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SOLAR CONCENTRATOR DEVELOPMENT IN THE UNITED STATES

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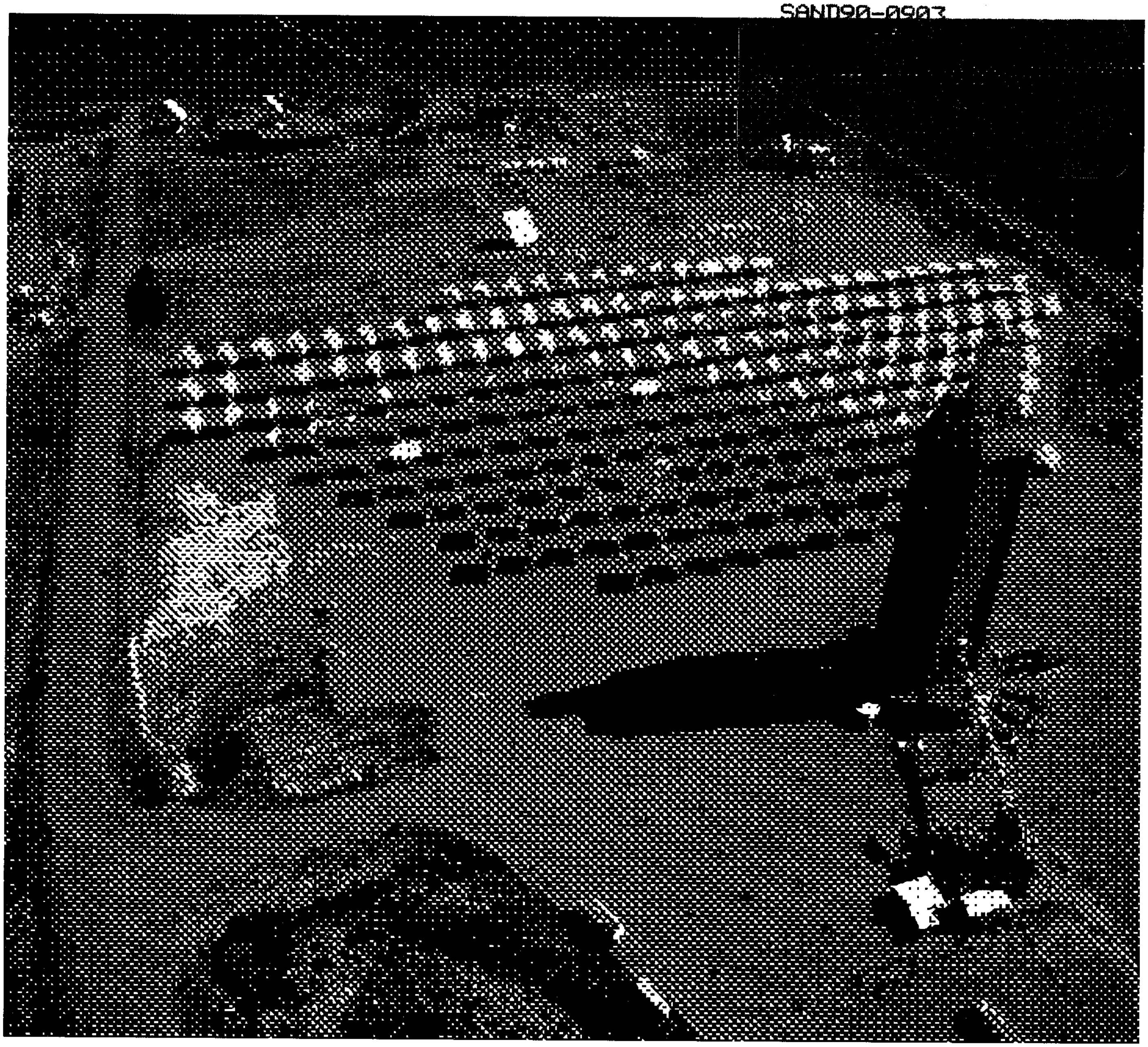

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SOLAR CONCENTRATOR DEVELOPMENT IN THE UNITED STATES[1]

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Abstract

Sandia National Laboratories leads the U.S. Department of Energy's solar concentrator development program in a joint effort with the Solar Energy Research Institute. The goal of DOE's program is to develop, build and test solar concentrators that are low in cost, have high performance, and long lifetimes. Efforts are currently focused on three areas: low-cost heliostats, point-focus parabolic dishes, and durable reflective films. The status and future plans of DOE's program in each area are reviewed.

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FOREWORD

The research and development described in this document were conducted within the U. S. Department of Energy's Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar radiation by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two- axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 meters in diameter track the sun in two axes and use mirrors to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100oC in low-temperature troughs to over 1500oC in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of the Department of Energy and its network of national laboratories, who work with private industry. Together they have established a cOmprehe~sive, goal-directed program to improve performance and provide technically proven options for eventual incorporation into the nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources.

Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to ensure a successful program.

1. Introduction

The design and fabrication of solar concentrators have been mainstays of the United States Department of Energy's solar thermal electric program since the program's inception nearly 15 years ago. Through DOE's efforts, significant reductions in concentrator costs, combined with improved performance and durability, have been achieved. Because concentrators represent the single largest cost of solar-electric systems, achieving optimal designs is essential to their future commercial viability. Currently, activities in DOE's concentrator development program center on low-cost heliostats for central receiver power plants and point-focus parabolic dishes for use with 25-kWe Stirling engines. The program is continuing to lower the cost of concentrators by simplifying them and by reducing their weight, while maintaining high performance. In addition, efforts are continuing to extend the lifetime and improve the performance of reflective films that can be used with all types of solar concentrators. Sandia National Laboratories leads DOE's concentrator development program in a joint effort with the Solar Energy Research Institute (SERI).

