·Visqueen	<.01	35,000	Poor	Poor	Smooth	$10. \times 10^{-5}$	-/-	2,900	1.10
EVA									
·#703	<.01	85,000	Good	Poor	Smooth	$10. \times 10^{-5}$	-/-	5,000	2.00
Polypropylene									
·EX-12	<.01	110,000	Poor	Poor	Smooth	$5. \times 10^{-5}$	-/20	6,000	1.38
·T-503	<.01	395,000	Poor	Fair	Smooth	$5. \times 10^{-5}$	550/10	20,000	2.11
·175 ASPX	<.01	450,000	Poor	Good	Smooth	$5. \times 10^{-5}$	500/8	16,000	2.65
·JR 1391	<.01	115,000	Poor	Fair	Smooth	$5. \times 10^{-5}$	-/-	5,000	1.40
Polystyrene									
·Tensilwrap	.05	350,000	Poor	Good	Smooth/ Matte	$4. \times 10^{-5}$	1200/5	9,000	1.95
PVC									
·C-107	.02	300,000	Good	Good	Polish	$4. \times 10^{-5}$	500/20	7,800	3.05
·Kings PVC	.02	300,000	Poor	Good	Polish	4.x10-5	-/-	7,200	1.44

Polycarbonate is an engineering thermoplastic that is most noted for its high impact resistance. However, it also has low water absorption and good mechanical properties. General Electric is a major supplier of polycarbonate and produces many varieties of polycarbonate film. The General Electric DL1900 film has a smooth surface finish and is available in thicknesses of up to 5 mils, but this grade of film contains no UV stabilizers. Mobay Corporation also produces 5, 7 and 10 mil polycarbonate films, but as off-the-shelf products they also do not contain UV absorbers. The General Electric 8030 film does come with UV stabilization and is available in thicknesses beginning at 7 mils. One surface of this film is glossy/smooth and the other side has a smooth/matte finish. Although polycarbonate film is relatively expensive compared to other polymer films, the cost of the film is small compared to the cost of the reflective acrylic film.

Polyester is a tough, widely used thermoplastic that has high strength and, more important for the replaceable reflector, has a high elastic modulus. The elastic modulus of polyester is nearly twice that of acrylic. The thermal expansion coefficient of polyester is very low; about five times lower than acrylic and just lower than the thermal expansion coefficient of aluminum. Although polyester is not stable to UV light, the addition of stabilizers can significantly improve its durability to UV exposure. Neither DuPont nor Hoechst Celanese supply UV-stabilized films, but ICI Americas and Martin Processing do. ICI Americas markets a UV stabilized film with a product number of 947. The film is available in only a 3-mil thickness. Martin Processing markets a UV-stabilized film in 3-, 5- and 7- mil thicknesses. The 3-mil thickness is called window film and is marketed through their Energy Control Products Division. The 5- and 7-mil film is marketed through their Industrial Division. Compared to the other polymer films listed in Table 1, polyester has a relatively high water absorption percentage. However, polyester is considerably more dimensionally stable than acrylic, as indicated by its lower coefficient of hygroscopic expansion (HCE). The 3M-measured value of ECP-305's HCE is 3.0x 10-5. Hoechst Celanese gives the HCE of its polyester as 0.7x10-5. DuPont uses an HCE value of 0.6x10-5 for Mylar. ICI Americas uses the same value as Hoechst Celanese.

Polyethylene, ethylene-vinyl acetate (EVA), and polypropylene are low-cost, olefin-based thermoplastics that have extremely low water absorption values. Unfortunately, polyethylene and EVA polymers suffer from very poor UV stability. EVA #703, supplied by Consolidated Thermoplastics, is unusual in that it has UV stabilizers added to it, allowing up to three years of outdoor use on greenhouses. To accommodate these large structures, EVA #703 is available in widths of up to 24 feet. The elastic moduli of polyethylene and EVA films are very low, ranging from 150,000 psi to below 35,000 psi. This is very poor considering the elastic modulus of acrylic, the material we intend to restrain, is 320,000 psi. The tensile strength of EVA and polyethylene are also typically low, ranging from 2,000 to 6,000 psi. More important, these polymers have low glass transition temperatures, allowing them to creep rapidly at room temperature - an unacceptable characteristic for the polymer backing sheet. Most polyethylenes and EVA's also have high thermal expansion coefficients, another negative characteristic. Further, it is difficult to adhesively bond polyethylene and EVA. Although the surface of the material can be treated to improve bondability, typically only one side is treated.

Polypropylene is superior to polyethylene and EVA in most respects. The elastic moduli of polypropylene films can be higher than acrylic, thermal expansion coefficients are lower than polyethylene and EVA, and tensile strengths are higher. Costs are also higher, but again, this is of little consequence for this application. Unfortunately, UV stability is poor and a commercially available, UV-stabilized polypropylene film has not been identified. Hercules is a major producer of polypropylene film. The Hercules T503 film is treated on both surfaces and hence has improved bondability. Unfortunately, the film is commercially available with a maximum thickness of only 2 mils. The polypropylene film with the highest elastic modulus (450,000 psi) is produced by Mobil (#175ASPX). This film also has the unusual characteristic of being easy to bond by virtue of a surface coat of acrylic on one surface and PVDC on the other. The film is commercially available in only a 1.7 mil thickness.

Polystyrene is another polymer that absorbs very little water, is inexpensive and has reasonably good mechanical properties. The elastic modulus of the oriented polystyrene film available from Tensilwrap is 350,000 psi, and the tensile strength is 9,000 psi. Although polystyrene has good bondability, UV stability is poor and polystyrene film is not available off the shelf with UV stabilizers. The thermal expansion coefficient of polystyrene is just under that of acrylic.

Polyvinyl chloride has a very low water absorption percentage (0.02%, ASTM D570) and good mechanical properties. However, without the addition of UV stabilizers, polyvinyl chloride has poor UV resistance. The polyvinyl chloride from Kings Specialties, and produced by Clockner Industries, is commercially available (in low quantity) as a clear, roller-polished film with no UV absorbers. With large orders of over 5,000 pounds, this film can be produced with UV stabilizers or with carbon black, which would also provide UV stability. The C-107 polyvinyl chloride film produced by VCF Packaging does have UV absorbers. The film is rigid, contains no plasticizers, and has a smooth, polished surface. The film is easy to bond to since it contains no plasticizers or additives that would affect the adhesive bond.

Table 3 indicates whether each polymer candidate is acceptable for each of the nine selection criteria. An X indicates that the particular film is not judged to be acceptable for the particular selection criterion. A ? indicates that the particular film may not be acceptable for the particular selection criterion. The question mark is used only for UV stability where the poor UV weathering characteristic of the particular polymer leads to uncertainty about its longevity as a backing sheet for the replaceable reflector. This uncertainty stems from the fact that only a small amount of UV light will impinge on the backing sheet, since it is protected to a large degree by the ECP-305. It is possible that polymers with known instability to UV light may still maintain their mechanical properties when protected in this manner. Only long-term testing will answer this question satisfactorily. Hence, a question mark is used to denote that UV stability may be a factor for certain polymers.

TABLE 3 - ACCEPTABLE AND NON-ACCEPTABLE CHARACTERISTICS OF NON-HYGROSCOPIC POLYMER FILMS

POLYMER	WATER ABSORPTION	ELASTIC MODULUS	UV STABILITY	BOND-ABILITY	SURFACE FINISH	THERMAL EXPANSION	TEAR STRENGTH	TENSILE STRENGTH	COST
POLYCARBONATE									
DL1900			?						
8030									
POLYESTER									
Mylar			?						
HC 4500			?						
ICI 947									
Llumar									
POLYETHYLENE									
JR 190		X	?	X				X	
Exxon LDPE		X	?	X		X		X	
Visqueen		X	?	X		X		X	
ETHYLENE-VINYL ACETATE									
EVA 703		X		X		X		X	
POLYPROPYLENE									
EX-12		X	?	X					
T-503			?						
175 ASPX			?						
JR 1391		X	?						
POLYSTYRENE									
Polystyrene			?						
POLYVINYL CHLORIDE									
C-107 PVC									
Kings PVC			?						

? Denotes Probably Not Acceptable
X Denotes Unacceptable

Both polycarbonate films are judged to be acceptable in all categories, except that the DL1900 film has somewhat less UV stability. The 8030 film has UV absorbers and hence is preferred. Since the 8030 polycarbonate film is available in acceptable widths (up to 48 inches) and acceptable thicknesses (7 mils and over), this film is a candidate for the backing sheet and was selected for small-scale testing, as described in Section 3.

Of the polyester films, the UV-stabilized ICI 947 and Martin Processing weatherized Llumar are shown to be acceptable in all categories. Both products are available in acceptable widths (over 48 inches) and were recommended for small-scale testing. The ICI 947 is available in only a 3-mil thickness, and the Llumar is available in 5-and 7-mil thicknesses.

None of the polyethylene films are judged to be acceptable, because of the low glass transition temperature of polyethylene (indicated by an X for unacceptable tensile strength), low elastic moduli, and poor bondability. Also, the thermal expansion coefficient of all the polyethylenes, except for the JR 190, is judged to be too high to be acceptable.

Ethylene-vinyl acetate is similarly unacceptable because of its low glass transition temperature, low elastic modulus, high thermal expansion coefficient, and poor bondability.

Two of the commercially available polypropylene films are unacceptable because of low elastic moduli. All the commercially available polypropylenes suffer from questionable UV stability. Unfortunately, neither of the two polypropylene films with acceptable elastic moduli is commercially available in a range of thicknesses. The Hercules T-503 film has a maximum thickness of 2 mils and the Mobil 175 ASPX film is available in only a 1.7-mil thickness. Of these two films, the 175 ASPX has the higher elastic modulus and also has good bondability due to its surface coats of acrylic and PVDC. Hence, the 175 ASPX was selected for small-scale testing as a possible backing sheet for the replaceable reflector.

The polystyrene film is judged to be acceptable in all categories except for questionable UV stability. The polystyrene film was therefore also selected for small-scale testing.

Both polyvinyl chloride films are judged to be acceptable in all mechanical categories. Although the 1- and 2-mil C-107 films have some UV stabilizing additives and hence are improved from a weathering perspective, the Kings Specialties film is available in 3- and 5-mil thicknesses. Given the uncertainty in the necessary amount of UV stability and the necessary film thickness, both films were selected for small-scale testing.

2.2 Suitable Adhesives

The fabrication of the replaceable reflector film requires the use of a pressure sensitive adhesive to attach the film to the concentrator. The desirable characteristics of the pressure sensitive adhesive used to construct a replaceable reflector film include:

Removable - Adhesion to the substrate should not increase to the point that the film cannot be cleanly removed. No adhesive buildup on the substrate can occur even after years of outdoor exposure.

Stable - The adhesive must remain tacky and sufficiently aggressive to maintain adhesion to the substrate even against outdoor exposure to moisture, temperature variations, and UV light. The UV-exposure criterion can be relaxed somewhat for this application. Edges of the adhesive will probably be sealed, and the bulk of the adhesive is protected by the metallized film and the polymer support layer.

No Outgassing - The adhesive must be chemically stable in that it does not outgas over time. Such outgassing can break the adhesive bond to the substrate, leading to potential adhesive failure of the film, or at the least would render the film no longer flat.

High Viscosity - The viscosity of the adhesive in the dissolved state should be high enough that it can be applied in a flat, uniform, predictable layer. This is particularly important for solar applications, for which specularity is of major importance. Desired viscosity lies in the range of 500 to 2000 cP.

Water Based - Water-based adhesives, as compared to adhesives dissolved in organic solvents, are to be preferred because of much reduced environmental and health concerns, both during manufacture and use.

Synthetic - Synthetic adhesives, as compared to natural adhesives such as rubber, maximize the predictability of adhesive properties between successive batches of materials.

Peel Strength - The adhesive must have sufficient peel strength to maintain adhesion to the heliostat metal membrane, while at the same time adhesion must not be so aggressive as to leave a deposit on the membrane, or impart force to the underlayer during removal that could cause permanent deformations in the metal substrate.

Flexibility - The adhesive must remain flexible to allow application of the reflective film stack, and also to conform to the variable curvature of the concentrator.

Availability and Cost - Most adhesives are produced as bulk liquids. Such adhesives can be applied to small reflective samples for testing purposes. However, much better specularity would probably be produced by having a converter apply the adhesive in a smooth uniform layer through the use of specialty coating equipment. A difficulty in this approach involves minimum quantity requirements.

An alternative approach is to use adhesive film tapes that can be laminated directly to the non-hygroscopic polymer layer. Such tapes, however, are much more expensive than bulk adhesives.

As a class of adhesives, most acrylics tend to embody the desired properties. They are synthetic, flexible, can be prepared in water-based latex form, can be laid down in very flat, predictable layers, and exhibit outstanding outdoor durability. Through suitable manipulation of copolymers and additives, it is possible to produce adhesives of widely differing properties to meet the demands of numerous adhesive applications. The crucial parameter regarding the construction of the proposed film is replaceability, and the ability to be able to apply the film to concentrators in the field. An adhesive can be replaceable in that it can be removed cleanly from a substrate, but may still be too aggressive to be easily applied in the field without the formation of bubbles and imperfections.

A review of adhesives that meet the needed requirements covered a wide variety of companies. The list of companies producing the base resins for pressure-sensitive adhesives is relatively short and includes major companies such as Dupont, Rohm and Haas, ICI, American Cyanamid and Ciba-Geigy. Some of these companies, such as Dupont, are little involved in the production of actual adhesives, whereas others, such as Rohm and Haas function both as suppliers of resins and producers of commercially available adhesives. Another category of manufacturer, such as H. B. Fuller, National Starch, and Valchem, produce bulk adhesives from base resins that may be usable directly or alternatively may be passed on to converters for conversion into saleable products, such as adhesive tapes. 3M Company is typical of another class of manufacturer that formulate purchased resins into commercial products. Other major adhesive producers in this class are Adchem and Avery.

The fragmented nature of the adhesives industry, the number of products available, the size of some of the producers, and the reluctance of suppliers to discuss highly proprietary manufacturing techniques complicates the task of evaluating candidate adhesives. Often, the required technical data are not available and there is very little consistency in the type of tests conducted to evaluate adhesive properties.

Table 4 lists properties of six adhesives that appeared to have the desired characteristics for the replaceable reflector. These six adhesives remained after the elimination of a much greater number of less suitable candidates.

TABLE 4 - ADHESIVE PROPERTIES

Adhesive Tapes

Tape	Carrier	Thickness (mils)	Peel Strength (oz./in) (to steel) Removable	Permanent	Cost ($/ft^2)
3M Y9415	polyester	3.0	4-5	15	0.83
3M Y9425	UPVC	5.5	14	49	0.99
Avery Fastape 702P	polyester	5.0	50	55	0.37

Adhesive Liquids

Adhesive	Type	Peel Strength (oz./in)	Viscosity (cP*)	Density (lb/gal)	Solids (%)	Coating Wt. (oz./yd^2)	Cost ($/lb)
H. B. Fuller PN 1026	Acrylic	12	200-800	8.3	46-48	0.8-1.0	0.70
Pierce & Stevens							
A7723A	Acrylic	20	3500	8.3	51	0.8	1.80
E9767AH	Solvent-based elastomeric	12	3750	6.4	30	0.6-0.8	1.10

* Viscosity test methods may not be consistent.

The adhesives listed in Table 4 were all shown to be removable based on short-duration coupon tests. The adhesive tapes were evaluated by laying them down on a flat aluminum substrate, and testing for removability after time periods of several hours, several days and finally after approximately two weeks . Both 3M adhesives were removable, without leaving a residue, and replaceable, in that they could be removed from the substrate and repositioned again. Considerable force was required to remove the Avery 702P adhesive from aluminum, but doing so left no residue, even after several days of contact. Once the adhesive had been applied to the substrate, however, the adhesive (alone without a backing sheet) could not be removed and replaced without the formation of wrinkles. The liquid adhesives were also shown to be removable and replaceable using small test coupons. The liquid adhesives were brushed onto polyester, polyvinyl chloride and polystyrene backing sheets, dried overnight, and then laid onto flat aluminum substrates.

Before beginning this research project, IST carried out initial testing of a removable reflective film supplied by 3M using 3M's low-tack Y-9415 adhesive. These tests demonstrated the durability of the adhesive to outdoor exposure over a period of almost two years. The adhesive also retained its tackiness over this time period, but as discussed in Section 2, the ECP-300/Y-9415 laminate was subject to wrinkles and "puckers" as the adhesive released from the underlying substrate. This adhesive was a candidate for the replaceable film stack that was designed to overcome the limitations of the original construction. As a baseline, therefore, it was used to compare other possible adhesives.

Adhesive Y-9415 is a double-coated film tape. The carrier is a polyester film coated on one side with a high tack adhesive (90° peel adhesion to steel--15 oz/inch) and on the other side with a low tack adhesive (4-5 oz/inch to paper). Total thickness of the adhesive is 0.003 inch (0.08 mm). The low tack adhesive is protected by a silicone-treated paper release liner. This adhesive finds commercial applications in "Post It" paper products. The low-tack adhesive is considerably less aggressive than any of the other candidates investigated.

While other products, such as masking tape, are replaceable and reusable over short periods of time, until the introduction of formulations that led to the commercialization of Y-9415, no other product on the market appeared to offer replaceability over extended time periods. A review of the 3M patent (No. 3,922,464) issued in November 1975 revealed that the bulk properties of the adhesive are based on a chemical formulation involving acrylic copolymers and minor quantities of additives. The patent does not answer the question of why, when applied, Y-9415 selectively releases at the external surface and not at the surface of the carrier film. Conversations with 3M personnel indicated that this property results through surface treatment of the polyester carrier to increase adhesion, and also treatments applied to the external low tack adhesive surface.

