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SOLAR CENTRAL RECEIVER PROTOTYPE HELIOSTAT—PHASE 1

Final Technical Report for September 30, 1977—June 24, 1978

October 1978

Work Performed Under Contract No. EG-77-C-03-1468

**Energy Systems Programs Department
General Electric Company
Schenectady, New York**

U.S. Department of Energy

Solar Energy

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SOLAR CENTRAL RECEIVER PROTOTYPE HELIOSTAT PHASE I

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FINAL TECHNICAL REPORT
30 SEPTEMBER 1977 — 24 JUNE 1978

GENERAL ELECTRIC
ENERGY SYSTEMS PROGRAMS DEPARTMENT
SCHENECTADY NEW YORK

PREPARED FOR
UNITED STATES DEPARTMENT OF ENERGY
SOLAR ENERGY DIVISION
UNDER CONTRACT EG-77-C-03-1468

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1.0 EXECUTIVE SUMMARY

The primary objective of the Department of Energy's Prototype Heliostat Contract with General Electric was to complete the preliminary design of a solar central receiver heliostat which would not exceed a \$72/M²-R installed cost/performance target. In-depth installation and manufacturing studies were required to provide validation of the cost estimates and to show the quantity levels at which the forecast values would be achieved.

General Electric's design has resulted in a 40% improvement in cost performance, namely, \$42.87/M²-R*.

The General Electric "Proof of Concept"
Stretch Frame Reflector Test

*1978 Dollars — 1 Million Units Per Year

The GENERAL ELECTRIC enclosed heliostat consists of an aluminized film reflector which is deployed on a lightweight, eight-strut frame mounted on a single pipe pedestal with azimuth and elevation drives and totally housed in an air supported enclosure. An open loop control system with self calibration capability directs centrally computed sun angles and steering commands to individual heliostats of a total system via 2-way multiplex methods over the field power distribution network. Totally mass-produced in conventional industrial factories, the preassembled components are shipped without restriction and are semi-automatically installed within 30 minute time cycles. Requiring no cleaning, the 30-year life cycle maintenance costs include two complete enclosure and reflector replacements.

TOTAL INSTALLED COST - \$1363* NET REFLECTIVITY - 0.578

General Electric Enclosed Heliostat

COSTS

Dollars/Square Meter	24.78
Dollars/Sq. Meter-Reflectivity	42.87
Dollars/Square Foot	2.30
Average Annual O&M Per Heliostat	49.09
30 Year O&M Per Heliostat/M2	26.77

PERFORMANCE

Enclosure Transmittance	0.85
Reflectivity	0.89
Surface Degradation (Average)	0.95
Aiming Accuracy (mrad)	2.80
Reflector Area (Square Meters)	55.00
Zipper Blockage	0.996

Top View

Side View

TOTAL INSTALLED COST

Enclosure	\$ 179
Heliostat	170
Foundation	325
Controls	130
Drives	117
Power Distribution	70
Installation	372

TOTAL INSTALLED COST \$ 1363

FEATURES

- Heliostat and Enclosure are 100% Mass-produced in Offsite Factories with No Shipping Restrictions for Lowest Cost and Maximum Quality Control
- Stretch Frame Concept Permits Great Size Flexibility
- Self-calibrating Heliostat Controls
- 2-Way Multiplex Power Line Communication
- Fail-safe Linear Motor Drives
- Simple Low-cost Reflector Replacement
- Automatically Located and Installed Heliostat and Enclosure Foundations
- Universal Automatic Foundation Machine — Will Install Boeing, McDonnell Douglas, Martin Solaramics, General Electric, and Other Heliostat Systems

Back View

SYSTEM

- Operational over Full Range of DOE Specification 001 Environment Requirements
- Surface Contour Accuracy — 97%
- Availability — 99%
- Minimum Spacing — Center to Center — 9.7 m
- Common Design For All Field Positions

HELIOSTAT

- 2 Mil Aluminized Polyethylene Terephthalate Reflector
- Automatic Reflector Tensioning
- Automatic Temperature Compensation
- Total Number of Parts — 160
- Foundation — 10 cm x 2 m Long Steel Pipe
- Focusing Option

CONTROLS & DRIVES

- $\pm 270^\circ$ Azimuth Rotation — $0.2^\circ/\text{sec}$. Max. Slew Rate
- 10° to 95° Elevation Rotation
- Central Plant Controller
 - Initialization
 - Calibration
 - Time
 - Ephemeris Data
 - Sun Angles
 - Steering and Pointing
 - Fault Monitoring — Each Heliostat every 5 seconds
 - Tower Position
 - Heliostat Addressing
 - 10 Heliostat Field Control Sectors
 - 2 Way Multiplex Power Line Communication
- Heliostat Controller
 - Compute Mirror Angles
 - Self-calibration
 - Fault Diagnostics, Automatic Stow
 - Motor Control
 - Lightning Protection
- 8 lb. Linear Stepping Motor Drives
- $0.0143^\circ/\text{step}$
- Portable Field Manual Controller
- Automatic Stowing in Event of Power Failure

ENCLOSURE

- Zipper Assembled
- 3 Mil UV Stabilized Polyethylene Terephthalate
- Max. Deflection @ 90 MPH Wind — 36 cm (14.2 in)
- Max. Material Stress 47.5 lb/in @ -30°C 36.8 lb/in @ $+50^\circ\text{C}$
- 6 Mil Full Polyethylene Ground Cover
- Blower — 50 CFM @ 1" H_2O — 15 Watts
- Foundation — Ring-shaped Bag Filled with Excavated Soil
- 30 Mil Reinforced Polyester Bag Material
- 3 ft. x 4.5 ft. Access Flap

INSTALLATION

- Automatic Heliostat Position Surveying
- Enclosure and Heliostat Foundations Installed By A Fully Automatic Foundation Machine (AFM)
- Power Distribution Cable (10 AWG) and Lightning Grounding Grid Wire Installed by AFM
- Enclosure Zippered to Foundation and Directly Inflated
- Heliostat Manually Assembled Inside Enclosure
- Functions provided by AFM can be tailored to meet any heliostat need
- Total Installation Cycle Time per Heliostat/Enclosure - 30 minutes

MAINTENANCE

- Washable Lifetime Blower Filter - 15 Month Normal Cycle
- Plug-In Modular Electronics and Motors
- Maintenance Costs Include An Assumption for 7 Day - 24 Hr coverage whether needed or not. Reduction to 5 Day - 40 Hr Week Reduces O&M Costs by \$6/M²
- Cleaning of Enclosures Not Required except under Severe Conditions
- Routine Annual Maintenance Cost Per Heliostat - \$18.67
- Enclosure Avg. Annual Replacement Cost (Twice in 30 yrs) - \$30.42

MANUFACTURING

- Price Matures at Approximately 250,000 Unit/Yr Level

Production Level per Year	Facility Size (M ²)	Number of Heliostats per Employee/yr	Degree of Automation %	Degree of Vertical Integration	Cost of Installed Heliostat (1978 Dollars)
1,000,000	68,000	2,232	90	High	\$1,363
250,000	27,500	1,656	86	High	\$1,443
25,000	3,700	581	40	Medium	\$2,597
2,500	1,400	78.6	5	Low	\$5,686

SHIPPING

• Enclosure Weight	77 lb.	• Total Weight	468 lb.
• Heliostat Weight	202 lb.		
• Foundation Weight	189 lb.	• Total Volume	75 cu. ft.

POTENTIAL IMPROVEMENTS

- **Materials**

Polyvinylidene Fluoride, identified late in Phase I, provides:

- Foldable Factory Assembled Enclosure
- Sealed "dust free" enclosure and heliostat installation
- Reduced installation wind problems
- Non-flammable enclosure system
- 5% Enclosure transmittance improvement
- 15-year life reduces O&M replacement to only one time, reducing O&M cost to \$18.47/m²
- Transparency to UV
- Rot resistance for foundation application

- **Design**

Several improvements are conceived to be incorporated during the hardware development phase.

- Significantly reduced cost of foundation materials through laminated approaches or new screw anchor and pipe designs
- Improved tension devices, alignment tools, and corner beams
- Further weight reduction in struts and pedestal parts
- A new disc type linear motor for balanced loads and lower cost wheels.
- A six-strut frame for improved contour accuracy
- Controlled focusing
- Reduced blower air requirements

- **Performance**

Increased enclosure transmittance and use of a second surface silvered reflector will raise the projected net reflectivity to 0.677.

- **Costs**

Above improvements can account for further installed cost reduction of 15%.

THIS FINAL REPORT

Phase II plans, originally to be a part of this final report, will now be issued in a separate document in response to a solicitation from Sandia Laboratories. It is anticipated, based on planning work that has been done, that a program of hardware development and materials development will be undertaken to demonstrate the Preliminary Design presented herein and to proceed with potential improvements.

This is the final report concluding the Phase I effort which was completed on schedule and within the contract funds. This report describes the work performed during Phase I and provides the complete Preliminary Design analysis and drawings of the heliostat system that were used as the basis for the manufacturing conceptual design and cost estimates. Complete costing data is included along with all of the assumptions and data used in studying the production processes. A detailed description of the control system design is given together with a full report on the breadboard testing of the linear motor drives and the self-calibrating control system.

Specifications and a conceptual design of the Automatic Foundation Machine are provided as well as a complete description of the installation process and its labor and time estimates.

This heliostat system offers significant cost-effective advantages for central receiver power plants and warrants a full hardware demonstration and material development program. Potential improvements already identified assure even greater power system attractiveness for utility ownership and operation.

2.1 SYSTEM DESCRIPTION

The descriptions in this Section (2.1) discuss highlights of the General Electric - designed heliostat system. More detailed descriptions are provided in the following sections.

The enclosed heliostat consists of an aluminized film reflector deployed on a lightweight, eight-strut frame which is mounted on a single pipe pedestal. Azimuth and elevation drives are also mounted on the pedestal. The entire assembly is housed in an air-supported enclosure. An open-loop control system with self-calibration capability directs centrally computed sun angle steering commands to the individual heliostats of the total system via two-way multiplex signals carried over the field power distribution network. Totally mass produced in conventional industrial factories, the preassembled components are shipped to the site without restriction and installed semi-automatically within 30 minute time cycles. The reflector has a surface area of 55m^2 . The enclosure has a surface area of $\approx 227\text{m}^2$ and a volume of $\approx 510\text{m}^3$. The overall dimensions of the system are shown in Figure 2-1. The system design satisfies all the requirements of DoE Specification 001, stated in Section 3.1.1, 3.5, 3.6, 3.7, 3.8, 3.9, 3.11 and 3.12 (Reference Appendix "A").

2.1.1 ENCLOSURE

The enclosure consists of three factory-shipped sections which are zippered together in the field. The enclosure is then zippered to the automatically installed foundation bag and inflated. The ground cloth is placed inside and fastened to the foundation bag. The blower is designed to provide 50 cfm at one inch of water while requiring 15 watts of power. The material stress on the enclosure and foundation bag is 47 lb/in. at -30°C . The maximum deflection of the enclosure surface is 15 inches in a 90 mph wind. The enclosure design satisfies all the requirements stated in Section 3.1.2 and 3.4 of DoE Specification 001 (Reference Appendix "A").

The optical characteristics of the enclosure are based on measurements from sample material:

3 mil Polyethylene Terephthalate (PET)	Specularity 1.00 within 3 mr cone
	Hemispherical
	Transmittance .85
3 mil Polyvinylidene Fluoride (PVDF)	Specularity 1.00 within 8.7 mr cone
	Transmittance .90

Figure 2-1. General Electric Heliostat

A more complete description of the structural design of the enclosure is contained in Section 2.4, and Section 6.0 contains a description of the enclosure installation.

2.1.2 HELIOSTAT

The heliostat is field assembled within the enclosure by a two-man team. The foundation pipe is automatically installed concurrently with the foundation bag by the Automatic Foundation Machine (AFM). The AFM also precisely records the heliostat location which is later used as initialization data for the controller, thus eliminating the need for a manual alignment. Prior to putting the support structure into the foundation pipe, the reflector surface assembly is installed. This involves inserting the struts into the hub, unrolling the reflector surface from its shipping container, and attaching it to the ends of the struts. The surface tension is then applied by releasing the tension wire collar to a precalibrated position. The struts are checked and aligned if necessary for coplanarity. The support structure and the reflector surface assembly are then placed in the foundation pipe. The reflector surface assembly provides automatic temperature compensation to maintain a constant stress at the center of the reflector. This assembly also has a mechanical failsafe device to move the reflector to a safe position in the event of power interruptions.

The mechanical drive assemblies provide for 360° azimuth and 10° to 95° elevation travel of the reflector surface. An eight-pound linear stepping motor, which requires 25 watts input power, provides 0.0143°/step resolution. Stress on the azimuth and elevation bearing assemblies is 100 psi. An optical aiming accuracy of ± 2.80 mr is achieved by maintaining the following tolerances:

Azimuth axis tilt $x \pm 0.5^\circ$

$y \pm 0.5^\circ$

Drive wheel dimensional tolerance $\pm .005$ inch

Non-orthogonality of drive axis 0.01°

Azimuth calibration alignment $\pm 0.5^\circ$

Elevation calibration alignment $\pm 0.25^\circ$

Alignment of mirror face with drive system axis 0.01°

Mounted on the hub perpendicular to the mirror is a sun sensor device used for self calibration of individual heliostats. The alignment of this device with the mirror surface must be within 0.1 min.

The heliostat design satisfies the requirement stated in paragraph 3.1.2.3 of the 001 Specification (Reference Appendix "A").

The optical characteristics of the reflector surface as measured from material are:

2 mil Polyethylene Terephthalate Specularity 0.99 within 1.1 mr cone
Reflectance 0.90

The surface contour accuracy, represented as the percent of optically usable reflector surface, that is expected for production reflectors is 0.95. This is based on the test data that is discussed in Section 2.5.

Additional details of the structural design of the heliostat are contained in Section 2.3, and the installation sequence is described in Section 6.0.

2.1.3 CONTROLS

Each heliostat has a local controller which moves the mirrors in response to commands from a central plant controller. The central plant controller will provide mode commands, sun angle, and tower position to the heliostat via a two-way serial digital transmission path, multiplexed on the power distribution system. Table 2-1 describes this control hierarchy. Each heliostat will compute its own mirror angle and transmit its status back to the central plant controller. The mode commands, which are implemented by steering the reflected beam to a fixed or moving point, are:

- Calibration and initialization
- Tracking
- Synthetic tracking
- Offset pointing
- Standby
- Acquisition
- Stow
- Emergency shutdown

except for the calibration and initialization mode, the other modes can be considered to be a common mirror steering mode, with the major difference the direction of the reflected beam.

TABLE 2-1
CONTROL HIERARCHY

Heliostat Controller	Central Plant Controller
<ul style="list-style-type: none"> ● Compute mirror angle ● Calibrate ● Control azimuth & elevation motors ● Diagnostic ● Report Status 	<ul style="list-style-type: none"> ● Time ● Sun angles ● Tower position ● Address ● Mode

By sending both tower and sun angle data to each heliostat, the number of steering modes is effectively reduced to one. In operating an open-loop control system the installation errors have to be known. A self-calibration mode, which uses the sun as a reference, automatically calculates installation alignment errors. These errors are then used to modify mirror steering commands.

Linear stepping motors are used to provide high resolution with a minimum number of parts. Gear trains and angle encoders are not needed, thereby simplifying the mechanical design.

For maintenance actions, central computer control can be overridden by a portable local control box. The local control box can access resident diagnostics as an aid in maintaining the heliostat.

The controls design satisfies all the requirements stated in Section 3.3 of the 001 Specification (Reference Appendix "A").

Both the power distribution system and the control electronics have built in lightning and surge protection. Additional details regarding the controls are discussed in Section 4.0.

2.1.4 PERFORMANCE

System performance is defined in terms of net reflectivity (R), which is a measure of the available insolation vs the reflected insolation. The factors considered in determining R are the enclosure specular transmittance (this term is squared since it interrupts both incoming and outgoing insolation), enclosure surface degradation or dirt accumulation (this term is also squared), reflector surface specular reflectance, and blockage due to structural interference. The R for production heliostats is:

Enclosure specular transmittance ($.85^2$)	0.722
Surface Degradation	0.904
Reflector Specular Reflectance	0.890
Structural Blockage	0.996
NET REFLECTIVITY	0.578

Utilization of PVDF would allow an increase in the transmittance to 0.90 resulting in an overall performance of .648. Other performance improvements are believed possible when a better understanding of actual hardware has been achieved.

Performance for the specific field positions identified in the 001 Specification are calculated in Section 2.2, and these evaluations include the effects of surface contour accuracy and aiming error.

The system performance satisfies all the requirements stated in Section 3.3 of the 001 Specification (Reference Appendix "A").

SYSTEM PERFORMANCE

2.1.5 COMPARISON WITH DOE OBJECTIVES

The following DOE objectives were used in developing and evaluating the system design.

1. The installed cost of a heliostat related to its performance and expressed as:
 $\$72/M^2 R$ Cost/Performance where R = Net Reflectivity
2. Life cycle maintenance costs on a per square meter of surface area basis:
 $\$65/M^2$ Life Cycle Maintenance Cost - 30 year life
3. A measure of performance based on the percent of reflected energy within a specified receiver for a particular operating scenario and typical field layout:
95% Reflected Energy on Target
4. The availability of the heliostat during operating hours of the power plant:
97% Availability

To achieve these objectives, a number of key considerations became apparent.

Cost/Performance:

- Design to cost
- Reflector size
- Enclosure specularity and transmittance
- Reflector specularity and reflectance
- Enclosure surface degradation
- Blockage

Life Cycle Maintenance Cost:

- Enclosure cleaning
- Material life
- Reflector surface degradation
- Blower filter maintenance
- Component reliability and maintainability

Percent Reflected Energy
on Receiver:

- Reflector surface contour accuracy
- Optical aiming accuracy
- Structural blockage
- Optimum reflector size for given field layout, tower height and receiver size
- Environmental operating range
- Focusing

Availability:

- Operating environment
- Automatic fault detection and location
- MTBF
- MTTR (modular component replacement)

The incorporation of these considerations into the design resulted in the following preliminary design figures:

	<u>DoE</u>	<u>GE</u>
Cost/Performance	\$72/M ² R	\$44/M ² R
Life Cycle Maintenance Cost/M ²	\$65/M ²	\$27/M ²
% Reflected Energy on Target (for field avg.)	95%	97%
Availability	97%	99%

2.2 SYSTEM SYNTHESIS AND DESCRIPTION

The evaluation of the design was based on satisfaction of the system requirements, results of trade-off studies, analysis of test data, and the conclusions of total system design reviews. In designing a cost-effective product, the requirements for cost and performance were considered equally important.

2.2.1 REQUIREMENTS

The bases for the system requirements are derived from the design objectives and DoE Specification 001: Solar Central Receiver Prototype Heliostat Requirements. The translation of the objectives into requirements is described below. Actual performance relative to these requirements is discussed in Section 2.2.4.

2.2.1.1 Cost/Performance

A cost management program (see Section 7.2) was implemented to establish cost and weight requirements for the major assemblies. The initial requirements for production quantities greater than 250,000 units/year were:

<u>Assembly</u>	<u>Weight(lbs)</u>	<u>Cost(\$)</u>
Reflector	69	94
Support Structure & Drives	36	50
Controls	32	52
Enclosure	366	710
Foundation	168	265
Installation	<u>15</u> (packaging)	<u>215</u>
<u>TOTAL</u>	686	1386

The size of the reflector is not stated as a requirement per se, but was determined as the result of a total system impact trade study (reference Section 2.2.2). A 55m² reflector is a cost-effective and reasonable size based on the data evaluated. For specific applications the optimum reflector size will be dependent on the overall plant configuration and on whether it is a focused or unfocused system. The net reflectivity (R) is primarily dependent on the optical properties of the enclosure and reflector materials. The requirements established for these were:

Enclosure: Specular Transmittance 0.85 within 4 mr cone

Reflector: Specular Transmittance 0.85 within 4 mr cone

Surface degradation of the enclosure is not defined in terms of measurable requirements. There is no scheduled enclosure cleaning for this system (reference

Section 2.2.2), consequently there is a term that accounts for surface degradation in the net reflectivity calculation.

Structural blockage of incoming insolation and reflected energy degrades the net reflectivity. The requirement defining allowable blockage is:

Blockage: < 0.02 (of reflector surface)

2.2.1.2 Life Cycle Maintenance Cost

The major contributor to life cycle maintenance cost would be a scheduled enclosure cleaning program. Based on an analysis of the data available to date (reference Section 2.2.2) the maintenance program for this system does not include scheduled enclosure cleaning. The following specific component requirements were established to achieve low life cycle maintenance costs:

Enclosure	≥ 10 year life minimum
Reflector	≥ 10 year life minimum
Foundation Bag	30 year life
Blower Motor	≥ 10 year life minimum
Blower Filter	≥ 10 year life, reusable

The total system design was selected to conform to the following requirements.

- Common design for all field locations (complete parts interchangeability).
- All maintenance actions must be capable of being performed by a maximum of two persons.
- Automatic fault detection and location will be provided both at the field and single unit level.
- Components requiring periodic maintenance will be pull-out/plug-in modules.
- High reliability design and components will be used where cost effective.

2.2.1.3 Percent Reflected Energy on Target

Three field locations were analyzed, and focusing was required in the far field heliostats to meet the 95% objective. Other characteristics included the following:

- Reflector surface contour accuracy 0.95 (usable area) (surface errors greater than 0.926 mr unacceptable)
- Optical aiming accuracy 2.80 mr
- Structural Blockage < 0.02 (of reflector surface)
- Environmental Operating Range Section 3.1.2
001 Specification

2.2.1.4 Availability

An enclosed system places all the active components, with the exception of the blower, in a protected environment. This factor, coupled with a maximum operating time of 12 hours in a low-stress operating scenario, provides high availability. Utilization of automatic fault detection and location in conjunction with pull-out/plug-in modules minimizes MTTR.

2.2.1.5 Solar Central Receiver Prototype Heliostat Requirements, 001 Specification

The compliance of the system design with the specification requirements is shown in Appendix A.

2.2.2 TRADE-OFF STUDIES

In determining the system design, a number of trade-off studies were performed. Those concerned with reflector size, enclosure cleaning, and reflector focusing will be discussed in the following paragraphs. Enclosure panel replacement and enclosure configuration will be discussed in paragraphs 2.4.1.2 and 2.4.1.1, respectively.

2.2.2.1 Reflector Size

The selection of the 55m² reflector was based on evaluation of the impact of size on cost, performance, manufacturing, installation, and maintenance. Reflector sizes from 30m² to 80m² were evaluated.

2.2.2.1.1 Cost. Cost data in \$/m² was developed for five major components directly affected by reflector size. The five components considered were:

- Reflector Surface
- Reflector Compression Struts
- Reflector Hub including wire cable and tension device
- Enclosure Material
- Enclosure Zippers

For each component, dimensions and weights were determined. A component cost factor based on dollars per pound determination was then applied to arrive at the final cost. The major component costs decreased uniformly. Because enclosure thickness varies with size and remains the same for a range of reflectors, this gave the overall cost data the appearance of having plateaus when plotted against reflector size. The total results are shown on Table 2-2, a graph of dollars per square meter versus reflector size is shown on Figure 2-2.

2.2.2.1.2 Performance. The evaluation of performance was based on a comparison of the reflected energy within the target area for various reflector sizes at the same

Test data on enclosure material shows no change in transmittance for the enclosure thicknesses required for the different reflector sizes. Plotting this curve as a function of $\$/m^2 R$ would essentially offset it by a constant value.

Figure 2-2. Dollars Per Square Meter

TABLE 2-2

TOTAL COST RESULTS

Reflector Size (m ²)	30	40	50	55*	60	70	80
<u>Mylar Surface</u>							
Weight (lb)	3.50	4.66	5.83	6.42	7.0	8.16	9.33
Cost (\$)	7.00	9.32	11.66	12.83	14.00	16.32	18.66
<u>Aluminum Struts</u>							
Weight - 8 (lb)	24.8	32.0	39.3	43.15	47.0	55.1	63.4
Cost (\$)	24.8	32.0	39.3	43.15	47.0	55.1	63.4
<u>Hub</u>							
Weight (lb)	6.06	7.0	7.83	8.20	8.57	9.26	9.90
Cost (\$)	9.10	10.50	11.75	12.31	12.86	13.89	14.85
<u>Enclosure</u>							
Weight (lb)	53.6	61.3	84.6	88.6	92.6	99.4	126.4
Cost (\$)	96.50	110.40	152.30	159.5	166.70	178.90	227.50
<u>Zippers</u>							
Weight (lb)	87.8	100.4	110.8	116.0	121.2	130.2	138.
Cost (\$)	153.70	175.70	193.90	203.0	212.10	227.90	241.50
<u>Totals</u>							
Total Cost (\$)	291.	338.	409.	431.	453.	492.	566.
Total Weight (lb)	175.8	205.4	248.4	262.4	276.4	302.1	347.
<u>Average Cost</u>							
\$/m ²	9.7	8.45	8.18	7.87	7.55	7.03	7.08
\$/lb	1.66	1.65	1.65	1.64	1.64	1.63	1.63

*Phase 1 Reflector Size recommendation

field positions. Based on the conclusions of Vant-Hull and Hilderbrandt¹ geometric effects generally limit the diameter of a reflector field to three to five times the tower height, with little comparative energy gain for those reflectors beyond 2.75 tower heights. The tower height used for this exercise was 250m, the field positions selected had slant ranges of 500m, 750m and 1200m, the receiver (cylindrical) dimensions were 17m wide by 25m high. The equation used to approximate the size of the projected image diameter (D_i) was:

$$D_i = \frac{2h}{\cos \theta} \left(\alpha_s + \frac{W \cos \theta}{2h} + \sigma + \epsilon \right)$$

where:

$\frac{h}{\cos \theta}$ = slant range to reflector from receiver, h is tower height

W = width of reflector

σ = optical aiming errors (3.22 mr)

ϵ = beam spread due to enclosure specularity (0.25 mr/mil)

α = sun half-angle (4.65 mr)

The values of D_i for the various reflector sizes at the three field positions are shown in Table 2-3. The data shows that for the 55m² reflector essentially all the reflected energy is intercepted by the receiver for slant ranges of ≤ 500 m. For slant range of ≤ 750 m, there will be some spillover in the azimuth plane. Beam profiles for the 45, 55, and 65m² reflectors for positions of 1200m, 750m, and 500m are shown on Figures 2-3, 2-4, and 2-5 respectively. The most efficient field positions are those within 687m (2.75 x 250m) of the tower; Figure 2-4 shows that for all heliostats within a slant range of 750m essentially the entire image is intercepted by the receiver. The beam profiles are based on equations developed by Vant-Hull². The reflector size required to reach a peak intensity of 950 watts/m² on the receiver from a slant range of 1200m would be approximately 90m². This size was not considered practical when evaluated from a total system aspect.

TABLE 2-3

IMAGE SIZE FOR VARIOUS REFLECTOR SIZES

Reflector Size	Enclosure*	D_i Slant Range		
		1200	750	500
30	4 mil	27.2	19.3	14.8
35	4 mil	27.7	19.7	15.3
40	4 mil	28.2	20.2	15.8
45	4 mil	28.6	20.6	16.2
50	5 mil	29.6	21.4	16.8
55	5 mil	30.0	21.8	17.2
60	5 mil	30.3	22.1	17.6
65	5 mil	30.7	22.5	17.9
70	5 mil	31.0	22.8	18.3
75	6 mil	31.9	23.5	18.8
80	6 mil	32.2	23.8	19.8

*Enclosure thickness based on internal pressure in effect at the time of the study (4.5" of H₂O).

Figure 2-3. Beam Profiles - Various Reflector Widths at 1200m Slant Range Normal Incidence on Reflector

Figure 2-4. Beam Profiles - Various Reflector Widths at 750m Slant Range Normal Incidence of Reflector

Figure 2-5. Beam Profiles - Various Reflector Widths at 500m Slant Range, Normal Incidence on Reflector

2.2.2.1.3 Manufacturing. The present available width of reflector material is 1.52m. In quantity production, the cost effective method of manufacturing the reflector will be from material rolls equal to the width of the reflector (8.14m for 55m²). Scaling up the equipment and processes from 1.52m to 8.14m appears to be technologically feasible, and it is the maximum scaling manufacturing analysts consider practical at this time. The problems of handling, packaging, and shipping larger reflectors and their associated larger enclosures also approaches practical limits. Based on the data evaluated and the factors considered, a 55m² reflector is presently considered a realizable manufacturing size.

2.2.2.1.4 Installation and Maintenance. The reflector size selection has a direct bearing on the number of crew people required for installation and maintenance. It has been a design requirement that the reflector assembly be capable of being assembled by two people. Based on hands-on experience with our 40m² test reflector, it is felt that 55m² is the maximum size that two people can handle. During initial installation the crew sizes versus number of heliostats would be constant (4 men putting up 80m² heliostats or 2 men putting up 40m²). The maintenance cycle is not an analogous situation, if you can have the same crew size maintaining fewer heliostats you have achieved a significant savings in life cycle costs. The 55m² reflector can be installed and maintained by two men.

2.2.2.1.5 Conclusion Reflector Size Trade Study. Figure 2-6 illustrates the results of the analysis of four areas that relate to reflector size. This recommendation is based on field layout and target size for a particular plant configuration. By design, GE Heliostat Reflector Size can easily be changed to optimize cost-performance for other plant configurations.

2.2.2.2 Enclosure Cleaning

The decision to have no scheduled enclosure cleaning was based on evaluation of the following factors:

- Cost of cleaning
- Performance improvement vs. cleaning
- Effect of cleaning on enclosure surface
- Fouling distribution vs. field position

Enclosure maintenance will include replacement of enclosure due to unacceptable UV degradation, patching of enclosure due to punctures or rips as they occur, and non-scheduled cleaning of selected enclosures due to a rare combination of weather events resulting in unacceptable transmissivity. The system performance calculation

*NOTE: This recommendation is based on field layout and target size for a particular plant configuration. By design, GE Heliostat Reflector Size can easily be changed to optimize cost-performance for other plant configurations.

Figure 2-6. Phase I Trade Study Results for Reflector Size

has a term that accounts for surface degradation due to no scheduled cleaning of enclosure surfaces.

2.2.2.2.1 Cost of Cleaning. Projected cleaning costs were based on a semi-automatic process involving the use of a specially designed cleaning machine. The machine would require two operating personnel and have a cycle time of 15 minutes per enclosure. The annualized cost of the cleaning machine was calculated at 5 dollars per enclosure. The annualized per enclosure costs for cleaning at different intervals is shown in Table 2-4.

TABLE 2-4
CLEANING COSTS VS. INTERVAL

	Cleaning Interval					
	1 wk	2 wk	4 wk	16 wk	26 wk	52 wk
Annualized Capital Cost	5	5	5	5.00	5	5
Annualized Labor Cost	520	260	130	32.66	20	10
Total Annualized Cost	525	265	135	37.66	25	15

Cleaning at a once a month interval would increase life cycle maintenance cost/m² by \$74. These costs were used in assessing the cost of performance improvements versus cleaning intervals which is discussed in the following paragraph.

2.2.2.2.2 Performance Improvement vs. Cleaning. An analysis of available data shows the necessity for scheduled cleaning is a strong function of geographical location. Studies of second surface acrylic mirrors (a very good optical model of an enclosed heliostat) by Gilligan³ show the effects of cleaning and non-cleaning on reflectance. For a twelve-month exposure period, tests in Florida showed negligible degradation, in Phoenix a degradation of ~ 50% (with strong angular dependence), and in Chicago a loss of ~ 90%. Similar studies by Rausch and Gupta⁴ showed that dirt accumulation on plastic (Mylar and Acrylic) is different from that observed on glass. The plastic surface accumulated a certain amount of dirt during the first nine weeks and then little additional accumulation during the next two years. Glass appears to keep accumulating dirt and, according to Berg⁵, if it is not removed every few days it can become strongly bonded. There appears little likelihood of this happening with plastics. The annualized cost of cleaning the enclosure every nine weeks is projected to be \$63. This is considered unacceptably high when data from Boeing⁶ indicates the performance improvement would not warrant the cost. The data shown in Table 2-5 for heliostat H0 and H2 is the basis of this conclusion.

TABLE 2-5

HELIOSTAT EFFICIENCY DATA

(From Ref. 6)

Test condition	Heliostat No.	Date	Time	Efficiency (percent)	Average efficiency
Dome clean	HO	11/19/76	1430	70	72 +1 -2
		3/30/77	1605	73	
		4/04/77	1009	72	69 +5
	H2	4/02/77	1309	64	
		4/02/77	1359	65	
		4/03/77	1655	71	
		4/03/77	1552	73	
		4/03/77	1558	74	
Uncleaned for 3 months	HO	2/11/77	1235	66	70 <u>±</u> 4
	H2	2/11/77	1100	70	
		2/10/77	1150	74	
Uncleaned for 5 months	H1	3/30/77	1240	62	65 +7 -3
		3/30/77	1514	63	
		4/02/77	1117	63	
		4/03/77	1503	72	

Additional data³ indicates that when plastic is exposed simultaneously to water and dust, washing is warranted; for all other conditions occasional rain is capable of restoring transmittance.

The present scheme is to wash those enclosures exposed to simultaneous water and dust on an as required basis. This is not expected to result in large annualized costs.

2.2.2.2.3 Effect of Cleaning on Enclosure Surface. The effect of periodic washing of the enclosure may result in the build-up of scratches on the surface. Plastics are more susceptible than glass to damage from washing procedures which involve any wiping or scuffing⁷. The scratching of the plastic surface may be almost as detrimental as the dirt that is being removed. An enclosure maintenance scheme that includes scheduled cleaning of plastic surfaces should not be initiated until the effect has been fully evaluated.

2.2.2.2.4 Foulings Distribution Vs. Field Position. All studies to date have concerned individual reflectors in relatively open areas. The distribution of dirt across a field of 20,000 heliostats will not be consistent, i.e., the perimeter heliostats will have some blocking effect on the rest of the field. Until data is developed to evaluate this effect, the adoption of a total field scheduled cleaning program appears to be premature.

The enclosure with its vertical sides does not present a convenient surface for dust adhesion. The addition of an anti-static ingredient in the material will further reduce the dirt adherence to the enclosure.

2.2.2.3 Focusing

A stretched surface reflector will have a focal length which is a function of the reflector elevation angle and the surface tension. This characteristic can be used to enhance system performance by reducing the size of the image at the receiver and therefore the amount of energy spillover. The larger the elevation angle (measured from zero at horizon pointing direction), the greater the sag and hence the shorter the focal length. Test data shows that increasing the tension increases the focal length. The ideal focal length is the slant range from the reflector to the receiver center. Gravity focusing causes the focal length to change as a function of elevation angle (for a fixed surface tension). Elevation angle is dependent on the time of day and time of year for any specific field position. As an example, a far field heliostat (slant range 1298m) would have the following focal lengths and image sizes at noon on the following dates:

Field Position Slant Range	Date	Elevation Angle at Noon	Focal Length at Constant Tension	Gravity Focused Image Diameter at Receiver
1298 m	Winter Solstice	22°	1000 m	18.2 m
	Equinox	35°	650 m	24.0 m
	Summer Solstice	47°	510 m	28.4 m

In assessing overall system performance using gravity focusing, the specific time and data selected will have a significant impact on the final result and not be representative of the system performance integrated over a year's operation for a set of representative field positions. The randomness of gravity focusing indicates that a controlled approach should be implemented. The stretched surface reflector with variable tension control of the General Electric preliminary design lends itself to controlled focusing. The development of various methods to implement focusing are being investigated and will be incorporated in prototype hardware.

The optimum focal length is a function of field position and the technique to implement it will keep the same focal length for all elevation angles. The net effect of focusing will be to reduce the image size (images) on the receiver to:

$$\text{image}_D = \sqrt{\sigma^2 + (\alpha + \epsilon)^2} \cdot L$$

where

σ = optical aiming accuracy (2.80 mr)

α = sun disc 1/2 angle (4.65 mr)

ϵ = enclosure dispersion 1/2 angle (1.5 mr)

L = slant range for receiver to heliostat,

and to increase the intensity distribution within the beam. The relative image sizes for focused and unfocused heliostats at slant ranges of 638m and 1298m are shown in Figures 2-7 and 2-8, respectively. From the aspect of image size the primary advantage of focusing is for far field heliostats.

IMAGE PROJECTION 25 M
FOR NEAR FIELD
HELIOSTAT SOUTH
OF TOWER

FOCUSED
IMAGE
(8.11 M)

UNFOCUSED
IMAGE
(15.9 M)

DISPERSION DUE
TO SUN DISC
ANGLE

DISPERSION DUE
TO ENCLOSURE

17 M

RECEIVER
(250M HIGH)

Figure 2-7. Idealized Beam Projection for 55m^2 Reflector at 638m Slant Range.

Figure 2-8. Idealized Beam Projections for 55m^2 Reflector at 1298m Slant Range

2.3 REFLECTOR/SUPPORT & DRIVE ASSEMBLY

The Preliminary Design reflector assembly is an extremely lightweight stretch frame in which the reflector surface is the primary tension member. The reflector design meets the stringent optical requirements for performance, as well as the program design requirements of lightweight, low cost, "totally" factory-assembled components, transportable, and minimum site assembly. Table 2-6 illustrates the low part count and weight of the reflector and drive assembly components. The low-

TABLE 2-6
HELIOSTAT ASSEMBLY

Item	Manufacturing Parts		Installation Shipping		Wgt.	
	Diff.	Total	Parts	Container	kg	lbs.
Reflector	15	57	17	- 3	33	(72)
Support/Drive Mech.	30	34	1	- 1	32	(70)
Elec.	25	63				
Az Drive Wheel	3	3	1	- 1	10	(22)
Foundation	3	3	1	A/R	17	(38)
Totals	76	- 160	20	- 5	92	(202)

cost design for material and minimum site labor were arrived at through numerous design iterations between Engineering, Manufacturing, and Installation design teams. Features of the mechanical design of the reflector and drive assemblies resulting from this Phase I effort include:

- Acceptable Weight/Cost Components
- All Component Parts Mass Producible
- Failsafe Mechanical Stow Position
- Size of Reflector Easily Changed
- Automatic Tensioning Device
- Minimum Parts Count
- All Component Parts Factory Assembled
- No Special Shipping Requirements
- Low Site Assembly & Alignment Time

These design features are described in more detail in the following paragraphs of this section.

2.3.1 REFLECTOR CONFIGURATION

The Preliminary Design reflector configuration is a 55m² octagonal reflector surface of metalized polyester film held in plane and tensioned by eight tubular compression struts and tension wires. These are supported by a reinforced structural plastic hub with a spring-loaded tensioning device. The reflector assembly is illustrated in Figure 2-9.

The principle parts of the reflector assembly are:

- Reflector Surface
- Reflector Corner Beams
- Struts
- Tensioning Wires
- Hub Assembly
- Tensioning Device

The reflector surface is a 0.05 mm (2 mil) thick, UV-stabilized, aluminized polyester film with an opaque rear surface. The mechanical properties of this material that influenced the reflector assembly structural design are tensile strength, weight, creep characteristics, and thermal coefficient of expansion. The stretch frame design required the development of an end attachment that distributes the strut concentrated corner load into the reflector surface without causing wrinkles. Typical corner attachments that were evaluated in Phase I are illustrated in Figure 2-10. This figure describes graphically the design-test iteration of a Low-Cost design. Each method tested was a more cost-effective use of material, with the final design still placing stresses on the material that are an order of magnitude less than the material's ultimate tensile strength.

The corner beam is a lightweight double cantilevered beam which transfers the load to the reflector surface from the strut. The two primary design requirements for the corner beam are that it must not produce wrinkles and that it must produce minimum 'peel' load on the reflector corner attachment loop adhesive. These requirements suggest the design to be a tapered airfoil shape with the largest depth in the highly loaded bending plane.

The eight strut assemblies each consist of the primary tube compression member with necessary end connections. The strut assembly is illustrated in Figure 2-11. The reflector end connection is designed to provide equal angular lines of force for the reflector mounting corner beam and the tensioning wire. The hub connection

Figure 2-9. Stretch Frame Reflector Subassembly

Figure 2-10. Corner Attachment Method Designs Evaluated

Figure 2-11. Strut Assembly

end has a strut coplanar adjusting screw for planar adjustment of the reflector surface. The length adjusting screw has a spherical end which mounts into sockets in the reflector hub.

The tensioning wire assembly forms the rear tension member(s) of the stretch frame and is factory-assembled to the reflector surface end of the strut assembly. The hub end is site assembled to the tensioning ring of the tensioning device by snapping the cable into factory-provided retaining slots in the ring.

The reflector hub is the central structural member of the reflector stretch frame and the most critical and precision component of the reflector assembly. The hub performs the following functions:

- Structural support for stretch frame members
- Reflector assembly support at elevation axis
- Mounting for elevation drive
- Mounting for calibration sun sensor
- Mounting for reflector coplanar alignment tool

The hub's initial function in the stretch frame truss is to provide the compression member between the strut(s) and tension wire(s). The reflector hub is illustrated in Figure 2-12. Since the hub is the central member of the reflector assembly, it also provides the structural interface mounting to the support and drive structure at the elevation axis. The elevation axis is located at the center of gravity of the reflector assembly. The hub assembly provides mounting provision for the elevation drive to ensure that the drive is concentric to the elevation axis. The unique calibration mode used in the Preliminary Design Heliostat requires that a sun sensor be mounted behind and parallel to the plane of the reflector surface. The reflector hub provides the mounting surface for the heliostat alignment sun sensor. To ensure that the reflector surface is parallel to the sun sensor plane, additional mounting surfaces are provided on the hub for mounting a frame coplanar alignment tool. The portable frame coplanar alignment tool is attached in the field as part of the installation alignment procedure. The reflector hub and sun sensor will be factory-assembled to the support and drive assembly to keep field installation labor costs to a minimum. Quality control supervision during factory assembly assures the precision of the elevation axis alignment.

Incorporation of the reflector tensioning device is an unusual feature of the heliostat stretch frame design. The tensioning device provides a means of simultaneously tensioning all eight (8) corners of the reflector surface. The other

Figure 2-12. Reflector Hub

major function of the tensioning device is to maintain the proper tension in the reflector surface for temperature excursions and a minor amount of reflector creep.

The Preliminary Design reflector stretch frame is readily adaptable to changes in reflector size as dictated by future size/cost trade-offs. Table 2-7 illustrates reflector diameter for various areas.

TABLE 2-7

Area m ² (ft ²)	Diameter (Tip to Tip) m (ft)
30 (322)	6.51 (21.9)
40 (430)	7.52 (24.7)
55 (532)	8.84 (29.0)
70 (753)	9.95 (32.6)
80 (861)	10.63 (35.9)

2.3.2 STRUCTURAL DESIGN

The Preliminary Design Heliostat reflector has been sized at 55m² (592 ft²). The collector subsystem design includes an air-supported enclosure to protect the heliostat reflector and support structure from the major environmental loads of wind, snow, and ice. The reflector assembly is designed for the effects of the following load conditions:

- Stretch Frame Loads
- Load Variations Due to Temperature Excursions (-30°C to +56°C)
- Installation Handling
- Gravity Loads

The stretch frame loads are the major design loads for the reflector components. The reflector design is based on providing minimum stress in the reflector material so as to minimize effects of long term creep in the material. The minimum stress must be large enough to provide the required optical properties of the reflector - i.e., to control the sag which forms a focal length parabolic reflector. Investigation has shown that the long term creep can be held to < 0.1%. Another property of the reflector material that was considered was the short term (< 2 days) stretch approximately 0.4%. The resulting stretch frame loads are 956N (215 lbs) at reflector corners, 1846N (415 lbs) compression on struts, 956N (215 lbs) on tensioning wire, and 2615N (588 lbs) on reflector hub. These loads and resulting reflector stress distribution are illustrated in Figure 2-13.

Because the General Electric heliostat reflector stretch frame uses numerous dissimilar materials, it was essential during the design to investigate the effects of differing thermal expansion rates.

The expansion analysis considered a temperature range from 55°C to -30°C, resulting in reflector tension stress variations from minus 70% to plus 40%. These stress differentials were judged to be unacceptable, necessitating the use of an automatic tensioning device, mounted on the reflector hub compression member (see Figure 2-14). By incorporating this automatic tensioning device in the system, a reduction in reflector tension stress variation to minus 15% and plus 12% is realized. The Preliminary Design reflector stretch frame loads including initial load and load changes due to temperature change are presented in Table 2-8.

TABLE 2-8
STRETCH FRAME TEMPERATURE COMPENSATION

			Initial	+70°F to -20°F -90° ΔT	+70°F to +130°F +60° ΔT
Mylar (Reflector)	Tension	N Lbs	956 215	812 183	1070 241
Aluminum (Strut)	Compression	N Lbs	1846 415	1569 353	2067 465
Steel (Tension Wire)	Tension	N Lbs	956 215	812 183	1070 241
Lexan (Hub)	Compression	N Lbs	2615 588	2223 500	2929 659
				-15%	+12%

The heliostat installation plan requires lifting the reflector and support structure by portable jacks positioned against the reflector stretch frame structure. These installation loads are still to be investigated but their effect will be minimized by the design of special installation tools.

Gravity loads due to the extremely lightweight of the stretch frame member will not cause major changes in member loads. The primary concern of gravity loads is in structural deflections in the reflector assembly. Reflector deflections have a direct effect on heliostat performance and are discussed in Section 2.3.4.

The design of the reflector assembly assures the lightest weight and least number of parts to keep both the cost and assembly time at a minimum. A summary of part count and weight of the reflector components are presented in Table 2-9.

