SERI/TP-253-2079
UC Categories: 59, 61, 63
DE84004433

Technical and Cost Potential for Lightweight, Stretched-Membrane Heliostat Technology

L. M. Murphy

January 1984

To be presented at the
ASME Sixth Annual Technical Conference
Las Vegas, Nevada
8-12 April 1984

Prepared under Task No. 1384.30
FTP No. 416-83

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche A01
Printed Copy A02

SERI/TP-253-2079

TECHNICAL AND COST POTENTIAL FOR LIGHTWEIGHT, STRETCHED-MEMBRANE HELIOSTAT TECHNOLOGY

L. M. Murphy

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80104

ABSTRACT

This paper presents the background and rationale and describes the development effort of a potentially low-cost, concentrating reflector design. The proposed reflector design is called the stretched-membrane concept. In this concept a reflector film—which can be metal, polymeric, or of a composite construction—is stretched on a hollow torroidal frame that offers a structurally efficient and optically accurate surface. Although the intent is to improve heliostat concentrator cost and performance for solar thermal applications, the collector design approach proposed here may well offer effective cost and performance opportunities for improving photovoltaic and solar daylighting applications as well. Some of the major advantages include a reflector, a support frame, and support structures that can be made extremely lightweight and low in cost because of the effective use of material with high average stress levels in the reflector and support frame; a 75% reduction in the weight of the reflector and support structure (down to the drive attachment) over the second-generation glass-and-metal heliostat concept; a better than 50% cost reduction for the reflector assembly and support structure compared to corresponding elements of the second-generation concept; and, finally, optical accuracies and an annual energy delivery potential close to those attainable with current glass-and-metal heliostats. In this paper we present results of initial design studies, performance predictions, and analysis, as well as results corresponding to subscale testing. We also include recommendations for further development and for resolving remaining issues.

INTRODUCTION

Large, structurally efficient and optically accurate solar reflectors and concentrators for solar thermal applications are feasible using stretched membrane technology. In this concept a high-strength structural film coated with a highly reflective surface is stretched uniformly on a structural frame (typically a lightweight hollow torroidal structure). The stretched-membrane concept is a structurally efficient method of attaining and supporting a large, optically accurate surface. By supporting the surface with tension rather than with bending and shear, as is done in normal cantilevered or edge-supported structures, more of the material can be worked to higher average stress levels, resulting in both lightweight and low-cost structures. Further, the stretched membrane can provide a reflective surface that tends to smooth out and attenuate surface irregularities emanating at the supports as well as other surface perturbations inside the support's periphery. This concept also appears to be especially suitable for polymer reflectors and membranes, making them not only lightweight and inexpensive but also easy to handle at the factory, in the field, and in transport.

The need for heliostats with dramatically improved cost and performance is discussed in detail in Murphy (1) and is largely based on the value-based cost goal analysis developed by a joint industry and the DOE cost goal committee (2). The resulting requirements are that heliostat field subsystems costing about $\$50$-$\$60/\mathrm{m}^2$ ($\$4.60$-$\$5.60/\mathrm{ft}^2$) (installed) and with performance levels similar to those of the current glass-and-metal heliostats are needed for widespread competitiveness with a broad range of conventional fuels. Further, the need and use of low-cost heliostat technology is not limited to solar thermal power applications but may potentially benefit large-scale photovoltaic applications and possibly daylight applications as well. In addition, improvements in heliostat technology cost and performance will benefit the solar-derived fuels technology, which is just now emerging.

The idea of using a stretched membrane for solar collectors has been around for some time. Meinel and Meinel (3) suggested using a stretched, metallized mylar film over a structural ring as early as 1976. Interest in practical applications of stretched membranes for both heliostats and point-focus, distributed-receiver dish systems has emerged in a number of groups in recent years. The Solar Energy Research Institute (SERI) and Sandia National Laboratories at Livermore, Calif., (SNLL) (4) investigated the potential of stretched-membrane heliostats. Other interested U.S. developers include Boeing (5) and the Jet Propulsion Laboratory (JPL). Several JPL subcontractors proposing stretched membranes for dishes include Summit Industries (6), Transolar, Inc. (6), and the AAI Corporation (6). The Lajet Co. has designed and is marketing a stretched-membrane parabolic dish using a commercially available metalized polymer membrane. Also, Saudi Arabia and Germany are jointly developing a large, metal, focusing spherical parabolic reflector formed from a stretched membrane and combined with a receiver and generator at the focal point for electricity applications (7).

In this paper we present an overview of the current status of the technical development of the stretched-membrane concept for heliostat applications. We focus primarily on the

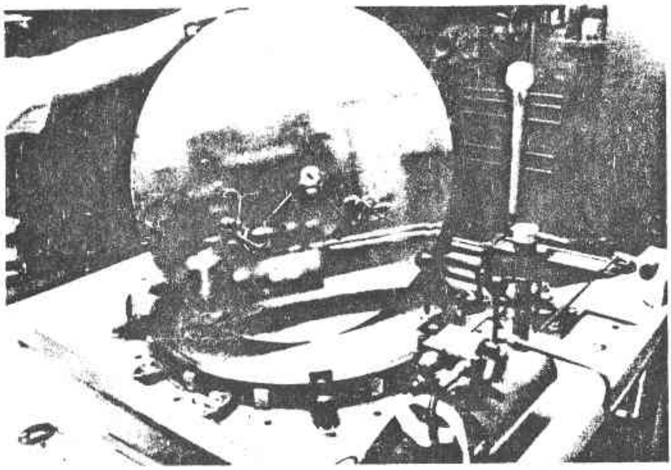

Fig. 1. STRETCHED-MEMBRANE HELIOSTAT (2-m DIAMETER) RESEARCH EXPERIMENT AT THE SERI TEST SITE

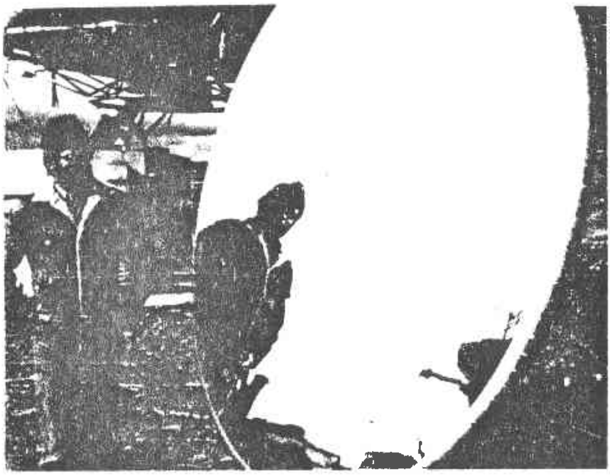

Fig. 2. ONE OF SEVERAL BENCH-SCALE (0.7-m-DIAMETER) MEMBRANE MODULES FABRICATED USING THE RING COMPRESSION TABLE.

