SOLAR COLLECTOR DESIGN AND FABRICATION PROGRAM FINAL REPORT

BR-10394

MAY 1978

Purchase Order 05-4571

RAYTHEON

RAYTHEON COMPANY
MISSILE SYSTEMS DIVISION

UNCLASSIFIED

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Prepared for
SANDIA LABORATORIES
SANDIA CORPORATION
Albuquerque, New Mexico 87115

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EXECUTIVE SUMMARY

This report describes the continuation of activities directed toward the installation and operation of a test point concentration collector at Sandia Laboratories, Albuquerque. A previous program had developed the requirements for and preliminary design of a 22 ft diameter point concentrator, using curved glass mirrors to focus energy into an annular aperture thereby heating fluid to 600°F. The principal objectives of this program were to produce detailed manufacturing drawings of the collector and procure and install the collector at Sandia for test and evaluation. These objectives were accomplished and the collector is currently being operated by Sandia personnel.

Foremost in the collector design and manufacturing problems addressed were those associated with the mirror support structure and the mirrors themselves. Mirror angular alignment accuracies on the order of a few milliradians were required to ensure reflected energy passage through the entrance aperture with minimal loss. This requirement was recognized as difficult, particularly in a collector whose manufacturing concept had not been demonstrated beforehand. Consequently the ability to perform individual mirror alignments was designed-in to reduce program risks to acceptable levels

During the course of manufacturing the mirrors and mirror support structure, various inaccuracies caused both to deviate from specification by significant amounts. The most significant problem was the tendency of the curved glass to relax to a flatter shape during silvering and cutting processes following annealing. Typically, the mirror radius of curvature increased approximately 25%, although larger and smaller increases were noted, occurring on a seemingly random basis. A solution to the problem was not attained during the program although an attempt to incorporate the unexpected radius growth into the mirror selection process was partially successful. The individual mirror alignment ability of the collector was utilized to minimize energy loss caused by the larger than expected spot size at the absorber entrance aperture.

The report contains a detailed description of requirements, design and manufacturing of collector major components, including the mirrors, mirror support structure, absorber and its support structure, and the pedestal and drives. Numerous illustrations of the in-process and finished and installed equipment are included. Also included are the requirements for the collector control system, automatic and manual, as well as a description of a fluid circulating system to maintain delivered fluid temperature at a preselected value.

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1.0 Introduction and Summary

This is a report on activities performed under contract with Sandia Laboratories, Albuquerque, New Mexico toward the development of point concentrators for Solar Total Energy Systems application. The contract was one of a series resulting in the design and fabrication of a 22 ft. diameter collector, and delivery of same to the Albuquerque test facility. Erection and engineering evaluation will be performed by Sandia personnel.

Figure 1-1 is an artist's concept of the point concentrator collector. The collector is a reflective quasi-parabola 22 ft. in diameter with an effective aperture of 375 ft^2. Concentrated solar energy is focussed in a 3 ft^2 annular entrance aperture to a cavity absorber located on the collector centerline. The absorber is cylindrical with a disc shaped upper section enclosed in a reflective canister. The absorber material is zirconium copper, plated with Harshaw black chrome selective coating. Absorber efficiencies of 90 percent are expected, attained by the relatively high energy concentration, the selective coating, minimization of reflected radiation leaving the absorber cavity, and the convection suppression effect of the cavity design.

The reflective quasi-parabolic design is implemented by spherical mirror segments hard mounted on an aluminum substructure. The mirrors are sagged, water white crystal glass, back silvered to provide maximum reflectance over the course of an expected twenty year life. Specular reflectance values on the order of 0.9 are expected from the mirrors.

The collector is driven in azimuth and elevation by dc stepping motors, computer controlled. The elevation drive system consists of a ball screw driven by a worm gear reducer from the

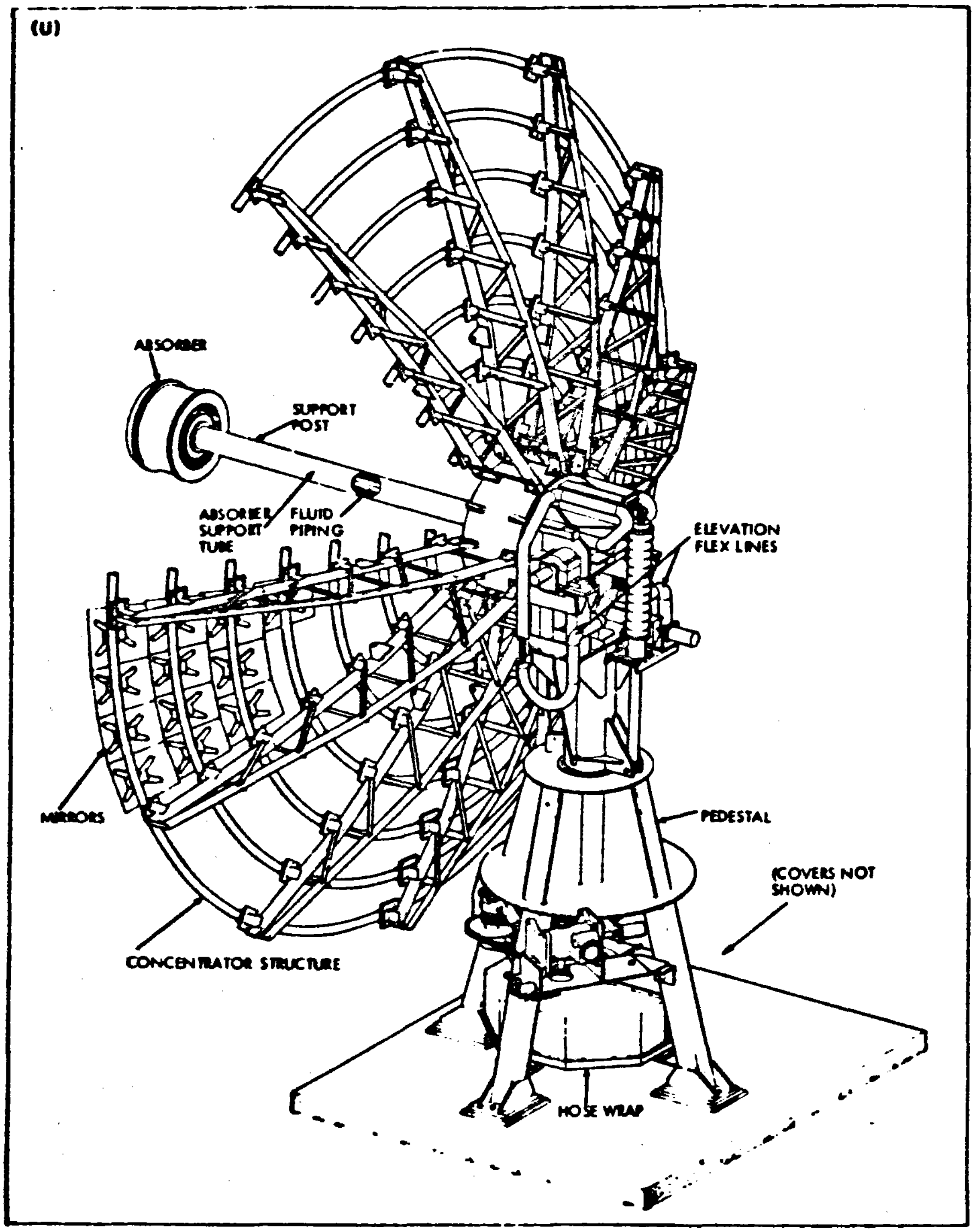

FIGURE 1-1. Point Concentrator Solar Collector

stepping motor. A double reduction chain drive and worm gear comprise the azimuth drive system.

1.1 Background

The subject development program is one of a series that began in early 1976, with an award to study the applicability of point concentrators to solar total energy systems per Sandia Laboratories requirements. Among the requirements were:

a) Fluid Delivery Temperature: ≈ 592°F

b) Heat Transfer Fluid: Therminol -66

c) Environmental Conditions (Partial):

Wind: Operate - 30 mph
Non-Operative - 90 mph

Hail: Survive 1/2" dia. hail at terminal velocity with no damage to major structural members

Insolation: Per curves supplied by Sandia typified by Figure 1-2.

d) Energy Delivery: 1.85 to 2.31 MBTU/day, depending on day of year, for a test field of collectors (three of this design).

The studies evaluated point concentrator collector designs applied to a "commercial" facility producing 10,000 kw thermal peak power with the objective of minimizing cost of net energy delivered from the field. At their conclusion, a set of operating requirements for optimized collectors were known, and these formed the basis of a detailed design activity aimed at producing three test collectors for use at Albuquerque. Table 1-1 lists the desired design goals for a three collector field.