TABLE 2-9

HELIOSTAT REFLECTOR PARTS & WEIGHT

Item	Manufacturing Parts		Installation Shipped		Wgt. (Lbs.)
	Diff.	Total	Parts	Cartons	
Reflector	1	1	1	1	8.0
Corner Beam	1	8	8	1	10.0
Strut Assembly (8)	4	32	8	1	43.6
Cable Assembly	1	8			2.2
Reflector Hub	3	3	*		5.3
Tensioning Device	5	5	*		3.0
TOTALS	15	57	17	3	72.1

*Factory installed to support structure

2.3.3 INSTALLATION ALIGNMENT

The reflector assembly is designed for easy field assembly with adjustment. The field adjustments required are:

- Set reflector plane
- Tension stretch frame

The special tooling used in the field for setting the reflector plane will have been aligned such that the plane behind the reflector will be normal to the sun sensor axis.

Alignment of the test frame reflector was accomplished using a laser. The laser tooling included a variable speed rotating head which projected a light beam out in a plane. This is standard equipment used by the construction industry.

An alternate to the laser equipment is a telescope with an eight-sided mirror such that the field of view would include all strut tips. A rotating 'cover' would allow viewing of either a single strut or all eight struts.

The reflector assembly parts are to be made on high precision automatic machinery. Hence final adjustments in the field will be small consisting of a length adjustment of the strut to bring the tips (reflector surface) into plane.

Tensioning of the reflector stretch frame must be done to all tension wires simultaneously. The tensioning device mounted on the hub assembly performs this function. It is designed to compress the spring against the tension wire collar. The tensioning device is illustrated in Figure 2-14.

Figure 2-14. Hub Assembly Tension Device

2.3.4 FOCUS

The reflector surface gravity deflections vary with elevation angle and surface tension resulting in variable focal lengths. "Smart focusing" of heliostat is only practicable in decreasing the focal length. The tensioning device provides a capability to use this phenomenon in providing 'partial' focal length control for the far field heliostats, i.e., higher tension reduces sag and increases focal length. The development of methods to implement this feature and the overall advantage of focusing will be explored during Phase II.

2.3.5 SUPPORT AND DRIVE ASSEMBLY

The enclosed heliostat support and drive unit is a lightweight dual axis (azimuth and elevation) pedestal that provides the structural support and interface for the reflector assembly. The support and drive structure, illustrated in Figure 2-15, consists of the following major components or assemblies:

- Elevation Axis
- Yoke/Pedestal Assembly
- Elevation and Azimuth Drives
- Lower Support and Foundation

Figure 2-15. Support and Drive Assembly

To ensure meeting the collector subsystem performance requirements the structural pedestal is designed to the following requirements:

• Azimuth Axis Tilt	0.7°
• Azimuth Angle Calibration	$\pm 0.5^\circ$
• Elevation Angle Calibration	$\pm 0.25^\circ$
• Axis Non-Orthogonality	0.01°
• Alignment Sun Sensor/Drive Axis	0.01°
• Alignment Reflector/Sun Sensor	0.01°
• Motor Drive Resolution	0.0143°
• Azimuth Slew	$\pm 270^\circ$
• Elevation Slew	+ 10° to + 95°

2.3.5.1 Elevation Axis

The elevation axis provides the structural interface connection between the reflector stretch frame hub and the pedestal yoke. The balanced lightweight reflector and the elimination of environmental loads allow a relatively short axial length between two low friction, self-lubricating bearings. The elevation drive wheel hub is structurally connected (keyed) to the reflector hub at the elevation axis to ensure concentricity of the outer drive rim with the elevation axis. The configuration of these items is illustrated in Figure 2-16.

2.3.5.2 Yoke/Pedestal Assembly

The yoke assembly is the rotating (azimuth slew) pedestal member that provides support for the reflector and elevation drive motor. The Preliminary Design yoke tube is 7.6 cm (3 in.) diameter aluminum tube with 0.5 cm (.19 in.) thick wall. The yoke is formed to provide clearance for the reflector stretch frame struts and tensioning wires during elevation slew. The elevation and azimuth axis mountings are an integral part of the yoke thus allowing for factory machining of the critical axis orthogonality requirement and azimuth drive wheel mounting. The drive wheel is keyed to the yoke to provide positive azimuth drive. In addition, the azimuth drive wheel transfers the reflector pointing axis calibration mark to the sensor mounted on the azimuth drive motor. The elevation motor support connects to this tube near the elevation axis. A wire harness support provides proper clearance of the elevation wire harness during the azimuth slew.

The azimuth axis support is provided by a "king post" type design. A thrust/radial bearing under the azimuth drive wheel provides vertical support. The moment connection is provided by the two radial bearing mounts machined on the yoke tube.

Figure 2-16. Elevation Axis

The lower radial bearing is allowed to float vertically in the outer king post support for fabrication ease and elimination of possible temperature expansion problems. The azimuth axis configuration is illustrated in Figure 2-17. Note that the outer king post or support member is the lower support tube.

2.3.5.3 Elevation and Azimuth Drives

The pedestal drives use a linear stepping motor modified to work on a 20-inch radius drive wheel(s). The same motor design will be used on both axes for commonality of components and ease of operation and maintenance. The drive system design requirements are:

- Drive Wheel Radius 0.5m (20.0 in.)
- Motor Resolution 0.0143°/step
- Drive Force 48.9 N (11 lb)
- Maximum Slew Rate 0.2°/sec
(Azimuth)

Figure 2-17. Azimuth Axis

The unique design feature of the preliminary design pedestal drive is the development of a molded reinforced structural plastic wheel with a ferrite-loaded outer rim to provide the magnetic platten for the linear motor. The platten face will consist of grooves 5mm (.020 in.) wide by 4mm (.015 in.) deep, spaced 10mm (.040 in.) center to center. The motor magnetic coupling will hold the motor to the platten with bearing-type wheels used to maintain a 0.23mm (1 mil) gap so as to provide the 48.9 N (11.0 lb) drive force. Magnetic operated latch devices will indicate cw or ccw rotation of the drive hubs to be used for rotational limit control.

An alternate rotor disc configuration is presently being considered in which the motor would be "U" shaped to fit around the disc edge. This design offers a 'balanced' dual motor with very low magnetic gap spacer wheel loading on the reinforced plastic disc. This design uses grooves on both sides of the rotor in the radial direction that are tapered along their length. This design offers a lighter unit with simpler tooling and ease of manufacture.

The linear stepping motor and platten offers a unique feature not available with gear drives. That is, in the event of power failure, the motor has 'zero' tangential holding power. Hence by means of reflector unbalance and a light spring in azimuth the unit will go to an automatic safe stow position.

These drives are shown in Figure 2-18.

2.3.5.4 Lower Support and Foundation

The lower support and foundation pipes are required to support the 730 N (164 lb) pedestal and reflector assemblies. Investigation into low cost stable light duty foundations resulted in the selection of a 'pile type' foundation for the heliostat. The selection of an 11 cm (4.5 in.) diameter foundation pipe provides ample strength against any unbalance moment loading (primarily erection) and for the 18.3 Nm (13.5 ft-lbs) drive torque resistance. Optimum length for this type foundation is 10 to 15 times the pipe diameter; hence a minimum embedded length of 1.5m (60 in.) is used for the preliminary design.

Corrosion of the earth-embedded steel foundation varies greatly with moisture content, texture, and composition of the soil. The specified Southwest soil is dry, coarse-textured, and contains salt deposits. Corrosion conditions are primarily near the ground line and of a type similar to atmospheric exposure. Prevention of corrosion can be accomplished by protective coatings, alloy selection, cathodic protection, and other means. The Preliminary Design selection is HSLA steel containing copper for corrosion resistance and a protective galvanized finish.

Figure 2-18. Elevation and Azimuth Drive Wheels

The use of an Automatic Foundation Machine (AFM) for installing the foundation pipe requires hardened 'saw type' teeth on the lower edge. The AFM affords other installation aids such as the capability to automatically survey the installed foundation location relative to the tower in three dimensions plus provide a pipe orientation bearing for use in the automatic calibration mode of the pedestal. The bearing requirement requires the use of a pin or key on the upper end of the foundation pipe.

2.3.5.5 Pointing Accuracy

The mechanical assembly tolerances illustrated in Figure 2-19 create primarily a bias error in the drive system pointing. The heliostat controller contains an automatic calibrate mode which provides an error correction algorithm into the drive command circuit so as to reduce the pointing accuracy error to within the system requirements of 0.2° (3 mr).

Figure 2-19. Mechanical Assembly Tolerances

2.4 ENCLOSURE PRELIMINARY DESIGN

The General Electric enclosure, shown in Figure 2-20, is an air-supported, transparent plastic structure. It has been designed to accommodate an automatically installed, earth-filled, plastic bag foundation as well as complete heliostat assembly and disassembly within its protective confines.

The enclosure preliminary design incorporates the following features:

- Flat panel construction for minimum cost.
- Sized to house a 55 square meter reflector with a 15 inch minimum internal clearance.
- Three zippered sections to permit rapid assembly and attachment to the plastic bag foundation ring.
- Designed with an inward-sloping bottom section to allow maximum packing density while still providing access for maintenance.
- Ground cloth to cover the earth within the enclosure to act as a vapor barrier and suppress vegetation growth and dust movement.
- Ability to factory assemble, package, and ship an entire enclosure with a minimum shipping volume.
- Ability to install complete enclosure within 30 minutes with minimal field labor.
- Designed with a compound top conical section for optimum solar energy transmittance and minimum shadowing and blocking.

The selected enclosure configuration has evolved through many trade-off studies involving engineering analyses that took manufacturing and installation processes into account. Specifically, the effects of environmental loads have been evaluated. Minimum parasitic power losses were a primary influence in the blower selection while still maintaining the required inflation pressure.

2.4.1 ENCLOSURE DESIGN

The design of the General Electric enclosure has undergone several changes beginning with the concept presented in the proposal, shown in Figure 2-21, up to the current concept shown in Figure 2-20. Initially, the proposal concept, along with three other design concepts, all configured for a 40m^2 reflector were compared on the basis of manufacturing costs, shipping and assembly difficulties, and panel replacement capability. This comparison is summarized in Table 2-10. The basic conclusion drawn from this trade-off study was that a flat panel design was more cost-effective and that an inward sloping bottom section allowed for higher field density while still providing access for maintenance vehicles.

Figure 2-20. General Electric Heliostat Enclosure

Figure 2-21. Proposal Concept of General Electric Enclosure

TABLE 2-10

Comparison of Enclosure Configurations

ENCLOSURE		REPLACEABLE PANELS				ZIPPER		COMMENTS
SHAPE	DESCRIPTION	LOCATION	QTY	AREA FT ²	WT. LBS.	LENGTH FT.	WT. LBS.
REV. C	27 FT. DIA. ON HORIZ. 23 FT. BASE DIA. 4 FT. HIGH ALL FLAT SECTIONS	TOP	1	70.7	1.5	502		USE OF FLAT PANELS RESULTS IN • LOW COST MFG. • ACCEPTABLE STRESS WRINKLES • SMALLEST PACKAGING • EASE OF ASSEMBLY • EFFICIENT PANEL REPLACEMENT
		TOP ANGLE	8	605.0	13.1			
		CENTER	8	848.2	18.4			
		BOTTOM (INC. BASE)	8	588.9	12.7			
		TOTAL	25	2112.8	45.7
REV. B	27 FT. DIA. ON HORIZ. 27 FT. BASE DIA. ALL FLAT SECTIONS	TOP	1	70.7	1.5	453.5		
		TOP ANGLE	8	605.0	13.1			
		BOTTOM (INC. BASE)	8	1463.2	31.7			
		TOTAL	17	2138.9	46.3
REV. A	HEMISPHERE MADE WITH GORES ATOP A CYLINDER 27 FT. BASE DIA. 4 FT. HIGH	POLAR CAP	1	25.1	.5	434		USE OF GORE SHAPED PANELS RESULTS IN • HIGHER MFG. COSTS • UNACCEPTABLE PACKAGE SIZES • HIGHER COST ASSEMBLY
		TOP	8	1120.0	24.2			
		BOTTOM (INC. BASE)	8	1074.4	23.3			
		TOTAL	17	2219.5	48.0
CLAM SHELL BACK WITH 3 ZIPPERED SECTIONS 28 FT. DIA. BASE	BACK SECTIONS	1 3	610 1455	13.2 31.5	352		
		TOTAL	4	2065	44.7			

DEPENDENT ON ZIPPER CHOICE

As a result of a reflector size/cost trade-off study (Section 2.2.2) 55 square meters was selected as the preliminary design mirror size. Consequently, the enclosure design was further modified resulting in the final selection shown in Figure 2-20. The current enclosure configuration includes those desirable features identified above, and, in particular, it is based upon the following considerations:

- Optimum solar energy transmittance
- Minimum shadowing and blocking

As shown in Figure 2-20 the total enclosure assembly consists of the following major components:

- Air supply system
- Three transparent plastic sections with edge zippers
- Foundation bag with ground cloth
- Access door

Each of these components is discussed in the following sections.

2.4.1.1 Configuration Studies

The shape of the General Electric enclosure, as shown in Figure 2-20, consists of a compound conical top section, a cylindrical middle section, and a bottom section that is an inverted truncated cone. This configuration has evolved through many engineering/manufacturing studies and is based upon:

- Use of flat panels for lowest cost
- Optimum solar energy transmittance
- Minimum shadowing and blocking

The cylindrical and conical sections are manufactured flat and rolled for shipping. The inward sloping bottom section reduces the foundation ring diameter and allows larger ground distance between enclosures to facilitate access.

2.4.1.1.1 Optimum Transmittance. The efficiency of light transmittance through the enclosure is a function of the incidence angle which is defined as the angle between the ray of sunlight and a normal to the surface. A typical graphical representation of the transmissivity as a function of incidence angle⁸ is shown in Figure 2-22. This figure implies that maximum transmittance corresponds to the smallest possible incidence angle. However, the incident sunlight going into the enclosure will have different incidence angles than the reflected sunlight leaving the enclosure. These differences are due to the various positions of the sun relative to the heliostat and of the heliostat relative to the receiver.

Figure 2-22. Transmissivity Versus Incidence Angle

Since all incidence angles cannot be individually minimized, the slope of the top cone has been chosen in a way that attempts to optimize the total efficiency of the entire field. This optimization has been accomplished by averaging the losses in transmittance for both incoming and outgoing energy for both near and far field positions.

For example, DoE Specification 001 defines three heliostat positions relative to the receiver, as shown in Figure 2-23. Tabulated on this figure are the corresponding tower vector elevation angles. These positions are taken to be representative of far and middle field heliostat locations.

The absorptivity of the receiver will significantly decrease with increasing incidence (or tower vector) angles. Based on studies by the University of Houston on the McDonnell Douglas and Sandia glass heliostats, a representative tower vector angle for an extreme near field position is taken to be 60 degrees.

Figure 2-23. DoE Specification 001 Heliostat Positions Relative to Receiver

The altitude angles of the sun at 12:00 noon for the equinox and the two solstices have been chosen to represent the range of incoming incident sunlight. From Ramsey and Sleeper⁹ these angles are 36°, 57° and 83° for the winter solstice, the equinox and the summer solstice, respectively, at 32°N latitude.

The relationship between these various angles is shown graphically in Figure 2-24 where α is the angle of either the incoming sun vector or the outgoing tower vector, β is the transmittance incident angle and γ is the slope of the top cone. For optimum transmittance it is desirable to have the angle β as near to zero as possible. When $\beta = 0$ the sum of α and γ equals 90 degrees. Thus, the slope γ that will make $\beta = 0$ can be calculated for any given vector angle α . This has been done and the results are shown in Table 2-11. Based on these calculations, for optimum transmittance, the slope of the top cone has been chosen as 45 degrees.

TABLE 2-11

SLOPE OF TOP CONE FOR OPTIMUM TRANSMITTANCE

<u>Heliostat Position</u>	Vector Angle α	Slope γ	Average
A	11	79	75
B	12	78	
C	23	67	
Near Field	80	10	30
<u>Sun Position</u>			
Summer Solstice	83	7	
Equinox	57	33	31
Winter Solstice	36	54	

Overall Average = 45°

2.4.1.1.2 Enclosure Blocking. An enclosure design that incorporates a single cone top section at a 45 degree angle would produce a peak that is approximately 10.7m (35.0 ft) above the ground. However, an enclosure this tall would cause blocking and shadowing of adjacent heliostats in the field. In view of this consideration, variations in cone angle were studied and compared with regard to the amount of material used and the area of potential blocking. The basic right regular cone was retained as the reference shape based upon manufacturing studies which have indicated the cost-effective approach of flat panel construction.

(A) GEOMETRY FOR NEAR FIELD HELIOSTATS AND INCOMING SUNLIGHT

(B) GEOMETRY FOR FAR AND MID FIELD HELIOSTATS

Figure 2-24. Solar Energy Incident Angle Geometry

Variation in peak height was accomplished by varying the cone angle between 10° and 45°, as shown in Figure 2-25. As shown in the previous section, the 45 degree angle is best for optimum transmittance. In order to maintain the minimum reflector clearance of 38.1 cm (15.0 in.) as dictated by wind deflection analyses, the height of the cylindrical middle section had to be adjusted accordingly. Thus, the difference in enclosure surface area is the sum of the changes in the top cone plus those in the cylindrical section. The comparative surface area calculations indicate that a cone angle of 45 degrees corresponds to the minimum usage of material.

Unacceptable blocking and shadowing may be caused by the upper portion of the 45° cone shown shaded in Figure 2-26a, or in the other extreme by the lateral portion of the 10° cone shown shaded in Figure 2-26b. Therefore, the obvious design choice that will induce the least shadowing and blocking is as shown in Figure 2-20. It combines the 45° cone angle from the cylindrical sides up to the point of minimum clearance with a 10° cone angle continuing up to the peak.

The compound cone design chosen for the GE enclosure provides an added benefit in that the 45 degree slope is a geometric optimum since it parallels the slant edge of the reflector. It utilizes the smallest amount of material and can be manufactured using flat panels throughout.

2.4.1.2 Enclosure Maintenance

The design of the GE enclosure, from the very beginning, has endeavored to include the capability of replacing individual panels by utilizing zippered connections. The approach was believed necessary in order to meet projected cost effective life cycles and maintenance. As described below, this design philosophy has been modified as a result of trade-off studies concerned with cost versus performance when scheduled maintenance includes periodic enclosure cleaning.

According to very meager test data in the literature, glass tends to accumulate dirt on the surface continually while plastic will accumulate dirt over a relatively short period of time and then very little more thereafter. Furthermore, any cleaning operation in itself may induce surface scratching that is more harmful than the dirt being removed. In view of these considerations, cleaning vs. no cleaning of the enclosure has been evaluated (see Section 2.2.2). The results indicate that it is more cost-effective not to include periodic cleaning in the enclosure maintenance program.

Figure 2-25. Variations of Enclosure Top one Angle

(a) Possible Blockage with 45° Cone

(b) Possible Blockage with 10° Cone

Figure 2-26. Top Cone Blockage

Zippered connections are incorporated in the enclosure for attachment to the foundation and along lines of abrupt change in shape. These latter zipper locations result from the use of flat panel construction to achieve low cost. The number of possible additional zipper locations is a function of total zipper blockage. In order to keep this blockage to less than 2% (see Section 2.2.1) it is possible to have eight, equally spaced, vertical panels. This assumes a zipper width of 1.72cm (0.5 in.) as projected for the high production volume.

As a result of the cleaning evaluation it has been concluded that UV degradation is the sole driving force in planning a replacement cycle for the enclosure material. Replacement would include only that material that is directly affected by the impinging sunlight. For the range in solar azimuth angle which varies from 87° for the winter solstice to 146° for the equinox to 220° for the summer solstice the impinging sunlight will cause UV degradation to at least three vertical panels in addition to the top conical section.

An evaluation of the maintenance costs for replacing just the top conical section and three or more vertical panels as compared to replacing the entire enclosure has indicated that it is more cost-effective to replace the entire enclosure. This result is primarily due to the incremental labor charges for additional zippering operations. Therefore, the GE enclosure design will not include replaceable vertical panels but rather the entire enclosure will be replaced as required.

In addition to the overall enclosure replacement there will be scheduled routine annual maintenance on the enclosure system. This will consist of repairing small material tears (non-catastrophic failures), replacing failed blowers (estimated at eleven per year for 20,000 heliostat field), and filter cleaning. Further discussion on maintenance procedures and costs will be found in Sections 6.7 and 7.3.

2.4.1.3 Air Supply System

A distinct advantage of an enclosed heliostat over an unenclosed design is that the range of operation is limited only by the ability of the air supply system to support the enclosure and maintain its structural rigidity when exposed to wind loads. Hence, the air supply system must operate on a continuous basis to keep the enclosure fully inflated at all times.

The major components of any air supply system are the blower unit, which provides the necessary air volume flow rate at the required static pressure, and an air filter, which minimizes dust intrusion. All this must be accomplished under continuous operation with the air supply system requiring minimum maintenance.

Standard design practice for air-supported structures advocates setting the internal static pressure equal to or slightly higher than the dynamic pressure corresponding to the maximum wind velocity that the structure must withstand. According to DoE Specification 001 the heliostat design must survive a wind speed of 40 m/s (90 mph). However, in determining the required static pressure for a cost-effective design, due consideration has been given to the expected frequency of various wind velocities as prescribed in the specification.

The wind speed frequency, shown cumulatively in Figure 2-27, indicates that for 99% of the time the wind velocity will be less than or equal to 14 meters per second (31.3 mph). Conversely, there is a 1% probability of the occurrence of a wind velocity greater than 14 m/s. As given, there is no indication as to the probability of the occurrence of the maximum survival wind velocity. To determine the probability of a wind speed of 40 m/s (90 mph) a Weibull distribution was prepared and is shown in Figure 2-28. This probability distribution was obtained by plotting each wind speed and corresponding cumulative frequency from Figure 2-27 and then finding the straight line that best fits the data. The open circles represent each of the respective data points. The dashed line at the upper left was drawn parallel to the distribution straight line in order to determine the characteristic shape factor.

From Figure 2-28 it can be seen that the intersection at 40 m/s is off the graph. However, its probability can be calculated from the equations that govern this distribution. The probability of the wind speed being equal to or less than some value X is given by:

$$P (< X) = 1 - e^{-\left(\frac{X}{\epsilon}\right)^b}$$

from which the probability of the wind speed being greater than X is

$$P (> X) = 1 - P (< X) = e^{-\left(\frac{X}{\epsilon}\right)^b}$$

where

ϵ = wind speed @ $P = 63.2\%$

b = shape factor

Therefore, with $\epsilon = 5.0$ m/s and $b = 1.4$ the probability that the wind speed will exceed 40 m/s is calculated from

$$P (> 40) = e^{-\left(\frac{40}{5}\right)^{1.4}} = 1.04 \times 10^{-8}$$

Figure 2-27. Frequency of Wind Speed Per DoE Specification 001

Figure 2-28. Wind Speed Probability Distribution

Thus, based on the frequency of wind speed as prescribed in DoE Specification 001 there is less than one chance in a hundred million that we will ever see a wind velocity of 90 mph.

The objective of this Phase I study has been to achieve a low cost heliostat design. With this objective in mind, and as a result of the very low probability of the occurrence of a 90 mph wind, the selection of a blower included an evaluation that considered the impact of incorporating an internal pressure that is less than the maximum dynamic wind pressure. This evaluation is summarized in Table 2-12.

TABLE 2-12

BLOWER INTERNAL PRESSURE EVALUATION

<u>Parameter</u>	<u>Effect of Lower Pressure</u>
• Size and Weight	Slight Decrease
• Initial Cost	Slight Decrease
• Parasitic Power	Decreases
• Enclosure Deflections	Increases
• Enclosure Stresses	Decreases

Apparently, the only penalty to pay for designing with lower internal pressure is the large deflections that will occur in the enclosure. This has been accounted for by allowing more internal clearance for the reflector which increases the size of the enclosure but does not significantly add to the enclosure cost itself. (A detailed discussion of enclosure deflections is contained in Section 2.4.2.3).

Based upon the above evaluation the minimum level of internal pressure has been chosen as 0.5 inches of water. This level of internal pressure corresponds to the dynamic wind pressure for 14 m/s wind velocity which is the maximum value during 99% of all time. In addition, allowance has been made for the pressure drop across the filter. For fiberglass filters this can be as much as 0.25 inches of water clean to 0.5 inches of water dirty. Therefore, the blower selection has been based upon an operating static pressure of 1.0 inches of water.

The required air volume flow rate is a function of the anticipated leakage from the enclosure over the entire range of operation. The enclosure material itself and all factory made seams have been considered to be impermeable. This is based upon DuPont data that shows the permeability of 3 mil Mylar to be 1.8×10^{-5} cfm for the GE enclosure. Thus, the only possible locations for air leakage to occur is along

the zipper lines or at the zipper joints. With the proper application of clear polyester tape each of these locations will be sealed such that the leakage is minimized. Consequently, the anticipated leakage from the GE enclosure will be less than 50 cfm at an equivalent static pressure of 1.0 inches of water.

Several blower manufacturers have been contacted and the most positive responses were received from the Chicago Blower Corporation and from Rotron, Incorporated. Each of these companies has recommended, for prototype and low volume production, one of their "off-the-shelf" models that can be modified to meet the requirements of the GE heliostat enclosure. For high volume production they have recommended new models, specially designed for low-cost and high reliability. At either production level the selected blower is a single phase, single speed, direct drive unit for which the power requirement is less than 15 watts.

The selection of an air filter system is critical since it represents potential labor intensive periodic maintenance. The primary requirement of the filter relates to dust intrusion which must be minimized in order not to seriously degrade heliostat performance. For application to the GE enclosure, two filter systems have been identified as suitable.

One filter consists of pleated Dacron laminated between two layers of screen cloth. According to the manufacturer (Air Maze) this filter has very high efficiency to small particulates. Specifically, 98% at 3 μ m, 99% at 5 μ m, and 100% at 10 μ m or larger. The second filter is all aluminum. Based on data supplied by the manufacturer (Research Products, Inc.) this filter has an efficiency of 76% when tested in accordance with the ASHRAE 52-68 code. This test code uses artificial dust of which approximately 53% is 5 μ m or less.

Both filters utilize full depth loading rather than surface loading and thus have low resistance to air flow and high dirt holding capacity. Both filters are washable; Dacron at 12 month intervals, Aluminum at 15 month intervals. The expected life of the aluminum filter is 30 years while that of the dacron filter is 15 years. At high production levels both filters are projected to have the same cost.

Neither the dacron filter nor the aluminum filter have been tested under conditions that relate to the heliostat applications in the Southwest. Therefore, before selecting any filter, a comparative evaluation is required that considers the following parameters:

- Usable Life
- Cleaning Interval
- Efficiency

2.4.1.4 Zipper Design and Selection

The GE enclosure is manufactured as three transparent plastic sections each having zippered edges. This approach was adopted to take advantage of low cost flat panel construction methods. In addition, it allows for these sections to be stacked, rolled, and delivered to the field with no restrictions on handling and shipping. Thus, the key element in the enclosure assembly and in maintaining its structural integrity is the zippered connection.

In this application the zipper design represents a unique concept. Factors that have been considered are:

- Zipper joint strength
- Ease of assembly
- Blockage of insolation and reflected energy

By far, the last factor has had the greatest influence on determining the number of zippers, their locations, and design.

Many zipper designs have been considered, three of which are shown in Figure 2-29. These zipper designs represent commercially available products that are compatible with the transparent plastic and foundation bag materials. Design (a) is a Z-TRAC zipper (Zippertubing Company) that is unacceptable because test results have shown it to have a joint strength of only 17.5 newtons per centimeter (10.0 lb/in.). (From the wind analysis results the required zipper joint strength is 47.5 lb/in.)

Four different sizes of design (b) from the Minigrip Company have been tested. Three of the four had joint strengths below the requirement while that of the fourth was in excess of 60 lb/in.

At present, the availability of design (c) is very limited but was considered because it was developed under DoE contract¹⁰. Its inventor claims that the joint strength is equal to that of the parent material.

Determining the location of zipper lines is primarily a function of the resulting solar blockage. For example, a single two inch wide zipper joint that is blocking both entering and reflected sunlight over the full width of the mirror will cause

$$2 \times \frac{27(2)(.0929)}{12(55)} \times 100 = 1.52\% \text{ Blockage}$$

Figure 2-29. Commercially Available Zipper Concepts

This value is representative of the Minigrip design when located at the horizontal joint between the top cone and the middle cylindrical section. Therefore in order to meet the 2% maximum blockage requirement (Section 2.2.1) the number of zipper lines that intersect the sunlight must be kept to a minimum. Based on this criteria the three enclosure sections will have horizontal zippers at their common joints as required for assembly. However, vertical zippers are limited to the back of the enclosure and in the lower cone section where they will not cause blockage. Typical zipper lines are shown in Figure 2-20.

In view of the above concern about zipper blockage the primary emphasis in this design area has been in achieving a zipper whose width is no greater than 1.27 cm (0.5 in.). In this way, the blockage can be kept to a minimum (less than 0.5%, worst case). Several concepts are presently under consideration, each representing a new design conceived especially for this application.

2.4.1.5 Access Panel Design

As shown in Figure 2-20, an access panel has been incorporated in the GE enclosure so that the interior is accessible to personnel and material. The access panel is located at the rear of the enclosure for two reasons: (a) personnel will be out of the direct path of the sunlight, and (b) the panel opening and zippered joint will not cause solar blockage.

The size of the opening was designed to be somewhat larger than necessary to allow two men to carry through an azimuth drive assembly (the single most bulky heliostat replaceable item). It will permit personnel access in an upright position and minimize the possibility of the zipper getting caught on clothing or material.

When the access door is open it represents a very large source of air leakage and dust intrusion. Each of these potential problems is easily overcome. For the air leakage, a secondary, high volume blower that is part of the maintenance equipment will be used. In order to minimize dust intrusion, a portable zip-on air lock (also part of maintenance equipment) will be used.

2.4.1.6 Enclosure Foundation

The General Electric enclosure foundation is a U-shaped bag that is buried in the ground to form an anchorage for the inflated enclosure. It has an outside diameter of 9.23m (27.0 ft). This bag, which is a chlorosulfidated polyethylene - material, is implanted in the ground by the Automatic Foundation Machine described in Section 6.3 and attached to the enclosure by the same zipper connection used with

the transparent panels. Factory made openings are provided in that portion that is above ground for the attachment of the air supply system.

Because the foundation bag is not an easily replaced component, it has conservatively been designed to withstand the maximum lift loads corresponding to the 40 m/s (90 mph) survival wind condition at a temperature of -30°C. From the wind analysis results (Section 2.4.2.2), the foundation material must withstand the maximum material stress of 83.1 N/cm (47.5 lb/in.).

The DoE Specification 001 states that site soil conditions correspond to a silty sand of loose to medium density having a unit weight of 1760 kg/m³ (110 lb/ft³). This value is assumed to represent the virgin soil before foundation installation. Hough¹¹ indicates that loose silty sand can have a unit weight as low as 85 lb/ft³ which is the value that has been used in the foundation bag design. In addition, both frictional effects and compacting of back fill are neglected.

The maximum material stress (uplift load) must be reacted by the weight of the soil backfilled into the foundation bag. Thus, for a design load of 83.1 N/cm (570 lb/ft) the required trench area is

$$\text{Area} = \frac{\text{Design Load}}{\text{Unit Weight}} = 0.62\text{m}^2 \text{ (6.7 sq ft)}$$

For a trench width of 0.76m (2.5 ft) the required minimum depth is

$$\text{Depth} = \frac{\text{Area}}{\text{Width}} = 0.82\text{m} \text{ (2.7 ft)}$$

To accommodate an assumed 2 degree (3%) grade the maximum size of the foundation bag is as shown in Figure 2-30.

2.4.1.7 Ground Cloth

A ground cloth will be used to cover the earth within the enclosure. Functionally, it acts as a vapor barrier and also suppresses vegetation growth and dust movement. The ground cloth is 0.15 mm (6 mil) opaque polyethylene that is made in two pieces to facilitate installation and replacement around the reflector support structure. To form a complete seal the ground cloth will be zippered to the foundation bag.

2.4.2 ENCLOSURE ANALYSIS

Section 2.4.1 describes the design of the GE enclosure which was based primarily on achieving low cost. In this section, we present the enclosure analysis to demonstrate that the chosen design meets all of the structural

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Figure 2-30. Enclosure Foundation Size

requirements contained in the DoE Specification 001. These requirements (see Table 2-13) consist of the maximum value or the expected range of the various parameters that may impact the performance and/or the integrity of the structure. One additional parameter, the internal static air pressure needed to support the enclosure is an integral part of the design and must also be included in the analysis.

Analytical investigations conducted during Phase I have shown that the primary requirements affecting the enclosure design are those due to wind and temperature. The temperature influence is important not only because the material strength properties are temperature dependent but likewise so is the wind loading since it is a function of the air density which is temperature dependent.

The design wind profile is specified by a power law which takes the form

$$V_z = V_{ref} \left(\frac{z}{z_{ref}} \right)^\alpha$$

where

V_z = wind velocity at height z above ground

V_{ref} = reference wind velocity

z_{ref} = reference height

α = exponent

From Table 2-13 the reference height is 10 meters, the exponent α is equal to 0.15 and since the heliostat is required to survive a maximum wind velocity of 40 meters per second (90 mph) this value has been chosen as the reference wind velocity. The resulting wind profile is shown in Figure 2-31 along with an outline of the enclosure.

2.4.2.1 Design Wind Loads and Temperature

As previously stated, the environmental conditions that effect the enclosure design primarily consist of wind velocities that range up to 40 m/s (90 mph) and an ambient temperature that varies from -30°C (-22°F) to 50°C (122°F). The critical design condition will be that combination of wind velocity and temperature that produces the lowest ratio of material strength to applied stress. This condition has been determined from a comparison of the temperature effects on both the material strength and the wind loading.

UV stabilized PET is commercially available at the present time, satisfies all structural requirements of the GE enclosure, and, therefore, has been used as the basis for all analyses to follow. A typical yield strength versus temperature curve for stabilized PET is shown in Figure 2-32.

TABLE 2-13

STRUCTURAL DESIGN REQUIREMENTS

(Ref. Section 3.1.2 of DoE Specification 001)

<u>REQUIREMENT</u>	<u>SPECIFICATION</u>	
● Reference Height	10 m (30 ft)	
● Wind Speed Frequency	Speed (m/s)	Frequency (%)
	0-2	29
	2-4	21
	4-6	19
	6-8	14
	8-10	8
	10-12	5
	12-14	3
	> 14	< 1
● Wind Rise Rate	0.01 m/s ²	
● Maximum Wind Gust	25 m/s (50 mph)	
● Survival Wind	40 m/s (90 mph)	
● Wind Profile	Exponential with height to 0.15 power	
● Dust Devils	17 m/s (40 mph)	
● Ambient Air Temperature	-30°C to 50°C	
● Earthquake	Seismic Zone 3	
● Snow Load	250 Pa (5 psf)	
● Rain	Average Annual	750 mm
	Maximum 24 hr	75 mm
● Ice	50 mm thickness	
● Hail	25 mm @ 23 m/s

Figure 2-31. Wind Profile for Enclosure Design

Figure 2-32. Enclosure Material (Stabilized PET) Yield Strength Versus Temperature

Wind loading is in the form of a dynamic pressure (q) which is given by

$$q = 1/2 \rho v^2$$

where

ρ = density of air

V = wind velocity

Since the air density varies with temperature, the dynamic wind pressure will likewise vary with temperature. A graphical comparison of the temperature effects on both the material yield strength and the wind loading (for constant velocity) is shown in Figure 2-33. Both curves represent the percent reduction over the temperature range of interest.

It can be seen that the material yield strength drops off more rapidly than the wind loading. Therefore, the obvious conclusion is that a combination of the maximum wind velocity and maximum temperature is the critical design condition for the enclosure. Even though it is believed that the chance of a 90 mph wind occurring at 50°C is very small, this design criteria was selected after extensive research could neither refute nor support it. This research is described in the following paragraphs.

Several references have been checked in order to determine the weather history for the Southwest. For example, the Handbook of Geophysics¹² presents a curve of maximum wind speed versus temperature (reproduced here as Figure 2-34) as recorded over a five-year observation period. Even though this figure gives the strongest measured wind, all of the data has been averaged for the twenty-two different weather stations throughout the United States. Thus, this curve is not strictly applicable to the Southwest.

The Weather Almanac¹³ contains a statistical summary of weather characteristics for various cities in the United States. Included are the normal, mean and extreme values of wind speed and temperature as recorded during the period from 1936 to 1975. The pertinent wind speed and temperature data for four (4) specific cities in the Southwest are presented in Table 2-14 for the months of June, July, August, and September. The one important piece of information that is missing from this data is the measured temperature corresponding to the maximum wind speed. Thus, no firm conclusion can be drawn here.

Figure 2-33. Percent Reduction in Yield Strength and Wind Loading as a Function of Temperature

Strongest wind (5 minute average) for temperature range observed during a five-year period at:

Caribou, Me.
Burlington, Vt.
Boston, Mass.
New York, N. Y.
Washington, D. C.
Hatteras, N. C.

Jacksonville, Fla.
Miami, Fla.
Galveston, Tex.
Oklahoma City, Okla.
Phoenix, Ariz.
Los Angeles, Calif.

San Francisco, Calif.
Tatoosh L, Wash.
Great Falls, Mont.
Salt Lake City, Utah
Wichita, Kansas

Minneapolis, Minn.
Chicago, Ill.
Buffalo, N. Y.
Pittsburgh, Pa.
Columbus, Ohio

Figure 2-34. Maximum Wind Speed - Temperature Relationship
(Reproduced from Handbook of Geophysics - Fig. 2-25)

TABLE 2-14

WIND SPEED AND TEMPERATURE DATA FOR 4 SPECIFIC CITIES
IN THE SOUTHWEST DURING SUMMER MONTHS

	<u>Phoenix Arizona</u>	<u>Tucson Arizona</u>	<u>Los Angeles California</u>	<u>Albuquerque New Mexico</u>
Temperature (°F)				
Max.	116	111	106	105
Min.	47	44	50	37
Mean	87	83	72	75
Wind Speed (mph)				
Max.	75	71	32	82
Mean	7	8	5	9

According to the National Climatic Center in Ashville, North Carolina, the only known correlation of wind speed versus temperature for the Southwestern part of the United States is a technical memo by Orton¹⁴. In a telephone conversation with NCC it was learned that there were 59 instances in which wind speeds in excess of 50 mph were recorded when the temperature was higher than 75°F. The maximum recorded temperature was 100°F. Here again, the limited data does not permit any firm conclusion.

Finally, Hull, et al¹⁵ report that dust-laden winds gusting to 32 m/s (7.15 mph) occurred in the northern two-thirds of Arizona during May, 1975. In addition, a severe sandstorm struck southern California on June 17-18, 1975 in which the wind speed reached 40 m/s (90 mph). Thus, we have recorded evidence of wind speeds reaching 90 mph in the Southwest. However, the temperature correlation is inconclusive since the month of June in Los Angeles (assuming it is representative of Southern California) can have temperatures ranging from 50°F to 106°F with a mean value of 68°F according to the Weather Almanac¹².

The investigation of whether or not a 90 mph wind can occur at a temperature of 50°C (1220°F) was undertaken on the basis that this design condition would be the driving force in determining the enclosure material thickness. Strictly speaking, this is not the case since the level of internal pressurization has a significant effect on the analysis which is presented in the following section.

2.4.2.2 Material Stresses

Loads on the enclosure and its foundation result from two primary sources, the internal pressure that is required to support the enclosure and the aerodynamic pressures induced by the flow of air across the surface. The internal pressure will produce a constant upward force that is uniformly distributed around the base of the enclosure. The value of this constant force is given by

$$F_p = P_i \times A_p$$

where

P_i = internal pressure

A_p = plan area of enclosure

The resulting material stress due to the internal pressure is obtained from the expression

$$W_p = \frac{F_p}{\text{Foundation Circumference}}$$

As described in Section 2.4.1.3, the design internal pressure for the GE prototype heliostat has been selected as 1.0 inches of water (5.2 psf). For the dimensions of the enclosure as shown in Figure 2-20 the plan area is 72.4m^2 (779.3ft^2). Thus, the constant upward force due to the internal pressure is

$$F_p = 18039 \text{ newtons (4056 pounds)}$$

and the corresponding material stress is

$$W_p = 6.98 \text{ N/cm (3.98 lb/in.)}$$

The aerodynamic forces on the enclosure consist of lift and drag components which are given by

$$F_l = (K_l)(q)(A)$$

$$F_d = (K_d)(q)(A)$$

where

F_l, F_d = aerodynamic lift, drag forces

K_l, K_d = shape coefficients for lift, drag

q = dynamic wind pressure

A = enclosure frontal area

The shape coefficients K_l and K_d were obtained from Hoerner¹⁶ and Sachs¹⁷. The dynamic wind pressure is given by

$$q = 1/2 \rho v^2$$

where

ρ = air density corrected for temperature

The lift and drag forces are based on a uniform velocity field. However, the specified wind profile is non-uniform, and in addition, the shape of the GE enclosure consists of multiple geometric forms. Therefore, the aerodynamic lift and drag forces must be determined by a summation of forces based on a uniform average pressure acting on incremental frontal areas. This calculation procedure results in the following forces:

<u>Temperature</u>	<u>F_L Newtons (lbs)</u>	<u>F_D Newtons (lbs)</u>
-30°C	78681 (17689)	51824 (11651)
+50°C	59416 (13358)	38609 (8680)

Results are presented here and in the remaining analyses for both temperature extremes since the maximum temperature (50°C) is critical for the enclosure material and the minimum temperature (-30°C) produces the maximum loading which is critical for both the foundation bag design and the design of all zipper joints and material seams.

The total upward force is obtained by adding the upward force due to internal pressurization to the aerodynamic lift forces. Thus, the total material stress (considered as a running load per unit length) consists of two parts; the first due to lift and the second due to drag. The stress caused by the total upward lift is given by

$$W_L = \frac{F_L + F_P}{\text{Foundation Circumference}}$$

The additional stress caused by drag forces comes from the induced overturning moment which is given by

$$M_D = \sum_i (F_{D_i} \times Z_i)$$

and the stress due to drag is given by

$$W_D = \frac{M_D}{\pi (\text{Foundation Radius})^2}$$

Therefore, the total material stress is

$$W_{\text{TOTAL}} = W_L + W_D$$

Substituting the appropriate enclosure dimensions (Figure 2-20) into these expressions result in the calculated loads and stresses presented in Table 2-15.

TABLE 2-15
WIND LOADS AND STRESSES

Temperature	-30°C	50°C
Total Lift		
Newtons (pounds)	96706 (21741)	77441 (17410)
W_L N/cm (lb/in.)	37.41 (21.36)	29.95 (17.10)
M_D N-m (lb-ft)	242997 (179234)	183487 (135340)
W_D N/cm (lb/in.)	45.69 (26.19)	34.50 (19.70)
W_{TOTAL} N/cm (lb/in.)	83.10 (47.45)	64.45 (36.8)

Selection of the enclosure material thickness has been based on these calculated stresses by comparing them to the allowable stresses. Allowable stress curves for various material thicknesses have been constructed using the yield strength data from Figure 2-32. The allowable stress curves for thicknesses of 2 mil, 3 mil and 4 mil are shown in Figure 2-35. Superimposed onto this figure are the calculated stresses from Table 2-15 which indicates that the selected enclosure material thickness of 3 mil is sufficient to withstand the maximum expected wind load throughout the specified temperature range.

The above wind analysis incorporated an internal pressure of 1.0 inches of water along with the 90 mph wind velocity. This is conservative since no consideration was given to either the blockage by adjacent enclosures or the effects of a perimeter fence.

2.4.2.3 Enclosure Deflection

The primary requirement of the enclosure is to protect the heliostat against the environment. As with any air-supported structure, this requirement translates into maintaining an internal pressure such that the enclosure can support its own weight and remain in tension at all times, thereby preserving its structural shape.

For any given wind loading, the higher the internal pressure, the stiffer will be the enclosure. Thus, it will better be able to withstand the wind load with less deflection but with higher material stress. Therefore, the choice of an internal pressure level is a trade-off between material stress and permissible deflections such that the operation of the heliostat is not interfered with.

Figure 2-35. Enclosure Material Stress Versus Temperature

Deflection analyses were conducted using a GE company proprietary finite element computer program. This program is capable of analyzing axisymmetric structures when subjected to non-axisymmetric loadings by utilizing fourier analysis techniques. For the deflection analysis the enclosure has been idealized as an assemblage of discrete elements interconnected at common node points as shown in Figure 2-36. The finite element model consists of 36 elements with 37 nodes equally spaced at 30.5 cm (12.0 in.) intervals. This analysis incorporated the high peaked single cone design and thus should be conservative for the lower peaked compound cone design, as shown in Figure 2-20, which has been selected for the prototype heliostat.

The techniques of fourier analysis permit the distributed wind loading (which is periodic with respect to the azimuth position) to be represented by a trigonometric series. On top of this wind loading a constant internal pressure is superimposed in order to obtain the total enclosure deflections. This has been done for a 90 mph wind combined with internal pressures varying from 1.0 to 5.0 inches of water. The wind loading was assumed to be acting at a zero degree angle of attack on a single enclosure without benefit of protection from either adjacent enclosures or a fence.

A typical deflection pattern is shown in Figure 2-37 indicating that the maximum deflection occurs at node 30 which is 884 cm (348 in.) above the ground. However, this node is above the highest point of the reflector traverse. Therefore, the critical position for enclosure deflection is not here but at node 28 which is at the extreme of the reflector traverse. The deflections of both nodes are given below as a function of the internal pressure.

DEFLECTIONS VS. INTERNAL PRESSURE

<u>Node</u>	<u>1.0</u>	<u>2.0</u>	<u>3.0</u>	<u>4.0</u>	<u>5.0</u>
30	13.86	12.95	12.05	11.15	10.28
28	13.64	12.60	11.55	10.51	9.47

Due to its protected environment the wind does not impose any restrictions upon the operation of an enclosed heliostat. Therefore, the cost effective approach would be to select an internal pressure that will minimize parasitic losses (e.g., blower requirements). As discussed in Section 2.4.1.3, the wind velocity will be less than or equal to 14 m/s (31.3 mph) for 99% of all time and that the minimum level of internal pressure corresponds to the dynamic wind pressure at this velocity. Thus, over the temperature range of -30°C to 50°C this dynamic wind pressure varies

Figure 2-36. Finite Element Computer Model for Deflection Analysis

Figure 2-37. Typical Deflection Pattern for 90 mph Wind

from 0.43 to 0.57 inches of water. At this value of internal pressure the enclosure deflections are extrapolated (see Figure 2-38) to be approximately 36.2 cm (14.25 in.) when subjected to a 90 mph wind. Consequently, the enclosure has been designed to accommodate an internal reflector clearance of 38.1 cm (15.0 in.).