reflector and the support structure (down to the drive attachment), which represent the largest fraction of the currently estimated total heliostat cost[1] [about 43% (1, 8, 9,)][2] and total weight (up to 85%, excluding the foundation). As such, the reflective module represents an important, but clearly not the only, collector element that requires further development. The effect of greatly reduced weight in the reflector and support structure should have a positive cost impact on other elements. However, additional development of drives, foundations, controls, and aerodynamic methods as well as other wind-avoidance schemes to reduce survival-level wind loading on the collector is both warranted and needed to meet installed heliostat field cost levels of $\$50-\$60/\text{m}^2$ ($\$4.60-\$5.60/\text{ft}^2$) and delivered energy costs of $\$5-\$6$/GJ ($\$5.3-\$6.4/10^6$ Btu). Specific development of the other component elements and suggestions for reducing costs was suggested in various other studies (10-13). As previously noted, this cost target is consistent with the goal of making solar thermal systems widely competitive with a range of conventional fuels, as defined by the value-based cost goal analysis. Reflector module and support structure development is a relevant and extremely important part of the total effort.

THE STRETCHED-MEMBRANE CONCEPT: TECHNICAL AND COST ISSUES

In this section, we summarize the findings based on the concept design, engineering, cost and performance analysis, and scale-model testing effort to date. Scale-model hardware that has been fabricated, designed, and tested includes: two prototype concentrators, 2 m (6.6 ft) in diameter, and a potentially low-cost two-axis tracking support base (see Fig. 1); seven stretched-membrane reflective modules of various designs, 0.7 m (2.3 ft) in diameter, and an initial prototype reflector, 3 m (9.8 ft) in diameter, based on a commercial trampoline to illustrate the concept.

Findings on Fabrication and Attachment Approaches

A number of findings on pre-tensioning, attachment, and support concepts emerged during this investigation of design approaches. First, membrane tension can be achieved by thermal expansion mismatch during assembly, mechanical ring or frame compression, mechanical means or simultaneous mechanical ring or frame compression (see Fig. 2), and mechanical tensioning. In Fig. 2 we see that an aluminum membrane is bonded to the support ring while the ring is held in compression. Upon releasing the compression on the ring, the membrane becomes tensioned.

Cable tensioning on the perimeter of the membrane offers yet another approach. Models 0.7 m (2.3 ft) in diameter[3] that used each of these tensioning methods (except the thermal mismatch approach) were fabricated and are discussed further later on. Although thermal mismatch approaches may be most effective in mass-production factory assembly, they are not easily done in the laboratory. When analyzing thermal mismatch approaches, we found that with membrane support frame structures, the coefficients of thermal expansion of the membrane and support ring should be fairly close for most practical applications.[4] In the laboratory environment, a combined ring-compression, membrane-tension approach is clearly the most straightforward and cheapest to implement, and it will probably add only a very small cost increment when mass-produced.

Next, we found that attaching the membrane to the support frame can be accomplished in several ways. We tried clamping, bonding, and welding procedures on a laboratory scale [0.7-m(2.3-ft)-diameter modules], and all approaches appear to be feasible for large-scale concepts for the tensions under consideration (required tensions for optimal designs are believed to be on the order of 12,250 to 26,270 N/m (70 to 150 lb/in.) (14). Note also that this range of tensions may allow us to use high-strength polymers such as Kevlar to take advantage of the benefits already noted. The most serious question to be resolved with respect to polymers is whether or not long-term creep can be eliminated or at least kept sufficiently low.

---

[1] Sandia National Laboratories (9) estimates second-generation heliostats to cost $\$110/\text{m}^2$ ($\$10.20/\text{ft}^2$) in 1980\$; expressed in 1982\$, this cost is $\$126/\text{m}^2$ ($\$11.70/\text{ft}^2$).

[2] If the optimized second-generation concepts (10, 11) are used for comparison, the corresponding number is approximately 53%.

[3] The cable-tensioned model was square and tensioned on two of four sides, providing uniform membrane tensions in one direction.

[4] Consider, for instance, if the support ring is steel and the membrane is a 0.254-mm (0.010-in.)-thick aluminum sheet, then a temperature increase of 10° F can decrease the membrane's tension by 10%.

Periodic clamping of the membrane to the support frame appeared to be the most expensive approach and does not appear to be economically attractive for field applications, although membrane change-out is most easily accomplished with this concept.[5] One other mechanical attachment approach (suggested by the Budd Co.) that appears promising is quite similar to the manner in which screens are attached to windows or doors; the membrane is forced into a crevice around the periphery of the support with a securing bead insert.

Bonding (Hysol 9320, provided by the Dexter Corp., was the bonding agent used in all SERI subscale tests) was the most reliable laboratory procedure in the absence of elaborate welding facilities and, based on preliminary costing, appears to be less expensive than periodic clamping but more expensive than welding for mass-production applications. However, in mass-production applications, production fixtures designed to facilitate rapid application of adhesive and assembly of parts to be bonded should permit fast-setting adhesives to be used and thus bring costs for the bonded approach more in line with welding costs. Furthermore, the adhesive approach may require less development than needed for welding the thin membrane while it is under tension. Initial tests with welds of metal membranes to support frames were unsuccessful because the thin membrane became warped and distorted (the same problem occurred with the membrane seams). However, subsequent laser welds on small, metal membrane samples were extremely encouraging. The integrity of the welds was quite good, and deformations close to the welds were almost imperceptable visually. Discussions with welding experts suggested that simultaneous spot-welds in production appear to be quite feasible and cost-effective.