2. Heliostats

Heliostats for central receiver power plants have been under development at Sandia for nearly 15 years, and several generations of heliostats using glass mirrors have been built and tested [1]. Sandia's current efforts center on developing large glass-mirror heliostats with reflective areas as large as 200 m^2, a low-cost heliostat drive, and advanced heliostats that use stretched-membrane reflectors.

2.1 Large Heliostats with Glass Mirrors

Sandia is currently evaluating the long-term performance of two large glass-mirror heliostats. They were built by Advanced Thermal Systems (ATS) and by the Solar Power Engineering Company (SPECO) and have reflective areas of 148 m^2 and 200 m^2, respectively. Both were installed at the National Solar Thermal Test Facility (NSTTF) in 1986 for Sandia's evaluation [2].

ATS's heliostat has 100 square mirror facets, each 1.2 m on a side. The mirrors are made of laminated glass with a 1-mm silvered layer bonded to a 3-mm substrate. The solar-averaged hemispherical reflectivity is 94%. Five mirrors are bonded to aluminized sheet metal supports to form one mirror module. The sheet metal supports are slightly curved to provide module focusing, and each of the 20 modules can be individually canted. In a recent letter to Sandia, ATS's David Gorman estimates this heliostat would sell for about \$120/m^2 at a production rate of 5000/year for 10 years [3].

SPECO's heliostat uses 72 1.5-m by 1.8-m glass mirrors. The mirrors are 3-mm thick glass with a solar averaged hemispherical reflectivity of 83%; the back side of the mirrors is protected with paint. Nine support pads fitted with threaded rods are bonded to each mirror to provide focusing. A pair of mirrors is combined in a mirror module that can be individually canted. During initial testing at Sandia, a gear in the elevation drive cracked under normal wind loads. The drive's manufacturer redesigned the elevation gear to strengthen it, and static load testing by Sandia indicated it meets the design specifications. The complete heliostat was reinstalled at Sandia in May 1990 and testing was resumed.

Sandia's preliminary evaluation of ATS's heliostat showed very good optical performance [2]; the heliostat drive and control system were found to meet all specifications. The good performance of this heliostat shows this technology is mature; however, Sandia continues to test both heliostats to determine their long-term optical performance and durability.

2.2 Stretched-Membrane Heliostats

In a stretched-membrane heliostat, the reflective surface is formed by metal foils stretched over both sides of a large-diameter metal ring, and the reflective surface is a silvered polymer film glued to the front membrane. A slight vacuum in the space between the two membranes is actively controlled to provide a concave, focused contour to the reflector, and in an emergency this space can be rapidly pressurized to defocus the mirror. Stardobtsev first described such a vacuum-focused solar concentrator using a polymer mirror in 1965 [4]. Efforts to develop membrane heliostats have been underway in the United States since the early 1980s, and more recently in both Spain and Germany [5,6].

In 1984, Sandia began to develop with private industry detailed designs for commercial-scale stretched-membrane heliostats. Under contract to Sandia, two first-generation membrane heliostats were designed and 50-m^2 prototype mirror modules (the part of a heliostat above its drive) were built [7,8] by Solar Kinetics, Inc. (SKI) and Science Applications International Corp. (SAIC). Sandia evaluated the mirror modules to determine their durability and optical performance [9,10]. The two design studies and Sandia's evaluation of the prototype mirror modules indicated that heliostats using stretched-membrane reflectors had the potential to cost significantly less than glass-mirror designs, with comparable optical performance.

In 1988, under contract to Sandia, SAIC and SKI each developed improved designs for a membrane heliostat. These second-generation designs incorporated a number of improvements suggested by the fabrication and testing of the first mirror modules, including better methods for tensioning the membranes, more efficient use of materials in both the membrane support ring and rear structure, and better focusing systems. SAIC's design uses 0.076 mm-thick (0.003 in) stainless steel membranes and is focused with a linear actuator attached to the rear membrane. SKI's design uses 0.25-mm-thick (0.010 in) aluminum membranes and is focused with a small fan mounted at the center of the front membrane. Complete descriptions of the two improved designs can be found in the reports to Sandia [11,12]. In addition to the improved designs, each contractor