The above deflection analysis is conservative in that blockage due to adjacent enclosures was not considered and the effects of a perimeter fence have been neglected. The effect of adjacent enclosures is a field layout related problem and will not be addressed during this Phase I program. However, a qualitative assessment of the effect of a perimeter fence has been reported¹⁸ which indicates that there may be a significant reduction in the material membrane stress when a fence is used.

2.4.2.4 Other Requirements

In addition to wind and temperature loads, the transparent plastic enclosure must withstand other environmental requirements as listed in Table 2-13. These other requirements (earthquake, snow, rain, ice and hail) are not critical to the design of the enclosure as will be shown in the following sections.

2.4.2.4.1 Earthquake. The GE enclosure can withstand the lateral force due to a Zone 3 earthquake as shown below. The analysis uses the Uniform Building Code approach¹⁹ which defines the seismic dynamic "g" load factor as

$$g = \frac{V}{W} = ZIKCS$$

where

- V = total lateral load at the base
- W = total weight
- Z = seismic zone coefficient
- I = occupancy factor
- K = coefficient depending on structure
- CS = base shear coefficient

Taking conservative values for each of the above coefficients gives a design "g" factor of 0.28. This factor is interpreted as a forcing acceleration at the base of the structure. Applying this acceleration factor to the combined mass of the enclosure plus that of the enclosed air results in a lateral force of 2117 N (476 lb). The radial deflection that would result from this lateral force is approximately 6% of that caused by the peak survival wind. Material stresses during an

Figure 2-38. Variation in Enclosure Deflection for a 90 mph Wind as Function of Internal Pressure

earthquake are expected to be much lower than those due to the wind loading since the larger non-uniform aerodynamic pressure distribution will be absent.

2.4.2.4.2 Snow. The downward force due to the specification snow load is 250 Pa (5 psf) which is approximately equal to the upward force due to the internal pressure. The snow load is expected to conform to a cosine distribution over the top of the enclosure. However, if we conservatively assume a uniformly distributed snow load on a flat membrane the size of the 10° top cone, the calculated deflection²⁰ is less than 14.8 cm (5.82 in.), and the corresponding material stress is 23.6 N/cm (13.5 lb/in.).

2.4.2.4.3 Rain. Rainfall will not cause any structural problems because it will roll off the sloped contour of the enclosure.

2.4.2.4.4 Ice. The specification ice loading will result in approximately the same distributed load as the snow loading. Thus, the deflections and stresses will be as stated in Section 2.4.2.4.2.

2.4.2.4.4 Hail. At the present time very little hailstone penetration data is available. However, Boeing¹⁸ reports that 0.05 mm (2 mil) PVF has survived in 15 m/s (125 mph) winds and eggsized hailstones. Stabilized PET, used in the GE enclosure, has an impact strength that is more than twice that of PVF. Therefore, hail is not expected to be a problem.

2.5 STRETCH FRAME TESTS

The Phase I Proof of Concept stretch frame testing was to demonstrate the optical feasibility of a heliostat reflector made from aluminized polyester film tensioned on an eight-point stretch frame. The Phase I program included stretch frame tests as well as component testing of reflector corner polyester film attachment methods, adhesives and bonding techniques.

A stretch frame was fabricated, assembled, and adjusted with the deployment of three different reflector assemblies, each representing improved techniques in manufacturing of the reflector and improved attachment methods.

The third assembly, shown in Figure 2-46, was used for the optical flatness evaluation described in this section. A surface contour accuracy of 94% was measured, and test data indicates it is reasonable to expect a value of 97 to 98% in production assemblies.

Figure 2-46. Test Reflector Surface

2.5.1 DESCRIPTION OF TEST STRETCH FRAME AND TEST REFLECTOR

The test stretch frame that was designed and built as part of the Phase I test activity is pictured at the Phase I test facility in Figure 2-39. The test frame consists of a pedestal stand, yoke, hub assembly, and eight lightweight struts. The strut assemblies are pinned at the hub and compression-loaded at the tip by the polyester film test reflector surface and the tensioning guy wires.

Figure 2-39. Test Stretch Frame and Phase I Test Facility

Adjustments are provided to vary the coplanarity of the eight strut tips and the loading of the polyester film. The test stretch frame was instrumented with a coplanar adjustment tool consisting of a helium neon laser. This tool allowed accurate alignment of the eight struts as well as measurement of strut tip deflection under various loads and elevation traverse. Figure 2-40 is a sketch showing the cross section of the test stretch frame with the laser mounted in the hub.

Figure 2-40. Test Stretch Frame Cross Section Depicting Use of Coplanar Alignment Laser

Instrumentation of the test stretch frame also included strain gauge type load cells contained in each tension guy wire. Each load cell was connected to a balancing and switching unit whose output fed a strain reading bridge. Each strain gauge load cell was calibrated over the usable load range using the same switching unit and bridge.

Figure 2-41 is a photograph of the attachment method hardware used in the optical acceptance test. The load at the strut tip for this photograph was 125 kg (275 lbs). The cross section of the attachment method hardware, Figure 2-42, shows a circular "corner beam" wrapped with a loop of 2 mil aluminized polyester film that was secured

Figure 2-41. Attachment Method Hardware Used for Optical Testing

to the backside of the reflector surface with 10.16 cm (4") of 2 mil thick transfer adhesive. Because the transfer adhesive has a relatively low tear strength, the angle the loop material makes with itself at the adhesive bond was kept to a minimum with an outer tubular "C" clamp. It should be noted that this hardware design is associated with a reflector that uses transfer adhesive as a bonding agent and is not proposed for the final design.

Figure 2-42. Cross Section of Test Frame Attachment Hardware

2.5.2 TEST STRETCH FRAME STABILITY ANALYSIS

A mathematical analysis of the test stretch frame provided information on contributions to reflector movement due to frame gravity loads and tensioning loads. The results of this analysis were pertinent to the test fixture used in the Phase I testing and provided information to write alignment procedures and to aid in data reduction.

2.5.3 TEST STRETCH FRAME REFLECTOR

The reflector surface used in the optical tests was fabricated by hand on a layout table constructed especially for this purpose.

The layout table shown in Figure 2-43 was constructed of wood covered with epoxy paint. The table is made up of 6 sections bolted together to form a 28' x 28' surface. The six sections were set on 6" x 6" x 28' beams that were shimmed to provide leveling of the surface to within 1/4".

Figure 2-43. Polyester Film Seam Fabrication and Layout Table Shown at GE Phase I Test Facility Layout Table and Seam Fabrication

The reflector surface was fabricated by seaming six pieces of 2 mil aluminized polyester film 1.24m (56 in.) wide by 7.62m (25 ft) long. The rectangle formed by the six pieces of seamed film was layed out and cut to the shape shown in Figure 2-44. The five seams were made in the test reflector surface by bonding the 1.42m wide samples together with 5.08cm (2 in.) wide aluminized polyester film coated with transfer adhesive. A cross section of the butt seam technique is shown in Figure 2-45. The butt seam technique employed in the fabrication process of the reflector used to obtain the optical evaluation data, minimized the effect of cockling by overlapping the samples to be joined, and cutting through the center of the overlap lengthwise to remove 5 cm (2 in.) from each edge.

Figure 2-44. Test Reflector Butt Seam Locations

Figure 2-45. Butt Seam Technique Used on Test Reflector

Figure 2-46 is a photograph of the reflector surface used in the optical evaluation testing. The slight wrinkling that appears where a butt seam intersects the very edge of the octagon is a result of wrinkles being present in the non-tensioned state due to the butt seam hand-fabrication process. These wrinkles are a result of a mismatch in lengthwise tension in the two samples to be joined, and the 5cm (2 in.) backing, at the moment the bond is made. Examination of Figure 2-46 will indicate that this type of wrinkling is apparent only in an area where there is very little stress acting along the length of the butt seam.

Figure 2-46. Test Reflector Surface

It should be noted that wrinkles due to the butt seam technique are a phenomenon associated with the fabrication of very small numbers of heliostat reflectors. Even a very small production quantity of reflector surfaces would warrant tooling, such as a vacuum table, that would completely eliminate butt seam related wrinkling. Large quantities of reflector surfaces will warrant the capital investment necessary to manufacture polyester film in a width sufficient to make a completely seamless (and wrinkleless) reflector surface.

2.5.4 STRETCH FRAME OPTICAL TEST DESCRIPTION

An optical test that was easy to implement and conduct indoors without costly equipment was devised to measure the flatness of the test reflector. The test was accomplished by obtaining a photograph of a suitably flat reference grid at a known magnification. A second photograph with the same magnification was taken of the test mirror reflecting the reference grid. The negatives of both photographs were enlarged identically on temperature stable film base. Analysis was done by comparing the images of the reference grid on the two transparencies. The degree of disparity between the reflected images and the direct image in the transparencies is related to the unflatness of the test mirror.

To determine how a disparity in the transparencies related to unflatness, the relationship of the physical dimensions in the test set up were analyzed. Figure 2-47 is an illustration of the optical test set up that describes the physical dimensions and the relationship between the reference grid object and the distance (H') in the film plane. Figure 2-47 also illustrates that a point in the reference grid object plane appears to be displaced by the distance H due to a slope of $\theta/2$ at a particular location on the mirror surface. A disparity between the images of the reflected grid on transparencies can be expressed as H' and from Figure 2-47 H' is related to θ by:

$$H' = \frac{S'}{S_1 + S_2} \cdot S_1 \cdot \tan \theta \quad (1)$$

where

$$1/S' = 1/F - 1/(S_1 + S_2) \quad (2)$$

The flatness criteria (expressed as θ in Figure 2-47) used to evaluate the test mirror is defined as: any local deformity in surface contour that will cause an angular dispersion of ≥ 0.93 mr of the reflected insolation is deemed unflat. The basis of this criterion is the conclusion by Vant-Hull² that errors comparable to one-fifth the sun disc half-angle will barely degrade performance and can be considered negligible.

Figure 2-47. Test Set-up Dimensions and Analysis

Solving equation 1 for H' using 0.93 mr ($\approx .05^\circ$) for θ , yields a film plane distance of $.014 \text{ cm}$ ($.0055 \text{ in.}$). The output data of the test were transparencies enlarged 4 to 1; thus, a disparity in the data transparency of $4 \cdot H'$ or $4 \cdot (.014 \text{ cm}) = .05 \text{ cm}$ ($.022 \text{ in.}$), relates to the flatness criteria. This amount of deviation was easily discernable using a lighted table - Figure 2-48. The sensitivity of this test technique to mirror flatness can be observed by referring to Figure 2-49. This figure is a photograph of the reflected image of a reference grid with a dimple intentionally placed in the test reflector of 0.24 cm ($3/32 \text{ in.}$).

Figure 2-48. Data analysis done with vernier calipers and lighted table. Transparency size is 40.64 cm (16 in.) $\times$ 50.8 cm (20 in.).

Figure 2-49. Optical Test Reflected Grid with
Induced Deformity of 0.24 cm (3/32 in.)

The output of the data analysis for this test is surface contour accuracy. This number is a percent of the total acceptably flat surface area to the total area of the reflector surface. The output from the transparency analysis was a contour plot of the Phase I test mirror shown in Figures 2-50 and 2-51. The surface contour accuracy represented by this contour plot is 94%. All measurements made in the Phase I program supported this number.

Figure 2-50. Contour Plot of Test Reflector Surface Effective Area

Figure 2-51. Blow Up of Contour Plot of Effective Area Made from Analyzing Test Photo

A sample calculation showing the evaluation of a contour plot is shown in Figure 2-52. By referring to this calculation it is apparent that the major cause of unflatness in the test reflector is the area of low tension between adjacent strut tips. If the area of non-flatness were decreased by 50% the surface contour accuracy would increase to 97%. An attachment method that would increase the tension in the edge area is under development and will be ready for test during Phase II.

2.5.5 TEST FRAME STABILITY TESTS

The test frame was tested for stability against load and elevation only to the extent necessary to show acceptability for the optical tests. With the decision to optimize manufacturing, installation, costs, and system performance by increasing the size of the GE Heliostat concept to a 55m^2 reflector came the decision to postpone frame stability tests until hardware closer in size and weight could be produced. Since analysis shows that any possible frame deviation due to elevation traverse would be caused by gravity loads on the frame members, weight is very important. The hardware used in the 40m^2 test stretch frame strut was not made with consideration to weight reduction and therefore was considerably heavier than a production heliostat frame counterpart. Even with this increased weight, the limited stability testing done in Phase I on the 40m^2 test frame showed a stability sufficient for production applications. This experience leads us to anticipate successful results for a stability test on a 55m^2 stretch frame.

The total possible flat reflective area of the test reflector photo is equal to the total octagonal area minus the triangular area of truncation due to the reflector end attachment method.

$$A_0 = \text{Total area of octagon} = 199.87 \text{ in}^2$$

$$A_T = \text{Octagonal area lost due to truncation} = 3.96 \text{ in}^2$$

$$A_0 - A_T = \text{Total possible flat test reflective area} = 195.91 \text{ in}^2$$

From the effective area contour plot Figure 2-50

$$\text{Total distorted area} = (A_1 + A_2 + A_3 + 2A_4 + 2A_5) \text{ 4 quadrants} = 22.804 \text{ in}^2$$

$$\text{Total \% flat test reflector area} = 88.36\%$$

Including effect of butt seams of corner adhesive areas.

Production Model reflector = total possible

$$\text{reflector area } [(A_1 - A_2 - (A_3 - A_5) - 2A_4)4]$$

$$450.89 \text{ ft}^2 - 26.59 \text{ ft}^2 = 424.3 \text{ ft}^2$$

Total % flat reflector area = 94.09% of Nth unit reflector surface made without butt seams and large corner patch adhesive are

Surface Contour Accuracy

0.94

Figure 2-52. Phase 1 Sample Calculation of Surface Contour Accuracy from Optical Flatness Test Photo

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SECTION 3

HELIOSTAT MATERIALS

3.1 SUMMARY

Candidate materials have been selected for the lightweight heliostat reflector substrate, the enclosure, the enclosure foundation, and the ground cover. UV-stabilized PET film is recommended for the reflector substrate. The same material is recommended for near-term use in design studies and prototype enclosures, but immediate development of biaxially-oriented polyvinylidene fluoride film is urged to permit its use as the enclosure material as soon as possible. The recommended foundation material is polyester-reinforced chlorosulfonated polyethylene; and stabilized, pigmented polyester is recommended for the ground cover.

3.1.1 GENERAL APPROACH

The process of materials evaluation and selection started with a definition of design/performance requirements which were established in coordination with the design engineering, manufacturing engineering, and systems analysis functions of the GE heliostat development team. These design/performance requirements were then related to known materials properties and to time-dependent phenomena affecting these properties. Based on the known properties and performance of available materials, coupled with cost considerations and engineering judgement, one primary and several alternate candidate materials were identified for each heliostat component. Late in the Phase I study, polyvinylidene fluoride was identified as a potentially attractive new film which has improved properties, except for its development status, over essentially all of the candidate materials that were examined. The Phase II materials program that is being formulated will include a major effort to validate the characteristics of polyvinylidene fluoride and to advance its film development status as well as to obtain comparative accelerated test data on the materials discussed in this section.

3.1.2 OVERALL SELECTION CRITERIA

The overall selection criteria employed in the evaluation and identification of potential candidate materials were based on technical adequacy for the intended

component application, fabricability, availability, and cost. Some or all of the following were considered in the evaluation process:

1. Engineering Properties

- Mechanical Properties - yield and ultimate strengths; creep resistance; resistance to edge tearing; and crazing resistance, as applicable.
- Optical Properties - transmittance, reflectance and specularity, as applicable.
- Environmental Compatibility - UV degradation resistance; expected life; mar resistance; compatibility with rain, snow, ice, and hail; fungus and rot resistance, where applicable.

2. Fabrication Characteristics

- Ease of handling for production and assembly.
- Ease of joining - heat sealing, thermal welding, adhesive bonding, stitching, etc.
- Producibility of film materials in desired dimensions.

3. Cost Factors

- Raw material costs.
- Processing or conversion costs, i.e. lamination or coextrusion, etc.
- Scrap reusability.
- Production quantity effects on projected costs.

4. Availability

- Present & projected availability of raw (constituent) materials.
- Sample availability.
- Availability of applicable experience and/or relevant test data.

In the sections that follow, specific component materials (i.e., for the enclosure, reflector, foundation, and ground cover) will be discussed and evaluated in accordance with the above general selection criteria and their respective design/performance requirements. A list of potential candidate materials will be defined for each component.

3.2 ENCLOSURE MATERIAL(S)

Table 3-1 summarizes materials property requirements for the enclosure. In an effort to identify suitable material(s) for the enclosure and the reflector, extensive vendor contacts and literature searches were performed. This, coupled with regular consultation with internal GE centers of expertise on plastic materials, culminated in a list of commercially available transparent plastic films with potentials for enclosure and reflector applications. Table 3-2 contains this list, also showing pertinent properties, applicable experience, and prices to the extent such information was available.

TABLE 3-1

SUMMARY OF MATERIALS PROPERTY REQUIREMENTS FOR THE ENCLOSURE

<u>Primary Requirements</u>	<u>Secondary Requirements</u>
<ul style="list-style-type: none">• ~ 85% transparency in 10 years (min.)• High strength and creep resistance up to 50°C and 8.47 kg/cm (47.5 lb/inch) tension at -30°C or 6.56 kg/cm (36.8 lb/inch) at +50°C• High UV-resistance• Mar resistance• High toughness (tear strength)	<ul style="list-style-type: none">• Readily joinable• Fungus-resistant• Low susceptibility to dust and grime collection and readily washable• Resistant to moisture, rain, snow, ice and atmospheric chemicals (pollutants)

The list of materials is not intended to be all-inclusive. Obviously, there are other transparent films besides those listed in Table 3-2. Polyethylene, polypropylene, polystyrene, and styrene-butadiene are examples. These films were not included because their weatherability is poor and they have no outstanding property of interest in this application to compensate for that weakness. The nylons, for example, seemed to be worthy of inclusion because of their unusual toughness which might be useful if they could be protected from ultraviolet light. Most of the other materials in the table are those which are frequently used or advocated for use outdoors. However, since both the enclosure and reflector substrate materials require high yield strength and resistance to creep, interest must center generally on the materials in the lower half of the table.

3.2.1 PRELIMINARY ASSESSMENT

The weatherability ratings are engineering estimates based generally on qualitative data. Where more quantitative information was available from actual outdoor exposure tests, the results of the tests are indicated in the "Applicable Experience"

TABLE 3-2

**TRANSPARENT POLYMER FILMS WITH POSSIBLE APPLICATION
TO THE GE HELIOSTAT SYSTEM**

	ROOM TEMPERATURE MECHANICAL PROPERTIES							WEATHERABILITY			MISCELLANEOUS					
	Tensile Strength PSI x 10 ⁻³ ASTM D882	Yield Strength PSI x 10 ⁻³ ASTM D638	Elongation at Failure, %	Tear Str. g/mil Propagating, ASTM D1012	Tear Str. g/mil Initial, ASTM D1004	Folding Endurance	Heat Distortion Temp. °C, 264 psi	Tensile Modulus PSI x 10 ⁻³	Resistance to Moisture - dimen- sional stability (Scale of 1 to 10)	Resistance to Sun- light, Est. years before significant degradation of prop.	Potential Heliosat Component Application	Applicable Experience - years of actual out- door exposure without significant degrada- tion of properties	Pounds Per Year produced	g/lb in large quantities	g/module x 10 ⁶	Flammability UL Standard 94 ASTM Oxygen Index
Cellulose Acetate	10	6	6-40	4-10	0.5-1	1000	60	300-600	2	2	Enclosure		2x10 ⁹	.75	1.25	V-2
Cell. Ac. Butyrate	7	4	40-70	5-10	31-48	1000	90	200-250	5	4	Enclosure	3.5		.85	3.4	HB
Cell Propionate	5	3		100	1.5	80	78	60	5	4	Enclosure					HB
FEP	3	0.2	250-300	125	175	10 ⁴	70	50	10	20	Enclosure Reflector	15 ⁺	5x10 ⁸	6.50	130	V-0
Polyvinyl Fluoride (PVF)	10	5-6	290	12-100	450-650	5-50x10 ³		200	10	10	Enclosure Reflector	3	10 ⁸	7.50	37.5	V-0 > 95
Ionomer	5	-		30	-	10 ⁴ -10 ⁵		30	9	1			10 ⁹	.70	23	V-0
Nylon 11	10	7	100	400-500		>10 ⁴	55	180	5	5	Enclosure			2.07	11.5	HB 25
Nylon 12	10	6	200	-	450	-	-	180	5	1	Enclosure			2.07	11.5	HB 25
Polycarbonate (PC)	8.5	8	10-100	20	724	>10 ⁵	140	300	9	3 ^C	Enclosure Reflector		10 ⁹	1.09	3.6	V-2 25
Polyethylene Tere- phthalate (PET)	25	15	300	20	804	>10 ⁵	120-125 ^B	550	9	0.3	Enclosure Reflector		10 ⁸	1.95	3.5	V-2
Stabilized Polyethylene Terephthalate (STAB. PET)	25	15	300	20	800	>10 ⁵	120-125 ^B	550	9	10	Enclosure Reflector	17		4.92 ^D	8.9	V-2
Polymethyl Methacrylate (PMMA)	10	8-10	3-5				70	400	9	6	Enclosure Reflector	6		.59	1.5	HB 19
Polyvinyl Chloride (PVC)	6		25	10-730	53-225		65	350-600	9	0.3	Enclosure Reflector			.27	.45	V-0 50
Polyvinylidene Fluoride (PVDF)	20A	12	200-300				111	230	10	10	Enclosure			4.55	19.3	V-0 46

A Oriented Laboratory Samples

B Non-Standard Test, conservatively low relative to standard tests.

C Stabilized version in development.

D Estimate by Martin Processing Co. for very large quantities.

column. Although polyvinyl fluoride (PVF) is not a new material, only about three years of outdoor exposure have been accumulated on type SE (solar energy) PVF, the type recommended for this type of application by the vendor. Older types have proven rather unsatisfactory as free-standing films in solar applications.

The current prices per pound of the various films are shown for comparison. The quoted prices are current market prices for carload or larger quantities and do not reflect any special discounts or economies which might be effected by a captive market. The price for stabilized polyethylene terephthalate (PET) is an estimate from Martin Processing Company based on production of thousands of tons annually in a dedicated plant facility. It represents about a 25% reduction in the current "large volume" price. The price of all the materials listed can therefore be expected to decrease (in 1978 dollars) at some high level of heliostat production. As discussed below in section 3.2.5, this may be especially true for stabilized PET.

When two materials have quite different mechanical or physical properties, the cost per pound may not be an adequate measure of their relative value. Since the heliostat system involves film applications where creep and/or yield strengths are of paramount importance, the tensile modulus is introduced in an attempt to compare polymers on the basis of cost relative to useful strength or resistance to creep. The figures in Table 3-2 show that (since creep rate is inversely proportional to modulus) for equivalent resistance to creep under a given force, the cost of FEP is about 100 times that of cellulose acetate.

3.2.2 STABILITY TO ULTRAVIOLET RADIATION

Potential enclosure materials have been selected with weatherability one of the prime considerations for a cost-effective, long-life material.

Normally the limiting factor in the weatherability of a polymeric material is its resistance to ultraviolet light. Plastics can be divided into three categories relative to their durability in outdoor exposure:

- Those that are transparent to ultraviolet light and are therefore not affected by it. Methyl silicones, acrylics, and (hydro) fluorocarbons are in this class.
- Those which can be protected by additives.
- Those which absorb the ultraviolet light but which can dissipate the absorbed energy as heat. These materials are generally inherently dark and unsuitable for heliostat enclosures.

The number of plastics that fall into the first category is quite small, However, polyvinylidene fluoride is in this class and is transparent to ultraviolet. Most of the enclosure materials that were examined fall into the second category and require an added UV stabilizer. Some 50 chemical compounds are available commercially to prevent degradation of polymers by UV radiation although only a few have been applied to films and an even fewer have successful long life test data to support the UV resistance claims.

The potential enclosure materials discussed below in Section 3.2.2 fall into two different categories. PET film is protected from ultraviolet light by a combination of materials which both screen it from the light and act as an energy-transfer agent while polyvinylidene fluoride (PVDF) film is transparent to the ultraviolet light and is not affected by it.

3.2.3 ENCLOSURE MATERIAL SELECTION

The selection of an enclosure material is driven by consideration of its optical and mechanical properties, environmental compatibility, and cost. The system design requires high specular transparency along with the weatherability to keep that degree of transparency throughout a useful lifetime. It requires a yield strength of 6.56 kg/cm (36.8 lb/inch) at 50°C, a strength that can be obtained with most plastics simply by making the film thick enough. But since the effective transparency of the enclosure decreases with increasing film thickness, it is desirable to use the thinnest possible film. Thicknesses of some representative plastic films required for this strength are shown in Table 3-3.

Transmittance properties of two thicknesses of UV stabilized PET film and of an unstabilized PET were measured. Total transmission was measured with a spectrophotometer equipped with an integrating sphere. Specular transmission was measured at 628 nm with a HeNe laser down to 0.5 milliradians. The total hemispherical solar transmittance of stabilized PET was 83.8% at thicknesses of both 0.051 and 0.127 mm (2 and 5 mils). Total transmission through 0.051 mm (2 mil) stabilized PET fell within a 4 milliradian cone angle; through 0.127 mm (5 mil) stabilized PET fell within a 6 milliradians. Total solar transmittance of unstabilized PET (4 mils) was 86.7%, all of which was contained within a 3.5 milliradian cone angle. The difference between the total solar transmittance of the stabilized and unstabilized PET's may well be due to the UV stabilizer in the former. The difference in specular transmittance, however, may be due to the stabilization or may be an inherent difference between the base materials.

Table 3-3

REQUIRED* YIELD STRENGTH (σ_y) AT
50°C FOR VARIOUS ENCLOSURE THICKNESSES

Thickness, mm (mils)	σ_y Req'd, MPa (psi)	
.051 (2)	127 (18,400)	No known transparent plastic film meets 127 MPa (18,400 psi) σ_y at 50°C
.076 (3)	84.6 (12,267)	Polyvinylidene fluoride (PVDF). Oriented samples have $\sigma_y = 96$ MPa (14,000 psi). Transmittance 90% within 0.5° cone angle.
		Stabilized polyethylene terephthalate (PET). Good UV resistance, good strength and creep resistance, transmittance about 85%. Little or no outgassing.
.127 (5)	50.7 (7,360)	Polycarbonate (PC) - $\sigma_y \approx 55$ MPa (8000 psi), good creep resistance, good transmission, UV resistance inadequate.
.152 (6)	42.3 (6,130)	Nylon 11 & 12 - σ_y at 50°C and creep resistance likely to be unacceptable because of low heat dist. temp., poor moisture resistance, UV resistance poor (Nylon 12) and marginal (Nylon 11).
.304 (12)	21.1 (3,066)	Polyvinyl fluoride (PVF) - σ_y at 50°C ≈ 20.7 MPa (3000 psi), creep resistance likely to be unacceptable, good UV resistance, cost at .254 mm (10 mil) + thickness prohibitively high, transparency likely to be impaired at high thickness.

* Calculated for 40.2 m/sec (90 mph) wind load at 50°C.

Clearly, stabilized PET film has the mechanical and optical properties needed for a heliostat enclosure; and since it is commercially available at the present time, it is recommended as the material for immediate use in prototype enclosures and design studies.

However, a recently developed material, biaxially-oriented polyvinylidene fluoride (PVDF) has some very significant advantages over PET. It appears that when this material becomes commercially available, probably in the first half of 1979, it will be the most appropriate choice for the enclosure. Fortunately, PVDF is not a new material. Only the biaxially-oriented form is new. Therefore, even though the material of interest is still in the development stage there is a large amount of pertinent data and experience. PVDF is non-flammable by both UL Standard 94 and ASTM D-2863-70. To be more precise, it is self-extinguishing in the UL test, and requires at least 46% oxygen to maintain combustion in the ASTM test. A second potentially significant advantage of PVDF is its solar transmittance which is about six percent higher than that of PET, partly because of the yellowing effect of the UV absorbers in the PET, and partly because of the lower index of refraction of the PVDF.

Along with non-flammability and outstanding solar transmittance, biaxially-oriented PVDF has a tensile strength of 124-138 MPa ($18-20 \times 10^3$ psi) and a tensile yield of about 96 MPa (14,000 psi). These values are very close to those of PET, and are higher than those of any other transparent plastic film. The total transmission values reported above are the total hemispherical solar transmissions integrated over fifty equal-energy intervals between 0.34 and 2.5 micrometers. This is distinctly different, but more meaningful for our purposes, than the total luminous transmittance as defined by ATDM D-1003. It is this latter value which is generally reported and which is about 88-90% for PET, but this transmittance has little significance in the present application.

3.2.4 WEATHERING EXPERIENCE

The effectiveness of the stabilizer combination in PET film is attested to by Martin Processing Company's experience with 15 years exposure of a 0.127 mm (5 mil) film of their stabilized PET on a greenhouse in Illinois. Yield strength of the material was essentially unaffected; ultimate strength, elongation and folding endurance were affected, but not critically. Transmission decreased generally about 10%, but about 20% in the shorter wavelength part of the visible spectrum. Visible lifetime for the enclosure application was conservatively estimated to be at

least 10 years.

ICI Americas indicates that an internally-stabilized polyester film is under development in their research laboratories in England. When this film is available for investigation it should be compared to the present stabilized PET, particularly if the cost is likely to be significantly lower.

Pennwalt Corporation has outdoor exposure data on PVDF film which covers at least seventeen years. There is, of course, a vast amount of experience with exposure of PVDF as a protective coating in chemical and industrial plants and as decorative or informative decals on automobile and truck exteriors. Although these films were not oriented, the important point is that their characteristics did not change during the seventeen years. It is reasonable to assume that the mechanical properties of the new biaxially-oriented films would be equally stable. If these predictions are borne out by experience, we can project a useful lifetime of a PVDF enclosure of fifteen or more years.

3.2.5 COST OF ENCLOSURE MATERIALS

There are at least three separate factors which must be considered in trying to estimate the cost of polymer film when it is being used at a rate of 4.5×10^6 - 4.5×10^7 kg/yr (10^7 - 10^8 lb/yr). We will use stabilized PET as an example since there is a great deal more experience with polyester than there is with oriented polyvinylidene fluoride. The cost of the base material, polyethylene terephthalate (PET), is \$1.03/kg (\$0.47/lb). This is not likely to change very much since 4.5×10^7 kg/yr (10^8 lb/yr) is a relatively small part of the total PET market which includes film, fabric, packaging, and bottles. In terms of oriented film, however, 4.5×10^7 kg/yr (10^8 lb/yr) is an extremely large market. In fact, 4.5×10^6 kg/yr (10^7 lb/yr) would require considerable capital investment on the part of manufacturers. The current price of high quality PET film is \$4.29/kg (\$1.95/lb).

For the enclosure application the PET film must be stabilized to prevent its rapid degradation by the ultraviolet component of sunlight. Stabilization of PET film is currently being done by Martin Processing, Inc. under U.S. Patent 3,943,105, issued March 9, 1976. The current price of Martin's UV stabilized PET film in 0.076 mm (3 mil) thickness is \$14.48/kg (\$6.58/lb), a premium of \$10.19/kg (\$4.63/lb) over the cost of the PET film, with a projected total price of \$10.82/kg (\$4.92/lb) for large quantities.

General Electric operates a production facility at the Outdoor Lighting

Department in Hendersonville, North Carolina where street-lighting globes made of polycarbonate are treated to make them stable to ultraviolet light. This process is covered by U.S. Patent 3,309,220, issued 3/14/67. The process covered by the GE patent is substantially similar to that of the Martin Processing patent, differing principally in the solvent and in the material being treated. Nevertheless, General Electric's cost experience should relate quite closely to the actual cost of stabilizing polyester film in a vertically integrated process. The cost of stabilization in an automated process is estimated at \$0.11/M².

This estimate is corroborated by the fact that DuPont formerly marketed a weather resistant grade of PET film at a price premium of \$0.55 to \$0.66/kg for 0.076 mm material. The market for this material was too small to interest DuPont, and the product line was dropped. It was then that Martin Processing, Inc. began to produce the stabilized film.

In the near term, the cost of UV-stabilized PET film will be \$14.48/kg (\$6.58/lb). At an intermediate level of activity this cost would be reduced to \$10.82/kg (\$4.92/lb). Were the level of activity sufficient to warrant a totally integrated process then there is every indication that the cost can be reduced to about \$5.50/kg (\$2.50/lb) or less.

At the present time the cost of PVDF is \$10.01/kg (\$4.55/lb). At a consumption rate of millions of kilograms per year, an estimate of the probable price is \$6.60-7.70/kg (\$3.00-\$3.50/lb). The extrusion and biaxial orientation of PVDF is essentially the same as the process used to produce PET film. Both major manufacturers of the latter add about \$3.30/kg (\$1.50/lb) to the raw material cost for the film forming process, so it seems reasonable to add the same amount for formation and orientation of PVDF film. This would bring the cost of PVDF film, in large volume, to about \$9.90-11.00/kg (\$4.50-\$5.00/lb). In a 0.076 mm (3 mil) thickness, PVDF covers about 7.56 m²/kg (37 ft²/lb), so the material cost for a 260 m² (2800 ft²) enclosure would be \$340-\$380. With all of the potential improvements that this film offers for heliostat enclosures including reduction of cost and improved performance, the use of PVDF is believed to be essential to the development of enclosed heliostat systems.

3.3 REFLECTOR MATERIALS

One of the ideas central to the concept of a lightweight heliostat is the use of an unsupported, tensioned film as a reflective surface. The GE concept imposes design requirements on the reflective surface which, in turn, impose requirements on the materials properties, as indicated in Table 3-4. In this case the most important materials property requirements are reflectance, yield strength, creep resistance, and overall stability of these properties over a long period of time. The importance of reflectance and its stability is self-evident. Yield strength and creep resistance are important because the film must maintain a minimum and predetermined load in order to maintain the desired degree of flatness.

TABLE 3-4
SUMMARY OF MATERIAL PROPERTY REQUIREMENTS FOR THE REFLECTOR

	<u>Primary Requirement(s)</u>	<u>Secondary Requirements</u>
Reflective Surface	<ul style="list-style-type: none">● High reflectivity (85%+)	<ul style="list-style-type: none">● High resistance to atmospheric corrosion and subsequent loss of reflectivity.
Substrate	<ul style="list-style-type: none">● High creep resistance up to 60°C and 5.17-6.89 MPa (750-1000 psi) tension	<ul style="list-style-type: none">● UV-stable, readily joinable, adequate toughness, moisture resistance (dimensionally stable), thermal expansion compatible with reflective coating and structure.
Protective Top Coating (for second-surface mirrors only)	<ul style="list-style-type: none">● High transparency (85%+) and impervious to moisture	<ul style="list-style-type: none">● Moisture resistance (dimensionally stable), strength and creep resistance would be desirable but not required.

3.3.1 REFLECTOR MATERIALS SELECTION

A metalized plastic film is a natural approach to a lightweight reflector; and since resistance to creep is an important consideration, polyester is the first material of choice. Published data²⁻¹⁰³ indicates that a first-surface aluminized polyester reflector would be acceptable, and such a reflector is recommended. However, our own experience and that of some commercial metalizers indicate that the exposed aluminum surface may be too fragile under certain circumstances and that in the event of moisture condensation (dew) it would suffer from significant

loss of specular reflectance. Therefore, consideration should also be given to back-up reflector materials in which the metal is protected by a thin, protective top layer, and hence the reflector is a second-surface rather than a first-surface mirror. Vendor information suggests that reflectance values for such second-surface mirrors are not substantially less than the values generally claimed for first-surface aluminized mirrors. In the event of some loss of reflectance due to the top coatings, silver might be considered in place of aluminum with approximately 5% higher reflectance. (Silver would require a protective coating also to prevent formation of silver sulfide.) The use of silver in place of aluminum would add about \$10 to the cost of a 55M² reflector, but the overall improvement in reflectance and increased useful life afforded by the protective coating may prove to be highly cost-effective. The protective top coat might be UV-stabilized polyester or an acrylic²².

Our reflectance measurements do not support the contention that second-surface aluminum mirrors are about equal to a first-surface mirror. A first-surface aluminum mirror on a 0.051 mm (2 mil) stabilized PET substrate was prepared. It had a total reflectance of 89.9%, of which 83% was within a 1.6 milliradian cone angle, and 100% within 3.7 milliradians. A second-surface aluminum/stabilized PET mirror, prepared by the same people, had a total reflectance of 78%, of which 92% was within 0.2 milliradian, and 99% within 4.1 milliradians. A second-surface mirror with an acrylic top coat had a total reflectance of 80.3%, of which 99% was within 5.5 milliradians. The most highly specular mirror tested was a first-surface aluminum mirror prepared by ICI America on one of their own materials. The aluminum coating was too thin, so the total reflectance was only 85.1%, but 99% of the reflected light fell within a 1.1 milliradian cone angle. Mirror reflectance is a subject suitable for further investigation during Phase II to determine whether specularity decreases with increasing thickness of the aluminum and whether there is then an optimum thickness short of opacity.

Another reflector concept is an aluminum foil about 0.025 mm (0.001") thick to keep the weight near that of the polyester film. Aluminum foils at that thickness are presently made only with a mill finish. Electropolishing and anodizing is normally done only on thicker material. However, the absence of creep and the potential stability and high reflectance make the aluminum foil an attractive alternate reflector material. These potential reflector materials are summarized in Table 3-5. It should be pointed out that since some UV radiation will inevitably

enter the enclosure, it may prove desirable, for maximum life, to include UV-resistant materials in either substrate and/or the coating. The proposed use of UV-stabilized PET film and/or an acrylic coating in Table 3-5 is to this end.

3.3.2 MIRROR BACKFACE REFLECTIVITY

In order to minimize stray reflections it is desirable to reduce the reflectivity of the rear surface of the mirror. One way to accomplish this is to use a pigmented film for the mirror substrate. However, at the present time, the only pigmented PET film is being manufactured by DuPont. This material lacks the smooth surface finish required for a highly specular mirror. A solution that will be explored more fully in Phase II is to laminate a 0.023 mm (0.092 mil) pigmented film to the back of a metalized smooth film. With sufficient demand, it is reasonable to expect the production of pigmented film with mirror quality surface properties will increase to fit the heliostat development time period.

Another company offered a second, slightly different, approach. They have the technology to produce a film with a smooth surface on one side and a translucent or even opaque surface on the other side. It is a product they have made in the past and could make today on request. A laboratory sample has been offered for evaluation, but has not yet been received.

TABLE 3-5

LIST OF POTENTIAL REFLECTOR MATERIALS

Materials	Kg (lbs)/Reflector	\$/Reflector ⁽¹⁾	Specular Reflectivity	Estimated ⁽²⁾ Life (Yrs.)	Relative Advantages or Disadvantages (Risk Potential)
PET/Al/Acrylic (Second Surface)	3.86 (8.5)	16.58	74%	5	Potential loss of acrylic transparency and ductility, loss of PET mech. prop.
PET/Al/Stab. PET (Second Surface)	3.86 (8.5)	36.25	72%	5-10	Potential degradation of PET mech. properties.
Stab. PET/Al/Stab. PET (Second Surface)	3.86 (8.5)	55.93	72%	10	Low risk.
Stab. PET/Ag/Stab. PET (Second Surface)	3.86 (8.5)	65.93	77%	10	Low risk.
Stab. PET/Al/PVDF (Second Surface)	4.35 (9.6)	54.67	-	15	Low risk.
Stab. PET/Al	3.36 (8.5)	55.93	89%	10	High specularity, high reflectivity.
Al Foil Al100 or Al145 electropolished and/or clear anodized, .001"	3.36 (8.5)	8.16 ⁽³⁾	80-85% ⁽⁴⁾	15+	Min. risk, needs no protective coating, strong and no creep deformation, maintains reflectivity for a long time, readily cleanable, not susceptible to dirt and dust collection.

(1) Present quoted prices.

(2) Assuming reasonable protection.

(3) Cost is based on mill-finish, additional cost for finishing is not available.

(4) Reflectivity is for mill-finish.

3.4 FOUNDATION MATERIAL(S)

The concept of the low-cost heliostat enclosure entails the cost-effectiveness of easily replaceable parts which can be changed inexpensively if required. With respect to the foundation material, however, the most cost-effective approach is to select a material with a full thirty-year plant life expectancy. The Phase I recommended baseline enclosure foundation material is polyester-reinforced chlorosulfonated polyethylene (CSPE). Long-term exposure experience has been obtained with polyester-reinforced CSPE.

About 10^5 m^2 (10^6 ft^2) of this material is being used by Pennsylvania Power and Light Company, Martins Creek, Pennsylvania as lining for settling ponds because of Pennsylvania's strict pollution control regulations. About twice that amount is being used, buried one-third meter (a foot) below the ground by Western Nuclear Power, Spokane, Washington to prevent ground water contamination by uranium tailings. General Electric uses the same material in water impoundments at plants in Erie, Pennsylvania and Aluckua, Florida; other industries use it to store a variety of chemicals ranging from hydrochloric acid to potassium hydroxide and calcium hypochlorite. It resists rain, wind, hail, snow and freeze-thaw cycles, will not crack from temperature changes down to -43°C , and because of its natural resistance to sunlight and ozone it does not have to be covered or protected.

Further investigation of foundation materials would be particularly useful in view of their importance to the overall cost-effectiveness of the heliostat system and the large proportion of the total cost that is represented by the foundation in the present design. The reinforced CSPE that is the Phase I recommended material was originally developed and optimized for other purposes. A modest development program could almost certainly lead to a more cost-effective laminated or coated material specifically designed for use as the enclosure foundation.

3.5 GROUND COVER MATERIAL

The ground on the inside of the heliostat enclosure will be covered completely by a material which will prevent plant growth and minimize entry of both dust and moisture from the ground into the enclosure. The ground cover will be either bonded permanently to the enclosure or attachable with a zipper or other sealing connector.

Structural requirements on this material are not stringent. It need only maintain its integrity when walked on occasionally by maintenance personnel. Therefore, it is believed that if the enclosure absorbs incident ultraviolet light, a pigmented polyethylene should be an adequate and cost-effective material for this application.

However, if the enclosure is transparent to ultraviolet light, as in the case of PVDF, the ground cover or enclosure ground diaphragm can be made of PVDF.

3.6 MOLDED STRUCTURAL PARTS

The base material for molded structural parts such as the reflector hub is polycarbonate. This material can be made self-extinguishing, Group 1, according to Underwriters' Laboratories Standard 94, and can be UV-stabilized. Polycarbonate, 40% glass-reinforced, was selected for the reflector hub and the drive sectors; polycarbonate, 20% glass-reinforced, for the kingpost. These materials are distinguished by their rigidity, creep resistnace, dimensional stability, and heat resistance. Their low and uniform shrinkage from mold dimensions allows design and production of precision parts. Other parts such as the elevation motor support and motor pivot brackets are to be made from foamed polycarbonate.

3.7 OUTGASSING OF MATERIALS

Surfaces most susceptible to damage by condensation of a foreign material are generally those used in optical systems. Materials for use in spacecraft must meet the most stringent outgassing requirements, and have therefore generated the majority of the outgassing data, but the most commonly observed example of the problem is the automobile windshield which acquires a haze from the plasticizer which has migrated from some of the highly plasticized vinyl so common in automotive interiors.

Polyester film is widely used in critical applications in spacecraft because of the almost complete absence of condensable volatile materials. This is reflected in the data reported by Campbell, Marriott, and Park²⁴ which showed 0.22% total weight loss of PET film after 24 hours in vacuum at 125°C when the film had been conditioned at 80% RH for four days. Under these circumstances the film should have contained as much as 0.6% water. In our own testing²⁵ we observed no weight loss after four days in vacuum at 60°C, nor was any deposit attributable to the polyester detectable on a test mirror using frustrated multiple internal reflectance infrared spectroscopy.

CSPE itself is essentially free of volatile contaminants except for < 1% of carbon tetrachloride which is entrapped in the polymer during manufacture. This is lost by diffusion within a few days or weeks after manufacture. However, in the subsequent processing and vulcanizing of CSPE into a finished product, several other materials are compounded with the CSPE to produce the desired properties. It will be necessary during Phase II to work with rubber compounders to specify CSPE formulations for minimum outgassing. Two materials frequently used in chlorosulfonated polyethylene formulations are stearamide and an aromatic processing oil. These additives should specifically be avoided. Fortunately, many formulations are known which do not contain either of these materials.

3.8 BONDING AND JOINING

An important concern in selecting a material for the heliostat enclosure is the methods available to join it to itself and to other materials. Unfortunately PET film cannot be heat sealed nor RF sealed. It can, however, be adhesively bonded or ultrasonically bonded. Adhesive bonding can be rapid, and a number of adhesives are available which can produce lap shear tensile strengths in 6.89-34.5 MPa (1000-5000 psi) range. Both thermoplastic and thermoset types are available. The former are easier to handle and may represent the lowest cost approach because of the speed with which the bond can be made. However, we are concerned about the possibility of long-term creep in such bonds when under stress at elevated temperatures, and prefer the more conservative approach of a thermoset adhesive. Our tentative recommendation for the adhesive is a polyester adhesive with an isocyanate curing agent. These adhesives produce a bond strength in excess of 8.9 kb/cm (50 lb/inch) with a 0.635 cm (0.25 inch) bond line. A polyurethane adhesive remains a strong contender, particularly for joining polyester to other materials such as, for instance, zipper closures. Some other products produce a very good bond with polyester, but in our experience thus far the relatively high temperature necessary to initiate cure has led to wrinkling and distortion of the PET.