We investigated two other new attachment and support approaches that do not require welding or bonding of the membrane to a rigid support ring. The first is a ring and bladder structural support and tensioning approach that was used to fabricate a number of 0.7-m(2.3-ft)-diameter modules and one of the 2-m(6.6-ft)-diameter reflective modules. This approach allows not only easy assembly, but it also results in a very uniform tension that can be easily varied. Furthermore, thermal expansion mismatch (between the frame and membrane) effects would also be greatly mitigated by the flexibility of the bladder and ring interface at the potential requirement and expense of pressure regulation in the bladder. This approach has been combined in several models with the laminated membrane concept, discussed later on, which permits variable focus, and we found it to be a very attractive approach for laboratory and possibly even field fabrication.

A second attachment concept uses a tensioned cable suspension system mounted on a structural support frame. It is currently being investigated for patentability.

We also addressed the question of whether to form very wide single-piece or joined membrane surfaces. Although metals of the extremely thin gauges needed are often only available in widths up to about 1 m (3.3 ft), polymer fabrication techniques can be adapted to form wide films. Initial metal prototypes built by SERI have used bonding with lap joints for seams. In the long run, however, other, more effective approaches seem to be desirable and possible.

One approach to making wide metal membrane films of uniform thickness was identified by the Budd Co. They use an electroplating concept in which a metal film of arbitrary thickness is deposited on a rotating drum that is partially submerged in an electrolytic bath. As the drum rotates out of the bath, the film peels off. Varying the chemistry of the bath can easily alter the strength characteristics of the film.

Another way to make wide metal films is to butt weld parallel metal strips using a laser. SERI's small sample laser weld tests were quite encouraging in this regard, and this process is apparently already in use in Germany (7). It can also be used for field applications.

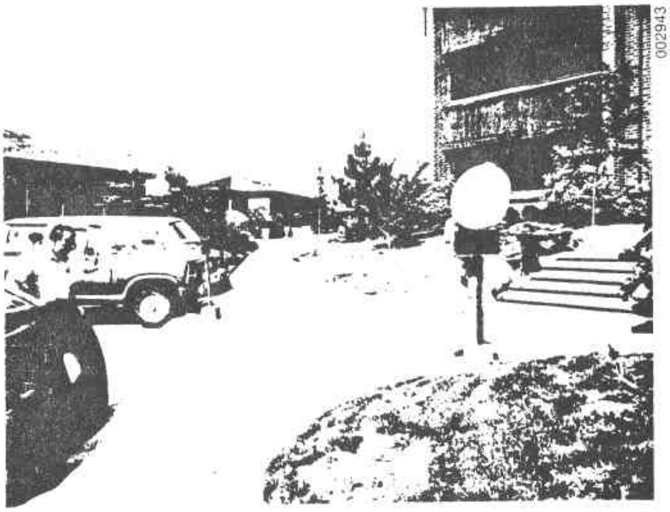

Fig. 3. **FOCUSING CAPABILITIES CORRESPONDING TO THE TWO-LAMINAE (0.7-m DIAMETER) STRETCHED-MEMBRANE REFLECTOR MODEL BEING DEMONSTRATED.**

A variable-focus, composite reflector concept using a stretched membrane has been under development for some time. The reflector is focused using a simple lamination and assembly procedure. First, a metal or polymer (e.g., Kevlar) membrane can be tensioned to a uniform state of plane stress. While it is in the tensioned state, a substrate is bonded uniformly to the back side of the main tension membrane. When the tension is then released, the composite plate system curves concavely in the external normal direction of the face. A wide range of material properties and thicknesses, subject to thermal expansion compatibility constraints, are potentially acceptable for the substrate. Several 0.7-m(2.3-ft)-diameter modules of this concept have been fabricated; one of the modules has just two laminae (using an FEK reflective surface), and others used glass backed by multiple laminae. Figure 3 illustrates the focusing capability of one of the bench-scale, 0.7-m-diameter composite reflector modules. The reflective surface in Fig. 3 is FEK-244, and the laminated membrane is a steel and aluminum sandwich.

This approach to focusing has two main benefits. The first is that changing the tension at the attachment to the support frame can vary the focus. The second, a very important feature, is that we can use a thin layer of glass on the front surface, so focusing will still occur and the glass will be kept in compression. Yet another benefit of this approach appears to be its favorable load deformation response in which curvature changes induced by pressures are partially compensated by curvature changes in the opposite direction caused by changes in the diaphragm loads. We are still investigating how far we can exploit this effect.

Focusing and Other Optical Requirements

The optical quality of the stretched-membrane concept is inherently very good because imperfections in both the ring planarity (in the plane of the membrane) and in the membrane itself tend to be smoothed out. Furthermore, as the support ring becomes larger, edge effects become less important. This has positive implications for manufacturing tolerances required for the support ring and associated optical accuracy. To put this in perspective, consider an allowable out-of-plane deformation tolerance of ±2 mm (±0.080 in.) from the nominal midplane of an 8-m(26.2-ft)-diameter ring. Then, for an

---

[5] In-plane and out-of-plane distorted regions between periodic attachment points die out exponentially in the radial direction, according to analysis. Visual observations support this result.

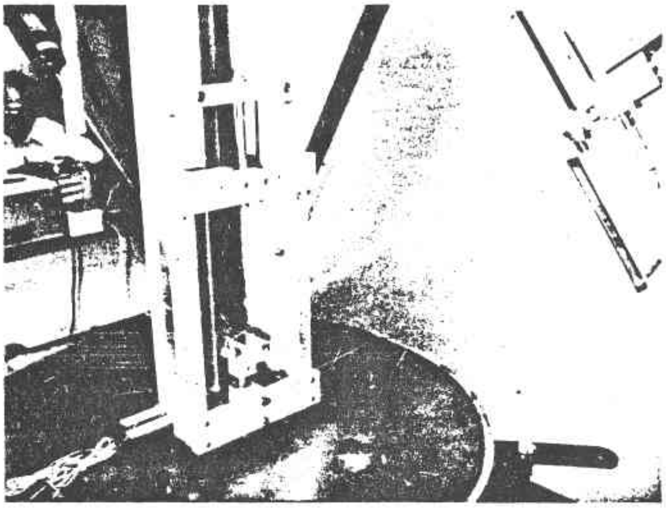

Fig. 4. **SURFACE QUALITY MEASUREMENTS BEING MADE ON A 0.7-m-DIAMETER STRETCHED-MEMBRANE REFLECTOR MODULE WITH THE SERI LASER RAY TRACE INSTRUMENT.**

