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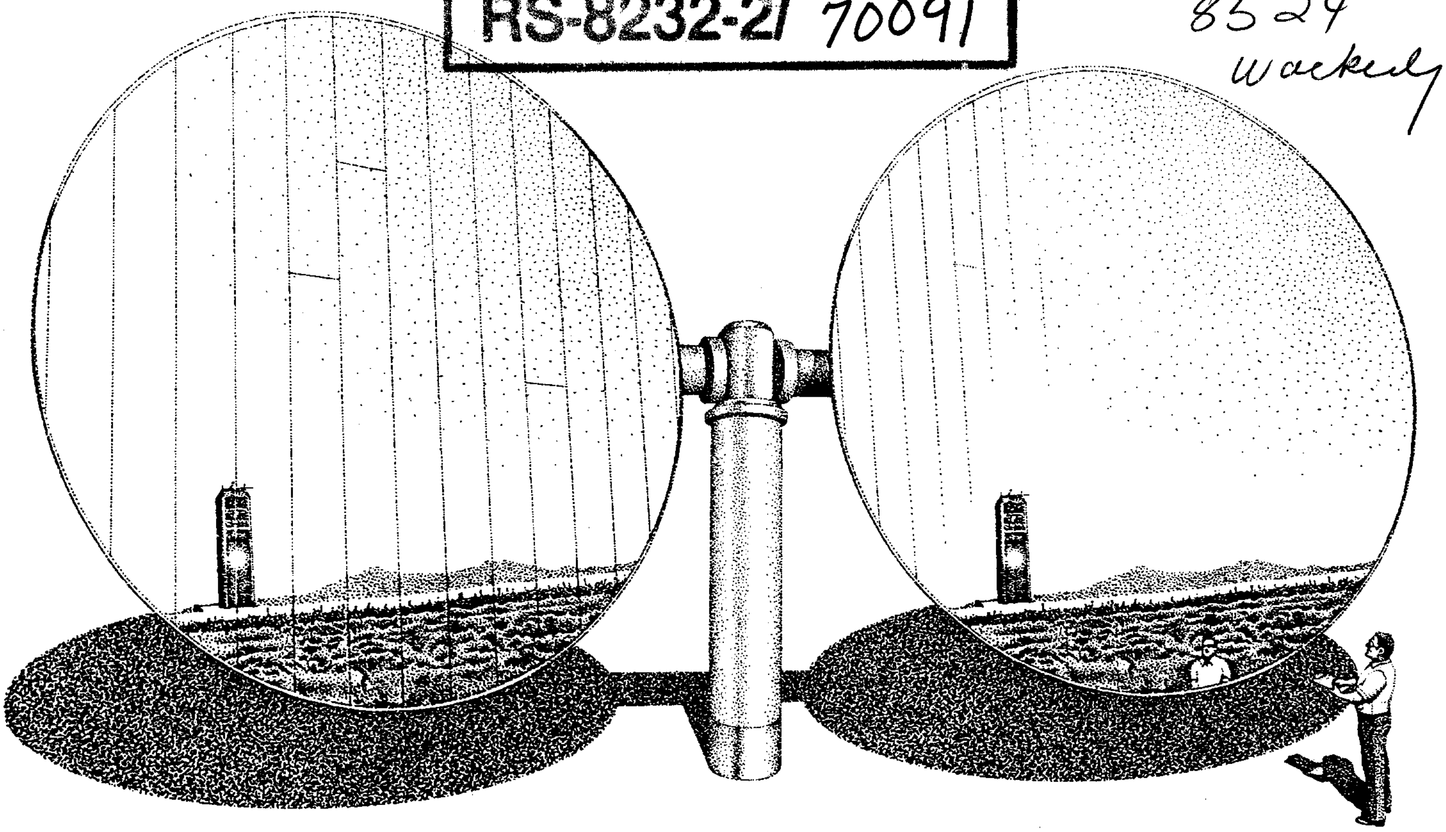

SELECTION AND DESIGN of a STRETCHED-MEMBRANE HELIOSTAT for TODAY'S MARKETS

Science Applications International Corporation

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SELECTION AND DESIGN OF A STRETCHED-MEMBRANE HELIOSTAT FOR TODAY'S MARKETS

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Sandia Contract 5-7867

ABSTRACT

Science Applications International Corporation has designed a complete, integrated stretched-membrane heliostat. The present state-of-the-art is a single-pedestal that does not take advantage of the unique characteristics of stretched-membrane mirror modules and does not allow face-down stow. It was desired to seek more cost-effective designs for use with stretched-membrane mirrors. Many stretched-membrane heliostat drive system designs were generated and evaluated relative to the pedestal design. The two most promising alternate designs were determined to be a dual module design and a shared support design. Further refinement and cost analysis led to the selection of the dual module heliostat as the preferred design. The dual module design was estimated to cost about 18% less than a pedestal heliostat over its lifetime, and was determined to have the best near-term development potential of all the designs studied. This design incorporates long-sought features such as face-down stow as well as proven technology such as the single pedestal-mounted drive unit. A 100-m^2 dual module heliostat was designed. Detailed design studies and manufacturing cost estimates were performed. The SAIC dual module heliostat is structurally optimized and cost efficient. At a production rate of 5,000 heliostats per year, the installed cost of the dual module heliostat is estimated to be \$107/m^2 (\$10/ft^2) and the total lifetime cost (including O&M costs) is estimated to be \$139/m^2 (\$13/ft^2).

ACKNOWLEDGEMENT

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Foreword

The research described in this report was conducted within the U. S. Department of Energy's Solar Thermal Technology Program. This program directs efforts to incorporate technically proven and economically competitive solar thermal options into our nation's energy supply. These efforts are carried out through a network of national laboratories that work with industry.

In a solar thermal system, mirrors or lenses focus sunlight onto a receiver where a working fluid absorbs the solar energy as heat. The system then converts the energy into electricity or uses it as process heat. There are two kinds of solar thermal systems: A central receiver system uses a field of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a receiver mounted on a tower. A distributed receiver system uses three types of optical arrangements—parabolic troughs, parabolic dishes, and hemispherical bowls—to focus sunlight onto either a line or point receiver. Distributed receivers may either stand alone or be grouped.

This report summarizes the design of a heliostat that uses a stretched-membrane reflector. The field of heliostats is the most expensive part of a central receiver power plant, so costs must be as low as possible for the technology to be commercially viable. Stretched-membrane heliostats are being developed because their simplicity and light weight should afford a considerable reduction in cost over current glass-mirror designs.

1.0 INTRODUCTION

Science Applications International Corporation (SAIC), under contract to Sandia National Laboratories (SNL), is developing advanced stretched-membrane heliostats for solar central receiver systems. In a previous contract, SAIC designed a 150-m^2 (1610-ft^2) commercial-scale stretched-membrane heliostat. In that design, the heliostat drive and support were specifically excluded from consideration; rather, a single, rear-mounted pedestal support -- as used with glass-metal heliostats -- was specified. However, such a support does not take full advantage of the unique structural characteristics of stretched-membrane reflectors, such as their natural ability to transmit loads from the membrane to the support ring. By using these characteristics, a more cost-efficient design may be possible. Moreover, a simple pedestal support does not allow face-down stow of the mirror module. This increases the degradation and soiling rates for the reflective surface, possibly leading to higher operating and maintenance costs.

The goals of this program were to determine if there are cost-effective alternatives to the pedestal heliostat design and to pursue the development of the most promising of these alternatives. Advanced designs identified in this program are expected to show cost savings in mass-production and performance improvements over current pedestal-mounted designs by allowing face-down stow, by reducing drive component costs, and by optimizing the structure for the characteristics of stretched-membrane heliostats.

The present development program has been pursued in phases. This report presents the results of the first two phases. In the first phase, many innovative heliostat drive concepts were identified, evaluated, and ranked in regard to their potential for cost savings and operational efficacy. This led to the selection of a preferred design for a stretched-membrane heliostat system. The second phase involved the detailed design of a complete heliostat based upon the Dual Module stretched-membrane heliostat concept, which was chosen because of lower cost and the best near-term development potential. Some of the drawings of the Dual Module heliostat design are included in this report.

2.0 EXECUTIVE SUMMARY

2.1 Results of Phase I

The purpose of Phase I was to generate innovative heliostat support designs for membrane heliostats and compare their operation and cost with a baseline pedestal design [1] to look for possible improvements. Preliminary results of the Phase I evaluation were presented to Sandia representatives at a review at SAIC on 7 February 1989. At that review, conceptual designs of many heliostat drives were presented, as shown in **Table 2.1-1.** Two rounds of down-selects were performed, in which many designs were eliminated based on cost or operational considerations. After evaluation, three innovative designs were identified as attractive alternates to the pedestal design. Those three designs were designated (1) the yoke drive, (2) the shared support drive, and (3) the dual module drive. These three innovative designs are pictured in **Figure 2.1-1.**

After the initial review, several additional tasks were identified by Sandia and included as part of the Phase I effort. First, two additional innovative designs, an airbag-supported heliostat and a design based on the General Electric Parabolic Dish Concentrator design (PDC-1), were evaluated and included in the overall ranking. After evaluation of their advantages and disadvantages, the two new heliostat drive designs were determined not to have significant advantages over the previously identified preferred designs. The two new designs were therefore rejected from further consideration.

Further refinement was requested on two of the most promising designs identified in the initial Phase I effort. The designs for the dual module and shared support heliostat drives were therefore improved, and further structural analysis was performed to allow better definition of component sizes and costs. An improved focus-control system design for the shared support design was identified in the course of these analyses, promising reduced cost and fewer components.

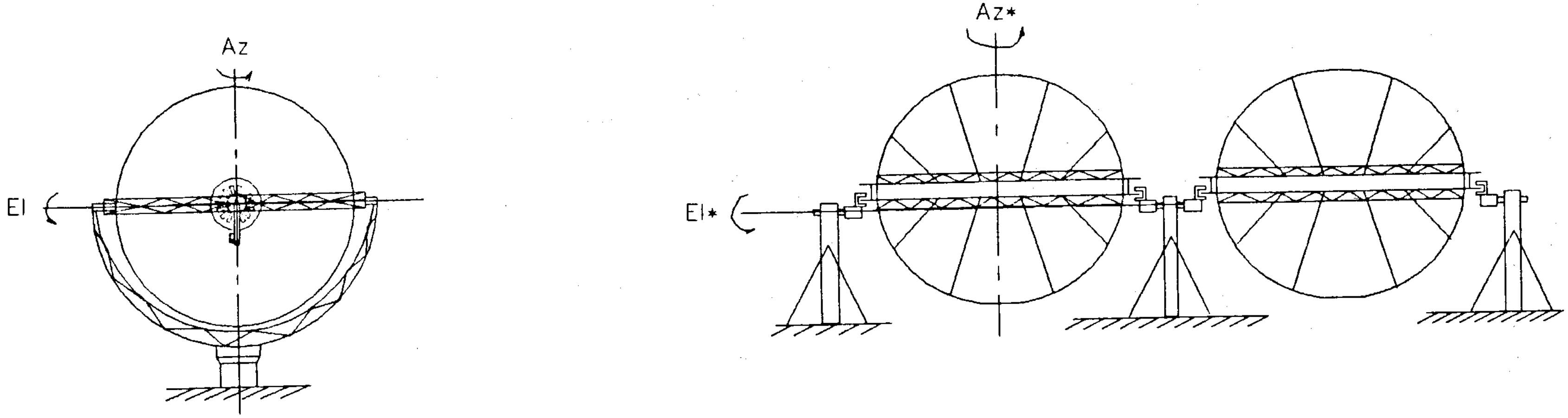
Finally, the inputs to the lifetime cost estimates were improved. Plant design data for the 100 MW solar thermal central receiver plant design generated in the APS study [2] was used. Soiling rates were obtained from a study [3] of inverted-stow heliostats; the optimum cleaning period was determined from a levelized energy cost analysis to be about every 8 days for a non-inverting heliostat and about every 10 days for heliostats with inverted stow capability. Based upon long-term reflector degradation data, the optimum period for reflector replacement was determined to be 10 years for non-inverting designs, and 15 years for inverting designs. Finally, the loss in reflected energy due to shading from the transverse ring in the shared support design was determined to be on the order of 5%.

The economic evaluation included consideration of wind-avoidance features (mechanical movement of the heliostat to reduce the effective force of wind loads) to reduce the cost of heliostats. This factor was found to be unimportant, due to the fact that the heliostat designs are deflection-limited at their maximum operating condition rather than stress-limited at their maximum survival condition in order to meet pointing and surface accuracy requirements. Therefore, little can be saved by incorporating wind-avoidance features for survival conditions, since the stresses at those conditions are not excessive.

HELIOSTAT DRIVE SYSTEM CONCEPTS EXAMINED

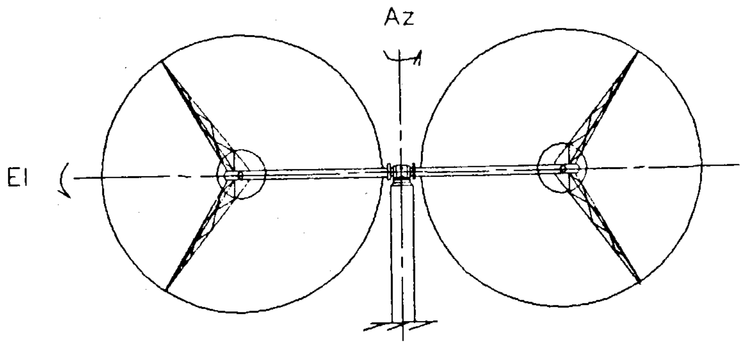
Pedestal
Dual Module
Shamrock
Weather Vane
Offset Dual Module
Shared Support
Centerless
Suitcase Centerless
Semi-Centerless
Yoke
Split Drive Dual Module
Double Centerless (Gimbal)
Twist
SKI
Folding Pedestal with Turntable
Circular Track
Single Point Support
Folding Pedestal
Jacked Axis
Slider
Totem Pole
Multi-Bar
Airbag
Scissors
GE PDC-1

Table 2.1-1. Innovative Collector Designs Identified in Phase I



Yoke Heliostat

Shared Support Heliostat



Dual Module Heliostat

Figure 2.1-1. SAIC Innovative Heliostat Designs Selected in Phase I

After the additional Phase I tasks were completed, a re-evaluation of the heliostat designs was made, with the results shown in **Figure 2.1-2.** The figure shows bar graphs of the total lifetime costs (including maintenance over the life of the system) of standard and wind-avoiding designs of 150-m^2 (1610-ft^2) heliostats with pedestal, shared support, dual module, and yoke drive systems. All three advanced designs show cost reductions compared to the pedestal baseline, with savings ranging from 7% to over 20%. The lowest projected cost is for the shared support design, due to low-cost drive components and the structural efficiency of the transverse ring design. The dual module design has a predicted cost scarcely higher than that of the shared support design.

Both the shared support and the dual module drive designs promise significant cost reductions from current pedestal-mounted designs. The shared support drive design shows the most potential for cost savings, but also is the most extreme change from current design practice. Therefore it has higher risk and would require more development effort. The dual module design shows potential for slightly less savings compared to the shared support design, but represents a near-term development approach that builds on and extends current design practices. Therefore, the dual module heliostat was chosen as the preferred design for further development in Phases II and III.

2.2 Results of Phase II

In Phase II, a detailed design of a commercial-scale dual module heliostat was performed. A 100-m^2 (1080-ft^2) area was selected, based upon considerations of available tooling and experience, risk, and component availabilities. Structural analyses were conducted to size and design the mirror module, the torque tube, the module support trusses, and the foundation/pedestal. Designs and specifications of other components and subsystems were also finalized and documented. **Figure 2.2-1** shows the final configuration of the commercial heliostat.

A set of design drawings was generated to allow manufacturing costs to be estimated. Detailed production cost estimates were generated for the pedestal design, the dual module design, and the multi-bar drive being developed under another contract. These costs included materials, labor, capital equipment, and estimated maintenance and operational costs over the lifetime of the units. The conclusion of these studies was that the dual module heliostat has the potential to reduce costs by about 20% compared to a the pedestal drive. In quantities of 5,000 per year, the dual module heliostat should be able to be produced for an installed cost of \$107/m^2 (\$10/ft^2), and should have a lifetime cost (i.e., including O&M costs) of about \$139/m^2 (\$13/ft^2).

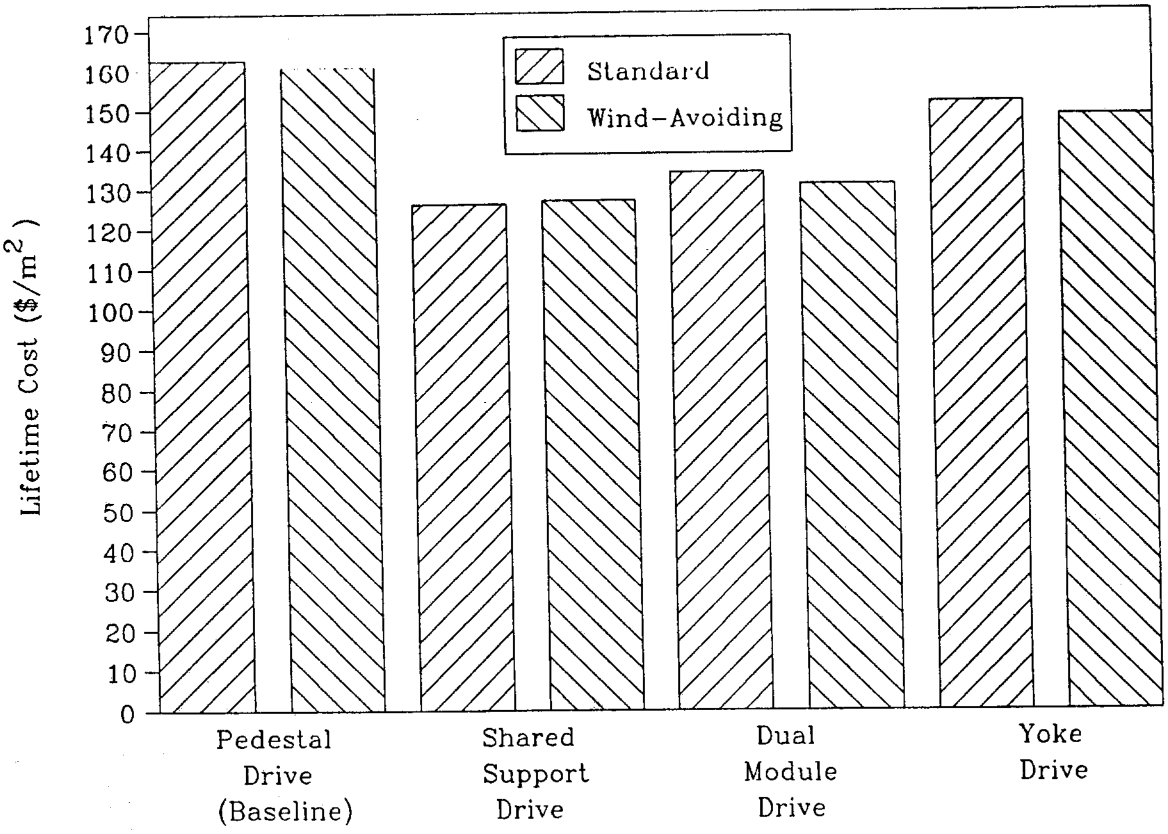


Figure 2.1-2. Cost Comparison of Heliostat Drive Designs

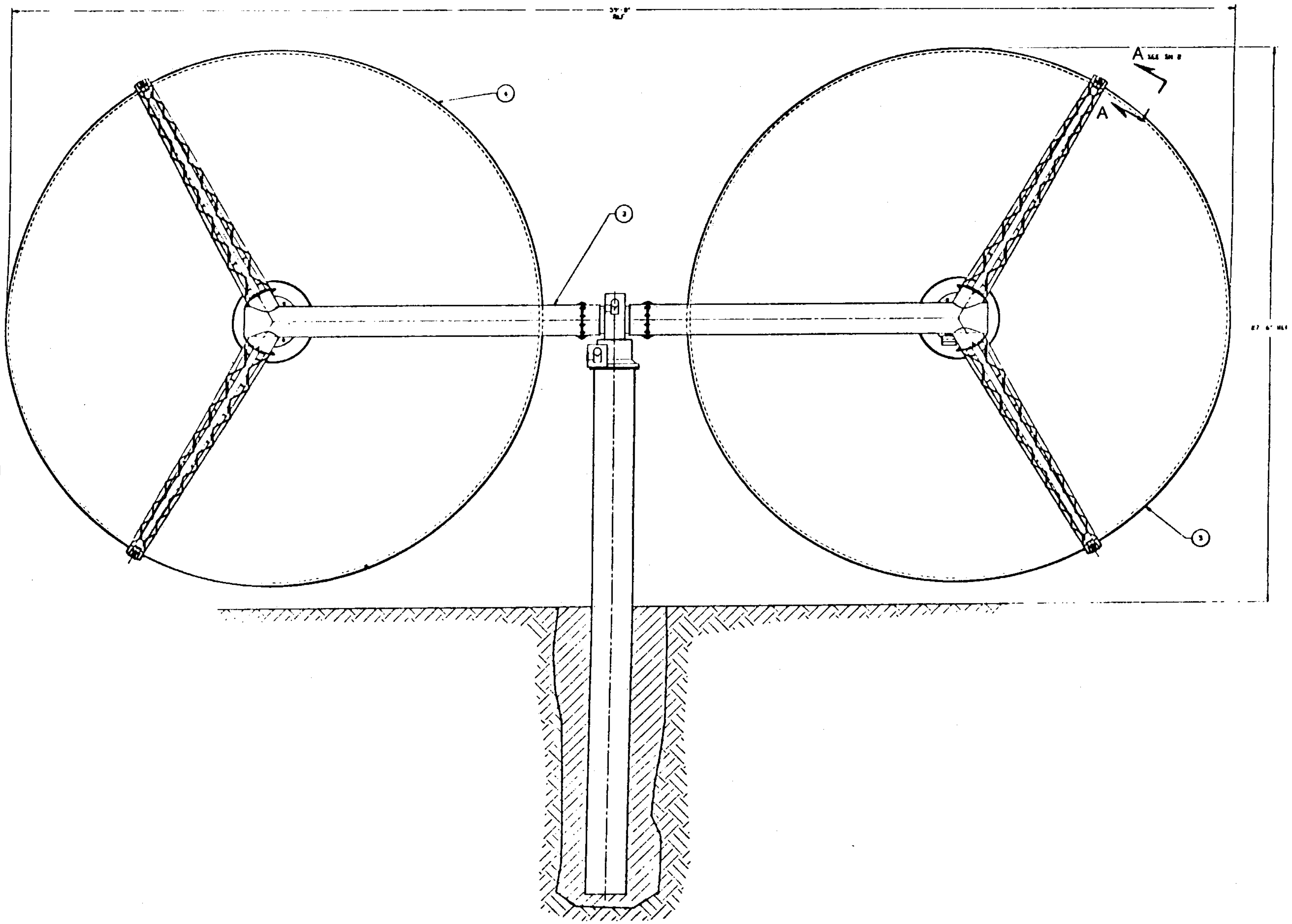


Figure 2.2-1. Commercial Dual Module Heliostat Design

3.0 APPROACH TO EVALUATING HELIOSTAT DRIVE SYSTEMS

3.1 Generation of Heliostat Drive System Concepts

In Phase I, the objective was to identify drive systems that could provide lower cost or better performance with stretched-membrane heliostats than a baseline pedestal drive. To accomplish this goal, existing drive concepts were first gathered from various sources through literature searches and personal contacts. However, this was an attempt to produce new concepts as well as evaluate existing concepts. So, "brainstorming" methods were used in order to stimulate new ideas.

In the brainstorming sessions, a group of people with varying backgrounds was gathered together and encouraged to generate new ideas. As ideas were produced, they were not judged but only recorded for later evaluation. In the session, people were encouraged to improve on existing ideas or combine ideas to form new ones. The only consideration was if the concepts proposed could work, not how difficult they would be to develop or control. Using these techniques, a large number of concepts was generated.

3.2 Qualitative Evaluations

Once ideas had been generated, either through brainstorming or as inputs of existing concepts, it was necessary to have a procedure for analyzing and comparing the various systems. In order to perform meaningful comparisons, a basis for comparison was established, as follows:

- 150-m^2 Heliostat Area
- 5,000 Heliostats Per Year Production Rate
- Soil Conditions Similar to Barstow, CA [2]
- Collectors with Face-up Stow Susceptible to Hail Damage Typical for Barstow, CA [4]
- Heliostat Support Structures Sized to Give Equal Optical Performance
- Wind Loads from the CSU Design Guide [5]

For each heliostat design, qualitative characteristics, advantages, and disadvantages or problems were identified. Then, a two-stage down-select procedure was used to weed out less competitive systems. In the first stage, those concepts which would clearly not function adequately, and those for which the disadvantages outweighed the advantages for use with stretched-membrane heliostats were eliminated. In the second stage, qualitative comparisons were made between the concepts to rank them in an approximate manner, and only the top few concepts were retained. In performing the second down-select, some of the considerations were as follows (order not significant):

- cost to manufacture
- complexity
- parts count
- mass
- pointing accuracy and precision

- reliability
- land use
- stability with regard to wind forces
- face-down vs. face-up stow capability
- number of foundations
- access for cleaning
- low profile
- parasitic energy use
- automatic stow capability
- development risk
- gear reduction needed
- amount of field assembly required

3.3 Quantitative Life-Cycle Cost Comparisons

Once a few systems had been identified that appeared best to meet the requirements, a more detailed analysis was performed on those systems to refine their designs and a life-cycle cost comparison was performed. Life-cycle costing was needed in order to account for performance and cost differences between different designs. These differences arise from such things as differing frequencies of reflective film replacement and washing between collectors with face-up and face-down stow capabilities, and shading losses in collectors (such as the Shared Support design) that have structures across the front of the reflective surface. The result of the comparison was a determination of which collector designs had the best potential for reduced cost compared to the pedestal design, while still meeting the performance criteria.

3.4 Ideal Stretched-Membrane Heliostat Drive/Support

In the course of the evaluations, a profile developed of an ideal heliostat drive and support, which served as a useful standard against which other systems could be judged. The characteristics of this ideal heliostat system are summarized below:

- Face-down stow to maximize reflective film lifetime and minimize cleaning requirements
- Efficient transfer of loads from the membrane to the ground
- High pointing accuracy and precision
- Use of standard gear motors rather than gearboxes
- Low gear motor torque loads -- center of force near center of reaction for wind and gravity loads
- Minimum support mass
- Minimum parts count
- Simple installation
- Minimum site preparation and foundation
- Low capital and maintenance costs

4.0 CONCEPTUAL DESIGNS FOR HELIOSTAT DRIVE SYSTEM

The heliostat drive concepts identified in this study were summarized in **Table 2.1-1. Table 4.0-1** categorizes the concepts by the characteristics of the drive systems. The first major division is between drive systems in which the rotation of the mirror module is about the center of the module, and those in which the center of the mirror module translates as motion occurs. Those designs in which rotation is about the center of the module have the characteristic that the center of pressure is close to the center of rotation, so that direct wind forces cancel out and the drive motors need only provide torque to overcome wind moment forces on the module.

Within the group of drive systems in which all rotations occur about the center of the module, the drives are further sub-divided into those with centered drives and those with rim drives. The major difference between these two types is that centered drives have the drive motor/gearbox at the axis of rotation, whereas rim drives have the drive unit at the rim of a circular ring. Rim drives have the advantage of a natural, built-in gear reduction so that motor gearing requirements are less. Since stretched-membrane heliostats have their structure at the periphery of the module anyway, rim drives sometimes provide an elegant interface. A general drawback of rim drives is that a transverse ring, which shades a portion of the module, is often required.

In the case of centered drives, only one configuration is possible by definition, since both rotation axes must pass through the center of the unit. The concepts employing this configuration tend to be pedestal-mounted, since a pedestal is the simplest structure with which to transfer loads from a single vertex to the ground. Single or multiple stretched-membrane mirror modules can be mounted on the pedestal to create the various concepts displayed in the table.

With rim drives, the azimuth and elevation drives can be either co-located or they can be separated, as shown in the table. If they are co-located, designs such as the shared support and centerless drive are encountered. If separate drive locations are used, the concepts shown in that column are encountered).

Within the group of drive systems that incorporate translation of the mirror module, systems can be separated depending upon whether or not one of the axes of rotation passes through the center of the module. In the case that one axis passes through the center of the module, there is a further subdivision based upon the location of the drive units: they can be either both ground-mounted, or one of the axes of rotation can move with the heliostat.

The final subdivision consists of systems in which the mirror module translates and no axes of rotation pass through the module center. These systems all depend upon multiple ground-based drive points with drive components that are used to position the module above the ground in the desired orientation.

In the following subsections, conceptual designs for each of the heliostat drive systems identified in Phase I are given. Where possible, they are divided into groups of concepts with significant similarities. In the description of each drive concept, general characteristics and good and bad points of each design are outlined. Almost all of the advanced drive concepts allow face-down

MIRROR MODULE CENTER ROTATION NO CENTER TRANSLATION				MIRROR MODULE CENTER TRANSLATES & ROTATES		
1) CENTER OF PRESSURE IS CLOSE TO CENTER OF ROTATION				1) CENTER OF PRESSURE & CENTER OF ROTATION ARE INDEPENDENT		
CENTERED DRIVES		RIM DRIVES		1 LINE, 1 POINT MOVEMENT		3 INDEPENDENT PTS. ON MIRROR MODULE
1) ROTATION AXES INTERSECTING AT 1 DRIVE BOX		1) ROTATION AXES INTERSECTING AT CENTER OF MIRROR MODULE		1) 1 ROTATION AXES THROUGH THE CENTER OF THE MIRROR MODULE		1) 0 ROTATION AXES THROUGH CENTER OF MIRROR
AZ DRIVE, EL DRIVE COLLOCATED		AZ DRIVE, EL DRIVE COLLOCATED	AZ DRIVE, 1 EL, NOT COLLOCATED	GROUND BASED EL GROUND AZIMUTH	1 AXIS BASED, 1 GROUND BASED DRIVE	3 GROUNDBASED DRIVE POINTS
SINGLE MODULE	MULTIPLE MODULE	SHARED SUPPORT CENTERLESS	SUITCASE CENTERLESS SEMI-CENTERLESS YOKE SPLIT DRIVE DUAL MODULE DOUBLE CENTERLESS TWIST	SKI FOLDING PEDESTAL W/ TURN TABLE CIRCLE TRACK SINGLE POINT	FOLDING PEDESTAL JACKED AXIS SLIDER TOTEM POLE	MULTI-BAR AIR SUPPORTED HELIOSTAT (SERI R. WOOD) SCISSOR
PEDESTAL	**DUAL MODULE** SHAMROCK WEATHER VANE OFFSET MODULE					

Table 4.0-1. Heliostat Drive System Categories

stow of the mirror module. Therefore, this feature is only mentioned in regard to a concept if it has other impacts.

4.1 Pedestal Heliostat Designs

In the following subsections, heliostat drive concepts are described that have in common a pedestal mounting approach. The baseline system is the simple pedestal drive, with a single mirror module. Other designs involved variations in mounting and number of mirror modules on the drive structure.

4.1.1 Pedestal Drive

The pedestal drive is the baseline against which the comparisons in this study are made. **Figure 4.1-1** shows the design for a commercial 150-m^2 stretched-membrane heliostat generated by SAIC in a previous contract [1]. The salient feature of the mirror module is the central hub with radial trusses to support the heliostat ring. In the commercial design, tapered tubular trusses were used for the radial trusses, and a rotated pentagon tubular frame hub was used.

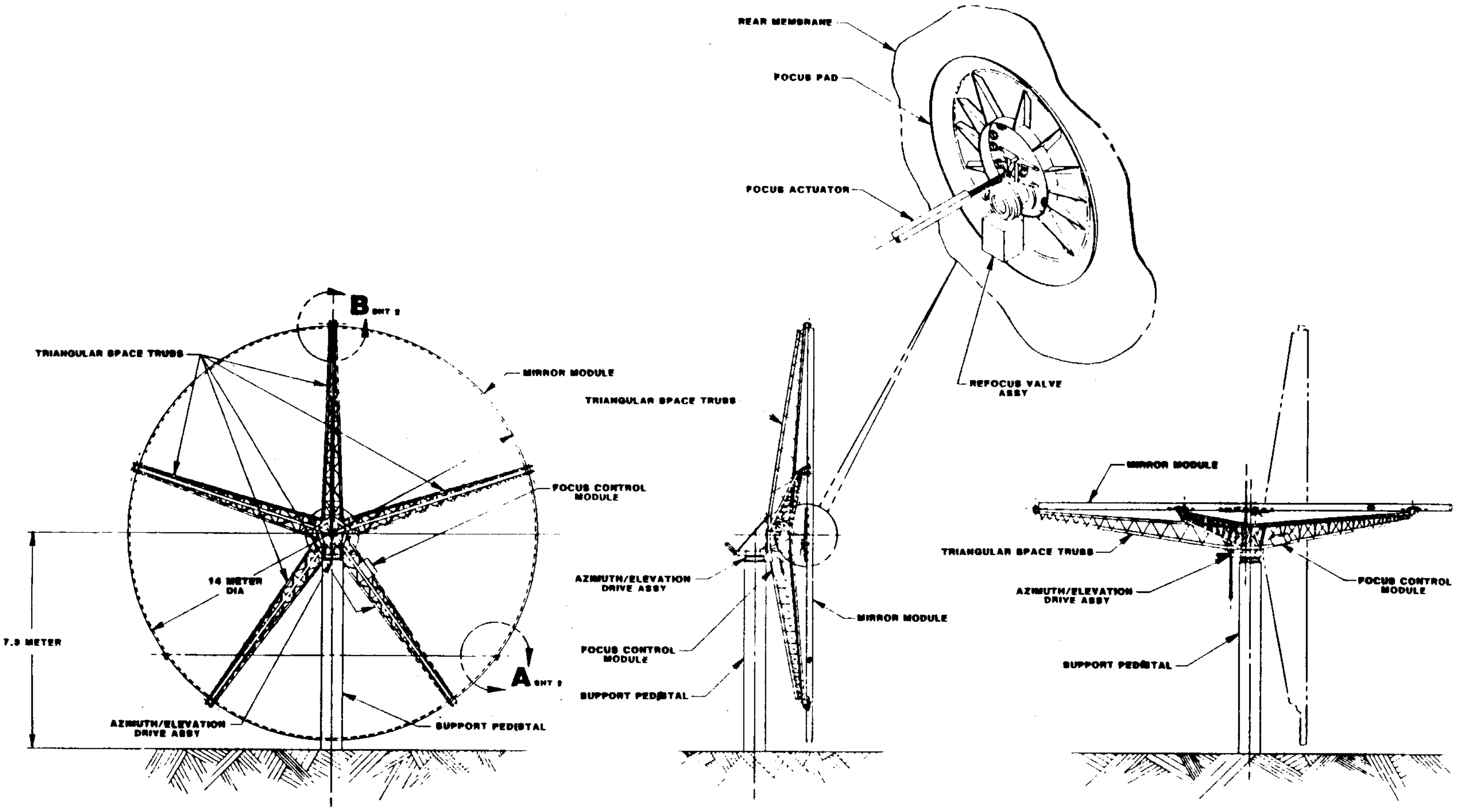
A single drive unit contains gear trains for both azimuth and elevation drives. The drive unit is mounted on top of the pedestal, and the heliostat hub attaches to it. Because the drive unit attaches to the center of the heliostat, it provides a convenient and strong attachment point for the focus-control actuator.

The pedestal used to support the collector prevents it from turning so as to face downward. For this reason, collectors are normally stowed vertically facing the horizon, except in high wind, when they are stowed in a face-up orientation. This arrangement leads to increased soiling and hail damage potential for the reflective surface.

4.1.2 Dual Module

The dual module configuration, shown in **Figure 4.1-2**, is an attempt to solve some of the problems inherent in the pedestal drive without altering the basic structure. As shown in the figure, the drive retains a single pedestal support with a centralized, azimuth/elevation drive unit mounted atop it. However, instead of a single mirror module, two mirror modules are attached to the drive unit, one on either side. A horizontal torque tube extends from the drive unit to the center of each mirror module. This tube provides a mounting location for the heliostat focus-control unit, as well as a support point for the heliostat ring near the pedestal. Two other support points for the ring are provided by trusses that extend from the end of the torque tube.

The dual module design has several advantages compared to the pedestal configuration. Chief among these, the placement of the modules off to the sides of the pedestal allows the mirror surfaces to be stowed face-down. Also, a dual module heliostat has a lower wind profile than a comparably sized pedestal drive. It also provides a low-risk, near-term commercialization path because it uses existing components (pedestals, drive units) and the scale-up factor from demonstrated technology for the mirror modules is not as large. The design leads to production of smaller modules in higher production volumes, lowering tooling costs and possibly leading to earlier economies of scale. One disadvantage of the dual module design is that it requires a larger clear-out circle for tracking. This could mean that the heliostat field would be lower in



REAR ELEVATION

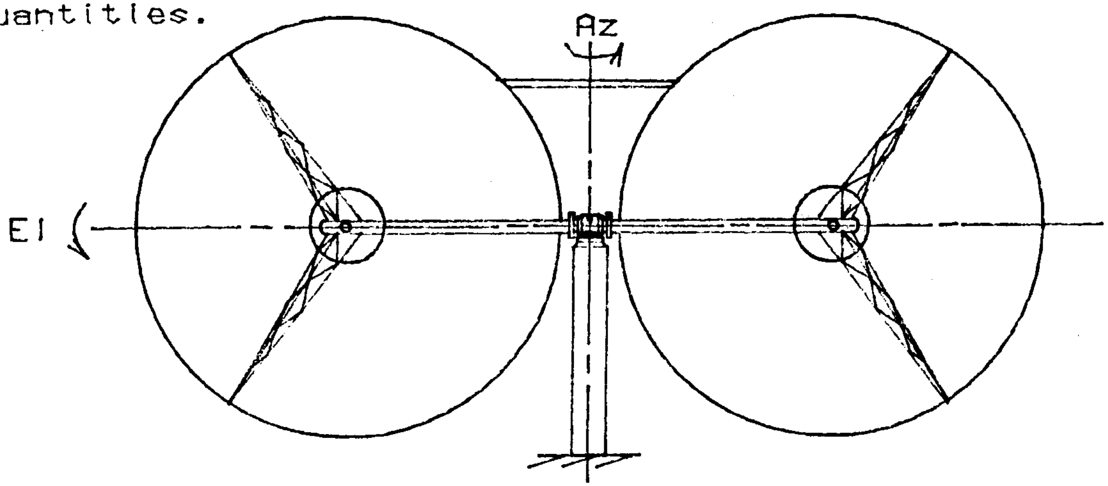
SIDE ELEVATION

STOWED POSITION

Figure 4.1-1. Commercial Pedestal Heliostat Design

Advantages
Face down stow.
Use of existing components.
Smaller modules to fabricate.
Double production volume.
Reduced wind load/unit area
Fairly simple structure.
Possible reduction in cost by using cables.
Near term commercialization possible.
Lower tooling cost for small quantities.

Disadvantages
High bending moment on torque tube(gravity, wind).
Higher perimeter to area ratio.
Two focus controls required.
Lower density field?



Status - Retained in second down select

Figure 4.1-2. Dual Module Heliostat Configuration density, increasing land costs and flux losses in a central receiver system. Another concern is aberration of the reflected image when the sun is off-axis from the heliostat, due to the fixed angle between the two mirror facets. Both of these concerns were considered by researchers at SNL, Albuquerque, and the conclusion was that they were not significant problems. Another characteristic of this drive compared to the pedestal drive are that two focus-control actuators are needed, although the actuators need not be so large, and therefore would be less expensive.

4.1.3 Shamrock

This drive, pictured in **Figure 4.1-3**, carries on the concept of the dual module drive, but with three mirror modules. The third module is mounted above the drive unit, and bracing connects it to the others. This design has advantages of face-down stow, use of existing drive components, and high production quantities of mirror modules. Disadvantages are a more complex structural support system, focus-control systems that are inconvenient to mount (and three are required), a high perimeter to area ratio, and high loads on the structure due to gravity and winds.

4.1.4 Weather Vane

This concept is shown in **Figure 4.1-4**. It is very similar to the dual module design, except that one of the mirror modules is larger than the other. The purpose of the difference in size is to provide wind avoidance -- the unbalanced modules create a moment on the heliostat that tends to feather it into alignment like a weather vane in strong winds (hence the name).

Advantages of the drive are similar to the dual module design, with the addition of wind avoidance. Disadvantages are that production of different sizes of mirror modules are required, which negates the advantage of quantity production, and that non-uniform wind loading is inherent in the design.

4.1.5 Offset Dual Module

Figure 4.1-5 shows a sketch of this concept. Like the weather vane, it is a variation of the dual module, which is meant to provide automatic feathering into a strong wind. It achieves this goal by offsetting one of the mirror modules further out from the drive unit. By making both mirror modules the same size, this design avoids one of the problems of the weather vane concept. However, there were concerns about the stability of this design in gusty winds and about the extra bending moments induced in the torque tube and drive unit by the offset.

4.2 Centerless Drive Concepts

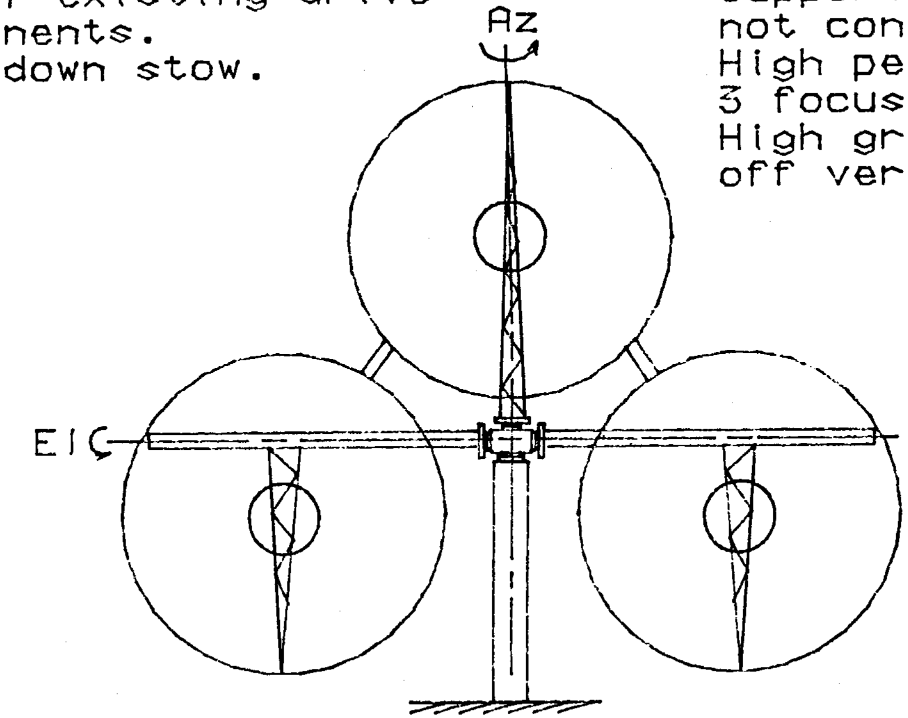
The drives described in the following subsections are characterized by their common use of centerless drives, which do not use a central pivot. Instead, these drives apply forces to and support the collector with a circular ring around the mirror module.

4.2.1 Centerless Drive

This drive concept consists of a rim-drive elevation drive mounted on a turntable azimuth drive system. As in the case of the shared support drive, the heliostat ring is supported at many points by cables from the transverse elevation ring.

Advantages
Small modules result in lower tooling cost for small quantities.
Use of existing drive components.
Face down stow.

Disadvantages
Complex structural support.
Very high torque tube moment.
Support of focus control not convenient.
High perimeter to area ratio.
3 focus controls required.
High gravity loads off vertical.

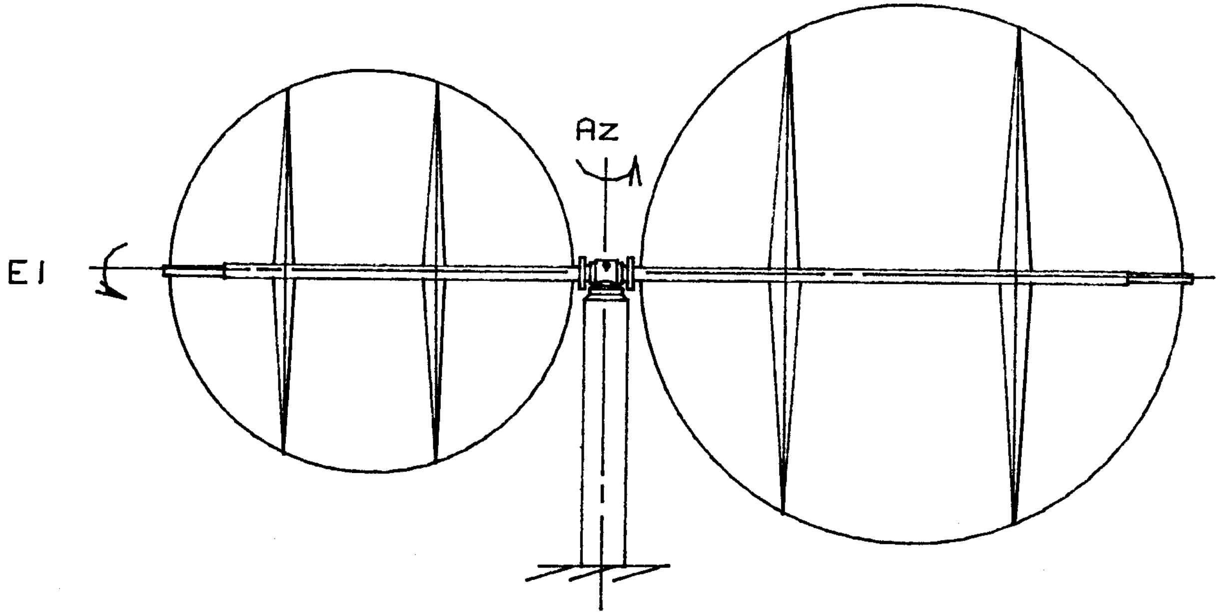


Status - Rejected in second downselect

Figure 4.1-3. Shamrock Drive Concept

Advantages
Face down stow.
Effective wind avoidance.
Use of existing components.

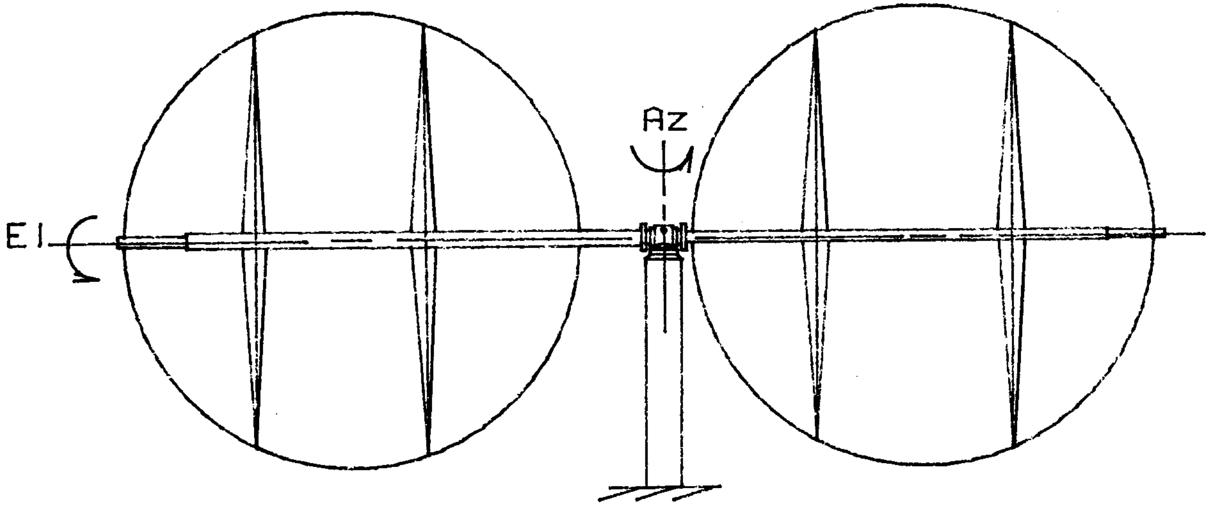
Disadvantages
Two mirror module sizes required.
Non-uniform wind and gravity loads.



Status - Rejected in first downselect

Figure 4.1-4. Weather Vane Drive Concept

Advantages	Disadvantages
Effective wind avoidance action.	High torque tube moments
Face down stow.	Maybe unstable in gusty winds.
	High elevation drive bending moment.



Status - Option to dual module design

Figure 4.1-5. Offset Dual Module Drive Concept

4.2.2 Shared Support

This unique drive is shown in **Figure 4.2-1.** As shown, the mirror modules are mounted between pedestals, which are "shared" between pairs of mirrors. A tilt and roll drive system is used: the roll system, based upon a rim drive, is mounted on a gear-driven tilt axis. The transverse ring used for the roll drive provides a multiple-point support for the mirror module ring through the use of cables.

Advantages of this drive are that it provides face-down stow, the tilt and roll components are co-located at the top of the pedestals (in fact, two modules could be driven by a single drive unit), the roll axis has natural gear reduction due to the rim drive, the mirror module rings can be made much less stiff due to the large number of supports, and the pedestals can be stiffened by the use of cables. Disadvantages are that this design represents a large departure from current practice and is therefore risky, there is poor access for cleaning of the mirror, the spacing limitations lead to increased shading/blocking losses, and the rim drive ring gear surfaces are exposed to the elements.

4.2.3 Suitcase Centerless

This concept is like the centerless drive, except that a tilt and roll drive motion is used. This is accomplished using a centered drive to rotate the mirror module within a centerless ring drive which provides the tilt motion. The concept is pictured in **Figure 4.2-2.** An external support with cable bracing is used to give added rigidity to the centerless ring against transverse wind forces. Advantages of the system are that it is easy to transport and install, the foundations are shallow, and face-down stow is possible. Disadvantages are that there is limited leverage on the roll axis (even if a cable system is used, there are positions of low torque), the tilt drive/support system is not yet developed, and the cabling system could be complex.

4.2.4 Semi-Centerless

In this variation of the suitcase centerless drive, pictured in **Figure 4.2-3,** the front half of the tilt ring is removed, and face-down stow is accomplished by rotating the mirror module 180° about the roll axis. The tilt drive is ground-mounted, and the roll drive is mounted on the moving centerless drive ring. Advantages, besides face-down stow, are that the heliostat can be feathered into the wind and brought to stow easily, that the drive motors see only moments and not full wind loads, and that the centerless tilt drive provides natural gear reduction. Disadvantages are poor lateral stiffness, and that the roll drive is not fixed to the ground, but must be able to move with the unit.