Current technology limits the formation of ultrasonic bonds in 0.076 mm (3 mil) polyester to about 30-36 m (100-120 feet) per minute, making it a possibly more costly joining process. However, there may be sufficient advantages to outweigh the cost disadvantage. First, seams made by ultrasonic bonding are about 0.8 mm (1/32") wide, resulting in negligible light blockage. Second, there is evidence that the ultrasonic bonding process does not affect the weatherability of the plastic. And third, bond strengths of ultrasonic seals consistently equal or exceed the yield strength of the parent film. The average breaking strength of nine butt seams 0.8 mm (1/32") wide was 98 MPa (14,300 psi).

PVDF can be heat sealed, ultrasonically sealed, or RF sealed. However, successful heat sealing of the oriented film is unlikely. Both ultrasonic and RF sealing should be investigated, as well as adhesive bonding with acrylic and epoxy adhesives.

4.1 CONTROLS AND DRIVES OVERVIEW

The solar power plant consists of a large number of heliostats which are controlled from a central computer. The heliostats are oriented to reflect the sun at a central receiver or at various locations within the envelope of the field. The heliostats are controlled in groups or as an entire field in order to regulate the power or thermal energy on the central receiver. The control design as defined consists of a two level digital distributive control system. (Fig. 4-1) The plant controllers will be located in the central plant and each heliostat has a local controller which moves the mirrors in response to commands from the central plant.

The central plant consists of one or more controllers which provide mode commands, sun angle, and reflected beam position data to each of the heliostats via a two-way serial digital transmission data link. The reflected beam position data defines the heliostat beam intersection point. Each heliostat computes its own mirror angle and transmits status back to the central plant. The plant controllers are implemented with minicomputers which contain accurate real time clocks and sun ephemeris data to compute the sun angles for the heliostat field. The mode command is transmitted at the plant controller level and is selected at a higher level central computer.

DOE Specification 001, Section 3.3.2, 3.3.3, 3.3.4 calls for several distinct modes which are initiated at the central plant.

- Acquisition
- Tracking
- Synthetic Tracking
- Offset Pointing
- Normal Shutdown
- Stowage/Traverse
- Emergency Shutdown
- Calibration and Initialization

Each of these modes can be accomplished by all the heliostats simultaneously or sequentially by groups. The first eight modes are performed by steering the reflected heliostat beams at a fixed point or at moving points within the heliostat field. Therefore, these eight modes are really subsets of a common mirror steering mode in which the reference points are variable or fixed.

Figure 4-1. Central Plant-Heliostat Control Division

In structuring the overall heliostat control, an analysis was made of the modes to be performed, the magnitude of computations to be accomplished, and an optimization of the computation distribution. The structuring of the heliostat controller was based on the following criteria:

- Simplifying the Communication Link
- Low Cost Controls
- Common Data to All Heliostat Controllers
- Common Controls for All Heliostats

Since low cost computation is available with a microcomputer-based control, it was determined that, in addition to the motor control, a large part of the steering algorithms can be effectively accomplished at the heliostat controller.

The major difference in all the mirror steering modes is the direction of the reflected beam. The computation distribution between central plant and heliostat controller was based primarily on minimizing the number of control modes at the heliostat and maintaining a common data format to all the heliostats. This was accomplished by transmitting both sun angle data, and reflected beam focus coordinate position information to all the heliostats from the plant controller. By selecting the computation distribution in this manner, the number of heliostat mirror steering modes commanded from central plant is reduced from eight to one.

As a result of simplifying the data transmission format, a single serial data line can be used to control a large number of heliostats from the plant controller. The cost of the communication is further reduced by using the power line to the heliostat as the communication medium, thus eliminating the need for separate control signal wires. The signal transmission is accomplished with a high frequency modulation of the serial data transmission on the power line. The data transmission is accomplished in two directions in order to provide status information for each heliostat at the central plant.

Direct continuous control of the heliostat movement is maintained from the central plant by continuously updating the heliostat commands at five second intervals. In the return direction, the status of each heliostat is monitored at one minute intervals.

Heliostat Controller

The microcomputer based controller performs the general functions of

- Automatic Self Calibration
- Mirror Angle Computation

- Initialization
- Diagnostic
- Motor Control

These functions are accomplished with a single microprocessor supported with 4,000 bytes of Memory, 256 bytes of Random Access Memory and parallel input-output interface circuitry. The software and hardware design is common to all the heliostats and provides a maximum utilization of the microcomputer computation capabilities.

The heliostat controller (Drawing 1) receives data from the central plant and selects one of four control modes via software logic:

- (1) Initialization
- (2) Mirror Pointing
- (3) Mirror Steering
- (4) Calibration

The initialization mode (1) performs the function of establishing the angle reference during the power startup. The initialization is required since the control drives are linear stepping motors and no angle encoders are used.

The mirror pointing (2) and mirror steering (3) modes direct the mirror drives to a specific angle in response to the data command from the plant controller. An open loop mirror steering mechanization was implemented in order to eliminate additional sensors and reduce the cost.

To efficiently operate with an open loop steering control, the drive system has to be accurately aligned or the installation errors have to be determined. Accurate alignment results in excessive installation labor, so in keeping with the low-cost heliostat objective, a computation scheme (calibration) (4) was devised which uses the sun as a reference and automatically estimates the individual mirror drive alignment errors. The calibration computation operates with a sun sensor in a closed loop sun steering mode and is conducted for a one-day period. The computed error coefficients are factored into the overall computation of the mirror angles at each heliostat. Once determined, the coefficients are stored in a non-volatile random access memory and are valid for all subsequent open loop mirror steering operations.

In addition to the modes commanded by the central plant, the heliostat controller will maintain a continuous diagnostic of various fault detectors and computation checks in order to determine the status of the controller. In the event

Drawing 1. : Heliostat Controller Configuration.

Figure 4-2. Plant Control Structure

of a fault detection the Diagnostic (5) routine will initiate a local stow to the angle reference points via initialize and send a fault status signal back to the central plant.

For operation at the local heliostat a manual mode (6) is implemented in the controller software which provides the capability of manipulating the control with a portable control panel. The portable panel will also provide a means of interrogating the status of the heliostat.

To further simplify the heliostat drives, linear stepping motors with a 40-inch diameter drive wheel was selected which provides a high resolution control with a minimum number of parts. The linear stepping motor drive allows positional accuracies of less than one minute of arc and eliminates the need for a gear train and an angle encoder thus greatly simplifying the mechanical design.

4.2 CENTRAL PLANT CONTROLLERS

4.2.1 The central plant controllers continuously coordinate the movement of the heliostats in response to the demands of the power plant for reflected energy on the power tower. The plant controller performs three basic functions:

- Command Control Modes and Address Heliostat
- Compute Heliostat Commands, Sun Angles, Reflected Beam Focus Coordinates
- Maintain Data Log of Heliostat Status

The control modes are determined on a field level by the central plant host computer and communicated to the plant controllers via a serial data link (Figure 4-2).

The plant controller also transmits the status of the heliostats back to the central plant host computer where the information is presented to the plant operators via line printers and CRT displays.

The central plant controllers provide the computation required to determine the sun direction cosines for all the heliostats in their control fields. The sun vector is calculated based on stored ephemeris data, the equation of time, and an accurate clock. The sun vector is transformed into three direction cosines corresponding to a vertical azimuth and elevation mirror axis coordinate frame oriented south for zero azimuth. The sun vector transmission occurs at five second intervals from the plant controller to the heliostats. The five second update rate assures a minimization of timing errors at the heliostat controller.

In addition to the sun vector, the plant controller transmits the coordinates of the reflected beam focus positions which are employed to calculate the mirror angles at the heliostat.

The mirror steering angles are computed by the heliostat based on the following equation:

$$\vec{U}_m = \frac{\vec{U}_s + \vec{U}_t}{\sqrt{2 [1 + \vec{U}_s \cdot \vec{U}_t]^{1/2}}}$$

where

U_s = sun vector

U_t = reflected beam vector

U_m = mirror normal vector

In order to provide common reflected beam vector data for all heliostats, the coordinates of the beam focus position, x, y, z , in the field is transmitted and the beam vector is computed at the heliostat.

Each heliostat controller is programmed during installation with its position relative to the tower. The reflected beam vector is computed at each heliostat by calculating the direction cosines determined by the relative coordinates of the heliostat and the beam focus position

$$\begin{aligned} \vec{U}_{TX} &= \frac{\Delta x}{\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}} \\ \vec{U}_{TY} &= \frac{\Delta y}{\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}} \\ \vec{U}_{TZ} &= \frac{\Delta z}{\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}} \end{aligned}$$

where

$$\Delta x = x_t - x_h$$

$$\Delta y = y_t - y_h$$

$$\Delta z = z_t - z_h$$

By defining the position of the reflected beam focus point at the central plant, the number of control modes at the heliostat is reduced, the data transmission is common to all heliostats and the mirror reflected beams can be continuously controlled from the central plant in a single mirror steering mode.

For the tracking mode, the mirror reflected beam is directed at the central receiver. In this case, the transmitted reflected beam focus position corresponds to the central receiver.

In the standby mode, it is desired to reflect the sun at a point 5° to one side of the central receiver. This is accomplished by transmitting to the heliostats a reflected beam focus position which corresponds to offsetting the reflected beams to the standby position.

Each of the other mirror steering modes is accomplished in the same manner, thus providing a transition of the focused energy to various points in the field envelope, with only one control function at the heliostat controller.

In addition to the mirror steering mode, three other modes are commanded from the central plant controller - calibration, initialization, and mirror pointing. These modes are explained in the description of the heliostat controller.

The plant controller also performs the function of interrogating the status of the heliostat field, transmitting the data to the central plant computer and logging the data for future analysis. The field status is maintained on an interval consistent with the data transmissions to the heliostats and ensuring safe operation of the Solar Power Plant.

The central plant controller function is divided between four minicomputers for the control of a large field. Each controller is directly linked to 25% of the field. Two minicomputers are delegated to controlling the east field and two computers for the west field. Each of the two computers is linked on the same system bus and will have the capability of controlling half the field in the event of a computer failure.

4.2.2 COMMUNICATION LINK

The coordinated control of the heliostat field requires that a continuous control be maintained between the central plant and the individual heliostats.

In addition to the control mode commands, it is also required that the status of each heliostat be maintained at the central plant on a continuous basis. These two requirements dictate that a two-way communication link is needed to fulfill the control specifications for the overall heliostat field.

The two-way communication link (Figure 4-3) is implemented with a serial data transmission from the central computer to the individual heliostats. Each central

POWER LINE TWO WAY COMMUNICATION LINK SCHEMATIC

Figure 4-3. Power Line Two Way Communication Link Schematic

computer serial data port services a sector of the heliostat field and transmits address, mode, and sun angle information as common data to all heliostats on the same line. The serial port also receives status information from each heliostat. The entire heliostat field is serviced by ten or more serial input/output lines which are multiplexed from the plant controllers. The transmit signals from the serial ports are converted to a frequency tone by means of an on-off keyed tone generator. The tone signals are coupled via a capacitor to the high voltage power line which services a 10% sector of the heliostat field. The AC power distribution system is employed as the signal transmission medium to each of the heliostats in the field.

At each heliostat, a filter receiver unit is employed to convert the frequency tones to serial data pulses for input to the heliostat microcomputer.

In order to transmit the status data from each heliostat to the central plant, a separate tone generator at each heliostat converts the serial output transmission from the microcomputer to frequency pulses which are coupled to the AC power line and transmitted back to the central computer. A receiver filter similar to that located at the heliostat will generate pulse data to the central plant controller serial input port.

The tone frequencies to be used for the serial transmissions range from 10 to 100 kHz at both the central computer and the individual heliostat.

The data transmissions to the heliostats will occur at five second intervals and take place at 120 baud (bits per sec). The transmission message takes approximately one second to complete, which leaves four seconds for interrogating the status of the individual heliostats.

The control word data transmission is initiated with a start bit (see Figure 4-4) for the purpose of synchronizing the heliostat receivers.

In order to provide the capability of controlling less than 10% of the heliostat field and for status interrogation, an address will be transmitted for groups of heliostats. For example, a sector which consists of 2048 heliostats is divided into groups of 512 and sub groups of 128 as pictorially shown in Figure 4-5.

The address identifies groups of 512 heliostats for mode control and further subdivides to subgroups of 128 for status interrogation.

Figure 4-4. Data From Central Control to Heliostat

Figure 4-5. Field Division

The modes which are commanded from the central plant at the heliostat are defined in four separate categories which can be identified with 2 bits.

Using the group and subgroup example, it is possible to accomplish the address and mode identification with 7 bits.

The bit structure for the start, address, and mode can be accomplished in 8 bits with the following format:

1	2	3	4	5	6	7	8
Start Bit	Group or Sector Mode Address	Group Address		Sub Group Address		Mode	

ADDRESS - MODE WORD

The group or sector mode bit identifies whether the sector is to be controlled in groups or as an entire sector. The group address consists of 2 bits and identifies one of four groups in the sector. The subgroups which are a subset of the groups further subdivide the group into 4 divisions.

The last two bits serve to identify the mode in which the entire sector or group will operate during the next interval. When operating with a group command, the mode of each heliostat group can be updated every 20 seconds. With the Sector address command, the mode can be changed every five seconds.

The next 96 bits of information contain the sun direction cosines and the reflected beam focus position. The sun direction cosines are used by all heliostats for updating the mirror position during calibration, tracking, and all other

modes which require sun vector information for steering the mirror. The sun vector represents the position of the sun at the beginning of the next five second interval.

The reflected beam focus position coordinates are directly related to the mode and group address. These coordinates are used for standby, acquisition, tracking, and stow modes where it is required to focus on the receiver or on a point remote from the central receiver.

The final 8 bits of data are the checksum of the total message sent from the central computer. This word is employed to validate the total 104 bit data transmission at the heliostat.

The data transmission takes place during the first second of each five second interval and has the same format for all transmissions.

The status interrogation of the heliostats occurs during the remaining four seconds of the transmit/receive interval. (See Figure 4-6) The subgroup to be interrogated is identified by the address transmitted in the data transmission to the heliostat. The identification of individual heliostats in a status interrogation for a subgroup is determined by the time of transmission after the command message. The time of status transmission during a status interrogation is programmed at each heliostat.

The status message format for each heliostat consists of three bits:

1	2	3
Start Bit	Fault	Stowed or Not Stowed

The first bit provides a start validation of the status message transmission. For an individual heliostat, the second bit indicates the presence of a fault as determined by the microcomputer control at the heliostat. The third bit identifies the stow position of the heliostat. Each heliostat has a local fault monitor mode which automatically places the mirror in a stow position. The third bit indicates whether the control was able to accomplish the automatic stow command.

Each 120 baud sequential heliostat status transmission will require 1/40 of a second which allows 128 heliostats to transmit status during a four-second interval.

The first second of a typical message is devoted to transmitting the command message to the heliostat field and the next four seconds are divided into 128 time

slots in which each heliostat in a subgroup transmits status condition. (See Figure 4-6) For a sector of 2048 heliostats on one plant controller serial input/output line, it will require 80 seconds to interrogate the status of the entire field.

4.2.3 HARDWARE

The power line communication link has been employed successfully for Automatic Meter Reading of power usage in domestic homes.

Several low cost transceiver designs for meter reading have been developed which are directly useable in the heliostat field control. Transceiver circuits designed with standard integrated circuits have been successfully demonstrated. The transceiver is employed at each heliostat and at the central plant controller serial input/output ports.

In addition to the transceivers, coupling capacitors are required at the central plant and heliostat. The low voltage coupling capacitors at the heliostats are incorporated into the transceiver. The interface to the power distribution system and the heliostat communication control link is presented in Figure 4-7. The central plant communication link couples to the high voltage transmission lines from the plant substation via a high voltage capacitor. In order to eliminate high frequency feedback between transmission lines, it is necessary to incorporate high frequency traps to isolate the power lines for the communication frequencies. The high frequency traps consist of an inductor and two capacitors.

4.3 HELIOSTAT CONTROLLER

4.3.1 CONTROLLER CONFIGURATION

The heliostat controller will interface with the plant controller via a power line serial communication link and provide parallel control outputs to drive the motors which control the heliostat mirror and elevation angles. The AC power line, Figure 4-8, will be the only input to the controller from the central plant. A transceiver at the heliostat filters out the 60 Hz power frequency and converts the frequency pulses to a digital serial input signal which is read by the microcomputer-based on controller. The microcomputer is supported with a small non-volatile and volatile random access memory (RAM) and a read only memory ROM. The ROM will contain the software program routines required for calculating the mirror angles, diagnostics, and translating the computation into drive pulses for moving the motors. In addition to driving the motors, the parallel input/output ports are

Message Timing

**Heliostat Status Transmission (3 Bits)
"Time Slot" Multiplexed**

Figure 4-6. Data From Heliostat Controller to Central Control

Figure 4-7. Power Distribution and Communication Link Interface

Figure 4-8. Heliostat Controller Hardware Block Diagram

employed to read the calibration detectors, motor movement detectors, the sun sensor output during calibration, a blower status signal and the manual control signals from a portable control panel. The portable manual control panel, in addition to control provides a local status interrogation of the diagnostic routine in the controller.

The calibration detector provides a signal to the microcomputer which signifies the zero reference position of the drive wheels. This detector is employed in lieu of an encoder and supplies a reference point in the initialize mode for resetting the angle counters. The drive system employs linear stepping motors to move azimuth and elevation drive wheels as shown in Figure 4-9. The linear stepping motor rides on a slotted magnetic steel platen which is located on the perimeter of a 40" diameter wheel. The stepping motor drive accurately positions the wheel to a $0.0143^\circ/\text{step}$ resolution. The wheel position is determined based on counting the pulses to the drive motor and ensuring that the motor moves one step for every pulse.

A motor movement detector is provided to monitor the actual motor movement in response to the computer commands. This device is employed as a diagnostic input to the controller and determines the integrity of the drive system. Both the calibration and motor movement detector are low-cost magnetic or optical devices which sense the slots in the motor platen.

A direction switch is furnished in order to determine the rotation direction for the azimuth and elevation drives to return to the calibration points.

The sun sensor is used for the calibration mode and is oriented perpendicular to the face of the mirror. The sensor provides a two-axis error output which is coupled directly to a comparator. The output from the sun sensor is read as logical signal levels on four output lines. All inputs and outputs to the heliostat microcomputer will be digital thus eliminating the need for high cost analog/digital interface circuits. A total of 43 parallel I/O ports have been identified.

4.3 CONTROLLER MODES

The controller modes are divided into two categories; modes related to control from the central plant, and modes which are initiated locally. The central control modes are:

- Initialization
- Calibration
- Mirror Steering
- Mirror Pointing

40 in. Diameter Drive Wheel

0.0143°/ Step

8 lb. Force

0.2°/ Sec. Max. Slew Rate

Figure 4-9. Linear Motor Drive

The local modes are:

Fault Detection

Manual

The heliostat is always in one of the central control modes during normal operation.

The fault detection mode is implemented as a continuous monitor and diagnostic of the heliostat controller.

The manual mode is initiated at the heliostat with a portable manual control panel which plugs into the controller.

Initialize Mode

When the power is first turned on, the position of the heliostat may not correspond to the angle counters which are used as the angle feedback for elevation, and azimuth during normal operation. The control system has several calibration slots on the 40 inch drive wheel which are used to orient the heliostat to a true south position during initialize process. (Figure 4-10)

A calibration detector is located near the motor drive and detects slots in the motor platen at designated reference angles. Logic in the computer and the direction switch determines the direction of travel and orients the heliostat at its maximum rate to the zero reference position. When the control has stabilized, the angle reference counters are reset to zero.

This mode is initiated by the central control whenever power is applied to the heliostats or if there is an indication of a reference discrepancy.

The completion of the initialization is indicated by the stow or not stowed flag during the status transmissions from the heliostat.

4.3.2.1 Calibrate Mode

The calibrate mode is employed during the initial set up of the heliostats and at periodic intervals over the life of the plant. The purpose of the calibrate mode (Figure 4-11) is to estimate the misalignment and installation errors $\Delta\theta_T$ for each heliostat. The calibrate algorithms are incorporated into the controller and, compute the individual misalignment error at each heliostat. The calibrate mode operates for a one day period and employs the sun as the reference source for automatically determining the heliostat misalignment errors. The sun sensor is located perpendicular to the face of the mirror and provides

Figure 4-10. Initialize Mode

Figure 4-11. Calibrate Mode

feedback signals to the controller which orients the mirror vector with the sun vector. At periodic intervals during a one day calibration period the true sun angles are compared to the mirror azimuth and elevation angles. The errors $\Delta\theta_A$ and $\Delta\theta_E$ are stored for 18 readings during the day. These error values are used in a linear least squares regression computation which estimates the installation error vector $\Delta\theta_T$. The output of the error coefficient computation algorithm will generate an error compensation model which will be employed in minimizing the errors during the open-loop mirror steering operation.

4.3.2.2 Mirror Steering Mode

As shown in Figure 4-12, in the mirror steering mode, the plant controller generates the true sun angles and reflected beam focus position which are used by the heliostat controller to compute the true mirror azimuth and elevation angles. The error compensation model, generated by the calibration mode and which is unique to each heliostat, corrects the true angles to correspond to the heliostat misalignment errors and commands a mirror angle which reflects the sun energy at the central receiver.

The mirror steering mode Figure 4-13 is employed during most of the normal operation functions for the solar power plant. The mirror steering mode receives sun angle and reflected beam focus position coordinates from the central controller and based on the heliostat relative position in the field, the controller calculates the reflected beam vector or direction cosines. Coupling the tower reflected beam vector data with the sun angle, the mirror azimuth and elevation angles are calculated by the mirror steering algorithm. These angles are corrected with the error model compensation algorithm producing mirror angles which correspond with the mirror and drive reference frame. In all modes, the mirror axis drives translator compares the absolute commanded angles with the angle counters and generates a series of pulses to the mechanical stepping motor drives in order to match the angle counters with the commanded angles.

The controller receives data every five seconds from the central computer and computes the azimuth and elevation mirror angles for a time period 5 seconds in the future. The translator converts the angle error to a pulse rate which generates the required number of pulses during the next 5 second interval to reduce the error to zero at the end of the interval.

The mirror steering mode (Figure 4-13) is an open loop control and does not require the presence of the sun for steering. The tracking and synthetic tracking

Figure 4-12. Mirror Steering Mode

4-25

Figure 4-13. Mirror Steering Mode

specifications are fulfilled by the mirror steering mode with a reflected beam focus coordinate position which corresponds to the central receiver.

By transmitting reflected beam focus coordinates which relate to the standby positions and stow trajectories, the mirror steering mode can be employed to move the focus point for a group of heliostats to follow a known path. Since the data update to the heliostats is at five-second intervals, a continuous control of the focus point can be maintained by the central plant.

4.3.2.3 Mirror Pointing

A mirror pointing mode has been incorporated which provides the capability of orientating all the mirrors to point in a specific direction. This mode provides the flexibility of orienting the mirrors in a specific direction at the completion of the stow command from the central plant or to any desired angle. This mode differs from the mirror steering mode in that the sun angle or vector information is ignored by the heliostat and the reflected beam focus coordinate position data is used to transmit the direction cosines for the mirror pointing angle. The direction cosines are converted directly to true mirror angles and are corrected at individual heliostats by the error compensation model (Figure 4-14).

This mode is also employed as a checkout of the calibration mode by commanding the mirrors to point at the sun and monitor the sun sensor output to ascertain whether the mirrors are within the limits of the pointing accuracy. During the calibration checkout phase of the mirror pointing mode, the diagnostic is programmed to monitor the sun sensor output and activate the fault flag if the sun is not within the prescribed pointing accuracy limits.

4.3.2.4 Manual Mode

The manual mode is activated locally by an operator and will provide a jog or slew capability which can be employed to move the mirror to a predetermined position.

Manual mode switches are furnished on a portable panel which plug into the main heliostat controller.

4.3.2.5 Fault Detection or Diagnostic Mode

The software in the controller incorporates a self monitor and diagnostic routine. The types of fault which will be monitored are:

Figure 4-14. Mirror Pointing Mode

- Drive wheel displacement monitor (Motor movement detector)
 - Motor Operation
 - Seized Bearings
 - Drive Circuitry
- Microprocessor Check
 - Memory check
 - Processor computation
- Data Transmission
 - Error check
 - Presence of transmission
- Calibration Checkout
 - Sun sensor output
- Blower Failure Switch

The diagnostic function is performed continuously in all control modes and sets a flag if a fault is detected. In addition to the fault flag a light will also be activated which can be clearly observed by personnel outside the heliostat enclosure.

4.3.3 CONTROL HARDWARE DESIGN

The heliostat controller is made up of three basic elements:

- Controller Electronics
- Sun Sensor
- Drive Motors plus Calibration Detectors

The controller electronics provide the interface with the central plant, the computation capability, the power output transistors for driving the motors, and the power supply. The control electronics are subdivided into four categories:

- Transceivers
- Microcomputer
- Motor Drive Electronics
- Power Supply

Each of these elements is fabricated from standard integrated circuits. The hardware design definition is based on existing components, but an area of future development should include, if the quantities demand it, a development program for integrating the microcomputer and the transceiver into one chip.

4.3.3.1 Transceiver

The transceiver, shown schematically in Figure 4-15, is fabricated from five standard integrated circuits, a power output transistor stage, an inductor, a

Figure 4-15. Transceiver Schematic

coupling capacitor, and miscellaneous components. The input/output power line shown on the left is coupled to the transceiver with a small capacitor and fed through a high pass filter to eliminate 60 cycle interference. The output of the high pass filter is processed by the tone detector which provides a serial data pulse output to the microcomputer when the tone is present on the power line. The tone pulses are synchronized with the power line voltage providing synchronous data transmission. The 120 cps clock is used by the microcomputer for synchronizing the serial data output with the power line. The microcomputer serial data output gates a high frequency oscillator and an output buffer gate which keys four output power transistors. The power transistors act as the transmitter to the power line via an inductor, which is required for impedance matching the transmitter to the power line. The transmission and receive frequencies are of different values to ensure communications decoupling.

The transceiver is a relatively simple circuit can be integrated with the microcomputer on the same printed circuit card.

4.3.3.2 Microcomputer

The microcomputer consists of four types of integrated circuit chips which provide all the computations and input-output requirements for the heliostat controller. These are:

- Micro Processor
- Read Only Memory (ROM)
- Random Access Memory (RAM)
- Non-Volatile Random Access Memory (EAROM)

Based on the microcomputer breadboard tests and the software analysis study, it is estimated that the total computation requirements can be met with 4000 Bytes of ROM and 256 Bytes of Volatile RAM memory. The interface with the micro computer is accomplished directly, in that parallel input output parts are provided with the RAM and ROM memory chips and the serial input output is incorporated on the CPU chip.

A survey of various microprocessor hardware available has revealed that the INTEL MCS-85 Micro Computer System offers many low cost advantages with respect to minimizing components, flexible input output capability, and high speed computation. Using the MCS-85 system components, the microcomputer can be mechanized with five integrated circuits, as shown in Figure 4-16, all connected to a common system data and control bus. The CPU selected is the INTEL 8085 which provides an entire microprocessor on a single chip with a 16-bit addressing capability. No external peripherals are required for buffering or serial I/O and the entire chip set

Figure 4-16. Microcomputer System Elements

operates with a common +5 volt power supply. The 8085 CPU is an 8-bit micro-computer with 16 bit address bus and an on-board clock. No external peripheral devices are required to interface with other memory chips. Two 8355 ROM chips provide 4000 Bytes and 32 parallel input/output ports. Sixteen of the bit ports are employed to control the drive electronics for the azimuth and elevation drive motors. The 16 remaining parallel I/O bit ports will be used for interfacing the sun sensor, the calibration, and the motor movement detector devices.

The 8155 INTEL chip furnishes the 256 bytes of volatile RAM Memory required for the heliostat controller and also provides 22 parallel I/O bit ports which are used for the manual control panel and the status interrogations interface. A timer is also located on the 8155 chip which is used for timing various clock interrupt routines in the software.

The remaining chip which is an Electronic Alterable Read Only Memory or a non-volatile RAM (EAROM) allows the capability of retaining the error coefficients, the heliostat coordinate position, and other fixed data in the event of a power off condition. The EAROM can be written or erased and will maintain its memory content in a power-off condition.

This device is manufactured by General Instrument and uses MNOS memory transistors. It can be interfaced directly to the system bus and is fully compatible with the 8085 computer structure. Six error coefficients, the heliostat coordinate position, and the calibration point offset are the fixed data required by the controller. This takes only 20 bytes of memory which is considerably less than the 64 bytes available.

As described previously, the computer hardware provides the capability of performing the automatic calibration procedure, the calculation of the mirror steering angles, the motor control, and a diagnostic of the local control.

4.3.3.3 Drive Electronics

The linear motor has a four-phase forcer and is wound in a bifilar manner (Figure 4-17). The bifilar wound motor permits operation with a single polarity supply voltage. Eight windings are required for a four-phase bifilar wound motor which necessitates that eight monolithic Darlington switches be employed for controlling the motor. Each of these switches is required to carry a maximum current of 0.5 amps. An integrated circuit package ULN-2800H is available from Sprague which provides eight switching transistors with diodes for inductive load protection. This high current Darlington transistor array interfaces directly with

TTL logic. All the logic for controlling the motors is implemented in the micro-computer with software. The logic requires an up-down counter and sequencing logic of the various phases for stepping the motor forward and reverse.

A method of decreasing the power voltage while the motor is not running is presently being investigated. One method, shown in Figure 4-17, requires two separate power voltages +10 and +20 with a voltage switch which would be controlled by the microcomputer. Another method would employ a pulse modulation of the power supply in order to reduce the average current to motor windings. This approach requires only one supply voltage and should result in a lower cost.

4.3.3.4 Sun Sensor

The sun sensor is a key element in the operation of the heliostat control system. This device provides the reference for calibrating the heliostat mirror drive system. The sun sensor consists of a housing, a lens, a quad cell solar detector, and electrical output leads. The sensor generates a two-axis output for elevation and azimuth and is used to orient the mirror face perpendicular to the sun vector. A photo of the device appears in Figure 4-18a which shows the housing and the lens. The lens has a filter to reduce the light intensity of the sun on the quadrant detector. Schematically, Figure 4-18b the sun sensor lens projects an image of the sun on the quadrant detector and produces a current in each of the four quadrants of the photosensitive substrate. The absolute gain of the sensor is not critical in that the control in the calibrate mode operates in a null mode. Therefore, the stability and alignment of the null are essential to the successful performance of the overall control.

In order to interface the quadrant detector to the micro computer, it is necessary to buffer the low level current output and take the difference of two output signals, as shown in Figure 4-19. The current and summing amplifier are critical in that null stability with temperature and sun intensity have to be maintained. The output of the difference amplifier provides the error signal for one axis and is interfaced with the computer through two comparators, which sense plus and minus errors. The comparator is a logic device which generates a voltage level when the signal error exceeds a designated value. The final output from the sensor consists of four digital signal lines which indicate an error threshold of ± 1 minute of arc. The final version of the sun sensor will incorporate the sensor interface electronics in the same housing as the quadrant detector.

Figure 4-17. Drive Electronics

Figure 4-18a. Sun Sensor

Figure 4-18b. Sensor Schematic

Figure 4-19. Sun Sensor Electronics

The sun sensor is designed to meet the following specifications:

Field of View	$\pm 10^\circ$
10% linearity	$\pm 2^\circ$
Null	± 1 minute of arc
Null stability	1 minute of arc

4.3.3.5 Power Supply

Several supply voltages will be required for the different devices in the heliostat controller. The primary supplies are +5 and ± 20 . The +5 volts are required for the computer logic. The ± 20 is required for running the sun sensor electronics package. A separate power supply of +20 will be provided for driving the linear motors. Other special voltages which require low current will be generated with DC to DC convertors or zener diodes.

4.3.3.6 Motor Movement and Calibration Detectors

Since the control drives are implemented without an encoder, motor movement and calibration reference detectors were designed for determining a positive indication of motor motion and establishing a reference for the angle counters in the microcomputer. In order to minimize the cost, the steel platen for the motor is used to ascertain the motor motion. Since the steel platen has a high permeability, it can be used directly as a means of measuring the motion of the drive wheel by sensing the movement of the slots in the platen. One scheme investigated on this program (Figure 4-20), employs a permanent magnet, a Hall-effect sensor, and a flux concentrator. The sensor is a no-contact device and can be fabricated at low cost. Two sensors are utilized; one as a reference which moves on a continuous portion of the steel strip and the other which senses the slots. As the motor moves, the magnetic field slot sensor varies and produces an output which, when compared with the reference sensor, amplified, and shaped, produces pulses as the slots pass.

In the same manner, calibration slots, or a small magnet, can be placed in the steel platen and sensed by a similar type sensor to establish a reference for the angle counters. These devices are reliable, easy to fabricate, and employ low-cost electronic sensing.

4.3.3.7 Linear Stepping Motors

The linear stepping motor operates in essentially the same manner as the rotary stepping motor with the main difference being that the motor moves in a

Figure 4-20. Motor Movement and Calibration Detector

straight line over a slotted magnetic steel surface. The linear motor employs a permanent magnet for supplying the steady-state magnetic field. The principle of operation is illustrated in Figure 4-21 for a motor with a two-phase forcer. The permanent magnet field is bucked out or reinforced by the field windings which exert a force on the motor and move it to a new equilibrium position. By alternating the current direction in each of the phases in the manner shown, the motor is made to incrementally step on the steel platen.

The linear motor designed for the heliostat controller is sized to generate 12 lb. of force and provide an incremental linear motion of 0.005 inches for each step. For the heliostat drive design, the motor remains fixed and drives a steel platen attached to the rim of a 40 inch diameter drive wheel. These wheels are directly coupled to the azimuth and elevation axis. The motor (Figure 4-22a) is 6" long, 2.3" wide, and 1.5" high. The motor rolls on four bearings which are adjusted to provide a 0.001 inch air gap between the motor and the platen. The platen (Figure 4-22b) are slots 0.020" wide and 0.015" deep, in a steel strip 0.080" thick. The motor has a four phase forcer which permits it to move in increments which are 1/4 of the 0.020" slot width. The motor is mounted to allow movement in the radial direction, and to be rigid in the tangential direction. This is accomplished with a leaf spring mount. This type of mount makes the motor insensitive to any non-concentricity of the wheel.

The motor size and design are dependent on many factors, such as:

• Inertia of the Load	500 ft/lb sec ²
• Maximum slew rate	0.2°/sec
• Angular Step resolution	.0143°/step
• Friction	1 ft/lb
• Diameter of the drive wheel	40 in.
• Unbalance torque	2 ft/lb
• Maximum Power	15 watts stopped 30 watts slew

The load inertia is made up of several sources which include the inertia of the mirror and the inertia of the moving air within the enclosure. The maximum inertia of the mirror and the air is calculated to be 500 ft/lb sec².

The maximum slew rate for the mirror was determined from the south field heliostat which exhibit a singularity point when the mirror vector is in a perpendicular position. In order to maintain positional accuracy on the receiver, it was determined that a 0.2°/sec velocity permits no degradation in pointing for mirror vectors with 1° of the vertical.

SINGLE AXIS, TWO PHASE FORCER
OPERATION

Figure 4-21. Linear Motor Operation

Figure 4-22a. Linear Stepping Motor

Figure 4-22b. Motor Platen

The angular step resolution was determined based on the physical step size of the four-phase motor, the size of the drive wheel, and the positional accuracy requirement. In order to meet the 0.2° reflected beam pointing requirement, the mirror pointing accuracy becomes 0.1° . The stepping resolution should be 10 times less than the pointing accuracy requirement. Using the 40 inch diameter wheel and the 0.005 inch motor step, a step resolution of $0.0143^\circ/\text{step}$ is achieved, which meets the pointing accuracy requirements of the control system. The average pointing error resolution realized from the stepping motor is one-half the actual step size which is 0.007° .

Measurements on a test fixture have revealed that with teflon bearings for axial alignment, and a needle bearing for thrust on the drive wheel, a 1 ft/lb friction level can be expected. The 40" diameter for the drive wheel was determined primarily by the angular stepping resolution required for the mirror axis drives.

The unbalance torques should be no more than twice the friction torque level. The linear stepping motor provides the inherent feature that when power is off, the only torques exerted on the drive wheel are friction and unbalance. The unbalance torque is used to bring the heliostat to a known position in the event of power failure.

The maximum power required to drive the motor is 30 watts for slew and 15 watts in a hold condition.

For the open loop heliostat control with no encoder feedback, the drive motor design has to provide no missed steps at the maximum slew rate.

The linear motor bread board tests have demonstrated that a stepping rate of 40 steps/seconds with no missed steps can be achieved with a 125 ft-lb-sec^2 inertia, and a 9.0 lb motor force. The maximum stepping rate is related to several quantities, the compliance of the inertia support, the total inertia, and the magnetic spring rate of the motor. The test fixture inertia support is representative of the compliance for the mirror structure, and demonstrates that for an inertial load of 500 ft-lb-sec^2 , a 9.0 lb motor force is adequate for a stepping rate of 10 steps/second. By increasing the force output to 12 lbs, a stepping rate equivalent to $0.2^\circ/\text{sec}$ can be achieved.

4.4 CONTROL SOFTWARE DEFINITION

Each heliostat mirror, controlled by a microcomputer, requires software which serves four general functions:

1. To restore commands and data transmitted from the central control computer.
2. To feed status information back to the central control computer.
3. To interact with heliostat control sensing devices.
4. To control the motor drives.

The heliostat microcomputer must meet the processing and memory requirements imposed by the above tasks.

The purpose of this section is to refine the logic concepts, generate the software flowcharts, and estimate the microcomputer memory and run-time requirements.

The primary modes which have to be implemented in software on the microcomputer are:

- Finding the mechanical zero reference marks (initialization)
- Determination of Error Coefficient (calibration)
- Reflecting sun on central receiver (mirror steering mode)
- Pointing mirror
- Manual
- Fault detection

In normal operation, the heliostat computer alternates between the execution of two computer programs: a priority interrupt program and lower-priority, interruptable executive operating program.

As shown in Figure 4-23, the clock interrupt routine interfaces directly with the serial input/output from the central plant controller and the output pulses to the motor drives. The executive program is the background program which is operating normally and coordinates the modes, calculates the algorithms, and performs the diagnostics. This program interfaces with the remaining inputs which consist of the sun sensor, the motion detector, manual, and calibration signals.

4.4.1 PRIORITY INTERRUPT PROGRAM

The interrupts are triggered by a real time clock; e.g., zero crossings of the 60-Hertz power line voltage. As soon as an interrupt is acknowledged by the operating program, a CLOCK interrupt service routine takes control.

Various flags (i.e., states of true-false logic variables) determine the precise nature of the action to be taken by the interrupt service routine. The options include:

Figure 4-23. Data Flow Diagram for Software Modules

- a) Plant controller message reception.
- b) Status feedback message transmission.
- c) Pulse transmission to heliostat azimuth and elevation drive motors
- d) Resetting the software clock counter upon reception of a synchronization signal.

The above tasks are accomplished by subroutines of the interrupt service routine.

The interrupt program, which services the high priority interrupting activity, uses the same registers and flags to accomplish its task as the executive program. Subroutines SAVE and RESTORE ensure that the status of the interrupted program is preserved, and that the registers and flags are restored to their condition at the time of the interrupt before returning control to the operating program.

4.4.2 EXECUTIVE OPERATING PROGRAM

The operating program controls computations whose precise timing is not critical provided they are completed within the current control cycle (a period of about 5 seconds).

These computations include algorithms for:

- a) Determination of system error parameters during calibration.
- b) Coordinate transformation and error compensation of desired mirror pointing angles during normal operation.
- c) Determination of required pulse rates and direction of travel for azimuth and elevation drives.
- d) Setting (or clearing) the flags whose status determines subsequent activities in the priority interrupt program.

4.4.3 PRINCIPAL SUBROUTINES

The CLOCK interrupt service routine calls four subroutines (besides SAVE and RESTORE):

<u>Name</u>	<u>Function</u>
FDBACK	To control the transmission of the heliostat feedback message to the central computer at the control tower.
PROTOCOL	To receive and store messages from the control tower.
PULSE(I)	To control the transmission of drive pulses to the azimuth (I=1) and elevation (I=2) motors.
SYNC	To lock the heliostat software clock onto the sync bit transmitted from the control tower at the end of each 5-second control cycle.

The operating program, called EXECUTIVE, calls nine subroutines:

<u>Name</u>	<u>Function</u>
CALIB	Logic control and computation of error parameters in calibration mode.
DIAGNOS	Control of diagnostic checks at start of each computational cycle of the operating program.
INIT	Find azimuth and elevation angle reference marks and set angle counters to zero (for initialization).
LOCAL	Implement local manually-inserted instructions.
PANG	Compute the corrected angle counts to point the mirror in a desired direction, and the azimuth and elevation pulse rates required to reach that position.
SANG	Compute the desired mirror position.
STEER	Control mirror movement in the stow mode.
SUNPOINT	Point mirror to sun and continue tracking the sun, using astronomical data for coarse (open-loop) control, sun sensor output for fine (closed-loop) control.

4.4.4 SUBORDINATE SUBROUTINES

Certain functions that are common to several of the above subroutines have been included in a subroutine RATE(I). This subroutine computes the direction of travel and the clock count per pulse period for the azimuth (I=1) and elevation (I=2) motors.

Other tasks have been delegated to subordinate subroutines for the purpose of simplifying the logic structure. Such subordinate subroutines include:

<u>Name</u>	<u>Function</u>
CALEND	Terminal computations at completion of calibration run.
CALMAT	Update the A-matrix and the B-vector elements during calibration run.
MOVCHK(I)	Set appropriate error flag if motor fails to respond to drive pulses.
SEARCH (I)	Direct the search for the zero reference marks during initialization.
SUNOUT (I)	Set (or clear) those flags that control azimuth (I=1) and elevation (I=2) drive pulses to be sent (or inhibited), in accordance with the output signals of the sun sensor during the calibration run.

4.4.5 SOFTWARE STRUCTURE

Figure 4-24 shows the connections between the principal and subordinate subprograms called by the CLOCK interrupt routine. Figure 4-25, similarly, depicts

Figure 4-24. Interrupt Program Connections

Figure 4-25. Executive Operating Program Connections

the connections for the subprograms called by the operating program. Each arrow indicates a call-return relationship between the principal (calling) subroutines and the subordinate (called) subroutines, respectively.

Any subprogram connected to the EXECUTIVE operating program is interruptible by the CLOCK interrupt program. The logic is designed (and will have to be tested to verify) that the interruption of a computation under the EXECUTIVE will not interfere with the proper signals (e.g., pulses to drive motors) being sent out by the CLOCK interrupt routine.

4.4.6 FLOW CHARTS AND ALGORITHMS

The flowcharts of the interrupt and operating programs and their subroutines are appended: Appendix A shows six flowcharts related to the CLOCK interrupt routine; Appendix B has fifteen more flowcharts pertaining to the operating program. Each group of subroutine flowcharts is presented in alphabetical order.

Purely algebraic computations can be readily encoded without the aid of a flowchart. Such algorithms are presented following the flowchart to which they belong.

4.4.7 COMPUTER REQUIREMENTS

4.4.7.1 Memory

Two kinds of computer memory must be specified:

1. RAM (Random Access Memory) - for flags, parameters, and variables whose value is subject to change from one heliostat to another, or from one time period to another.
2. ROM (Read-Only Memory) - principally for programming code that is common to all the heliostats and not subject to change with time or operating conditions.

Appendix C lists statistics pertaining to the flags, parameters, variables, and algorithmic statements occurring in the different programs and subprograms of the heliostat software system. The following totals are representative lower bounds:

Flags:	36 @ 1 bit each
Parameters and Variables:	72 @ 16 bits each
Statements:	56 conditional branches
	33 subroutine calls
	218 other statements

Actual memory requirements will be much larger than these minimal counts. The suggested specification of 256 bytes of RAM storage allows a margin of about 2:1 for deficiencies in the above counts for flags, parameters and variables. This margin is considered adequate.

In the case of algorithmic statements, the translation to words of storage is difficult to estimate. Much depends on the complexity of the statements and on the coding skill of the programmer. The counts shown above are incomplete. For example, they lack a number of significant mathematical subroutines, such as trigonometric functions, matrix inversion and multiplication, etc. As a result, the estimate of 4K ROM storage must be considered a tentative minimum requirement. The chance that 4K ROM will prove adequate is 2:1.

4.4.7.2 Processing Time

Processing time is not expected to be a problem during normal operation of the heliostat, when the desired mirror angles change slowly from one control period to the next.

Likewise, processing time is not a critical factor during initialization, calibration, or manual operation (under local control).

The most serious situation arises when the mirror angles change rapidly. However, based on tests to date (with the prototype demonstration heliostat), it appears likely that the microcomputer can easily keep up with the required computational load, even under extreme conditions such as would be encountered during a sudden change of mode (e.g., from "STEERING" to "STOW").

4.5 ERROR ANALYSIS

4.5.1 SOURCES OF ERROR

In order to accurately position the reflected beam on a central receiver 18 x 25 meters, which is 1200-1300 meters away from the heliostat, it was determined by computer simulation that the reflected beam pointing accuracy has to be less than 0.2°, which results in a mirror positioning accuracy of 0.1°. The low-cost heliostat control is predicated on an open-loop mirror steering algorithm, which necessitates either an accurate alignment of the mirror axis drive system or a method of determining the alignment errors. In the General Electric control approach, an automatic calibration procedure is employed which estimates the major sources of error for individual heliostats. The calibration system is based on using the sun as a reference and a calibration error model for determining the mirror drive alignment errors.

