J. Martinez

SERI/TR-253-1818
DE83009408

May 1983

Technical and Cost Benefits of Lightweight, Stretched-Membrane Heliostats

L. M. Murphy

SERI

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Operated for the
U.S. Department of Energy
under Contract No. EG-77-C-01-4042

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 $4.50
Printed Copy $8.50

SERI/TR-253-1818
UC Categories: 59, 61, 63
DE83009408

Technical and Cost Benefits of Lightweight, Stretched-Membrane Heliostats

L. M. Murphy

May 1983

Prepared under Task No. 1384.30
WPA 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. EG-77-C-01-4042

PREFACE

This work was performed for the U.S. Department of Energy under the general guidance of Cliff McFarland of the Division of Solar Thermal Technology. The author is thankful for the many helpful consultations with Dan Sallis of Dan-ka Products. Barry Butler of the Solar Thermal Materials and Research Division at SERI provided the initial impetus for using the stretched-membrane concept for heliostats.

L. M. Murphy, Group Manager
Thermal Systems and Engineering Branch

Aproved for
SOLAR ENERGY RESEARCH INSTITUTE

John Thornton, Chief
Thermal Systems and Engineering Branch

Barry Butler, Manager
Solar Thermal and Materials Research Division

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

This report presents the background, the rationale, and a description of the development effort at SERI of a novel and 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, which offers a structurally efficient and optically accurate surface. The collector design approach proposed here, although it is intended primarily to improve heliostat concentrator cost/performance for solar thermal applications, may well offer effective cost/performance opportunities for improvements in photovoltaic and solar daylighting applications as well. Some of the major advantages presented and supported in the report that are apparent with this approach are as follows:

- The reflector, support frame, and support structures can be made extremely lightweight and low in cost because this concept makes the most effective use of material with high average stress levels in the reflector and support frame. Furthermore, the weight and structural advantages are anticipated to cascade to some extent through the whole system; additional development of other collector subsystem elements is clearly still required to meet long-term cost/performance goals adopted by the U.S. Department of Energy (DOE).
- Typically, a 75% reduction in the weight of the reflector and support structure (down to the drive attachment) can be anticipated for the stretched-membrane concept in comparison to the second-generation glass/metal heliostat concept.
- The concept is extremely simple, using fewer parts than traditional glass/metal heliostats. The predicted cost for the reflector assembly and support structure is about $20/m^2, compared with about $55/m^2 for corresponding elements of the second-generation concept. Most of this cost savings accrues from the much greater structural efficiency and corresponding lower weights of the stretched-membrane concept.
- The stretched-membrane reflector provides a very accurate optical surface, which can be maintained under anticipated environmental loads. Optical accuracies and annual energy delivery potential close to those attainable with current glass/metal heliostats are envisioned. Hence, the cost/performance improvement potential appears to be significant with this concept.

Results of design studies, performance predictions, and analysis, as well as results corresponding to subscale testing, are presented. Recommendations for further development and for resolving remaining issues are also included.

SECTION 1.0

INTRODUCTION

The need for heliostats that cost considerably less than current second-generation glass/metal heliostats has been established in a recent value-based cost goal analysis [1,2]. Edelstein et al. indicate that when fairly aggressive, but attainable, performance levels are assumed and when system costs of $\$172/m^2$ (1982$)* can be attained, the potential exists for solar thermal systems to penetrate the IPH and electric generation markets significantly [1]. Furthermore, for system costs below $\$115/m^2$, which corresponds to a delivered energy cost of roughly $5-$6/GJ, solar thermal systems can be competitive with a wide range of conventional fuels in many areas of the United States. Another study [3] shows that in the long run, heliostat costs are expected to account for roughly 50% to 60% of system installed cost. Hence, based on the $\$115/m^2$ installed costs, for significant potential market penetration, heliostat costs must be around $\$60/m^2$ when fairly high levels of performance are assumed. To put this development requirement in perspective, consider that the estimated cost of installed, mature second-generation glass/metal heliostats is approximately $\$126/m^2$.** There is, then, a need to reduce second-generation heliostat costs by at least $\$60/m^2$ if solar thermal systems are to be widely competitive with conventional fuels, according to the value-based cost goal analysis.

There is also a need for inexpensive heliostats in applications other than those associated with solar thermal technology. For example, buildings research programs are currently considering the possible application of heliostats for daylighting [5]. Further, the use of heliostats for photovoltaic (PV) applications is appearing more attractive and likely, since two-axis tracking can increase cell energy output in many cases by 40% on an annual basis [6] compared with a nontracking system. Furthermore, Copeland has already determined a $5-$6/GJ delivered energy cost [6] as the level at which solar thermally derived fuels will become economically competitive.

Improving the cost/performance (or cost of delivered energy on an annual basis) of collector subsystems has always been a major focus of DOE's collector development programs. In managing the heliostat development effort for DOE, Sandia National Laboratories has had considerable success with helping to evolve mature glass/metal heliostats to the point where a further cost/performance improvement of roughly 25% appears to be attainable [8,9]. Glass/metal heliostats are characterized by consistent high-performance requirements and by the fairly stringent design requirements particular to these concepts. Cost/performance improvements have resulted by taking advantage of, among other things, mass production techniques and lower-weight concepts. Building on this substantial body of experience, both SERI and Sandia have considered other concepts that represent radical departures from the glass/metal concept (such as the enclosed heliostat discussed below). In addition, for some time SERI has advocated an approach that not only emphasizes the use of low-cost, novel materials but also includes the design of innovative, environmentally adaptive, less robust structural concepts that are inherently low-cost and that may meet somewhat less stringent performance and/or

*1982$ will be used throughout.

**Of the five second-generation designs developed through DOE funding, three had estimated costs below $\$130/m^2$ (in 1982$). See Ref. [4].

structural requirements (at least in initial design phases), as defined in the development of earlier generations of concentrating collectors. In following this approach while building on previous learning, further significant cost reductions appear feasible. In pursuing this approach in relation to the stretched-membrane concept, SERI is now colloborating with Sandia National Laboratories in Livermore (SNLL).

One potentially low-cost DOE-supported design that has received significant development attention is the polymer enclosed concept, in which the reflective structure is protected from environmental loads and can, therefore, be made much less expensively than the current glass/metal concept. Such designs have been developed for DOE by General Electric [10] and Boeing [11]. Based on these design concepts, potential collector costs have been estimated to be under $\$60/m^2$ [10,11]. More mature concepts, corresponding to high production levels, are estimated to cost around $\$35/m^2$ [10,12]. However, because the optical performance of these systems is currently rather poor* and the life of the enclosure is limited, a significant amount of research is still needed to attain the required cost/performance levels as defined by cost goal analysis. The research required to reach acceptable performance/cost levels has been defined in a recent SERI study [13].

Another approach that SERI has initiated under DOE's sponsorship is an innovative, lightweight concept known as the stretched-membrane concept. The stretched-membrane concept extends the reflector technology of the enclosed heliostat concept (in which a stretched, thin-flim polymer reflective surface is used) to the point where no enclosure is required to withstand environmental loads.** With appropriate stretched-membrane reflector designs, initial studies and experiments indicate that this approach may lead to heliostat collector costs as low as the most optimistic cost estimates for enclosed concepts, while providing optical performance levels fairly close to those of second-generation glass/metal heliostats.

The idea of using a stretched membrane for solar collectors has been around for some time; the first reference to it known to the author occured in 1976 when Meinel and Meinel suggested using a stretched, metallized mylar film over a structural ring [14]. 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. Both SERI [15] and SNLL [16,17] have been investigating the potential of, and performing research on, stretched-membrane heliostats. U.S. industry developers, including Boeing [18] and some under the general direction of the Jet Propulsion Laboratory (JPL), who have proposed stretched membranes for dishes include Summit Industries [19], Transolar, Inc. [19], the AAI Corporation [19], and the Lajet Co. [20]. Also, Saudi Arabia and Germany are jointly developing a large, metal, stretched-membrane dish for electricity applications [25].

*The net effective reflectance of enclosed heliostats has been estimated to be approximately 0.56, using currently available enclosure materials and commercial polymer reflector films, whereas the corresponding second-generation glass/metal heliostat reflectance is around 0.92 [13]. Note, however, that the same study also stated that there is significant potential to improve the optical performance of enclosed heliostat systems dramatically.

**Commercial concepts for small-diameter stretched-membrane parabolic dishes have already been proposed and commercially fabricated [19, 20].

One major advantage of the stretched-membrane concept is that it 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, which results 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. Also, this concept appears to be especially suitable for polymer reflector/membranes that could be not only lightweight and inexpensive but also easy to handle at the factory, in the field, and in transport.

This paper presents an overview of the current status of the technical development of the stretched-membrane concept at SERI and appropriate related activities. The major focus of this paper is on the reflector and the support structure (down to the drive attachment), which represent the largest fraction of the currently estimated total heliostat cost (about 43%)* 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 $\$50$-$\$60/m^2$ and delivered energy costs of \$5-\$6/GJ. Specific development of the other component elements, along with suggestions for reducing costs, has been suggested in various other studies [8, 9, 22, 23]. As noted above, 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.