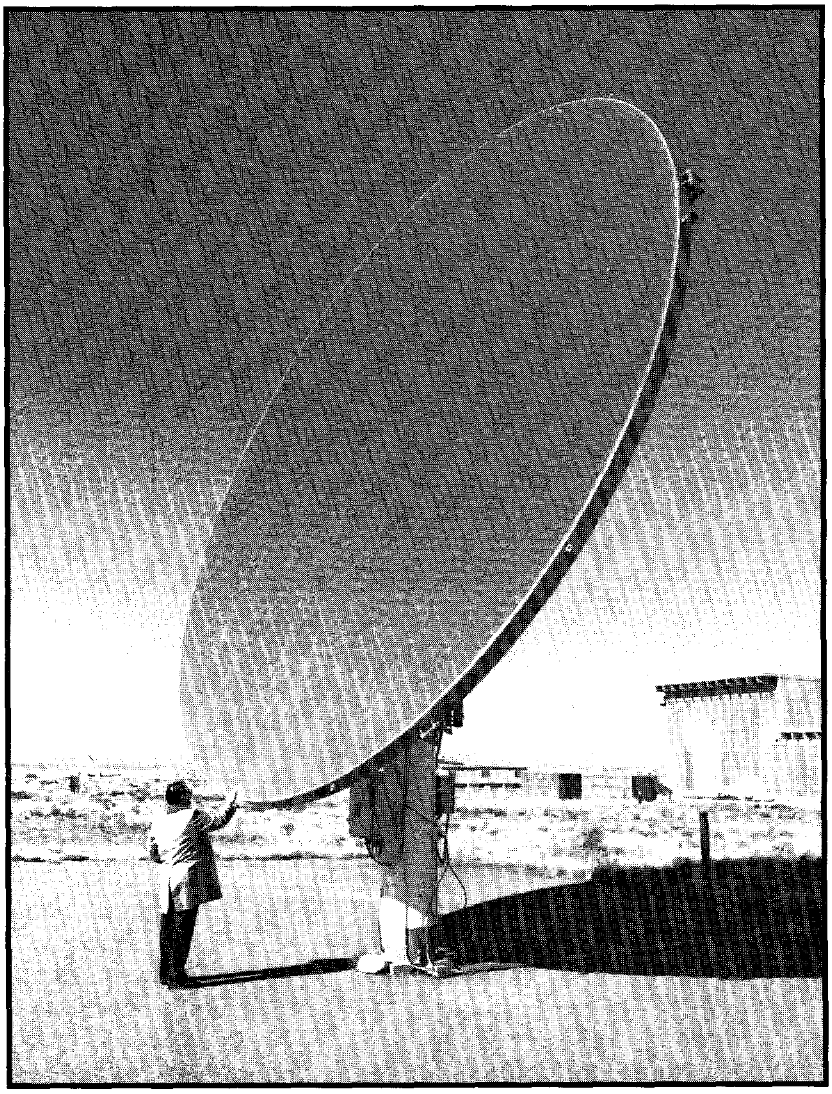

Figure 1.
Second-generation stretched-membrane mirror module built by SAIC. The reflective area is 50-m^2. The membranes are 0.076-mm-thick stainless steel with a silvered-acrylic film bonded to the front membrane.

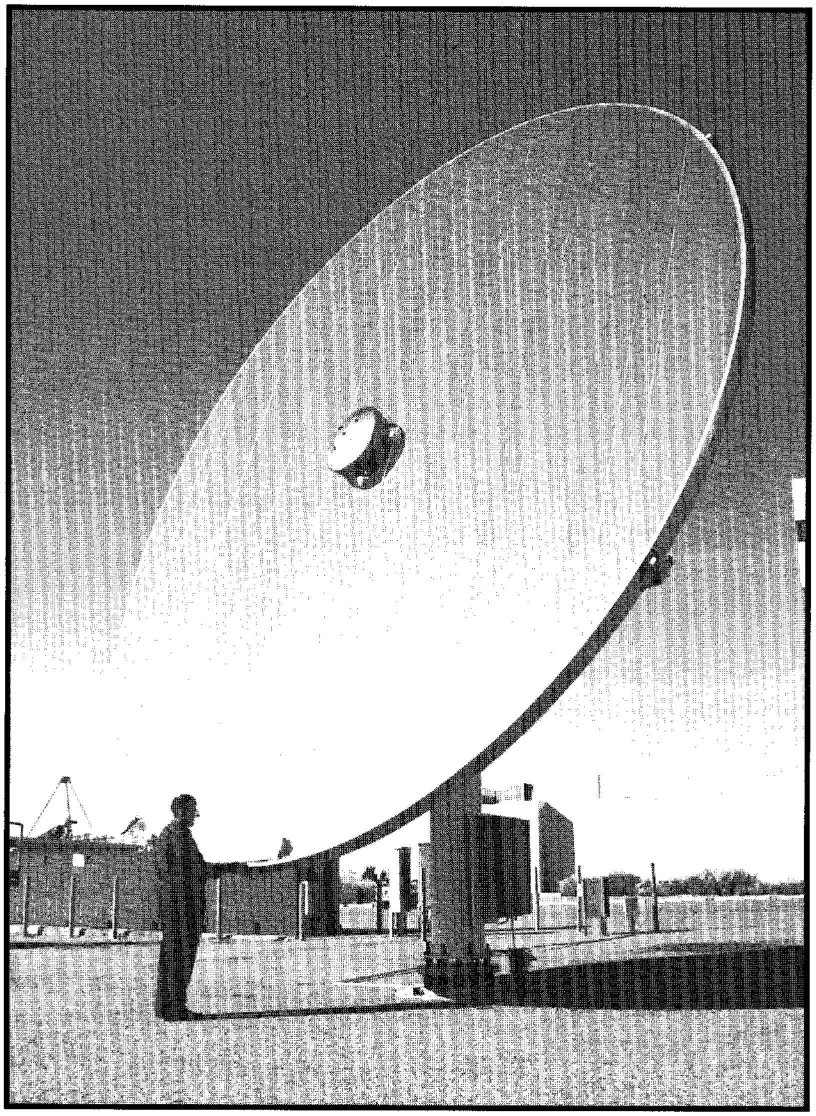

Figure 2.

Second-generation stretched-membrane mirror module built by SKI. The reflective area is 50-m^2. The membranes are 0.25-mm-thick aluminum with a silvered-acrylic film bonded to the front membrane. The module's focusing fan is mounted at the center of the front membrane.

installed a second-generation 50-m^2 mirror module at the NSTTF for Sandia to evaluate. The two mirror modules are shown in Figures 1 and 2.

Sandia's evaluation showed that the size and shape of the reflected beams were indicative of reflectors with nearly ideal parabolic contours; the measured mirror-normal errors were about 1.4 ± 0.2 mrad (1 sigma). The performance of the reflectors in windy conditions and their durability were also found to be excellent. Complete details of Sandia's evaluation can be found in its reports [13,14].

In both the first- and second-generation of membrane heliostats, efforts were concentrated on the mirror module because its design seemed the most challenging, and Sandia's evaluation indicates the mirror modules are now adequate to meet the needs of most current applications. Thus, the developmental activities with private industry are now being concluded with the design of fully-integrated, market-ready heliostats. SAIC has selected a 100 m^2-dual-module heliostat for commercialization [15] (Figure 3) and SKI a 50-m^2, single-module unit [16]. One key advantage of the dual-module design is that it can be stowed face down, which should extend the life of the reflective surface. A prototype of SAIC's 100-m^2 heliostat will be evaluated at the NSTTF in 1991.