Prior to developing the error model, the sources of error were investigated. The mechanical errors considered were:

Pedestal tilt errors

Drive wheel dimensional tolerance

Non-orthogonality of drive axis

Alignment of azimuth with true south

Alignment of elevation axis with vertical

Alignment of mirror face with drive system axis

Motor drive resolution

Heliostat position coordinates error

Alignment of Sun sensor with mirror face

Unbalance load torque errors

Motor compliance

Structure compliance

In addition to the mechanical sources of error, the sun vector computation errors were also considered in the open loop positioning of the heliostat mirror. The available sun position data vs. time is accurate to seconds of arc, and any errors incurred for the sun vector calculation will result either from computation or not having an accurate time base. In order to ensure that computation is not a factor, all the algorithms for computing vectors, both in the plant controller and the heliostat, are performed with a 16-bit representation of the vector direction cosines. Timing errors are minimized in that an accurate clock will be maintained in the plant controller where the sun vector calculation is determined. Non-precision real time clocks will be incorporated into the heliostat controllers for sequence timing and other time multiplexing function.

In developing the error model, only deterministic errors were evaluated which relate to the mechanical alignment errors. In reviewing these mechanical errors, only those sources of error which relate to the alignment of the drive system and the dimensional tolerance of the drive wheel were incorporated into the error model. The selection was based on identifying those errors around which a linear model could be formulated and those errors which were deemed critical in obtaining an accurate open-loop mirror pointing.

Pedestal Axis tilt

Azimuth and Elevation bias

Drive wheel dimensional tolerance

The remaining mechanical errors primarily relate to the fabrication tolerances of the heliostat parts. Since the remaining errors are tied to the mechanical fabrication, a tighter control over these sources can be maintained.

A controls error budget was established for the mechanical error sources shown in Table 4-1. Although the error for the pedestal tilt, azimuth, bias and elevation bias appears high, it is expected that these errors will be reduced by a factor of ten with the error model. The large tolerance on these errors will minimize the installation and alignment procedure for individual heliostats.

By taking an R.S.S. of all the error sources presented, and using a ten to one error reduction for those errors considered in the model, the predicted reflected beam pointing accuracy is 0.188° .

4.5.2 ERROR MODEL

An error model has been developed which provides an efficient error calibration for heliostat control system. The model consists of two linear equations which relate the mechanical system errors to the azimuth and elevation angles. The model has a decoupled structure such that the azimuth errors and the elevation errors are orthogonal. A six-step correction scheme for the track mode is derived. Simulation results are presented for a set of mechanical offset errors along with stochastic measurement errors for the sun sensor. It is found that the algorithm is capable of reducing reflected beam pointing errors by a factor of 20 to 1 and produced reflected beam displacements of less than 1.5 meters for a 1,300 meter far field heliostat. Sensitivity of the algorithm for the offset errors is also presented. It is concluded that the crucial error is due to tilt in the azimuth wheel axis from the vertical.

4.5.2.1 Description

The sources of deterministic errors considered in the error model are shown below.

<u>Sources of Error</u>	<u>Error Designation</u>
1. Azimuth and elevation bias	a_1, a_6
2. Mirror pedestal tilt	a_2, a_3
3. Drive wheel radius tolerance	a_4, a_5

Let X, Y, and Z axes denote true south, east, and vertical directions with origins at the center of the heliostat mirror. This is called a true coordinate system. Due to error sources (1) and (2), the mirror coordinate system $x'y'z'$ may not coincide with xyz as shown in Figure 4-26. It is assumed that $x'y'z'$ axis is an orthogonal set. Consider unit vectors in the z' , y' , x' directions denoted by $U_{z'}$, $U_{y'}$, $U_{x'}$. If the errors are assumed small, then, after neglecting second order terms, we have

TABLE 4-1

CONTROLS AND DRIVES ERROR BUDGET

● Azimuth Axis Tilt	x	$\pm 0.5^\circ$
	y	$\pm 0.5^\circ$
● Drive Wheel Dimensional Tolerance		$\pm .005$ Inch
● Non-Orthogonality of Drive Axis		0.01°
● Azimuth Calibration Alignment with South		$\pm 0.5^\circ$
● Elevation Calibration Alignment with Vertical		$\pm 0.25^\circ$
● Alignment of Sun Sensor with Mirror		$.01^\circ$ min. $\angle$
● Sun Sensor Null Bias		$.02^\circ$
● Alignment of Mirror Face with Drive System Axis		$.01^\circ$
● Motor Drive Resolution		0.0143°

Figure 4-26. Error Model Coordinate Axes Frame

$$U_{z'} = \begin{bmatrix} a_1 \\ -a_3 \\ 1 \end{bmatrix} \quad U_{x'} = \begin{bmatrix} 1 \\ a_2 \\ -a_1 \end{bmatrix} \quad U_{y'} = \begin{bmatrix} -a_2 \\ 1 \\ a_3 \end{bmatrix}$$

where a_1 , a_2 , and a_3 are offsets to be estimated and can be interpreted as rotation of mirror axis vectors about y, z, and x axis respectively. A unit sun vector can be defined in the true coordinate system relative to vertical and true south as

$$U_s = \begin{bmatrix} x_s \\ y_s \\ z_s \end{bmatrix}$$

The sun vector in $x'y'z'$ - axis is given by

$$\begin{aligned} x_{s'} &= x_s + a_2 y_s - a_1 z_s \\ y_{s'} &= -a_2 x_s + y_s + a_3 z_s \\ z_{s'} &= a_1 x_s - a_3 y_s + z_s \end{aligned} \quad (1)$$

4.5.2.1.1 Equation for Azimuth Error Calibration. Let θ_m° denote azimuth angle generated with an actual wheel. Then

$$\tan \theta_m^\circ = \frac{y_{s'}}{x_{s'}} \quad (2)$$

Now consider the effect of deviation in the radius of azimuth wheel from the nominal value. It is assumed that the unknown radius is r_2 and $a_4 \frac{\Delta r_2}{r_0} = \frac{r_2 - r_0}{r_0}$ where r_0 is the assumed radius, then

$$\theta_m^\circ = \frac{M\Delta}{r_2} \quad \text{Actual azimuth angle}$$

$$\theta_m = \frac{M\Delta}{r_0} \quad \text{Measured azimuth angle}$$

where M is advance of the azimuth wheel. Δ is step size of the motor (cm/step)

For small errors, we have from Taylor series expansion

$$\begin{aligned} \cos \theta_m^\circ &\approx \cos \theta_m + a_4 \theta_m \sin \theta_m \\ \sin \theta_m^\circ &\approx \sin \theta_m - a_4 \theta_m \cos \theta_m \end{aligned} \quad (3)$$

From equations (1), (2) and (3), and (Neglecting higher-order terms) a definition of the azimuth error in terms of the various error coefficients can be generated

$$\begin{aligned} \sin (\Theta_m - \Theta) &\approx \cot \alpha \sin \Theta_m a_1 \\ &+ \cot \alpha \cos \Theta_m a_3 \\ &- \cos (\Theta_m - \Theta) a_2 \\ &+ \Theta_m \cos (\Theta_m - \Theta) a_4 \end{aligned} \quad (4)$$

α and Θ are true elevation and azimuth angles of the sun vector respectively, relative to vertical and true south.

For small errors it is assumed that

$$\begin{aligned} \cos (\Theta_m - \Theta) &\approx 1 \\ \sin (\Theta_m - \Theta) &\approx \Theta_m - \Theta \end{aligned}$$

Now equation (4) can be approximated by

$$(\Theta_m - \Theta) \sin \alpha = (\cos \alpha \sin \Theta) a_1 + (\cos \alpha \cos \Theta) a_3 - (\sin \alpha) a_2 + \Theta (\sin \alpha) a_4 \quad (5)$$

This equation relates the azimuth error angle to the error vector in terms of the true angles α and Θ .

4.5.2.1.2 Equation for Elevation Error Calibration. Let α_m denote the angle between the unit vector U_z , and sun vector U_s . Then

$$\begin{aligned} \cos \alpha_m &= U_z \cdot U_s \\ &= X_s a_1 - Y_s a_3 + Z_s a_5 \end{aligned} \quad (6)$$

The actual radius of the elevation wheel may not be the nominal value r_0 . Let

$a_5 \triangleq \frac{\delta r_1}{r_0} = \frac{r_1 - r_0}{r_0}$ where r_1 is the actual radius. The other source of error in the measurement of the elevation angle is due to a reference bias denoted by a_6 . Then

$$\begin{aligned} \alpha_m^\circ &= \frac{N\Delta}{r_1} + a_6 \quad \text{actual elevation angle} \\ \alpha_m &= \frac{N\Delta}{r_0} \quad \text{measured elevation angle} \end{aligned} \quad (7)$$

Where N is advance of the elevation wheel.

Now, assuming a_5 and a_6 are small, then

$$\cos \alpha_m^\circ \approx \cos \alpha_m - a_6 \sin \alpha_m + a_5 \alpha_m \sin \alpha_m \quad (8)$$

From equations (6) and (8)

$$\cos \alpha_m - \cos \alpha = x_s a_1 - y_s a_3 - \alpha_m \sin \alpha_m a_5 + \sin \alpha_m a_6 \quad (9)$$

Consider the relation

$$\frac{\cos \alpha_m - \cos \alpha}{\sin \alpha_m} = \frac{\cos \alpha_m - \cos [\alpha_m - (\alpha_m - \alpha_1)]}{\sin \alpha_m} \approx -\alpha_m + \alpha$$

Equation () can be approximated as

$$-\alpha_m = \cos \theta a_1 - \sin \theta a_3 - \alpha a_5 + a_6 \quad (10)$$

The error model equation can be written as

$$\begin{bmatrix} (\theta_m - \theta) \sin \alpha \\ \alpha - \alpha_m \end{bmatrix} = \begin{bmatrix} \cos \alpha \sin \theta & -\sin \alpha & \cos \alpha \cos \theta & \theta \sin \alpha & 0 & 0 \\ \cos \theta & 0 & -\sin \theta & 0 & -\alpha & 1 \end{bmatrix} \underline{a} + \underline{\varepsilon}$$

where $\underline{a}^T = (a_1, a_2 \dots a_6)$. $\underline{\varepsilon}$ is residual error not accounted by the model.

It is seen that the deviations in azimuth and elevation angles affect the first and second equation respectively.

Estimation Algorithm for the Error Model

During the calibration mode, the heliostat tracks the sun in a closed loop manner using reference data from a sun sensor mounted perpendicular to the mirror. The input to the error model obtained from this operation is the position of the drive wheels. Define response vector as

$$\underline{g}(k) = \begin{bmatrix} [\theta_m(k) - \theta(k)] \sin \alpha(k) \\ \alpha(k) - \alpha_m(k) \end{bmatrix}$$

and matrix as

$$H(k) = \begin{bmatrix} \cos \alpha(k) \sin \theta(k) & -\sin \alpha(k) & \cos \alpha(k) \cos \theta(k) & \theta(k) \sin \alpha(k) & 0 & 0 \\ \cos \theta(k) & 0 & -\sin \theta(k) & 0 & -\alpha(k) & 1 \end{bmatrix}$$

$$k = 1, 2, \dots, N$$

where N is total number of observations. From equation (11),

$$\underline{q}(k) = H(k) \underline{a} + \underline{\varepsilon}(k) \quad (12)$$

From a least-squares algorithm, estimate of the parameters is given by

$$\hat{\underline{a}} = \left[\sum_{k=1}^N H^T(k) H(k) \right]^{-1} \left[\sum_{k=1}^N H^T(k) \underline{q}(k) \right] \quad (13)$$

Open Loop Tracking Algorithm

In this mode of heliostat operation, the mirror pointing vector is corrected for the offset errors determined by the calibration mode. A six step algorithm is presented as a means of compensating for the offset errors.

1. Estimate the mirror pointing vector.

$$\underline{R}_M = \underline{U}_s + \underline{U}_t = \begin{bmatrix} x_M \\ y_M \\ z_M \end{bmatrix}$$

where $\underline{U}_t$ is a unit reflected beam vector assumed known for a given location of the heliostat. $\underline{R}_M$ is not a unit vector.

2. Estimate mirror pointing vector in mirror coordinates. From equation (1)

$$\underline{R}'_M = \begin{bmatrix} x'_M \\ y'_M \\ z'_M \end{bmatrix} = \begin{bmatrix} x_M + \hat{a}_2 y_M - \hat{a}_1 z_M \\ -\hat{a}_2 x_M + y_M + \hat{a}_3 z_M \\ \hat{a}_1 x_M - \hat{a}_3 y_M + z_M \end{bmatrix}$$

3. Estimate actual mirror azimuth angle.

$$\theta_M^\circ = \tan^{-1} \left[\frac{y'_M}{x'_M} \right]$$

4. Estimate advance of the azimuth wheel. Based on calculated error coefficient a_4

$$M = \frac{\theta_M^\circ}{\Delta} y_0 \left[1 + \hat{a}_4 \right]$$

5. Estimate actual mirror elevation angle.

$$\alpha_m^\circ = \tan^{-1} \left[(x_M' + y_M')^{1/2} / z_M' \right]$$

6. Estimate advance of the elevation wheel based on calculated error coefficient a_6

$$N = \frac{r_0}{\Delta} [1 + \hat{a}_5] [\alpha_m^\circ - \hat{a}_6]$$

Simulation Results

Effectiveness of the error model in reducing the heliostat pointing errors was considered in the following work. The following offsets are assumed.

$a_1 = 0.7^\circ$	Rotation about y axis
$a_2 = 0.5^\circ$	Rotation about z axis
$a_3 = 0.7^\circ$	Rotation about x axis
$a_4 = 0.001$	Azimuth wheel radius
$a_5 = 0.001$	Elevation wheel radius
$a_6 = 0.5^\circ$	Rotational offset in elevation angle

A latitude of 32°N is assumed. The target consists of a vertical cylinder 17m diameter by 25m high, the center of which is elevated 250m above ground level. The McDonnell Douglas configuration for the heliostat field is considered. It is assumed that a heliostat is 1,200 meters north and 430 meters east of the central tower. For notational convenience, summer solstice, autumnal equinox and winter solstice are represented as day 180, 90 and 0 respectively. The sun sensor noise is represented by a stochastic process with measurement bias of $1/60$ degree and variance of $1/60$ degree. A calibration day is divided into eighteen equal intervals. The least-squares algorithm given by equation (13) is used to estimate the model parameters.

Tracking performance has been evaluated both for a calibration day and other days of the year. The results for 100 samples are given in Figures 4-27 and 4-28 samples 1 - 49 represents morning, 51 - 100 represent afternoon, and sample 50 represents noontime for the track day. Note that the duration of a day for tracking is six hours (winter solstice) for Figure 4-27 and 4-28. x- and y-axis represent horizontal and vertical directions with origin at the center of the receiver. It is seen that without the error correction model the pointing errors are more than 30 meters. However, with the use of error model the pointing errors are less than 1.5 meters.

Figure 4-27. Heliostat Errors

Thus with the use of the algorithms presented in this report a 20 to 1 reduction in the pointing errors is possible. Similar simulation results for different calibration and track days with sun sensor were obtained.

4.5.2 SENSITIVITY ANALYSIS

In the previous section performance of the error model was estimated for a set of offsets. The pointing errors in the reflected beam as a function of changes in the offset values are now considered. The heliostat and tower configuration is assumed to be the same as before. The performance is analyzed for calibration day 180 (summer solstice) and track day zero (winter solstice). Nominal values of the heliostat errors are the same as before. The pointing errors as a function of error due to the rotation of mirror axis about y-axis are shown in Figure 4-29. Multiplier 1 corresponds to the nominal values of the offset errors. Multiplier 6 denotes the error in rotation about y-axis multiplied by 6 while other errors remain the same. Average values and maximum values are for a day. It is seen that average and maximum pointing errors after correction are small for multipliers up to ± 2 . This is equivalent to $\pm 1.4^\circ$ errors in the offset. For larger errors the error model is no longer valid and results in unacceptable performance. The pointing error as a function of errors due to the rotation of the mirror axis about x-axis is shown in Figure 4-30. It is seen that the errors up to $\pm 1.4^\circ$ can be tolerated. The other errors and their effects on the performance are given in Figures 4-31 through 4-34. The error model seems quite powerful to account for these errors and does not have significant effect of the heliostat performance. From the above analysis the following conclusions are drawn.

1. The alignment of the azimuth axis with true vertical is critical.
2. The errors due to the wheels radii, elevation and azimuth offsets can be accounted for by the error model.

4.6 CONTROL AND DRIVES BREADBOARD TEST SUMMARY

As a part of the Phase I Design Study, a breadboard testing task of the critical components and concepts was conducted to provide early hands-on experience which will assist in a proper Phase II design. The breadboard tests were divided into three subtests which include:

- Calibration Algorithm Test and Evaluation
- Microprocessor Tracking Algorithm Test
- Linear Stepping Motor Drive Evaluation

ROTATION ABOUT Y AXIS

NOMINAL VALUE = 0.7°

Figure 4-29. Rotation about Y-axis

ROTATION ABOUT X-AXIS

NOMINAL VALUE = 0.7°

Figure 4-30. Rotation about X-axis

ROTATION ABOUT Z - AXIS

NOMINAL VALUE = 0.5%

Figure 4-31. Rotation about Z-axis

AZIMUTH WHEEL RADIUS ERROR

NOMINAL VALUE = -0.1 %

Figure 4-32. Azimuth Wheel Radius Error

ELEVATION WHEEL RADIUS ERROR

NOMINAL VALUE = 0.1 %

Figure 4-33. Elevation Wheel Radius Error

NOMINAL VALUE = 0.5 DEG.

Figure 4-34. Rotational Offset Error in Elevation Angle

Calibration Algorithm Test

The purpose of the Calibration Algorithm test was to evaluate the error compensation model using actual physical hardware and computer components. For the purpose of this test and the microprocessor tracking algorithm test, a simulated mirror axis drive system was constructed. The simulated drive plus PDP-8 minicomputer, shown in Figure 4-35 uses conventional stepping motors for the drives with a gear reduction of a 100 to 1 to achieve a $0.018^\circ/\text{step}$ resolution. A small mirror is moved in azimuth and elevation which is used to reflect the sun on a target in order to measure the pointing errors of the system. In addition to the mirror, a sun sensor is located on the mirror mount and provides the feedback signal for the closed loop sun tracking.

In conjunction with the drive simulator, a PDP-8 minicomputer was employed for programming the algorithms and driving the stepping motors. Conventional drive electronics are utilized as the interface between the computer and the stepping motors.

The calibration algorithm tests were divided into two subtests. The first test encompassed the mechanization of the closed loop sun tracking algorithm and error model calibration algorithm. Sun tracking tests were conducted which generated the data needed to compute the error coefficients for the error compensation model.

The second test demonstrated the mirror steering algorithm and the error compensation during a normal operating period. Data was taken of the reflected beam on a target to determine the pointing accuracy with and without error compensation.

Field Test Site

In order to accomplish the two calibration algorithm tests, the mirror drive axis simulator Figure 4-36 was located at a test facility which allowed a full view of the sun during the day and a building for positioning a target to measure the relative pointing accuracy performance. The electronics and computer were located in a trailer which was used as a control room. The target (Figure 4-37) was located 200 ft from the heliostat at an angle of 6° to the horizontal. The target consisted of a reflective surface with a one foot grid structure. A typical sun image is shown on the target which has a horizontal 2.4° subtended angle and a 1.2 vertical angle. The pointing accuracy data was recorded by taking pictures of the target at discreet times during the day.

Figure 4-35. PDP-8 Minicomputer and Mirror Axis Drives Simulator

Figure 4-36. Field Test Installation

Figure 4-37. Mirror Target

Microprocessor Breadboard Test

The microcomputer used to control the heliostat is of a special design to minimize component count, reduce cost and optimize performance. The purpose of this test was to develop a system based on existing components, assess the hardware requirements for an operating system, and demonstrate the dynamic performance of the controller. The results of this development task determines the type of microcomputer required, the memory requirements, and additional components, if required. This test also evaluated the power line interface with the host computer and the dynamics of the heliostat controller with the mirror axis drives simulator.

The breadboard microcomputer was constructed using the INTEL MCS-85 computer system. Figure 4-38. The 8085 CPU, the 8755 EPROM and the 8155 RAM chips are the basic components used in the design of the microcomputer breadboard test. In addition to the microcomputer, a power line serial input receiver and peripheral input output switches were also fabricated to demonstrate the feasibility of the controller.

Three control modes were programmed on the microcomputer which included

- Mirror Pointing

- Mirror Steering

- Mirror Initialization

The total software package for these modes totaled less than 2000 bytes. All the basic elements for the heliostat controller are included in the breadboard and initial performance with the drive simulator indicated successful performance.

Figure 4-38. Breadboard Microcomputer

Results of Calibration and Tracking Test

Several calibration and tracking results were obtained with the test apparatus developed under this contract. Problems were encountered with bias errors in the sun sensor and associated electronics. These were partially resolved by the sun sensor vendor. The experience emphasized the importance of using an accurate sun seeking device if useable calibration coefficients are to be obtained. Problems were also encountered with clouds. Local weather conditions, together with the time limitations imposed by the contracts, required that calibration data be taken on days that were sunny 90% of the time. If small, wispy clouds occluded the sun, errors were introduced in the calibration data. Test results for the error calibration scheme are shown in Table 4-2. For these tests the drive assembly was tilted 1.0° to the west and offsets of $.5^\circ$ degrees and $.69^\circ$ were inserted in the azimuth and elevation drives respectively. The calibration algorithm was then exercised for five hours and 61 points at 5 minute intervals were used to compute the coefficients. Sufficient data was collected to allow evaluation of confidence limits for the coefficients "off-line." The resulting coefficients are tabulated in Table 4-3. The results show that all "true" coefficient values fall within the 95% confidence intervals. Some of these intervals are fairly large however, this reflects the fact that over the calibration interval chosen, coefficient pairs A5 and A6; A1 and A4 were highly correlated. The ability of the error model to fit the experimentally obtained errors is shown in Figure 4-38. The effects of slight cloud cover can be seen by examining this plot which illustrates the importance of performing the calibration on a clear day.

Examining the tracking results shown in Figures 4-40 and 4-41 illustrates the amount of error reduction achieved. This data is summarized in Table 4-4. Without compensation, the RMS azimuth error was .65 degrees and had a peak value of $-.874$ degrees. With compensation, these values were reduced to .044 and $-.115$ degrees respectively. This represents an error reduction of about 10:1. Likewise the RMS elevation error was .527 degrees, uncompensated, with a peak value of $-.920$ degrees. After compensation these values were reduced to .112 and $-.23$ degrees respectively -- a reduction of about 4.5:1.

These best results illustrate the robustness of the error model and its ability to reduce heliostat installation errors to an acceptable level.

TABLE 4-2

EXPERIMENTAL TRACKING DATA SUMMARY

Calibration Test Conditions

Heliostat location: Schenectady, New York

Latitude = 42.83° longitude = 73.88°

Calibration day: June 28, 1978

Declination angle = 23.283°

Calibration interval: 9 a.m. - 2 p.m. est./dst.
or 5 hours

Errors introduced to heliostat:

1.09° axis declination west

$.504^{\circ}$ azimuth offset

$.693^{\circ}$ elevation offset

TABLE 4-3

CALIBRATION TEST RESULTS (June 28, 1978)

Estimated Coefficient	Estimate	99% Confidence Interval
A1 (north - south tilt)	- $.165^{\circ}$	$\pm 0.15^{\circ}$
A2 (azimuth offset)	+ $.575^{\circ}$	$\pm 0.09^{\circ}$
A3 (east-west tilt)	+ $.724^{\circ}$	$\pm 0.048^{\circ}$
A4 (azimuth radius)	+ .25%	$\pm 0.33\%$
A5 (elevation radius)	+1.56%	$\pm 0.6\%$
A6 (elevation offset)	+ $.668^{\circ}$	$\pm 0.27^{\circ}$

TABLE 4-4

TRACKING TEST RESULTS (June 29 and 30, 1978)

Reflected Beam Errors Uncompensated (degrees)

	<u>Average</u>	<u>RMS</u>	<u>Peak</u>
Azimuth	-.624	.650	-.874
Elevation	-.350	.527	-.920

Reflected Beam Errors Compensated (degrees)

	<u>Average</u>	<u>RMS</u>	<u>Peak</u>
Azimuth	-.023	.044	-.115
Elevation	-.035	.112	-.230

Improvement Ratio (uncomp./comp.)

	<u>Average</u>	<u>RMS</u>	<u>Peak</u>
Azimuth	27.2	14.8	7.6
Elevation	9.9	4.7	4.0

Figure 4-39. Plot of Residuals from Error Calibration Test

Figure 4-40. Tracking Errors Uncompensated

Figure 4-41. Tracking Errors Compensated by Error Model

4.6.3 LINEAR DRIVE MOTOR TESTS

The purpose of this test is to design, fabricate and evaluate a unique rotary drive mechanism which will be used to position heliostats in azimuth and elevation. This drive system utilizes a linear stepping motor positioned at the periphery of a drive wheel to impart lateral motion to the rim of the wheel which in turn rotates the wheel about its axis. Positioning capability is provided by the stepping characteristics of the motor and the slotted steel platen mounted on the rim of the wheel. Motion verification and initial position setting is provided by pickoffs utilizing the magnetic characteristics of the slots.

A 4-phase linear stepping motor with a pole face machined to match the radius of curvature of the drive wheel has been selected for this test evaluation. This provides the capability of a .005 inch step resolution which translates to a $\pm 0.01432^\circ$ positioning capability, which is well within the error budget allotted to the drive system.

The motor is capable of providing a 8# of force and is mounted on roller bearings which ride on the platen surface. Translating this to a 20 inch radius, a torque capability of about 12 ft/lbs is attainable when consideration is given to bearing friction and motor air gap. Maximum slew rate is designed to be $0.2^\circ/\text{sec}$.

The test fixture (Figure 4-42) including the drive wheel and motor mount was fabricated to evaluate the motor performance with various inertia loads and determine the angular positional accuracy. A steel platen was etched and strapped on the perimeter of the drive wheel.

The platen consists of a 0.071" thick strip of 1010 steel which is etched at 0.020" intervals to provide the poles required by the motor. The etched platen is made such that a bearing surface is provided for the roller bearings on each side.

Solid-state linear output "hall effect" sensors are used to sense the presence of a pole or slot. These motion detectors are used for both "wheel motion verification" and for "initial point" referencing.

The rotation position of the drive wheel is measured by reflecting a laser beam off a mirror positioned at the center of rotation (Figure 4-42). The reflected beam was measured on a perpendicular wall and was able to detect a one step discrepancy in motor motion.

Figure 4-42. Linear Motor Test Fixture

The following tests were performed with the linear motor test fixture.

1. Position accuracy tests

The ability of the drive to position with required accuracy (under various loads

2. Slew rate evaluation as a function of load

3. Maximum torque measurement running and static

4. Power consumption

5. Failsafe feature evaluation of unbalance torque is used to preload drive wheel which will be employed to bring the drive wheel to a preset "stow" position upon loss of power. The performance of the motor was evaluated with an unbalance torque.

In addition to the motor tests the performance of a simple magnetic pickoff (Figure 4-43 to detect the slots in the steel platen was evaluated. These detectors were attached to the motor and sensed calibration reference slots as well as the 0.020 inch platen slots.

Linear Motor Test Results

Initial tests evaluated positional accuracy with minimum inertia (i.e., 2 slug-ft²). Results showed that positional beam accuracies of 0.01432 degree $\pm$ 0.005 degrees could be attained on a repeatable basis.

Inertia was increased to 127 slug-ft² and positional accuracy was again verified. Slew rate input (pulse rate) was increased up to 0.6°/sec before the motor drive exhibited loss of stepping control. This inertia represents about a 20% increase over the current estimates of the heliostat structure. Accuracy of positioning under high slew rates was verified by observing the position of the reflected laser beam between two calibration points and counting the number of pulses required to drive the wheel from one point to the other and back. Loss of one or more counts between points was considered a failure.

Force measurements on the motor indicated an output torque of approximately 13 ft-lb (144 oz-in) over the full operating range. Holding torque was measured at 25 ft-lbs. The possibility of using a spring force to restore the heliostat to a stow position upon loss of motor power was also evaluated. It was found that a force of 2 ft-lbs would be required to overcome the residual force of the motor. The ability to use such a device will depend entirely on the design of the azimuth and elevation bearings.

Hall sensors were successfully used to magnetically detect the slots in the platen as the drive wheel moved. A typical output is shown in Figure 4-44.

Figure 4-43. Linear Motor with Motion Detectors

Figure 4-44. Output of Hall Sensors Measuring Slot Location

The use of a Hall sensor to sense calibration slots was verified in the bearing surface of the platen. Using a similar sensor, it was found possible to position the drive with one step ± 0.0143 degrees repeatably.

Finally the power requirement of the motor was measured. For the unit being tested it was found that 120 watts was required. This motor was purposely oversized since the maximum slew rates were unavailable when the initial design was done. This motor has the capability of generating 12 ft/lbs at slew rates of 200 steps second. This slew rate is approximately 10 to one greater than required for this application. A redesigned motor would have a maximum of 20 steps (0.27°/sec) a second slew capability and would require 30 watts when moving and 15 watts when holding.

Based on these tests the following conclusions and recommendations can be made.

1. The linear motor concept for positioning large heliostats in azimuth and elevation is sound and practical.
2. Hall sensors can be used to send and validate motor motion and to initially position the heliostat.
3. Other approaches for sensing motor motion and for initial positioning should be investigated.
4. Chemical etching of the drive wheel platen is a cost-effective way of producing the platen. However integration of the platen to a 360° drive wheel will require further design effort. The use of ferrite impregnated plastic-cast wheels should also be looked at.
5. A redesign of the current linear motor should be made to obtain a low power version that is properly sized for the application.

5.0 MANUFACTURING CONCEPTUAL DESIGN

The result of the Phase I manufacturing design effort is the conceptual determination of the facilities, equipment, tooling, manpower, raw materials, material handling, quality control, and cost requirements needed to achieve the production of 2,500 heliostats as a one time purchase, and the steady state production levels of 25,000, 250,000 and 1 million heliostats per year.

The significant data resulting from the manufacturing design is presented in Table 5-1. This table illustrates the maturing of the preliminary design heliostat costs at approximately the 250,000/yr production level.

TABLE 5-1

Production Level	Facility Size (m ²)	Number of Heliostats per Employee/Yr	Degree of Automation %	Degree of Vertical Integration	Cost of Installed Heliostat (1978 Dollars)
2,500	400	78.6	5	LOW	\$ 5686
25,000	3700	581	40	MEDIUM	\$ 2597
250,000	27,500	1656	86	HIGH	\$ 1443
1,000,000	68,000	2232	90	HIGH	\$ 1363

The manufacturing process studies examined each part of the heliostat system as it was being developed in the preliminary design and provided feasibility and cost assessment through three specific reviews during the course of the Phase I program. All of the process data was directed towards finalizing the inputs for the manufacturing and cost estimate work sheets which are shown in Section 5.1.

For each level of production, equipment was selected and estimated to provide total investment cost summaries and to provide sizing information for determining rates and facility sizes. Figures 5-1 and 5-2 are facility sizing diagrams to show the results of the selected levels of vertical integration and equipment layout studies for the 25,000 and 250,000 production level cases. The 25,000 unit facility requires 43 direct labor personnel, primarily on a 5-day, 2 shift basis. Maximum capacity without expansion is 30,000 heliostats per year, limited by reflector fabrication.

The 250,000 heliostat per year facility is a highly automated facility, split into two buildings to accommodate more expansion potential. There are 151 direct labor people in this plant. This represents 1656 heliostats per person versus

581 heliostats per person at 25,000 per year demonstrating the large increase in automation that is justified at this level of production by the elimination of 279 people which would be required if the automation level had remained the same.

The capacity of this facility on a normal operating schedule is 250,000 per year based on the limiting areas of die casting, final assembly, reflector fabrication, and ground cloth fabrication. Through the addition of overtime and/or a limited third shift in these areas, the plant output could be increased to 300,000 heliostats per year without affecting the other areas or operations.

The one million unit production facility was considered to be multiples of the 250,000 unit plant with appropriate adjustment in film-making capability. Two full lines of film machinery would be required. Also, increased material handling equipment is reflected in the worksheets.

Vacuum metalizing of plastic film is now limited to 2.4 meter (7.87 ft.) widths based on equipment size - the technology has no known limit. Therefore, vacuum metalizing 8.53 meter (28 ft.) widths is possible but the equipment will be expensive based on the basic technology of placing the whole material roll and the take-up reel in the vacuum tank. Technology is now emerging that will eliminate the need for these reels to be in the tank, which will greatly reduce the cost of such equipment. The manufacturing plan contains the vacuum metalization of a one-piece reflector only at 1,000,000 per year, and contains vacuum metalizing equipment to handle 2.13 meter (7 ft.) material at 250,000 per year.

Cutting the reflector to shape can be readily accomplished through the use of a multi-headed water knife, which is a numerically controlled or tracer controlled water jet which delivers a high pressure stream of water .13 mm (.005 in.) wide. The cutting would be performed while the film is held in place on a vacuum table and a chemically treated swab removes the aluminum at the reflector center. The reflector would then be moved via belt conveyor to another table where loadstraps with adhesive will be automatically transported from their fabricating lines by overhead rubber suction devices and placed under the edges of the reflector. Pressure would be applied until the adhesive is quickly cured, the reflector is rolled up on protected tynes and slipped into a compartment in the shipping container.

Process studies included detailed examination of raw material sizing, minimizing scrap and reprocessing and specific packaging studies for special components.

PLASTIC FILM FABRICATION

1727.9 SQ M
(18600 SQ FT)

STORAGE & RECEIVING

865.8 SQ M
(9320 SQ FT)

FABRIC FABRICATION

555.5 SQ M
(5980 SQ FT)

**STRUCTURAL
FABRICATION**

92.9 SQ M
(1000 SQ FT)

OFFICES

185.8 SQ M
(2000 SQ FT)

ASSEMBLY

185.8 SQ M
(2000 SQ FT)

SHIPPING

92.9 SQ M
(1000 SQ FT)

3706.6 SQ M
(39900 SQ FT)

SCALE

5 0 5 10 15 20

METERS

5-5/6

SCALE

Figure 5-2. Manufacturing Facility for 250,000 Heliostats/Year

An example of a special packaging problem associated with the installation studies is that of the reflector assembly shown in Figure 5-3.

Figure 5-3. Example of Special Packaging Problem -
Preparing the Reflector for Shipment

5.1 MANUFACTURING AND COST ESTIMATE WORK SHEETS

The following tabular pages are the detailed results of all of the manufacturing studies at the four different production levels. This data provides the basis for all of the capital cost estimates presented in Section 7.0.

COLLECTOR CAPITAL INVESTMENT COST
2500 PRODUCTION LEVEL

4400 Collector Equipment		11339.85
4410 Reflective Unit	1589.00	
4420 Drive Unit	1104.50	
4421 Azimuth Drive	115.62	
4422 Elevation Drive	33.23	
4423 Motors	780.65	
4424 Position Indicators	-	
4425 Power Distribution	175.00	
4430 Control and Instrumentation	814.88	
4431 Sensor	234.38	
4432 Field Control Electronics	424.25	
4433 Control Signal Dist. Equip.	156.25	
4440 Foundation and Site	1771.98	
4450 Heliostat Support and Protection	4004.42	
4451 Heliostat Support Structure	883.92	
4452 Heliostat Protective Encl.	3087.53	
4453 Lightning Protection	32.97	
4460 Field Assembly and Checkout	1056.00	
4470 Design and Engineering	0	
Other 1) Manufacturing Facility	450.00	
2) Packaging & Transportation	549.07	
4800 Distributables and Indirect Costs		2874.45
4810 Construction Facilities, Services, G&A, & Fee	1385.80	
4820 Spare Parts	96.66	
4830 Architectural Engineering Service	32.30	
4849 Construction Management	38.86	
4850 Plant Startup and Checkout	28.80	
4860 Contingency	1292.03	
TOTAL		<u>14214.30</u> Per Year
		<u>5685.71</u> Per Heliostat

4410

ACCOUNT NUMBER

Reflector Unit

ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
1) Strut Adjustment Cap (8) Material-Die Cast Aluminum Purchased CPT to Dwg. Tooling-Die	2500 -	\$ 8.00(a) -	\$ 20 10 (b)	\$ 5 -	\$ - -	\$ 25 10
2) Strut Tube (8) Material-Aluminum-Purch. Cpt to Dwg.	2500	72.00(b)	180	45	-	225
3) Strut Handwheel, Socket Ball & Pin(8) Mat-Steel-Purch. Cpt to Dwg	2500	8.64(c)	21.6	5.4	-	27
4) Strut Cable (8) Mat-Solid Steel Wire Equip. Cutting & Crimping Labor. 1/3 of a Man Year	2500 - - .31	0.96(b) - - 9766.00	2.40 2.50(b) 3.22	0.6 - 0.81	- - 4.83	- 3.00 2.50 8.86
5) Strut End Cap (8) Mat-Die Cast Aluminum Purch. Cpt to Dwg. Tooling-Die	2500 -	8.56(a) -	21.40 10 (b)	5.35 -	- -	26.75 10.00
6) Reflector Hub (1) Mat-Polycarbonate -Purch. Cpt to Dwg. Tooling-Mold	2500 -	13.27(d) -	33.18 45.00(b)	8.29 -	-	- 41.47 45.00
7) Reflector Hub Tail Section (1) Mat-Aluminum-Purch-Cpt to Dwg.	2500	3.00(b)	7.50	1.88	-	9.38
8) Reflector Tensioning Speed Handle(1) Mat-Die Cast Aluminum Tooling-Die	2500	2.02(a)	5.05 10.0(b)	1.26	-	6.31 10.00

5-10

4410

ACCOUNT NUMBER

Reflector Unit

ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
9) Reflector Tensioning Cable Collar(1) Mat-Die Cast Aluminum Tooling-Die	2500	\$ 2.27(a)	\$ 5.68 10.0 (b)	\$ 1.42	\$	\$ 7.10 10.0
10) Reflector Tensional Spring(1) Purchased Complete	2500	5.00(b)	12.50	3.13	-	15.63
11) Reflector Hub Heli Coil (1) Purchased Complete	2500	0.03(b)	.08	0.02	-	0.10
12) Reflector Corner Beam (8) Mat-Die Cast Aluminum Tooling-Die	2500	11.52(a) -	28.80 20.00(b)	7.20	-	36.00 20.00
13) Reflector Surface- (1) Mat. Metalized-P.E.T. Equipment-Fabrication Line Labor	2500 2 (Men)	75.94 (e) - 9,766	189.85 400.00 (b) 19.53	47.46 - 4.88	- - 29.30	237.31 400.00 53.71
14) Reflector Corner Load Strap (8) Material-Stabilized P.E.T. Equipment-Fabrication Line Labor	2500 9 (Men)	5.50 (e) - 9,766	13.75 100.00 (b) 87.89	3.44 - 21.97	- - 131.83	17.19 100.00 241.69
4410 Total						\$1589.00

Notes 4410

- a) Engineering estimate based on current price of aluminum ingots, estimate of die cast equipment cost/hour and estimate of casting time.
- b) Engineering estimate.
- c) Engineering estimate based on current price of cold rolled steel, labor estimate and cost per hour of machine time.
- d) Engineering estimate based on carload lot of polycarbonate, vendor budgetary estimate on equipment cost per hour, and estimate of molding time.
- e) Vendor quote.

4420

ACCOUNT NUMBER

DRIVE UNIT

ACCOUNT DESCRIPTION

FACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
4421 - Azimuth Drive						
1. Azimuth Drive Wheel (1) Material: Polycarbonate Purchased complete	2500	\$36.00 (a)	\$90.00	\$ 22.50	-	\$112.50
2. Azimuth Drive Wheel Keeper (1) Material: Polycarbonate Purchasing Complete	2500	1.00	2.50	0.63	-	3.13
TOTAL 4421						\$115.63
4422 - Elevation Drive						
1. Elevation Drive Sector Material: Polycarbonate Purchased Complete	2500	10.57 (a)	26.43	6.61		33.04
2. Elevation Drive Sector Bolt (1) Purchased Complete	2500	0.06 (b)	0.15	0.04		0.19
4422 TOTAL						\$ 33.23

4420

ACCOUNT NUMBERDRIVE UNITACCOUNT DESCRIPTIONFACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
4423 MOTORS						
1. Drive Motors (2) Purchased Complete - Allied Plant	2500	\$240.00(c)	\$600.00	\$150.00	-	\$ 750.00
2. Drive Motor Pivot Pin (2) Purchased	2500	.25(d)	0.63	0.16	-	0.79
3. Drive Motor Pivot Bracket (2) Material: Polycarbonate Tooling: Mold	2500	3.15(e)	7.88 20.00(b)	1.97 -	-	9.85 20.00
4423 TOTAL						\$ 780.64
4424 Position Indicators - Included in 4423-1						
4425 Power Distribution and Emergency Power Field Equipment (P/H)	2500	56.00(f)	140.00	35.00		175.00
4425 TOTAL						175.00
4420 TOTAL						1104.50

NOTES 4420

- a) Engineering estimate based on a car load lot of Polycarbonate - Vendor budgetary estimate on equipment cost per hour, and estimate of molding time.
- b) Engineering estimate
- c) Engineering estimate based on motors purchased from Allied Plant
- d) Engineering estimate based on current price of cold rolled steel, machine time estimate and equipment cost per hour.
- e)
- f) Based on current catalog pricing of GE Power Distribution Equipment and engineering estimates.