An assessment of where SERI stands today in the development process is given here, along with some preliminary design factor trends and parameter trade-offs. Clearly, more development is needed to validate these initial encouraging results and to better bound the cost potential of this concept. We expect, however, that the cost/performance level of the stretched-membrane concept represents a dramatic improvement over those of existing glass/metal concepts, even though stretched membranes may meet somewhat less stringent design requirements and have a somewhat lower performance level than those defined for second-generation glass/metal heliostats. The major cost reduction benefit from the stretched-membrane concept results mainly from the reduction in weight. Hence, since the performance of the stretched-membrane concept is anticipated to be quite close to that of the second-generation concept, cost/performance of the collectors should improve commensurately. Although there is a limit to the cost reductions that result from the structural optimization and weight reductions that can be attained, further improvements along this line appear to be feasible. Also, in terms of predicted costs for the reflector assembly and support structure, it is important to note that although there is a dramatic reduction in the cost-per-unit-area with the stretched-membrane concept, the cost-per-unit-weight is relatively close to that of the second-generation concept; hence, because of its simplicity, the current concept may be somewhat more attractive than what we have presented here.

---

*If the optimized second-generation concepts [8, 9] are used for comparison, the corresponding number is approximately 53%.

SECTION 2.0

THE STRETCHED-MEMBRANE CONCEPT

2.1 THE SERI EFFORT TO DATE

To date, SERI's effort has focused on concept design, engineering, cost and performance analysis, and scale-model testing. We have studied structural design aspects of stretched membranes and support structures, including analysis of linear and nonlinear deformation, buckling of the support frame, thermal mismatch considerations, wind spillage effects, and the optimal strength and sizing of the membrane's support structure. Several stretched-membrane concepts have been costed. We have also designed and fabricated a number of bench-scale and field-test-scale hardware elements, including two prototype concentrators 2 m in diameter and a potentially low-cost two-axis tracking support base (see Figure 2-1); seven stretched-membrane reflective modules of various designs 1 m in diameter, which were tested for optical accuracy using a SERI-designed laser ray trace instrument test bed; and a reflector 3 m in diameter based on a commercial trampoline as an initial prototype [15]. We also tested a number of mechanisms for attaching membranes to support structures that are appropriate to either low or high production levels and evaluated seven candidate metallized polymers as potential reflective surfaces for stretched-membrane and other innovative concentrators [35].

2.2. DESIGN, FABRICATION, AND ATTACHMENT APPROACHES

A number of findings on pretensioning, attachment, and support concepts emerged during this investigation of design approaches. First, membrane tension can be achieved by means of several approaches, including thermal expansion mismatch during assembly, mechanical ring or frame compression, mechanical membrane tension, and simultaneous mechanical ring or frame compression (see Figure 2-2) and membrane tension. Cable tensioning on the perimeter of the membrane offers yet another approach. Models 0.7 m in diameter* that employed each of these tensioning methods (except the thermal mismatch approach) have been fabricated and will be discussed further later on. While thermal mismatch approaches may turn out to be most effective in mass-production factory assembly, they are not easily accomplished in the laboratory. A specific finding that emerged from the analysis of thermal mismatch approaches is that, when we are considering membrane support frame structures, the coefficients of thermal expansion of the membrane and support ring should be fairly close for most practical applications.** 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 in mass-production applications.

---

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

**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%.

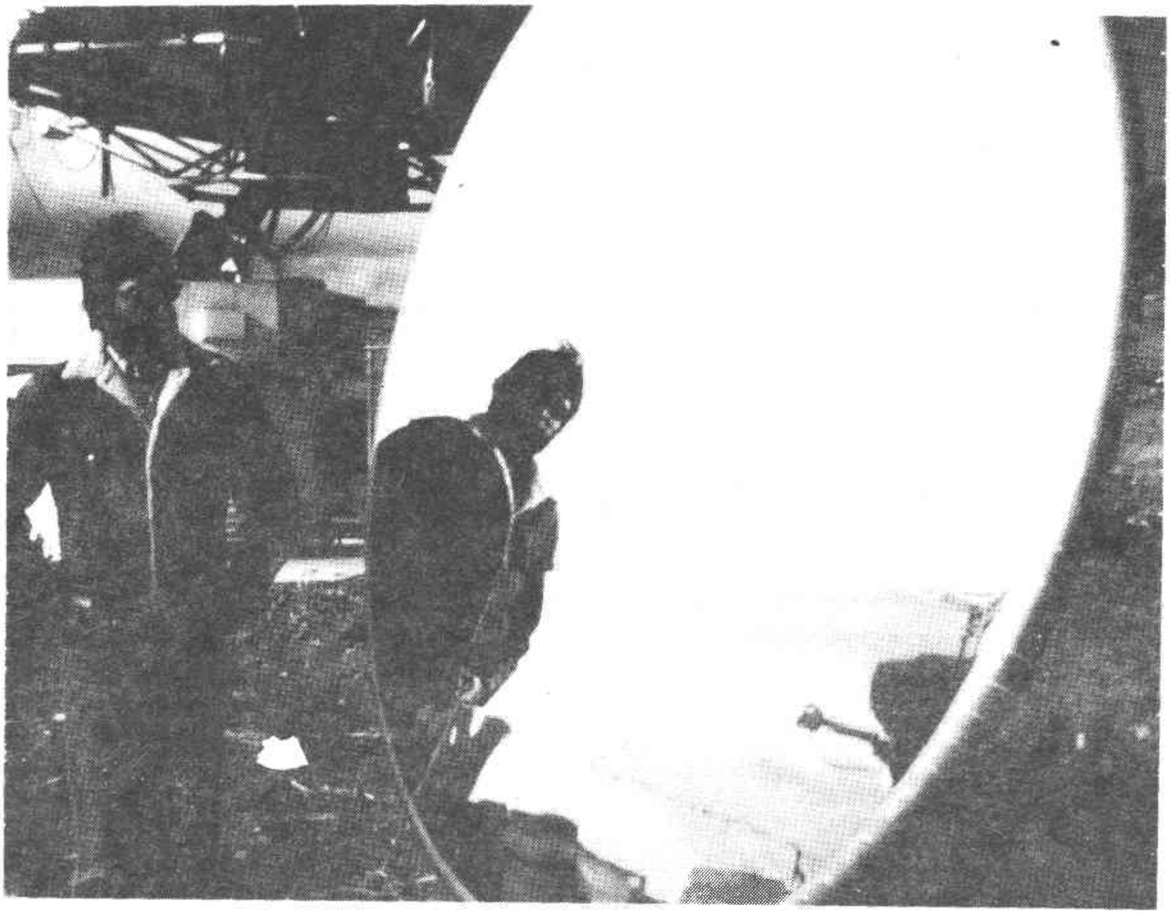

Figure 2-1. 2-m-Diameter Stretched-Membrane Heliostat Research Experiment at the SERI Test Site

