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LOW-COST POINT-FOCUS SOLAR CONCENTRATOR, PHASE I FINAL REPORT

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Winston Lowe -- Structural Design

Vijay Kulkarni -- Structural Analysis

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Audie Price -- Production Plan

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SECTION 1

INTRODUCTION AND SUMMARY

This report presents the results of Acurex's six-month preliminary design study for the Jet Propulsion Laboratory's Low-Cost Point-Focus Solar Concentrator (LCPFSC) development program. The LCPFSC program is an element of the Point-Focus Distributed Receiver Technology (PFDRT) project at JPL, funded by the U.S. Department of Energy under an interagency transfer agreement with NASA. In this study, Acurex has taken a novel approach for a low-cost point-focus concentrator from the conceptual stage through design tradeoffs to preliminary design, including an extensive costing of the design in mass production.

The most important result of our design effort is that the Acurex concept has been found to meet or surpass the cost and performance targets set by the PFDRT project namely:

- The installed cost of the concentrator is $\$127/m^2$ (in 1978 dollars) for the specified mass-production scenario; this is significantly lower than the PFDRT target of $\$150/m^2$. Perhaps more importantly, we have identified a number of ways in which the initial cost may be further reduced with more detailed design and analysis.
- The concentrator achieves a reflector efficiency of 90 percent, meeting the PFDRT goal.

Reflector efficiency is conservatively defined here to be the thermal power delivered to the receiver divided by the solar flux incident on the reflector surface. If reflector efficiency is alternately defined to be the solar reflectance of the reflective material, this design does even better, with a 95 percent efficiency.

This low first cost and high optical performance, coupled with low operating and maintenance costs, gives a very low life-cycle cost of delivered thermal energy. Expressed as the levelized busbar cost of thermal energy ($\overline{BBEC}_{th}$) per JPL methodology, the net energy cost from our design is 13.1 mills/kW_{th}-hr.

It is also important that the preliminary design presented here is consistent with other PFDRT objectives and parallel programs, in four primary areas:

- The design is based entirely on state-of-the-art technology; no significant developments are required to manufacture the concentrator as specified.
- This concentrator can achieve high system reliability, since almost all components are already in volume production in similar forms and have long histories of reliable usage.
- The preliminary design was carried out for mass production of the concentrator, with full consideration given to manufacturing engineering. At the same time, the design can be easily prototyped because of the current availability of almost all components.
- The optimum size found for this design (102 m^2) is a good match for the 15 kWe receiver/engine designs being developed under separate JPL programs.

In addition, this concentrator meets all design requirements specified by JPL for this program, and is based on practical design solutions in every possible way. During our design effort, the emphasis was on finding innovative applications of practical, state-of-the-art hardware; and extensive engineering analysis was used where appropriate to ensure the results are technically sound. In addition, to ensure economic soundness, a detailed and thorough costing was performed in parallel with the design, including conceptual plans for manufacturing, installation, and operation.

A summary description of the Acurex preliminary design is given below in Section 1.1. Section 1.2 describes the design philosophy we have used to achieve a cost-effective design for mass production. In Section 1.3, a brief outline of the remainder of the report is given as an aid to the reader.

1.1 PRELIMINARY DESIGN SUMMARY

The Acurex concentrator design (Figure 1-1) is based on the "faceted compressed paraboloid reflector" concept, which involves the use of three distinct paraboloidal reflector surfaces to reduce the side profile of the concentrator. The lower profile due to this "Fresnel" approach reduces wind load and thus reduces overall structural weight and cost. This may be contrasted to conventional "dish" designs having higher wind loadings, which directly impact the cost; in fact, the effect of "compressing" the reflector surface is a 40 percent decrease in side wind load relative to a dish of the same aperture size. This is an extremely important concept, since the cost of solar concentrators is dominated by the structural considerations required to survive high winds. Reduction of the wind loading allows the use of a lighter structure -- and because

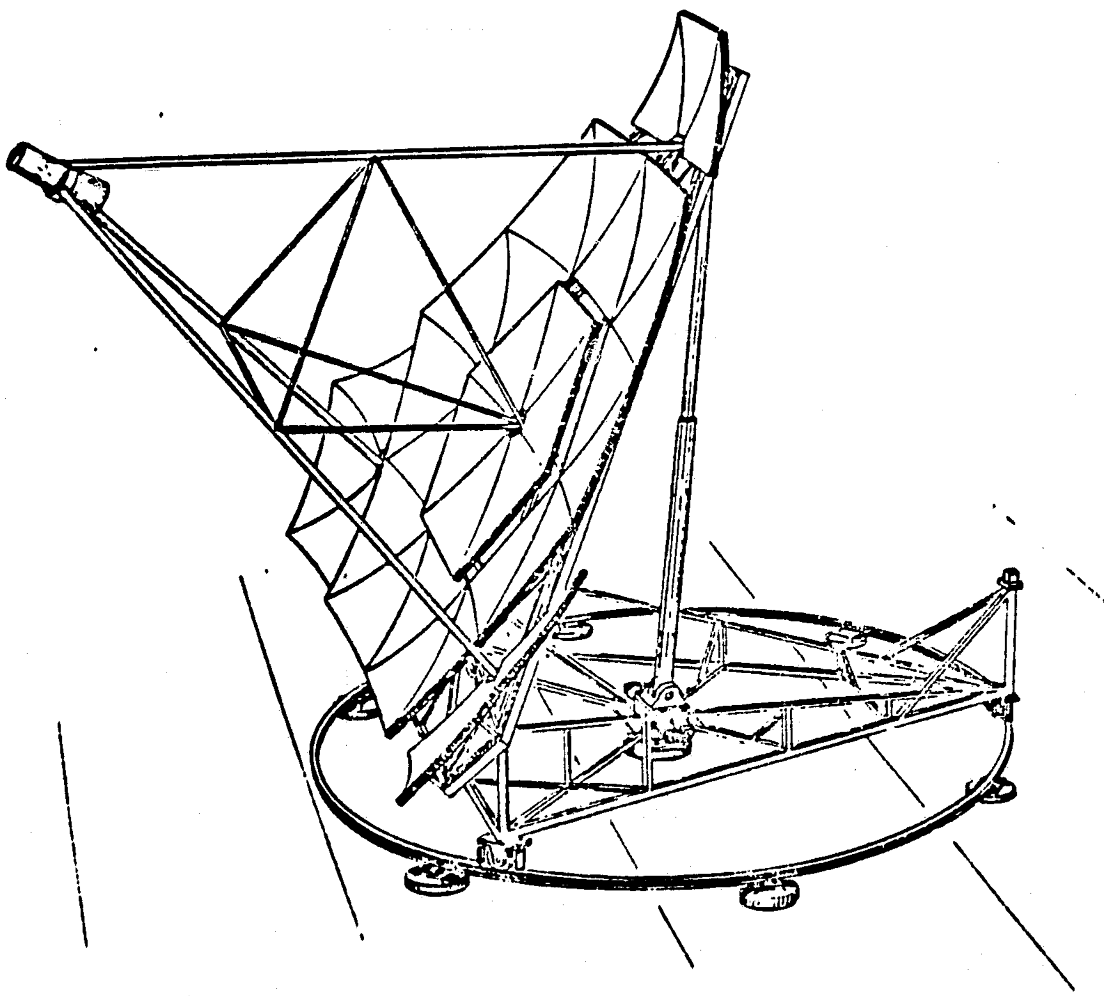

Figure 1-1. Acurex faceted compressed paraboloid concentrator.

the cost of almost any fabricated item in mass production is directly proportional to the item's weight, a light structure is essential to lowering the concentrator cost.

A second important aspect of our design is the shape of the reflector in plan view, characterized as a truncated triangle -- that is, a triangular reflector with the three apexes removed. This concept again results in low wind load, low weight, and therefore low cost in mass production. The triangular shape takes advantage of the wind's boundary layer at the earth's surface; since most of the triangle is close to the ground where the wind speed approaches zero, the frontal wind load is minimized. This effect results in about a 14 percent advantage over the frontal wind loads experienced by a circular shape (e.g., a conventional paraboloid dish). The frontal wind loads will be further reduced because of the gaps which exist between the three paraboloid sections to prevent shading. Also, as can be seen in Figure 1-1, the reflector structure is mounted close to the ground and is hinged near the base, to take further advantage of the lower windspeed in the boundary layer. The concentrator will stow in a horizontal position whenever the windspeed exceeds a predetermined value (nominally 30 mph).

A third key element of our design is the use of thin back-silvered glass (flex glass) on panels made of sheet molding compound (SMC), a structural plastic consisting of polyester resin and glass fibers. The 33 triangular panels, or facets, which comprise the reflector surface are fabricated by molding SMC and flex glass in a single pressing operation. The result of this unique combination of materials is excellent optical performance at low cost, due to several factors:

- Thin back-silvered glass is the best reflective material available with known technology; it has the highest solar reflectance and best specularity of all potential reflectors
- SMC can be molded to very accurate surface contours with existing technology, thus contributing to high optical performance
- Both flex glass and SMC are low cost in quantity production, and the reflector panel fabrication technique is inherently inexpensive

The remaining salient features of our design are illustrated in Figure 1-1. The 33 triangular reflector panels, nominally 8 feet in altitude to permit easy shipping, are mounted on a lightweight space frame (the reflector support structure) fabricated with structural steel tubing of optimal cross-sectional shapes (round, square and rectangular). The reflector support structure is hinged at two points near the base, where it mounts to the base support structure. The base support structure, also fabricated of light steel tubing, rides on a raised steel I-beam track with three wheels and rotates about a center pivot. Both the center pivot and the I-beam circular track are mounted on concrete piers. Elevation of the reflector support structure and rotation of the base support structure are both provided by hydraulic actuators. The elevation drive is a single-stage double acting cylinder, while the azimuth drive is a rotary actuator located at the center pivot.

The hydraulic elevating cylinder permits rapid, smooth downward rotation of the reflector structure to the horizontal stow position, where the reflector is close to the ground to minimize wind loads. Our design calls for stowing of the concentrator when the windspeed exceeds 30 mph, since such windspeeds are rare, occurring less than 1 percent of the time during daylight hours in the southwest United States.

A final design feature shown in Figure 1-1 is the receiver support structure, a reinforced tripod of steel tubing which attaches to the reflector support structure directly over the two hinge points and the hydraulic cylinder termination point. This design carries the receiver loads directly to the foundation and thus reduces the strength requirements for the reflector and base support structure. As noted in Section 2.4, this also makes the concentrator design and cost relatively insensitive to variations in the receiver weight.

The concentrator size for the preliminary design has been set at 1098 ft^2 (102 m^2) net aperture area. The reflector surface is 47.5 feet (14.5 m) wide at the widest point near the base, and the raised circular track is 38.9 feet (11.9 m) in diameter. For this size, the concentrator delivers 61.3 kW_{th} (net) at the design point of 800 W/m^2 incident direct radiation. This corresponds to about 15 kWe in electrical output from the engine/generator, assuming nominal receiver and engine efficiencies (it should be noted that the receiver/engine design is not part of this program, but is being carried out under a parallel JPL program).

1.2 DESIGN PHILOSOPHY

The primary goal of the LCPFSC program is the development of a concentrator with significant improvements in cost-effectiveness relative to current designs. "Cost-effectiveness" as used here has a specific meaning: low life-cycle cost of delivered thermal energy. Also, the design and costing basis for the concentrator is mass production, nominally at the rate of 100,000 units per year. To achieve good

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cost-effectiveness (measured as $\overline{BBEC}_{th}$, in mills/kW_{th}-hr), it is necessary to obtain the best possible performance (given by the net thermal power delivered to the receiver, in kW_{th}) at the lowest possible life-cycle cost (given by an annualized cost, in $/year, which includes capital, maintenance and replacement costs for 30 years). Thus our design effort has been a careful optimization to minimize $\overline{BBEC}_{th}$ by trading off the key performance parameters with the associated life-cycle costs. Because capital installed cost is the dominant cost factor and is directly related to weight for mass production, the most important tradeoffs involved component performance and weight, with wind load being the primary determinant of weight (these design tradeoffs are described in Section 2.2).

The result of applying this design philosophy to our concept is a quantifiable set of characteristics, in terms of both performance and cost, which result in excellent cost-effectiveness. Those characteristics of the design which determine the primary performance parameters are summarized in Table 1-1. The combination of thin flex glass, sheet molding compound, and an optimized space frame is the key to the high overall performance which this design achieves.

Those characteristics of the design which contribute to low life-cycle cost are summarized in Table 1-2. The table breaks down the cost into four major areas: manufacturing, shipping, installation, and operation and maintenance. Of these, manufacturing cost is most significant, so most of the design effort was aimed at minimizing the cost out of the factory -- primarily by minimizing component weights. It can be seen from the table that several of the design features have benefits in more than one cost area; for example, light weight results in lower

TABLE 1-1. RELATIONSHIP BETWEEN DESIGN FEATURES AND PERFORMANCE PARAMETERS

Desired Performance Parameter	Associated Design Feature	Parameter Value
High Reflectance	Back-Silvered Thin Glass	$R_{s,2\pi}$ = 95%
Low Specularity	Back-Silvered Thin Glass	σ_ω = 0.1 mrad
Low Slope Error	Sheet Molding Compound	σ_s = 1 mrad
Small Panel Deflection	Iso-Grid SMC	σ_{dp} = 0.36 mrad
Small Structural Deflection	Optimized Space Frame	σ_d = 0.8 mrad
Low Pointing Error	Small Receiver Deflection High-Accuracy Tracking Precise Positional Accuracy	σ_p = 3.5 mrad

TABLE 1-2. DESIGN FEATURES RESULTING IN LOWER LIFE-CYCLE COST

Cost Area	Related Design Features
Manufacturing Cost	Light Weight ● Low Front Wind Load ● Low Side Wind Load ● Rapid Stow Close to Ground ● Optimized Space Frame ● Thin Glass ● Optimized SMC panels Standard Materials Standard Manufacturing Technology
Shipping Cost	Light Weight Common Carrier Shipping ● 8 Foot Height Limit ● 40 Foot Length Limit Close Packing
Installation Cost	Light weight Standard Materials Standard Procedures Rapid Panel Alignment Easy Access to Components Factory Subassemblies
Operation and Maintenance Costs	Low Parasitic Power Easy Access To Components Reliable Hardware Long-Life Materials

shipping and installation costs, in addition to lower manufacturing cost. An important ingredient in our design approach was this "holistic" viewpoint; all four cost areas were considered in the tradeoffs which led to the design and component specifications. This factor, and the other elements of our design philosophy summarized above, is developed in more detail in Sections 2 and 3.

1.3 REPORT SUMMARY

This report's organization corresponds to the major tasks carried out during this program (with the exception of Task 1, Parameter Optimization, which was reported separately in November 1978). Task 2, Preliminary Design, is discussed in Section 2 below. Most of the technical effort on this program was applied to Task 2 to ensure that all essential areas of the design were addressed in sufficient detail. The major subtasks of Task 2, and their corresponding report sections, are:

- Concentrator design -- Section 2.2
- Reflective panel fabrication and testing -- Section 2.3
- Performance analyses -- Section 2.4

In addition, Section 2.1 describes the Task 2 design approach in more detail.

In Task 4, Assessment of Production Implementation, a complete costing of the preliminary design was carried out; the results are summarized in Section 3. The major subtasks in the costing, and the associated sections, are:

- Costing methodology -- Section 3.1
- Production plan -- Section 3.2
- Installation plan -- Section 3.3
- Operating and maintenance plan -- Section 3.4

The costs developed in Sections 3.2 through 3.4 are summarized in Section 3.5. Background details of the costing are given in Appendices A and B.

SECTION 2
PRELIMINARY DESIGN

The primary objective of the preliminary design task (Task 2) was to refine the baseline concept to further reduce the life-cycle cost of delivered energy ($\overline{BBEC}_{th}$) for the concentrator. Specific goals of this effort were:

- Development of the preliminary drawing package
- Analysis of component requirements and preliminary specification of components
- Demonstration of state-of-the-art fabrication techniques for SMC/flex glass panels
- Verification of panel slope error values
- Assessment of design impact due to changes in receiver/engine weight or receiver operating temperature.

To ensure a cost-effective design of the Low-Cost Point-Focus Solar Concentrator (LCPFSC), Acurex employed a systems design approach which accounts for the interactive nature of the design by basing component and subsystem tradeoffs on systems-level analysis. This is an essential element in designing for minimum life-cycle cost of delivered thermal energy (minimum $\overline{BBEC}_{th}$). The basic steps involved in all tradeoffs were as follows:

- Conceptualize options
- Analyze impact of options on system cost/performance
- Select best option based on lowest system $\overline{BBEC}_{th}$

Since the primary objective of this design is improved cost-effectiveness at high-volume production rates, we concentrated our preliminary design efforts in the major cost/performance areas. These were:

- Reflective panels
- Structure
- Foundation/track
- Drives

The tracker/control subsystem and the electrical design may significantly impact the design and fabrication costs at low production volumes; however, at mass production levels (consistent with the 100,000 units per year design target), these elements of the design will reach predictably low cost levels. Since these costs are less dominant than those listed above, less emphasis was placed on the preliminary analysis and tradeoffs for the tracker/controls and electrical subsystems.

The starting point for the preliminary design effort was the baseline design and the optimized set of parameters from the Task 1 effort (Reference 2-1). The baseline design concept has remained fundamentally intact. Through comprehensive tradeoffs, however, the design has been refined to significantly improve overall cost-effectiveness. Major tradeoffs were made in the areas of:

- Reflector panel support structure
- Foundation/track

- Drives
- Concentrator size

The discussion of the preliminary design effort is broken into four major sections. Section 2.1 gives an overview of the design; Section 2.2 presents a detailed description of the preliminary design and design tradeoffs; and Section 2.3 covers the sample panel fabrication and testing. Finally, Section 2.4 discusses the performance analysis effort along with an assessment of the sensitivity of the design to proposed changes in receiver operating temperature or receiver/engine weight.

2.1 DESIGN OVERVIEW

As noted in Section 1, the key element of our design philosophy was the reduction of wind loads on the concentrator to reduce structural weight and, in turn, decrease mass-production costs. Three characteristics of the concentrator design which contribute to a cost-effective design through reduction of wind loads are:

- Compressed (Fresnel) paraboloidal reflecting surface
- Truncated triangular aperture shape
- Horizontal stow position close to the ground

The total concentrator weight which results from these design characteristics is 14,760 lb, or 13.4 lb/ft^2 based on net aperture area. This weight, which is broken down by components in Table 2-1, is considered to be conservative; further reductions are anticipated during detailed design.

Compressed (Fresnel) Paraboloid

The reflecting surface is comprised of 33 individual triangular reflective panels grouped into three (3) different paraboloids with a

TABLE 2-1. CONCENTRATOR COMPONENT WEIGHT BREAKDOWN

Component	Weight per Concentrator (lbs)
Flex glass	500
SMC panel	3,100
Panel attachment hardware	440
Panel support structure	3,750
Receiver support structure	1,200
Base support structure	1,670
Azimuth drive	650
Elevation actuator	350
Controls and electrical	500
Track	600
TOTAL	14,760

common focal plane at the receiver aperture (Figure 2-1). The reduction in projected area due to "compressing" the paraboloidal surface reduces the side wind load by approximately 40 percent. This allows a lighter base support structure than would otherwise be possible with corresponding reductions in foundation and track loading.

Gaps separating the three paraboloids from each other result from spacing to eliminate blockage of reflected light. The pressure relief effect from the gaps further reduces the wind loading but was not included in the load analysis. This will be an area of investigation during the detailed design effort which will result in further weight and cost reductions.

Truncated Triangular Aperture Shape

The basic shape of the concentrator (Figure 2-2) is triangular, which takes advantage of the earth's boundary layer effect and realizes approximately 14 percent reduction (relative to a circular dish of equal area) in wind load due to having most of the area close to the ground. The inherently rigid triangular theme is carried throughout the structural system in the shape of the base support structure and in the placement of structural members to form space frames. Because triangles are rigid configurations, the resulting structures can be lighter.

Another advantage of the Acurex triangular concentrator is the ability to carry receiver/engine support structure loads directly to the base support structure and foundation with minimal impact on the panel support structure design. The benefit derived from this aspect of the design will be discussed in more detail in Section 2.4.4 (receiver/engine modification impact on concentrator design). As indicated in that section,

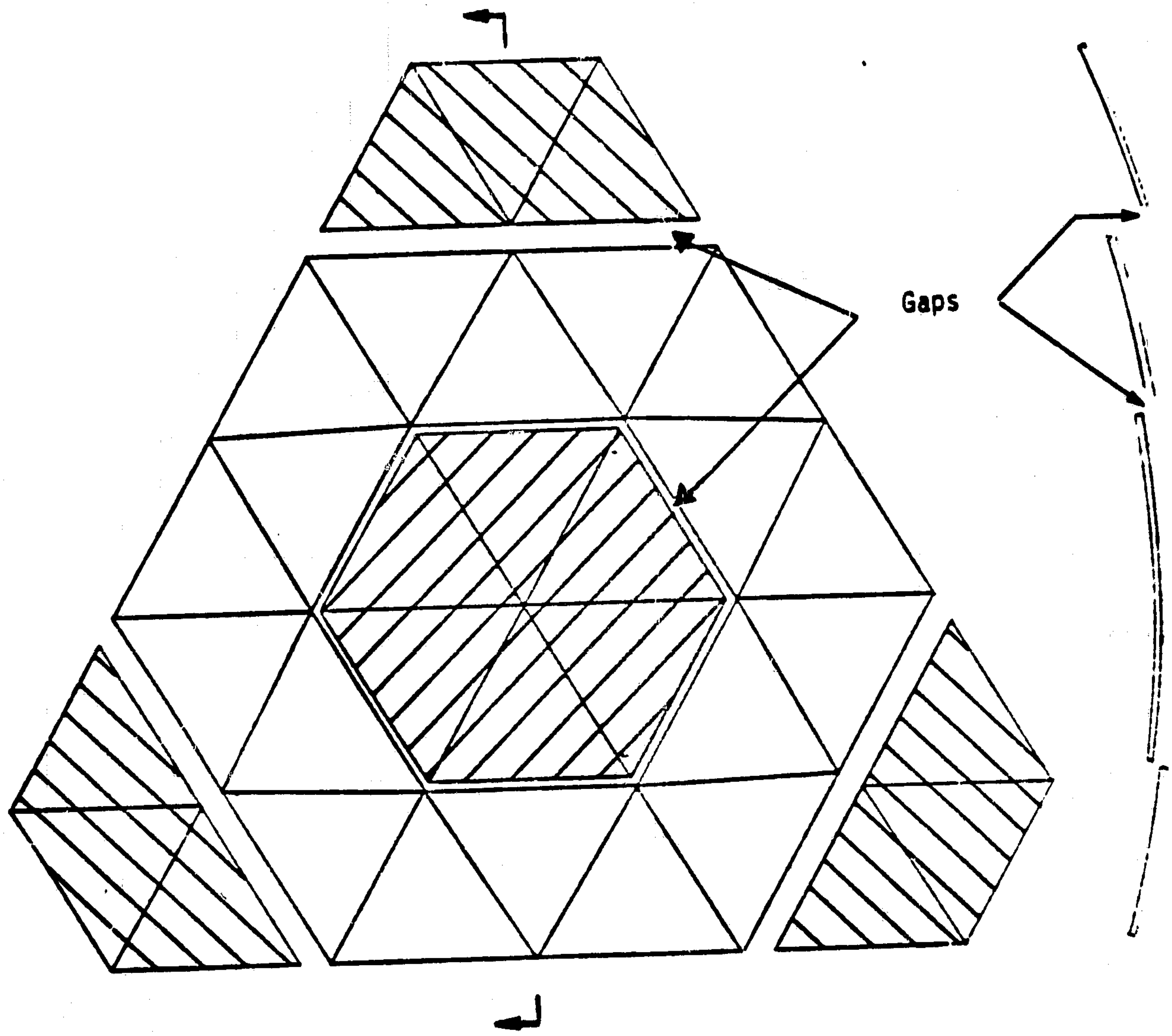

Figure 2-1. Compressed (Fresnel) paraboloid.

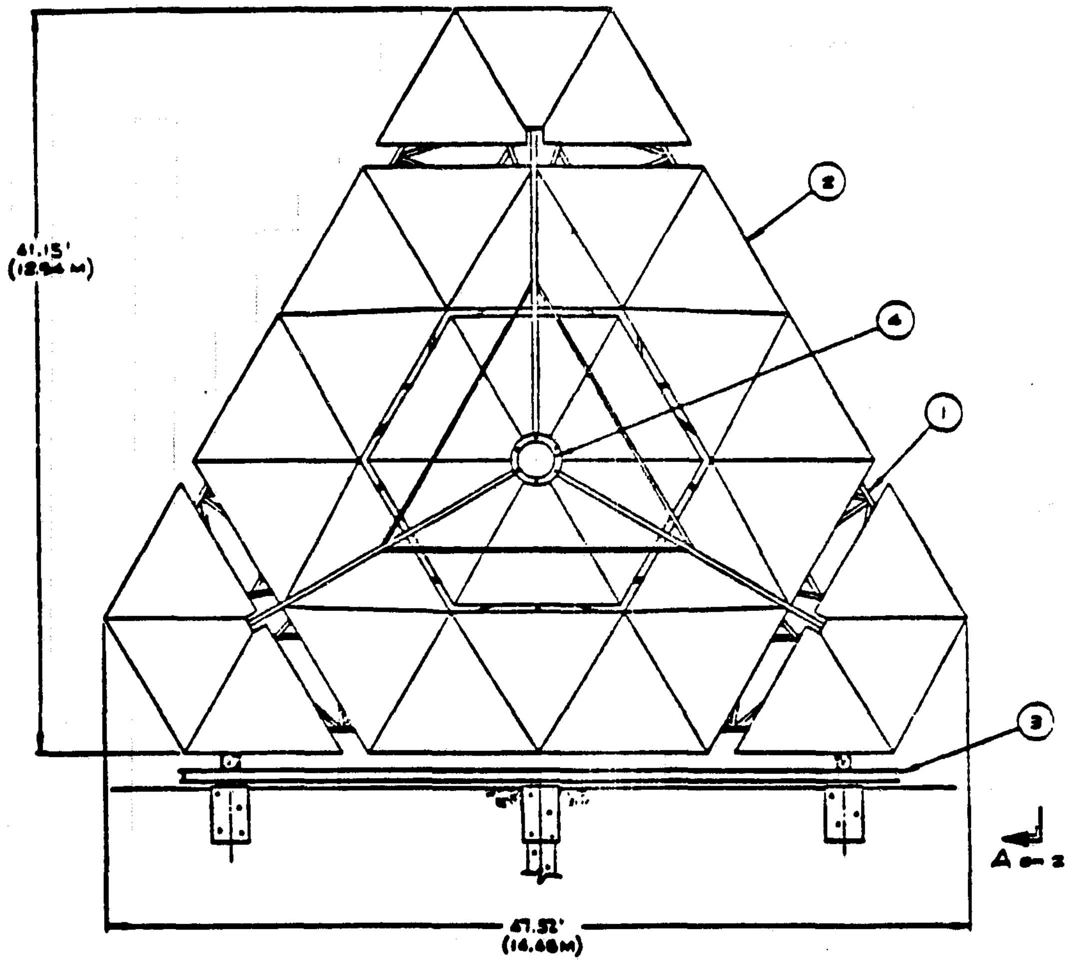

Figure 2-2. Truncated triangle concentrator aperture.
(Excerpt from Drawing 6848-001, Sheet 1)

the concentrator design is insensitive to variations in receiver/engine weight.

Horizontal Stow

Since the concentrator structural design is dominated by the requirement to survive a 100 mph wind without damage, the ability to slew to a horizontal stow position close to the ground significantly reduces the wind loads and therefore structure weight. A slew rate of approximately 80^{o}/minute is achieved through the use of a variable flow hydraulic elevation actuator to quickly lower the concentrator when wind velocities exceed 30 mph (nominally).

A horizontal stow position (Figure 2-3) reduces the frontal area of the concentrator and by stowing close to the ground, further benefit is derived from the earth's boundary layer effect in reduced wind velocity. The panel support structure is hinged about 8 1/2 feet above the ground where the wind velocity is 86 mph as compared to 100 mph (free stream velocity) at 30 feet above the ground. The hinge elevation is determined by:

- The reflective panel overhang of 6 1/2 feet beyond the hingeline on the panel support structure
- The 1 foot clearance specified between the panel and the track (when the concentrator is pointing at the horizon)
- The 1 foot elevation of the top of the track (Figure 2-2)

An additional benefit derived from the low stow configuration is reduced installation and maintenance costs due to ground level accessibility.

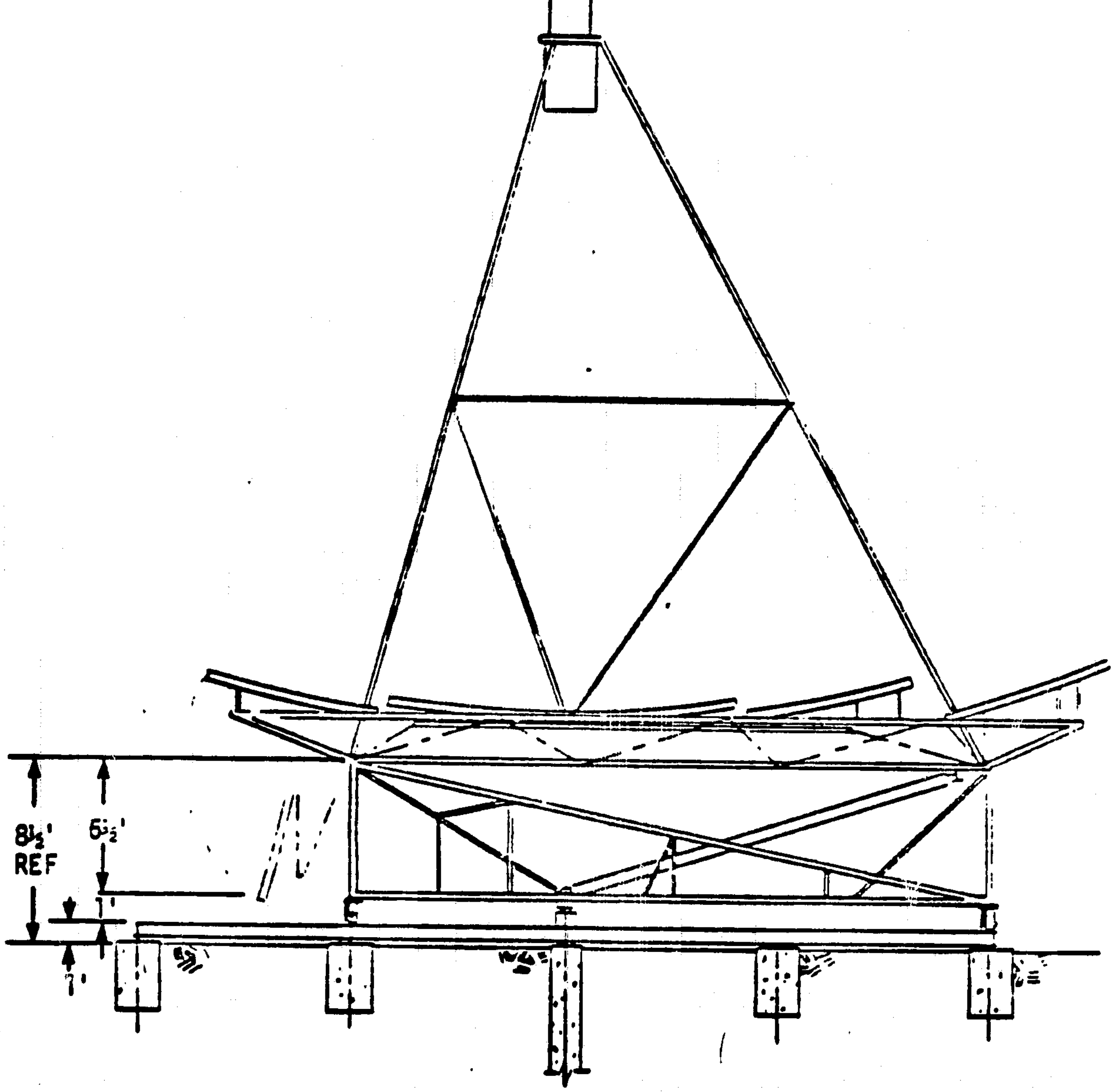

Figure 2-3. Horizontal stow configuration.

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2.2 CONCENTRATOR DESIGN

this section presents a detailed description of the concentrator preliminary design and the tradeoffs involved in developing the design. The design task was divided into subtasks corresponding to the major subsystems which make up the concentrator. The subsystem designs are described in the following sections:

- Section 2.2.1 -- Reflective Panels
- Section 2.2.2 -- Structures
- Section 2.2.3 -- Foundation and Drive
- Section 2.2.4 -- Tracker and Controls
- Section 2.2.5 -- Electrical

As noted above, most of the design effort was applied to the first three subsystems listed here, so Sections 2.2.1 through 2.2.3 constitute most of the discussion which follows. Throughout the discussion, figures which are taken from the drawing package submitted with this report are so referenced.

2.2.1 Reflective Panel Design

The reflective panels are a composite construction of a thin (0.5 mm, 0.028 inch) back-silvered glass mirror with a sheet molding compound (SMC) supporting structure (Figure 2-4). Sheet molding compound is a composite of polyester resin with chopped glass fiber reinforcement. Details of the panel design, attachment links and alignment are covered in the following subsections.

2.2.1.1 Reflective Panel Design Objectives

It was concluded during the Task 1 design effort that a cost-effective concentrator design should utilize a high performance, durable, reflecting medium in order to meet the 30 year life-time

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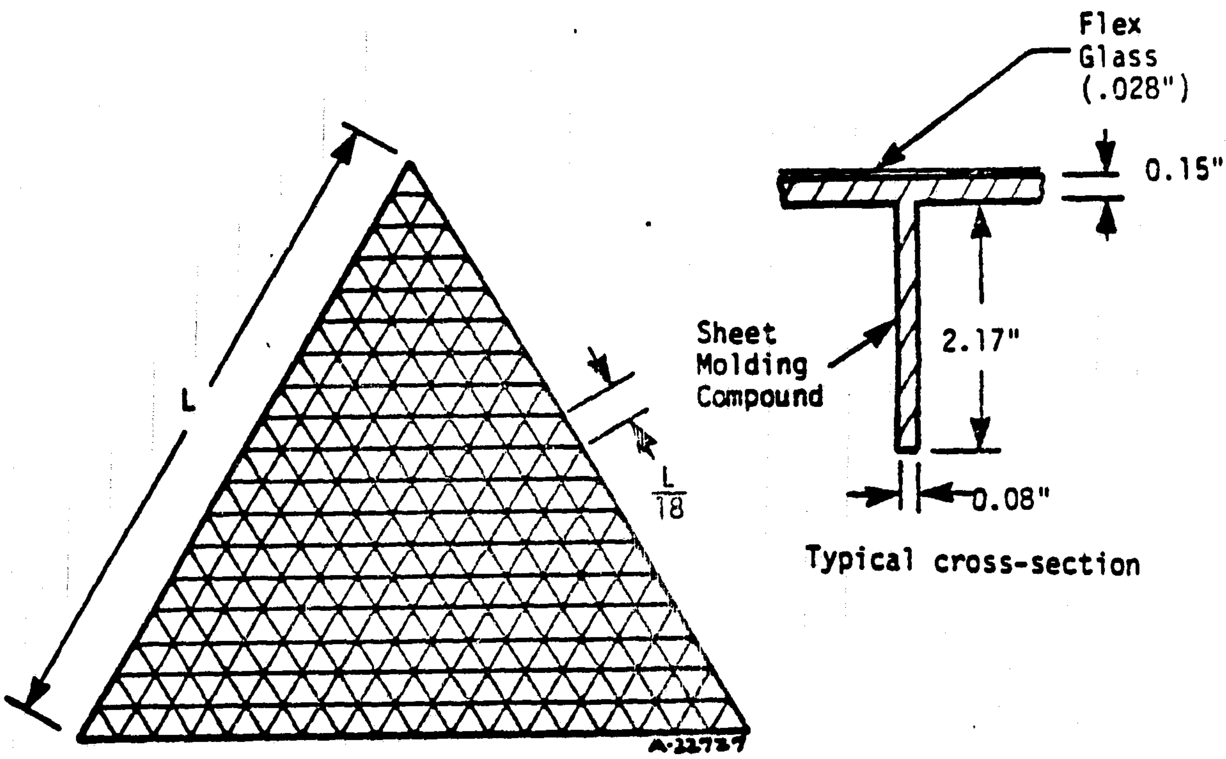

Figure 2-4. Reflective panel isogrid backing.

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requirement as specified in the statement of work. In order to meet this design goal, the following performance and structural design objectives were identified and met as indicated:

Performance

- High reflectance and excellent (low) specularity are achieved by the use of a back-silvered glass mirror
- Low slope error is provided by the press-molded SMC
- High stiffness is obtained with an isogrid backing structure optimized for low cost through low weight
- Minimum angular deflection of the panel results from the selection of optimum support point locations on the panel

Structural

- Hail impact survival is provided by the SMC face sheet
- Over-stressing the glass mirror due to 100 mph wind load deflection is prevented by the SMC isogrid backing
- Thermal cycling (-20°F to 140°F) effects are minimized by matching the SMC coefficient of thermal expansion to that of the glass mirror

2.2.1.2 Flex Glass Reflector

The flex glass reflector was chosen because of its high performance and durability characteristics. In terms of performance, the back-silvered reflecting surface provides the highest practical solar hemispherical reflectance ($R_{s,2\pi}$ = 0.95), while the glass itself has excellent specularity (σ_{ω}<0.1 mrad). Glass is highly abrasion resistant and is also resistant to most common, natural degrading substances (e.g., bird droppings, plant secretions, etc.) which lends to its durability.

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TABLE 2-2. SHEET MOLDING COMPOUND PROPERTIES[a]

Compressive strength:	28,000 psi
Tensile strength:	12,500 psi
Flexural strength:	28,000 psi
Modulus:	1.30×10^6 psi tensile 1.35×10^6 psi flexural
Specific gravity:	1.85
Mean coefficient of thermal expansion[b]:	from -60^oF to 115^oF $11.5 \times 10^{-6}/^oF$ from 115^oF to 300^oF $3.0 \times 10^{-6}/^oF$

[a]Properties listed are for the specific SMC formulation used to fabricate test panel
[b]Can be altered to match glass coefficient of thermal expansion

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The isogrid structure supports the face sheet and provides a high degree of stiffness at a minimal cost in weight. The grid stiffening imparts isotropic macroscopic properties to the structure; hence the term, isogrid. The isogrid/face sheet structure serves to limit the glass stresses resulting from deflections induced by 100 mph winds. The wind velocity used in the analysis was 86 mph due to the boundary layer effect and the low stow elevation.

The Isogrid Design Handbook (Reference 2-2) was consulted in designing the isogrid structure to define the theoretical optimum combination of grid parameters such as rib thickness, grid depth and spacing, and face sheet thickness. Because the face sheet thickness is a function of the hail impact survival specification, the parameter dimensions indicated in Figure 2-4 deviate somewhat from the theoretical optimum combination. Another factor which contributed to the deviation from optimum is a minimum rib thickness to grid depth ratio which can be reasonably manufactured. The finite element analysis code ANSYS was used to analyze the grid design to verify conformance to the wind survival specification.

As previously stated, there are 33 individual panels but within that group of 33 there are seven different panel configurations (Figure 2-5). The nominal size is an equilateral triangle with 9.25-foot sides which corresponds to an 8-foot altitude. The 8-foot height was determined to be a maximum panel size which is shippable by common commercial carrier with reasonable packing (cushioning) allowance. Refer to Drawing 6848-003 for a complete listing of panel dimensions.

A nominal size panel without glass weighs 94 pounds, approximately 50 percent of which is in the face sheet. Panel weight reductions may be

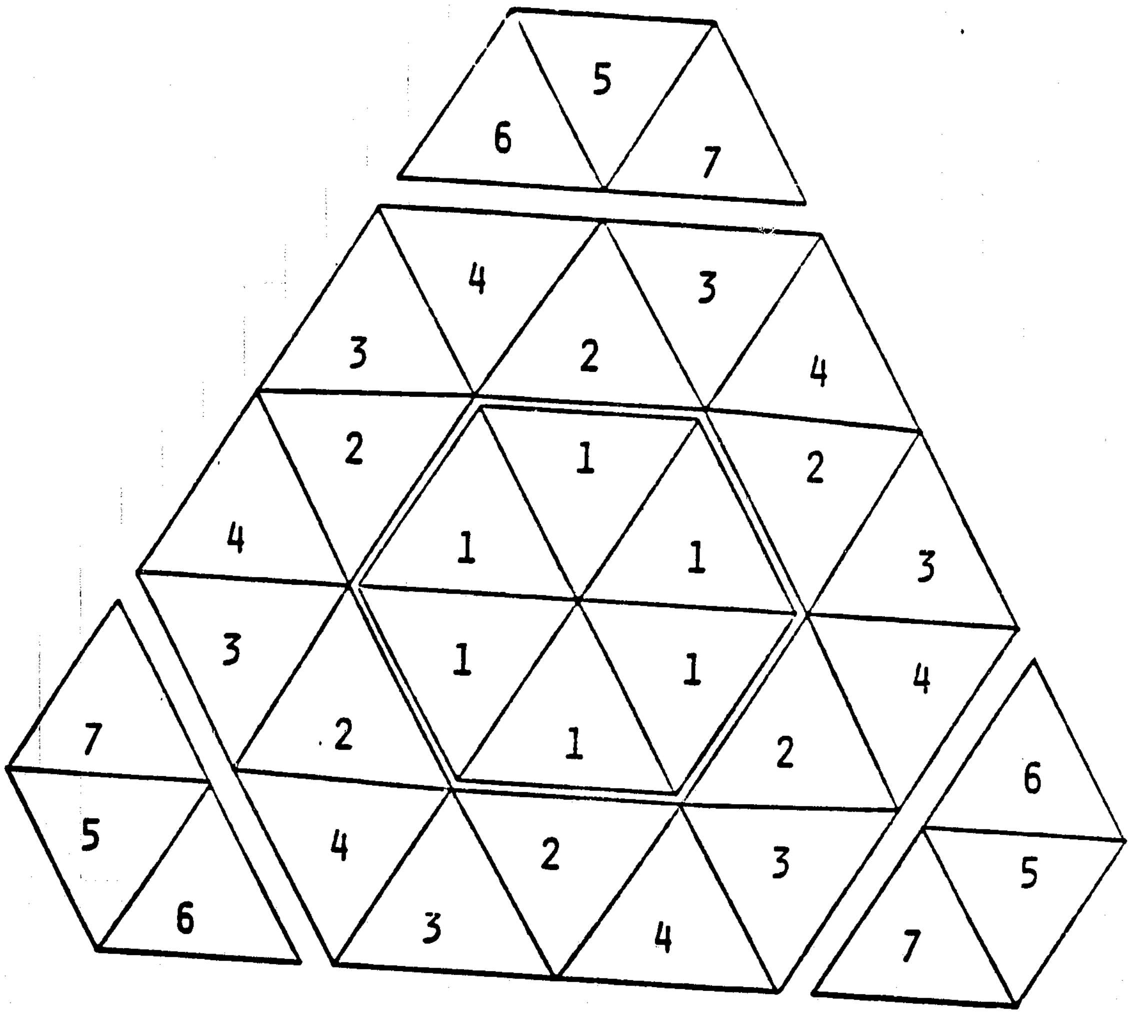


Figure 2-5. Seven different panels comprise reflector.

possible through reductions in the hail and wind survival specifications. This would have a cascading effect throughout the design resulting in both weight and cost reductions.

2.2.1.4 Panel Support Points

The panels are supported at the three points which tend to minimize panel distortions due to bending. An iterative analysis using the ANSYS finite element code was performed to optimize the support point locations. The analysis indicated that support points on the angle bisector at a distance 35 percent of the altitude of the triangular panel in from the apex of the triangle yield minimum panel deflections. The support points indicated on Drawing 6848-003 are at 33 percent the altitude in order to coincide with the isogrid nodes. This provides additional support by means of the intersecting isogrid ribs. Threaded metal inserts for attachment link connection can be molded in place during the panel manufacturing process. The inclusion of metallic inserts of this nature is common practice and grid nodes are ideal locations since the amount of additional SMC material required to form a boss around the insert is minimized (refer to Drawing 6848-003, Sheet 2).

Panel distortions are characterized by the standard deviation term σ_{dp} which was determined as follows. The panel distortions due to panel weight and wind were analyzed to determine local rotational deflections about orthogonal x and y reference axes. The standard deviation of the rotational deflections about each axis was then determined for both weight- and wind-induced distortions. The wind-induced standard deviations were then weighted by the national average wind speed frequency distribution and convolved with the weight-induced standard deviations.

The average of the resultant standard deviations of the rotational deflections about the x and y axes is σ_{dp} = 0.3555 mrad.

2.2.1.5 Attachment Links

The panel attachment scheme is shown in Figure 2-6 and on Drawing 6848-001, Sheet 3. There are three different attachment links per panel which work in conjunction to meet the following design criteria:

- Permit rapid panel alignment (focus on receiver aperture)
- Allow for thermal "breathing" (expansion and contraction) of the panel
- Provide vertical and lateral stability

Link A is rigidly attached to the panel support structure and is fixed in length (Figure 2-7). Link B is attached to the panel support structure at a hinged clevis joint. The hinge axis is oriented perpendicular to a line between Link A and and Link B. The clevis height relative to the structure can be varied for alignment purposes. Link C is attached to the structure with a variable height rod end bearing.

Each link is attached to the panel with a ball joint rod end bearing which is threaded into the metal insert mentioned in the previous subsection. The ball joints reduce the moments applied to the panel and allow the panel to hinge about the axis between two ball joints while the third link is adjusted to align the panel. By adjusting the heights of the structure attachment joints at Links B and C, the panel can be rapidly aligned by the procedure described in the following subsection.

The hinged clevis at Link B will allow the panel to expand and contract thermally between Links A and B. The ball joints on either end of Link C accommodate the thermal expansion/contraction between Link C and

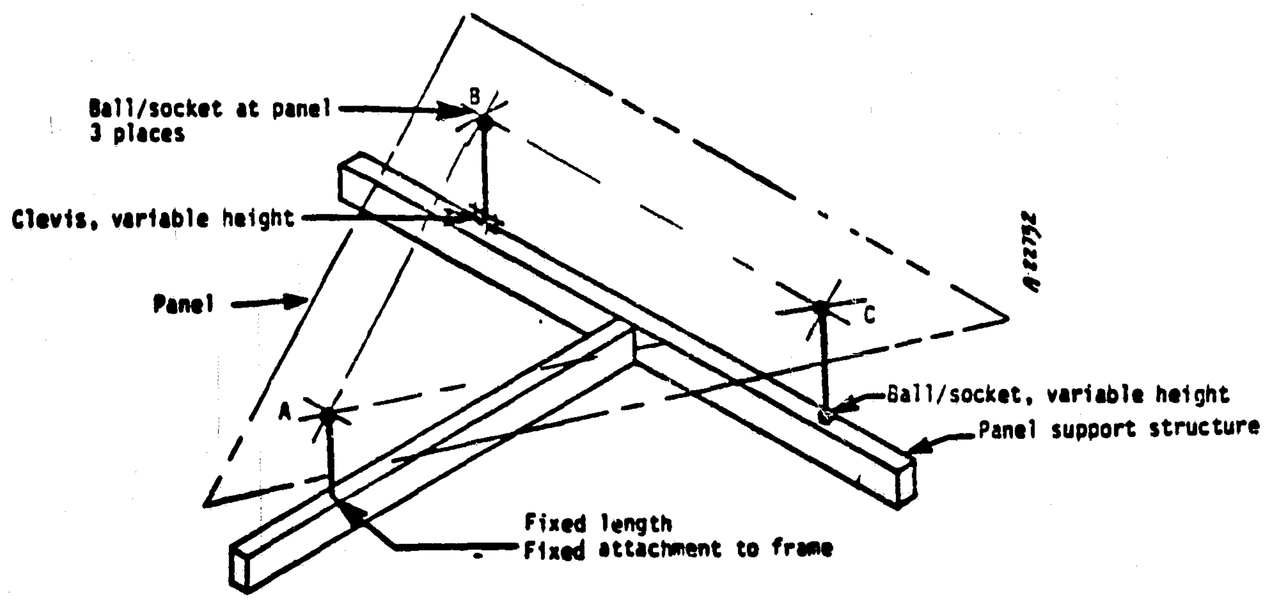


Figure 2-6. Reflective panel attachment scheme.