A relatively new addition to the 3M line of replaceable adhesives is Y-9425. This also is a double-coated film tape using acrylics but with an unoriented polyvinyl chloride (UPVC) liner. The overall adhesive thickness has been increased to 0.0055 inch (0.14 mm), along with increases in peel strength of both adhesives (low tack--12 oz/inch to steel, high tack--45 oz/inch to steel). This adhesive has found applications such as the attachment of replacement advertisements on taxi cabs. Both the low-tack and high-tack 3M adhesives are available in widths up to 47".

Avery 702P is a double-coated acrylic adhesive on a polyester carrier. Overall thickness is 0.005 inch. The same adhesive is used on both sides of the tape, although the adhesive on the release liner is thicker. The 180° peel strength on stainless steel one minute after adhesion is 50 oz/inch. This is considerably higher than Y-9425, and puts this product in the medium-to-high tack range of adhesive strengths.

The advantage of bulk adhesives compared to film tapes is their cost. Coating rates are typically less than one ounce per square yard to produce an adhesive layer several tenths of a mil thick. Liquid adhesive costs are therefore less than one cent per square foot compared to almost a dollar for Y-9425. Bulk adhesives could achieve the desired features for the reflective laminate in a very thin single layer. To test such adhesives for removability, however, they must be applied to a substrate. In production, adhesive would be applied to the carrier by roll-coating or an equivalent process. The adhesive would then be dried in a tunnel drier and a release liner applied. In the laboratory, adhesive can be applied by brushing, spraying or dripped from a rod. Using such techniques, liquid adhesive thickness and flatness is more difficult to control, as is the drying process. Unlike tapes, where the carrier is selected and possibly treated to achieve superior adhesion compared to adhesion on the substrate, the necessity of maintaining adhesion to the plastic support layer in preference to the metal substrate, introduces another variable.

H. B. Fuller's PN 1026 is a water-based acrylic pressure sensitive adhesive. It appeared to be a promising candidate adhesive. Peel strength is reported by the manufacturer at 12 oz./inch, which is slightly less than Y-9425.

Pierce and Stevens #A7723A is also a water-based acrylic pressure sensitive adhesive. Peel strength at 20 oz/inch places it in the low to moderate range, in terms of adhesives, as well as making it considerably more aggressive than Y-9425 transfer tape. The recommended means of application is by roll coating.

While most of the adhesives recommended by manufacturers as removable were water-based acrylics, one candidate for the proposed application, Pierce and Stevens #E9767AH, is a solvent-based elastomeric adhesive. Solvent-based adhesives are faster drying than the water-based variety. Peel strength as reported by the manufacturer is the same as Fuller's PN 1026 and slightly less than Y-9425. Again, roll coating is the recommended application procedure.

3 SCREENING OF REPLACEABLE REFLECTOR CANDIDATES

Given the large number of possible polymer/adhesive candidates for the replaceable reflector, a number of screening tests were used to identify the candidates best suited for the proposed application. Small hand-made samples were made to evaluate the bond strengths of the adhesives, the replaceability of the various polymer/adhesive combinations, mechanical stability, and surface smoothness.

3.1 Bond Strengths of Polymer/Adhesive Candidates

Section 2.2 described six adhesives that were identified to be good candidates to allow for removability of the replaceable reflector. Three of these adhesive candidates are tapes and three are liquid adhesives.

The bond strength of the adhesive to the aluminum substrate governs the ease with which the reflector can be applied and replaced. A low-tack/low-bond strength adhesive is preferable from this perspective. However, the adhesive must also be sufficiently strong to hold the reflective sheet in place and, to some degree, resist the hygroscopic growth of the ECP-305/polymer backing sheet. Peel strengths of the candidate adhesives were given in Table 4 and are summarized again below in Table 5 along with shear-strength data. The shear-strength data are based on measurements performed at IST.

TABLE 5 - ADHESIVE PEEL AND SHEAR STRENGTHS

Adhesive	Peel Strength (oz/inch)	Shear Strength (oz/inch)
3M Y-9415 adhesive tape with polyester carrier	4-5	8
3M Y-9425 adhesive tape with UPVC carrier	14	30
Avery Fastape 702P with polyester carrier	50	200
H.B. Fuller PN 1026 acrylic water based	12	20
Pierce and Stevens A7723A acrylic water based	20	32
Pierce and Stevens E9767AH elastomeric, solvent based	12	20

Shear strength was measured using one-inch wide strips of 5-mil polyvinyl chloride film that were adhesively bonded together as lap joints with one inch of overlap. Polyvinyl chloride was chosen since this polymer exhibited good adhesion to all seven of the adhesive candidates. The samples strips were then hung vertically and loaded in tension until failure. The shear-strength values given in the table indicate the one-inch strips were sufficiently strong in shear to hold for at least 24 hours.

The Avery Fastape 702P exhibited the highest shear strength. This is consistent with its higher peel strength as well. The Y-9415 adhesive tape had the lowest shear and lowest peel strengths. The other five adhesives had similar peel and shear strengths.

3.2 Replaceability of Polymer/Adhesive Candidates

As discussed in Section 2.1, seven polymer films were recommended for further evaluation and testing as replaceable reflector backing sheets. These seven candidates are listed below. The 7-mil thickness of Martin Llumar was not immediately available from Martin Processing, so a 5-mil thickness of the same material was substituted instead.

POLYMER BACKING SHEET CANDIDATES

Polycarbonate, General Electric 8030, 7 mils
Polyester, ICI 947, 3 mil
Polyester, Martin Llumar, 7 or 5 mils
Polypropylene, Mobil 175 ASPX, 1.7 mils
Polystyrene, Tensilwrap, 5 mils
Polyvinyl chloride, VCF C-107, 2 mils
Polyvinyl chloride, Kings, 5 mils

The polypropylene film was the thinnest of all the candidate films. Unfortunately, a thicker polypropylene film could not be found commercially. Dr. Paul Schissel of SERI suggested two additional sources of polypropylene films, Courtaulds Film and Packaging and Quantum Performance Films. Both of these companies were contacted, but neither supplies a polypropylene film that is thicker than the 1.7 mil film.

To evaluate the ease of lamination and the removability of the various polymers/adhesives, samples of approximately 1 x 3 inches were fabricated for each of the candidate constructions. Since there were seven polymer candidates and six adhesive candidates, forty-two small-scale samples were made. All of these samples were fabricated by hand. These samples were made using only the polymers and the adhesives. ECP-305 was not laminated to the top side of the polymer backing sheet since the polymer-to-adhesive surface and the adhesive-to-aluminum substrate were the areas of interest for these samples.

In the case of the adhesive tapes, the high-tack side of the tape was adhered to the polymer sample and then the release liner was removed from the low-tack side of the tape. This low-tack adhesive surface was then bonded to a 0.040-inch aluminum substrate and smoothed out, starting from one edge and proceeding to the other. The liquid adhesives were brushed onto the polymer backing sheet samples, left to dry overnight, and then bonded to 0.040-inch aluminum substrates.

Initially after a two-day interval, the polymer/adhesive samples were tested for removability. Removability testing was repeated again after three weeks. The results of these tests are summarized in Table 6. To be acceptable, the polymer-/adhesive sample had to be removable from the metal substrate without residue. In addition, the sample had to be removed and reattached without the formation of wrinkles and had to achieve essentially the same strength as the original bond.

TABLE 6 - SMALL-SCALE SAMPLE TEST RESULTS OF REMOVABILITY

POLYMER	ADHESIVE TAPES			LIQUID ADHESIVES		
	Y-9415	Y-9425	702-P	PN 1026	A7723A	E9767AH
Polycarbonate, GE 8030, 7 mil	Y	Y	N	Y	Y	N
Polyester, ICI 947, 3 mil	Y	Y	N	N	N	N
Polyester, Martin Llumar, 5 mil	Y	Y	N	Y	Y	N
Polypropylene, Mobil 175ASPX, 1.7 mil	Y	Y	N	Y	N	N
Polystyrene, Tensilwrap, 5 mil	Y	Y	N	N	N	N
Polyvinyl chloride, VCF C-107, 2 mil	Y	Y	N	Y	Y	Y
Polyvinyl chloride, Kings, 5 mil	Y	Y	N	Y	Y	Y

Y = ACCEPTABLE
N = NOT ACCEPTABLE

All of the Y-9415 and Y-9425 samples were judged to be acceptable. These samples all lifted cleanly off the substrate and were easy to reposition and reattach to the substrate without forming wrinkles. The more aggressive adhesive of the Y-9425 samples required slightly more force to peel away as compared to the Y-9415 samples.

The Avery Fastape 702-P samples were all judged to be unacceptable . The extremely high tack developed by the 702-P tape made removal difficult. The high peel strength of the adhesive required forces high enough that the polymer films were often permanently deformed during removal. These deformations resulted in wrinkles when the samples were reattached to the aluminum substrate. Although the 702-P samples were cleanly removable from the aluminum substrate after two days of adhesion, after three weeks of adhesion they were not. A small amount of residue was left on the aluminum as the samples were peeled away and removed. It is likely that this adhesive would leave even more residue if it were left on the substrate for even longer time periods.

The H.B. Fuller PN 1026 was the most successful of the liquid adhesives. This adhesive was judged to be acceptable when used with the polycarbonate film, the 5-mil polyester film, the 1.7-mil polypropylene film, and the two polyvinyl chloride films. The PN 1026/3-mil polyester sample was not acceptable because a large amount of adhesive residue was left on the aluminum when the sample was removed. The PN 1026/polystyrene sample failed within the polystyrene itself when removed from the substrate. Large portions of the adhesive and polystyrene film were left on the aluminum substrate.

The polystyrene film also failed during removal with the other two liquid adhesives, A7723A and E9767AH. As with the PN 1026, portions of the polystyrene film were left on the substrate (along with the adhesive) when removal was attempted. The amount of polystyrene and adhesive that was left behind could be minimized, but not eliminated, by reducing the rate at which the sample was peeled away.

The Pierce and Stevens adhesive A7723A was judged acceptable for the polycarbonate, 5-mil polyester, and polyvinyl chloride films. With the exception of the polystyrene film, as described above, the A7723A samples that were judged unacceptable left small amounts of adhesive residue on the aluminum substrate when the samples were peeled away.

The Pierce and Stevens liquid adhesive E9767AH was judged unacceptable for every polymer except the polyvinyl chloride films. As with the A7723A adhesive, adhesive residue was left behind on the aluminum substrate. In general, the E9767AH left larger amounts of residue behind than did the A7723A adhesive. Even when the adhesive was removed relatively cleanly without residue, the adhesive would break or separate from the film as the sample was being removed and then re-adhere back to the polymer film. This adhesive "stringiness" tended to increase as the removal rate of the sample was increased.

Of all the adhesives considered, the 3M tapes (Y-9415 and Y-9425) and the Pierce and Stevens PN 1026 had the best removability/replaceability characteristics. These three adhesives were therefore selected for continued testing and evaluation. The PN 1026 liquid adhesive was considered further only in combination with the 7-mil polycarbonate film, the 5-mil polyester film, the 1.7-mil polypropylene film, and the two polyvinyl chloride films since it did not demonstrate acceptable characteristics with the other polymer films. The 3M films were considered further for all seven polymer films because they were judged acceptable in all cases.

3.3 Small-Scale Immersion Tests

As a first step in evaluating the mechanical stability of the remaining candidate replaceable reflectors, small-scale reflective samples were prepared, applied to an aluminum substrate and immersed in room-temperature water. The samples were approximately 6 x 10 inches in size. The tests were intended to identify whether the various constructions could withstand immersion without forming "puckers" or wrinkles due to swelling of the acrylic reflective film.

As a measure of the applicability of this test, an ECP-305/Y-9415 laminate (no polymer backing sheet) was applied to aluminum sheet and immersed in water. As had been observed by IST personnel using similar samples provided by 3M during 1989, the ECP-305/Y9415 laminate (without use of a polymer backing sheet) formed "puckers" or wrinkles. These wrinkles formed within two hours after immersion. Hence this sample confirmed that the immersion test is meaningful, and that it provides an indication of the kind of mechanical instability that IST had observed to occur outdoors under varying conditions of humidity.

Nineteen laminates were fabricated by hand for water immersion testing. Seven of these were ECP-305/polymer/Y-9415 laminates, one for each of the candidate polymer films. Another seven of these were ECP-305/polymer/Y-9425, again one for each of the candidate polymer films. The final five laminates were ECP-305/polymer/PN 1026, one for each of the five polymer films that demonstrated acceptable replaceability characteristics with the PN 1026 adhesive.

The adhesive tape laminates were fabricated by first applying the high-tack surface of the adhesive tape to one side of the polymer film. The low-tack side of the adhesive tape was always covered with a paper release liner for protection from dirt and dust. Next, the ECP-305 film was applied to the other side of the polymer film. The completed laminate was then smoothed out by hand onto the aluminum substrate. The liquid adhesive samples were prepared by brushing the adhesive onto one side of the polymer film, and allowing the adhesive to dry overnight. The polymer was then applied to the aluminum substrate. Finally, the ECP-305 was applied to the uncoated side of the polymer. After a minimum waiting period of 24 hours, the reflective samples were immersed in room temperature water in a vertical position. None of the samples were edge taped.

The samples were inspected periodically after immersion: first after two hours; and thereafter every 24 hours. The item of greatest interest was whether some of the samples would develop wrinkles or "puckers", as shown by the ECP-305/Y-9415 laminates. In fact, none of the laminates with polymer backing sheets developed wrinkles or "puckers," even after two weeks of immersion. This indicates that the polymer backing sheet may be limiting the hygroscopic growth of the laminate, as was originally postulated with this reflector construction. Also, none of the laminates developed any delaminations. While this is encouraging, it is possible that "puckering" and delamination did not occur, in part, because of the small size of the samples.

The only negative observation during these immersion tests was that the Y-9415 laminates began separating from the aluminum substrate after several days of water immersion. Apparently, when submerged for extended periods of time, water penetrating from the edge of the composite causes the low-tack adhesive to separate from the substrate. The Y-9425 and the PN 1026 adhesive laminates did not exhibit this characteristic. Although the observed separation under water is a negative result, it was recognized that extended immersion may be too severe a test. Additional testing on samples located outdoors (see Section 4) addressed this issue.

3.4 Surface Smoothness of Small-Scale Samples

The same samples that were fabricated for the water immersion tests also provided information regarding the smoothness of the candidate replaceable reflectors. It was obvious from visual examination that polymer backing sheets less than 5 mils in thickness resulted in such poor surface smoothness that reflector specularity would be severely degraded. Apparently, the surface irregularities introduced by the 3M adhesive tapes and the hand-applied liquid adhesive were significant enough that at least a 5-mil polymer backing sheet thickness would be necessary. This criterion eliminated the 1.7-mil polypropylene film, the 3-mil polyester film, and the 2-mil polyvinyl chloride film.

Of the two adhesive tapes, the Y-9415 was somewhat smoother, probably due to its thinner adhesive layers. Large surface irregularity is apparently a characteristic of the two 3M adhesive tapes. The PN 1026 liquid adhesive, however, offers the potential of improved surface smoothness through improved application methods. Perhaps through working with an adhesives coating converter, the PN 1026 could be applied in a way that would significantly improve the specularity of the resulting reflector laminate.

3.5 Final Candidates Suitable for Large-Scale Testing

Although PN1026 adhesive looks like a promising adhesive candidate, it was determined that the two commercial adhesive tapes (Y-9415 and Y-9425) were the only realistic options for the near-term deployment of a replaceable reflector on a stretched-membrane heliostat. This was because both the short contract time frame and the small area of the heliostat precluded working with an adhesive converter. This is not to say that liquid adhesives will not ultimately provide a preferred alternative. In fact, the liquid adhesive offers many advantages; much lower cost, potentially improved specularity and a thinner construction by simply coating the low-tack replaceable liquid adhesive on the back of the polymer backing sheet, rather than laminating the adhesive tape (in roll form) to the polymer backing sheet.

Since the remaining adhesive choices were Y-9415 and Y-9425 and the screening tests described above served to narrow the acceptable polymers to polycarbonate, polyester, and polyvinyl chloride, the remaining candidate constructions for the replaceable reflector were

ECP-305/7 mil polycarbonate/Y-9415
ECP-305/5 mil polyester/Y-9415
ECP-305/5 mil polyvinyl chloride/Y-9415
ECP-305/7 mil polycarbonate/Y-9425
ECP-305/5 mil polyester/Y-9425
ECP-305/5 mil polyvinyl chloride/Y-9425.

Section 4 describes additional research and testing that further narrowed the available choices.

4 MANUFACTURE AND TESTING OF REPLACEABLE REFLECTOR CANDIDATES

On the basis of the small-scale testing and screening described in Sections 2 and 3, the best candidates for the replaceable reflector demonstration were:

ECP-305 / 7 mil polycarbonate / Y-9415
ECP-305 / 5 mil polyester / Y-9415
ECP-305 / 5 mil polyvinyl chloride / Y-9415
ECP-305 / 7 mil polycarbonate / Y-9425
ECP-305 / 5 mil polyester / Y-9425
ECP-305 / 5 mil polyvinyl chloride / Y-9425.

Both the polycarbonate (PC) and the polyester (PET) films contain UV stabilizers, but the polyvinyl chloride (PVC) does not. PVC film was of particular interest though because it has an extremely low water absorption rate, a characteristic that is expected to enhance mechanical stability of the replaceable reflector laminate.

To select the candidate that was the best choice for the 50-m^2 heliostat at the Central Receiver Test Facility in Albuquerque, larger samples of these reflector candidates were fabricated, evaluated for specularity, and subjected to immersion testing.