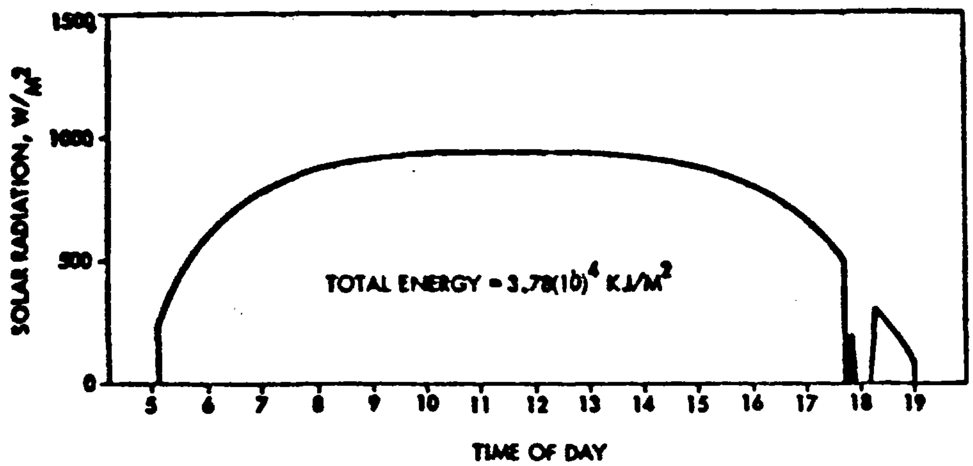

FIGURE 1-2. Average Sunny Summer Day Direct Normal Incident Solar Radiation

TABLE 1-1

THREE COLLECTOR FIELD DELIVERED THERMAL ENERGY

	SUMMER SOLSTICE	FALL EQUINOX	WINTER SOLSTICE	SPRING EQUINOX
Net Incident Energy: MBTU/Day	3.75	3.32	2.82	3.37
Predicted Conversion Efficiency, Percent	.80	.80	.80	.80
Net Collected Energy, MBTU/Day	3.00	2.66	2.26	2.70
Piping Losses/Day	0.32	0.26	0.23	0.26
Night Losses, MBTU/Day	0.11	0.11	0.11	0.11
Net Delivered Energy MBTU/Day	2.57	2.29	1.92	2.33
Minimum Required, MBTU/Day	2.31	1.85	1.95	1.85

Collected energy goals for a single collector at the absorber were determined by dividing the Net Collected Energy values among three collectors.

Amendments to the basic study contract resulted in the beginning of the final collector design process in late 1976. At the beginning of the current contract, the design was at the layout stage, awaiting detailed manufacturing drawings leading to fabrication.

1.2 Program Objectives

The continuation of the collector development program to the hardware stage was to be accomplished as follows:

Raytheon company would complete manufacturing drawings for all collector hardware, fabricate the collector (principally via subcontract) supervise its installation at Albuquerque and perform limited experimental evaluation.

Sandia Laboratories would design and implement site support activities per Raytheon requirements consisting of a computerized control system, a data acquisition system, a fluid circulating system, and a foundation to which the pedestal would mount.

In addition, Raytheon would perform limited design of three-collector field control and fluid circulating systems.

The collector installation was planned for the Solar Collector Test Facility at Sandia's Albuquerque site, and it would make use of various services already in existence at that location.

During the course of the program the objectives were changed such that the collector was installed at one of the industrial research areas to the North of the Collactor Test Facility, and the installation and evaluation task was assumed

1.3 Program Summary

The collector design and fabrication program has been concluded with hardware delivery to Sandia Laboratories. Most significant design goals established largely have been upheld during the fabrication; experimental evaluation will determine the degree of success of the design process.

A significant problem developed during the program with an unexpected growth in the mirror radius during cutting and plating operations after annealing. Corrective actions undertaken by the vendor were unsuccessful, with the delivered glass averaging from 20-50% above specified curvature radius.

Figures 1-3, 1-4 and 1-5 show the assembled collector, the energy absorber and one of the sagged glass mirrors and mounting hardware respectively. The collector has been assembled and is currently being checked out and tested by Sandia Labs personnel.

The collector is shown mounted on concrete piers at one of the Industrial Research areas at the Albuquerque test facility. A closed-loop via shaft encoder position control system has been designed and implemented for initial operation.

Data acquisition is via a Sandia supplied HP 2100S computer located in Building 832 at the test site.

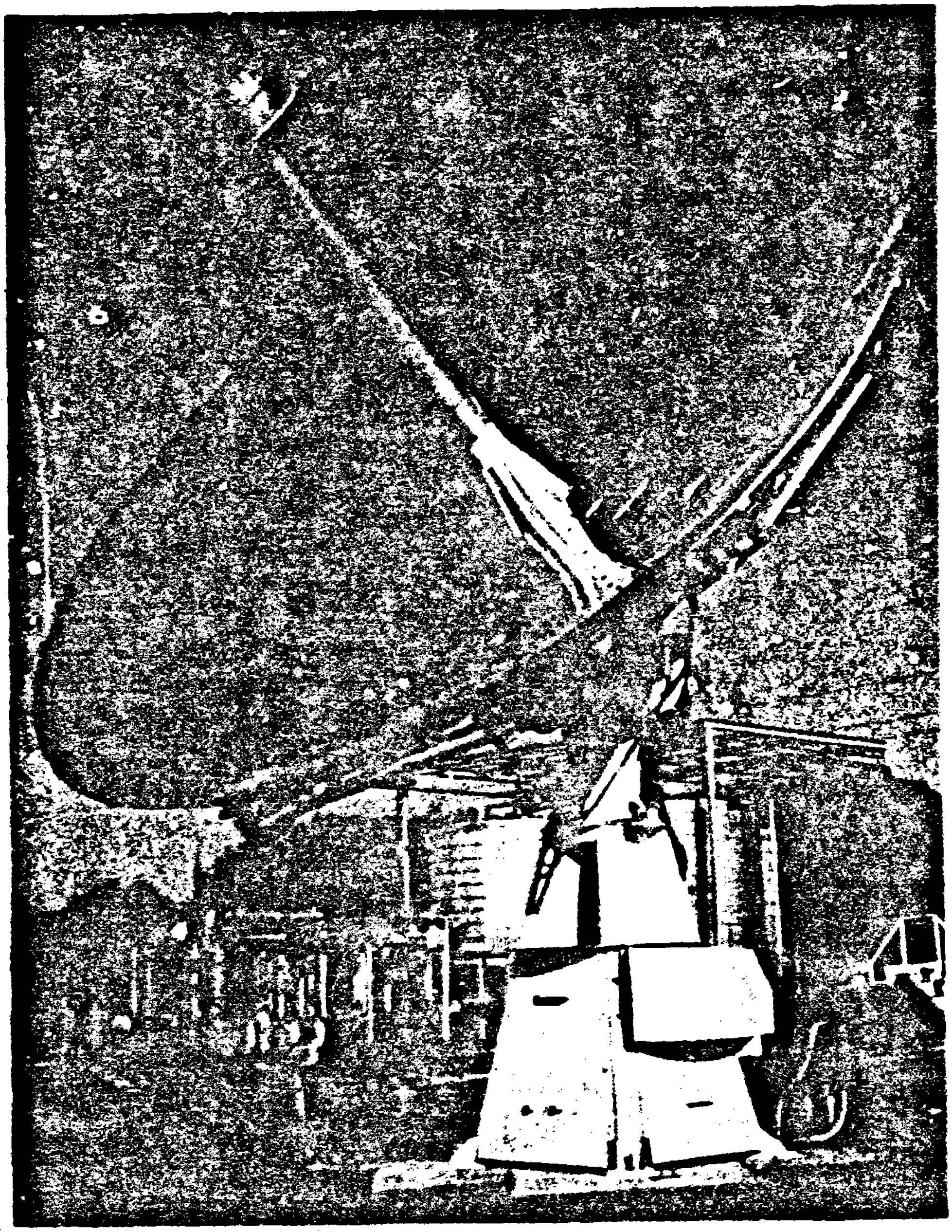

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FIGURE 1-3. Mount and Collector

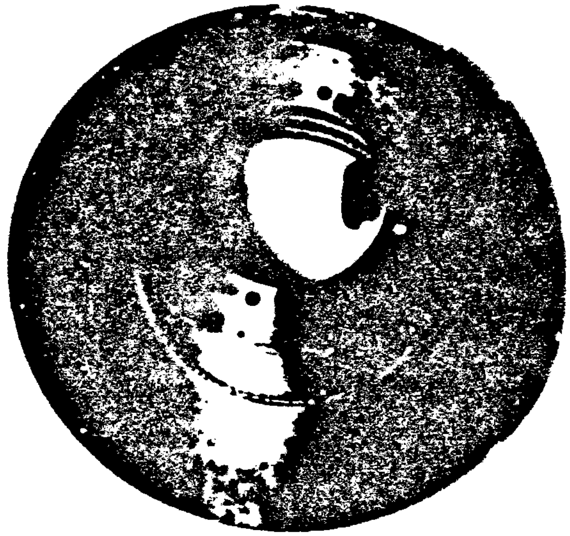

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FIGURE 1-4. Energy Absorber

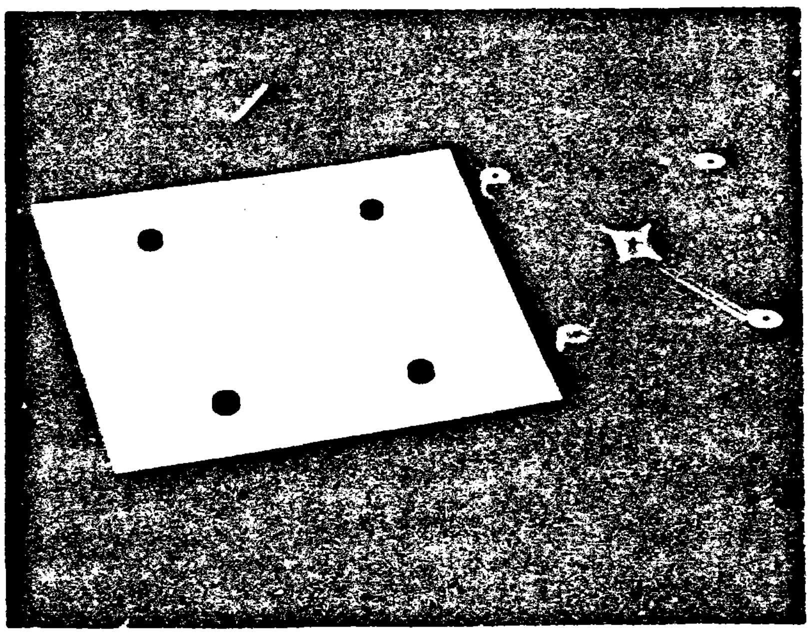

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FIGURE 1-5. Curved Glass Mirror and Mounting Hardware

2.0 Design Requirements

2.1 Collector Subsystem Requirements

The collector subsystem as used in a solar Total Energy System is understood to include collectors that focus and convert solar radiant energy, a fluid circulating system to transport the converted energy to a storage system, and whatever control devices are required to ensure the satisfactory operation of the subsystem. Collector subsystem requirements for the Sandia installation are listed below.