4.2.5 Double Centerless (Gimbal)

This concept is shown in **Figure 4.2-4.** It is very much like the suitcase centerless drive, but employs centerless drive units for both the tilt and roll axes. The main advantage is the gear reduction produced by the rim drives. Disadvantages include high weight (three structural rings the size of the heliostat are required), poor mounting strength (all mounts are to circular rings above the ground), and a large amount of blockage of the mirror by the transverse drive rings.

Advantages

Co-located drives.

Azimuth drive has natural gear reduction.

Possibility of driving two modules w/ one elevation drive.

Lightweight heliostat ring.

Cable support of pedestals possible.

Simple structure.

Can be used with dishes also.

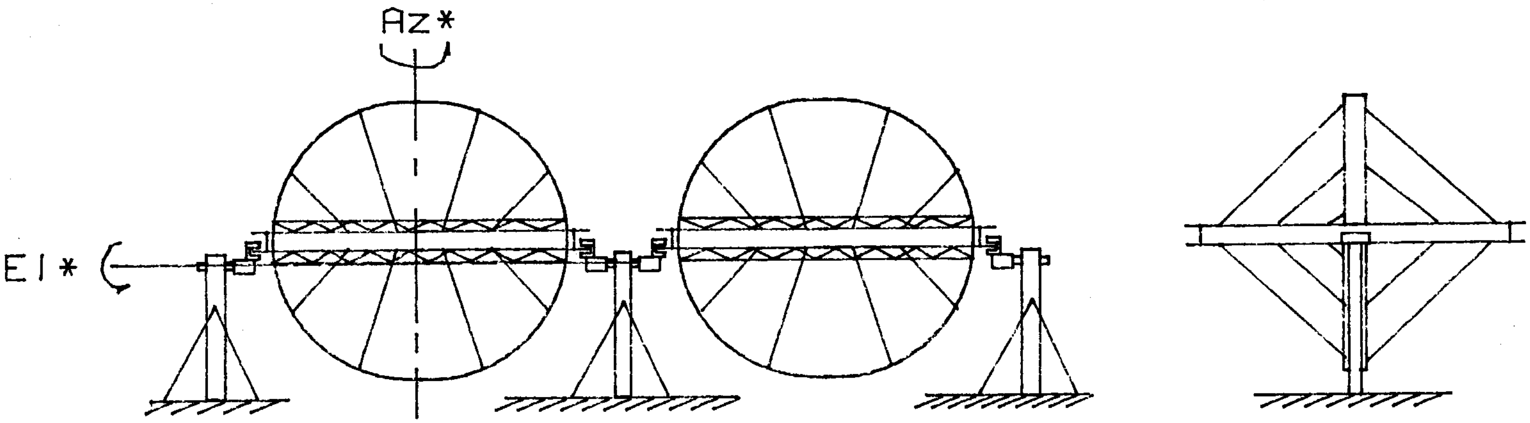
Disadvantages

More development required for azimuth drive/support.

Poor cleaning access.

Mirror shading.

Azimuth drive components exposed to elements.

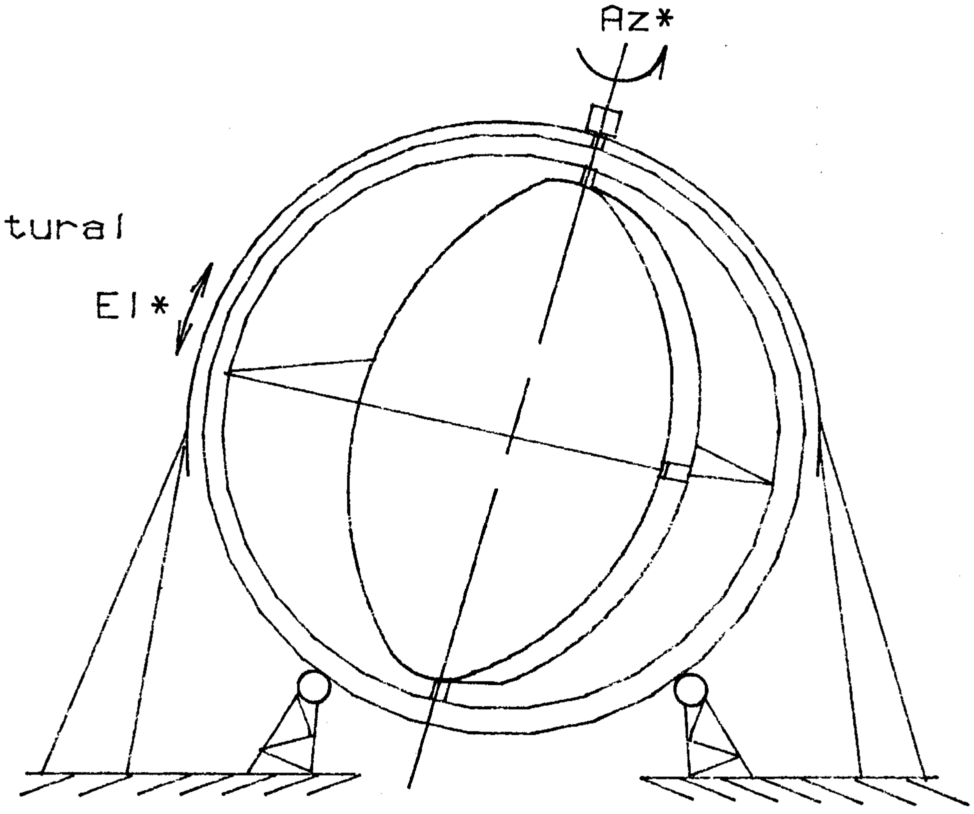


Status - Retained in second downselect

Figure 4.2-1. Shared Support Heliostat

Advantages
Easy transport.
Shallow foundations.
Elevation drive has natural gear reduction.
Limited torque on azimuth drive.
Face down stow.

Disadvantages
Complex cable locking system.
Poor support for loads perpendicular to outside ring.
More development required for elevation drive/support.



Status - Eliminated in second downselect

Figure 4.2-2. Suitcase Heliostat Drive Concept

Advantages

Face down stow.

Can be easily feather into wind and stow from any position.

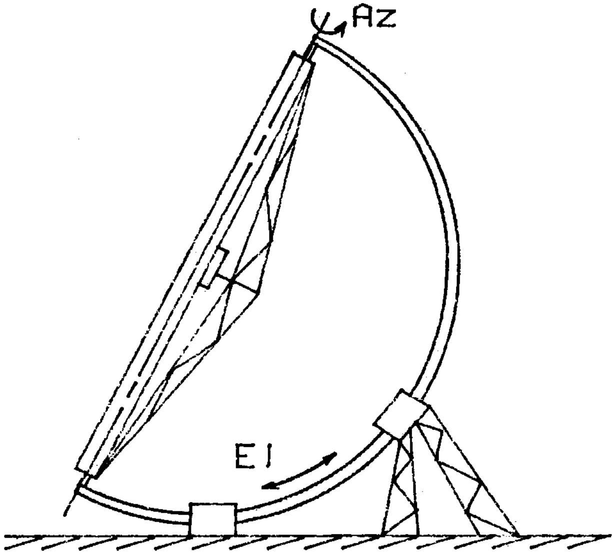
Drive motors see only moments and forces.

Gear reduction not needed on elevation.

Disadvantages

Azimuth drive not fixed to ground.

Poor lateral resistance to wind loads.

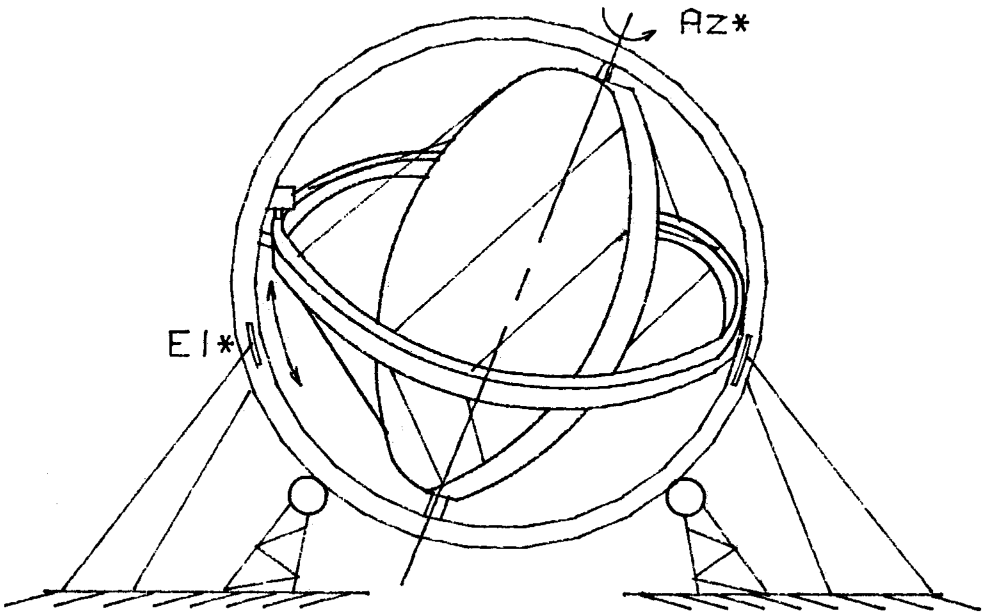


Status - Rejected in second downselect

Figure 4.2-3. Semi-Centerless Heliostat Concept

Advantages
- High drive motor mechanical advantage.
- Good module ring support.
- Face down stow.

Disadvantages
- Poor resistance to lateral loads.
- Complex assembly.
- High shading loss.
- Difficult washing.



Status - Rejected in second downselect

Figure 4.2-4. Double Centerless (Gimbal) Heliostat Concept

4.2.6 General Electric PDC-1

This design, pictured in **Figure 4.2-5**, was developed by General Electric Co. for a dish collector. It is similar to the centerless drive except that the PDC-1 has supporting pivots on the edges of the heliostat ring on the elevation axis instead of using the elevation drive ring as the support element for the heliostat ring. Advantages of this design are its large base to resist overturning moments and provide lateral stiffness and the rim drive approach, which provides natural gear reduction and thereby reduces drive costs. Disadvantages include a large number of field-assembled parts leading to high installation costs, a high parts count, and a large number of foundations.

4.3 Rigid Arm Drive Concepts

The concepts described in this section have in common with one another their reliance on rigid support arms for positioning the mirror module.

4.3.1 Scissors

This concept is pictured in **Figure 4.3-1**. The heliostat is mounted on tracks, and motion of the support arms in the tracks provides the tracking of the collector. The advantage of this concept is that it has many identical drive components. Disadvantages include high member and module loads, exposed drive components, difficulty inverting for stow, and complex movement.

4.3.2 Circular-Track

This concept is pictured in **Figure 4.3-2**. As shown in the figure, the mirror module is mounted on a horizontal circular track, around which it can move to perform azimuth tracking. Two support arms extend behind the mirror module to the track, and their ends are moved around the track to provide elevation tracking. Advantages of this design are that it has a low profile, transfer of loads to the ground is efficient, tracking control is straightforward, and it has good mechanical advantage on each of the tracking axes. Disadvantages are that the tracking elements are exposed to the weather and the pointing accuracy is sensitive to ground movements.

4.3.3 Folding Pedestal

The folding pedestal drive is shown in **Figure 4.3-3**. It has the form of a tilt and roll drive, with tilt controlled by the movement of the support arms and roll about the collector supports at the top and bottom of the mirror module. The advantages of the concept are a low profile, easy drive access with all parts of the drive system at or near ground level, easy focus-control actuator support, and face-down stow. The design can be made able to achieve "over the shoulder" operation by proper sizing of the folding pedestal. Disadvantages include multiple linkages, an increase clearance requirement between collectors, and high tilt drive moments.

4.3.4 Folding Pedestal with Turntable

In this variation of the folding pedestal drive, the roll drive is replaced with a ground-mounted turntable to provide azimuth tracking in the same manner as the centerless drive or PDC-1 Drive. This reduces problems with the roll portion of the drive, but at the expense of more support structure, foundations, and complexity.

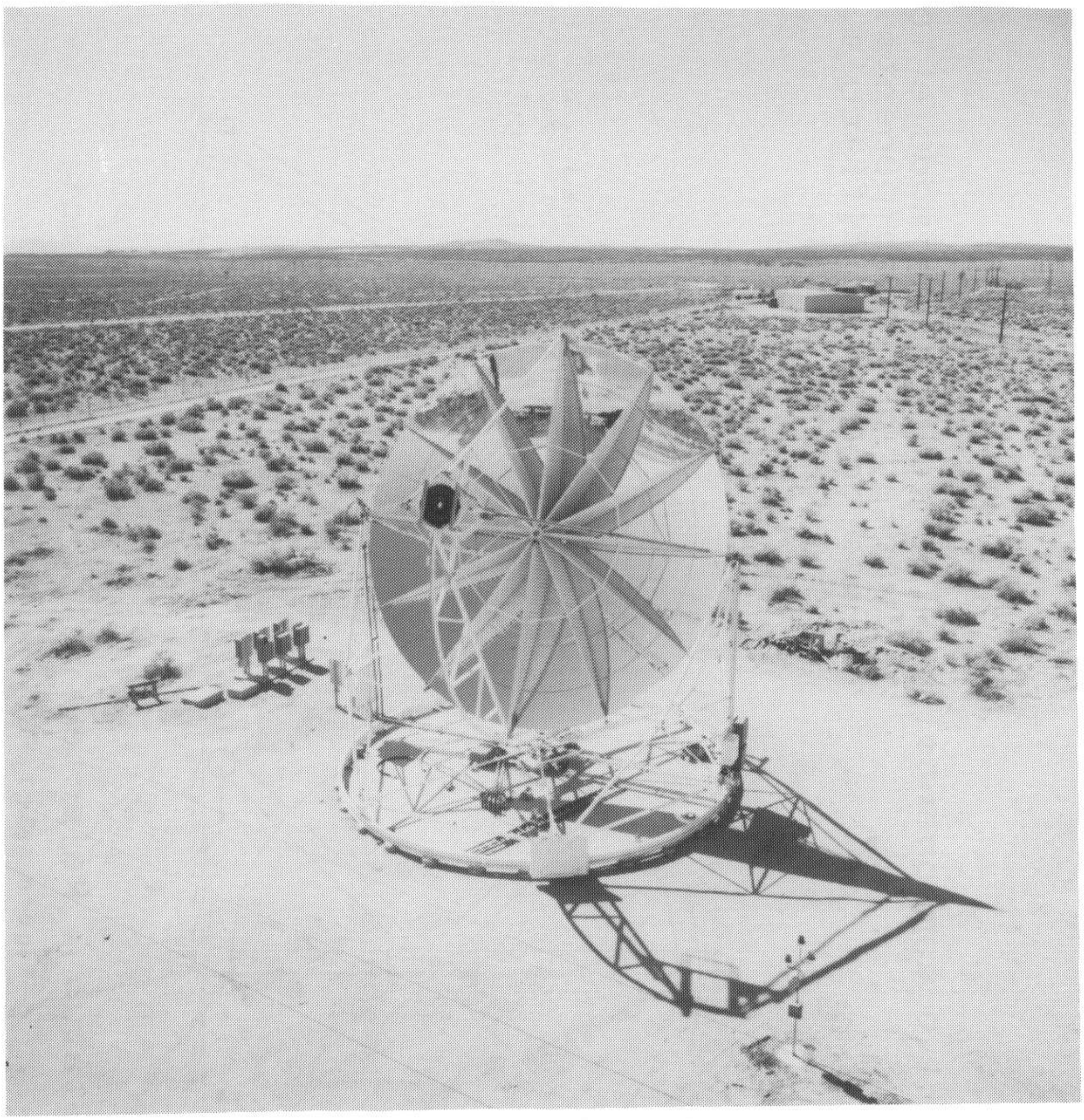
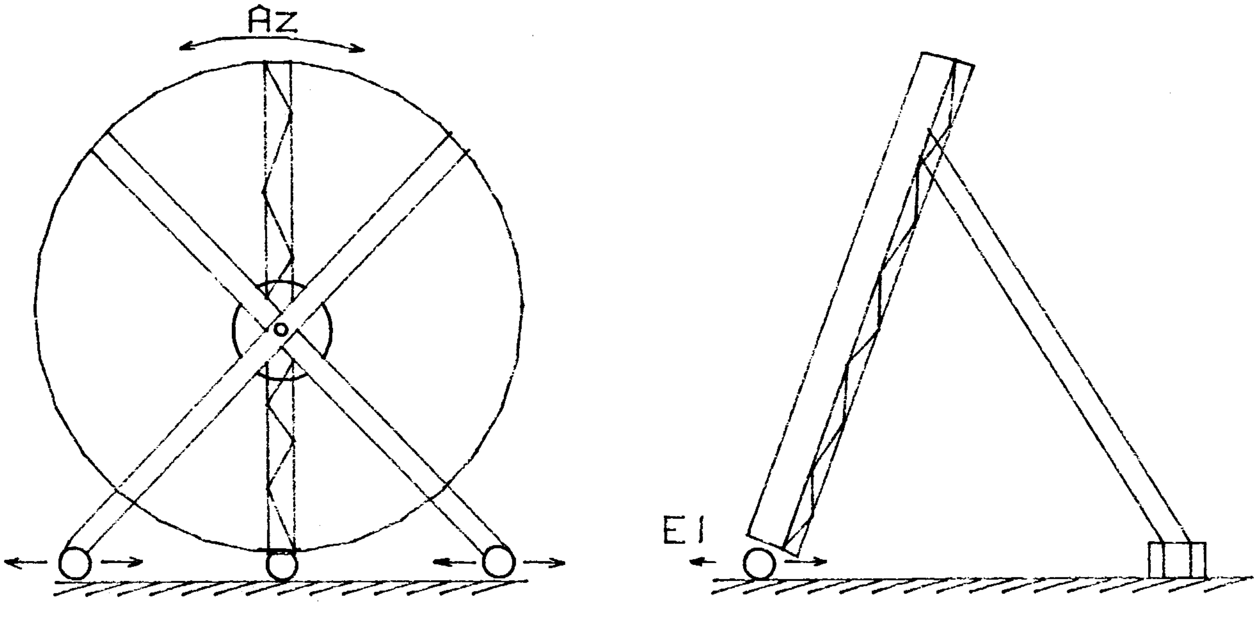


Figure 4.2-5. General Electric PDC-1 Concept

Advantages
Identical drive components.

Disadvantages
High member and module loads.
Exposed drive components.
Face down stow difficult.
Complex movement.



Status - Rejected in first down select

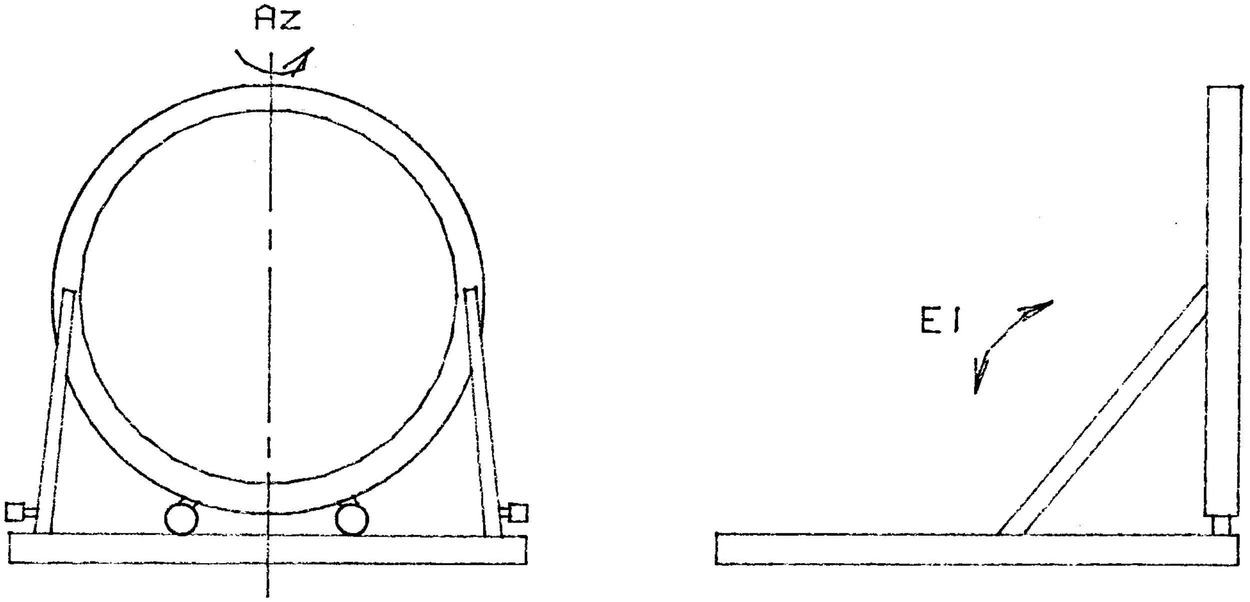
Figure 4.3-1. Scissors Drive Concept

Advantages

- Low profile.
- Efficient transfer of loads to ground.
- High drive mechanical advantage.
- Face down stow.

Disadvantages

- Exposed tracking components.
- Sensitive to ground movement.
- Awkward positions required.
- Multiple linkages required.

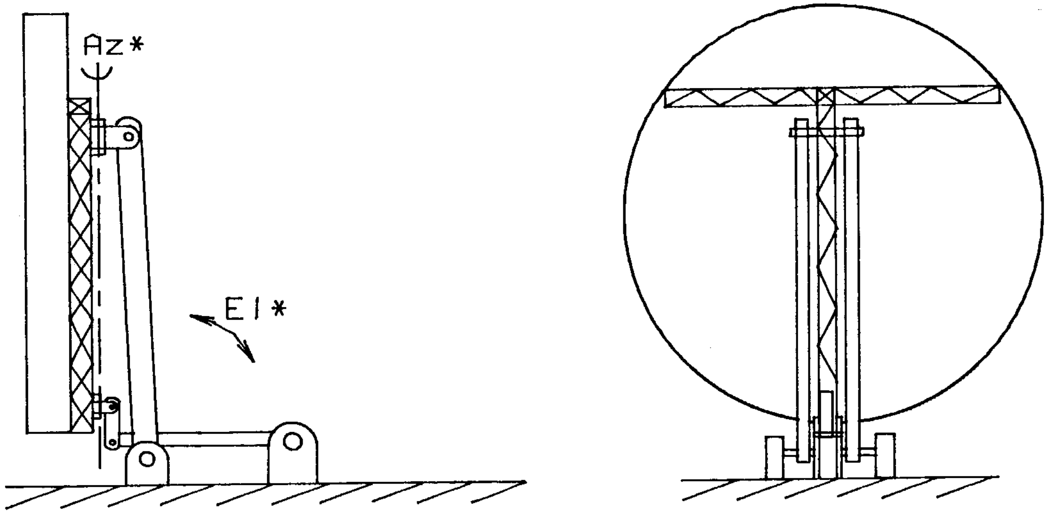


Status - Rejected in first downselect

Figure 4.3-2. Circular-Track Drive Concept

Advantages
Three support points.
Low profile.
Easy drive access.
Focus control support.
Max moment occurs at max force.
Face down stow.
Over shoulder capable.

Disadvantages
Multiple linkages.
High elev. drive moment.
Increase clearance required.



Status - Eliminated in second downselect

Figure 4.3-3. Folding Pedestal Drive Concept

4.3.5 Jacked Axis

This design is shown in **Figure 4.3-4.** It consists of a fixed lower support and a linear tracked actuator at the top of the mirror module which provides the tilt drive. The mirror module rotates about the axis defined by the upper and lower supports to track in roll. The concept has good mechanical advantage on the tilt drive, simplicity, and good coupling of loads to the ground, and face-down stow is possible by rotating the mirror module 180° about its roll axis. Disadvantages include poor lateral strength, high loads on the roll drive, and exposed drive components.

4.3.6 Slider

This design is similar in action to the folding pedestal and jacked axis drives, except that the tilt action is performed, as shown in **Figure 4.3-5**, by movement of a rigid arm along a track behind the collector. Advantages are similar to those listed above for the folding pedestal. Disadvantages include poor lateral strength, a large space requirement for face-down stow, sensitivity to ground movement, and exposed drive components.

4.3.7 Multi-Bar

The multi-bar drive is a unique concept being developed by Dan-Ka, Inc. of Denver, Colorado. As shown in **Figure 4.3-6**, by a clever geometric arrangement this concept uses the motions of two ground-mounted arms attached to the mirror module to position it in any desired orientation. Advantages of the design are simplicity of the drive structure, face-down stow, and good load distribution to the ground. Disadvantages are high forces and moments on the ground-mounted portions of the drive and the number of expensive ball joints necessary for the drive.

4.4 Other Concepts

4.4.1 Airbag

This design, pictured in **Figure 4.4-1**, uses an inflated vinyl bag to support the mirror module against gravity. The concept was developed by Rick Wood of the Solar Energy Research Institute. Azimuth and elevation drive is accomplished through cables attached to the mirror module that work against the inflated bag pressure. The system is designed to stow by deflating the air bag, allowing the mirror module to come to rest face-up on a ground-level foundation. The main advantage of this drive system is its very low cost compared to steel structures, due to the innovative air-cushion support. Also, it has a low profile at stow and can provide automatic defocus and automatic stow upon loss of power.

Many disadvantages identified for this system stemmed from a concern about the operational efficacy and dynamic behavior of the air bag/mirror module/cable system under wind and gravity loads. It was feared that the air bag would be subject to large deflections due to wind loads, because of its high surface area. Buckling of the bag at low heliostat elevation angles was also a concern, as was the membrane strength required to support gravity loads under those conditions. In order to maintain positional accuracy in winds, a high internal pressure would be necessary, which would increase structural and parasitic energy requirements. There were uncertainties about the positioning accuracy of the cable system and the lifetime of the air bag. Finally, the system has a face-up stow, which would increase cleaning requirements and environmental degradation.

Advantages

Minimize height of collector off ground.

Face down stow.

Simple pivots & rotation bearings.

Gravity loads mainly taken by simple pedestal.

No foundation moment.

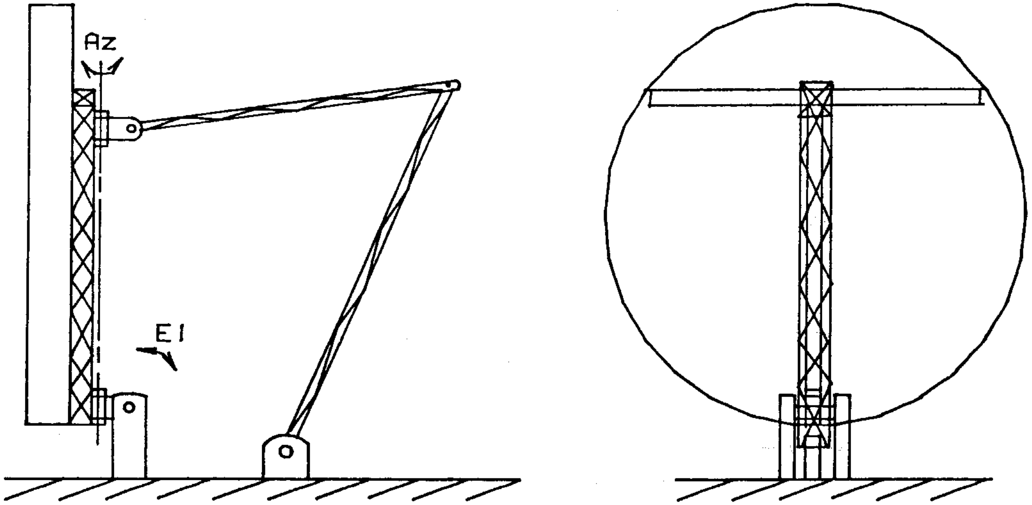
Disadvantages

Elevation drive must counteract wind forces as well as moments.

Clearance area is 2x collector unless module can pivot 180 deg.

Distributed foundation.

Lots of parts.



Status - Rejected in second down select

Figure 4.3-4. Jacked Axis Drive Concept

Advantages
Face down stow.

Disadvantages
High structure loads.
Exposed drive components.
Poor lateral load support.
High space requirement.
Sensitive to ground movement.

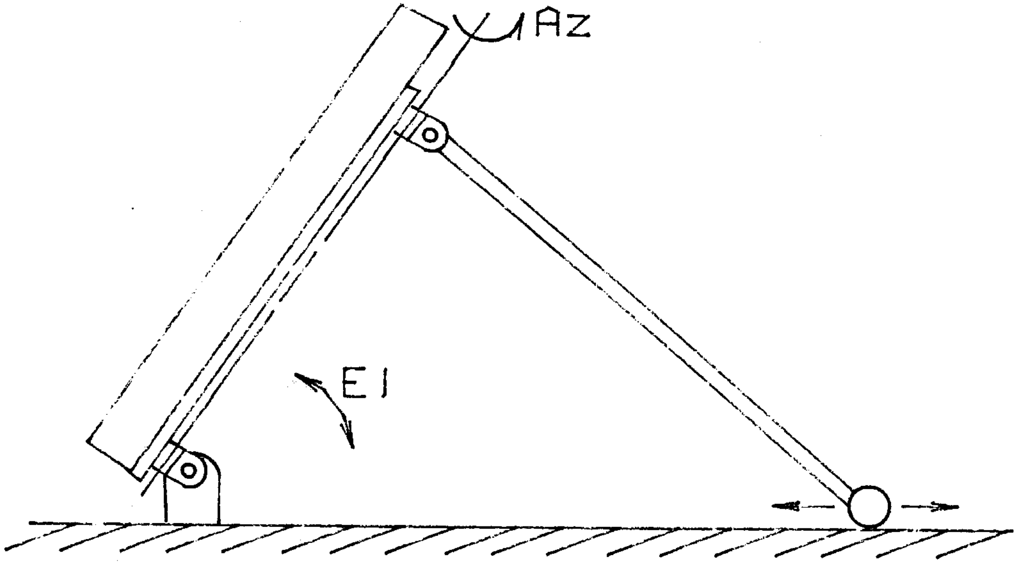


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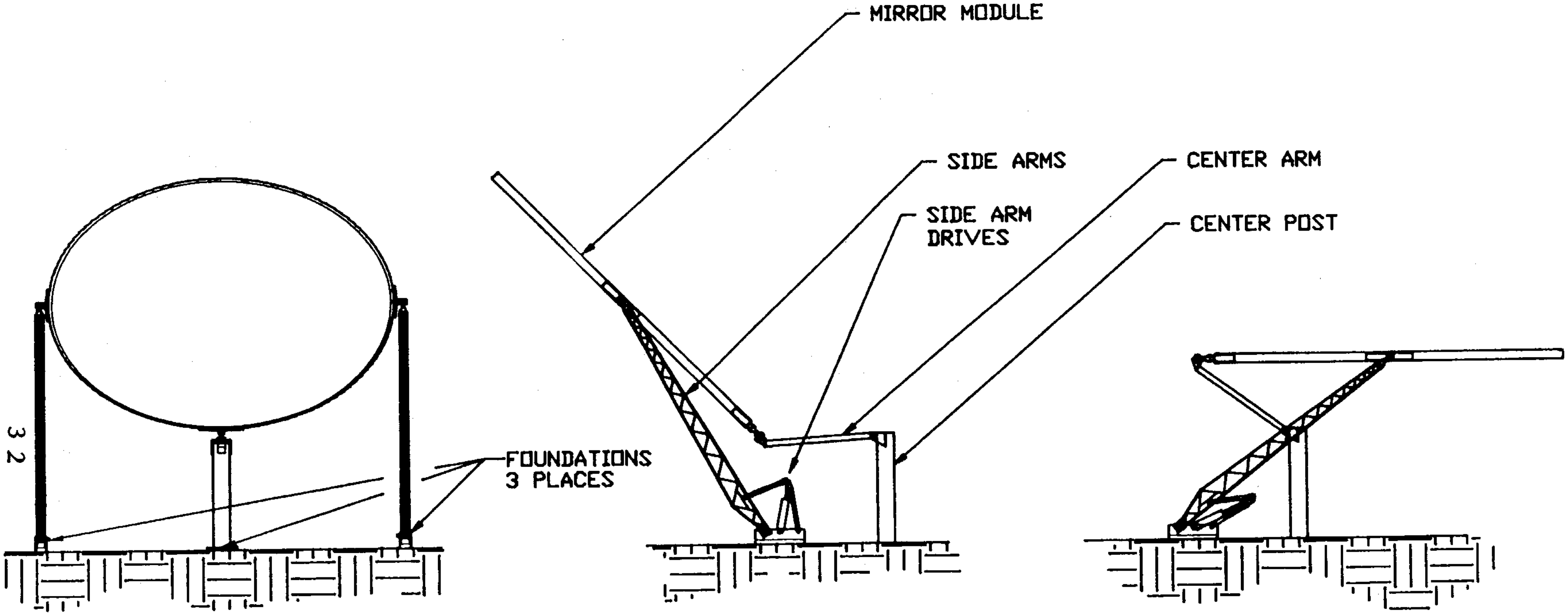
Figure 4.3-5. Slider Heliostat Drive Concept



REAR ELEVATION

SIDE ELEVATION

STOWED POSITION

8 METER
(26 FEET)

Figure 4.3-6. Multi-Bar Heliostat Drive Concept

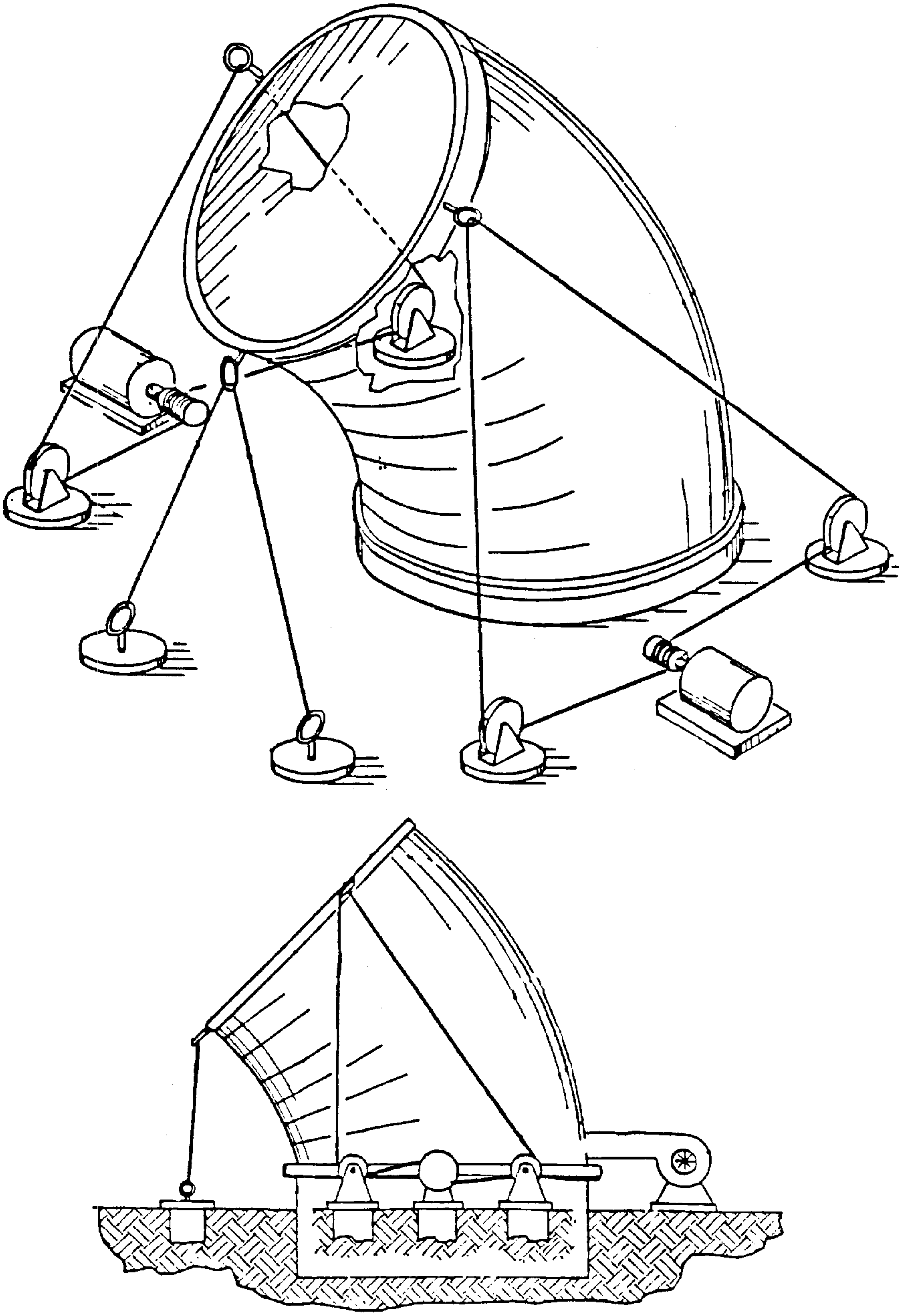


Figure 4.4-1. Airbag Heliostat Drive Concept

4.4.2 Yoke

This concept is shown in **Figure 4.4-2.** Variations of this drive have been widely used in antenna supports and was it used in the heliostats built at the Central Receiver Test Facility at SNL. Advantages of this drive include simplicity of the drive structure, easy installation, and adaptability to wind avoidance. Disadvantages are high loads (bending and twisting) on the yoke structure, high overturning moments on the azimuth drive, and poor (two-point) support of the mirror module.

4.4.3 Twist

This concept is pictured in **Figure 4.4-3.** It consists of an offset rotational element which provides the "elevation" tracking, and a centered drive on a yoke-like mirror module support for "azimuth" tracking. The drive action is neither azimuth-elevation nor tilt-roll, but rather the "elevation" drive, being offset from the center of the yoke, allows the angle of the "azimuth" drive relative to the earth to be varied, and then the heliostat is rotated about the "azimuth" drive to the desired position. This drive has similar advantages to a yoke drive. Disadvantages include high moments on the pedestal, high drive motor loads, and a relatively high profile.

4.4.4. Split Drive Dual Module

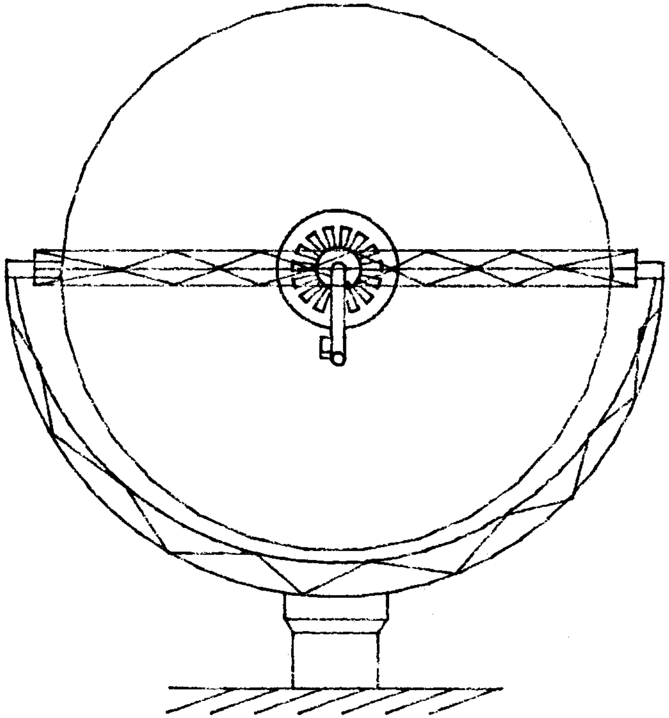
In the split drive dual module, the elevation angle of the mirrors is adjusted by two separate drives, located at the center of pressure of each module. Otherwise, its form is similar to the dual module design. This drive has the disadvantage of unnecessary duplication of drive components compared to the dual module heliostat design.

4.4.5 Single-Point Support

The simplest imaginable support, this concept is shown in **Figure 4.4-4.** Essentially, it consists of a foundation with a drive unit mounted at ground level to which the mirror module is attached at one point. A truss is shown in the figure reaching up to the focus-control system to provide support for the actuator. Advantages of this concept are simplicity and a minimum number of elements. A major disadvantage is that the mirror module is only supported at one point, so it would have to be very stiff to meet pointing error requirements. Also, the drive unit would have very high moments on it.

Advantages
Face down stow.
Simple structure.
Adaptable to wind avoidance.
Easy installation.

Disadvantages
Elevation drive imparts torque on mirror module.
High overturning moment on azimuth drive.
High twisting and bending loads on yoke structure.

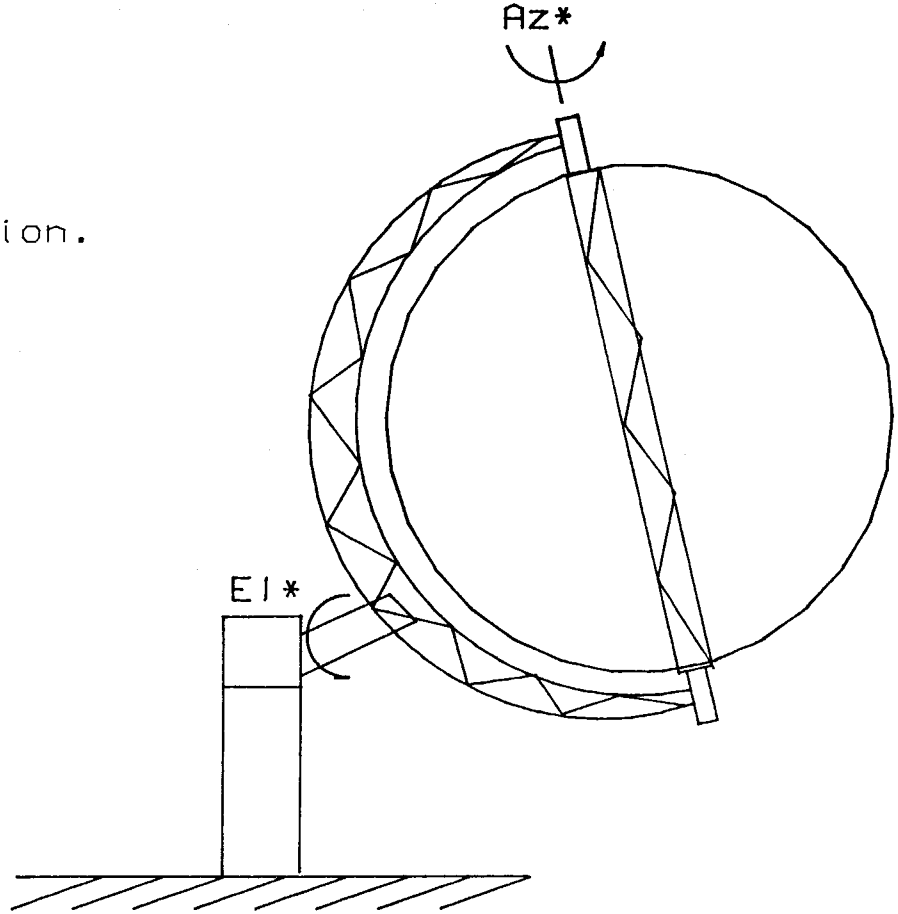


Status - Retained in second downselect

Figure 4.4-2. Yoke Heliostat Concept

Advantages
Polar tracking action.
Simple structure.
Face down stow.

Disadvantages
High drive loads.
High base moments.
High profile.

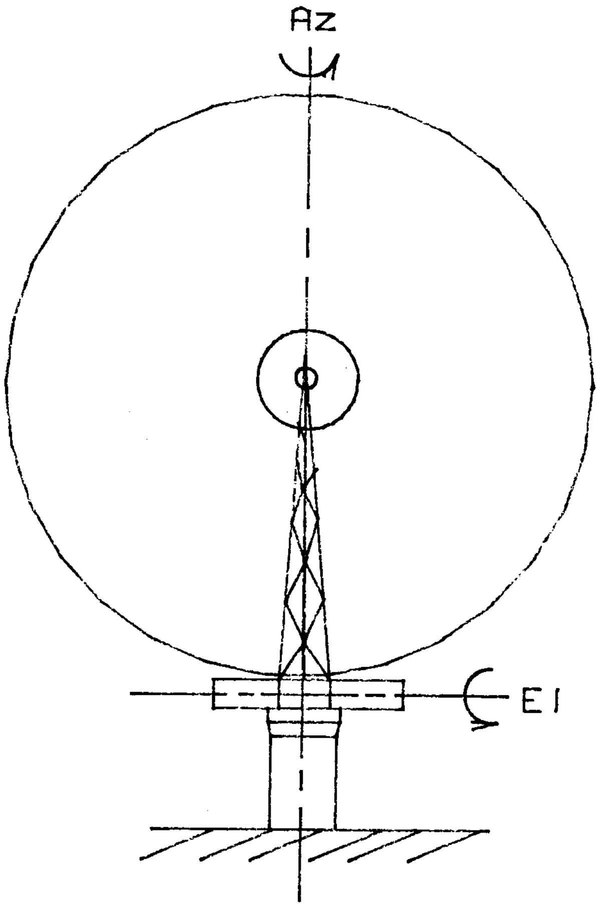


Status - Eliminated in first downselect

Figure 4.4-3. Twist Drive Concept

Advantages
Very simple structure.
Face down stow.

Disadvantages
Higher mirror module loads.
High elevation drive loads.
High azimuth drive bending moment.
Poor planarity control.



Status - Eliminated in first downselect

Figure 4.4-4. Single-Point Support Drive Concept

5.0 QUALITATIVE ASSESSMENTS AND DOWNSELECTS

The literature review and brainstorming sessions led to identification of a large number of concepts for evaluation. As described in an earlier section, the concepts identified during brainstorming sessions were not always feasible, but were recorded in order not to limit creativity. However, once innovative concepts had been generated, it was necessary to limit the number of concepts to be examined. This section describes the process and results of the qualitative assessments that were performed.

A few of the concepts were special cases. For instance, the pedestal drive was the baseline concept against which all the others were compared. Therefore, except for analysis to establish its estimated manufactured cost, it was not included in the evaluations. Another special case was the multi-bar heliostat, which is under evaluation under a separate Department of Energy program (Small Business Innovative Research). Finally, the SKI heliostat drive concept which employs spokes to attach the heliostat ring to a central post was not evaluated since it is being evaluated under a separate program.

The downselect process on the remaining concepts was carried out in two stages. In the first stage, those concepts for which serious doubts were present about their ability to function adequately, and those for which disadvantages outweighed the advantages for use with stretched-membrane heliostats, were eliminated. Of the 22 concepts at this point, 11 were eliminated from further consideration at this stage. The eleven concepts eliminated, and reasons for their elimination, are as follows:

Weather Vane

Production of two different-sized modules negates any advantage of the doubled production rate. Moments generated during operation could cause problems in the drive units.

Scissors

This was felt to be too complex in its motion, and required large tracked drive units which would be costly. Stresses in the drive arms would be very high at some orientations.

Folding Pedestal/Turntable

The turntable support would be difficult to build. High moments would be present in the bottom mirror module support. The two-point support would lead to a heavy mirror module and high loads on the mirror module ring.

Circular Track

The foundations and track would be expensive to produce, sensitive to ground motion, and exposed to the atmosphere. The drive arms would have some awkward positions in which loads would be high. Multiple linkages would be necessary on the drive arms.

Jacked Axis

The lateral strength would be poor, leading to questions of pointing accuracy and wind resistance. The elevation arm would have high compressive stresses, so buckling would be a concern. Two-point support would lead to a heavy ring and high forces for the roll axis drive.

Slider

This has similar problems to the jacked axis. In addition, it requires a track on the ground that is exposed to the atmosphere.

Totem Pole

This has the same disadvantages as the jacked axis concept.

Airbag

There were concerns about the pointing accuracy of this concept in winds. Also, the durability of the air bag and its strength requirements were of concern. The face-up stow position, although providing good wind-avoidance, would lead to high soiling and hail damage.

Twist

This has very high moments on the pedestal, and offers no real advantages over a yoke mount.

Split Drive Dual Module

This was seen as having no advantages over the normal dual module concept, except for reduced moment of the elevation drive units.

Single Point Support

This concept would require a very heavy heliostat ring and a very stiff mirror module, in order to limit the deflection of the module. The drive unit would be exposed to high torques, although it would be solidly mounted on the ground.

In the second stage, qualitative comparisons were made between the remaining concepts in order to rank them in an approximate manner. This allowed us to quickly determine those with significant advantages and those that were less interesting. The purpose of this ranking was to allow selection of the top few concepts for further study. In performing the second selection, some of the considerations were as follows (order not significant):

- estimated manufacturing cost
- complexity
- parts count
- mass
- pointing accuracy and precision
- reliability
- land use
- stability with regard to wind forces
- face-down vs face-up stow capability
- number of foundations
- access for cleaning
- low profile
- parasitic energy use

- automatic stow capability
- development risk
- gear reduction needed
- amount of field assembly required

These considerations allowed the field to be narrowed from eleven concepts to the three concepts that seemed to have the best potential for cost reduction and performance. The three selected concepts were the dual module, the shared support, and the yoke drive. Some reasons for not selecting the other concepts are given in the following paragraphs, followed by descriptions of the expected benefits from the selected systems.

The offset dual module design is in many respects similar to the dual module. It was therefore eliminated from further evaluation as a separate concept, but held as an option to the dual module concept if wind-avoidance had been shown to be an issue. Wind-avoidance was later found not to be a significant issue, so this concept was dropped from evaluation in favor of the dual module design.

The centerless drive concepts were considered as good on the whole, but there were concerns about their support (mainly for those concepts with vertical tilt-drive rings) and the cost and performance penalties (blocking and shading) associated with transverse tracking rings. Of the centerless concepts, the shared support drive was considered to have the most likelihood of low cost and efficient performance.

The folding pedestal rigid arm drive concept suffered from a requirement for carrying large compressive and bending loads in long, thin elements, leading to concerns about buckling. It also had relatively poor lateral strength, leading to concerns about its stability. Finally, it relied on a two-point heliostat support approach, which would lead to high mirror module costs.

The dual module system is expected to have many advantages. It builds upon present experience in pedestal drive, module fabrication, and torque tube design. The drive is balanced from a force point of view, so that drive motors need only deal with moment loads on the heliostat. The positioning of the drive is straight-forward, with no anomalous positions or limits. Face-down stow is provided, as well as feathering into the wind if desired. Finally, the supporting structure is robust and efficient.