4.1 5 to 7 mil Y-9415 Laminates

Since small-scale testing had demonstrated that the Y-9415 adhesive tape resulted in better specularity than the Y-9425 tape, the three replaceable reflector candidates using Y-9415 were investigated first. A full roll (72 yards long) of Y-9415 adhesive tape was purchased in a 28.25-inch width so that it could easily be set up on a laminating machine to cover the 24-inch width of the ECP-305. Small rolls (about 50 feet in length) of polycarbonate (GE 8030, 7 mil), polyester (Martin Processing Llumar, 5 mil), and polyvinyl chloride film (Kings, 5 mil) were also purchased. These three films were purchased in off-the-shelf stock roll widths of 36 to 40 inches.

Although the film-to-sheet laminating equipment owned by Industrial Solar Technology could have been used to prepare the desired laminates, equipment more suitable for film-to-film lamination was located at Plastiprint Inc. in the Denver area, and its equipment was used for preparation of the laminate samples. Plastiprint's laminator feeds materials from two unwind rolls together through rubber rollers to form the lamination, which is then rewound onto a rewind roll. The width capacity of the machine is 50 inches. The Plastiprint equipment allowed for direct lamination of one roll of material to another, but it was not able to provide for side by side lamination of two rolls of material (such as ECP-305) onto a single, wider roll of material (such as polyester). Hence, the maximum width of the replaceable reflector produced on the equipment was 24 inches, the width of the ECP-305. The laminating machine is shown in Figure 3.

The ECP-305/polymer/Y-9415 laminates were prepared in a two-step lamination process. Initially ECP-305 was laminated to the polymer film as the first step, and then the ECP-305/polymer laminate was passed through the laminator a second time for lamination to the Y-9415. Although the polyvinyl chloride lamination

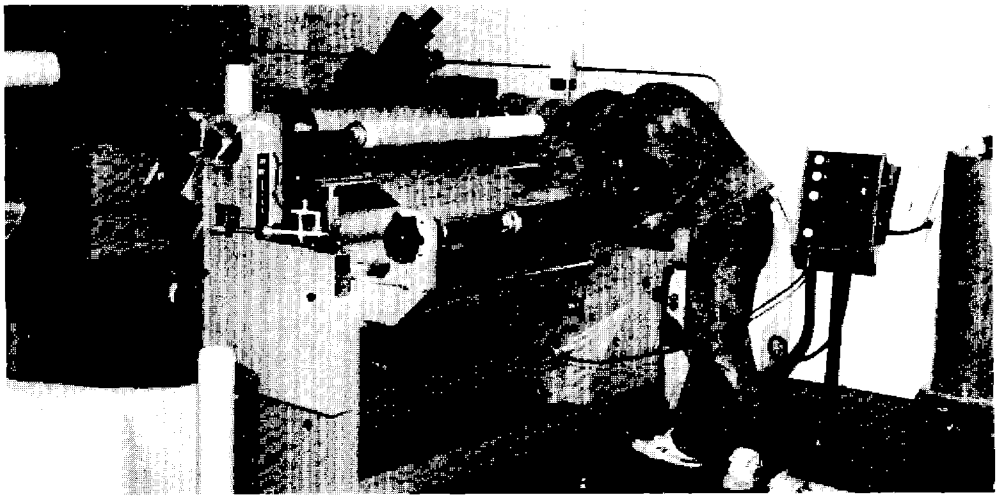

Figure 3 - Lamination of replaceable reflector

was accomplished successfully, the polyester and polycarbonate laminations developed wrinkles during lamination. The wrinkles occurred during the second step of the process when the Y-9415 was being laminated to the ECP-305/polymer laminate. Since the ECP-305 was laminated first in the two-step process, these difficulties resulted in a significant wastage of ECP-305, by far the most expensive component in the laminate. Although a number of machine adjustments were made, the wrinkling was not eliminated. It was concluded that the large difference in widths of the laminate materials was the likely cause of the wrinkling problem. The laminating process was repeated, this time with the purchase of polycarbonate and polyester films slit to 31-inch widths. In addition, to limit wastage of ECP-305, lamination was accomplished by first laminating the Y-9415 to the polymer with lamination of the ECP-305 as the second step. This technique yielded good results.

Another lesson learned during these first lamination trials was that the Y-9415 release liner should be wound on the outside of the completed lamination in order to avoid puckering of the release liner. When wound on the inside, the release liner releases from the low-tack adhesive surface in thin strips that extend from one side of the roll to the other (along the 31-inch dimension). Although the release of the liner does not disturb the optical quality of the 305/polymer/Y-9415 lamination, it provides a opening for dirt and dust to accumulate on the Y-9415.

With the successful preparation of the three Y-9415 laminations, mid-scale samples were prepared for water immersion to test for puckering or delamination. Rectangular samples of the laminates were cut to about 42 x 24 inches. Two of the four edges (one long edge and one short edge) were cut with razor blades, and the other two edges were cut with sharp scissors. Both types of cuts looked very good and had no obvious irregularities. The two longer edges were cut about 3/16-inch away from the ECP-305 edge so that the ECP-305 was not itself cut. Since acrylic is quite brittle, avoiding having to cut the ECP-305 eliminates any small fractures or irregularities that could occur during the cutting process. This left a 3/16-inch wide border of polymer/Y-9415 between the long edges and the ECP-305. These variations in cutting method and edge geometry were made to see whether one type of edge would demonstrate better mechanical stability than another.

The rectangular samples were then smoothed by hand onto a 4 x 10 foot, 0.040-inch thick aluminum sheet that had been previously cleaned with detergent, rinsed with water, and then lightly wiped with tack rags to remove particles. The reflective laminates were smoothed by hand with a soft cotton cloth, starting from one of the 24-inch edges and working to the other edge. The release liner on the back of the laminates was gradually removed as the laminates were smoothed into place. Two people were required for this process; one to smooth the laminate into place, and the other to help position the laminate initially and remove the release liner during application. The application of these samples proceeded quite easily and produced a relatively smooth, specular reflective surface. The only problem was the appearance of several small "bumps" on the reflector as the laminate was smoothed out. These "bumps" were traced to small pieces of the polymer/adhesive that had fallen from the razor-cut edges onto the exposed side of the Y-9415 adhesive as the release liner was removed.

Following application of these rectangular samples to the aluminum sheet, all four edges of the samples were edge taped with ECP-244 edge tape. On the edges with the 3/16-inch borders, two strips of edge tape were applied so that the edge of the ECP-305 was covered as well as the edge of the polymer/Y-9415 laminate. These edge-taped samples were then left overnight before immersion in water.

The aluminum sheet with the mid-size replaceable reflector samples was immersed horizontally in a large immersion pool (see Figure 4) formed by filling a plastic-covered wooden framework with water.

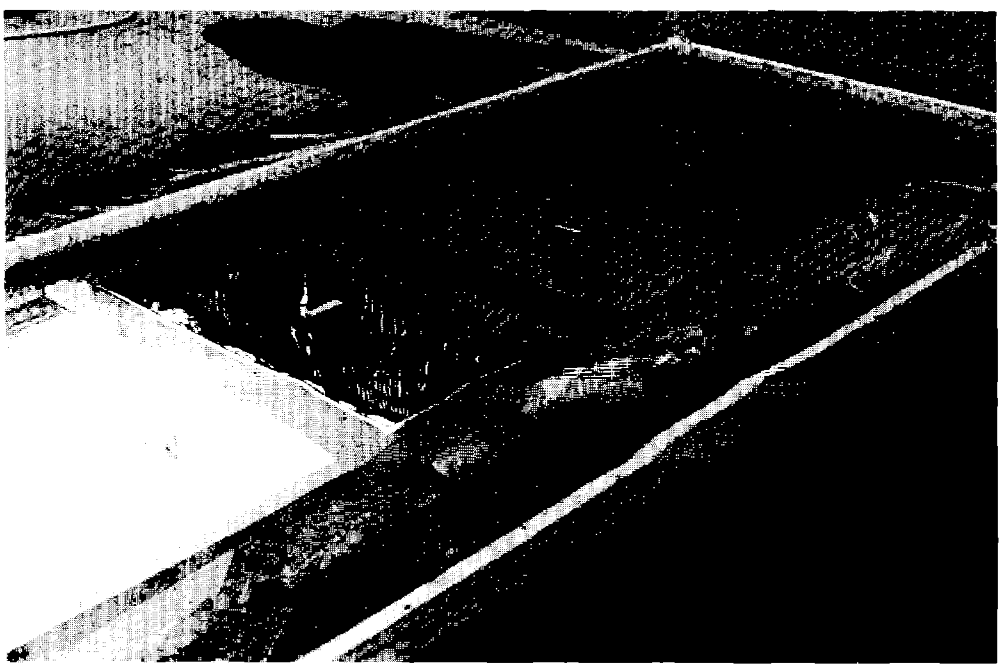

Figure 4 - Immersion of mid-size replaceable reflector samples

The immersion test was designed to stress the laminations through hygroscopic expansion of the polymers, especially the acrylic. Hygroscopic expansion data for acrylic indicates that immersing acrylic in water results in hygroscopic growth somewhat larger than exposing the acrylic to 100% humidity. Hence this immersion test may be somewhat severe compared to the conditions the replaceable reflector may experience in the field. The immersion test also provides some data regarding the degree to which the replaceable reflector laminate may be subject to delamination at the acrylic/silver interface. Based on SERI tests, it is known that ECP-305 mounted on aluminum is subject to delamination after several days of immersion in water. Although solving the delamination problem is not the focus of this replaceable reflector development program, the delamination issue is very important, and hence it was judged appropriate to investigate whether the candidate laminations would delaminate after immersion in water.

Unfortunately, all three Y-9415 laminations began to "pucker" or "wrinkle" after immersion in water for only about one hour. The "puckers" generally began at corners of the rectangular samples and grew progressively larger. After twelve hours of immersion the samples were severely "puckered." Long "fingers" of the laminate had lifted away from the aluminum sheet, spreading from one edge of the samples to the other. Figure 5 shows the long "fingers" that developed during immersion testing of the ECP-305/polyester/Y-9415 laminate. Apparently the hygroscopic expansion of the acrylic produced enough stress that the Y-9415 could not keep the laminate secured to the aluminum substrate. Interestingly, none of the three samples delaminated at their razor-cut or scissor-cut edges, even after seven days of immersion.

Figure 5 - Failure of ECP-305/polyester/Y-9415 laminate during immersion testing

4.2 5- to 7-mil Y-9425 Laminates

Since the Y-9415 samples had "puckered" during the immersion tests, the more aggressive Y-9425 adhesive was investigated next. A full roll (72 yards long) of Y-9425 adhesive tape was purchased, again in a 28.25-inch width so that it would easily be set up on a laminating machine to cover the 24-inch width of the ECP-305. Additional small rolls of polycarbonate (GE 8030, 7 mil), polyester (Martin Processing Llumar, 5 mil), and polyvinyl chloride film (Kings, 5 mil) were purchased in 31-inch widths. Samples of the three polymer candidate backing materials were laminated with Y-9425 and then ECP-305, in the same manner as described above for the Y-9415 laminates.

After the successful preparation of the three Y-9425 laminations, mid-scale samples were prepared for water immersion to test for puckering or delamination of the laminate. As with the Y-9415 samples, rectangular samples of the laminates were cut to about 42 x 24 inches. Again, two of the four edges were cut with razor blades, and the other two edges were cut with sharp scissors. The two longer edges were cut this time about 1/16 inch (as compared to 3/16 inch previously) away from the ECP-305 edge so that the ECP-305 was not itself cut.

The rectangular samples were then smoothed by hand onto a 4 x 10 foot, 0.040-inch thick aluminum sheet in the same manner as the Y-9415 samples had been. Unfortunately, the appearance of the reflector was relatively poor. Although there were very few of the small "bumps" that had been evident with the Y-9415 samples, the overall specularity of the reflector was relatively poor. Although the 305/polymer/Y-9425 laminates looked very specular when rolled up on a tubular core after lamination, as soon as the samples were smoothed out onto the aluminum sheet, the specularity greatly decreased. The irregularities of the Y-9425 adhesive were clearly the cause of this decrease in specularity.

As with the Y-9415 samples, the Y-9425 samples were taped with ECP-244 edge tape before immersion in water. This time, however, because of the 1/16 inch border, a single strip of edge tape could be used on all four sides of the rectangular laminate samples.

None of the Y-9425 laminations "puckered" or wrinkled during immersion in water. The laminations were immersed for seven days and then removed to dry. The higher tack of the Y-9425, relative to the Y-9415, was sufficient to resist any tendency of the laminate to wrinkle or "pucker." This is in sharp contrast to the lower-tack Y-9415, which released from the aluminum sheet after only short-term immersion in water. In addition to this resistance to wrinkling or "puckering," the laminates also demonstrated no tendency to delaminate. None of the three Y-9425 laminates suffered from a single delamination occurrence. While these tests are a positive sign, field test conditions are different and these test results do not mean that the ECP-305 will not delaminate in the field.

4.3 10- to 15-mil Y-9425 Laminates

Although the 5- to 7-mil Y-9425 laminates had demonstrated excellent mechanical stability, the relatively poor specularity of the samples was a concern. To improve the specularity, two principal paths existed: a thinner and less irregular adhesive, or a thicker polymer film. Although a thinner and less irregular low-tack adhesive could be used in place of the Y-9425, the Y-9415 adhesive had already been shown to have insufficient tack to maintain the mechanical stability of the lamination, and the liquid adhesives that had been considered earlier in this research program had previously been dismissed. As described in Sections 2.2 and 3.5, liquid adhesives offer many advantages, but would require more development time than was available for this research project, which was aimed at the near-term deployment of a replaceable reflector on the SKI heliostat. Thicker polymer films were therefore the preferred avenue of producing a more specular replaceable reflector. It was expected that by increasing the thickness of the polymer film, the irregularities of the underlying adhesive would have a reduced impact on the ECP-305 side of the lamination.

Small rolls of 10-mil thick polycarbonate, polyester, and polyvinyl chloride film were purchased in 31-inch widths. However, Martin Processing, the supplier of the ultraviolet-stabilized polyester films, does not manufacture the film above a 7-mil thickness. Therefore, a 10-mil thick non-ultraviolet-stabilized polyester film (DuPont Type A) was purchased. The polyvinyl chloride film also did not have ultraviolet stabilizers, as was the case with the 5-mil thick product used and tested previously.

In the same manner as described above, samples of the three polymer candidate backing materials were laminated with Y-9425 and then ECP-305. The thicker films were somewhat more difficult to laminate because their stiffness made the films harder to set up and handle. However, all three laminations proceeded successfully, and rectangular samples of the laminates were again cut to about 42 x 24 inches. All four edges of the rectangular samples were cut with a sharp scissors, with the two longer edges of the rectangular sample cut about 1/16 inch away from the ECP-305 edge so that the ECP-305 was not itself cut.

The rectangular samples were then smoothed by hand onto a 4 x 10 foot, 0.040-inch thick aluminum sheet in the same manner as the previous samples. The appearance of the reflector samples was significantly improved relative to the 5- and 7-mil samples of the same construction. Still, however, the irregularities of the Y-9425 adhesive were visually apparent.

Before immersing these three 10-mil reflector samples, an additional sample was made. This sample was a 12 x 40-inch lamination of ECP-305 directly onto Y-9425 without an intermediate polymer separating the acrylic film from the removable adhesive. Without the intermediate polymer, this 305/Y-9415 laminate had poor specularity, as expected. However, this was not of particular concern since the sample was only made to determine the role of the intermediate polymer in minimizing or eliminating "puckering" and/or delamination.

As a more severe test of the potential for delamination of the ECP-305, none of the four Y-9425 samples was edge taped with ECP-244 before immersion in water.

The laminations were immersed for seven days and then removed to dry. Then the samples were again immersed for another week and again removed to dry. None of the three Y-9425 laminations with an intermediate polymer film layer "puckered" or wrinkled during immersion in water. This was in sharp contrast to the 305/Y-9425 laminate (with no intermediate polymer layer) that developed long wrinkles across the 12-inch dimension of the sample. The wrinkles developed about every 10 to 12 inches along the sample. Hence, this is strong evidence that the intermediate polymer film plays an important role in minimizing or eliminating wrinkling or "puckering." Also, the 305/Y-9425 lamination developed four delaminations during the immersion/drying tests. The first delamination occurred about three days after immersion and the rest occurred within two days thereafter. The delaminations generally occurred on the sample in the same areas where wrinkles had developed. The polyvinyl chloride and the polycarbonate laminates did not delaminate at all. The polyester laminate did develop one small delamination at the corner of the sample. Hence, again the samples with intermediate polymer films demonstrated better resistance to delamination.

4.4 Specularity Measurements

The discussion above indicated that the surface smoothness and hence the specularity of the reflector samples varied greatly depending upon the construction of the laminates, the adhesive that was used, and the thickness of the intermediate polymer film. Visual observations served as a means of comparing one reflector specimen to another. To quantify specularity, Tim Wendelin measured directional errors in the reflected images of the laminate samples utilizing SERI's LANSIR [3] instrument. Nine samples, approximately 10 inches square, were made out of materials from the trial laminations discussed above. In addition, three more samples were made for the specularity tests: ECP-305 alone, a 305/15 mil PVC/Y-9425 laminate, and a 305/15 mil PC/Y-9425 laminate. The 15-mil polymer film samples were made in the same manner and on the same equipment as the 5-, 7-, and 10-mil thick samples. However, it was found that this considerable increase in thickness made the lamination process very difficult and cumbersome. In fact, a high-quality lamination could not be made without considerable wastage. Although such a thick film was clearly not a viable candidate for the replaceable reflector, samples of this thickness were included for LANSIR measurement so as to provide more data on how laminate specularity varies with polymer film thickness. The construction of the twelve samples provided to SERI for LANSIR testing are listed below.