In addition to developing improved designs for membrane heliostats, the central receiver program has provided estimates of the cost to produce them; these estimates are used in systems studies of central receiver power plants. Because the initial tooling costs for membrane heliostats are fairly expensive, the cost for heliostats is strongly related to the number produced per year and number of years of production, and cost estimates have been developed for a variety of production scenarios. While in the early days of the program, production scenarios were on the order of 50,000 heliostats per year [7,8], more recent cost estimates have been prepared for production rates of 2500 to 5000 per year over a 10-year period [15,16]. (A production rate of 5000 units per year corresponds to about one 100-MWe central receiver plant per year.) A recent summary of the price of membrane heliostats has been developed by Kolb et al. [17]. The installed prices were estimated to be about \$90 to \$110/m^2 at a production rate of 5000/year for 10 years. The present value of replacing the reflective film was estimated to be between \$2 and \$17/m^2, depending on the cost of the film and its replacement interval. The wide variation in the price of membrane heliostats is due to considerable uncertainty in the cost of the reflective film, which affects both the initial and replacement costs, and in the film's lifetime. (3M's reflective film, ECP-305, estimated to cost \$16/m^2 for this production scenario [15], is a significant portion of a heliostat's price; estimates for the case of multiple suppliers of the film are as low as \$3.50/m^2 [8].) We anticipate the price of membrane heliostats would drop considerably at higher production rates.

2.3 Heliostat Drives

A heliostat's drive is one of its most costly components, and therefore the development of drives has always been an important part of DOE's efforts [1]. In 1986, Sandia began working with Peerless-Winsmith, Inc., to develop a drive that incorporated the best features of previous units and could be mass produced in quantities of 50,000 per year. Peerless surveyed commercially available mechanisms to determine their suitability for incorporation into the drive's design [18]. For the azimuth portion of the drive, a gear-tooth planocentric mechanism driven by a differential, spur-gear planetary reducer was

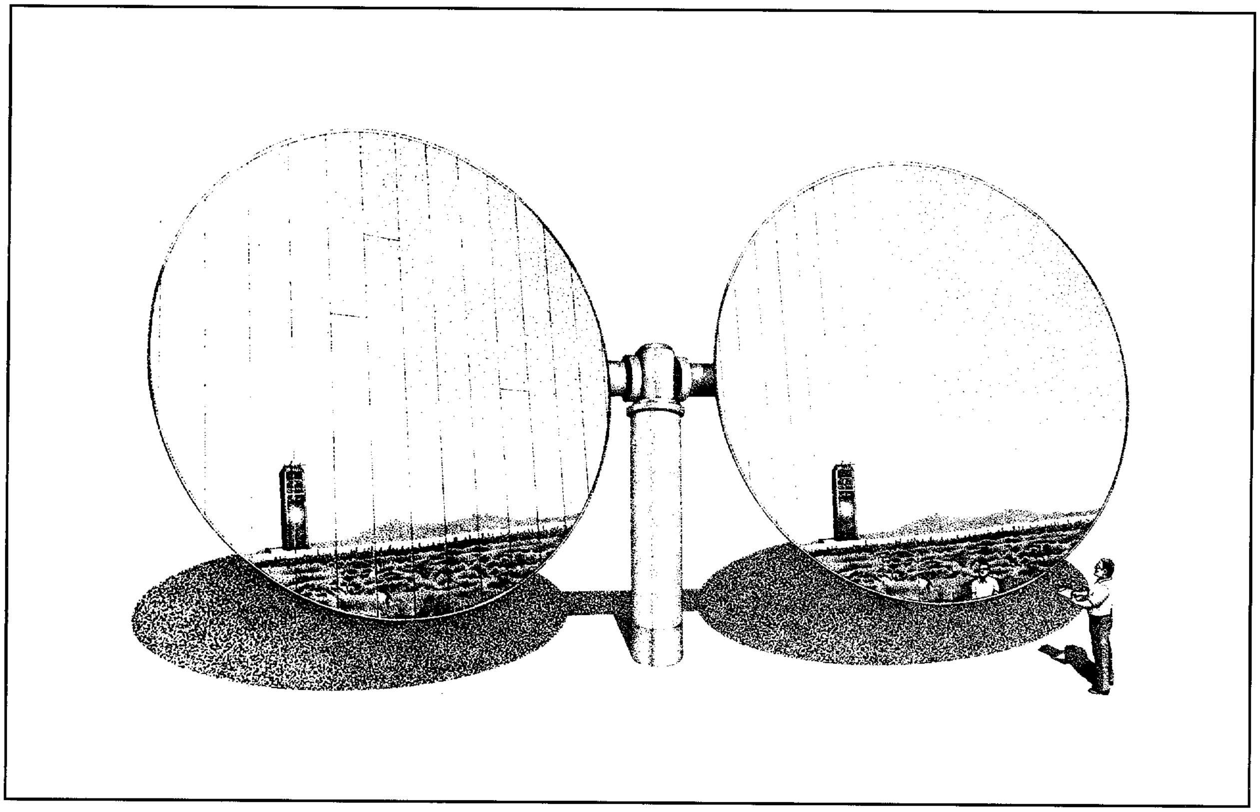

Figure 3. A schematic of SAIC's 100-m^2 dual-module heliostat. The heliostat will be installed at Sandia in late 1990.

selected; for the elevation drive a worm-gear driving a ball screw was chosen [18]. In a letter to Sandia, Peerless estimated the price of the drive in 1989 dollars to be about \$20/m^2 at a production rate of 5000/year for 10 years and about \$16/m^2 at a production rate of 50,000/year. Three prototypes of the drive were fabricated for Sandia's evaluation. Currently, Sandia is performing operational testing of the drive using ATS's 150-m^2 heliostat and two concentrating photovoltaic trackers. Based on preliminary testing, the drive meets all its specifications.