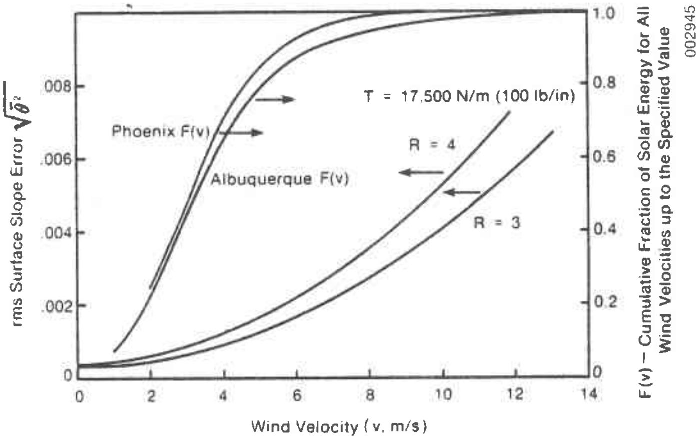

Fig. 5. **RMS SURFACE SLOPE ERROR CAUSED BY WIND- AND WEIGHT-INDUCED MEMBRANE DEFORMATIONS, AND CUMULATIVE FRACTION OF AVAILABLE SOLAR ENERGY AS A FUNCTION OF AMBIENT WIND VELOCITY.**

imperfection having 3 cycles around the ring, the resulting root-mean-square (rms) slope error for the surface (in the absence of other surface imperfections) is less than 0.5 mrad. Hence, for the larger modules in which edge effects will be more effectively attenuated and in larger commercial production environments where quality control can be maintained on support-frame accuracy, we feel we can attain very accurate surfaces. Membrane-surface contour accuracies considerably better than 2 mrad should be attainable.

Conceptual-scale reflective modules and initial prototypes built at SERI to date have verified analysis predictions. For the small, flat modules, 0.7 m (2.3 ft) in diameter, where virtually no care was taken to ensure in-plane uniformity (the models were intended primarily for investigations on structural fabrication and attachment approaches), we measured the surface accuracy using SERI's laser ray trace instrument (see Fig. 4). This showed measured rms values for surface normal deviations of 4-5 mrad, which agree with predictions based on support-ring nonuniformities.

Focusing is another issue of concern. There is a need for good focusing capability that becomes more pronounced for larger heliostats usually associated with larger plant sizes, which in turn necessitates larger field sizes.[6] In addition, for a given deviation from perfect focus, the refected image size at the receiver will vary linearly with the distance from the heliostat to the receiver. Note that the enclosed heliostat designs rely on gravity sag of the membrane, which results in some focusing (14,15), but the adequacy of this approach must still be demonstrated. Further, enclosed collectors have typically used low membrane tensions [about 350 N/m (2 lb/in.)], which might enhance the potential of using gravity focusing. However, visual observations of the 5-m (16.4-ft)-diameter research experiments built in 1977 by Boeing indicated that the reflected image from the heliostats shimmered in even light winds (i.e., excitation of the enclosure, even though very weakly coupled to the reflector inside, still disturbed the reflector at these low membrane tensions). Other provisions for focusing in addition to gravity may be necessary for unenclosed reflectors, since the tensions required to mitigate wind effects are approximately 12,250-26,270 N/m (70-150 lb/in.), depending on size and design (16).

There are several potentially attractive approaches to focusing other than with gravity. One is the double-membrane approach in which a partial vacuum is pulled between the membranes, allowing the reflective surface to curve spherically concave towards the receiver. Another approach is the curved multiple-laminae approach discussed earlier [see Fig. 3, in which the focusing capability of a double-laminae, stretched-membrane scale (0.7-m) model is demonstrated]. Several DOE contractors and commercial organizations have suggested or used the vacuum approach for thermal dishes (6,7,17). Koshalm's work is noteworthy (7) because he used vacuum-induced plastic deformation of the membrane to form the reflective surface, while Bracewell and Price (18), used a pressurization technique to form metal reflective surfaces plastically. Other approaches, such as putting a slightly pressurized polymer enclosure over just the reflective surface, have also been suggested. All of these approaches produce a shallow, spherical surface that quite closely approximates a parabolic surface. The relative surface-quality and engineering merits of these various approaches are yet to be assessed. We are currently evaluating the curved laminated-membrane concept and analyzing its general structural and optics as it relates to both single- and double-membrane concepts (16,19).

We can estimate the effect of wind and weight loading on the optical quality of the surface of a tensioned membrane by determining the rms surface normal error for a given assumed loading condition and corresponding deformation. Figure 5 illustrates the results of wind and insolation correlations (20) and, for comparision, the effect of wind loading on rms surface error, Fig. 5 shows the rms surface error as a function of wind velocity for two membrane radii. The membrane was assumed to be aluminum with a polymeric reflector surface, to have an areal mass density of 1.2 kg/m^2 (0.25 lb/ft^2), and to be oriented at a constant nominal orientation with the surface normal at 60° above the horizon. The membrane tension is assumed to be constant at 17,500 N/m (100 lb/in.). Wind-induced loading is assumed to be normal to the reflective surface and to correspond to the dynamic wind pressure loading at the corresponding wind velocity.

Figure 5 illustrates two main points; that wind-loading deformation degrades the optical quality of the stretched membrane very little at low velocities, and that for over most of the practical range of interest, the membrane will on the average have very good optical quality, even though at higher design velocities the optical quality may be degraded significantly. We selected relative directions for the wind and

---

[6] A recent study on enclosed heliostats with low net reflectivity showed that focusing can reverse the annual delivered energy by 35% as compared to flat reflectors.

heliostat orientation to be close to the worst possible case (i.e., corresponding to maximum pressure loading). A rear-surface windscreen could partially alleviate the back-loading problem. Furthermore, we are currently investigating some aerodynamic approaches that could significantly reduce the load normally anticipated on the reflective membranes.