The twelve samples were mounted onto 10-mil thick aluminum sheets. A 10-mil thickness was chosen because it is the same thickness as the aluminum used on the SKI heliostat that is to be retrofited with the replaceable reflector. The aluminum sheets were made 25 inches square, the size appropriate for LANSIR testing. Each of the four aluminum sheets was large enough to hold four of the replaceable reflector samples, one sample in each corner.

Appendix B contains the LANSIR test report issued by SERI. Specularity is a term used to indicate the optical accuracy of the reflective material itself and is often quantified as the standard deviation of the reflected rays, measured in mrad, from a perfectly reflected ray. The results of the LANSIR tests are summarized in Table 7 below. The reflected image from the samples were characterized with an elliptical-normal distribution, so rms beam spread is given along both the major axis of the reflected image and the minor axis. Some of the samples exhibit essentially circular-normal behavior and hence their rms values for both the major axis and the minor axis are nearly equal.

Table 7 - Specularity Errors for Replaceable Reflector Candidates

Sample No. IST	Sample No. SERI	Construction of Laminate Sample	Specularity, mrad Major	Specularity, mrad Minor
1	2	ECP-305 / 7 mil PC / Y-9415	1.0,	0.7
2	3	ECP-305 / 5 mil PVC / Y-9415	1.2,	0.9
3	1	ECP-305 / 5 mil PET / Y-9415	0.9,	0.9
4	11	ECP-305 / 7 mil PC / Y-9425	2.5,	1.5
5	12	ECP-305 / 5 mil PVC / Y-9425	3.2,	1.8
6	10	ECP-305 / 5 mil PET / Y-9425	2.9,	1.7
7	7	ECP-305 / 10 mil PC / Y-9425	2.1,	1.3
8	5	ECP-305 / 10 mil PVC / Y-9425	2.3,	1.3
9	8	ECP-305 / 10 mil PET / Y-9425	1.7,	1.1
10	6	ECP-305 / 15 mil PC / Y-9425	1.9,	1.4
11	9	ECP-305 / 15 mil PVC / Y-9425	2.1,	1.6
12	4	ECP-305 alone	1.4,	1.2

Since LANSIR testing requires tensioned samples, the LANSIR values may be somewhat lower than for a replaceable reflector sample applied in the field on an already tensioned heliostat or a non-tensioned concentrator, such as a parabolic trough. However, the LANSIR values are useful for relative comparisons. These data confirm many of the visual observations described above regarding the specularity of the different constructions. The Y-9415 laminates have considerably better specularity than the Y-9425 laminates, even when a 10-mil polymer thickness is used with the Y-9425. Also, increasing the polymer film thickness from 5 or 7 mils to 10 mils is shown to significantly improve the specularity of the Y-9425 laminates. Increasing the thickness even further to 15 mils is shown to result in little or no improvement. The ECP-305 sample alone shows a specularity only slightly better than the 10-mil laminates using the Y-9425 adhesive. Hence, the use of either one of these 10-mil constructions should result in a replaceable reflector that has optics about equal to the use of ECP-305 laminated directly onto an aluminum substrate. This is surprising given the inherent irregularities of the Y-9425 adhesive. The LANSIR results also show that the specularity of many of the samples depends on orientation.

4.5 Selection of Replaceable Reflector Construction

Research and testing results on the replaceable reflector supported the following conclusions regarding the preferred construction of the replaceable reflector:

1) The 3M adhesive tape Y-9425 appears to have properties suitable for the replaceable reflector. The adhesive is strong enough to keep the reflector laminates secured to the aluminum substrate, even when exposed to drastic changes in relative humidity, as evidenced by the water immersion tests.

2) A polymer film thickness of 10 mils is necessary to minimize the loss of specularity that the Y-9425 adhesive tape introduces. Film thicknesses of 7 mils and below yield somewhat poorer specularity using the Y-9425 adhesive tape.

3) Of the three polymer film candidates that were tested at 10 mil thicknesses, polycarbonate has performed the best. No delaminations, "puckering," or wrinkling have occurred with the polycarbonate film. Also, the specularity of the polycarbonate laminate is entirely adequate and nearly as good as ECP-305 mounted directly on aluminum. In addition, of the three remaining polymer candidate 10-mil films, only the polycarbonate film offers ultraviolet stabilization, a property that is desirable for the replaceable reflector.

Based on this information, the construction selected for the replaceable reflector to be retrofit to the SKI heliostat was a lamination of ECP-305 / 10-mil polycarbonate / Y-9425. The polycarbonate has a product designation of 8030 and is produced by General Electric. As discussed in Section 2.1, this film contains ultraviolet stabilizers, has a very low water absorption rate, is an on-the-shelf stock item, and has a very smooth polished surface. Other attributes include a thermal expansion coefficient less than for acrylic and a propagating tear strength that is fifteen times greater than acrylic.

The ECP-305 / 10-mil polycarbonate / Y-9425 construction was measured on SERI's LANSIR equipment to have a specularity error of 2.1 mrad/1.3 mrad (major axis/minor axis). The values for ECP-305 alone on the 10 mil aluminum substrate were measured to be 1.4 mrad/1.2 mrad. Hence, the replaceable reflector laminate has larger specularity errors than ECP-305 alone. However, from a systems perspective, there will be very little difference in optical performance. This small difference in specularity is extremely small when compared to other sources of optical errors, such as slope error. SERI's LANSIR report states, "Systems analysis has shown that a specularity error of 3.0 mrad is considered adequate for solar thermal purposes and that reducing the specularity much below this value yields diminishing benefits."

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5 DEMONSTRATION OF REPLACEABLE REFLECTOR

To provide for demonstration of the replaceable reflector concept, the 50-m^2 SKI heliostat was to be retrofit with the replaceable reflector laminate. The front and rear SKI heliostat membranes are each constructed of eleven strips of 0.010-inch aluminum coil stock that are each 30 inches wide. The aluminum strips are welded together to form the membranes. The heliostat is 8 meters in diameter and is shown in Figure 6. A more complete description of the heliostat can be found in a Sandia report that describes the optical performance of the first stretched-membrane heliostats [4].

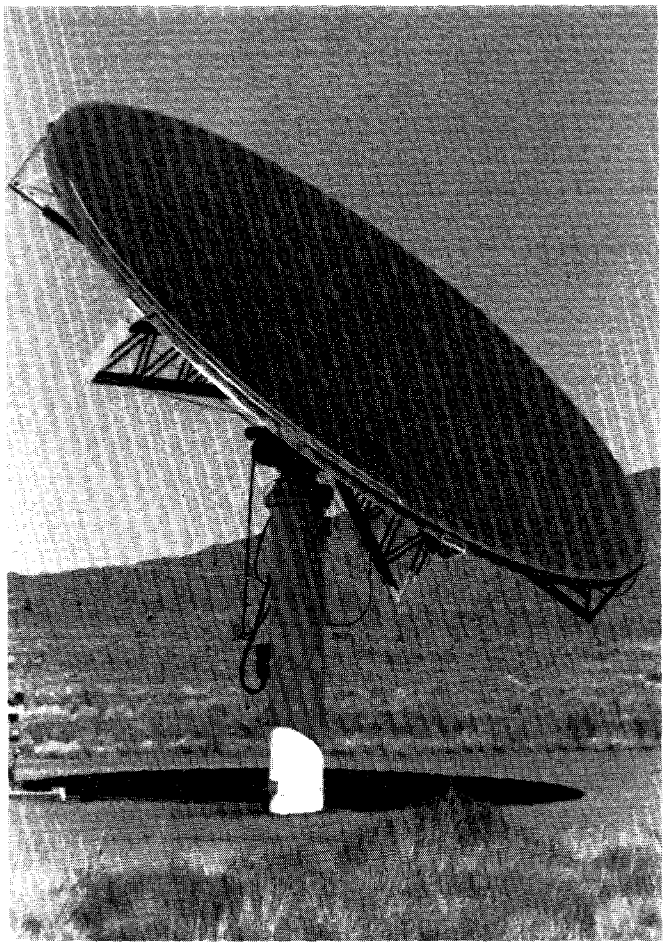

Figure 6 - SKI's 50-m^2 prototype stretched-membrane heliostat

Based on the test results discussed in Section 4, the construction selected for the replaceable reflector retrofit on the SKI heliostat was a lamination of ECP-305 / 10-mil polycarbonate / Y-9425. The polycarbonate has a product designation of 8030 and is produced by General Electric. This film contains ultraviolet stabilizers, has a very low water absorption rate, is an on-the-shelf stock item, and has a very smooth polished surface. Other attributes include a thermal expansion coefficient less than for acrylic and a propagating tear strength that is fifteen times greater than acrylic.

5.1 Replaceable Reflector Construction

A small production run of the replaceable reflector material was made to produce enough material to cover the heliostat. Three full 150-foot-long rolls of ECP-305 were used. The polycarbonate was supplied as one single roll 500 feet long, although during lamination it was discovered that the roll contained a seam. The Y-9425 has a standard length of 72 yards, and therefore three rolls were necessary in order to eliminate any Y-9425 splices in the final laminate. The laminate was made of 24-inch wide ECP-305, 28-inch wide polycarbonate film, and 26-inch wide Y-9425. After being slit, the final replaceable reflector laminate was 24-1/8 inch wide, allowing for a small gap along the edges of the ECP-305. The extra widths of the polycarbonate and the Y-9425 simply allow for easier lamination.

Since the width of the heliostat strips (between the welds) is 28.61 inches, the heliostat strips were to be covered with two pieces of the replaceable laminate. The first piece was 24-1/8 inches in width (24 inches of ECP-305 with a 1/16-inch gap along each side of the ECP-305), and the second piece was 3 inches in width (including a 1/16-inch gap along one side of the ECP-305). The 3 inch wide pieces were slit from a 24-1/8-inch wide roll of the replaceable laminate. The two strips are separated by a 0.25-inch gap, and the gap was covered with 0.5-inch wide edge tape. The original configuration of the heliostat used two widths of ECP-300 laminated directly onto the 0.010-inch aluminum membrane: the first ECP-300 width was 15.28 inches wide, and the second ECP-300 width was 11.875 inches wide, separated by a 0.25-inch gap. Hence, the 27-1/8-inch total width of the replaceable laminate strips was about equal to the 27.15-inch total width of the ECP-300 strips originally used on the heliostat.

5.2 Application of Replaceable Reflector to SKI Heliostat

The actual demonstration of the replaceable reflector was completed during the week of October 22 through 26, 1990. The replaceable reflector laminate was applied to the 50-m^2 SKI heliostat at the Central Receiver Test Facility at Sandia National Laboratories in Albuquerque, New Mexico.

The replaceable reflector laminates will typically be placed over a metallic substrate. However, for the first demonstration of the concept, the SKI heliostat that was already covered with ECP-300 was retrofit.

Complete removal of the existing ECP-300 would have been extremely difficult and could have damaged the heliostat. Consequently, the replaceable reflector laminates were placed directly over the existing ECP-300, except in areas where the ECP-300 had delaminated. These areas were repaired as explained below. The SKI heliostat membrane had also been damaged by hail. Small dents covered the surface of the 0.010-inch aluminum membrane, making this first retrofit a particularly severe test of the replaceable reflector concept.

The procedure that was used for installing the replaceable reflector laminates on the heliostat is provided below. In accordance with this procedure, all the edges of the replaceable reflector laminate were edge taped. The straight edges of the replaceable reflector were taped with 0.5-inch wide ECP-244 edge tape. Around the perimeter of the heliostat, the edge tape had to follow a curved path. About 20% of the perimeter was covered with 1-inch wide Tedlar edge tape and the rest of the perimeter was covered with 0.5-inch wide ECP-244 edge tape. In total, 42 manhours of time was devoted to washing the heliostat, repairing the heliostat, and covering the heliostat with replaceable reflector film.

Replaceable Reflector Application Procedure

Application of the reflector was carried out on calm days to ensure that the reflector laminates were positioned accurately and that a minimum of airborne dirt and dust was present. A temperature of at least 50°F was necessary to ensure adequate adhesion. The task was carried out by two people.

1) Washing the heliostat.

Preparation for the retrofit required that the heliostat be positioned in a nearly vertical orientation, and that the pressure washer and water tank be located at the bottom of the heliostat next to the manlift.

The heliostat was washed from the platform of the manlift, starting at the top, as shown in Figure 7. The pressure washer pump unit was left near ground level while the high-pressure hose bridged the distance between the pressure washer and the spray wand. A pressure of 500 psi was used to ensure that the ECP-300 did not delaminate during washing. No detergents or other wash agents were used. The objective of the washing step was to rid the heliostat of as much dirt and contamination as possible so that good adhesion to the replaceable reflector was possible and so that the presence of small particles that could cause optical irregularities on the heliostat was minimized.

After rinsing the heliostat, rags were used to wipe off any remaining dirt and to dry the reflective surface. Although wiping with rags caused some small scratching of the existing ECP-300, this was not considered a problem, since the surface was to be covered with the replaceable reflector strips.

Figure 7 - Washing the heliostat

2) Repairing the ECP-300 on the heliostat.

Some areas of the ECP-300 had delaminated on the SKI heliostat. These delaminations were a separation of the acrylic from the silver and resulted in a loss of flatness in the affected area and reduced adhesion to the substrate. To minimize the optical effect of these delaminations and to help minimize further growth of these delaminations, the affected areas were removed before the replaceable reflector was applied. The manlift was positioned so that the people in the manlift could reach the affected area, and a single-edge razor was used to cut the ECP-300 around the area of the delamination. Care was taken to cut the ECP-300 without scratching the aluminum membrane. Also, all razor cuts were made as smooth as possible, avoiding sharp corners. The affected area was then peeled away from the heliostat membrane. Typically, only the top acrylic layer of the ECP-300 was peeled away during this operation, leaving the silver layer and the adhesive layer, as shown in Figure 8. It is best to leave these layers on the heliostat membrane since removal of the adhesive layer is extremely difficult and often leads to greater surface irregularities than if the adhesive layer is just left in place. Once the damaged area of ECP-300 was removed, the newly exposed edge of ECP-300 was edge taped with 1/2-inch wide ECP-244 edge tape. The edge tape was expected to help prevent further delamination from these areas. The delaminated areas totaled about 9% of the total aperture area of the heliostat.

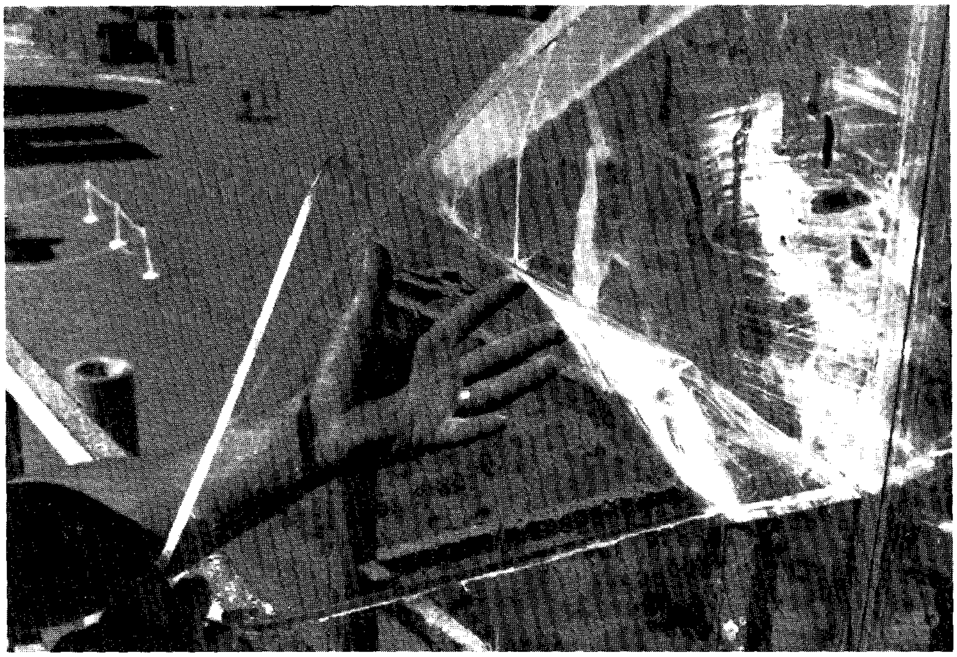

Figure 8 - Removing acrylic film to repair delaminated sections of heliostat

3) Applying the first 24-1/8-inch wide strip of replaceable reflector.

The first strip was applied along the center of the heliostat. This strip was about 25 feet in length, the longest on the heliostat.

The 24-1/8-inch replaceable reflector material was wound in 150 foot lengths on a 3-inch core. Scissors had been found to give an excellent cut and were used to trim the material to the proper length once the material was applied to the heliostat.

To apply the replaceable reflector film, the roll was placed on a steel shaft so that it would unroll as it is applied. The steel shaft was supported by two step ladders about 4 feet above the manlift platform. The safety rail around the perimeter of the manlift was covered with rags, so that as the material was unrolled and applied, the material would not be scratched or abraded (see Figure 9).