3. Parabolic Dishes

Currently, the development of commercial dish-Stirling systems is the largest component in DOE's solar thermal electric program. Efforts in the concentrator program center on developing stretched-membrane dishes that use both single and multiple facets [19]. The goal of the dish-concentrator development program is a point-focus dish capable of being integrated with a 25-kWe Stirling engine. The nominal dish f/D ratio for this application is around 0.6. In addition to working on the dish concentrator, Sandia works actively on the other parts of the system, including thermal receivers [20] and Stirling engines [21]. The first commercial units are expected to be ready in the mid-1990s.

3.1 Single-Facet Dish

In the single-facet approach, one large stainless-steel membrane is formed to the desired parabolic contour using both uniform and non-uniform pressure loading. The non-uniform loading is provided by water on top of the membrane, and the uniform loading is provided by a vacuum below the membrane. After the membrane is formed, a separate polymer-film reflector is drawn down onto it with a slight vacuum. A similar concept for forming the optical membrane has been developed in Germany, though thin glass mirrors are used [22,23].

Efforts to demonstrate the feasibility of the single-facet dish began at Sandia in 1987. In a multi-phase program under contract to Sandia, Solar Kinetics, Inc., designed and built a 7-m diameter dish [24-26]. For the optical surface, SKI uses 0.1-mm-thick 304 stainless steel membranes welded from 91-cm-wide strips. The space behind the front membrane is enclosed with a polyester cloth membrane impregnated with PVC. The front membrane is held with a vacuum of about 11 cm of water. The membranes and ring are supported by a central hub and spokes—similar in concept to a bicycle wheel.

To allow the optical performance of this first prototype dish to be characterized, a reflective membrane of aluminized polyester was used even though it is expected to be a material with a short life. (The silvered acrylic film used on heliostats could not be used because acrylic is too brittle to be stretched to the required f/D of 0.6 [26]; alternative reflective materials are currently being evaluated.) The polyester reflective film is held with the same vacuum that stabilizes the metal membrane. Complete details of SKI's design can be found in its report to Sandia [26]. Based on laser ray-trace measurements, SKI estimated the dish to have a slope error of of 3.6 mrad (1 sigma). The prototype dish was installed at the NSTTF in July 1990 for Sandia's evaluation (Figure 4); Sandia's tests will be performed on-sun and will determine the optical performance of the 7-m dish. SKI is currently developing the design and cost estimates for an 11-m dish, which is large enough to power a 25-kWe Stirling engine.

In fabricating the first 7-m dish, SKI demonstrated the feasibility of rolling up the front membrane after it had been plastically formed to its parabolic shape. This important simplification allows the front membrane to be formed at a central location using a single set of tooling, then shipped to the site for installation. Previously, it had been planned to use the dish's support ring for the forming process. Thus, the dish's support ring is simplified because it is not required to carry the high loads of the forming process [26].

3.2 Multi-Facet Dish

In a parallel effort begun in 1989, Sandia is also developing a dish using multiple stretched-membrane facets. This concept builds on the membrane heliostat technology and thus, has the possible advantage of being fielded sooner than the single-facet dish [19]. The approach is to use twelve 3.6-m-diameter stretched-