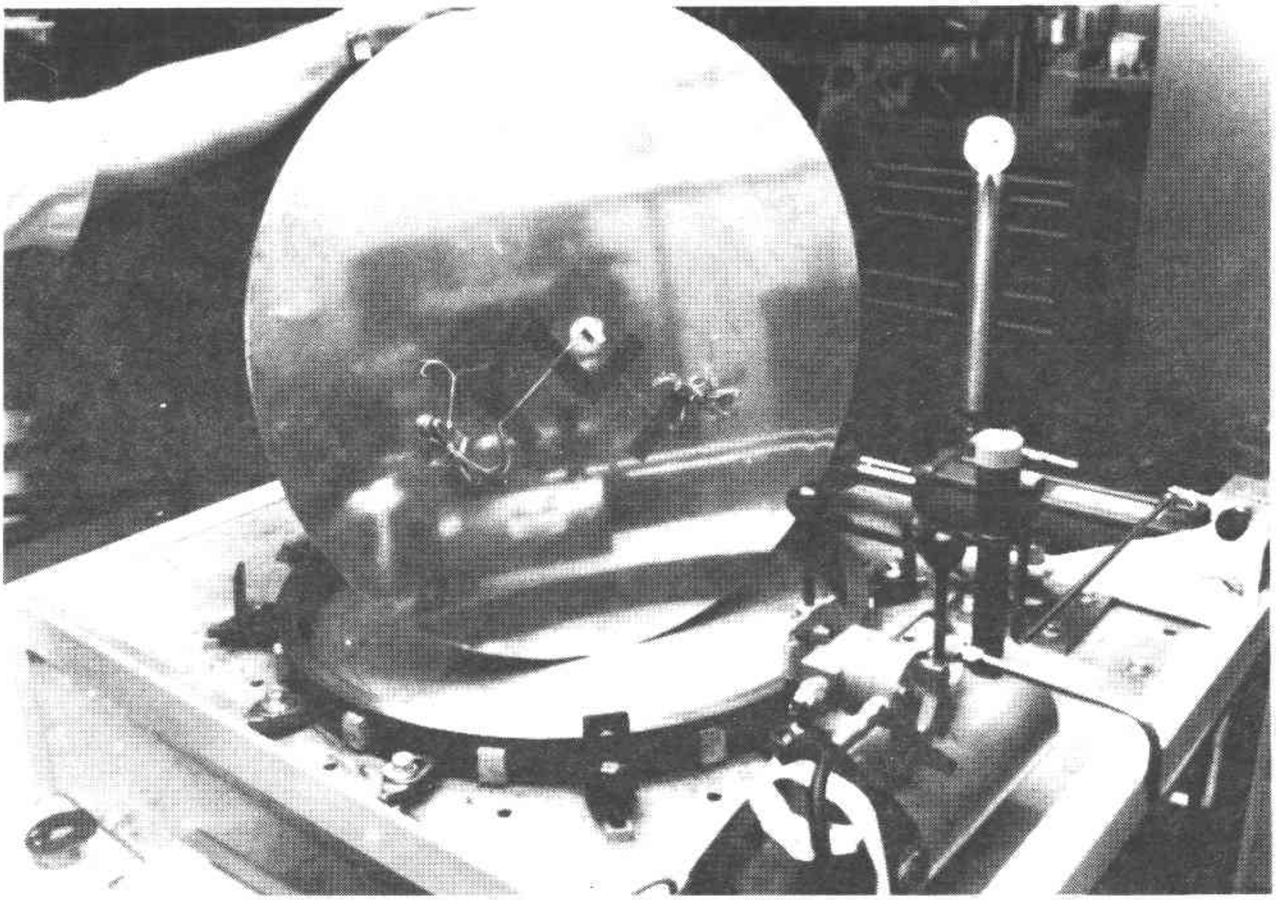

Figure 2-2. One of Several Bench-Scale (0.7-m-Diameter) Membrane Modules Fabricated Using the Ring Compression Table
(In this case, an aluminum membrane is bonded to the support ring while the ring is held in compression. Upon the release of the compression on the ring, the membrane becomes tensioned.)

Next, we found that attachment of the membrane to the support frame can be accomplished in a number of ways; clamping, bonding, and welding procedures were all tried on a laboratory scale (0.7-m-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 12250 to 26270 N/m (70 to 150 lb/in.) [26]. 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.

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, though membrane change-out is most easily accomplished with this concept.* One other mechanical attachment approach, suggested by the Budd Co. [24], 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, it 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 possibly bring costs for the bonded approach more into line with welding costs. Furthermore, the adhesive approach may require less development than we would need for welding the thin membrane while it is under tension stress. Initial tests with welds of metal membranes to support frames were unsuccessful because the thin membrane became warped and distorted (the same 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.

Two other novel attachment and support approaches have been investigated that do not require welding or bonding of the membrane to a rigid support ring. The first is a ring/bladder structural support and tensioning approach that has been used to fabricate a number of 0.7-m-diameter modules and one of the 2-m-diameter reflective modules. This approach allows not only easy assembly but it also results in a very uniform tension that can easily be varied. Furthermore, thermal expansion mismatch effects would also be greatly mitigated by the flexibility of the bladder/ring outer face. This approach has been combined in several models with the laminated membrane concept, discussed later on, which permits variable focus and has been found to be a very attractive approach for laboratory and possibly even field fabrication. A second novel attachment concept

---

*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.

employs a tensioned cable suspension system mounted on a structural support frame;* it is currently being investigated for patentability.

The question of whether to form very wide single-piece or joined membrane surfaces has also been addressed. While metals of the extremely thin gages needed are often readily available only in widths up to about 1 m, polymer fabrication techniques appear to be already currently adaptable to forming wide films. Initial metal prototypes built by SERI have employed bonding with lap joints for seaming purposes. In the long run, however, other, more effective approaches are both desirable and possible. One approach to making wide metal membrane films of uniform thickness which may prove attractive is electroplating. The Budd Co. uses an electroplating concept [24] in which a metal film of arbitrary thickness is deposited on a rotating drum that is partially submerged in an electrolytic bath. The strength characteristics are also fairly easily altered with this concept by varying the chemistry of the bath. Another approach to making wide metal films is to use parallel metal strips with laser welds. SERI's small sample laser weld tests were quite encouraging in this regard, and this process is apparently already in use in Germany [25]; it is said to be suitable for field applications.

A variable-focus, stretched-membrane, composite reflector concept has been under development for some time. Focusing is achieved by means of 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. In addition to focusing, two other benefits can be attained with this approach. The first is that changing the tension at the attachment to the support frame can vary the focus. The second, possibly very important, feature is that a thin layer of glass on the front surface can be used so that focusing will still occur and the glass will be kept in compression. A wide range of material properties and thicknesses, subject to thermal expansion compatibility constraints, are potentially acceptable for the substrate. Several 0.7-m-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 2-3 illustrates the focusing capability of one of the bench-scale, 0.7-m-diameter composite reflector modules. 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. The extent to which this effect can be exploited is still under investigation.

2.3 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 from

*The GE stretched membrane uses a somewhat related support frame concept with attachment at only eight small strips spaced uniformly around the circumference of the stretched membrane.

Figure 2-3. Focusing Capabilities Corresponding to the Two-Laminae (0.7-m-Diameter) Stretched-Membrane Reflector Model Being Demonstrated
(The reflective surface is FEK-244 and the laminated membrane is a steel/ aluminum sandwich.)

the nominal plane of an 8-m-diameter ring. Then, for an 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 milliradian (mrad). Hence, for the larger modules, anticipated to be of most interest, 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, it is felt that very accurate surfaces can be attained. 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 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), optical measurements made with the SERI laser ray trace instrument (see Figure 2-4) resulted in 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, however, and it is readily demonstrated that for heliostats there is a need to focus large, single-piece reflector surfaces.* In addition, for a given deviation from perfect focus, the refected image size at the receiver will vary as the slant range (the distance from the heliostat to the receiver). Hence, the need for good focusing capability is more pronounced at larger plant sizes, which in turn necessitate larger field sizes. Note that the enclosed heliostat designs have relied on gravity focusing [10,11], 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-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 on the order of 12250-26270 N/m (70-150 lb/in.), depending on size and design [26].

There are a number of 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-laminate approach discussed earlier [see Figure 2-3, in which the focusing capability of a double-laminae stretched-membrane scale (0.7-m) module is demonstrated]. The vacuum approach for thermal dishes has been suggested or employed by a number of DOE contractors and commercial organizations [16,19,20,25,27]. Koshalm's work is noteworthy [25] because vacuum-induced plastic deformation of the membrane is used to form the reflective surface, while in Bracewell and Price [28], a pressurization technique is used 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 [29]. All of these approaches produce a shallow, spherical surface that quite closely approximates a parabolic surface. The relative surface-quality merits of these various approaches are yet to be assessed. Specifically, the major advantage of the active vacuum focusing

*A recent study on enclosed heliostat concepts with low effective reflectivity for the baseline 30-MW_t plant studied showed that perfectly flat reflectors delivered on the average 35% less energy than perfectly focused collectors [7].