Structural Behavior of Membranes and Support Structures

For the range of membrane materials, tensions, and sizes under consideration required for optical accuracy, the stretched membranes behave linearly (i.e., the membrane tension remains very nearly constant, equal to the pre-tension after loading). Furthermore, for this case, deformation is independent of membrane thickness, and the membrane, if it is loaded uniformly with pressure from wind and weight environments, will deform very nearly into a shallow spherical surface. At very large pressures (caused by wind velocities exceeding 20 m/s) the membrane/support structure will behave in an increasingly nonlinear fashion—the membrane will deform somewhat less than is predicted by linear theory. This is caused by additional diaphragm stretching (and increased membrane tension), which effectively adds more stiffness to the system. It is also interesting to note that as the support frame becomes more compliant, the effect of increased diaphragm stretching is reduced and the response becomes more linear again. The required membrane support frames are sufficiently compliant so that localized hard points caused by support struts and other attachments are also effectively isolated from the membrane deformation process at small distances from the attachment points. These effects for a circular membrane and support ring are illustrated in Fig. 6, where the fractional increase in membrane tension and the ratio of the nonlinear to linear deformation are shown as a function of membrane tension for several applied membrane pressures and support frame stiffnesses. In Fig. 3 we see that the deformation ratio corresponds to the total nonlinear membrane center deformation divided by linear membrane deformation (both measured in the center of the membrane). A pressure loading of $P_0 = 50$ N/m^2 (1.05 lb/ft^2) corresponds to the approximate maximum loading from a 9 m/s wind. The baseline system corresponds to R = 4 m (13.1 ft), a frame radial stiffness of $K_n = 13.3 \times 10^6$ Pa (2000 psi), and a membrane thickness of 0.254 mm (0.010 in.).

The main membrane support frame currently represents the largest mass element in the stretched-membrane concept, and, as such, it offers the greatest opportunities for further mass and cost reductions. The most effective support frame designs from a material-use perspective are toroidal shell shapes that carry the membrane-induced radial loads in compression rather than in bending or torsion. Thus, whenever possible, the membrane should not load the frame eccentrically, causing twisting moments about the cross-section shear center. As far as we know, there is no advantage to polygonal shapes for large, single, heliostat reflector modules. However, in considering smaller, multiple modules mounted on a single support structure and base (as on the second-generation base), polygonal frames, although permitting better module surface packing factors on the support frame, suffer greatly from a material weight and cost perspective. The induced bending and shear stresses (in the frame) do not permit optimal use of the material. Also, the assembly procedures required to compress the frame, so the resulting frame and membrane assembly permits uniform membrane tension, are more complex than for the circular shape. The packing factor advantages do not outweigh the material and weight requirement disadvantage. We found the shape of the most effective toroid cross-section to be generally noncircular and to require an out-of-plane bending moment of inertia at least 100% greater than the in-plane bending moment of inertia to prevent gross structural out-of-plane buckling.

It is not clear how serious the gross buckling problem is, since it is not expected to result in catastrophic failure. Specifically, analysis indicates that the membrane will greatly enhance the in-plane stability of the ring, since the initiation of radially inward (outward) collapse in one section of the support ring will be accompanied by sharply decreasing (increasing) radial membrane loads, which will greatly retard deformation. Out-of-plane, support-ring stability is a somewhat more complex phenomenon, but similar arguments can be made about the enhancing stability of the membrane and frame combination. Analysis has confirmed this. Note that tests on small-scale rings [0.7 m (2.3 ft) in diameter] indicate that tension loads 25% higher than those corresponding to classical out-of-plane buckling loads for the support ring have been tried without causing the support ring to fail.

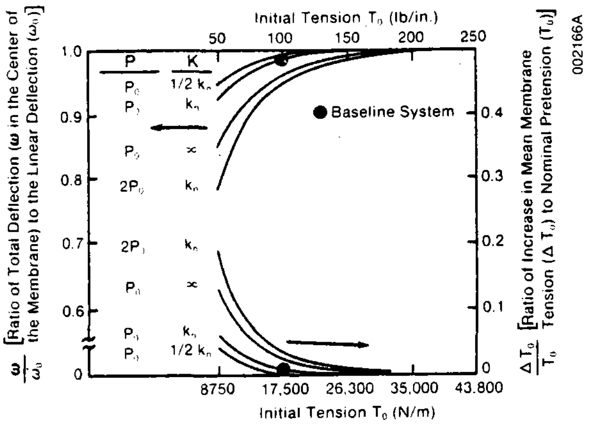

Fig. 6. MEMBRANE CENTER DEFORMATION RATIO AND FRACTIONAL TENSION INCREASE AS A FUNCTION OF INITIAL MEMBRANE TENSION FOR SEVERAL PRESSURE LOADINGS AND SUPPORT RING STIFFNESSES.

For frames larger in diameter, the most serious buckling problem appears to be localized buckling (or crippling) of thin-wall structures. Although this particular difficulty is easily obviated by increasing the thickness of the cross-section wall appropriately, it could represent a fundamental limitation to using very thin walls in the support frame. Approaches that will be investigated further, to utilize thin-frame wall structures and enhance local stability, include packing the toroidal cavity with foam and pressurization. Furthermore, pressure-stiffened tubular structures for the support struts and the membrane support ring are promising. Finally, high-strength nonmetallic materials such as carbon fiber composites may offer advantages in stretched-membrane frame design. We will also study composites later in the development process.

Materials Design and Cost Trends

From a performance and cost perspective, the stretched-membrane structural designs studied are quite light compared with other designs. The mass for these initial designs[7] (including the reflective surface, membrane, steel support frame, and support struts down to but not including the drive system) are on the order of 7.5 kg/m^2 (1.5 lb/ft^2) to 10.0 kg/m^2 (2.0 lb/ft^2). Corresponding areal mass densities for second-generation glass and metal concepts are on the order of 32 kg/m^2 (6.5 lb/ft^2) to 36 kg/m^2 (7.4 lb/ft^2). Note that although the anticipated weights for the stretched-membrane concept appear to be low, analysis indicates that significantly more progress in this direction may be possible, as we will discuss later on. To put these weights in perspective, see the evolution of design weight trends for heliostats shown in

---

[7] The geometric parameters for the design discussed here correspond to a circular reflector with a nominal radius of 4 m (13 ft) and a membrane thickness of 2.54×10^{-4} m (0.010 in.). A polymeric reflective surface is also assumed.