2.1.1 Interfaces and Requirements

2.1.1.1 Interfaces

a) The solar collector field subsystem will be confined to the boundaries of one of the Industrial Research areas.

b) The heat transfer fluid used by the collector field subsystem may be selected by the contractor. The heat transfer fluid used by the Sandia Solar Total Energy System is Therminol 66, manufactured by Monsanto Co.

c) The collector field subsystem shall pump the Therminol 66 from a supply line and return it to a return line. If the contractor chooses Therminol 66 as his heat transfer fluid, the fluid drawn from the supply line may be used by the subsystem. If the contractor chooses a different fluid, the Therminol 66 must be heated by a heat exchanger at the output of the subsystem, driven by the other fluid.

2.1.1.2 Temperature Requirements

The contractor may design the subsystem to operate at one of two output temperature options. The high temperature option is compatible with the Sandia Total Energy System and thus should be selected if possible.

a) High Temperature Option

The temperature of the Therminol 66 as it is returned to the return line must be 592°F ±5°F (311°C ±3°C) under steady-state conditions. The nominal temperature of the Therminol 66 in the supply line will vary from season to season as follows:

1) Winter solstice - 470°F (243°C)

2) Spring equinox - 468°F (242°C)

3) Summer soltice - 486°F (252°C)

4) Fall equinox - 468°F (242°C)

b) Low Temperature Option

The temperature of the Therminol 66 as it is returned to the return line must be 450°F ±2°F (232°C ±1°C) under steady-state conditions. The nominal temperature of the Therminol 66 in the supply line will vary from season to season as follows:

1) Winter solstice - 339°F (171°C)

2) Spring equinox - 324°F (162°C)

3) Summer solstice - 349°F (176°C)

4) Fall equinox - 324°F (162°C)

2.1.1.3 Performance Requirements

The nominal minimum energy the solar collector subsystem is required to deliver per day varies from season to season as follows:

a) High Temperature Option

1) Winter solstice - 1.95 MBTU/day (2.05×10^6 kj/day)

2) Spring equinox - 1.85 MBTU/day (1.95×10^6 kj/day)

3) Summer solstice - 2.31 MBTU/day (2.44×10^6 kj/day)

4) Fall equinox - 1.85 MBTU/day (1.95×10^6 kj/day)

b) Low Temperature Option

1) Winter solstice - 2.43 MBTU/day (2.55×10^6 kj/day)

2) Spring equinox - 2.46 MBTU/day (2.28×10^6 kj/day)

3) Summer solstice - 2.60 MBTU/day ($2.75. \times 10^6$ kj/day)

4) Fall equinox - 2.16 MBTU/day (2.28×10^6 kj/day)

The low temperature option must provide more energy per day because the energy output is used to drive an organic rankine cycle turbine for the generation of the electricity and the cycle efficiency is reduced due to the lower available temperature. For this reason, the low temperature option will tend to be penalized when it is rated alongside the high temperature option subsystems.

The proposed subsystem must be designed to meet the above daily energy output requirements on the dates of the solstices and equinoxes under the following conditions and assumptions.

1) "Average sunny days", are assumed. These are defined for each of the four seasons by Figure 2-1.

2) Assumed temperature data for each of these days as listed. (Listing not included).

3) A wind speed of 5 m/sec (11.2 mi/hr) normal to the absorber is assumed.

4) Assume that solar noon coincides with clock noon.

5) The installation site is located at 35° North latitude and an altitude of 5400 ft. mean sea level.

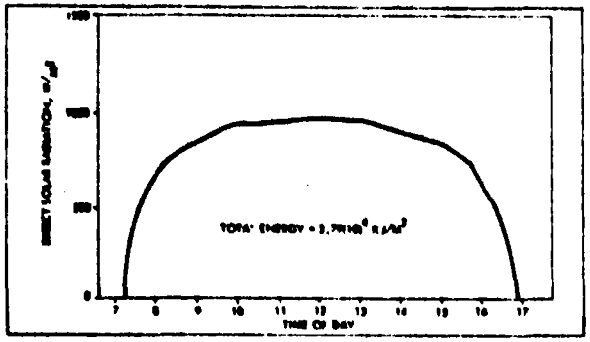


FIGURE 2-1a. Average Sunny Winter Day Direct Normal Incident Solar Radiation

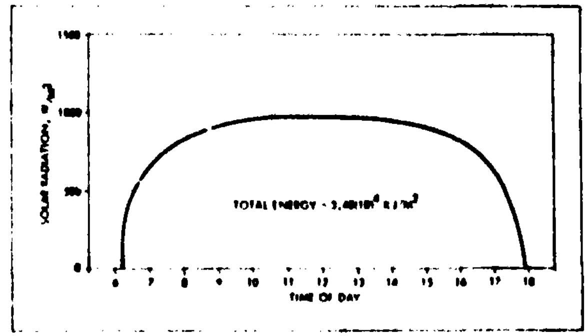


FIGURE 2-1b. Average Sunny Spring Day Direct Normal Incident Solar Radiation

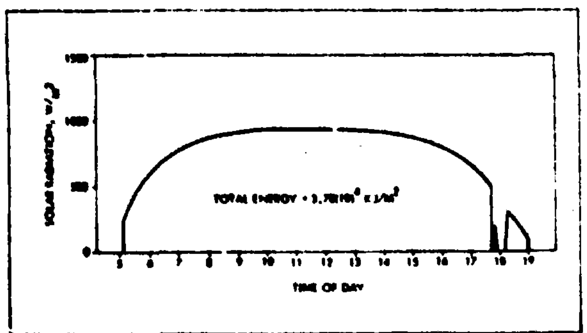


FIGURE 2-1c. Average Sunny Summer Day Direct Normal Incident Solar Radiation

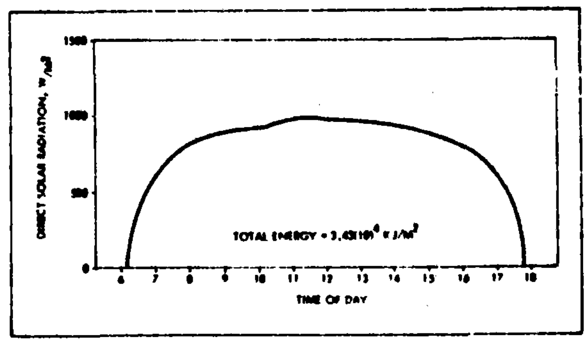


FIGURE 2-1d. Average Sunny Fall Day Direct Normal Incident Solar Radiation

2.1.1.4 Operating Requirements

a) At start-up time each morning the fluid in the supply line will be at ambient temperature. Provisions must be made to accept this cold fluid until the supply line is filled with fluid at the nominal temperature by the storage tank.

b) At start-up time and other times of transient operation, the temperature of the Therminol 66 being returned may vary from its steady tolerance by not more than 18°F (10°C). The volume of Therminol 66 passed at this temperature may not exceed 10.57 gallons (40 liters).

c) The maximum allowed film temperature of Therminol 66 is 705°F(374°C) and its maximum allowed bulk temperature is 650°F (343°C). Safeguards must be provided to ensure that Therminol or other heat transfer fluids are not overheated under any circumstances.

d) Commercial power will be provided for the subsystem auxiliary power, but attention is requested in keeping power consumption to a minimum. Excessive auxiliary power consumption will penalize the rating of a subsystem.

e) The collectors must be structurally capable of surviving a 90 mph wind. In addition, they must be structurally rigid enough to operate in a 30 mph wind. The collector should withstand hailstones of 1/2 inch diameter without damage, and hailstones of 1 inch diameter without structural or mechanical mechanism damage.

2.1.2 Test Collector Requirements Allocation

2.1.2.1 Collector

Given the collector subsystem requirements, system analyses performed under a preceding program determined that the collector subsystem should consist of three collectors producing energy at each absorber as shown in Table 2-1. In that table, the "Net Collected Energy" values are at the absorber; "Piping Losses" include intra-collector as well as field interconnecting piping. Consequently, the immediate goals of the collector design and fabrication program is to design a system to produce the energy values shown in Table 2-1 at the absorber, with the appropriate insolations.

The energy delivery is affected by numerous system and component performance characteristics, including:

TABLE 2-1

SINGLE COLLECTOR ABSORBED ENERGY

	SUMMER SOLSTICE	FALL EQUINOX	WINTER SOLSTICE	SPRING EQUINOX
Absorbed Energy MBTU/day	1.00	0.87	0.76	0.90

a) Collector aperture,

b) Mirror specular reflectance,

c) Absorber aperture size,

d) Mirror/structure alignments, manufacturing tolerances and pointing error,

e) Absorber radiation and convection performance.

The systematic combination of the above should result in less than 25 percent energy loss when operating at 600°F.

Parameter values for the collector are:

a) Aperture Size: Twenty-two ft. diameter collector, with 3 ft. diameter nonreflectorized center hub section. Resulting aperture size ≈ 375 ft^2.

b) Mirror Specular Reflectance: 92 percent specified and agreed to by vendor. Mirrors are Schott B-270 water white crystal glass, rear surface silvered. Total reflectance measurements at Sandia Laboratories yielded values of ≈0.95 for the glass/plating combination. (Figure 2-2).

c) Absorber Aperture Size: Given the basic design concept of an annular input aperture, the objective is to gather as much energy as possible while minimizing reradiation and convection losses. Initial sizing calculations indicated that a 5 inch annular dimension, formed by a 9 1/2 inch inner radius and 14 1/2 inch outer radius would pass ≈97 percent of the input energy. Provisions were made to provide additional (or less) aperture area by providing removable aperture plates on the absorber cover. Their removal would increase the aperture size 40 percent.