4430

ACCOUNT NUMBERCONTROL & INSTRUMENTATIONACCOUNT DESCRIPTIONFACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
4431 Sun Sensor Purchased (1)	2500	\$ 75.00(a)	\$ 187.50	\$ 46.88	-	\$ 234.38
4432 Field Control Electronics						
1. Cable Stand-Off (3) Purchased Complete	2500	.75(b)	1.9	.47	-	2.37
2. Wire Harness - Sun Sensor (1) Purchased Complete Allied Plant	2500	6.00(b)	15.00	3.75		18.75
3. Controller (1) Purchased Complete - Allied Plant	2500	108.00(a)	270.00	67.50		337.50
4. Wire Harness - Blower & Motors (1) Purchased Complete Allied Plant	2500	21.00(b)	52.50	13.13		65.63
4432 TOTAL						\$ 424.25
4433 Control Signal Distribution (P/H)	2500	50.00(a)	125.00	31.25		\$ 156.25
4430 TOTAL						\$ 814.88

4430 NOTES

a) Engineer estimate based on current piece part prices

b) Engineer estimate

4440

ACCOUNT NUMBERFOUNDATION & SITEACCOUNT DESCRIPTION

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>FACTORS</u>		
				<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
1) Enclosure Foundation (1)						
Material-Chlorosulfonated	2500	\$ 250.00 (a)	\$625.00	\$156.25	-	\$ 781.25
Polyethylene	-	-	-	-	-	-
Equipment - Fabrication Line		-	18.75 (b)	-	-	18.75
Labor	1.5 (men)	9,766	14.65	3.66	\$21.98	40.29
2) Foundation Pipe (1)						
Purchased Complete	2500	100.00 (b)	250.00	62.5		312.5
3) Foundation Pipe Drive Flange (1)	INCLUDED IN 440-2					
4) Foundation Pipe Alignment Pin (1)						
Purchased Complete	2500	.30 (b)	.75	.19		.94
5) Site Installation (P/H)						
Equipment	2500	-	112.50	-	-	112.50
Labor	(e) 17 hours @ \$11.90		505.75	-	-	505.75
4440 TOTAL						1771.98

NOTES 4440

- a) Material price based on carload of Chlorosulfonated Polyethylene
 b) Engineering estimate
 e) Based on Installation Study

4450

ACCOUNT NUMBER

HELIOSTAT SUPPORT AND PROTECTION

ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
4451 HELIOSTAT SUPPORT STRUCTURE						
1) Yoke Tube (1) Material-Aluminum Purchased Complete	2500	\$ 100.00(a)	\$ 250	\$ 62.5	-	\$ 312.5
2) Yoke Pivot Mount (1) Material - Aluminum Purchased Complete	2500	2.20(a)	5.50	1.38	-	6.88
3) Yoke Pivot Bearing (2) Material - Nylon Compound Tooling - Mold	2500	0.70(b)	1.75 25.00(a)	0.44 -	-	2.19 25.00
4) Yoke Pivot Shaft Material - Cold Rolled Steel Purchased Complete	2500	0.50(c)	1.25	0.31		1.56
5) Yoke Pivot Shaft Roll Pins (2) Purchased Complete	2500	0.05(a)	0.13	0.03		0.16
6) King Post Material - Polycarbonate Tooling - Mold	2500	8.41(d)	21.03 50.00(a)	5.26 -	- -	26.29 50.00
7) King Post Radial Thrust Bearing (1) Material - Nylon Compound	2500	0.70(b)	1.75	0.44	-	2.19
8) King Post Radial Bearing (1) Material - Nylon Compound	2500	0.70(b)	1.75	0.44		2.19
9) King Post Alignment Pin Material - Cold rolled steel Purchased Complete	2500	0.30(c)	0.75	0.19		0.94
10) Lower Support Tube (1) Material - Steel	2500	90.00	225.00(a)	56.25		281.25
11) Support Bracket Elevation Motor (1) Material - Polycarbonate Tooling: Mold	2500	1.88(d)	4.70 15.00	1.18		5.88 15.00
12) Support Bracket Clamp (1) Purchased Complete	2500	0.15(a)	0.38	0.09		0.47

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4450

ACCOUNT NUMBER

HELIOSTAT SUPPORT AND PROTECTION

ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
13) Final Assembly (-)						
Equipment:			\$ 3.00			\$ 3.00
Labor	2 (men)	\$9,766	19.53	\$ 4.88	\$ 29.30	53.71
14) Sub-Assembly (-)						
Equipment			41.00			41.00
Labor	2 (men)	9,766	19.53			53.71
4451 TOTAL						\$ 883.92
4452 PROTECTIVE ENCLOSURE						
1) Enclosure Top Panel (1)						
Material - Stabilized PET	2500	19.68(e)	49.20	12.3	-	61.50
Equipment - Fabrication Line			131.00	-	-	131.00
Tooling			50.00	-	-	50.00
Labor	1.5 (men)	9,766	14.65	3.66	21.98	40.29
2) Enclosure Truncated Cone Panel (1)						
Material - Stabilized PET	2500	176.09(e)	440.23	110.06	-	550.29
Equipment - Fabrication Line			24.41	-	-	24.41
Tooling			25.00	-	-	25.00
Labor	6 (men)	9,766	58.59	14.65	87.89	161.13
3) Enclosure Vertical Panel (1)						
Material - Stabilized PET	2500 (e)	225.60(e)	564.00	141		705.00
Equipment - Fabrication Line			113.00			113.00
Tooling			20.00			20.00
Labor	6 (men)	9,766	58.59	14.65	87.89	161.13
4) Enclosure Access Door Zipper (1)						
Material	2500	6.40 (a)	16.00	4.0	-	20.00
5) Enclosure Zipper (1 set)						
Material	2500	115.50	288.75	72.19		360.94

4450

ACCOUNT NUMBERHELIOSTAT SUPPORT AND PROTECTIONACCOUNT DESCRIPTIONFACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SJBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
6) Ground Cloth (1)						
Material	2500	\$ 10.80 (a)	\$ 27.00	\$ 6.75	-	\$ 33.75
Equipment			50.00 (a)			50.00
Tooling			100.00 (a)			100.00
Labor	2.75 (men)	9,766	26.85	6.71	\$ 40.28	73.84
7) Blower Assembly (1)						
Purchased	2500	130.00 (a)	325.00	81.25		406.25
4452 TOTAL						\$3087.53
4453 LIGHTNING PROTECTION						
1) Ground Wire Terminal (1)						
Purchased	2500	.02 (a)	.05	.01		.06
2) Ground Wire (Heliostat) (1)						
Purchased Allied Plant	2500 (a)	1.53 (a)	3.83	.96		4.79
3) Varistors (3)						
Purchased Allied Plant	2500	4.50 (e)	11.25	2.81		14.06
4) Field Cabling (P/H)						
Purchased Allied Plant	2500	4.50 (a)	11.25	2.81	-	14.06
4453 TOTAL						\$ 32.97
4450 TOTAL						\$4004.42

NOTES 4450

- a) Engineer estimate
- b) Vendor estimate on process cost per hour and current price of nylon
- c) Engineering estimate based on current price of cold rolled steel, labor estimate and cost per hour of machine time
- d) Engineering estimate based on car load lot of polycarbonate, vendor budgetary estimate on equipment cost per hour, and estimate of molding time
- e) Vendor quote

4460

ACCOUNT NUMBER

FIELD ASSEMBLY AND CHECKOUT

ACCOUNT DESCRIPTION

FACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
1) Installation - Supply Function (P/H)						
Labor - 2 hours (a)	2 x 2500 @ \$11.90/hour		\$ 59.50		IN 4810	\$ 59.50
2) Installation - Enclosure (P/H)						
Equipment			25.00			
Labor - 12 hours (a)	12 x 2500 @ \$11.90/hour		357.00	-	-	357.00
3) Installation-Heliostat (P/H)						
Labor - 15 hours (a)	16 x 2500 @ \$11.90/hour		476.00	-	-	476.00
Equipment			50.00			50.00
4) Installation - Power (P/H)						
Distribution-Labor 2 hrs (a)	2 x 2500 @ \$15.20/hour		76.00	-	-	76.00
Equipment			12.50	-	-	12.50
4460 TOTAL						\$ 1056.0

5-15
6

NOTES 4460

a) Based on installation study

4470

ACCOUNT NUMBER

Design and Engineering

ACCOUNT DESCRIPTION

FACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL</u> <u>(000)</u>	<u>G&A</u> <u>(000)</u>	<u>OVERHEAD</u> <u>(000)</u>	<u>TOTAL</u> <u>(000)</u>
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System Cost

OTHERACCOUNT NUMBERFACILITY & TRANSPORTATIONACCOUNT DESCRIPTION

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL</u> <u>(000)</u>	<u>FACTORS</u> <u>G&A</u> <u>(000)</u>	<u>OVERHEAD</u> <u>(000)</u>	<u>TOTAL</u> <u>(000)</u>
1) Building (leased) (a)						\$ 300.00
2) Material Handling Equipment (a)						100.00
3) Tool Room (a)						50.00
TOTAL						\$ 450.00
1) Packaging	2500	\$ 115.70 (a)	\$ 289.25	\$ 72.32	-	\$ 361.57
2) Transportation	2500	60. (a)	150.00	37.50	-	187.50
TOTAL						549.07

NOTES - OTHER

a) Engineering estimate

4800

ACCOUNT NUMBERDISTRIBUTABLES AND INDIRECT COSTACCOUNT DESCRIPTIONFACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
4810 Construction Facilities, Service G&A Fee (P/F) \$1474.25 x 94%						\$ 1385.80
1474.25 is the Field direct labor from Account 4440 and 4460						
4820 Spare Parts (P/H) 1% of 4400 less Field Direct Labor (.01 x \$9865.6 = 98.66)						98.66
4830 Architectural Engineering Service Engineer estimate (Fix Fee)						32.30
4848 Construction Management (P/F) based on 2 1/2% of Field Direct Labor (\$1474.25 x 2.5%)						36.86
4850 Plant Startup and Checkout						28.8
4860 Contingency 10% of all the above 4400, 4810 - 4850						\$ 1292.03

COLLECTOR CAPITAL INVESTMENT COST
25K PRODUCTION LEVEL

4400 Collector Equipment		54364.36
4410 Reflective Unit	6768.49	
4420 Drive Unit	6565.51	
4421 Azimuth Drive	725.00	
4422 Elevation Drive	237.25	
4423 Motors	3853.26	
4424 Position Indicators	-	
4425 Power Distribution	1750.00	
4430 Control and Instrumentation	4873.44	
4431 Sensor	1718.75	
4432 Field Control Electronics	2764.06	
4433 Control Singal Dist. Equip.	390.63	
4440 Foundation & Site	9972.82	
4450 Heliostat Support & Protection	20653.99	
4451 Heliostat Support Structure	2735.47	
4452 Heliostat Protective Encl.	18652.60	
4453 Lightning Protection	265.92	
4460 Field Assembly and Checkout	3728.50	
4470 Design and Engineering	0	
Other 1) Manufacturing Facility	595.76	
2) Packaging and Transportation	1205.85	
4800 Distributables and Indirect Costs		10555.69
4810 Construction Facilities, Services, G&A, & Fee	3822.04	
4820 Spare Parts	371.61	
4830 Architectural Engineering Service	323.00	
4849 Construction Management	101.65	
4850 Plant Startup and Checkout	36.00	
4860 Contingency	5901.87	
 TOTAL		 64920.05
		Per Year
		 2596.79
		Per Heliostat

4410

ACCOUNT NUMBER

REFLECTOR UNIT

ACCOUNT DESCRIPTION

FACTORS

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	G&A (000)	OVERHEAD (000)	TOTAL (000)
1) Strut Adjustment Cap (8)						
Material - Die Cost Aluminum	25000	5.20 a	130.0	32.5	-	162.50
Tooling - Die			3.25 b	-	-	3.26
2) Strut Tube (8)						
Material - Aluminum	25000	69.60 c	1740.00	435.0	-	2175.00
Equipment - Pressing Machine			15.30 d			15.30
Labor	2 men	9,766	19.53	4.88	29.30	53.71
3) Strut Hand Wheel Socket Ball & Pin (8)						
Material - Steel-Purchased	25000	8.32 c	208.0	52.00		360.00
Complete to Drawing						
4) Strut Cable (8)						
Material - Solid Steel Wire	25000	.96 c	24.00	6.0		30.00
Equipment - Cutting & Crimping			16.28 e			16.28
Labor	.33 men	9,766	3.22	0.81	4.38	8.86
5) Strut End Cap (8)						
Material - Die Cost Aluminum	25000	6.00 a	150.00	37.50	-	187.50
Purchased Complete to Drawing			3.26 b			3.26
Tooling - Die						
6) Reflector Hub (1)						
Material - Polycarbonate	25000	13.00 f	325.00	81.25	-	406.25
Purchased Complete to Drawing			7.32 g			7.32
Tooling: Die						
7) Reflector Hub Tail Section (1)						
Material - Aluminum	25000	2.80 c	70.00	17.50		87.50
Purchased Complete to Drawing						
8) Reflector Tension Speed Handle (1)						
Material - Die Cast Aluminum	25000	1.05 a	26.25	6.56	-	32.81
Tooling - Die			3.26 b	-	-	3.26
9) Reflector Tensioning Cable Collar (1)						
Material - Die Cast Aluminum	25000	1.10 a	27.50	6.88	-	34.38
Tooling - Die			3.26 b	-	-	3.26
10) Reflector Tensioning Spring (1)						
Purchased Complete	25000	4.00 c	100.00	25.0	-	125.00

4410

ACCOUNT NUMBER

REFLECTOR UNIT

ACCOUNT DESCRIPTION

				FACTORS		
PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	G&A (000)	OVERHEAD (000)	TOTAL (000)
11) Reflector Hub Heli Coil (1) Purchased Complete	25000	.02 c	.50	0.13	-	0.63
12) Reflector Corner Beam (8) Material - Die Cast Aluminum Tooling - Die	25000	11.20 a	280.00 6.51 h	70.0		350.00 6.51
13) Reflector Surface Material - Metalized PET Equipment - Fabrication Line Labor	25000 6 men	61.60 f 9,766	1540.00 391.58 j 58.59	385.00 14.65	 87.89	1925.00 391.58 161.13
14) Reflector Corner Loadstrap (8) Material - Stabilized PET Equipment Fabrication Line Labor	25000 3 men	5.00 e 9,766	125.00 81.38 k 29.30	31.25 7.32	 43.94	156.25 81.38 80.56
4410 TOTAL						6768.49

NOTES 4410

- a) Engineering estimate based on current price of aluminum ingots, estimate of die cast equipment cost/hour and estimate of casting time
- b) Tooling - \$20,000 die with a useful life of 10 years
- c) Engineering estimate
- d) Tooling - \$75,000 die with a useful life of 10 years
- e) Equipment - \$80,000 cutting and crimping machine with a useful life of 10 years
- f) Engineering estimate based on carload lot of polycarbonate, vendor budgetary estimate on equipment cost per hour, and estimate of molding time
- g) Tooling - \$45,000 mold with a useful life of 10 years
- h) Tooling - \$40,000 die with a useful life of 10 years
- i) Vendor quote
- j) Equipment - \$1,925,000 Film Fabrication Line with a useful life of 10 years
- k) Equipment - \$400,000 Loadstrap Fabrication Line with a useful life of 10 years

4420.
ACCOUNT NUMBER

DRIVE UNIT
ACCOUNT DESCRIPTION

FACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
4421 Azimuth Drive						
1) Azimuth Drive (1) Material - Polycarbonate Purchased Complete	25000	22.40 a	560.00	140	-	700.00
2) Azimuth Drive Wheel Keeper (1) Material - Polycarbonate Purchased Complete	25000	0.80 c	20.00	5.0	-	25.00
TOTAL 4421						725.00
4422 Elevation Drive (1)						
1) Elevation Drive Sector Material - Polycarbonate Purchased Complete	25000	7.54 a	188.55	47.14	-	235.69
2) Elevation Drive Sector Bolt (1) Purchase	25000	0.05 b	1.25	0.31		1.56
TOTAL 4422						237.25

4420

ACCOUNT NUMBER

DRIVE UNIT

ACCOUNT DESCRIPTION

FACTORS

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	G&A (000)	OVERHEAD (000)	TOTAL (000)
4423 Motors						
1) Drive Motors (2) Purchased Complete - Allied Plant	25000	\$ 120.00 c	3000	750		3750.00
2) Drive Motor Pivot Pin (2) Purchased	25000	0.15 d	3.75	0.94	-	4.69
3) Drive Motor Pivot Bucket (2) Material - Polycarbonate		3.05 a	76.25	19.06	-	95.31
Tooling Mold	25000	-	3.26 e		-	3.26
4423 TOTAL						3853.26
4424 Position Indicators - Included in 4423-1						
4425 Power Distribution and Emergency Power Field Equipment (E/H)		56.00 f	1400.00	350.00	-	1750.00

4420 TOTAL

6565.61

NOTES 4420

- a) Engineering estimate based on carload lot of polycarbonate, vendor budgetary estimate on equipment cost per hour and an estimate on molding time.
- b) Engineering estimate
- c) Engineering estimate based on purchased from Allied Plant
- d) Engineering estimate based on current price of cold rolled steel, machine time estimate and equipment cost per hour
- e) Tooling \$20,000 mold with a useful life of 10 years
- f) Based on current catalog pricing of GE Power Distribution Equipment and engineering estimates

4430

ACCOUNT NUMBERCONTROL & INSTRUMENTATIONACCOUNT DESCRIPTIONFACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
4431 Sun Sensor (1) Purchased Complete	25000	\$ 55. a	1375	343.75		1718.75
4432 Field Control Electronics						
1) Cable Standoff (3) Purchased Complete	25000	.45 b	11.25	2.81		14.06
2) Wire Harness - Sun Sensor (1) Purchased Complete Allied Plant	25000	5.00 b	125.0	31.25		156.25
3) Controller (1) Purchased Complete - Allied Plant	25000	65.00 a	1625.	406.25		2031.25
4) Wire Harness - Blower & Motors (1) Purchased Complete Allied Plant	25000	18. b	450	112.50		562.50
4432 TOTAL						2764.06
4433 Control Signal Distribution (P/H)	25000	12.50	312.50	78.13		390.63
4430 TOTAL						4873.44

a) Engineering estimate based on current piece part prices

b) Engineering estimate

4440

ACCOUNT NUMBERFOUNDATION & SITEACCOUNT DESCRIPTIONFACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
1) Enclosure Foundation (1)						
Material - Chlorosulfonated Poly-ethylene	25000	\$ 220.0 a	5500.00	1375.0	-	\$ 6875.00
Equipment - Fabrication line			101.88 b			101.88
Labor	2 men	9766	19.53	4.88	29.30	53.71
2) Foundation Pipe (1)						
Material		56. c	1400.	350.		1750
Equipment			32.27 d			32.27
Labor	2 men	9766	19.53	4.88	29.30	53.71
3) Foundation Pipe Drive Flange (1)						
Purchase	25000	.40 e	10.	2.50		12.50
4) Foundation Pipe Alignment Pin (1)						
Purchase Complete	25000	.20 e	5.	1.25		6.25
5) Site Installation (P/H)						
Equipment			750			750
Labor	1 hour f	13.50	337.50			337.50
4440 TOTAL						9972.82

NOTES 4440

- a) Material price based on carload of Chlorosulfonated Polyethylene
 b) Equipment - \$500,000 Fabrication Line with a 10 year useful life
 c) Material estimate based on carload lot of steel tubing
 d) Equipment \$160,000 swaging and welding machine with a useful life of 10 years
 e) Engineering estimate
 f) Based on Installation Study

4450

ACCOUNT NUMBERHELIOSTAT SUPPORT STRUCTUREACCOUNT DESCRIPTION

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>FACTORS</u>		
				<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
4451 HELIOSTAT SUPPORT STURCTURE						
1) Yoke Tube (1)						
Material - Aluminum	25,000	13.13 a	328.25	82.06		410.31
Equipment			95.62 (b)			95.62
Labor	2 mer.		19.53	4.88	29.30	53.71
2) Yoke Pivot Mount (1)						
Material - Aluminum		2. c	50.	12.50		62.50
Purchased Complete	25,000					
3) Yoke Pivot Bearing (2)						
Material - Nylon Compound		.60 d	15.	3.75		18.75
Tooling - Mold	25,000		4.07 (e)			4.07
4) Yoke Pivot Shaft (1)						
Material - Cold Rolled Steel		.45 c	11.25	2.81		14.06
Purchased Complete	25,000					
5) Yoke Pivot Shaft Roll Pins						
Purchased Complete	25,000	.04 c	1.	.25		1.25
6) King Post (1)						
Material - Polycarbonate		8.31 c	207.75	51.94		259.69
Tooling - Mold	25,000		8.14 (h)			8.14
7) King Post Radial Thrust Bearing (1)						
Material - Nylon Compound	25,000	.60 d	15.	3.75		18.75
8) King Post Radial Bearing						
Material - Nylon Compound	25,000	.60 d	15.	3.75		18.75
9) King Post Alignment Pin						
Material - Cold rolled steel		.20 c	5.	1.25		6.25
Purchased Complete	25,000					

4450

ACCOUNT NUMBERHELIOSTAT SUPPORT AND PROTECTIONACCOUNT DESCRIPTIONFACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
10) Lower Support Tube (1)						
Material	25,000	45. g	1125.	281.25		1406.25
Equipment			40.69 i			40.69
11) Support Bracket Elevation Motor (1)						
Material - Polycarbonate	25,000	1.78 f	44.50	11.13		55.63
Tooling: Mold			4.07 j			4.07
12) Support Bracket Clamp (1)						
Purchased Complete	25,000	.10 c	2.50	.63		3.13
13) Final Assembly						
Equipment			1.32			1.32
Labor	4 men	9,766	39.06	9.77	58.59	107.42
14) Sub-Assembly						
Equipment			10.82			10.82
Labor	5 men	9,766	48.83	12.21	73.25	134.29
4451 TOTAL						2735.47

4450

ACCOUNT NUMBERHELIOSTAT SUPPORT AND PROTECTIONACCOUNT DESCRIPTIONFACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
4452 PROTECTIVE ENCLOSURE						
1) Enclosure Top Panel (1)						
Material - Stabilized PET	25,000	16.40 k	410.	102.50		512.50
Equipment			218.74 (1			218.74
Tooling			32.55 (n			32.55
Labor	3 men		29.30	7.33	43.95	80.58
2) Enclosure Truncated Cone Panel (1)						
Material - Stabilized PET	25,000	146.70 k	3667.50	916.88		4584.38
Equipment - Fabrication Line			671.34 (n			671.34
Labor	8 men	9766	78.12	19.53	117.18	214.83
3) Enclosure: Vertical Panel (1)						
Material - Stabilized PET	25,000	188.80 k	4720.	1180		5900
Equipment - Fabrication Line			437.39 o			437.39
Labor	4 men	9766	39.06	9.77	58.59	107.42
4) Enclosure Access Door Zipper (1)						
Material	25,000	5.60 c	140.	35		175
5) Enclosure Zipper (1 set)						
Material	25,000	75.50	1887.50	471.88		2359.38
6) Ground Cloth (1)						
Material - P.E.	25,000	9.80 c	245.	61.25		306.25
Equipment			61.03			61.03
Labor	2 men		19.53	4.88	29.30	53.71
7) Blower Assembly (1)						
Purchased Complete		62 c	1550.	387.50		1937.50
4452 TOTAL						17652.6

4453

ACCOUNT NUMBER

HELIOSTAT SUPPORT AND PROTECTION

ACCOUNT DESCRIPTION

FACTORS

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	G&A (000)	OVERHEAD (000)	TOTAL (000)
4453 LIGHTING PROTECTION						
1) Ground Wire Terminal (1) Purchased	25,000	.02 c	.50	.10		.60
2) Ground Wire (1) Purchased Allied Plant	25,000	1.53 p	38.25	9.56		47.81
3) Varistor (3) Purchased Allied Plant	25,000	2.46 p	61.5	15.38		76.88
4) Field Cabling (P/H) Purchased Allied Plant	25,000	4.50 p	112.50	28.13		140.63
4453 TOTAL						265.92
4450 TOTAL						20653.99

NOTES 4450

- a) Material - Based on carload lots of aluminum tubing
- b) Equipment - \$470,000 for tube bending, punching and weld machine with a 10 year useful life
- c) Engineering estimate
- d) Material - current price of nylon compound
- e) Tooling - \$25,000 mold with a useful life of 10 years
- f) Engineering estimate based on carload lot of polycarbonate, vendor budgeting estimate on equipment cost per hour and estimate of molding time
- g) Material - Based on carload lots of steel tubing
- h) Tooling - \$50,000 mold with a useful life of 10 years
- i) Equipment \$200,000 swaging/expanding equipment with a useful life of 10 years
- j) Tooling - \$25,000 for two molds with a useful life of 10 years
- k) Vendor quote
- l) Equipment - \$1,075,000 fabrication line with a 10 year useful life
- m) Tooling - \$200,000 ultrasonic weld tooling with a 10 year useful life
- n) Equipment - \$3,300,000 fabrication line with a 10 year useful life
- o) Equipment - \$2,150,000 fabrication line with a 10 year useful life
- p) Engineering estimate based on purchased from Allied Plant

4460

ACCOUNT NUMBERFIELD ASSEMBLY AND CHECKOUTACCOUNT DESCRIPTION

ACCOUNT DESCRIPTION					FACTORS			
PART DESCRIPTION		QUANTITY	COST PER UNIT		SUBTOTAL (000)	G&A (000)	OVERHEAD (000)	TOTAL (000)
1)	INSTALLATION-SUPPLY FUNCTION (P/H)							
	Labor	(a)	2 men	@ 11.90	595.			595.00
2)	Installation-Enclosure							
	Labor	(a)	3 men	@ 11.90	892.50			892.50
3)	Installation - Heliostat							
	Labor	(a)	6 men	@ 11.90	1785.			1785
4)	Installation - Power							
	Distribution	(a)	1.2 men	@ 15.20	456			456
4460 TOTAL								3728.50

NOTES 4460

a) Based on Installation Study

4470

ACCOUNT NUMBER

DESIGN AND ENGINEERING

ACCOUNT DESCRIPTION

FACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL</u> <u>(000)</u>	<u>G&A</u> <u>(000)</u>	<u>OVERHEAD</u> <u>(000)</u>	<u>TOTAL</u> <u>(000)</u>
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System Cost

Other

ACCOUNT NUMBER

Facility & Transportation

ACCOUNT DESCRIPTION

FACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL</u> <u>(000)</u>	<u>G&A</u> <u>(000)</u>	<u>OVERHEAD</u> <u>(000)</u>	<u>TOTAL</u> <u>(000)</u>
(1) Building (a)						233.38
(2) Material Handling (a)						166.96
(3) Tool Room (a)						81.38
(4) Utilities, Safety & Environment Equipment (a)						106.08
(5) Land (a)						7.96
Total						595.76
(1) Packaging						414.76
(2) Transportation						
Equipment			116.96(a)			116.96
Expenses						120.00
Labor	13 (men)	15,500(a)	201.50	50.38	302.25	554.13
Total						1205.85

Notes Other

(a) Based on Engineering Estimates

4800

ACCOUNT NUMBERDistribution and Indirect CostACCOUNT DESCRIPTIONFACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
4810 Construction Facilities, Services G&A Fee (P/E) is the Field Direct Labor from Account #4440 & 4460 x 94% (4066 x 95%)						3822.04
4820 Spare Parts (P/H) .75% of 4400 Less Field Direct Labor (50298.36 x .75%)						377.24
4830 Architectural Engineering Service Engineering Estimate considered a Fix Fee \$12.92 (P/H)						323.00
4849 Construction Management (R/H) Based on 2 1/2% of Field Direct Labor (4066 x 2.5%)						101.65
4850 Plant Startup and Checkout						36.00
4860 Contingency 10% of all the above Accounts 4400, 4810-4850 (59018.66 x 10)						5901.87

COLLECTOR CAPITAL INVESTMENT COST
250K PRODUCTION LEVEL

4400 Collector Equipment 283959.72

4410 Reflective Unit 28131.37

4420 Drive Unit 41472.84

4421 Azimuth Drive 5219.91

4422 Elevation Drive 2208.21

4423 Motors 16544.72

4424 Position Indicators -

4425 Power Distribution 17500.00

4430 Control and Instrumentation 32634.14

4431 Sensor 9375.00

4432 Field Control Electronics 19352.89

4433 Control Signal Dist. Equip. 3906.25

4440 Foundation & Site 74868.76

4450 Heliostat Support & Protection 54707.11

4451 Heliostat Support Structure 10611.96

4452 Heliostat Protective Encl. 41785.76

4453 Lightning Protection 2309.39

4460 Field Assembly and Checkout 37285.0

4470 Design and Engineering 0

Other 1) Manufacturing Facility 3989.50

2) Packaging & Transportation 11346.00

4800 Distributables and Indirect Costs 76844.13

4810 Construction Facilities, Services,
G&A, & Fee 38220.4

4820 Spare Parts 1216.50

4830 Architectural Engineering Service 3230.00

4849 Construction Management 1016.50

4850 Plant Startup and Checkout 360.38

4860 Contingency 32800.35

TOTAL 360803.85

Per year

1443.23

per Heliostat

4410
ACCOUNT NUMBER

Reflector Unit
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY (250,000)	COST PER UNIT	FACTORS			
			SUBTOTAL (000)	G&A (000)	OVERHEAD (000)	TOTAL (000)
1. Strut Adjustment Cap (8)						
Material - Die Cast Aluminum		.53 a	132.50	33.13		165.63
Equipment			245.96 b			245.96
Tooling			13.02			13.02
Labor	2 men	9766	19.53	4.88	29.30	53.71
2. Strut Tube (8)						
Material - Aluminum		35.28 a	8820.-	2205.-		11025.-
Equipment			383.18 e			383.18
Tooling						
Labor	8 men	9766	78.12	19.53	117.18	214.83
3. Strut Handwheel Socket Ball & Pin (8)						
Material: Die Cast Aluminum		.58 a	145.-	36.25		181.25
Equipment			61.70 f			61.70
Labor	2 men	9766	19.53	4.88	29.30	53.71
4. Strut Cable (8)						
Material - Solid Steel Cable		.76 g	190.-	47.50		237.50
Equipment			34.48 l			34.48
Labor	2 men	9766	19.53	4.88	29.30	53.71
5. Strut End Cap (8)						
Material - Die Cast Aluminum		1.01 a	252.50	63.13		315.63
Equipment			181.98 i			181.98
Tooling			19.53 j			19.53
Labor	2 men	9766	19.53	4.88	29.30	53.71

4410
ACCOUNT NUMBER

Reflector Unit
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY (250,000)	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
6. Reflector Hub (1)						
Material - Polycarbonate		10.43 k	2607.50	651.88		3259.38
Equipment			95.06 l			95.06
Tooling			7.32 m			7.32
Labor	9 men	9766	87.89	21.97	131.83	241.69
7. Reflector Hub Tail Section (1)						
Material - Aluminum						
Purchase Complete to Drawing		2.60 g	650.-	162.50		812.50
8. Reflector Tensening Speed Handle (1)						
Material		.10 a	25.-	6.25		31.25
Equipment Included 4410 - 1						
Tooling			23.05 n			23.05
Labor Included 4410 - 1						
9. Reflector Tensioning Cable Collar (1)						
Material - Die Cast Aluminum		.10 a	25.-	6.25		31.25
Equipment Included in 4410 - 1						
Tooling			23.05 n			23.05
Labor Included in 4410 - 1						
10. Reflector Tensioning Spring (1)						
Purchased Complete		2.50 g	625.-	156.25		781.25
11. Reflector Hub Helicoil (1)						
Purchased complete		.01 g	2.50	.63		3.13

4410

ACCOUNT NUMBER

Reflector Unit

ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY (250,000)	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
12. Reflector Corner Beam (8)						
Material - Die Cast Aluminum		3.43 a	857.50	214.38		1071.88
Equipment			263.35			263.35
Tooling			19.53			19.53
Labor	2 men	9766	19.53	4.88	29.30	53.71
13. Reflector Surface						
Material Metalized P.E.T.		16.22 s	4055.-	1013.75		5068.75
Equipment			1659.03 q			1659.03
Labor	21 men	9766	205.07	51.27	307.60	563.94
14. Reflector Corner Loadstrap (1)						
Material P.E.T.		2.00 s	500.-	125.-		625.00
Equipment			122.06 r			122.06
Labor	3 men	9766	29.30	7.32	43.94	80.56
TOTAL 4410						28131.37

Notes 4410

- a. Material based on current price of aluminum ingots.
- b. Equipment: \$760,000 for two die-cast machines (10 year life), 240,000 for 4 robots (5 year life) and \$60,000 for two threaders (10 year life).
- c. Tooling: \$80,000 for two dies (10 year life).
- d. Material based on current price of aluminum sheet stock.
- e. Equipment: \$1,000,000 for two rolling mills (10 year life), \$360,000 for 6 robots (5 year life) and \$300,000 for four pressing machines.
- f. Equipment: \$125,000 Multi-purpose line (10 year life), \$50,000 clean & rust treatment line (5 year life) and \$60,000 robot (5 year life).
- g. Engineering estimate.
- h. Equipment \$170,000 cold heading machine (10 year life).
- i. Equipment: \$700,000 for 2 die casting machines (10 year life) and \$120,000 for two robots (5 year life).
- j. Tooling: \$120,000 die with a 10 year life.
- k. Material based on carload lot of Polycarbonate.
- l. Equipment: \$50,000 automatic drill machine (10 year life), \$20,000 ultrasonic bonding machine (5 year life), 25,000 for three Hopper Driers (10 year life), \$325,000 for three injection molding machines (15 year life), \$40,000 for two adhesive machines (5 year life) and \$20,000 pressing machine (5 year life).
- m. Tooling: \$45,000 for 3 molds (10 year life).
- n. Tooling: \$40,000 Die (2 year life).
- o. Equipment: \$1,040,000 for two die cast machines (10 year life), \$120,000 for two robots (5 year life), and \$60,000 for two wire brush machines (10 year life).
- p. Tooling: \$120,000 die (10 year life).

Notes 4410

- q. Equipment: \$7,580,000 Extrusion, metalizing, fabrication and U.V. Line (10 year life).
- r. Equipment: \$600,000 Fabrication line (10 year life).
- s. Material: Raw material price for F.E.T. and Stabilizer.

4420

ACCOUNT NUMBER

Drive Unit

ACCOUNT DESCRIPTIONFACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u> (250,000)	<u>COST PER UNIT</u>	<u>SUBTOTAL</u> (000)	<u>G&A</u> (000)	<u>OVERHEAD</u> (000)	<u>TOTAL</u> (000)
4421 Azimuth Drive						
1. Azimuth Drive (1)						
Material - Polycarbonate		14.99 a	3747.50			4684.38
Equipment			241.26 b			241.26
Tooling			21.81 c			21.81
Labor	2 men	9766	19.53	4.88	29.30	53.71
2. Azimuth Drive Wheel Keeper (1)						
Material - Polycarbonate		.70 d	175.-	43.75		218.75
4421 TOTAL						5219.91
4422 Elevation Drive						
1. Elevation Drive Sector (1)						
Material - Polycarbonate		6.25 a	1562.50	390.63		1953.13
Equipment			179.95 e			179.95
Tooling			12.04 f			12.04
Labor	2 men	9766	19.53	4.88	29.30	53.71
2. Elevation Drive Sector Bolt (1)						
Purchased Complete		.03 d	7.50	1.88		9.38
4422 TOTAL						2208.21

4420
ACCOUNT NUMBER

Drive Unit
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY (250,000)	COST PER UNIT	SUBTOTAL (000)	FACTORS		TOTAL (000)
				G&A (000)	OVERHEAD (000)	
4423 Motors						
1. Drive Motors (2) Purchased Complete - Allied Plant		\$52 d	13000	3250		16250.00
2. Drive Motor Pivct Pin (2) Material - Cold rolled Steel Equipment) Labor) Included in 4451 - 9		.04 g	10.0	2.5		12.50
3. Drive Motor Pivct Bracket (2) Material - Polycarbonate Equipment Tooling Labor		.40 a	100.00	25.00		125.00
			63.62 h			63.62
			13.02 i			13.02
	3 men	9766	29.30	7.33	43.95	80.58
4423 TOTAL						16544.72

5-48

4420
ACCOUNT NUMBER

Drive Unit
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY (250,000)	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
4424 Position Indicators - Included in 4423-1						
4425 Power Distribution & Emergency Power Field Equipment (P/H)		56 j	14000	3500		17500.00
4420 TOTAL						

Notes 4420

- 5-49
- a. Material: Based on carload lots of Polycarbonate
 - b. Equipment: \$1,000,000 injection molding machine (15 year life) \$200,000 transfer molding machines (15 year life), \$30,000 mixing equipment (10 year life), 25,000 Hopper drier (10 year life) and \$200,000 Handling Equipment (15 year life)
 - c. Tooling: 134,000 for 4 molds (10 year life)
 - d. Engineering estimate.
 - e. Equipment: \$1095000 for two injection and transfermolding lines (15 year life)
 - f. Tooling: \$74,000 for 4 dies (10 year life)
 - g. Material: Based on current price of cold rolled steel.
 - h. Equipment: \$300,000 for four Injection molding machines (15 year life), \$60,000 drill machine (10 year life), and \$20,000 hopper drier (10 year life)
 - i. Tooling: \$80 for 4 dies (10 year life)
 - j. Based on Installation Study.

4430

ACCOUNT NUMBER

Control & Instrumentation

ACCOUNT DESCRIPTION

				FACTORS		
PART DESCRIPTION	QUANTITY (25¢,000)	COST PER UNIT	SUBTOTAL (000)	G&A (000)	OVERHEAD (000)	TOTAL (000)
4431 Sun Sensor (1) Purchased Complete		30.00 a	7500.-	1875.-		9375.-
4432 Field Control Electronics						
1. Cable Stand-Off Purchased Complete		.24 b	60.-	15.-		75.-
2. Wire Harness - Sun Sensor (1)						
Material		2.57 b	642.50	160.63		803.13
Equipment			25.43 c			25.43
Labor	1 man	9766	9.77	2.44	14.66	26.87
3. Controller (1) Purchased Complete - Allied Plant		50.00 a	12500.-	3125.-		15625.-
4. Wire Harness - Blower & Motors (1)						
Material		8.78 b	2195.-	548.75		2743.75
Labor Equipment included in 4432-2	2 men	9766	19.53	4.88	29.30	53.71
4432 TOTAL						19352.89
4433 Control Signal Distribution (P/H)		12.50 a	3125.0	781.25		3906.25
4430 TOTAL						2634.14

Notes 4430

- a. Engineering estimates based on current piece part prices.
 b. Engineering estimate.
 Equipment: \$125,000 cut, strip and crimp machine (10 year life).

4440
ACCOUNT NUMBER

Foundation & Site
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY (250,000)	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
1. Enclosure Foundation (1)						
Material - Chlorosulfonated Polyethylene		201.01 a	50252.5	12563.13		62815.63
Equipment - Fabrication Line			2277.93 b			2277.93
Labor	10 men		97.66	24.42	146.49	268.57
2. Foundation Pipe (1)						
Material - Steel		6.80 c	1700.00-	425.-		2125.-
Equipment			356.04 d			356.04
Labor	2 men		19.53	4.88	29.30	53.71
3. Foundation Pipe Drive Flange (1)						
Material - Steel		.35 c	87.5	21.88		109.38
Equipment						
Tooling						
Labor						
4. Foundation Pipe Alignment Pin (1)						
Material		.04 c	10.-	2.5		12.5
Labor						
5. Site Intallation (P/H)						
Equipment		\$ 12.00 e	3000.-			3000.-
Labor	1 man	@ 13.50	3375.-			3375.-
4440 TOTAL						74393.76

Notes 4440

- a. Material based on current price of chlorosulfonated Polyethylene.
- b. Equipment: \$10,000,000 calender roll set (10 year life) and 1,180,000 for two fabrication lines (10 year life).
- c. Material based on current price of cold rolled steel.
- d. Equipment: \$1,750,000 tube fabrication and swaging line (10 year life).
- e. Based on Installation Study.

4450

ACCOUNT NUMBER

Heliostat Support and Protection
ACCOUNT DESCRIPTION

PART DESCRIPTION		QUANTITY (250,000)	COST PER UNIT	SUBTOTAL (000)	FACTORS G&A (000)	OVERHEAD (000)	TOTAL (000)
4451	Heliostat Support Structure						
1.	Yoke Tube (1)						
	Material - Aluminum		13.13 a	3282.50	820.63		4103.13
	Equipment			125.58 b			125.58
	Labor	2 men	9766	19.53	4.88	29.30	53.71
2.	Yoke Pivot Mount (1)						
	Material - Extended Aluminum		1.50 c	375.-	93.75		468.75
	Purchased Complete						
3.	Yoke Pivot Bearing (2)						
	Material: Nylon Compound		.36 d	90.-	22.50		112.50
	Equipment			8.22 e			8.22
	Tooling			18.- f			18.-
	Labor	1 man	9766	9.77	2.44	14.66	26.87
4.	Yoke Pivot Shaft (1)						
	Material - Cold Rolled Steel		.17 g	42.50	10.63		53.13
	Equipment			75.70 h			75.70
	Labor	6 men	9766	9.77	2.44	14.66	26.87
5.	Yoke Pivot Shaft Roll Pins (2)						
	Purchased Complete		.02 c	5.-	1.25		6.25
6.	King Post						
	Material: Polycarbonate		6.88 i	1720.-	430.-		2150.-
	Equipment			72.14 j			72.14
	Tooling			15.26 k			15.26
	Labor	3 men	9766	29.30	7.33	43.95	80.58

5-53

4450

ACCOUNT NUMBER

Heliostat Support and Protection

ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY (250,000)	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
7. King Post Radial Thrust Bearing (1) Material - Nylon Compound Equipment) Tooling) Included in 4451-3 Yoke Pivot Bearing Labor)		.39 d	97.50	24.38		121.88
8. King Post Radial Bearing (1) Material - Nylon Compound Equipment) Tooling) Included in 4451-3 Yoke Pivot Bearing Labor)		.36 d	90.-	22.50		112.50
9. King Post Alignment Pin (1) Material - Cold Rolled Steel Equipment Labor		.04 g	10.-	2.50		12.50
			61.54 l			61.54
	1 man	9766	9.77	2.44	14.66	26.87
10. Tower Support Tube Material - Steel Equipment Labor		5.19 g	1297.50	324.38		1621.88
			216.07 m			216.07
	2 man	9766	19.53	4.88	29.30	53.71
11. Support Bracket - Elevation Motor (1) Material - Polycarbonate Equipment Tooling Labor		1.18 i	295.-	73.75		368.75
			78.61 n			78.61
			9.15 o			9.15
	3 men	9766	29.30	7.33	43.95	80.58
12. Support Bracket Clamp (1) Purchased Complete		.05 c	12.5	3.13		15.63

4450

ACCOUNT NUMBER

Heliostat Support and Protection

ACCOUNT DESCRIPTION

<u>PART DESCRIPTION</u>	<u>QUANTITY</u> (250,000)	<u>COST PER UNIT</u>	<u>SUBTOTAL</u> (000)	<u>FACTORS</u>		
				<u>G&A</u> (000)	<u>OVERHEAD</u> (000)	<u>TOTAL</u> (000)
13. Final Assembly (-)						
Equipment			5.94 p			5.94
Labor	16 men	9766	156.24	39.06	234.36	429.66
4451 TOTAL						10611.96

4450

ACCOUNT NUMBER

Heliostat Support and Protection

ACCOUNT DESCRIPTION

FACTORS

PART DESCRIPTION	QUANTITY (250,000)	COST PER UNIT	SUBTOTAL (000)	G&A (000)	OVERHEAD (000)	TOTAL (000)
4452 Protective Enclosure						
1. Enclosure Top Panel						
Material: Stabilized P.E.T.		1.61 q	402.50	100.63		503.13
Equipment			109.86 r			109.86
Tooling			32.55 s			32.55
Labor	4 men	9766	39.06	9.77	58.59	107.42
2. Enclosure Truncated Cone Panel (1)						
Material: Stabilized P.E.T.		14.44 q	3610.-	902.50		4512.50
Equipment			1374.22 t			1374.22
Tooling						
Labor	12 men	9766	117.18	29.30	175.77	322.25
3. Enclosure Vertical Panel (1)						
Material: Stabilized P.E.T.		18.51 q	4627.50	1156.88		5784.38
Equipment			1927.57 u			1927.57
Tooling						
Labor	15 men	9766	146.48	36.62	219.72	402.82
4. Enclosure Access Door Zipper (1)						
Material		4.80 c	1200.-	300.-		1500.-
5. Enclosure Zipper (1 set)						
Material - Polyurethane		21.90 c	5475.-	1368.75		6843.75
Equipment			79.34 y			79.34
Tooling			13.02 w			13.02
Labor	9 men	9766	87.89	21.97	131.84	241.70

4450
ACCOUNT NUMBER

Heliostat Support and Protection
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY (250,000)	COST PER UNIT	SUBTOTAL (000)	FACTORS		TOTAL (000)
				G&A (000)	OVERHEAD (000)	
6. Ground Cloth						
Material		7.84 c	1870.-	467.50		2337.50
Equipment			193.27 x			193.27
Tooling						
Labor	7 men	9766	68.36	17.09	112.53	187.98
7. Blower Assembly						
Purchased		49.- c	12250.-	3062.50		15312.50
4452 TOTAL						41785.76

4450

ACCOUNT NUMBER

Heliostat Support and Protection

ACCOUNT DESCRIPTION

FACTORS

PART DESCRIPTION	QUANTITY (250,000)	COST PER UNIT	SUBTOTAL (000)	G&A (000)	OVERHEAD (000)	TOTAL (000)
4453 Lightning Protection						
1. Ground Wire Terminal (1) Purchased Complete		.01 c	2.50	.63		3.13
2. Ground Wire Heliostat (1) Purchased Allied Plant		1.53 c	382.5	95.63		478.13
3. Varistor (3) Purchased Allied Plant		1.35 c	337.5	84.38		421.88
4. Field Ground Cabling (P/H) Purchased Allied Plant		4.50 c	1125.-	281.25		1406.25
4453 TOTAL						2309.39

5-58

Notes 4450

- a. Based on current price of aluminum sheet stock.
- b. Equipment: \$400,000 Tube bender & rolling mill (10 Year life), \$60,000 Robot (5 year life), 20,000 Punching Machine (10 year life) and \$100,000 Welder (10 year life).
- c. Engineering estimate.
- d. Material: Based on current price of Nylon Compound.
- e. Equipment: \$50,000 Injection molding machine with a useful life of 15 years.
- f. Tooling: \$18,000 Mold with a useful life of 1.3 years.
- g. Material based on current price for cold rolled steel.
- h. Equipment: \$50,000 cut-off & chamfer machine (10 year life), \$100,000 clean & rust treat equipment (5 year life) \$60,000 automatic drilling machine (10 year life), and \$100,000 conveyor (10 year life).
- i. Material: Based on carload lots of Polycarbonate.
- j. Equipment: \$250,000 for 2 Injection Molding Machines (15 year life), \$60,000 Robot (5 year life) \$50,000 Spin Welder (15 year Life) and \$15,000 Hopper drier (10 year life).
- k. Tooling: \$75,000 for two molds with a useful life of 10 years.
- l. Equipment: \$100,000 conveyor (10 year life), \$50,000 cut-off & chamfer machine (15 year life) and 100,000 clean & rust treat machine (5 year life).
- m. Equipment: \$500,000 auto-fabrication line (10 year life), \$100,000 clean and rust treat line (5 year life) and \$300,000 swaging/expander machine (10 year life).
- n. Equipment: \$80,000 for 2 Injection Molding Machines (15 year life) and \$23,000 Grinding machine (10 year life), \$180,000 for three Robots (5 year life) and \$10,000 Hopper Drier (10 year life).
- o. Tooling: \$45,000 for two molds (10 year life).

Notes 4450

- p. Equipment: \$18,000 Fixtures Final Assembly (5 year life).
- q. Material: Raw material price for P.E.T. and Stabilizer
- r. Equipment: \$555,000 Fabrication and slitter line (10 year life).
- s. Tooling: \$200,000 (10 year life).
- t. Equipment: \$6,755,000 Extrusion, U.V. Stabilization and Fabrication line (10 year life).
- u. Equipment: \$9,475,000 Extrusion, U.V. Stabilization and Fabrication line (10 year life).
- v. Equipment: \$390,000 Extrusion and Slitter line (10 year life).
- w. Tooling: \$80,000 (10 year life).
- x. Equipment: \$950,000 Film line (10 year life).