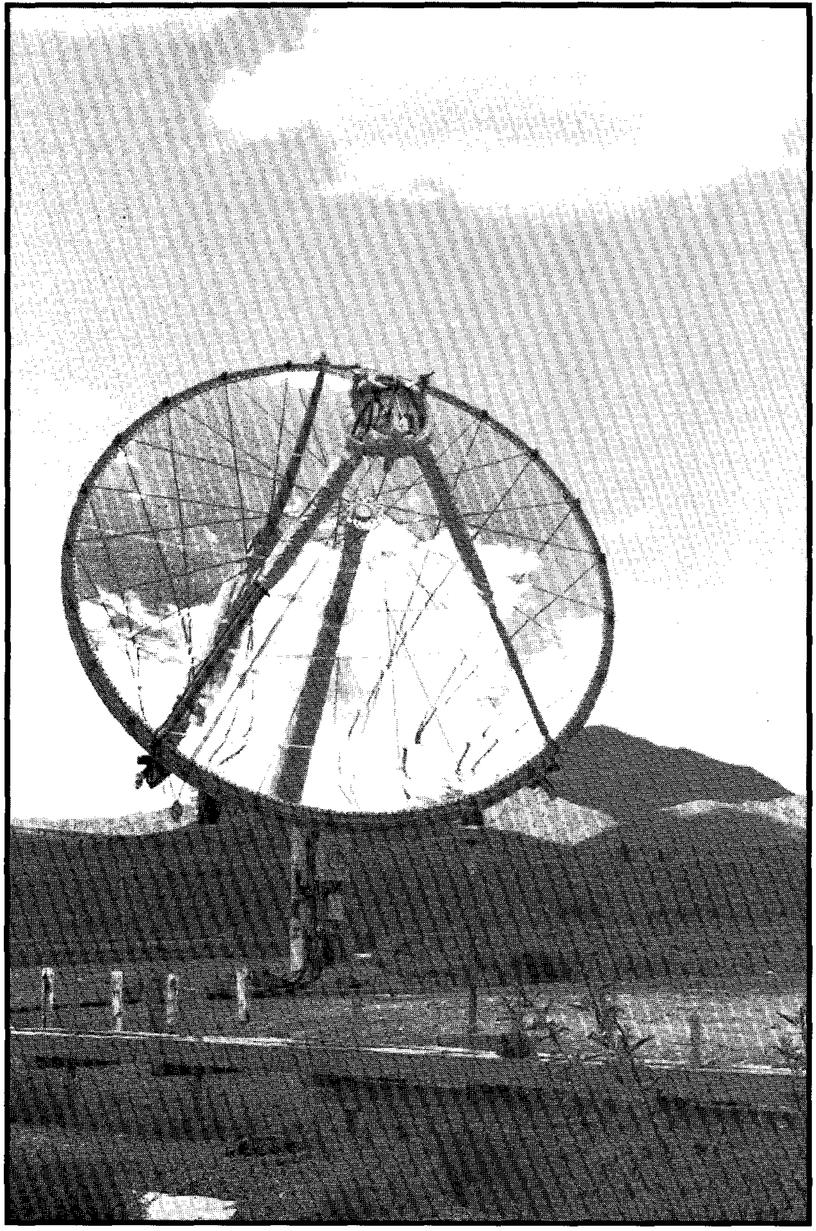

Figure 4.
A prototype of the optical element for a single-facet stretched-membrane dish. The dish is 7-m in diameter and is currently being tested at Sandia.

membrane facets—the largest size that can be practically transported (Figure 5). The facets are similar in design to those used in a membrane heliostat—two metal membranes stretched over a metal ring. Two different approaches to creating the desired parabolic contour are being pursued. In one, the facets are plastically formed with a uniform pressure loading, an approach similar to that taken with the single-facet dish. The formed facet is then stabilized with a slight vacuum, which can be varied to adjust the facet's focal length. In the second approach, the facets are elastically formed with a vacuum; this approach is similar to that used with a membrane heliostat, though the vacuum required to focus the facet is significantly greater. In both cases, a polymer film reflector is attached to the front metal membrane.

The f/D ratio for these facets is much smaller than that for a membrane heliostat (3 versus 30 to 50); therefore, one of the key technical issues of the multi-facet approach will be how well the facets can be formed to the required parabolic contour. In addition, because of the increased astigmatic aberrations of any facet concentrator, the multi-facet concentrator will be about 8% less efficient than a comparable single-facet design. [19].

Under contract to Sandia, SAIC and SKI have each built two 3.6-m facets for evaluation. SKI's facets were plastically formed and SAIC's elastically formed. Both designs use 3M's ECP-305 silvered-acrylic film bonded to the front membrane. An example is shown in Figure 6. Using a scanning laser ray trace system, SERI measured slope errors of about 2.2 ± 0.2 mrad (1 sigma) for SKI's facet and about 3.1 ± 0.2 mrad for SAIC's. Each contractor is currently improving the design of its facet. In parallel with the design and fabrication of the facets, WG Associates has designed a structure to support the dish's facets, and its pedestal, drive and controls. (The current plan is to use a modified version of the low-cost heliostat drive.) Fabrication and testing at Sandia of a complete dish are planned for 1991.

4. Reflective Films

The Solar Energy Research Institute has principal responsibility in DOE's solar thermal electric program for developing reflective films. SERI's performance goals for silvered polymer films are a five-year life with a specular reflectance greater than 90% into a 4-mrad, full-cone acceptance angle. The reflectance goals were met some time ago [27], and current emphasis is on increasing the durability of the film in the environment. Recent work at SERI has demonstrated significant progress toward increased optical durability for silvered polymer reflective materials.

For a number of years, SERI has worked in partnership with the 3M Company to develop improved reflective films [28,29]. The concept that has evolved uses a 1000-angstrom layer of silver between a 0.1-mm-thick film of PMMA (acrylic) and an adhesive. UV absorbers are added to the PMMA. A commercial film, ECP 300A, was developed by 3M in 1985 and has been undergoing accelerated weathering tests and outdoor tests near Denver, Albuquerque, Miami, and Phoenix. This film has maintained a reflectance of over 90% after several years of outdoor exposure at a commercial trough facility near Denver. At Phoenix, performance was maintained for only two years, perhaps because of the high summer temperatures. ECP-300A was also used on the two generations of stretched-membrane mirror modules that have been