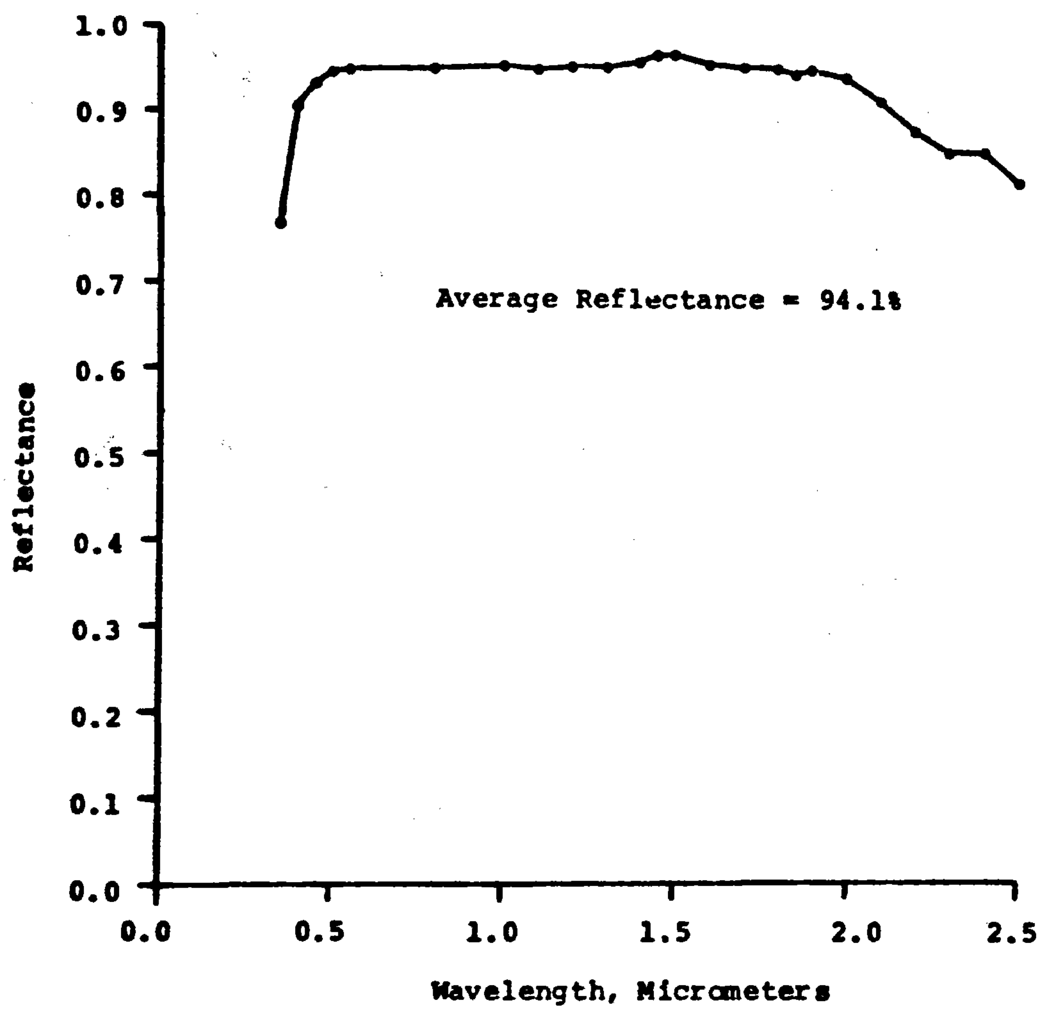


FIGURE 2-2. Total Reflectance Data for Raytheon/Schott Mirrors

d) Mirror/Structure Alignments, etc.: These Factors serve to form and direct the concentrated energy beam to the absorber aperture, which is then sized to accommodate 97 percent of the possible energy. The analysis required to specify the beam is extensive, and is discussed in depth in Section 3.

e) Absorber Thermal Performance: Previous studies had indicated that with Harshaw Black Chrome selective plating, and the geometry to be used, that peak absorber efficiencies would be above 90 percent at 600°F fluid outlet temperature and peak insolation.

Combining the above factors with the specified insolation for each day yields a requirements allocation in reasonable agreement with that required to attain the goal. For example, on a summer solstice day, 375 ft^2 of aperture collects 1.24 MBTU. The expected energy delivery, greatly simplified, would be:

$$1.24 \times .92 \times .97 \times .90 = 1.00 \text{ MBTU/day,}$$

the desired value.

The essence of the design and fabrication program is to ensure that the above values are attained or bettered as the concept is reduced to practice.

The remaining requirements applicable to the collector are those of wind and hail survivability. The design approach taken was to survive these effects in any orientation. Previous experimental studies, established that the 1/2 inch hail and worst-case wind loads are easily survived by the 1/8 inch glass with the planned mounting technique.

2.1.2.2 Ancillary Systems

The ancillary systems are:

a) Control,

b) Instrumentation,

c) Fluid Circulating System.

The program had two tasks in these areas:

a) Define ancillary requirements for the single collector test at the Solar Collector Test Facility.

b) Define (partially) ancillary systems for future installation in one of the Industrial Research areas to support a three-collector field.

This section presents the requirements for ancillary systems for the single collector, and Section 5 presents further information on the three collector field requirements.

2.1.2.2.1 Control

As envisioned by the control systems designers, the collector drive and control system operated on a quasi open loop basis, with a control processor providing the number of steps to be taken by the drive stepper motors at each time update. At selected locations (index points) in each axis, the time to reach position for each axis would be compared with desired time via shaft encoders to determine the accuracy of the approach. The shaft encoders perform the aforementioned indexing function, provides axis pointing data, and a closed loop axis positioning capability if one should prove necessary.

Specific collector control requirements imposed on the Sandia control system designers are:

a) Sun Follow : The control system should cause the collector to follow the apparent sun position within an accuracy of ±0.5 mr.

b) Startup and Shutdown: The control system should cause the collector to acquire the sun at any time during the day, and cease following at any time during the day. If the sun is to be acquired or following ceased any time other than sunrise or sunset, the control system must provide that the line-of-sight between the collector optical axis and the calculated solar position, θ_{O-S}, be changed at a rate of no less than 4 deg/min within the range of 2 mr $\leq \theta_{O-S} \leq$ 10 degrees.

c) Stow: The control system should be capable of driving the collector to two stow positions which may be either: a) maximum elevation or; b) minimum elevation and east north east azimuth direction. Stow position: a) minimizes wind induced static loading on the collector, and b) represents the location furthermost away from the sun for use when wind load is not a factor. The selection of final stow position for a given operations scenario must take into consideration personnel safety during a stow with insolation.

Stow initiation should occur manually and/or automatically. Automatic stow initiators include:

1) A signal from the absorber over temperature protection switch that the absorber temperature is above a preset maximum, to be determined via tests.

2) A control system self-determination that the line-of-sight angle error is greater than 2 mr.

d) Error Compensation: The control system should incorporate error compensation terms similar to those shown as follows:

$$\Delta E = \varepsilon_1 + \varepsilon_2 \sin A + \varepsilon_3 \cos A$$

$$\Delta A = \varepsilon_4 + \varepsilon_5 \tan E + \varepsilon_6 \sin A \tan E + \varepsilon_7 \cos A \tan E$$

where

ε_1 = elevation bias

ε_2 = gravity droop effect

ε_3 = verticality error

ε_4 = azimuth bias

ε_5 = cross-level error

$\varepsilon_6, \varepsilon_7$ = location errors

Initially these errors will be set to zero. Tests and analyses will select values for the error parameters at a later date.

e) Fault Protection: The collector control system should be designed to minimize damage to the collector in the event of equipment or service failures. This includes, as a minimum, stow capability in case of electrical power failure and protection of drive system components from overload by driving at maximum torque into the mechanical stops.

2.1.2.2.2 Instrumentation

The instrumentation requirements for the single collector were to provide sufficient data to determine the degree to which the collector design met its goals, and other data judged to be of value. Since Sandia Laboratories provides as part of the collector test facility extensive and complete environmental data, these requirements were applied to only the absorber (temperature data), fluid system (inlet and outlet temperature) and axes (position).

2.1.2.2.3 Fluid Circulating System

The fluid circulating system for the test collector was provided as part of the collector test facility. Functional requirements were simply to provide sufficient flow to prevent absorber overheating over all operating temperature ranges and to provide sufficient flexibility within the collector to allow motion in the azimuth and elevation axes. Requirements are stated in Section 5.

2.1.3 Test Collector Interfaces

By contractual agreement, collector test services were provided by Sandia Laboratories as shown in Figure 2-3. An interface control document was generated to establish and control the interface at the fluid circulatory system, the data acquisition and control systems, and the foundation. An electrical enclosure was provided at the base of the collector and was the terminus of the control and data wiring provided by Raytheon.