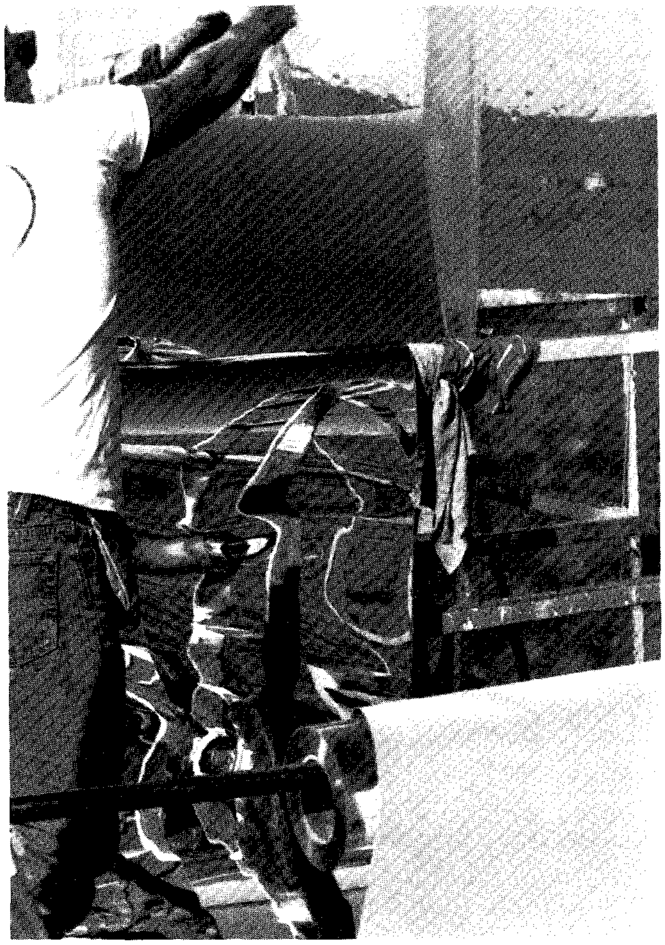

Figure 9 - Applying a roll of replaceable reflective film

A strip approximately 6 feet long of the replaceable reflector film was unwound. The manlift was then positioned so that the top of the strip could be held by one person (on the second or third step of a stepladder) at the top of the area that was to be covered, while the second person (about 6 feet lower, kneeling on the manlift platform) positioned the reflective material against the heliostat so that the material would run directly down the heliostat along the proper line. One edge of the strip was positioned 5/8 inch from the centerline of the membrane weld. Once the reflective strip was positioned directly over the portion of the heliostat that was to be covered, about 12 inches of the release liner on the back of the material was peeled away at the top and allowed to drape down. As the person on the stepladder peeled away this portion of the release liner, the person lower down kept the replaceable reflector material firmly in place so that the alignment of the material along the proper line was maintained. With the release liner removed, the top person repositioned the upper portion of the reflective strip, and applied the 12 inches of exposed adhesive against the heliostat. A soft cotton cloth (see Figure 10) was used to smooth the replaceable reflector against the heliostat, working from one edge to the other. With the top 12 inches of the strip secured, the rest of the strip was then applied in the same manner as the top 12 inches. The release liner on the back of the laminate was peeled away (see Figure 11) about 4 feet at a time, and the strip was smoothed into place while the lower person held the material near the platform of the manlift to ensure proper placement of the material. The manlift was lowered as application of the strip proceeded from the top to the bottom of the heliostat. If the line of the reflective material began to run askew, the person at the bottom applied sideways pressure to gradually bring the material back to its proper position.

Figure 10 - Smoothing the replaceable reflector into place with a soft cloth

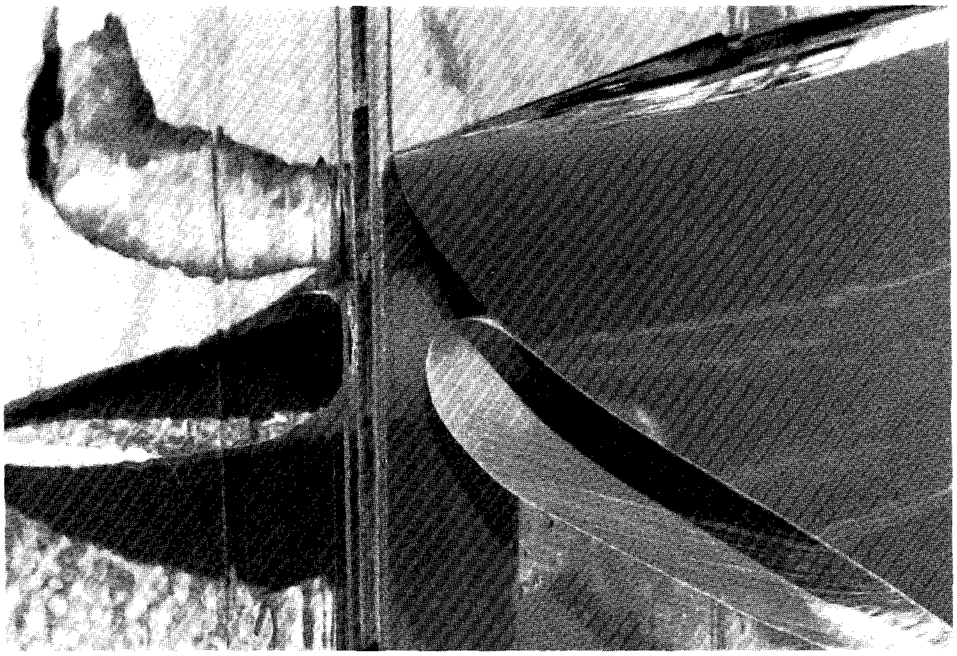

Figure 11 - Peeling away the replaceable reflector release liner

With the strip secured from top to bottom, the ends of the strip were cut to match the heliostat perimeter. A felt tip pen was used to mark the desired edge cut, using a curved metal edge guide as a marking template. A few inches of the reflective strip was then peeled away from the heliostat so that the marked edge could be cut with a scissors (see Figure 12). After cutting, the reflective strip was again smoothed onto the heliostat with a soft cloth.

4) Applying the first 3-inch wide strip of replaceable reflector.

The distance between centerlines of the membrane welds is 28.61 inches. Therefore, in addition to the 24-1/8-inch strip already applied, another reflective strip had to be applied along the central portion of the heliostat. This second strip was 3 inches wide. This strip was applied in exactly the same manner as the 24-1/8-inch strip, except that the 3-inch strips were wound in only 16 to 26 foot lengths. The 3-inch strip was positioned 1/4 inch away from the edge of the 24-1/8-inch strip. This resulted ideally in a gap just under 5/8 inch between the outside edge of the 3-inch strip and the centerline of the heliostat membrane weld. After smoothing the 3-inch strip onto the heliostat, the top and bottom edges were cut in the same manner as the 24-1/8-inch strips.

Figure 12 - Trimming the replaceable reflector at the ends of the heliostat

5) Edge taping the 24-1/8-inch strip and the 3-inch strip.

All edges of the two reflective strips were edge taped with 1/2-inch wide ECP-244 edge tape. If the 1/4-inch gap between the 24-1/8-inch strip and the 3-inch strip was maintained reasonably accurately, one strip of edge tape was sufficient to cover both edges of the two strips. Care was taken during the application of the edge tape to ensure a good seal and that the tape was pressed hard against the heliostat.

6) Applying the rest of the reflective strips and finishing with edge tape.

The rest of the reflective strips were applied in the same manner as described in steps 3 through 5. In total, eleven strips of both the 24-1/8-inch width and nine strips of the 3-inch width were applied. Starting from the center portion of the heliostat first and working to the outside edges of the heliostat required progressively shorter pieces of reflective strips. Proceeding in this manner resulted in very little wastage of the reflective laminate since the remnant from the first 150-foot roll was used on one of the outer (shorter) strips. Figure 13 shows the SKI heliostat completely covered with the replaceable reflector, but untrimmed around some edges of the heliostat.

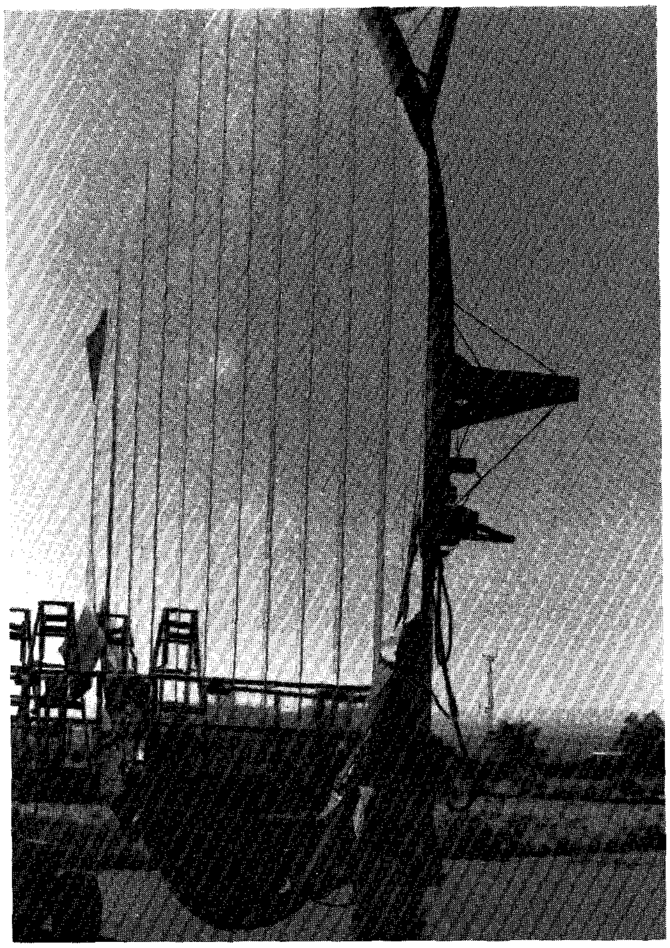

Figure 13 - SKI heliostat, covered with replaceable reflector but untrimmed

Materials and Equipment List
Manlift
Pressure Washer with 100 foot hose
Water tank with water
Extension cord to provide electric power to the pressure washer
Soft cotton cloths
Tack rags
ECP-244 1/2-inch wide edge tape
Single-edge razor blades
Sharp scissors
Two metal edge guides with R_{curv} = 12.7 feet
Replaceable Reflector Laminates (3-inch and 24-1/8-inch widths)
Two step ladders
Steel shaft to support reflective material rolls

6 SUMMARY

Stretched-membrane heliostats use thin metal membranes that are stretched over both sides of a large-diameter metal ring. The front membrane is covered with a reflective polymer film that has a high solar reflectance. 3M Company's ECP-305 is regarded as the preferred reflective film for stretched-membrane heliostats because it has a solar reflectance of about 93%. However, ECP-305 will degrade in time due to both corrosion of the silver layer and delamination at the silver-to-acrylic interface. Until long-term durability of the film against both corrosion and delamination has been demonstrated, it is essential that the film be replaceable. 3M uses a very aggressive adhesive on this film, and once it is laminated, replacement is difficult and time consuming. This report describes research conducted to develop and demonstrate a replaceable reflector, a reflective film that can be easily removed and replaced.

Acrylic is the polymer of choice for reflective films because of its excellent clarity and good weathering resistance. Unfortunately, acrylic is hygroscopic. When exposed to water or humid air, acrylic tends to expand. When strongly bonded to a solid substrate, such as metal, hygroscopic growth is constrained by the substrate. The adhesive used by 3M on ECP-305 is a high-strength pressure-sensitive adhesive that provides an aggressive bond to the metal substrate that resists hygroscopic growth of the acrylic. The use of this aggressive adhesive however, makes ECP-305 difficult to remove should it need to be replaced. Hence, while a relatively high-strength adhesive is needed to resist hygroscopic growth of ECP-300, this high-strength bond is inconsistent with film replacement.

Use of a low-tack adhesive on ECP-305, will produce a reflective film that is easy to remove. In fact, 3M made some experimental samples in 1988 using a removable, low-tack 3M adhesive. However, in outdoor testing, "puckers" developed due to release of the low-tack adhesive from the underlying substrate. Hence, while the use of a low-tack adhesive allows for easy film replacement, it does not yield a stable reflective surface.

These observations suggested an alternate, more stable configuration for a replaceable reflector. This involved laminating ECP-305 reflective film to a smooth, non-hygroscopic polymer backing sheet, and in turn laminating this backing sheet to a heliostat membrane using a low-tack, removable adhesive. The polymer backing sheet must be non-hygroscopic so that the dimensional stability of the reflective laminate is improved in order to prevent "puckering" of the reflective laminate.

The primary design issues for the replaceable reflector involved selecting a low-tack adhesive and a polymer backing sheet that, when laminated to ECP-305, would demonstrate mechanical stability as well as providing for easy removal in the field. Other desirable characteristics of the replaceable reflector include: smooth surface finish, so that specularity of the ECP-305 is maintained; UV stability, so that properties do not degrade outdoors; high tear resistance, to eliminate tearing of the reflective film during installation or removal; and low cost, so that overall reflective surface cost is minimized.

The best choices for the removable adhesive and the polymer backing sheet were determined through several stages of screening and testing. The short time duration of this project limited options to products that were commercially available. In order to narrow the wide range of commercially available adhesives and polymer films, a list of selection criteria was developed. Commercially available adhesives and polymer films were ranked according to these selection criteria. As a result, seven polymer films and six adhesives were identified as possible candidates for the replaceable reflector. To identify those products best suited for the replaceable reflector, a number of small-scale screening tests were performed. These screening tests were conducted using small hand-made samples to evaluate: adhesive bond strength, replaceability of the various polymer/adhesive candidates, mechanical stability and surface smoothness.

Of all the adhesives considered, two 3M tapes (Y-9415 and Y-9425) and an H.B. Fuller Company liquid adhesive (PN 1026), demonstrated excellent removability and replaceability, and had the best overall characteristics. Unfortunately, it was determined that development and testing of the liquid adhesive for the replaceable reflector would require more time than was available for this project. Hence, the two commercial adhesive tapes (Y-9415 and Y-9425) were the only realistic options for the near-term deployment of the replaceable reflector.

The screening tests also served to narrow the acceptable polymers to polycarbonate (PC), polyester (PET), and polyvinyl chloride (PVC). All three polymers have much lower water absorption characteristics than acrylic, possess acceptable mechanical properties, and are available in films that are thick enough to allow for good specularity. The polycarbonate and the polyester films contain UV stabilizers, but the polyvinyl chloride does not. PVC film was of particular interest, though, because it has an extremely low water absorption rate, a characteristic that was expected to enhance mechanical stability of the replaceable reflector laminate.

To select which of the final candidates was the best choice for demonstration on the 50-m^2 heliostat at the Central Receiver Test Facility in Albuquerque, large samples of the final reflector candidates were fabricated, evaluated for specularity, and subjected to immersion testing. Small-scale testing had demonstrated that the Y-9415 adhesive tape resulted in better specularity than the Y-9425 tape, and therefore the replaceable reflector candidates using Y-9415 were investigated first. Three ECP-305/polymer/Y-9415 laminations were prepared, using 7-mil PC, 5-mil PET, and 5-mil PVC.

Specularity testing performed by SERI characterized the specularity errors from the reflector samples with an elliptical-normal distribution, so specularity errors were measured along the sample's major axis and minor axis. All three of the Y-9415 samples tested by SERI had better specularity than ECP-305 without a polymer backing sheet. Alone, ECP-305 had a specularity error of 1.4 mrad/1.2 mrad (major axis/minor axis). The polycarbonate laminate had a specularity error of 1.0 mrad/0.7 mrad); the polyvinyl chloride's values were 1.2 mrad/0.9 mrad; and the polyester's specularity errors were 0.9/0.9 mrad.

To determine their mechanical stability, rectangular samples of the Y-9415 laminates were cut to about 42 x 24 inches, smoothed onto an aluminum substrate, edge taped, and immersed in water. The water immersion test was designed to stress the laminations through hygroscopic expansion as well as to test for delamination potential. Unfortunately, all three Y-9415 laminations began to "pucker" after immersion in water for only about one hour. These Y-9415 laminations clearly did not possess enough mechanical stability to ensure that they would stay in place on a heliostat membrane. However, none of the three samples delaminated, even after seven days of immersion.

Since the Y-9415 samples "puckered" during the immersion tests, the more aggressive Y-9425 adhesive was investigated next. Using the same films, three ECP-305/polymer/Y-9425 laminations were prepared. Unfortunately, specularity of the Y-9425 reflective samples was poor compared to the Y-9415 samples. Testing by SERI showed that the Y-9425 PC laminate had a specularity error of 2.5 mrad/1.8 mrad; and the PET's specularity errors were 2.9 mrad/1.7 mrad. As with the Y-9415 samples, rectangular samples of the Y-9425 laminates were cut to about 42 x 24 inches and tested by immersing in water. None of the Y-9425 laminations "puckered" when tested in this manner. These laminates also demonstrated no tendency to delaminate.

Although the 5- to 7-mil Y-9425 laminates had demonstrated excellent mechanical stability, the specularity of these samples was questionable. To improve the specularity, thicker polymer films were used. Rolls of 10-mil thick PC, PVC, and PET film were laminated with Y-9425 and ECP-305. The specularity of the 10-mil polymer reflector samples was significantly improved relative to the 5- and 7-mil samples of the same construction. SERI specularity tests showed that the 10-mil PC/Y-9425 laminate had a specularity error of 2.1 mrad/1.3 mrad; the 10-mil PVC's values were 2.3 mrad/1.3 mrad; and the 10-mil PET's specularity values were 1.7 mrad/1.1 mrad. Rectangular samples of the laminates were again cut to about 42 x 24 inches and subjected to the water immersion test. As a more severe test of the potential for delamination of the ECP-305, these Y-9425 samples were not edge taped before immersion in water. None of the three Y-9425 laminations "puckered" during immersion in water, and the polyvinyl chloride and the polycarbonate constructions showed no delaminations. The polyester laminate developed one small delamination at the corner of the sample.