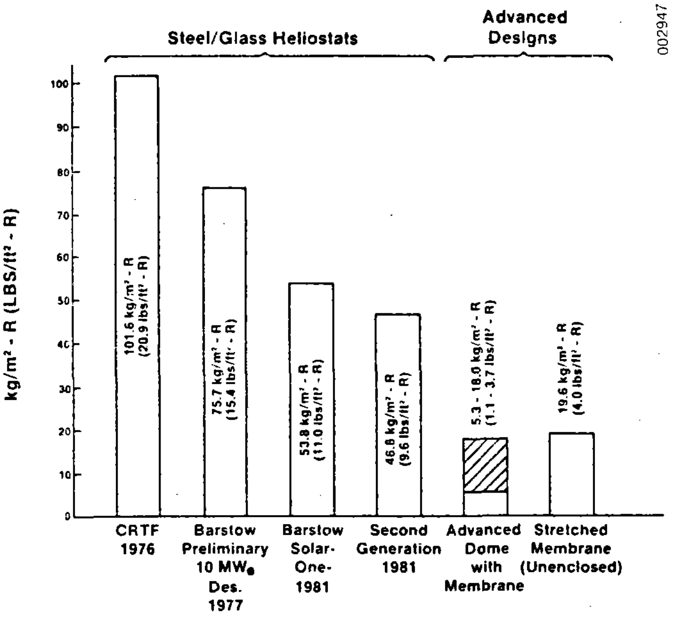

Fig. 7. **WEIGHT EVALUATION OF PRIOR AND CURRENT HELIOSTAT CONCEPT.**

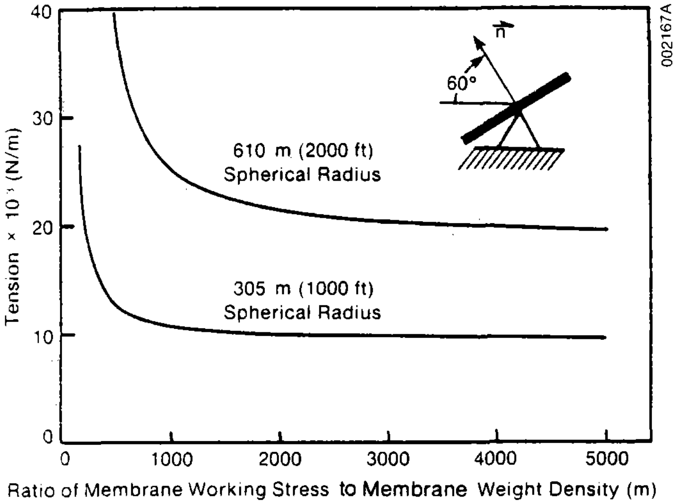

Fig. 8. **REQUIRED MEMBRANE DESIGN TENSION AS A FUNCTION THE OPERATING STRESS AND WEIGHT RATIO.**

Fig. 7. The heliostat's weight (this includes the drive and pedestal down to the foundation) per unit area of reflective surface and per unit net effective reflectivity (R) for six designs (and three concept generations) is shown as a function of time. The general trend has been for the weights to drop dramatically over time. In addition, the potential for further weight reductions appears significant and this will be the focus of future studies.

As previously noted, the support frame offers the most significant opportunity for mass and cost reductions. In the preliminary unoptimized designs studied, the frame was approximately three times as massive as the reflective membrane; but in future low-mass designs, it could represent as much as 90% of the membrane and support frame combination. Preliminary unit cost estimates for this concept are also encouraging. For the design shown, the initial cost estimates (for the heliostat through the support struts) is approximately \$30/m^2 (\$2.80/ft^2) for low-production scenarios (5-100 units) and about \$20/m^2 (\$1.90/ft^2) for high-production scenarios (25,000 units).[8] Corresponding high-production-level costs for second-generation glass-and-metal heliostats are about \$55/m^2 (\$5.10/m^2).

Figures 8 through 11 provide a sense of the design effects that impact weight and cost trends, and point out how further improvements might be made. A specific design point is assumed in these curves as shown in Murphy (1).[9] For the applied design wind- and weight-loading, Fig. 8 illustrates how the required membrane tension, corresponding to a maximum permissible curvature change (two levels are given) varies with the operating-stress and weight of the membrane. For a specified wind- and weight-induced loading, the tension is the level required to limit the corresponding curvature change in the membrane to the value indicated. The working stress and weight ratio varies as different materials and thicknesses are selected. The trends of the curves can be seen by noting that at low operating-stress and weight ratios, most of the tension goes into supporting the material weight, while at higher operating-stress and weight ratios, a constant tension is approached that corresponds to supporting the wind loading (the material weight becomes negligible).

In Fig. 11, the same required tension and design case corresponding to Fig. 8 is illustrated as a function of operating stress in the membrane for several materials at the 305-m (1000-ft) radius-of-curvature level. The abscissa in this figure is simply the abscissa in Fig. 8 multipled by the weight density. The corresponding required membrane thicknesses of the materials depicted in Fig. 11 are shown in Fig. 10. To keep the frame load and hence the total weight of the heliostat low, the trend to using thinner materials at higher levels of stress is desirable. However, little benefit is gained once the knee of either of the curves in Figs. 9 and 10 is passed. Further these apparent implications in favor of thin layers cannot be carried to an extreme. It is readily seen that at high stress levels, very thin metal materials on the order of 0.1 mm (0.004 in.) would be required. Not only would these thin metal materials be difficult to manufacture, handle, and protect from rupture by sharp objects, but they would most probably be expensive. Very light, optimally designed polymer membranes appear to have significant potential. They would appear to offer a good combination of relatively low tension and working stress, along with potentially good toughness, durability, ease of handling, and they are now easily manufactured in the required thickness range.

The trend in the weight of stretched-membrane systems is seen in Fig. 11. Here, the weight per unit reflective area is plotted as a function of working stress in the membrane.[10] The most interesting feature of this illustration is that the support frame is the dominant weight driver, as noted previously. Hence, although the weight of the membrane is a secondary

---

[8] The cost analysis performed at SERI corresponds to that of a stretched-membrane reflector and support structure, down to the drive attachment, and was limited in scope, as only material and labor unit prices were derived and no independent manufacturing flows were developed. However, resulting production-related costs are assumed to be consistent with those developed in more detailed second-generation heliostat cost studies.

[9] The baseline design case corresponds to a wind velocity of 8.9 m/s (20 mph) face-on to the heliostat, 57.5 Pa (1.2 lb/ft^2) local wind pressure, a reflector areal mass (mounted on the structural membrane) of 0.488 kg/m^2 (0.1 lb/ft^2), and an orientation angle of 60° (between the nominal normal to the heliostat face and the horizontal).

[10] It is interesting to note that the support struts in the initial conceptual designs require roughly one-third to one-half of the material needed in the support ring.

effect, the tension on the membrane dramatically affects the mass, and therefore, the cost. Initial lightweight designs can theoretically be lightened further. Just how much the mass can be reduced will be the subject of future study.