The shared support design has the potential for cost reduction due to the efficient use of materials. The drive system has naturally high gear reduction on the roll axis, and the dual pedestal support makes for a strong structure. Sharing of drives between pairs of mirror modules could reduce drive costs. The transverse ring, besides giving high gear reduction, gives support to the mirror module ring so that it can be made lighter.

The yoke heliostat's main advantage is simplicity of structure. Although the yoke is a significant structural element, it is simple in design and efficient.

6.0 PRELIMINARY ANALYSES AND COST ESTIMATES

The following subsections summarize the analyses and estimates that support the initial cost estimates. Section 6.1 discusses the manufacturing scenario, and the estimates of capital equipment and labor costs. Section 6.2 describes the structural analyses that were performed to size components. Section 6.3 presents the initial estimates that were made for cleaning and reflective film replacement costs. Finally, Section 6.4 presents the initial cost estimates for the selected heliostat designs.

6.1 Baseline Manufacturing Scenario

In order to estimate heliostat costs, the manufacturing scenario from an earlier contract [1] was updated. In that contract a heliostat cost based upon a production rate of 50,000 heliostats per year was generated. In order to provide a more realistic estimate in today's energy market, the production rate was reduced to 5,000 heliostats per year. This reduction in the production rate has large consequences for the design of the manufacturing plant and how the production is carried out.

The basic parameters for the current study are as follows:

- 5,000 heliostats produced per year
- 150-m^2 (1610-ft^2)heliostats
- Construction of one 100 MW_e (341 MBTU/h) plant per year
- One site active at a time
- 250 8-hr work days per year (with a 2 week plant shutdown for moving to the next site)

These assumptions result in a production rate of 20 heliostats per day of operation, or 24 minutes per heliostat.

Since in this scenario only one plant is being built at a time, it makes sense to consolidate all of the manufacturing activities at the location of the solar plant, so that overhead and transportation costs can be minimized. Thus, it was assumed that all manufacturing activities, from welding of membranes to assembly and installation of the finished heliostats, were carried out at one facility located at the solar plant site. This facility was assumed to have been installed and to operate for the one-year construction period of the plant, after which the building would be turned over to the plant and the tooling would be transported to the next plant site and set up during the two-week manufacturing plant shutdown.

The calculations began with consideration of the membrane welding. First, it was determined how the welding needed to be done, and estimates were made of how long the welding would take with different welder configurations. Then, using the required production rate of 40 membranes per day, the best configuration in terms of minimizing personnel and production space was determined. Next, production area and personnel requirements for each of the activities associated with the manufacture of a heliostat were estimated. Then, the costs of the building and equipment were estimated and the cost per heliostat was annualized. Finally, adjustments were made to the materials costs of various components and manpower requirements were allocated to the various components of the heliostat to obtain an updated cost per component.

6.1.1 Membrane Welding

The basic assumptions in the welding analysis were that 3-mil stainless steel foil would be available in 0.61-m (24-in.) width rolls, and that an overlap of 0.01-m (0.39-in.)would be used in welding the seams. With these assumptions, 24 strips of foil would be necessary to produce the desired 14.0-m (46-ft) membrane diameter. The 24 strips would, in fact, produce a total width of 14.4-m (47.23-ft).

It was determined that cutting the membrane to form hexagonal or octagonal shapes would not necessarily produce a simplification of the process and would waste the material. In order to use angled cuts to reduce material waste, the strips would either have to be stored up for use on the other half of a membrane, or else every other strip would have to be turned over after being cut. This would be a difficult handling problem. Even if these things were done, a hexagonal cut would result in only 80% material utilization, and an octagonal cut would result in 85% utilization.

Rather than cutting the membrane strips in a geometric shape, therefore, it was decided to cut each piece square, and make the strips just long enough to provide a minimum finished diameter. Since the welding produces a membrane of 14.4-m width, that was the diameter chosen, so that the membrane would be circular. Thus, each strip of foil was assumed to be cut perpendicular to the length, so as to form a minimum 14.4-m diameter of finished surface. This gives the necessary 14.0-m diameter for the heliostat ring, with a 0.2-m (7.9-in.) allowance around the edge for tooling. **Figure 6.1-1** shows how the membrane would look, and the lengths of the strips making up the membrane are given in the following table:

Strip Numbers	Length (m)
1 and 24	5.8
2 and 23	8.0
3 and 22	9.5
4 and 21	10.7
5 and 20	11.7
6 and 19	12.5
7 and 18	13.1
8 and 17	13.6
9 and 16	14.9
10 and 15	14.2
11 and 14	14.4
12 and 13	14.4
Total	142.8-m per half-membrane, or 285.6-m per membrane

The lengths of each strip would be marked on the cutting/welding tables to simplify the measurement process (see below). The total amount of material needed for a single membrane is 0.61*285.6 = 174.2-m^2 (1875-ft^2). Of this, 153.9-m^2 (1656-ft^2) is usable, which gives an 88% utilization of materials. The amount of welding needed for one membrane is 285.6-m (937-ft). At 2.7-m/min (8.9-ft/min), this translates into 105 minutes of welding.

Once the number and length of the weld seams were determined, the next step was to lay out the welding hall so as to achieve the desired production rate. Production rates for several configurations, with from one to eight weld heads, were estimated. With multiple weld heads, the total length of weld per pass is reduced due to the difference in weld length for different strips. However, the set-up time for the weld and the number of weld passes that are needed affect the total time needed for welding a membrane. All weld rate calculations were based upon the same general welder configuration, consisting of a stationary weld table, a traversing welder, and a take-up roller parallel to the table (see **Figure 6.1-2**). The foil was assumed to be unrolled onto the long, flat table and cut to length. Then, it would be positioned for welding and secured in position using a vacuum. Next, the roll-resistance welder would traverse an overhead trolley along the length of the edge of the foil to weld it to the existing membrane. Finally, the newly welded membrane would be rolled up onto the long take-up roller and the free edge positioned on the table for the next weld. With multiple weld heads, the table would be made wider, and several strips would be positioned and welded together at one time by a gang of roll-resistance welders. If it would be more efficient, multiple rolls of foil could be used at the end of the table. Another idea, identified but not investigated, was the possibility of having the foil feed into the welder directly from the roll as the welds were made (see **Figure 6.1-3**).

The welder configurations considered included single-head, tandem single-head, dual-head, dual-head tandem, six-head, and eight-head. The tandem configurations involved using two roll-resistance welders on the same seam, working in tandem. These configurations were investigated in order to speed up the welding portion of the process. The multiple-head welders are expected to both speed up the welding process by performing multiple seams at once, and also to reduce the floor space and manpower requirements for the welders by reducing the number of weld stations required to meet the production demands.

With 24 strips of stainless steel foil per membrane, 23 seams would be needed. Therefore all but the single-head configurations involved a pass in which one of the weld heads would not be used. For the dual-head configuration, 12 weld passes would be required for each membrane, and for the six- and eight-head configurations, four and three passes would be required, respectively.

The time estimate for welding a membrane is as follows for the single-head welder configuration (note: in many of the following calculations, the average seam length of 12.3-m was used, which gives a welding time of about 5 minutes):

Roll out/cut strip	1 min
Position for welding	4
Weld	5
Roll up onto take-up roller	1
	----------
	11 min per seam
	x 23 seams
	----------
	253 min (4.2 hour) per membrane

For 40 membranes per day, this translates to 168 hours of welding per day, which would require 21 parallel lines. Similar time estimates for the other configurations are summarized in the following table:

	Dual-Head	Single-Head Tandem	Dual-Head Tandem	6-Head	8-Head
Roll out/cut strip	2	1	2	4	6
Position for weld	6	4	6	10	10
Weld	5	2.5	2.5	5	5
Roll up onto take-up	1	1	1	1	2
Minutes per seam	14	8.5	11.5	20	23
Hours per membrane	2.8	3.3	2.3	1.3	1.2
No. parallel lines	14	17	12	7	6

From the table, it can be seen that adding weld heads reduces the required number of parallel lines significantly. Having two weld heads operating in tandem has relatively little effect because of the time overhead involved in getting the strips cut and aligned. Finally, the addition of weld heads above six results in only a small advantage.

Weighing the relative advantages of the various configurations, the six-head weld station configuration was selected for further consideration. In this configuration, a membrane would be completed in four passes of the welder. Seven weld stations operating in parallel would produce 40 membranes per day with allowance for downtime and maintenance.

6.1.2 Space, Manpower, and Capital Cost Estimates

In the following paragraphs the indoor manufacturing and storage space and the manpower requirements for the manufacturing facility are estimated. In many cases, the same values have been used as those presented in the existing SAIC heliostat production scenario using individual site assembly plants. This production scenario was documented in Reference 11 and updated in Reference 1. In a few cases, labor has been added to achieve the desired production rate of 20 heliostats per day instead of 16 per day, which was used in the estimates for site plants.

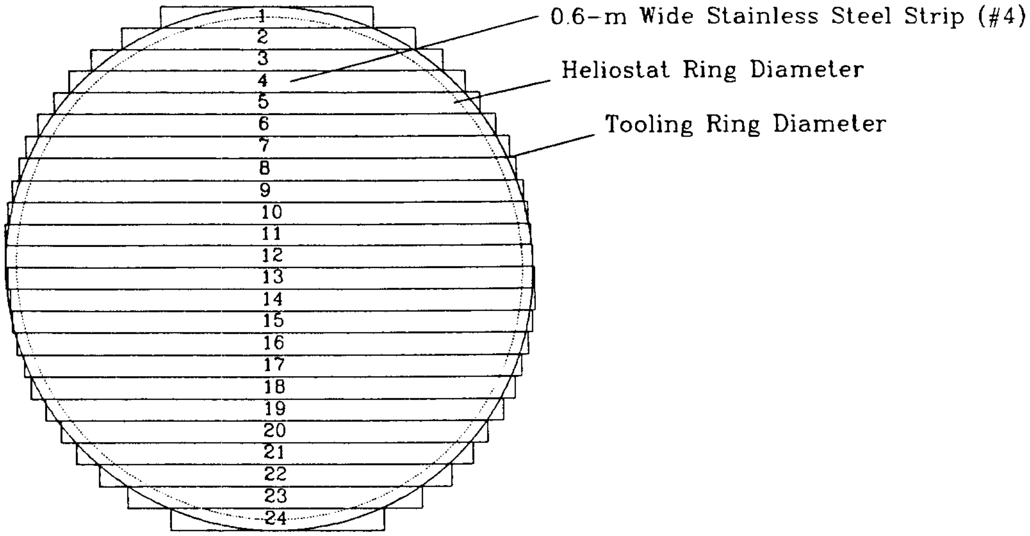


Figure 6.1-1 Heliostat Membrane Welding Pattern

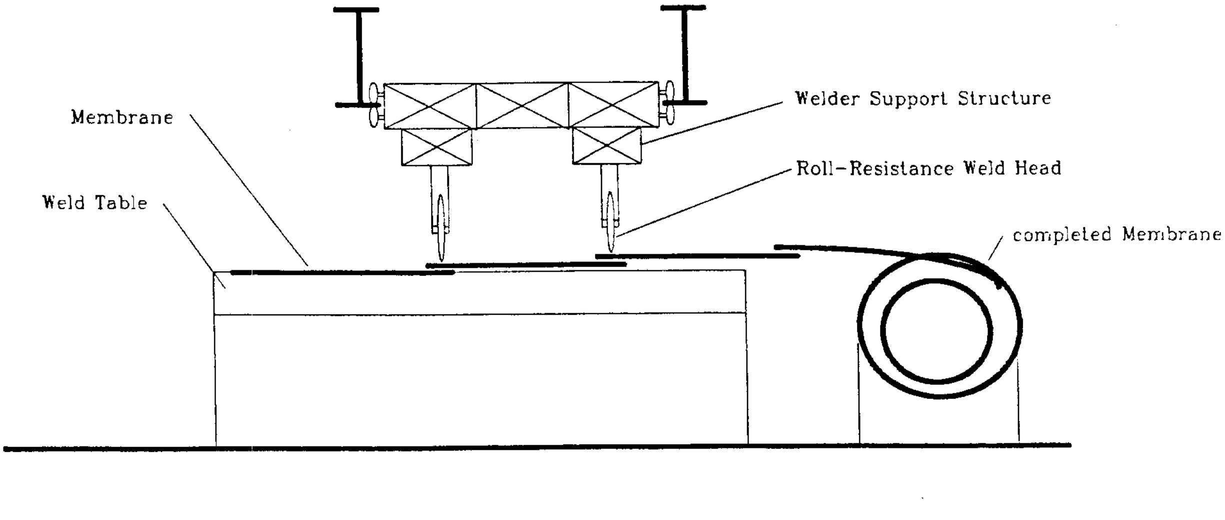


Figure 6.1-2. Welder Configuration

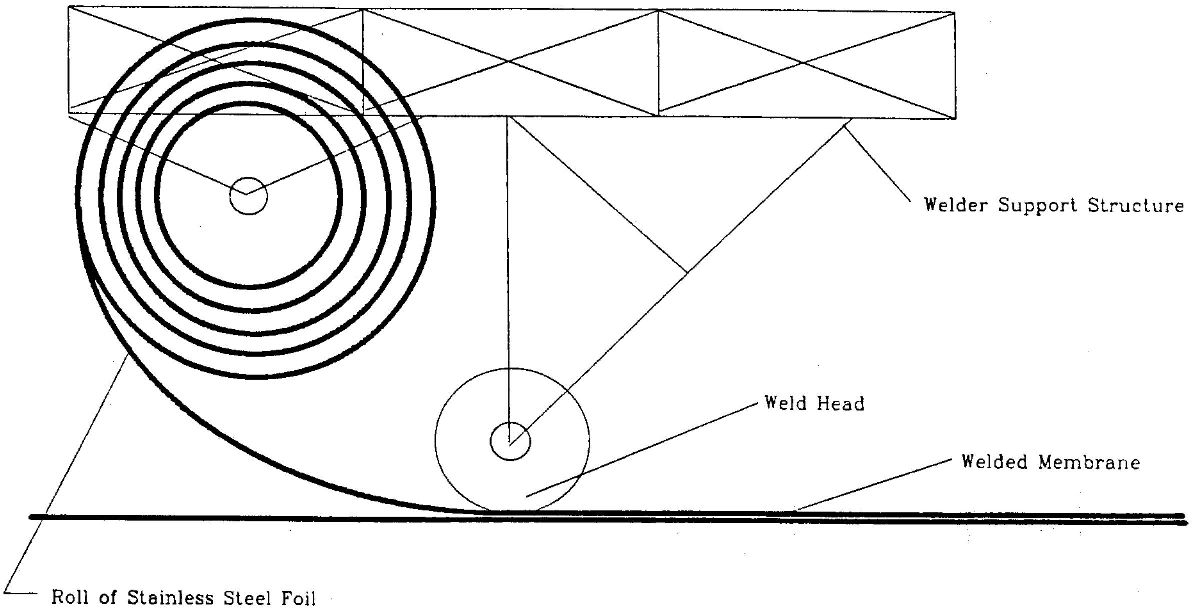


Figure 6.1-3 Direct Feed of Stainless Steel Foil to Weld Head

Membrane Welding - Each weld station consists of a two-meter aisle, a 4 x 15-m (13 x 49-ft) welding table, and a 2-m take-up roller, for an area of 120-m^2 (1290-ft^2). There are seven of these stations, for a total area of 840-m^2 (9040-ft^2). Allowing for indoor storage of 10 membranes (one quarter of a day's production), at 2 by 15-m (6.5 x 49-ft) per membrane, adds another 300-m^2 (3230-ft^2), for a total of 1140-m^2 (12,250-ft^2).

Each welding station will require two technicians, for a total of 14. There will also be two supervisors and one maintenance technician, for a total of 17 persons.

Ring Rolling - Like the previous production scenario, one ring-rolling jig is considered sufficient to supply the production needs. In order to speed production, two persons are added, to give a total of 9. The area required for ring rolling is about 15 x 15-m (49 x 49-ft). An area for vertical storage of rings is assumed to require another 2 x 15-m (6.5 x 49-ft) of floor space, for a total of 255-m^2 (2750-ft^2).

Membrane Attachment - Two parallel stations are envisioned, with four technicians per station and one supervisor, for a total of nine persons. This is two more persons than in the existing production scenario. The attachment stations are assumed to require 15 by 15-m (49 x 49-ft) each, and a storage area for about 10 mirror modules requiring another 10 by 15-m (33 x 49-ft). The total area required is, therefore, 600-m^2 (6450-ft^2).

Focus-Control Assembly - For the focus-control pad assembly, it is estimated that five technicians and one supervisor will be needed. The area requirements are two assembly areas of 3 by 3-m (10 x 10-ft), an area 5 by 5-m (16.5 x 16.5-ft) for storage of raw stock, and an area of 2 by 3-m (6.5 x 10-ft) for storage of finished pads. For the assembly of the electronic controls, two technicians and a 5 by 5-m (16.5 x 16.5-ft) area are estimated. So the total is eight persons and a total area of 89-m^2 (957-ft^2).

Fasteners and Attachments - It was assumed that the fabrication of gussets, brackets, and other attachment items would be carried out in a general machine shop which would also be used by the maintenance personnel. It is estimated that two persons, a welder and a technician/machinist, will be required to fabricate the fasteners and attachments. The machine shop is estimated to require a 10 x 10-m (33 x 33-ft) area, for a total of 100-m^2 (3280-ft^2).

Structural Support - The fabrication of the trusses is estimated to require two process lines, each with three persons, and a supervisor. The area requirement is estimated to be 10 x 10-m. Fabrication of the pedestal and hub is estimated to require six persons (four for hubs, and two for pedestals). So, the total personnel requirement is 13 persons, and the area required for these activities is 100-m^2 (3280-ft^2).

Module Assembly - Like the existing production scenario, assembly of the mirror modules to the structural supports is estimated to require two parallel stations. A total of eight persons at the two stations is estimated to allow production at the necessary level. This represents an addition of one person per station compared to the existing scenario. The area required is estimated to be 15 x 15-m (49 x 49-ft) for each assembly station. Buffer storage is expected to be outdoors.

Field Assembly and Checkout - This is expected to follow the existing production scenario. A total of 10 persons is required, and no indoor space.

Shipping/Receiving - Because materials for the entire heliostat production process must be handled, the shipping and receiving portion of the facility is estimated to be somewhat larger than that for the field sites in the existing production scenario. The personnel estimate is for one manager, two dock people, and one warehouse person, for a total of four persons. Shipping and receiving is estimated to require about 10 x 10-m of indoor storage, as well as about 10 x 20-m of outdoor storage. The total building area required is 100-m^2.

Maintenance - It is estimated that two machinists and two mechanics would be required to perform general maintenance on the equipment in the plant. They would use the machine shop described above under Attachments and Fasteners.

Front Office - Since all production would be in one facility, the front offices were assumed to be co-located at the site. The following estimates are made for the personnel requirements:

Purchasing: 1 manager/order analyst
1 buyer

Accounting: 1 controller
2 clerks

Engineering: 1 manager
2 plant/production engineers

Marketing: 1 manager
2 market specialists (Utility and IPH)

Corporate: 1 president
1 vice president
2 secretaries
15 persons

The area required for each person is estimated to be 10-m^2 (110-ft^2), for a total of 150-m^2 (1610-ft^2) of office space.

The totals of these estimates for the production facility are 73 direct labor persons, 23 indirect persons (i.e., front office plus shipping and receiving and maintenance staff), and a requirement for about 3,000-m^2 (32,275-ft^2) of high-bay and office building. Using rates of \$320/m^2 (\$30/ft^2)for the building, the total cost is estimated to be \$960,000. In addition, field equipment is expected to cost about \$160,000 (the same as in the existing production scenario), and production equipment is estimated to cost \$6,050,000 (estimated at 1/6 of the production equipment cost in the existing scenario).

Totalling all of the capital items, the total capital cost of the manufacturing facility is estimated to be \$7,170,000. This is about 1/7 of the capital costs in the existing production estimate. To estimate the cost of the capital equipment per heliostat, the following analysis was used:

- 10 year life
- 12% interest rate
- Capital Recovery Factor = 0.17698
- Total building costs equal to purchase of one building over 10 years (site owner to take over production facility building after completion of construction)

Annual cost = \$7,170,000 * .17698 = \$1,270,000

Cost per heliostat = \$1,270,000 / 5,000 = <u>\$254</u> (\$1.70/m^2)

In the heliostat cost estimates, the labor costs are allocated to the appropriate items to which they contribute. However, an estimate of the overall labor costs per heliostat may be made as follows: 73 direct persons cost approximately \$4,555,200 at \$30/hour and 2,080 hours per year. They produce 5,000 heliostats per year, giving a unit cost of about \$911 per heliostat. Similarly, 23 persons as indirect labor, at \$40/hour, contribute a cost of about \$1,913,600, for a unit cost of about \$383 per heliostat. Thus the total labor cost per heliostat is approximately \$1,294 (\$9/m^2).

6.1.3 Heliostat Materials Cost

The heliostat materials costs for the baseline pedestal drive were updated using the above labor and capital equipment estimates and the new materials estimates for the foundation, pedestal, drive, and so on from information received from SNL [6] . The estimate was done in First Quarter 1988 dollars, consistent with previous estimates. A breakdown of the updated total heliostat cost including labor, capital equipment, and other materials costs is given in **Appendix C.**

The modifications to the cost estimate compared to the one which was performed as part of the Heliostat Design Improvement program are described below:

Drive System - The cost for a Winsmith drive unit was estimated to be \$14.32/m^2 (\$1.33/ft^2) at a production rate of 50,000 per year, in April 1988 dollars. Therefore, for a 150-m^2 (1610-ft^2) heliostat, the cost would be \$2148. For the reduced production rate of this study, and to allow for consistency between estimates, estimates for individual drive components were developed. These estimates are summarized in **Table 6.1-1.**

	Cost ($/m² at 5,000 units/year)	
	Azimuth Drive	Elevation Drive
Shared Support		
Wind-avoiding	2.47	6.94
Non-wind-avoiding	2.47	9.13
Dual Module		
Wind-avoiding	7.14	6.41
Non-wind-avoiding	10.98	8.43
Yoke		
Wind-avoiding	7.69	6.94
Non-wind avoiding	11.82	9.13
Pedestal		
Wind-avoiding	7.14	4.26
Non-wind-avoiding	10.98	5.60

For wind-avoiding designs add:		
	Torque Limiter	$368.60
	Slip Sensor	35.00
	Re-Reference System	100.00
		$503.60 ($3.36/m²)

Table 6.1-1. Estimated Costs of Drive Components

Pedestal - A cost estimate of a pedestal was performed, and a cost of $1,484 was arrived at as follows:

Tube: 34.5-ft. = 10.516-m long
28.5-in. = 0.724-m diameter
0.5-in. = 0.013-m thick
Flange: 28.5-in. = 0.724-m diameter
0.75-in. = 0.019-m thick

Density of steel = 489.6 lb/ft³ = 7842 kg/m³
Cost of steel = $0.265/lb = $0.584/kg

Materials cost: Tube: 3.1416*.724*.013*10.516*7842*.584 = $1424
Flange: $3.1416*(0.724)^2*0.019*7842*.584/4$ = $36
=======
Total Materials $1460

Fabrication Labor: 0.8 hours * $30/hour = $24
=======
Total $1484

Foundation - Reference 6 gave an estimate of $200 for foundation costs for comparable size heliostats. This value was adjusted for inflation from January 1, 1987 dollars by adding 6%, which yielded $212 as the estimated cost.

The labor cost for installation of the pedestal was given as about $45. This amount was included as part of the labor costs for field assembly and checkout given above. Expressed on a per-heliostat basis, that cost is:

10 persons * 8 hours/day * $30/hour / 20 heliostats/day = $120

It seemed reasonable that about 40% of this cost ($45*1.06 = 40% of $120) could be allocated to installation of the pedestal, so no adjustment of this value was made.

Field Wiring - The value given by Alpert was $125, and this was adjusted for inflation to give $133.

Labor - Using the labor estimates given in the preceding section, the direct labor was allocated to the appropriate physical components of the heliostat. The results are summarized in the following table:

Component	Persons	Production Labor Category
Mirror Module		
Front Membrane	8.5	Membrane Welding
	4.5	Membrane Attachment
Rear Membrane	8.5	Membrane Welding
	4.5	Membrane Attachment
Ring	6	Ring Rolling
Focus-Control Pad	6	Focus-Control Ass'y
Focus-Control Electronics	2	Focus-Control Ass'y
Module Support Structure		
Attachments/Fittings	2	Fasteners and Attachments
Foundations		
Pedestal	2	Structural Support Fab.
Drive System		
Structural Elements	11	Structural Support Fab.
Module Assembly	8	Module Ass'y
Installation	10	Field Ass'y/Checkout
Indirect Labor	15	Front Office
	4	Maintenance
	4	Shipping/Receiving

Total	96 persons	

6.2 Structural Analysis

In order to provide a baseline for comparison, several structural analyses were conducted. The goal of these analyses was to size structural members of the selected drive designs so as to meet a set of support structure deflection design points. This approach allowed all the drives to be compared on the basis of equal performance. Wind loads were based upon data from Reference 9, for isolated heliostats in an open-country environment. The operating wind load was taken to be 31.25 mph, which resulted in 50 mph peak winds for survival in any orientation. The operation specifications also require survival in 90 mph peak winds (58 mph mean winds) in stow orientation but the 50 mph peak winds in any orientation were determined to be a more severe loading condition. The geometry of the wind loading is shown in **Figure 6.2-1**, and the wind loads are presented in **Table 6.2-1.**

To guide in the design of components, several criteria were used. Maximum stresses were limited to 60% of yield. Maximum mirror module slope error was limited to 0.6-mRad, and pointing error was limited to 1.5-mRad due to structural deflection. All heliostat rings were assumed to have a rectangular tube cross-section with a 3:1 aspect ratio and 0.090-in. wall thickness.

The drive concepts involved various numbers of support points for the mirror module. The 0.6-mRad slope error allowance was used with a model of the allowable ring deflection vs. slope error to determine maximum allowable ring deflections. (See **Appendix D.**)

The allowable deflections were used, along with a finite element analysis, to determine the required sizes of heliostat rings and their masses vs. the number of supports. The results are shown in **Figure 6.2-2.** In addition, it was determined that for mirror modules with fewer than five supports, increasing the thickness of the membranes from 0.003-in. to 0.005-in. would be necessary.

For the shared support and yoke drives, a focus-control support truss was designed to span the back of the collector module. This truss was sized to carry the focus-control actuator loads to the module support points under operational conditions. The weight of this truss was estimated to be 590 kg (1300 lb).

6.3 Initial Cleaning and Reflective Film Replacement Cost Estimates

The cost of heliostat cleaning and reflective film replacement were estimated for inverting and non-inverting heliostats. Cleaning frequencies of 12 times per year for inverting and 16 times per year for non-inverting heliostats were determined. Minimum-cost reflective film replacement intervals of 11 years and 7 years for inverting and non-inverting collectors were determined. The analysis behind these costs is presented in the following subsections.

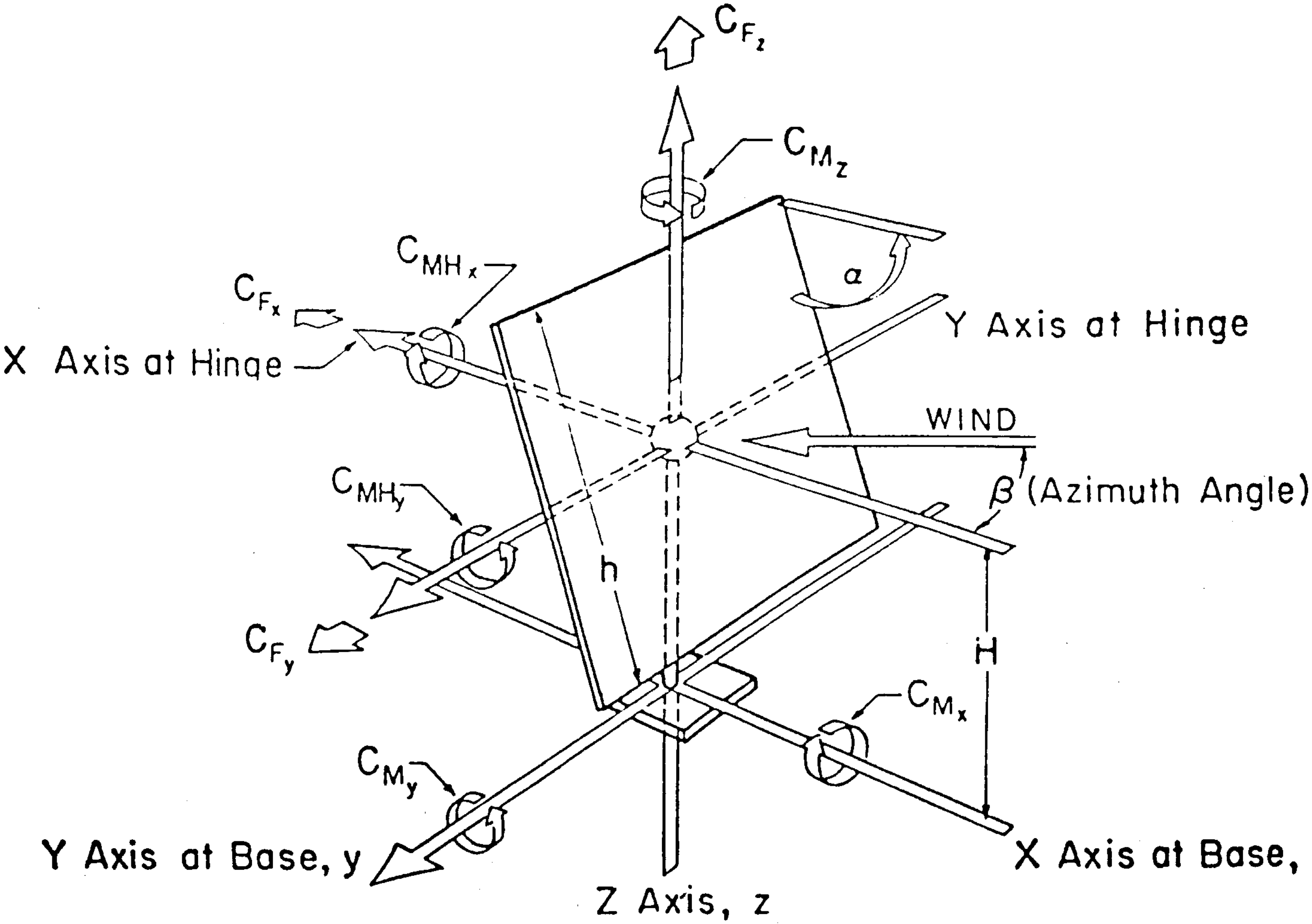


Figure 6.2-1. Wind Load Calculation Geometry

FORCES AND MOMENTS FOR 150 m^2 STAND ALONE HELIOSTAT

(Mean Wind = 31.25 mph, Peak Wind = 50 mph)

Component	α	β	Mean Value	Peak Value
F_x	90°	0°	* 7295 lb	* 14591 lb
F_x	30°	0°	3648 lb	7660 lb
F_x	90°	65°	5836 lb	13496 lb
F_z	90°	0°	1094 lb	3648 lb
F_z	30°	0°	* 4924 lb	* 10213 lb
F_z	90°	65°	1094 lb	1824 lb
M_{Hy}	90°	0°	18457 lb-ft	41498 lb-ft
M_{Hy}	30°	0°	* 41948 lb-ft	* 100675 lb-ft (1)
M_{Hy}	90°	65°	3356 lb-ft	25169 lb-ft
M_z	90°	0°	0	58727 lb-ft (2)
M_z	30°	0°	0	25169 lb-ft (3)
M_z	90°	65°	* 41948 lb-ft	* 117454 lb-ft
M_y	90°	0°	* 184571 lb-ft	* 364946 lb-ft
M_y	30°	0°	109064 lb-ft	226518 lb-ft
M_y	90°	65°	137589 lb-ft	322999 lb-ft

Where, α = Elevation Angle
β = Azimuth Angle
F_x = Drag Force
F_z = Lift Force
M_{Hy} = Moment About Horizontal Axis
M_z = Moment About Vertical Axis
M_y = Moment About Base

* Maximum Value

(1) Wind from the back. (Slightly lower value for wind from the front.)

Table 6.2-1. Forces and Moments for 150-m^2 Stand-Alone Heliostat

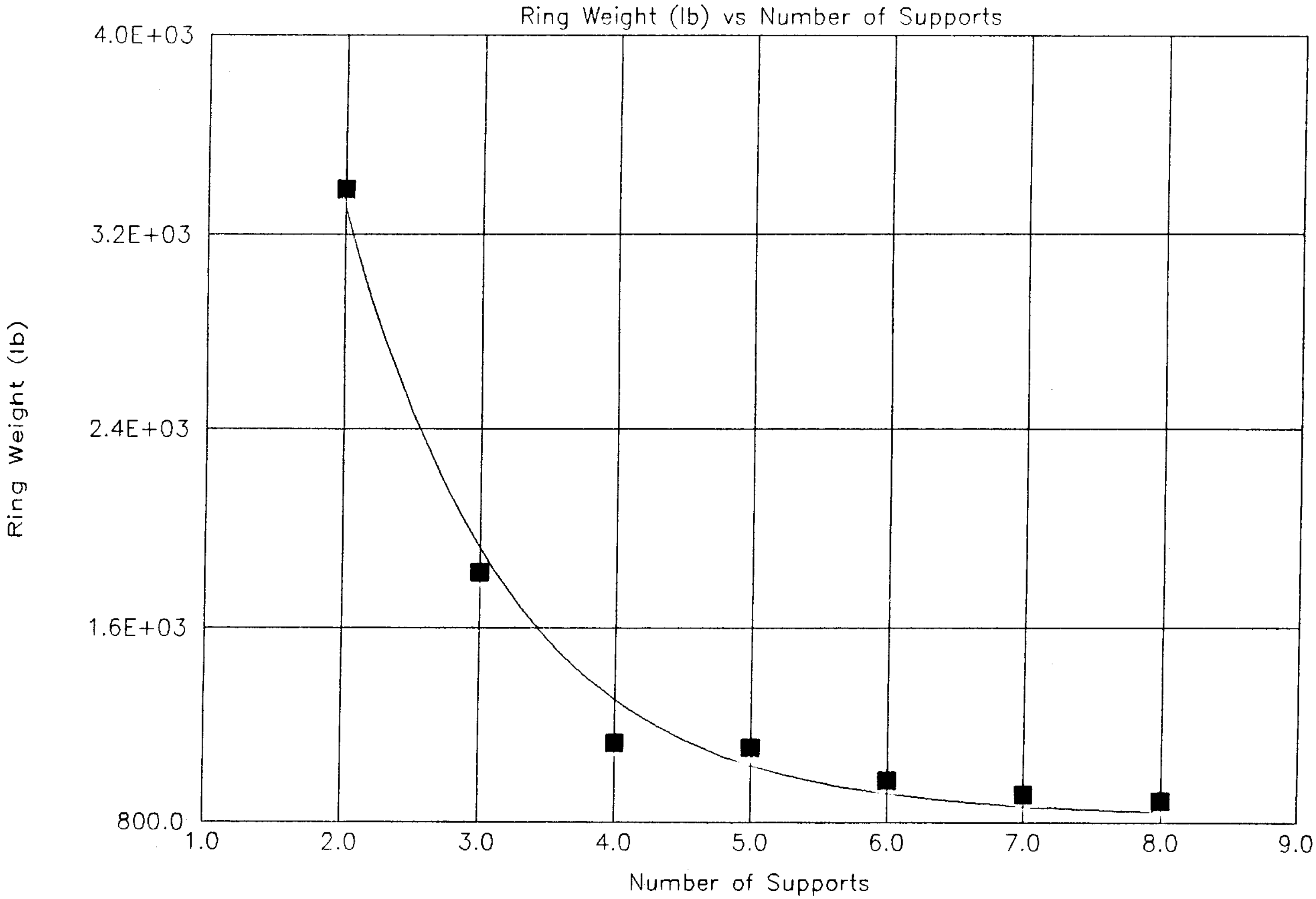


Figure 6.2-2. Heliostat Ring Weight vs. Number of Supports

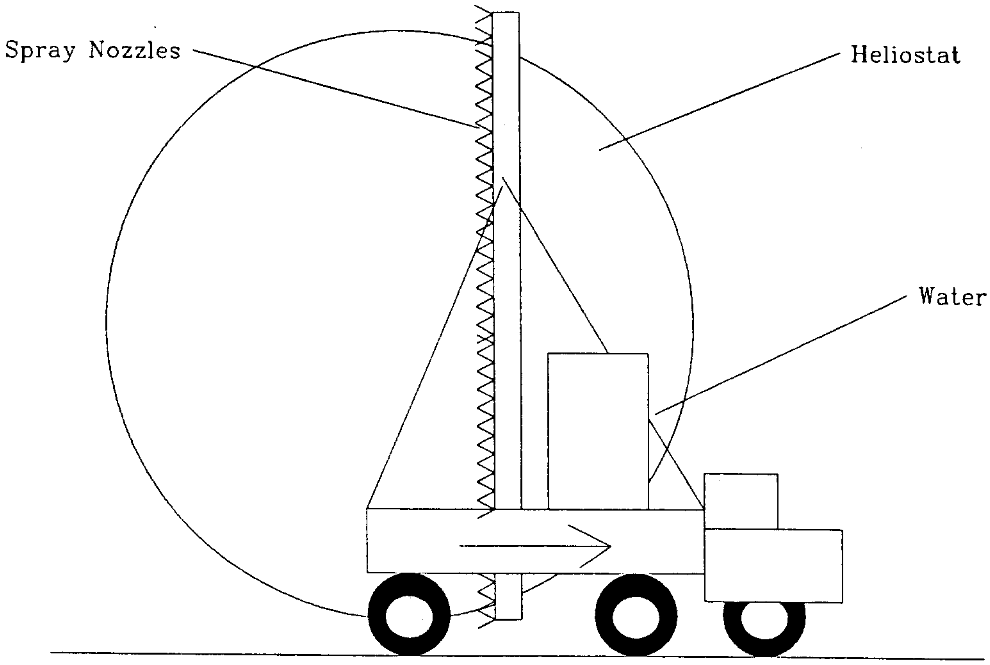
6.3.1 Heliostat Cleaning

To calculate the cost of heliostat washing, three factors are needed: (1) an estimate of heliostat soiling rates, (2) an estimate of capital equipment costs for cleaning, and (3) an estimate of direct costs for cleaning. The first of these three factors was obtained from the study performed by SNL to assess inverting heliostats [4]. The values are given in the following table:

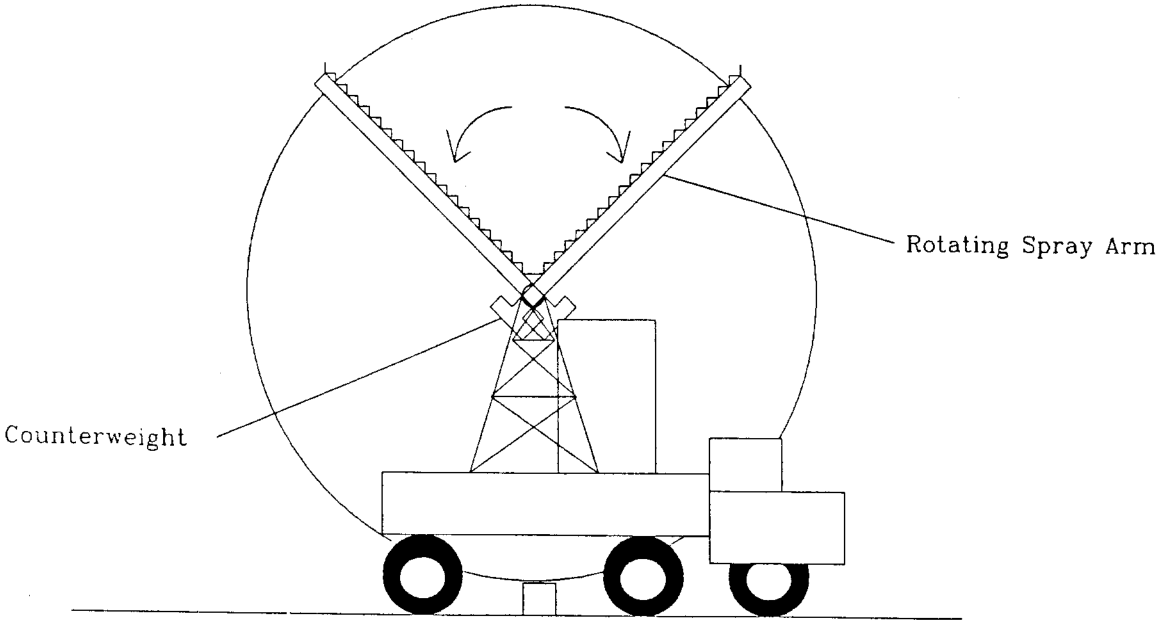
Type of Heliostat	Daily Reflectance Loss Due to Soiling (%)
Inverting	0.27
Non-Inverting	0.38

Using these values, cleaning frequencies of 12 times per year for inverting, and 16 times per year for non-inverting heliostats, were estimated. These frequencies were chosen to give approximately equal performance for the two types of collectors. The capital equipment cost for heliostat cleaning was estimated using the Foster-Miller cleaning system as a basis [7]. The washing system design was not developed in detail. The basic design is a truck-mounted high-pressure water spray unit, which can spray the heliostat as the truck is driven past or, with the truck parked in position, can spray over the heliostat (see **Figure 6.3-1**). To avoid scratching the surface, no direct-contact brushes are used on the reflective film, . Other basic assumptions are as follows:

- 1.5 minutes per heliostat (projected from 0.5 minutes per 50-m^2 heliostat)
- Water usage 121 liters per collector (based on 0.02 gal/ft^2)
- Fuel consumption of truck 45.4 liters/hour (based on 12 gal/hour)
- Fuel cost is $0.264/liter ($1.00/gal)
- 0.5 hours to reload truck
- 30-year life of truck
- One-man crew
- Truck sized for 60 heliostat washes before reloading (based on 2, 1000-gal tanks)
- Water cost $0.066/liter ($0.025/gal), for deionized water



(a) Mobile Heliostat Washing System with Moving Truck



(b) Mobile Heliostat Washing System with Stationary Truck

Figure 6.3-1. Mobile Heliostat Washing System Configurations

The cost estimate for a single truck-mounted system for washing heliostats is as follows:

$36000	Truck
1000	Control System
5400	Water Tanks
2000	Spray System Support
1000	Hose and Cable
600	Nozzles
500	12V DC Motor for Driving Wash Unit
300	Valves
300	Water Pump, powered from PTO on Truck
500	Miscellaneous Plumbing
500	Miscellaneous Electrical
$48100	Direct Cost
4810	Contingency (10%)
$52910	Total Direct Cost
15873	Markup (30%)
$68783	Cost in 1985 Dollars
13137	Inflation to January 1987 Dollars
$81920	Total Estimated Cost

To calculate the direct costs associated with cleaning a heliostat, it is first necessary to know the average time to clean one heliostat. This value is 1.5 minutes for washing plus 0.5 minutes (30 minutes/60 heliostats) for reloading the truck, or a total of 2.0 minutes. Using the assumed costs given above, the direct cost estimate is as follows:

$0.40	Gasoline
1.25	Labor @ $30/hour, 0.8 plant efficiency
0.80	Water
$2.45	Total

A single cleaning unit as defined above could clean about 60,000 heliostats per year.

6.3.2 Reflective Film Replacement

In order to estimate reflector replacement costs, similar factors are needed as are required for the cleaning cost estimate: (1) average reflectance degradation rates for inverting and non-inverting collectors, (2) estimated capital costs, and (3) direct costs for reflector replacement.

Two factors are important to reflectance degradation over the long term: reflective film degradation due to weathering, and effects of hail on non-inverting collectors. The degradation of ECP-300 reflective film has been documented for the Shenandoah Solar Total Energy Project over a period of about 1-1/2 years [8]. Using those data, an average environmental degradation rate of 1.6% per year was calculated.

Hail damage is much more difficult to estimate. Hail tends to be variable even on a local scale, and hail frequency and intensity vary widely even at a particular location. Average hail frequencies have been determined and plotted for the United States [4]. These data indicate that the Barstow area has an incidence of less than one hailstorm per year. An average of 0.5 hailstorms per year was therefore assumed. Direct experience with hail damage on stretched membrane heliostats is limited to the prototype heliostats installed at SNL, Albuquerque. Hail damage after one storm was estimated to consist of approximately 200 dents per square meter, with dents of about 7-mm (1/4-in.) in size. Assuming these dents to be slightly elongated to a shape of 7 x 10-mm (0.25-in. x 0.4-in.) due to angle-of-incidence effects, this corresponds to 1.4% damaged area per storm. For the analysis, damage of 2% per storm was assumed, giving a total estimate of the damage due to hail of about 1% degradation in area per year. This is essentially equivalent to 1% degradation in reflectance per year, and was used as such.

Combining the environmental degradation and damage due to hail, the estimated long-term degradation rates for inverting and non-inverting heliostats can be determined. Allowing for a reduction of 4% resulting from the reduction in reflectance due to cleaning, the results are:

Type of Heliostat	Annual Degradation Rate
Inverting	1.53%
Non-Inverting	2.49%

The capital cost for equipment needed to remove and replace heliostat reflectors was estimated at $60,000. Film replacement has not yet been tested on this type of heliostat. For the purposes of this study it was assumed that a specialized piece of equipment would be available which would remove the old reflective film by spraying a solvent and peeling off the loosened material. It was assumed that this unit would strip one 0.6-m (2-ft) width at a time, at a speed of about 6-m/min (19.7-ft/min). A second specialized unit would laminate a new reflective film onto the clean metal. It was assumed that this unit could apply the 0.6-m wide foil at a rate of 30-m/min(98.4-ft/min).

Direct costs for reflector replacement were based on the following assumptions:

- Replacement done insitu (i.e., with heliostats mounted to drive units in the field)
- 10.6-m^2 (114-ft^2) of reflector removed per liter of solvent (analogous to 400-ft^2/gal for paint). This value could be improved with solvent recovery.
- $2.64/liter for solvent ($10/gal)
- $16.145/m^2 ($1.50/ft^2) reflector film cost
- Two-man crew

The time estimate to replace the reflector on a single heliostat is as follows:

24.0 min	Align on new panel to be stripped (1 min ea. x 24 strips)
47.2	Strip 0.6-m panels (283.4-m @ 6-m/min)
9.4	Laminate panels (283.4-m @ 30-m/min)
9.4	Apply edge seal tape and spray sealant (283.4-m @ 30-m/min)
2.0	Move to next heliostat
92.0 minutes	

With an 80% plant efficiency factor, it would take a single team approximately 5.5 years to replace the reflectors in the entire plant. The direct costs associated with replacement of a heliostat reflector are estimated as:

\$113	Labor (2 persons @ \$30/hour x 1.5 hours / 0.8)
18	Gasoline (1.5 hr @ 45.4 liter/h x \$0.264/liter)
38	Solvent
2731	Reflector cost
\$2900	Total Cost

Reflector replacement costs were calculated using these values for replacement periods between 3 and 15 years. Present values of the future replacement costs were calculated, with the results shown in **Table 6.3-1.**

Replacement Period	Present-Value Cost	Annualized Cost
3	\$ 12,400	\$ 9,440,000
5	6,800	5,180,000
6	5,400	4,110,000
7	4,200	3,200,000
10	2,620	2,000,000
15	1,265	963,000

Table 6.3-1 Reflector Replacement Costs vs. Replacement Period

The costs in **Table 6.3-1** were used to calculate optimum replacement periods based on minimizing the busbar cost of electricity from the plant. Cost data from Reference 7 was used to estimate the effect of the maintenance costs on the busbar cost of electricity, as follows:

$$\text{bbec} = \frac{C + aC_w + bA}{KR}$$

where,

bbec = busbar cost of electricity
C = capital cost of plant
a = factor for maintenance costs
C_w = annualized maintenance costs
b = factor for operating costs
A = annual operating costs
K = factor relating reflectivity and energy production
R = average reflectivity of mirrors

The results of the replacement cost analysis are shown in **Figure 6.3-2.** The figure shows that the minimum cost for an inverting heliostat occurs with reflector replacement at ten-year intervals. For non-inverting collectors, the minimum occurs at about 7 years.

6.4 Initial Cost Estimates of Promising Drive Concepts

Using the results of the previous section, cost estimates for the four most promising drive concepts identified in the Phase I effort were constructed. The results are summarized in **Table 6.4-1.** Detailed cost estimates are given in **Appendix A.** The estimate for the pedestal drive used the baseline manufacturing scenario values given in the previous subsection. For the others, slight modifications were necessary to account for changes in design, assembly, and installation of the heliostats. These modifications are described in the following subsections for each of the drive systems.

For pedestal drives, drive unit costs were based upon Peerless-Winsmith's low cost drives. For the yoke design, a Winsmith drive with a double wall thickness and a second set of load bearings was costed. For the dual module, shared support, and yoke elevation drives, the ATS large-area heliostat drive unit formed the basis for costing. Finally, off-the-shelf gear motor prices were used for the shared support azimuth drive.

For wind avoidance, the cost of torque limiters, slip sensors, and a re-referencing system were added to the cost of the heliostat.

6.4.1 Yoke

The activities for production of the mirror module for a yoke heliostat are unchanged from those for a pedestal heliostat. The changes come in the fabrication of the structural support elements and the assembly of the unit. The structure of the yoke heliostat is simpler than a pedestal unit, so it was estimated that only one line with four persons would be necessary. The elimination of the hub fabrication eliminates four persons, but two additional persons were estimated to be needed to fabricate the focus-control truss. Although module assembly would be simpler for a yoke drive, there would be more assembly of drive components, so the personnel for module assembly as a whole was estimated to remain the same. The net results of these changes was a reduction of five persons for manufacturing, and a reduction of 25-m^2 (270-ft^2) in the building requirement.

The mirror module for a yoke heliostat must be significantly stronger than that for a Pedestal drive, since it is supported at only two points. The estimated mass of a ring for those conditions was 1535 kg (3385 lbs). The thickness of the membranes was increased to 0.005-in. to increase the stiffness of the module. The yoke assembly was estimated to weigh about 454 kg (10,000 lbs). A very stiff yoke is needed to counteract the bending loads and moments placed on it by the mirror module during operation. The truss for the focus-control system added another 590 kg (1300 lbs). Finally, the pedestal for a yoke drive extends only to the surface, so the mass was reduced to 1060 kg (2336 lbs).