4460
ACCOUNT NUMBER

Field Assembly and Checkout
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY (250,000)	COST PER UNIT	SUBTOTAL (000)	FACTORS		TOTAL (000)
				G&A (000)	OVERHEAD (000)	
1. Installation - Supply Function (P/H) Labor a	2 men	@ 11.90	5950.-			5950.-
2. Installation - Enclosure (P/H) Labor a	2 men	@ 11.90	8925.-			8925.-
3. Installation - Heliostat (P/H) Labor a	6 men	@ 11.90	17850.			17850.-
4. Installation - Power (P/H) Labor a	1.2 men	@ 15.20	4560.			4560.-
4460 TOTAL						37285.-

a. Based on Installation Study

4470

ACCOUNT NUMBER

Design and Engineering

ACCOUNT DESCRIPTION

FACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL</u> <u>(000)</u>	<u>G&A</u> <u>(000)</u>	<u>OVERHEAD</u> <u>(000)</u>	<u>TOTAL</u> <u>(000)</u>
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System Cost

Other

ACCOUNT NUMBER

Facility & Transportation

ACCOUNT DESCRIPTION

FACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL</u> <u>(000)</u>	<u>G&A</u> <u>(000)</u>	<u>OVERHEAD</u> <u>(000)</u>	<u>TOTAL</u> <u>(000)</u>
<u>Facility</u>						
(1) Building (a)						\$ 1 620.90
(2) Material Handling (a)						804.
(3) Production Control (a)						65.1
(4) Tool Room (a)						406.88
(5) Utilities, Safety & Environment Equipment (a)						1 060.80
(6) Land (a)						31.82
Total Facility						\$ 3 989.5
<u>Transportation</u>						
(1) Packaging						3 760.71
(2) Transportation						
Equipment (b)			\$ 1 057.16			1 057.16
Operating Expenses (a)			1 200.			1 200.
Labor	(125)	15500	1 937.50	484.38	2 906.25	5 328.13
Total Transportation						\$11 346.00

Notes Other

(a) Engineering Estimate

(b) Vendor Quote

4800

ACCOUNT NUMBER

Distributables and Indirect Cost

ACCOUNT DESCRIPTION

				<u>FACTORS</u>		
<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL</u> <u>(000)</u>	<u>G&A</u> <u>(000)</u>	<u>OVERHEAD</u> <u>(000)</u>	<u>TOTAL</u> <u>(000)</u>
4810 Construction Facilities G&A and Fee 40660 x 94% is the Field Direct Labor from Account #4440 & 4460 x 94% (40660 x 94%)						38220.4
4820 Spare Parts .5% of 4400 less Field Direct Labor (283959.72 - 40660 = 243299.72 x .005)						1216.50
4830 Architectural Engineering Service Engineering Estimate considered a Fix Fee \$12.92 (P/H)						3230.00
4849 Construction Management Based on 2 1/2% of Field Direct Labor (40660 x 2.5%)						1016.50
4850 Plant Start Up and Checkout						360.38
4860 Contingency 10% of all the above Accounts 4400, 4810-4850 (283959.72 44043.78 = 328003.5 x .10)						<u>32800.35</u>
4800 TOTAL						76844.13

COLLECTOR CAPITAL INVESTMENT COST
1M PRODUCTION LEVEL

4400	Collector Equipment		1065463.8
4410	Reflective Unit	105763.88	
4420	Drive Unit	160343.60	
4421	Azimuth Drive	20475.23	
4422	Elevation Drive	8723.78	
4423	Motors	61144.59	
4424	Position Indicators	-	
4425	Power Distribution	70000.00	
4430	Control and Instrumentation	111464.54	
4431	Sensor	31250.00	
4432	Field Control Electronics	64589.54	
4433	Control Signal Dist. Equip.	15625.00	
4440	Foundation & Site	292447.87	
4450	Heliostat Support & Protection	192624.69	
4451	Heliostat Support Structure	31185.78	
4452	Heliostat Protective Encl.	152528.91	
4453	Lightning Protection	8900.00	
4460	Field Assembly and Checkout	149140.00	
4470	Design and Engineering	0	
Other	(1) Manufacturing Facility	10645.39	
	(2) Packaging & Transportation	43033.84	
4800	Distributables and Indirect Costs	297468.6	
4810	Construction Facilities, Services, G&A&Fee	152881.6	
4820	Spare Parts	2257.06	
4830	Architectural Engineering Service	12920.00	
4849	Construction Management	4066.0	
4850	Plant Startup and Checkout	1441.00	
4860	Contingency	123902.94	
TOTAL		1362932.4	
		per year	
		<u>1362.94</u>	
		per heliostat	

4410
ACCOUNT NUMBER

Reflector Unit
ACCOUNT DESCRIPTION

FACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
1) Strut Adjustment Cap(8)						
Material-Die Cast Aluminum	1 million	.53a	530.-	132.50		662.50
Equipment			457.27b			457.27
Tooling			39.06c			39.06
Labor	(4 men)	9,766	39.06	9.77	58.09	107.42
2) Strut Tube (8)						
Material-Aluminum	1 million	35.28a	35.280	8820.-		44100.-
Equipment			114954e			1149.54
Tooling						
Labor	(24 men)		234.36	58.59	351.54	644.49
3) Strut Handwheel Socket Ball & Pin (8)						
Material: Die Cast Aluminum	1 million	.58a	580.-	145		725.-
Equipment			246.81 f			246.81
Labor	(8 men)	9,766	78.12	19.53	117.18	214.83
4) Strut Cable (8)						
Material - Solid Steel Cable	1 million	.76 g	760.-	190.-		950.-
Equipment			61.03 h			61.03
Labor	(2 men)	9,766	19.53	4.88	29.30	53.71
5) Stut End Cap (8)						
Material-Die Cast Aluminum		1.01 a	1010.-	252.50		1262.50
Equipment			557.02 i			557.02
Tooling			65.10 j			65.10
Labor	(8 men)		78.12	19.53	117.18	214.83

4410
ACCOUNT NUMBER

Reflector Unit
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
6) Reflector Hub (1)						
Material-Polycarbonate	1 million	10.43 k	10 430.-	2607.50		13037.50
Equipment			275.04 l			275.04
Tooling			21.97 m			21.97
Labor	(27 men)	9,766	263.66	65.91	395.48	725.05
7) Reflector Hub Tail Section (1)						
Material-Aluminum	1 million	1.38 a	1380.00	345.00		1725.-
Equipment			61.98 n			61.98
Tooling			4 o			4.00
Labor	(3 men)		29.30	7.32		80.56
Purchase Complete		9,766				
8) Reflector Speed Handle (1)						
Material - Aluminum	1 million	10 a	100.-	25-		125.-
Equipment			75.78 p			75.78
Tooling			80.- q			80.-
Labor	(2 men)		19.53	4.88	29.30	53.71
9) Reflector Tensioning Cable Collar (1)						
Material-Die Cast Aluminum	1 million	.10 a	100.-	25.-		125.-
Equipment			69.63r			69.63
Tooling			80.- q			80.-
Labor	(2 men)	9,766	19.53	4.88	29.30	53.71
10) Reflector Tensioning Spring (1)						
Purchased Complete		2.00 g	2000.-	500.-		2500.-
11) Reflector Hub Helicoil (1)						
Purchased Complete		.01 g	10.00	2.50		12.50

4410
ACCOUNT NUMBER

Reflector Unit
ACCOUNT DESCRIPTION

					<u>FACTORS</u>		
		<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL</u>	<u>G&A</u>	<u>OVERHEAD</u>	<u>TOTAL</u>
<u>PART DESCRIPTION</u>				<u>(000)</u>	<u>(000)</u>	<u>(000)</u>	<u>(000)</u>
12)	Reflector Corner Beam (8)						
	Material-Die Cast Aluminum	1 million	3.43	3430.-	857.50		4287.50
	Equipment			801.14 s			801.14
	Tooling			65.10 t			65.10
	Labor	(8 men)	9,766	78.12	19.53	117.18	214.83
13)	Reflector Surface (1)						
	Material - Metalized PET	1 million	16.22 u	16 220.-	4055.-		20 275.-
	Equipment			5347.79 v			5347.59
	Labor	(39 men)	9,766	380.84	95.21	571.25	1047.30
14)	Reflector Corner Loadstrap (8)						
	Material - PET		2.00	2000.-	500.-	2500.00	2500.-
	Equipment			366.19 w			366.19
	Labor	(9 men)	9,766	87.89	21.97	131.83	241.69
TOTAL 4410							105763.88

NOTES 4410

- a. Material Based on current price of Aluminum
- b. Equipment: \$1125,000 for five die cast machines (10 year life), \$600,000 robots (5 year life) and \$150,000 for 5 threaders (10 year life)
- c. Tooling: \$240,000 for six dies
- d. Material based on current price of aluminum sheet stock.
- e. Equipment: \$3,000,000 for six rolling mills (10 year life), \$1,080,000 for 18 robots (5 year life) and \$900,000 for 12 pressing machines
- f. Equipment: \$500,000 for four multi-purpose lines (10 year life), \$200,000 for four clean & rust treatment lines (5 year life) and \$240,000 for four robots (5 year life)
- g. Engineering estimate
- h. Equipment: 300,000 for two automated cold heading machines. (10 year life)
- i. Equipment: 1,960,000 for eight die casting machines (10 year life) and \$480,000 for eight robots (5 year life)
- j. Tooling: \$400,000 for eight dies (10 year life)
- k. Material based on carload lot of polycarbonate.
- l. Equipment: \$150,000 for three automatic drill machine (10 year life), \$60,000 ultrasonic bonding machine (5 year life), 25,000 for three hopper driers (10 year life), \$975,000 for 10 injection molding machines (15 year life), \$120,000 for six adhesive machines (5 year life) and \$60,000 for three pressing machines (5 year life).
- m. Tooling: \$135,000 for ten dies (10 year life)
- n. Equipment: \$80,000 threadrolling and cut-off machine (15 year life) and \$240,000 for 4 robots (5 year life)
- o. Tooling: \$4,000 threading die (1 year life)
- p. Equipment: \$275,000 die cast machine, trim and threading line (10 year life) and \$60,000 robot (5 year life)
- q. Tooling \$80,000 Die (1 year life)

- r. Equipment: \$245,000 die cast machine and trimer (10 year life) and \$60,000 robot (5 year life)
- s. Equipment: \$3,160 for eight die cast machine and wire bursh lines (10 year life) \$480,000 for eight robots (5 year life) and \$700,000 central melt furnace for all die cast parts (10 year life)
- t. Tooling \$400,000 dies (10 year life)
- u. Material - Raw material price for P.E.T. and Stabilizer.
- v. Equipment - \$26,165,000 Extrusion, metalizing, fabrication and U.V. line (10 year life) and a \$150,000 Silo and transfer system (15 year life).
- w. Equipment - \$1,800,000 fabrication line (10 year life)

4420
ACCOUNT NUMBER

Drive Unit
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
4421 Azimuth Drive						
1. Azimuth Drive (1)						
Material Polycarbonate	1 million	14.99 a	14990.-	3747.50		18,737.50
Equipment			965.04 b			965.04
Tooling			87.24 c			87.24
Labor	(8 men)		78.12	19.53	117.18	214.83
2. Azimuth Drive Wheel Keeper (1)						
Material: Polycarbonate	1 million	.355 a	355.-	88.75		443.75
Labor	1 man	9,766	9.77	2.44	14.66	26.87
TOTAL 4421						20 475.23
4422 Elevation Drive						
1. Elevation Drive Sector (1)						
Material-Polycarbonate	1 million	6.25 a	6250.-	1562.50		7812.50
Equipment			610.79 e			610.79
Tooling			48.16 f			48.16
Labor	8 men	9,766	78.12	19.53	117.18	214.83
2. Elevation Drive Sector Bolt (1)						
Purchased Complete		.03 a	30.-	7.50		37.50
TOTAL 4422						8723.78

4420
ACCOUNT NUMBER

Drive Unit
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS			TOTAL (000)
				G&A (000)	OVERHEAD (000)		
4423 Motors							
1. Drive Motors (2)							
Purchased Complete - Allied Plant	1 million	48.00 d	48000	12000			60000
2. Drive Motor Pivot Pin (2)							
Material- Cold Rolled Steel	1 million	.04 g	40	10	-		50
Equipment			69.76 h				69.76
Labor	2 men	9,766	19.53	4.88	29.30		53.71
3. Drive Motor Pivot Bracket (2)							
Material-Polycarbonate	1 million	.40 a	400	100	-		500.00
Equipment			180.60 i				180.60
Tooling			48.83 j	-	-		48.83
Labor	9 men	9.766	87.89	21.97	131.84		241.69
TOTAL 4423							61144.59

4420

ACCOUNT NUMBER

Drive Unit

ACCOUNT DESCRIPTION

FACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL</u> <u>(000)</u>	<u>G&A</u> <u>(000)</u>	<u>OVERHEAD</u> <u>(000)</u>	<u>TOTAL</u> <u>(000)</u>
4424 Position Indicators - Included in 4423-1						
4425 Power Distribution & Emergency Power Field Equipment (P/H)	1 million	\$56.00 k	56000.00	14000.0		70,000.00

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TOTAL 4420

160343.60

Notes 4420

- a. Material based on carload lot of Polycarbonate.
- b.
- b. Equipment: \$4,000,000 Injection molding machine (15 years life), \$800,000 transfer molding machine (15 year life), \$120,000 mixing equipment (10 year life), \$100,000 hopper drier (10 year life) and \$800,000 handling equipment (15 year life).
- c. Tooling: \$536,000 for molds (10 year life).
- d. Engineering estimate.
- e. Equipment \$3,730,000 for five injection and transfer molding lines (15 year life).
- f. Tooling \$296,000 molds (10 year life).
- g. Material based on current price of cold rolled steel.
- h. Equipment: \$100,000 cut off and chamfer machine (15 year life) \$100,000 clean & rust treatment machine (5 year life) and \$100,000 conveyor (10 year life).
- i. Equipment: \$975,000 for thirteen injection molding machines (15 year life), \$60,000 automatic drill (10 year life) and \$40,000 hopper drier (10 year life).
- j. Tooling \$300,00 (10 year life).
- k. Based on installation study.

4430

ACCOUNT NUMBER

Control & Instrumentation

ACCOUNT DESCRIPTION

FACTORS

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	G&A (000)	OVERHEAD (000)	TOTAL (000)
4431 Sun Sensor (1) Purchased Complete	1 million	25.00 a	25000-	6250-		31250-
4432 Field Control Electronics						
1. Cable Stand-Off (3) Purchased Complete	1 million	.15 b	150-	37.50		187.50
2. Wire Harness - Sun Sensor (1) Material		2.57 b	2570.00	642.50	-	3212.50
Equipment			30.64 c			30.64
Labor	1 man	9766.00	9.77	2.44	1466	26.87
3. Controller (1) Purchased complete Allied Plant	1 million	40.00 a	4000.00	1000.00	-	50000.00
4. Wire Harness- Blower & Motors (1) Material	1 million	8.78 b	8780.00	2195.00	-	10975.00
Equipment			76.45 d			76.45
Labor	3 men	9766.00	29.30	7.33	43.95	80.58
TOTAL 4432						64589.54
4433 Central Signal Distribution (A/H)	1 million	12.50 a	12500	3125	-	15625
TOTAL 4430						111464.54

NOTES 4430, 4431, 4432 & 4433

- a. Engineering estimates based on current piece part prices
- b. Engineering estimate
- c. Equipment: \$150,000 cut, strip, and crimp machine (10 year life)
- d. Equipment: \$375,000 cut, strip, and crimp machine (10 year life)

4440
ACCOUNT NUMBER

Foundation & Site
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
1. Enclosure Foundation (1)						
Material-Chlorosulfonated Polyethylene	1 million	201.01 a	201010.-	5025.25		251262.50
Equipment-Fabrication Line			5517.55 b			5517.55
Labor	26 men	9766	253.92	63.48	380.87	698.27
2. Foundation Pipe (1)						
Material - Steel	1 million	6.80 c	6800.-	1700.-		8500.-
Equipment			439.93 d			439.93
Labor	6 men	9766	58.60	14.65	87.89	161.14
3. Foundation Pipe Drive Flange (1)						
Material-Steel	1 million	.17 c	170.-	42.50		212.50
Equipment			40.75 e			40.75
Tooling			11.52 f			11.52
Labor	2 men	9766	19.53	4.88	29.30	53.71
4. Foundation Pipe Alignment Pin (1)						
Material	1 million	.04 c	40.-	10.-		50.-
Labor						
5. Site Installation (P/H)						
Equipment	1 million	12.00 g	12000.-			12000.-
Labor		13.50 g	13500.-			13500.-
4440 TOTAL						292447.87

5-77

Notes 4440

- a. Material based on current price of chlorosulfinated polyethylene
- b. Equipment: 20,000,000 callender roll set (10 year life) and 7,080,000 fabrication line (10 year life)
- c. Material based on current price of cold rolled steel.
- d. Equipment 1,800,000 tube fabrication and swaging line (10 year life) \$60,000 robot (5 year life) \$100,000 clean & rust treatment machine and \$100,000 conveyor (10 year life).
- e. Equipment: \$200,000 punch press (10 year life).
- f. Tooling: \$20,000 Die (2 year life)
- g. Based on Installation Study

4450
ACCOUNT NUMBER

Heliostat Support and Protection
ACCOUNT DESCRIPTION

PART DESCRIPTION		QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		
					G&A (000)	OVERHEAD (000)	TOTAL (000)
4451	Heliostat Support Structure						
1.	Yoke Tube (1)						
	Material - Aluminum	1 million	5.78 a	5780.00	1445.00		7225.00
	Equipment			266.87 b			266.87
	Labor	4 men	9766.	39.06	9.77	58.59	107.42
2.	Yoke Pivot. Mount (1)						
	Material - Extended Aluminum	1 million	1.25 c	1250.00	312.50		1562.50
	Purchased Complete						
3.	Yoke Pivot Bearing (2)						
	Material-Nylon Compound	1 million	0.36 d	360.00	90.00		450.00
	Equipment			9.04 e			9.04
	Tooling			4.48 f			4.48
	Labor	1 man	9766.	9.77	2.44	14.66	26.87
4.	Yoke Pivot Shaft (1)						
	Material - Cold Rolled Steel	1 million	0.17 g	170.00	42.50		212.50
	Equipment			85.87 h			85.87
	Labor	2 men		19.53	4.88	29.30	53.71
5.	Yoke Pivot Shaft Roll Pins (2)						
	Purchased Complete	1 million	.02 c	20.00	5.00		25.00
6.	King Post (1)						
	Material: Polycarbonate	1 million	6.88 i	6880.00	1720.00		8600.00
	Equipment			165.94 j			165.94
	Tooling			40.69 k			40.69
	Labor	12 men	9766.	117.68	29.30	175.77	322.25

4450
ACCOUNT NUMBER

Heliostat Support and Protection
ACCOUNT DESCRIPTION

FACTORS

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL (000)</u>	<u>G&A (000)</u>	<u>OVERHEAD (000)</u>	<u>TOTAL (000)</u>
7. King Post Radial Thrust Bearing (1)						
Material - Nylon Compound	1 million	0.39 d	390.00	97.50		487.50
Equipment			15.96 l			15.96
Tooling			4.07 m			4.07
Labor	1 man	9766.	9.77	2.44	14.66	26.87
8. King Post Radial Bearing (1)						
Material - Nylon Compound	1 million	0.36 d	360.00	90.00		450.00
Equipment			9.86 n			9.86
Tooling			4.07 m			4.07
Labor	1 man	9766.	9.77	2.44	14.66	26.87
9. King Post Alignment Pin (1)						
Material - Cold Rolled Steel	1 million	.04 g	40.00	10.00		50.00
Equipment			69.75 o			69.75
Labor	2 men	9766.	19.53	4.88	29.30	53.71
10. Lower Support Tube (1)						
Material - Steel	1 million	5.19 g	5190.00	1297.50		6487.50
Equipment			431.02 p			431.02
Labor	6 men		58.59	14.65	87.89	161.13
11. Support Bracket - Elevation Motor (1)						
Material - Polycarbonate	1 million	1.18 i	1180.00	295.00		1475.00
Equipment			205.86 q			205.86
Tooling			32.55 r			32.55
Labor	9 men		87.89	21.97	131.84	241.70

4450
ACCOUNT NUMBER

Heliostat Support And Protection
ACCOUNT DESCRIPTION

			FACTORS			
PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	G&A (000)	OVERHEAD (000)	TOTAL (000)
12. Support Bracket Clamp (1) Purchased Complete	1 million	.05 i	50.00	12.50		62.50
13. Final Assembly (-) Equipment			23.08 s			23.08
Labor	64 men	9766	624.96	156.24	937.44	1718.64
4451 TOTAL						31195.78

4450
ACCOUNT NUMBER

Heliostat Support And Protection
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
4452 Protective Enclosure						
1. Enclosure Top Panel (1)						
Material: Stabilized P.E.T.	1 million	1.61 t	1610.00	402.50		2012.50
Equipment			244.13 u			244.13
Tooling			32.55 v			32.55
Labor	7 men	9766.	68.38	17.09	102.54	187.99
2. Enclosure Truncated Cone Panel (1)						
Material: Stabilized P.E.T.	1 million	14.44 t	14440.00	3610.00		18050.00
Equipment			3278.48 w			3278.48
Labor	28 men		273.42	68.36	410.13	751.91
3. Enclosure Vertical Panel (1)						
Material: Stabilized P.E.T.	1 million	18.51 i	18510.00	4627.50		23137.50
Equipment			4930.31 x			4930.31
Labor	36 men	9766.	351.54	87.89	527.31	966.74
4. Enclosure Access Door Zipper (1)						
Material	1 million	4.00 c	4000.00	1000.00		5000.00

4450
ACCOUNT NUMBER

Heliostat Support and Protection
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		TOTAL (000)
				G&A (000)	OVERHEAD (000)	
5. Enclosure Zipper (1 set)						
Material	1 million	21.90 c	21,900.00	5475.00		27375.00
Equipment			290.92 g			290.92
Tooling			39.06 z			39.06
Labor	33 men		322.25	80.56	483.38	886.19
6. Ground Cloth (1)	1 million	7.48 c	7480.00	1870.		9350.00
Material			539.11 a'			539.11
Tooling	17 men		166.01	41.50	249.01	456.52
Labor						
7. Blower Assembly (1)	1 million	44.00 c	44000.00	11000.		55000.00
Purchased						
4452 TOTAL						152528.91

4450
ACCOUNT NUMBER

Heliostat Support and Protection
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		TOTAL (000)
				G&A (000)	OVERHEAD (000)	
4453 Lightning Protection						
1. Ground Wire Terminal (1) Purchased Complete		.01 c	10.-	2.50		12.50
2. Ground Wire Heliostat (1) Purchased Allied Plant		1.53 c	1530.-	382.50		1912.50
3. Varistors (3) Purchased Allied Plant		1.08 c	1080.-	270.-		1350.-
4. Field Ground Cabling (P/H) Purchased Allied Plant		4.50 c	4500.-	1125.-		5625.-
4453 TOTAL						8900.-

Notes 4450

- a. Based on current price of aluminum sheet stock.
- b. Equipment: \$900,000 tube bender & rolling mill (10 year life), 180,000 for three robots (5 year life), \$20,000 punching machines (10 year life) and \$100,000 welder (10 year life).
- c. Engineering estimate.
- d. Material based on current price of nylon compound.
- e. Equipment: \$55,000 injection molding machine and conveyor (15 year life).
- f. Tooling: \$22,000 mold (10 year life)
- g. Material based on current price for cold rolled steel.
- h. Equipment: \$100,000 cut-off & chamfer machine (10 year life), \$100,000 clean & rust treat equipment (5 year life) \$60,000 automatic drill machine (10 year life) and 100,000 conveyor (10 year life)
- i. Material based on carload lots of polycarbonate.
- j. Equipment 650,000 for eight injection molding machine (15 year life), 120,000 for two robots (5 year life), 100,000 for two spin welders (15 year life) and 15,000 for two hopper drier (10 year life).
- k. Tooling: \$20,000 (10 year life).
- l. Equipment: \$50,000 injection molding machine (15 year life), \$20,000 regrend machine (10 year life), \$10,000 hopper drier (10 year life) and \$10,000 conveyor (15 year life)
- m. Tooling: \$20,000 (10 year life).
- n. Equipment: \$50,000 injection molding machine (15 year life) and \$10,000 conveyor (15 year life).
- o. Equipment: \$100,000 for two cut off & chamfer machine, 100,000 cleaning and rust treatment machine (5 year life), and \$100,000 conveyor (10 year life).

Notes 4450

- p. Equipment: \$1,000,000 automatic fabrication line (10 year life), \$200,000 for two cleaning and rust treatment lines (5 year life), \$120,000 for two robots (5 year life), \$400,000 for two swaging and expanding machines and \$200,000 conveyor (10 year life).
- q. Equipment: \$240,000 for six injection molding machines (15 year life) \$20,000 for two grinding machines (10 year life), \$480,000 for 8 robots (5 year life) and 20,000 hopper tour (10 year life).
- r. Tooling: \$160,000 (10 year life).
- s. Equipment: \$70,000 (5 year life)
- t. Material - Raw material price for P.E.T. and stabilizer
- u. Equipment: \$1,200,000 fabrication and slitter line (10 year life).
- v. Tooling: 200,000 (10 year life).
- w. Equipment: \$16,075,000 Extrusion, U.V. Stabilization and Fabrication line (10 year life) and \$50,000 silo & pneumatic system (15 year life).
- x. Equipment: \$24,235,000 Extrusion, U.V. stabilization and Fabrication Line (10 year life).
- y. Equipment: \$1,430,000 Extrusion and slitter line (10 year life)
- z. Tooling: \$240,000 (10 year life).
- a. Equipment: \$2,650,000 Film line (10 year life).

4460
ACCOUNT NUMBER

Field Assembly and Checkout
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		TOTAL (000)
				G&A (000)	OVERHEAD (000)	
1. Insulation- Supply Function (P/H) Labor a	2 men	@ 11.90	23800			23800
2. Installation - Enclosure (P/H) Labor a	3 men	@ 11.90	35700			35700
3. Installation - Heliostat (P/H) Labor a	6 men	@ 11.90	71400			71400
4. Installation - Power (P/H) Labor a	1.2 men	@ 15.20	18240			18240
4460 TOTAL						149140

a Based on Installation Study

4470
ACCOUNT NUMBER

Design and Engineering
ACCOUNT DESCRIPTION

<u>PART DESCRIPTION</u>	<u>QUANTITY</u>	<u>COST PER UNIT</u>	<u>SUBTOTAL</u> <u>(000)</u>	<u>FACTORS</u>			<u>TOTAL</u> <u>(000)</u>
				<u>G&A</u> <u>(000)</u>	<u>OVERHEAD</u> <u>(000)</u>		
<u>Systems Cost</u>							

Other
ACCOUNT NUMBER

Facility & Transportation
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		TOTAL (000)
				G&A (000)	OVERHEAD (000)	
FACILITY						
1. Building a						4045.00
2. Material Handling a						2438.00
3. Production Control a						244.13
4. Tool Room a						651.00
5. Utilities, Safety & Environmental Equipment a						3182.40
6. Land a						84.86
TOTAL FACILITY						10645.39
TRANSPORTATION						
1. Packaging a						13500.00
2. Transportation						
Equipment b			3621.34			3621.34
Operating Expenses a			4600.00			4600.00
Labor	500 men	\$15500	7750.00	1937.50	11625	21312.50
TOTAL TRANSPORTATION						43033.84
a. Engineer Estimate						
b. Vendor quote						

4800
ACCOUNT NUMBER

Distributables and Indirect Cost
ACCOUNT DESCRIPTION

PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS		
				G&A (000)	OVERHEAD (000)	TOTAL (000)
4810 Construction Facilities, Services, G&A and Fee is the Field Direct Labor from account #4440 & 4460 x 94% (13500 + 149,140) x 94%						152881.60
4820 Spare Parts .25% of 4400 less Field Direct Labor (1065463.8 - 162640) x .0025						2257.06
4830 Architectural Engineering Service						12920.00
4849 Construction Management based on 2 1/2% of Field Direct Labor (162640 x 2.5%)						4066.00
4850 Plant Start-up and Checkout						1441.00
4860 Contingency 10% of all of the above accounts 4400, 4810, 4850 (1239029.4 x 10%)						123902.94
4800 TOTAL						<u>297468.60</u>

6.0 INSTALLATION PROCESSES

The General Electric heliostat installation scheme identified in the original proposal for Phase I was based on minimizing field labor and installation time through the use of an automatic foundation machine and the maximum production and assembly of parts in the factory. The results of the Phase I study have shown that this approach indeed can be realized and results in the low figure of \$372 per heliostat for the total installation cost at high production levels. The automatic foundation machine (AFM) establishes the time cycle for each heliostat installation at 30 minutes and the installation team expands a total of 14 man-hours for each station.

The installation plan described in this section includes a description of the following features:

- Automatic Heliostat Position Surveying
- Enclosure and Heliostat Foundations Installed by a Fully Automatic Foundation Machine (AFM)
- Power Distribution Cable (10 AWG) and Lightning Grounding Grid Wire Installed by AFM
- Enclosure Zippered to Foundation and Directly Inflated
- Heliostat Manually Assembled Inside Enclosure

The functions performed by the automatic foundation machine are automatic heliostat position location, automatic cable burial, center post insertion and enclosure ring trench foundation bag installation. Cost estimates for the automatic foundation machine based on installing 1,000,000 units per year levies a \$7.30 charge per heliostat for the amortization of the machines. As presented in the executive summary, a recent development in our evaluation of the automatic foundation machine shows that, with only minor modifications, the machine can be universally adapted to the installation of any type of heliostat. Automatic location, center post drilling and placement and cable burial are common to all current designs. Only additional ground inserts, leveling or trenching would be peculiar to each type but one machine can easily be envisioned to accommodate these variations. Cost savings as proposed by the Automatic Foundation Machine concept can then be realized for any heliostat system and could be developed as a single machine concept for the solar thermal system industry.

As Phase I proceeded, the installation conceptual design was based on a hardware concept selected at approximately the midpoint of the program to facilitate generation of a baseline set of data to represent the overall processes and their

costs. As the program neared the close, several major new innovations or findings occurred which will undoubtedly greatly improve the automated minimum labor approach and these are listed below for general reference prior to the detailed description of the conceptual study activities of Phase I. They are:

- The identification of polyvinylidene flouride as an enclosure film permits total factory assembly of the enclosure together with its ground cover (of the same material) to provide a completely sealed assembly which can be folded and shipped to a site for simple anchoring and dust free inflation.
- A concept of "blister" packed heliostat components permit clean air lock entry into enclosures for internal assembly and maintenance of heliostats.
- The unit construction concept described in the first item above permits consideration of several types of foundation methods including the ring bag concept described in this section. Conventional screw anchors, grouted inserts, and ring wire anchors are all feasible and can be installed by the AFM.

The remainder of this section describes the processes which were conceived and examined in detail and used as the basis for installation and maintenance cost estimates. They consist of

- Pre-Installation Activities
- The Automatic Foundation Machine
- Supply Activities
- Enclosure Erection
- Heliostat Installation
- Distribution and Lightning Protection System
- Operation and Maintenance Consideration

6.1 PRE-INSTALLATION ACTIVITIES

For purposes of this program, the following assumptions were made relative to a particular power plant and heliostat field site:

- Land costs were not considered as part of the heliostat costs.
- General grading and clearing were also assumed to be part of power plant costs.
- Soil conditions would conform in general to DoE Specification 001.
- Potential sites would be generally level with a maximum local grade at any heliostat station of $\pm 3\%$.

Installation activities have included the setup of a heliostat supply and installation headquarters, the surveying of the field, and the installation of the entire heliostat system including the power distribution network and the heliostat plant master control station.

Figure 6-1. Artist's Sketch of Automatic Foundation Machine

Pre-installation activities are estimated to be the following routine functions:

- Establishment of site survey benchmarks and automatic survey reference stations.
- Establishment of a secure heliostat supply receiving area with installation headquarters and AFM and other vehicle service and supply facilities.

Temporary construction facilities requirements are expected to be minimal, since heliostat components will come to the site on a schedule compatible with the field assembly processes, and be in packages designed for all weather conditions. Items, including tools, needing protection from the environment will come to the site stored in their own dedicated trailers.

6.2 AUTOMATIC FOUNDATION MACHINE

To reduce field labor costs, a machine was conceived to combine and automate several of the common construction functions associated with each heliostat station. For the GE heliostat these functions are:

- To accurately survey and locate the center hole for mounting the heliostat.
- To trench and bury the power distribution cable and lightning grid wire between heliostat stations.
- To trench and bury the power distribution cable between heliostat stations.
- To drill into the ground the heliostat support pipe foundation.
- To trench, insert plastic, fill with excavated soil, and close the GE ring bag enclosure foundation

Figure 6-1 is an artist's sketch of this machine. Other features conceived as a part of the machine system are:

- Self Powered
- Laser Guided
- Self Leveling
- 24 Hour Operating Capability
- Self Propelled
- Computer Program Positioned
- Automatic Installation Program

The machine was conceived by GE and the individual functions and overall machine feasibility were reviewed, augmented and verified by Ingersoll-Rand Automation Equipment Division. Several in-depth conceptual drawings were prepared to explore the general arrangements and operability of the installation functions. They are shown in Figures 6-2 through 6-6 and are:

- Automatic Foundation Machine Overview Drawing #SK-200-E78-001
- Cable Laying Module-Drawing #SK-200-F-78-002

- Foundation Pipe Drilling Module - Drawing #SK-200-F-78-003
- Trenching, Bag Deployment, Backfilling and Compacting Module - Drawing #SK-200-E-78-004
- Foundation Bag Container, Insertion Module - Drawing #SK-200-E-78-005

The method that is utilized for the installation of cabling is very analogous to existing continuous cable laying techniques. The design consists of a rotating wheel with rock cutting studs mounted on its periphery, a plow for cable placement, and two cable reels (power and communication cable and lightning grounding cable). This installation process is continuous and takes place during AFM movement from one heliostat location to another.

The second installation process accomplished by the AFM is the insertion of the heliostat support foundation pipe. The foundation pipe drilling module is a direct adaptation of a commercially available rock drill unit. This module consists of a unit storage cartridge and a drilling apparatus. The installation process for the reflector support pipe begins with a pipe foundation being automatically withdrawn from a factory assembled cartridge containing approximately (20) foundation pipe units. Once withdrawn the foundation pipe is placed in a guide and a drilling type action commences until sensors detect that the foundation pipe is in the desired location.

For extreme conditions where the soil consists of loose sandy materials, a low amplitude high frequency vibrating motor will be attached to the heliostat pipe installation assembly. The low amplitude high frequency motion of the motor will tamp the soil to an acceptable consistency. For areas where boulders or rock shelves are anticipated, the heliostat foundation pipe position will be pre-drilled with commercially available drills and stems which can be inserted in guides used to install the heliostat foundation pipe. It should be noted that heliostat foundation pipes widths and lengths are easily modified without substantially altering the AFM design.

After the heliostat foundation pipe has been drilled to its design location, the exact field positions and alignment will automatically be recorded and printed in computer memory. This memory will be packaged and attached to the installed pipe foundation for eventual insertion into the heliostat drive and control module.

The third major installation process accomplished by the AFM is an Excavator-Assembly and is designed to:

- Excavate a circular trench
- Insert an enclosure foundation bag
- Backfill and tamp soil placed in the foundation bag

Like the Foundation Pipe drilling module, the excavator is designed to meet various soil conditions and is a commercially available trenching unit. The depth of the trench can be adjusted along with the type of excavating teeth used. The excavation teeth arrangement consists of rock cutting studs and soil removal pans alternately spaced and designed to meet a wide range of soil conditions.

Following the excavator assembly is the enclosure foundation bag installation unit. This device serves as a holder, containing a factory assembled cartridge which holds a complete foundation bag, and, as a slip form to prevent the newly excavated trench walls from collapsing. The foundation bag installation unit directly follows the excavator in a circular path. During this travel, the foundation bag material folded in its cartridge is pulled out. Soil is excavated by the excavator assembly and at the same time placed between the rear of the cartridge and holder. This soil is then tamped. After initial hold down, the backfilled soil provides sufficient frictional resistance to pull the foundation bag material from its cartridge as it travels along the designated path.

A second concept introduced by Ingersoll-Rand eliminates the folded and cartridge packed bags and uses a rolled and folded continuous sheet of foundation material making manufacture and installation easier and lower cost. This concept also uses conventional ground storage and recovery devices to minimize machine storage and conveyor mechanisms.

As stated earlier, the estimated average total cycle time for a complete AFM installation sequence is 30 minutes including the movement between stations. Two men will monitor the operation and perform remedial manual operations. The total man hour requirement for each automatic installation sequence is 1 man hour. Time and motion studies conducted by GE Company and Ingersoll-Rand Company indicate that the time required for the Automatic Foundation Machine to install the reflector foundation pipe and the enclosure foundation bag is twenty minutes. The soil density used in this study was "silty sand of loose to medium density" per Department of Energy Specification 001, Section 3.4.1 - "Site Characteristics". Ten additional minutes have been allotted to the cycle time to account for machine startup and movement to the next heliostat location.

CABLE LAYING OPERATION

- 1) MODULE IS SELF-CONTAINED WITH ITS OWN LIMIT SW.'S, CONTROL VALVES (IF AIR OR HYD. CYL.'S ARE USED) & ETC. THE UMBILICAL PLATE HAS CONNECTIONS FOR POWER SUPPLY, AIR OR HYD. IF USED, & FOR CONTROL WIRES TO MAIN CONTROL ROOM; ALSO A BOLT HOLE PATTERN TO MOUNT TO BASE MACHINE
- 2) CABLE REEL IS SET ON LIVE ROLLERS BY A CRANE ON CABLE SUPPLY TRUCK; CABLE IS THEN HAND FED THRU GUIDES & ROLLERS FOR INITIAL START; A DRAG BRAKE WILL BE PROVIDED TO PREVENT EXCESSIVE UNWINDING OF CABLE
- 3) A VARIABLE SPEED CHAIN DRIVE WILL DRIVE THE DIGGER WHEEL
- 4) ONCE THE DIGGING WHEEL IS DOWN TO SET DEPTH, IT WILL REMAIN THERE FOR THE INSTALLATION OF ONE ROW OF HELIO-STATS
- 5) WHEN VEHICLE TRAVERSE IS INITIATED (WHILE IN CABLE LAYING MODE) THERE WILL BE A TIME DELAY OF A FEW SEC'S TO ALLOW DIGGING WHEEL TO BEGIN ROTATION
- 6) A METHOD TO SENSE DIGGING WHEEL LOAD CONDITIONS WILL BE EMPLOYED EITHER THRU THE USE OF LOAD CELLS OR TORQUE SENSORS, OR A COMBINATION OF BOTH; THESE SENSORS WILL CONTROL THE RPM OF THE DIGGING WHEEL & TRAVERSE SPEED OF BASE MACHINE THRU A MICRO-PROCESSOR, THUS ACTING AS CONTROL & SAFETY DEVICE
- 7) DIGGING WHEEL RPM, TORQUE, LOAD & MACHINE TRAVERSE SPEED WILL BE DISPLAYED IN MAIN CONTROL ROOM; MANUAL CONTROLS WILL BE PROVIDED BUT WILL BE INTERLOCKED BY MAX. LIMITS ON WHEEL LOADING & RPM TO PREVENT DAMAGE TO MODULE & BASE MACHINE
- 8) CABLE IS BURIED AS MACHINE MOVES FROM (1) HELIO-STAT LOCATION TO THE NEXT (914.4 TO 1219.2 MM) AT APPROX. 457.2 MM PER MIN. (15' / MIN.)

CABLE LAYING MODULE (PORTION OF AUTOMATIC FOUNDATION MACH.)

K. Lamm APRIL 4, 1978

REV 1

SK-200-F-78-002

Figure 6-3. Cable Laying Module (Drawing SK-200-F-78-002)

Figure 6-4. Foundation Pipe Drilling Module (Dwg. #SK-200-F-78-003)

Figure 6-5. Trenching, Bag Deployment, Backfilling and compacting Module (#Dwg. SK-200-E-78-004)

Figure 6-6. Foundation Bag Container, Insertion Module (Dwg. #SK-200-E-78-005)

The cost associated with the manufacturing and engineering of an AFM were developed with the assistance of Ingersoll-Rand Company. The data on the cost curve of Figure 6-7 indicated that the mature cost of the AFM on a per heliostat basis is \$7.30. The cost figures are based on amortization over an expected 10-year life of the machine.

The conceptual cost estimate for the first machine prepared jointly by GE-IR is shown in Table 6-1.

6.3 HELIOSTAT POSITION SUPPLY ACTIVITIES

After Automatic Foundation Machine functions have been completed at a particular location, that location would be serviced by a supply team. The team's activities consist of the following steps:

- Install ground cloth over the area bounded by the outside periphery of the enclosure foundation bag.
- Place factory assembled packages containing heliostat pedestal and reflector components on top of the ground cover. All components for a completed heliostat except the aluminized reflector roll (due to size) will be placed in the enclosure foundation. Once the enclosure is assembled and inflated, heliostat erection can be performed within the protective environment of the enclosure, minimizing assembly "down-time" due to exiting and entering the enclosure.
- Place factory packaged enclosure components container on the outside edge of the enclosure foundation.
- Position enclosure blower.
- Connect lightning grounding cable and the power and communication cable to the blower.

Supply activities which include servicing the Automatic Foundation Machine will require two (2) personnel for a duration of (1) hour, thus labor needs for supply activities are two (2) man-hours.

6.4 ENCLOSURE INSTALLATION

The enclosure is delivered to the site from the factory in a single roll consisting of two top sections and the enclosure side section. The installation begins by removing the enclosure shipping container and unrolling the enclosure roll.

Protective sheaths of paper, packaged with the enclosure, protect the enclosure components and permit them to be unrolled and repositioned with a minimum of dust or damage.

The third step is the zippering together of the enclosure sections. This zippering process includes:

Figure 6-7. AFM Cost Curve

TABLE 6-1
1ST AFM UNIT MATERIAL COST

Activity	Manufacturer	Cost \$
1.0 Chassis		
1.1 Framing	American Bridge	\$190,000
1.2 Connectors	American Bridge	60,000
1.3 Control Cab	Ingersoll-Rand	50,000
1.4 Railing and Flooring	IKG Industries	20,000
1.5 Others	-	<u>30,000</u>
	SUB-TOTAL	\$350,000
2.0 Foundation Pipe Installation Assembly		
2.1 Drill Unit Mechanism	Acker	\$100,000
2.2 Storage Unit	Ingersoll Rand	40,000
2.3 Transfer From Storage Unit	Ingersoll Rand	60,000
2.4 Sensors	Minn-Honeywell	30,000
2.5 Others	-	<u>20,000</u>
	SUB-TOTAL	\$250,000
3.0 Cabling Installation Assembly		
3.1 Cable Reel Holder	Verneer	\$ 10,000
3.2 Cable Trench Excavator	Verneer	20,000
3.3 Cable Placement Unit	Verneer	15,000
3.4 Sensors	M-4	5,000
3.5 Others	-	<u>5,000</u>
	SUB-TOTAL	\$ 55,000
4.0 Enclosure Foundation Installation Assembly		
4.1 Framing	Ingersoll-Rand	\$ 15,000
4.2 Conveyors	Barber-Green	10,000
4.3 Excavator	Barber-Green	60,000
4.4 Foundation Material Storage	J-R	25,000
4.5 Foundation Material Placement	J-R	200,000
4.6 Soil Compaction Unit	Davis	30,000
4.7 Sensors	M-H	20,000
4.8 Others	-	<u>50,000</u>
	SUB-TOTAL	\$410,000
5.0 Leveling System		
5.1 Leveling Pads	Joyce-Criland	\$ 25,000
5.2 Others	M-H	<u>5,000</u>
	SUB-TOTAL	\$ 30,000

TABLE 6-1 (Cont'd)
1ST AFM UNIT MATERIAL COST

Activity	Manufacturer	Cost \$
6.0 Power and Communications		
6.1 Wheel Drive Assembly	Caterpillar	\$180,000
6.2 Steering Mechanisms	Drott Manue	45,000
6.3 Electric Power Generation	Detroit Diesels	100,000
6.4 Lighting & Wiring	General Electric	40,000
6.5 Communications System	General Electric	5,000
6.6 Others	-	35,000
	SUB-TOTAL	\$405,000
7.0 Control and Guidance System		
7.1 Computer	General Electric	\$ 80,000
7.2 Position Acquisition	Hewlett-Packard	30,000
7.3 Recorder	M-H	10,000
7.4 Sensors	-	50,000
7.5 Others	-	50,000
	SUB-TOTAL	\$200,000

Total First Produced Unit Material Cost \$1,704,000

- Enclosure top and side section zippering
- Zipper enclosure to its foundation

Once zippering procedures are completed, the enclosure is inflated. This requires the use of a portable installation blower that initially inflates the enclosure.

The final steps in enclosure installation are:

- Connect and activate Enclosure Blower
- Deactivate installation blower
- Clean site

Time and Motion studies have revealed that the enclosure installation process requires three (3) man-hours for completion.

6.5 HELIOSTAT INSTALLATION

The heliostat has been designed so that the reflector is assembled in a horizontal position, at a height of approximately 2 (two) meters. The installation uses special tools to aid in the process.

The assembly process is illustrated in the following figures:

- Heliostat Assembly Tools Placement (Figure 6-8)
- Hub and Pedestal Temporary Assembly Position (Figure 6-9)
- Reflector Roll Mounting (Figure 6-10)
- Initial Reflector Attachment to Struts (Figure 6-11)
- Optical Alignment Tool Placement (Figure 6-12)
- Reflector Assembly Lifting Arrangement (Figure 6-13)

Once a reflector assembly installation (6 man-hours total) is complete, the reflector assembly crew removes the Heliostat installation tooling for placement at the next assembly site.

6.6 TYPICAL TOTAL HELIOSTAT INSTALLATION SEQUENCE

A typical cycle for the installation of a complete Heliostat at any location is shown in Figure 6-14- "Typical Total Heliostat Installation Sequence". The cycle time for the Automatic Foundation Machine is 0.5 hours, for supply 1 hour, for enclosure installation 1.5 hours and for Heliostat Assembly 2 hours. Thus, to maintain a complete Heliostat installation cycle time of 0.5 hour, 2 supply teams, 3 enclosure installation teams and 4 Heliostat assembly teams are required.

in addition to a 2 man AFM team. This teaming arrangement is presented in Figure 6015 - "Heliostat Installation Activity Chart".

The total man-hours associated with the installation of a complete heliostat was determined to be 14 man-hours. These man-hours requirements were derived using a productivity factor of 0.78.

Special tools and shipping containers, with the exception of the reflector roll, containing heliostat parts are placed in the enclosure.

Figure 6-8. Heliostat Assembly Tools Placement

The hub holder tool is placed in position onto the foundation pipe, and the heliostat hub and pedestal assembly is placed into the hub holder tool.

Figure 6-9. Hub and Pedestal Temporary Assembly Position

Struts #5 and #6 are placed into the reflector hub, and the reflector roll holder tools are mounted in position on struts #5 and #6. The reflector roll is brought to the enclosure, and its shipping container removed. The reflector roll is mounted to the holding tools that are attached to struts #5 and #6.

Figure 6-10. Reflector Roll Mounting

Struts #1 and #2 are inserted into their respective hub positions and their tension cables attached. The reflector material is unrolled and connected to struts #1 and #2. Struts #3, #4, #5, and #6 are subsequently inserted and attached to the reflector in the same manner. Reflector holder tools are removed, struts #7 and #8 are inserted and attached to the reflector.

Figure 6-11. Initial Reflector Attachment to Struts

The laser alignment beacon is attached, reflector aligned, and strut wires tensioned.

Figure 6-12. Optical Alignment Tool Placement

The laser alignment beacon is removed, reflector assembly lifted using the lifting jacks, and the heliostat pedestal is placed onto the foundation pipe. Final electrical "hook-ups" are made and the system tested.