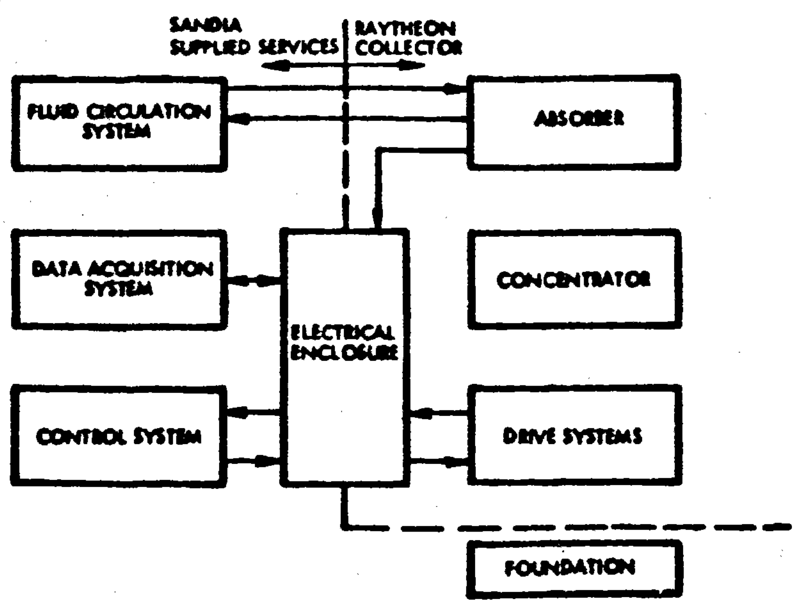


FIGURE 2-3. Raytheon/Sandia Services Interface

3.0 Collector Design and Fabrication

3.1 Concentrator

3.1.1 Mirror Radius of Curvature Requirements

The Solar Concentrator uses 228 spherical mirrors on seven rings to redirect solar energy to the absorber. The entrance aperture is an annulus with an opening of ±2.5 inches around a mean radius of 12 inches. The plane of the aperture is 120 inches from the concentrator center.

Mirror ring radii and distance from the dish reference point is shown in Figure 3-1 and given in Table 3-1.

TABLE 3-1

SIGNIFICANT CONCENTRATOR DIMENSIONS

RING NO.	x (Inches)	y (Inches)	θ (Arc Deg.)	L (Inches)
1	.437	26.483	3.453	120.437
2	3.052	43.387	7.512	121.087
3	6.828	60.142	11.522	122.986
4	11.745	76.789	15.450	126.162
5	17.653	92.953	19.171	130.493
6	24.560	108.896	22.717	136.006
7	32.345	124.452	26.032	142.579

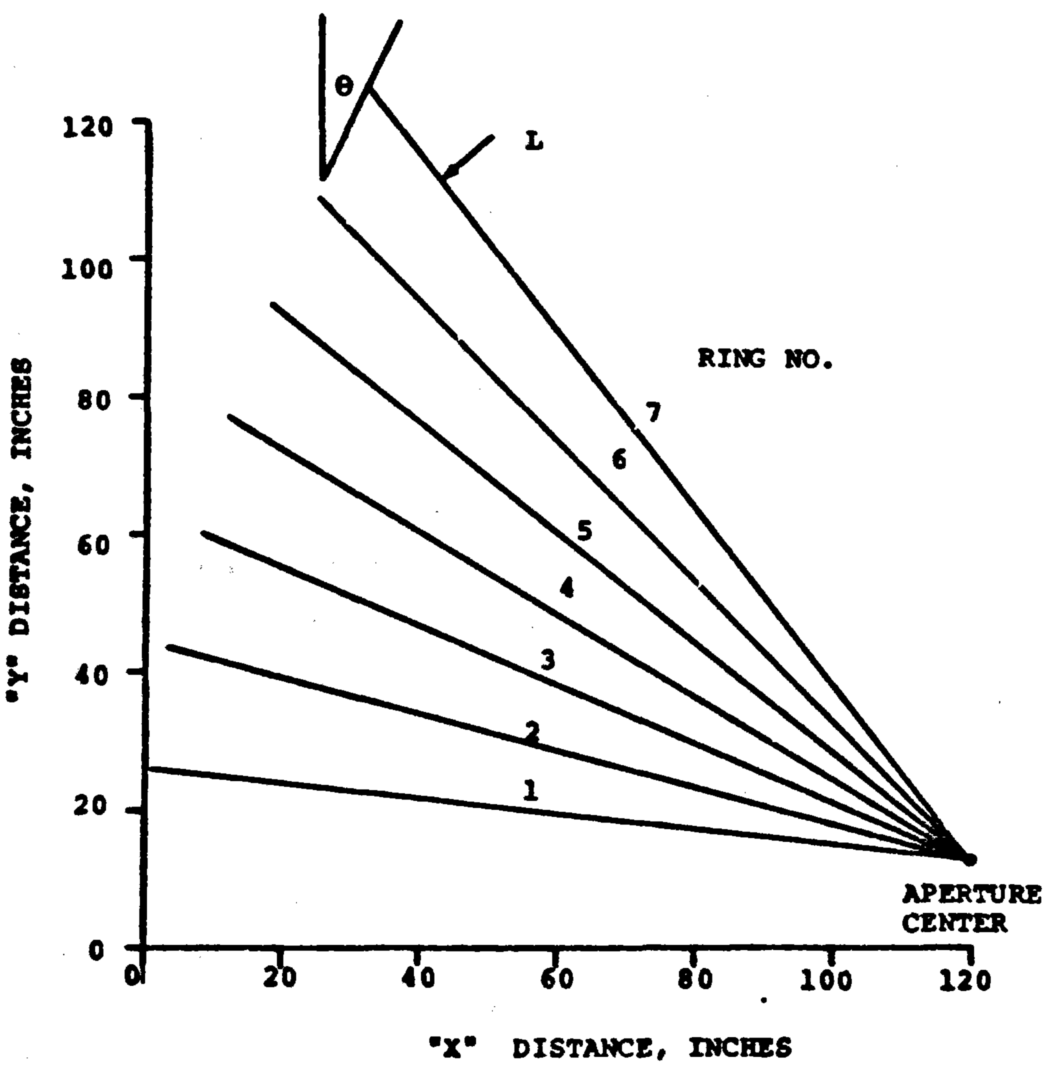


FIGURE 3-1. Concentrator Geometry Data

The tilt angle of the mirror (θ) and the distance between the mirror and the aperture (L) are also given in Table 3-1. The minimum spot size in the y direction is achieved if the radius of curvature of the mirror is*

$$R = \frac{2L}{\cos\theta}$$

and the dimensions of the spot in the plane of the aperture are

$$S_1 = \frac{2\xi L}{\cos 2\theta}, \quad S_2 = 2r\sin^2\theta + 2\xi L$$

where

S_1 = radial direction

S_2 = circumferential direction

r = mirror half dimension = 9 inches

ξ = half angle of the sun = 0.0045 radians

The spot size for perfect mirrors is given in Table 3-2.

TABLE 3-2

PERFECT MIRROR SPOT SIZE

RING NO.	R (Inches)	$\frac{2\xi L}{\cos 2\theta}$ (Inches)	$2r\sin^2\theta + 2\xi L$ (Inches)
1	241.312	1.092	1.149
2	244.270	1.128	1.397
3	251.031	1.203	1.825
4	261.784	1.323	2.413
5.	276.309	1.497	3.116
6	294.888	1.744	3.908
7	317.354	2.087	4.750

* Appendix A gives the derivation of the equation.

The original mirror specification, Appendix B, assumed that a glass manufacturer can achieve a radius of curvature with a reasonable tolerance. Therefore, in order to minimize costs, two radii of curvature were chosen - Rings 1-4 250 ±10 inches, Rings 5-7 295 ±10 inches. The S_1 and S_2 values (from Appendix A) for perfect mirrors are:

$$\frac{\left(2r\left|\cos\theta - \frac{2L}{R}\right| \mp L\right)}{\cos 2\theta}, \quad \left(2r\left|1 - \frac{2L\cos\theta}{R}\right| \mp L\right)$$

Table 3-3 gives the minimum and maximum spot sizes for perfect mirrors that meet the specification.

TABLE 3-3

MINIMUM AND MAXIMUM SPOT SIZE FOR PERFECT MIRRORS

RING NO.	R (INCHES)	L (INCHES)	θ (ARC DEG.)	S_1 (INCHES)	S_2 (INCHES)
1	240 260	120.437	3.453	1.191 2.393	1.117 2.438
2	240 260	121.087	7.512	1.457 2.246	1.097 2.468
3	240 260	122.986	11.522	2.084 1.864	1.183 2.427
4	240 260	126.162	15.450	3.159 1.462	1.376 2.298
5	285 305	130.493	19.171	2.158 3.536	3.605 4.626
6	285 305	136.006	22.717	2.565 2.529	3.377 4.416
7	285 305	142.579	26.032	5.074 3.153	2.332 4.162

When Schott Optical Company started to make the spherical mirrors, the accuracy of the radius of curvature was poorer than anticipated, therefore, it was decided that the radius of curvature of each mirror be measured. To maximize yield and at the same time to minimize spot size, the radius of curvature specification was changed so that any radius of curvature between 236.3 inches and 329.8 inches can be used in an appropriate ring. Table 3-4 gives the new specification and the associated spot size.

TABLE 3-4

SPOT SIZES FOR SEVEN DIFFERENT RADIUS OF CURVATURE MIRRORS

RING NO.	R (INCHES)	L (INCHES)	θ (ARC DEG.)	S_1 (INCHES)	S_2 (INCHES)
1	236.3 246.3	120.437	3.453	1.476 1.458	1.399 1.512
2	239.3 249.3	121.087	7.512	1.512 1.501	1.150 1.754
3	246.0 256.0	122.986	11.522	1.595 1.575	1.472 2.160
4	256.0 267.6	126.762	15.450	1.780 1.763	2.035 2.776
5	267.6 285.0	130.493	19.171	2.203 2.158	2.593 3.605
6	285.0 304.8	136.006	22.717	2.565 2.514	3.377 4.407
7	304.8 329.8	142.579	26.032	3.171 3.080	4.152 5.153

3.1.2 Relationship Between Slope Errors and Radius of Curvature Variations

The measurements that were made on the mirrors were radius of curvature measurements at nine different points on the mirror (See Figure 3-2). Appendix 3 lists the radius of curvature measurement for each glass segment manufactured. The radius of curvature for the mirror was taken as the mean of the nine measurements and the slope error was assumed to be proportional to the standard deviation of the nine measurements. The following analysis establishes the relationship between the slope error and the radius of curvature variation.