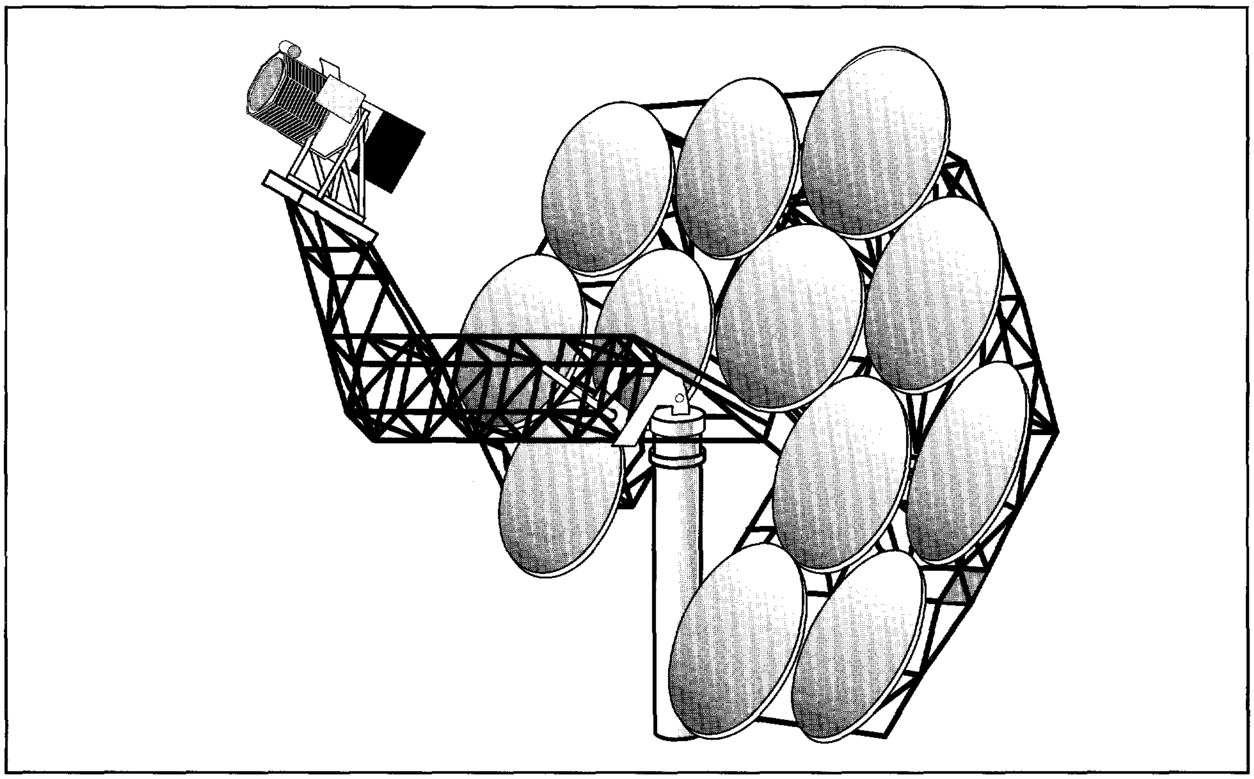

Figure 5. A schematic of the multi-facet dish for use with a 25-kWe Stirling system. There are 12 facets, each 3.6-m in diameter. The first prototype dish will be tested at Sandia in 1991.

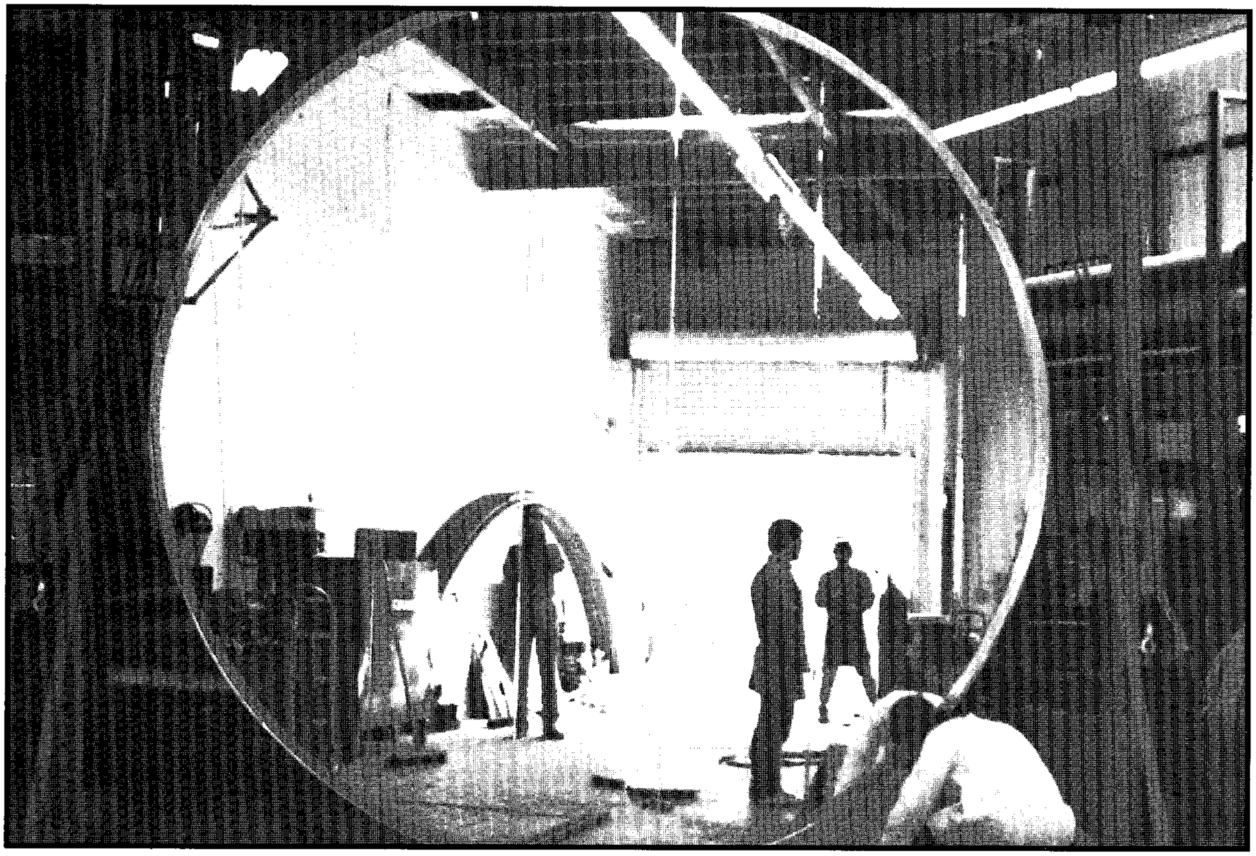

Figure 6. A prototype facet for the multi-facet dish. The facet is 3.6-m in diameter. The membranes are made of stainless steel and use 3M's silvered-acrylic film, ECP-305, as the reflector.

exposed for up to four years in Albuquerque with good results [14].

In 1989, again as a result of the cooperative effort with SERI, 3M began producing an improved film, ECP-305, that is expected to be three times more durable than the earlier, ECP-300A film. Tests of the new film's lifetime are currently underway, and efforts are continuing at SERI to extend the film's current 5-year expected lifetime; Figure 7 shows some recent laboratory results for accelerated aging for several films. Accelerated aging is performed in a Weather-Ometer, which is useful for comparing alternative films, though difficult to relate to real time. The improved corrosion resistance of the ECP-305 over the 300A can be readily seen. Results for an experimental film that has a thin layer of material in front of and behind the silver layer are also shown. In these laboratory tests, the experimental film is much less susceptible to silver corrosion than either of 3M's two previous films.