Based on all these tests, the construction selected for the replaceable reflector retrofit on the SKI heliostat was a lamination of ECP-305 / 10 mil PC / Y-9425. The polycarbonate has a product designation of 8030 and is produced by General Electric. The film contains ultraviolet stabilizers, has a very low water absorption rate, is an on-the-shelf item, and has a very smooth polished surface. Other attributes include a thermal expansion coefficient less than acrylic and a propagating tear strength fifteen times greater than acrylic.

To demonstrate the replaceable reflector concept and to provide a real-time field test, the chosen construction was applied to the 50-m^2 SKI heliostat at the Central Receiver Test Facility at Sandia National Laboratories in Albuquerque. Because the heliostat was already surfaced with ECP-300, the existing reflective film was covered with the replaceable reflector film. The SKI heliostat membrane had also been damaged by hail. Small dents covered the entire surface of the 0.010 inch aluminum membrane, making this first demonstration a particularly severe test of the replaceable reflector concept.

Before having the replaceable reflector applied to it, the heliostat was positioned in a nearly vertical position and then washed from a manlift, using a pressure washer. After washing, the heliostat was wiped dry and any delaminated areas of the old ECP-300 were repaired. Starting from the center portion of the heliostat and working to the outside edges, strips of the replaceable reflector were smoothed onto the heliostat using soft cotton cloths. The manlift was lowered as the strip application proceeded from the top to the bottom of the heliostat. The release liner on the back of the replaceable reflector was removed progressively as the film was applied. Once completed, the SKI heliostat was stowed facing upward about 5° from horizontal.

Sandia will monitor the condition of the replaceable reflector to determine whether the replaceable film maintains its adhesion to the heliostat and whether the replaceable reflector suffers from delamination or degrades in other ways.

The materials costs of the replaceable reflector laminate totals about $39/m^2$ for low quantity purchases, based on the costs tabulated below. The major materials expense is the cost of the ECP-305 silver film. The cost of laminating the ECP-305 film and the Y-9425 adhesive to the polycarbonate film is estimated to total 1.60/m^2. Labor costs for applying the replaceable film to a concentrator are estimated to be $15/m^2$, based on the time required to apply the replaceable reflector laminate to the 50-m^2 heliostat.

Cost Component	Cost ($/m^2)
Y-9425 Adhesive	10.66
ECP-305 Film	24.23
Polycarbonate Film	4.31
Lamination	1.60
Installation Labor	15.00
Total Cost	55.80

This research represents a first effort in the realm of replaceable solar reflectors, and hence many additional areas exist for further work. One area that deserves attention, but was beyond the scope of this first effort, is the development of a low-tack liquid adhesive to replace the adhesive tape that was used for this first demonstration. A liquid adhesive offers many advantages; lower cost, improved specularity, the potential for thinner polymer backing sheets, and a simpler construction by simply coating the low-tack replaceable liquid adhesive on the back of the polymer backing sheet, rather than laminating the adhesive tape to the polymer backing sheet. Initially, small sample rolls could be coated with adhesive to obtain the desired properties. This could be accomplished in the laboratory of the liquid adhesive manufacturer and then scaled up to a commercial-scale at an adhesives coating facility so that larger widths could be obtained for testing at a field installation.

Accelerated weathering of various laminate constructions is another research area, and would determine how different polymers and/or adhesives impact corrosion rates of the silver. The introduction of a non-conducting polymer backing sheet into the reflector construction is expected to be beneficial. Also, more extensive delamination testing is necessary to determine whether the laminate construction will reduce delamination problems. The delamination issue by itself deserves more attention, since the inherent weakness of the acrylic/-silver interface appears to be a limiting factor in the commercial viability of the silver film. The replaceable reflector should also be pursued using other reflective films than ECP-305. Aluminized reflective films, or possibly other silvered films, should be included in future research and development efforts, since the replaceable reflector concept is applicable to reflective films other than ECP-305. In fact, the replaceable reflector may be even more appropriately applied to reflective films with less durability but lower in costs than ECP-305.

This research investigation achieved its major goals of identifying a replaceable reflector concept that offers easy replacement, defining and selecting commercially available materials for this reflector construction, showing that the construction can be successfully manufactured, and demonstrating the replaceable reflector concept on a stretched-membrane heliostat.

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APPENDIX A
HYGROSCOPIC GROWTH ANALYSIS

Lamination of a stable, non-hygroscopic substrate below the acrylic reflector ECP-305 is expected to reduce swelling of the overall acrylic/substrate laminate. When humidity levels increase and the acrylic swells due to moisture absorption, the non-hygroscopic substrate is expected to resist the hygroscopic growth of the acrylic. If the laminate of the non-hygroscopic substrate/acrylic is sufficiently constrained in growth, it is anticipated that the reflector will not wrinkle and that the replaceable reflector will stay flat against the heliostat membrane.

The degree to which swelling of the acrylic/substrate must be constrained is not known, but was evaluated through testing of sample reflector laminates. However, to identify those mechanical properties that play an important role in limiting hygroscopic growth of the laminate, a simple analysis of the hygroscopic growth of a reflector laminate follows. This simple analysis assumes that the top layer of the laminate is hygroscopic (e.g. acrylic) and that the bottom layer of the laminate is non-hygroscopic.

If the acrylic layer, by itself, is exposed to humidity, the acrylic will grow in length by an amount characterized by its hygroscopic coefficient of expansion.

$$L_2 = L_1 + L_1 \times h \times \Delta H \qquad (1)$$

where L_1 = initial length
L_2 = final length of acrylic
h = hygroscopic coefficient of expansion, in/in/%RH
ΔH = change in relative humidity, %

When a non-hygroscopic substrate is laminated to the acrylic with an ideal (completely rigid) adhesive, the hygroscopic growth of the acrylic will tend to also extend the non-hygroscopic substrate, which will place the non-hygroscopic substrate in tension. This tension will be opposed by a compressive stress in the acrylic layer. This balance of forces is given by:

$$F_{a,c} = F_{b,t} \qquad (2)$$

where $F_{a,c}$ = compressive force developed in acrylic layer
$F_{b,t}$ = tensile force developed in non-hygro. layer
and

$$F_{a,c} = A_a \times e_a \times E_a \qquad (3)$$

$$F_{b,t} = A_b \times e_b \times E_b \qquad (4)$$

where A_a = cross-sectional area of acrylic layer
e_a = compression-induced strain in acrylic
E_a = elastic modulus of acrylic
A_b = cross-sectional area of non-hygro. layer

e_b = tension-induced strain in non-hygro. substrate
E_b = elastic modulus of non-hygro. material

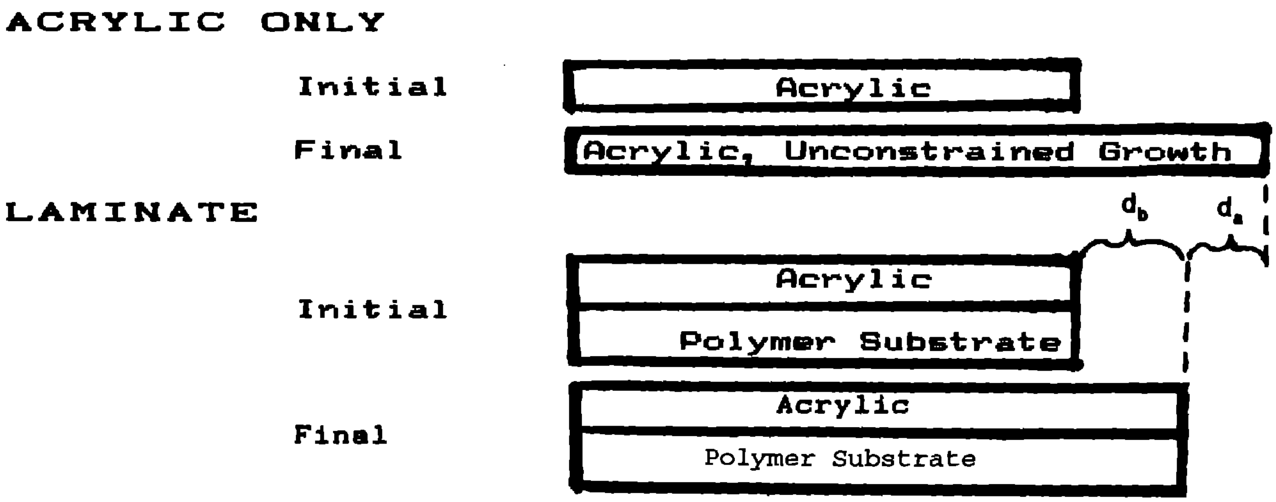
Since the compressive force must equal the tensile force in the laminate:

$$A_a \times e_a \times E_a = A_b \times e_b \times E_b \qquad (5)$$

and

$$e_a = \frac{A_b \times e_b \times E_b}{A_a \times E_a} \qquad (6)$$

The sum of the two elastic deformations, $d_a + d_b$, equals the hygroscopic elongation of the acrylic in the unlaminated condition.



The strains of the acrylic and the non-hygroscopic substrate are related to the compressive deformation d_a, and the tensile elongation d_b as follows:

$$e_a = \frac{d_a}{L_2} = \frac{d_a}{L_1 \times [1 + h \times \Delta H]} \qquad (7)$$

$$e_b = \frac{d_b}{L_1} \qquad (8)$$

Hence,

$$L_2 - L_1 = d_b + d_a = L_1 \times e_b + L_1 \times [1 + h \times \Delta H] \times e_a \qquad (9)$$

Substituting for e_a (from Eq. 6) into Eq. 9:

$$L_2 - L_1 = L_1 \times e_b + L_1 \times [1 + h \times \Delta H] \times \frac{A_b \times e_b \times E_b}{A_a \times E_a} \tag{10}$$

Solving for the ratio of the unrestrained elongation of the acrylic (by itself) to the actual elongation of the laminate:

$$\frac{L_2 - L_1}{d_b} = \frac{L_2 - L_1}{L_1 \times e_b} = 1 + [1 + h \times \Delta H] \times \frac{A_b \times E_b}{A_a \times E_a} \tag{11}$$

Since the ratio of the cross-sectional areas is equal to the ratio of the material thicknesses, the equation can be rewritten as:

$$\frac{L_2 - L_1}{d_b} = 1 + [1 + h \times \Delta H] \times \frac{t_b \times E_b}{t_a \times E_a} \tag{12}$$

where t_a = thickness of acrylic layer
t_b = thickness of the non-hygroscopic layer

Hence, the important physical properties are the elastic moduli and the thicknesses of the materials.

For example, using the properties of acrylic:

E_a = 320,000 psi $\qquad$ t_a = .003 inch $\qquad$ h = 3.0×10^{-5} in/in/% RH

Assume a 6 mil layer of a non-hygroscopic material with an elastic modulus equal to acrylic and an 80% change in relative humidity.

$$\frac{L_2 - L_1}{d_b} = 1 + [1 + .00003 \times 80] \times \frac{.006 \times 320{,}000}{.003 \times 320{,}000} = 3.005$$

Therefore, for this example, the unrestrained acrylic would elongate about three times as much as the laminate that is restrained by the non-hygroscopic material.

The non-hygroscopic material must have sufficient strength to carry the stress that develops during hygroscopic expansion of the acrylic. For a two material lamination as just considered in the above analysis, the stress in the non-hygroscopic material is given by:

$$\sigma_b = E_b \times \frac{e_b}{1 - \mu_b} \tag{13}$$

where μ_b = Poissons ratio for the non-hygroscopic material

Hence, to calculate the stress, we need to find the strain e_b. To do this we rearrange equation 10 to get:

$$L_2 - L_1 = L_1 \times e_b \times [1 + (1 + h \times \Delta H) \times \frac{A_b \times E_b}{A_a \times E_a}] \qquad (14)$$

Solving for e_b,

$$e_b = \frac{L_2 - L_1}{L_1 (1 + [1 + h \times \Delta H] \times \frac{A_b \times E_b}{A_a \times E_a})} \qquad (15)$$

or

$$e_b = \frac{h \times \Delta H}{1 + [1 + h \times \Delta H] \times \frac{A_b \times E_b}{A_a \times E_a}} \qquad (16)$$

Now that we have a relatively simple expression for the strain in the non-hygroscopic material, we can easily calculate the stress using equation 13.

For the physical properties assumed in the earlier example [E_a = 320,000 psi, t_a = .003 inch, h = 3.0×10^{-5} in/in/% RH] and further assuming $E_b = E_a$, t_b = .006 inch, and Poissons ratio is 0.38, for an 80% change in relative humidity:

$$e_b = \frac{3.0 \times 10^{-5} \times 80}{1 + [1 + 3.0 \times 10^{-5} \times 80] \times \frac{.006}{.003}} = 0.0008 \frac{inch}{inch}$$

The stress developed in the non-hygroscopic material is therefore:

$$\sigma_b = E_b \times \frac{e_b}{1 - \mu_b} = 320,000 \times \frac{.0008}{1 - 0.38} = 413\ lb/inch^2$$

Hence, for this example, the stress developed in the non-hygroscopic film is relatively small. Typically, the developed stress will be small compared to the tensile strength of the non-hygroscopic polymer.

APPENDIX B - LANSIR SPECULARITY TEST REPORT

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December 4, 1990

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Industrial Solar Technology
5775 W. 52nd Ave.
Denver, CO 80212

Dear Randy,

Enclosed are the LANSIR reports on the replaceable film samples. Over all they appear to be adequate in terms of performance with specularity ranging from less than 1.0 mrad σ to slightly greater than 3.0 mrad σ. The σ_{spec} increases more or less with the sample numbering system used. Samples #1 and #2 exhibited circular-normal behavior and the smallest σ_{spec} while sample #12 exhibited the most significant amount of pronounced elliptical-normal scatter (approximately 3.0 mrad σ_{major} by 1.8 mrad σ_{minor}).

Systems analysis has shown that a σ_{spec} of 3.0 mrad is considered adequate for solar thermal purposes and that reducing the specularity much below this value yields diminishing benefits. Certainly the majority of samples tested perform better than this.

Enclosed with the reports are thermal video prints of the largest spot size for each sample along with a print of the image resulting from the optical flat used as a reference. This gives you an idea of the magnitude and directionality of the scatter associated with each sample.

I hope this information meets your needs. Of course, if you have any questions please do not hesitate to call me.

Sincerely,

Tim Wendelin

cc: Bim Gupta
Gary Jorgensen
Terry Penney

LANSIR Optical Characterization Report Form

A. General Information
1. SERI LANSIR Test Report # : IST01
2. Title : Test of IST Replaceable Reflective Film Sample
3. Test Article Provided By : Industrial Solar Technology
4. Measurements Performed By : Tim Wendelin
5. Date of Test : 11/90
6. Date of Report : 11/30/90

B. Description of Test Article
1. Reflector Material : ECP-305
2. Substrate Material : 5 mil PET/9415 on 10 mil Aluminum
3. Tensioning method: Biaxial tensioning frame
4. Tension (lbs./inch): 36
5. Length of time at this tension (hrs.): 0
5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	73	0.72	0.47
2.0	Centered	91	0.91	0.77
4.0	Centered	-7	0.91	0.89

D. Discussion of Test Results

Overall, this sample exhibited excellent specular properties with scatter less than 1.0 mrad at all sampling sizes. There appears to be some evidence of scattering features in the 1.0 to 3.0 inch size range, however at these small values it is not considered significant and, in fact, may be in the noise. Some directionality exists in this range as well, but disappears at the larger sampling sizes.

E. List of Figures

1. Schematic of LANSIR system
2. Characterization of Scatter with Elliptical-normal Distribution
3. Definition of Orientation Angle, Φ

LANSIR Optical Characterization Report Form

A. General Information
1. SERI LANSIR Test Report # : IST02
2. Title : Test of IST Replaceable Reflective Film Sample
3. Test Article Provided By : Industrial Solar Technology
4. Measurements Performed By : Tim Wendelin
5. Date of Test : 11/90
6. Date of Report : 11/30/90

B. Description of Test Article
1. Reflector Material : ECP-305
2. Substrate Material : 7 mil PC/9415 on 10 mil Aluminum
3. Tensioning method: Biaxial tensioning frame
4. Tension (lbs./inch): 36
5. Length of time at this tension (hrs.): 0
5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	57	0.64	0.49
2.0	Centered	3	0.77	0.67
4.0	Centered	-8	1.02	0.73

D. Discussion of Test Results

Overall, this sample exhibited excellent specular properties with scatter less than or equal to 1.0 mrad at all sampling sizes. There appears to be some evidence of scattering features in the 1.0 to 4.0 inch size range, however at these small values it is not considered significant and, in fact, may be in the noise. Some directionality exists in this range as well, but it also is not considered significant.

E. List of Figures

1. Schematic of LANSIR system
2. Characterization of Scatter with Elliptical-normal Distribution
3. Definition of Orientation Angle, Φ

LANSIR Optical Characterization Report Form

A. General Information
   1. SERI LANSIR Test Report # : IST03
   2. Title : Test of IST Replaceable Reflective Film Sample
   3. Test Article Provided By : Industrial Solar Technology
   4. Measurements Performed By : Tim Wendelin
   5. Date of Test : 11/90
   6. Date of Report : 11/30/90

B. Description of Test Article
   1. Reflector Material : ECP-305
   2. Substrate Material : 5 mil PVC/9415 on 10 mil Aluminum
   3. Tensioning method: Biaxial tensioning frame
   4. Tension (lbs./inch): 36
   5. Length of time at this tension (hrs.): 0
   5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	41	1.34	0.88
2.0	Centered	37	1.19	0.81
4.0	Centered	23	1.22	0.93

D. Discussion of Test Results

Overall, this sample exhibited excellent specular properties with major axis scatter slightly larger than 1.0 mrad at all sampling sizes. There is no evidence of scattering features in the 1.0 to 4.0 inch size range as illustrated by the steady values of σ_{major} and σ_{minor} over this range. Some directionality exists in this range as well, but it is not considered significant.