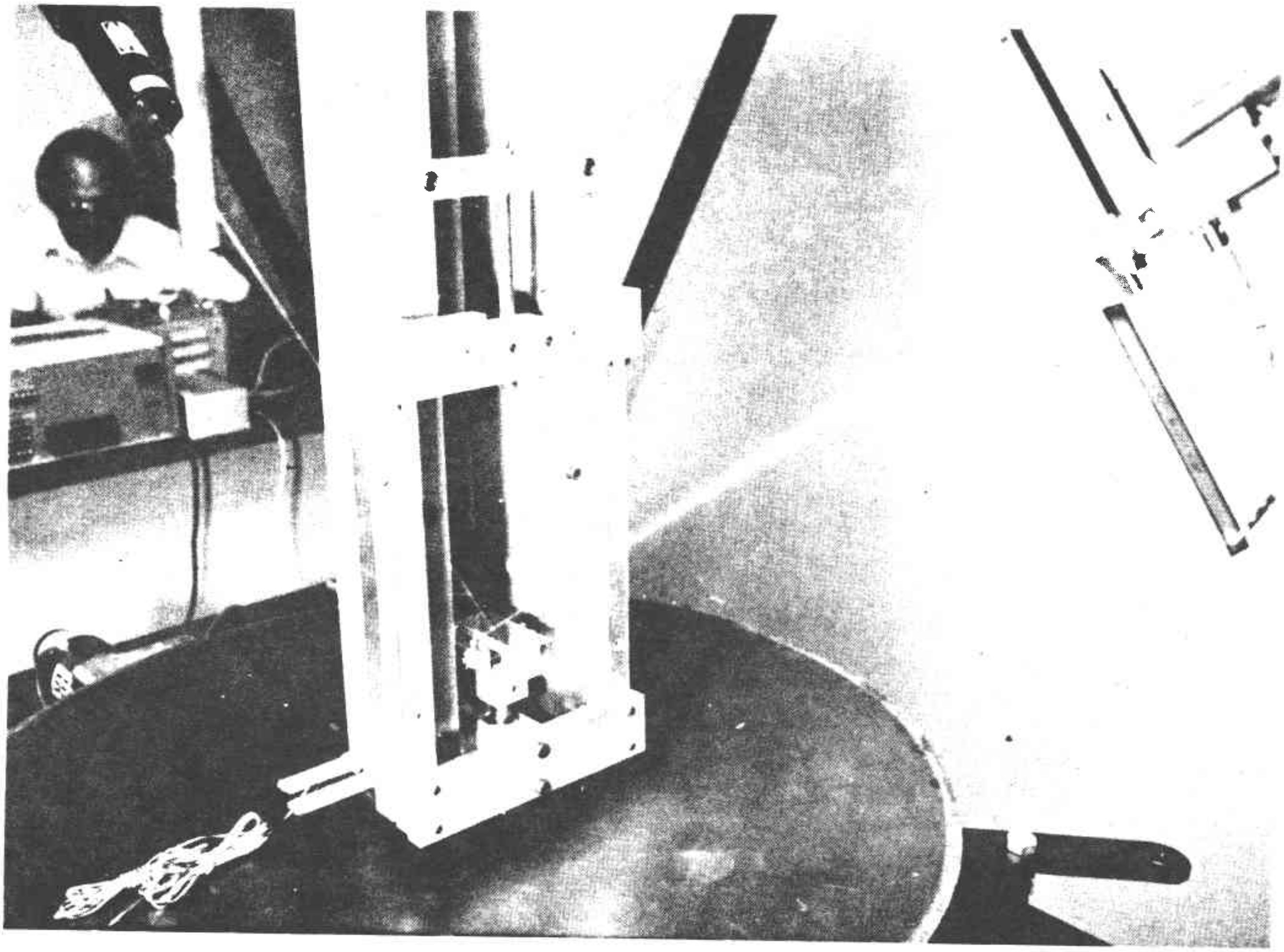

Figure 2-4. Surface Quality Measurements Being Made on a 0.7-m-Diameter Stretched-Membrane Reflector Module with the SERI Laser Ray Trace Instrument

approach for unenclosed heliostats is its potentially better adaptability to wind environments. Its extra pumping elements, control, power consumption, service life, and maintenance must be traded off against the simplicity of the laminated curved-membrane approach which we discussed earlier. A structural evaluation of the curved laminated-membrane concept is currently being carried out [30], as well as a more general structural and optical analysis of the concept relating to both single- and double-membrane concepts [26,31].

The effect of wind and weight loading on the optical quality of the surface of a tensioned membrane can be estimated by determining the rms surface normal error for a given assumed loading condition and corresponding deformation. Figures 2-5 and 2-6 illustrate the results of wind and solar insolation correlations [32] along with, for comparision purposes, the effect of wind loading on rms surface errors. Shown in Figure 2-5 is 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, 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 17500 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. The wind-insolation correlation in the same figure is the cumulative fraction of insolation available for all wind velocities up to the level specified.

Figure 2-6 presents the same rms surface error information as Figure 2-5, but the wind-insolation correlation there is the fraction of insolation available at a given wind velocity. This pair of curves illustrates two main points. The first is that wind-loading deformation degrades the optical quality of the stretched membrane very little at low velocities, and the second is that 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. Note that the example in Figures 2-5 and 2-6 potentially represents an upper estimate for expected energy loss, since the relative directions for the wind and heliostat orientation were selected to be close to the worst possible case (i.e., corresponding to maximum pressure loading). A rear-surface wind screen is anticipated to be capable of partially alleviating the back-loading problem. Furthermore, some aerodynamic approaches currently being investigated could significantly reduce the load normally anticipated on the reflective membranes.

2.4 STRUCTURAL BEHAVIOR OF MEMBRANES AND SUPPORT STRUCTURES

For the range of membrane materials, tensions, and sizes under consideration that are required for optical accuracy, the stretched membranes behave in a linear manner. That is, for the linear case, the membrane tension remains very nearly constant (equal to the pretension) 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 (due to 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 of interest are sufficiently

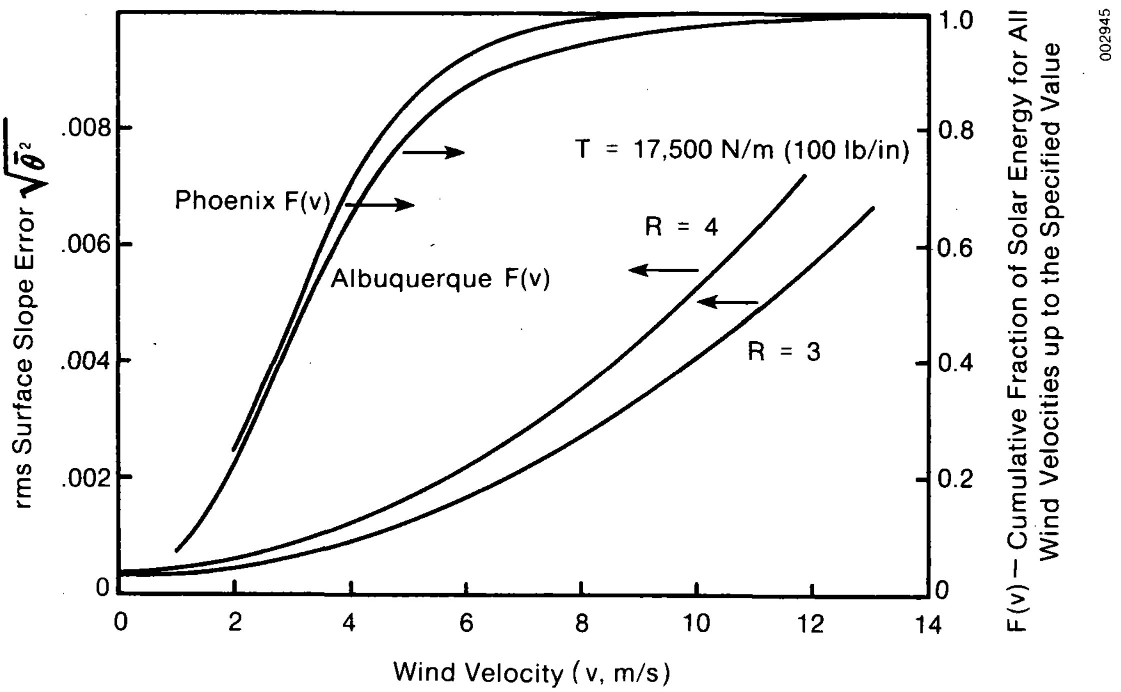

Figure 2-5. RMS Surface Slope Error Caused by Wind- and Weight-Induced Membrane Deformations, and Cumulative Fraction of Available Solar Energy as a Function of Ambient Wind Velocity
(Cumulative fraction of solar energy is the total fraction of solar energy available for the range of wind velocities up to the specified level. Design conditions are noted in the figure. Wind-insolation correlation data are from Ref. 32 and weight-induced deformations are assumed to be relative to the perfect desired surface.)

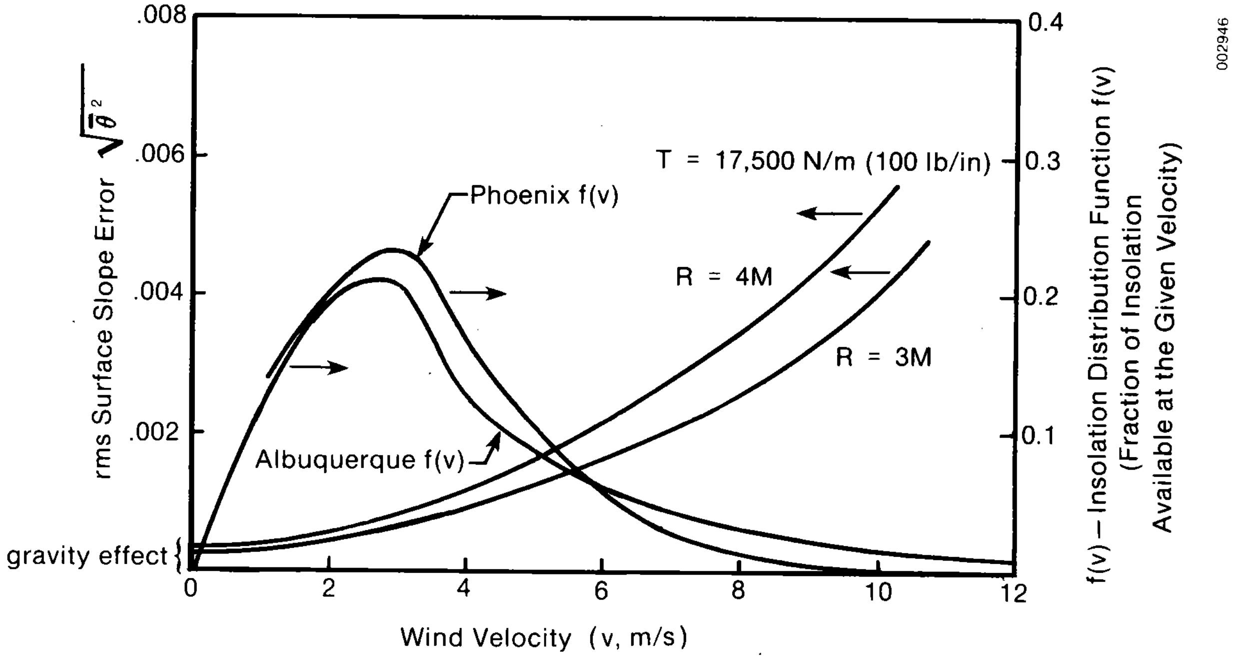

Figure 2-6. RMS Surface Slope Error Caused by Wind- and Weight-Induced Membrane Deformations and Fraction of Insolation Available at a Given Velocity. (Both are a function of velocity. See also the notes in Figure 2-5.)