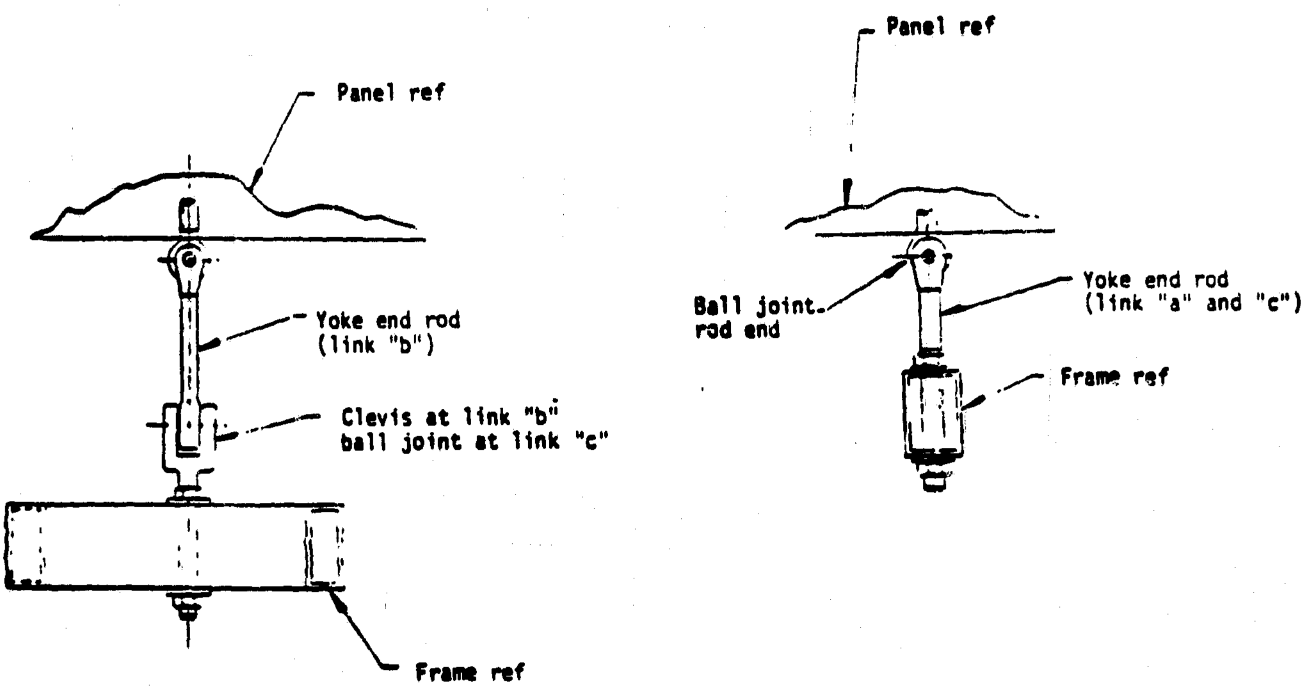


Figure 2-7. Attachment link details.

the other two. The rotational deflection due to thermal effects has been determined to be less than ± 0.005 mrad.

Lateral stability is achieved by the bending resistance provided by Link A and the torsional resistance provided by the hinged clevis at Link B. Vertical stability is provided by the tension/compression nature of the three links.

2.2.1.6 Panel Alignment

Rapid panel alignment is accomplished with a scope temporarily attached to the underside of the panel as shown schematically in Figure 2-8 and a target temporarily attached to the receiver. This simple approach requires minimal auxiliary equipment in the form of a scope mounted to a bracket (Figure 2-9) which interfaces with features molded into the panel isogrid structure. A panel is aligned by adjusting Links B and C to change panel attitude, thereby aligning the scope cross hairs on the target. This procedure can be performed at any time of day and is dependent only upon the availability of sufficient light to view the target through the scope.

The maximum number of different scope brackets required is seven, corresponding to the seven different panels comprising the 33. It is probable that this requirement can be reduced by designing the bracket/panel interface features such that one scope and bracket can be used to align more than one type of panel. It should be pointed out that Figure 2-9 is a schematic representation, and the actual design of the scope bracket would most likely have a "foot-print" covering several grid bays as opposed to the one bay shown in Figure 2-9. In so doing, the effects of local tolerances on alignment are reduced. The anticipated accuracy of alignment has been determined to be within 0.5 mrad.

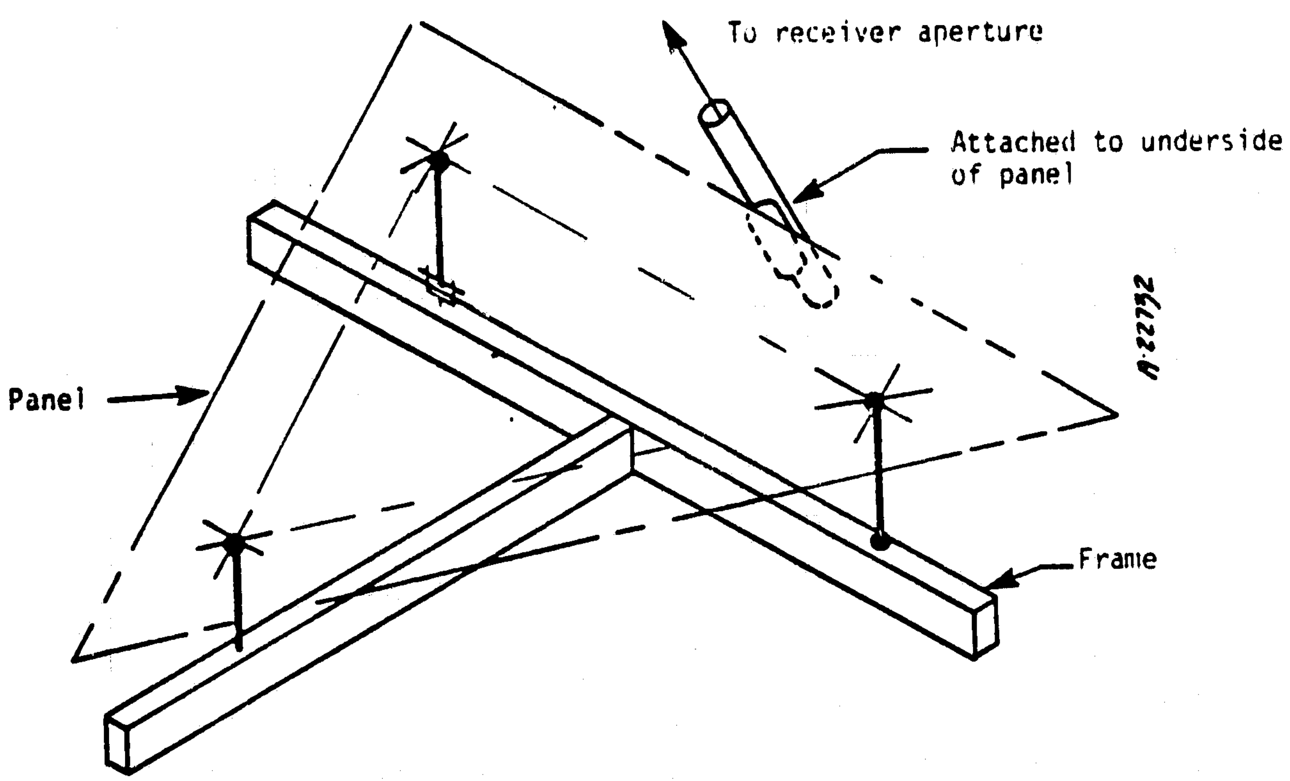


Figure 2-8. Panel alignment scheme.

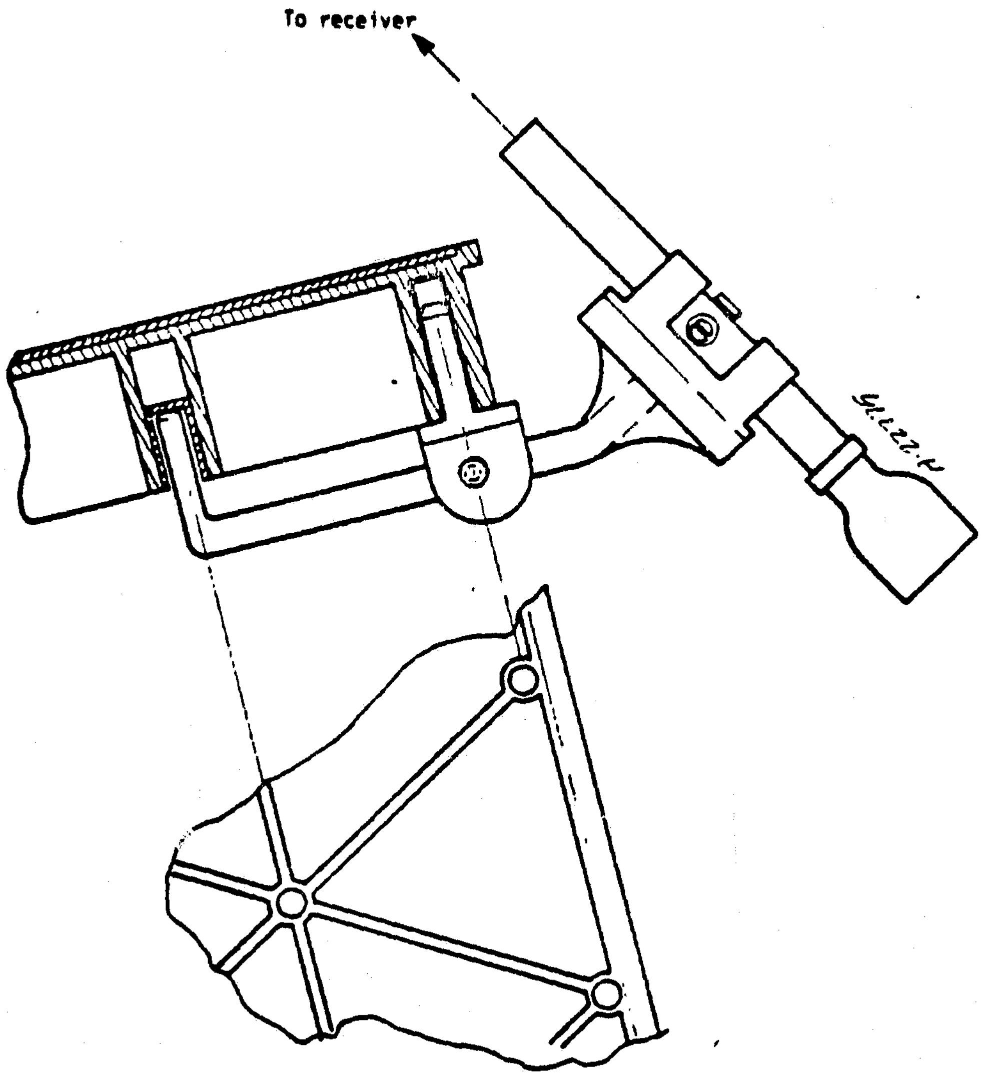


Figure 2-9. Alignment scope.

2.2.2 Structure Design

The primary goal of the structural preliminary design effort was to reduce structure weight (refer to Table 2-1 for weight summary). This was achieved by arriving at a stress-limited design with tubular steel structural members designed to the following safety factors:

Working loads:

- 2.0 combined stress; based on material yield strength
- 4.0 buckling; based on the critical buckling load.

Survival loads:

- 1.5 combined stress; based on material yield strength
- 3.0 buckling; based on the critical buckling load

Material specifications are indicated on the drawings and are tabulated in Table 2-3 for convenience. The panel support structure, receiver support structure and base support structure (Figure 2-10) will be discussed in the following subsections.

TABLE 2-3. STRUCTURAL MEMBER MATERIAL SPECIFICATIONS

Tubular	Steel, ASTM A500, GRB
Plate	Steel, ASTM A36
Pipe	Steel, ASTM A53

2.2.2.1 Panel Support Structure (Space Frame)

The flat frame panel support structure baseline design defined in Task 1 - Parameter Optimization has been extensively redesigned. The systems-level optimization analysis procedure used led to a lightweight tubular steel space frame design (Figure 2-11). As previously stated, the structure is stress-limited in the 100 mph wind survival loading condition.

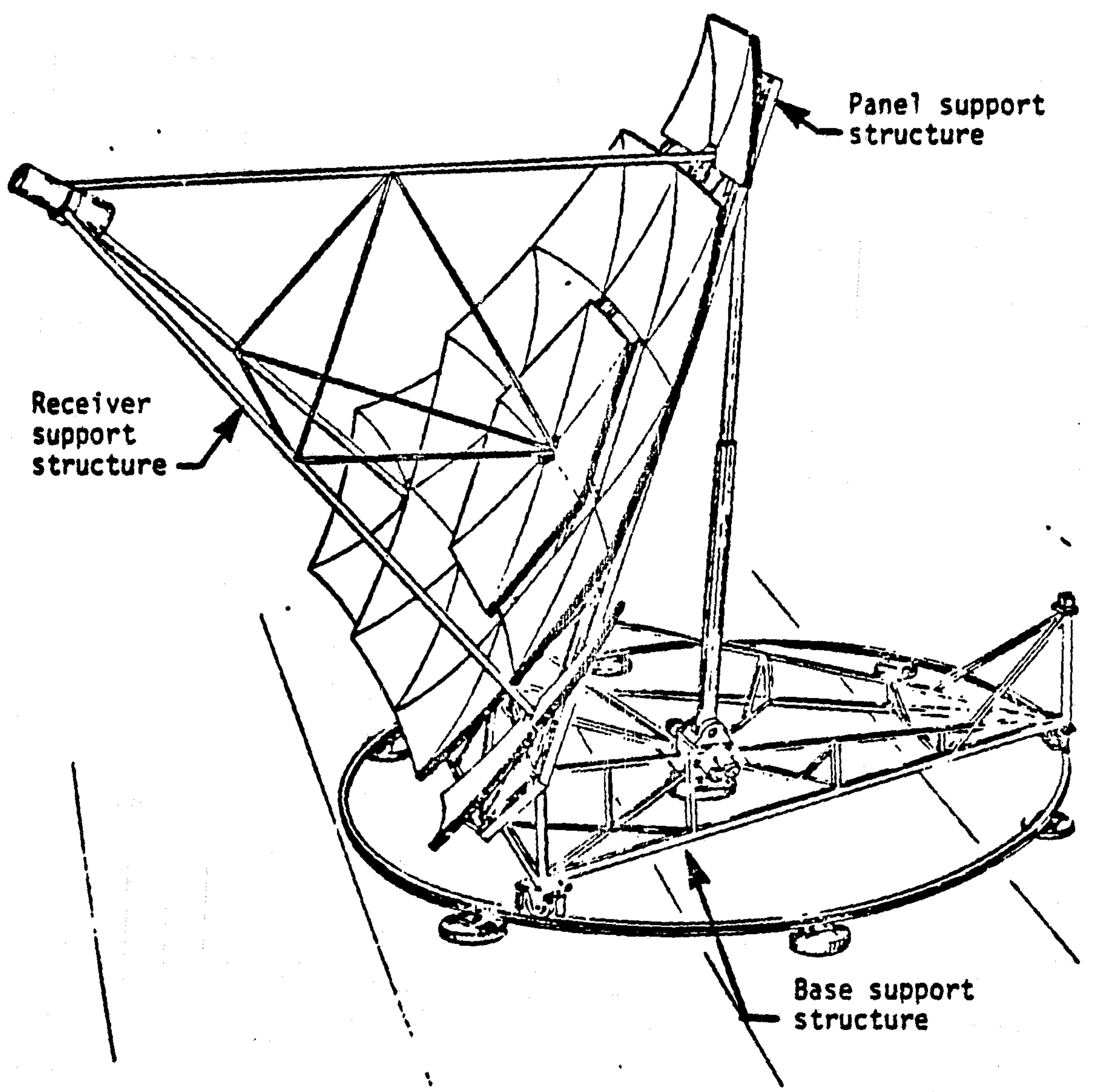


Figure 2-10. Major structural components.

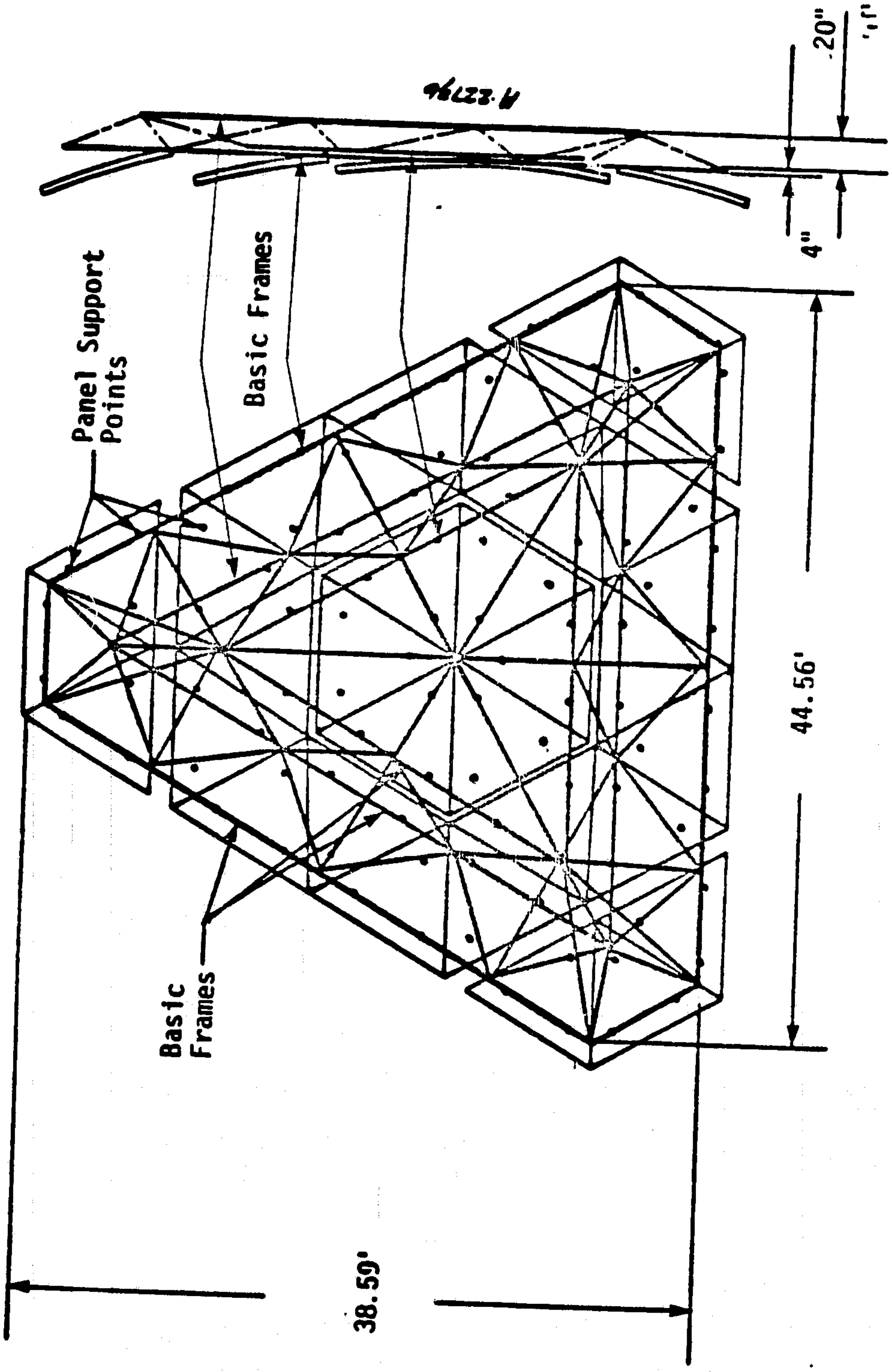


Figure 2-11. Panel support structure (space frame).

The proposed design is a result of several iterations of the following tradeoff procedure:

- Frame configuration determined
- Stresses and deflections calculated
- Deflections statistically analyzed and weighted
- $\overline{BBEC}_{th}$ (figure of merit) calculated

Each of these steps is described in further detail below.

Frame Configuration

The baseline flat frame of Task 1 resulted from locating members to best coincide with panel support attachment points. This approach was used once again in the preliminary design phase to generate the space frame. There are three basic triangular frames, each at a different elevation, with diagonals connecting the three frames to each other to provide rigidity (Figure 2-11). The resulting structure is stiffer than a flat frame of equal weight and can therefore be lighter in weight and lower in cost for equivalent deflections. The initial member sizes specified resulted in a 4080 pound structure. As will be discussed later, the member sizes were optimized based on the type and magnitude of loads which reduced the structure weight to 3750 pounds.

Stress and Deflection Analysis

Once the frame geometry and member sizes were specified, the finite element structural analysis code ANSYS was employed to determine member stresses and structural deflections at the panel attachment points. Three ANSYS runs were conducted at this point to determine structural deflections under (1) 30 mph wind loading only, (2) weight only, and (3) member stresses under weight and 100 mph wind loading.

The actual wind velocity used in the analysis was 86 mph due to the earth's boundary layer effect and the low-stow elevation of the concentrator design. The following assumptions were made in order to simplify the analysis and to be conservative:

- Wind and weight loads were taken to act in the same direction
- A uniform pressure distribution was applied on the panel surfaces
- Pressure relief afforded by Fresnel gaps was ignored

Deflection Statistical Analysis

The panel support point deflections calculated by ANSYS were analyzed to determine panel rotational deflections due to weight and due to a 30 mph wind. The standard deviation and the average of the wind-induced rotational deflections were then weighted by the national average wind speed frequency distribution to obtain a statistical representation of the spreading effect due to wind induced structural deflections. The value of the structural deflection error due to wind as characterized by σ_{wd} was then convolved with the standard deviation of rotational deflections due to weight, σ_{wt}, to determine the overall structural deflection, σ_{ds}, expected under normal operation.

Calculation of Figure of Merit ($\overline{BBEC}_{th}$)

The structure weight and deflection values were input into the performance analysis code to calculate the $\overline{BBEC}_{th}$ figure of merit. In brief, the cost-effectiveness of a lighter weight, less stiff structure is assessed by this code (see Section 2.4).

Results

Several iterations of the procedure described were required to reduce the weight to 3750 pounds (see Figure 2-12). The member cross-sections specified (refer to Drawing 6848-002) are various sizes of square, rectangular and round structural tubing and pipe. Each member is sized to survival load safety factors of 1.5 on material yield, or in the case of buckling critical members, 3.0 on the critical buckling load as determined by the well known Euler buckling equation:

$$P_{cr} = (\pi^2 EI)/\ell^2.$$

The maximum loading occurs in the 100 mph wind condition. The panel support structure is stress limited in this condition. Further weight reduction may be possible through a more detailed loading analysis (e.g., variable pressure distribution) and a reduction in the survival wind specification.

The resulting structural deflections under structure and panel weight, plus wind deflections weighted by the national average wind speed frequency distribution, is 0.81 mrad.

Panel Support Structure Subassemblies

A requirement set down in the statement of work is that the concentrator must be shippable by common commercial carrier. This sets maximum size limitations on items shipped (96" x 106" x 40'). The panel support structure is broken down into mass-producible shop subassemblies as shown in Figure 2-13. This approach maximizes shipping density and reduces field assembly time. There are 3 each of side, corner and interior truss subassemblies plus 15 loose members. Each of the 31 joints of the structure will require field assembly work. Twenty-one of the

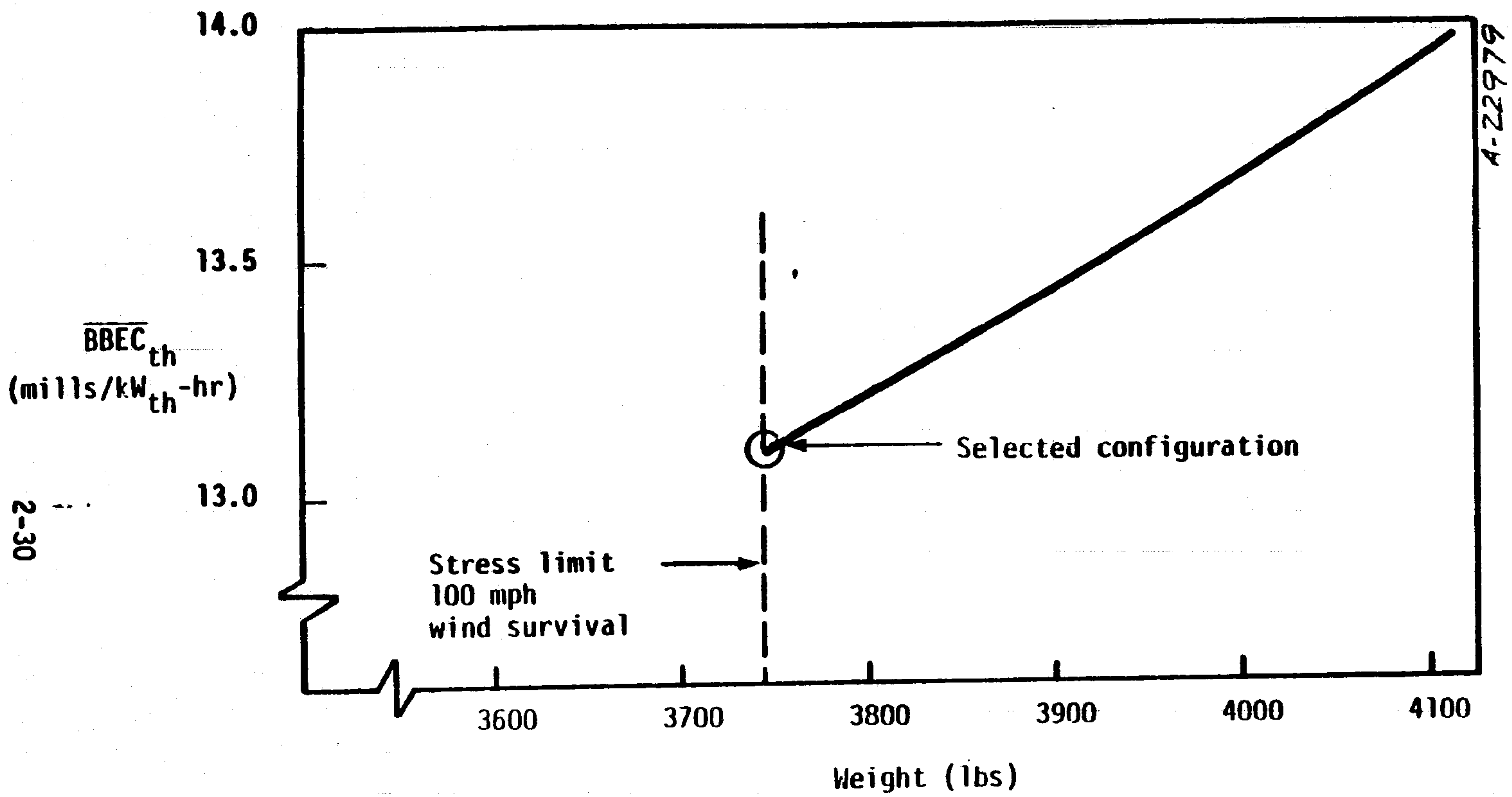


Figure 2-12. Space frame optimization.

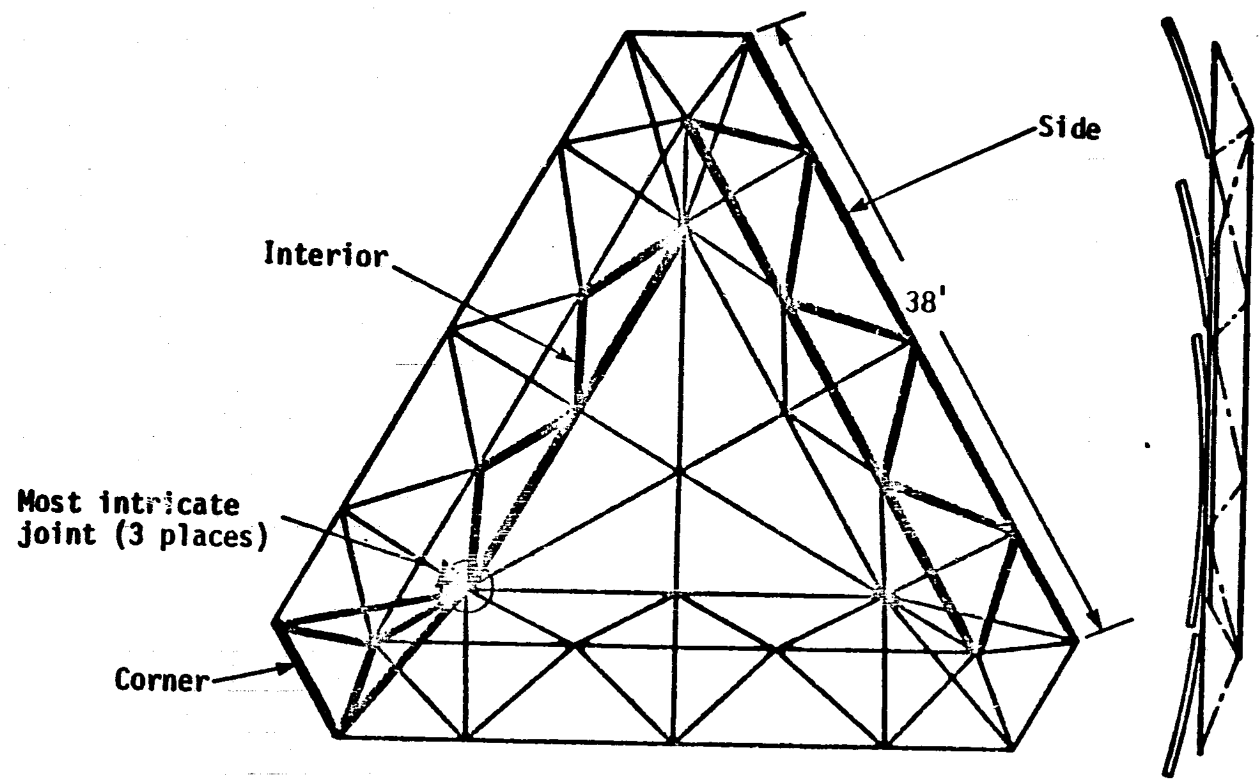


Figure 2-13. Space frame sub-assembly breakdown.

joints involve joining 2 pieces; 6 joints involve 3 pieces and 4 joints involve 6 pieces. The most intricate joint is shown in Figure 2-14 and is comprised of 3 subassemblies and 3 loose members. Figure 2-15 describes a sequence which can be used to assemble this joint in the field.

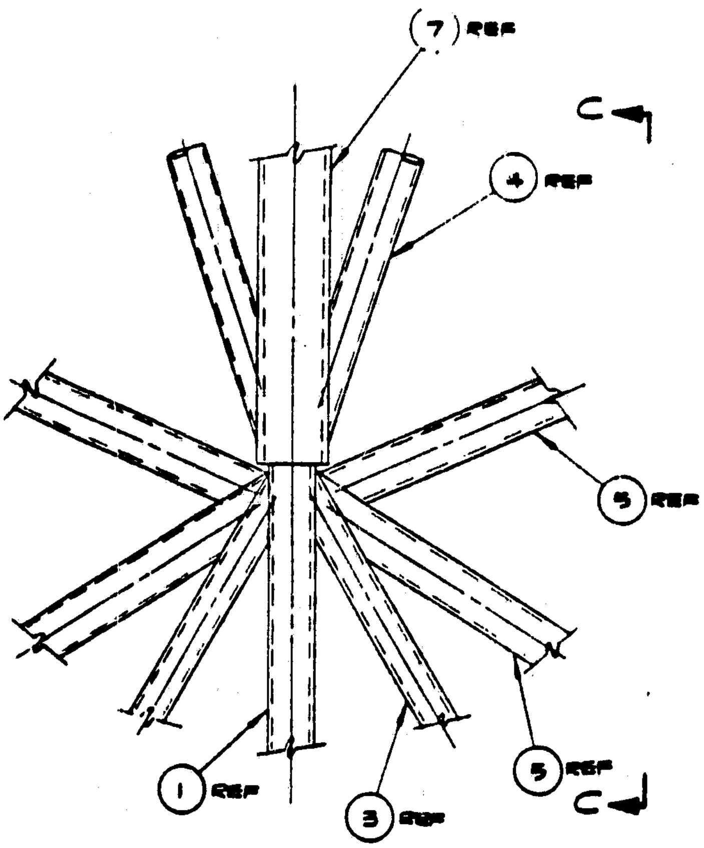
A thorough analysis to determine the most cost-optimum breakdown will be conducted during the detailed design phase.

2.2.2.2 Receiver Support Structure

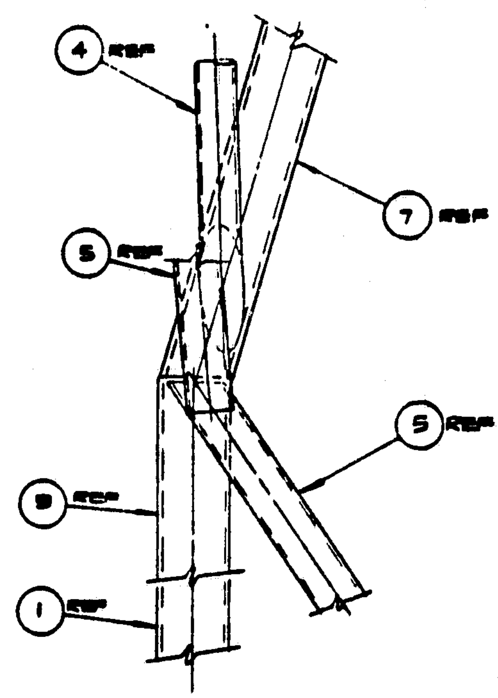
The receiver support structure is a tubular steel tripod arrangement with midspan crossties and braces added to resist buckling (Figure 2-16). A mounting flange is provided for the attachment of the receiver/engine package, which was determined to weigh 860 pounds. It should be pointed out that the receiver corresponding to the weight specified is optimally sized as determined by Reference 2-3. The support structure weighs 1200 pounds and is buckling critical in the stowed configuration under a 100 mph wind plus earthquake loading of 1.0 g vertical and 0.25 g lateral.

The tripod configuration is a natural extension of the triangular concentrator configuration. Although the braces tie into the center of the panel support structure, they serve to stiffen both structures, while the primary load path is down the tripod legs to the base support structure and to the elevation actuator. There is minimal impact on the panel support structure in terms of carrying receiver/engine loads to the foundation. Because of this, the major impact of receiver/engine size and weight variation is on the base support structure and the foundation.

The shading loss is 2.3 m^2, 26 percent of which is due to the receiver/engine package. The blockage of reflected light rays by the



DETAIL B



VIEW C-C

Figure 2-14. Joint detail. (Excerpt from Drawing 6848-002, Sheet 2)

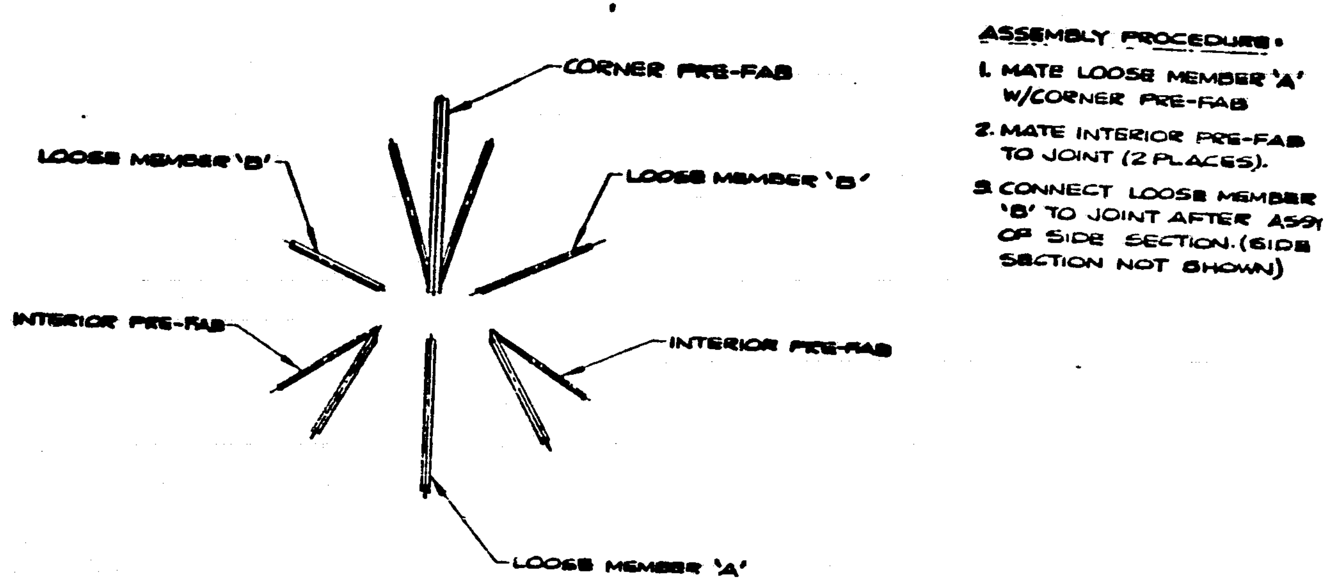


Figure 2-15. Joint assembly. (Excerpt from Drawing 6848-002, Sheet 2)

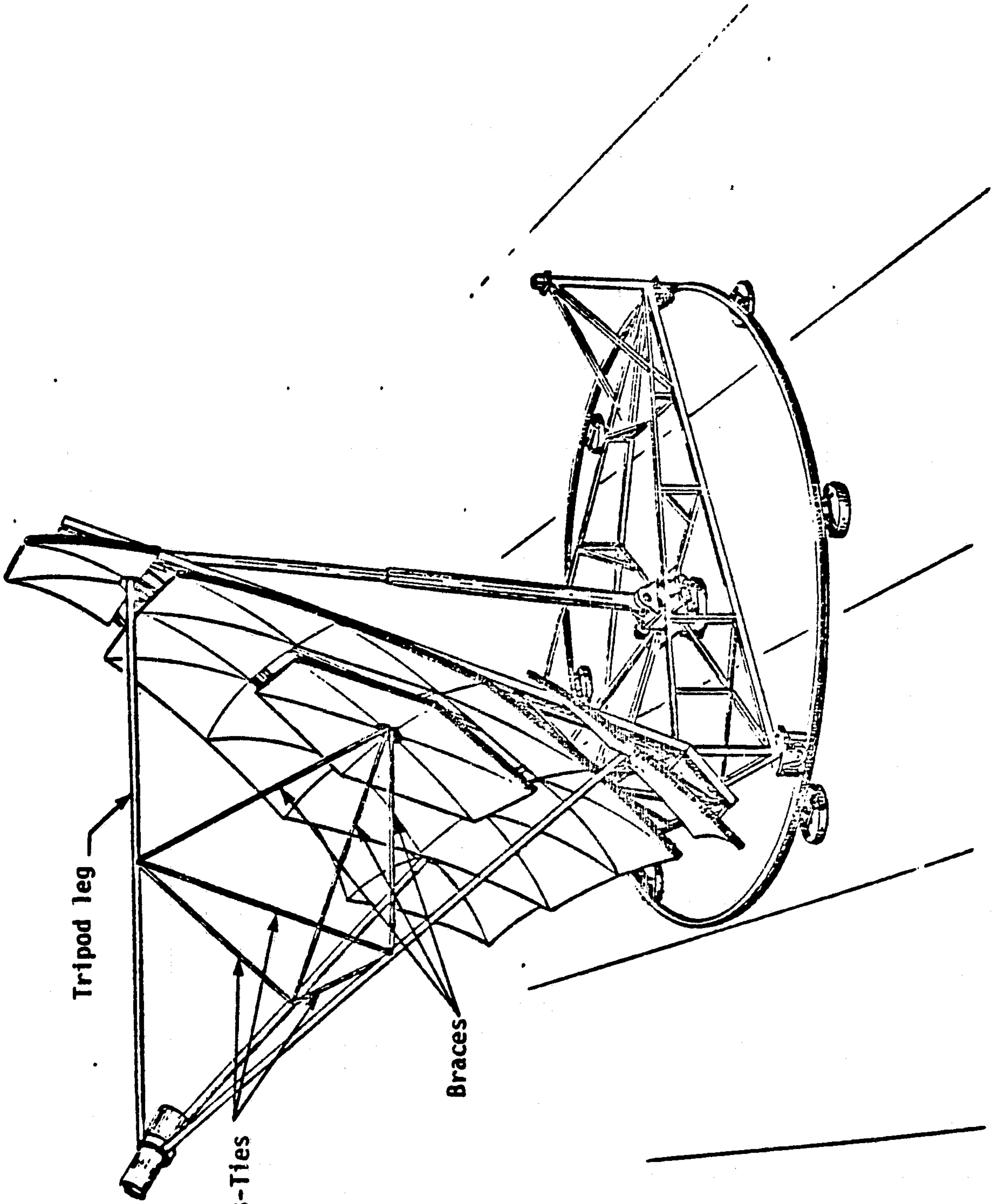


Figure 2-16. Receiver support structure components.

receiver/engine support structure amounts to 4.3 m^2, resulting in a net concentrator aperture area of 102 m^2.

Receiver deflections were determined by the finite element structural analysis code ANSYS. The receiver centerline pitch is 8.5 mrad. The aperture centerline displacement is 0.61" including the sag and pitch contributions (Figure 2-17). These displacements result in negligible performance degradation.

The structure components can be shipped by common commercial carrier and field erected after assembly of the panel support structure.

2.2.2.3 Base Support Structure

The concentrator base support structure is a triangular shaped tubular steel space frame (Figure 2-18). The basic triangle size corresponds to the lowermost frame of the panel support structure. Primary structural members include: (1) the basic triangular frame; (2) six radial members emanating from the central rotary actuator location out to the corners and midspan points of the basic frame; (3) three vertical members, two of which interface with the panel support structure with self-aligning ball bearing hinges, the third providing a support when the concentrator is stowed; and (4) diagonal members which support the vertical members. Secondary structural members provide buckling resistance.

The radial and basic frame members are sized to carry the moments induced by the center rotary actuator torque. The design torque is that required to resist the weather vaning effect of a 30 mph wind plus 20 percent gusts incident at 45^{o} to the concentrator while pointed at the horizon. The vertical and diagonal members are sized to carry the reaction loads generated by worst case front, back, or side wind loading

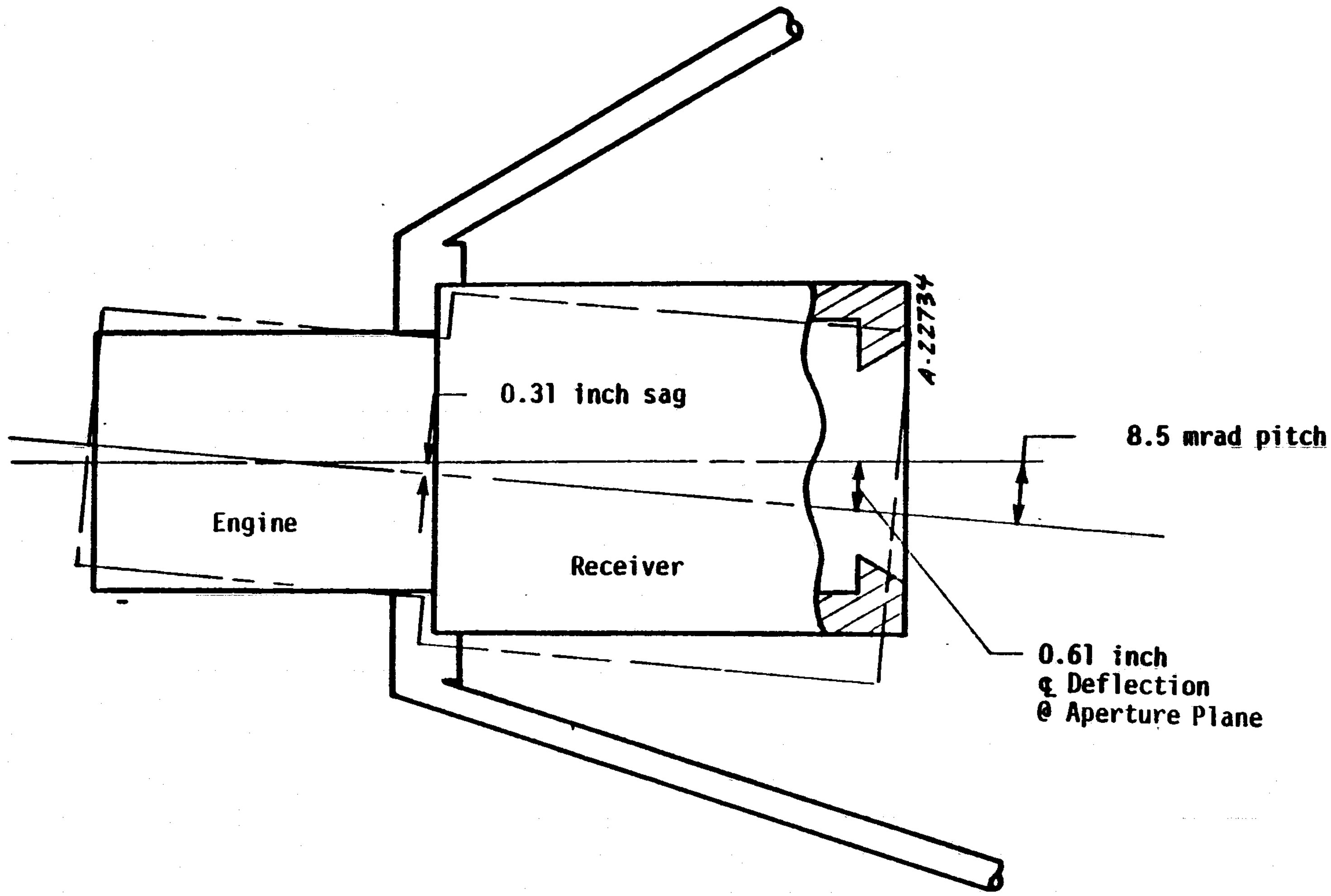


Figure 2-17. Receiver deflections.