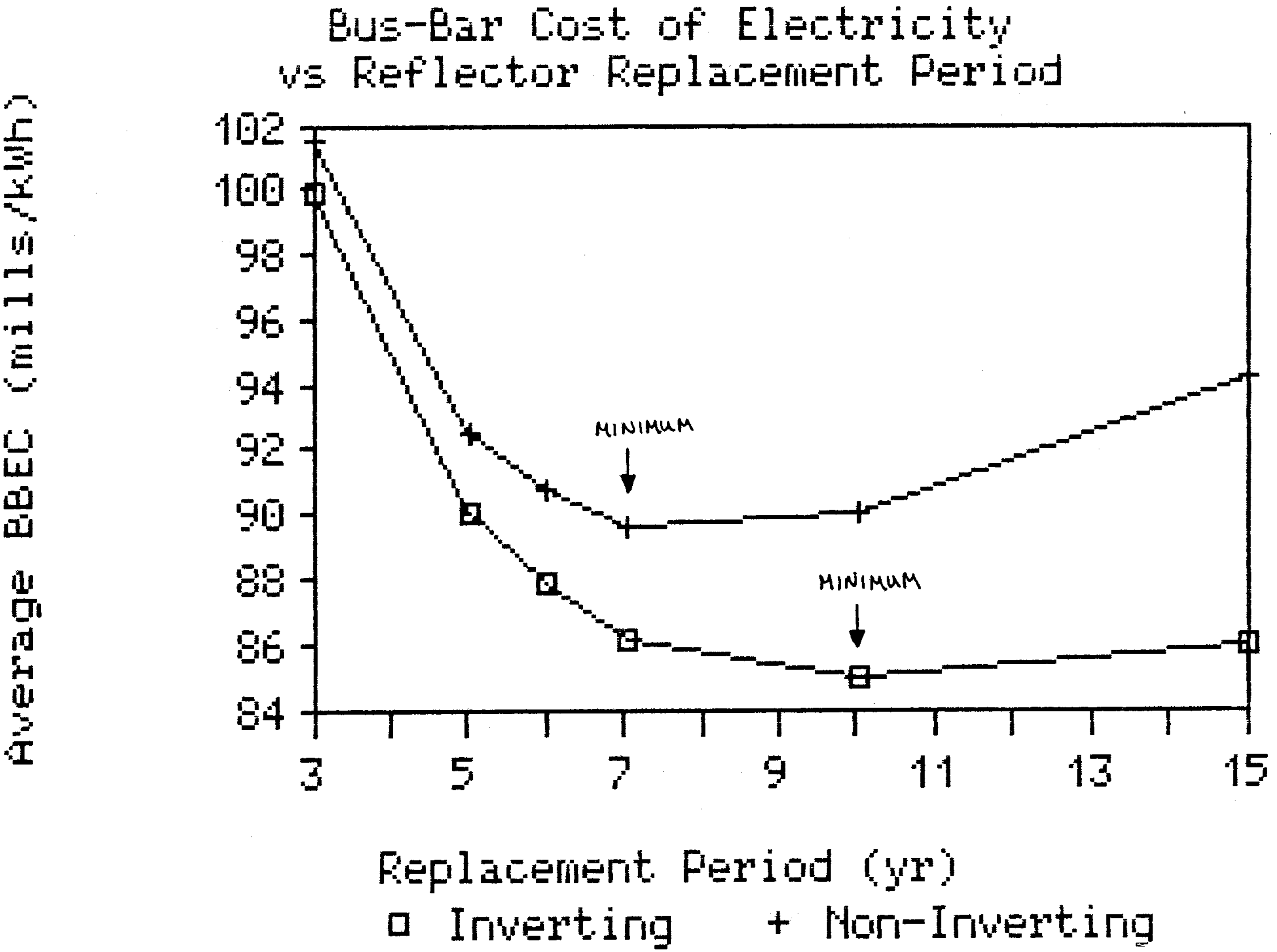


Figure 6.3-2. Estimated Busbar Cost of Electricity vs. Reflector Replacement Period

HELIOSTAT COST COMPARISON

Heliostat Cost Calculation
5000 Unit/year Production Rate

2/3/89

	Pedestal		Shared Support		Dual Module		Yoke	
	Standard	Wind-Avoiding	Standard	Wind-Avoiding	Standard	Wind-Avoiding	Standard	Wind Avoiding
Mirror Module(s)								
Ring(s)	359	359	307	307	600	600	969	969
Membranes	1400	1400	1400	1400	1388	1388	2125	2125
Focus Control System	920	920	920	920	1307	1307	920	920
Reflector	2700	2700	2700	2700	2700	2700	2700	2700
Structural Support								
Module Support	3088	3088	632	552	1013	1013	2754	2754
Focus Control Support	12	12	356	356	12	12	356	356
Foundations/Pedestals	1696	1696	1696	1696	1696	1696	891	891
Drive System								
Azimuth Drive	1646	1071	482	428	1646	1071	1772	1153
Elevation Drive	840	638	1369	1042	1264	962	1369	1042
Torque Limiter		504				504		504
Controls	100	100	100	100	100	100	100	100
Assembly/Installation	456	456	456	456	456	456	456	456
Total Direct Costs	13219	12945	10420	9958	12182	11808	14414	13971
Buildings & Capital Eqpt.	254	254	271	271	250	250	254	254
Indirect Labor	368	368	368	368	368	368	368	368
ROI/Taxes @ 20%	2768	2713	2212	2220	2560	2485	3007	2918
Selling Price	16609	16281	13270	12816	15359	14910	18043	17511
Price/Square Meter	111	109	88	85	102	99	120	117
Cleaning	609	609	501	501	422	422	422	422
Reflector Replacement	4200	4200	2620	2620	2620	2620	2620	2620
Servicing	453	453	525	525	453	453	453	453
Total Lifetime Cost	21870	21542	16916	16462	18854	18405	21538	21006
Cost Per m**2	145.80	143.61	112.77	109.75	125.69	122.70	143.58	140.04

Table 6.4-1 Initial Heliostat Cost Comparison

6.4.2 Dual Module

The production of dual module heliostats involves the same procedures as pedestal drives, but sizes and production rates are changed. Mirror module production, for instance, is changed to 40 units per day, but they are 75-m^2 (810-ft^2) in area. It was estimated that five parallel lines with 8-head welders would be needed, with approximately the same total capital costs as for the baseline. Because of the smaller module size, handling would be easier, and approximately five persons and 190-m^2 (2050-ft^2) of area could be saved. Likewise, ring rolling was estimated to require two fewer people and 115-m^2 (1240-ft^2) less production area. Membrane attachment, on the other hand, would require four stations, and a total of 14 persons. Also, the focus-control assembly would need one additional person. Fastener/attachment and truss fabrication were estimated to remain the same except for a slight reduction in floor space, because fewer trusses would be required but more hubs and attachments. Overall, one person less and 377-m^2 (4060-ft^2) less space for manufacturing would be required.

Considering materials costs, the torque tube for the dual module was estimated to weigh 1032 kg (2275 lbs), and each of the trusses was estimated to be 113 kg (250 lbs). Two smaller focus-control actuators and two valves would be required, but only a single controller.

6.4.3 Shared Support

The production scenario for the shared support drive is similar to the pedestal, except that an additional ring must be rolled for the transverse roll-axis ring. A truss and hub assembly are not required, but module assembly was estimated to be more complex. The net effect on the production costs was the addition of a single person, 225-m^2 (2420-ft^2) of building space, and $400,000 in capital equipment.

In terms of materials and component costs, the transverse ring was estimated at 560 kg (1235 lbs), and the rods from the ring to the mirror module were estimated to weigh 177 kg (390 lbs). Other costs were similar to the pedestal drive.

7.0 REFINEMENT OF PROMISING DESIGNS

The structural designs of the dual module and shared support heliostat drives were further developed as part of the extension of Phase I activities. The designs were analyzed in greater detail in an attempt to minimize uncertainties in both structural design criteria and structural components. Design criteria were examined and refined. Structural components were further analyzed utilizing closed-form analytical techniques as well as extensive finite element analysis. The analysis resulted in a dual module design with a slightly heavier torque tube and a slightly lighter triangular support truss. The refined shared support design resulted in the use of a wide flanged beam section for the transverse ring and a slightly larger mirror module support ring. An innovative focus-control actuation method was identified for the shared support design which eliminated the need for a truss spanning the rear of the module. The overall structural weight decreased slightly for the shared support Design. These optimizations are described in the following subsections.

7.1 Dual Module

Structural optimization of the dual module design included torque tube and truss size optimization, evaluation of pedestal cable supports, and evaluation of a spreader system designed to minimize bending loads in the torque tubes and support trusses. Upon close examination of the deflection distribution, it was determined that SAIC's innovative rear membrane modulation focus-control system transferred the vast majority of the operational forces and moments directly onto the torque tubes. Therefore, it was determined that the torque tube would be designed to operate within the deflection and rotation limitations imposed by the optical requirements, and the support trusses would be designed based on maximum stress under survival loading conditions. These criteria produced a slightly heavier torque tube and slightly lighter triangular support trusses. The finite element model of the triangular truss is shown in **Figure 7.1-1.** A view of the truss deflected under applied loading is shown in **Figure 7.1-2.** Iteration of the beam sizes and truss geometry led to the current truss configuration.

The torque tube structural analysis determined that the section required to meet the bending criterion was approximately the same section that was required to meet the torsion criterion. This fact eliminated the benefit of using a spreader system, which would have transferred much of the bending loads in the torque tubes into compressive loads.

Analysis was performed to determine the benefit of using cable supports on the pedestal. Although the cables could provide significant savings in material, it was determined that the increased installation labor and field maneuvering difficulties created by cables would virtually eliminate any cost savings.

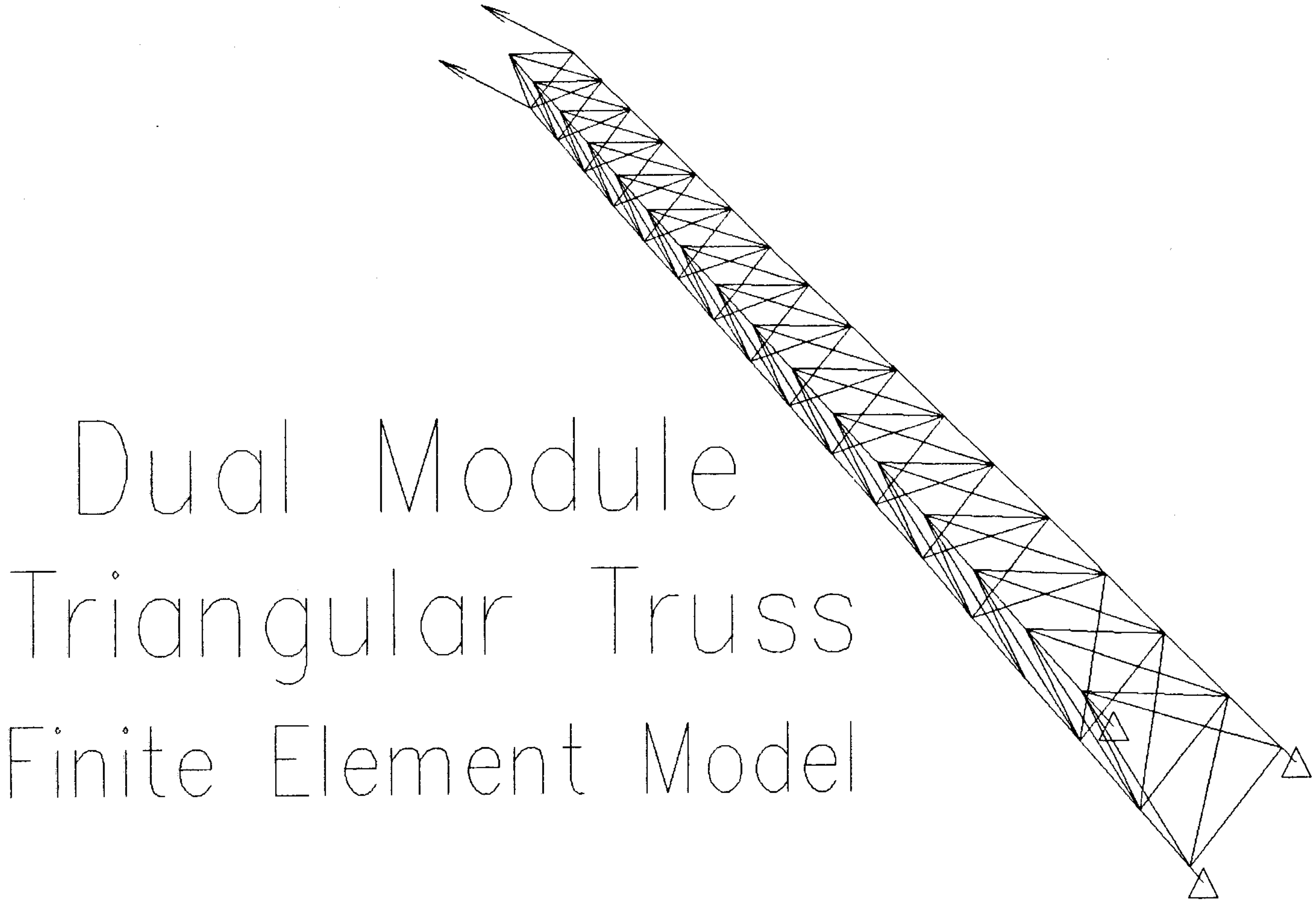


Figure 7.1-1 Finite Element Model of Improved Dual Module Truss

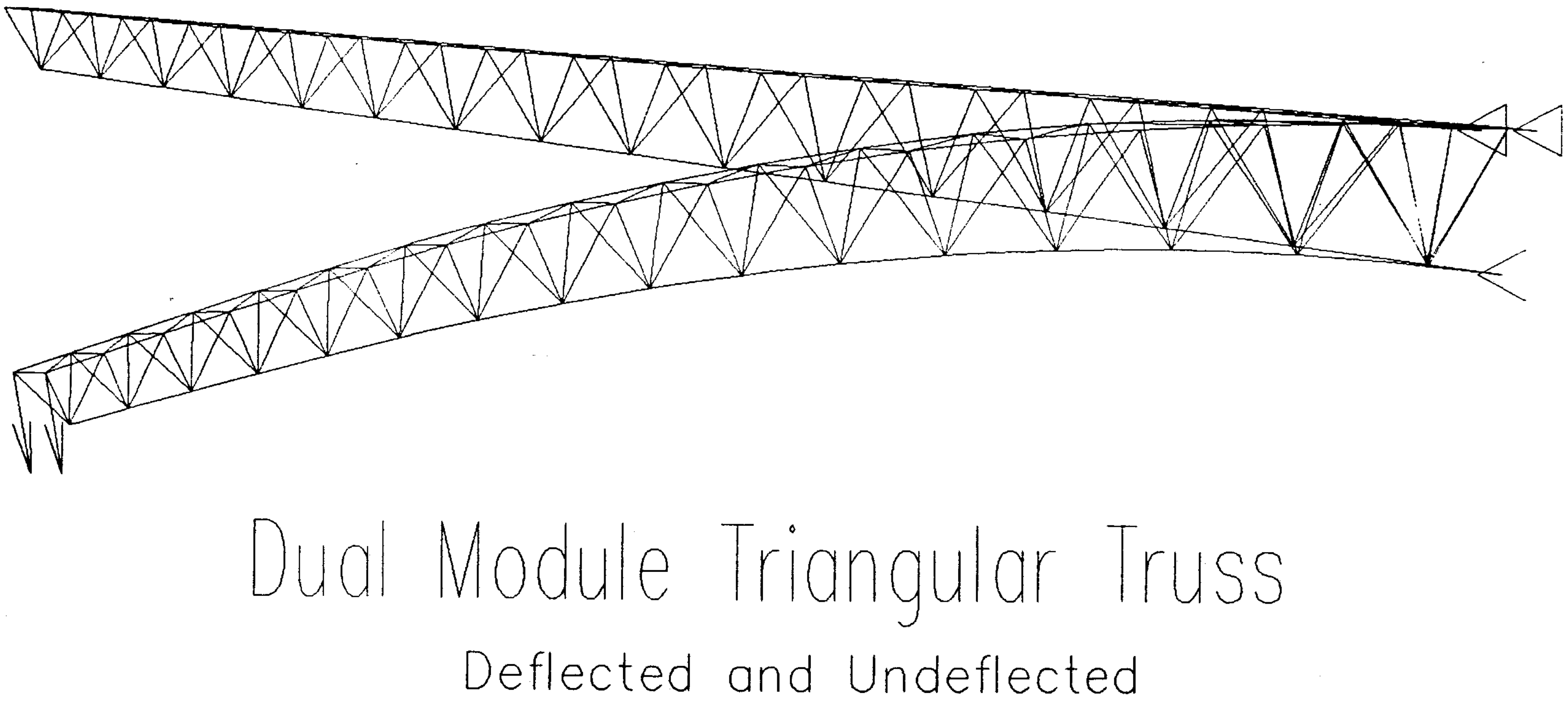


Figure 7.1-2. Dual Module Truss Deflection

Only very minor mass changes resulted from the optimization of the dual module heliostat. They are summarized below:

Torque Tube changed from 1032 kg (2275 lbs) to 1150 kg (2535 lbs)
Mirror Module Support Trusses changed from 451 kg (995 lbs) [4 @ 113 kg (248.7 lbs)] to 417 kg (920 lbs), [4 @ 104 kg (230 lbs)]

7.2 Shared Support

Structural optimization of the shared support design included detailed analysis of the mirror module ring, transverse ring, and connecting rods. A finite element model was developed to size the structural members. The finite element model of mirror module ring, membranes, transverse ring, and connecting rods is shown in **Figure 7.2-1.** Results of this analysis showed that a three-to-one aspect ratio rectangular ring is required for the mirror module ring. Since the connecting rod system will virtually eliminate out-of-plane loading on the transverse ring, a section with a large moment of inertia about one axis was the most appropriate choice. A wide flange I-beam was chosen for this section. The finite element model deformed under applied loading is shown in **Figure 7.2-2.**

A modified focus-control actuation system was developed for the shared support design and is shown in **Figure 7.2-3.** This actuation method would eliminate the use of a truss spanning the back of the mirror module for focus-control linear actuator mounting. The focus-control pad would be actuated by a cable system which would be attached to the transverse ring and the focus pad. A spring mounted on the cables would be used to keep them in tension under all loading conditions. The cable with the spring would be attached to the transverse ring and the focus pad through a small hole in the front membrane. The other cable would be attached to the back of the focus pad and connected to a winch mounted on the transverse ring. For focusing, the winch would pull the cable against the tension of the spring to pull the focus pad into position. For defocusing, the winch would release the cable and the tension in the spring would pull the focus pad forward. This system would also provide an automatic defocus under conditions of no power.

Due to the structural analysis and design optimization, several component costs were modified from the initial estimates. For the most part, these were refinements to the design and did not have large cost effects. One significant exception to this was the cable-based focus-control system

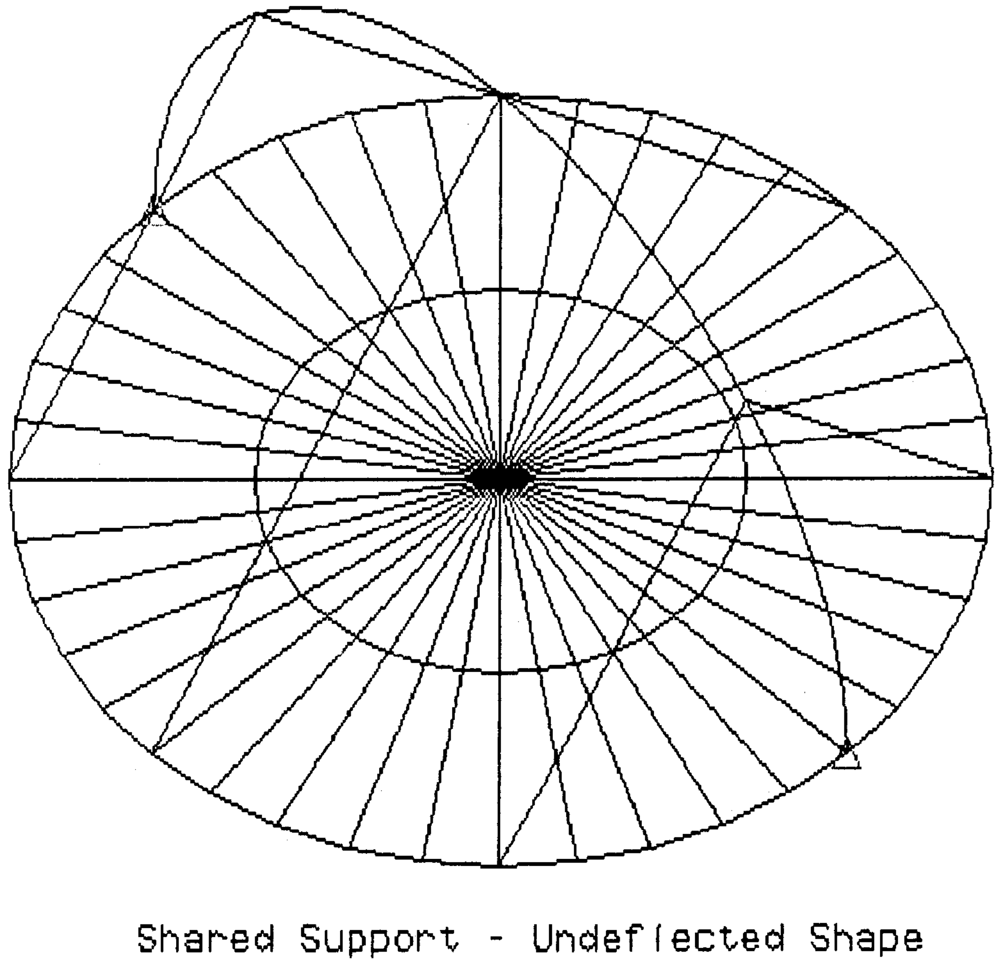


Figure 7.2-1 Shared Support Undeflected Shape

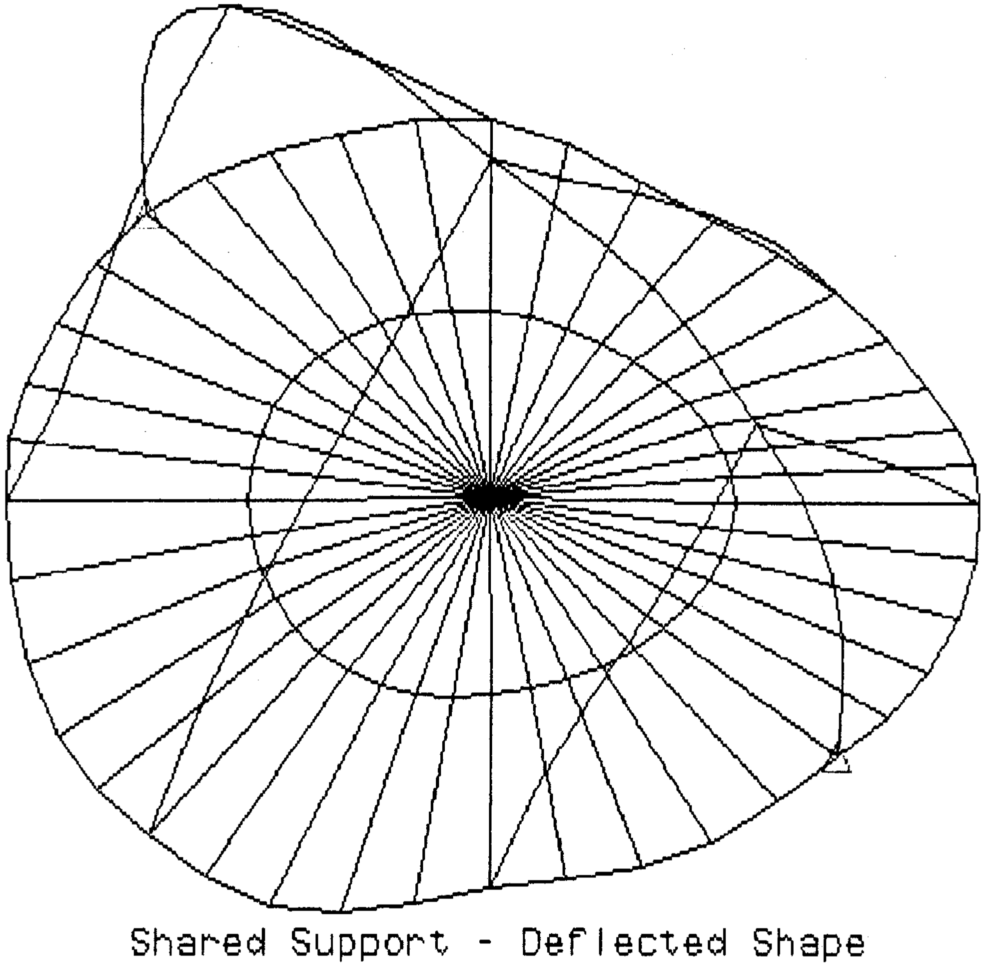


Figure 7.2-2 Shared Support Heliostat Ring -- Deflected Shape

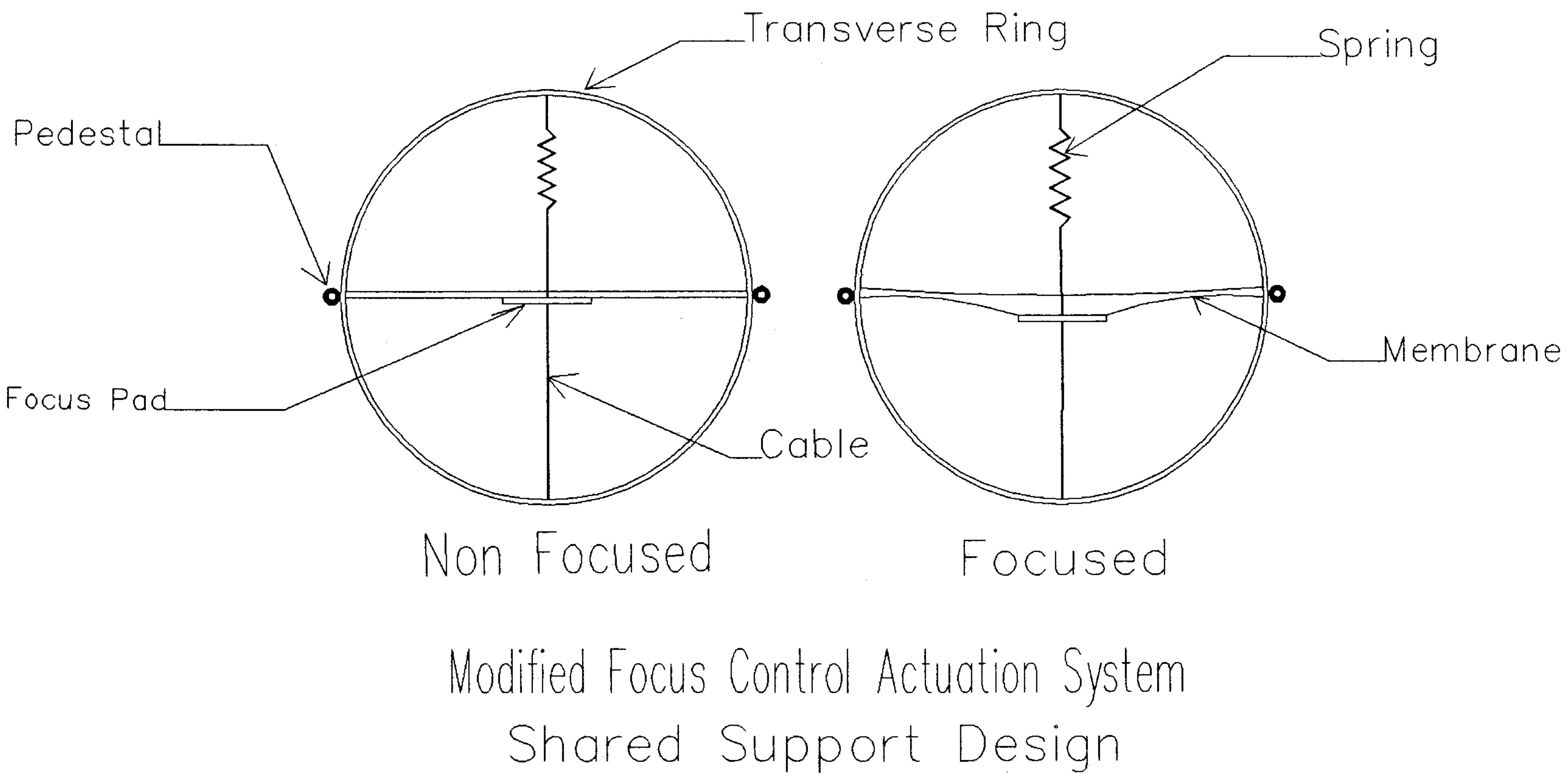


Figure 7.2-3 Modified Focus Control Actuation System for Shared Support Heliostat

design which was developed for the shared support heliostat design. That design led to the deletion of the truss across the heliostat back to hold the focus-control actuator, as well as to a reduction in other components for mounting it. The following table gives a summary of the component changes:

Heliostat Ring changed from 888 lbs. to 1,061 lbs.
Transverse Ring changed from 1,264 lbs. to 2,023 lbs.
Steel Rods changed to: 157-ft @ 2.67 lb/ft (1-in.) for the standard design
    157-ft @ 1.504 lb/ft (3/4-in.) for wind-avoiding design
Focus-Control Truss deleted
Focus Pod Gusset deleted
Actuator Mounting Gusset deleted
Actuator Stiffening Gusset deleted
Actuator Mounting Block changed to 10 lbs.

An analysis of the shading and blocking of the mirror module by the transverse ring of the shared support heliostat was carried out. This analysis is presented in **Appendix B.** The analysis indicated that approximately 5% of the heliostat area would be shaded or blocked by the transverse ring in the shared support design. In order to account for this, a 5% penalty was added to the total lifetime cost of that system. This penalty accounts for extra heliostats that would need to be added to the plant to provide the rated plant power.

8.0 UPDATED COST ESTIMATES

8.1 Updated Heliostat Maintenance Costs

The costs for heliostat washing and reflector replacement presented in the Phase I review in February 1989 were preliminary in nature. SAIC updated those costs as part of the extension of Phase I using the design for a 100-MW_e (341 MBTU/h) first commercial plant generated by the APS study [2] as a basis. In particular, the plant design, capital costs, economic assumptions, and annual energy delivery values from the APS study were used. To these, SAIC added an estimate of washing and replacement capital and direct costs to obtain total costs. Then, using a Levelized Energy Cost (LEC) analysis, optimum washing and reflector replacement periods were calculated. The details of the analysis are given in the following sub-sections; the overall results of this analysis, for inverting and non-inverting heliostats are shown in **Figures 8.1-1** and **8.1-2.**

Figure 8.1-1 gives the levelized cost of electricity from the plant vs. the washing period ignoring the cost of reflector replacements. For the inverting design, the optimum washing period is about once every 10 days. For the non-inverting design, the optimum washing period is about once every 8 days. These periods are considerably shorter than the initial estimates of six-to-eight cleanings per year for inverting and nine-to-twelve cleanings per year for non-inverting heliostats. However, they are consistent with the experience at Solar One, where it has been estimated that cleaning the field every two weeks would be cost-effective [9].

Figure 8.1-2 shows the cost of electricity as a function of the number of times the reflectors are replaced over the 30-year life of the plant. The curves include the cost of washing at the optimum frequency as well as costs for film replacement. For the inverting heliostat, the optimum lies between one and two replacements over the plant life, and for the non-inverting design, two or three replacements are optimum. This agrees with the estimates made earlier of reflector replacement at about 10-year intervals over the life of a non-inverting design, and only one reflector replacement at 15 years for inverting designs. For the set of conditions used in this study, the minimum electricity cost is about 14.4 cents/kWh with inverting heliostats, and about 15.2 cents/kWh with non-inverting heliostats.

8.1.1 Levelized Cost Calculation

In order to determine the optimum periods for cleaning and for reflector replacement, it is necessary to calculate the levelized cost of energy produced by the plant for various cleaning and replacement periods. This type of analysis is necessary because the effect of increased periods is to reduce the average reflectivity of the heliostats and thereby the energy produced by the plant.

The analysis procedure given in the Sandia Central Receiver Design Handbook [10] was used to estimate levelized energy costs. From the recent central receiver design study performed by APS [2], the following data were obtained for the first commercial 100-MW plant:

- 5946 heliostats per plant
- 148.64-m^2 (1600-ft^2) per heliostat
- FCR = 0.105 (Fixed Charge Rate)
- CRF = 0.0766 (Capital Recovery Factor based on 6.5% discount rate)
- CC = $350.038 million total plant capital cost (January 1987 $)
- $4.517 million/year O&M Costs including cleaning and replacement
- \$1.30/m^2/year (0.12/ft^2) annualized cost for cleaning
- \$7.27/m^2 (\$0.67/ft^2) present-value cost for reflector replacement
- 0.94 initial reflectivity
- rho = 0.91 Average Reflectivity
- 322 GWh/year delivered energy

Using the cost data given above, the annualized cost of operation and maintenance without reflector replacement or cleaning was determined. This was done by calculating the annualized costs for those items and subtracting them from the total annualized O&M cost. The annualized reflector replacement cost is obtained by multiplying by the CRF and the area of the heliostats:

$$\$0.49 \text{ Million/year} = \$7.27 \times 0.0766 \times 148.64 \times 5946.$$

The annualized cost of cleaning is

$$\$1.15 \text{ Million/year} = \$1.30 \times 148.64 \times 5946.$$

Subtracting these values from the total annualized O&M cost gives the desired value of the O&M costs without cleaning or replacement costs:

$$C_{o\&m} = \$2.877 \text{ Million/year} = \$4.517 - 0.49 - 1.15.$$

Next, it was assumed that the energy production is, to first order, proportional to the reflectivity of the heliostats. This enabled calculation of a factor for the energy production as a function of the reflectivity, as follows:

$$Q_{del} = * R$$

$$K = Q_{del}/R = (322 \text{ GWh/year})/0.91 = \underline{353.85 \text{ GW/year}}.$$

Finally, the levelized energy cost is expressed as:

$$LEC = \frac{(CC + CC_{o\&m}) * FCR + C_{o\&m} + C_{cleaning} + PVC_{replacement} * CRF}{K * R}$$

where: $CC_{o\&m}$ is the capital cost of cleaning equipment,
$C_{cleaning}$ is the annualized cleaning cost,
$PVC_{replacement}$ is the present value of reflector replacement costs, and
R is the average reflectivity of the heliostats.

8.1.2 Optimum Cleaning and Film Replacement Periods

Since the time scale for film degradation requiring reflector replacement and soiling, which is removed by cleaning are so different, the analyses of the two cases were performed separately. The levelized cost equation was applied first to the problem of cleaning, assuming no long-term degradation. In that case, the costs associated with replacement of the reflectors were initially set to zero. The initial reflectivity was set to 99% of the reflectivity for new ECP-300 (0.94). Then, the average reflectivity for various cleaning periods was calculated due to soiling for inverting and non-inverting heliostats. The corresponding capital and direct costs for cleaning were also calculated as a function of the cleaning period. Finally, the levelized cost for each case was determined. The results of these calculations are shown in **Figure 8.1-1**, for both inverting and non-inverting collectors. The average reflectance obtained at the optimum cleaning period for each collector configuration was then used as the initial reflectance for the reflector replacement period calculation. The capital and annualized direct costs for the washing at the optimum conditions were likewise added to the LEC equation. Finally, the capital and direct costs for reflector replacement were calculated as a function of the number of times the reflectors were replaced. The resulting LEC curves for inverting and non-inverting collectors are shown in **Figure 8.1-2**. Finally, tabular values used to generate both figures are given in **Table 8.1-1**.

8.2 Heliostat Cost Comparison

After all the studies described in the preceding sections were completed, the cost estimates produced in the initial Phase I effort for four heliostat designs were updated. The four designs included the baseline pedestal drive for comparison, and three improved drive designs: the shared support, the dual module, and the yoke drive. The results of the comparison are presented in **Figure 8.2-1**, and a detailed cost breakdown for each heliostat design is given in **Appendix C**. The following paragraphs describe the changes and modifications made to the cost estimates from the initial Phase I effort.

Using the results of the cleaning and replacement analyses, the cleaning and replacement costs for each drive design were updated. Of the designs costed, only the pedestal drive was a non-inverting design. For the pedestal drive, a cleaning period of 8 days (46 washes per year) was optimum, and the reflector replacement period was taken to be 10 years (two replacements over the 30 year life of the plant). For the other designs, a washing period of about 10 days (39 washes per year) was used, with a reflector replacement period of 15 years (one replacement over the life of the plant).

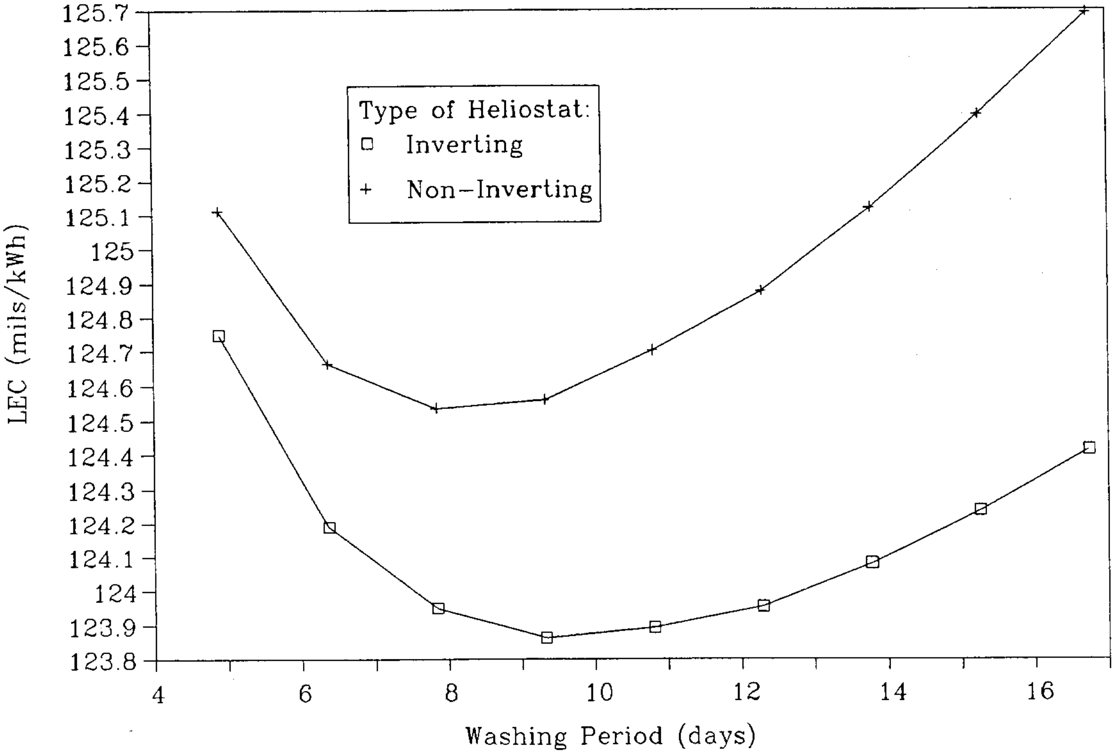


Figure 8.1-1 Effect of Heliostat Cleaning on the Cost of Electricity from a 100 MW Solar Thermal Power Plant

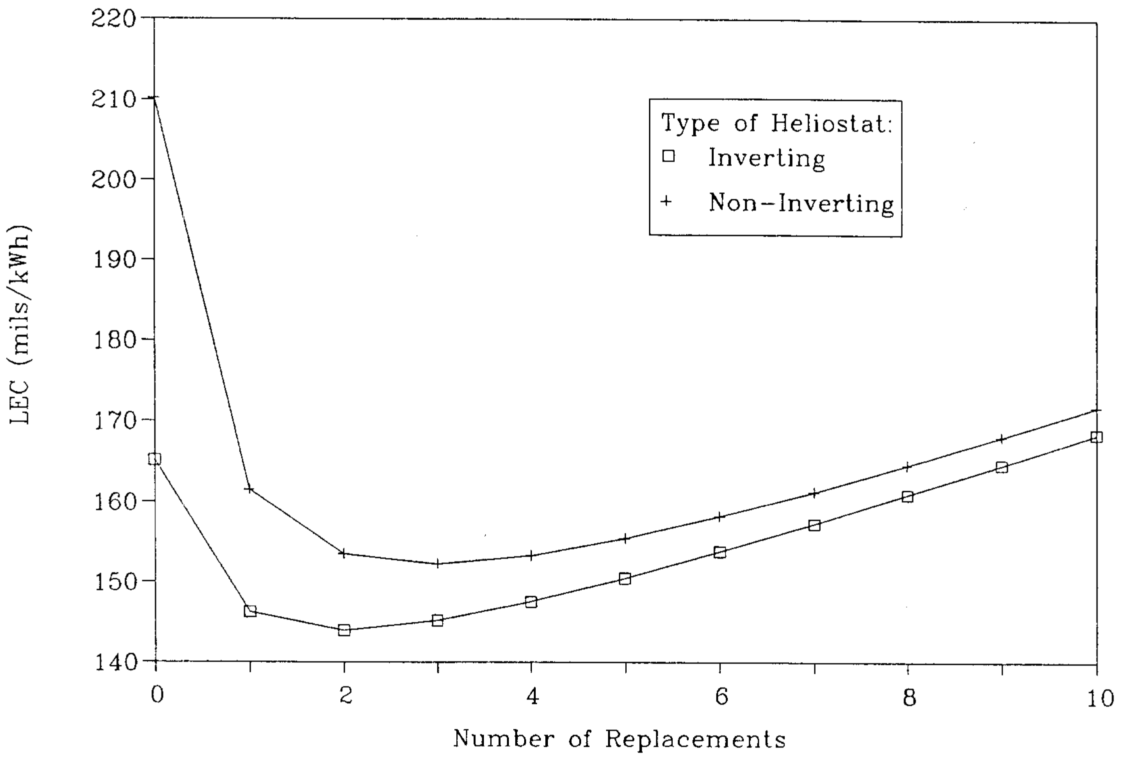


Figure 8.1-2 Effect of Reflector Replacement on the Cost of Electricity from a 100 MW Solar Thermal Power Plant

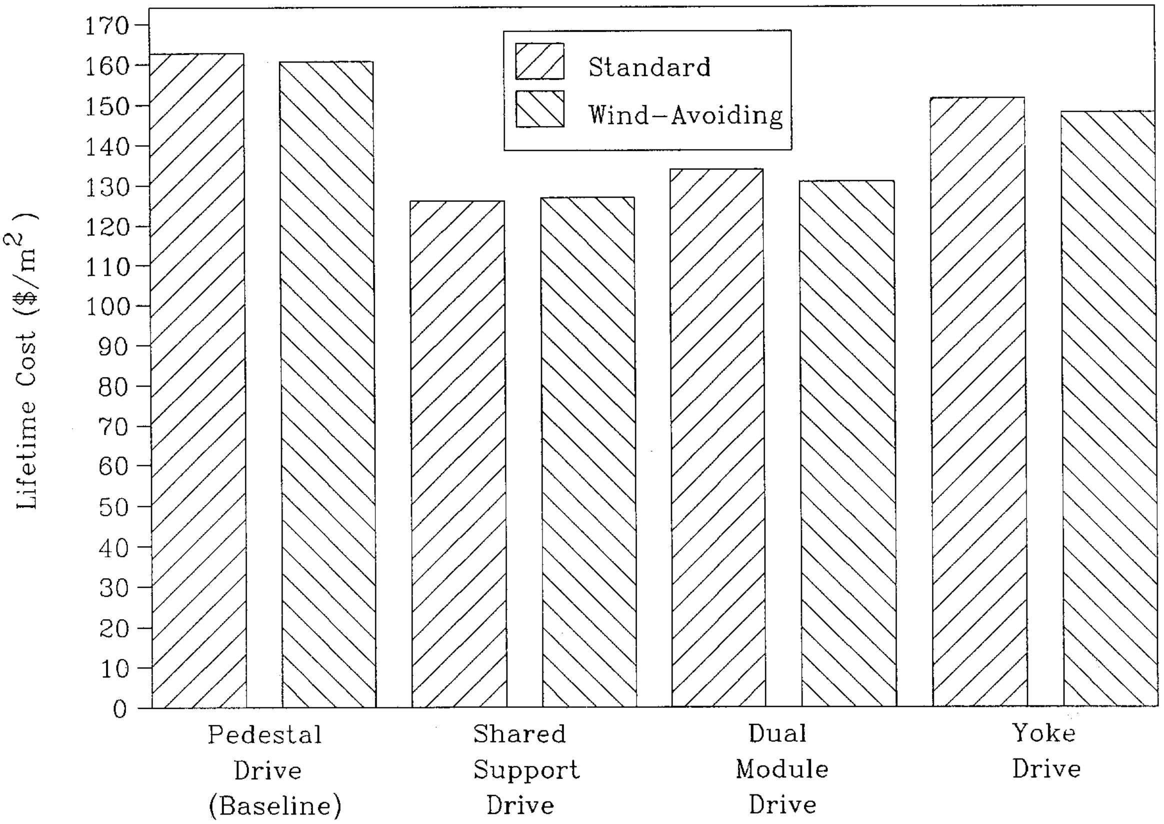


Figure 8.2-1. Cost Comparison of Four Heliostat Concepts at Production Rate of 5000/Year

Maintenance Costs for 100 MW Solar Thermal Plant
Using APS Study First-Plant Baseline Costs
Inverting Heliostat Design

Optimum Washing Frequency

========================

5946.00 Number of Heliostats
0.931 Initial Reflectivity (99% of new)
-0.0027 Daily Reflectivity Degradation Rate
2.45 Direct cost per wash per heliostat
-0.0038 Daily Reflectivity Degradation Rate
81920.00 Cost for Truck (to wash 60,000 heliostats per year)

Average Reflectivity	Washing Period [days]	Annual No. of Washes	Direct Costs for Washing [$M/yr]	No. of Trucks	Capital Equipment [$M]	Energy Delivered [Gwh]	LEC [mils/kWh]
0.924	4.89	74.66	1.09	8.00	0.66	326.96	124.75
0.922	6.37	57.30	0.83	6.00	0.49	326.25	124.19
0.920	7.85	46.49	0.68	5.00	0.41	325.54	123.95
0.918	9.33	39.11	0.57	4.00	0.33	324.83	123.86
0.916	10.81	33.75	0.49	4.00	0.33	324.13	123.89
0.914	12.30	29.68	0.43	3.00	0.25	323.42	123.95
0.912	13.78	26.49	0.39	3.00	0.25	322.71	124.08
0.910	15.26	23.92	0.35	3.00	0.25	322.00	124.24
0.908	16.74	21.80	0.32	3.00	0.25	321.30	124.42

Non-inverting Heliostat Design

Average Reflectivity	Energy Delivered [Gwh]	LEC [mils/kWh]
0.921	326.01	125.11
0.918	325.01	124.66
0.916	324.01	124.54
0.913	323.02	124.56
0.910	322.02	124.70
0.907	321.03	124.88
0.904	320.03	125.12
0.902	319.03	125.40
0.899	318.04	125.69

Optimum Reflector Replacement Period

==================================

0.918 Average Reflectance when New
-0.0153 Annual Reflectance Degradation Rate
60000.00 Capital Cost per rig (to replace field in 5.5 years)
2900.00 Single Heliostat Direct Replacement Cost

Replacement Period [years]	No. of Replacements	Average Reflectance	Annualized Direct Costs [$M/yr]	Replacement Rigs Required	Capital Equipment Cost [$M]	Energy Delivered [Gwh]	LEC [mils/kWh]
2.727	10.00	0.90	13.21	3.00	0.18	317.45	168.41
3.000	9.00	0.90	11.89	2.00	0.12	316.71	164.61
3.333	8.00	0.89	10.57	2.00	0.12	315.81	160.90
3.750	7.00	0.89	9.25	2.00	0.12	314.68	157.28
4.286	6.00	0.89	7.93	2.00	0.12	313.23	153.79
5.000	5.00	0.88	6.60	2.00	0.12	311.30	150.50
6.000	4.00	0.87	5.28	1.00	0.06	308.59	147.52
7.500	3.00	0.86	3.96	1.00	0.06	304.53	145.15
10.000	2.00	0.84	2.64	1.00	0.06	297.76	144.02
15.000	1.00	0.80	1.32	1.00	0.06	284.23	146.23
30.000	0.00	0.69	0.00	0.00	0.00	243.63	165.15

0.916 Average Reflectance when New
-0.0249 Annual Degradation Rate

Average Reflectance	Energy Delivered [Gwh]	LEC [mils/kWh]
0.88	312.11	171.66
0.88	310.91	168.06
0.87	309.44	164.59
0.87	307.61	161.28
0.86	305.25	158.20
0.85	302.10	155.47
0.84	297.69	153.31
0.82	291.09	152.26
0.79	280.07	153.53
0.73	258.05	161.52
0.54	191.96	210.20

Table 8.1-1. Tabular Maintenance Cost Data

In order to compare the effects of the cleaning and reflector replacement costs on each of the heliostat designs, both the capital and direct costs were converted to present value total costs per heliostat. This involved dividing the annualized maintenance costs by the Capital Recovery Factor (0.0766, based on a discount rate of 6.5% for 30 years) to obtain an equivalent present value initial cost. The results of these calculations are given in **Table 8.2-1**.

The values given in **Table 8.2-1** were used to update the lifetime maintenance costs for each of the heliostat designs. In the case of the shared support design, an additional 10% penalty was added to the cleaning cost to account for the reduced accessibility to the reflector caused by the transverse ring. An additional 5% penalty was added to the total cost of that design for the reduction in energy reflected to the receiver due to blocking and shading of the mirror by the transverse ring.

	Inverting Collector ($)	Non-Inverting Collector ($)
Cleaning Cost		
Capital Cost	55	65
Direct Costs	1255	1495
Total	$1310	$1560
Reflector Replacement		
Capital Cost	10	10
Direct Costs	2900	5800
Total	$2910	$5810

Table 8.2-1 Per-Heliostat Costs for Cleaning and Reflector Replacement

8.3 Conclusions from Phase I

In the Phase I and its extension, several tasks were completed. First, many designs for heliostat drives were identified and evaluated. Several were seen to have possibilities for reduced cost compared to the previously identified designs. Initial cost estimates were made for the most promising candidate drive systems. Further design refinements were made to the shared support and the dual module drive designs to reduce the uncertainty in their design. Finally, cost estimates were updated with improved O&M analyses and with refined design information. The conclusions of the initial Phase I activity were confirmed by the additional detailed studies -- both the shared support and dual module designs promise significant cost reductions compared to current pedestal heliostat designs.