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 Figure 2-7.

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 even more mass and cost reductions. The most effective support frame designs from a material-use perspective have been found to be toroidal shell shapes that carry the membrane-induced radial loads in compression rather than in bending and/or torsion. Thus, whenever possible, the membrane should not load the frame eccentrically, causing moments about the cross-section shear center.* The author is not aware of any advantage to be gained from 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-shaped frames, although they permit 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 that the resulting frame and membrane assembly permits uniform membrane tension, are more complex than for the circular shape. The packing factor advantages do not appear to outweigh the material and weight requirement disadvantage. The shape of the most effective toroid cross section was found to be generally noncircular and to require an out-of-plane bending moment of inertia at least 50% 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, it is felt 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 the failure mode of deformation. Out-of-plane, support-ring stability is a somewhat more complex phenomenon, but similar arguments can be made about the membrane potentially enhancing stability. Note that tests on small-scale rings (0.7 m in diameter) have indicated 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.

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, that 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 (1) packing the toroidal cavity with foam and (2) pressurization. Furthermore, pressure-stiffened tubular structures for the support struts as well as for the membrane support ring appear from preliminary analysis to have significant potential merit. Finally, high-strength nonmetallic materials such as carbon fiber composites may offer advantages in stretched-membrane frame design; composites, too, will be studied later in the development process.

---

*In some situations, it has been found that the required frame-wall thickness (and, thus, the frame weight) can increase by a factor of three if the frame is loaded eccentrically rather than through the shear center of the ring cross section [33].

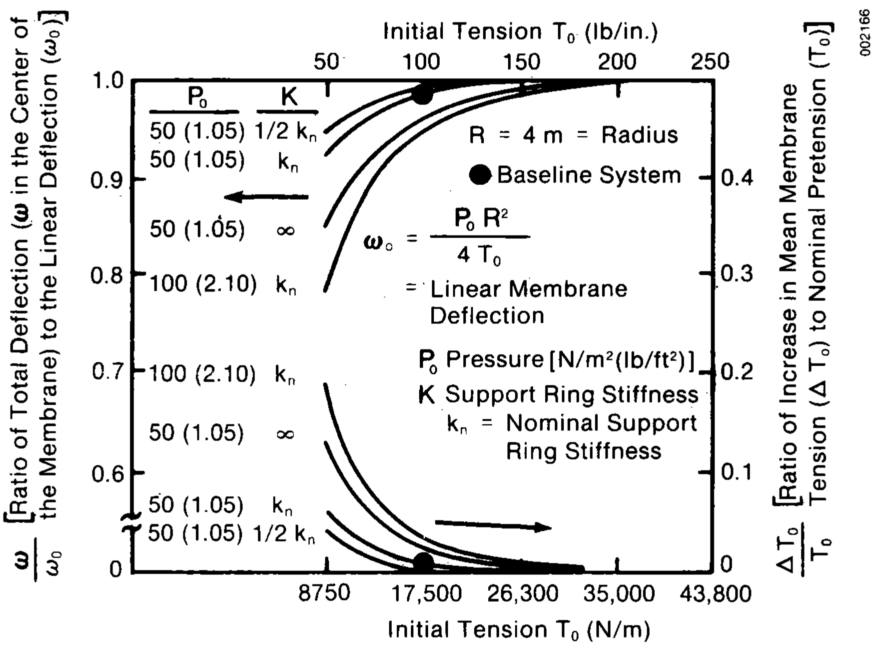

Figure 2-7. Membrane Center Deformation Ratio and Fractional Tension Increase as a Function of Initial Membrane Tension for Several Pressure Loadings and Support Ring Stiffnesses
[The deformation ratio corresponds to the total nonlinear membrane deformation divided by linear membrane deformation (both measured in the center of the membrane). A pressure loading of 50 N/m^2 corresponds to the approximate maximum loading from a 9-m/s wind.]

SERI

SECTION 3.0

MATERIALS DESIGN AND COST TRENDS

The stretched-membrane structural designs that have been studied from a performance and cost perspective are quite light in comparison with other designs. The mass for these initial designs* (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/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 Figure 3-1. The heliostat's weight (this includes the drive and pedestal down to the foundation) per unit area of reflective surface for six designs (and three concept generations) is shown as a function of time. The general trend has been for weights to drop dramatically over time. In addition, the potential for further weight reductions appears significant; this will be the focus of future studies.

It is also important to note from the analyses performed to date that the support frame offers the most significant opportunity for mass and cost reductions. In the preliminary unoptimized designs studied to date, the frame is 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/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 for low-production scenarios (5-100 units) and about \$20/m^2 for high-production scenarios (25,000 units). Corresponding high-production-level costs for second-generation glass/metal heliostats are about \$55/m^2.

Figures 3-2 through 3-5 provide a sense of the design effects that impact weight and cost trends, and to point out how further improvements might be made. A specific design point is assumed in these curves.¶ For the applied design wind- and weight-loading, Figure 3-2 illustrates how the required membrane tension, corresponding to a maximum permissible curvature change (two levels are given) varies with the operating-stress/weight (of the membrane). The working stress/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/weight ratios, most of the tension goes into supporting the

---

*The geometric parameters for the design discussed here correspond to a circular reflector with a nominal radius of 4 m and a membrane thickness of 2.54×10^{-4} m. A polymeric reflective surface is also assumed.

**See the Appendix for a description of the concept and the costing work that corresponds to these estimates.

¶The 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).

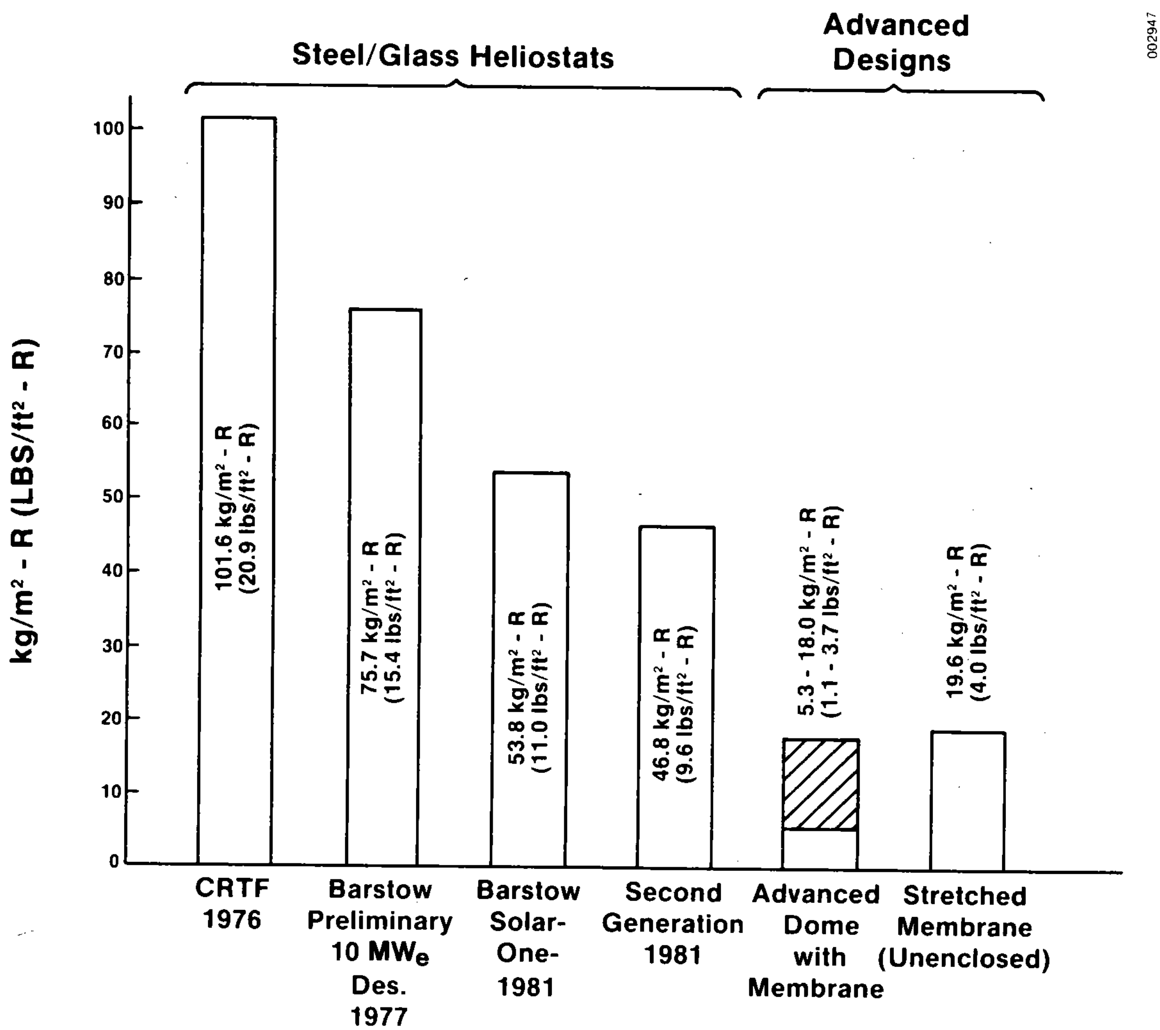

Figure 3-1. Weight Evaluation of Prior and Current Heliostat Concepts (Here, the real weights are presented per unit net effective reflectivity R. The cross-hatched area represents a range of estimates.)