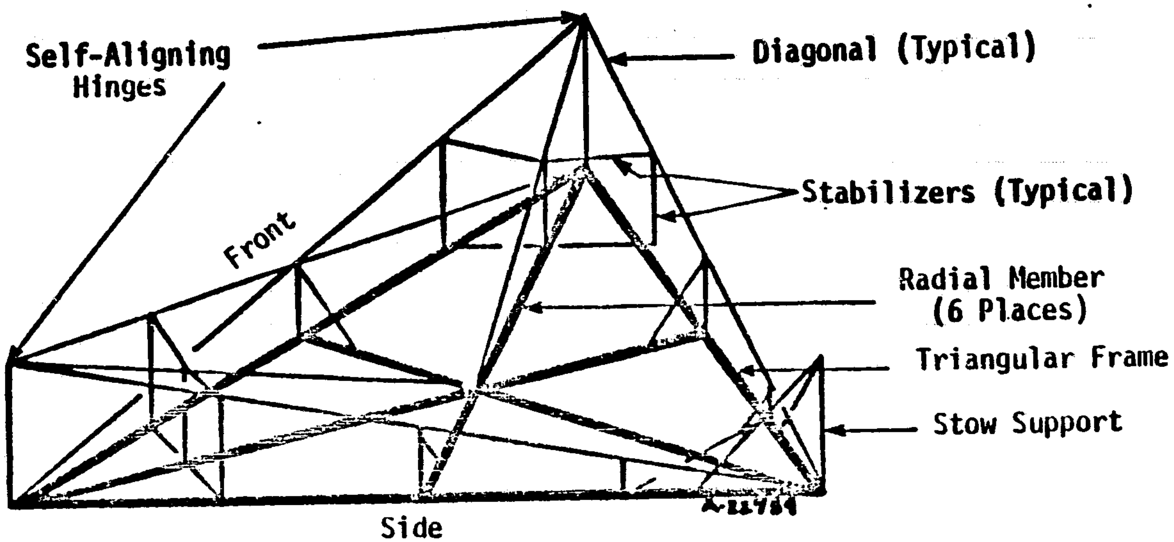


Figure 2-18. Base support structure perspective view.

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conditions. The buckling stabilizers are located to reduce the effective length of buckling critical members.

The vertical stow support serves to: (1) support the panel support structure during installation or maintenance of the elevation actuator and (2) minimize the panel support structure rotation induced by 100 mph side wind loads when in the stowed configuration.

The primary structure members are designed to 2.0 (combined working stress) and 3.0 (buckling due to survival loads) safety factors previously mentioned in Section 2.2.3. The structure weight is 1670 pounds. A more detailed finite element analysis would be conducted during the detail design task to further reduce structure weight and cost.

The active two-axis tracker system will compensate for static structural deflections. Dynamic deflections induced by 20 percent gusts over 30 mph result in 3.1 mrad rotational deflections. Deflections at lower prevailing wind velocities would decrease proportionately with the square of the velocity ratio.

2.2.3 Foundation and Drive Design

The objective of the foundation and drive design subtask was to determine the most cost-effective combination which meets the environmental and performance specifications in the statement of work. The approach was to conceptualize alternatives, compare the costs, advantages and disadvantages, and choose the most promising of these alternatives. The predominant factor in selecting an alternative was the initial cost of components. The costs of the various alternatives were based on a common baseline concentrator with a 30-year life span.

Of the environmental conditions specified, wind load while tracking was the most significant in determining the size of the foundation and drive components. The wind load affects sizing directly as drag loads which must be reacted, and indirectly as structural weight which must be supported. The triangular, compressed reflector takes advantage of the earth's boundary layer, thereby reducing the wind loads (Reference 2-4.) This effect was considered in developing the reaction loads in the drive and foundation.

A discussion of the selection tradeoffs and a description of the final choice follow.

2.2.3.1 Foundation/Track Selection

The methodology described above was used to determine the most cost-effective foundation. The Unified Building Code (UBC) guidelines (Reference 2-5) were used to design the foundation. Since foundations serve to transfer loads into soils, soil characteristics as well as imposed loads must be considered. Two soil types were used for the analysis: a "typical" soil with 2000 lbs/ft^2 bearing pressure allowable, and a "poor" soil of 1000 lbs/ft^2 bearing pressure allowable. As allowed in Table 29-B of the UBC, the bearing pressure was increased 20 percent for each foot of depth, and doubled for piers because they are isolated.

Five alternative foundations were sized, costed and compared. The results are shown in Table 2.4. All of the options consist of a circular track which supports the wheeled concentrator. The first four alternatives rely on a center pier to react the lateral loads. In the fifth option the wheels are captured by the track to react these loads.

Options two and three utilize a counterweight on the base support structure to counteract the overturning moment caused by the receiver weight and wind. However, this scheme imposes major structural requirements on the base support structure. The structure must be very

TABLE 2-4. FOUNDATION SELECTION

Foundation	Relative Cost		Remarks
	Typical Soil	Poor Soil	
Center pier Raised track No counterweight	1.2	1.6	Increased center pier loading
Center pier Raised track Counterweight	1.0	1.3	Major impact on base support
Center pier Concrete track Counterweight	1.4	1.6	Labor intensive, major impact on base support
Center pier Matting track Counterweight	--	--	No matting material suitable for 30 years
Captured wheel track No center pier No counterweight	1.8	1.9	Subject to clogging major impact on base support and drive

stiff and heavy to transfer the loads from the center pivot to the counterweight. Removing the weight imposes an uplift load into the centerpivot. The tradeoff is between the cost of an enlarged center pier versus the cost of a concrete counterweight and heavier base support structure. Enlarging the center pier is more cost-effective.

The matting track was conceived as an inexpensive alternative to the formed steel beam track. Although its initial cost is lower, its life expectancy is also much lower. Replacement costs over a 30-year lifetime result in a relatively high life cycle cost for this concept.

A captured wheel track design eliminates the center pier and overturning moments are reacted by the track. This reduces the reaction loads because the effective reaction lever arm is three times as long as with a center pier. Unfortunately, the potential reductions in track section size and pier size cannot be realized. The localized stresses of the wheels on the track dictate a minimum track section size and each pier must be large enough to react the maximum uplift load. In addition, eliminating the center pier restricts the drive options as they must operate off the track wheels, and this results in a more expensive drive/foundation design.

2.2.3.2 Foundation/Track Design

The foundation/track design selected is shown in plan view in Figure 2-19. The concentrator is supported by a raised track mounted on six cast-in-place concrete piers. A center concrete pier anchors the concentrator.

This conclusion is consistent with Acurex's foundation studies for parabolic trough solar collectors. These studies have shown that concrete piers cast into drilled holdes are the most economical foundations for

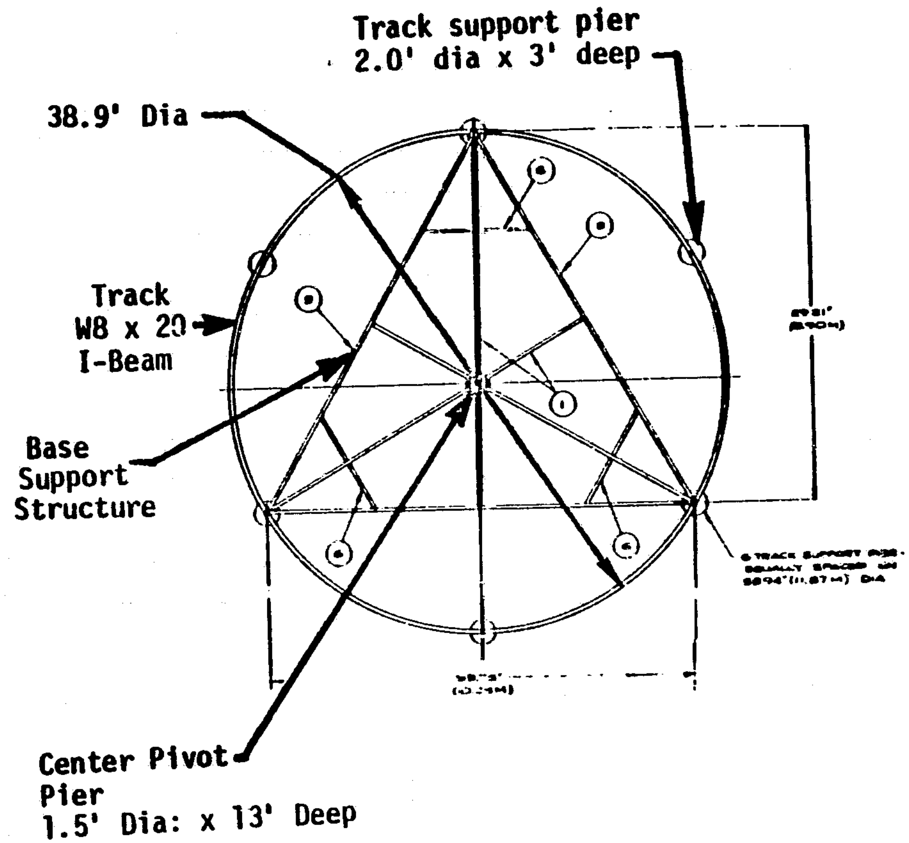

Figure 2-19. Foundation plan view. (Excerpt from Drawing 6848-004, Sheet 1)

solar collectors installed in the Southwest. The sandy gravel and clay soils of this area correspond to the "typical" and "poor" soil defined above.

The concrete piers will be made by:

- Drilling holes of appropriate diameter and depth
- Dropping a cage of reinforcing bars into the holes
- Aligning the anchor bolts
- Pouring the concrete.

The center pier will be placed by survey and the track piers aligned from it.

The center pier is 1.5 feet in diameter and 13 feet deep. Its size is determined by the combined loading of quartering winds. Such a wind imposes lateral forces, overturning moments and rotational torques on the concentrator. Consequently, the center pier experiences lateral, uplift, and twist forces. These forces must be resisted simultaneously by lateral bearing against the soil, pier weight, and soil friction on the pier sides.

A collar mounts to the top of the center pier as shown in Figure 2-20. By using opposed nuts on the anchor bolts, the fitting can be aligned to the track in height and tilt. After this alignment, the gap between the collar and the center pier is grouted.

The track piers are 2 feet in diameter and 3 feet deep. Their cross sectional area is determined by the allowable soil bearing pressure. A pier should extend below the maximum frost penetration. Three feet is adequate for approximately half of the U.S.

Anchor bolts cast into the track piers will mate with the track as shown in Figure 2-21. Opposed nuts are used for leveling the track. Standard construction tolerances of ±0.25 inches are acceptable as the

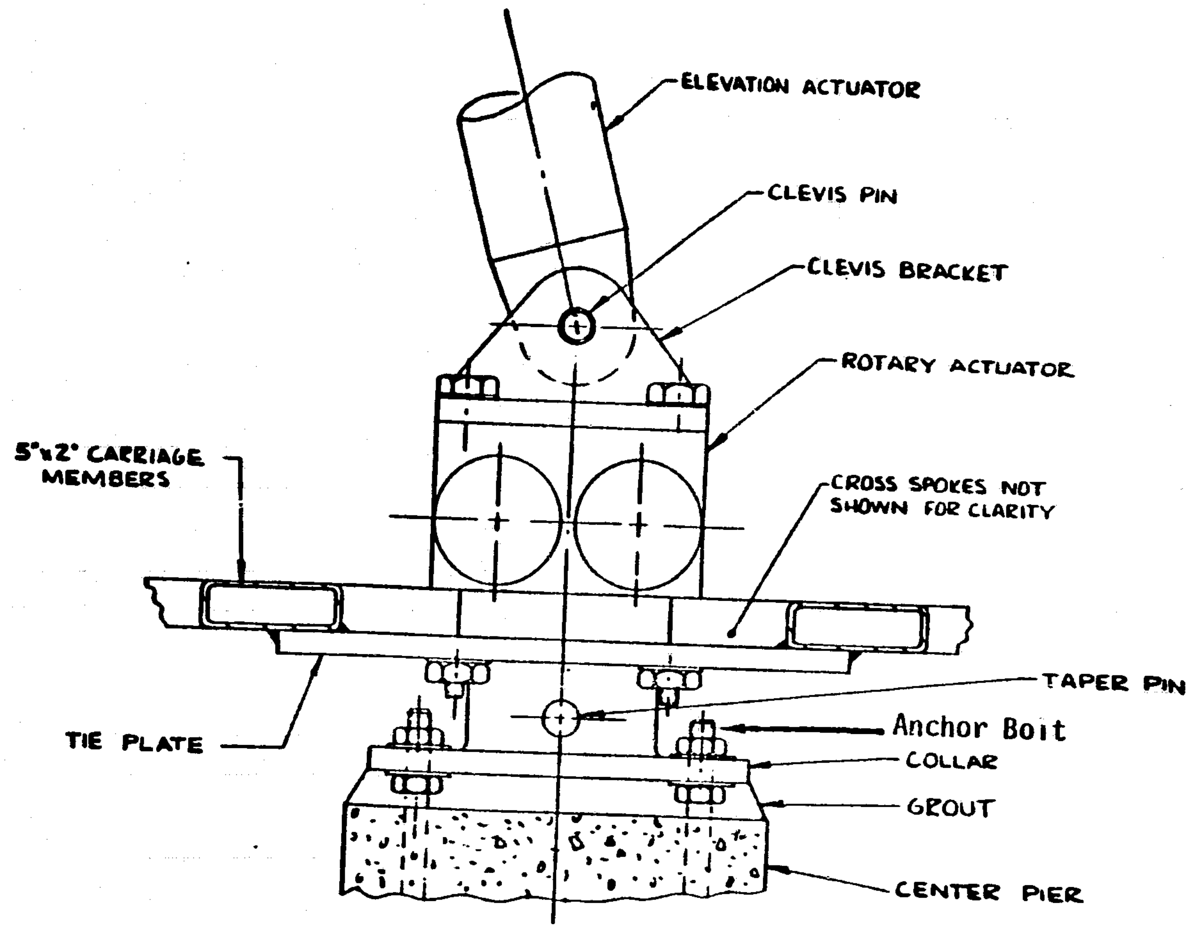

Figure 2-20. Center pivot arrangement. (Excerpt from Drawing 6848-001)

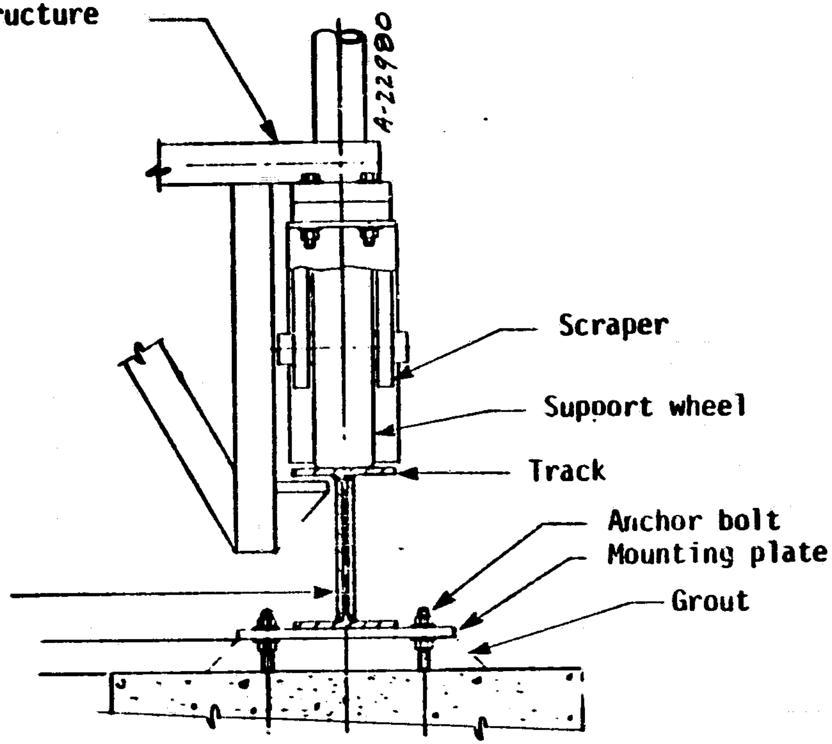

Figure 2-21. Track attachment. (Excerpt from Drawing 6848-004)

active tracker system will compensate for any misalignment by adjusting the concentrator.

The track itself is a W8 x 20 I-beam. It is divided into six segments and roll-formed to a 19.5 foot radius. The segments of this size are easily transportable. They are spliced at the track piers by butt welding and overlapping splice plates. The mounting plates are also welded to the track.

The primary loads in the track are bending with some torsion. Consequently, a wide flange I-section is more efficient than a rectangular tube section. Also, the local contact stresses under the wheels require that the top surface of a rectangular tube section be 0.75 inches thick, making the section too large to be cost-effective.

Thermal expansion of the track is accommodated with radial mounting slots. There is a slip plate between the pier and the track mounting plate which is grouted to the pier.

2.2.3.3 Drive Selection

Tables 2-5 and 2-6 show the alternatives evaluated for the elevation and azimuth drives and their relative merits. All the components of each alternative must be state-of-the-art technology, have high positional accuracy to meet the tracking requirements and have a life span of 30 years encompassing 11,000 tracking cycles. In addition, the elevation drive must have two-speed capability. A "low" speed is required for tracking the sun and a "high" speed is required to retract the concentrator to the stowed position in high winds.

An emergency power source is needed for stowing the concentrator in the event of a power failure. For a hydraulic drive system, emergency power can be provided by a pressurized gas accumulator. An electrical

TABLE 2-5. ELEVATION DRIVE TRADEOFF

Tradeoff Factor	Hydraulic Cylinder	Ball Screw	Hingeline Gear Box	Rack and Pinion
Relative cost	1.0	2.8	1.8	2.3
2-speed operation	Vary flow	2-speed motor	2-speed motor	2-speed motor
Rigidity	Good	Good	Poor	Good
Parasitic power	Low	Med.	High	High
Precision	Good	Good	Poor	Good
Reliability	Excel.	Good	Good	Good
Maintainability	Excel.	Good	Good	Good
Durability	Excel.	Wear Problems	Good	Wear Problems

TABLE 2-6. AZIMUTH DRIVE TRADEOFF

Tradeoff Factor	Central Rotary Actuator	Central Gear Box	Outboard Traction Wheels	Outboard Chain and Sprocket	Outboard Cable and Drum	Outboard Cog and Rail
Relative cost	1.0	2.0	1.0	1.0	1.0	3.0
Parasitic power	Low	Med.	Low	Low	Low	Low
Precision	Good	Poor	Poor	Good	Good	Fair
Reliability	Excl.	Good	Good	Fair	Fair	Fair
Maintainability	Excl.	Good	Good	Fair	Fair	Fair
Durability	Excl.	Fair	Good	Poor	Poor	Fair

drive system requires an auxiliary generator or a battery pack for emergency power.

The hydraulic cylinder meets all the design requirements for the elevation drive and is the least expensive (see Table 2-5). The other three alternatives are expensive, subject to wear, and difficult to operate with two speeds. The hingeline gear box would also have a major adverse structural impact on the reflective panel support structure.

Having selected the hydraulic cylinder for the elevation drive, hydraulic actuation for the azimuth drive became desirable. One motor and control system can be used to control both drives. Hydraulic gear motors could be used to drive any of the outboard drives or the central gear box listed in Table 2-6. However, this type of motor is unsuitable. It would operate at very low efficiency with the intermittent duty cycle. They also require relatively high maintance. Electric motors could be used, but they require a hybrid electrical/hydraulic control system. Also, the reduction ratios needed for either type of motor would be high.

Although the outboard drives have the inherent mechanical advantage of the collector radius, there are problems mechanizing them. Traction wheels fail to meet the design requirements, as any ice or snow on the track may cause the wheel to slip. Chain/sprocket, cable/drum, and cog/rail designs are all subject to corrosion, stretch, wear, and clogging.

Central drives avoid the outboard drive problems by positively attaching to the pivot and enclosing all the mechanical parts, but they are more critical of backlash and positional accuracy. Rotary actuators and gear boxes that meet the tracking backlash and accuracy requirements are avilable, however. The gear boxes which would provide the reduction ratios and positional accuracy required are expensive, because they have multi-stage gearing.

The rack and pinion hydraulic rotary actuator has only one gear set stage which can be preloaded to reduce backlash. The positional accuracy set required for sun tracking is obtainable with proper control system design. Since these actuators are relatively inexpensive and meet all the design requirements, they were selected for the aximuth drive.

2.2.3.4 Drive Design

The locations of the drive actuators on the concentrator are shown in Figure 2-22. The elevation drive is a single-stage, double-acting hydraulic cylinder with a 3.5-inch bore, a 2-inch diameter shaft and a 17-foot stroke. The stroke is long enough to lower the receiver within fourteen feet of the ground for servicing. The actuator is mounted with spherical rod ends to allow for misalignments and structural deflections. Elevation speed is controlled by varying the hydraulic fluid flowrate. Emergency stow power is provided with an accumulator. Proper filtering of the hydraulic fluid should allow maintenance-free operation of the actuators over the 30-year lifespan of the concentrator.

The azimuth drive is a rack and pinion type hydraulic rotary actuator with a 234,000 inch pound capacity. Figure 2-23 is a cutaway view of the actuator. Four single-acting hydraulic cylinders are connected in pairs by geared racks. The racks mesh with a pinion gear integral with the output shaft. Rotary motion is obtained by applying pressure to one cylinder of each pair. The backlash of the gears is less than .1 degrees in standard production. This is adequate for solar tracking and can be reduced even further if necessary by preloading.

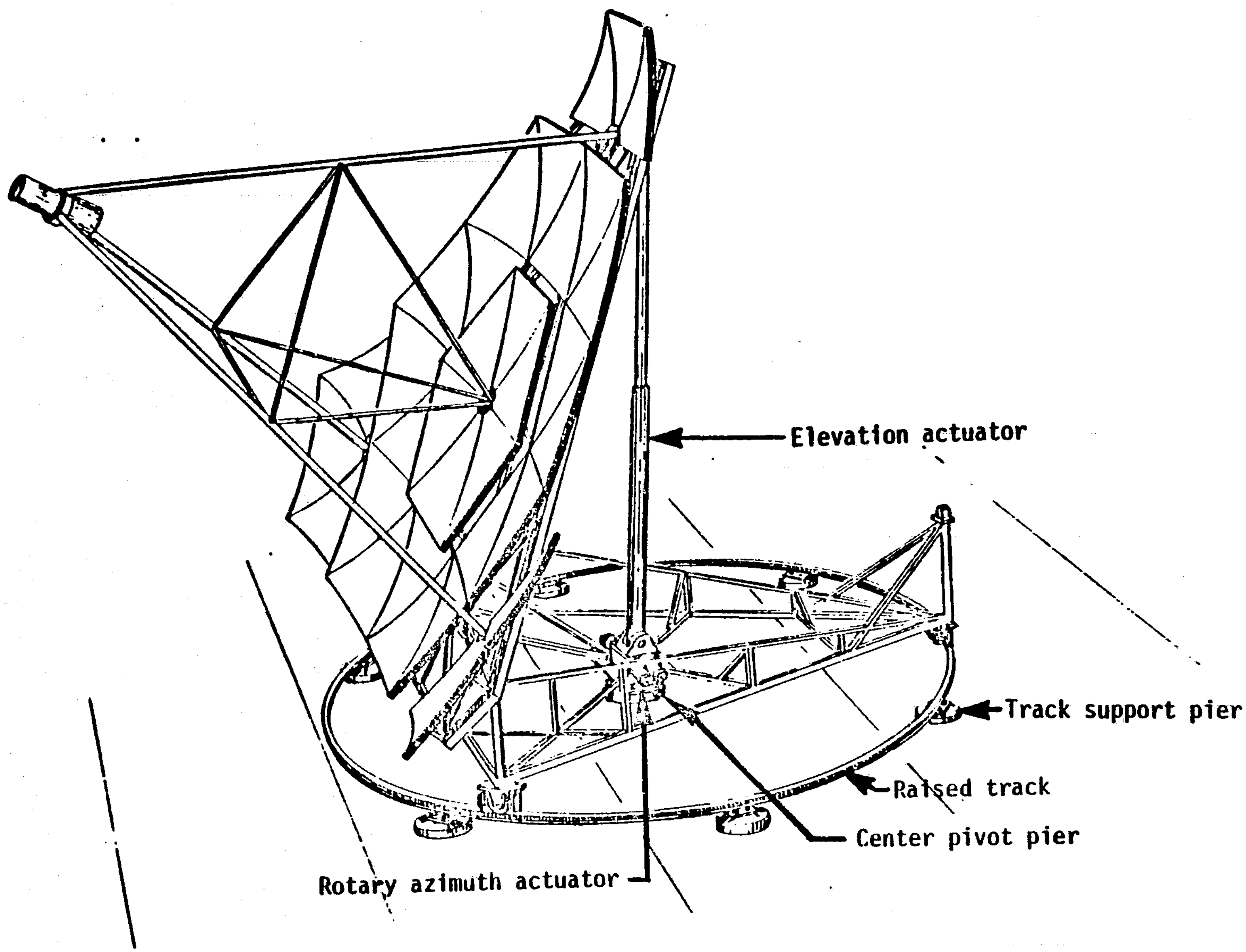

Figure 2-22. Foundation and drive components.

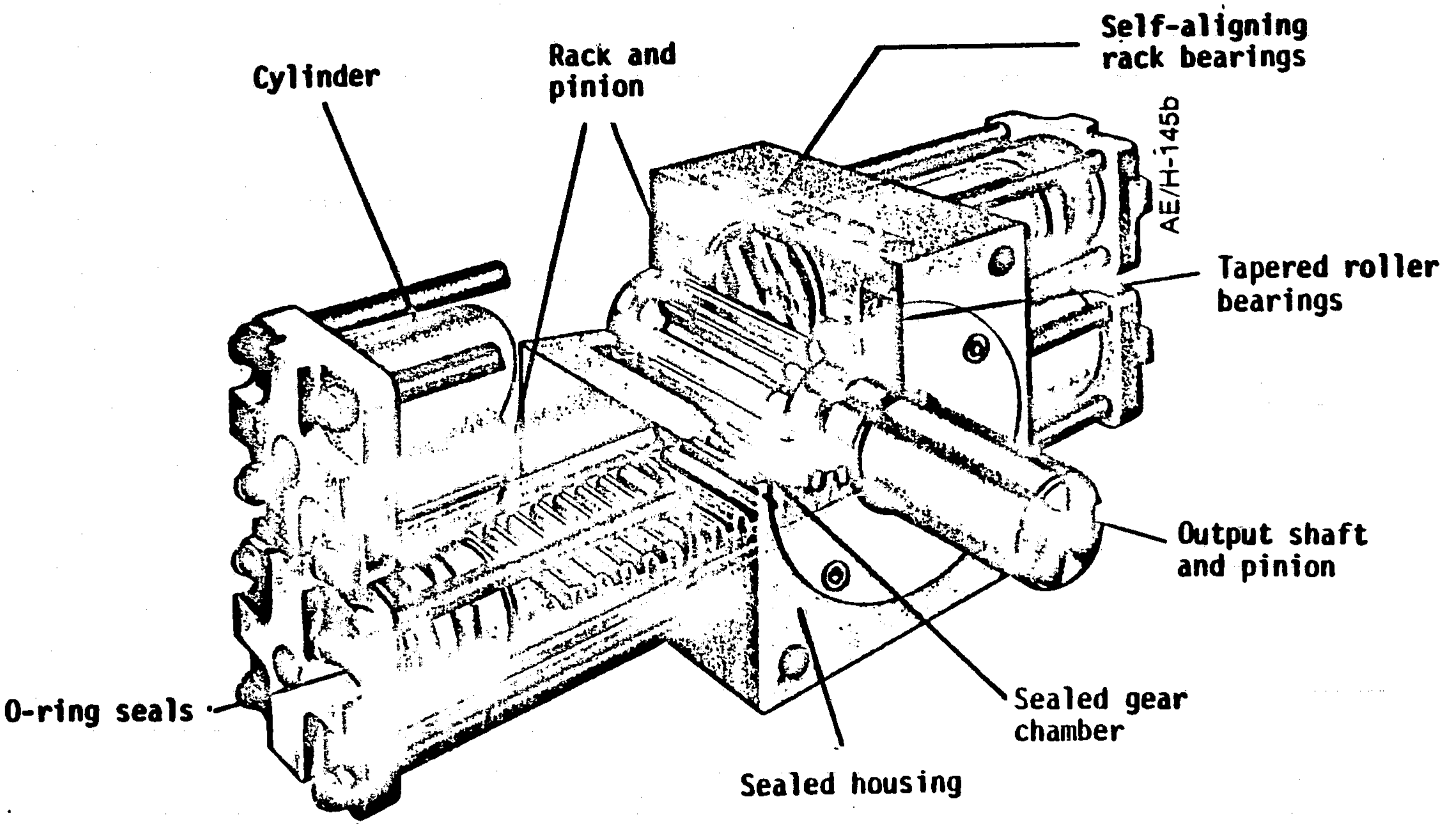

Figure 2-23. Rack and pinion rotary actuator.

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The unit incorporates dual tapered roller bearings which will function as the pivot bearings for the concentrator. Using the capacity formulas for actuators of this type now in production, the bearings will have twice the capacity needed for this application. The whole actuator is sealed and should last the 30-year lifespan of the concentrator with no maintenance.

2.2.3.5 Hydraulic Power and Control

The hydraulic circuit used to control the actuators is shown in Figure 2-24. Since the flowrate required while tracking is low and intermittent, parasitic power consumption can be minimized by using a small hydraulic pump to charge an accumulator and driving the actuators off the accumulator. A pressure switch at the accumulator energizes the pump only when the pressure falls below a preset limit. The accumulator is also used to provide emergency stow capability.

The elevation cylinder is controlled by a three-position, four-way solenoid valve spring loaded closed. When solenoid B is energized the cylinder is extended, raising the concentrator structure. Solenoid A is energized to lower the structure during active tracking. The elevation tracking rate of 5 degrees per minute is obtained through the adjustment of the variable pressure-compensated control orifices. A pair of pilot operated check valves are incorporated into the circuit at the cylinder to lock the cylinder securely when the solenoids are disengaged (such as when the concentrator is on target or in the stowed position). These valves are operated by pressure in the supply line to the cylinder.

Stowing is facilitated by solenoid C. In normal operation, solenoid C is energized and no flow is allowed through its valve. Upon command from the control logic or during a power failure, solenoid C is

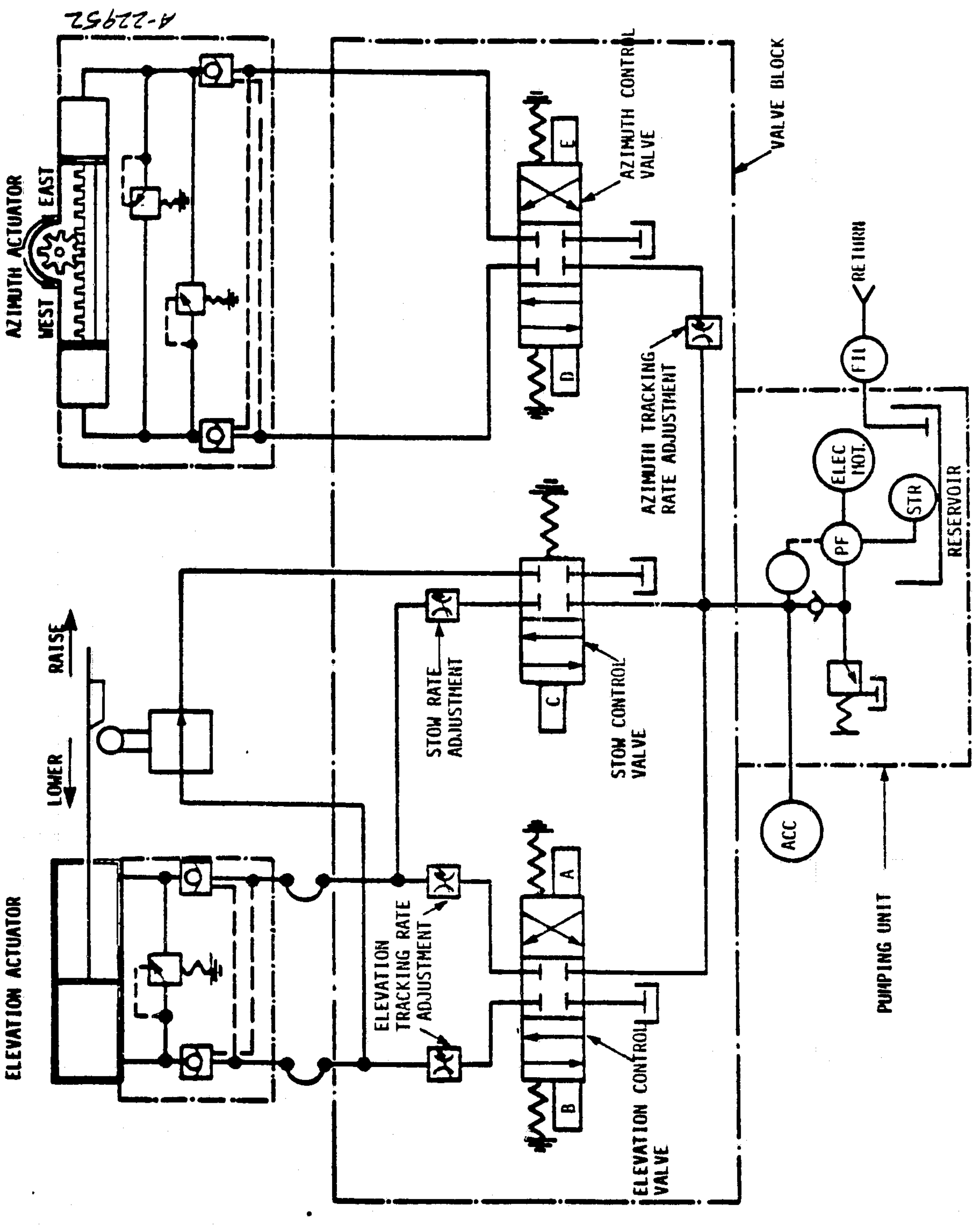

Figure 2-24. Hydraulic control system.

deenergized and the accumulator discharges into the elevation cylinder, driving it down to the stow position. The control logic is incapable of energizing solenoid B while solenoid C is deenergized. A stowing rate of 80 degrees per minute is adjusted by the variable orifice in the stow line. As the structure folds toward its stow position, a cam-operated valve is used to restrict the return flow, decelerating the structure as it approaches its final stow position.

The azimuth actuator is controlled through solenoids D and E on a three-position, four-way valve. This valve is also spring loaded closed. The azimuth tracking rate of 10 degrees per minute is obtained by adjusting the variable orifice. Similar to the elevation actuator, pilot operated check valves are used to lock the actuator into position when the solenoids are disengaged.

Pressure relief valves protect both actuators from overloads by allowing restricted flow between the cylinders. The concentrator can move, relieving the overload.

The various hydraulic components will be built into modules as outlined in Figure 2-24. Each of the modules is an enclosed unit sealed against dirt and water contamination. The solenoid valves and variable orfices are built into a single block similar to the one shown in Figure 2-25. Utilizing the valves simplifies installation and facilitates mass production. The block will mount directly to the pumping unit without hoses. The pilot check valves and pressure relief valves will be built into their respective actuators.

The pumping unit -- consisting of the motor, pump and reservoir -- is also a packaged module (similar to the one shown in Figure 2-26). The accumulator, filter, and valve block will be

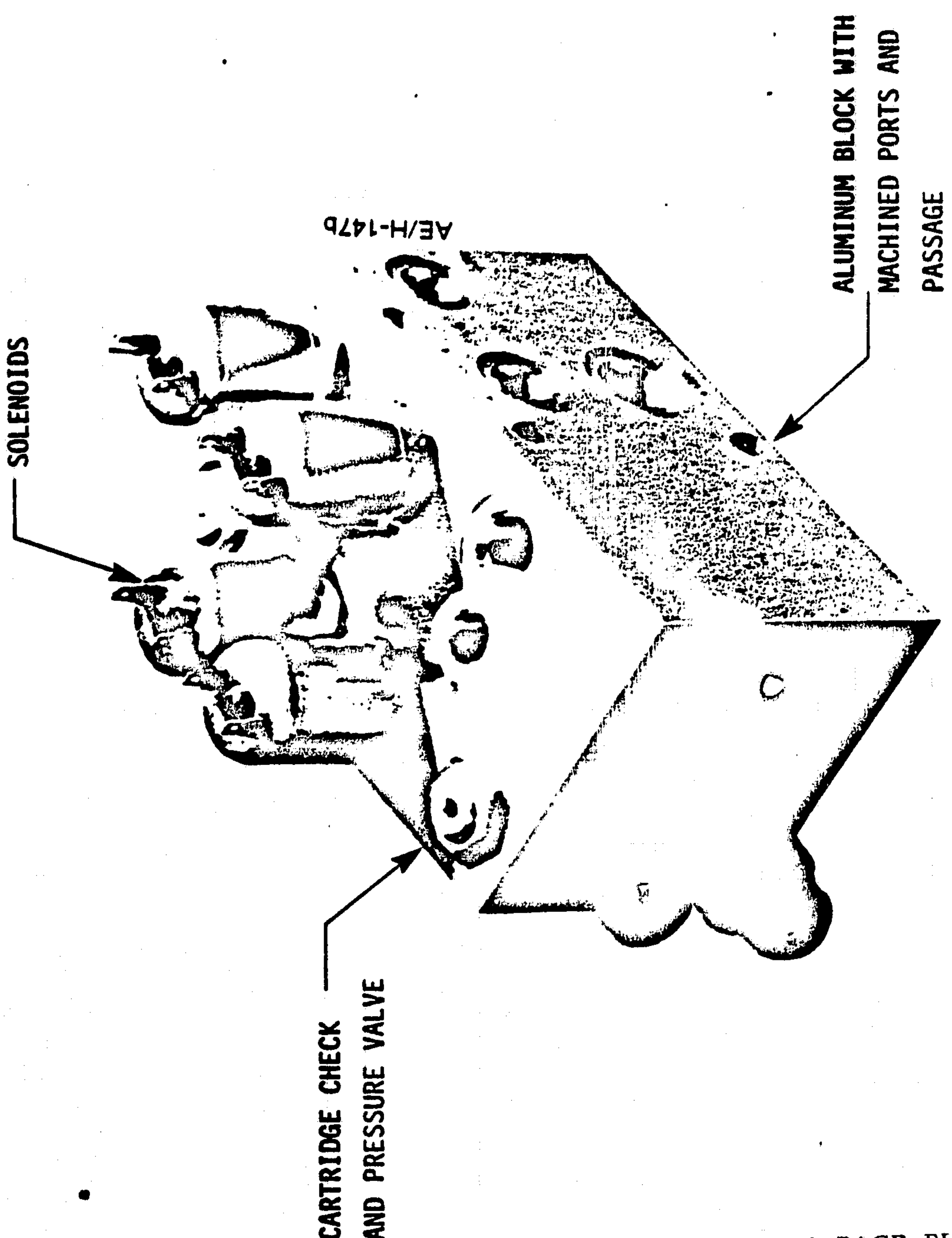

Figure 2-25. Integrated hydraulic circuit.

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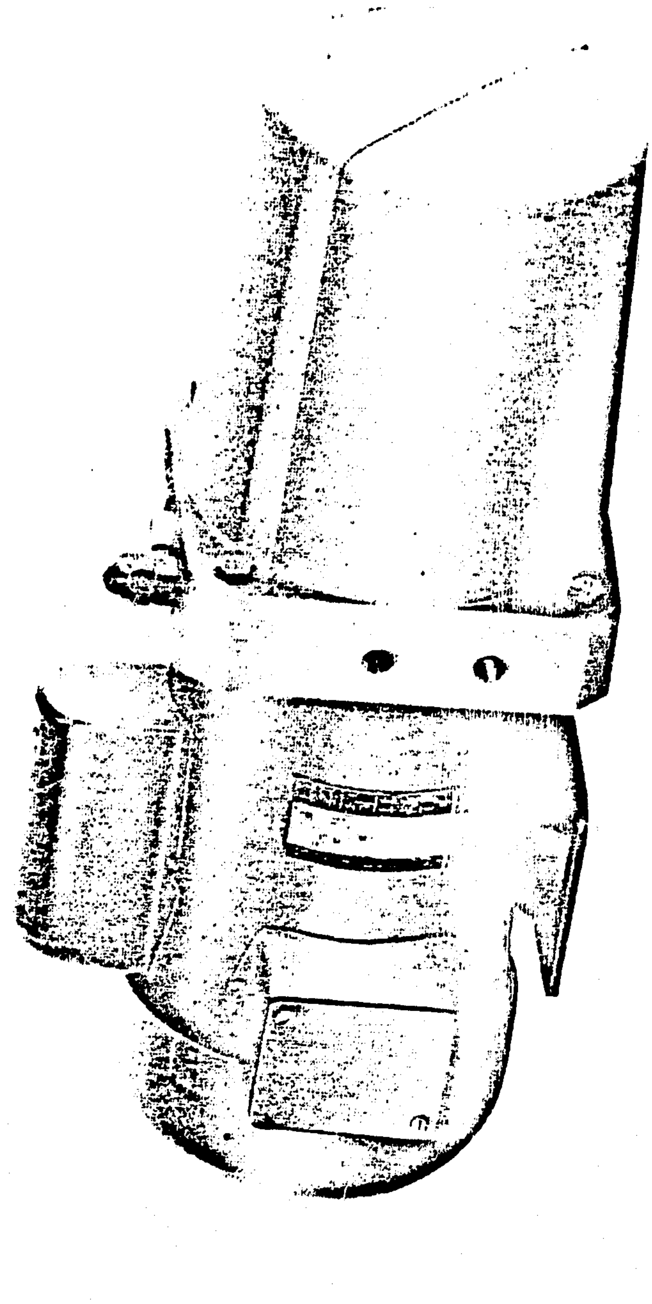

Figure 2-26. Hydraulic power unit.

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factory-assembled on the unit, making it an easily handled and installed package. Each concentrator will have a pumping unit mounted to its base support structure. This arrangement (1) avoids pumping 3000 psi fluid onto a rotating concentrator, (2) minimizes fluid frictional losses, (3) simplifies purging and (4) provides a stand alone concentrator module. The only field hydraulic connections will be between the pumping unit, actuators and cam valve.

The average power consumption of the hydraulic system is 80 Watts based on a 10-hour tracking day with ±90 degrees of elevation travel at 5 degrees per minute and ±270 degrees azimuth travel at 10 degrees per minute. The power unit was assumed to be driven by a 1/4 HP electric motor, and the control valves by 40 watt solenoids. A conservative rule of thumb for the pumping unit is that 1 HP is required to pump 1 gpm at 1500 psi.

The entire drive system can be prototyped with off-the-shelf components. These components are adaptable to high volume production and significant cost savings can be expected with value and manufacturing engineering efforts.

2.2.4 Tracker and Controls Design

Due to its relatively low cost in mass production, the tracker and control subsystem does not offer the potential for significant cost reductions through design efforts at the preliminary stage. The objectives of the preliminary design of this subsystem were therefore to:

- Determine the tracker and control subsystem requirements
- Determine the most practical control scheme
- Establish the external interface requirements.

Requirements

The control of a two-axis tracking solar concentrator must include several features. The control system must not only track the sun with a high degree of accuracy, but must also protect the concentrator in the event of a system power failure, high wind condition, or receiver/engine malfunction.

The tracker must have the capability of initially acquiring the sun's position following startup, and accurately tracking its position throughout the day. Systems-level performance tradeoffs performed during the Task I optimization effort (Reference 2-1) indicated that an effective pointing error of approximately 3.5 mrad (0.2^o) will provide a sensible balance between performance and attainable tracking accuracies.

To effectively design for the low stowed drag profile (see Section 2.2.3), the concentrator must be driven to stow in high wind conditions. Further, to protect the receiver/engine package, the concentrator must desteer the image in the event of a receiver/engine malfunction. In the event of a system power failure, it would be prudent to stow the concentrator to protect the receiver and the structure from over temperature and high wind loads, respectively.

In order to minimize the formation of dew and the buildup of dirt on the reflective panels, and to minimize the consumption of parasitic power, it is best to store the concentrator in a vertical position (looking at the horizon) during its inoperative nighttime hours. In this "retire" position the concentrator is poised for morning startup with a minimum expenditure of tracking energy.

Manual overrides must be included to allow service of the concentrators. A keylock will be required, however, to override the stow protection controls.

Control Scheme

In order to achieve maximum output from the concentrator, it must be able to quickly acquire the sun's position following a short duration cloud cover. This can be effected through a high slew rate tracking capability utilizing an active solar sensor with a wide field of view. As with all strictly active tracking schemes, however, such an approach must include provisions for initial acquisition of the sun's position and differentiation between bright objects (such as clouds or white buildings) and the sun.

An alternative is to utilize a computer-based control scheme, which accurately predicts the sun's position as a function of date and time, coupled with a positional feedback system utilizing shaft encoders to properly position the concentrator. This approach, however, requires high quality positional feedback devices, a very stiff structure, and accurate initial alignment and calibration. It is further subject to misalignment due to foundation settling.

The control scheme selected, therefore, was a sensible combination of these two approaches. Coarse synthetic tracking will be included to maintain the concentrator within $\pm 5^{\circ}$ of the sun's true position. This will be achieved through the use of a microcomputer based control system with one unit per concentrator. Low-cost feedback devices will be used at the center rotary actuator and the elevation bearings to coarsely sense the concentrator's actual position. An active shadowband sun sensor will be used to override the synthetic tracker to control to within ± 3.5 mrad

(0.2°). The control system will include vibration filtering to separate the sun's actual motion from low frequency concentrator flutter due to gusty wind loading.

We have developed single axis trackers for our parabolic trough collectors and have a proof-of-concept prototype two-axis shadowband tracker (see Figure 2-27) installed on two of our prototype two-axis concentrators. The integration of the active and synthetic tracking capabilities will, however, require development work. While no commercially available tracker will currently meet these requirements, we have identified at least two units under separate development which look extremely promising as prototype tracking units.

The mass production concept would employ a separate microcomputer for each concentrator to minimize system communication links and maintain the modularity of the design. Prototype trackers, on the other hand, could probably be most cost-effectively served with a single minicomputer system similar to those developmental units mentioned above.

Interface Requirements

The tracker and control system will require auxiliary power to drive the logic and valving and to feed power to the hydraulic power unit. A simple representation of the signal inputs and outputs is given in Figure 2-28. Both the stow command, which is assumed to come from a system wind sensor, and the receiver malfunction signals are considered to be external to the tracker/control system and as such are treated with optical isolation to simplify system interface requirements. Through optically coupled signal inputs, the control system can directly accept a variety of unconditioned input signals.