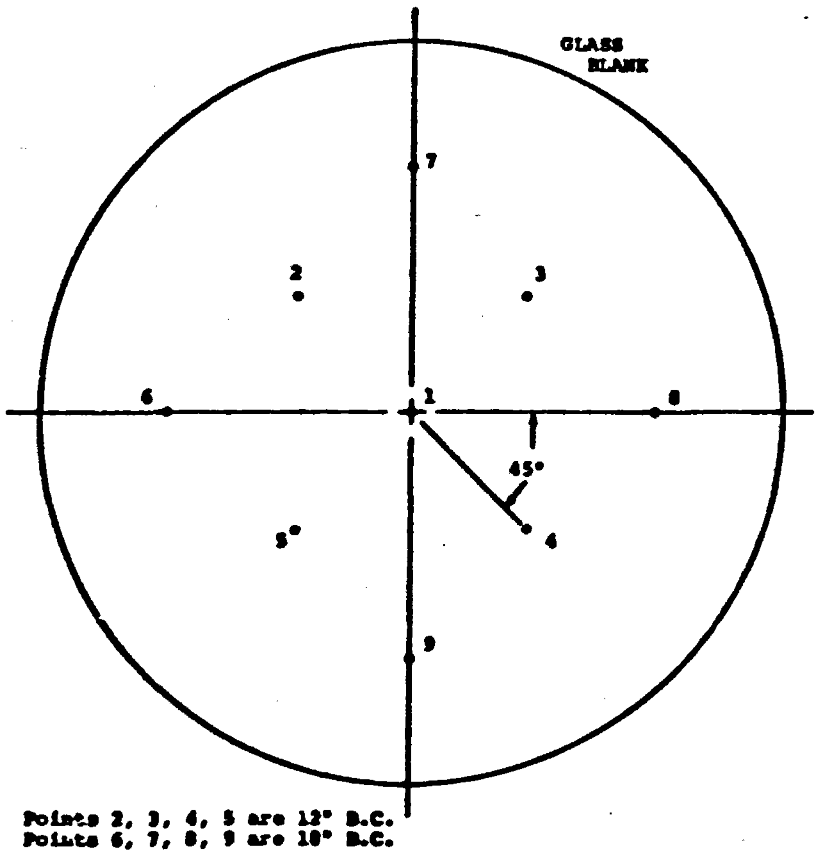


FIGURE 3-2. Location of Spherometer Measurement Points.

Let the equation of the surface in polar coordinates be

$$r = R + \Delta R \cos n\theta$$

where

$$r = (x^2 + y^2)^{1/2}$$

$$\theta = \tan^{-1} \frac{y}{x}$$

R = Nominal radius

ΔR = Maximum variation in radius

The slope of the surface is

$$\phi = \tan^{-1} \frac{dy}{dx} = \tan^{1} \frac{\frac{dr}{d\theta} \sin \theta + r \cos \theta}{\frac{dr}{d\theta} \cos \theta - r \sin \theta}$$

The normal to the surface is

$$90° - \phi = \tan^{-1} \frac{-1}{dy/dx} = \theta - \tan^{-1} \frac{1}{r} \frac{dr}{d\theta}$$

The radius of curvature of the surface is

$$RC = r \frac{\left[1 + \left(\frac{1}{r} \frac{dr}{d\theta}\right)^2\right]^{3/2}}{1 + 2\left(\frac{1}{r} \frac{dr}{d\theta}\right)^2 - \frac{1}{r} \frac{d^2 r}{d\theta^2}}$$

For the assumed surface

$$r = R + \Delta R \cos n\theta$$

$$\frac{1}{r} \frac{dr}{d\theta} = - \frac{n \Delta R \sin n\theta}{R + \Delta R \cos n\theta}$$

$$\frac{1}{r}\frac{d^2r}{d\theta^2} = -\frac{n^2\ \Delta R\cos n\theta}{R + \Delta R\cos n\theta}$$

and for $\frac{\Delta R}{R} << 1$

$$90 - \phi \approx \theta + \frac{n\Delta R}{R}\sin n\theta$$

$$RC \approx R - (n^2-1)\ \Delta R\cos n\theta$$

The slope error is approximately

$$\Delta\phi \approx \frac{n\Delta R}{R}\sin \Delta\theta$$

If the mirror has one cycle of the radius of curvature variation

$$\overline{RC} = \frac{n}{2\pi}\int_{-\pi/n}^{\pi/n} (RC)\ d\theta = R$$

$$\sigma_{RC} = \left\{ \frac{n}{2\pi}\int_{-\pi/n}^{\pi/n} [(RC) - \overline{RC}]^2\ d\theta \right\}^{1/2} = \frac{(n^2-1)\Delta R}{\sqrt{2}}$$

or

$$\sigma_{RC} = R\,\frac{(n^2-1)}{\sqrt{2n}}\,\Delta\phi$$

and

$$\frac{RC}{R} = \frac{(n^2-1)}{\sqrt{2n}}\ \Delta\phi \approx \frac{n\Delta\phi}{\sqrt{2}}$$

For

$$\Delta\phi < .002$$

$$n = 75$$

$$\frac{\sigma_{RC}}{R} < .21$$

The use of the standard deviation of many radius of curvature measurements as a measure of the slope error assumes that the slope errors result from low frequency spatial effects over the mirror. High frequency spatial effects such as draw lines do not enter into this type of evaluation.

3.1.3 Mirror Manufacturing Tolerance

There were the basic assumptions in the mirror selection approach that the curvature measurements, taken after annealing and before cutting and drilling, would accurately represent the delivered item. Such was not the case. The first set of glass (≈2/3 of total) delivered to the United States deviated significantly from the planned radius values, see Table 3-5, and Figure 3-3.

The system impact of such a deviation from desired radius of curvature is to reduce collection efficiency by increasing the concentrated beamwidth at the aperture, causing large amounts of energy to impinge on the aperture plates, or even absorber cover. Figures 3-4 and 3-5 demonstrate the effect of larger than desired radius mirrors at the absorber, particularly in the aperture plane. The ray traces shown are for ideal mirrors (no slope errors, draw lines, etc.) using an actual solar disc as a source. As can be seen, the broadened solar image virtually fills the aperture in the radial direction, causing significant energy losses by

TABLE 3-5

FIRST GROUP MIRROR DATA SYNOPSIS, AS SHIPPED

PART NO.	APPROXIMATE RADIUS PER SPECIFICATION	ACTUAL AVERAGE	ACTUAL MIN./MAX.
	(MM)	(MM)	(MM)
1	6125	7506	6816/8159
2	6200	7940	7602/8772
3	6375	8115	7680/8793
4	6650	8227	7555/9213
5	7025	8412	7631/9479
6	7500	9180	8543/10158
7	8050	9259	8306/10870