In addition to reducing the rate of silver corrosion, SERI is addressing a second failure mode called "tunneling." Tunneling, a separation of the silver and acrylic, has been observed sporadically in almost all applications of 3M's films, and is usually associated with the presence of moisture. Generally, if the tunnels are not repaired soon after they first appear, a maze of tunnels can propagate over the mirror's surface (water lying on the surface can produce tunnels in a few days). Tunneling is believed to be caused by stresses induced at the silver/polymer interface by differential thermal and hygroscopic expansion. Such stresses may overcome the weak adhesion between the polymer and silver. The adhesion at the interface is initially weak and is further weakened by exposure to moisture. SERI is investigating the causes of tunneling and is developing methods to increase the adhesion between the silver and the acrylic and of applying and sealing the edges of the film to eliminate tunneling. The addition of the extra layer of material between the silver and acrylic also appears to reduce the film's susceptibility to tunneling.

Even with the progress in extending the lifetime of the reflective film, it will likely be necessary to replace the film in the course of a concentrator's anticipated 30-year life. Currently, 3M uses a strong adhesive that bonds its ECP-305 film very tightly to the metal substrate, which makes replacing the film difficult. Sandia is working to develop a replaceable film by bonding the silvered-acrylic film to a separate polymer substrate that would be lightly glued to the substrate. A demonstration of a replaceable reflective film using one of the existing stretched-membrane mirror modules is planned at Sandia in late 1990. The approach should also be appropriate for use on parabolic troughs and the multi-facet dish.

5. Summary

Currently, the main thrust of DOE's concentrator program for solar electric applications is in the area of stretched-membrane concentrators for both heliostat and point-focus dishes. Stretched-and point-focus dishes. Stretched-membrane concentrators offer the possibility of significant cost savings over comparable concentrators using glass mirrors. The eventual availability of a durable, low-cost reflective film is, however, crucial to their success. In the interim, because of the high cost of 3M's film and the uncertainty in its useful life, alternative materials are being considered for membrane concentrators, including thin silvered-glass mirrors. In fact, for the single-facet dish, thin glass mirrors, as used by Schlaich in Germany [22,23], may be the best alternative because a silvered-acrylic film cannot conform to the required small f/D of 0.6.

Sandia and SERI's joint program for DOE continues to develop heliostats, dishes, and reflective films. The heliostat program is planned to be completed in 1991, the first multi-facet dish is planned to be fabricated for testing in 1991, and the first 11-m single-facet dish in 1993. Research to extend the life of the reflective films is continuing at SERI.

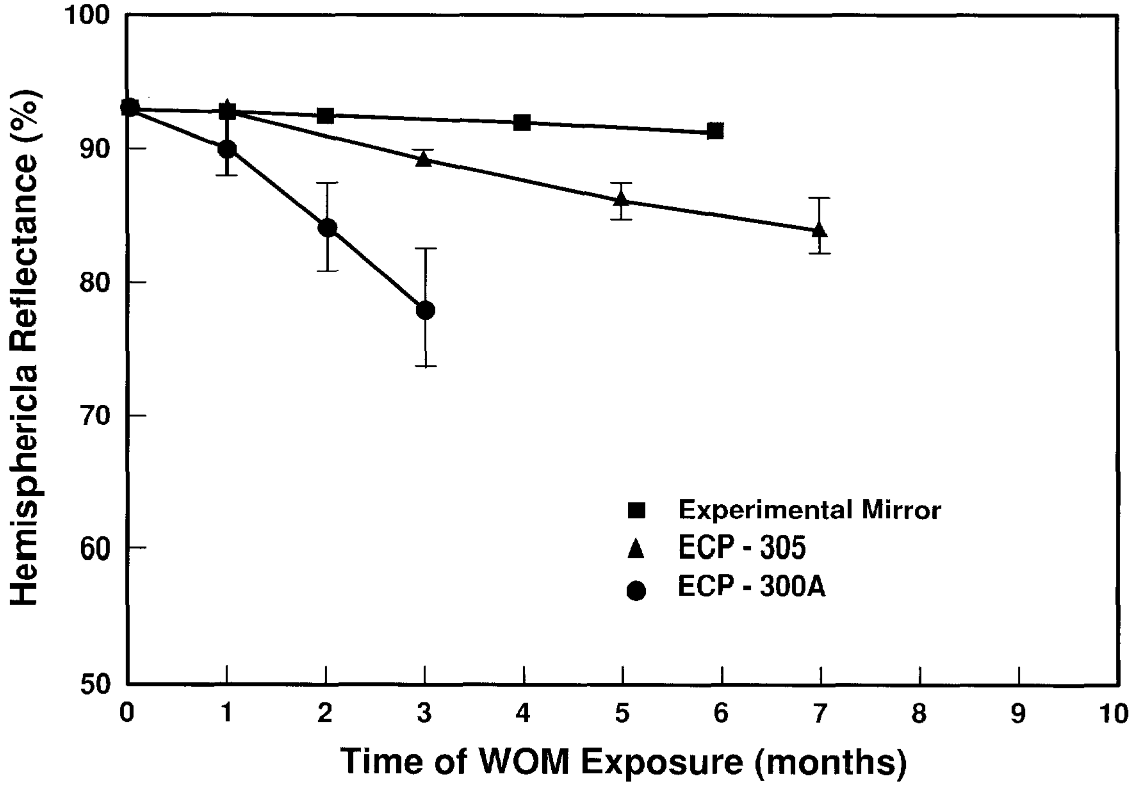

Figure 7. Accelerated aging at SERI of two of 3M's films, the older ECP-300A and the improved ECP-305. In addition, an experimental film developed at SERI using interlayers on either side of the silver is showing significantly lower rates of corrosion. The x-axis is time in a Weather-Ometer, which cannot be directly related to real time.

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