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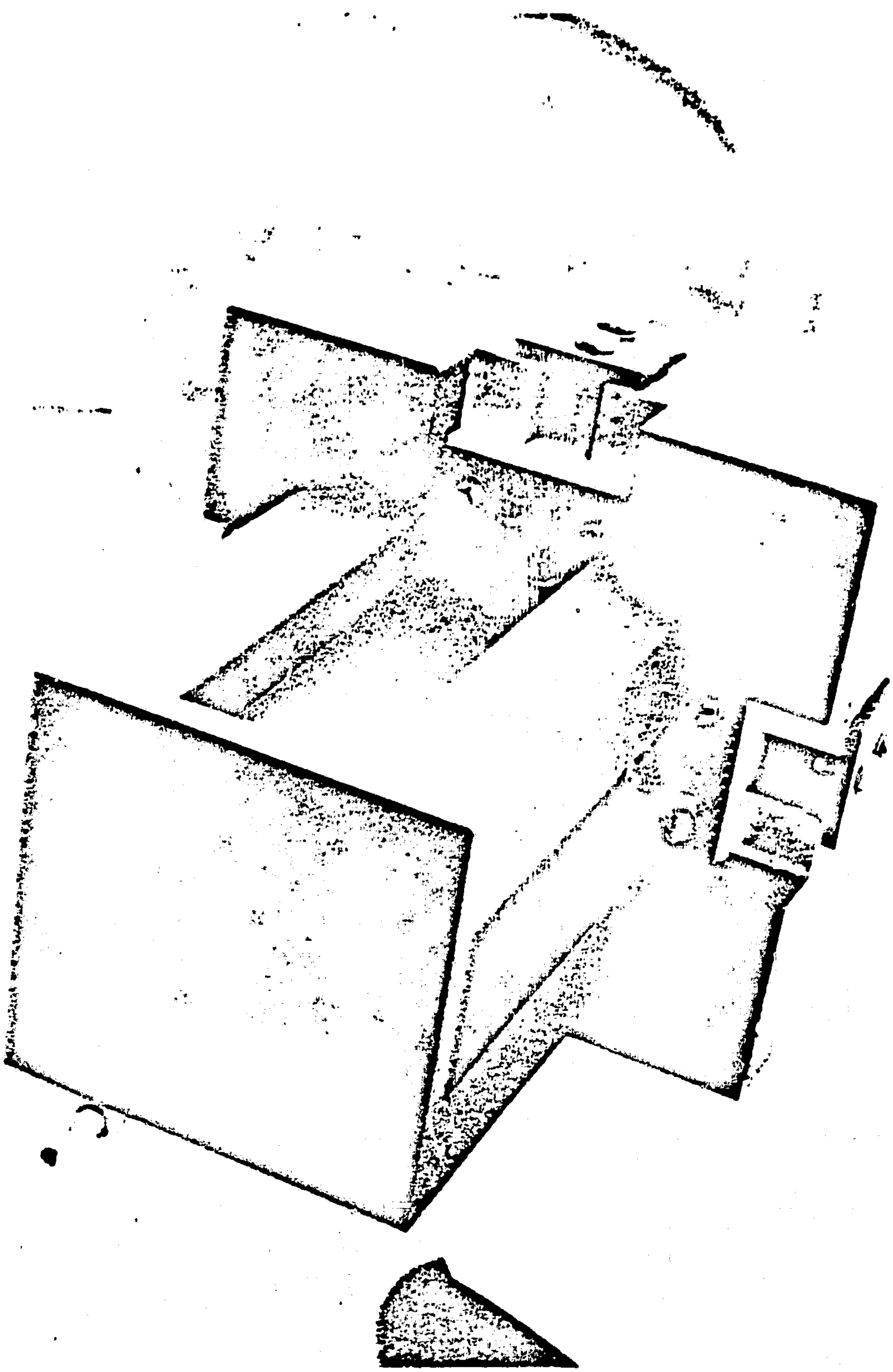

Figure 2-27. Proof-of-concept two-axis shadowband prototype.

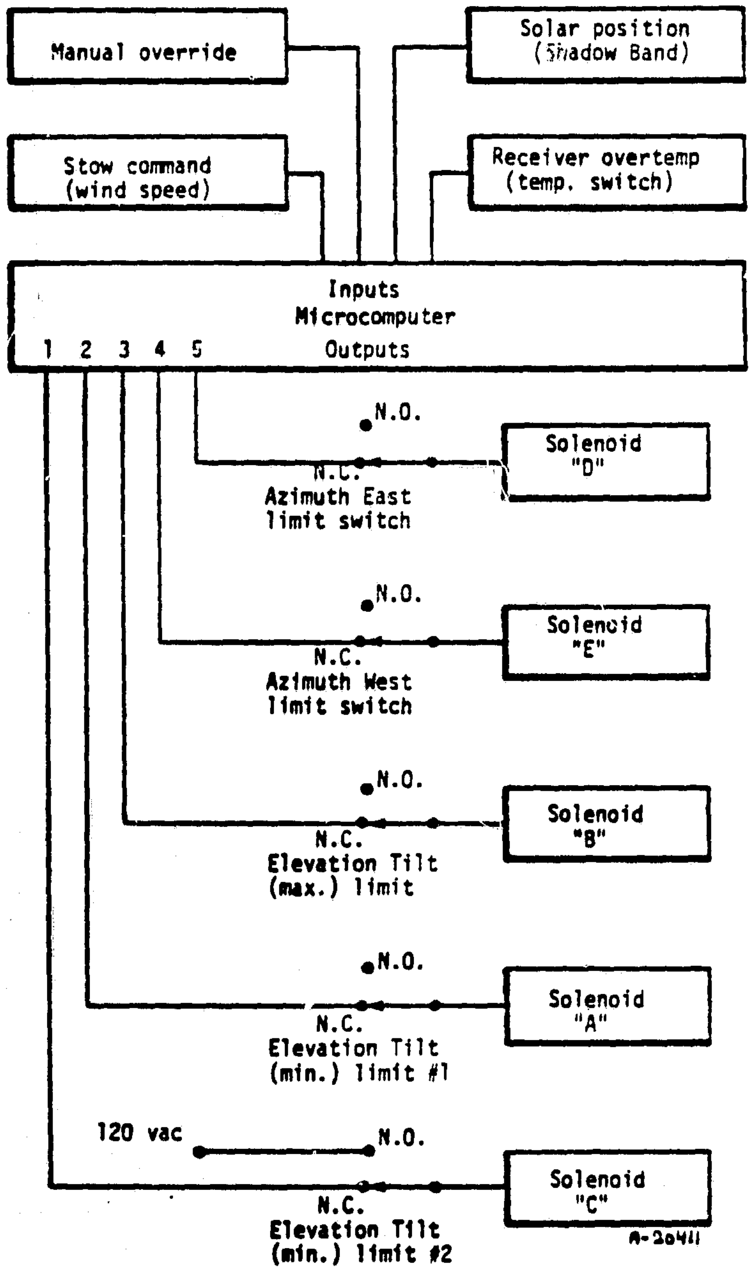

Figure 2-28. Control system inputs.

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For ease of installation, all of the electronics and control components will be incorporated in a single tracker/control box which will ride with the hydraulic power unit on the base support structure. Only the auxiliary power input, a system stow command signal and monitoring and data acquisition lines will need to be flexibly coupled to the ground.

2.2.5 Electrical Design

The objectives of the preliminary electrical design effort were similar to those for the tracker and control subsystem. They were to (1) identify the preliminary electrical requirements and (2) establish the receiver/generator and external system interface requirements. Again, the electrical subsystem will in mass production have a relatively small impact on the concentrator's cost-effectivenss.

Requirements

Three basic electrical requirements must be met by this design. They are (1) provide auxiliary power for the tracker and control system, (2) provide protection and cabling for the generator and its output, and (3) provide lightning protection for the concentrator. Each of these are straightforward requirements which can be met cost-effectively with standard design practice.

An analysis of the parasitic power requirements of the drive and control subsystems (see Section 2.2.3) indicated that a single 120 V/1ϕ/60 Hz circuit with a standard 15 amp capacity would be adequate for all auxiliary power.

Based on rough estimates of the electrical output of the receiver/engine/generator at a peak radiant flux of 1000 W/m^2, approximately 19 kW of electrical power must be delivered from the focal point to the system interface point. Assuming a "Y" connected

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480 V/3ϕ/60 Hz generator, a 30 amp circuit capacity would be required. These values were used for equipment costing and to evaluate the impact of cabling on the design of the receiver support structure. As indicated by the phantom lines on sheet 2 of Drawing 6848-001 (the concentrator assembly side view), the cabling will be routed through the receiver support pipes. This eliminates the need for additional conduits and will yield a clean and simple design.

Lightning protection can be effected through various approaches. In large field applications, it is at times most cost-effective to utilize separate very tall lightning arrestor poles which can be located throughout the field to serve as the grounded discharge path. For single unit or small field installations, however, the simple use of structure mounted lightning arrestors and a dedicated ground path through the structure works well. This approach has been assumed for the preliminary design and is consistent with the costing of Section 3.

Very simple interfaces will serve the electrical subsystems. Fused disconnects will be provided at the perimeter of the foundation/track to interface with both system supplied auxiliary power (120 V/1ϕ/60 Hz) and generated power (480 V/3ϕ/60 Hz). An additional fused disconnect will be mounted at the receiver/generator interface to protect the generator from shorted wires between it and the perimeter disconnect. The perimeter disconnect is provided to allow ease of service. The lightning grounding system will simply interface with a ground rod driven at each concentrator.

2.3 EXPERIMENTAL EVALUATION OF REFLECTIVE PANELS

This section describes the panel fabrication and testing subtask. Section 2.3.1 discusses the objective and constraints of the substask, while Sections 2.3.2 and 2.3.3 present the panel design and fabrication.

The evaluation of the test panels is presented in Section 2.3.4, and conclusions are presented in Section 2.3.5.

2.3.1 Objectives and Constraints

The cost-effectiveness of the Acurex Point Focus Concentrator depends to a large extent on the performance and durability of the reflective panels. At this time, the most promising state-of-the-art design for a high-performance low-cost reflective panel is a structure of glass-fiber reinforced sheet molding compound with a thin silvered glass face sheet. This design combines low fabrication cost, a rigid lightweight structure, and good surface accuracy with a durable, high-performance reflecting surface. Initial cost and performance calculations substantiated this as a winning combination, but were subject to some estimated inputs relative to panel surface accuracy. Since little information is presently available concerning the achievable surface accuracy of a flex glass SMC composite mirror, some sample test panels were fabricated and tested to determine the standard deviation of the slope errors present in each mirror panel. The test panels were fabricated using three different procedures to permit comparisons in terms of cost and presently-achievable mirror quality, and to choose the procedures most suitable for prototyping and for future mass production. The choice of three manufacturing methods, rather than one, increased chances of producing a panel in a short time with a surface accuracy indicative of the current state-of-the-art.

The scope and comprehensiveness of the experiment was tempered by a severe time constraint. Fortunately, the effects of this constraint was only felt in the area of panel design, and in the freedom to pursue any significant experimentation to improve mirror quality above levels obtained from a first effort. The existence and availability of a high-quality laser ray tracing facility, at Sandia Laboratories in Albuquerque, allowed the evaluation of the mirror surface accuracy to be uncompromised.

2.3.2 Panel Design

The full-scale panel design incorporates a minimum thickness glass-fiber reinforced SMC structure with a 2.25 inch-deep interlocking isogrid pattern of stiffening ribs covering the entire rear surface of the panel (see Figure 2-5). The front surface consists of back-silvered low-iron glass conformed to the proper contour and joined to the structure with a bond joint. The bond joint can be formed by the SMC binder or by a suitable adhesive applied after molding and cure of the structure.

It was felt that the test panel should duplicate as much of the configuration of the full scale panel as was feasible. As mentioned in the previous section, time constraints precluded design of a panel specially suited to this task; however, we were fortunate in locating an existing mold used by Sandia Laboratories for the production of experimental heliostat panels. The Sandia panels were 24 inches square, with a 50-foot focal length paraboloidal reflecting surface.

The panel employed a rib-stiffened structure with a pattern somewhat similar to isogrid, which was designed to allow a one inch overhang of the structural face sheet along the edges of the panel. The size of the Sandia panel was slightly smaller than initially desired, but adequate to satisfy test requirements, and coincidentally resulted in a perfect size match for the largest flex glass mirror sheets available for immediate delivery. The differences in the reinforcing rib pattern and depth were considered to be of minor importance. An exception to this was the inheritance of a turned-down edge problem discovered in the Sandia panels and thought to be associated with the overhang of the mirror face structure at the panel edges. Duplication of the full-scale focal length was important, however, since this would force the glass to assume the same curvature and, within the size limitations of the mirror sheet, duplicate the bending stresses in the full-scale mirror. Membrane stress levels would depend upon the sheet size used to make up a full-scale panel.

The focal length discrepancy was corrected by machining a new contoured insert for the mold and substituting it for the existing insert. Figure 2-29 shows the components of the mold and illustrates the loading scheme for one of the manufacturing methods evaluated. Figure 2-30 shows the test panel produced by the modified mold. The variation in the face thickness of the structure from 0.150 to 0.500 inches results from the change in the front surface contour to achieve a 25-foot focal length.

The SMC formulation used for the test panels is one of two formulations currently available from Haveg Industries (the fabricator of the test panels) for molding. Both compounds offer a good match to the expansion characteristics of glass from 60° to $300^{\circ}F$. Other formulations can be matched to a chosen glass over a wider temperature range than those currently available. Presently, the choice of a particular glass, and the availability of expansion coefficient data as a function of temperature for the chosen glass, have temporarily delayed refinements in the SMC formulations. Some properties for the two Haveg formulations are listed in Table 2-7. The choice of Havamold 9220-30 for the test-panels was strongly influenced by it availability (a quantity of this material was recently manufactured for a Sandia panel evaluation program, and a small amount of this was available for the test panels).

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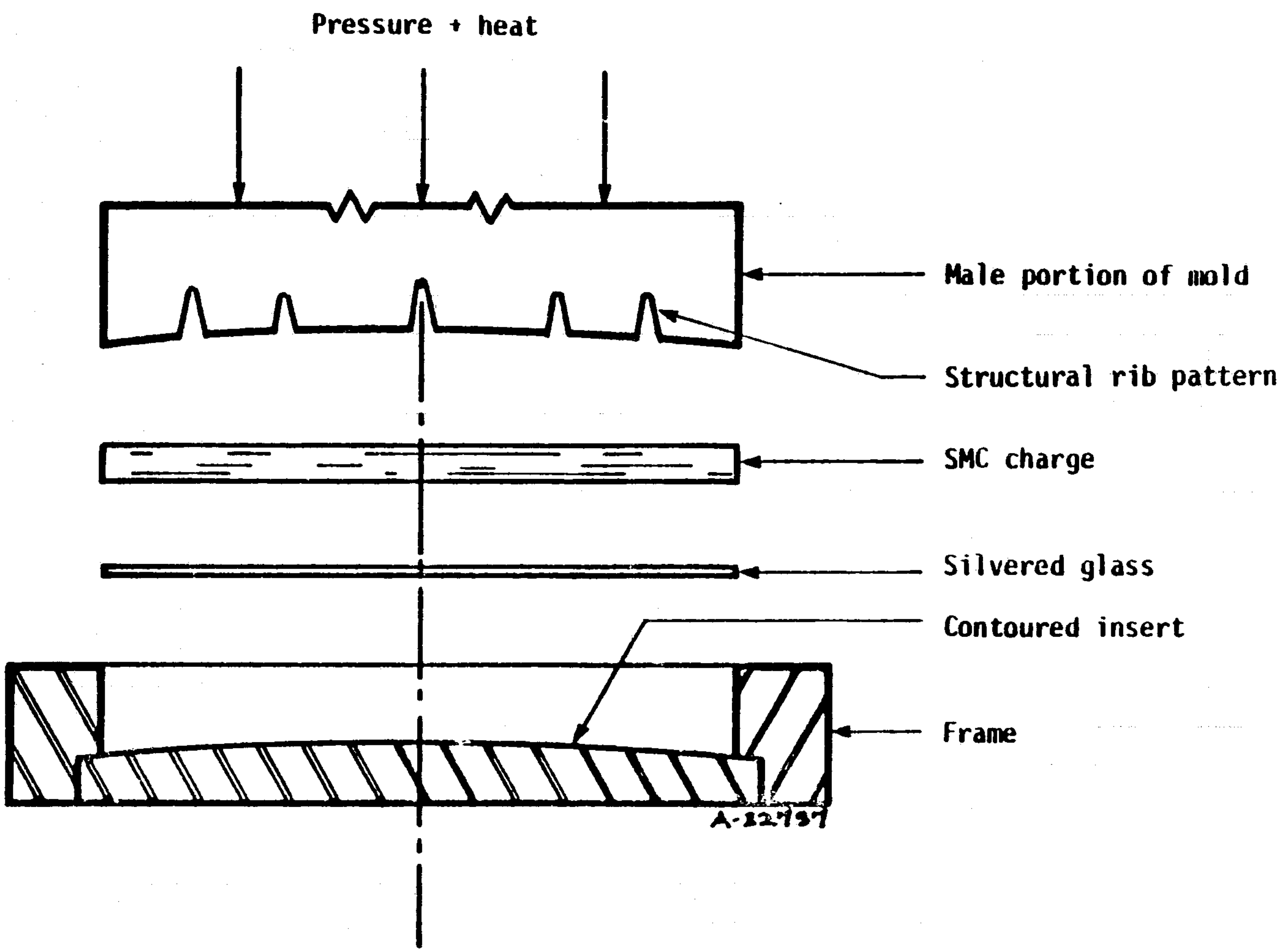

Figure 2-29. Test panel mold configuration.

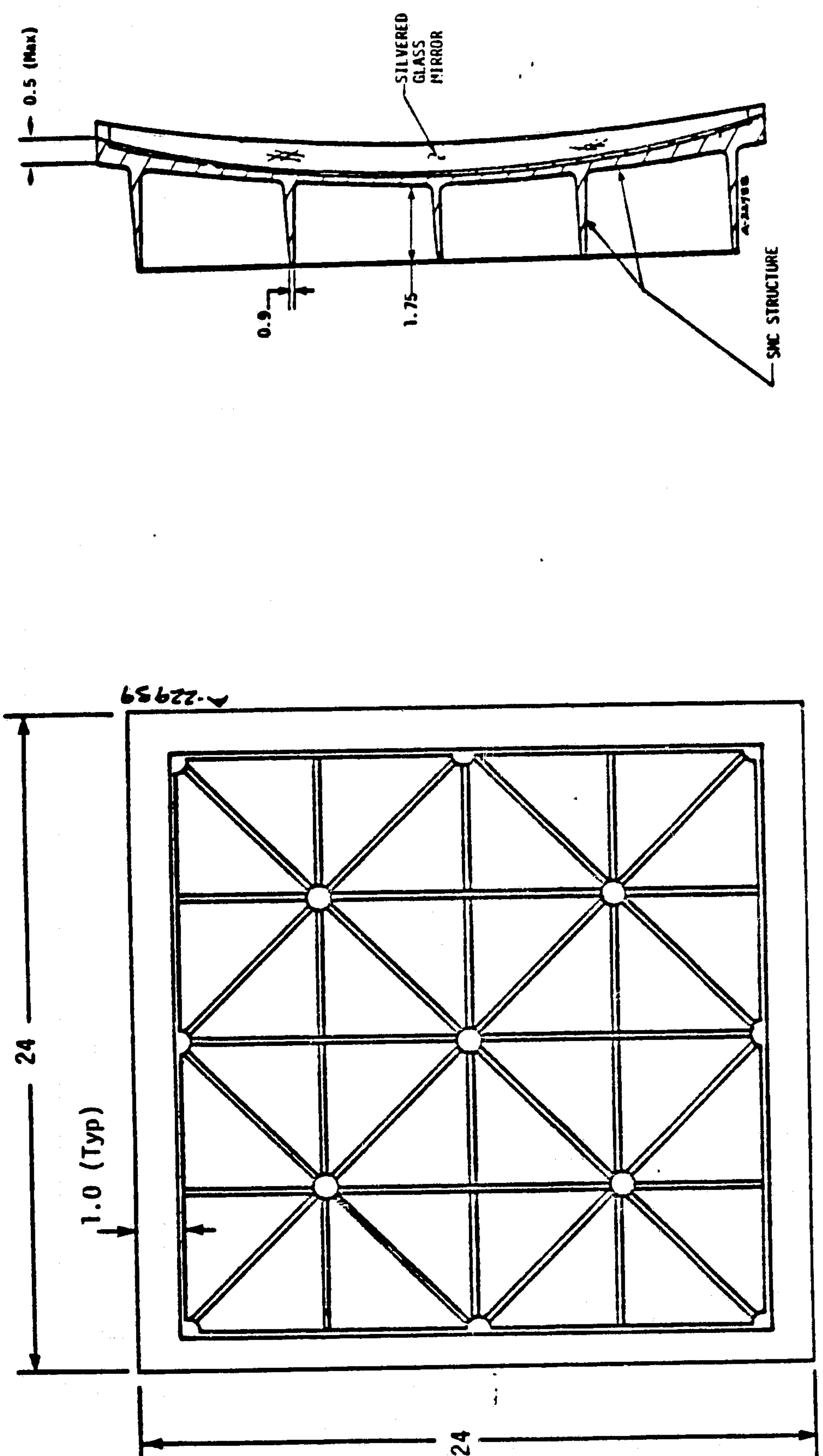

Figure 2-30. Test panel produced by modified Sandia mold.

TABLE 2-7. HAVEG SHEET MOLDING COMPOUNDS FOR JOINING TO GLASS

Formulation	Specific Gravity	Tensile Strength, psi	Young's Modulus psi x 10^6	Projected Cost @ 3M lb/yr
Havamold 9220-30	1.85	12,500	1.3 x 10^6	$0.65/lb
Havamold 9640-50	1.25	12,300	1.0 x 10^6	$0.76/lb

An alternate choice, Havamold 9640-50, or further formulation refinements will be considered for full-scale panels. The lighter 9640-50 formulation offers a potential reduction in cost by reducing panel weight below values assumed for the preliminary design. Since a reduction in the modulus of elasticity accompanies the weight savings, a more detailed examination of panel behavior in a 100 mph wind is necessary before a choice can be made.

2.3.3 Panel Fabrication

The paramount objective of the panel fabrication was the production of a panel which typified the surface quality attainable with the present state-of-the-art. To ensure successful attainment of this objective, three different manufacturing methods were used to fabricate the panels. The three approaches would hopefully allow the circumventing of manufacturing problems which might be specific to one of the methods and, as a bonus, would allow a rating of the methods in terms of suitability for prototype production and longer term potential for high volume production.

The three manufacturing methods chosen were:

1. Integral molding of the glass/SMC panel in one molding cycle.
2. Fabrication of the panels in two molding cycles (first the structure is molded and cured, then the glass and a thin

laminating SMC sheet is added and the panel repressed and cured to form a composite structure).

3. Molding and curing of the structure, and subsequently bonding the silvered glass face sheet to the structure with a suitable adhesive using the female portion of the mold as a bonding fixture (two adhesives were evaluated for this application).

As soon as the modified mold was assembled, panels were fabricated using each of the methods cited above. Representative panels produced with each manufacturing method are shown in Figure 2-31. All panels exhibited visually discernable waviness to some degree. The reflected light patterns from each panel (Figure 2-31) provided a very sensitive qualitative indication of mirror surface topography. The following is a listing of the predominant topological features seen in Figure 2-31 with probable causes for each feature.

Panel I -- Single Step Molding

The diagonal line patterns crisscrossing the mirror surface are a print-through of the structural rib pattern on the rear of the panel. This effect was observed on the Sandia program and was thought by Haveg to be related to the face thickness of the structure, or to material shrinkage at the rib/face junction. These indentations are very shallow in depth ($\leq$0.001 inch) and are difficult to locate on the unmirrored structure. However, the small line width of the depression produces a measurable local slope error which is easily discerned in the reflected image. Since the face thickness of our SMC structure varies from 0.150 to 0.500 inches from center to corners as a result of the focal length modification, we are able to observe that face thickness has no effect upon the intensity of the rib print-through. This effect is now believed

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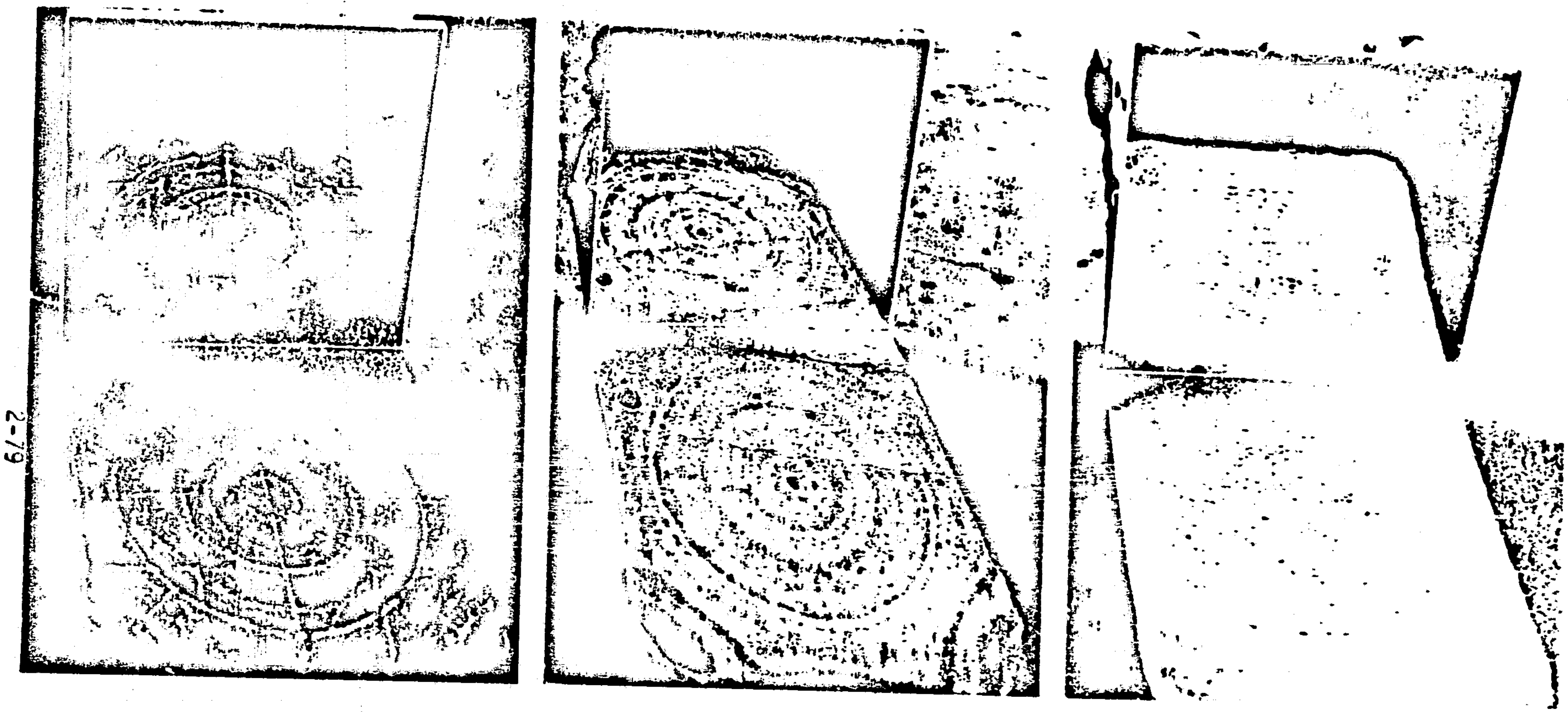

PANEL NO. 1
SINGLE STEP MOLDED

PANEL NO. 2
2 STEP MOLDED

PANEL NO. 3
BONDED GLASS

Figure 2-31. Test panels.

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to be due to shrinkage of the higher local volume of material at the rib/face junction. This effect is enhanced by the anisotropic nature of the SMC properties. When the mold cavity is charged with SMC and the heat and pressure applied for molding, the SMC flows transversely across the panel face and axially into the rib cavities of the mold. This flow pattern results in a random transverse glass fiber orientation across the panel face, with the fibers turning to an axial orientation across the rib/face junction in response to the flow pattern. This produces a panel with high flexural strength and rigidity and a structurally sound interface between reinforcing ribbing and the panel face. However, the anisotropic nature of a glass fiber reinforced polymer structure results in differences in structural properties and material shrinkage rates parallel to and normal to the direction of fiber orientation. This effect is thought to enhance the local volume shrinkage phenomena at the rib/face intersections.

There are viable paths for minimization or elimination of rib print-through. One method, demonstrated in Panel II, is a modification to the molding procedure which eliminated print-through. Another approach is to modify the SMC formulation to attempt to reduce or eliminate shrinkage. Zero shrinkage has been achieved in several SMC formulations; however, our application requires simultaneous attainment of thermal expansion properties, low density, and low shrinkage at low cost. Feasibility of optimizing a SMC formulation for all of these variables must be evaluated.

The second observable feature in the mirror topology is a system of concentric ripples progressing outward from the center of the panel, resembling ripples in a stream after a stone is dropped. Noticing that the pattern is present to about the same degrees in Panels I and II but is almost absent in Panel III, one can eliminate any structural buckling effect in the glass since the mirror contour is essentially identical in each case. Careful examination of Panels I and II reveals a high degree of similarity in the patterns, right down to the fine structure of the ripples. Suspecting that the cause might be in the tooling, a thin sheet of FEK reflective film was applied to an unmirrored structure using the surface tension of a thin water film between the FEK and the SMC structure to hold the film in place. Observation of the reflected light patterns from this panel revealed the same concentric ripple pattern in the unmirrored structure. The pattern was then be traced to a system of concentric ripples in the tool caused by variations in the hand polishing procedure of the tool face, probably to polish out local areas of roughness caused during the machining of the face contour. The patterns were strongly impressed into the glass sheet by the high (1000 psi) molding pressures applied to the glass in Panels I and II, but were only slightly impressed in Panel III under the much lower (1 psi) clamping pressures required for adhesive bonding of the glass to the structure. Also observed in the test of the unmirrored panel were the effects of the turned-down edge, which was inherited with the tooling. This verified that the turned edge was indeed related to the structure design and not attributable to the glass/SMC interface.

Panel II -- 2-Step Molded Panel

Visual inspection of Panel II and its reflected light patterns disclosed the same concentric ring pattern as Panel I, but the rib pattern print-through evident in Panel I was not present. Since shrinkage at the rib/face junction occurred during curing of the structure, the thin SMC sheet used to laminate the glass to the precured structure was able to fill the local depressions in the face of the structure, eliminating any evidence of the rib pattern on the mirror surface. Absence of the diagonal rib patterns considerably improved the visual appearance of Panel II.

Panels III and IV -- Bonded Glass Panels

Two adhesives, Versilok 506 and Versilok 551*, were used to fabricate bonded glass panels for this experiment. Versilok 506 was available at the time the first panels were bonded, while Versilok 551 was still in transit to Haveg Industries. Versilok accelerator No. 4 was used to initiate the adhesive cure cycle yielding a cure time of 10 minutes to achieve 75 percent of cured structural properties. An alternate accelerator, which would result in much longer pot life, was not obtainable in time for the experiment.

Panel III was successfully bonded with Versilok 506, which has a very high viscosity (25,000 to 125,000 cps), after two unsuccessful attempts to achieve a uniform thickness bond line. The principal difficulty was in migration of the viscous adhesive in the glass/SMC interface from an irregular to a uniform thickness prior to setting. Panel III was visually superior to either of the molded panels, showing no trace of rib print-through and only subtle traces of the concentric tool markings. Reflected light patterns from this panel revealed a relatively featureless surface, with a low amplitude random oriented ripple uniformly covering the surface. This ripple is believed to be caused by residual variations in bond joint thickness.

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*Hughson Chemical Company, Erie, Pennsylvania.

Panel IV was bonded with Versilok 551, which has a much lower viscosity (60 to 100 cps). Again, accelerator No. 4 produced the same very short pot life of 10 minutes. It was believed that the much lower viscosity would improve mirror quality by producing a more uniform bond line. Visual inspection of Panel IV showed a further reduction of surface waviness, but the improvement was small. It is possible that during a ten minute cure cycle, the adhesive viscosity increases rapidly enough to override any benefit resulting from lower initial viscosity. During prototype panel fabrication, use of an alternate accelerator producing a longer pot time should be investigated to determine if any further improvement in quality can be achieved.

2.3.4 Evaluation of Test Panels

Quantitative evaluation of test panel precision was accomplished at Sandia Laboratory's ray tracing facility. The ray tracing apparatus, just recently modified to two-dimensional ray tracing, is currently being used to evaluate candidate mirror panels supplied by manufacturers throughout the country for use in heliostat and other solar concentrator applications.

The apparatus is linked to an on-line computer which controls its operation and processes data gathered from the test. Figure 2-32 is a sketch of the ray tracer showing its principle components. Figure 2-33 is a photograph of the apparatus with one of the Acurex panels ready for test. The device consists of a driven carriage containing a helium-neon laser and the return spot position detector, a stepper motor driven table which moves the mirror in a direction normal to the carriage, associated signal processing electronics, and an on-line computer. The reflected beam position sensor is located approximately 6 inches from the mirror

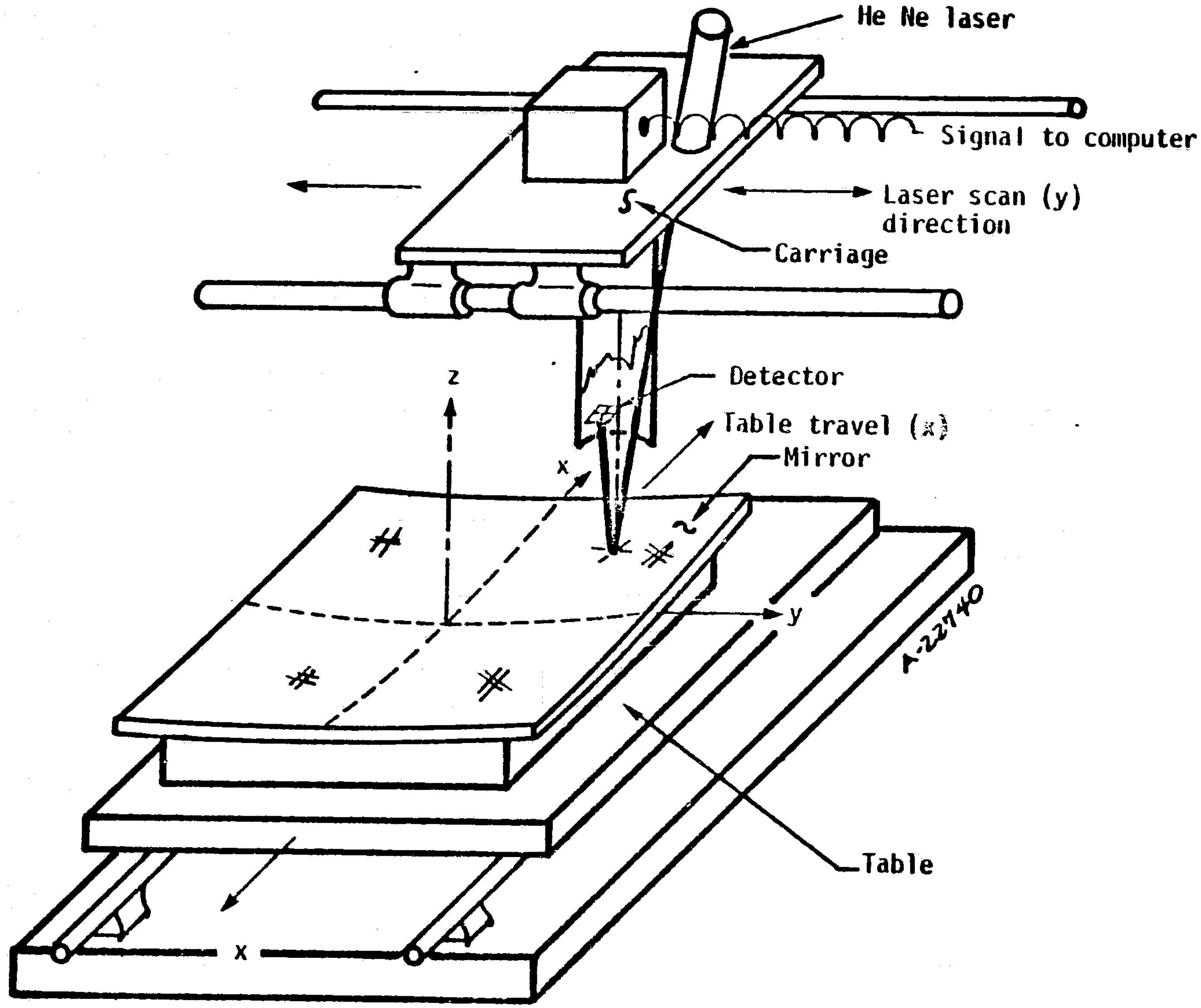

Figure 2-32. Sandia ray trace apparatus.

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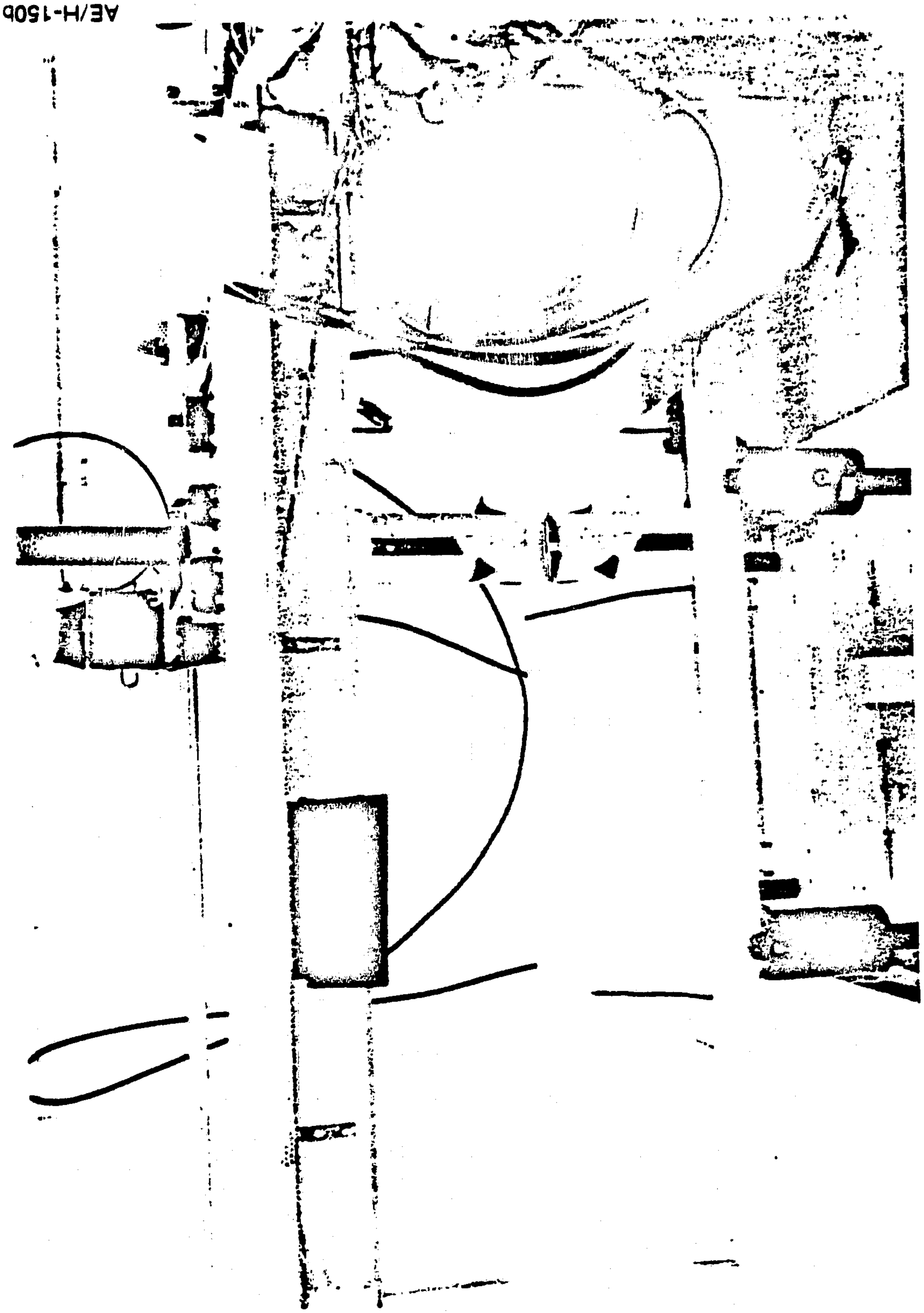

Figure 2-33. Apparatus with test panel.

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surface and measures the local slope of the mirror by sensing the reflected image position.

The sensor accurately determines the position of the reflected beamspot relative to its own center and forwards this information as a continuous analog output from its four (±x, ±y) terminals. The device scans the mirror in a raster fashion, similar to that used in television imaging systems. The computer is programmed to record position and slope information at predetermined intervals in the scan. The scanning is accomplished by traversing the mirror in the y-direction with the motor-driven carriage containing the laser and sensor. As the carriage reaches the predetermining limit of its scan, the stepper motor-driven table will move the mirror a preset distance in the x-direction and the carriage will scan the mirror in the return direction along a path parallel to the original scan.

The ray tracing system was very recently updated to handle bidirectionally curved mirrors (i.e., paraboloids, spheres, etc.) by Dr. Bruce Hanshe of Sandia Laboratories, who subsequently determined the RMS value of measurement uncertainty to be 0.10 milliradians. The present apparatus can survey an area of up to 72 by 18 inches, these restrictions being imposed by the maximum travel of the carriage and mirror table. The control/data-processing computer is programmed from a video display/keyboard terminal located at the ray tracer. The computer controls the data gathering process, compares the matrix of slope values to those of the design paraboloid and computes slope error values for each of the locations surveyed. It will then generate a map of surface slope errors relative to the design paraboloid, and will compute the two best fit paraboloids to the x and y slope values. Also computed are RMS values of the x and y slope errors relative to the design and best fit paraboloids, and a map of surface slope errors based on the best fit paraboloid. The resulting information provides a rather comprehensive evaluation of the mirror surface quality.

The test window available to Acurex for panel tests at Sandia was two days in length, with the possibility of acquiring a third day if required. Since the lower viscosity bonding agent had not yet arrived at Haveg Industries on the day before the test, the completed mirrors were transported to Sandia for evaluation. The test program strategy was to evaluate as many of the panels as possible, with preference given to the highest quality panels.

The first day of the test schedule was utilized for setting up to accommodate the Acurex panels, and some programming changes made to tailor the output information to the specific needs of these tests. Also accomplished during the first day was a coarse general exploratory survey of a 16" x 24" area centered on the panel, to assay the panel in general and to explore the limits of the turned-down edge condition inherited with the mold. This was followed at the close of the day by a detailed survey of a 4" x 24" area extending along one edge of the panel from corner to corner.

Satisfied that the general topology of the panel was understood, the following day was devoted to detailed surveys of the available panels. Considering the geometric limits to the survey area imposed by limits of travel inherent in the apparatus, it was decided that survey data used to evaluate mirror performance would be gathered over a 17-inch square area centrally located on the panel. The choice of a 17-inch width to the scan area was dictated by the 18 inch maximum travel of the mirror table. It was felt that inaccuracies introduced by combining data from two independent setups into the curve fitting and statistical error evaluation routines would degrade the accuracy of the output. Also the program modifications necessary to accomplish this task would further delay the ray tracing and might jeopardize the test by consuming the remainder of the scheduled test time at the expense of the tests.

The use of a non-symmetrical survey area (such as 17 x 24 inches) was considered to be unwise. Since the program computers best fit paraboloid separately for x and y slope values, an assymetrical survey area might artifically introduce a discrepancy between x and y best fit paraboloids and mask the degree to which circular symmetry was achieved. This would artifically bias the choice of a best fit paraboloid and hence the results of the evaluation. It was further noted that, since the inherited turned edge problem was related to the Sandia structural rib pattern rather than to the glass/SMC lamination, it would obscure the demonstration of the attainable accuracy with a glass/SMC composite with overriding effects specific to an existing off-optimum rib design. Thus it was felt that the choice of an orthogonally symmetric survey area, as large as would be practical with a single setup, would yield the most meaningful results.

Data was gathered at 0.100 inch intervals along the 17-inch scan, with scans spaced 0.500 inch apart, resulting in 5985 slope values, which are then resolved in their respective x and y components by the computer. This produced a comprehensive statistical data sample for each of the panels. In the interest of consistency, an exploratory scan of the 16 x 24 inch central area, and a detailed edge survey was conducted on each panel. As was expected, the edge condition was reproduced in detail in each of the panels.

On the second test day, Panels II and III were surveyed and evaluated. Figures 2-34 and 2-35 depict the slope-error maps for these panels. One can easily see the circular ripple pattern due to tool irregularities in Panel II and its considerably attenuated counterpart in Panel III. The survey lines are spaces 0.5 inches apart on the mirror surface. This spacing between lines also represents a 5 milliradian slope error in the individual traces. Although Panel III has a much smoother surface, the maximum amplitudes of the local errors are similar (5 to 7 mrad for Panel II and 5 mrad for Panel III). Figure 2-36 shows a similar map for Panel IV, which was fabricated during the day of test setup at Sandia and surveyed on the third test day. It reveals a topology very similar to that of Panel III, indicating no appreciable improvement between a high viscosity adhesive carefully applied, and a low viscosity adhesive for the same short cure time.

Table 2-8 presents a summary of the test results for the three panels evaluated at Sandia. As can be seen, the resulting slope error standard deviations for the entire surveyed area are well below the target value of 2.4 milliradians assumed for the initial performance estimates of the concentrator. The bonded panels (III and IV) yielded significant improvements in slope error over the 2-step integral molding. The single-step integrally molded panel (I) and a second panel bonded with the low viscosity adhesive (V) were not ray traced due to lack of available test time at Sandia. Panel V was fabricated in an attempt to evaluate consistency of quality for a given fabrication process. However, a comparison between Panels III and IV satisfies that requirement, despite

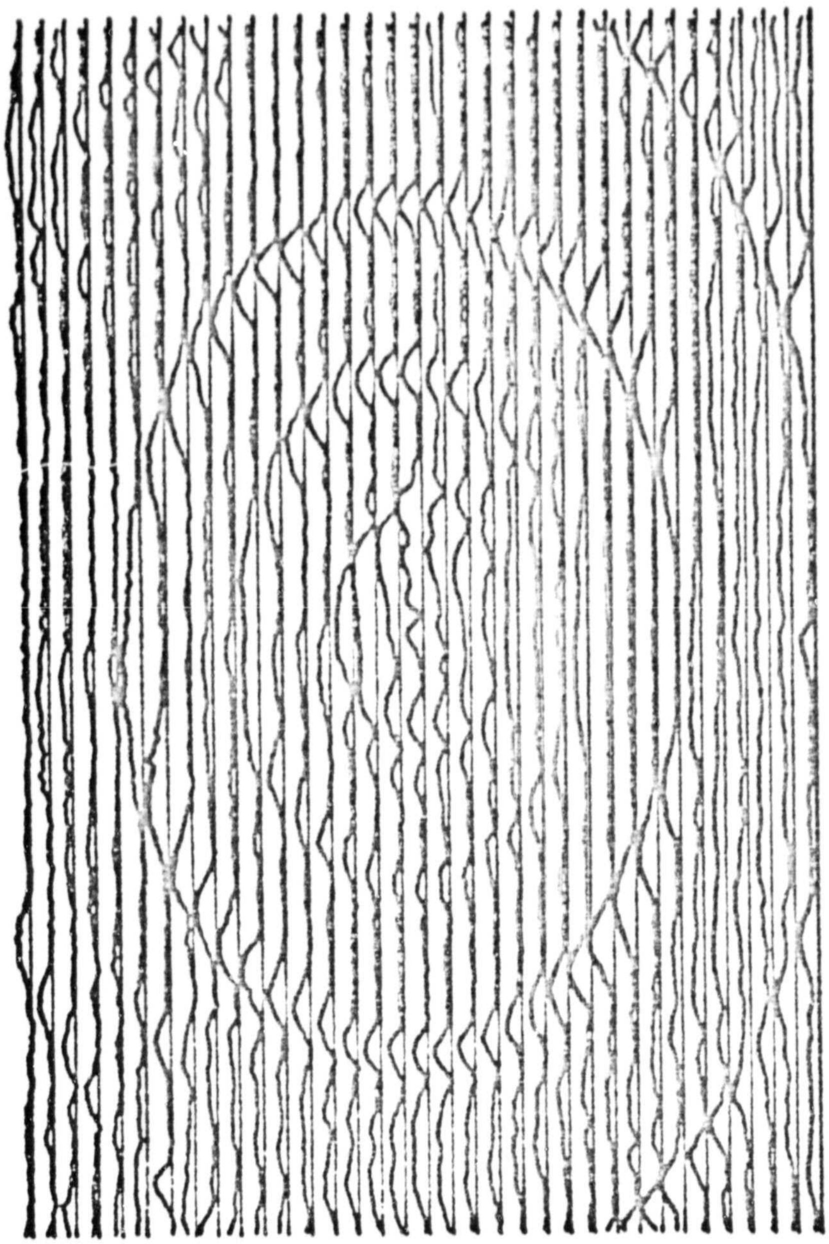

Figure 2-34. Slope-error map - Panel II.