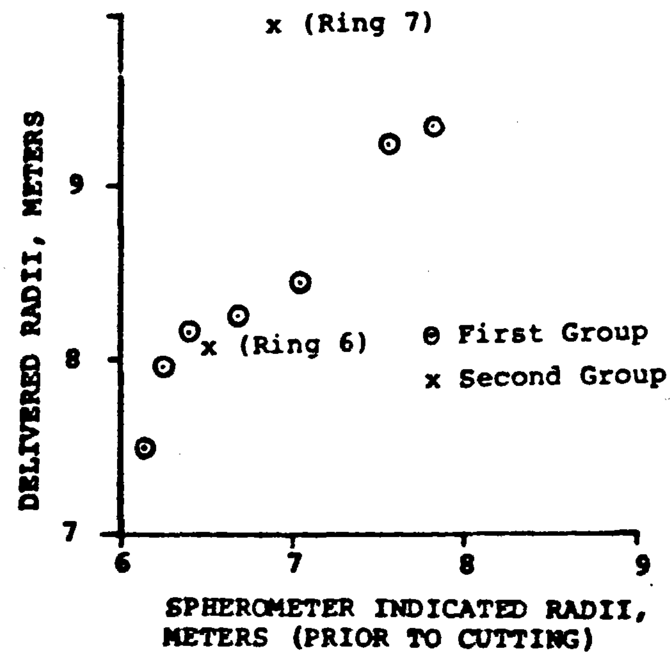


FIGURE 3-3. Expected Vs. Realized Radii

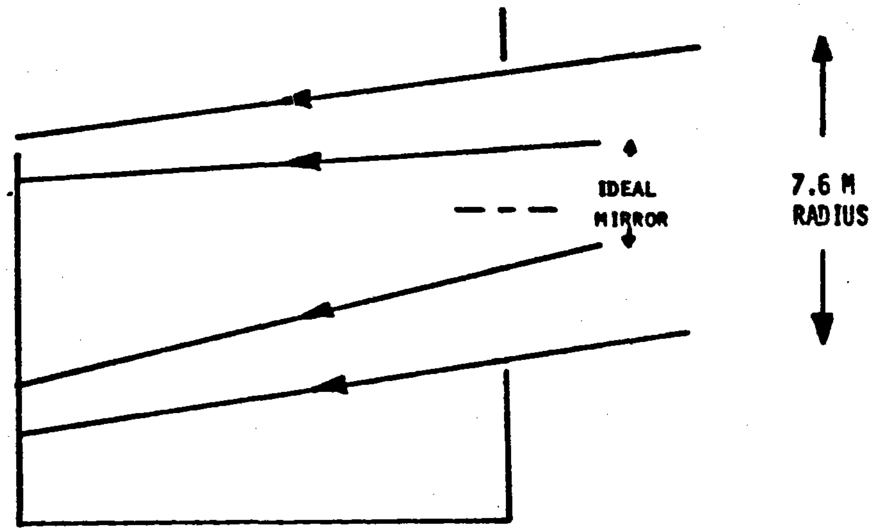


FIGURE 3-4. Ring 1 Pattern

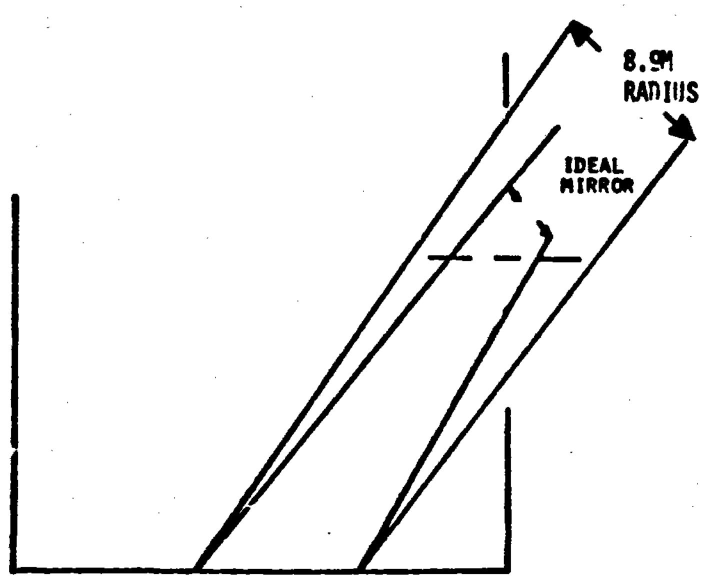


FIGURE 3-5. Ring 7 Pattern

spillover when additional beam spreading effects are included, such as mirror misalignment, angular tolerances, etc. Figure 3-6 which considered real mirrors (within specification) and structure tolerance effects, demonstrates how the beam spreads to fill the aperture. Clearly, use of mirrors significantly deviating from specification would result in correspondingly reduced system efficiencies. An intensive effort on the part of the vendor, Schott Optical, revealed that the radius error occurred after the annealing operation, which had not been expected, and that no simple solution was available. There is some evidence that the radius deviation is repeatable and future systems can include it as an additional factor in the mirror selection process.

However, in the current program the principal concerns became disposition of the mirrors that had been manufactured, and what if anything could be accomplished with the remaining blanks, destined for rings 6 and 7. The absorber design, and the glass mounting system had been designed to accommodate fairly substantial errors on the part of the glass, or any of many other beam spreading components. To wit, the mirror mounts and absorber aperature plates were each designed to allow great flexibility in aligning individual mirrors and accommodating larger than planned beams at the aperature. The system performance penalty of using the built-in devices was estimated at a 5 percent reduction in efficiency, a value probably within the accuracy level of the calculations. If in an extreme case, the absorber cover were to be removed completely, system performance could suffer efficiency penalties at 10 percent.

The problem was resolved as follows:

a) The mirrors for Rings 1-5, those first delivered, were used as is.

b) Mirrors for Rings 6 and 7, which had not been manufactured at the time the problem was noted, were manufactured using small radius glass, and their curvatures were as shown in Table 3-6.

c) Mirrors for all rings were individually aligned, using data taken during manufacture as a guide.

As can be seen from Table 3-6, the blanks selected for the second cutting operation were well below the desired radius in an attempt to acheive an acceptable end product. The radius growth phenomena continued with the ring 6 mirrors behaving nearly as expected, and ring 7 mirrors for surpassing any previous values of radius growth. The ring 7 results might not be as poor as indicated, in that fewer data points (five per mirror) were taken. The points were in the vicinity of holes which may cause a local perturbation, and the spherometer sensitivity at large radii was such that a small silver or paint buildup in the vicinity of the data point could significantly offset the reading. The partial success demonstrated by the ring 6 mirrors (see Figure 3-3 and Table 3-6) indicates that given additional work on the problem, it will be possible to deliver mirrors within specification, and thereby acheive superior optical performances from the collector.

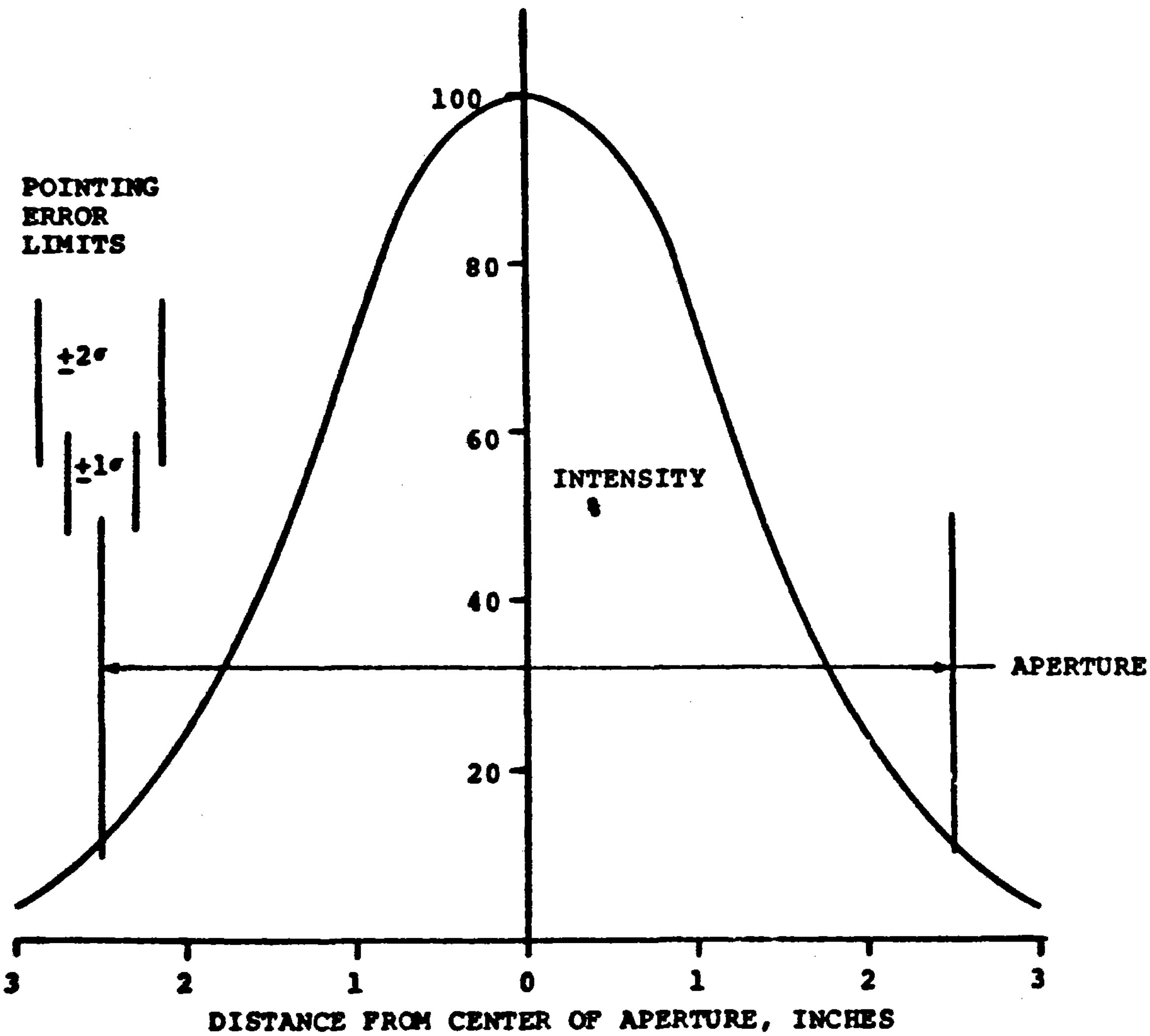


FIGURE 3-6. Energy Distribution at Aperture

TABLE 3-6

SECOND GROUP (RING 6 AND 7) MIRROR DATA SYNOPSIS

Ring	Average Blank Radius After Annealing (max/min)	Average Mirror Radius as Received (max/min)	Radius Specification	Average Radius Error, %
6	6528 (6910/5826)	8044 (10140/6690)	7500	7
7	7024 (7304/6757)	9869* (12 500*/6830)	8050	23

*A 12,500 mm radius volume was assumed for any mirror whose average was above 12,500 mm, due to spherometer calibration limitations.

3.1.4 Concentrator Structure

The approach adopted in the structural design of the concentrator was to build the structure as accurately as possible, within the constraints of existing fabrication techniques and economic considerations and to attach the mirror segments to this structure without requiring subsequent optical alignment. This approach was implemented in such a manner that alignment of each mirror segment, using optical techniques, was possible should such a procedure become either necessary or desired during evaluation of the collector performance, as it indeed did.

An additional constraint imposed upon the concentrator structural design was that it be capable of assembly at the site from easily transportable parts and subassemblies without the use of extensive on-site assembly jigs and tools.

3.1.4.1 Concentrator Design

The concentrator optical surface is comprised of 228 spherically curved mirror segments, the dimensions of which were constrained to a maximum of approximately 18 inches square because of glass fabrication limitations. The reflector parabola was then approximated by individual spherical mirror segments with two different radii of curvature (later changed to seven radii) to permit a feasible approach to the glass sagging process. Each segment was made as large as possible to minimize the number of mirrors required. This approach resulted in seven concentric rings of trapezoidal mirror segments as shown in Figure 3-7. To minimize the effect of mirror dimensional tolerances and structural assembly tolerances, each ring of mirror segments overlaps the next inner ring. Segments within each ring are separated by a gap of approximately 0.2 inch.

Each ring of mirror segments is mounted on a concentric structural support ring by a four-point attachment bracket. The mirrors are bolted to the brackets (Figure 3-8) using elastomeric grommets and accurately machined bushings to limit the attachment preload. The structural support rings are attached to 12 simple plane-frame trusses which are bolted to a central hub. The hub is supported on the collector elevation axis.

The following paragraphs describe each of the above components in more detail.

3.1.4.1.1 Mirrors

The reflecting surface is made up of 228 mirror segments. These segments are described in Raytheon Specification No. MP778340 (Appendix 2) from which Figure 3-9 is taken. The use of spherical mirror segments reduces the cost of the glass sagging tools while at the same time, avoiding the necessity of accurately orienting the segment in the plane of the reflecting surface.