Wind-avoiding designs were considered in Phase I for each of the heliostat drive systems as a method of decreasing cost. It was felt that if wind-avoidance could reduce structural strength requirements, savings in structural parts might more than pay for the hardware (slip clutches, etc.) needed to provide the wind avoidance. As the analyses progressed, it became clear that in most cases, deflection criteria at the maximum operating wind speed determined structural strengths, rather than the maximum stress criteria under survival loads. Thus, in most cases, it was found that savings due to wind-avoiding design were insignificant or nonexistent.

The shared support drive design shows the highest potential for cost savings, but also represents the most extreme change from current design practice. Therefore it has higher risk and would require more effort for its development. SAIC estimated at the end of the Phase I effort that production of a 100-m^2 prototype heliostat based upon the shared support design would require $850,000 in further development.

The dual module design showed potential for slightly less savings compared to the pedestal design, but it represents a near-term development approach that builds on and extends current design practices. SAIC estimated that a prototype 100-m^2 (1080-ft^2) dual module heliostat (i.e., consisting of two 50-m^2 (540-ft^2)mirror modules) could be produced for $625,000.

As a result of these conclusions, the decision was made to proceed with the design of a dual module heliostat in Phase II of this program, with eventual construction of a prototype in Phase III. The design of the resulting dual module heliostat is described in the succeeding sections of this report.

9.0 DESCRIPTION OF THE DUAL MODULE HELIOSTAT

An assembly drawing of the SAIC dual module heliostat is shown in **Figure 9.0-1**. The heliostat is composed of two 50-m^2 (540-ft^2) mirror modules mounted on a torque tube type drive system producing 100-m^2 (1080-ft^2) total reflective surface area. Each of the mirror modules is supported at three points. Two trusses connected to each end of the torque tube extend to attachment brackets at the perimeter of each mirror module, and the third attachment bracket is extended directly from the torque tube to a third support point. The torque tubes are attached to a drive unit mounted on a single pedestal for purposes of tracking in the azimuth and elevation directions.

Stainless steel foil membranes are welded to both sides of the carbon steel rings providing closed, airtight plenums. In order to compensate for changes in pressure on the front reflective membrane due to wind loading, an active focus-control system is utilized. A single focus-control computer continuously monitors two independent LVDT mechanical position indicators (one for each mirror module) that measure the position of the front membranes. The proper front membrane position is maintained by modulating a linear actuator attached to a focus pad on the rear membrane of each module. Refocus valves are included to periodically compensate for air leaks in the mirror modules. A more detailed description of each of the components is provided below.

The A500 carbon steel ring is made of rectangular tube cross-section with a height of 20-cm (8-in.) and a width of 5-cm (2-in). Its wall thickness is .5-cm (.1875-in). The dimensions of the ring were determined based on a mirror module with three truss support points and a maximum allowable slope error of 2.5-mRad.

The Type 201 stainless steel foil membranes welded to the ring are .005-in. thick. They are roll resistance lap-seam welded from 61-cm (24 in.) wide rolls of coil stock. The membranes are welded directly to the top and bottom surface of the ring as shown in **Figure 9.0-2**. The membranes are tensioned prior to welding in a manner that imparts uniform circumferential and radial stress over the entire surface. A single weld pass is made around the circumference of the ring while the membrane is under tension. The tension is then released along the perimeter of the membrane and another seam weld is made between the first weld and the outer diameter of the ring.

ECP-305 silverized polymer reflective film is laminated to the stainless steel foil to form the reflective surface of the mirror module. The reflective film is applied in strips slightly narrower than the width of the stainless steel strips. Therefore, the reflective film is not laminated over the overlapping welds of the membrane. A dry lamination process is used to apply the film to the stainless steel foil prior to the seam welding process. Once membrane welding has been completed, an aluminized acrylic reflective tape is applied over the welds and over the two edges of the reflective film adjacent to the welds. Finally a sealant is applied at each edge of the tape.

As can be seen in **Figure 9.0-3**, there are three equidistant support points on the ring. Two trusses radiating from the tip of the torque tube are used to support the mirror module, with a third support bracket attached to the torque tube close to the drive. **Figure 9.0-4** shows a detailed drawing of the triangular support trusses. The triangular truss configuration provides

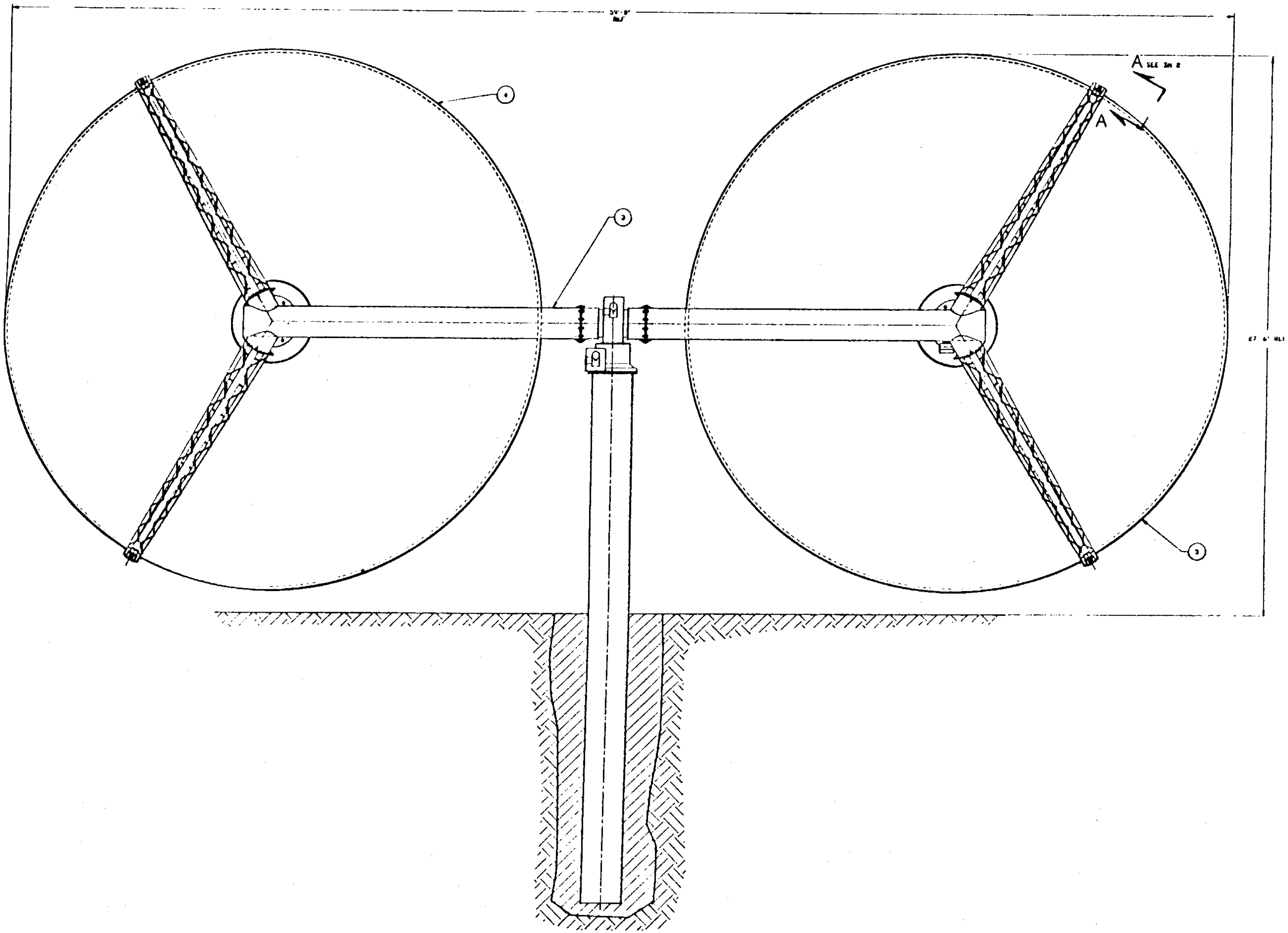


Figure 9.0-1. Assembly Drawing of SAIC Dual Module Heliostat

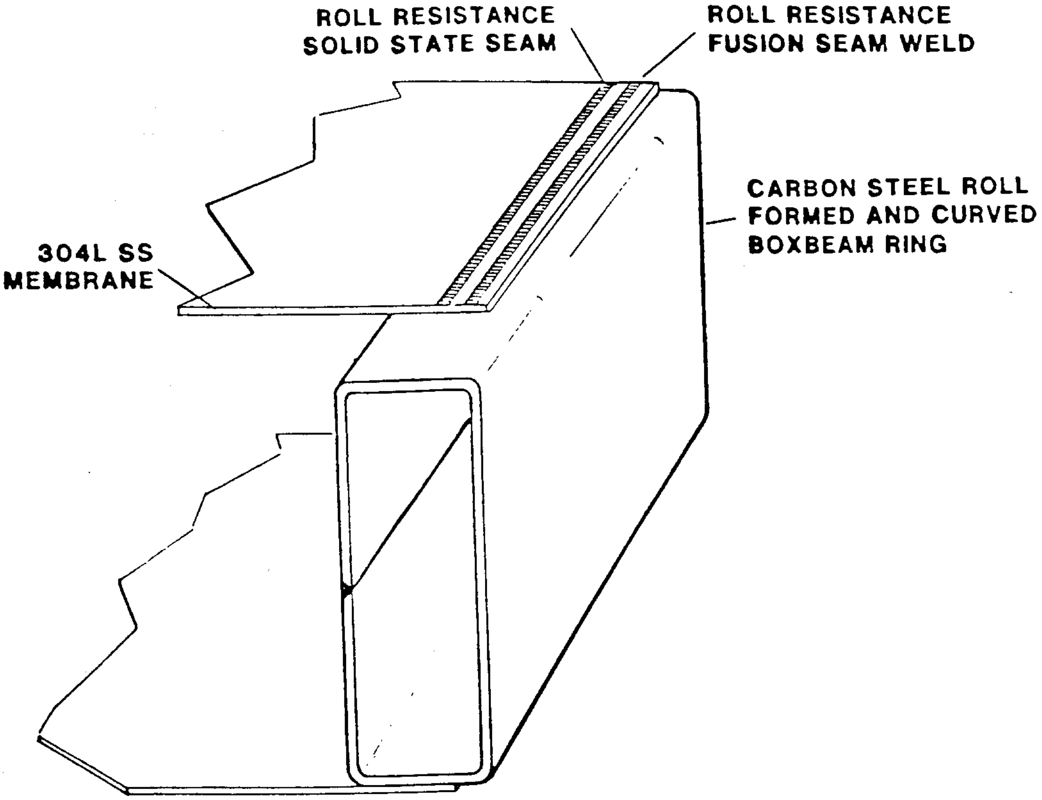
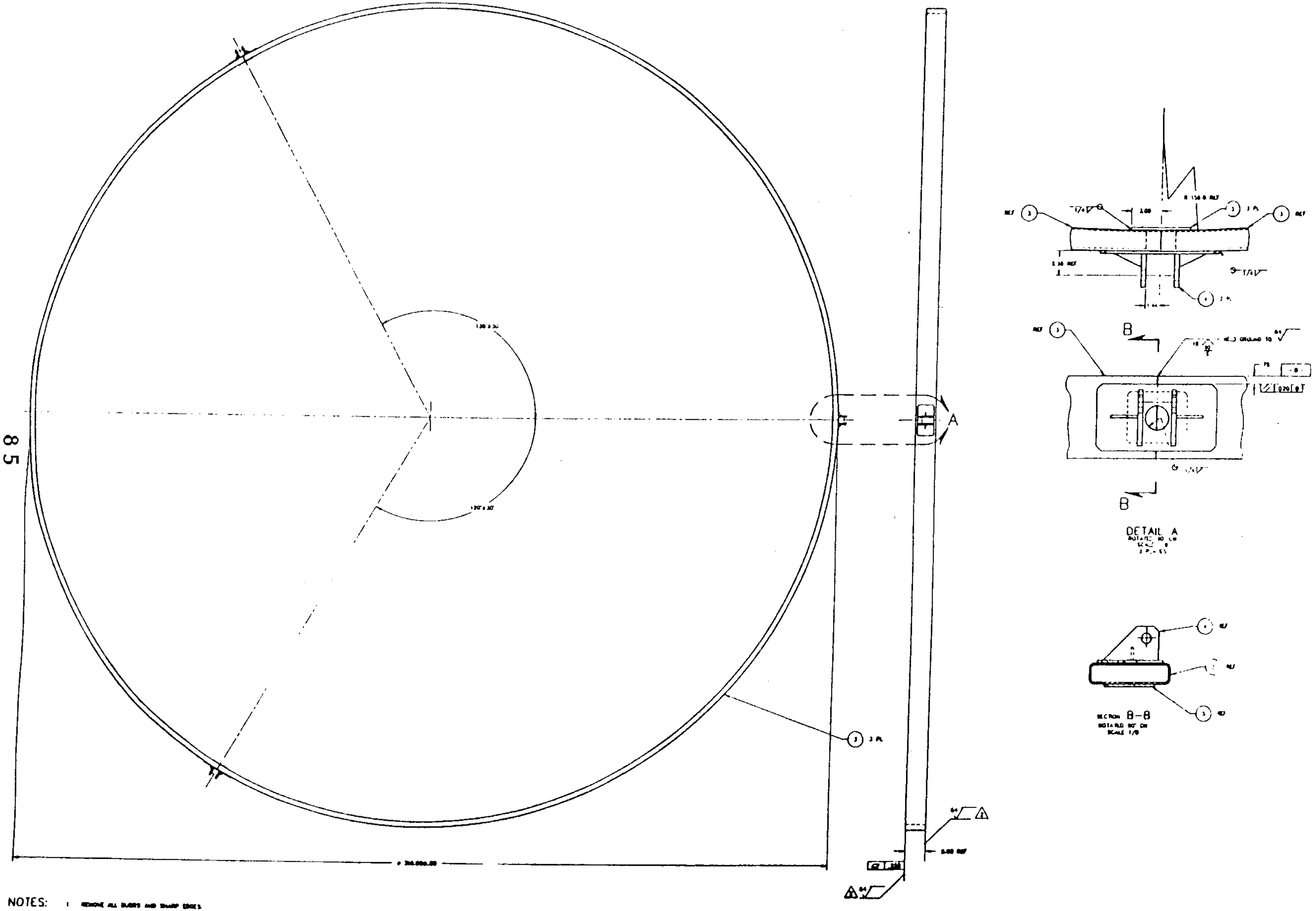


Figure 9.0-2. Membrane to Ring Attachment



NOTES: 1 REMOVE ALL BURRS AND SHARP EDGES.
⚠ GROUND SURFACES AND ALL THRU HOLES STAY FREE OF FINISH

Figure 9.0-3. Ring Assembly

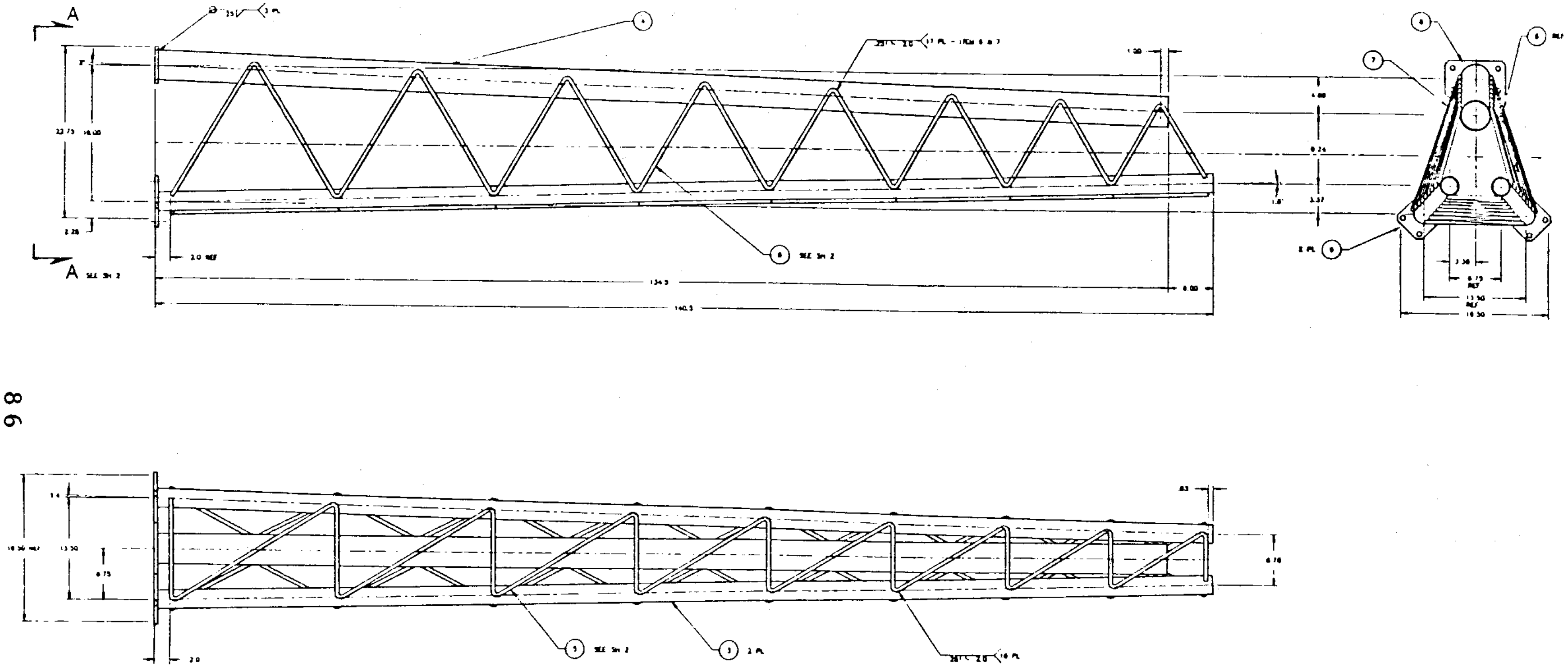


Figure 9.0-4. Truss Detail

considerable lateral and torsional stiffness as well as the required out-of-plane stiffness, thereby eliminating the need for any complex inter-truss bridging cables. At the base, the truss has a width of 35-cm (13.5-in.) and a depth of 46-cm (18.0-in.) centerline-to-centerline while at the tip it has a width of 17-cm (6.75-in.) and a depth of 23.5-cm (9.24-in). This tapered triangular truss configuration provides optimum stiffness vs. weight characteristics and simplicity of installation and assembly.

Figure 9.0-5 shows the triangular truss with the tip attachment mechanism used to attach the truss tip to the support ring. This attachment method provides appropriate degrees of freedom for attachment so that the trusses impart no out-of-plane or in-plane forces onto the ring. The pivoting motion, with the extension/retraction capability of the connecting rod, allows the attachment point to be aligned with the attachment bracket without stressing the members. The three support points provide an attachment plane for the ring, which eliminates the need to force a fit with any connections that are out of tolerance.

The third support point for the mirror module is provided by using a 21.6-cm (8.5-in.) pipe as a standoff from the torque tube to the mirror module. As shown in **Figure 9.0-6**, a rod end extends from a plate welded to the top of the pipe to the ring attachment bracket. This rod end, with the truss-to-ring attachment mechanisms shown in **Figure 9.0-6**, provides the mirror module with enough pointing adjustment to perform in-field "fine tuning" of the modules, resulting in extremely accurate alignment. Once the modules have been aligned, the alignment mechanisms will be secured providing very stiff attachments.

The focusing of the mirror modules is achieved by utilizing the focus/defocus assembly shown in **Figure 9.0-7**. This assembly consists of a focus/defocus pad, a linear actuator, and a refocus valve. The focus/defocus pad is made of two circular pieces of an aluminum honeycomb material, which sandwich the center of the rear stainless steel membrane. The edges of the pad are rounded by attaching aluminum pipe around its perimeter to reduce stress concentrations in the membrane as the pad is being actuated in and out. This pad is moved in and out by the linear actuator,which is attached on one end to a bracket welded onto the focus/defocus pad. The other end is mounted on the torque tube. As shown in **Figure 9.0-8**, the rear membrane is actuated in or out depending on the wind conditions to maintain the appropriate curvature of the front membrane.

The front membrane position is determined through the use of a LVDT mounted on the support truss, extending through the rear membrane and attaching to the front membrane. As the front membrane position is changed due to wind or other factors, the LVDT position is changed, which produces a voltage output change, thereby signalling the control system to perform an adjustment.A refocus valve is included in the focus/defocus assembly. This valve is utilized to compensate for possible air leaks in the system. There are maximum retraction and extension positions for the linear actuator. If the front membrane position needs modification, and the linear actuator has reached its maximum position, then the system will perform a refocus procedure that will open the refocus valve, drive the actuator to its neutral position, wait for the plenum pressure to stabilize, close the valve and then continue to focus. Under optimum manufacturing and operational conditions, this procedure would never be necessary because the amount of air in the plenum would always be constant. This feature has been added to the system to compensate for any air leaks that may occur under less than ideal conditions. The SAIC dual

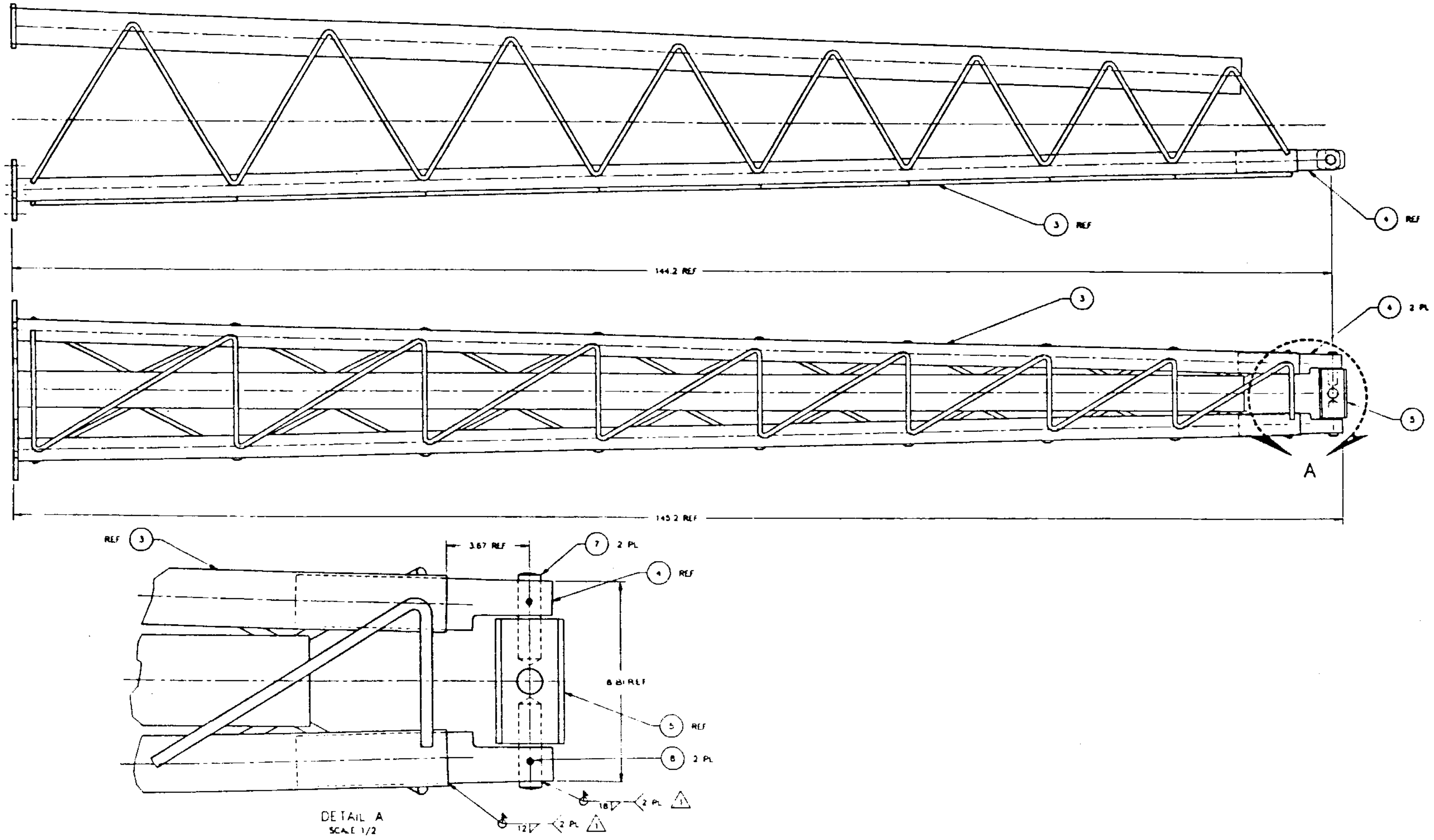


Figure 9.0-5. Truss Assembly

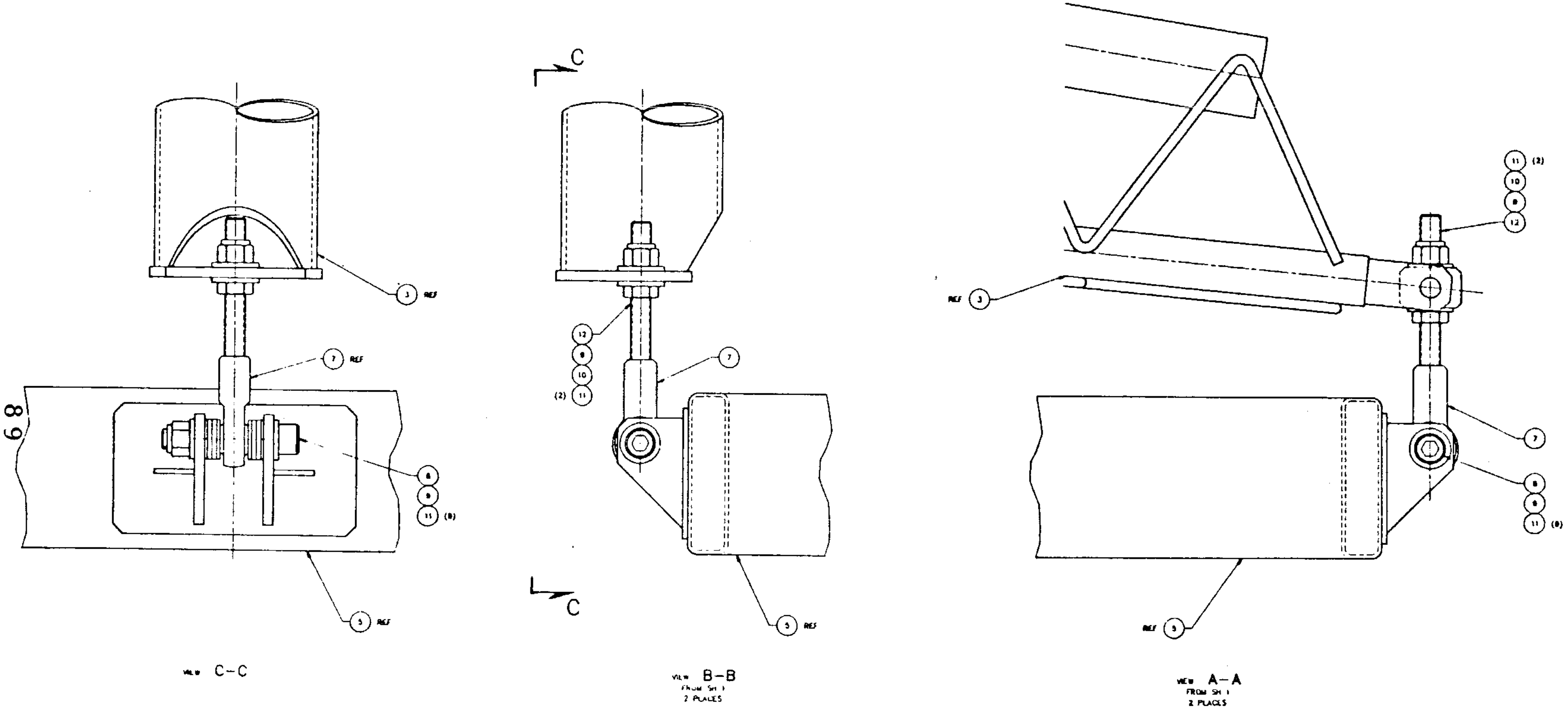


Figure 9.0-6. Ring Attachments

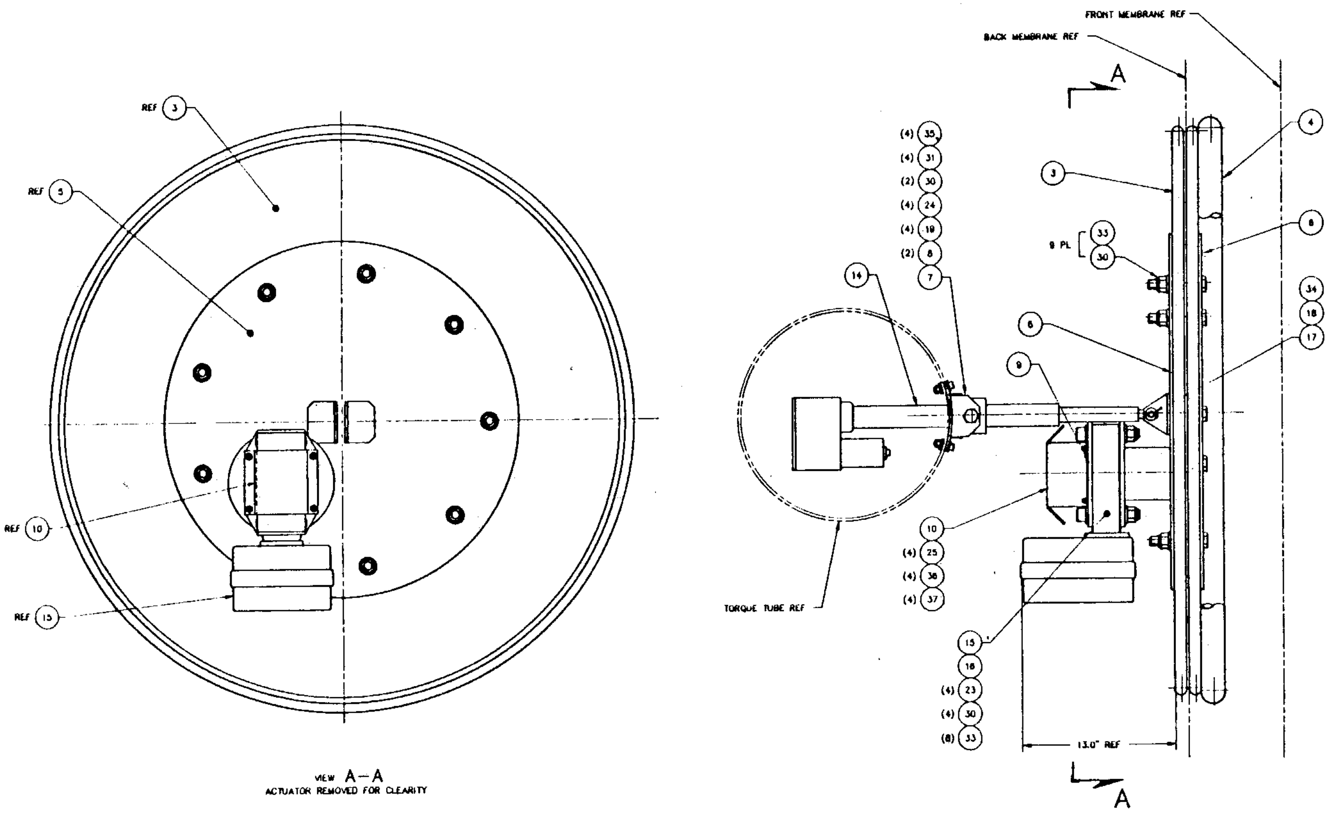


Figure 9.0-7. Focus/Defocus Assembly

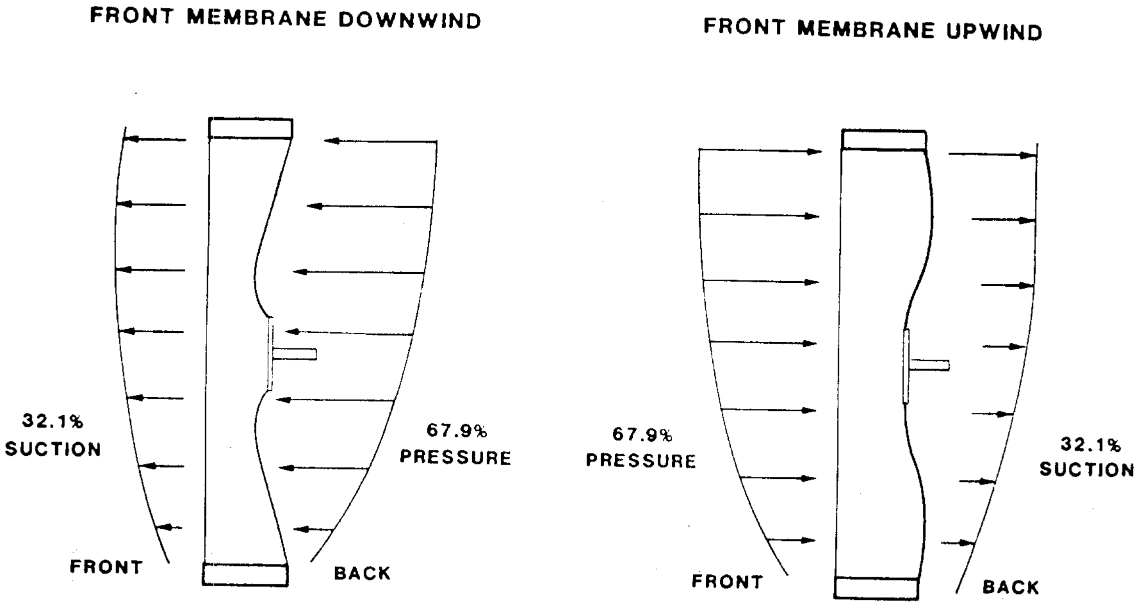


Figure 9.0-8. Mirror Module Wind Loading

module heliostat control system requirements include active, closed-loop control of two independent focus-control systems, closed-loop azimuth and elevation drive positioning, open-loop sun position calculations and azimuth and elevation drive position calculations, and emergency defocus capability. The control system for the SAIC dual module heliostat consists of a single Z80-based microprocessor located in an enclosure next to the heliostat, and a 80386-based microcomputer located in the control tower. The 80386 computer located in the control tower will perform the open-loop sun position calculations and the azimuth and elevation drive position calculations. The on-board Z80 computer will control the focusing of both mirror modules and will control the azimuth and elevation positioning as well as the emergency defocus command on an interrupt basis.

The focus-control logic diagram is shown in **Figure 9.0-9**. Variables can be remotely set, and sent from the 80386 in the control tower to the on-board Z80 microprocessors. These variables control such information as refocus position, stow position, focal point, and the LVDT deadband in which there is no action taken. A set of optimized default variables are stored in the Z80's ROM. They can be changed remotely and will remain in effect until the Z80 loses power or receives updated information from the 80386. Once these variables are set the control system examines the LVDT output and takes the appropriate action. The system oscillates between mirror modules continuously as shown in **Figure 9.0-10** until an interrupt signal is received. Once an interrupt signal is received, the Z80 will stop what it is doing, remembering its current state, and perform the interrupt command. The interrupt signals include the following:

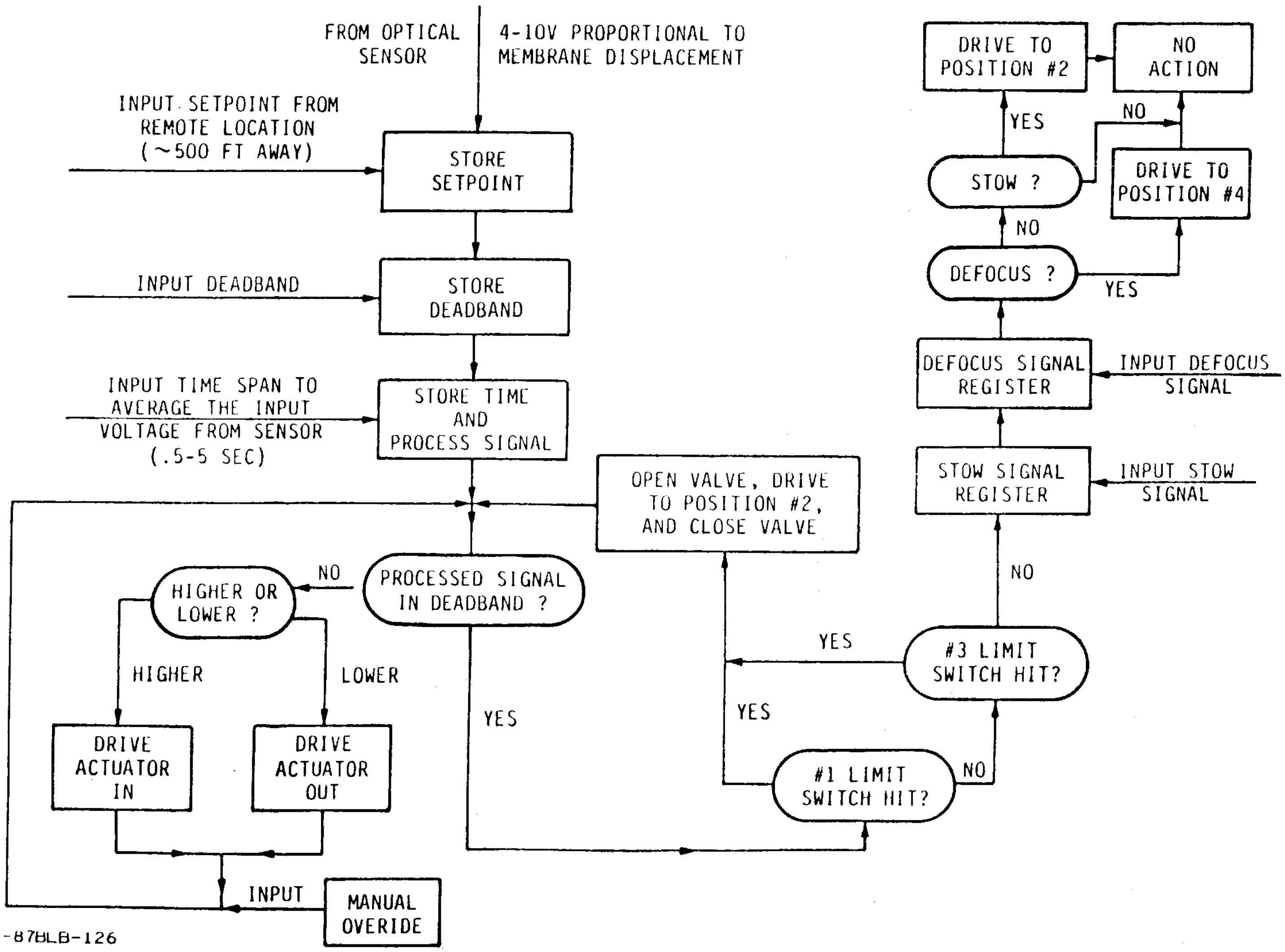
- Drive Position Change

- Defocus Command

- Stow Command

Upon receipt of a drive position change interrupt, the Z80 will suspend program execution, execute the interrupt command, which would be to change the azimuth and elevation position of the drive, and resume program execution. Upon receipt of a defocus or stow position interrupt, the program execution is halted, the interrupt command is executed, and the Z80 does nothing until it receives another command.

FOCUS CONTROL LOGIC



SAIC-87BLB-126

Figure 9.0-9. Focus Control Logic

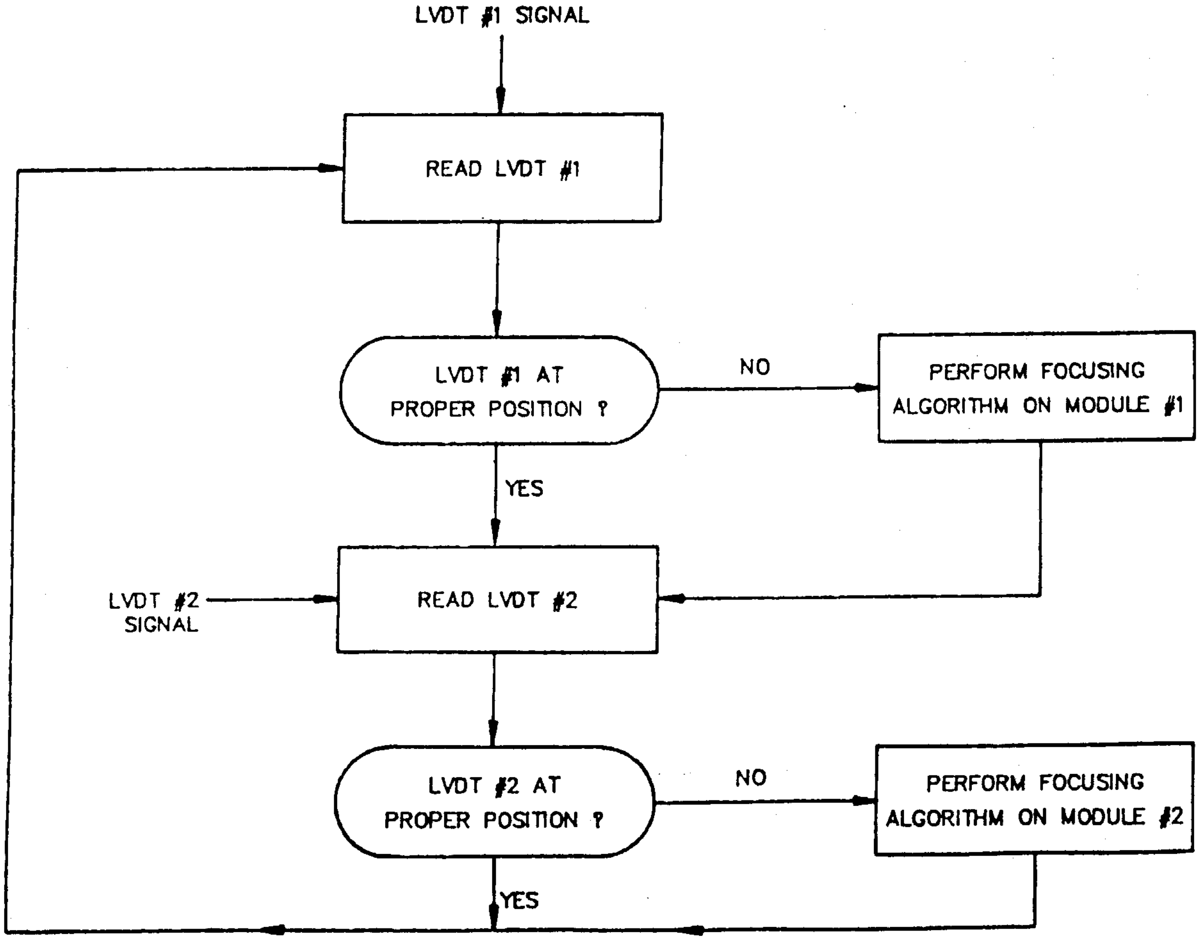


Figure 9.0-10. Z80 Microprocessor Control Logic

Figure 9.0-11 shows the focus-control linear actuator reference positions. The four marked positions in this figure represent physical locations on the linear actuator shaft. The text associated with each position shows the mode the focus-control system is in if the shaft position is moved to the reference plane, which remains fixed in space (in actuality the reference plane is a fixed point on the linear actuator housing). Each of these positions has default values stored in the Z80's ROM, but they can all be changed by using the control program running in the 80386 in the tower and sent down to the Z80. A brief description of each position is provided:

MAX RETRACTION	If the actuator hits this position, the module will go through a refocus cycle. Then continue the focusing algorithm.
NEUTRAL POSITION	This is the position to which the actuator will be driven upon receipt of a stow command.
MAX EXTENSION NORMAL OPERATION	If the actuator hits this position or if the LVDT hits a predetermined position under normal operation conditions, the module will go through a refocus cycle. Then continue the focusing algorithm.
DEFOCUS EXTENSION	This is the position to which the actuator will be driven upon receipt of a defocus command if the LVDT defocus position has not been reached.

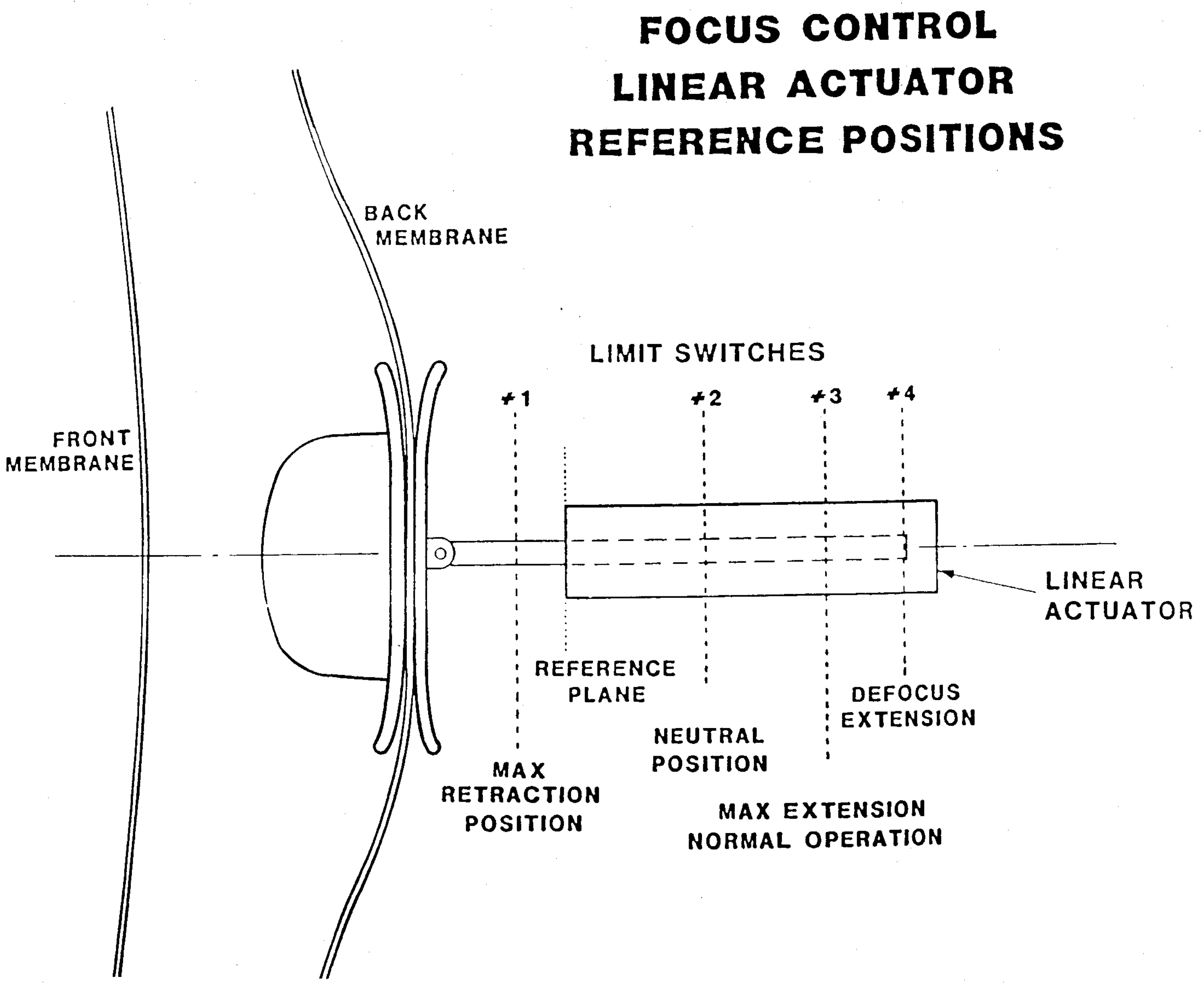


Figure 9.0-11. Focus Control Linear Actuator Reference Positions

10.0 DESIGN STUDIES FOR DUAL MODULE HELIOSTAT

Once the SAIC dual module heliostat was selected as the concept to be designed in Phase II, detailed design and analysis work began on the mechanical components. The initial phase of this process focussed on optimization and validation of the large structural components. Classical analytical techniques as well as extensive finite element analysis were performed on the trusses, torque tube, pedestal, and ring/membrane mirror module system. The design loads were based on operational and survival wind load conditions. The loads were determined using "Wind Load Design Guide For Ground Based Heliostats" [5]. The maximum operational mean wind speed used was 50.3 km/hr (31.25 mph). Under a mean wind of 50.3 km/hr (31.25 mph) peak wind gusts of up to 80.5 km/hr (50.0 mph) could be generated. These two conditions therefore characterized the design loads used. **Table 10.0-1** shows the resultant loads generated by these winds. **Figure 6.2-1** shows the geometry referenced in this table.

With the wind loads defined, it was necessary to analyze all components for operational deflections and survival stresses. The heliostat is required to be fully operational under 50.3 km/hr (31.25 mph) wind loading. This means that structural members must not have deflections large enough to create out-of-tolerance slope and pointing errors under the force of 50.3 km/hr (31.25 mph) wind. Under 80.5 km/hr (50.0 mph) wind loading the only requirement on the heliostat is that it not sustain any permanent deformation or damage.

Figure 10.0-1, shows a freebody diagram for the mirror module under operational conditions. This diagram shows that under operational wind loading, the reaction forces on the support ring are equal to P*A, which is the pressure change across the front membrane times the front membrane surface area. The load on the actuator therefore is equal to the wind load minus P*A. As the wind load increases, the force on the front membrane greater than that which would cause the module to be focussed, is reacted directly in the linear actuator.

Under survival loading the focus-control system will be sent a stow signal which will cause the linear actuator to remain fixed in the stow position. Since the actuator position is fixed and is not increasing its actuating force to compensate for the wind, as the wind load increases, the reaction forces on both the ring and actuator increase proportionally. It was determined analytically that 1/3 of the load is reacted at the actuator and 2/3 of the load is reacted at the ring. A freebody diagram for the mirror module under survival loading conditions is shown in **Figure 10.0-2.**

Once the survival and operational loading conditions were established, it was necessary to determine allowable stress limits and deflection criteria based on pointing accuracy requirements. Based on standard structural design practice, the maximum stress was limited to 60% of the material's yield stress. Pointing accuracy requirements were calculated based on the target dimensions on the receiving tower and the largest focal image size from a module in the field. The resulting allowable pointing error was determined to be 2.5-mRad. The maximum allowable mirror module slope error was also determined to be 2.5-mRad in order to balance accuracy and cost/design considerations.