E. List of Figures

   1. Schematic of LANSIR system
   2. Characterization of Scatter with Elliptical-normal Distribution
   3. Definition of Orientation Angle, Φ

LANSIR Optical Characterization Report Form

A. General Information
1. SERI LANSIR Test Report # : IST04
2. Title : Test of IST Replaceable Reflective Film Sample
3. Test Article Provided By : Industrial Solar Technology
4. Measurements Performed By : Tim Wendelin
5. Date of Test : 11/90
6. Date of Report : 11/30/90

B. Description of Test Article
1. Reflector Material : ECP-305
2. Substrate Material : 10 mil Aluminum
3. Tensioning method: Biaxial tensioning frame
4. Tension (lbs./inch): 36
5. Length of time at this tension (hrs.): 0
5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	94	1.22	1.12
2.0	Centered	77	1.29	1.20
3.0	Centered	76	1.35	1.22

D. Discussion of Test Results

Overall, this baseline or reference sample exhibited excellent specular properties with major axis scatter slightly larger than 1.0 mrad at all sampling sizes. There is no evidence of significant scattering features in the 1.0 to 4.0 inch size range as illustrated by the steady values of σ_{major} and σ_{minor} over this range. Very little directionality if any is evident in this range.

E. List of Figures

1. Schematic of LANSIR system
2. Characterization of Scatter with Elliptical-normal Distribution
3. Definition of Orientation Angle, Φ

LANSIR Optical Characterization Report Form

A. General Information
   1. SERI LANSIR Test Report # : IST05
   2. Title : Test of IST Replaceable Reflective Film Sample
   3. Test Article Provided By : Industrial Solar Technology
   4. Measurements Performed By : Tim Wendelin
   5. Date of Test : 11/90
   6. Date of Report : 11/30/90

B. Description of Test Article
   1. Reflector Material : ECP-305
   2. Substrate Material : 10 mil PVC/9425 on 10 mil Aluminum
   3. Tensioning method: Biaxial tensioning frame
   4. Tension (lbs./inch): 36
   5. Length of time at this tension (hrs.): 0
   5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	83	1.92	1.12
2.0	Centered	80	2.13	1.32
4.0	Centered	87	2.31	1.34

D. Discussion of Test Results

This sample exhibits moderate directional scatter. The orientation of the elliptical-normal distribution is very consistent throughout the sample size range. There also appears to be a slight increase in the σ_{major} and σ_{minor} values indicating the presence of scattering features in this range. The maximum scatter of 2.31 mrad is still well below the 3.0 mrad level. Systems analysis has shown that for solar thermal purposes, this value represents the cutoff below which further reductions will not improve systems cost/performance. In other words, specularity values less than 3.0 mrad are considered adequate for solar thermal purposes.

E. List of Figures

1. Schematic of LANSIR system
2. Characterization of Scatter with Elliptical-normal Distribution
3. Definition of Orientation Angle, Φ

LANSIR Optical Characterization Report Form

A. General Information
   1. SERI LANSIR Test Report # : IST06
   2. Title : Test of IST Replaceable Reflective Film Sample
   3. Test Article Provided By : Industrial Solar Technology
   4. Measurements Performed By : Tim Wendelin
   5. Date of Test : 11/90
   6. Date of Report : 11/30/90

B. Description of Test Article
   1. Reflector Material : ECP-305
   2. Substrate Material : 15 mil PVC/9425 on 10 mil Aluminum
   3. Tensioning method: Biaxial tensioning frame
   4. Tension (lbs./inch): 36
   5. Length of time at this tension (hrs.): 0
   5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	75	1.48	1.32
2.0	Centered	94	1.71	1.34
4.0	Centered	96	1.87	1.40

D. Discussion of Test Results

This sample exhibits slight directional scatter of moderate size. The orientation of the elliptical-normal distribution is more or less consistent throughout the sample size range. There also appears to be a very slight increase in the σ_{major} and σ_{minor} values indicating the possibility of scattering features in this range. Overall, this sample performs well for solar thermal applications.

E. List of Figures

   1. Schematic of LANSIR system
   2. Characterization of Scatter with Elliptical-normal Distribution
   3. Definition of Orientation Angle, Φ

LANSIR Optical Characterization Report Form

A. General Information
1. SERI LANSIR Test Report # : IST07
2. Title : Test of IST Replaceable Reflective Film Sample
3. Test Article Provided By : Industrial Solar Technology
4. Measurements Performed By : Tim Wendelin
5. Date of Test : 11/90
6. Date of Report : 11/30/90

B. Description of Test Article
1. Reflector Material : ECP-305
2. Substrate Material : 10 mil PC/9425 on 10 mil Aluminum
3. Tensioning method: Biaxial tensioning frame
4. Tension (lbs./inch): 36
5. Length of time at this tension (hrs.): 0
5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	-3	1.95	1.16
2.0	Centered	-4	2.09	1.22
4.0	Centered	-3	2.11	1.27

D. Discussion of Test Results

This sample exhibits directional scatter of moderate size. The directionality is very evident from the ellipticity of the distribution. The orientation of the elliptical-normal distribution is very consistent throughout the sample size range as well as the distribution size.

E. List of Figures

1. Schematic of LANSIR system
2. Characterization of Scatter with Elliptical-normal Distribution
3. Definition of Orientation Angle, Φ

LANSIR Optical Characterization Report Form

A. General Information
1. SERI LANSIR Test Report # : IST08
2. Title : Test of IST Replaceable Reflective Film Sample
3. Test Article Provided By : Industrial Solar Technology
4. Measurements Performed By : Tim Wendelin
5. Date of Test : 11/90
6. Date of Report : 11/30/90

B. Description of Test Article
1. Reflector Material : ECP-305
2. Substrate Material : 10 mil PET/9425 on 10 mil Aluminum
3. Tensioning method: Biaxial tensioning frame
4. Tension (lbs./inch): 36
5. Length of time at this tension (hrs.): 0
5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	-5	1.39	1.12
2.0	Centered	-8	1.56	1.10
4.0	Centered	-1	1.66	1.09

D. Discussion of Test Results

This sample exhibits slight directional scatter of moderate size. The orientation of the elliptical-normal distribution is consistent throughout the sample size range as well as the distribution size. Overall, this is a good specular sample.

E. List of Figures

1. Schematic of LANSIR system
2. Characterization of Scatter with Elliptical-normal Distribution
3. Definition of Orientation Angle, Φ

LANSIR Optical Characterization Report Form

A. General Information
   1. SERI LANSIR Test Report # : IST09
   2. Title : Test of IST Replaceable Reflective Film Sample
   3. Test Article Provided By : Industrial Solar Technology
   4. Measurements Performed By : Tim Wendelin
   5. Date of Test : 11/90
   6. Date of Report : 11/30/90

B. Description of Test Article
   1. Reflector Material : ECP-305
   2. Substrate Material : 15 mil PVC/9425 on 10 mil Aluminum
   3. Tensioning method: Biaxial tensioning frame
   4. Tension (lbs./inch): 36
   5. Length of time at this tension (hrs.): 0
   5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	0	2.28	1.46
2.0	Centered	7	1.99	1.55
4.0	Centered	3	2.07	1.60

D. Discussion of Test Results

This sample exhibits moderate directional scatter. The orientation of the elliptical-normal distribution is consistent throughout the sample size range as well as the distribution size. This indicates that there are no significant scattering features in the sample size range.

E. List of Figures

   1. Schematic of LANSIR system
   2. Characterization of Scatter with Elliptical-normal Distribution
   3. Definition of Orientation Angle, Φ

LANSIR Optical Characterization Report Form

A. General Information
   1. SERI LANSIR Test Report # : IST10
   2. Title : Test of IST Replaceable Reflective Film Sample
   3. Test Article Provided By : Industrial Solar Technology
   4. Measurements Performed By : Tim Wendelin
   5. Date of Test : 11/90
   6. Date of Report : 11/30/90

B. Description of Test Article
   1. Reflector Material : ECP-305
   2. Substrate Material : 5 mil PET/9425 on 10 mil Aluminum
   3. Tensioning method: Biaxial tensioning frame
   4. Tension (lbs./inch): 36
   5. Length of time at this tension (hrs.): 0
   5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	93	2.88	1.50
2.0	Centered	89	2.79	1.70
4.0	Centered	90	2.86	1.73

D. Discussion of Test Results

This sample exhibits moderate directional scatter. The orientation of the elliptical-normal distribution is consistent throughout the sample size range as well as the distribution size. This indicates that there are no significant scattering features in the sample size range.

E. List of Figures

   1. Schematic of LANSIR system
   2. Characterization of Scatter with Elliptical-normal Distribution
   3. Definition of Orientation Angle, Φ

LANSIR Optical Characterization Report Form

A. General Information
1. SERI LANSIR Test Report # : IST11
2. Title : Test of IST Replaceable Reflective Film Sample
3. Test Article Provided By : Industrial Solar Technology
4. Measurements Performed By : Tim Wendelin
5. Date of Test : 11/90
6. Date of Report : 11/30/90

B. Description of Test Article
1. Reflector Material : ECP-305
2. Substrate Material : 7 mil PC/9425 on 10 mil Aluminum
3. Tensioning method: Biaxial tensioning frame
4. Tension (lbs./inch): 36
5. Length of time at this tension (hrs.): 0
5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	-6	1.89	1.34
2.0	Centered	-2	2.42	1.50
4.0	Centered	-1	2.50	1.47

D. Discussion of Test Results

This sample exhibits moderate directional scatter. The orientation of the elliptical-normal distribution is consistent throughout the sample size range. The specular performance of this sample approaches the 3.0 mrad ceiling above which appropriate changes to improve the specularity should be considered. The increase in distribution size along the major axis of the elliptical shape suggests the presence of scattering features within this size range.

E. List of Figures

1. Schematic of LANSIR system
2. Characterization of Scatter with Elliptical-normal Distribution
3. Definition of Orientation Angle, Φ

LANSIR Optical Characterization Report Form

A. General Information
   1. SERI LANSIR Test Report # : IST12
   2. Title : Test of IST Replaceable Reflective Film Sample
   3. Test Article Provided By : Industrial Solar Technology
   4. Measurements Performed By : Tim Wendelin
   5. Date of Test : 11/90
   6. Date of Report : 11/30/90

B. Description of Test Article
   1. Reflector Material : ECP-305
   2. Substrate Material : 5 mil PVC/9425 on 10 mil Aluminum
   3. Tensioning method: Biaxial tensioning frame
   4. Tension (lbs./inch): 36
   5. Length of time at this tension (hrs.): 0
   5. Other Parameters Unique to Test Article / Configuration: None.

C. Test Results

Sampling size (inches)	Location on sample	Φ (degrees)	σ_{major} (mrad)	σ_{minor} (mrad)
1.0	Centered	0	2.68	1.68
2.0	Centered	1	2.88	1.67
4.0	Centered	-2	3.18	1.76

D. Discussion of Test Results

This sample exhibits directional scatter. The orientation of the elliptical-normal distribution is consistent throughout the sample size range. This sample exhibited the worst specular properties of all tested. The maximum value of 3.18 mrad is near the suggested ceiling for solar thermal applications.

E. List of Figures

1. Schematic of LANSIR system
2. Characterization of Scatter with Elliptical-normal Distribution
3. Definition of Orientation Angle, Φ

LANSIR II

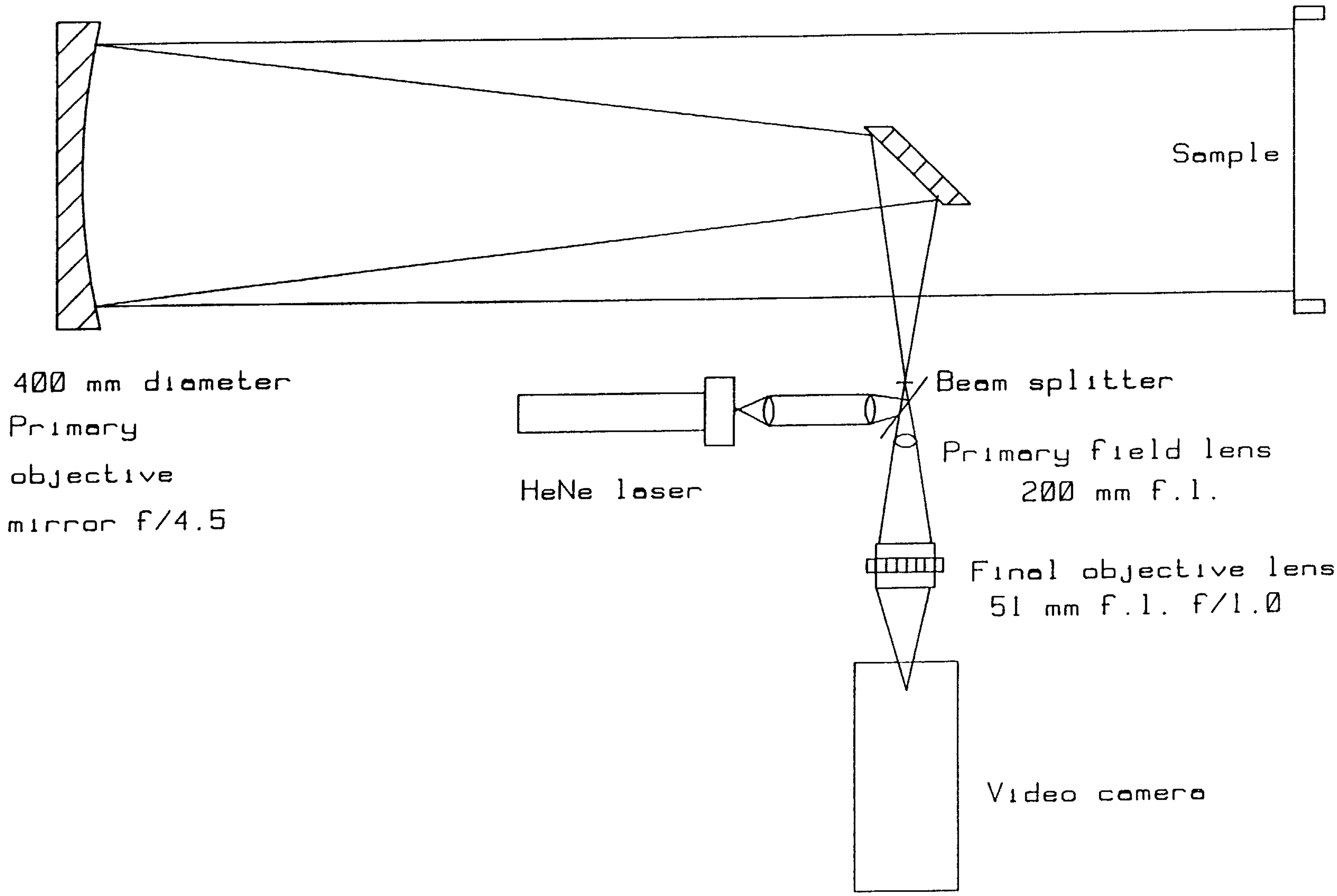


FIGURE 1

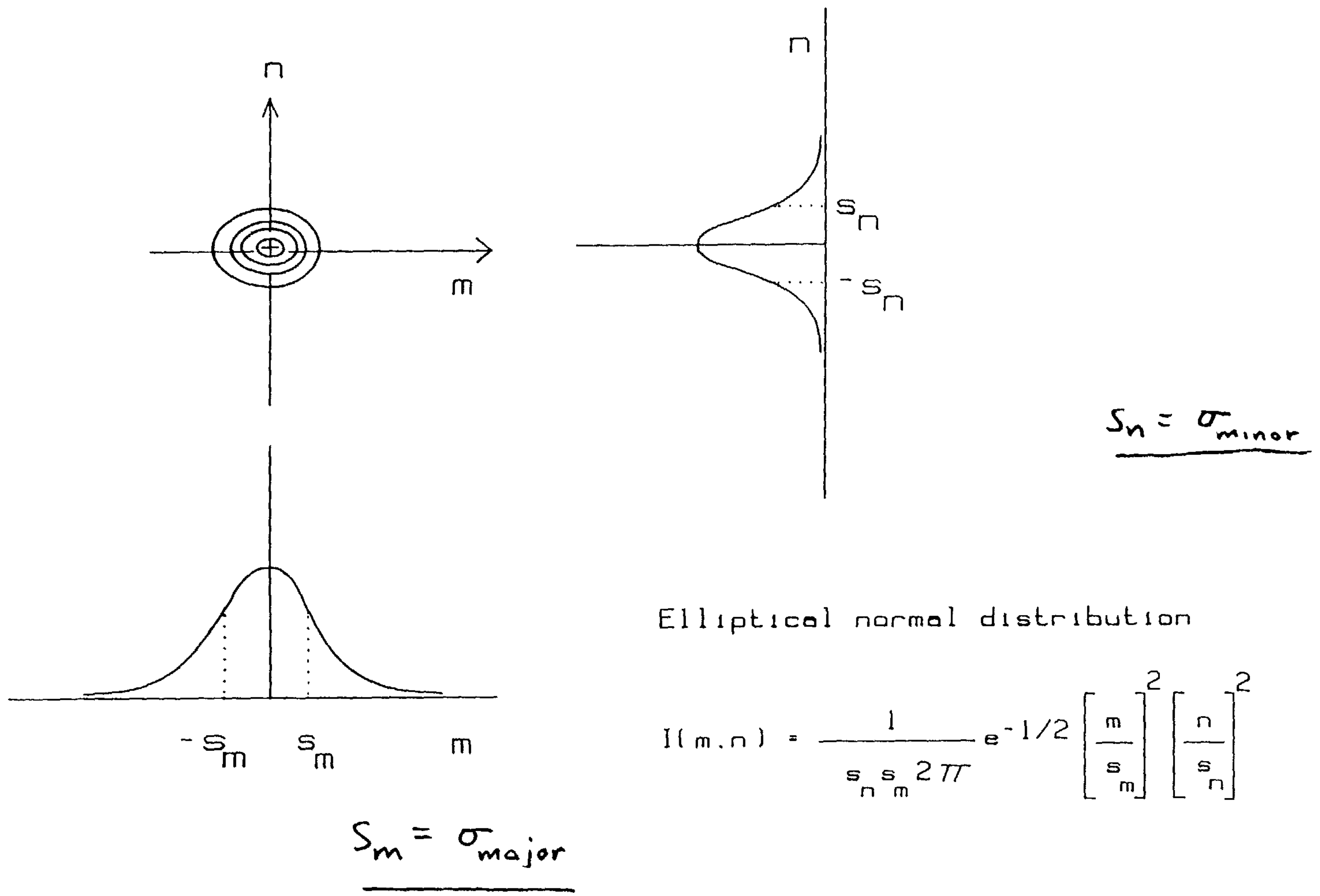

n
m
n
s_n
$-s_n$
$S_n = \sigma_{minor}$
$-s_m$
s_m
m
$S_m = \sigma_{major}$
Elliptical normal distribution
$I(m,n) = \frac{1}{s_n s_m 2\pi} e^{-1/2 \left[\frac{m}{s_m}\right]^2 \left[\frac{n}{s_n}\right]^2}$