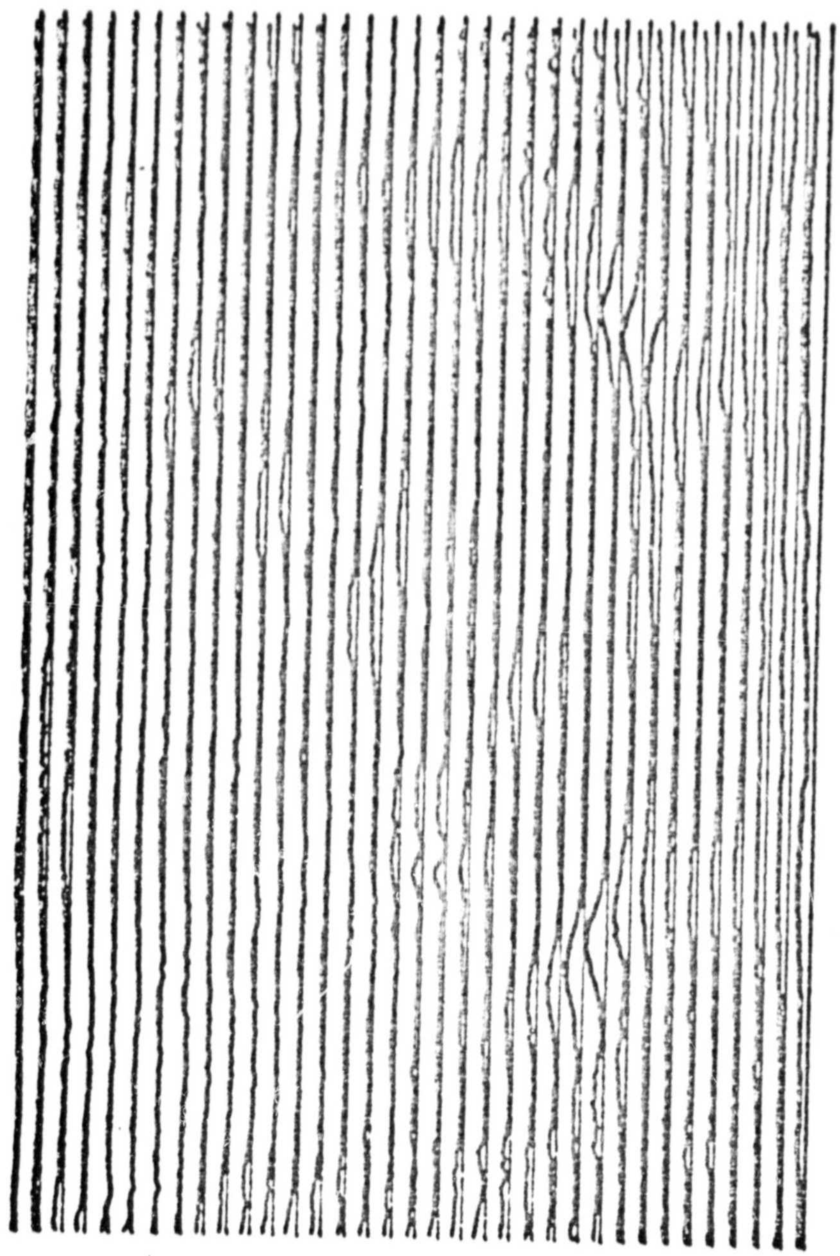

Figure 2-35. Slope-error map - Panel III.

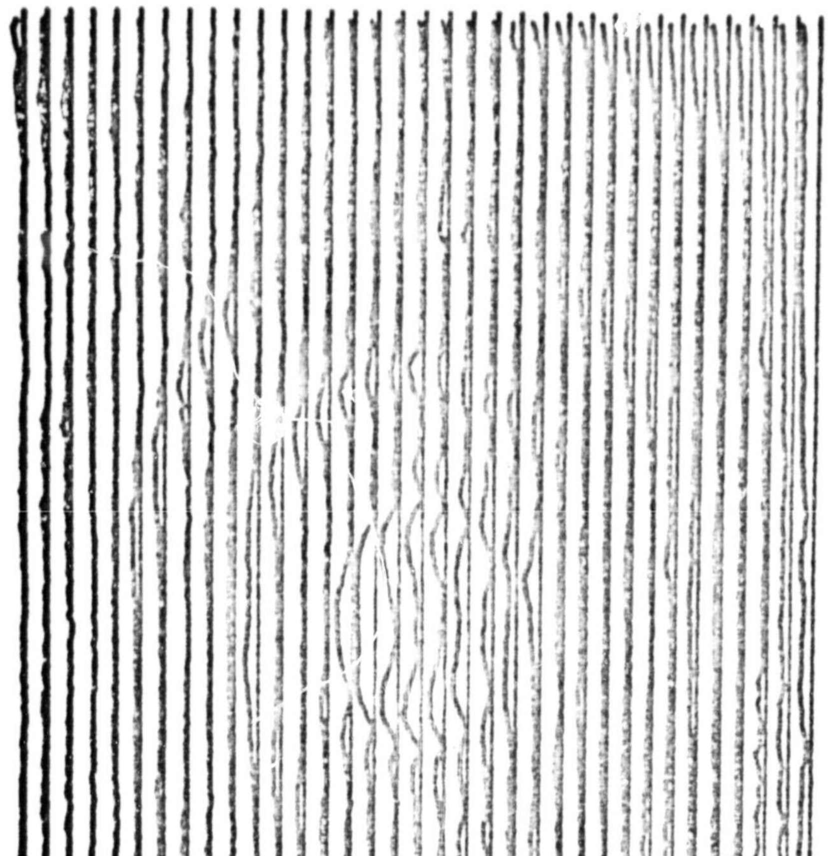

Figure 2-36. Slope-error map - Panel IV.

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TABLE 2-8. PANEL FABRICATION AND TEST SUMMARY

Panel	Visual Appearance		Slope Errors (Std. Dev.)		
	Rib Print-through	Circular Pattern	X (mrad)	Y (mrad)	Design (mrad)
I Single-step molded	Yes	Yes	--	--	2.4
II Two-step molded	Subtle	Yes	1.36	1.30	2.4
III Bonded, adhesive #1	No	Subtle	0.97	0.85	2.4
IV Bonded, adhesive #2	No	Subtle	0.93	0.94	2.4

the differences in adhesive viscosity. Panel V was visually indistinguishable from Panel IV in surface quality.

All panels fabricated produced a slightly longer than expected focal length. The focal lengths produced were approximately 8.5 meters for the bonded panels as compared to a design value of 7.62 meters. Values were reasonably consistent for the two bonded panels and were slightly longer for the 2-step molded panel.

The consistency of the overshoot was typical of springback effects in plastic molding. The effects are commonly corrected by modifying the contour of the mold. Time did not permit an extensive survey of the tool to determine its best fit paraboloid, so the possibility exists that a portion of this error is in the tool. Reported values of slope error are relative to the best fit paraboloids, since springback effects would be removed from production panels by mold correction. It is noteworthy, however, that the slope error standard deviation values are increased by approximately 60 percent when compared to the design paraboloid. These increased values still fall below the 2.40 milliradian value assumed for the initial design. The relatively consistent focal lengths produced by the bonded panels suggest that the majority of the overshoot is correctable by mold modification, possibly leaving a random panel-to-panel variation in focal length of as much as 1 percent or 2 percent. This would increase the reported slope error values by approximately 5 to 10 percent, yielding error values very close to 1 milliradian.

2.3.5 Conclusions

From the results achieved in a short two month experiment, it can be concluded that composite mirror panels of glass-fiber reinforced sheet molding compound and silvered flex glass can be manufactured with the required precision using current state-of-the-art methods. All panels evaluated surpassed initial slope error estimates by a considerable margin (0.95 mrad as compared to 2.40 mrad). This margin will allow some compromise in precision to occur during scale-up, if required, while maintaining a sufficient degree of precision to guarantee high-performance concentrator optics. An increase in the slope error standard deviation from the measured 1 milliradian value to 2 milliradians in the full scale panels would result in a 3 percent loss in concentrator performance and a corresponding 3 percent increase in busbar energy cost.

Although all panels evaluated were satisfactory, bonding of the silvered glass to a prefabricated SMC panel produced a superior quality mirror. This technique would most likely be used for initial panel production. The impact of the additional processing step upon panel cost is small and, in the long term, further developments in integral molding techniques will allow panels of comparable quality to be produced in a single fabrication step.

2.4 PERFORMANCE ANALYSIS

This section presents the results of the performance analysis subtask. Included in the analysis is a determination of the net thermal output of the concentrator at the receiver aperture and life-cycle cost per unit energy delivered by the concentrator. The methodology used in the analysis is identical to that developed in the Parameter Optimization Task, Task 1 (see Reference 2-1).

Section 2.4.1 presents a review of the performance/cost methodology. Section 2.4.2 presents an update of the design parameters, such as rim angle, slope error, and concentrator size, which were first presented in Task 1 and which will serve as the input to the performance analysis. A summary of the cost/performance of the concentrator is then given in Section 2.4.3. Finally, Section 2.4.4 presents the results of an analysis to determine the impact of certain modifications to the receiver/engine module on the design and performance of the concentrator.

2.4.1 Review of Methodology

This section presents a review of the methodology used to evaluate the performance and cost-effectiveness of the concentrator design. As mentioned above, the procedure described here was developed in Task 1 and has been used in all systems-level tradeoffs performed throughout the program.

Figure 2-37 gives a representation of the relationship of the key steps to determine concentrator performance and cost-effectiveness. As shown in the figure, the approach includes the calculation of:

1. The net thermal output of the concentrator at the receiver aperture, in kW_{th}
2. The annualized, or life-cycle, cost of the concentrator, in dollars per year
3. The base year busbar energy cost, $\overline{BBEC}_{th}$, in mills/kW_{th}-hr

A description of each of these steps follows.

Thermal Output Modeling

The solar flux distribution at the focal plane of the concentrator is dependent upon the concentrator shape, the rim angle, ψ, and the combined spreading effects due to surface irregularities and other optical errors. While the flux distribution is nonuniform, typically it is relatively symmetrical about its peak intensity. This allows a simple characterization of the flux by an intercept factor curve which represents the ratio of power intercepted by an aperture of a given radius to the

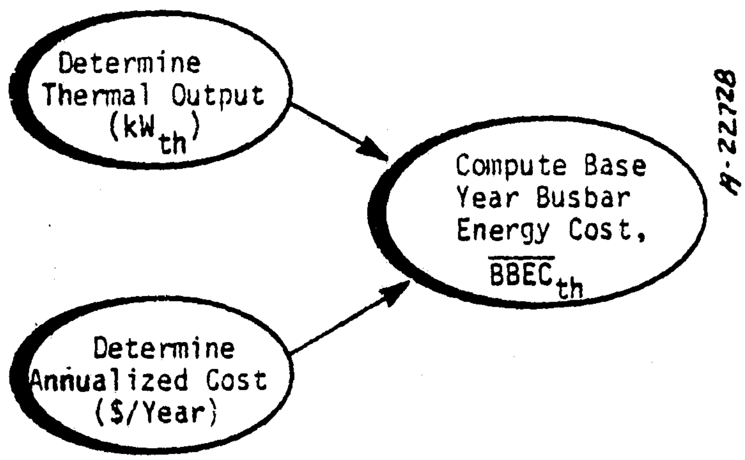

Figure 2-37. Approach used to determine concentrator cost/performance.

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total radiant power reflected by a concentrator of a given size. Since radiant heat loss from the receiver cavity is directly proportional to receiver aperture area, it is necessary to trade off the effects of aperture area on heat loss and intercept factor to maximize the net thermal output.

The energy balance at the receiver can be expressed by the following relationship:

$$\dot{Q}_{net} = \left[\dot{Q}_i \ \alpha G \left(\Phi_1 R' \ + \Phi_2 R'_2\right) - Q_r\left(\frac{A_r}{A_{c,p}}\right)\right] A_{c,p}$$

where:

$\dot{Q}_{net}$ = Net power to receiver (kW_{th})

$\dot{Q}_i$ = Incident solar flux

α = Effective receiver absorptance

G = Shading factor (1-shading)

Φ_i = Intercept factor for convolved error of σ_i*

R_i = Solar spectrum weighted reflectance for convolved error of σ_i

$\dot{Q}_r$ = Receiver loss coefficient (kW/m^2)

A_r = Receiver aperture area (m^2)

$A_{c,p}$ = Projected collector area (m^2)

For any given case, the relationship between intercept factor and the $A_r/A_{c,p}$ ratio must be determined. This allows an optimization of the receiver aperture diameter for maximum net thermal output.

The intercept factor curve is primarily a function of the concentrator geometry, rim angle, sun shape, and the optical error cone, which is characterized by σ*, the dispersion of a circular normal probability density function. The concept of a statistically determined optical error cone greatly simplifies the analysis and allows a simple means of representing the combined effects of various errors.

The optical error cone was considered to be composed of four independent error types. Each error type was characterized by the standard deviation of a normal distribution which represents the statistical nature of the error. They were:

- Specularity, σ_ω
- Slope error, σ_s
- Structural deflection, σ_d
- Pointing error, σ_p

Specularity was used to account for the scattering effect of microscopic surface irregularities in the reflective materials used to face the reflector panels. Pettit (Reference 2-6) has shown that the reflectance profile of these materials can be adequately described by either a single normal distribution or the sum of two normal distributions. Much of the commonly reported data have been measured at a monochromatic wavelength of 0.5 μm. For modeling purposes, these 0.5 μm values for reflectance and specularity were used with reflectance scaled to match the solar spectrum averaged hemispherical reflectance value, $R_{s,2\pi}$.

Slope error was used to represent the macroscopic effect of deviations in the local surface normals of the reflective panels from the ideal values for the theoretcial reflector shape. Since slope error represents the variation in surface normals, the effect on the reflected rays is doubled.

The deflection of the reflector support structure (relative to its hinge points and elevation actuator attachment point) has the effect of mispointing each of the reflector panels to varying degrees. Since receiver support loads are transmitted directly to the lower support structure, only the wind and gravitational forces on the panels and upper structure affect the deflection. With the symmetrical support structure and relatively uniform loading, the aggregate effect of the structural deflection will be to spread the solar image on the focal plane.

For analysis purposes the effect of diurnal and seasonal wind load variations on the structural deflection was modeled as a two dimensional normal distribution with a dispersion of σ_d. As with slope error, the impact on the reflected beam is doubled.

At any instant in time, the effect of tracker pointing error or receiver deflection is to offset the sun's image at the focal plane relative to the center of the receiver aperture. Long term performance, however, depends on the frequency of occurence or distribution of these errors. A review of the proposed tracking scheme (see Reference 2-1) led to a statistical representation of pointing error with a standard deviation of σ_p.

Since each individual error was characterized as a normal distribution, the combined effect of all four error types could also be represented as a normal distribution. Assuming circular symmetry, the one-dimensional normal distributions with standard deviations of σ_i became two-dimensional distributions with dispersions of σ_i. The effective optical error cone was therefore represented by a circular normal density function with a dispersion, σ^*, equal to the convolution of the individual errors:

$$\sigma^* = \left[\sigma^2 + (2\sigma_s)^2 + (2\sigma_d)^2 + \sigma_p{}^2\right]^{1/2}$$

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Intercept factor curves were generated for the truncated triangular concentrator geometry for various rim angles (ψ) and convolved optical error cone values (σ^*). Figure 2-38 presents the intercept factor curves generated for the 45^{0} rim angle. The "Helios" optical code developed at Sandia Laboratories (Reference 2-7) was employed to calculate the flux distribution on the focal plane of the concentrator.

Annualized Cost Model

A simplified version of JPL's life-cycle cost model (Reference 2-8) was used to determine the annualized cost of the concentrator. The life-cycle cost of owning and operating the concentrator can be described by the following relationship:

$$\overline{AC}(YB) = C_1 \left[C_2 \text{ (Capital)} + \Sigma\, C_{3,i} \text{ (Replacement)}_i + C_4 \text{ (Maintenance)} \right]$$

where:

Capital = Initial capital investment (in price-year dollars)

Replacement = Periodic major replacement cost occuring at known interval, I, following year of first commercial operation (in price-year dollars)

Maintenance = Annual maintenance cost (in price-year dollars)

C_1 = Constant to convert year of first commercial operation dollars to base-year dollars

C_2 = Constant to convert initial capital expenditure (in price-year dollars) to year of first commercial operation annualized cost

$C_{3,i}$ = Constant to convert capital expenditure (in price-year dollars) at some interval I after year of

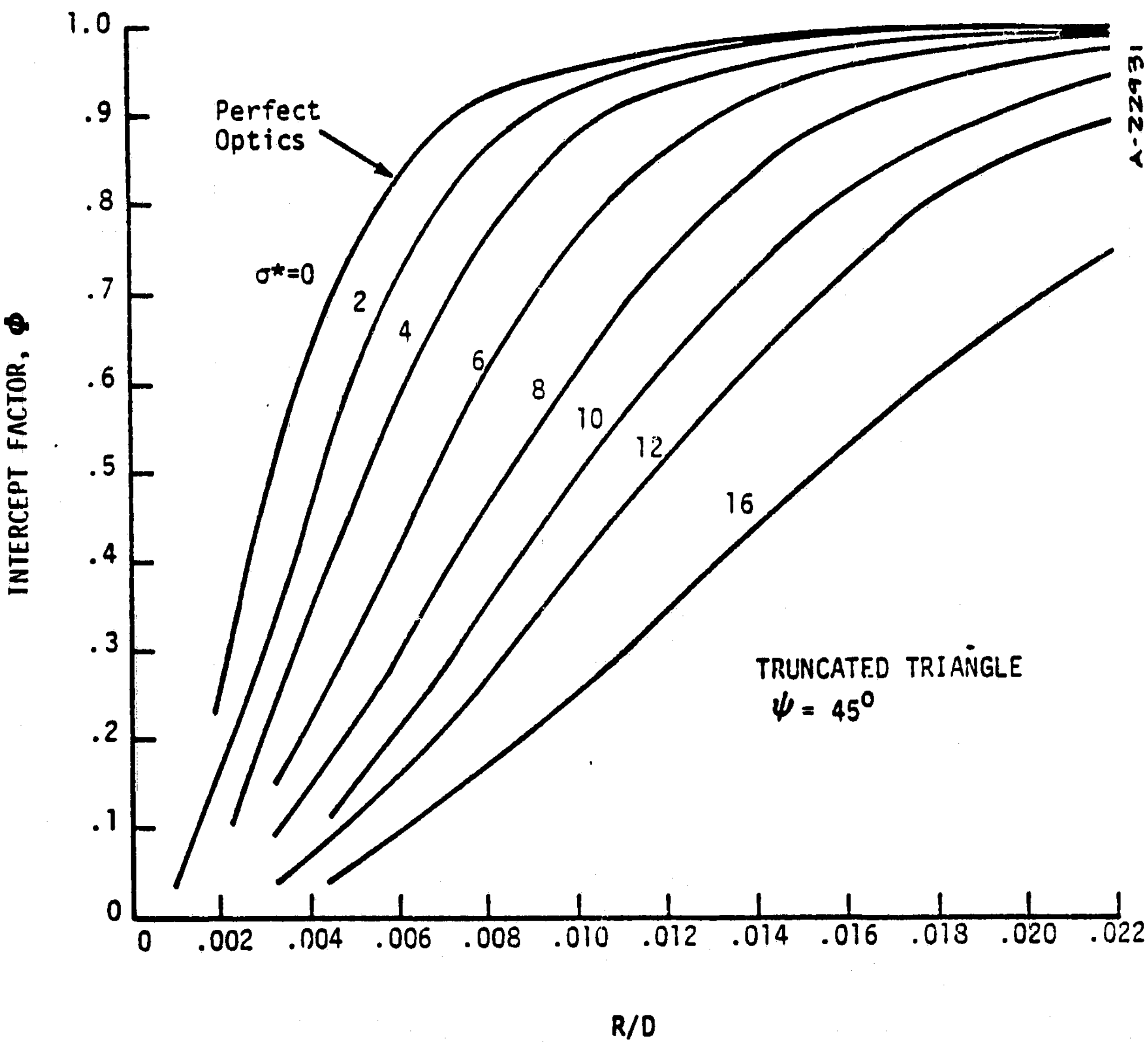

Figure 2-38. Variation of intercept factor with σ*.

first commercial operation to year of first commercial operation annualized cost

C_4 = Constant to convert annual maintenance expenditure (in price-year dollars) to year of first commercial operation annualized cost.

The appropriate values for constants C_1 through C_4 are listed in Table 2-9 along with the basic economic parameters (Reference 2-8) from which they were derived.

Busbar Energy Cost Model

The base year busbar energy cost, which represents the cost of delivered energy, was computed as the ratio of the base year annualized cost of installing and operating the concentrator divided by the annual net thermal output. All calculations were based on an assumed 3000 hours of annual operation with an incident beam radiation of 800 W/m^2:

$$\overline{BBEC}_{th(YB)} = \frac{AC_{(YB)}}{3000\ (\dot{Q}_{net}\ (800\ W/m^2))}$$

2.4.2 Parameter Review and Revision

This section provides an update of the design parameters, which were first presented in Task 1 (Reference 2-1). Based upon the results of the Preliminary Design, the values of certain parameters have changed. These changes occurred due to:

- Results of the panel fabrication and testing subtask
- Recent information on the optical properties of flex-glass
- Improved panel support structure.

As first outlined in Task 1, the design parameters are:

- Rim angle

TABLE 2-9. COST MODEL PARAMETERS

C_1 = 0.7107

C_2 = 0.2087

C_3 = f(I)

I	C_3
5	0.6972
8	0.4055
15	0.1367
25	0.1031
30	0

C_4 = 3.0385

YB = Base year = 1978

YP = Price year = 1978

YCO = Year of first commercial operation = 1985

N = System lifetime = 30 years

k = Discount rate = 8 percent

g = General escalation rate = 5 percent

g_c = Capital cost escalation rate = 5 percent

g_m = Maintenance cost escalation rate = 6 percent

FCR = fixed charge rate = 0.1483

CRF = Capital recovery factor = 0.08883

- Reflector backing material, as characterized by its macroscopic slope error
- Reflective material, as characterized by reflectance and specularity
- Structural member size, as characterized by deflection error
- Pointing accuracy
- Concentrator size

Table 2-10 presents a comparison of the Task 1 design parameter values with the updated Task 2 values. A discussion of the comparison follows.

<u>Rim Angle</u> (ψ)

The rim angle of the concentrator has been maintained at 45°. As shown in Reference 2-1, this is the optimum rim angle for the Acurex concentrator configuration, since it yields the smallest image on the focal plane, thus minimizing radiative losses at the receiver.

<u>Slope Error</u> (σ_s)

The results of the panel fabrication and testing subtask (Section 2.3) demonstrated that a slope error of 1.0 mrad (standard deviation) can be achieved for the flex glass/SMC reflective panels. This value is less than half that suggested in Reference 2-9 and used in Task 1.

<u>Reflectance</u> ($R_{s,2\pi}$)

The hemispherical reflectance of clean, low-iron flex glass is 95 percent, as in Task 1.

<u>Specularity</u> (σ_ω)

Conversations with personnel at Sandia Laboratories in Albuquerque have indicated that, within the tolerances of their equipment, flex glass is essentially 100 percent specular (i.e., has a low specularity, σ_ω).

TABLE 2-10. UPDATE OF DESIGN PARAMETER VALUES

Parameter	Task 1 Parameter Optimization	Task 2 Preliminary Design
Rim angle, ψ	45°	45°
Slope error, σ_s	2.4 mrad	1.0 mrad
Reflectance, $R_{s,2\pi}$	0.95	0.95
Specularity, σ_ω	1.1 mrad	<0.1 mrad
Structural deflection, σ_d	0.8-1.2 mrad	0.89 mrad
Pointing error, ε_p	3.5 mrad	3.5 mrad
Concentrator net aperture area, A_N	83.0 m^2	102.0 m^2

This differs from the information used in Task 1, which indicated that the standard deviation of the dominant specularity distribution was 1.1 mrad. In subsequent analyses, the latter value was determined to be a result of dust particles being trapped between the glass and the vacuum platen. The thin, flexible glass was conforming to the contours of the particles, and the resulting microscopic slope errors were mistaken for specularity errors.

Based upon the above findings, it is evident that back-silvered, low-iron flex glass gives the optimum combination of high reflectance and low specularity.

Structural Deflection (σ_d)

The convolved standard deviation of structural deflection for the optimized panel support structure (.81 mrad) and reflective panels (.36 mrad) is 0.89 mrad (see Section 2.2). This was within the range of optimum deflection determined in Task 1. It should be noted here that simultaneously doubling the slope error and structural deflection error values given in Table 2-10 results in a decrease in concentrator performance of only 6 percent.

Pointing Error (σ_p)

In both Tasks 1 and 2 the combined effect of positional tolerances (including receiver deflection) and tracker control limitations were assessed to be approximately 3.5 mrad ($\pm$ 0.2 degree). These errors are easily achievable with current drive and tracker technology.

Concentrator Net Aperture Area (A_N)

As indicated in Section 2.2, the reevaluation of the panel support structure required that a detailed optimization be performed on the space frame to determine both optimum member size and concentrator aperture size. For a given concentrator size, member sizes were selected which resulted in the lowest weight (and, therefore, lowest busbar energy cost), stress-limited design. This was done over a large range of concentrator aperture areas, for both the 22- and 33-panel configurations.

Figure 2-39 presents the results of the optimization. As shown on the figure, the concentrator size which gives a minimum cost of delivered energy has a net aperture area of 102 m^2 (33-panel configuration). This is a 23 percent increase over the Task 1 concentrator size.

It should be noted that the selected concentrator size is at the shipping limit for both the reflective panels and a shop-fabricated space frame. Increasing the size further would increase the number of panels, complexity of the panel support structure and number of field erection operations required.

2.4.3 Performance Summary

The updated values of the design parameters were input into the performance model described above to yield a net thermal output at the receiver aperture of 61.3 kW_{th}. This is based on

- 800 W/m^2 insolation
- 1700^{o}F receiver operating temperature
- 90 percent annual average reflectance
- National average wind distribution.

(Since deflection due to wind loading is about 12 percent of that due to weight, the output is decreased by only 0.2 percent at 30 mph). The above power output represents a 3 percent improvement in performance/unit area over the Task 1 value.

Given the above thermal output and the costs developed in Task 4 for a 100,000 unit/year production rate, the $\overline{BBEC}_{th}$ for the concentrator

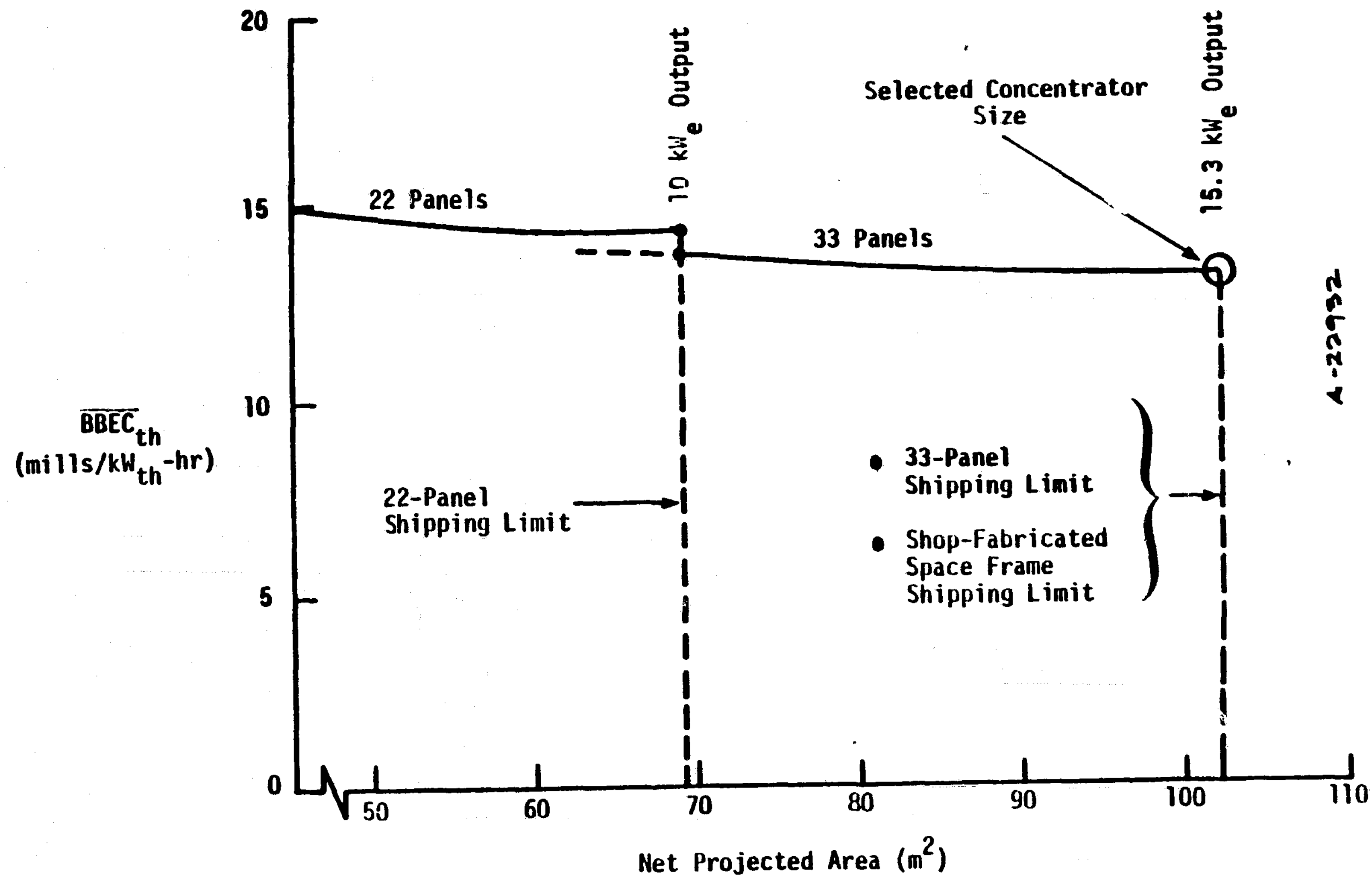

Figure 2-39. Selection of concentrator size.

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is 13.1 mills/kW_{th}-hr (based upon 3000 hour of annual operation). This represents a 41 percent reduction in the cost of delivered energy from the Task 1 value.

2.4.4 Receiver/Engine Modifications

One of the objectives of Phase I was to determine the effects on the concentrator design and performance of certain modifications to the receiver/engine package, in order to aid JPL in its Receiver Development Program. The two modifications, to be investigated separately, were

- Lowering the receiver operating temperature from 1700 to 1200°F
- Varying the receiver/engine weight.

Sections 2.4.4.1 and 2.4.4.2, respectively, describe the results of these analyses. Section 2.4.4.3 presents the conclusions.

2.4.4.1 Lower Receiver Operating Temperature

An analysis was performed to determine the impact on the concentrator design of lowering the receiver operating temperature to 1200°F in order to interface with a Rankine engine.

Effects

The effects of lowering the receiver temperature are

- Higher net thermal performance
- Possibility of further cost/performance trade-offs
- Reduction of $\overline{BBEC}_{th}$.

The higher net thermal output is a result of the lower radiation losses at the receiver, and a higher intercept factor, due to the increase in optimized aperture size. It should be noted, however, that overall concentrator/engine system performance may drop due to decreasing engine efficiency as temperature is lowered. Figure 2-40 presents plots of

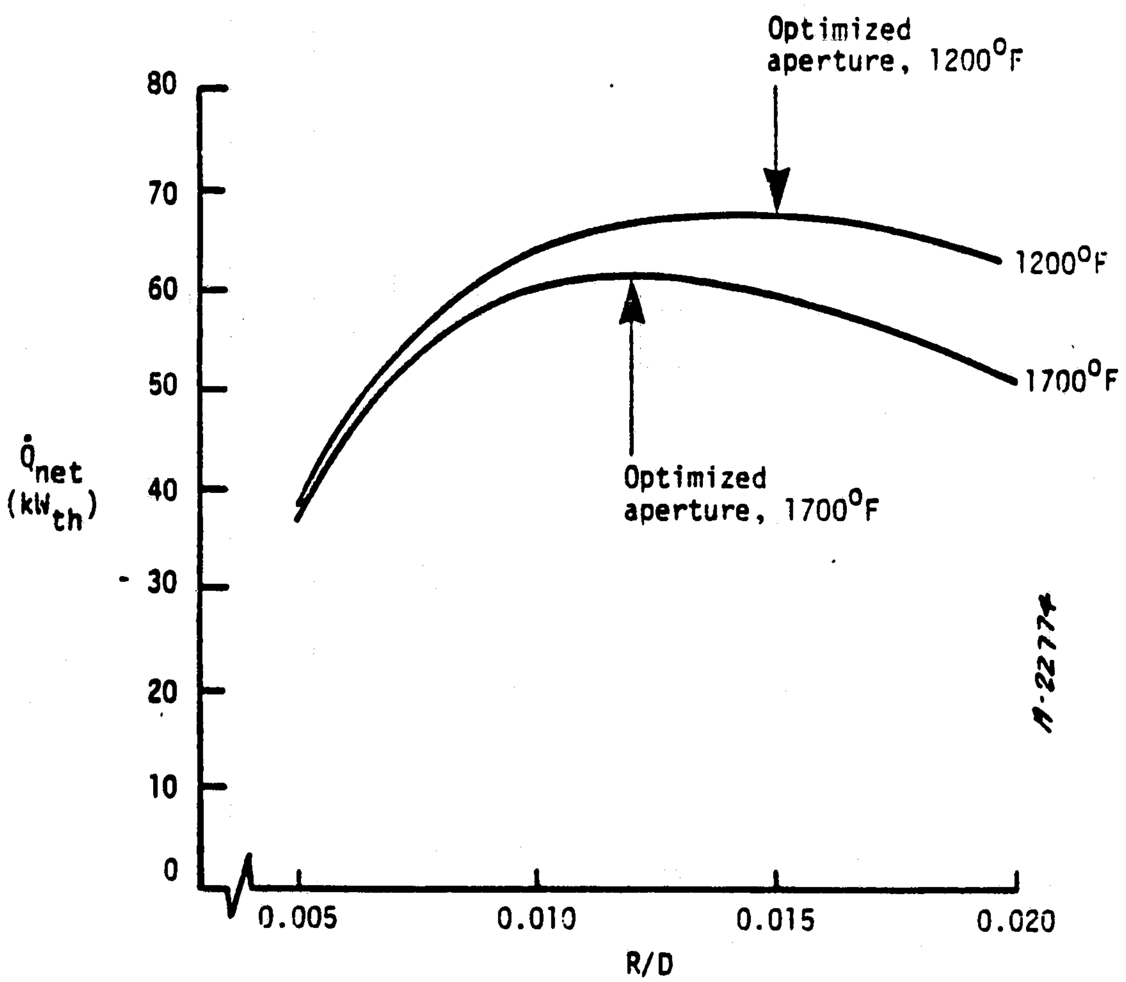

Figure 2-40. Effect of operating temperature on optimized receiver aperture.

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thermal output versus normalized receiver aperture size for operating temperatures of 1200 and 1700°F. As shown in the figure, the reduction in operating temperature yields a 25 percent increase in aperture which, in turn, gives an increase in intercept factor from 94.5 percent to 98 percent.

Since a higher thermal output is achieved by decreasing the receiver operating temperature, further cost/performance trade-offs might be indicated which could lead to further concentrator cost reductions. At the very least, the lowered temperature will decrease the $\overline{BBEC}_{th}$ (mills/kW_{th}-hr) due to the increase in thermal performance.

Analysis Approach

The approach taken to determine the cost/performance impact on the concentrator of lowering the receiver operating temperature was as follows:

1. Determine which components could be modified
2. Determine effect of modifications on $\overline{BBEC}_{th}$.

Each component of the concentrator was examined for possible cost reductions at the expense of increased errors. The effects of the identified modifications upon cost, performance and $\overline{BBEC}_{th}$ were then determined.

Results

It was determined that, due to the nature of the concentrator design, the lowered receiver operating temperature has negligible impact upon the design of the key components which impact overall performances:

- Reflective panels
- Space frame
- Tracker
- Drive

Additional weight cannot be taken out of the panels or space frame, since these components are stress-limited at the 100 mph wind survival condition. Increasing the deadband or backlash in the tracker and drive has negligible impact upon the costs of these units in mass production, since the accuracies assumed are readily achievable with current technology.

Based on this information, the performance of the concentrator was determined for the concentrator design at the lower receiver operating temperature, 1200^oF. At this condition, the net useful thermal power at the receiver is 67.7 kW_{th}, 10 percent greater than the output at 1700^oF.

The impact of the lower receiver temperature upon the concentrator cost is negligible. Due to the higher thermal output, there is an increase in receiver/engine weight of approximately 3 percent. The required weight increase of the structure carrying the receiver load (receiver support, base support and foundation) is, however, very small. It has already been indicated that the costs of the panels, space frame, tracker, and drive are also unaffected. Therefore, the decrease in cost of delivered energy, $\overline{BBEC}_{th}$, is due only to the increased thermal output at the lower temperature. For an operating temperature of 1200^oF, the $\overline{BBEC}_{th}$ is 11.9 mills/kW_{th}-hr.

2.4.4.2 Variation of Receiver/Engine Weight

The structural components which carry the receiver/engine package were designed based upon receiver/engine weights and dimensions furnished by JPL. The purpose of this subtask was to determine the sensitivity of the concentrator design and performance to receiver/engine weight. Two cases were investigated:

1. Receiver/engine weight 10 percent of furnished value
2. Receiver/engine weight 200 percent of furnished value

Effects

Because the receiver/engine weight is taken out from the receiver support through the base frame to the foundation, only these components are affected by changes in weight at the focal plane. A key consideration in the Acurex concept was to minimize the impact of receiver loads on the paraboloidal surface, thus ensuring a low weight structure with high accuracy. Neither the space frame, nor the panels themselves are affected by changes in receiver/engine weight.

Analysis Approach

The approach taken to determine the cost/performance impact on the concentrator of varying the receiver/engine weight was as follows:

1. Maintain structural deflection
2. Determine required change in receiver supporting structures
3. Determine cost impact of changes
4. Determine $\overline{BBEC}_{th}$

As mentioned above, the space frame and panels are not affected by loads at the focal plane. Therefore, the deflections of these components are unaffected, as is the performance of the concentrator (receiver support deflections are negligible relative to the other errors). The impact upon $\overline{BBEC}_{th}$ of varying receiver weight is then solely determined by cost variations.

Results

The results of the receiver/engine weight analysis are presented in Table 2-11. As shown in the table, the variation of receiver/engine weight from 86 to 1720 lbs results in an overall structure weight

TABLE 2-11. IMPACT OF RECEIVER/ENGINE WEIGHT VARIATIONS

Case	Receiver/Engine Weight (lbs)	Structure[a] Weight (lbs)	Capital Cost ($)	$BBEC_{th}$ (mills/kW_{th}-hr)
Baseline	860	14,760	12,946	13.1
10%	86	14,601	12,890	13.1
200%	1720	14,893	12,992	13.1

[a]Excluding foundation

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variation of only 2 percent and a capital cost range of slightly under 1 percent. Finally, the impact on $\overline{BBEC}_{th}$ is less than 1 percent. This indicates that the concentrator performance is very insensitive to variations in receiver/engine weight.

2.4.4.3 Conclusions

As shown in Section 2.4.3, reducing the receiver operating temperature below the 1700°F design point results in an increase in performance above 61.3 kW_{th}, due to lower radiative losses and a higher intercept factor. It was also shown that the only design impact of a lower operating temperature results from a slightly larger (and heavier) receiver/engine package, which is required to match the increased thermal output. Even significant changes in receiver/engine weight from the design value, however, have negligible impact upon the capital cost of the concentrator. This is due to the fact that the receiver/engine loads are taken out to the base and foundation, bypassing the performance-critical panel support structure completely. This information indicates that the concentrator is optimally designed for engines (i.e., Rankine) requiring temperatures below the design point (1700°F).

An equally important benefit of the concentrator design is that increases in operating temperature, up to some critical temperature above 1700°F, will likewise not impact the design. This is important, because, although concentrator performance decreases with increasing temperature, engines become more cost-effective. (The optimum concentrator/engine design point will have to be determined later in the Receiver Development Program.)

Figure 2-41 is a schematic representation of the effect of receiver operating temperature upon the optimized concentrator structural

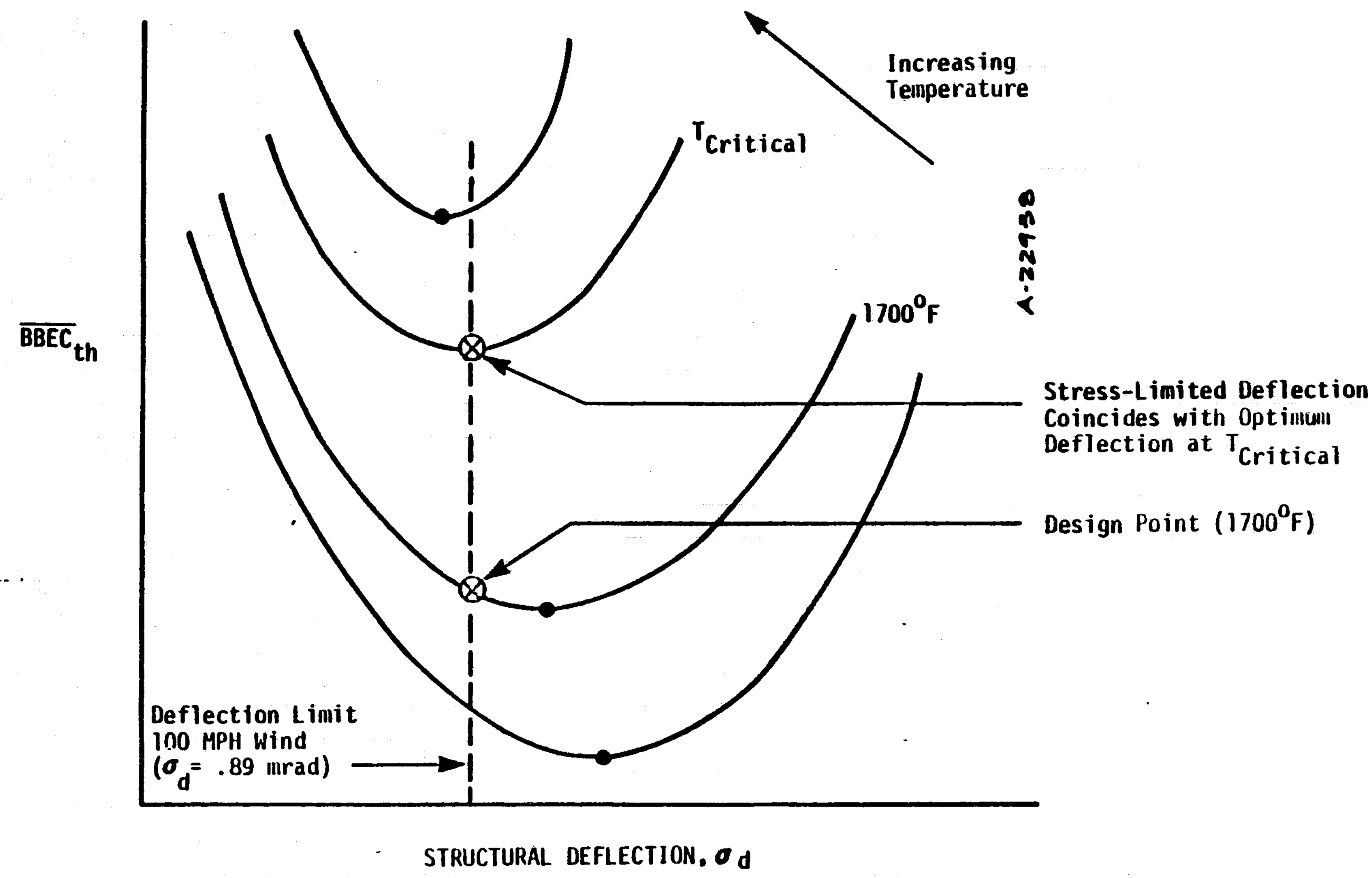

Figure 2-41. Effect of receiver operating temperature upon optimized structural deflection.

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deflection for the national average wind distribution (NAWD). Drawn on the plot is the 100 mph wind survival deflection limit (0.89 mrad). Note that the optimum deflection for the NAWD is greater than the deflection limit of 0.89 mrad until a critical operating temperature, $T_{CRITICAL}$, is reached. For any receiver operating temperature below $T_{CRITICAL}$, therefore, including the 1700^{o}F design point, the proposed concentrator design is optimal, given the 100 mph wind survival specification. Above $T_{CRITICAL}$, the optimum structural design would be heavier, allowing a smaller defection than the proposed design.

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SECTION 3

ASSESSMENT OF PRODUCTION IMPLEMENTATION

The primary objective of Task 4, Assessment of Production Implementation, was to estimate the levelized receiver energy cost for the Low-Cost Point-Focus Solar Concentrator for production rates from 100 to 100,000 units per year. This was accomplished via a detailed analysis of costs for mass-production, installation, and operation and maintenance. These costs were used to determine the levelized cost of thermal energy from the concentrator. The levelized thermal energy cost is expressed as the levelized Busbar Energy Cost, $\overline{BBEC}_{th}$ (in mills/kW_{th}-hr). In computing the $\overline{BBEC}_{th}$, all costs accrued over the life of the concentrator are accounted for and levelized to allow for the time value of money.

The following sections present the efforts conducted under this task. The first section describes the costing methodology used. The next three sections detail the development and costing of the production, installation, and operation and maintenance plans. Finally, the costs are summarized and $\overline{BBEC}_{th}$ values are presented.

3.1 COSTING METHODOLOGY

This section reviews the methodology followed in developing costs for implementation of the concentrator. The general costing methodology is presented, and the procedure by which the developed costs are scaled to other production rates is discussed.

3.1.1 Overview of Costing Methodology

The basic method used in determining costs was a bottom-up approach. The various components of the concentrator and field activities were divided into small elements so that an accurate cost determination for each element could be made.

In order to track each element of the cost a Cost Breakdown Structure (CBS) was used. The CBS divides the overall costing into smaller components and activities and assigns numbers to them. The seven major CBS elements and their CBS numbers are:

- 1000 - Reflective Panels
- 2000 - Drive Subsystem
- 3000 - Control/Electrical Subsystem
- 4000 - Raised Track
- 5000 - Structure
- 6000 - Installation
- 7000 - Operations and Maintenance

All costs are accounted for by CBS element. The detailed list of CBS elements is given in Table 3-1.