FORCES AND MOMENTS FOR 50 m^2 STAND ALONE HELIOSTAT

(Mean Wind = 31.25 mph, Peak Wind = 50 mph)

Component	α	β	Mean Value	Peak Value
F_x	90°	0°	* 2087 lb	* 4175 lb
F_x	30°	0°	1044 lb	2192 lb
F_x	90°	65°	1670 lb	3862 lb
F_z	90°	0°	313 lb	1044 lb
F_z	30°	0°	* 1409 lb	* 2922 lb
F_z	90°	65°	313 lb	522 lb
M_{Hy}	90°	0°	2985 lb-ft	6784 lb-ft
M_{Hy}	30°	0°	* 6784 lb-ft	* 16282 lb-ft (1)
M_{Hy}	90°	65°	543 lb-ft	4071 lb-ft
M_z	90°	0°	0	9498 lb-ft (2)
M_z	30°	0°	0	4071 lb-ft (3)
M_z	90°	65°	* 6784 lb-ft	* 18996 lb-ft
M_y	90°	0°	* 29850 lb-ft	* 59022 lb-ft
M_y	30°	0°	17639 lb-ft	36635 lb-ft
M_y	90°	65°	22252 lb-ft	52238 lb-ft

* Maximum Values

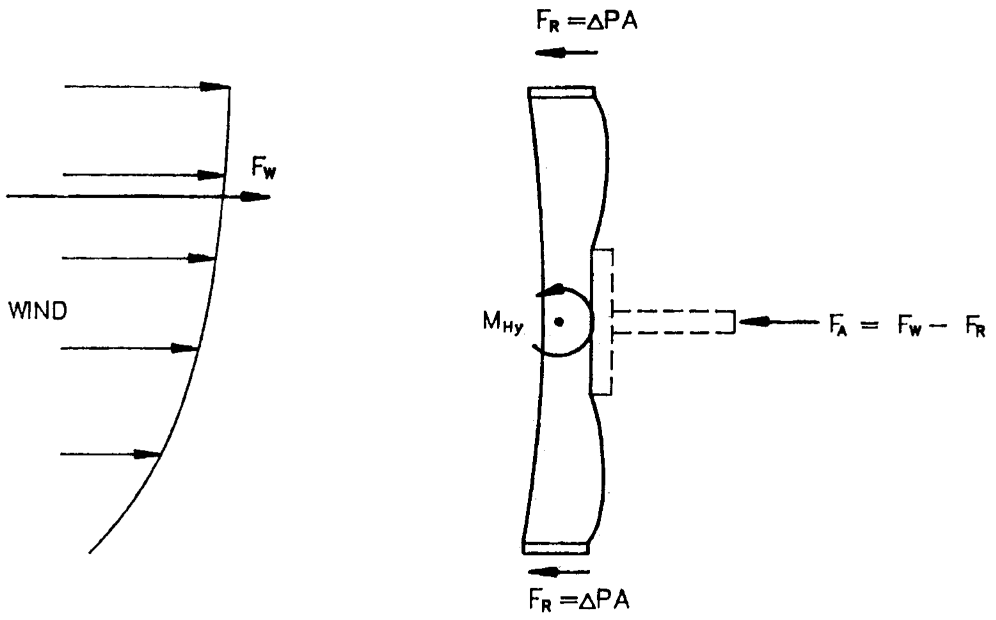
(1) Wind from the back. (Slightly lower value for wind from the front.)

(2), (3) Transient loading which can reverse direction.

Where, α = Elevation Angle
β = Azimuth Angle
F_x = Drag Force
F_z = Lift Force
M_{Hy} = Moment About Horizontal Axis
M_z = Moment About Vertical Axis
M_y = Moment About Base

Table 10.0-1. Forces and Moments for 50-m^2 Stand Alone Heliostat

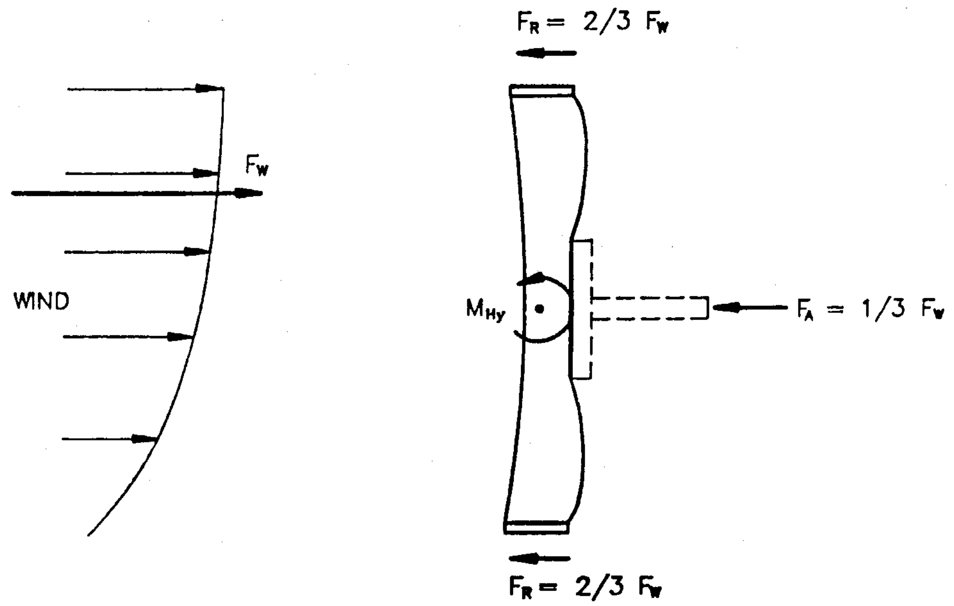
FREEBODY DIAGRAM FOR MIRROR MODULE (OPERATIONAL).



A – MEMBRANE SURFACE AREA
ΔP– PRESSURE DIFERENCE REQUIRED ACROSS FRONT MEMBRANE FOR FOCUS
F_W – RESULTANT WIND FORCE
F_R – REACTION FORCE ON RING
M_{Hy}– REACTION MOMENT ABOUT ELEVATION AXIS
F_A – ACTUATOR FORCE ON REAR FOCUS PAD

Figure 10.0-1. Freebody Diagram for Mirror Module Under Operational Load

FREEBODY DIAGRAM FOR MIRROR MODULE (SURVIVAL).



F_W – RESULTANT WIND FORCE
F_R – REACTION FORCE ON RING
M_{Hy} – REACTION MOMENT ABOUT ELEVATION AXIS
F_A – ACTUATOR FORCE ON REAR FOCUS PAD

Figure 10.0-2. Freebody Diagram for Mirror Module Under Survival Load

10.1 Heliostat Size

Previous studies have shown that the heliostat cost per unit area curve is fairly flat in the range of 100 - 200-m^2 (1070 - 2150-ft^2). Since economic and near-term commercialization factors were considered during Phase I downselect, these factors were also considered during the size selection for the SAIC dual module heliostat. SAIC has built several 50-m^2 (538-ft^2) mirror modules and has experience and tooling for this size module. Therefore, it was determined that retaining 50-m^2 (538-ft^2) module size provides the least cost path to full scale build. This module size will provide 100-m^2 (1070-ft^2) of reflective surface area for the SAIC dual module heliostat.

10.2 Mirror Module Design

The mirror module analysis is a very complex problem. Due to the very small bending stiffness of the thin membranes, linear small deflection theory is inadequate to provide an accurate representation of the stress vs. strain relationship in the mirror module. The combined ring/membrane system provides a very stiff structure. Any out-of-plane or torsional loading that would tend to cause compression on one membrane would be compensated for by tension in the other membrane. Although linear theory can provide much insight and reasonable estimates of the mirror module's behavior under loading, a complete non-linear finite element analysis was also performed to characterize the stress vs. strain relationship in the mirror module.

A non-linear, large deflection analysis was performed using the ANSYS Engineering Analysis System on a Cray X-MP Supercomputer. **Figure 10.2-1** shows the finite element model nodal points with the applied loading and displacement constraints. **Figure 10.2-2** shows the finite element mesh of the ring/membrane system. As can be seen in these figures, the equivalent wind load was applied directly to the ring and not to the membranes. As mentioned above, under operational conditions, the ring load remains relatively constant. Since the main goal of this analysis was to characterize the ring/membrane coupling relationship and not the membrane response to loading, applying the load directly to the ring was appropriate.

After some iteration between membrane thickness and ring size, the components were sized to keep structural deflections within the above-mentioned slope error requirements. **Figure 10.2-3** shows a highly magnified plot of the mirror module deformed under wind loading. **Figure 10.2-4** shows a shaded image of the front membrane. The shading of this image is based on out-of-plane deflections. By examining this image it can be seen that the largest deflection occurred between the torque tube attachment point (at the right in this image) and the upper truss attachment point located 120° counterclockwise from the torque tube attachment point. **Figure 10.2-5** shows von Mises stress shading of the front membrane under the given loading conditions.

10.3 Support Structure Design

The support structure was given a pointing accuracy requirement of 2.5-mRad. In order to meet this requirement, the pointing accuracy was translated into allowable structural deflections. The allowable deflection was distributed among the various components in the structure so that the overall structural deflections remained within tolerance. The major structural components to which the deflection budget was distributed were the trusses, the torque tube and the pedestal.

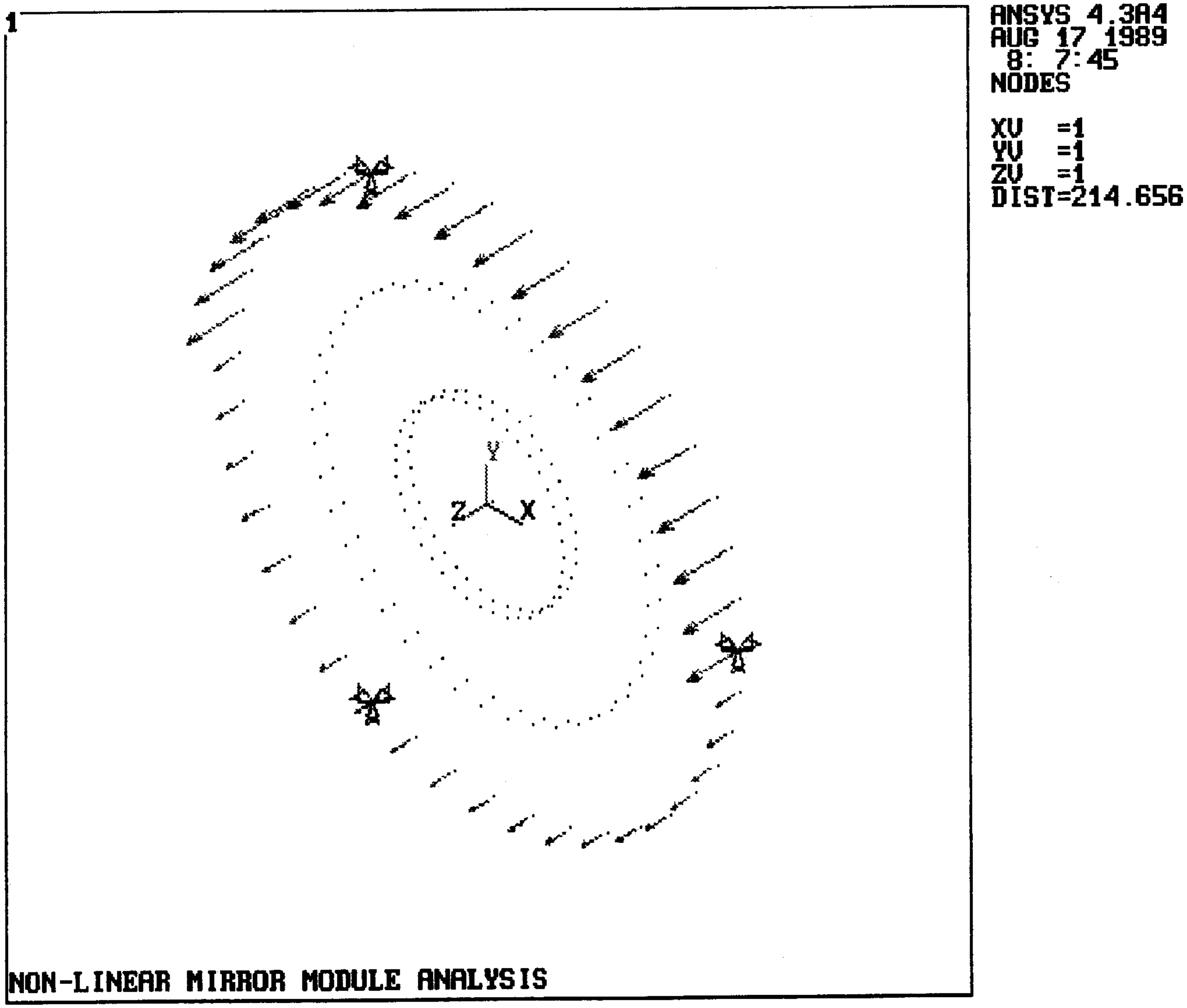


Figure 10.2-1. Finite Element Model Nodal Points

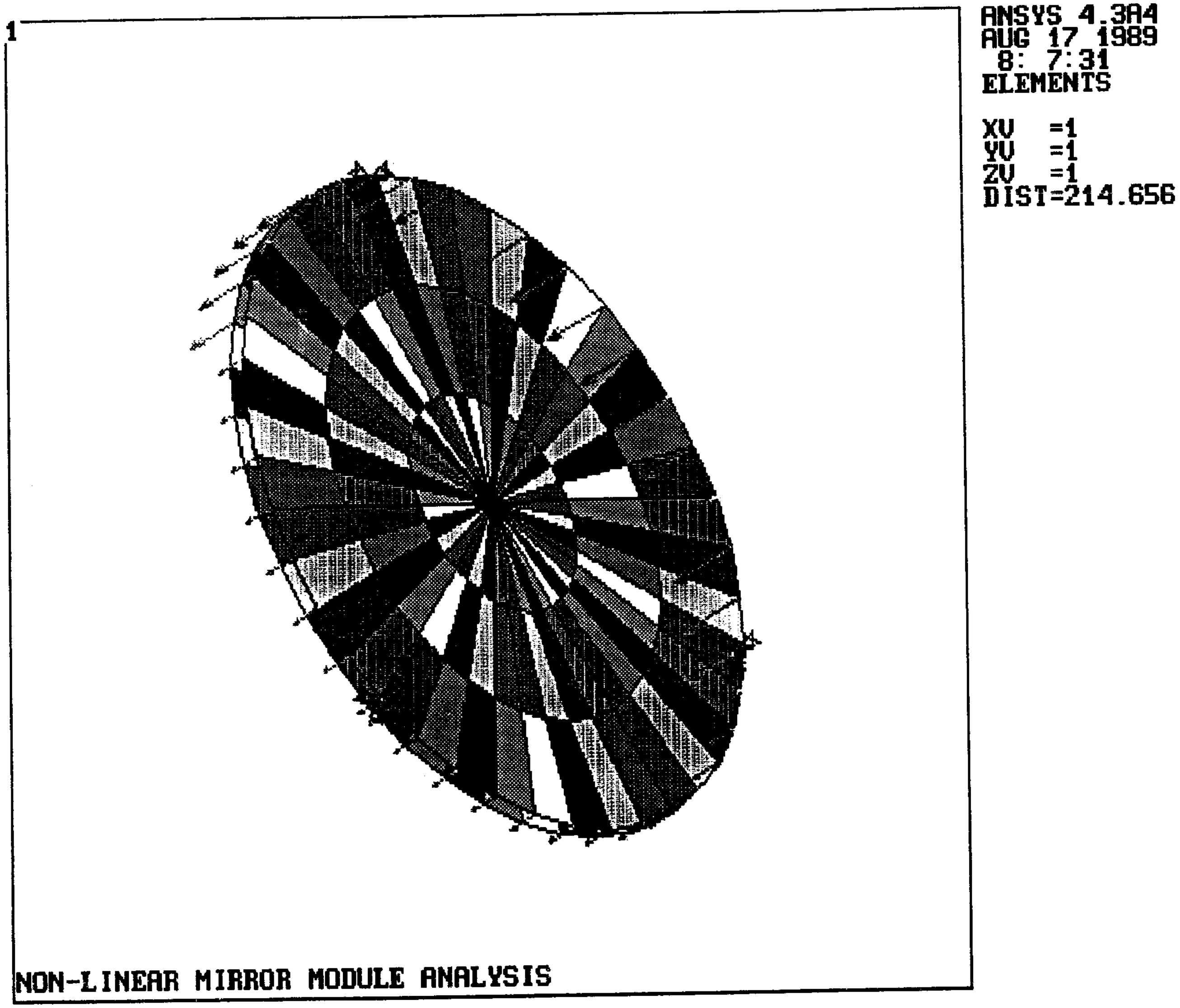


Figure 10.2-2. Finite Element Mesh

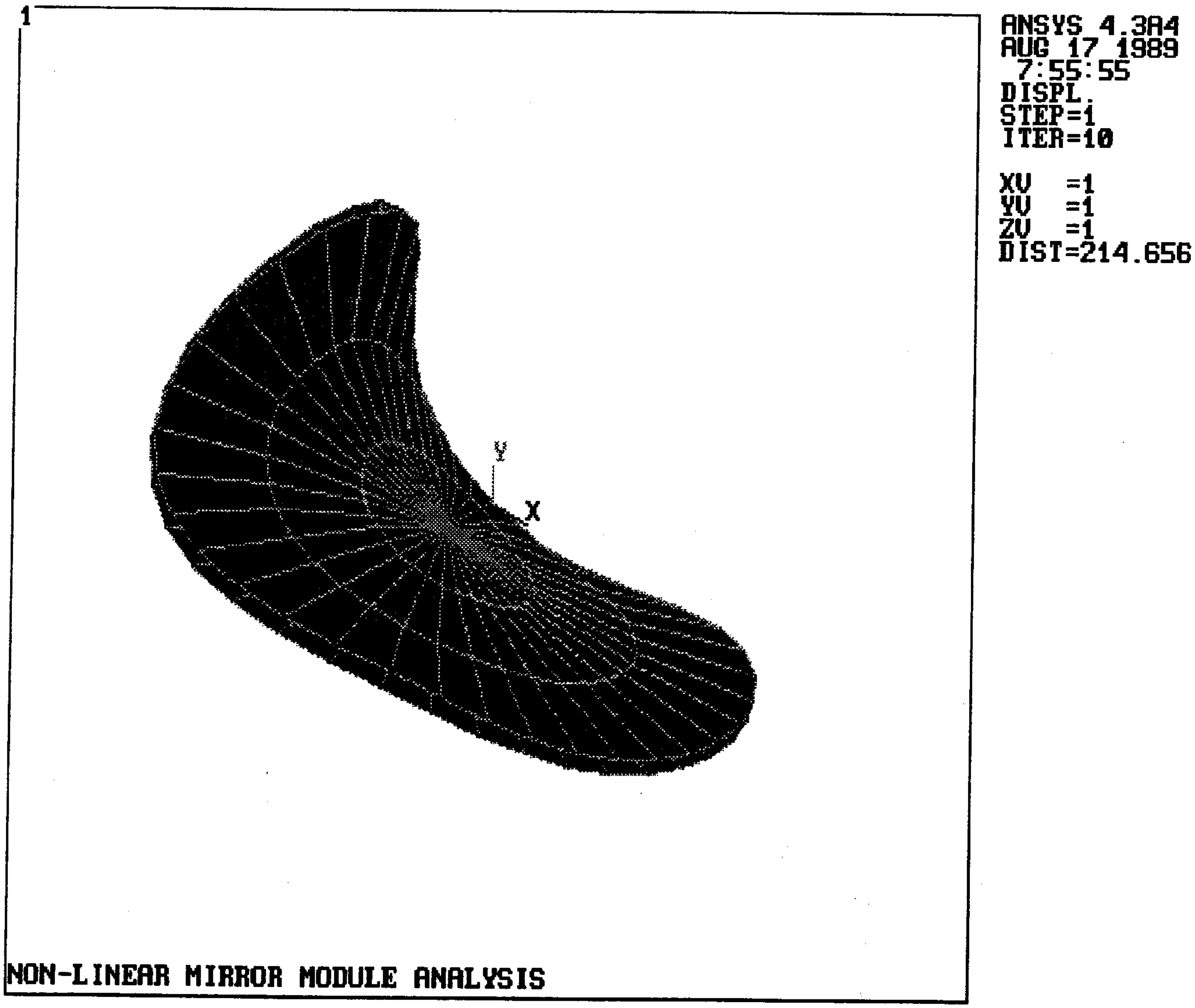


Figure 10.2-3. Deformed Mirror Module

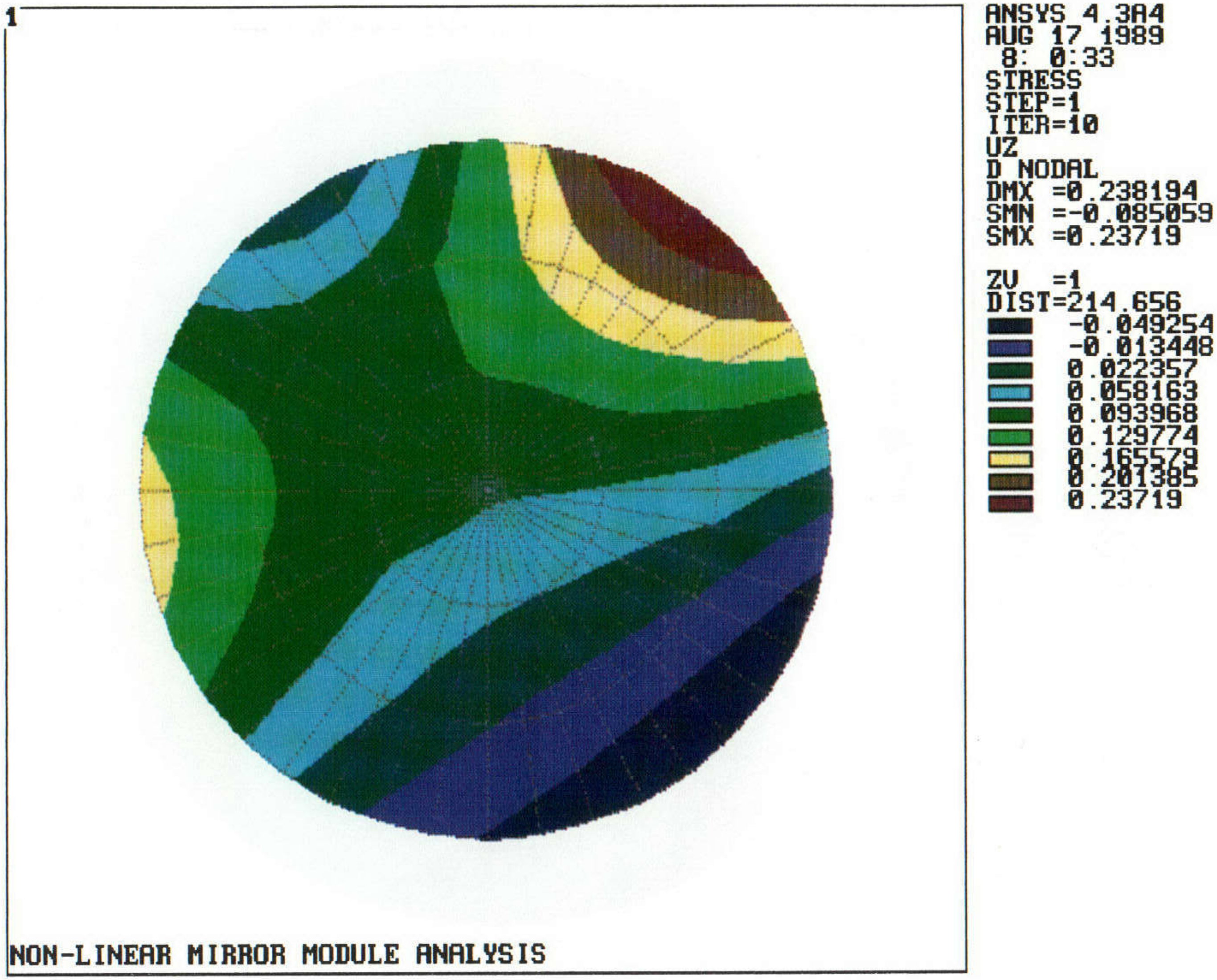


Figure 10.2-4. Front Membrane Deflection Shading

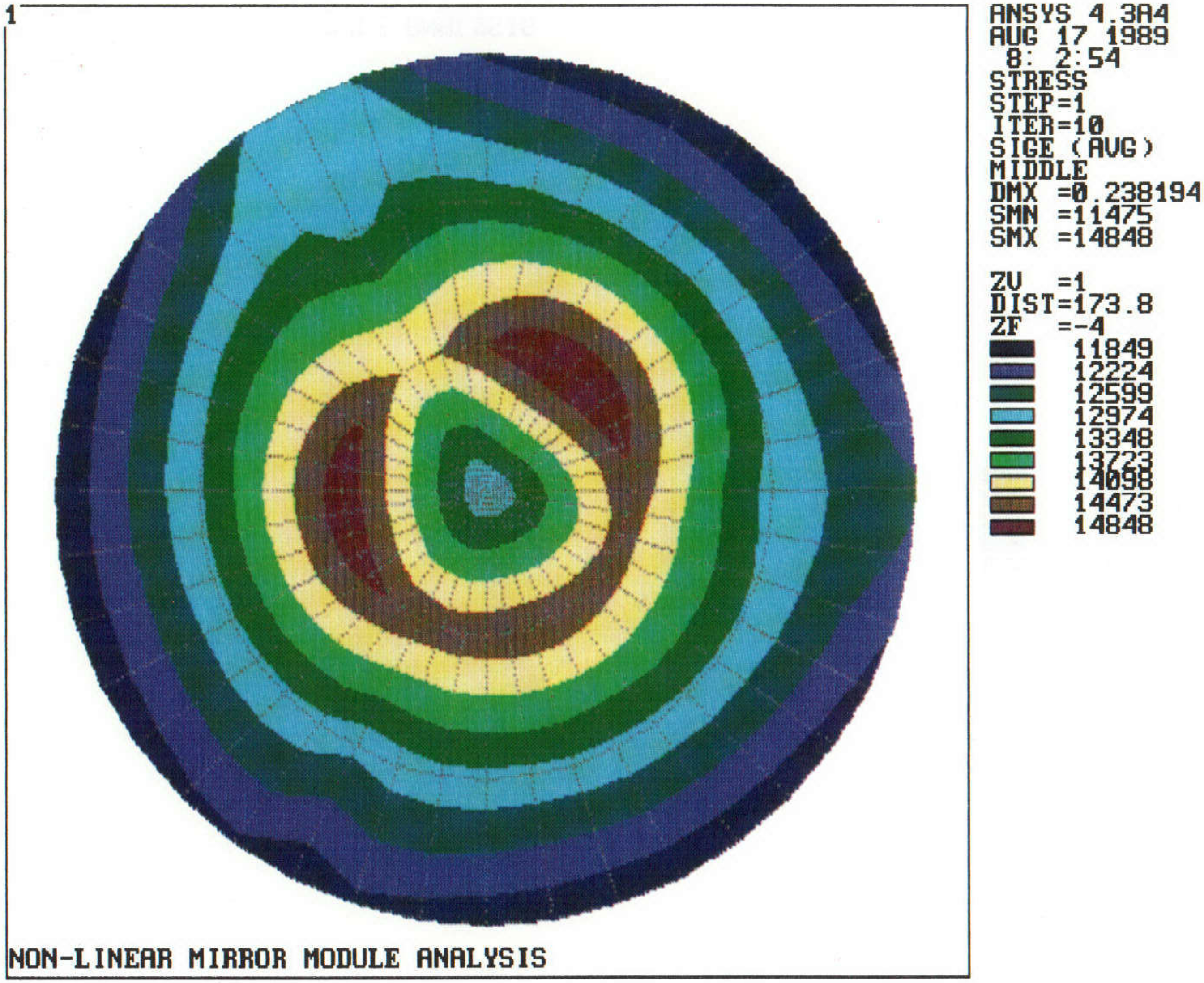


Figure 10.2-5. Front Membrane Von Mises Stress Shading

For both the torque tube and truss, the final designs were dictated by deflection criteria at operational conditions. The designs of the torque tube and truss are further described in the following subsections.

10.3.1 Torque Tube Size

Analysis was performed by modeling the torque tube as a cantilevered beam fixed at the location of the drive unit. Under operational conditions, most of the forces and moments acting on the module are transferred directly through the rear membrane modulation focus-control system to the torque tube. Therefore, in the analysis, the loads were applied to the tip of the torque tube. The tube was analyzed under various loading conditions corresponding to the mirror module in positions determined to give high loads in the structure.

Under worst operational loading conditions, the torque tube had a maximum tip deflection of .17-in. This deflection translates to a pointing error of 1-mRad.

10.3.2 Module Support Truss Design

The allowable truss tip out of plane deflection was determine to be .12-in. Detailed finite element analysis was performed on the truss using Supersap, a PC-based finite element analysis package. Various truss configurations were examined to determine the best method of supporting the mirror modules. It was determined that a mirror module configuration with three support points would provide enough structural stiffness while limiting the number of mirror module deflection mode shapes and fabrication cost.

Figure 10.3-1 shows the finite element model of the triangular truss. **Figure 10.3-2** shows the truss deformed under the force of a 50.3 km/hr (31.25 mph) wind load. The truss design was governed by the pointing accuracy requirements of the mirror module. Component sizing was based on structural deflections under operational loading rather than stress in the members under survival loading.

10.4 Heliostat Drive Design

Figure 10.4-1 shows the resultant loads on the heliostat drive system. This figure was sent to various drive manufacturers for evaluation and price quotes. The price quotes have been received and are being evaluated. Final drive selection will be performed as part of the fabrication and assembly portion of the program. A drive with 360° elevation angle rotation is required in order to implement the face-down stow capability of the dual module heliostat.

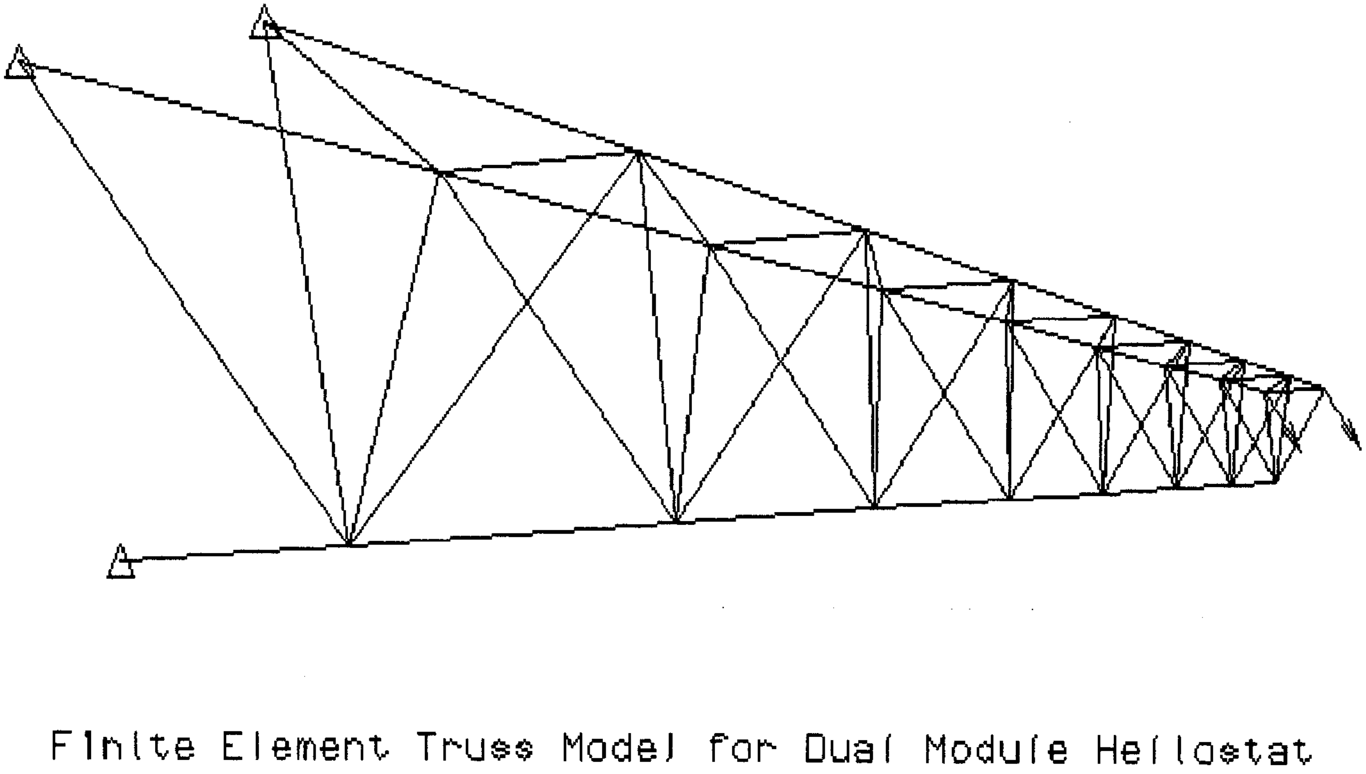


Figure 10.3-1. Triangular Truss Finite Element Model

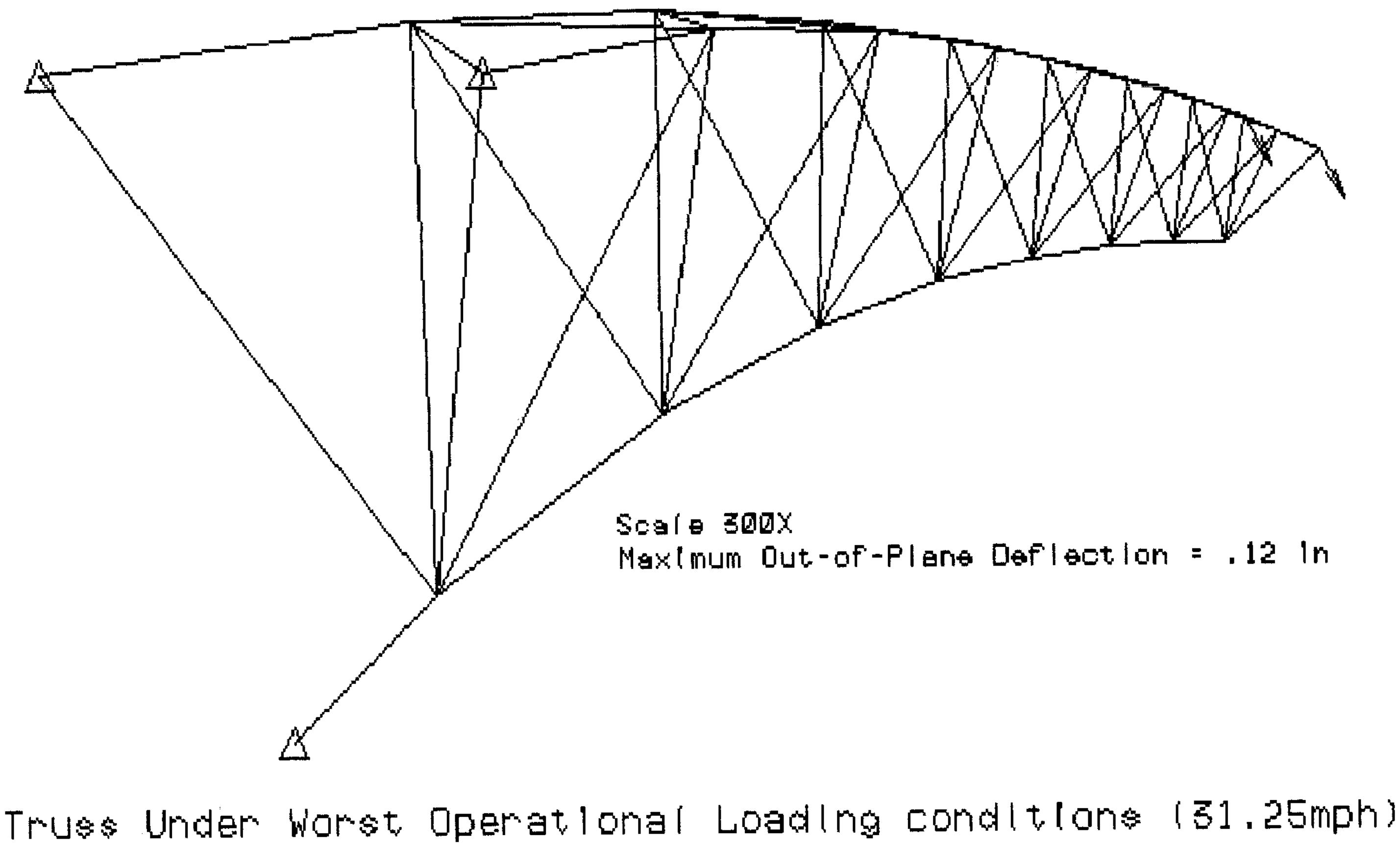


Figure 10.3-2. Deformed Triangular Truss Model

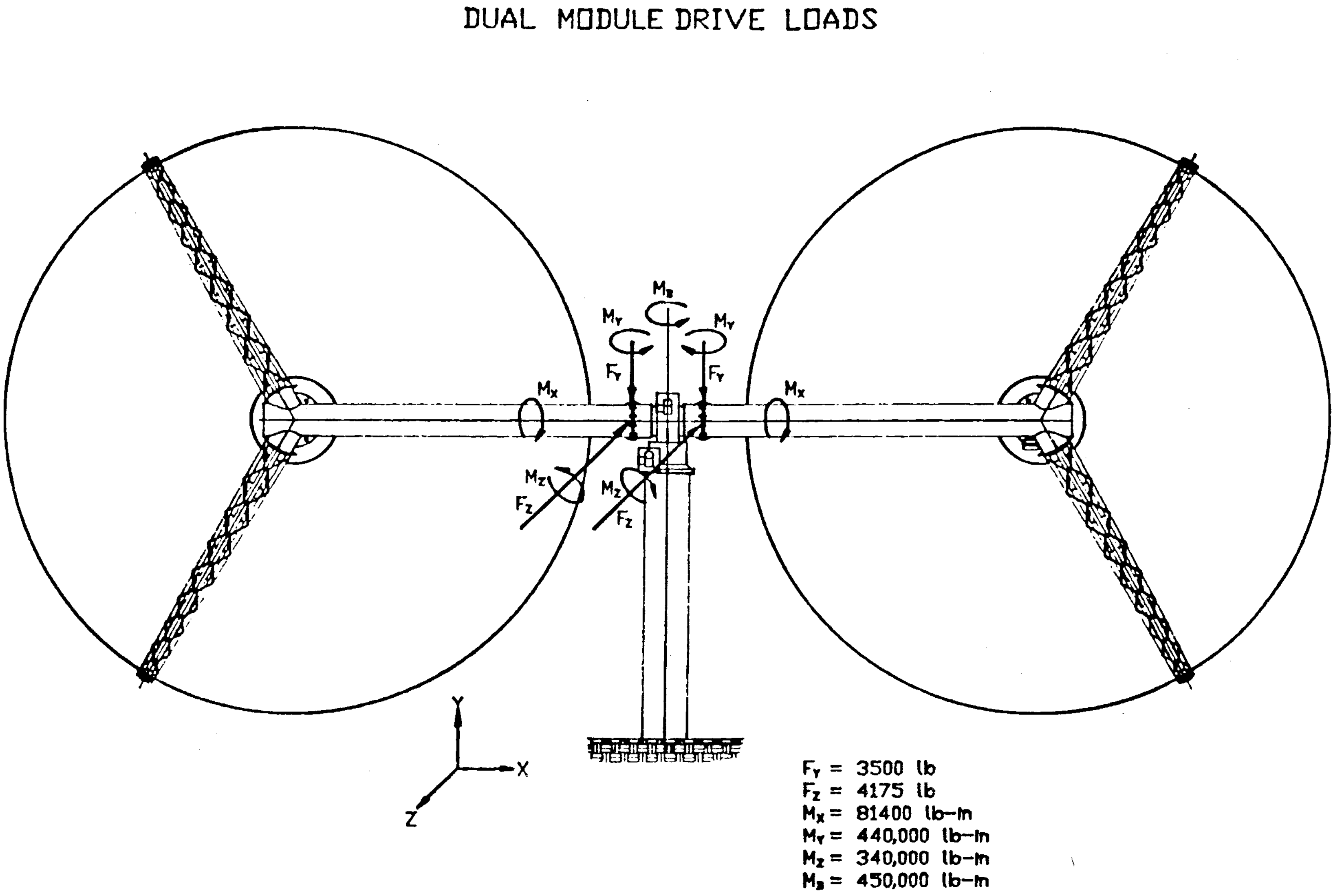


Figure 10.4-1 Resultant Loads on Heliostat Drive System

11.0 DETAILED MANUFACTURING COST ESTIMATES

In the course of the Phase I studies, most of the information for the manufacturing analysis of the dual module heliostat was developed. Details of the manufacturing scenario are therefore contained in Sections 6.1, 6.4.2, and 7.1. For the final estimate, it was only necessary to update the preceding cost estimate with the changes that occurred during the Phase II design work. A cost estimate for the multi-bar drive was not made during Phase I, so it was necessary to perform analysis to establish changes to the baseline manufacturing scenario and to estimate materials costs for that design. This effort drew upon the information available from the ongoing SBIR program in which Dan-Ka, Inc. is designing and constructing a prototype 50-m^2 (540-ft^2) multi-bar heliostat. SAIC is supplying the mirror module for that program and has access to design data. The following paragraphs summarize the results of the cost analysis. The subsections detail additional manufacturing process changes required for each of the two designs.

The results of the cost analyses are shown in **Figure 11.0-1**, in which are presented bar graphs of the estimated lifetime costs of the baseline pedestal heliostat, the dual module heliostat, and the multi-bar heliostat. These costs are for 150-m^2 unit sizes, and include levelized costs of cleaning and maintenance over the life of the collector. **Table 11.0-1** gives an overview of the costs, and **Appendix D** contains the detailed cost elements in tabular form. As shown in the table, the estimated cost of the multi-bar heliostat is marginally better than the pedestal heliostat, and the estimated cost of the dual module heliostat is about 20% less.

It should be noted that the dual module and pedestal heliostat costs are much better known at this point. Two prototype pedestal mirror modules have been constructed by SAIC, and the detailed design of a dual module heliostat is part of this report. Although the estimate for the multi-bar heliostat is less certain, specific elements of the multi-bar heliostat, which led to its relatively high cost, can be identified as follows:

- The membrane thickness was increased to 0.005-in., in order to stiffen the mirror module. In addition, the heliostat ring was made significantly stronger (and hence, heavier), to provide needed module stiffness. These are necessary because the multi-bar asymmetrical three-point support system leaves the entire upper half of the mirror module (where the wind loads are highest) unsupported. The effect is therefore similar to a two-point support system.

- The drive actuators, taken to be machine screw linear actuators, are a significant expense.

- Finally, installation costs for the Dan-Ka heliostat were slightly higher than for the other units, because the installation procedure involves three foundations and the setting of three drive elements in place before the mirror module is installed. With a pedestal, only one foundation and one component must be installed.

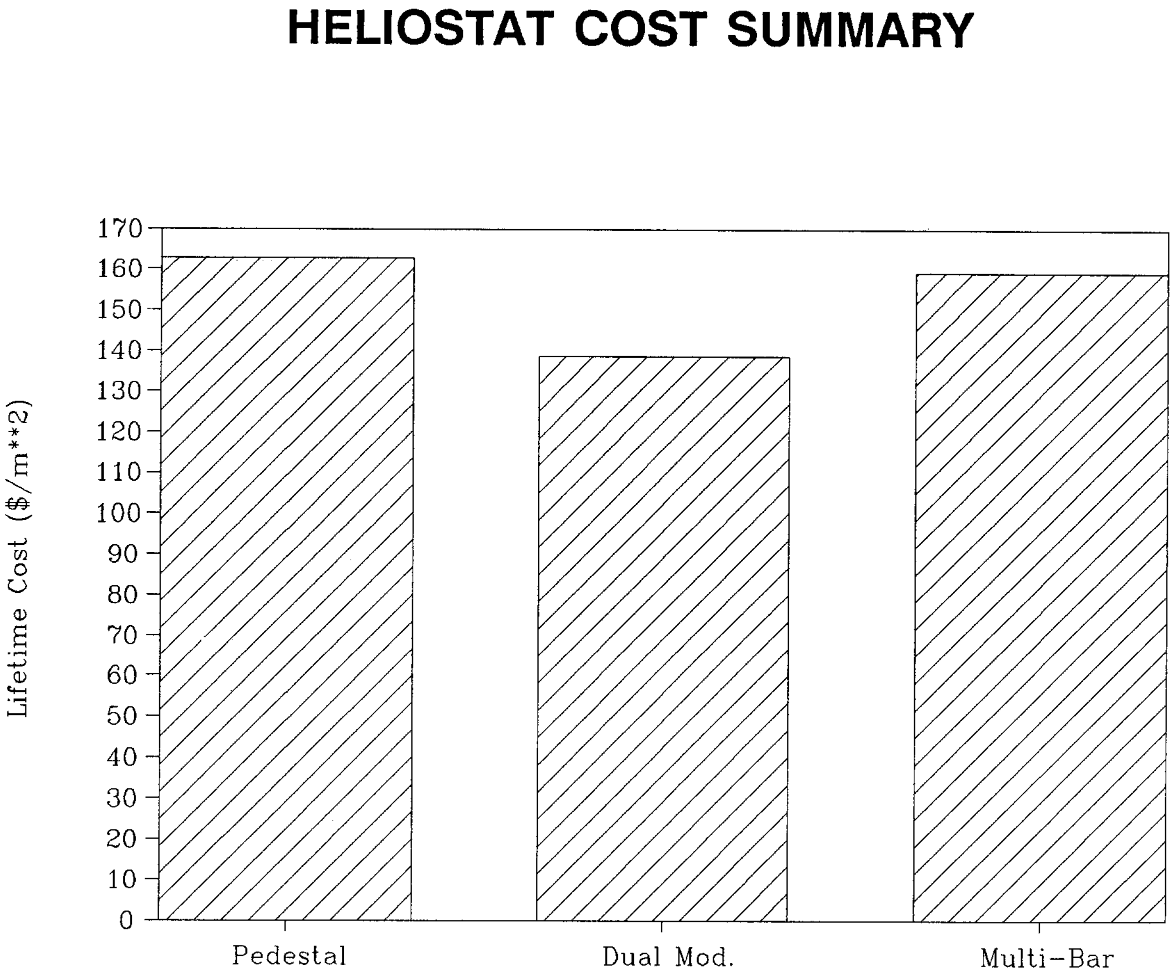


Figure 11.0-1 Lifetime Cost Overview for the Three Selected Heliostat Designs

	Pedestal	Dual Mod.	Multi-Bar
Mirror Module(s)			
Ring(s)	359	600	1059
Membranes	1400	2113	2125
Focus-Control System	920	1307	920
Reflector	2700	2700	2700
Structural Support			
Module Support	3088	921	975
Focus-Control Support	12	12	381
Foundations/Pedestals	1696	1696	636
Drive System			
Azimuth Drive	1646	1646	6000
Elevation Drive	840	1264	
Controls	100	100	100
Assembly/Installation	456	456	491
Total Direct Costs	13219	12816	15388
Buildings & Capital Equip.	254	250	254
Indirect Labor	368	368	368
ROI/Taxes @ 20%	2768	2687	3202
Selling Price	16609	16120	19212
Price/Square Meter	110.72	107.47	128.08
Cleaning	1560	1310	1310
Reflector Replacement	5810	2910	2910
Servicing	453	453	453
Total Lifetime Cost	24431	20793	23885
Total Cost/Square Meter	162.88	138.62	159.23

Table 11.0-1. Lifetime Cost Overview for the Three Selected Heliostat Designs

11.1 Dual Module

In the course of the detailed design, the torque tube and truss masses were altered very slightly. The values for the 100-m^2 (1,080-ft^2) unit designed in Phase II of the present program were scaled by a factor proportional to the heliostat area in order to obtain masses for a 150-m^2 unit for comparison. The values for the 100-m^2 unit were 566 kg (1248 lb) for the torque tube and 80 kg (176 lb) for each of the four trusses. These scaled to 849 kg (1872 lb) for the torque tube of a 150-m^2 heliostat, and 120 kg (264 lb) for each of the trusses.

11.2 Multi-Bar

An evaluation of changes needed in the manufacturing scenario for multi-bar heliostats was carried out. None of the membrane fabrication, ring rolling, or focus-control activities would be changed for this design compared to the baseline pedestal drive. In the area of fasteners and attachments, two additional persons were added to the manufacturing plant for the machining of the ball joints and sockets that are required for the multi-bar drive. It was decided that in-house production of these specialty items would probably be more cost effective than obtaining them from outside vendors.

Considering the fabrication of structural supports, the multi-bar drive has two drive arms, a short pedestal, a bottom truss, and a focus-control support truss instead of the pedestal, hub, and five support trusses of the baseline Pedestal drive. It was estimated that the focus-control truss was approximately equivalent to two support trusses, and the two support arms were approximately equal to the other three trusses in complexity and fabrication time. The pedestal and bottom truss of the multi-bar unit were considered to be less complex than the larger pedestal and hub assembly of the pedestal drive. So, it was estimated that two fewer people would be necessary in that area of structural support fabrication.

Module assembly of the multi-bar heliostat is considerably simpler than that required for a pedestal unit. Instead, most of the assembly occurs in the field. So, the labor for module assembly was reduced to two persons, to assemble the focus-control truss assembly. However, the field assembly was increased to 19 persons to account for the increased number of activities needed to install a multi-bar heliostat. The estimate of installation labor for a multi-bar heliostat was as follows:

Prepare and pour three foundations	2 persons, 1 hour	2 man-hours
Install the two support arms	2 persons, 1 hour	2
Wire and check out the actuators	1 person, 1 hour	1
Install the bottom support truss	2 persons, 1/2 hour	1
Install mirror module	3 persons, 1 hour	1.5
	Total:	7.5 man-hours

Other changes were required in the materials costs for the multi-bar drive. The most significant are mentioned at the beginning of this section; namely, the increased strength of the heliostat ring and the increased thickness of the membranes. The support structure element masses were estimated based upon extrapolation of the 50-m^2 prototype component masses. For the 50-m^2 prototype, the total support structure mass is estimated at 892 kg (1966 lb). For a 150-m^2 heliostat, this was extrapolated by a factor of 1.5 determined by comparison of the heliostat ring sizes required for 50-m^2 (540-ft^2) and 150-m^2 p1610^2) pedestal heliostats. The resulting total mass was divided between the components as follows:

Support Arms -- 2 ea. X 483 kg (1065 lb)	966 kg (2130 lb)
Center Support/Pedestal	372 kg (820 lb)
Total:	1338 kg (2950 lb)

The cost of the linear actuators for the multi-bar drive was obtained from a manufacturer of worm gear linear actuators. The specifications for the actuator were extrapolated from the design of the 50-m^2 multi-bar prototype under construction at Dan-Ka Products, Inc. The 50-m^2 heliostat requires 20 ton actuators, which was extrapolated linearly to 60 tons for the 150-m^2 heliostat. The length of throw is about 3-m (10-ft.) in the 50-m^2 design, which was increased to 4.5-m (15-ft.) for the 150-m^2 module. Because of the orientation of the linear actuators, they operate in compression only when they are not fully extended. This characteristic may allow a relaxation of the requirements on them for buckling stability and allow a cost reduction. However, sufficient details of the loads on the actuators were not available so this was not investigated.