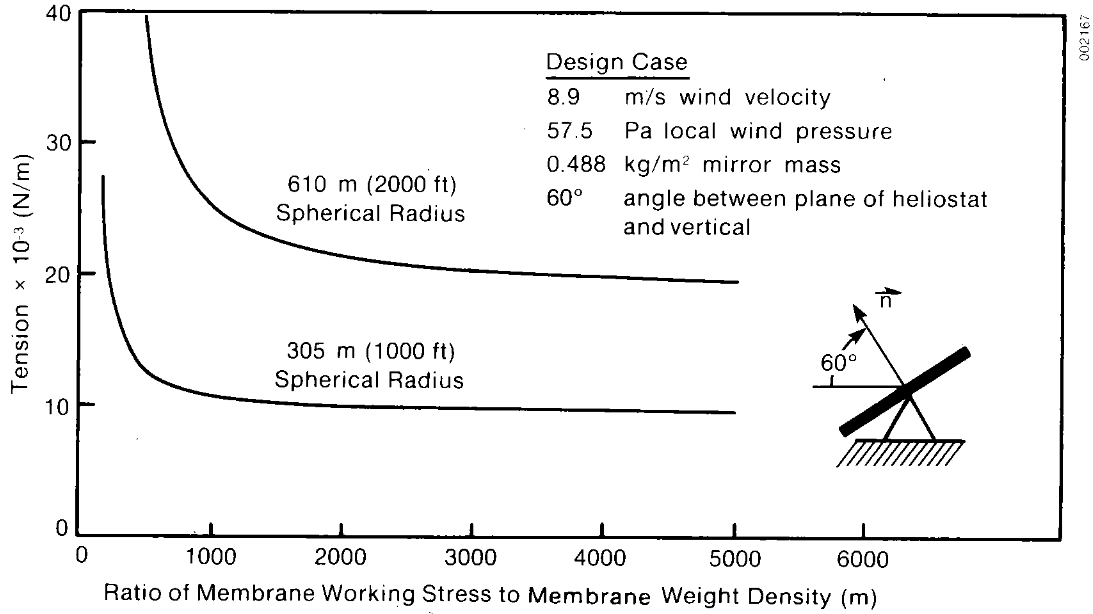

Figure 3-2. Required Membrane Design Tension as a Function of the Operating Stress/ Weight Ratio (Corresponding to the design case. See note in the figure. For a specified wind- and weight-induced loading, the tension is the level required to limit the corresponding curvature change in the membrane to the value indicated.)

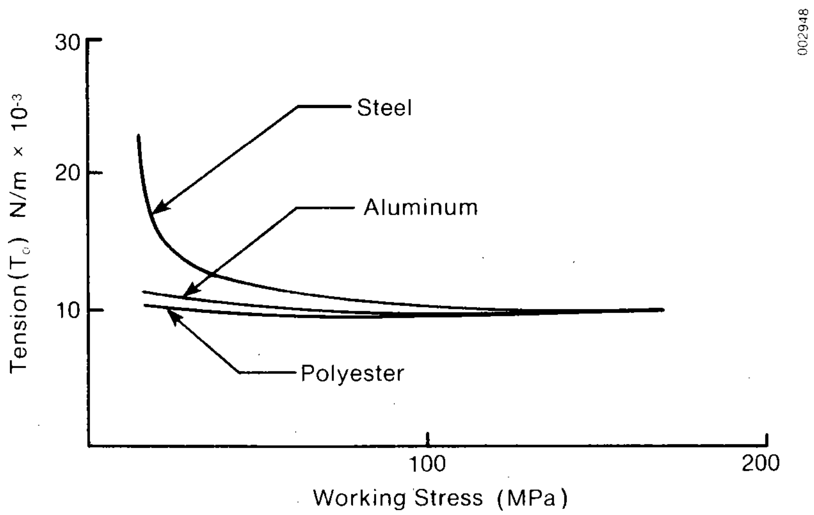

Figure 3-3. Required Membrane Design Tension as a Function of Membrane Working Stress for Several Membrane Materials [Corresponding to the design case shown in Figure 3-2. The radius of curvature is the 305-m (1000-ft) case. The abscissa in this figure is simply the abscissa in Figure 3-2 multiplied by the weight density.]

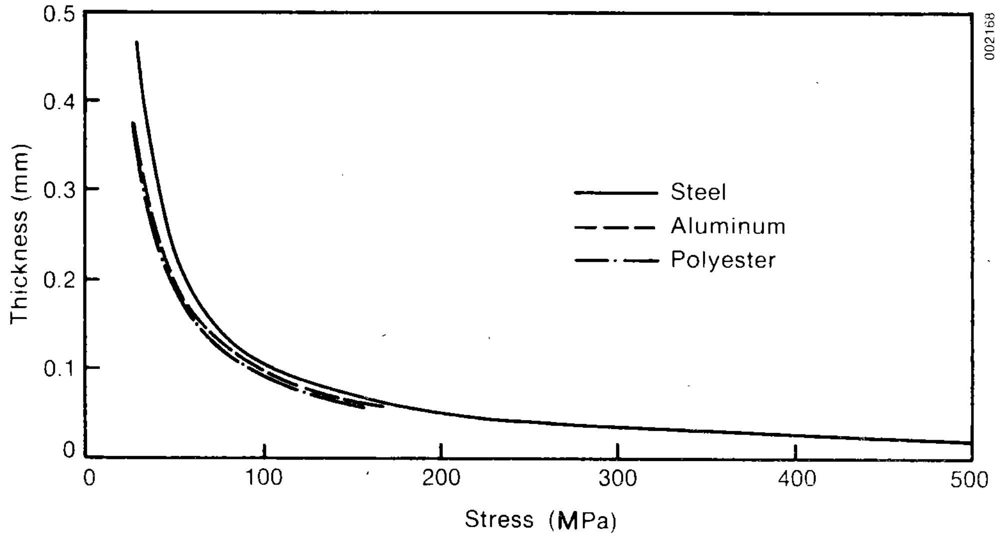

Figure 3-4. Membrane Thickness as Function of Working Stress for Several Materials (Corresponding to the design case shown in Figure 3-2.)

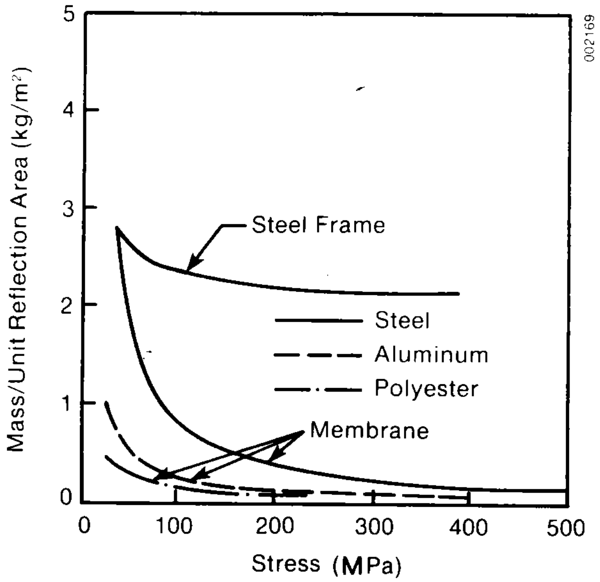

Figure 3-5. Membrane and Support Frame Mass for Several Materials per Unit Reflective Area as a Function of Working Stress (Corresponding to the design case shown in Figure 3-2.)

material weight, while at higher operating-stress/weight ratios, a constant tension is approached that corresponds to supporting the wind loading (the material weight becomes negligible). In Figure 3-3, the same required tension 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 corresponding thicknesses of the materials depicted in Figure 3-3 are shown in Figure 3-4. It is apparent that in order 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. It is interesting to note in this context that polymer materials may offer the best combination of low tensions and fairly low working stresses. This tendency to favor thinner materials is, of course, only justified up to a point. Little benefit is gained once the knee of either of the curves in Figures 3-3 and 3-4 is passed. 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. It is in this area of very light, optimally designed membranes that high-strength polymers would appear to have significant potential. Not only can they be used efficiently in the range of tensions of interest but they are easily (and currently) manufactured in the required thickness range.

The trend in the weight of stretched-membrane systems is seen in Figure 3-5; here, the weight per unit area is plotted as a function of working stress in the membrane.* 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 effect, the tension on the membrane dramatically affects the mass, and therefore, the cost.** Initial lightweight designs can, in theory at least, be lightened further. Just how much the mass can be reduced will be the subject of future study.

Numerous materials 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 ([34], for example), seven candidate metallized polymers were evaluated for possible application on metallic or other structural membranes. Candidate metallized polymers included configurations employing acrylics, Teflon, silicates, and polycarbonates [35]. 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, only the optical aspects were studied in the initial effort. Results of this study are currently being documented [35].

Candidate samples were exposed to accelerated combinations of heat, relative humidity, pollutants, and ultraviolet 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 exposure. When UV was not present, the samples weathered well. There-

*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.