Numerous material issues relating to weight reductions, as well as structural and fabrication issues, have been noted here. However, work on materials to date has been confined to the evaluation of polymer reflective surfaces. In particular, following a review of previous work [Boeing Engineering (21), for example], we evaluated seven candidate metallized polymers for possible application on metallic or other structural membranes. Candidate metallized polymers included configurations employing acrylics, Teflon, silicates, and polycarbonates (22). Even though metallized polymers that also function as structural membranes eventually may be feasible and quite desirable, none of the metallized polymers currently available appear to be structurally adequate for this purpose. Since the initial designs focused on metallic structural membranes that do not require a strength contribution from the polymer reflective surface, we only studied the optical aspects initially. Results of this study are currently being documented (22).

Candidate samples were exposed to accelerated combinations of heat, relative humidity, pollutants, and ultraviolet (UV) radiation for time intervals of 4, 24, and 56 days. Then hemispherical reflectance and diffuse light-scattering measurements were used to characterize degradation effects optically. All silvered polymer candidates degraded rapidly. Visual degradation was especially dramatic and the silvered samples were particularly sensitive to UV radiation exposure. When UV was not present, the samples weathered well. Therefore, Masterson et al. (23) recommended that the possibility of a silvered mirror inside a UV screening polymer enclosure should be explored further. (Note that no commercially available silvered polymer reflector has yet been developed specifically for solar applications.) Aluminized polymers, although they exhibit lower initial reflectances than silvered polymers, were very resistant to accelerated weathering (although some delamination was observed). In particular, 3-M Co. products (YS-91 and FEK-244) showed virtually no degradation after 56 days of accelerated exposure.

Additional tests are currently underway at SERI to investigate temperature (which is known to be important with silver/glass mirrors) and UV radiation effects further. Thus, humidity and pollution, which Masterson et al. found were not important in the absence of UV radiation in the first series of tests, are being omitted in the current round of tests.

CONCLUSIONS AND RECOMMENDATIONS

Numerous design challenges and development issues remain to be resolved regarding stretched-membrane heliostats. However, the solutions to these problems appear to be readily manageable. Initial investigations are encouraging in that preliminary weights, costs, and performance predictions are within ranges that will make solar thermal systems broadly competitive with conventional fuels. This low-cost approach may assist developers of sun-fuels and solar daylighting, as well. As noted, this approach may also provide developers of PV systems with a cost-effective way of greatly enhancing performance using a low-cost, two-axis tracking platform.

The major cost and performance potential benefits for the stretched-membrane concept accrue primarily from the large weight reductions that appear to be attainable, while maintaining very good performance, and because the stretched-membrane concept is inherently much less complex in terms of the design of its various interfaces and the number of parts required. Current structural analysis and testing shows that it is feasible to build stretched-membrane concentrator modules (down to the drive attachment) that are one-fourth the weight,

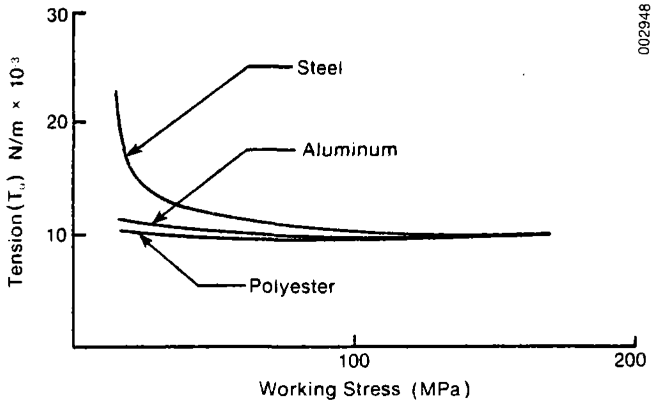

Fig. 9. REQUIRED MEMBRANE DESIGN TENSION AS A FUNCTION OF MEMBRANE WORKING STRESS FOR SEVERAL MEMBRANE MATERIALS.

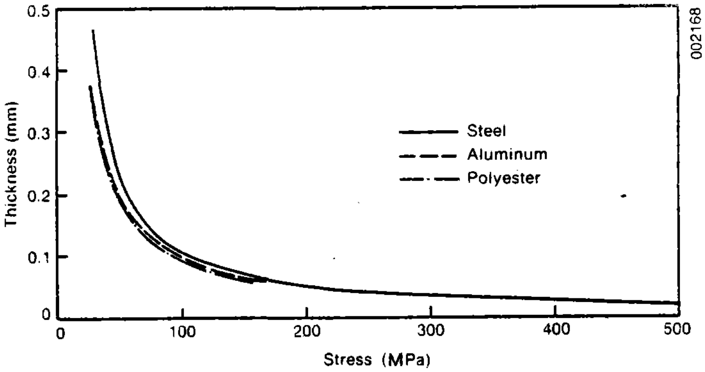

Fig. 10. MEMBRANE THICKNESS AS FUNCTION OF WORKING STRESS FOR SEVERAL MATERIALS.

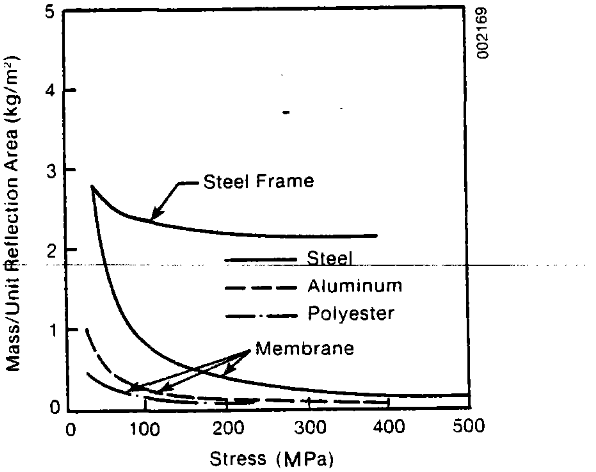

Fig. 11. MEMBRANE AND SUPPORT FRAME MASS FOR SEVERAL MATERIALS PER UNIT REFLECTIVE AREA AS A FUNCTION OF WORKING STRESS.

and roughly one-half the cost of, second-generation glass and metal heliostats. The most promising opportunities for even greater weight reductions appear to be in the area of the support-frame design. Preliminary analysis indicates that the performance of the stretched-membrane concept could be quite close to that of current designs.