Within each CBS element costs are accrued in the areas of :

- Direct Labor
- Materials
- Tooling and Equipment
- Indirect costs

For instance, in order to produce the reflective panels (CBS 1000), a certain number of direct labor hours and a certain amount of materials

TABLE 3-1. COST BREAKDOWN STRUCTURE

Subsystem	Assembly	Subassembly	Component
1000 Reflective Panels	Panel Type 1 (6 req.)	--	1001 Glass mirror
	Panel Type 2 (6 req.)		1002 Sheet molding compound
	Panel Type 3 (6 req.)		1002 Attachment hardware
	Panel Type 4 (3 req.)		
	Panel Type 5 (3 req.)		
	Panel Type 6 (3 req.)		
	Panel Type 7 (6 req.)		
2000 Drive System	2100 Azimuth drive	--	2101 Hydraulic rotary actuator
			2102 Collar
	2200 Elevation drive	--	2201 Hydraulic single stage cylinder
			2202 Clevis bracket
	2300 Support wheels	--	2301 Steel wheels w/sealed bearings
	2400 Hydraulic power	--	2401 Pump/motor unit
			2402 Accumulator
3000 Controls/ Electrical	3100 Tracker	3110 Sun sensor	3111 Two axis sun sensor
		3120 Position sensing	3121 Position potentiometers (2)
		3130 Micro-computer	3131 Electronics
			3132 Enclosure
	3200 Hydraulic control	--	3201 Solenoid control valves (3)
			3202 Stow control cam valve
			3203 Valve block
			3204 Hydraulic lines (6)
	3300 Electrical	3310 Power out	3311 Cable
			3312 Fused disconnects (2)
		3320 Power in	3321 Cable
			3322 Fused disconnect
		3330 Control in/out	3331 Cable
		3340 Cabling interface	3341 Flex conduit
			3342 Flex conduit connectors
		3350 Lightning protection	3351 Lightning arrestor
			3352 Ground straps (panel support to base support)
			3353 Ground rod
			3354 Cable

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TABLE 3-1. Continued

Subsystem	Assembly	Subassembly	Component
4000 Raised Track	4100 Track	--	4101 Track sections 4102 Mounting plates
5000 Structure	5100 Panel support	5110 Side truss (3) 5120 Interior truss (3) 5130 Corner truss (3) 5140 Loose members	5101 Steel tubing
	5200 Base support	5210 Front truss 5220 Side truss (2) 5230 Interior truss (2) 5240 Loose members	5201 Steel tubing
	5300 Receiver support	5310 Loose members 5320 Receiver mount	5311 Steel tubing 5321 Steel plate

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TABLE 3-1. Continued.

Task	Sub-Task	Activity	Sub-Activity
6000 Installation	6100 Site preparation	--	6101 Clear and grade 6102 Layout foundations 6103 Prepare work area 6104 Setup tooling 6105 Setup shelter 6106 Move on
	6200 Foundation installation	6210 Pier installation	6211 Bore pier holes 6212 Install rebar cages 6213 Install forms 6214 Align studs 6215 Pour concrete 6216 Clean up and move on
		6220 Track installation	6221 Mount track segments 6222 Level segments 6223 Torque attach bolts 6224 Grout
	6300 Concentrator assembly and installation	6310 Base support frame assembly and installation	6311 Assemble subtrusses 6312 Install hydraulic components 6314 Transport to foundation and hoist onto track 6315 Adjust rotary actuator mounting bolts 6316 Grout
		6320 Reflector assembly and installation	6321 Assemble panel support structure 6322 Install interior reflective panels 6323 Assemble receiver support 6324 Attach receiver support to reflector 6325 Install exterior reflecting panels 6326 Install electical components 6327 Install tracker and sensors 6328 Transport and install on base
	6400 Adjustment and checkout	6410 Panel alignment	6411 Mount target to receiver 6412 Mount scope 6413 Adjust panel

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TABLE 3-1. Concluded

Task	Sub-Task	Activity	Sub-Activity
		6420 Drive adjustment	6421 Connect field power
			6422 Adjust tracking and stow rates
			6423 Adjust sun sensor and tracker
7000 Operations and maintenance	7100 Scheduled maintenance	7100 Reflective panels	7111 Cleaning
		7120 Drive system	7121 Fluid and filter replacement
		7140 Track	7141 Painting
		7150 Structure	7151 Painting
	7200 Unscheduled maintenance	7210 Reflective panels	7211 Panel replacement
		7220 Drive system	7221 Azimuth drive replacement
			7222 Elevation drive replacement
			7223 Support wheel replacement
			7224 Pump/motor replacement
			7225 Accumulator replacement
		7230 Control/Electrical	7231 Microprocessor replacement
			7232 Hydraulic valve replacement
			7234 Flexible hydraulic lines replacement

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are required. In addition these laborers use special tooling and equipment whose cost must be amortized over the number of concentrators produced. And finally there are certain indirect costs such as management, supervisors, inventory, facilities, etc. Thus, the CBS is used to divide the overall system into small enough elements that the direct labor, material, tooling, and indirect costs can be accurately determined for each element.

Once the cost of each CBS element is determined the costs are used to calculate the annualized life cycle cost of the concentrator ($/unit/year). The annualized cost is then combined with the concentrator's thermal performance (kW_{th}-hr/year) to determine the levelized cost of thermal energy expressed as the levelized Busbar Energy Cost, $\overline{BBEC}_{th}$ (mills/kW_{th}-hr). This entire procedure is summarized schematically in Figure 3-1.

In performing the cost analysis, 1979 dollars were used. Further, no fee (profit) or G&A (corporate and selling expense) costs were included, as fee and G&A are dependent on the type of corporation conducting the business and the marketplace and not on the cost of the particular concentrator design. Typical values of fee plus G&A at large scale production range between 6 and 10 percent.

Also, each production plant was assigned a 100 mile radius area for fields installation. Each plant will be located at the center of the area in which it is to install fields. This applies at the larger production levels as multiple plants will be built. The size of each collector field was assumed to be 100 concentrators which gives a nominal electrical output of 1.5 megawatts.

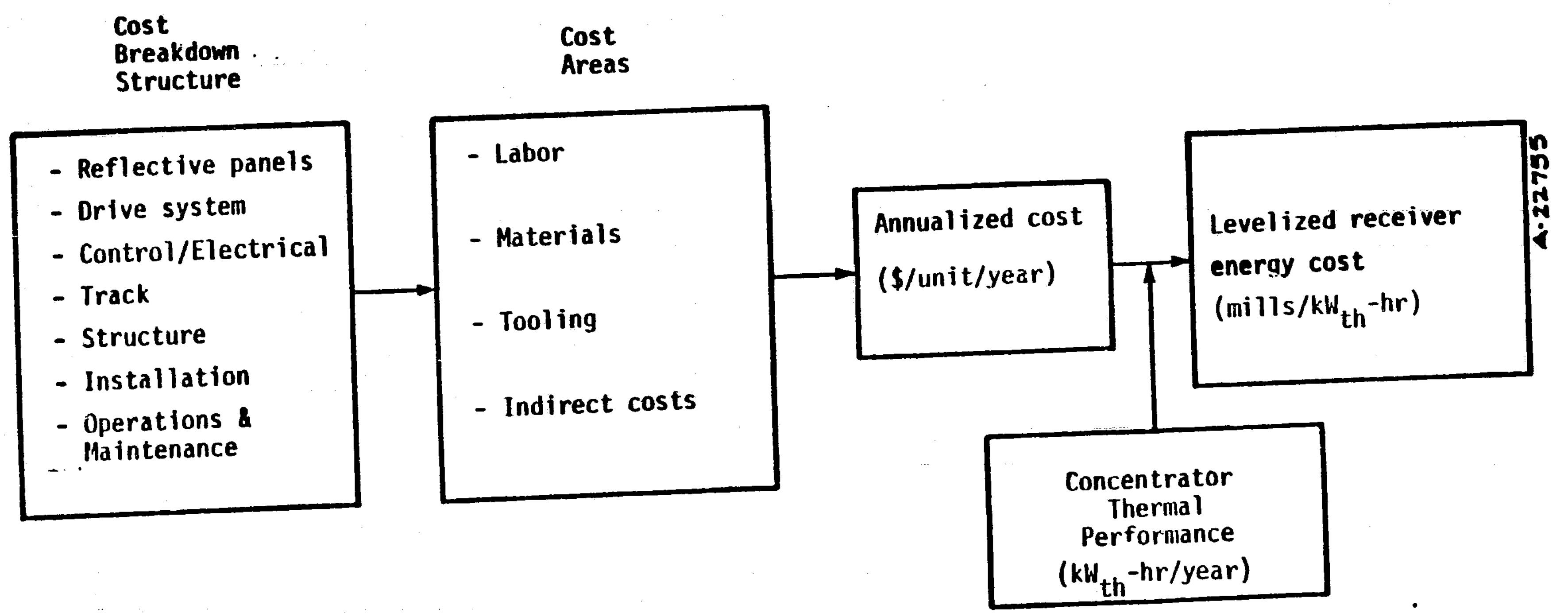

Figure 3-1. Overview of costing methodology.

3.1.2 Cost Scaling

The detailed production and cost analysis described above was performed for the "critical" mass production rate. The "critical" mass production rate is defined as the smallest rate at which labor and tooling for mass production may be used to maximum efficiency. To determine costs for other higher and lower production rates, a cost scaling approach has been developed. (In typical production planning, scaling refers to adjustments for non-variable costs only. However, in this report, scaling will refer to adjustments for production rate changes in all costs.)

Figure 3-2 shows a general application of cost scaling for various production rates. As the figure shows, the production plan was developed for a certain "critical" production rate. There exists such a "critical" production rate because there is a minimum rate at which the type of processes and operations used in mass production can be used to full efficient capacity. For example, the plastic presses which are required will have capacity which will be unused at lower production rates.

As the figure shows, different scaling relationships are applied for production rates higher and lower than the "critical rate". Also, as the figure shows, there exists a sinusoidal-like variation in costs at higher production rates. This is due to the fact that as production rate increases, a noninteger number of plants are required and plants are used at over or under efficient capacity.

The scaling to lower production rates is based on the assumption that there is little reduction possible in the tooling necessary to accomplish the specified processes. Therefore, there will be little reduction in costs for tooling, indirect labor, and the facility. This

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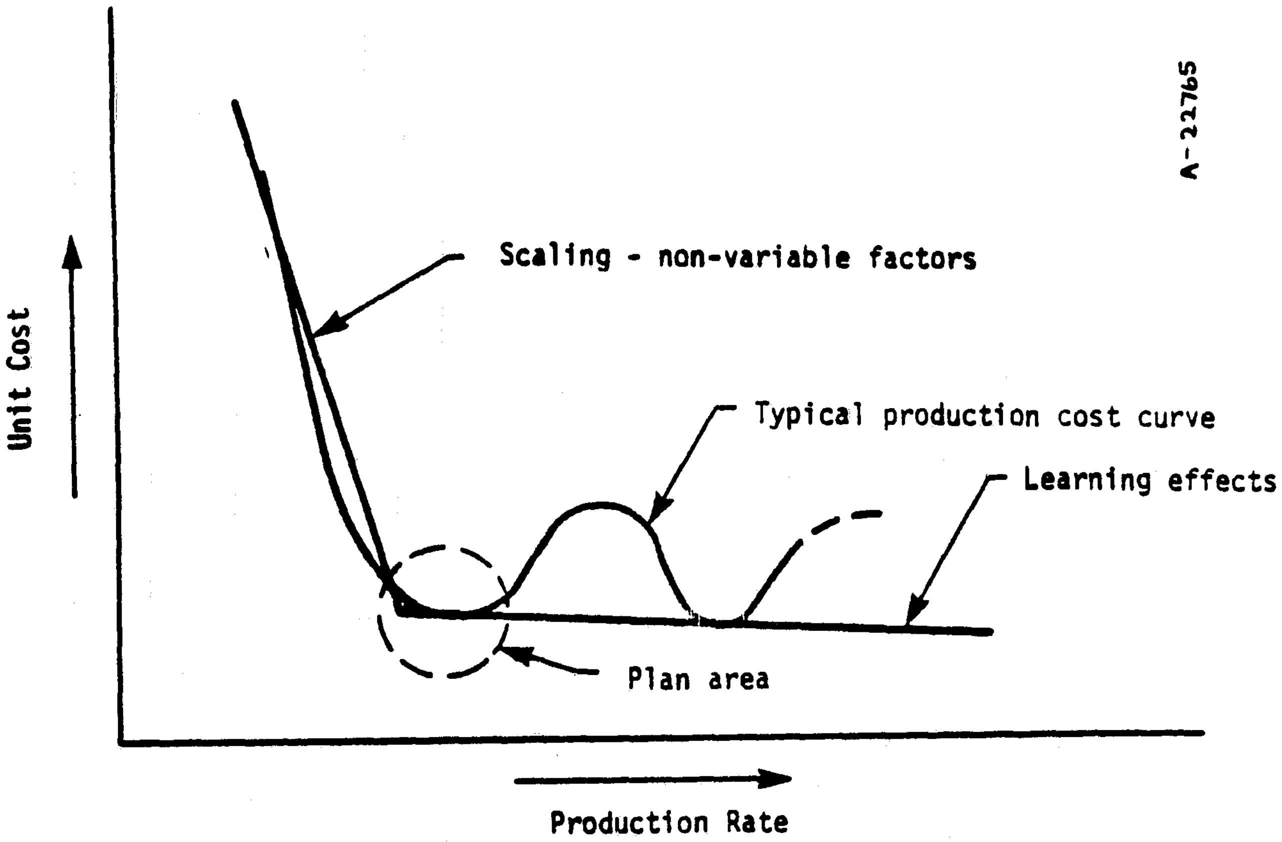

Figure 3-2. Cost scaling with production rate.

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results in a large increase in total cost per unit as production rate is decreased.

Direct labor input per unit also will increase as production level decreases due to learning effects and inefficiencies in operation of the plant at lower than optimum rates. Also, material cost increases will be seen as the plant purchases decrease.

To account for these cost increases, a learning curve type cost adjustment is used for scaling to lower rates. For labor, an 85 percent learning curve was applied. 85 percent is a typical value from industry for mass production processes. The curve is applied via the equation:

$$\text{Cost @ X/year} = \text{Cost @ Y/year} \left(\frac{Y}{X}\right)^{\frac{-\log .85}{\log 2}}$$

The material cost reduction curve is applied via the same equation, with a 95 percent curve. This value is based on industry experience and reflects the mix between raw materials and purchased parts and is validated by vendor quotes obtained during this effort.

These curves and the resulting general scaling factors will be applied to the scaling to lower production rates. However, there exists many specifics in the application of these curves to the detailed production plan and these specifics will be covered in the sections in Section 3.2 on the costing of those plans.

Scaling to higher production rates is based on a combined learning/material curve factor which assumes that as successive optimum plants are built, experience will yield moderate improvements in utilization of labor, tooling, and the facility. Also, material cost reductions will be experienced as production rate increase continues. Therefore, to scale to higher rates, a 95 percent curve for all costs will be applied.

3.2 PRODUCTION PLAN

A production plan is required in order to establish the costs to manufacture the Low-Cost Point-Focus Solar Concentrator. The following sections present this plan. Section 3.2.1 shows the general production plan, addressing the facilities which will be required and the overall flow of purchased parts and fabricated assemblies to the site. Following are the detailed production plans for the reflective panels and the structural steel assemblies and the purchasing plan for the drive and control/electrical components.

3.2.1 General Production Plan

The general production plan shows the overall approach to mass production fabrication and purchasing for this concentrator design, based on the detailed plans presented in the following sections. This general production plan and material flow is shown schematically in Figure 3-3. In this plan, the reflective panels, structural assemblies, and control microprocessor are manufactured in individual plants. Purchased components for the drive and control/electrical systems are shipped directly to the field.

The following sections present the detailed production and purchasing plans.

3.2.2 Reflective Panels Production Plan

This section presents the production plan for the reflective panels (CBS 1000) and develops the material, labor, tooling, and facility costs for manufacture of the SMC panels.

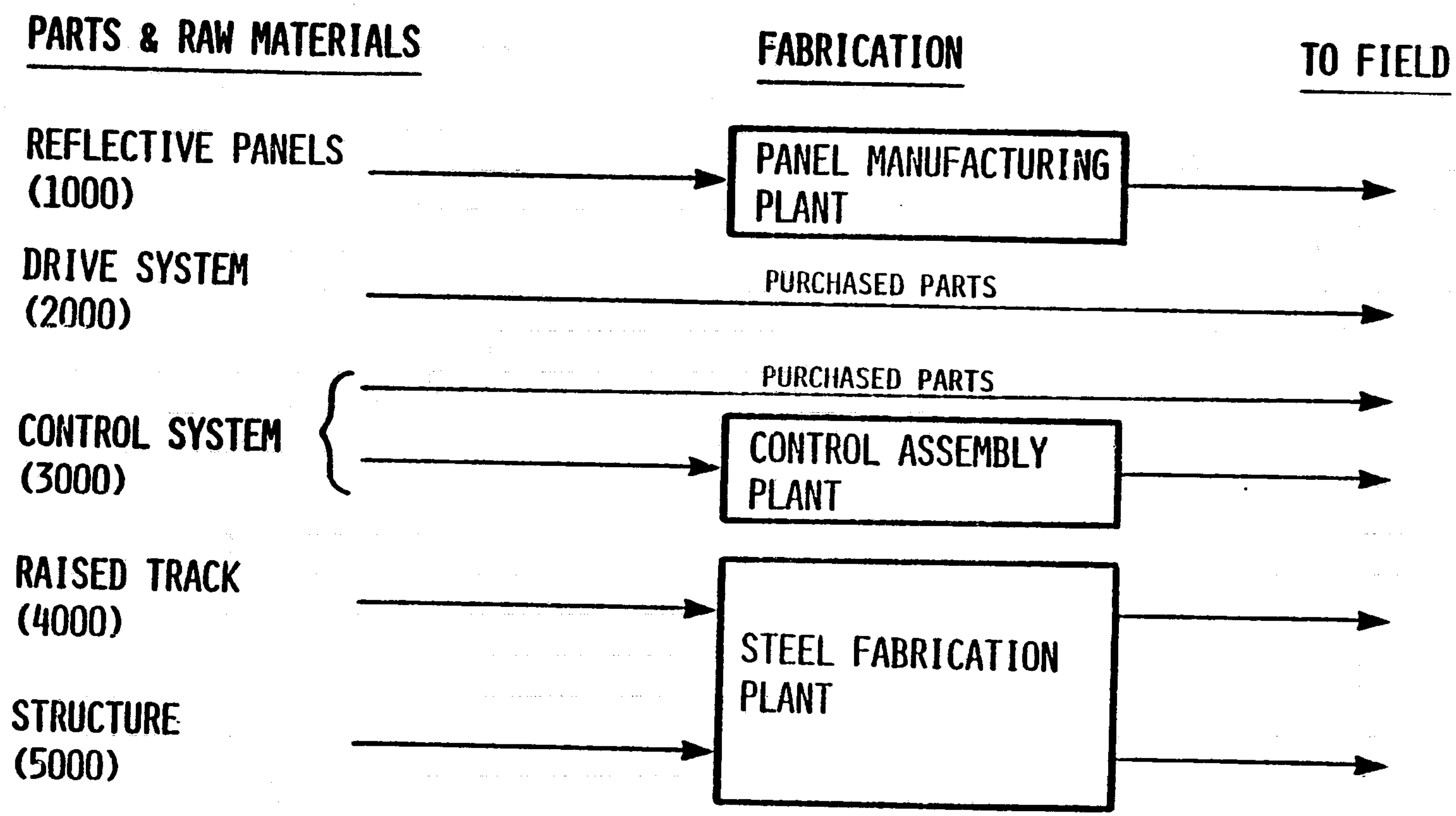

Figure 3-3. General production plan and material flow.

In this plan, it is expected that this operation will be housed in a separate manufacturing plant. The facility requirements for plastic panel fabrication are distinct from those required for structural steel fabrication, and it is expected that there would be no gain in housing both operations in the same facility.

The panels to be produced by this facility are characterized as follows (see Figure 3-4):

- 33 panels per concentrator
- 7 panel configurations
- 6 each of 4 types, 3 each of 3 types
- Panel construction: Flex glass mirror with sheet molding compound (SMC) backing and attachment hardware
- Panel dimensions: Nominal 9' equilateral triangle, approximately 2.5" thick isogrid

Concentrator assembly refers to the complete set of panels for one concentrator. Panel assembly refers to one mirror/SMC panel.

The following sections present the work performed in developing the detailed production plan for the panels. The make or buy analysis and materials requirements are described first, then the process outline, output rate balance, and tooling requirements are presented. Requirements for direct and indirect labor and other indirect costs are developed next and finally, a cost summary is presenced for the reflective panel manufacture.

3.2.2.1 Make-or-Buy Analysis

For this type of conceptual manufacturing planning, the make-or-buy analysis reviews the options for purchase or fabrication of assemblies,

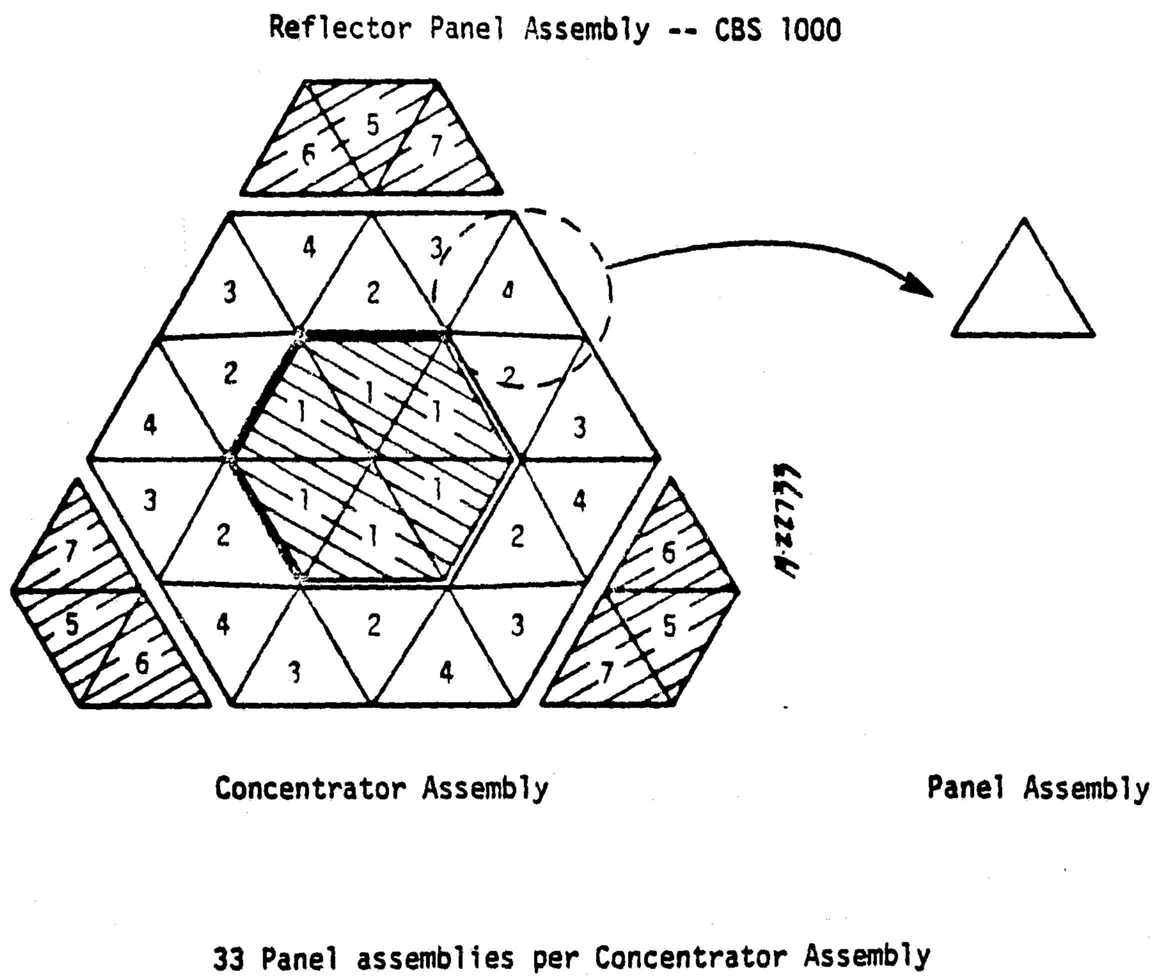

Figure 3-4. Reflective panel requirements.

subassemblies, and components and selects the general purchasing/ manufacturing approach to be used.

For the main assembly and each of its components, there are three primary considerations used to determine the make or buy decisions. First, is there an outside supplier who can produce the item and provide a credible quote? Second, is the technology to produce the item available? It may not be available due to its proprietary nature or lack of readily available experience or information to predict the cost and ultimately produce the item. Third, are there positive investment economics to produce the item in-house? Using these three considerations, a detailed make or buy analysis will produce a conceptual purchasing/manufacturing plan which minimizes cost and risk.

For the reflective panels, the make-or-buy analysis was conducted using these considerations and the decisions are presented in Table 3-2. These decisions are used as the basis to develop the material requirements and production processes described in following sections.

Given that SMC is the major cost component of the panel, it is appropriate to more closely consider its make-or-buy decision. Since production of SMC for input as a raw material can be considered separately from the panel production, a separate production plan and cost estimate for the SMC was prepared.

Most volume users of SMC make their SMC in-house. (This means in-house production from purchased resins, glass fibers, fillers and additives as opposed to purchase of SMC sheets in rolls.) Conventional practice maintains that once a molder requires 1/2 to 1 million pounds per year of SMC, it is cost effective to "make" it. Molders who make their own SMC include General Motor's Oldsmobile Division, who reportedly has

TABLE 3-2. PANEL ASSEMBLY MAKE-OR-BUY DECISION

Material	Cost per Assembly	Outside Supplier	"Make" Technology	Investment Economics	Make or Buy
Panel Assembly	N/A	No	Yes	Yes	M
Glass mirrors	$28	Yes	No	Unknown	B
SMC	50	Yes	Yes	Yes	M
Primer	1	Yes	No	No	B
Attach hardware	5	Yes	Yes	Unknown	B
Package material	8	Yes	Yes	Unknown	B

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one of the most modern SMC lines in the U.S. and White Truck, who makes a molding in excess of 100 pounds for a truck-tractor tilt-cab*.

Other than the reduction of direct costs, there are other benefits. With in-house SMC production, more "tailoring" through additives and constiuent ratio variation can be accomplished to enhance the molding characteristics and reduce scrap losses. The SMC can consequently be made "hotter" (cure faster) since shelf stability, which suffers with shorter curing material, is less a consideration when in-house SMC production can be keyed to in-house demand for SMC.

There is considerable experience and technology available for establishing an SMC production line. Five companies in the U.S. manufacture and sell SMC production machines. Companies which produce resin, which is the most important and highest technology element of SMC, offer a great deal of technical support for an SMC facility.

The two primary elements in SMC are the polyester resin and the fiber glass. Prices are approximately $0.40/pound and $0.45/pound respectively. Fillers, which cost approximately $0.02/pound, constitute a significant fraction of SMC. The fractional material cost of the SMC is:

				$/lb
Resin	45% b/w @ $0.40/lb		=	$0.18
Glass	35% b/w @ 0.45/lb		=	0.16
Filler	20% b/w @ 0.02/lb		=	0.01
		Material cost		$0.35
Allowance for additives to match glass thermal expansion				$0.10
		Material Cost		$0.45/lb

*This compares to a reflective panel weight of 94 lbs. SMC.

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Direct labor to produce the SMC is estimated to add approximately $0.05/lb. to the cost. Utilizing $4.00/hr labor, as the panel facility does, this is equivalent to 80 lbs/man hr. Overhead for supervisorial labor, facility, and equipment should be $0.10/lb. or 200 percent of direct labor. Scrap and waste should add $0.05/lb. or approximately 10 percent.

Using these values, the costs are:

	$/lb
Material	0.45
Direct labor	0.05
Overhead	0.10
Scrap and waste	0.05
Total	0.65

This cost of $0.65/lb. compares conservatively with costs experienced by other firms producing SMC for in-house use. This also is a significant cost reduction over purchased SMC which for this application would be $1.00 to $1.10 per pound.

3.2.2.2 Production Process and Output

Having determined which items to buy and which to make, the next step in production planning is to develop a production process. The process we have developed for fabrication of the reflective panels is shown in Figure 3-5. The fabrication process consists of the following steps:

1. Prep mirror for bonding -- In this step the mirror will be cleaned and prepared for application of an adhesive primer.

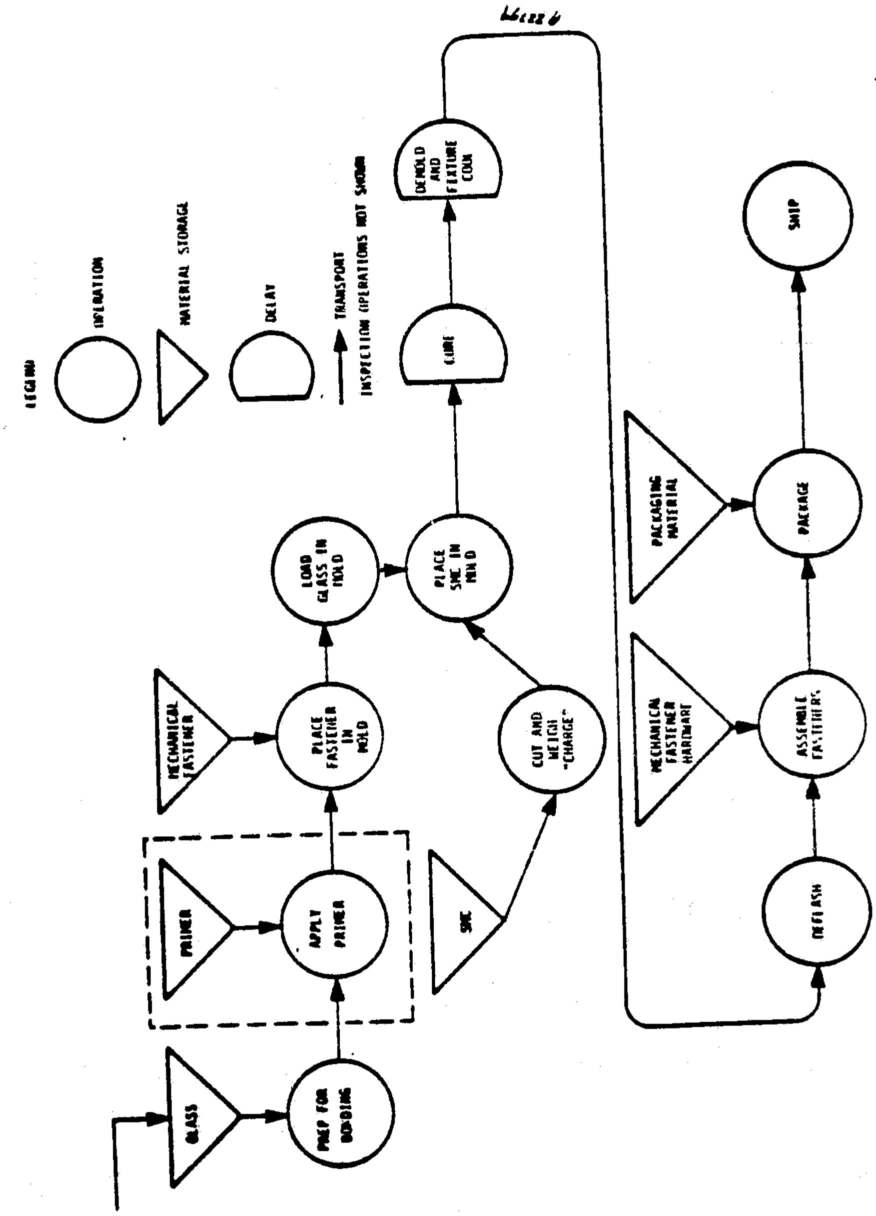

Figure 3-5. Production process-reflective panels.

2. Apply adhesive primer -- The low viscosity liquid primer will be applied to the bonding surface of the mirror with an airless sprayer, or by paint roller.
3. Cut and weigh SMC charge -- Using a "spreading" machine, separating material will be stripped from the SMC stock, and the sheet will be stacked and cut to length. The "charges" will be weighed and make-up material added to bring the charge weight into the acceptable range.
4. Load mold -- The mirror will be placed in the mold using mechanical handling equipment.
5. Place fasteners in mold -- The inserts to which the attachment hardware will mount are placed in the mold for integral molding into the back of the panel assembly.
6. Load SMC in mold -- Using handling equipment the SMC will be placed in the mold.
7. Cure -- The press containing the male/female metal mold will be closed and the panel will cure due to the application of the mold heat.
8. Demold -- The bonded and molded panel will be removed from the mold, placed in a fixture to maintain configuration, and allowed to cool.
9. Deflash -- The rough edges will be smoothed.
10. Assemble -- The unit will be assembled to the attachment hardware.
11. Package -- The unit will be packaged.

Calculation of Optimum Production Rate

As explained in Section 3.1.3, on cost scaling, there exists a facility which is the lowest production rate plant in which the tooling for a particular process is used to full efficient capacity. This concept is called the minimum size optimum facility. The following section develops the output rate for this facility for the reflective panels production process.

The critical element in this process is the molding operation utilizing the panel molding press. Using the press cycle time, optimum number of presses, and plant/personnel capacity factors, the output rate and optimum plant capacity is calculated.

Each of the panels is fabricated in a molding process at a rate of about 10 pieces per hour, or a cycle time of six minutes. There are seven panel configurations and an assembly requires 33 panels. Three configurations are used three times each while four configurations are used six times each. Therefore the minimum number of required press work stations is seven. However, to achieve full utilization of the press equipment, there should be two presses each for the panels used 6 times per assembly and one press each for the panels used 3 times per assembly. Therefore an efficient size plant requires 11 presses.

The capacity of the plant is developed based on these factors:

Number shifts per day	3
Days per year	250
PF&D* factor	88%
Plant capacity factor	88%

*Personal, fatigue, and delay

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Number of presses	11
Scrap factor	2%
Cycle time	6 minutes

Using these factors, the facility output rate is:

500,000 panel assemblies per year or

15,000 concentrator assemblies per year

Finally, a station balance analysis is performed to determine the number of stations required for the remaing operations and therefore the tooling and direct labor requirements and costs. The station balance uses information on the output of the various operations, which is shown in Table 3-3.

3.2.2.3 Materials Requirements and Costs

The detailed results of the materials requirements analysis for the reflective panels are shown in Appendix A (Table A-1). Overall, the total cost of materials, including scrap, yield losses, and freight to site is \$3150 (\$31/m^2) per concentrator assembly and \$95 per panel.

The initial unit requirements per concentrator are derived from the design information. Yield and scrap factors are used when applicable; yield covers normal process waste such as SMC "flash" during panel molding, scrap covers breakage and damage of components during production. These are applied to determine the total material required per concentrator produced. Cost per unit and freight cost are applied to determine the total material cost per concentrator.

3.2.2.4 Tooling Requirements and Costs

The detailed results of the tooling requirements analysis are shown in Appendix A (Table A-2). The amortized cost of tooling for the panels is \$145.50 (\$1.43/m^2) per concentrator or \$4.40 per panel.

TABLE 3-3. OPERATIONS OUTPUT -- REFLECTIVE PANELS

Operation	Cycle Time	Number Men Required	Pieces per Shift
Prep and prime glass	6 minutes	2	70
Prepare SMC charge	2 minutes	6	210
Load glass Load SMC Mold Demold } Press	6 minutes	2	70
Cool	6 minutes	Included above	Included above
Deflash	4 minutes	2	105
Mechanical assembly	8 minutes	2	52

The tooling cost is determined using the results of the station balance to establish the number of stations required and engineering estimates of the cost of the tooling required.

3.2.2.5 Direct Labor

The work stations are man-loaded to yield the direct labor requirement. The labor requirements and costs for the panel work stations are shown in Appendix A (Table A-3).

The man-loadings per station from Table 3-3 and the number of stations from the tooling requirements table determine the labor requirements. The men per operation per shift is calculated and therefore the man-hours per concentrator per operation is determined. This is used to calculate the labor cost.

The labor required in the plant will be unskilled, earning \$4 per hour. Total direct labor cost will be \$370 ($3.63/m^2$) per concentrator or \$11 per panel.

3.2.2.6 Indirect Costs

Indirect costs are those which are not assigned directly to the production of the panels but will instead be applied as an overhead factor to the direct labor. These costs are for variable and non-variable indirect labor, inventory, fringe benefits, facility, process energy and indirect materials. The costs developed here are then used to calculate a net overhead rate to be applied to the direct labor.

Indirect labor includes variable and non-variable categories.

- Variable Indirect Labor

  This category accounts for engineering and supervisorial personnel whose level of staffing is proportional to the production rate and direct labor required. The staffing is

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primarily based on industry rules of thumb. Table 3-4 shows the variable indirect labor requirement. The cost is $1,170,000 per year or $78 per concentrator assembly.

- Non-Variable Indirect Labor

  This category develops the costs for plant management and facility maintenance which do not vary as production rate varies. These requirements, also based on industry rules of thumb, are shown in Table 3-5. The cost is $600,000 per year or $40 per concentrator assembly.

Inventory

Inventory cost accounts for the expense of maintaining inventory at the plant. This cost includes the cost of money, spoilage, and shrinkage and is estimated to be 1.5 percent a month or 18 percent a year. Table 3-6 shows the inventory cost development. The inventory cost is $477,000 per year ($32/concentrator).

Fringe Benefits

Fringe benefits are estimated to be 21 percent of the total payroll. This includes insurance, tax payments, holidays, vacations, etc., and is applied to variable and non-variable payroll.

Facility

The facility space requirements and costs for the panel production plant are developed in Table 3-7. The total space requirements are 80,105 ft^2. For a plant of this size and type, the gross rent is about 35¢/ft^2/month. The facility cost is therefore $336,000 per year.

Process Energy Requirement

The gross rent includes the cost of utilities for normal plant functions, lighting, hot water, etc. However, significant additional

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TABLE 3-4. VARIABLE INDIRECT LABOR -- PANEL ASSEMBLY

Category	Number Required	Annual Pay Rate ($ 000)	Total ($ 000)
Foremen	12	16	$ 192
General Foreman	3	22	66
Superintendent	1	30	30
Quality Assurance Manager	1	30	30
Quality Assurance Engineer	2	25	50
Project Engineer (DES)	1	28	28
M & P Engineer	1	25	25
Manufacturing Engineer	2	25	50
Inspectors	30	13	390
Planner MCO/PCO	2	18	36
Expediter MCO/PCO	9	13	117
Tool Maintenance	6	16	96
Nurse -- First Aid	3	20	60
TOTAL			$1,170

Cost per concentrator assembly = $78

TABLE 3-5. NON-VARIABLE INDIRECT LABOR -- PANEL ASSEMBLY

Category	Number Required	Annual Pay Rate ($ 000)	Total ($ 000)
Plant Manager	1	42	$ 42
Engineering Manager	1	35	35
Personnel Manager	1	28	28
Personnel Clerks	1	30	30
Accounting Manager	6	15	90
Accounting Clerks	3	13	39
Cost Accountant	1	23	23
Purchasing Agent	1	25	25
Purchasing Clerk	3	14	42
Shipping/Receiving Clerk	6	14	84
Stockroom Clerk	3	13	39
Facility Maintenance	5	14	70
Secretaries	4	13	52
TOTAL			$ 599

Cost per concentrator assembly = $40.

TABLE 3-6. PANEL INVENTORY COST

	Inventory[1] Held	Value ($1,000)
SMC	1/2 month	$1,045
Mirror	1 month	1,148
Primer	1 month	60
Attachment	1 month	219
Package	1/2 month	176
Total Inventory Value		$2,648
Inventory Cost @ 18%		$ 477

[1]In terms of months of stock at the 15K/year rate.

TABLE 3-7. SPACE REQUIREMENTS -- PANEL FACILITY

CATEGORY	RATIONALE	SPACE REQ. (ft^2)
Production	• See Table 3-8 • Based on tooling requirements	14,830
SMC & primer storage	• 2 weeks SMC production /2.2 million pounds • Density approximately 115 lbs/ft^3 • Primer stored also • Refrigerated storage - 10 ft high	3,000
Mirror storage	• 1 month production/42,000 mirrors • 100 mirrors per 9' X 6' X 9'H container	26,000
Attachment hardware & packaging storage		2,000
Office space	• 53 People (Max. at one time) @ 175 ft^2/person	9,275
Receiving		9,000
Shipping		6,000
Maintenance		10,000
TOTAL FACILITY REQUIREMENT		80,105

TABLE 3-8. PANEL PRODUCTION FLOOR SPACE REQUIREMENTS

Work Station	Number Required	Planform Area (ft)	Total Area (ft^2)
Prep glass	10	12 x 12	1,440
Prep SMC	3	50 x 13	1,950
Presses	11	30 x 10	3,300
Cool	11	20 x 10	2,200
Deflash	7	12 x 10	840
Mech. Ass'y	14	12 x 10	1,680
Aisles	@ 30%		3,420
Total Production Floor Space			14,830 ft^2

energy will be used for heating the SMC molds and operating the refrigerated storage.

The 11 molds will be kept heated 24 hours per day, 7 days per week. They are kept at 350^{0}F and consist of two 12 ft. x 12 ft. steel sections. Based on a heat transfer rate estimate and assuming a steam heating system, the plant should require 8×10^{10} BTU/year of natural gas which will cost \$200,000 at \$2.50/10^{6} BTU.

The refrigerated storage, 3000 ft^{2} x 10 ft. high at 40^{0}F, should require 5×10^{4} kWh/year which will cost \$2,000 at 4¢/kWh.

Total process energy cost is \$202,000/year.

Indirect Materials

Indirect materials include variable category items, such as mold release, and non-variable indirect category items, such as facility maintenance supplies. Variable indirect materials are estimated to be \$400,000/year and non-variable to be \$200,000/year.

Net Overhead Rate

The indirect costs are input into the cost tables in Appendix A as an overhead factor applied to the direct labor. The overhead factor is 147 percent. Table 3-9 summarizes the components that make up this rate.

For the SMC production, the overhead has been previously estimated at 200 percent.

3.2.2.7 Cost Scaling and Summary

To obtain the total costs of production for the reflective panels at production rates between 100 and 100,000 concentrators per year, the costs developed for 15,000 concentrators per year must be scaled to these other rates.

TABLE 3-9. PANEL PRODUCTION OVERHEAD RATE (@ 15K/YEAR)

Category	Cost Per Year ($000)
Variable indirect	$1,170
Non-variable indirect	599
Inventory	477
Indirect fringe	371
Facility	366
Process energy	202
Indirect material	600
	$3,755
D.L. base $198/conc. x 15,000/year	$2,970
Rate $\frac{\$3755}{\$2970}$ + 21%[1] = 147%	

[1]Direct fringe.

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The 15,000/year costs are scaled to production levels of 100, 1,000, and 100,000 per year via the learning and material cost relationships discussed in Section 3.1.3. The specific manner in which these relationships are applied and the scaled costs are shown in Tables 3-10 and 3-12. All cost factors shown are relative to the 15,000/year costs. The approach to scaling to the 100/year rate is to operate the 1,000/year plant at reduced capacity. In actual practice the 100/year plant would be generically different but time constraints prevented preparing an alternate production plan.

A summary of production costs at production rates of 100, 1,000, 15,000 and 100,000 per year is shown in Table 3-13. The total production cost for the reflective panels at 15,000/year is $4,301 per concentrator assembly ($42/m^2) or $130 per panel. At 100,000/year the costs are $3,742 per concentrator assembly ($37/m^2) or $113 per panel.

3.2.3 Structural Steel Production Plan

In this section the costs are developed for the structural steel components of the Point Focus concentrator. These components are for the Raised Track (CBS 4000) and Structure (CBS 5000) CBS elements. The assemblies to be produced in this structural steel fabrication plant are:

- Track sections
- Structure sub-assemblies
  - Panel support
  - Base support
  - Receiver support

The plant will be sized to produce assemblies for 15,000 concentrators per year, to match the output of the optimum reflective panel plant.

TABLE 3-10. DIRECT COSTS SCALING -- REFLECTIVE PANELS

PRODUCTION RATE	DIRECT LABOR	MATERIAL	TOOLING
15 K/Year	• Cost -- $370/Conc.	• Cost -- $3150/Conc. (including $81 -- freight to site)	• Cost -- $146/Conc.
1 K/Year	• SMC production labor eliminated • Remaining direct labor $198/Conc. @ 15 K/Year • 85% learning curve -- 1.88 factor • Cost -- $372/Conc.	• In-House SMC production not cost effective @ 1 K/Year, therefore purchase • @ 15 K/Year, bought SMC cost - $1.10/lb. • @ 15 K/Year, total material cost would be $4844/Conc. • 95% Material cost curve -- 1.22 factor • Cost -- $5991/Conc (including $81 - freight to site)	• Tooling Reduced due to reduced production • 7 presses still required for continuous operation • New tooling requirements developed in Table 3-11 • Cost -- $979/Conc.
100/Year	• Switch to $6/hr. labor vs. $4/hr -- 1.5 increase • 85% learning curve -- 3.23 factor • Cost $958/Conc.	• 95% material cost curve -- 1.45 factor • Cost -- $7224/Conc. (including $200 - freight to site)	• No further reduction in tooling total cost • Cost -- $9790/Conc.
100K/Year	• 95% learning/material curve -- 0.87 factor • Cost -- $322/Conc.	• 95% learning/material curve -- 0.87 factor • Cost -- $2742/Conc. (freight scaled also)	• 95% learning/material curve -- 0.87 factor • Cost -- $127/Conc.

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TABLE 3-11. 1000/YEAR PLANT TOOLING REQUIREMENTS
(1,000 CONC. ASSY/YEAR -- 66 PANEL/SHIFT)

Tooling	Number Required	Cost ($1,000)
Glass prep	1	$ 12
Spreader	1	1,200
Press	7	4,900
Cool fixture	7	140
Deflash	1	70
Material handling	-	200
Mech. assembly	2	50
		$6,572
@ CRF 0.149[1]		$979 K
Tooling cost per concentrator		$979

[1]Capital recovery factor at 10 year life and 8% interest

TABLE 3-12. INDIRECT COSTS SCALING -- REFLECTIVE PANELS

PRODUCTION RATE	VARIABLE INDIRECT LABOR	NON-VARIABLE INDIRECT LABOR	FRINGE BENEFITS	INVENTORY	FACILITY
15K/year	• 39% of non-SMC Prod. Direct Labor • $1170 K total • $78/Conc.	• $599 K total • $40/Conc.	• 21% of all labor • $66/Conc.	• $477 K total • 1.0% of material cost • $32/Conc.	• $336 K Total • $14/Conc.
1K/year	• 85% learning curve appl. • 73% of direct labor • $272/Conc.	• Total held constant • $600/Conc.	• 21% of all labor • $261/Conc.	• 1.0% of material • $59/Conc.	• Reduce total by 25% • $252K total • $252/Conc.
100/Year	• 85% learning curve • 126% of direct labor • $1207/Conc.	• Total held constant • $6,000/Conc.	• 21% of all labor • $1715/Conc.	• 1.0% of material cost • $70/Conc.	• Same total as 1K/year • $2,520/Conc.
100 K/Year	ALL INDIRECT COSTS SCALED VIA 95% LEARNING/MATERIAL CURVE				

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TABLE 3-12. Continued

PRODUCTION RATE	PROCESS ENERGY	VARIABLE INDIRECT MATERIALS	NON-VARIABLE INDIRECT MATERIALS	TOTAL OVERHEAD
• 15 K/year	• $202 K total • $14/Conc.	• $400 K total • $27/Conc.	• $200 K total • $13/Conc.	• SMC mixing overhead -- $343/Conc. • Total indirect -- $635/Conc.
• 1 K/year	• Reduce total by 25% • $151 K total • $151/Conc.	• 85% Labor curve & 95% Material curve • 2.29 factor • $62/Conc.	• Reduce total by 25% • $150 K total • $150/Conc.	• Total Indirect -- $1807/Conc.
• 100/year	• Same total as 1 K/year • $1510/Conc.	• 85% labor curve & 95% material curve • 4.68 factor • $126/Conc.	• Same total as 1 K year • $1500/Conc.	• Total Indirect -- $14,648/Conc.
• 100 K/year				• Total Indirect - $552/Conc.

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TABLE 3-13. COST SCALING SUMMARY -- REFLECTIVE PANELS
(in $/Conc.)

RATE	DIRECT LABOR	MATERIAL	TOOLING	INDIRECT	TOTAL
100/year	$958	$7,224	$9,790	$14,648	$32,620
1K/year	372	5,991	979	1,807	9,149
15K/year	370	3,150	146	635	4,301
100K/year	322	2,741	127	552	3,742

The following sections present the materials requirements and costs, processes and operations balance, and the labor and overhead costs.