**The cost here corresponds to the material only.

fore, Masterson et al. recommended that the possibility of a silvered mirror inside a UV screening dome should be explored further [35]. (It is interesting to note that no commercially available silvered polymer reflector has been developed yet that is specifically intended 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 effects further. Thus, humidity and pollution, which were found not to be important in the absence of UV in the first series of tests, are being omitted in the current round of tests.

SECTION 4.0

CONCLUSIONS AND RECOMMENDATIONS

Numerous design challenges and development issues remain to be resolved in regard to 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 by means of a low-cost, two-axis tracking platform.

One important point that should be reemphasized here is that the cost benefit inherent in the stretched-membrane concept derives pirmarily from the large weight reductions that appear to be attainable. It is worthy of note that the cost per unit weight predicted for this concept is somewhat higher than that generally accepted for the second-generation heliostat concept. Hence, the predicted costs for the stretched-membrane concept presented here appear quite attainable, and even further reductions may be achieved in the future. This is 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.

From structural analysis and testing performed to date, it appears feasible to build stretched-membrane concentrator modules (down to the drive attachment) that are more than four times lower in weight than, and roughly one-half the cost of, second-generation glass/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/performance improvement over the second-generation glass/metal designs, much development work still remains to fully verify and realize that potential. A closely coordinated industry and laboratory development effort is recommended, therefore. In terms of system cost/performance, more detailed costing and production analyses are warranted and detailed comparisons, where the cost of delivered energy on an annual basis is used as the figure of merit, with second-generation heliostats are needed. 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 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 materials 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 materials issues include possible cost reductions through the development of polymer mirror laminates and polymer composite structural elements (i.e., the frame).

In terms of mechanical/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, the in-plane stability question, relating to the main support ring, needs further investigation, and the applicability of structural-stability scaling relationships must be verified through the testing of increasingly larger hardware elements. Furthermore, snap-through ("oil canning") of laminated, curved membrane reflectors and aerodynamic load-reduction schemes for the reflector assembly should be studied.

SECTION 5.0

REFERENCES

1. Edelstein, R.; et al. February 1982. Final Presentation of the Solar Thermal Cost Goals Committee. Presented to the U.S. Dept. of Energy, Washington, D.C., February 26, 1982.

2. Edelstein, R. B. August 1981. "Value-Based Costs for Advanced Solar Thermal Systems." Review of Polymer Requirements for Solar Thermal Energy Systems. Proceedings of a workshop sponsored by DOE and SERI, Alexandria, VA. SERI/CP-251-1419. Golden, CO: Solar Energy Research Institute; pp. 75-110.

3. Thornton, J.; et al. August 1980. Final Report: A Comparative Ranking of 0.1-10 MWe Solar Thermal Electric Power Systems, Volume 1, Summary of Results. SERI/TR-351-461. Golden, CO: Solar Energy Research Institute.

4. Second Generation Heliostat Evaluation—Summary Report. January 1982. SAND 81-8024. Livermore, CA: Sandia Livermore Heliostat Division, Sandia National Laboratories. Note that this report estimates second-generation heliostats to cost $\$110/m^2$ in 1980 dollars; expressed in 1982 dollars this cost is $\$126/m^2$.

5. Robbins, Claude; Hunter, Kerri. November 1982. Personal Communications. Solar Energy Research Institute, Golden, CO. (303) 231-7060. The use of heliostats for daylighting is currently being evaluated with a small-scale experiment at the SERI test site that is aimed at determining a cost/performance value that will make such an application cost-effective.

6. White, Art. November 1982. Personal Communication. Arco Solar, Woodland Hills, CA. (213) 700-7383.

7. Copeland, R. J. November 1982. Personal Communications. Solar Energy Research Institute, Golden, CO. (303) 231-1012.

8. McDonnell Douglas Astronautics Co. May 1982. Optimization of the Second Generation Heliostat and Specification. Contractor Report MDC 9762, Sandia Report SAND 82-8181. Prepared for Sandia National Laboratories, Livermore, CA.

9. Martin Marietta Corp. May 1982. Second Generation Heliostat Optimization Studies. Contractor Report MEK-82-1700, Sandia Report SAND 82-8275. Prepared for Sandia National Laboratories, Livermore, CA.

10. Solar Central Receiver Prototype Heliostat, Phase I, Final Technical Report. October 1978. SAN-1468-1. Schenectady, NY: The General Electric Co.

11. Solar Central Receiver Prototype Heliostat, Vol. I, Final Technical Report. June 1978. SAN/1604-1. Seattle, WA: Boeing Engineering and Construction Co.

12. Gillette, R. August 1981. "Heliostat Environmental Protective Enclosures." Review of Polymer Requirements for Solar Thermal Energy Systems. Proceedings of a workshop sponsored by DOE and SERI, Alexandria, VA. SERI/CP-251-1419. Golden, CO: Solar Energy Research Institute; pp. 277-326.

13. Murphy, L.; et al. October 1982. A Systems Study of the Polymer/Enclosed Heliostat and A Comparison with Glass/Metal Heliostats. SERI/SP-253-1791. Golden, CO: Solar Energy Research Institute.

14. Meinel, A. B. and Meinel, M. P. 1976. Applied Solar Energy—An Introduction. Reading, MO: Addison-Wesley Publishing Co. p. 245.

15. Dolan, J.; Butler, B. January 1980 to the present. Personal Communications. Solar Energy Research Institute, Golden, CO. (303) 231-7267. Under Barry Butler's direction, Jim Dolan initiated the development of the first conceptual model to demonstrate a configuration of a stretched membrane in October 1979. The concept was demonstrated in a large-scale experiment first in 1980 at SERI when glass tiles were mounted on a 3-m-diameter trampoline structure.

16. Brumleve, T. October 1981 through December 1982. Private Communications. Sandia National Laboratories, Livermore, CA. (415) 532-2941. Tom notes that SNLL's development effort was initiated in 1980.

17. Mavis, C. L.; et al. Forthcoming. A Description and Assessment of Solar Central Receiver Systems Technology. SAND 82-8023. Livermore, CA: Sandia National Laboratories.

18. A Conceptual Design Study of Point Focusing Thin-Film Solar Concentrators. November 1981. Final report for the Jet Propulsion Laboratory. Seattle, WA: Boeing Engineering and Construction Co.

19. Jaffe, L.D. Dish Concentrators for Solar Thermal Energy: Status and Technology Development. DOE/JPL-1060-48. (JPL Publication 81-43). The Jet Propulsion Laboratory. Pasadena, CA: California Institute of Technology.

20. McGlaum, Monte. April 1982. Personal Communication. Lajet Energy Co. Abilene, TX. (915) 969-8800.

21. Thostesen, J. August 1981. "Point-Focus Concentrator for Development Status." Review of Polymer Requirements for Solar Thermal Energy Systems. Proceedings of a workshop sponsored by DOE and SERI, Alexandria, VA. SERI/CP-251-1419. Golden, CO: Solar Energy Research Institute; pp. 137-246.

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

23. Laterally Loaded Drilled Pier Research. Vols. 1 and 2. January 1982. EPRI EL-2197. Prepared by GAI consultants. Palo Alto, CA: Electric Power Research Institute.

24. Dickhart, W. June 1982. Personal Communications. June 1982. The Budd Co., Fort Washington, PA. (215) 643-2950.

25. Khoshalm, B. H. 1983. "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). Sheraton Inn Lakewood, Lakewood, CO, April 11-14, 1983.

26. Murphy, L.; Sallis, D. Forthcoming. Structural Design and Cost Perspectives for Stretched-Membrane Heliostats. Technical report in preparation. Golden, CO: Solar Energy Research Institute.

27. Photovoltaic Concentrator with Plastic Film Reflector. Final Report. November 1981. Contract No. 13-5060. Seattle, WA: Boeing Engineering and Construction Co.

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

29. Gillette, Roger. October 1982. Personal Communications. Boeing Engineering and Construction Co., Seattle, WA. (206) 575-5474.

30. Murphy, L. Forthcoming. Structural Load and Deformation Analysis of a Variable-Focus Laminated-Membrane Reflector. Technical report in preparation. Golden, CO: Solar Energy Research Institute.

31. Brumleve, T. D.; Napolitano, L. Forthcoming. Conceptual Design and Analysis of a Prestressed Membrane Heliostat. Report in preparation. Livermore, CA: Sandia National Laboratories.

32. Randall, P. E.; Grandjean, N. R. April 1982. Correlation of Insolation and Wind Data for SOLMET Stations. SAND 82-0094. Albuquerque, NM: Sandia National Laboratories.

33. Sallis, Dan. October 1982. Personal Communication. Dan-ka Products, Denver, CO. (303) 825-1063. Dan has supported the development of the concept by means of numerous consultations and analyses during this project.

34. Boeing Engineering and Construction Co. July 1980. Plastic Film Performance Improvement for Heliostats. Final Report. Prepared for Sandia Laboratories, Livermore, CA, under contract 83-0035D (SAND 79-8185), Seattle, WA.

35. Masterson, K.; et al. Forthcoming. Reflectance of Selected Metallized Polymer Films Subjected to Accelerated Exposures. Golden, CO: Solar Energy Research Institute.