FIGURE 2

LANSIR II

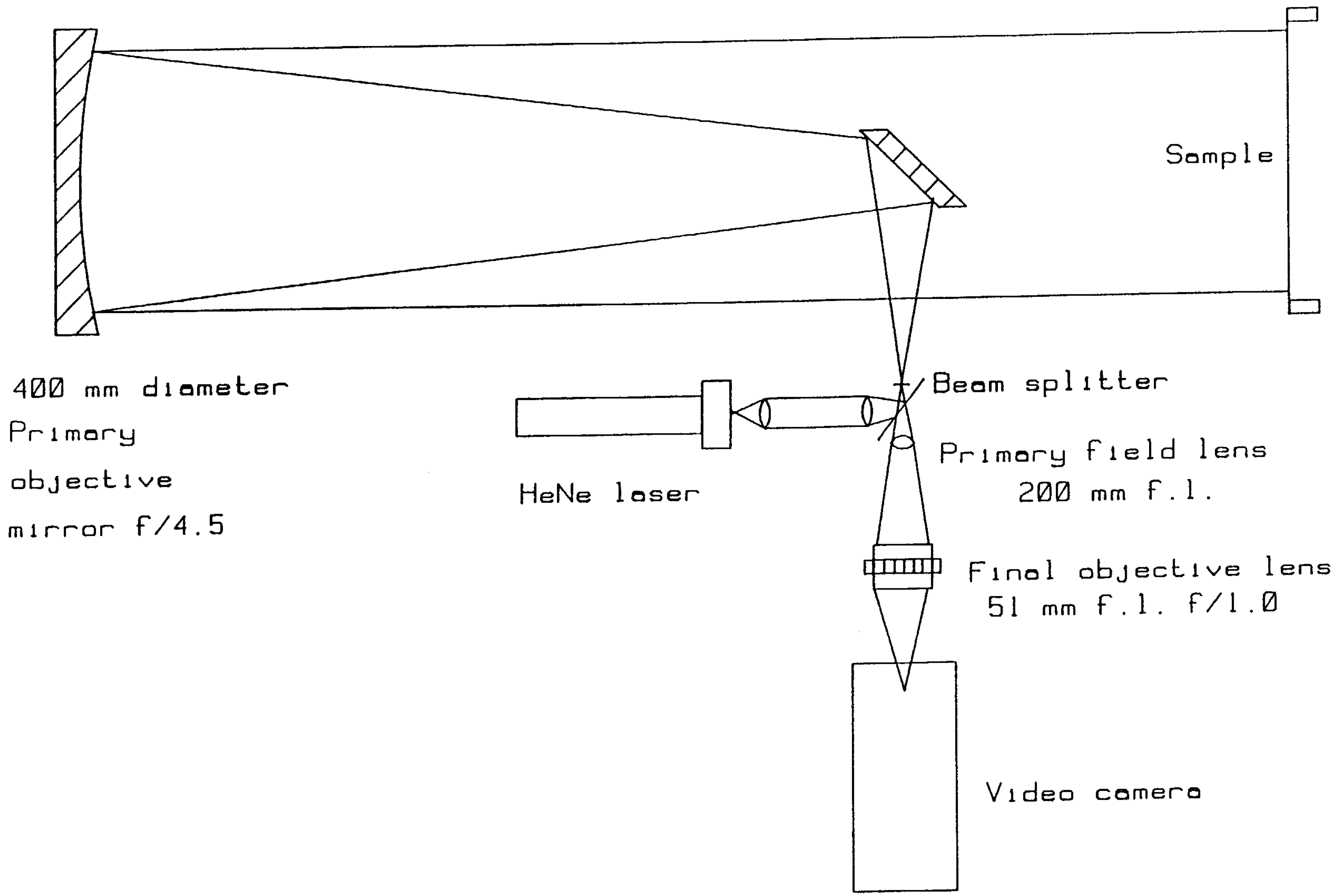


FIGURE 1

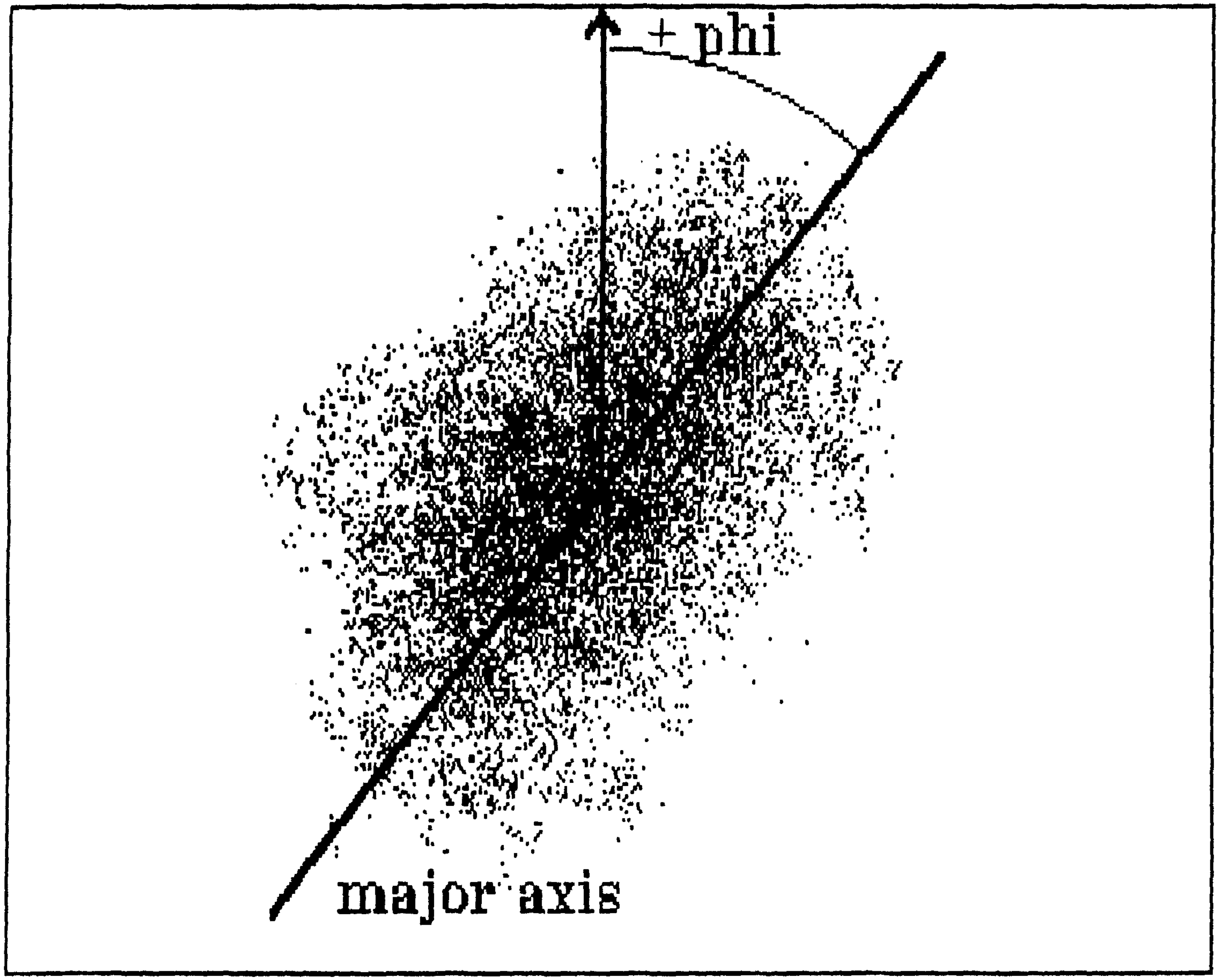
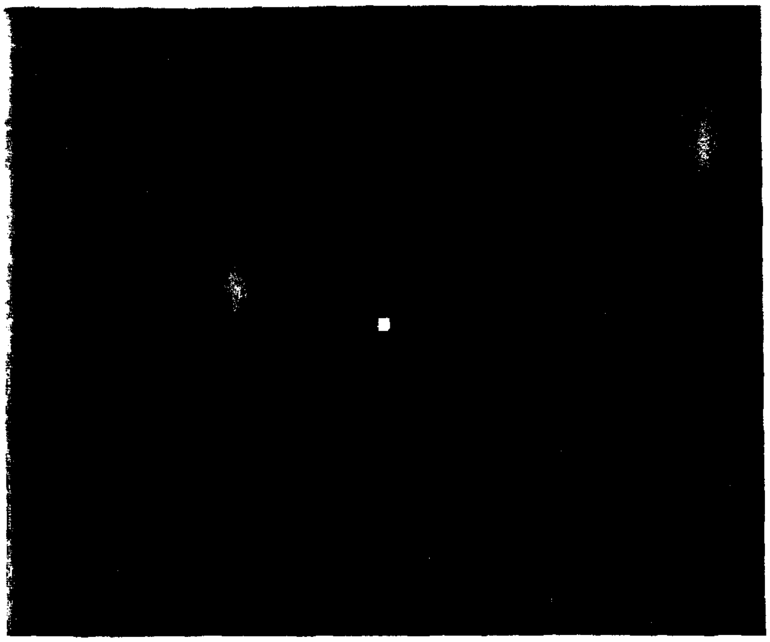
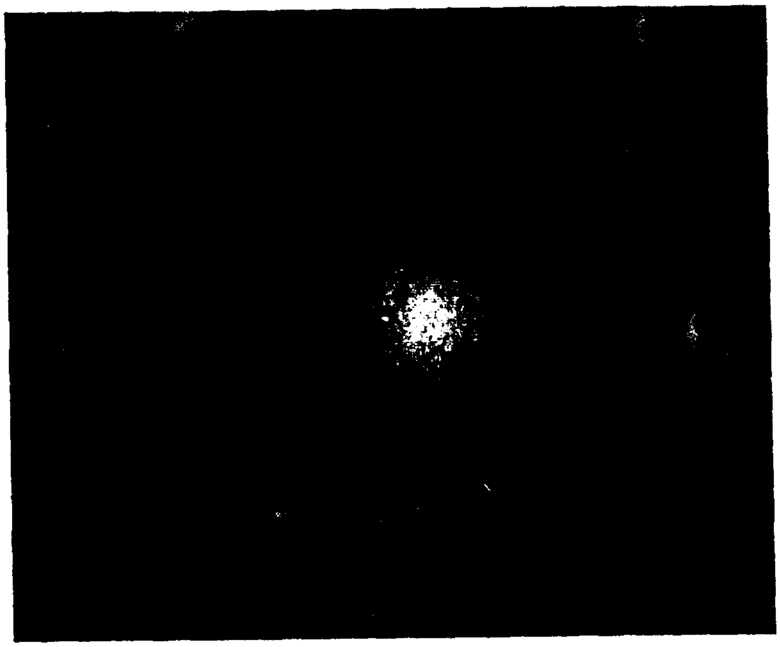


FIGURE 3



Standard Optical Flat

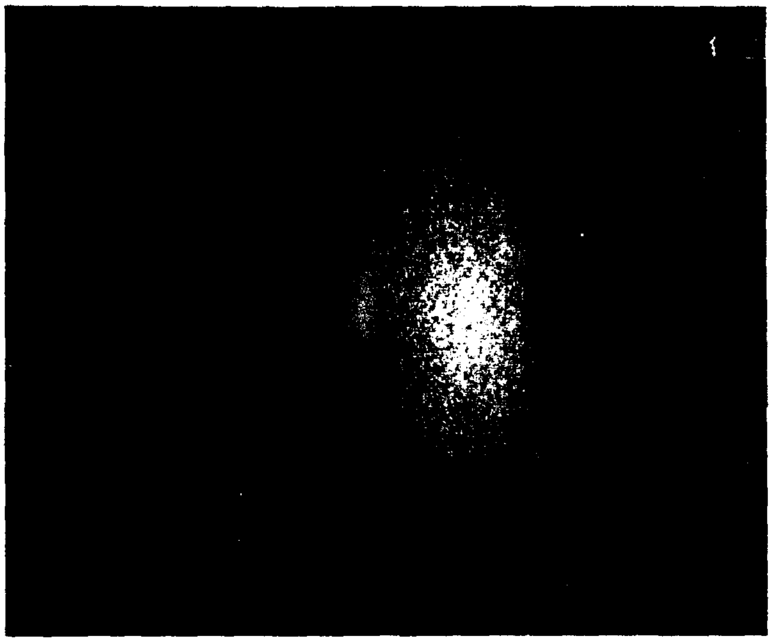


IST Ø1

IST Ø2

IST Ø3

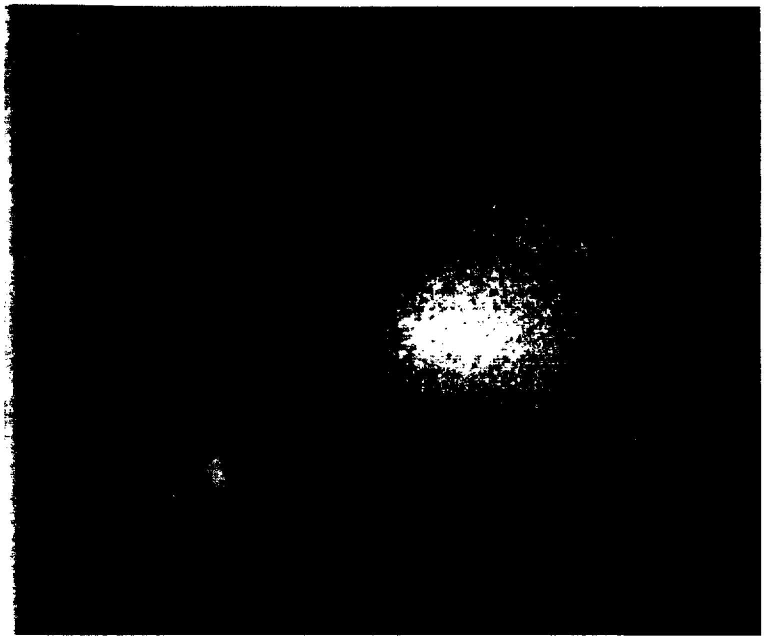
IST Ø4



IST Ø5

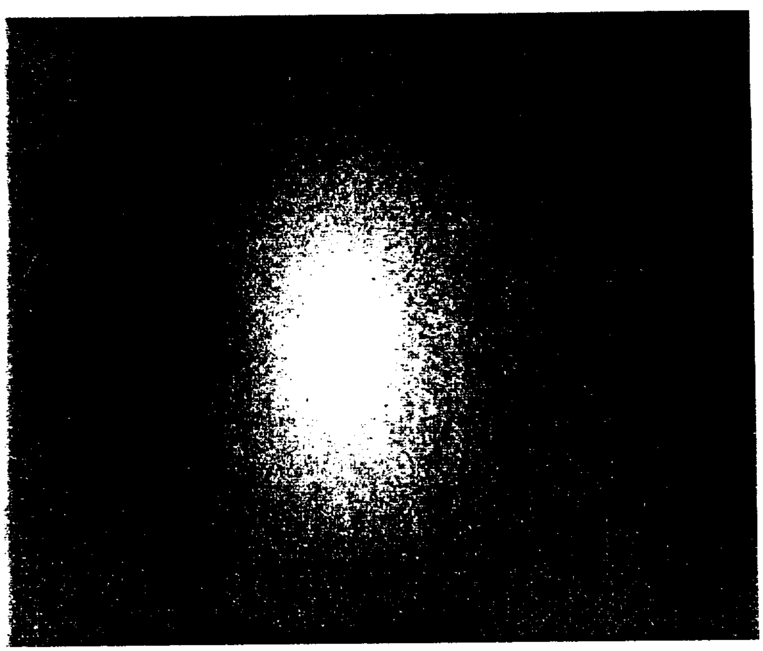
IST Ø6

IST Ø7



ISTØ8

ISTØ9



IST1Ø

IST11

IST 12

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