12.0 CONCLUSIONS

Science Applications International Corporation has developed the first integrated stretched-membrane heliostat system. Many innovative heliostat concepts were identified and evaluated in the first phase of this program in terms of cost effectiveness and near-term development potential. The SAIC dual module heliostat was chosen, and a detailed design has been completed. This heliostat is structurally optimized and cost efficient. Commercially available components were used in the design wherever possible to facilitate small-scale production as well as mass production. Aside from some minor development, such as the control system electronics, drive procurement, and foundation design, the design is complete.

The dual module design incorporates long-sought features such as face-down stow, as well as proven technology such as the single-unit drive system. The design is optimized from a structural and economic viewpoint. This heliostat represents an advancement in heliostat technology. Both capital and O&M costs are expected to be reduced significantly compared to the pedestal design.

The heliostat will be fabricated and demonstrated in Phase III of the program. Commercialization and marketing of this advanced heliostat will then be possible.

13.0 REFERENCES

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APPENDIX A

INITIAL COST ESTIMATES OF HELIOSTAT DRIVES

APPENDIX A

Heliostat Cost Calculation
5000 Unit/year Production Rate
2/3/89

	Pedestal		Shared Support		Dual Module		Yoke	
	Standard	Wind-Avoiding	Standard	Wind-Avoiding	Standard	Wind-Avoiding	Standard	Wind Avoiding
Mirror Module(s)								
Ring(s)	359	359	307	307	600	600	969	969
Membranes	1400	1400	1400	1400	1388	1388	2125	2125
Focus Control System	920	920	920	920	1307	1307	920	920
Reflector	2700	2700	2700	2700	2700	2700	2700	2700
Structural Support								
Module Support	3088	3088	632	552	1013	1013	2754	2754
Focus Control Support	12	12	356	356	12	12	356	356
Foundations/Pedestals	1696	1696	1696	1696	1696	1696	891	891
Drive System								
Azimuth Drive	1646	1071	482	428	1646	1071	1772	1153
Elevation Drive	840	638	1369	1042	1264	962	1369	1042
Torque Limiter		504				504		504
Controls	100	100	100	100	100	100	100	100
Assembly/Installation	456	456	456	456	456	456	456	456
Total Direct Costs	13219	12945	10420	9958	12182	11808	14414	13971
Buildings & Capital Eqpt.	254	254	271	271	250	250	254	254
Indirect Labor	368	368	368	368	368	368	368	368
ROI/Taxes @ 20%	2768	2713	2212	2220	2560	2485	3007	2918
Selling Price	16609	16281	13270	12816	15359	14910	18043	17511
Price/Square Meter	111	109	88	85	102	99	120	117
Cleaning	609	609	501	501	422	422	422	422
Reflector Replacement	4200	4200	2620	2620	2620	2620	2620	2620
Servicing	453	453	525	525	453	453	453	453
Total Lifetime Cost	21870	21542	16916	16462	18854	18405	21538	21006
Cost Per m**2	145.80	143.61	112.77	109.75	125.69	122.70	143.58	140.04

Pedestal Drive
Standard

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.65	156.00	523.32	679.32		
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	564.63	720.63		
Ring	0.30	72.00	287.22	359.22		
Sub-Total	1.60	384.00	4075.51		4459.51	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	350.00	350.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	161.40	161.40		
Equilibration Valve		0.00	77.55	77.55		
Sub-Total	0.40	96.00	824.44		920.44	
Structural Support						
Module Support	0.65	156.00	2932.40	3088.40		
Focus Control Support		0.00	11.86	11.86		
Sub-Total	0.65	156.00	2944.26		3100.26	
Drive System						
Azimuth Drive		0.00	1646.40	1646.40		
Elevation Drive		0.00	840.00	840.00		
Control Box		0.00	100.00	100.00		
Sub-Total	0.00	0.00	2586.40		2586.40	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	1460.14	1484.14		
Sub-Total	0.10	24.00	1672.14		1696.14	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	4.20	1009.00	12209.75	13218.75	13218.75	

```
Buildings & Capital Eqpt.                                                  253.79
Indirect Labor                     1.15                                    368.00 @$40/hr
                                                                         =========
    Total Production Cost                                                 13840.54
    ROI/Taxes @ 20%                                                        2768.11
===========================================================================
    Selling Price                                                       $ 16608.64
                                                                       ($   110.72 per m**2)
Operation and Maintenance
    Cleaning                                 0.00               608.63           16 washes/year
    Reflector Replacement                    0.00              4200.00           Replacement period 7 yrs
    Servicing                      1.89    452.64               452.64           1 hour each year gen'l maint.
                     Sub-Total     1.89    452.64        0.00              5261.27
===========================================================================
    Total Lifetime Cost                                                 $ 21869.91
                                                                       ($   145.80 per m**2)


Detailed Material Costs
========================                         Unit                 Subsystem
                                Qnty   Unit      Cost        Total     Totals  Comments
-------------------------------------------------------------------------------------
Mirror Module
Front Membrane                233.42 lb          2.242      523.32    523.32 3 mil annealed 304L SS
Reflector                    1800.22 ft^2          1.5     2700.34   2700.34 $1.50 per ft**2; 1602.2 ft**2
Rear Membrane                 233.42 lb          2.419      564.63    564.63 3 mil half-hard 304L SS
Heliostat Ring               1083.85 lb          0.265      287.22    287.22 A500B Carbon Steel (from coil)

Focus Control System
Focus Control Pad                                                     113.92
    Doubler Plate              37.50 lb          0.255        9.56
    Focus Pad Honeycomb        30.67 lb          0.477       14.63
    Focus Pad Center Ring      18.68 lb          0.265        4.95
    Focus Pad Center Pad       51.80 lb          0.265       13.73
    Focus Pad Inner Ring       17.88 lb          0.277        4.95
    Focus Pad Outer Ring       25.43 lb          0.284        7.22
    Membrane Inner/Outer R      2.00 ea              2        4.00
    Pod Dish                  130.67 lb          0.277       36.20
    Pod Center Pad             51.80 lb          0.265       13.73
    Pod Center Ring            18.68 lb          0.265        4.95
Focus Control Actuator          1.00 ea            350      350.00    350.00
Focus Control Elect.                                                  121.57
    Control Box                 1.00 ea             25       25.00
    Logic Circuit Board         1.00 ea          71.57       71.57
    Power Supply                1.00 ea             25       25.00
Focus Control Sensor                                                  161.40
    LVDT                        1.00 ea         133.68      133.68
    LVDT Power Supply           1.00 ea          27.72       27.72
Equilibration Valve                                                    77.55
    Damper Valve                1.00 ea          74.28       74.28
    Valve Mounting Spool       12.34 lb          0.265        3.27

Structural Support
Module Support                                                       2932.40
    Mounting Trunnion         103.57 lb          0.255       26.41
    Mounting Gusset           102.60 lb          0.255       26.16
    Truss Tubes - 3"          230.00 ft            1.4      322.00
    Truss Tubes - 4"          115.00 ft            1.9      218.50
    Truss Wire - 1/2"         850.87 lb           0.22      187.19
    Hub Tube - 3"             188.01 lb           4.45      836.64
    Hub Tube - 4"              13.27 lb           8.35      110.80
    Hub Tube - 4" (10 ga)      61.42 lb           6.19      380.19
    Hub Tube - 11"             77.10 lb           8.35      643.79
    Top Pentagon Joint          5.00 ea             15       75.00
    Bottom Pentagon Joint       5.00 ea             20      100.00
    Pins - Truss-to-Hub         6.40 lb          0.255        1.63
    Mounting Hdwre             16.00 lb          0.255        4.08
Focus Control Support                                                  11.86
    Pod/Focus Pad Gussets      20.14 lb          0.265        5.34
    Actuator Mtg. Block         2.67 lb           0.26        0.69
    Actuator Mtg. Gusset        1.86 lb          0.265        0.49
    Actuator Stiff. Gusset     20.14 lb          0.265        5.34

Drive System
Azimuth Drive                   1.00 ea         1646.4     1646.40   1646.40 $7.84/m**2 +40% for 5,000/yr
Elevation Drive                 1.00 ea            840      840.00    840.00 $4/m**2 +40% for 5,000/yr
Control Box                     1.00 ea            100      100.00    100.00 included in above

Module Assembly                                               0.00      0.00

Foundations
Concrete Pads                   1.00 ea            212      212.00    212.00 Dan Alpert's letter
Pedestal(s)                                                          1460.14
    Steel Tube               5374.81 lb          0.265     1424.33           Design based on D. Alpert's letter
    Top Cap                   135.14 lb          0.265       35.81           Design based on D. Alpert's letter
```

```
Field Wiring                   1.00 lot           107        107.00    107.00 Phase 1 estimate

Installation                                                   0.00      0.00
=====================================================================================
Total                                                                12209.75


=================================
|   Pedestal Drive              |
|   Wind-Avoiding               |
=================================

                               Labor     Labor      Mat'l       Total      Subsystem
Assembly/Component           (Man-day)   Cost       Cost        Cost         Cost    Comments
--------------------------------------------------------------------------------------------------------------------
Mirror Module
    Front Membrane               0.65    156.00     523.32      679.32
    Reflector                              0.00    2700.34     2700.34
    Rear Membrane                0.65    156.00     564.63      720.63
    Ring                         0.30     72.00     287.22      359.22
                   Sub-Total     1.60    384.00    4075.51                  4459.51

Focus Control System
    Focus Control Pad            0.30     72.00     113.92      185.92
    Focus Control Actuator                 0.00     350.00      350.00
    Focus Control Elect.         0.10     24.00     121.57      145.57
    Focus Control Sensor                   0.00     161.40      161.40
    Equilibration Valve                    0.00      77.55       77.55
                   Sub-Total     0.40     96.00     824.44                   920.44

Structural Support
    Module Support               0.65    156.00    2932.40     3088.40
    Focus Control Support                  0.00      11.86       11.86
                   Sub-Total     0.65    156.00    2944.26                  3100.26

Drive System
    Azimuth Drive                          0.00    1071.00     1071.00
    Elevation Drive                        0.00     638.40      638.40
    Torque Limiter                         0.00     503.60      503.60
    Control Box                            0.00     100.00      100.00
                   Sub-Total     0.00      0.00    2313.00                  2313.00

Module Assembly                  0.40     96.00       0.00       96.00       96.00

Foundations
    Concrete Pads                          0.00     212.00      212.00
    Pedestal(s)                  0.10     24.00    1460.14     1484.14
                   Sub-Total     0.10     24.00    1672.14                  1696.14

Field Wiring                     0.55    133.00     107.00      240.00      240.00 labor from D. Alpert letter

Installation                     0.50    120.00       0.00      120.00      120.00
----------------------------------------------------------------------------------
    Subtotal Direct Costs        4.20   1009.00   11936.35    12945.35    12945.35

Buildings & Capital Eqpt.                                                  253.79
Indirect Labor                   1.15                                      368.00 @$40/hr
                                                                        =========
    Total Production Cost                                                13567.14
    ROI/Taxes @ 20%                                                       2713.43
==================================================================================
    Selling Price                                                     $ 16280.56
                                                                      ($  108.54 per m**2)

Operation and Maintenance
    Cleaning                               0.00                 608.63              16 washes/year
    Reflector Replacement                  0.00                4200.00              Replacement period 7 yrs
    Servicing                    1.89    452.64                 452.64              1 hour each year gen'l maint.
                   Sub-Total     1.89    452.64       0.00                  5261.27
==================================================================================
    Total Lifetime Cost                                               $ 21541.83
                                                                      ($  143.61 per m**2)

Detailed Material Costs
========================                           Unit                 Subsystem
                               Qnty    Unit        Cost        Total     Totals  Comments
--------------------------------------------------------------------------------------------------------------------
Mirror Module
Front Membrane                233.42 lb           2.242       523.32    523.32 3 mil annealed 304L SS
Reflector                    1800.22 ft^2           1.5      2700.34   2700.34 $1.50 per ft**2; 1602.2 ft**2
Rear Membrane                 233.42 lb           2.419       564.63    564.63 3 mil half-hard 304L SS
Heliostat Ring               1083.85 lb           0.265       287.22    287.22 A500B Carbon Steel (from coil)

Focus Control System
Focus Control Pad                                                       113.92
    Doubler Plate              37.50 lb           0.255         9.56
```

Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	1.00	ea	350	350.00	350.00	
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					161.40	
LVDT	1.00	ea	133.68	133.68		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					77.55	
Damper Valve	1.00	ea	74.28	74.28		
Valve Mounting Spool	12.34	lb	0.265	3.27		
Structural Support						
Module Support					2932.40	
Mounting Trunnion	103.57	lb	0.255	26.41		
Mounting Gusset	102.60	lb	0.255	26.16		
Truss Tubes - 3"	230.00	ft	1.4	322.00		
Truss Tubes - 4"	115.00	ft	1.9	218.50		
Truss Wire - 1/2"	850.87	lb	0.22	187.19		
Hub Tube - 3"	188.01	lb	4.45	836.64		
Hub Tube - 4"	13.27	lb	8.35	110.80		
Hub Tube - 4" (10 ga)	61.42	lb	6.19	380.19		
Hub Tube - 11"	77.10	lb	8.35	643.79		
Top Pentagon Joint	5.00	ea	15	75.00		
Bottom Pentagon Joint	5.00	ea	20	100.00		
Pins - Truss-to-Hub	6.40	lb	0.255	1.63		
Mounting Hdwre	16.00	lb	0.255	4.08		
Focus Control Support					11.86	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Drive System						
Azimuth Drive	1.00	ea	1071	1071.00	1071.00	$5.1/m**2 +40% for 5,000/yr
Elevation Drive	1.00	ea	638.4	638.40	638.40	$3.04/m**2 +40% for 5,000/yr
Torque Limiter					503.60	
Slip Clutch	1.00	ea	368.60	368.60		
Slip Sensor	1.00	ea	35.00	35.00		
Re-Reference System	1.00	ea	100.00	100.00		
Control Box	1.00	ea	100	100.00	100.00	included in above
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					11936.35	

Shared Support
Standard

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.65	156.00	523.32	679.32		
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	564.63	720.63		
Ring	0.30	72.00	235.32	307.32		
Sub-Total	1.60	384.00	4023.61		4407.61	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	350.00	350.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	161.40	161.40		

```
    Equilibration Valve                     0.00       77.55       77.55
                   Sub-Total      0.40     96.00      824.44                 920.44

Structural Support
    Module Support                0.65    156.00      475.71      631.71
    Focus Control Support                   0.00      356.36      356.36
                   Sub-Total      0.65    156.00      832.07                 988.07

Drive System
    Azimuth Drive                 0.05     12.00      470.20      482.20            add'l labor for drive fab.
    Elevation Drive                         0.00     1369.20     1369.20
    Control Box                             0.00      100.00      100.00
                   Sub-Total      0.05     12.00     1939.40                1951.40

Module Assembly                   0.40     96.00        0.00       96.00      96.00

Foundations
    Concrete Pads                           0.00      212.00      212.00
    Pedestal(s)                   0.10     24.00     1460.14     1484.14
                   Sub-Total      0.10     24.00     1672.14                1696.14

Field Wiring                      0.55    133.00      107.00      240.00     240.00 labor from D. Alpert letter

Installation                      0.50    120.00        0.00      120.00     120.00
---------------------------------------------------------------------------------
    Subtotal Direct Costs         4.25   1021.00     9398.66    10419.66   10419.66

Buildings & Capital Eqpt.                                                    270.50 recalculated for this drive
Indirect Labor                    1.15                                       368.00 @$40/hr
                                                                          =========
    Total Production Cost                                                  11058.16
    ROI/Taxes @ 20%                                                         2211.63
===================================================================================
    Selling Price                                                      $ 13269.79
                                                                       ($    88.47 per m**2)
Operation and Maintenance
    Cleaning                                0.00                501.10              12 washes/year
    Reflector Replacement                   0.00               2620.00              Replacement period 10 yrs
    Servicing                     1.89    452.64                525.00              1 hour each year gen'l maint.
                   Sub-Total      1.89    452.64        0.00                3646.10
===================================================================================
    Total Lifetime Cost                                                $ 16915.89
                                                                       ($   112.77 per m**2)


Detailed Material Costs
========================                          Unit                   Subsystem
                                 Qnty  Unit       Cost          Total     Totals  Comments
------------------------------------------------------------------------------------------
Mirror Module
Front Membrane                 233.42 lb         2.242         523.32    523.32 3 mil annealed 304L SS; 89% mat'l utilization
Reflector                     1800.22 ft^2         1.5        2700.34   2700.34 $1.50 per ft**2; 1602.2 ft**2
Rear Membrane                  233.42 lb         2.419         564.63    564.63 3 mil half-hard 304L SS' 89% mat'l utilization
Heliostat Ring                 888.00 lb         0.265         235.32    235.32 A500B Carbon Steel (from coil)
Focus Control System
Focus Control Pad                                                        113.92
    Doubler Plate               37.50 lb         0.255           9.56
    Focus Pad Honeycomb         30.67 lb         0.477          14.63
    Focus Pad Center Ring       18.68 lb         0.265           4.95
    Focus Pad Center Pad        51.80 lb         0.265          13.73
    Focus Pad Inner Ring        17.88 lb         0.277           4.95
    Focus Pad Outer Ring        25.43 lb         0.284           7.22
    Membrane Inner/Outer R       2.00 ea             2           4.00
    Pod Dish                   130.67 lb         0.277          36.20
    Pod Center Pad              51.80 lb         0.265          13.73
    Pod Center Ring             18.68 lb         0.265           4.95
 Focus Control Actuator          1.00 ea           350         350.00    350.00
 Focus Control Elect.                                                    121.57
    Control Box                  1.00 ea            25          25.00
    Logic Circuit Board          1.00 ea         71.57          71.57
    Power Supply                 1.00 ea            25          25.00
 Focus Control Sensor                                                    161.40
    LVDT                         1.00 ea        133.68         133.68
    LVDT Power Supply            1.00 ea         27.72          27.72
 Equilibration Valve                                                      77.55
    Damper Valve                 1.00 ea         74.28          74.28
    Valve Mounting Spool        12.34 lb         0.265           3.27

 Structural Support
 Module Support                                                          475.71
    Transverse Ring           1264.50 lb         0.265         335.09
    3/4" Steel Wire            265.00 ft       0.39856         105.62           1.504 lb/ft, $.265/lb
    Fittings - Turnbuckles       1.00 lot           35          35.00
 Focus Control Support                                                   356.36
    Pod/Focus Pad Gussets       20.14 lb         0.265           5.34
```

Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Truss	1300.00	lb	0.265	344.50		
Drive System						
Azimuth Drive					371.20	
Gear Motor	1.00	ea	151.00	151.00		
Mounting Hardware	1.00	lot	11.00	11.00		
Gear Track	72.00	ft	1.10	79.20		
Passive Bearings	1.00	lot	45.00	45.00		
Ring Support Bearings	1.00	lot	85.00	85.00		
Elevation Drive	1.00	ea	1369.2	1369.20	1369.20	$6.52/m**2 +40% for 5,000/yr
Control Box	1.00	ea	100	100.00	100.00	
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					9299.66	

Shared Support
Wind-Avoiding

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.65	156.00	523.32	679.32		
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	564.63	720.63		
Ring	0.30	72.00	235.32	307.32		
Sub-Total	1.60	384.00	4023.61		4407.61	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	350.00	350.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	161.40	161.40		
Equilibration Valve		0.00	77.55	77.55		
Sub-Total	0.40	96.00	824.44		920.44	
Structural Support						
Module Support	0.65	156.00	395.54	551.54		
Focus Control Support		0.00	356.36	356.36		
Sub-Total	0.65	156.00	751.90		907.90	
Drive System						
Azimuth Drive	0.05	12.00	416.20	428.20		add'l labor for drive fab.
Elevation Drive		0.00	1041.60	1041.60		
Torque Limiter		0.00	503.60	503.60		
Control Box		0.00	100.00	100.00		
Sub-Total	0.05	12.00	2061.40		2073.40	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	1460.14	1484.14		
Sub-Total	0.10	24.00	1672.14		1696.14	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	4.25	1021.00	9440.48	10461.48	10461.48	
Buildings & Capital Eqpt.					270.50	
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					11099.98	
ROI/Taxes @ 20%					2220.00	
Selling Price					$ 13319.98	
					($ 88.80	per m**2)

Operation and Maintenance						
Cleaning		0.00		501.00		12 washes/year
Reflector Replacement		0.00		2620.00		Replacement period 10 yrs
Servicing	1.89	452.64		525.00		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		3646.00	
Total Lifetime Cost					$ 16965.98	
					($ 113.11	per m**2)

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Module						
Front Membrane	233.42	lb	2.242	523.32	523.32	3 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	233.42	lb	2.419	564.63	564.63	3 mil half-hard 304L SS
Heliostat Ring	888.00	lb	0.265	235.32	235.32	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	1.00	ea	350	350.00	350.00	
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					161.40	
LVDT	1.00	ea	133.68	133.68		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					77.55	
Damper Valve	1.00	ea	74.28	74.28		
Valve Mounting Spool	12.34	lb	0.265	3.27		
Structural Support						
Module Support					395.54	
Transverse Ring	1083.85	lb	0.265	287.22		6x6, 13ga. ring
5/8" Steel Wire	265.00	ft	0.27666	73.31		1.044 lb/ft, $.265/lb
Fittings - Turnbuckles	1.00	lot	35	35.00		
Focus Control Support					356.36	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Truss	1300.00	lb	0.265	344.50		
Drive System						
Azimuth Drive					317.20	
Gear Motor	1.00	ea	127.00	127.00		
Mounting Hardware	1.00	lot	11.00	11.00		
Gear Track	72.00	ft	1.10	79.20		
Passive Bearings	1.00	lot	35.00	35.00		
Ring Support Bearings	1.00	lot	65.00	65.00		
Elevation Drive	1.00	ea	1041.6	1041.60	1041.60	$4.96/m**2 +40% for 5,000/yr
Torque Limiter					503.60	
Slip Clutch	1.00	ea	368.60	368.60		
Slip Sensor	1.00	ea	35.00	35.00		
Re-reference System	1.00	ea	100.00	100.00		
Control Box	1.00	ea	100	100.00	100.00	
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					9341.48	

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|  Yoke                             |
|  Standard                         |
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                                   Labor      Labor     Mat'l       Total     Subsystem
Assembly/Component               (Man-day)   Cost      Cost        Cost        Cost   Comments
---------------------------------------------------------------------------------------------
Mirror Module
    Front Membrane                  0.65     156.00     872.20     1028.20
    Reflector                                  0.00    2700.34     2700.34
    Rear Membrane                   0.65     156.00     941.05     1097.05
    Ring                            0.30      72.00     897.03      969.03
                Sub-Total           1.60     384.00    5410.61                5794.61

Focus Control System
    Focus Control Pad               0.30      72.00     113.92      185.92
    Focus Control Actuator                     0.00     350.00      350.00
    Focus Control Elect.            0.10      24.00     121.57      145.57
    Focus Control Sensor                       0.00     161.40      161.40
    Equilibration Valve                        0.00      77.55       77.55
                Sub-Total           0.40      96.00     824.44                 920.44

Structural Support
    Module Support                  0.40      96.00    2658.22     2754.22            reduced labor for ass'y
    Focus Control Support                      0.00     356.36      356.36
                Sub-Total           0.40      96.00    3014.58                3110.58

Drive System
    Azimuth Drive                              0.00    1772.40     1772.40
    Elevation Drive                            0.00    1369.20     1369.20
    Control Box                                0.00     100.00      100.00
                Sub-Total           0.00       0.00    3241.60                3241.60

Module Assembly                     0.40      96.00       0.00       96.00      96.00

Foundations
    Concrete Pads                              0.00     212.00      212.00
    Pedestal(s)                     0.10      24.00     655.08      679.08
                Sub-Total           0.10      24.00     867.08                 891.08

Field Wiring                        0.55     133.00     107.00      240.00     240.00 labor from D. Alpert letter

Installation                        0.50     120.00       0.00      120.00     120.00
-----------------------------------------------------------------------------------
    Subtotal Direct Costs           3.95     949.00   13465.31    14414.31   14414.31

Buildings & Capital Eqpt.                                                     253.50 recalculated for this drive
Indirect Labor                      1.15                                      368.00 @$40/hr
                                                                           =========
    Total Production Cost                                                   15035.81
    ROI/Taxes @ 20%                                                          3007.16

===================================================================================
    Selling Price                                                        $ 18042.97
                                                                        ($   120.29 per m**2)
Operation and Maintenance
    Cleaning                                   0.00                 422.10            12 washes/year
    Reflector Replacement                      0.00                2620.00            Replacement period 10 yrs
    Servicing                       1.89     452.64                 452.64            1 hour each year gen'l maint.
                Sub-Total           1.89     452.64       0.00                3494.74
===================================================================================
    Total Lifetime Cost                                                  $ 21537.71
                                                                        ($   143.58 per m**2)


Detailed Material Costs
=========================                       Unit                    Subsystem
                              Qnty    Unit      Cost         Total       Totals   Comments
----------------------------------------------------------------------------------------------
Mirror Module
Front Membrane              389.03    lb        2.242        872.20      872.20 5 mil annealed 304L SS
Reflector                  1800.22    ft^2      1.5         2700.34     2700.34 $1.50 per ft**2; 1602.2 ft**2
Rear Membrane               389.03    lb        2.419        941.05      941.05 5 mil half-hard 304L SS
Heliostat Ring             3385.00    lb        0.265        897.03      897.03 A500B Carbon Steel (from coil)

Focus Control System
Focus Control Pad                                                        113.92
   Doubler Plate              37.50   lb        0.255          9.56
   Focus Pad Honeycomb        30.67   lb        0.477         14.63
   Focus Pad Center Ring      18.68   lb        0.265          4.95
   Focus Pad Center Pad       51.80   lb        0.265         13.73
   Focus Pad Inner Ring       17.88   lb        0.277          4.95
   Focus Pad Outer Ring       25.43   lb        0.284          7.22
   Membrane Inner/Outer R      2.00   ea        2              4.00
   Pod Dish                  130.67   lb        0.277         36.20
   Pod Center Pad             51.80   lb        0.265         13.73
   Pod Center Ring            18.68   lb        0.265          4.95
```

Focus Control Actuator	1.00 ea	350	350.00	350.00	
Focus Control Elect.				121.57	
Control Box	1.00 ea	25	25.00		
Logic Circuit Board	1.00 ea	71.57	71.57		
Power Supply	1.00 ea	25	25.00		
Focus Control Sensor				161.40	
LVDT	1.00 ea	133.68	133.68		
LVDT Power Supply	1.00 ea	27.72	27.72		
Equilibration Valve				77.55	
Damper Valve	1.00 ea	74.28	74.28		
Valve Mounting Spool	12.34 lb	0.265	3.27		
Structural Support					
Module Support				2658.22	
Yoke	10031.00 lb	0.265	2658.22		
Focus Control Support				356.36	
Pod/Focus Pad Gussets	20.14 lb	0.265	5.34		
Actuator Mtg. Block	2.67 lb	0.26	0.69		
Actuator Mtg. Gusset	1.86 lb	0.265	0.49		
Actuator Stiff. Gusset	20.14 lb	0.265	5.34		
Truss	1300.00 lb	0.265	344.50		
Drive System					
Azimuth Drive	1.00 ea	1772.4	1772.40	1772.40	$8.44/m**2 +40% for 5,000/yr
Elevation Drive	1.00 ea	1369.2	1369.20	1369.20	$6.52/m**2 +40% for 5,000/yr
Control Box	1.00 ea	100	100.00	100.00	
Module Assembly			0.00	0.00	
Foundations					
Concrete Pads	1.00 ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)				655.08	
Steel Tube	2336.88 lb	0.265	619.27		Design based on D. Alpert's letter
Top Cap	135.14 lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00 lot	107	107.00	107.00	Phase 1 estimate
Installation			0.00	0.00	
Total				13465.31	

Yoke
Wind-Avoiding

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.65	156.00	872.20	1028.20		
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	941.05	1097.05		
Ring	0.30	72.00	897.03	969.03		
Sub-Total	1.60	384.00	5410.61		5794.61	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	350.00	350.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	161.40	161.40		
Equilibration Valve		0.00	77.55	77.55		
Sub-Total	0.40	96.00	824.44		920.44	
Structural Support						
Module Support	0.40	96.00	2658.22	2754.22		reduced .25 man-day for simplified design
Focus Control Support		0.00	356.36	356.36		
Sub-Total	0.40	96.00	3014.58		3110.58	
Drive System						
Azimuth Drive		0.00	1152.90	1152.90		
Elevation Drive		0.00	1041.60	1041.60		
Torque Limiter		0.00	503.60	503.60		
Control Box		0.00	100.00	100.00		
Sub-Total	0.00	0.00	2798.10		2798.10	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	655.08	679.08		
Sub-Total	0.10	24.00	867.08		891.08	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter

Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	3.95	949.00	13021.81	13970.81	13970.81	
Buildings & Capital Eqpt.					253.50	
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					14592.31	
ROI/Taxes @ 20%					2918.46	
Selling Price					$ 17510.77	
					($ 116.74	per m**2)
Operation and Maintenance						
Cleaning		0.00		422.10		12 washes/year
Reflector Replacement		0.00		2620.00		Replacement period 10 yrs
Servicing	1.89	452.64		452.64		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		3494.74	
Total Lifetime Cost					$ 21005.51	
					($ 140.04	per m**2)

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Module						
Front Membrane	389.03	lb	2.242	872.20	872.20	5 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	389.03	lb	2.419	941.05	941.05	5 mil half-hard 304L SS
Heliostat Ring	3385.00	lb	0.265	897.03	897.03	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	1.00	ea	350	350.00	350.00	
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					161.40	
LVDT	1.00	ea	133.68	133.68		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					77.55	
Damper Valve	1.00	ea	74.28	74.28		
Valve Mounting Spool	12.34	lb	0.265	3.27		
Structural Support						
Module Support					2658.22	
Yoke	10031.00	lb	0.265	2658.22		
Focus Control Support					356.36	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Truss	1300.00	lb	0.265	344.50		
Drive System						
Azimuth Drive	1.00	ea	1152.9	1152.90	1152.90	$5.49/m**2 +40% for 5,000/yr
Elevation Drive	1.00	ea	1041.6	1041.60	1041.60	$4.96/m**2 +40% for 5,000/yr
Torque Limiter					503.60	
Slip Clutch	1.00	ea	368.60	368.60		
Slip Sensor	1.00	ea	35.00	35.00		
Re-reference System	1.00	ea	100.00	100.00		
Control Box	1.00	ea	100	100.00	100.00	
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					655.08	
Steel Tube	2336.88	lb	0.265	619.27		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					13021.81	

DUAL MODULE
Standard

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.60	144.00	523.32	667.32		reduced labor for production
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	564.63	720.63		
Ring	0.30	72.00	527.88	599.88		
Sub-Total	1.55	372.00	4316.17		4688.17	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	525.00	525.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	295.08	295.08		
Equilibration Valve		0.00	155.10	155.10		
Sub-Total	0.40	96.00	1210.67		1306.67	
Structural Support						
Module Support	0.65	156.00	856.55	1012.55		
Focus Control Support		0.00	11.86	11.86		
Sub-Total	0.65	156.00	868.41		1024.41	
Drive System						
Azimuth Drive		0.00	1646.40	1646.40		
Elevation Drive		0.00	1264.20	1264.20		
Control Box		0.00	100.00	100.00		
Sub-Total	0.00	0.00	3010.60		3010.60	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	1460.14	1484.14		
Sub-Total	0.10	24.00	1672.14		1696.14	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	4.15	997.00	11184.98	12181.98	12181.98	
Buildings & Capital Eqpt.					249.50	calculated for this production scenario
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					12799.48	
ROI/Taxes @ 20%					2559.90	
Selling Price				$	15359.38	
				($	102.40	per m**2)
Operation and Maintenance						
Cleaning		0.00		422.10		12 washes/year
Reflector Replacement		0.00		2620.00		Replacement period 10 yrs
Servicing	1.89	452.64		452.64		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		3494.74	
Total Lifetime Cost				$	18854.12	
				($	125.69	per m**2)

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Modules						
Front Membrane	233.42	lb	2.242	523.32	523.32	3 mil annealed 304L SS; 89% mat'l utilization
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	233.42	lb	2.419	564.63	564.63	3 mil half-hard 304L SS' 89% mat'l utilization
Heliostat Ring	1992.00	lb	0.265	527.88	527.88	A500B Carbon Steel (from coil); 2, 75 m**2 modules
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		

Focus Pad Outer Ring	25.43 lb	0.284	7.22		
Membrane Inner/Outer R	2.00 ea	2	4.00		
Pod Dish	130.67 lb	0.277	36.20		
Pod Center Pad	51.80 lb	0.265	13.73		
Pod Center Ring	18.68 lb	0.265	4.95		
Focus Control Actuator	2.00 ea	262.5	525.00	525.00	75% of 150 m^2 cost, due to smaller actuators
Focus Control Elect.				121.57	
Control Box	1.00 ea	25	25.00		
Logic Circuit Board	1.00 ea	71.57	71.57		
Power Supply	1.00 ea	25	25.00		
Focus Control Sensor				295.08	
LVDT	2.00 ea	133.68	267.36		
LVDT Power Supply	1.00 ea	27.72	27.72		
Equilibration Valve				155.10	
Damper Valve	2.00 ea	74.28	148.56		
Valve Mounting Spool	24.68 lb	0.265	6.54		2 ea
Structural Support					
Module Support				856.55	
Torque Tube	2275.00 lb	0.265	602.88		
Trusses	994.80 lb	0.255	253.67		Four trusses, each 248.7 lb
Focus Control Support				11.86	
Pod/Focus Pad Gussets	20.14 lb	0.265	5.34		Estimated as the same
Actuator Mtg. Block	2.67 lb	0.26	0.69		
Actuator Mtg. Gusset	1.86 lb	0.265	0.49		
Actuator Stiff. Gusset	20.14 lb	0.265	5.34		
Drive System					
Azimuth Drive	1.00 ea	1646.4	1646.40	1646.40	$7.84/m**2 +40% for 5,000/yr
Elevation Drive	1.00 ea	1264.2	1264.20	1264.20	$6.02/m**2 +40% for 5,000/yr
Control Box	1.00 ea	100	100.00	100.00	
Module Assembly			0.00	0.00	
Foundations					
Concrete Pads	1.00 ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)				1460.14	
Steel Tube	5374.81 lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14 lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00 lot	107	107.00	107.00	Phase 1 estimate
Installation			0.00	0.00	
Total				11184.98	

DUAL MODULE
Wind-Avoiding

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.60	144.00	523.32	667.32		reduced labor for production
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	564.63	720.63		
Ring	0.30	72.00	527.88	599.88		
Sub-Total	1.55	372.00	4316.17		4688.17	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	525.00	525.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	295.08	295.08		
Equilibration Valve		0.00	155.10	155.10		
Sub-Total	0.40	96.00	1210.67		1306.67	
Structural Support						
Module Support	0.65	156.00	856.55	1012.55		
Focus Control Support		0.00	11.86	11.86		
Sub-Total	0.65	156.00	868.41		1024.41	
Drive System						
Azimuth Drive		0.00	1071.00	1071.00		
Elevation Drive		0.00	961.80	961.80		
Torque Limiter		0.00	503.60	503.60		
Control Box		0.00	100.00	100.00		
Sub-Total	0.00	0.00	2636.40		2636.40	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		

Pedestal(s)	0.10	24.00	1460.14	1484.14		
Sub-Total	0.10	24.00	1672.14		1696.14	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	4.15	997.00	10810.78	11807.78	11807.78	
Buildings & Capital Eqpt.					249.50	calculated for this production scenario
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					12425.28	
ROI/Taxes @ 20%					2485.06	
Selling Price				$	14910.34	
				($	99.40	per m**2)
Operation and Maintenance						
Cleaning		0.00		422.10		12 washes/year
Reflector Replacement		0.00		2620.00		Replacement period 10 yrs
Servicing	1.89	452.64		452.64		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		3494.74	
Total Lifetime Cost				$	18405.08	
				($	122.70	per m**2)

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Modules						
Front Membrane	233.42	lb	2.242	523.32	523.32	3 mil annealed 304L SS; 89% mat'l utilization
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	233.42	lb	2.419	564.63	564.63	3 mil half-hard 304L SS' 89% mat'l utilization
Heliostat Ring	1992.00	lb	0.265	527.88	527.88	A500B Carbon Steel (from coil); 2, 75 m**2 modules
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	2.00	ea	262.5	525.00	525.00	75% of 150 m^2 cost, due to smaller actuators
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					295.08	
LVDT	2.00	ea	133.68	267.36		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					155.10	
Damper Valve	2.00	ea	74.28	148.56		
Valve Mounting Spool	24.68	lb	0.265	6.54		2 ea
Structural Support						
Module Support					856.55	
Torque Tube	2275.00	lb	0.265	602.88		
Trusses	994.80	lb	0.255	253.67		Four trusses, each 248.7 lb
Focus Control Support					11.86	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		Estimated as the same
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Drive System						
Azimuth Drive	1.00	ea	1071	1071.00	1071.00	$5.1/m**2 +40% for 5,000/yr
Elevation Drive	1.00	ea	961.8	961.80	961.80	$4.58/m**2 +40% for 5,000/yr
Torque Limiter					503.60	
Slip Clutch	1.00	ea	368.60	368.60		
Slip Sensor	1.00	ea	35.00	35.00		
Re-Reference System	1.00	ea	100.00	100.00		
Control Box	1.00	ea	100	100.00	100.00	
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					10810.78	

APPENDIX B

ANALYSIS OF SHADING AND BLOCKING BY A TRAVERSE RING

APPENDIX B

ANALYSIS OF SHADING AND BLOCKING BY A TRANSVERSE RING

An analysis was performed in order to estimate the performance penalty associated with the transverse ring of the Shared Support drive system. First, the shaded path due to a transverse ring was calculated as a function of the incidence angles to the collector. Then, an estimate was made of the worst-case shading effect due to the transverse ring and the mirror module support cables. Finally, a reasonable average value was selected for use in the cost comparisons. The result of this analysis was that, for the 150-m^2 Shared Support heliostat design, the loss in reflected energy amounts to about 5% of the total.

B.1 Shading Analysis

To determine the equation of the line of shade formed on a heliostat by a transverse ring, consider a coordinate system fixed to the heliostat with the origin at the center of the heliostat surface, the x_1 and x_2 axes in the plane of the heliostat, and the transverse ring in the x_2-x_3 plane, as shown in **Figure B.1**. Then, as shown in the figure, the angle of incidence of an incoming light beam can be expressed by the angles α and β, where α is the angle from the normal to the heliostat in the x_2-x_3 plane (azimuth relative to the heliostat normal), and β is the angle from the heliostat normal in the x_1-x_3 plane (elevation relative to the heliostat normal).

Let $\mathbf{\hat{a}} = (a_1,a_2,a_3)$ be the unit vector in the direction of the incoming beam of light. Then $\alpha = \tan(a_1/a_2)$, and $\beta = \tan(a_1/a_3)$. If the coordinate system is normalized so that the radius of the heliostat is 1, the transverse ring has the equation $b_2^2 + b_3^2 = 1$. The problem is to find the locus of points $\mathbf{x}$ which are the projection of the transverse ring in the direction such that $x_3 = 0$ (i.e., the intersection with the surface of the heliostat). This is accomplished as follows:

> From a point $\mathbf{b} = (0,b_2,b_3)$ on the transverse ring, the line with direction $\mathbf{\hat{a}}$ is $\mathbf{x} = \mathbf{b} + p\mathbf{\hat{a}}$, where p is a scalar parameter. This yields the following expressions:
>
> $$x_1 = 0 + pa_1$$
>
> $$x_2 = b_2 + pa_2$$
>
> $$x_3 = b_3 + pa_3$$
>
> From the condition that $x_3 = 0$, one obtains the result that $p = -b_3/a_3$. Also, from the equation for the transverse ring, $b_3 = \sqrt{1 - b_2^2}$. Substituting these expressions, one obtains, for the equation of the shaded line:
>
> $$x_1 = -a_1/a_3 \sqrt{1 - b_2^2}$$
>
> $$x_2 = b_2 - a_2/a_3 \sqrt{1 - b_2^2}$$

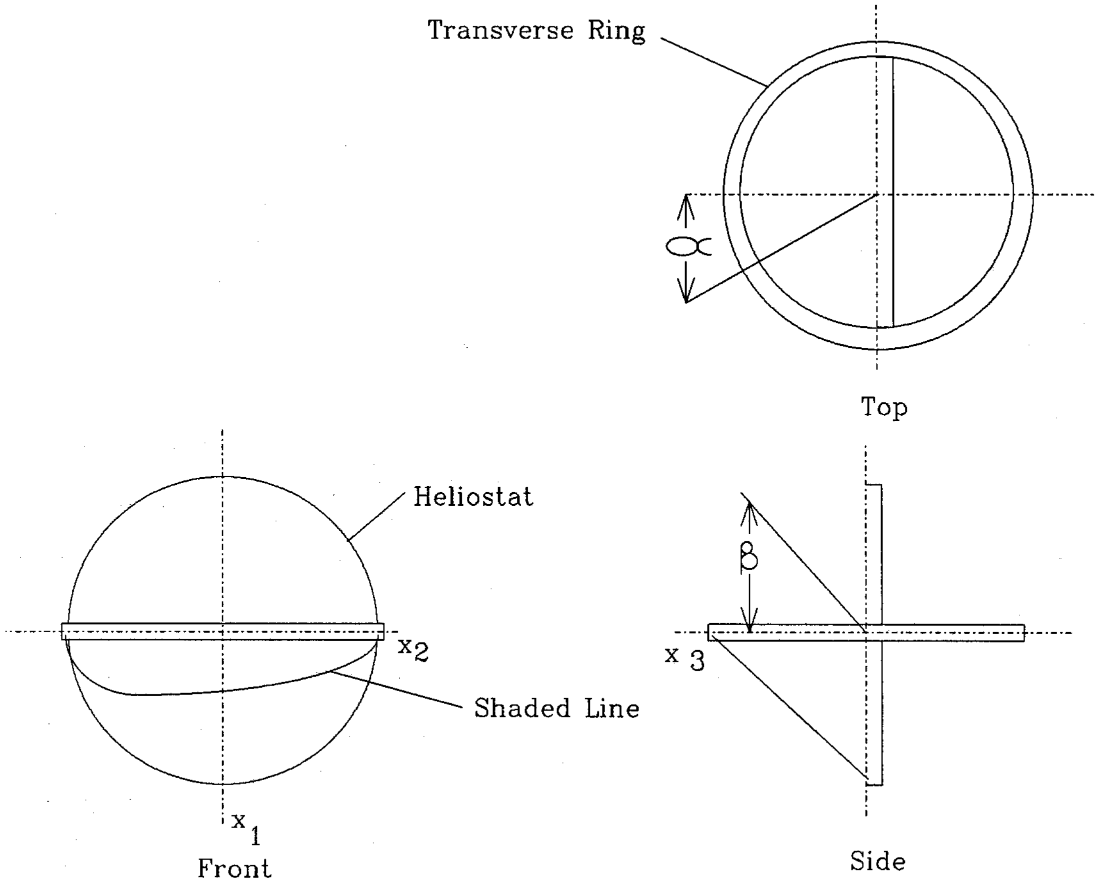

Figure B.1 Coordinate System for Heliostat Shading Calculation

$x_3 = 0$

This expression was used to generate shading profiles on a heliostat for a variety of values for α and β. As an example, **Figure B.2** shows the results of these equations for incidence angles $\alpha = 30°$ and $\beta = 30°$. The next step was to calculate the length of the shade profile for a variety of incidence angles. An important part of this calculation is to limit consideration to that portion of the shade line that actually falls within the heliostat boundaries. This was done numerically, with the results shown in **Figure B.3**. In that figure, the length of the shadow line cast on the heliostat is plotted as a function of the angle β for various values of α. Over a wide range of α and β values, the shaded length is approximately two times the radius of the heliostat (i.e., about the diameter of the heliostat). For small values of α, the shaded length increases with β. The maximum possible shaded length is π times the radius, at $\alpha = 0°$, $\beta = 45°$. This corresponds to the shade line from the transverse ring extending to the perimeter of the heliostat and shading it. For larger values of β, the shaded length decreases as more and more of the shadow falls off the heliostat completely. Finally, when both α and β are large, the shaded length decreases because only a small portion of the shadow falls on the collector.

B.2 Shading/Blocking Loss

Without a detailed calculation of the average incidence angles for a heliostat field over the year, it was necessary to estimate the effect of incidence angle on the shading from a transverse ring. Over a wide range of α and β, the analysis in the last section showed that the length of the shaded region is approximately twice the radius of the heliostat. This, then, can be used as a first guess. The radius of a 150-m^2 heliostat is 7.0 m, giving a shaded length of 14.0 m. From the structural analysis, the optimum shape of the transverse ring was determined to be a flat, wide ring. A maximum cross-section can be calculated for the ring at an angle of 45° from the transverse ring plane, yielding a width of 28.7 cm. Thus, as a worst case, the shaded area is approximately 4.02 m^2. At the same time a shaded area exists, there is an equal area of the heliostat (symmetrically arranged) which has its reflection blocked by the transverse ring. Therefore, the total blocked area due to the transverse ring is twice the value given above, or about 8.05 m^2. This corresponds to 5.2% of the gross area of the heliostat.

Additional heliostat area is blocked and shaded by the cables which support the heliostat ring from the transverse ring. These cables have a total length of 23.9 meters on the front side of the collector. Considering this to be the blocked length, and considering the double effect mentioned in the preceding paragraph, the total blockage due to these cables is about 1.22 m^2, or about 0.8% of the heliostat area.

Combining the effects of the transverse ring and the cables, the worst-case blockage is about 9.27 m^2, or 6% of the heliostat surface. To obtain an average value from this number is not straightforward, as mentioned above. As a conservative estimate, a reduction of 5% of the heliostat surface area was used. It was felt that this value is reasonable in view of the variations in incidence angle which occur for collectors in different areas of the field at different times.

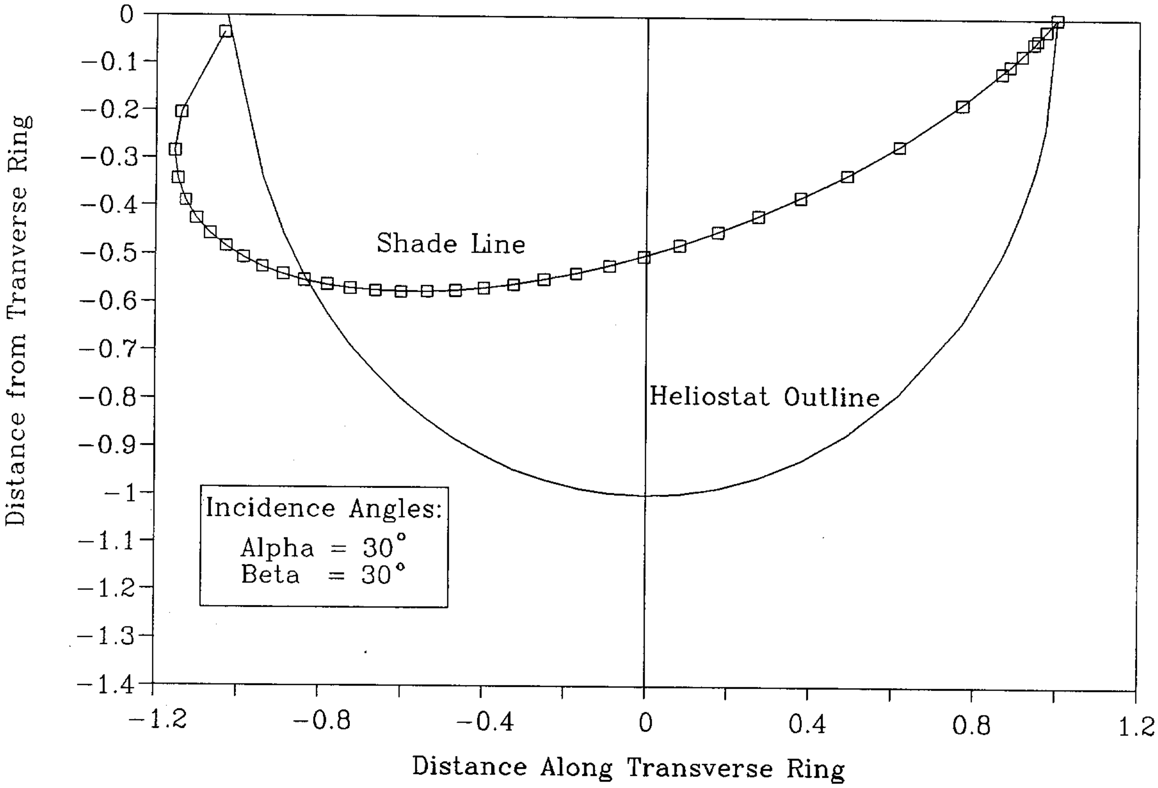

Figure B.2 **Shading Profile on Heliostat Due to a Transverse Ring**

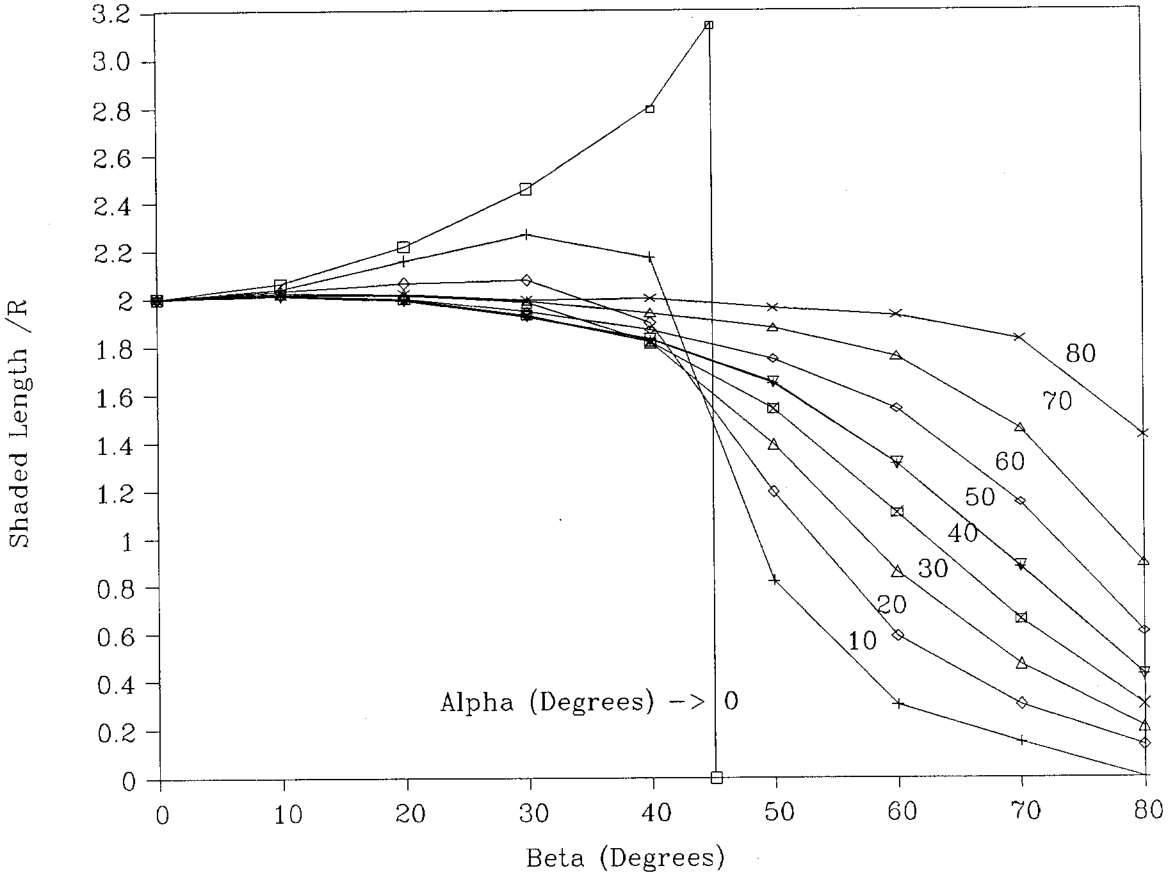

Figure B.3 Length of Shaded Line on Heliostat Due to a Transverse Ring

APPENDIX C

COST BREAKDOWNS FOR PHASE II HELIOSTAT DESIGNS

APPENDIX C

A.2 Pedestal Heliostat

Pedestal Drive
Standard

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.65	156.00	523.32	679.32		
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	564.63	720.63		
Ring	0.30	72.00	287.22	359.22		
Sub-Total	1.60	384.00	4075.51		4459.51	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	350.00	350.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	161.40	161.40		
Equilibration Valve		0.00	77.55	77.55		
Sub-Total	0.40	96.00	824.44		920.44	
Structural Support						
Module Support	0.65	156.00	2932.40	3088.40		
Focus Control Support		0.00	11.86	11.86		
Sub-Total	0.65	156.00	2944.26		3100.26	
Drive System						
Azimuth Drive		0.00	1646.40	1646.40		
Elevation Drive		0.00	840.00	840.00		
Control Box		0.00	100.00	100.00		
Sub-Total	0.00	0.00	2586.40		2586.40	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	1460.14	1484.14		
Sub-Total	0.10	24.00	1672.14		1696.14	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	4.20	1009.00	12209.75	13218.75	13218.75	
Buildings & Capital Eqpt.					253.79	
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					13840.54	
ROI/Taxes @ 20%					2768.11	
Selling Price					$ 16608.64	
					($ 110.72	per m**2)
Operation and Maintenance						
Cleaning		0.00		1560.00		46 washes/year
Reflector Replacement		0.00		5810.00		Replacement period 10 yrs
Servicing	1.89	452.64		452.64		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		7822.64	
Total Lifetime Cost					$ 24431.28	
					$ 162.88	per m**2

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Module						
Front Membrane	233.42	lb	2.242	523.32	523.32	3 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	233.42	lb	2.419	564.63	564.63	3 mil half-hard 304L SS
Heliostat Ring	1083.85	lb	0.265	287.22	287.22	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	1.00	ea	350	350.00	350.00	
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					161.40	
LVDT	1.00	ea	133.68	133.68		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					77.55	
Damper Valve	1.00	ea	74.28	74.28		
Valve Mounting Spool	12.34	lb	0.265	3.27		
Structural Support						
Module Support					2932.40	
Mounting Trunnion	103.57	lb	0.255	26.41		
Mounting Gusset	102.60	lb	0.255	26.16		
Truss Tubes - 3"	230.00	ft	1.4	322.00		
Truss Tubes - 4"	115.00	ft	1.9	218.50		
Truss Wire - 1/2"	850.87	lb	0.22	187.19		
Hub Tube - 3"	188.01	lb	4.45	836.64		
Hub Tube - 4"	13.27	lb	8.35	110.80		
Hub Tube - 4" (10 ga)	61.42	lb	6.19	380.19		
Hub Tube - 11"	77.10	lb	8.35	643.79		
Top Pentagon Joint	5.00	ea	15	75.00		
Bottom Pentagon Joint	5.00	ea	20	100.00		
Pins - Truss-to-Hub	6.40	lb	0.255	1.63		
Mounting Hdwre	16.00	lb	0.255	4.08		
Focus Control Support					11.86	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Drive System						
Azimuth Drive	1.00	ea	1646.4	1646.40	1646.40	$7.84/m**2 +40% for 5,000/yr
Elevation Drive	1.00	ea	840	840.00	840.00	$4/m**2 +40% for 5,000/yr
Control Box	1.00	ea	100	100.00	100.00	included in above
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					12209.75	