36. Jorgensen, G. June 1982. "Glazing Survey." Internal Memorandum. Golden, CO: Solar Energy Research Institute.

37. Manufacturing and Cost Evaluation of Second-Generation Heliostats. Vol. I. September 1981. PNL-3967. Richland, WA: Pacific Northwest Laboratories.

SERI

APPENDIX A

COMPARABLE COST ESTIMATES OF SEVERAL VARIATIONS OF A STRETCHED-MEMBRANE REFLECTOR AND SUPPORT SYSTEM: PRELIMINARY COSTING APPROACH

The cost analysis presented in this appendix corresponds to that of a stretched-membrane reflector and support structure, down to the drive attachment. Note that this analysis is preliminary and limited in scope. Because of this limited scope, no independent manufacturing flows were developed, but resulting production-related costs are assumed to be consistent with those developed in more detailed second-generation heliostat cost studies. Material and labor unit prices were, however, derived. Clearly, more detailed costing studies are both warranted and needed as this concept evolves. It is felt, however, that this approach should provide reasonable estimated costs for comparative purposes.

The manufacturing and construction costs of the concept illustrated in Figure A-1 were developed for three levels of production (the prototype, 2500 units per year, and 50,000 units per year). The prototype cost estimate was based on state-of-the-art production methods using unit prices geared to single-unit production. Cost estimates for production rates of 2500 units and 50,000 units per year represent user costs and were based on unit prices for material and labor, which include rolled-up transportation and installation costs. Estimates that correspond to the 2500-unit production rate assume a limited degree of production line sophistication. Furthermore, the material and labor unit prices corresponding to the 50,000-unit production are in quite close agreement with estimates derived in Refs. [4] and [37].* Results of the costing are tabulated in Table A-1. Although these costs appear to be quite low in comparison to comparable costs of second-generation glass/metal heliostats** of $54.50/m^2 ($5.07/ft^2), it is also interesting to compare the cost per unit weight. The corresponding second-generation cost per unit weight is $0.16/N ($0.70/lb). Thus, it is readily seen that the relative advantage of the stretched-membrane system lies in the weight reductions achieved with this concept. Furthermore, because of the simplicity of the concept's design, the current cost estimate might be too high if second-generation glass/metal reflector costs/unit are used as the standard of comparison.

*Note that the Boeing Co., Martin Marietta Corp., McDonnell Douglas Corp., Northrop Corp., and Westinghouse all contributed to the studies in Refs. [4] and [37].

**This corresponds to the average of the two most cost-effective designs, as reported in Ref. [4]. The costs here are in 1982$. Again, the comparison is made only for the reflector and the support structure, down to the drive attachment.

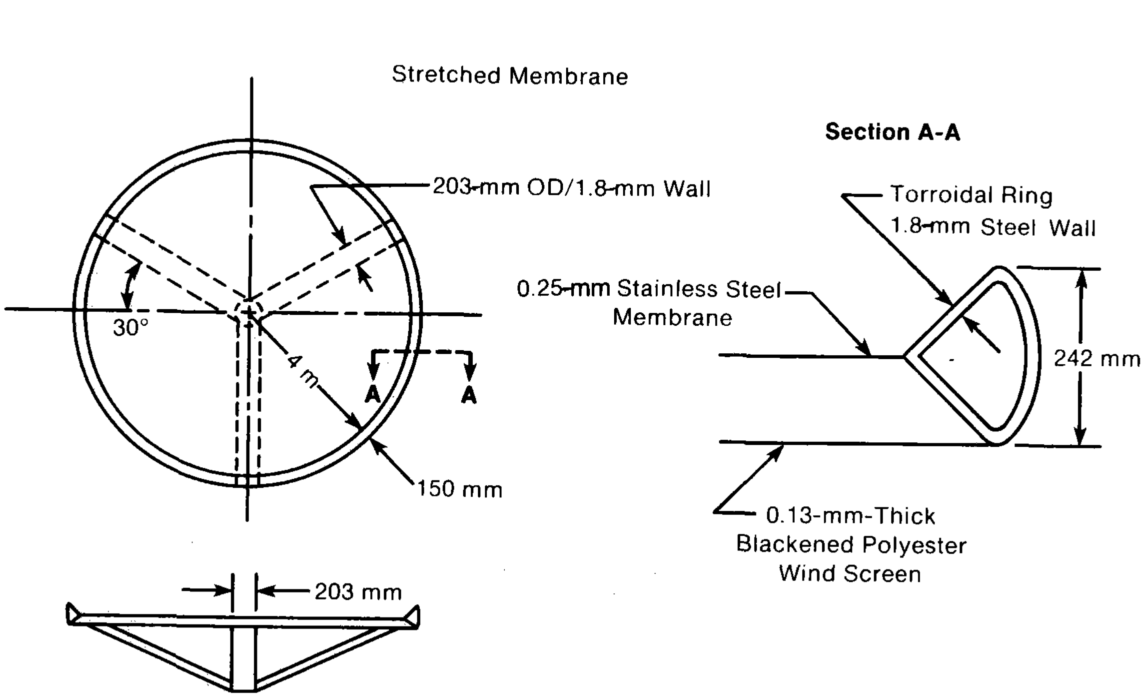

Figure A-1. Full-Size Conceptual Design Stretched-Membrane Reflector and Support Frame (8 m in diameter; used for cost estimates.)

Table A-1. Cost Estimates for Various Reflector/Frame and Support-Strut Options

	Option 1			Option 2			Option 3			Option 4		
Reflector Area = 50.3m^2(541 ft^2) Nominal tension = 17500N/M(100 lb/m)	• Stainless steel membrane • Flat reflector • YS-91 reflector surface • Total weight = • 4030N (906 lb)			• Rust inhibited steel membrane • Flat reflector • YS-91 reflector surface • Total weight = 4030N (906 lb)			• Rust inhibited steel membrane/ 2-layer laminate • Curved laminate reflector • YS-91 reflector surface • Total weight = 4226 (950 lb)			• Rust inhibited steel membrane/ 2-layer laminate • Curved laminate reflector • Thin silvered glass reflector 0.25 mm (0.010 m) thick • Total weight = 4475N (1006 lb)		
Cost Item / Production Rate (No. of Units)	Prototype	2500	50,000	Prototype	2500	50,000	Prototype	2500	50,000	Prototype	2500	50,000
Support Ring ($)		223	152		223	152		223	152		223	152
Membrane ($)		406	276		162	110		139	129		189	129
Reflector ($)		103+	70+		103+	70+		103+	70+		103+	70+
		244	166		244	166		244	166		1082	736
Wind Screen ($)		244	166		244	166		244	166		244	166
Support Struts ($)		76	52		76	52		76	52		76	52
Total ($)	1720	1296	882	1228	1052	716		1079	735		1917	1305
$/N($/lb)	0.43 (1.90)	0.32 (1.42)	0.23 (1.00)	0.30 (1.36)	0.26 (1.16)	0.18 (0.80)		0.26 (1.14)	0.17 (0.78)		0.43 (1.81)	0.29 (1.30)
$/m^2($/ft^2)	34.20 (3.18)	25.7 (2.39)	17.54 (1.63)	24.42 (2.27)	20.9 (1.94)	14.24 (1.32)	—	21.45 (2.00)	14.60 (1.35)	—	38.11 (3.54)	25.94 (2.41)

Document Control Page	1. SERI Report No. SERI/TR-253-1818	2. NTIS Accession No.	3. Recipient's Accession No.

4. Title and Subtitle
Technical and Cost Benefits of Lighweight, Stretched-Membrane Heliostats

5. Publication Date
May 1983

6.

7. Author(s)
L. M. Murphy

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

10. Project/Task/Work Unit No.
1384.30

11. Contract (C) or Grant (G) No.
(C)
(G)

12. Sponsoring Organization Name and Address

13. Type of Report & Period Covered
Technical Report

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)
This report contains a description of (1) a novel, lightweight, heliostat reflective module and support structure called the stretched-membrane concept; (2) anticipated engineering and system benefits of the stretched-membrane concept, and (3) analytical and testing rationale supporting these anticipated benefits. Summaries of prior work and of SERI's effort to date on the concept are also given. Finally, recommendations for further development that will be necessary to realize the full cost/performance potential of the concept are presented. Results indicate that a 75% reduction in the weight of the reflective module and support structure relative to that of second-generation glass/metal heliostats can potentially be achieved. Also, preliminary costing indicates that the stretched-membrane approach could potentially result in per-unit-area costs of ca. $\$20/m^2$ for the reflective module and support structure, compared with about $\$55/m^2$ for the corresponding elements of the second-generation concept. The performance of the stretched-membrane reflective module, assuming it employs a high-quality reflector surface, is anticipated to be close to that obtainable with the second-generation glass/metal heliostat concept.

17. Document Analysis
a. Descriptors Cost ; Design ; Focusing ; Heliostats ; Mechanical Structures ; Performance ; Polyesters ; Polymers ; Solar Reflectors ; Weight

b. Identifiers/Open-Ended Terms

c. UC Categories
58, 61, 63

18. Availability Statement
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

19. No. of Pages
41

20. Price
$8.50

Form No. 8200-13 (6-79)