3.2.3.1 Materials Requirements

The raw materials required for the structural assemblies are rectangular and round steel tubing. The total requirement for this tubing is approximately 6200 pounds per concentrator. At 15,000 concentrators per year, this is a demand of 93 million pounds of steel tubing per year.

At these levels of demand, the question should be asked: should the steel tubing be purchased or manufactured in-house from plate stock? Based on discussions with steel fabricators, the cost breakpoint for make-or-buy on the tubing should occur at output rates between 15 K and 100 K concentrators per year. It is expected that there should be a 4 to 6¢/lb reduction in the price of tubing due to this change over the 15 to 100 K range. For this plan we shall consider that steel tubing is purchased.

Additionally, there is a material requirement for I-beam sections and mounting flanges for the raised tracks.

Materials requirements and costs for the track and structure are listed in Appendix A (Table A-1). The total cost of materials* for the track is $1022/concentrator and for the structure is $2150/concentrator.

3.2.3.2 Operations/Tooling

The operations to produce the required steel weldments are shown in schematic form in Figure 3-6.

The tooling to support these operations and their costs are shown in Appendix A (Table A-2).

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*Includes freight to site.

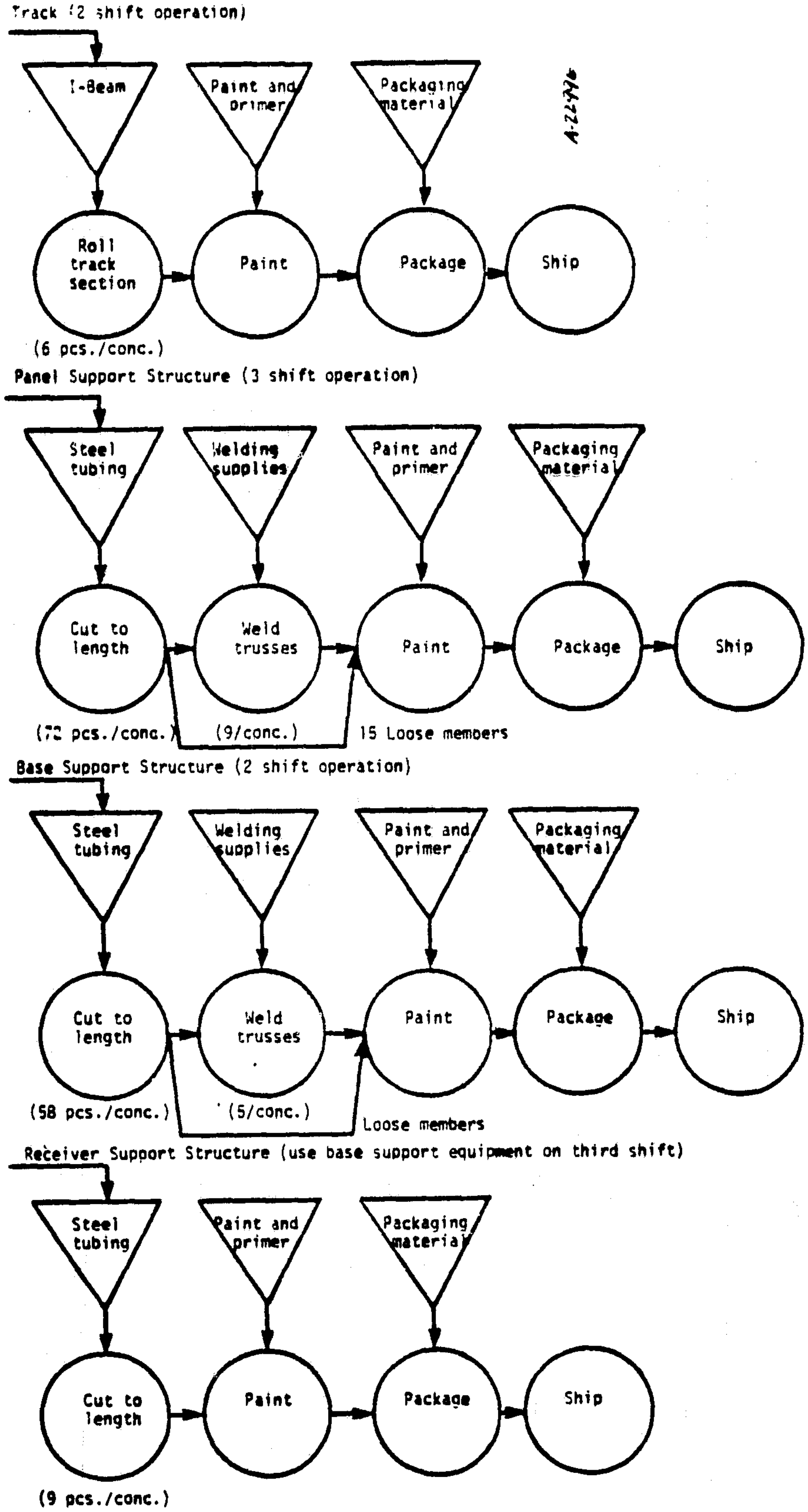

Figure 3-6. Production process -- structure/track.

The total amortized tooling costs for structural steel fabrication are shown in Table 3-14:

TABLE 3-14. TOTAL TOOLING AND DIRECT LABOR COSTS

CBS Element	$/Concentrator	
	Tooling	Direct Labor
Track	3.70	13.20
Structure		
Panel Support	11.50	39.00
Base Support	12.67	21.00
Receiver Support	2.83	7.20
Total	27.00	67.20

3.2.3.3 Direct Labor

Based upon the work stations, the direct labor man-loading is developed. For the structural steel plant, the labor will earn $6.00/hr. The direct labor requirements and costs are presented in Appendix A (Table A-3). The overall costs for direct labor are shown above.

3.2.3.4 Indirect Costs

The indirect cost categories cover those costs not directly assignable to production; direct costs are direct labor, material and tooling. The indirect cost categories to be developed are:

- Variable Indirect Labor
- Non-Variable Indirect Labor

- Facility
- Inventory
- Fringe Benefits
- Indirect Materials

The variable indirect labor consists primarily of supervisors and engineers and the requirements are presented in Table 3-15. The cost is $439,000 per year.

Non-variable indirect labor consists of plant management and maintenance personnel and is shown in Table 3-16. The total cost is $354,000 per year.

The facility area requirements are:

	ft^2
Production area	15,000
Storage	24,000
Office*	6,000
Miscellaneous	10,000
Total	60,000 ft^2

At a gross rent of 35¢/ft^2/month, the total cost of the facility will be $252,000/year.

The inventory cost is derived from the value of the material for structure and track for one concentrator which is $3130. The inventory to be stored will be 1 1/2 month supply of material or $5.9 million in value. At an inventory cost of 18 percent/year, the inventory cost per concentrator is $70 or $1,057,000 total.

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*29 people @ 175 ft^2/person.

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TABLE 3-15 VARIABLE INDIRECT LABOR -- STRUCTURAL STEEL FACILITY

Category	Number Required	Annual Pay Rate ($ 000)	Total ($ 000)
Foremen	3	16	$ 48
General Foreman	1	22	22
Quality Assurance Manager	1	30	30
Project Engineer	1	28	28
Manufacturing Engineer	1	25	25
Inspectors	6	13	78
Planner MCO/PCO	2	18	36
Expediter MCO/PCO	4	13	52
Tool Maintenance	5	16	80
Nurse -- First Aid	2	20	40
Total Indirect Variable Payroll			$ 439

TABLE 3-16 NON-VARIABLE INDIRECT LABOR -- STRUCTURAL STEEL FACILITY

Category	Number Required	Annual Pay Rate ($ 000)	Total ($ 000)
Plant Manager	1	37	$ 37
Engineering Manager	1	33	33
Personnel Manager	1	28	28
Accounting Manager	1	30	30
Personnel Clerks	1	15	15
Accounting Clerks	2	13	26
Cost Accountant	1	25	25
Purchasing Agent	1	25	25
Purchasing Clerk	1	14	14
Shipping/Receiving Clerk	2	14	28
Stockroom Clerk	3	13	39
Facility Maintenance	2	14	28
Secretaries	2	13	26
Total Non-Variable Indirect Labor			$ 354

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Fringe benefits will average 21 percent of salary for all personnel.

Indirect materials are estimated to be $150,000/year variable and $300,000/year non-variable.

The overhead rate, which applies all indirect costs as a percentage of the direct labor, is 246 percent. Table 3-17 summarizes the components that make-up the overhead note.

3.2.3.5 Cost Scaling and Summary

The cost of production for the structural steel components at production rates between 100 and 100,000 concentrators per year are derived via scaling of the cost at the 15,000 per year rate plan.

The 15,000/year costs are scaled to other production levels (100, 1,000, and 100,000/year) via the learning and material cost curve relationships discussed in Section 3.1.3. The specific manner by which these relationships are applied is shown in Table 3-18. All cost factors shown are relative to the 15K/year costs.

The approach for scaling to the lower production rates is based upon using the 15K/year plant at reduced capacity. In actual practice, it is likely that a generically different plant would be used at these lower rates but time constraints prevented preparation of an alternate production plan.

A detailed structural steel production cost summary at the 15K/year production rate is shown in Table 3-19. The total track cost is $1,072 per concentrator ($11/m^2) and the total structure cost is $2,410 per concentrator ($24/m^2).

A summary of production costs for the structural steel components at rates of 100, 1,000, 15,000 and 100,000 concentrators per year is shown in Table 3-20. This shows that the total track cost at 100K/year is $932

TABLE 3-17 STRUCTURAL STEEL PLANT OVERHEAD RATE DEVELOPMENT

Category	Cost ($1,000)
Variable Indirect	439
Non Variable Indirect	354
Facility	254
Inventory	1,057
Indirect Fringe	167
Indirect Material	450
TOTAL INDIRECT	$2,729K
Direct Labor -- $80.40/Conc x 15K/Year	$1,206K
OH Rate	

$$\frac{\$2{,}719K}{\$1{,}206K} + 21\% = 246\%$$

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TABLE 3-18. COST ADJUSTMENT FACTORS -- STRUCTURAL STEEL PRODUCTION PLANT

Cost Category	Rate		
	1,000/year	100/year	100,000/year
Material	• 95% material cost curve • Factor -- 1.22	• 95% material cost curve • Factor -- 1.45	• 95% general curve • Factor -- 0.87
Direct labor	• 85% learning curve • Factor -- 1.88	• 85% learning curve • Factor -- 3.23	↓
Tooling	• Same total expense	• Same total expense	
Indirect costs	• Net indirect factor -- 6.64	• Net indirect factor -- 48.9	
Inventory	• 2.2% material cost	• 2.2% material cost	
Variable indirect labor	• 85% learning curve • @ 15 K/year -- 55% of direct labor • Factor -- 103% of direct labor	• 85% learning curve • Factor -- 177% of direct labor	
Non-variable labor	• Same total expense	• Same total expense	
Facility	• Same total expense	• Same total expense	
Indirect material	• Total expense less 25%	• Total expense less 50%	
Fringe benefits	• 21% of all labor	• 21% of all labor	

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TABLE 3-19 STRUCTURE PRODUCTION COST SUMMARY - 15K/YEAR
(in $/Conc.)

	Material	Direct Labor	Overhead	Tooling	Total
4000 Track	$1,022	$13	$ 33	$ 4	$1,072
5000 Structure					
Panel Support	1,302	39	96	11	1,448
Base Support	609	21	52	13	695
Receiver Support	239	7	18	3	267
TOTAL 5000	$2,150	$67	$166	$27	$2,410

TABLE 3-20. TRACK COST SUMMARY
(in $/Conc.)

Rate	Material[1]	Direct Labor	Indirect Labor	Tooling	Total
100/year	$1,501[1]	$ 42	$ 1,614	$ 560	$ 3,717
1 K/year	1,244[2]	24	219	56	1,543
15 K/year	1,022[2]	13	33	3.70	1,072
100 K/year	889	11	29	3.20	932

[1]Includes freight to site @ 2.5% (common carrier)
[2]Includes freight to site @ $12

STRUCTURE COST SUMMARY
(in $/Conc.)

Rate	Material[1]	Direct Labor	Indirect Labor	Tooling	Total
100/year	$3,154[1]	$216	$ 8,117	$ 4,050	$15,537
1 K/year	2,616[2]	126	1,102	405	4,249
15 K/year	2,150[2]	67	166	27	2,410
100 K/year	1,871	59	144	23	2,097

[1]Includes freight to site @ 2.5% (common carrier)
[2]Includes freight to site @ $28

per concentrator ($9/m^2) and the total structure cost is $2,097 per concentrator ($21/m^2).

3.2.4 Purchased Parts

This section develops the requirements and costs for purchased parts for the Drive (CBS 2000) and the Control/Electrical (CBS 3000) components.

The requirements and costs for these items are shown in detail in Appendix A (Table A-1). Costs for drive components are based on scaled vendor quotes or engineering estimates, as Table A-1 indicates. Costs for control/electrical components are obtained from standard construction estimating guides, scaled vendor quotes, and engineering estimates as is also indicated.

The total material costs for these catagories, including purchasing overhead and freight are:

2000 Drive	$3,151/conc. ($31/m^2)
3000 Control/Electrical	$ 959/conc. ($ 9/m^2)

The control microprocessor will be made in-house and an electronics assembly plant is included in the general manufacturing plan for that reason. However, the microprocessor is shown in the detailed cost development as a fabricated cost as the production plan would be for very standard electronics assembly and the cost can be estimated without a production plan.

The scaling relationships used to obtain the drive and control/electrical components costs for production rates of 100, 1,000 and 100,000 per year are shown in Table 3-21. The factors are referenced to the costs for the 15 K/year rate.

TABLE 3-21. COST SCALING FACTORS -- PURCHASED PARTS

Production Rate	Material	Purchasing Overhead	Freight
1 K/year	• 95% material cost curve • 1.22 factor	• Increase to 10% of material cost	• Remains 2.5% of material cost
100/year	• 95% material cost curve • 1.45 factor	• Increase to 20% of material cost	• Remains 2.5% of material cost
100 K/year	• 95% general cost reduction curve -- 0.87 factor applied to all costs.		

The summary of drive end control/electrical components costs at the various production rates in shown in Table 3-22. At 100 K/year the costs will be:

2000 Drive	\$2,741/conc. (\$27/m^2)
3000 Control/Electrical	\$ 834/conc. (\$8/m^2)

3.2.5 Production Cost Summary

The detailed production costs for a production rate of 15,000 concentrators per year and the scaled costs to 100, 1,000, and 100,000 concentrators per year are summarized in Table 3-23.

The table shows that at the 15K/year rate the production cost of the concentrator, as delivered to the site, is \$11,893 per concentrator or \$117/M^2. At the 100K/year rate the cost is \$10,346 per concentrator or \$101/M^2.

As part of the work on this task, a search was made to find independent validation of the cost estimate produced here. A suitable candidate was found in the conceptual manufacturing plan prepared by McDonnell Douglas (MDAC) for its prototype heliostat for the solar central receiver program. Generically, the MDAC heliostat is somewhat similar to the Acurex point focus concentrator. Both are two axis tracking steel structures with glass mirror relfective surfaces. Utilizing data presented in their report (Reference 3-1), comparisons can be made to the MDAC heliostat in several areas.

As the MDAC report prepared costs for four production rates, a rate was selected to compare to the Acurex concentrator 100K/year rate. The production level selected was 250K heliostats/year. On an area basis, at 49M^2/heliostat, this is equivalent to 120K concentrators/year. On a

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TABLE 3-22. PURCHASED PARTS COST SUMMARY
(in $/Conc.)

Category/Rate	Material	Purchasing	Freight	Total
2000 Drive				
100/year	$4,331	$866	$108	$5,308
1K/year	3,644	364	91	4,099
15K/year	2,987	89	75	3,151
100K/year	2,599	77	65	2,741
3000 Control/Electrical				
100/year	1,318	264	33	1,615
1K/year	1,109	111	28	1,248
15K/year	909	27	23	959
100K/year	791	23	20	834

TABLE 3-23. PRODUCTION COST SUMMARY

CBS Element	100 $/conc.	1K $/conc.	15K $/conc.	100K $/conc.
1000 Reflective Panels				
Material	7,224	5,991	3,150	2,741
Labor and OH	15,606	2,179	1,005	874
Tooling	9,790	979	146	127
	32,620	9,149	4,301	3,742
2000 Drive				
Material	5,308	4,099	3,151	2,741
3000 Control/Electrical				
Material	1,615	1,248	959	834
4000 Track				
Material	1,501	1,244	1,022	889
Labor and OH	1,656	243	46	40
Tooling	560	56	4	3
	3,717	1,543	1,072	932
5000 Structure				
Material	3,154	2,616	2,150	1,871
Labor and OH	8,333	1,228	233	203
Tooling	4,050	405	27	23
	15,537	4,249	2,410	2,097
TOTAL f.o.b. site	58,827	20,288	11,893	10,346
In $/m^2$	576	199	117	101

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weight basis, at 3870 lbs./heliostat, this is equivalent to 68K concentrators/year.

The first area in which validation was sought was in fabricated cost of steel structure. The MDAC heliostat included two fabricated steel elements; the mirror backing structure and the heliostat support structure (pedestal). Table 3-24, which compares the heliostat and concentrator structural cost/weight, shows that there is a very close comparison between the values produced independently by the two plans.

A second comparison is-how material intensive are the estimated fabrication costs of the two devices? Using data from Table 3-23 for the concentrator, the material cost is 89 percent of the total cost. For the heliostat, MDAC cost summary data was used to calculate a material cost percentage of 90 percent. Again a very close correspondence was seen.

The third comparison was in total fabrication cost/weight of the device. For the Acurex concentrator at $10,346 and 14,160 pounds it is 73¢/lb. For the MDAC heliostat at $1,981 and 3,871 pounds the value is 51¢/lb. In this case the concentrator cost is conservative relative to the heliostat.

These three comparisons have been made with values from independently produced production plans and show that the costs compared for the concentrator correlate well with the MDAC heliostat work.

3.3 INSTALLATION PLAN

An installation plan for the Low-Cost Point-Focus Concentrator was developed to obtain a cost for field assembly and installation. A basic set of ground rules were first established and then assembly, installation and checkout procedures were formulated. The various activities of the procedure were costed. In keeping with the overall

TABLE 3-24. HELIOSTAT-CONCENTRATOR STRUCTURE COST PER UNIT WEIGHT COMPARISON

Steel Structures	Weight	Fabricated Cost	Cost/lb.
MDAC @ 250K/year			
Mirror backing structure	864 lb.	$ 299	$0.35
Heliostat support structure	373 lb.	$ 125	$0.34
Acurex @ 100K/year			
Track	2600 lb.	$ 932	$0.36
Structure	6020 lb.	$2097	$0.35

costing approach, costs were tabulated for the various installation activities in the areas of direct labor, materials, equipment, and overhead.

The basis for the costing is given in Section 3.3.1, the installation procedure in Section 3.3.2 and a discussion of the cost in Section 3.3.3

3.3.1 Costing Basis

For the purpose of this costing, a field was assumed to consist of 100 concentrators arranged in 10 rows of 10 concentrators on 80 foot centers; i.e., concentrators are spaced approximately 2 effective diameters appart. The electrical output from a field of 100 concentrators is nominally 1.5 megawatts.

The terrain was assumed to be relatively flat without large ravines or hills and with light brush cover. A two acre assembly area was included. The use of this assembly area is described in the installation section which follows.

The concentrator parts were assumed to be shipped to the field from the factory as subassemblies. All fabrication will be performed at the factory and only assembly is performed in the field. The reflector and base structure subassemblies are assembled on jigs. The hydraulic and electronic components are shipped as modular units which are bolted to the structure. The interconnecting hydraulic tubing is precut and formed at the factory. End fittings are also assembled to the tube ends. Wire harnesses are factory assembled and are terminated with disconnect plugs.

Only assembly and installation of concentrator units was costed. Installation of piping and wiring amongst concentrators, fencing, central control facilities or roads was not included. The only work included pertaining to the field as a whole was clearing and grading. Water and electricity was assumed to be available.

It was also assumed that a dedicated solar concentrator installation company would be formed. This company would purchase the necessary equipment, hire the required work force and provide construction management.

Assembly, installation and checkout work required for the receiver/engine package was not included in this installation plan. It was assumed this work would be done by others.

3.3.2 Installation Procedure

Figure 3-7 is a flow diagram of the major activities of the installation procedure, and Table 3-25 is a list of the cost breakdown structure elements derived from the procedure. The procedure divides the installation task into four major subtasks: (1) site preparation, (2) foundation installation (3) concentrator assembly and installation, and (4) concentrator adjustment and checkout. A labor crew is organized to handle each subtask as shown in Table 3-26. The crews are sized to complete their tasks in approximately five weeks on a field of 100 concentrators. This time span includes one week for such contingencies as weather and parts availability. As a crew finishes its work at one site it would move on to the next site. After 15 weeks, work at four sites could be progressing simultaneously as the crews succeed each other. With this through-put scheme, 1000 concentrators could be installed into 10 fields in a year by one team of crews. A detailed discussion of each step in the procedure is given in the following paragraphs.

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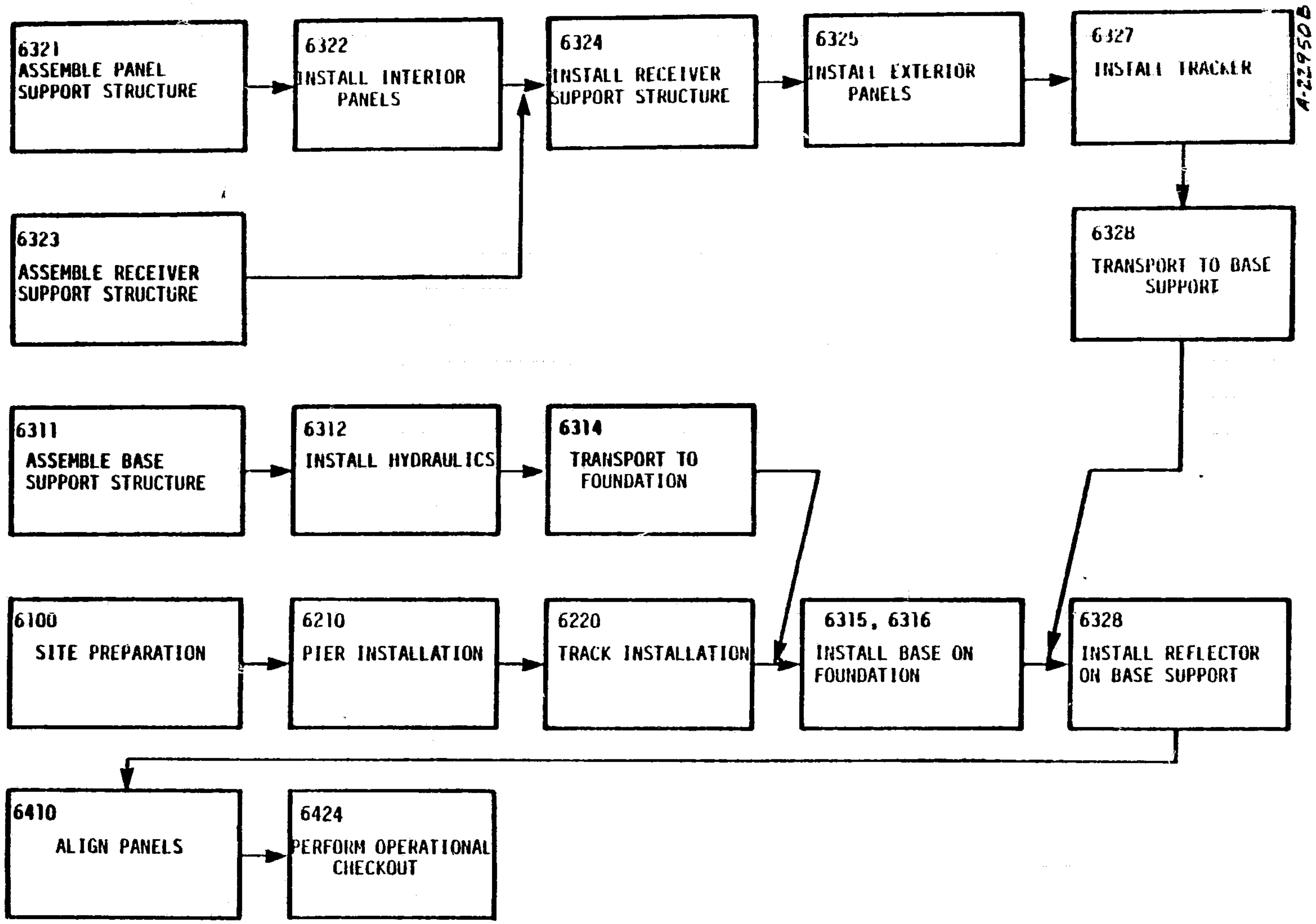

Figure 3-7. Installation flow diagram.

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TABLE 3-25 CBS ELEMENTS

CBS Element	Activity
6100	Site preparation
6101	Clear and grade
6102	Layout foundations
6103	Prepare work area
6104	Setup tooling
6105	Setup shelter
6106	Move on
6200	Foundation installation
6210	Pier installation
6211	Bore pier holes
6212	Install rebar cages
6213	Install forms
6214	Align studs
6215	Pour concrete
6216	Clean up and move on
6220	Track installation
6221	Mount track segments
6222	Level segments
6223	Torque attach bolts
6224	Grout
6300	Concentrator assembly and installation
6310	Base support frame assembly and installation
6311	Assemble subtrusses
6312	Install hydraulic components
6313	Install electrical components
6314	Transport to foundation and hoist onto track
6315	Adjust rotary actuator mounting bolts
6316	Grout
6320	Reflector assembly and installation
6321	Assemble panel support structure
6322	Install interior reflective panels
6323	Assemble receiver support
6324	Attach receiver support to reflector
6325	Install exterior reflecting panels
6326	Install electrical components
6327	Install tracker and sensors
6328	Transport and install on base
6400	Adjustment and checkout
6410	Panel alignment
6411	Mount target to receiver support
6412	Mount scope
6413	Adjust panel
6420	Drive adjustment
6421	Connect field power
6422	Adjust tracking and stow rates
6423	Adjust sun sensor and tracker
6424	Perform functional checkout

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TABLE 3-26 INSTALLATION CREWS

CBS Element	Crew Members	Number
6100 Site Preparation	Dozer Operator	2
	Truck Driver	2
	Surveyor	4
	Laborer	4
6200 Foundation Installation	Drill Rig Operator	1
	Laborer	10
	Cement Finisher	2
6300 Concentrator Assembly and Installation	Assemblers	12
	Forklift Driver	1
	Crane Operator	2
	Truck Driver	2
6400 Concentrator Adjustment and Checkout	Assemblers	4
	Mechanics	4

Site Preparation

The first task in installing a field of concentrators is to clear away any brush and grade the area. This is accomplished with bulldozers. The brush and large rocks are hauled away with dump trucks. Once the area is cleared and graded, the survey crews will layout the foundation piers.

The assembly jigs, work sheds and field office are installed in the assembly area. Since the assembly area will have intensive traffic, it is covered with 6 inches of gravel. This will prevent the area from deteriorating into a quagmire or dust bowl.

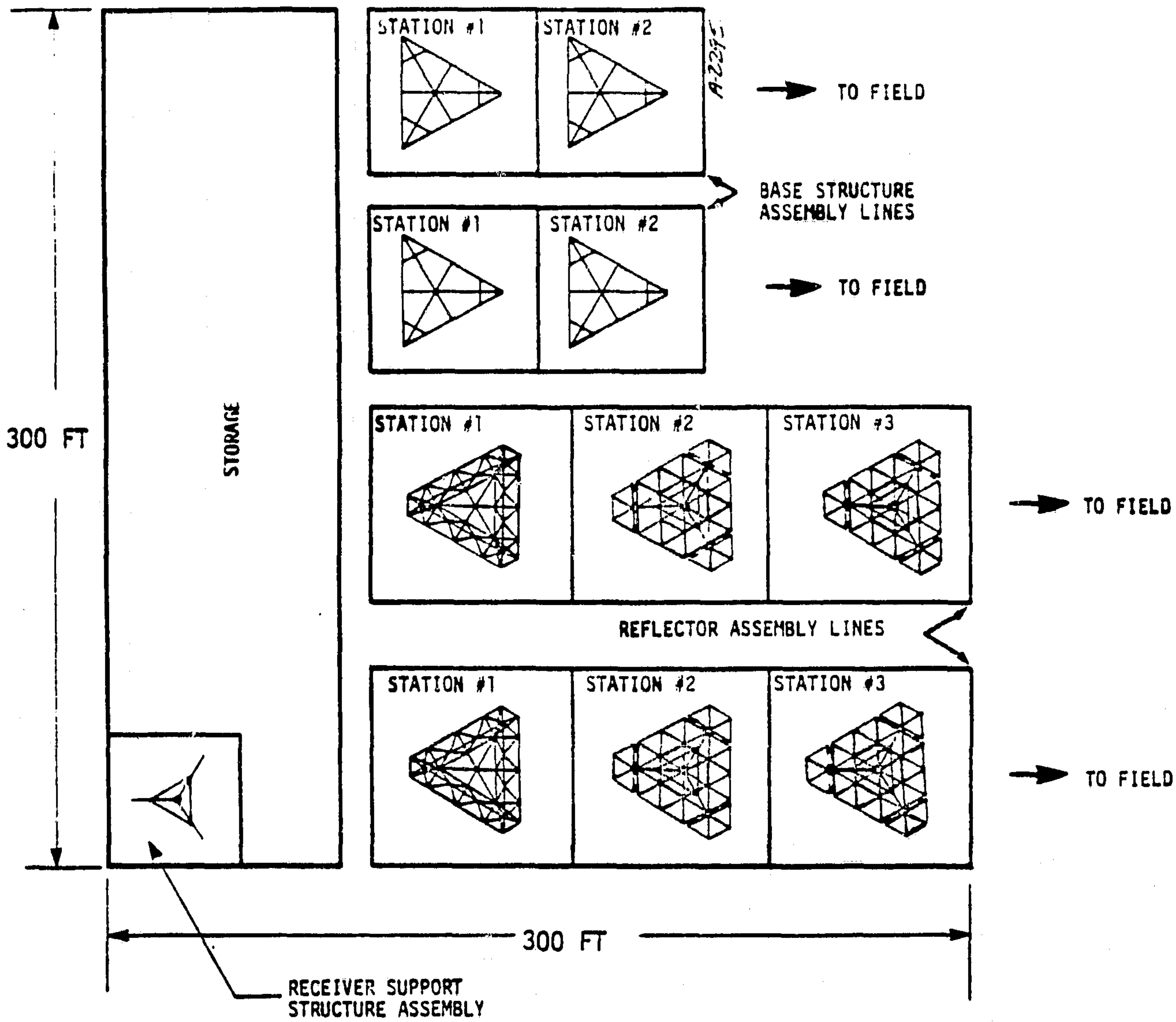
Foundation Installation

The piers are made by drilling a hole, inserting a prefabricated reinforcing bar cage, aligning the anchor bolts and pouring the concrete. A short circular concrete form is required for each pier to extend them above grade. These forms are reusable.

The raised metal track is assembled on the piers. Each segment is hoisted onto a pair of track piers, then leveled and centered relative to the center pier. The leveling and centering will be facilitated with alignment tools and is accomplished by adjusting the nuts on the anchor bolts. Once the track segments are level and centered, they are joined together and the anchor nuts tightened. The gap between the track and pier is then grouted.

Concentrator Assembly and Installation

The assembly of the major concentrator subassemblies is accomplished on short production lines as shown in Figure 3-8. As the major subassemblies come off the assembly lines they are carried by trucks to the foundations and mounted.



Base Support Structure Assembly Line

Station 1: Subtruss Assembly
Station 2: Hydraulic and Electrical Installation

Reflector Assembly Line

Station 1: Subtruss Assembly
Station 2: Panel and Receiver Support Installation
Station 3: Tracker and Electrical Installation

Figure 3-8. Assembly area.

The base support structure assembly line has two stations. At the first station the subtrusses are joined. The hydraulic and electrical components are installed at the second station. The entire hydraulic system is installed, interconnected, purged and functionally checked at this point.

Once hoisted onto the foundation the center pier anchor bolt nuts are adjusted to compensate for height variations. The mounting fitting is grouted to the center pier after the adjustments are made.

The reflector assembly line has three stations. The reflective panel support structure is assembled at the first station. The panels are installed in two groups to avoid interferences when the receiver support structure is installed. The 24 interior panels are installed followed by the receiver support structure at the second station. The nine corner panels, the tracker unit, sun sensor units and electrical wiring are installed at the final station.

After the reflector is assembled, it is transported by truck into the field and mounted on a base structure. It is attached by hinge pins at the two bearings and the elevation actuator rod end. All the electrical connections between the reflector and the base structure are made with disconnect plugs in junction boxes.

Concentrator Adjustment and Checkout

Once the concentrator is assembled on the foundation the hydraulic valves and the sun sensors are adjusted and the panels aligned. The panel alignment technique is described in Section 2.2.2.6. With completion of adjustment of the panels and controls, the concentrator is ready for system checkout.

3.3.3 Cost Summary

Table 3-27 gives the summary of the costs for the installation procedure described above. Supporting tables are found in Appendix B (Tables B-1 through B-4). The labor hours, equipment operating costs, overhead rates, and construction material costs were developed from the information in Building Construction Cost Data (Reference 3-2), Process Plant Construction Estimating Standards (Reference 3-3), and Acurex personnel's experience.

Table B-1 tabulates the labor hours required to install 100 concentrators. The second column of the table lists the minimum number of men required to accomplish the task. To maintain the five week installation schedule for each major subtask, some crew sizes were increased incrementally. The number of labor man-hours, and therefore the cost per concentrator remains constant but the calendar time to do the job is reduced.

A representative average labor rate of $10.00/hour was used. Skilled equipment operators earn more but unskilled and semiskilled workers less. The work force is predominantly from the latter category.

Table B-2 tabulates the costs related to the materials required for the installation. The major material expense is for concrete, anchor bolts and reinforcing cages. Equipment operating costs other than labor man-hours are included in this table. These latter costs are primarily for fuel.

The cost related to purchasing construction equipment and major tooling are listed in Table B-3. The purchase price was converted to a yearly expense by using a capital recovery factor. For this purpose an interest rate of 8 percent and an equipment life of 10 years was assumed.

TABLE 3-27 INSTALLATION COST SUMMARY

CBS Element	Labor Hr/conc.	Labor $/conc.	Mat'l $/conc.	Equip. $/conc.	Indirect $/conc.	Total $/conc.
6100 Site Preparation	25.6	256	522	25	220	575
6200 Foundation	10	100	407	34	86	619
6300 Concentrator assembly and installation	60.1	601	30	45	517	1,190
6400 Checkout	10.5	105	2	9	90	204
TOTAL	106	1,060	522	113	913	2,600

Labor Rate = $10/hour
Indirect Rate = .86 x (labor)

The cost per concentrator was determined by dividing the annual cost by the annual through-put of 1000 concentrators per year.

The final table (Table B-4) lists the indirect cost rates. These rates were applied against the labor costs and were obtained from construction estimating handbooks (References 3-2 and 3-3).

The installation activity is labor intensive. This is evident from the relative costs (see Table 3-27). The only significant materials to be purchased are for the foundations. Also, the construction of foundations and field assembly are not condusive to automation. Installation and assembly aids will be used wherever possible. Assembly jigs will be used for joining the concentrator structural components and alignment tools will be used for locating the foundations.

As mentioned previously, the costing is based on a team of four crews sized to install 1000 concentrators per year in fields of 100 concentrators. Larger field sizes can be broken into 100 concentrator increments. Larger annual installation rates can be accomodated by incrementally increasing the number of teams. Each team of crews will install 1000 concentrators per year. The cost per concentrator would be unchanged as each crew functions as an independent entity.

For installation rates less than 1000 concentrators per year the cost per concentrator increases significantly. The primary reason for this cost increase is that establishing a dedicated concentrator installation operation is no longer feasible. Therefore, for a production rate of 100 concentrators per year the installation effort would be subcontracted to construction and mechanical contractors.

Based on estimates from subcontractors that have installed solar systems for Acurex, the installation costs for a production rate of 100 concentrators per year are:

6100	Site preparation	$ 840/Conc.
6200	Foundations	1900
6300	Concentrator assembly and installation	4700
6400	Checkout	400
	Total	$7800/Conc.

3.4 OPERATION AND MAINTENANCE PLAN

This section describes the requirements and costs for operating and maintaining the concentrator. This analysis is based on costs unique to this concentrator; costs for maintenance of roads, site, and field related items are not included. The only operations cost is therefore for parasitic power. Maintenance consists of scheduled and unscheduled maintenance tasks.

The basic assumptions used in preparing this plan are:

- Thirty year life of concentrator
- 100 unit field
- Fields located within 15 miles of each other (this impacts traveling time to fields)

The following sections present the scheduled and unscheduled maintenance plans.

3.4.1 Scheduled Maintenance

Scheduled maintenance tasks are those activities which are performed at specified periods to maintain performance or for preventive maintenance. The elements of the concentrator which will have scheduled maintenance are the reflective panels, drive system, and structure.

3.4.1.1 Reflective Panels

Cleaning is the only scheduled maintenance required for the panels. The cost of cleaning will depend on the method employed, its cost per cleaning, and the frequency chosen. The frequency is based on an economic trade off of the cost of reflectance loss over time and the cost of the cleaning frequency. This cost trade off is developed in the following paragraphs.

Cost per cleaning

Experience at Sandia with the glass mirror heliostats has led them to recommend the following cleaning method:

1. Fog on 2.5 gal/1000 ft^2 (0.027 gal/m^2) de-ionized (DI) water/detergent mix
2. Allow to sit on surface for short time
3. Rinse with power spray of 12.5 gal/1000 ft^2 (0.13 gal/m^2) DI water

The costs for supplying the DI water and detergent are shown in Table 3-28a. The total cost is 0.84¢/m^2/washing.

Labor hours required for the concentrator cleaning are developed in Table 3-28b. These are based on Sandia estimates of time requirements scaled upward on an area basis and with a 1.25 factor applied to allow for extra time to maneuver the cleaning equipment around the receiver support. The total time required for concentrator cleaning will be 16 minutes for a two man crew.

The cost for the cleaning labor is developed in Table 3-28c. The field overhead rate shown of 60 percent is typical of the overhead for the

TABLE 3-28. CLEANING COSTS
a) MATERIAL COST

• DI water	-- 0.16 gal/m^2 @ 1¢/gal[1]	0.16¢/m^2
• Detergent	-- 40:1 dilution @ $10/gal[2]	0.68¢/m^2
Total		0.84¢/m^2/washing

b) LABOR REQUIREMENT

• For a two man crew:	
• Spray detergent	110 seconds
• Detergent dwell time	30 seconds
• Rinse	340 seconds
• Transit and setup	120 seconds
	10 minutes
• 75% field labor efficiency • 1.2 -- Tank filling, transit to field	6 minutes
Total	16 minutes/washing

c) LABOR COST

• Semi-skilled labor @ $6.00/hr	
• Field overhead rate @ 60%	
• Two man crew	
• Time per concentrator: 16 minutes	
• Total cost per washing: $5.12/conc.	
Total	5.0¢/m^2/washing

[1]Sandia estimate for large capacity reverse osmosis process
[2]Sandia estimates

maintenance workers of a large utility. The total labor cost is 5.0¢/m^2/washing.

The equipment required for field cleaning will be a cherry picker with a manually moveable arm with spray heads attached. The estimated cost for the spray truck and the other cleaning system equipment is $30,000 and it has a 10 year life. Operations and maintenance for the truck will cost $2,500/year. Therefore, the yearly cost of the equipment will be:

Equipment	$30,000 x CRF 0.014*	=	$4,470
O&M		=	$2,500
Total Yearly Cost			$6,970

How many fields a truck/crew will cover is based on an economic trade-off between amortized equipment cost and response time to a so-called muddy rain (light rain on dust accumulation on mirrors). Sandia experience indicates that these incidents will happen about three times per year and cause a 40% loss in reflectance. Lack of rapid response will result in loss of energy collection and revenue. The cost trade-off analysis is presented in Table 3-29. The result of the trade-off is that one cleaning truck will cover four fields.

The total equipment cost is ammortized over four fields and is $0.17/m^2/N/cleaning (where N is the number of cleanings per year).

The summary of costs for cleaning of the concentrator is presented in Table 3-30. The total cost per cleaning is dependent on the number of cleanings per year and is expressed as (5.8¢ + 17¢/N)/m^2 cleaning.

*Capital recovery factor @ 8 percent interest

TABLE 3-29. FIELDS SERVED PER TRUCK COST TRADE-OFF

(n is the number of fields covered by one set of cleaning equipment)

• Average response time per concentrator @ n fields served (100 conc. x 16 min/conc. x n fields)/2	0.55 n days
• Cost of 40% reflectance loss per day per concentrator $\frac{14 \text{ mills/kW}_{th}\text{-hr} \times 60 \text{ kW}_{th} \times 3000 \text{ hr} \times 40\%}{365 \text{ days}}$	\$ 2.76/day
• Cost of average response time (0.55 n days) x (\$2.76/day) x (3 incidents/year)	\$ 4.55 n/conc.
• Cost of equipment amortization per field \$6,970/(n fields x 100 conc/field)	\$69.70/n/conc.

• Total cost – Cost = (\$4.55 n + \$69.7/n)/conc.

• Final minimum – $\frac{d\,Cost}{dn} = 4.55 - 69.7/n^2 = 0$

n = 3.9 fields

Cost @ 3 fields = \$36.88/conc

Cost @ 4 fields = \$35.62/conc

• Therefore, each washing crew and truck will cover <u>four</u> fields

TABLE 3-30. TOTAL CLEANING COST

	Cost per Cleaning
• Water	0.16¢/m^2
• Detergent	0.68¢/m^2
• Labor	5.0¢/m^2
• Equipment	17¢/m^2/N
Total cost	(5.8¢ + 17¢/N)/m^2

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Cost of Reflectance Loss

Studies at Sandia (Reference 3-4) on reflectance loss vs. cleaning frequency for silvered glass mirrors have developed curves showing test data for mirrors cleaned at various frequencies. These curves show reflectance measured every 2 days for 2, 6, 12 day cleaning cycles. Reflectance values were averaged from these curves and are presented in Figure 3-9 as loss of R (reflectance) units in percent. (Other data in the same study indicate that the extrapolation shown is valid.)

Performance analysis estimates that, at an average reflectance of 0.90, the concentrator will deliver about 60 kW_{th}* to the receiver for 3000 hrs per year. Preliminary economic analysis has set the $\overline{BBEC}_{th}$ to be about 15 mills/kW_{th}-hr*. The value of energy to the receiver over a year is therefore approximately $2,700. The cost of losing 1 percent in reflectance on an average annual basis is $30.

The value of the average reflectance losses are therefore:

Cleaning Cycle Days	Cost of Loss
2	$ 45
6	90
12	120
30	150

A cost of cleaning frequency equation is derived from the summary of washing cost per square meter:

*Nominal values for this trade-off study only.

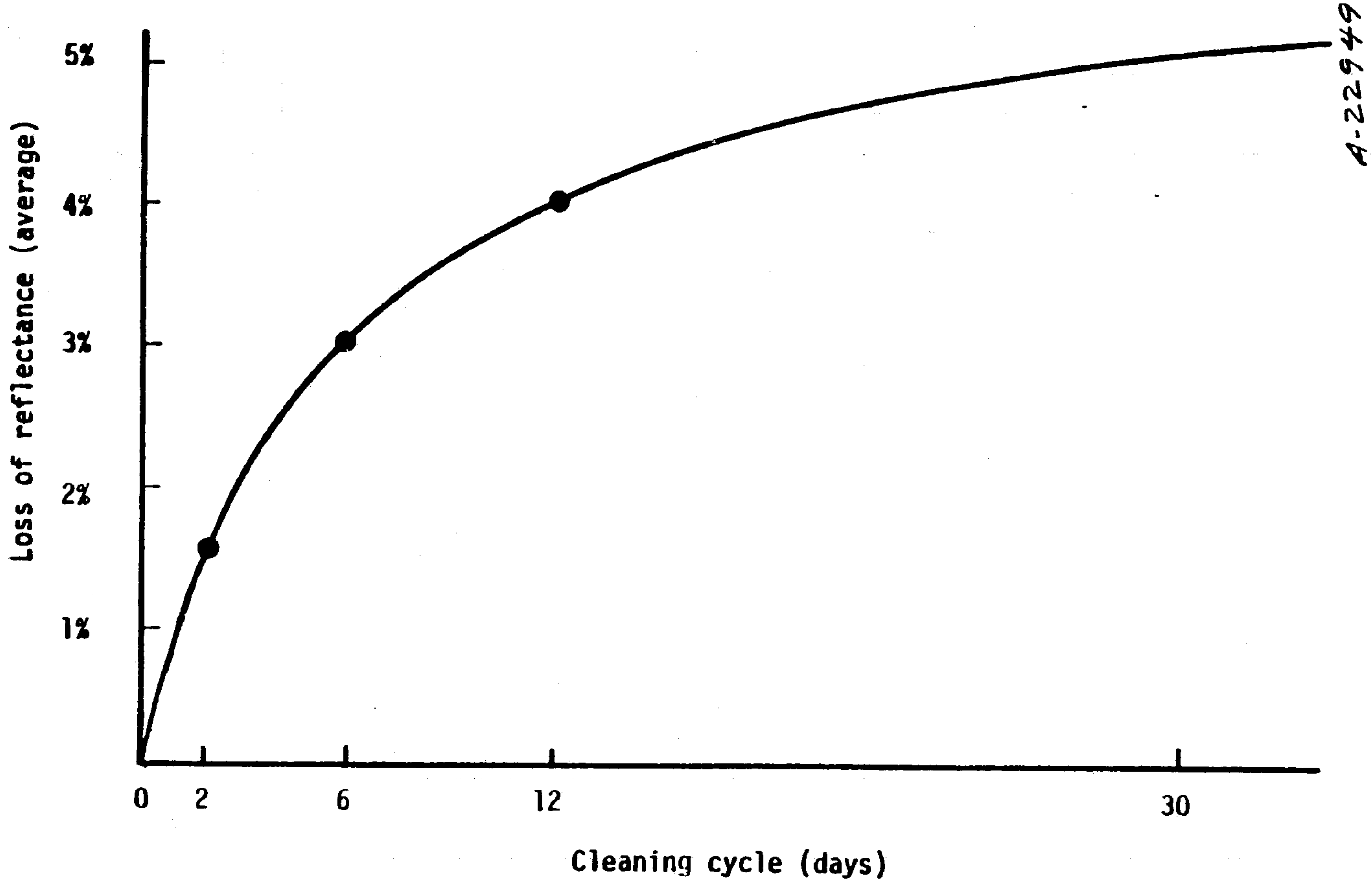

Figure 3-9. Loss of average reflectance vs. time.

Cost = $101.92m^2(365/D)(5.8¢ + 17¢\ (D/365)/m^2$

(where D equals the cleaning period, 365/D is the cleanings per year)

or Cost = \$2,158/D + \$17.33

Cleaning Frequency

Knowing the cost of reflectance loss and of cleaning frequency, the lowest cost cleaning period can be selected. The following table shows the cost buildup:

Cleaning Period			Cost (\$/conc.)
Days	Refl. Loss	Cleaning	Total
2	\$ 45	\$ 1,096	1,141
6	90	377	467
12	120	197	317
30	150	89	239

The cost continues to decline past the 30-day cleaning period. However, as the response to muddy rain incidents dictates one truck to four fields and there exists a requirement that the reflectance not fall below 85 percent to avoid irreversible degradation, longer cleaning periods are not feasible. Therefore, the 30-day cleaning period will be used. The cleaning approach will be:

- One washing per month per field
- One truck used for four fields
- Immediate response to "muddy rain" incidents
- Washing cost of: 7.3¢/M^2/washing
  \$7.42/conc./washing
  \$89/conc./year

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3.4.1.2 Drive System, Track, and Structure

The remaining scheduled maintenance tasks are yearly replacement of the hydraulic fluid and filter and five year touchup painting of the track and structure. The requirements and costs of material and labor for these tasks are listed in Tables 3-31 and 3-32. This information is based upon vendor information and Acurex experience.