Figure 6-13. Reflector Assembly Lifting Arrangement

Figure 6-14. Typical Total Installation Sequence

HELIOSTAT INSTALLATION ACTIVITY CHART

AFTER THIS POINT IN TIME, A HELIOSTAT IS COMPLETED EVERY 30 MINUTES.

NOTES:

1. NUMBERS DISPLAYED IN CHART CORRESPOND TO A HELIOSTAT POSITION.
2. CYCLE TIME FOR HELIOSTAT INSTALLATION - 30 MINUTES.

Figure 6-15. HelioStat Installation Activity Chart

6.7 POWER DISTRIBUTION AND LIGHTNING PROTECTION

To illustrate the General Electric installation approach for power distribution, a McDonnell Douglas field layout for a 10 MW Solar Central Receiver power plant was used. The heliostat locations for this field layout are illustrated in Figure 6-16.

In developing the power distribution methodology, requirements in various sections of Specification 001 "Solar Central Receiver Prototype Heliostat Requirements" are addressed. To fulfill Section 3.3.7.2 titled "Acquisition" in Specification 001, the Heliostat Field has been divided into ten (10) separate segments. These segments are equally divided on either side of a north-south centerline that passes through the solar central receiver and adhere to guidelines set forth in Section 3.3.2.6 titled "Receiver/Storage-Inverse" of Specification 001. Figure 6-17 illustrates the sectioning of the field layout.

The installation of the power distribution cable and the lightning protection grid is accomplished by the Automatic Foundation Machine. The path of the AFM in completing this installation is shown in Figure 6-18.

The arrangements in Figures 6-16 and 6-18 are selected to maintain the shortest distance between heliostats. Heliostat units located in the outer section of the field are arranged along a series of concentric circles whose center is coincident with the central receiver. "Near Field" heliostats are located along spirals originating from the same center. The spiral arrangement is convenient for the Automatic Foundation Machine travel.

It should be noted that in Figure 6-17 - "Field Segmentation", each segment has 10% of the total number of Heliostats in the field. A 100 MW plant field layout is segmented the same as is shown for the 10 MW plants.

Because a large number of heliostats are distributed over a vast area the auxiliary power distribution system is a significant portion of the overall equipment investment. Due to long cable runs, the conductor cross-sections are selected on the basis of line voltage drops (IR) rather than current density. The distribution system methodology is to minimize the cable investment by selecting the smallest practical conductor cross-sections consistent with acceptable line voltage drops.

The power requirement of 70 watts per heliostat corresponds to a total station auxiliaries power demand of 1,400 KW for the 20,000 heliostat field.

Figure 6-16. MDAC 10 MW Field

Figure 6-17. GE Field Divisions

Figure 6-18. GE Field Cabling Layout

The heliostat control signals are sent from the central control area to each heliostat via the auxiliary power distribution cables. This makes it necessary for the power to be distributed over single-phase lines.

The proposed distribution system, as depicted in Figure 6-19 - "Power & Communication Schematic", starts with a 1500 kVA, 3-phase main transformer which supplies a distribution switchboard with 10 single-phase feeders, one for each field section of 2,000 heliostats. The main transformer secondary voltage will be a 4160 volts line-to-line so that the single-phase line-to-neutral feeder distribution voltage will be 2400 volts.

The ten heliostat sector transformers, rated 150 kVA each, are located near the center of their respective sectors. These transformers step down the 2400 main distribution feeder voltage to 480 volts for distribution and group transformers supplying heliostats.

The 480 volt power is distributed via panel boards, located adjacent to the sector transformers, to 50 heliostat group transformers located throughout each field sector. Each heliostat group transformer, rated 3 kVA - 480/220 volts supplies the 40 heliostats with 240 volt single-phase power. Closed loop distribution and redundant feeder cables as well as switchgear and transformers can be used independent on actual heliostat system layouts.

6.7.1 LIGHTNING PROTECTION

In formulating a lightning protection scheme for the GE Heliostat the following considerations were made:

- Should lightning strike an individual heliostat, that heliostat is assumed destroyed.
- Although the solar central receiver tower will act as lightning rod, it can only be expected to provide protection to those heliostats which are close to the tower -- say within a "tower height" radius.
- The Heliostat Foundation Pipe (made of steel and extends approximately 1.5 meters into the ground) should not be considered as providing adequate grounding. Lightning charge must be prevented from entering the power and communication system either through heliostat wiring or across the ground surface or both.

To protect a heliostat field, a lightning grounding grid is proposed. The grid would consist of a #6 AWG base, buried copper wire (American National Standards Institute (ANSI) publication titled "Lightning Protection, C-5"). This cable would be installed with the power and communication cable by the Automatic Foundation Machine as shown in Figure 6-20, "Lightning Cable Placement".

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Figure 6-20. Lightning Cable Placement

Cross connections would be made at heliostat row ends or closer if required. These cross connections need not be buried and can go from one blower housing in one row to a blower housing in another row. It should be noted that a lightning ground grid cable would be attached to the blower housing and then to the heliostat itself.

As an additional line of defense, three Metal Oxide Varistors (MOV) will be placed on the power junction connection at each blower.

Figure 6-21 shows the placement of three Metal Oxide Varistors. These three MOV's provide a path back to the lightning ground grid should a lightning power surge enter the power and communication cable.

6.8 FINAL FIELD ASSEMBLY ACTIVITIES

Final field assembly procedure essentially consists of power and communication hook-up, installation of field monitoring and control equipment and final system checkout. Labor requirements for these activities to be approximately 1 man-hour per installed heliostat of a 100 MW facility.

6.9 OPERATION AND MAINTENANCE PROCESSES (O&M)

A key element of the GE Preliminary design heliostat operation and maintenance cost trade-off is the adoption of the "no cleaning" assumption and the acceptance of the 10% average performance degradation. The O&M costs are based on utilization of enclosure and reflector materials whose useful life is estimated at 10 years requiring 2 replacements in the 30 year overall system life basis. The new polyvinylidene fluoride films with their 15 year life can significantly reduce these costs.

Every heliostat station is equipped with automatic fault monitoring electronics (every 2 minutes). A "plug-in" fault analyzer connection is mounted on the enclosure blower. The use of automatic fault monitoring and the fault analyzer provide for early detection and quick assessment of any individual collector failure.

The operational and maintenance activities are divided into three categories, Scheduled Routine Annual Maintenance, Non-Scheduled Routine Annual Maintenance, and Scheduled Replacement Maintenance. Table 6-2 is the maintenance activity list for these three categories. The routine scheduled maintenance requires only filter cleaning. The activities for the non-scheduled annual maintenance are enclosure repair, blower replacement, reflector replacement and drive and control repairs. The

Figure 6-21. Line Diagram Showing Placement of Metal Oxide Varistors for Lightning Protection

TABLE 6-2
MAINTENANCE ACTIVITY LIST

Item	Annual Maintenance		Replacement Maintenance	Procedure
	Schedule	Unscheduled		
Filter	x			Remove, replace and clean on site.
Blower		x		Remove and replace on failure
Ground Cloth Enclosure			x x	Remove and replace Disassemble Heliostat, remove and replace
Lower Support		x		Remove and replace on failure
Wire Harness		x		Remove and replace on failure
Drive Motor and Detector		x		Remove and replace on failure
Controller		x		Remove and replace on failure
Azimuth Drive Hub		x		Raise reflector assembly, remove and replace on failure
Radial and Thrust Bearings		x		Replace on failure
King Post		x		Replace on failure
Yoke		x		Replace on failure
Yoke Flange Bearing		x		Remove and replace
Elevation Drive Sector		x		Remove and replace
Sun Sensor		x		Disassemble Heliostat and replace
Reflector Surface Asm.		x	x	Remove and replace
Reflector Tensioning Assembly		x		Lower reflector assembly, and remove and replace
Strut Assembly		x		Repair electrical or remove and replace as required
Field Cables		x		Repair electrical or remove and replace as required
Power Distribution		x		Repair electrical or remove and replace as required
Control Signal Distribution		x		Repair electrical or remove and replace as required
Lightning Protection		x		Repair electrical or remove and replace as required

scheduled replacement maintenance occurs on a ten year cycle and requires replacement of the enclosure and the reflector surface. The following section will describe the processes involved in each of these activities. The associated costs are found in the Section 7.3, Heliostat Operation & Maintenance costs.

Scheduled Routine Annual Maintenance

The Scheduled Routine Annual Maintenance requires cleaning the blower filter on a 12 or 15 month cycle depending on final trade-off studies on filter selection. This reduced scheduled routine annual maintenance action plan was accomplished by using:

- the protective environment of the enclosure
- results of the enclosure cleaning trade-off study in Section 2.2.2.2
- permanently lubricated bearing surfaces based on the low torque requirements of the drive

Routine cleaning of the filter is accomplished by simply replacing the filter cartridge with a clean filter. The actual cleaning of either proposed permanent aluminum or polyester fabric filters will be accomplished in the central plant maintenance building with soap and water using equipment similar to commercial available dish washing equipment. The use of a central cleaning facility eliminates the need for specialized field maintenance equipment, reduces the inventory of new filters, and eliminates the cost of disposing non-reusable filters.

Periodic cleaning of the filters provides for a functional activity to be performed when visually inspecting the collector system for Non-Scheduled Routine Annual Maintenance items.

Non-Scheduled Routine Annual Maintenance

This activity is initiated by the automatic fault detection system that reviews the status of each collector every 2 minutes, or by periodic visual inspection. Individually controlled collectors give quick feedback on their operational status and provide the ability to perform maintenance while the field is operational. Adjacent collectors are not affected by individual failures.

Small holes or tears in the enclosure are repaired with transparent tape. Catastrophic failures are predicted to occur at a rate of less than 0.1% per year. A catastrophic failure occurs when an enclosure cannot be repaired using simple patching techniques or blower replacement. A catastrophic failure will not be repaired until scheduled replacement maintenance activity is performed.

A blower failure or small leak is detected by a pressure sensing device located inside the enclosure or by visual inspection. This fault will be remedied by cleaning a dirty filter or making a small repair to the enclosure. Replacement of the blower motor is simplified by the use of a plug-in electrical connection and a quick clamp blown installation method. The blower motor and centrifugal fan are replaced as one unit. All maintenance activities can be performed by semi-skilled personnel.

Reflector surfaces are replaced during the scheduled replacement activity. The enclosure does not have to be taken down to replace the reflector if performed as part of Routine Annual Maintenance. For replacement, the reflector assembly is lowered to approximately 2 meters above ground level, using the reflector assembly lifting tools, hub holder tool, and reflector holder tools (as described in Section 6.5). The reflector and the struts are now removed and the new reflector is installed following the reflector assembly techniques described in Section 6.5.

Azimuth and elevation drive component repairs are greatly reduced by the simplicity of the linear motor drive system. Motors can be replaced as plug-in units and, with the exception of the azimuth drive wheel and azimuth bearings, all other drive train parts can be replaced in the stow position.

Electronic control malfunctions are monitored at the central plant and repair crews will be dispatched to the malfunctioning heliostat. Upon arrival at the site a control analyzer is connected to a quick disconnect on the blower housing, and a set of program commands will determine what has malfunctioned. Because of the simple lightweight design, all active replacement parts are carried on a small maintenance truck capable of maneuvering between the closely packed collectors near the base of the central receiver tower.

Scheduled Replacement Maintenance

Scheduled Replacement Maintenance is performed on the enclosure and reflector using installation procedures in Section 6.4 and 6.5.

7.1 GENERAL

The primary output of the manufacturing conceptual design study is the cost estimate data base reported in Section 5.1. This, together with time and labor estimates of the installation processes described in Section 6.0, has resulted in the following overall results at the four specified levels of production.

TABLE 7-1

HELIOSTAT COSTS (1978 Dollars)

Production Level	Installed Equipment Investment Costs (in thousands of dollars)	Operation & Maintenance Costs \$/m ²	Heliostat Installed Cost	Heliostat Cost \$/m ² -R
1,000,000	171,619	26.77	\$1363	42.88
250,000	64,254	27.24	\$1443	45.39
25,000	13,351	50.48	\$2597	81.09
2,500	1,264	79.73	\$5686	178.83

7.2 DESCRIPTION OF CAPITAL COST ESTIMATION METHODS

Operating and Maintenance costs were conservative estimated values utilizing maximum Mean Time Between Failures (MTBF) for the critical items. The protective environment of the enclosure for most components, plug-in replacements, and the choice of highly reliable components provides credibility for the maintenance estimates. Figure 7-1 presents the basic cost-coding format.

All costs are stated in 1978 dollars with no escalation factors. The following paragraphs briefly describe the sample worksheet format (Figure 7-2) and how the data was developed.

7.2.1 ACCOUNT STRUCTURE AND NOMENCLATURE

The Account Numbers (Figure 7-2, Item 1) and Account Description (Item 2) were taken directly from the revised contract suggested format for all low-cost heliostats. A drawing has been provided to show how the General Electric Prototype Design fits into the Capital Cost Account Structure and illustrates the nomenclature used for the components (Figure 7-3). To aid in defining where parts have been placed in the cost account structure, the subsystem title has been included in the

part description (e.g., - the Elevation Drive Sector Bolt). The number of each part included in each heliostat is denoted by the number in parenthesis following the Part Description (Figure 7-2, Item 3).

7.2.2 MATERIAL

Under the part description, the material (Figure 7-2, Item 4) is listed and the form it is purchased in is designated. An example is the reflector strut which is made of aluminum, at the 2500 production quantity it is purchased complete to drawing, at the 25,000 heliostat/year rate it is purchased as a tube and formed to drawing, and at two higher rates (250K and 1 million) it is purchased as sheet stock and manufactured to drawing. The number that appears in the quantity column is one of four specified production rates of 2500 one time production quantity or the steady-state production rates of 25,000, 250,000 and 1 million heliostats per year.

Collector Capital Investment Cost

- 4400 Collector Equipment
 - 4410 Reflective Unit
 - 4420 Drive Unit
 - 4421 Azimuth or Horizontal Drive
 - 4422 Elevation or Vertical Drive
 - 4423 Motors
 - 4424 Position Indicators or Encoders
 - 4425 Power Distribution and Emergency Supply
(Optional or \$/m² is desirable)
 - 4430 Control and Instrumentation
 - 4431 Sensor or Calibration Equipment
 - 4432 Field Control Electronics
 - 4433 Control Signal Distribution Equipment
(Optional or \$/m² is desirable)
 - 4440 Foundation and Site
 - 4450 Heliostat Support and Protection
 - 4451 Heliostat Support Structure
 - 4452 Heliostat Protective Enclosure
 - 4453 Lightning Protection
 - 4460 Field Assembly and Checkout
 - 4470 Design and Engineering
- 4800 Distributables and Indirect Costs
 - 4810 Temporary Facilities, Equipment, etc.
 - 4820 Spare Parts
 - 4830 Architectural Engineering Services
 - 4849 Construction Management
 - 4850 Plant Startup and Checkout
 - 4850 Contingency

Figure 7-1. Basic Format

CAPITAL COST WORK SHEET						
① ACCOUNT NUMBER						
② ACCOUNT DESCRIPTION						
PART DESCRIPTION	QUANTITY	COST PER UNIT	SUBTOTAL (000)	FACTORS G&A (000)	OVERHEAD (000)	TOTAL (000)
PART ③						
MATERIAL ④	PRODUCTION X STANDARD RATE	COST/HELIOSTAT	= PRODUCTION STANDARD COST OF MOTOR	+ 25%		= Total Cost of Material
EQUIPMENT ⑤			CRF*			= Total Cost of Equipment
TOOLING ⑥			EXPENSE OR CRF*			= Total Cost of Tooling
LABOR ⑦	TOTAL MEN FOR THAT x OPERATION	APPLIED DIRECT LABOR COST/MAN	COST OF APPLIED DIRECT LABOR/ OPERATION	+ 25%	+150%	= Total Cost of Labor

*Capital Recovery Factor is Based on 10% Interest for Life of Item Being Costed.

Figure 7-2. Sample Work Sheet

Figure 7-3. Capital Cost Account Structure Drawing

The material cost per heliostat is stated in standard cost. The standard cost of material is defined as the cost of material needed to produce the part on the specified equipment. The material which is removed as part of the operation is considered a part of the standard cost while all other scrap material is accounted for in the overhead rate under "Losses" (Figure 7-4).

The cost of material is based on the present market information and only justifiable reductions due to volume considerations have been used. Vertical integration also affects the final cost of each part when comparing different production levels. The higher the level of vertical integration in each part the lower the cost of that part. At lower levels of production the raw material cost could actually be the same as high levels but because of the longer distribution channels the cost of the final part must pay the expense incurred because of low vertical integration.

The material Subtotal is the product of the production rate times the standard cost of material. The Subtotal cost of material is increased by 25%, to account for General and Administrative Expenses incurred. The result is the Total cost of the material for that part(s).

7.2.3 EQUIPMENT AND TOOLING

The cost of the manufacturing equipment (Figure 7-2, Item 5) appears in the Subtotal column. The equipment need was analyzed and a selection was made by the Automation System Operation of the General Electric Manufacturing Engineering Consulting Services. This group has a proven record of automated equipment performance, with over 25 years experience in this field. The manufacturing processes contained in this cost estimate are current technologies and GE possesses most of these processes in its diversified manufacturing operations.

The cost of the Automatic Foundation Machine (AFM) was a combined effort of the Ingersoll-Rand Company and the Installation and Service Engineering Business Division of the General Electric Company. The AFM has been developed around proven subsystems of trench excavation, pipe drilling, and automatic alignment devices. The unique feature of the AFM in the GE heliostat installation process has two distinct advantages -- it will reduce direct field labor and total installation period can be reduced by the use of multiple machines.

The cost of durable Tooling (Figure 7-2, Item 6) appears in the Subtotal column. Durable tooling is defined as tooling with an expected minimum life of 2 years and its function is directly related to the manufacturing of the product.

Machine molds and dies are considered durable tooling. Small hand tools and short life tooling (less than 2 years) are categorized as non-durable tooling and appear in the overhead rate as Non-Durable Tools and Supplies.

APPLIED DIRECT LABOR (A.D.L.)

Days/Yr	365
Less Weekend	-104
Weekdays/Yr	261
Shut Down	5
Inventory	-3
Less O.H. Items	
Holiday	10
Vacation	10
Losses (2%)	5.5
Allowances (2%)	5.5
Sick Days - Pd.	2
- Unpd.	2
A.D.L. Days/Yr	218

@ 8 Hrs/Day @ \$5.60*/Hr = \$9766/Yr (ANI/year)

*Hourly Rates for NC Machine Operator

Figure 7-4. Applied Direct Labor

Equipment and durable Tooling are stated in terms of a Capital Recovery Factor (CRF) to amortize the investment. This method suggested by the contract is a uniform end-of-year payment procedure to repay the investment at a stated interest rate and over a specified time period. A conservative interest rate of 10% was used. The repayment period was the expected life of the equipment or tooling as specified by the manufacturer. Knowing the interest rate and the repayment period the CRF is found in compound interest tables for each capital investment. The CRF method is a common method for amortizing or depreciating an investment over its expected useful life.

7.2.4 LABOR

The labor factors are based on a GE mass production facility located in the Eight State Market Area for the manufacturing portion and the field labor factors

are based on a national average of actual field labor rates for the installation portion. In reality there are many factors which will effect final labor rates. This method is a viable, realistic, and conservative approach to the problem.

The manufacturing labor (Figure 7-2, Item 7) is based on the GE mass production facility for producing Central Air Conditioning Units in Tyler, Texas. The rate estimate was developed using a numerically controlled machine operator wage factor. This directly compares to the type personnel which will be employed in the proposed heliostat facility. The wage was broken down into the Applied Direct Labor (Figure 7-4). Applied Direct Labor is the time each operator is actively engaged in producing the product, overhead accounts for all other paid time such as holidays, vacations, losses, etc. On the 2,500 production level an 85% learning curve was applied to determine the number of men required to complete each operation. All other production levels assumed that at steady-state production, that all laborers were off the learning curve for the time period being costed. The Cost of Applied Direct Labor is the product of the number of men actively engaged in that operation times the cost of each man (ADL/year).

Direct Field Hourly Labor Rates (Figure 7-5) were developed for three classification of workers used in the installation process (direct refers to only those workers who are actively engaged in the installation process). The Field Laborer classification applies to the personnel needed to erect the enclosure, erect the Reflector and Drive Assembly and perform the supply function. The electrician classification applies to the power distribution equipment installers. For the AFM a heavy equipment operator and heavy equipment oiler (assistant) were averaged to determine the labor rate (Total installation time was 1 hour - 1/2 hour elapsed time for the operator and his assistant).

Field Labor Rates*

<u>Classification</u>	<u>Hourly Rate w/Fringe Benefits</u>	
Laborer	\$11.90	
Electrician	\$15.20	
Heavy Equipment Operator	\$15.02	} \$13.50
Heavy Equipment Oiler	\$11.94	

*1st Quarter 1978 - National Average of 120 Location

Figure 7-5. Field Labor Rates

7.2.5 OVERHEAD RATES

The total cost of labor is the cost of applied direct labor/operation plus 25% adder for General and Administrative expenses and 150% for the Factory Overhead Rate (Figure 7-6) includes expenses associated with the Applied Direct Labor such as

	<u>% of ADL</u>
● Allowances (Idle, Training and Personal Time)	2
● Losses (Scrap, Rework)	2
● Benefits (Vacation, Holidays, Overtime Premium, Night Shift Bonus, Sick Time, Pension, Savings & Security, and Insurance for All Employees)	60
● Wages, Salaries, Indirect Labor Cost (Included All Non-Manufacturing Employees)	55
● Non-Durable Tools and Supplies	7
● Maintenance Materials	7
● Tax and Insurance	6
● Utilities	<u>11</u>
	150

Figure 7-6. Factory Overhead

allowance for idle time, training, personal time, losses, and benefits. All non-manufacturing support personnel such as maintenance men, management, material handlers, quality control man power, etc., are included in the Factory Overhead rate. Other miscellaneous items such as maintenance materials, property taxes, insurance for the facility and utilities are part of the Factory Overhead Rate. The factory overhead rate structure was developed by comparing several high volume GE departments as they relate to the heliostat production plan.

The field overhead rate is classified under Construction Facilities, Service, G&A, and Fee and is applied to the Field Director Labor (Figure 7-7). The rate was developed considering overhead rates for power generation construction sites and how they would be applied to an automated installation process.

7.2.6 INDIRECT COST

The rationale for the Spare Parts estimate started with a normal spare part estimate of 1% of 2,500 production level. As more experience is gained in manufacturing and installing heliostats, many of the problems leading to the need for spare parts can be overcome resulting in a lower cost for spare parts at the higher production levels. (Figure 7-8)

CONSTRUCTION FACILITIES, SERVICES, G&A, & FEE

	<u>% of Field Labor</u>
Field Superintendent	3.5
Assistant Superintendent	4.2
Field Accountants	3.0
Clerical	2.0
Field Engineers	5.5
Field Cost Engineer	.1
Risk Insurance	1.0
Watchman	4.0
Material Receiving and Warehouse	5.0
Safety and First Aid Personnel	.1
Field Resident Manager	.1
Installed Heliostat Maintenance and Operation	1.5
Telephone, Telegraph, TWX	1.2
Payroll Tax and Insurance	17.03
Staff Payroll Burden	7.0
General Expendable Supplies	3.2
Safety Equipment and Supplies	1.0
Small Tools	3.6
Construction Equipment	5
Temp. Facilities	1
G&A and Fee	<u>25</u>
	94.03%

Figure 7-7. Field Overhead Rate

2500	1%
25K	.75%
250K	.50%
1M	.25%

Figure 7-8. Spare Parts

Architectural Engineering Service, Construction Management, and Plant Startup and Checkout are a function of the total plant system (Figure 7-9). A representative field of 20,000 heliostats was chosen to estimate these costs. The architectural and engineering service considered field layout with regards to heliostat location, cable locations, and site surveying. Construction Management is an independent firm hired by the utility to oversee the construct costs, schedule and quality of work. Plant Startup and checkout is associated with central computer and power distribution equipment. Individual heliostats are checked out as part of the heliostat installation process. The cost of these activities are:

• Architectural Engineer Service	\$12.92
• Construction Management	\$ 5.38
• Plant Startup and Checkout	\$ 1.44

Figure 7-9. Indirect Cost per Heliostat - All Levels

The contingency estimate of 10% was developed considering the high level of detail on the engineering design, the depth of analysis in the Manufacturing study and the thoroughness of the installation estimates.

7.3 HELIOSTAT CAPITAL COST SUMMARY

The Capital Cost estimates represents the central theme of the entire program of producing a Low Cost Heliostat. This cost includes all costs from field survey through acceptance for operation, with the exception of land cost. The General Electric design approach has resulted in cost estimates that underrun the DoE target cost/performance value by 40%, representing a breakthrough for central receiver plant economics.

7.4 HELIOSTAT OPERATIONS AND MAINTENANCE COST

The DoE cost objective of the O&M program was established at $65/m^2$ over a thirty year life. The methodology used in development of the data base needed for the OEM cost study was a statistical method using the Mean Time Between Failures (MTBF) and the Mean Time To Replace (MTTR). The annual maintenance plan is based on a conservative 24 hours a day 2 men per shift coverage seven days a week with one day shift supervision. The schedule replacement plan will be completed on a contracted basis in the tenth and twentieth year of operation.

COLLECTOR CAPITAL INVESTMENT COST
2500 PRODUCTION LEVEL

4400	Collector Equipment	\$4535.94
4410	Reflective Unit	635.60
4420	Drive Unit	441.80
4421	Azimuth Drive	46.25
4422	Elevation Drive	13.29
4423	Motors	312.26
4424	Position Indicators	-
4425	Power Distribution	70.00
4430	Control and Instrumentation	325.95
4431	Sensor	93.75
4432	Field Control Electronics	169.70
4433	Control Signal Dist. Equip.	62.50
4440	Foundation and Site	708.79
4450	Heliostat Support and Protection	1601.77
4451	Heliostat Support Structure	353.57
4452	Heliostat Protective Encl.	1235.01
4453	Lightning Protection	13.19
4460	Field Assembly and Checkout	422.40
4470	Design and Engineering	0
Other	(1) Manufacturing Facility	180.00
	(2) Packaging and Transportation	219.63
4800	Distributables and Indirect Costs	1149.77
4810	Construction Facilities, Services, G&A, & Fee	554.32
4820	Spare Parts	38.66
4830	Architectural Engineering Service	12.92
4849	Construction Management	15.54
4850	Plant Startup and Checkout	11.52
4860	Contingency	<u>516.82</u>
TOTAL		\$5685.71
		TOTAL PER HELIOSTAT

COLLECTOR CAPITAL INVESTMENT COST
25K PRODUCTION LEVEL

4400 Collector Equipment	\$2174.57
4410 Reflective Unit	270.74
4420 Drive Unit	262.62
4421 Azimuth Drive	29.00
4422 Elevation Drive	9.49
4423 Motors	154.13
4424 Position Indicators	-
4425 Power Distribution	70.00
4430 Control and Instrumentation	194.94
4431 Sensor	68.75
4432 Field Control Electronics	110.56
4433 Control Signal Dist. Equip.	15.63
4440 Foundation and Site	398.91
4450 Heliostat Support and Protection	826.16
4451 Heliostat Support Structure	109.42
4452 Heliostat Protective Encl.	706.10
4453 Lightning Protection	10.64
4460 Field Assembly and Checkout	149.12
4470 Design and Engineering	0
Other (1) Manufacturing Facility	23.83
(2) Packaging and Transportation	48.23
4800 Distributables and Indirect Costs	422.22
4810 Construction Facilities, Services, G&A, & Fee	152.86
4820 Spare Parts	14.86
4830 Architectural Engineering Service	12.92
4849 Construction Management	4.07
4850 Plant Startup and Checkout	1.44
4860 Contingency	<u>236.07</u>
TOTAL	\$2596.79
TOTAL PER HELIOSTAT	

COLLECTOR CAPITAL INVESTMENT COST
250K PRODUCTION LEVEL

4400	Collector Equipment	\$1135.85
4410	Reflective Unit	112.53
4420	Drive Unit	165.89
4421	Azimuth Drive	20.88
4422	Elevation Drive	8.83
4423	Motors	66.18
4424	Position Indicators	-
4425	Power Distribution	70.00
4430	Control and Instrumentation	130.54
4431	Sensor	37.50
4432	Field Control Electronics	77.41
4433	Control Signal Dist. Equipment	15.63
4440	Foundation and Site	297.58
4450	Heliostat Support & Protection	218.83
4451	Heliostat Support Structure	42.45
4452	Heliostat Protective Encl.	167.14
4453	Lightning Protection	9.24
4460	Field Assembly and Checkout	149.14
4470	Design and Engineering	0
Other (1)	Manufacturing Facility	15.96
(2)	Packaging and Transportation	45.35
4800	Distributables and Indirect Costs	307.38
4810	Construction Facilities, Services, G&A, & Fee	152.88
4820	Spare Parts	4.87
4830	Architectural Engineering Service	12.92
4849	Construction Management	4.07
4850	Plant Startup and Checkout	1.44
4860	Contingency	131.20
TOTAL		\$1443.23

TOTAL PER HELIOSTAT

COLLECTOR CAPITAL INVESTMENT COST
1M PRODUCTION LEVEL

4400	Collector Equipment	\$1065.47
4410	Reflector Unit	105.76
4420	Drive Unit	160.34
4421	Azimuth Drive	20.48
4422	Elevation Drive	8.72
4423	Motors	61.14
4424	Position Indicators	-
4425	Power Distribution	70.00
4430	Control and Instrumentation	111.47
4431	Sensor	31.25
4432	Field Control Electronics	64.59
4433	Control Signal Dist. Equip.	15.63
4440	Foundation and Site	292.45
4450	Heliostat Support and Protection	192.63
4451	Heliostat Support Structure	31.20
4452	Heliostat Protective Encl.	152.53
4453	Lightning Protection	8.90
4460	Field Assembly and Checkout	149.14
4470	Design and Engineering	0
Other	(1) Manufacturing Facility	10.65
	(2) Packaging and Transportation	43.03
4800	Distributables and Indirect Costs	297.47
4810	Construction Facilities, Services, G&A&Fee	152.88
4820	Spare Parts	2.26
4830	Architectural Engineering Service	12.92
4849	Construction Management	4.07
4850	Plant Start Up and Check Out	1.44
4860	Contingency	<u>123.90</u>
TOTAL		\$1362.94

TOTAL PER HELIOSTAT

7.4.1 DATA DEVELOPMENT

The largest single expense item in the maintenance process is for the repair and replacement of the enclosure. The data development will show the basic methods and typical assumptions. The life for an enclosure made of polyethylene terephthalate based on Martin Processing Co. data would be seventeen (17) years. UV degradation was judged to limit life to 10 years. The MTBT for the zipper was considered and accidental damage was estimated. These factors generated a normal distribution (Figure 7-10).

Figure 7-10. Single Enclosure MTBF

Figure 7-10 shows the MTBF for an enclosure left for its full expected life of 17 years. When the scheduled replacement maintenance cycle is considered the following curve is generated (Figure 7-11).

Figure 7-11. Enclosure MTBF with 10 Year Replacement

The MTBF of 445 failures per year occurred in the tenth year of operation and represents the worse case prior to the planned replacement of the entire enclosure. To use the worse case in the maintenance cost estimate is a conservative and acceptable practice.

The material estimates used in the maintenance cost estimates were developed using the data from the capital cost estimates with an additional costs added for the special handling and shipping considerations. The maintenance cost estimates are developed for each of the four production levels required by the contract and stated in terms of the target cost in dollars per square meter and dollars per heliostat.

The labor rate for the annual maintenance and scheduled replacement maintenance is \$10.80 based on a National Average for field laborers. A different overhead rate was used for each category. The replacement maintained overhead used was a typical contractor overhead rate of 84%. The overhead rate for annual maintenance is 60%. The different overhead rates reflect the general differences between contractor labor and a stable utility labor force.

7.4.2 COST DATA SUMMARY

The maintenance cost summary is developed in two formats: one based on annual cost per heliostat (Figure 7-12) and the second on the 30 year maintenance cost per square of reflector surface. (Figure 7-13) The estimates are generated from the material cost for each production level. The costs are developed on a heliostat site of 20,000 units except for the 2,500 production level where 2,500 units was the field size.

Production Level	Routine Annual Maint.	Replacement Maint.	Total
1,000,000	\$18.67	\$ 30.42	\$ 49.09
250,000	\$18.75	\$ 31.19	\$ 49.94
25,000	\$19.20	\$ 73.34	\$ 92.54
2,500	\$20.19	\$125.99	\$146.18

Figure 7-12. Total Annual Maintenance Cost Per Heliostat

Production Level	Routine Annual Maint.	Replacement Maint.	Total
1,000,000	\$10.18	\$16.59	\$ 26.77
250,000	\$10.23	\$17.01	\$ 27.24
25,000	\$10.47	\$40.01	\$ 50.48
2,500	\$11.01	\$68.72	\$ 79.73

Figure 7-13. Total 30 Year Maintenance Cost/m²

7.4.3 OTHER CONSIDERATIONS

Some utilities use an alternate maintenance staffing method of one shift coverage, 5 days a week. This is different and could be a viable alternative. (Figure 7-14) The cost associated with reduced coverage was estimated and this may be increased slightly due to any O.T. requirement but was not considered for this comparison. The annual cost per heliostat could be reduced by up to \$12.20 and the 30 year maintenance cost per square meter of reflector surface by \$6.65 at all production levels. This rationale will be further explored in Phase II.

	Total 30 Year Maintenance Cost/m ²	Total Annual Maintenance Cost/Heliostat
Present Method	\$26.77	\$49.09
Alternate 1 Shift Method	\$20.12	\$36.89

Figure 7-14. Alternate Staffing Methods Comparison

New enclosure materials such as PVDF could have important impact on the cost of maintenance. Reduced routine maintenance due to a one piece fabricated enclosure. The U.V. stability properties of PVDF suggest that one time replacement could be cost effective. Further consideration for PVDF will be given as data becomes available to complete a trade-off study.

The total cost of maintenance is the second of the three important elements in the cost performance equation. Comparing the GE maintenance cost of \$26.77 (based on the estimate for 1 million heliostats/year production level) to the DoE cost target of \$65/m² (over the thirty year life) gives very favorable results.

7.4.4 MAINTENANCE COST DATA

The maintenance cost data section provides a breakdown of the Routine Annual Maintenance and Replacement Maintenance Cost for each production level. The mutual replacement cost reflect the cost of manufacturing at each respective production level. The two maintenance categories are further subdivided into the individual activities, estimated number of actions (frequency of the activity per year), material cost and labor estimates. Four different methods were used to state the total cost of Maintenance. The first method is the Total 30 Year Cost of maintenance. The Second method is Field Annual Cost and is simply the Total 30 Year Cost provided on an annualized basis. The Annual Cost per Heliostat is the Field Annual Cost divided by the field size to show the cost of an individual heliostat. The 30 Year Maintenance Cost Per Square Meter of Reflector Surface is 30 year cost of maintenance for each square meter of reflector surface. These four methods of describing the cost of O&M are used to provide a complete understanding of the maintenance plan.

TOTAL MAINTENANCE COST

Based on Material Cost at 1,000,000 Heliostats/Year Production Level
(For a 20,000 Unit Site)

Activity	Total 30 Year Cost	Field Annual Cost	Annual Cost Per Heliostat	30 Year Maintenance Cost Per Square Meter of Reflector Surface
Routine Annual Maintenance	\$11,201,940	\$373,398	\$18.67	\$10.18
Replacement Maintenance	\$18,253,590	\$608,453	\$30.42	\$16.59
TOTAL	\$29,455,530	\$981,851	\$49.09	\$26.77

TOTAL MAINTENANCE COST

Based on Material Cost at 250,000 Heliostats/Year Production Level
(For a 20,000 Unit Site)

Activity	Total 30 Year Cost	Field Annual Cost	Annual Cost Per Heliostat	30 Year Maintenance Cost Per Square Meter of Reflector Surface
Routine Annual Maintenance	\$11,255,370	\$375,179	\$18.75	\$10.23
Replacement Maintenance	\$18,718,380	\$623,946	\$31.19	\$17.01
TOTAL	\$29,973,750	\$999,125	\$49.94	\$27.24

TOTAL MAINTENANCE COST

Based on Material Cost at 25,000 Heliostats/Year Production Level
(For a 20,000 Unit Site)

Activity	Total 30 Year Cost	Field Annual Cost	Annual Cost Per Heliostat	30 Year Maintenance Cost per Square Meter of Reflector Surface
Routine Annual Maintenance	\$11,518,290	\$383,943	\$19.20	\$10.47
Replacement Maintenance	\$44,005,590	\$1,466,853	\$73.34	\$40.01
TOTAL	\$55,523,880	\$1,850,796	\$92.54	\$50.48

TOTAL MAINTENANCE COST

Based on Material Cost at 2,500 Production Level
(For a 2,500 Unit Site)

Activity	Total 30 Year Cost	Field Annual Cost	Annual Cost Per Heliostat	30 Year Maintenance Cost per Square Meter of Reflector Surface
Routine Annual Maintenance	\$1,514,010	\$ 50,468	\$ 20.19	\$11.01
Replacement Maintenance	\$9,448,950	\$314,965	\$125.99	\$68.72
TOTAL	\$10,962,990	\$365,433	\$146.18	\$79.73

ROUTINE ANNUAL MAINTENANCE COST

1,000,000 Production Level
(For a 20,000 Unit Site)

Activity	Annual Action Based on Reliability Estimates	Material Cost per Action	Personnel	Field Annual Cost
Enclosure Repair* (Non-Catastrophic)	445	\$ 1.00	2 1/3 (Total Maintenance Crew - 24 Hours/Day, 7 Days/Week)	Materials \$ 21,830 Labor <u>\$351,568</u> TOTAL \$373,398
Blower Replacement	11	\$34.16		
Filter Cleaning	20,000	\$.50		
Reflector Replacement	13	\$32.28		
Drives Repair	359	\$25.00		
Control Repair	359	\$ 4.50		

*Assumed 0.1% Non-Repaired
Closeouts Per Year

ROUTINE ANNUAL MAINTENANCE COST

250,000 Production Level
(For a 20,000 Unit Site)

Activity	Annual Action Based on Reliability Estimates	Material Cost Per Action	Personnel	Field Annual Cost
Enclosure Repair* (Non-Catastrophic)	445	\$ 1.08	2 1/3 (Total Maintenance Crew - 24 Hours/Day, 7 Days/Week)	Materials \$ 23,611 Labor \$351,568 TOTAL \$375.179
Blower Replacement	11	\$38.00		
Filter Cleaning	20,000	\$.50		
Reflector Replacement	13	\$35.11		
Drives Repair	359	\$28.87		
Control Repair	359	\$ 5.27		

*Assumed 0.1% Non-Repaired
Closeouts Per Year

ROUTINE ANNUAL MAINTENANCE COST

25,000 Production Level
(For a 20,000 Unit Site)

Activity	Annual Action Based on Reliability Estimates	Material Cost Per Action	Personnel	Field Annual Cost
Enclosure Repair* (Non-Catastrophic)	445	\$ 6.25	2 1/3 (Total Maintenance Crew - 24 Hours/Day, 7 Days/Week)	Materials \$ 32,375 Labor \$351,568 TOTAL \$383,943
Blower Replacement	11	\$ 47.94		
Filter Cleaning	20,000	\$.50		
Reflector Replacement	13	\$118.44		
Drives Repair	359	\$ 40.95		
Control Repair	359	\$ 7.87		

*Assumed 0.1% Non-Repaired
Closeouts Per Year

ROUTINE ANNUAL MAINTENANCE COST

2500 Production Level
(For a 2,500 Unit Site)

Activity	Annual Action Based on Reliability Estimates	Material Cost Per Action	Personnel	Field Annual Cost
Enclosure Repair* (Non-Catastrophic)	56	\$ 10.65	(Total Maintenance Crew - 24 Hours/Day, 7 Days/Week)	Materials \$ 6,522 Labor \$43,946 TOTAL \$50,468
Blower Replacement	1	\$ 99.98		
Filter Cleaning	2,500	\$.50		
Reflector Replacement	2	\$441.97		
Drives Repair	45	\$ 68.88		
Control Repair	45	\$ 13.16		

*Assumed 0.1% Non-Repaired
Closeouts Per Year

REPLACEMENT MAINTENANCE

1,000,000 Production Level
(For a 20,000 Unit Site)

Activity	Action	Material Cost	Labor	Field Annual Cost
Teardown and Replacement of Both the Enclosure and the Reflector Surface	20,000 Every 10 Years	\$138.42 per Heliostat	16 Man-Hours per Heliostat	Materials \$184,560
				Labor \$423,893
				TOTAL \$608,453

REPLACEMENT MAINTENANCE

250,000 Production Level
(For a 20,000 Unit Site)

Activity	Action	Material Cost	Labor	Field Annual Cost
Teardown and Replacement of Both the Enclosure and the Reflector Surface	20,000 Every 10 Years	\$150.04 per Heliostat	16 Man-Hours per Heliostat	Materials \$200,053
				Labor \$423,893
				TOTAL \$623,946

REPLACEMENT MAINTENANCE

25,000 Production Level
(For a 20,000 Unit Site)

Activity	Action	Material Cost	Labor	Field Annual Cost
Teardown and Replacement of Both the Enclosure and the Reflector Surface	20,000 Every 10 Years	\$782.22 per Heliostat	16 Man-Hours per Heliostat	Materials \$1,042,960
				Labor \$ 423,893
				TOTAL \$1,466,853

REPLACEMENT MAINTENANCE

2,500 Production Level
(For a 2,500 Unit Site)

Activity	Action	Material Cost	Labor	Field Annual Cost
Teardown and Replacement of Both the Enclosure and the Reflector Surface	2,500 Every 10 Years	\$1,571,872 per Heliostat	16 Man-Hours per Heliostat	<div>Materials \$261,978</div> <div>Labor \$ 52,987</div> <div>TOTAL \$314,965</div>

8.0 GENERAL

During the course of the Phase I studies, several desirable design changes have been identified for the heliostat, its enclosure, and the installation processes. These changes, as described in the following sections, offer potential improvements in the areas of cost and/or performance. They represent ideas that were brought forth as a result of the Phase I study but were too late to be included in the evaluation process.

8.1 HELIOSTAT ASSEMBLY

Potential improvements are discussed below for the following heliostat components:

- Stretch Frame Strut
- Support Post Joint
- Disc Drives
- Tension and Alignment Mechanisms
- Focusing
- Reflector Surfaces
- Corner Beams
- Six Strut Mirror

8.1.1 STRETCH FRAME STRUT

The Preliminary Design reflector assembly uses a tubular member (described in Section 2.3.1) with formed ends for the compression loads. The rather long length > 4m (13 ft) requires large 'r' (radius of gyration) values to reduce the column λ/r ratio. This design results in inefficient use of material (low material stress). A possibly more efficient strut design may involve the use of a lightweight (small diameter) strut with tension ties to provide the lateral stability.

8.1.2 SUPPORT POST JOINT

The support and drive assembly (described in Section 2.3.5), used for installation, manufacturing, and costing, specified a second joint in the support below the king post section. This joint serves no function and will be deleted on prototype designs. Improved connection techniques will be employed to reduce potential tolerance problems.

8.1.3 DISC DRIVES

The Preliminary Design drive wheel employed the circumferential rim for the 5mm (.020 in.) spacer grooves required for the drive motor. The alternate rotor disc configuration illustrated in Figure 2-18 has the following advantages:

- Balanced magnetic coupling
- Low drive motor 'loads' on wheel
- Simplified wheel manufacturing
- Lower tooling costs

8.1.4 REFLECTOR SURFACES

Silvered 1st and 2nd surface reflectors made with single and multiple film surfaces should be examined for potential reflectance improvement of up to five percent.

8.1.5 CORNER BEAMS

As field experience is gained through the manufacture and deployment of prototype hardware, it is expected that simplified and lower cost solutions to corner beams will be developed.

8.1.6 SIX-STRUT MIRROR

A trade-off study of improved surface contour accuracy and reduced cost versus potentially increased packing factor should be made using the test of a six-point stretched reflector.

8.1.7 TENSION AND ALIGNMENT MECHANISMS

Since only paper studies have been performed in the Phase I effort, marked improvement through actual hardware development is anticipated for the automatic tensioning provisions in the hub and for the type and method to be used in production hardware for strut alignment.

8.1.8 INSTALLATION METHODS

As prototype heliostat systems are built and experience is gained throughout the installation and testing of the pedestals and reflectors, radically new and improved techniques are expected for packaging, handling, and installing these units to reduce time and manpower requirements.

8.1.9 FOCUSING

As presented in Section 2.2.2, focusing will enhance performance of the heliostat field and is particularly adaptable to the stretched film reflectors. Several concepts are currently under evaluation and would be proposed for prototype hardware.

8.2 ENCLOSURE ASSEMBLY

The following potential improvements relate to the enclosure assembly:

- Factory Assembled Enclosure Design
- Reduced Blower Requirements
- Materials

8.2.1 FACTORY ASSEMBLED ENCLOSURE DESIGN

The use of polyvinylidene fluoride permits reconsideration of procedures for factory assembling and folding the enclosure for shipment to the field. Using the ground cover as a permanently mounted diaphragm, a totally factory-assembled enclosure is "factory clean" and can be installed in this condition without opening it to dirty field installation environments. Concepts are being generated for heliostat assembly within these "sealed" enclosures to preserve this "clean room" approach and solve the "wind during installation" problem.

8.2.2 REDUCED BLOWER REQUIREMENTS

Using the factory assembled unit described above, zipper requirements are minimized and air leakage can be significantly reduced thus reducing blower costs and parasitic power loads. Inflation "stay" time is also enhanced.

8.2.3 MATERIALS

Significant improvements can potentially be made in performance, capital cost, and life cycle through continued materials development. Polyvinylidene fluoride has already been cited as a relatively near-term contender for the enclosure as well as for the foundation bag material.

Laminated fabric, scrim, and metallic approaches to buriable and automatically installation foundation sheets can yield up to 50% reduction in cost and provide acceptable rot resistant characteristics to assure 30-year or longer life.