Although this concept appears to represent a potentially dramatic cost and performance improvement over the second-generation glass-and-metal designs, much development work still remains to fully verify and realize that potential. We therefore recommend a closely coordinated industry and laboratory development effort. More detailed costing and production analyses are warranted and detailed comparisons with second-generation heliostats where the cost of delivered energy on an annual basis is used as the figure of merit. Optical analyses of surface accuracy for both undisturbed and wind- and weight-loaded membranes correlated with and confirmed by experiments should be used to support these system performance studies. These analytical and testing studies should include the impact assessment of membrane seams, nonuniform and backside pressure loading, and ring imperfections. Optimization studies are needed that include the effects of weight reduction limitations, size constraints, and the applicability of scaling relationships. Ultimately, we must determine whether improvements in drives and controls, as well as wind-reduction and wind-avoidance schemes, can further reduce costs.

Near-term material issues include determining the availability of durable, highly reflective polymer films for use with metallic structural membranes. Bonding or welding of membranes (both to the main structural frame and in the forming of wide sheets from multiple narrow sheets) in large-scale production environments should be more fully understood. Testing and industry involvement are warranted at an early stage. Long-term material issues include possible cost reductions by developing polymer mirror laminates and polymer composite structural elements (i.e., the frame).

In terms of mechanical and structural design, the most important issues include refining the definitions of practical limits for further weight reductions (including the establishment of more precise buckling criteria for both local and gross stability as a function of heliostat size and design tension) and determining ways to enhance the buckling resistance of thin, tubular structures. In particular, we need to investigate the inplane stability question regarding the main support ring and to verify the applicability of structural-stability scaling relationships by testing increasingly larger hardware elements. Furthermore, we need to study the snap-through process (oil canning) of laminated, curved membrane reflectors and aerodynamic load-reduction schemes for the reflector assembly.

REFERENCES

1. Murphy, L. M., Technical and Cost Benefits of Lightweight, Stretched-Membrane Heliostats, SERI/ TR-253-1818, Solar Energy Research Institute, Golden, Colo., 1983.

2. Edelstein, R. B., "Value-Based Costs for Advanced Solar Thermal Systems." Review of Polymer Requirements for Solar Thermal Energy Systems. Proceedings of a workshop held in Alexandria, Va., SERI/CP-251-1419, Solar Energy Research Institute, Golden, Colo., 1981, pp. 75-110.

3. Meinel, A. B. and Meinel, M. P., Applied Solar Energy—An Introduction, Addison-Wesley, Reading, Mo., 1976, p. 245.

4. Mavis, C. L., et al., A Description and Assessment of Solar Central Receiver Systems Technology, SAND 82-8023, Sandia National Laboratories, Livermore, Calif., forthcoming.

5. Boeing Engineering, A Conceptual Design Study of Point Focusing Thin-Film Solar Concentrators, Boeing, Seattle, Wash., 1981.

6. Jaffe, L. D., Dish Concentrators for Solar Thermal Energy: Status and Technology Development, DOE/JPL-1060-48, Jet Propulsion Laboratory, Pasadena, Calif., 1981.

7. Khoshalm, B. H., "50-kW Solar Membrane Concentrator," Presented at the Solar Thermal Collectors Workshop (sponsored jointly by the Saudi Arabian National Center for Science and Technology and the United States Department of Energy), Lakewood, Colo., 11-14 April 1983, Midwest Research Institute (SOLERAS Project), Kansas City, Mo., proceedings forthcoming.

8. Thornton, J., et al., A Comparative Ranking of 0.1-10-MWe Solar Thermal Electric Power Systems: Summary of Results, Vol. 1, SERI/TR-351-461, Solar Energy Research Institute, Golden, Colo., 1980.

9. Sandia National Laboratories, Second Generation Heliostat Evaluation—Summary Report, SAND 81-8024, Sandia Livermore Heliostat Division, Livermore, Calif., 1982.

10. McDonnell Douglas Astronautics Co., Optimization of the Second Generation Heliostat and Specification, SAND 82-8181, Sandia National Laboratories, Livermore, Calif., 1982.

11. Martin Marietta Corp., Second Generation Heliostat Optimization Studies, SAND 82-8275, Sandia National Laboratories, Livermore, Calif., 1982.

12. Murphy, L., Recommended Subelement Cost Goals for Advanced-Generation Heliostats, SERI/SP-253-1791, Solar Energy Research Institute, Golden, Colo., 1982.

13. GAI Consultants, Laterally Loaded Drilled Pier Research, Vols. 1 and 2, EPRI EL-2197, Electric Power Research Institute, Palo Alto, Calif., 1982.

14. General Electric, Solar Central Receiver Prototype Heliostat, Phase I, Final Technical Report, SAN/1468-1, GE, Schenectady, N.Y., 1978.

15. Boeing Engineering, Solar Central Receiver Prototype Heliostat, Vol. 1, SAN/1604-1, Boeing, Seattle, Wash., 1978.

16. Murphy, L., Sallis, D., Structural Design and Cost Perspectives for Stretched-Membrane Heliostats, SERI/ TR-253-2101, Solar Energy Research Institute, Golden, Colo., forthcoming.

17. Boeing Engineering, Photovoltaic Concentrator with Plastic Film Reflector. Contract No. 13-5060, Boeing, Seattle, Wash., 1981.

18. Bracewell, R. N., Price, K. M., "Parabolic Reflectors Formed by Inflation," Solar Energy, Vol. 27, No. 6, 1981, pp. 535-537.

19. Brumleve, T. D., Napolitano, L., Conceptual Design and Analysis of a Prestressed Membrane Heliostat, Sandia National Laboratories, Livermore, Calif., forthcoming.

20. Randall, P. E., Grandjean, N. R., Correlation of Insolation and Wind Data for SOLMET Stations, SAND 82-0094, Sandia National Laboratories, Albuquerque, N.M., 1982.

21. Boeing Engineering, Plastic Film Performance Improvement for Heliostats, SAND 79-8185, Sandia, Livermore, Calif., 1980.

22. Masterson, K., and Jorgensen, G., "Reflectance of Selected Metallized Polymer Films Subjected to Accelerated Exposures," SERI memorandum, Solar Energy Research Institute, Golden, Colo., July 1982.