3.4.1.3 Scheduled Maintenance Cost Summary

Using the cost data developed here, the total cost of scheduled maintenance is:

Yearly	$/conc.
Panel Washing	89.48
Fluid/Filter Replacement	36.00
	$125.48
Five-Year	
Painting	
Track	26.00
Structure	130.00
	$156.00

3.4.2 Unscheduled Maintenance

The unscheduled maintenance approach selected for the concentrator is the "repair upon failure" approach. In this, no periodic replacement of components is performed and they are only replaced upon failure.

This approach was selected on the basis of a preliminary economic analysis of the costs of periodic replacement vs. repair upon failure. This analysis indicated that there was a cost advantage to the repair upon failure approach. This is due to two main factors. First, the use of high reliability long-life components in a low duty cycle manner means

TABLE 3-31. SCHEDULED MAINTENANCE LABOR

CBS Element/Activity	Freq.	Time Req.	Men Req.	Man Hrs/ Conc.	$/Man Hour (Loaded)	$/ Conc.	$/ M^2
7100 Scheduled Maintenance							
7110 Panels							
7111 Washing	12/year	16 min.	2	6.4	9.60	61.44	0.60
7120 Drive							
7121 Fluid and filter replacement	1/year	1 hr.	1	1.0	16.00	16.00	0.16
						77.44	0.76
7140 Track							
7141 Painting (touch-up)	1/5 year	1 hr.	1	1.0	16.00	16.00	0.16
7150 Structure							
7151 Painting (touch-up)	1/5 year	5 hr.	1	5.0	16.00	80.00	0.78
						96.00	0.94

TABLE 3-32. SCHEDULED MAINTENANCE MATERIALS

CBS Element/Description	Freq.	Units/ Conc./ Action	Total Units Req.	Cost/ Unit	$/ Conc.	$/ M^2
7100 Scheduled Maintenance						
7110 Panels						
7111 Washing						
De-ionized water	12/year	17.2 gal.	206 gal.	.01	2.06	0.02
Detergent	12/year	0.7 gal.	0.86 gal.	10.00	8.60	0.08
					10.66	0.10
7120 Drive						
7121 Fluid and Filter	1/year	--	--	20.00	20.00	0.21
					30.66	0.19
7140 Track						
7141 Paint	1/5 year	1 gal.	1 gal.	10.00	10.00	0.10
7150 Structure						
7151 Paint	1/5 year	5 gal.	5 gal.	10.00	50.00	0.49
					60.00	0.59

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that their failure rate wil be low over the nominal 30 year life of the concentrator. Secondly, the cost implications relative to field performance or damage due to any failure are very small.

In this approach the components are allowed to fail before replacement. Therefore, to estimate the costs for repair and replacement over the life of the concentrator, an approach has been applied to determine an average failure rate of the components over the life of the concentrator.

Based on the duty cycle of each component, an average lifetime is estimated. Then, a replacement rate as a function of year of operation is estimated. For the shorter life components the replacement rate will reach a steady state value before the 30 year life of the concentrator is achieved. For the longer life components, the replacement rate will still be increasing at that point. Using vendor information and related Acurex experience, the average replacement rates over the 30 year concentrator life have been estimated and are shown in Table 3-33.

Based on these estimates, the labor and material costs per 100 unit field are developed and presented in Tables 3-34 and 3-35.

The summarized costs for unscheduled maintenance are:

Labor	$14.62/conc./year
Materials	43.14/conc./year
TOTAL	$57.76/conc./year

It should be noted that this analysis shows that the total cost of the approach taken is low and that a doubling in expected failure rates would only result in an increase of approximately $60/conc./year in cost. This is due to the high reliability approach adopted for the design.

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TABLE 3-33 AVERAGE REPLACEMENT RATES

Component	Average Replacement Rate	Actions/ Year (100 unit field)
Reflective Panels	0.1%	3
Drive		
Azimuth Drive	1%	1
Elevation Drive	1%	1
Support Wheels	0.06%	0.2
Pump/Motor	6%	6
Accumulator	3%	3
Control		
Microprocessor	1%	1
Valves	6%	24
Hydraulic Lines	3%	18

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TABLE 3-34. UNSCHEDULED MAINTENANCE LABOR (For 100 unit field) $A_n = 102m^2$

CBS Element /Activity	Freq. per 100 Unit Field	Time Req.	Men Req.	Man Hrs./ Field	$/Man Hour Loaded	$/ Field
7200 Unscheduled Maintenance						
7210 Panels						
7211 Panel Replacement (remove, replace, align)	3/yr	3 hrs.	2	18	16.00	288.00
7220 Drive System						
7221 Azimuth drive replacement	1/yr	3 hrs.	3	9	16.00	144.00
7222 Elevation drive replacement	1/yr	3 hrs.	3	9	16.00	144.00
7223 Support wheel replacement	0.2/yr	1 hrs.	2	0.4	16.00	6.40
7224 Pump/motor replacement	6/yr	1.5hrs.	1	9	16.00	144.00
7225 Accumulator replacement	3/yr	1 hr.	1	3	16.00	48.00
				30.4		486.40
7230 Control/Electrical						
7231 Microprocessor replacement	1/yr	1 hr.	1	1.0	16.00	16.00
7232 Hydraulic valve replacement	24/yr	1 hr.	1	24.0	16.00	384.00
7234 Flexible hydraulic lines replacement	18/yr	1 hr.	1	18.0	16.00	288.00
				43.0		688.00
				91.4		$1,462.40
				Per conc./yr.		$ 14.62 ($0.01/m^2)

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TABLE 3-35. UNSCHEDULED MAINTENANCE MATERIALS (For 100 unit field) $A_n = 102\ m^2$

CBS Element/Description	New/ Over-haul	#/ Field	Cost/ Unit	Purch. Freight OH	Total Cost/ Unit	$/ Field
7200 Unscheduled maintenance						
7210 Panels						
7211 Panel replacement	N	3/yr	130	10%	143.00	429.60
7220 Drive system						
7221 Azimuth drive	OH	1/yr	200	--	200.00	200.00
7222 Elevation drive	OH	1/yr	100	--	100.00	100.00
7223 Support wheel	N	0.2/yr	100	10%	110.00	22.00
7224 Pump/motor	OH	6/yr	100	--	100.00	600.00
7225 Accumulator	OH	3/yr	30	10%	33.00	99.00
						1021.00
7230 Control/Electrical						
7231 Microprocessor	OH	1/yr	75	--	75.00	75.00
7232 Hydraulic valves	N	24/yr	100	10%	110.00	2,640.00
7233 Flexible hydraulic lines	N	18/yr	7.50	10%	8.25	148.50
						2,863.50
						$4,314.10
				Per conc/year		$ 43.14 ($0.04m2)

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3.4.3 Operations and Maintenance Cost Summary

The total costs for operations and maintenance are summarized in Table 3-36. The parasitic power use is based on the power requirements of the drive and controls and on an assumption of a present typical delivered electrical energy cost.

The total costs are equal to approximately $220/conc./year in operations and maintenance expense. This is equivalent to $2.20/$m_2$/year or $22,000 per 100 unit field. These low costs result from the high reliability, low maintenance components selected for the concentrator.

3.5 COST SUMMARY

The total installed cost for the Low-Cost Point Focus Concentrator is presented in Table 3-37. The table sums the production and installation costs for each of the four production rates studied. Note that installation costs will be approximately constant for 1 K - 100K/year and will increase significantly at 100/year.

The operations and maintenance costs were not scaled because at 100/year, there would eventually be enough fields for efficient operation. The operation and maintenance costs are summarized below:

	$/conc./year
Yearly Maintenance	$183
Parastic Power	10
Total yearly expense	$193
Five-year maintenance expense	$156

The total installed cost of the concentrator is below the JPL cost goal of $150/$m^2$. Also, operations and maintenance costs are

TABLE 3-36. OPERATION AND MAINTENANCE COST

	(Cost per concentrator per year)		
Yearly Maintenance	Scheduled 7100	Unscheduled 7200	Total
Reflective Panels	$ 89	$ 7	$ 96
Drive	36	15	51
Control	0	36	36
TOTAL	$125	$58	$183
Five-Year Maintenance			
Track	26	0	26
Structure	130	0	130
TOTAL	$156	0	$156

Parasitic Power -- (240 kW-h/year @ 4¢/kW-h) - $10

TABLE 3-37. TOTAL INSTALLED COST SUMMARY
(in $/Conc.)

CBS CATEGORY	Production Rate			
	100	1K	15K	100K
1000 Reflective Panels	32,650	9,149	4,301	3,742
2000 Drive System	5,308	4,099	3,151	2,741
3000 Control/Electrical	1,615	1,248	959	834
4000 Track	3,717	1,543	1,072	932
5000 Structure	15,537	4,249	2,410	2,097
TOTAL Production Cost	58,827	20,288	11,893	10,346
6000 Installation	7,800	2,600	2,600	2,600
TOTAL Installed Cost	66,627	22,888	14,493	12,946
In $/m^2$	653	224	142	127

approximately equal to the goals established by Sandia for the heliostat program of $65/$m^2$ over a 30 year life.

The cost summaries developed here and in other parts of this section may be used to determine the cost significant aspects of the design.

One, the design is material intensive. Material, excluding foundation materials, constitute 89 percent of the production costs at 100K/year and 71 percent of the total installed costs (Table 3-38). This confirms the design philosophy of achieving cost reduction primarily through weight reduction. Also, this implies good accuracy in cost estimates at the higher production rates as raw material and purchased parts requirements and costs can be estimated with good accuracy.

Of the remaining costs, installation is 20 percent of the total and factory labor and overhead is 8 percent. Factory tooling is 1 percent of the total installed cost at the 100,000/year production rate. This indicates that large increases in tooling cost to support increased automation would reduce overall cost, yet not reduce the costs significantly. Also these figures indicate that installation cost reduction should receive the most attention after material cost reduction.

Levelized Busbar Energy Cost

The cost values developed for total installed cost and operations and maintenance costs have been utilized in the JPL life cycle cost analysis methodology, together with the thermal performance estimates, to develop the levelized busbar energy cost ($\overline{BBEC}_{th}$) for the various production rates. Table 3-39 shows the $\overline{BBEC}_{th}$ values calculated. They are plotted in Figure 3-10.

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TABLE 3-38. INSTALLED COST BREAKDOWN
(at 100 K Concentrators per year)

	% of Installed Cost
Production	
Material	71
Direct labor	3
Tooling	1
Indirect	5
	80
Installation	
Material	4
Direct labor	8
Equipment	1
Indirect	7
	20
Total	100

TABLE 3-39. LEVELIZED BUSBAR ENERGY COST
(in $/Conc.)

	Production Rate			
	100	1K	10K	100K
Total Installed Cost	$66,627	$22,888	$14,493	$12,946
Operation & Maintenance Cost				
Yearly	193	193	193	193
Five Year	156	156	156	156
$\overline{BBEC}_{th}$ (mills/kW_{th}-hr)	56.4	21.0	14.4	13.1

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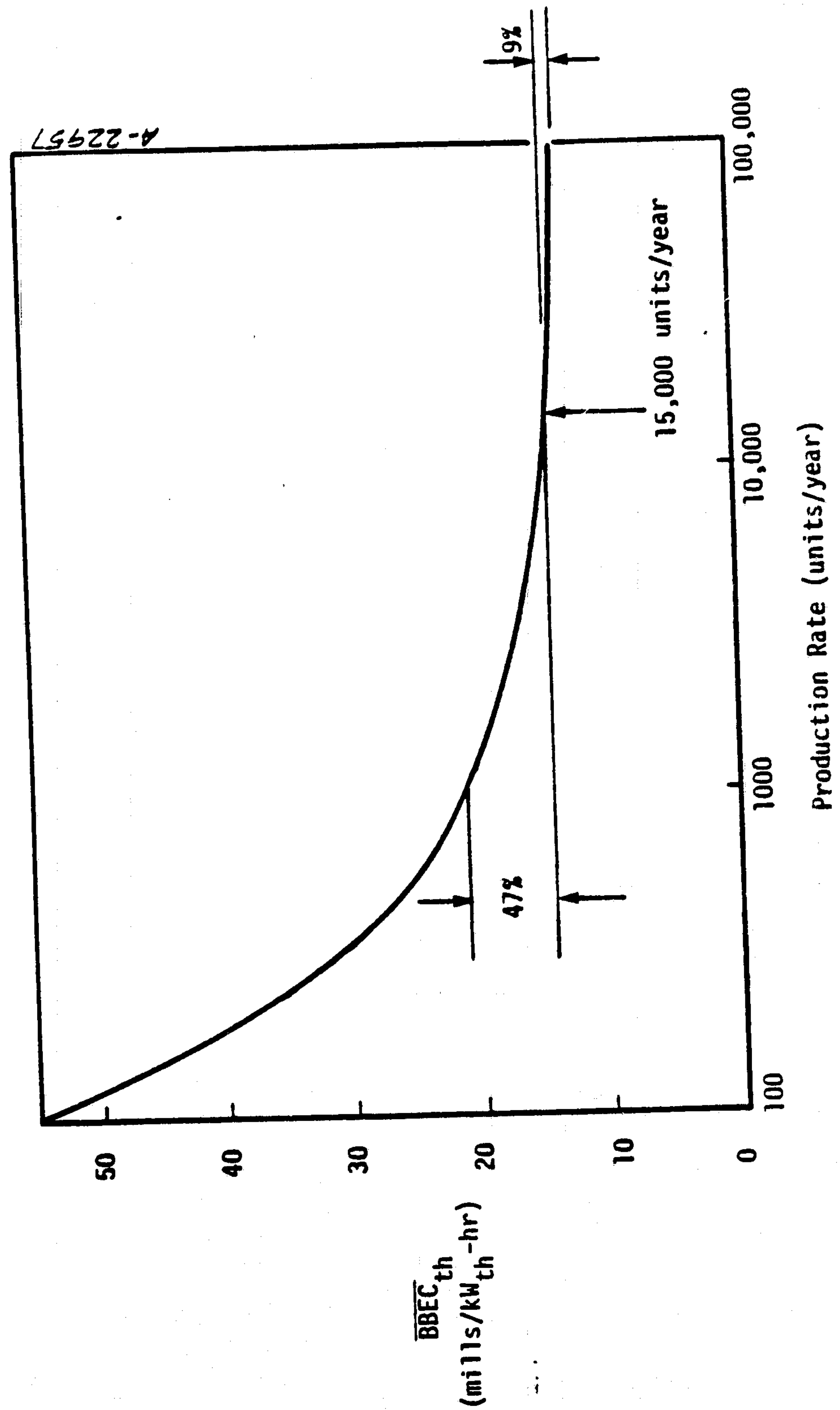

Figure 3-10. Levelized busbar energy cost plot.

Areas for Potential Cost Reduction

The production plan presented here is a conceptual plan and there are areas in which additional study have potential for achieving cost savings.

In determining areas for cost reduction, it is important to understand what elements of the cost buildup have the greatest impact. Table 3-40 shows a percentage breakdown by the various cost categories of the levelized cost of delivered thermal energy ($\overline{BBEC}_{th}$). The breakdown of $BBEC_{th}$ is used as the basis for discussion because it more accurately reflects the cost of the concentrator as it includes operation and maintenance costs.

The table shows that almost 60 percent of the $\overline{BBEC}_{th}$ is due to initial costs of materials used at the factory and during installation. This indicates that the greatest reduction in cost can be achieved by reductions in material costs.

Also, as factory tooling and installation equipment costs are only 2 percent of the total, significant increases in the costs of these categories would be warranted in order to achieve savings in material and labor. Maintenance costs are also a good means for potential cost reductions as they consititue 20 percent of the $\overline{BBEC}_{th}$ cost. Panel cleaning itself is 40 percent of the maintenance cost and therefore 8 percent of the total.

Using these observations as guidelines, the following areas have been identified in which significant cost reductions may be achieved through additional study:

Reflective Panels

- Reduction in panel weight through detailed analysis and testing
- Reduction in panel weight through the addition of glass microsphere filler
- Higher plant output through alterations in the SMC formulation to speed cure times
- Reduced labor input via use of a highly automated facility

Structural Steel Components

- Reduction in steel weight through detailed analysis and testing
- Reduction of raw material cost via in-house production of steel tubing from sheet stock
- Reduction of steel weight with use of optimized cross section members via in-house production of steel tubing
- Reducted labor input via use of a highly automated facility

Installation

- Reduced field labor through use of automated steel fabrication machines which would be cost-effective for installation of fields not limited by the 100 unit size

Maintenance

- Reduced labor for cleaning through use of more automated cleaning equipment

TABLE 3-40. $\overline{BBEC}_{th}$ COST BREAKDOWN
(@ 100K concentrators per year)

	% of $\overline{BBEC}_{th}$
Production	
Material	56
Direct labor	3
Tooling	1
Indirect	4
	64
Installation	
Material	3
Direct labor	6
Equipment	1
Indirect	6
	16
Operation and maintenance	
Material	8
Labor	12
	20
Total	100

REFERENCES FOR SECTION 3

3-1. Solar Central Receiver Prototype Heliostat CDRL Item B.d, Final Technical Report, Volume II, McDonnell Douglas Astronautics Corp., MDC G 7399, prepared under DOE Contract E6-77-C-03-1605, August 1978.

3-2. Building Construction Cost Data 1978, R. S. Means Co. Inc., 1978.

3-3. Process Plant Construction Estimating Standards, Richardson Engineering Services, Inc., 1978.

3-4. J. M. Freese, "Effects of Outdoor Exposure on the Solar Reflectance Properties of Silvered Glass Mirrors," SAND 78-1649, September 1978, available through NTIS.

APPENDIX A

DETAILED PRODUCTION COST TABLES

This Appendix contains the detailed production cost tables referenced in Section 3. The contents are as follows:

- Table A-1 -- Materials Requirements and Costs
- Table A-2 -- Tooling and Equipment Requirements
- Table A-3 -- Manufacturing Direct Labor
- Freight Costs

TABLE A-1. MATERIALS REQUIREMENTS AND COSTS A_n = 102 m^2

CBS Element	Description	Raw Mat'l or Purch. Part	Unit Req./ Conc.	Yield Loss (%)	Scrap (%)	Total Req./ Conc.	$/ Unit	Freight In/ Unit	Total $/ Unit	$/ Conc.	$/ m^2
1000 Reflective Panels											
1001 Glass mirror	Silvered drawn glass (0.7 mm thick)	RM	112 m^2	0%	5%	118 m^2	7.53[1]	2.5%	7.72	910.96	8.93
1002 Sheet molding compound	Overall SMC req. 33 @ 94 lb. = 3102 lb										
	Resin - 45% by weight	RM	1400 lb	7%	10%	1650 lb	0.40[2]	2.5%	0.41	676.50	
	Glass fiber -35% by weight	RM	1090 lb	7%	10%	1280 lb	0.45[2]	2.5%	0.46	588.80	
	Filler - 20% by weight	RM	620 lb	7%	10%	730 lb	0.02[2]	2.5%	0.021	15.33	
	Additives (for thermal expansion matching)	RM	(10¢/lb)	--	--	--	0.10[2]	2.5%	0.103	376.98	
	Glass/SMC bonding primer (0.3 gal/panel)	RM	9.9 gal.	3%	15%	11.7 gal.	4.00[2]	2.5%	4.10	47.97	
										1,705.58	16.72
1003 Attachment hardware	See design data	PP	33	0%	3%	34	5.00[2]	2.5%	5.13	173.25	1.70
10001 Shipping material	Shipping protection for panels	RM	33	--	3%	34	8.00[2]	2.5%	8.20	278.80	2.73
										3,069.58	30.09
							Freight to Site			80.80	0.79
										3,150.38	30.88

[1]Vendor quote at 15K/year
[2]Acurex estimate
[3]Scaled vendor quote

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TABLE A-1. (Continued)

CBS Element	Description	Raw Mat'l or Purch. Part	Unit Req./Conc.	Yield Loss (%)	Scrap (%)	Total Req./Conc.	$/Unit	Freight In/Unit	Total $/Unit	$/Conc.	$/m²
2000 Drive System											
2100 Azimuth Drive	2101 Hydraulic rotary actuator	PP	1	--	--	1	1870[3]	--	1870	1,870.00	
	2102 Collar	PP	1	--	--	1	70[2]	--	70	70.00	
										1,940.00	19.02
2200 Elevation Drive	2201 Hydraulic single stage cyclinder	PP	1	--	--	1	300[2]	--	300	300.00	
	2202 Clevis bracket	PP	1	--	--	1	70[2]	--	70	70.00	
										370.00	3.63
2300 Support wheels	2301 Steel wheels w/sealed bearings	PP	3	--	--	3	100[2]	--	100	300.00	
2400 Hyraulic supply	2401 Pump/motor	PP	1	--	--	1	164[3]	--	164	164.00	
	2402 Accumulator	PP	1	--	--	1	213[3]	--	213	213.00	
										377.00	3.70
										2,987.00	29.28
							Plus 3% purchasing OH			84.61	0.83
							Freight to site @ 2.5%			74.68	0.73
										3,151.29	30.90

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TABLE A-1. (Continued)

CBS Element	Description	Raw Mat'l or Purch. Part	Unit Req./ Conc.	Yield Loss (%)	Scrap (%)	Total Req./ Conc.	$/ Unit	Freight In/ Unit	Total $/ Unit	$/ Conc.	$/ m^2
3000 Control/ Electrical System											
3100 Tracker											
3110 Sun Sensor	3111 Two-axis sun sensor	RM	1	--	--	1	25.00[2]	--	25.00	25.00	
3120 Position Feedback	3121 Position Potentiometer	PP	2	--	--	2	25.00[2]	--	25.00	50.00	
3130 Micro-computer	3131 Electronics	RM	1	--	--	1	100.00[2]	--	100.00	100.00	
	3132 Enclosure	PP	1	--	--	1	20.00[3]	--	20.00	20.00	
										120.00	
										195.00	1.91
3200 Hydraulic control	3201 Solenoid control valves	PP	3	--	--	3	82.00[3]	--	82.00	246.00	
	3202 Stow control Cam valve	PP	1	--	--	1	20.00[2]	--	20.00	20.00	
	3203 Valve block	PP	1	--	--	1	123.00[3]	--	123.00	123.00	
	3204 Hydraulic lines	PP	6	--	--	6	7.50[2]	--	7.50	45.00	
										434.00	4.25
3300 Electrical											
3310 Receiver power out	3311 Cable, 3 conduc. #8 w/#10 ground	PP	80 ft.	--	--	80 ft.	0.70[3]	--	0.70	56.00	
	3312 Fused disconnect	PP	2	--	--	2	35.00[3]	--	35.00	70.00	
										126.00	
3320 Electrical power in	3321 Cable, #10 THW	PP	60 ft.	--	--	60 ft.	0.06[3]	--	0.06	3.60	
	3322 Fused disconnect	PP	1	--	--	1	35.00[3]	--	35.00	35.00	
										38.60	

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TABLE A-1. (Continued)

CBS Element	Description	Raw Mat'l or Purch. Part	Unit Req./ Conc.	Yield Loss (%)	Scrap (%)	Total Req./ Conc.	$/ Unit	Freight In/ Unit	Total $/ Unit	$/ Conc.	$/ m^2
3300 Electrical (continued)											
3330 Control Signals in/out	3311 Cables, #14 THW	PP	80 ft.	--	--	80 ft.	0.03[3]	--	0.03	2.40	
3340 Cabling/ field interface	3342 Flex conduit 2"	PP	8 ft.	--	--	8 ft.	3.30[3]	--	3.30	26.40	
	3342 Flex conduit connectors	PP	2	--	--	2	10.00[3]	--	10.00	20.00	
										46.40	
3350 Lightning Protection/Ground	3351 Lightning Arrestor	PP	2	--	--	2	5.00[3]	--	5.00	10.00	
	3152 Ground straps panel support-base	PP	2	--	--	2	2.00[3]	--	2.00	4.00	
	3153 Group Rod-15	PP	1	--	--	1	41.00[3]	--	41.00	41.00	
	3154 Cable, 4/0 copper	PP	10 ft.	--	--	10 ft.	1.16[3]	--	1.16	11.60	
										66.60	
										280.00	2.75
										909.00	8.91
							Plus 3% Purch. OH			27.27	0.27
							Freight to site @ 2.5%			22.73	0.22
										959.00	9.40

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TABLE A-1. (Continued)

CBS Element	Description	Raw Mat'l or Purch. Part	Unit Req./ Conc.	Yield Loss (%)	Scrap (%)	Total Req./ Conc.	$/ Unit	Freight In/ Unit	Total $/ Unit	$/ Conc.	$/ m²
4000 Raised Track											
4100 Raised track sections	4101 Track I-beam W8 x 20 Sections	RM	122 ft.	0%	3%	126 ft.	7.00[2]	2.5%	7.18	904.68	
	41011 Paint and primer	PP	0.3 gal.	10%	3%	0.3 gal.	10.00[2]	2.5%	10.25	3.08	
	41001 Packaging Materials	PP	1	--	2%	1.02	40.00[2]	2.5%	41.00	41.82	
4200 Mounting plates	4202 Mounting flanges	PP	164 lb.	0%	3%	169 lb.	0.35[2]	2.5%	0.36	60.84	
										1,010.42	9.91
								Freight to site		11.90	0.12
										1,022.32	10.02

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TABLE A-1. (Concluded)

CBS Element	Description	Raw Mat'l or Purch. Part	Unit Req./ Conc.	Yield Loss (%)	Scrap (%)	Total Req./ Conc.	$/ Unit	Freight In/ Unit	Total $/ Unit	$/ Conc.	$/ m^2
5000 Structure											
5100 Panels support structure	5101 Steel tubing	RM	3750 lb.	0%	3%	3,860 lb.	0.30[2]	2.5%	0.3075	1,186.95	
	5102 Paint and primer	PP	0.7 gal.	10%	3%	0.8 gal.	10.00[2]	2.5%	10.25	8.20	
	51001 Welding supplies	RM	1	--	--	1	20.00[2]	2.5%	20.50	20.50	
	51002 Packaging material	RM	1	0%	2%	1.02	65.00[2]	2.5%	66.63	67.96	
										1,283.61	12.58
5200 Base support structure	5201 Steel tubing	RM	1670 lb.	0%	3%	1720 lb.	0.30[2]	2.5%	0.3075	528.90	
	5202 Paint and primer	PP	0.4 gal.	10%	3%	0.5 gal.	10.00[2]	2.5%	10.25	5.13	
	52001 Welding supplies	RM	1	--	--	1	15.00[2]	2.5%	15.38	15.38	
	52002 Packaging material	RM	1	0%	2%	1.02	50.00[2]	2.5%	51.25	52.28	
										601.69	5.90
5300 Receiver support structure	5311 Steel tubing	RM	550 lb.	0%	3%	567 lb.	0.30[2]	2.5%	0.3075	174.35	
	5312 Paint and primer	PP	0.2 gal.	10%	3%	0.2 gal.	10.00[2]	2.5%	10.25	2.05	
	5321 Receiver mount	PP	50 lb.	0%	3%	52 gal.	0.35[2]	2.5%	0.35	18.72	
	53001 Packaging material	RM	1	--	2%	1.02	40.00[2]	2.5%	41.00	41.82	
										236.74	2.32
								Freight to site		28.25	0.28
										2,150.49	21.08

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TABLE A-2. TOOLING AND EQUIPMENTS 20 CONC/HR -- 15,000 CONC/YEAR, $A_n = 102\ m^2$

CBS Element	Operation	Tooling	Pieces Tool/ Shift	Number of Tools	Cost/ Tool ($1,000)	Total Cost ($1,000)	$/ CONC*	$/ m^2
1000 Reflective Panels								
1001 Glass Mirror	Prepare glass	Glass prep fixture	70	10	12	120	1.20	0.01
1002 Sheet Molding Compound	Prepare SMC	Spreader	210	3	1,200	3,600	36.00	
	Press panel	Press/mold	70	11	700	7,700	77.00	
	Cool panel	Cool fixture	70	11	20	220	2.20	
	Deflash panel	Deflash fixture	105	7	70	490	4.90	
	Material handling	Material handling	--	--	--	2,000	20.00	
						14,100	141.00	1.38
1003 Attachment	Attach hardware and package panels	Mechanical assembly fixtures	52	14	30	420	4.20	0.04
						14,550	145.50	1.43
4000 Track								
4100 Raised Track	Roll track section	I-beam radiusing device	180[1]	1	250	250	2.50	
	Paint	Paint station	--	1	100	100	1.00	
	Package	Packaging equipment	180[1]	1	20	20	2.00	
							3.70	0.04

*At 10 year tool life, interest rate = 8%
CRF = 0.149; at 15,000 CONC/year
Total cost x 1 x 10^{-5} = $/CONC
[1]Two shift operation

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APPENDIX A-2. (Concluded)

CBS Element	Operation	Tooling	Pieces Tool/ Shift	Number of Tools	Cost/ Tool ($1,000)	Total Cost ($1,000)	$/ CONC*	$/ m^2
5000 Structure								
5100 Panel Support Structure	Cut-to-length	Press--OBI w/feeding mechanism and stops	1,440	1	400	400	4.00	
	Fixture Weld -- A	Fixture	60	1	175	175	1.75	
	Fixture Weld -- B	Fixture	60	1	150	150	1.50	
	Fixture Weld -- C	Fixture	60	1	100	100	1.00	
	Paint	Paint station (2 shift)	--	1	250	250	0.25	
	Package	Package equipment	--	--	--	75	0.75	
						1,150	11.50	0.11
5200 Base Support Structure	Cut-to-length	Press--OBI w/feeding mechanisms and stops	1,740 (2 shifts)	1	267[1]	267	2.67	
	Fixture weld -- A	Fixture } 1 shift	60	1	175	350	3.50	
	Fixture weld -- B	Fixture } 1 shift	60	2	175	350	3.50	
	Fixture weld -- C	Fixture } 1 shift	60	2	150	150	1.50	
	Paint	Paint station (1 shift)	--	1	125[4]	125	1.25	
	Package	Package equipment (1 shift)	--	--	--	25[2]	0.25	
						1,267	12.67	0.12
5300 Receiver Support Structure	Cut-to-length	Press[3]	540	1	133[1]	133	1.33	
	Paint	Paint station[3]	--	--	125[4]	125	1.25	
	Package	Package equipment[3]	--	--	--	25[2]	0.25	
						283	2.83	0.03
						2,700	27.00	0.26

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*At 10 year tool life, interest rate = 8%
CRF = 0.149; at 15,000 CONC/year,
Total cost x 1 x 10^{-5} = $/CONC
[1]Total tool cost $400,000 -- apportioned between base and receiver support
[2]Divided between base and receiver support
[3]Use base equipment on third shift
[4]Total tool cost $250,000

Table A-3. MANUFACTURING DIRECT LABOR AT 20 CONC/SHIFT -- 15,000 YEAR, $A_n = 102\ m^2$

CBS Element	Operation	Pieces/ Station/ Shift	Stations	Men/ Station	Men Req'd	Man/Hrs. CONC	$/ Man Hr.	$/ CONC	Overhead	Total $/ CONC	$/m²
1000 Reflective Panels											
1001 Glass Mirror	Prep glass	70	10	2	20	8.0	4.00	32.00	147%	79.04	
1002 Sheet Molding Compound	SMC production	(3430 lb/CONC @ 80 lb/man hr)			107	42.9	4.00	171.50	200%	514.50	
	Prepare SMC charge for molding	[illegible]	3	6	18	7.2	4.00	28.80	147%	71.14	
	Load mold/press panel	70	11	2	11	8.8	4.00	35.20	147%	86.94	
	Deflash	105	7	2	14	5.6	4.00	22.40	147%	55.33	
	Material handling	--	--	--	8	3.2	4.00	12.80	147%	31.62	
1003 Attachment Hardware	Attach hardware and package panel	52	14	3	42	16.8	4.00	67.20	147%	165.98	
						92.5		369.9		1004.55	9.85
4000 Track											
4100 Raised Track	Roll track	180 (2 shifts)	1	4	4	1.1	6.00	6.60	246%	22.84	
	Paint	--	1	2	2	0.5	6.00	3.00	246%	10.38	
	Package	180 (2 shifts)	1	1	1	0.3	6.00	1.80	246%	6.23	
	Material handling	--	--	1	1	0.3	6.00	1.80	246%	6.23	
						2.2		13.20		45.67	0.45

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TABLE A-3. (Concluded)

CBS Element	Operation	Pieces/ Station/ Shift	Stations	Men/ Station	Men Req'd	Man/Hrs. CONC	$/ Man Hr.	$/ CONC	Overhead	Total $/ CONC	$/m²
5000 Structure											
5100 Panel Support Structure	Cut members to length	1,420	1	3	3	1.2	6.00	7.20	246%	24.91	
	Fixture weld -- A	60	1	3	3	1.2	6.00	7.20	246%	24.91	
	Fixture weld -- B	60	1	3	3	1.2	6.00	7.20	246%	24.91	
	Fixture weld -- C	60	1	2	2	0.8	6.00	4.80	246%	16.61	
	Paint (2 shift)	--	1	2	2	0.5	6.00	3.00	246%	10.38	
	Package	--	--	2	2	0.8	6.00	4.80	246%	16.61	
	Material handling	--	--	2	2	0.8	6.00	4.80	246%	16.61	
						6.5		39.00		134.94	1.32
5200 Base Support Structure	Cut members to length	1,260	1 (2 shift)	3	3	0.8	6.00	4.80	246%	16.61	
	Fixture weld -- A	60	1*	3	3	0.4	6.00	3.20	246%	11.07	
	Fixture weld -- B	60	2*	3	6	0.8	6.00	4.80	246%	16.61	
	Fixture weld -- C	60	2*	2	4	0.5	6.00	3.00	246%	10.38	
	Paint	--	1*	2	2	0.3	6.00	1.80	246%	6.23	
	Package	--	1*	2	2	0.3	6.00	1.80	246%	6.23	
	Material handling	--	1*	3	3	0.4	6.00	2.40	246%	8.30	
						3.5		21.00		72.66	0.71
5300 Receiver Support Structure	Cut to length	540	1*	2	2	0.3	6.00	1.80	246%	6.23	
	Paint	--	1*	2	2	0.3	6.00	1.80	246%	6.23	
	Package	--	1*	2	2	0.3	6.00	1.80	246%	6.23	
	Material handling	--	1*	2	2	0.3	6.00	1.80	246%	6.23	
						1.2		8.20		24.91	0.24
						11.2		67.20		232.51	2.28

*One shift

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Freight Costs

Freight to site costs are assigned to the material cost buildup and have been developed in the following manner.

A dedicated fleet of trucks and trailers will be used for shipment. Shipping from the factory to sites within a 100 mile radius will run on a three shift basis, five days/week. At each site, a three day inventory of concentrator subassemblies will be stored during installation upon the trailers they are shipped on.

Each standard truck trailer has been estimated to hold either:

- Two sets of reflective panels (66 individual) per trailer - size limited
- Four sets of structure/track per trailer - weight limited*

Each trip to a site will average 70 miles or a round trip of 140 miles. Assuming an average speed of 40 miles per hour with a half-hour turnaround at each end, the total driver time per trip is 4.5 hours. At a driver cost of $20/hour (loaded), each trip will cost $90.

The panel shipment cost is based on the following:

One truck and trailer will be able to ship panels for 200 concentrators/month (4.5 hours/trip x 5 trip/day @ 2 conc./trip). The equipment required is:

One truck	@ $ 50K ea.	$ 50K
Eighteen trailers**	@ $ 16.7K ea.	$300K
Total		$350K

---

*Four sets @ 8,620 lbs/set = 17 tons vs. 20 ton limit
**One on road, one at factory, 16 for field inventory at 2 fields at 100 conc./month

CRF* (10 years, 8%) - 0.149

Yearly Cost	$ 52K
@ (100 trips/month) (140 mi/trip) (20¢/mile/O&M cost)	
Total O&M cost	$ 34K
Total Yearly Equipment Cost	$ 86K
or @ 2400 conc./year	$ 35.80 per conc.
Labor cost @$90/trip,2 conc./trip	$ 45.00 per conc.
Total shipping costs - panels	$ 80.80 per conc.
or @ 4040 lbs..conc	2.0¢/lb.

The structure shipping cost is:

One truck and trailer will ship structure and track for 400 concentrators per month (5 trips/day @ 4 conc./trip). Therefore, the equipment required is:

1 truck @ $50K each	$ 50K
18 trailers @ $16.7K each	$300K
	$350K

This indicates the total yearly equipment cost will be the same as for the panels:

Total yearly equipment cost	$86K
@ 4800 conc./year	$17.90 per conc.
Total labor cost	
@ $90/trip 4 conc./trip	$22.50 per conc.
Total shipping cost - structure/track	$39.40 per conc.
or @8,620 lbs.	$ 0.5¢/lb.

*Capital recovery factor

APPENDIX B

DETAILED INSTALLATION COST TABLES

This Appendix contains the detailed installation cost tables referenced in Section 3. The contents are as follows:

- Table B-1 -- Installation Labor
- Table B-2 -- Installation Material
- Table B-3 -- Installation Equipment
- Table B-4 -- Installation Indirect Costs

TABLE B-1. INSTALLATION LABOR

CBS Element	Activity	Time Required Hr/Field	Men Required	Man Hrs/ CONC	$/ Man Hr	$/ CONC	$/ m²
6100	Site preparation						
6101	Clear and grade	28	4	1.12	10.00	11.20	0.11
6102	Layout foundations	234	2	2.68	10.00	26.80	0.25
6103	Prepare work area	16	5	0.80	10.00	8.00	0.075
6104	Setup tooling	16	4	0.64	10.00	6.40	0.060
6105	Setup shelter	8	5	0.40	10.00	4.00	0.038
6106	Move on	40	5	20.00	10.00	200.00	1.88
	Subtotal			25.6		256.00	2.41
6200	Foundation installation						
6210	Pier installation						
6211	Bore pier holes	64	2	1.28	10.00	13.00	0.12
6212	Install rebar cages	23	2	0.46	10.00	4.60	0.043
6213	Install forms	43	1	0.43	10.00	4.30	0.040
6214	Align studs	23	2	0.46	10.00	4.60	0.043
6215	Pour concrete	39	2	0.78	10.00	7.80	0.073
6216	Clean up and move on	21	2	0.42	10.00	4.20	0.040
6220	Track installation						
6221	Mount track segments	50	4	2.00	10.00	20.00	0.19
6222	Level segments	50	2	1.00	10.00	10.00	0.094
6223	Torque attach bolts	80	2	1.60	10.00	16.00	0.15
6224	Grout	160	1	1.60	10.00	16.00	0.15
	Subtotal			10.00		100.00	0.94

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TABLE B-1. (Continued)

CBS Element	Activity	Time Required Hr/Field	Men Required	Man Hrs/ CONC	$/ Man Hr	$/ CONC	$/ m^2
6300	Concentrator assembly and installation						
6310	Base support frame ass. and inst.						
6311	Assemble subtrusses	200	5	10.0	10.00	100.00	0.94
6312	Install hydraulic components	200	4	8.0	10.00	80.00	0.75
6313	Install electrical components	100	2	2.0	10.00	20.00	0.19
6314	Transport to foundation and hoist onto track	50	4	2.0	10.00	20.00	0.19
6315	Adjust rotary act. mounting bolts	50	2	1.0	10.00	10.00	0.094
6316	Grout	56	1	0.56	10.00	5.60	0.053
6320	Reflector assembly and installation						
6321	Assemble panel support structure	300	5	15.0	10.00	150.00	1.41
6322	Install interior reflective panels	218	4	8.7	10.00	87.00	0.82
6323	Assemble receiver support	100	4	4.0	10.00	40.00	0.38
6324	Attach reflector support to reflector	25	4	1.0	10.00	10.00	0.094
6325	Install exterior reflective panels	82	4	3.3	10.00	33.00	0.31
6326	Install electrical components	100	2	2.0	10.00	20.00	0.19
6327	Install tracker and sensors	50	1	0.5	10.00	5.00	0.047
6328	Transport and install on base	50	4	2.0	10.00	20.00	0.19
	Subtotal			60.1		601	5.65

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TABLE B-1. (Continued)

CBS Element	Activity	Time Required Hr/Field	Men Required	Man Hrs/ CONC	$/ Man Hr	$/ CONC	$/ m^2
6400	Adjustment and checkout						
6410	Panel alignment						
6411	Mount target to receiver	16	2	0.32	10.00	3.20	0.030
6412	Mount scope (33 times/conc)	250	1	2.5	10.00	25.00	0.24
6413	Adjust panel (33 times/conc)	250	2	5.5	10.00	55.00	0.52
6420	Drive adjustment						
6421	Connect field power	33	2	0.66	10.00	6.60	0.062
6422	Adjust tracking and stow rates	25	1	0.25	10.00	2.50	0.024
6423	Adjust sun sensor and tracker	25	1	0.25	10.00	2.50	0.024
6424	Perform functional checkout	50	2	1.0	10.00	10.00	0.094
	Subtotal			10.5		105.00	0.99

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TABLE B-2. INSTALLATION MATERIAL

CBS Element	Activity	Item	Quantity/ CONC	$/ Unit	$/ CONC	$/ m^2
6100	Site preparation					
6101	Clear and grade	Dozer operating cost	0.28 hr	6.10/hr	1.71	0.016
6102	Layout foundations	Survey markers	20	0.05/ea	1.00	0.0094
6103	Prepare work area	Gravel	16 yd^3	5.00/yd^3	80.00	0.75
		Tractor operation	0.035 hr	6.10/hr	0.21	0.0020
6104	Setup tooling	Crane operation	0.08 hr	1.95/hr	0.16	0.0015
6105	Setup shelter					
6106	Move on					
	Subtotal				83.08	0.78

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TABLE B-2. (Continued)

CBS Element	Activity	Item	Quantity/ CONC	$/ Unit	$/ CONC	$/ m^2
6200	Foundation installation					
6210	Pier installation					
6211	Bore pier holes	Drill operation	0.64 hr	4.10/hr	2.62	0.25
6212	Install rebar cages	Rebar cages Anchor bolts Crane operation	145 lbs. 28 0.23 hr	0.45/lbs* 3.70/ea 1.95/hr	65.25 104.00 0.45	0.61 0.98 0.0042
6213	Install forms					
6214	Align studs					
6215	Pour concrete	Concrete	2.93 yd^3	70/yd^3	205.00	1.93
6216	Clean up and move on					
6220	Track installation					
6221	Mount track segments	Crane operation	0.50 hr	1.95/hr	0.98	0.0092
6222	Level segments					
6223	Torque attach bolts	Air wrench operation	0.80 hr	1.05/hr	1.00	0.94
6225	Grout	Nonshrink, metalic grout	0.84/ft^3	34/ft^3	28.00	0.26
6226	Clean up and move on					
	Subtotal				407.00	3.83

*Includes forming and ties

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TABLE B-2. (Continued)

CBS Element	Activity	Item	Quantity/ CONC	$/ Unit	$/ CONC	$/ m^2
6300	Concentrator assembly and installation					
6310	Base support frame assembly and installation					
6311	Assemble subtruses	Forklift operation Air wrench operation	0.50 hr 2.00 hr	2.70/hr 1.35/hr	1.35 2.70	0.013 0.025
6312	Install hydraulic components	Crane operation	0.25 hr	1.95/hr	0.49	0.0046
6313	Install electrical components					
6314	Transport to foundation and hoist onto track	Truck operation Crane operation	0.25 hr 0.25 hr	2.65/hr 3.50/hr	0.66 0.88	0.0062 0.0083
6315	Adjust rotary act. mounting bolts					
6316	Grout	Nonshrink metalic grout	0.29 ft^3	34/ft^3	10.00	0.094
6320	Reflector assembly and installation					
6321	Assemble panel support structure	Forklift operation Air wrench operation	0.75 hr 3.00 hr	2.70/hr 1.35/hr	2.03 4.05	0.19 0.038
6322	Install interior reflective panels	Crane operation	2.18 hr	1.95/hr	4.25	0.040
6323	Assemble receiver support	Crane operation	0.25 hr	1.95/hr	0.49	0.046
6324	Attach receiver support to reflector	Crane operation	0.25 hr	1.95/hr	0.49	0.0046
6325	Install exterior reflective panels	Crane operation	0.82 hr	1.95/hr	1.60	0.015
6326	Install electrical components					
6327	Install tracker and sensors					
6328	Transport and install on base Install on base	Truck operation Crane operation	0.25 hr 0.25 hr	2.65/hr 3.50/hr	0.66 0.88	0.0062 0.0083
	Subtotal				30.00	0.29

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TABLE B-2. (Concluded)

CBS Element	Activity	Item	Quantity/ CONC	$/ Unit	$/ CONC	$/ m^2
6400	Adjustment and checkout					
6410	Panel alignment					
6411	Mount target to receiver support	Cherry picker operation	0.16 hr	4.10/hr	0.66	0.0062
6412	Attach scope to panel					
6413	Adjust panel					
6420	Drive adjustment					
6421	Connect field wiring					
6422	Adjust tracking and stow rates					
6423	Adjust sun sensor and tracker	Cherry picker operation	0.25 hr	4.10/hr	1.02	0.0096
6424	Perform functional checkout					
	Subtotal				1.68	0.016

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TABLE B-3. INSTALLATION EQUIPMENT

CBS Element	Item	Cost/ Unit	Quantity	Cost/* CONC
6100	180HP bulldozer	45,000	2	17.88
	10T dump truck	20,000	2	5.96
	Transit	1,000	2	0.30
	Light truck	5,000	1	0.75
	Subtotal			24.89
6200	Drill rig	150,000	1	22.35
	1T forklift	10,000	1	1.49
	3T flatbed truck	20,000	2	5.96
	Air compressor, 60 CFM	500	2	0.15
	Light truck	5,000	2	1.49
	5T self-propelled crane	20,000	1	2.98
	Subtotal			34.42
6300	Assembly jigs	20,000	10	29.80
	2T forklift	15,000	1	2.24
	5T self-propelled crane	20,000	2	5.96
	3T flatbed truck	20,000	1	2.98
	5T flatbed truck	30,000	1	4.47
	Air compressor, 250 CFM	1,000	1	0.15
	Storage bins	1,000	1	0.15
	Subtotal			45.75
6400	Cherry picker	25,000	2	7.45
	Light truck	5,000	1	0.75
	Alignment scope	500	5	0.37
	Alignment target	100	5	0.07
	Subtotal			8.64

*Tool cost based on:
- -- 10 yr tool life
- -- Interest rate = 8 % (capital recovery factor = .149)
- -- 1000 conc./yr

$$\$/\text{conc} = \frac{(\text{tool cost})\ (0.149)}{1000}$$

TABLE B-4. INSTALLATION -- INDIRECT COSTS

Category	Description	Percent of Labor Cost
Labor	Supervision	10
	Inspectors	5
	Planner/expediter	5
	Equipment maintenance	3
	Personnel	4
	Accounting	2
	Purchasing/receiving	1
	Subtotal	30%
Inventory	(Not required)	--
Fringe benefits	Workmens' Comp	7.6
	Social Security	6.1
	Unemployment	4.8
	Other	10.0
	Subtotal	28.5%
Facilities and Utilities	Small tools	3.0
	Utilities	1.0
	Other	5.0
	Subtotal	9.0
Materials	Consumables	1.0
	Equipment parts	5.0
	Subtotal	6.0
Other	Bonds	1.0
	Permits	0.5
	Insurance	1.0
	Travel and per diem	10.0
	Subtotal	12.5%
	TOTAL	86

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