```
==================================
|   Pedestal Drive                |
|   Wind-Avoiding                 |
==================================

                             Labor    Labor     Mat'l       Total     Subsystem
Assembly/Component         (Man-day)  Cost      Cost        Cost       Cost   Comments
-------------------------------------------------------------------------------------
Mirror Module
    Front Membrane             0.65   156.00     523.32      679.32
    Reflector                            0.00   2700.34     2700.34
    Rear Membrane              0.65   156.00     564.63      720.63
    Ring                       0.30    72.00     287.22      359.22
                Sub-Total      1.60   384.00    4075.51                4459.51

Focus Control System
    Focus Control Pad          0.30    72.00     113.92      185.92
    Focus Control Actuator               0.00    350.00      350.00
    Focus Control Elect.       0.10    24.00     121.57      145.57
    Focus Control Sensor                 0.00    161.40      161.40
    Equilibration Valve                  0.00     77.55       77.55
                Sub-Total      0.40    96.00     824.44                 920.44

Structural Support
    Module Support             0.65   156.00    2932.40     3088.40
    Focus Control Support                0.00     11.86       11.86
                Sub-Total      0.65   156.00    2944.26                3100.26

Drive System
    Azimuth Drive                        0.00   1071.00     1071.00
    Elevation Drive                      0.00    638.40      638.40
    Torque Limiter                       0.00    503.60      503.60
    Control Box                          0.00    100.00      100.00
                Sub-Total      0.00      0.00   2313.00                2313.00

Module Assembly                0.40    96.00       0.00       96.00      96.00

Foundations
    Concrete Pads                        0.00    212.00      212.00
    Pedestal(s)                0.10    24.00    1460.14     1484.14
                Sub-Total      0.10    24.00    1672.14                1696.14

Field Wiring                   0.55   133.00     107.00      240.00     240.00 labor from D. Alpert letter

Installation                   0.50   120.00       0.00      120.00     120.00
-----------------------------------------------------------------------
    Subtotal Direct Costs      4.20  1009.00   11936.35    12945.35 12945.35

Buildings & Capital Eqpt.                                              253.79
Indirect Labor                 1.15                                    368.00 @$40/hr
                                                                    =========
    Total Production Cost                                            13567.14
    ROI/Taxes @ 20%                                                   2713.43
=======================================================================
    Selling Price                                                 $ 16280.56
                                                                 ($   108.54 per m**2)
Operation and Maintenance
    Cleaning                             0.00                1560.00          46 washes/year
    Reflector Replacement                0.00                5810.00          Replacement period 10 yrs
    Servicing                  1.89   452.64                  452.64          1 hour each year gen'l maint.
                Sub-Total      1.89   452.64       0.00                7822.64
=======================================================================
    Total Lifetime Cost                                           $ 24103.20
                                                                  $   160.69 per m**2
```

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Module						
Front Membrane	233.42	lb	2.242	523.32	523.32	3 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	233.42	lb	2.419	564.63	564.63	3 mil half-hard 304L SS
Heliostat Ring	1083.85	lb	0.265	287.22	287.22	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	1.00	ea	350	350.00	350.00	
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					161.40	
LVDT	1.00	ea	133.68	133.68		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					77.55	
Damper Valve	1.00	ea	74.28	74.28		
Valve Mounting Spool	12.34	lb	0.265	3.27		
Structural Support						
Module Support					2932.40	
Mounting Trunnion	103.57	lb	0.255	26.41		
Mounting Gusset	102.60	lb	0.255	26.16		
Truss Tubes - 3"	230.00	ft	1.4	322.00		
Truss Tubes - 4"	115.00	ft	1.9	218.50		
Truss Wire - 1/2"	850.87	lb	0.22	187.19		
Hub Tube - 3"	188.01	lb	4.45	836.64		
Hub Tube - 4"	13.27	lb	8.35	110.80		
Hub Tube - 4" (10 ga)	61.42	lb	6.19	380.19		
Hub Tube - 11"	77.10	lb	8.35	643.79		
Top Pentagon Joint	5.00	ea	15	75.00		
Bottom Pentagon Joint	5.00	ea	20	100.00		
Pins - Truss-to-Hub	6.40	lb	0.255	1.63		
Mounting Hdwre	16.00	lb	0.255	4.08		
Focus Control Support					11.86	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Drive System						
Azimuth Drive	1.00	ea	1071	1071.00	1071.00	$5.1/m**2 +40% for 5,000/yr
Elevation Drive	1.00	ea	638.4	638.40	638.40	$3.04/m**2 +40% for 5,000/yr
Torque Limiter					503.60	
Slip Clutch	1.00	ea	368.60	368.60		
Slip Sensor	1.00	ea	35.00	35.00		
Re-Reference System	1.00	ea	100.00	100.00		
Control Box	1.00	ea	100	100.00	100.00	included in above
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					11936.35	

A.3 Shared Support Heliostat

Shared Support
Standard

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.65	156.00	523.32	679.32		
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	564.63	720.63		
Ring	0.30	72.00	281.17	353.17		
Sub-Total	1.60	384.00	4069.45		4453.45	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	350.00	350.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	161.40	161.40		
Equilibration Valve		0.00	77.55	77.55		
Sub-Total	0.40	96.00	824.44		920.44	
Structural Support						
Module Support	0.65	156.00	682.18	838.18		
Focus Control Support		0.00	2.65	2.65		
Sub-Total	0.65	156.00	684.83		840.83	
Drive System						
Azimuth Drive	0.05	12.00	470.20	482.20		add'l labor for drive fab.
Elevation Drive		0.00	1369.20	1369.20		
Control Box		0.00	100.00	100.00		
Sub-Total	0.05	12.00	1939.40		1951.40	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	1460.14	1484.14		
Sub-Total	0.10	24.00	1672.14		1696.14	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	4.25	1021.00	9297.26	10318.26	10318.26	
Buildings & Capital Eqpt.					270.50	recalculated for this drive
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					10956.76	
ROI/Taxes @ 20%					2191.35	
Selling Price					$ 13148.11	
					($ 87.65	per m**2)
Operation and Maintenance						
Cleaning		0.00		1441.00		39 washes/year + 10% for inaccessibility
Reflector Replacement		0.00		2910.00		Replacement period 15 yrs
Servicing	1.89	452.64		525.00		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		4876.00	
Subtotal					18024.11	
5% Penalty for Shadowing By Transverse Ring					901.21	
Total Lifetime Cost					$ 18925.32	
					$ 126.17	per m**2

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Module						
Front Membrane	233.42	lb	2.242	523.32	523.32	3 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	233.42	lb	2.419	564.63	564.63	3 mil half-hard 304L SS
Heliostat Ring	1061.00	lb	0.265	281.17	281.17	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	1.00	ea	350	350.00	350.00	may use different actuator
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					161.40	
LVDT	1.00	ea	133.68	133.68		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					77.55	
Damper Valve	1.00	ea	74.28	74.28		
Valve Mounting Spool	12.34	lb	0.265	3.27		
Structural Support						
Module Support					682.18	
Transverse Ring	2023.00	lb	0.265	536.10		
1" Steel Rod	157.00	ft	0.70755	111.09		2.67 lb/ft, $0.265/lb
Fittings - Turnbuckles	1.00	lot	35	35.00		
Focus Control Support					2.65	
Actuator Mtg. Block	10.00	lb	0.265	2.65		estimate of brackets to hold cable system
Drive System						
Azimuth Drive					371.20	
Gear Motor	1.00	ea	151.00	151.00		
Mounting Hardware	1.00	lot	11.00	11.00		
Gear Track	72.00	ft	1.10	79.20		
Passive Bearings	1.00	lot	45.00	45.00		
Ring Support Bearings	1.00	lot	85.00	85.00		
Elevation Drive	1.00	ea	1369.2	1369.20	1369.20	$6.52/m**2 +40% for 5,000/yr
Control Box	1.00	ea	100	100.00	100.00	
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					9198.26	

Shared Support
Wind-Avoiding

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.65	156.00	523.32	679.32		
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	564.63	720.63		
Ring	0.30	72.00	281.17	353.17		
Sub-Total	1.60	384.00	4069.45		4453.45	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	350.00	350.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	161.40	161.40		
Equilibration Valve		0.00	77.55	77.55		
Sub-Total	0.40	96.00	824.44		920.44	
Structural Support						
Module Support	0.65	156.00	633.67	789.67		
Focus Control Support		0.00	2.65	2.65		
Sub-Total	0.65	156.00	636.32		792.32	
Drive System						
Azimuth Drive	0.05	12.00	416.20	428.20		add'l labor for drive fab.
Elevation Drive		0.00	1041.60	1041.60		
Torque Limiter		0.00	503.60	503.60		
Control Box		0.00	100.00	100.00		
Sub-Total	0.05	12.00	2061.40		2073.40	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	1460.14	1484.14		
Sub-Total	0.10	24.00	1672.14		1696.14	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	4.25	1021.00	9370.75	10391.75	10391.75	
Buildings & Capital Eqpt.					270.50	
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					11030.25	
ROI/Taxes @ 20%					2206.05	
Selling Price					$ 13236.30	
					($ 88.24	per m**2)
Operation and Maintenance						
Cleaning		0.00		1441.00		39 washes/year + 10% for inaccessibility
Reflector Replacement		0.00		2910.00		Replacement period 15 yrs
Servicing	1.89	452.64		525.00		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		4876.00	
Subtotal					18112.30	
5% Penalty for Shadowing by Transverse Ring					905.61	
Total Lifetime Cost					$ 19017.91	
					($ 126.79	per m**2)

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Module						
Front Membrane	233.42	lb	2.242	523.32	523.32	3 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	233.42	lb	2.419	564.63	564.63	3 mil half-hard 304L SS
Heliostat Ring	1061.00	lb	0.265	281.17	281.17	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	1.00	ea	350	350.00	350.00	may use different actuator
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					161.40	
LVDT	1.00	ea	133.68	133.68		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					77.55	
Damper Valve	1.00	ea	74.28	74.28		
Valve Mounting Spool	12.34	lb	0.265	3.27		
Structural Support						
Module Support					633.67	
Transverse Ring	2023.00	lb	0.265	536.10		6x6, 13ga. ring
3/4" Steel Wire	157.00	ft	0.39856	62.57		1.504 lb/ft, $.265/lb
Fittings - Turnbuckles	1.00	lot	35	35.00		
Focus Control Support					2.65	
Actuator Mtg. Block	10.00	lb	0.265	2.65		
Drive System						
Azimuth Drive					317.20	
Gear Motor	1.00	ea	127.00	127.00		
Mounting Hardware	1.00	lot	11.00	11.00		
Gear Track	72.00	ft	1.10	79.20		
Passive Bearings	1.00	lot	35.00	35.00		
Ring Support Bearings	1.00	lot	65.00	65.00		
Elevation Drive	1.00	ea	1041.6	1041.60	1041.60	$4.96/m**2 +40% for 5,000/yr
Torque Limiter					503.60	
Slip Clutch	1.00	ea	368.60	368.60		
Slip Sensor	1.00	ea	35.00	35.00		
Re-reference System	1.00	ea	100.00	100.00		
Control Box	1.00	ea	100	100.00	100.00	
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					9271.75	

A.4 Dual Module Heliostat

Dual Module
Standard

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.60	144.00	523.32	667.32		reduced labor for production
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	564.63	720.63		
Ring	0.30	72.00	527.88	599.88		
Sub-Total	1.55	372.00	4316.17		4688.17	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	525.00	525.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	295.08	295.08		
Equilibration Valve		0.00	155.10	155.10		
Sub-Total	0.40	96.00	1210.67		1306.67	
Structural Support						
Module Support	0.65	156.00	906.38	1062.38		
Focus Control Support		0.00	11.86	11.86		
Sub-Total	0.65	156.00	918.24		1074.24	
Drive System						
Azimuth Drive		0.00	1646.40	1646.40		
Elevation Drive		0.00	1264.20	1264.20		
Control Box		0.00	100.00	100.00		
Sub-Total	0.00	0.00	3010.60		3010.60	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	1460.14	1484.14		
Sub-Total	0.10	24.00	1672.14		1696.14	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	4.15	997.00	11234.81	12231.81	12231.81	
Buildings & Capital Eqpt.					249.50	calculated for this production scenario
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					12849.31	
ROI/Taxes @ 20%					2569.86	
Selling Price				$	15419.17	
				($	102.79	per m**2)
Operation and Maintenance						
Cleaning		0.00		1310.00		39 washes/year
Reflector Replacement		0.00		2910.00		Replacement period 15 yrs
Servicing	1.89	452.64		452.64		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		4672.64	
Total Lifetime Cost				$	20091.81	
				($	133.95	per m**2)

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Modules						
Front Membrane	233.42	lb	2.242	523.32	523.32	3 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	233.42	lb	2.419	564.63	564.63	3 mil half-hard 304L SS
Heliostat Ring	1992.00	lb	0.265	527.88	527.88	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	2.00	ea	262.5	525.00	525.00	75% of 150 m^2 cost
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					295.08	
LVDT	2.00	ea	133.68	267.36		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					155.10	
Damper Valve	2.00	ea	74.28	148.56		
Valve Mounting Spool	24.68	lb	0.265	6.54		2 ea
Structural Support						
Module Support					906.38	
Torque Tube	2535.00	lb	0.265	671.78		
Trusses	920.00	lb	0.255	234.60		Four trusses, each 230 lb
Focus Control Support					11.86	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		Estimated as the same
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Drive System						
Azimuth Drive	1.00	ea	1646.4	1646.40	1646.40	$7.84/m**2 +40% for 5,000/yr
Elevation Drive	1.00	ea	1264.2	1264.20	1264.20	$6.02/m**2 +40% for 5,000/yr
Control Box	1.00	ea	100	100.00	100.00	
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					11234.81	

Dual Module
Wind-Avoiding

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.60	144.00	523.32	667.32		reduced labor for production
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	564.63	720.63		
Ring	0.30	72.00	527.88	599.88		
Sub-Total	1.55	372.00	4316.17		4688.17	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	525.00	525.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	295.08	295.08		
Equilibration Valve		0.00	155.10	155.10		
Sub-Total	0.40	96.00	1210.67		1306.67	
Structural Support						
Module Support	0.65	156.00	906.38	1062.38		
Focus Control Support		0.00	11.86	11.86		
Sub-Total	0.65	156.00	918.24		1074.24	
Drive System						
Azimuth Drive		0.00	1071.00	1071.00		
Elevation Drive		0.00	961.80	961.80		
Torque Limiter		0.00	503.60	503.60		
Control Box		0.00	100.00	100.00		
Sub-Total	0.00	0.00	2636.40		2636.40	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	1460.14	1484.14		
Sub-Total	0.10	24.00	1672.14		1696.14	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	4.15	997.00	10860.61	11857.61	11857.61	
Buildings & Capital Eqpt.					249.50	calculated for this production scenario
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					12475.11	
ROI/Taxes @ 20%					2495.02	
Selling Price					$ 14970.13	
					($ 99.80	per m**2)
Operation and Maintenance						
Cleaning		0.00		1310.00		39 washes/year
Reflector Replacement		0.00		2910.00		Replacement period 15 yrs
Servicing	1.89	452.64		452.64		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		4672.64	
Total Lifetime Cost					$ 19642.77	
					($ 130.95	per m**2)

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Modules						
Front Membrane	233.42	lb	2.242	523.32	523.32	3 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	233.42	lb	2.419	564.63	564.63	3 mil half-hard 304L SS
Heliostat Ring	1992.00	lb	0.265	527.88	527.88	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	2.00	ea	262.5	525.00	525.00	75% of 150 m^2 cost
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					295.08	
LVDT	2.00	ea	133.68	267.36		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					155.10	
Damper Valve	2.00	ea	74.28	148.56		
Valve Mounting Spool	24.68	lb	0.265	6.54		2 ea
Structural Support						
Module Support					906.38	
Torque Tube	2535.00	lb	0.265	671.78		
Trusses	920.00	lb	0.255	234.60		Four trusses, each 230 lb
Focus Control Support					11.86	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		Estimated as the same
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Drive System						
Azimuth Drive	1.00	ea	1071	1071.00	1071.00	$5.1/m**2 +40% for 5,000/yr
Elevation Drive	1.00	ea	961.8	961.80	961.80	$4.58/m**2 +40% for 5,000/yr
Torque Limiter					503.60	
Slip Clutch	1.00	ea	368.60	368.60		
Slip Sensor	1.00	ea	35.00	35.00		
Re-Reference System	1.00	ea	100.00	100.00		
Control Box	1.00	ea	100	100.00	100.00	
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					10860.61	

A.5 Yoke Heliostat

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==================================
|  Yoke                           |
|  Standard                       |
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                              Labor     Labor    Mat'l      Total    Subsystem
Assembly/Component          (Man-day)   Cost     Cost       Cost       Cost   Comments
------------------------------------------------------------------------------------
Mirror Module
    Front Membrane              0.65   156.00    872.20    1028.20
    Reflector                            0.00   2700.34    2700.34
    Rear Membrane               0.65   156.00    941.05    1097.05
    Ring                        0.30    72.00    897.03     969.03
                Sub-Total       1.60   384.00   5410.61               5794.61

Focus Control System
    Focus Control Pad           0.30    72.00    113.92     185.92
    Focus Control Actuator               0.00    350.00     350.00
    Focus Control Elect.        0.10    24.00    121.57     145.57
    Focus Control Sensor                 0.00    161.40     161.40
    Equilibration Valve                  0.00     77.55      77.55
                Sub-Total       0.40    96.00    824.44                920.44

Structural Support
    Module Support              0.40    96.00   2658.22    2754.22            reduced labor for ass'y
    Focus Control Support                0.00    356.36     356.36
                Sub-Total       0.40    96.00   3014.58               3110.58

Drive System
    Azimuth Drive                        0.00   1772.40    1772.40
    Elevation Drive                      0.00   1369.20    1369.20
    Control Box                          0.00    100.00     100.00
                Sub-Total       0.00     0.00   3241.60               3241.60

Module Assembly                 0.40    96.00      0.00      96.00      96.00

Foundations
    Concrete Pads                        0.00    212.00     212.00
    Pedestal(s)                 0.10    24.00    655.08     679.08
                Sub-Total       0.10    24.00    867.08                891.08

Field Wiring                    0.55   133.00    107.00     240.00     240.00 labor from D. Alpert letter

Installation                    0.50   120.00      0.00     120.00     120.00
-----------------------------------------------------------------------------
    Subtotal Direct Costs       3.95   949.00  13465.31   14414.31 14414.31

Buildings & Capital Eqpt.                                              253.50 recalculated for this drive
Indirect Labor                  1.15                                   368.00 @$40/hr
                                                                    =========
    Total Production Cost                                            15035.81
    ROI/Taxes @ 20%                                                   3007.16
=============================================================================
    Selling Price                                                 $ 18042.97
                                                                 ($   120.29 per m**2)
Operation and Maintenance
    Cleaning                             0.00              1310.00            39 washes/year
    Reflector Replacement                0.00              2910.00            Replacement period 15 yrs
    Servicing                   1.89   452.64               452.64            1 hour each year gen'l maint.
                Sub-Total       1.89   452.64      0.00               4672.64
=============================================================================
    Total Lifetime Cost                                           $ 22715.61
                                                                 ($   151.44 per m**2)
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Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Module						
Front Membrane	389.03	lb	2.242	872.20	872.20	5 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	389.03	lb	2.419	941.05	941.05	5 mil half-hard 304L SS
Heliostat Ring	3385.00	lb	0.265	897.03	897.03	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	1.00	ea	350	350.00	350.00	
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					161.40	
LVDT	1.00	ea	133.68	133.68		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					77.55	
Damper Valve	1.00	ea	74.28	74.28		
Valve Mounting Spool	12.34	lb	0.265	3.27		
Structural Support						
Module Support					2658.22	
Yoke	10031.00	lb	0.265	2658.22		
Focus Control Support					356.36	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Truss	1300.00	lb	0.265	344.50		
Drive System						
Azimuth Drive	1.00	ea	1772.4	1772.40	1772.40	$8.44/m**2 +40% for 5,000/yr
Elevation Drive	1.00	ea	1369.2	1369.20	1369.20	$6.52/m**2 +40% for 5,000/yr
Control Box	1.00	ea	100	100.00	100.00	
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					655.08	
Steel Tube	2336.88	lb	0.265	619.27		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					13465.31	

Yoke
Wind-Avoiding

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.65	156.00	872.20	1028.20		
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	941.05	1097.05		
Ring	0.30	72.00	897.03	969.03		
Sub-Total	1.60	384.00	5410.61		5794.61	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	350.00	350.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	161.40	161.40		
Equilibration Valve		0.00	77.55	77.55		
Sub-Total	0.40	96.00	824.44		920.44	
Structural Support						
Module Support	0.40	96.00	2658.22	2754.22		reduced .25 man-day for simplified design
Focus Control Support		0.00	356.36	356.36		
Sub-Total	0.40	96.00	3014.58		3110.58	
Drive System						
Azimuth Drive		0.00	1152.90	1152.90		
Elevation Drive		0.00	1041.60	1041.60		
Torque Limiter		0.00	503.60	503.60		
Control Box		0.00	100.00	100.00		
Sub-Total	0.00	0.00	2798.10		2798.10	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	655.08	679.08		
Sub-Total	0.10	24.00	867.08		891.08	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	3.95	949.00	13021.81	13970.81	13970.81	
Buildings & Capital Eqpt.					253.50	
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					14592.31	
ROI/Taxes @ 20%					2918.46	
Selling Price					$ 17510.77	
					($ 116.74	per m**2)
Operation and Maintenance						
Cleaning		0.00		1310.00		39 washes/year
Reflector Replacement		0.00		2910.00		Replacement period 15 yrs
Servicing	1.89	452.64		452.64		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		4672.64	
Total Lifetime Cost					$ 22183.41	
					($ 147.89	per m**2)

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Module						
Front Membrane	389.03	lb	2.242	872.20	872.20	5 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	389.03	lb	2.419	941.05	941.05	5 mil half-hard 304L SS
Heliostat Ring	3385.00	lb	0.265	897.03	897.03	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	1.00	ea	350	350.00	350.00	
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					161.40	
LVDT	1.00	ea	133.68	133.68		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					77.55	
Damper Valve	1.00	ea	74.28	74.28		
Valve Mounting Spool	12.34	lb	0.265	3.27		
Structural Support						
Module Support					2658.22	
Yoke	10031.00	lb	0.265	2658.22		
Focus Control Support					356.36	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Truss	1300.00	lb	0.265	344.50		
Drive System						
Azimuth Drive	1.00	ea	1152.9	1152.90	1152.90	$5.49/m**2 +40% for 5,000/yr
Elevation Drive	1.00	ea	1041.6	1041.60	1041.60	$4.96/m**2 +40% for 5,000/yr
Torque Limiter					503.60	
Slip Clutch	1.00	ea	368.60	368.60		
Slip Sensor	1.00	ea	35.00	35.00		
Re-reference System	1.00	ea	100.00	100.00		
Control Box	1.00	ea	100	100.00	100.00	
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					655.08	
Steel Tube	2336.88	lb	0.265	619.27		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					13021.81	

APPENDIX D

DETAILED COST BREAKDOWNS FOR HELIOSTAT DRIVE SYSTEMS

APPENDIX D

C.1 Pedestal Drive

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.65	156.00	523.32	679.32		
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	564.63	720.63		
Ring	0.30	72.00	287.22	359.22		
Sub-Total	1.60	384.00	4075.51		4459.51	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	350.00	350.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	161.40	161.40		
Equilibration Valve		0.00	77.55	77.55		
Sub-Total	0.40	96.00	824.44		920.44	
Structural Support						
Module Support	0.65	156.00	2932.40	3088.40		
Focus Control Support		0.00	11.86	11.86		
Sub-Total	0.65	156.00	2944.26		3100.26	
Drive System						
Azimuth Drive		0.00	1646.40	1646.40		
Elevation Drive		0.00	840.00	840.00		
Control Box		0.00	100.00	100.00		
Sub-Total	0.00	0.00	2586.40		2586.40	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	1460.14	1484.14		
Sub-Total	0.10	24.00	1672.14		1696.14	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	4.20	1009.00	12209.75	13218.75	13218.75	
Buildings & Capital Eqpt.					253.79	
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					13840.54	
ROI/Taxes @ 20%					2768.11	
Selling Price					$ 16608.64	
					($ 110.72	per m**2)
Operation and Maintenance						
Cleaning		0.00		1560.00		46 washes/year
Reflector Replacement		0.00		5810.00		Replacement period 10 yrs
Servicing	1.89	452.64		452.64		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		7822.64	
Total Lifetime Cost					$ 24431.28	
					$ 162.88	per m**2

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Module						
Front Membrane	233.42	lb	2.242	523.32	523.32	3 mil annealed 304L SS; 89% mat'l util
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	233.42	lb	2.419	564.63	564.63	3 mil half-hard 304L SS'
Heliostat Ring	1083.85	lb	0.265	287.22	287.22	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	1.00	ea	350	350.00	350.00	
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					161.40	
LVDT	1.00	ea	133.68	133.68		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					77.55	
Damper Valve	1.00	ea	74.28	74.28		
Valve Mounting Spool	12.34	lb	0.265	3.27		
Structural Support						
Module Support					2932.40	
Mounting Trunnion	103.57	lb	0.255	26.41		
Mounting Gusset	102.60	lb	0.255	26.16		
Truss Tubes - 3"	230.00	ft	1.4	322.00		
Truss Tubes - 4"	115.00	ft	1.9	218.50		
Truss Wire - 1/2"	850.87	lb	0.22	187.19		
Hub Tube - 3"	188.01	lb	4.45	836.64		
Hub Tube - 4"	13.27	lb	8.35	110.80		
Hub Tube - 4" (10 ga)	61.42	lb	6.19	380.19		
Hub Tube - 11"	77.10	lb	8.35	643.79		
Top Pentagon Joint	5.00	ea	15	75.00		
Bottom Pentagon Joint	5.00	ea	20	100.00		
Pins - Truss-to-Hub	6.40	lb	0.255	1.63		
Mounting Hdwre	16.00	lb	0.255	4.08		
Focus Control Support					11.86	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Drive System						
Azimuth Drive	1.00	ea	1646.4	1646.40	1646.40	$7.84/m**2 +40% for 5,000/yr
Elevation Drive	1.00	ea	840	840.00	840.00	$4/m**2 +40% for 5,000/yr
Control Box	1.00	ea	100	100.00	100.00	included in above
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					12209.75	

C.2. Dual Module

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.60	144.00	872.21	1016.21		reduced labor for production
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	941.06	1097.06		
Ring	0.30	72.00	527.88	599.88		
Sub-Total	1.55	372.00	5041.49		5413.49	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	525.00	525.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	295.08	295.08		
Equilibration Valve		0.00	155.10	155.10		
Sub-Total	0.40	96.00	1210.67		1306.67	
Structural Support						
Module Support	0.65	156.00	765.36	921.36		
Focus Control Support		0.00	11.86	11.86		
Sub-Total	0.65	156.00	777.22		933.22	
Drive System						
Azimuth Drive		0.00	1646.40	1646.40		
Elevation Drive		0.00	1264.20	1264.20		
Control Box		0.00	100.00	100.00		
Sub-Total	0.00	0.00	3010.60		3010.60	
Module Assembly	0.40	96.00	0.00	96.00	96.00	
Foundations						
Concrete Pads		0.00	212.00	212.00		
Pedestal(s)	0.10	24.00	1460.14	1484.14		
Sub-Total	0.10	24.00	1672.14		1696.14	
Field Wiring	0.55	133.00	107.00	240.00	240.00	labor from D. Alpert letter
Installation	0.50	120.00	0.00	120.00	120.00	
Subtotal Direct Costs	4.15	997.00	11819.11	12816.11	12816.11	
Buildings & Capital Eqpt.					249.50	calculated for this production scenario
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					13433.61	
ROI/Taxes @ 20%					2686.72	
Selling Price				$	16120.34	
				($	107.47	per m**2)
Operation and Maintenance						
Cleaning		0.00		1310.00		36 washes/year
Reflector Replacement		0.00		2910.00		Replacement period 15 yrs
Servicing	1.89	452.64		452.64		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		4672.64	
Total Lifetime Cost				$	20792.98	
				($	138.62	per m**2)

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Modules						
Front Membrane	389.03	lb	2.242	872.21	872.21	5 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	389.03	lb	2.419	941.06	941.06	5 mil half-hard 304L SS'
Heliostat Ring	1992.00	lb	0.265	527.88	527.88	A500B Carbon Steel (from coil);
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	2.00	ea	262.5	525.00	525.00	75% of 150 m^2 cost
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					295.08	
LVDT	2.00	ea	133.68	267.36		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					155.10	
Damper Valve	2.00	ea	74.28	148.56		
Valve Mounting Spool	24.68	lb	0.265	6.54		2 ea
Structural Support						
Module Support					765.36	
Torque Tube	1872.00	lb	0.265	496.08		Estimated as 1.5 x 100 m**2 heliostat
Trusses	1056.00	lb	0.255	269.28		Estimated from 50 m**2 modules
Focus Control Support					11.86	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		Estimated as the same
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Actuator Stiff. Gusset	20.14	lb	0.265	5.34		
Drive System						
Azimuth Drive	1.00	ea	1646.4	1646.40	1646.40	$7.84/m**2 +40% for 5,000/yr
Elevation Drive	1.00	ea	1264.2	1264.20	1264.20	$6.02/m**2 +40% for 5,000/yr
Control Box	1.00	ea	100	100.00	100.00	
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	1.00	ea	212	212.00	212.00	Dan Alpert's letter
Pedestal(s)					1460.14	
Steel Tube	5374.81	lb	0.265	1424.33		Design based on D. Alpert's letter
Top Cap	135.14	lb	0.265	35.81		Design based on D. Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					11819.11	

C.3 Multi-Bar Drive

Assembly/Component	Labor (Man-day)	Labor Cost	Mat'l Cost	Total Cost	Subsystem Cost	Comments
Mirror Module						
Front Membrane	0.65	156.00	872.21	1028.21		
Reflector		0.00	2700.34	2700.34		
Rear Membrane	0.65	156.00	941.06	1097.06		
Ring	0.30	72.00	987.39	1059.39		
Sub-Total	1.60	384.00	5501.00		5885.00	
Focus Control System						
Focus Control Pad	0.30	72.00	113.92	185.92		
Focus Control Actuator		0.00	350.00	350.00		
Focus Control Elect.	0.10	24.00	121.57	145.57		
Focus Control Sensor		0.00	161.40	161.40		
Equilibration Valve		0.00	77.55	77.55		
Sub-Total	0.40	96.00	824.44		920.44	
Structural Support						
Module Support	0.53	126.00	848.98	974.98		
Focus Control Support	0.13	30.00	351.02	381.02		
Sub-Total	0.65	156.00	1200.00		1356.00	
Drive System						
Hydraulic Rams		0.00	6000.00	6000.00		
Control Box		0.00	100.00	100.00		
Sub-Total	0.00	0.00	6100.00		6100.00	
Module Assembly	0.10	24.00	0.00	24.00	24.00	
Foundations						
Concrete Pads		0.00	636.00	636.00	636.00	
Field Wiring	0.55	132.00	107.00	239.00	239.00	labor from D. Alpert letter
Installation	0.95	228.00	0.00	228.00	228.00	
Subtotal Direct Costs	4.25	1020.00	14368.43	15388.43	15388.43	
Buildings & Capital Eqpt.					253.79	
Indirect Labor	1.15				368.00	@$40/hr
Total Production Cost					16010.22	
ROI/Taxes @ 20%					3202.04	
Selling Price					$ 19212.27	
					($ 128.08	per m**2)
Operation and Maintenance						
Cleaning		0.00		1310.00		39 washes/year
Reflector Replacement		0.00		2910.00		Replacement period 15 yrs
Servicing	1.89	452.64		452.64		1 hour each year gen'l maint.
Sub-Total	1.89	452.64	0.00		4672.64	
Total Lifetime Cost					$ 23884.91	
					$ 159.23	per m**2

Detailed Material Costs

	Qnty	Unit	Unit Cost	Total	Subsystem Totals	Comments
Mirror Module						
Front Membrane	389.03	lb	2.242	872.21	872.21	5 mil annealed 304L SS
Reflector	1800.22	ft^2	1.5	2700.34	2700.34	$1.50 per ft**2; 1602.2 ft**2
Rear Membrane	389.03	lb	2.419	941.06	941.06	5 mil half-hard 304L SS'
Heliostat Ring	3726.00	lb	0.265	987.39	987.39	A500B Carbon Steel (from coil)
Focus Control System						
Focus Control Pad					113.92	
Doubler Plate	37.50	lb	0.255	9.56		
Focus Pad Honeycomb	30.67	lb	0.477	14.63		
Focus Pad Center Ring	18.68	lb	0.265	4.95		
Focus Pad Center Pad	51.80	lb	0.265	13.73		
Focus Pad Inner Ring	17.88	lb	0.277	4.95		
Focus Pad Outer Ring	25.43	lb	0.284	7.22		
Membrane Inner/Outer R	2.00	ea	2	4.00		
Pod Dish	130.67	lb	0.277	36.20		
Pod Center Pad	51.80	lb	0.265	13.73		
Pod Center Ring	18.68	lb	0.265	4.95		
Focus Control Actuator	1.00	ea	350	350.00	350.00	
Focus Control Elect.					121.57	
Control Box	1.00	ea	25	25.00		
Logic Circuit Board	1.00	ea	71.57	71.57		
Power Supply	1.00	ea	25	25.00		
Focus Control Sensor					161.40	
LVDT	1.00	ea	133.68	133.68		
LVDT Power Supply	1.00	ea	27.72	27.72		
Equilibration Valve					77.55	
Damper Valve	1.00	ea	74.28	74.28		
Valve Mounting Spool	12.34	lb	0.265	3.27		
Structural Support						
Module Support					848.98	
Side Arms	2130.00	lb	0.255	543.15		
Center Support	820.00	lb	0.255	209.10		
Ball Joints/Sockets	365.00	lb	0.265	96.73		estimate
Focus Control Support					351.02	
Pod/Focus Pad Gussets	20.14	lb	0.265	5.34		
Actuator Mtg. Block	2.67	lb	0.26	0.69		
Actuator Mtg. Gusset	1.86	lb	0.265	0.49		
Back Truss	1300.00	lb	0.265	344.50		
Drive System						
Hydraulic Rams	2.00	ea	3000	6000.00	6000.00	estimate
Control Box	1.00	ea	100	100.00	100.00	included in above
Module Assembly				0.00	0.00	
Foundations						
Concrete Pads	3.00	ea	212	636.00	636.00	Dan Alpert's letter
Field Wiring	1.00	lot	107	107.00	107.00	Phase 1 estimate
Installation				0.00	0.00	
Total					14368.43	

APPENDIX E

STRUCTURAL/OPTICAL COUPLING EQUATIONS DERIVATION

Appendix E

*STRUCTURAL/OPTICAL COUPLING EQUATIONS DERIVATION

As shown in **Figure B-1** for a circular ring of radius a, lying in or near the x-y plane, center at origin, the z-displacement (out-of-plane) is given by:

$$z(a,\theta) = \sum_{n=0}^{\infty} A_n \cos[n(\theta+\phi_n)] \qquad [1]$$

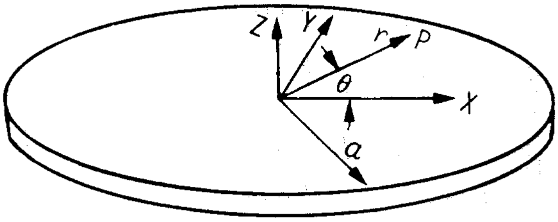

Figure B-1 Coordinate System

An ideal membrane supported by this ring will take the shape defined by

$$z(r,\theta) = \sum_{n=0}^{\infty} A_n (r/a)^n \cos[n(\theta+\phi_n)] \qquad [2]$$

(Note:

n=0 term is piston motion, or simple z displacement with no rotation nor deformation.

n=1 term is simple rigid body rotation, which is a pointing or tracking error, not slope error.

n=2 term is the so-called potato chip shape.

n>2 term are similar saddle shapes with n high spots and n low spots on the circumference of the rim.

(All can coexist, and the displacements linearly superimpose.)

* Obtained from the Solar Energy Research Institute

MEMBRANE/FRAME DEFORMATION RELATED POINTING OR TRACKING ERROR

An effective pointing or tracking error results from deformation of the ring frame structure due to asymmetrical loading (most wind loads). This is independent of the deformation of the support structure due to the same loads, and causes an additional error, which should be included in design calculations.

The effective angular rotation is given by

$$\beta = A_1/a \tag{3}$$

SHAPE CHANGES, n > 1 TERMS.

The $n = 0$ and 1 terms are simple translation and rotation of the membrane/frame, and do not constitute shape changes. We therefore classify the $n > 1$ terms as contributing to slope error. For computing slope errors, we include only the $n = 2, 3, 4, \ldots$ terms.

SLOPE AT A POINT ON THE MEMBRANE

At any point P on the membrane surface, the magnitude of the slope is given by

$$\gamma_p = \left[\left(\frac{dz}{dr}\right)^2 + \left(\frac{1}{r}\frac{dz}{d\theta}\right)^2\right]^{1/2} \tag{4}$$

For a surface defined by [2], the slope at point P, relative to average mirror normal direction, is

$$\gamma_p = \left\{\left[\frac{d}{dr}\sum_{n=2}^{\infty} A_n\,(r/a)^n \cos[\,n(\theta+\phi_n)]\right]^2 + \left[\frac{1}{r}\frac{d}{d\theta}\sum_{n=2}^{\infty} A_n\,(r/a)^n \cos[\,n(\theta+\phi_n)]\right]^2\right\}^{1/2}$$

(continued)

$$= \left\{ \left[\sum_{n=2}^{\infty} \frac{n\, A_m}{a^m} \quad r^{n-1} \cos[\, n(\theta + \phi_n)] \right]^2 \right.$$

$$\left. + \left[\frac{1}{r} \sum_{n=2}^{\infty} \frac{n\, A_m}{a^m}\, r^n \sin[\, n(\theta + \phi_n)] \right]^2 \right\}^{1/2}$$

$$= \left\{ \left[\sum_{n=2}^{\infty} \frac{n\, A_m}{a^m} \quad r^{n-1} \cos[\, n(\theta + \phi_n)] \right]^2 \right.$$

$$\left. + \left[\sum_{n=2}^{\infty} \frac{n\, A_m}{a^m} \quad r^{n-1} \sin[\, n(\theta + \phi_n)] \right]^2 \right\}^{1/2} \qquad [5]$$

SURFACE RMS SLOPE

$$\gamma_{RMS} = \left[\frac{\int_A \gamma_p^2 \; dA}{\int_A dA} \right]^{1/2} , \quad dA = r\, d\theta\, dr ,$$

$$\pi a^2 \left[\gamma_{RMS} \right]^2 = \int_0^a \int_0^{2\pi} \left[\sum_{n=2}^{\infty} \frac{n\, A_m}{a^m} \quad r^{n-1} \cos[\, n(\theta + \phi_n)] \right]^2 r\, d\theta \quad dr$$

$$+ \int_0^a \int_0^{2\pi} \left[\sum_{n=2}^{\infty} \frac{n\, A_m}{a^m} \quad r^{n-1} \sin[\, n(\theta + \phi_n) \;] \right]^2 r\, d\theta \quad dr \qquad [6]$$

$$= \int_0^a \int_0^{2\pi} \left[\sum_{n=2}^{\infty} \left(\frac{n\, A_m}{a^m} \right)^2 r^{2n-2} \cos^2 [\, n(\theta + \phi_n) \;]\; r\, d\theta \quad dr \right.$$

(continued)

$$+\int_0^a\int_0^{2\pi}\sum_{n=2}^{\infty}\left(\frac{n\,A_n}{a^n}\right)^2 r^{\,2n-2}\sin^2\left[\;n(\theta+\phi_n)\;\right] r\,d\theta\,dr$$

$$+\,2\int_0^a\int_0^{2\pi}\sum_{\substack{n=2\\m=n+1}}^{\infty}\left(\frac{n\,A_n}{a^n}\right)\left(\frac{m\,A_m}{a^m}\right) r^{m+n-2}\cos\left[n(\theta+\phi_n)\right]\cos[m(\theta+\phi_m)]r\,d\theta\,d$$

$$+\,2\int_0^a\int_0^{2\pi}\sum_{\substack{n=2\\m=n+1}}^{\infty}\left(\frac{n\,A_n}{a^n}\right)\left(\frac{m\,A_m}{a^m}\right) r^{m+n-2}\sin[n(\theta+\phi_n)]\sin[m(\theta+\phi_m)]\;r\,d\theta\,dr$$

or,

$$\pi a^2\left[\gamma_{RMS}\right]^2=\int_0^a\int_0^{2\pi}\sum_{n=2}^{\infty}\left(\frac{n\,A_n}{a^n}\right)^2 r^{2n-1}\,d\theta\,dr$$

$$+\,2\int_0^a\int_0^{2\pi}\sum_{\substack{n=2\\m=n+1}}^{\infty}\left(\frac{n\,A_n}{a^n}\right)\left(\frac{m\,A_m}{a^m}\right) r^{m+n-1}$$

$$\left[\cos[n(\theta+\phi_n)]\cos[m(\theta+\phi_m)]+\sin[n(\theta+\phi_n)]\sin[m(\theta+\phi_m)]\right]d\theta\,dr$$

$$=\;2\pi\sum_{n=2}^{\infty}\left(\frac{n\,A_n}{a^n}\right)^2\int_0^a r^{2n-1}\,dr$$

$$+\,2\int_0^a\sum_{\substack{n=2\\m=n+1}}^{\infty}\left(\frac{n\,A_n}{a^n}\right)\left(\frac{m\,A_m}{a^m}\right) r^{m+n-1}\int_0^{2\pi}\cos[n(\theta+\phi_n)-m(\theta+\phi_m)]\,d\theta\,dr$$

$$=\;2\pi\sum_{n=2}^{\infty}\left(\frac{n\,A_n}{a^n}\right)^2\frac{a^{2n}}{2n}$$

(continued)

$$+ 2 \int_0^a \sum_{\substack{n=2 \\ m=n+1}}^{\infty} \left(\frac{n A_n}{a^n}\right)\left(\frac{m A_m}{a^m}\right) r^{m+n-1} \int_0^{2\pi} \cos[(n-m)\theta + n\phi_n - m\phi_m]\, d\theta\, dr$$

$$\pi a^2 \left[\gamma_{RMS}\right]^2 = 2\pi \sum_{n=2}^{\infty} \left(\frac{n A_n}{a^n}\right)^2 \frac{a^{2n}}{2n}$$

Finally, we see that the RMS "slope error" ($n>1$ terms in deformation expression) is given by

$$\left[\gamma_{RMS}\right]^2 = \sum_{n=2}^{\infty} n \left(\frac{A_n}{a}\right)^2 \qquad [7]$$

where the values of A_n are the coefficients from the ring deformation equation [1], and "a" is the radius of the ring.

PROCEDURE FOR ESTIMATING RMS SLOPE ERROR AND POINTING ERROR

If, by experiment or by finite element analysis, one obtains estimates of the frame z-displacement at many points, N, around the frame, then a fit of equation [1] can be made to those data. This involves finding the A_n and 0_n for a suitable number of terms in the equation for instance, by a least squares method. For numerical stability it is suggested that the number of terms be limited to one less than the square root of the number of data points you have, that is.

$$z(a, \theta) = \sum_{n=0}^{k} A_n \cos[n(\theta + \phi_n)] \; , \; k < \sqrt{N} - 1$$

Then, having obtained the A_n values, equation [7] can be used to estimate the RMS slope of the frame.

EXAMPLE

Consider a flat membrane/frame rigidly supported at six points. A uniform wind load is imposed, causing a deflection of the rim that is for the most part n=6 buckling, with a little n=12, 18, 24, ... thrown in. For our purposes, we might assume that it is pure n=6. Suppose that on the 6-m diameter ring, the deflection is found to be 10-mm. The equation for the ring would then be

$$z(a, \theta) = A_0 + A_6 \cos[6(\theta + \phi_6)]$$

or,

$$z(3, \theta) = -0.005 + 0.005 \cos[6\theta] .$$

In this case, there is an average 5-mm displacement of the whole membrane frame with a 5-mm amplitude cosine wave superimposed. There is no tilt or pointing error, since $A_1 = 0$. The RMS slope error is

$$\gamma_{RMS} = \sqrt{6}\ \frac{0.005}{3.0} = 0.00408 = 4 \text{ mrad.}$$

If the displacement is given by

$$z(3, \theta) = -0.0055 + 0.005 \cos[6\theta] + 0.001 \cos[12\theta],$$

which is more likely (due to a distributed wind load reacted by point supports), then the RMS slope error is

$$\gamma_{RMS} = \left[6\left(\frac{0.005}{3.0}\right)^2 + 12\left(\frac{0.001}{3.0}\right)^2\right]^{1/2} = 4.24 \text{ mrad.}$$

So, even though the edge displacement is the same, the relatively small higher order term appreciably increases the RMS slope error. Therefore, the higher order terms should not be neglected.

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