3.1.4.1.2 Mirror Mounting

It was decided to mechanically attach the mirrors to their mounting brackets using elastomeric grommets and preload bushings. Structural tests were conducted on a typical mounting configuration and the detail approach was found to be acceptable. Adhesive mounting was rejected after considerable investigation and discussion with potential mirror suppliers.

The individual mirror segments are isolated from any loads imposed by structural deformation of the supporting structure by the mounting bracket. The mounting bracket design was traded off in considerable detail and the resulting configuration is a flat casting with four mirror attachment points and a flat machined mounting surface which is bolted to a machined pad on the support structure ring. Two bolts are used to ensure radial alignment of the mirror segment which is relatively not critical. The use of individual mirror support brackets permits accurate machining to fit the mirror curvature using standard machine tools. The large number of support brackets required indicated that a casting should be used for this part.

3.1.4.1.3 Mounting Rings

An aluminum tube of circular cross section was chosen for the structural mounting rings which support the mirrors and tie the trusses together into a rigid space frame. The circular tube was chosen primarily on the basis of structural efficiency, availability and ease of fabrication into the ring configuration. The mounting rings are attached to the trusses by 12 pads machined accurately to restrain the ring in a plane normal to the axis of the reflector. Machined pads are also provided on the opposite side of the ring to which are bolted the individual mirror support brackets. These pads are made from a common casting accurately welded to the rolled ring to provide mirror tilt angle and ring attachment points.

3.1.4.1.4 Trusses

Twelve welded aluminum alloy trusses of rectangular tube and angle members are used and conform to the 30 degree repeating pattern of the mirror segments. No curved members are used and fitting of the individual members is reduced to a minimum by an overlapping joint construction technique. Pads to attach the mirror support rings are welded to the trusses and are machined after assembly to provide the proper location of the ring attachment points. The trusses are attached to machined lugs at the front and rear periphery of the central hub which also contains the elevation axis and elevation drive arm. To ensure angular accuracy of the trusses relative to the hub axis, these attachment points are match drilled and reamed on assembly.

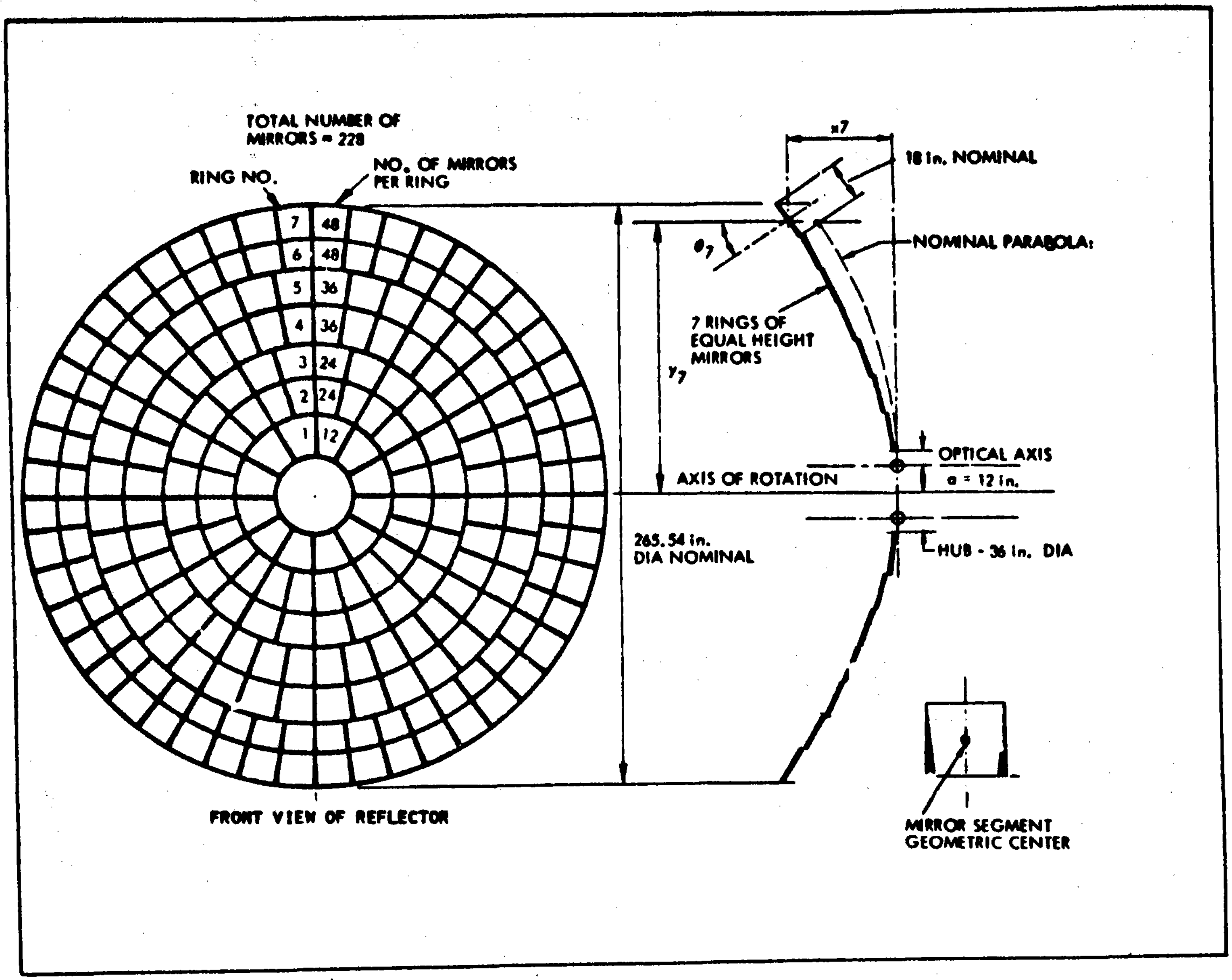


FIGURE 3-7. Concentrator Mirror Layout

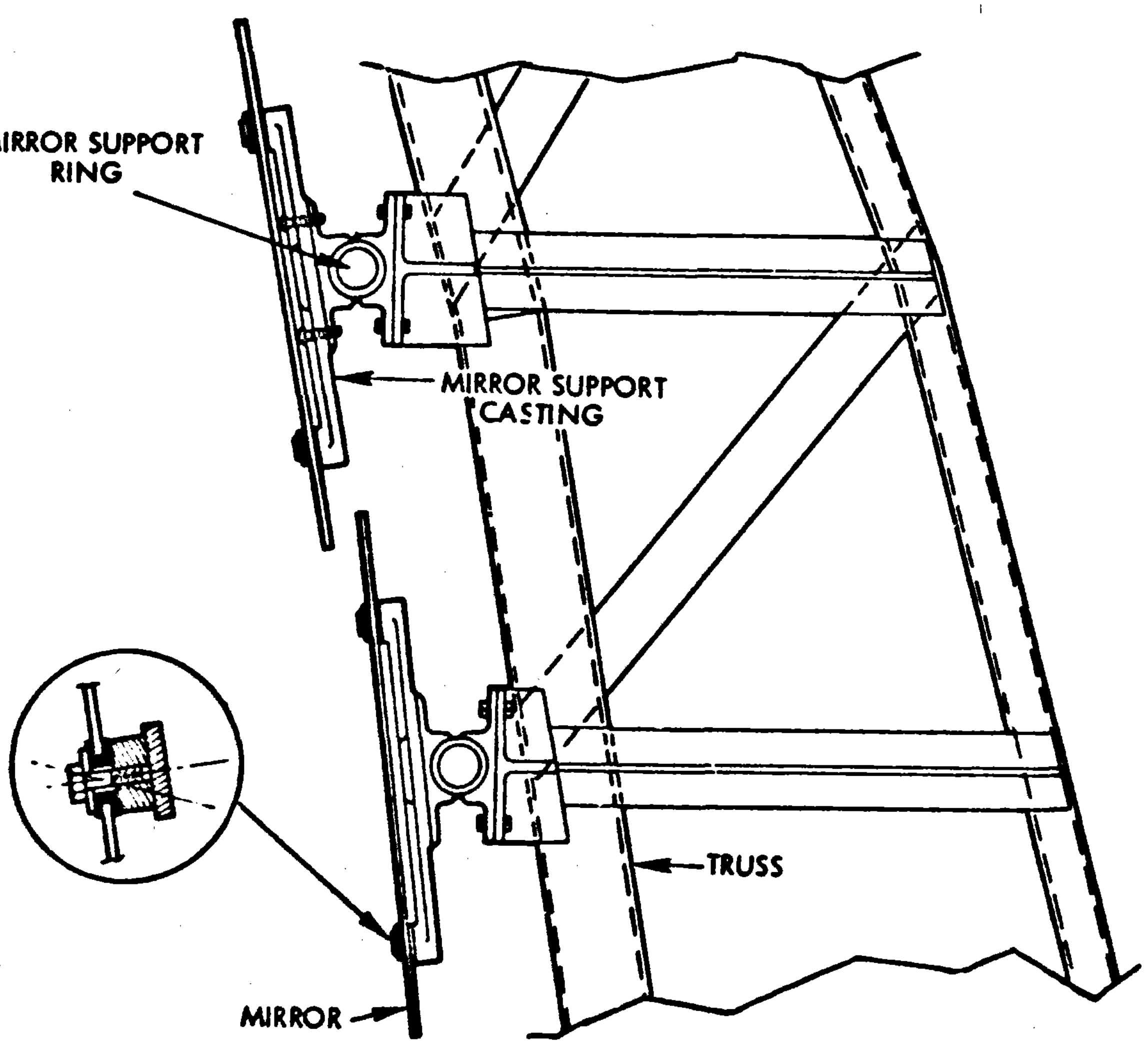
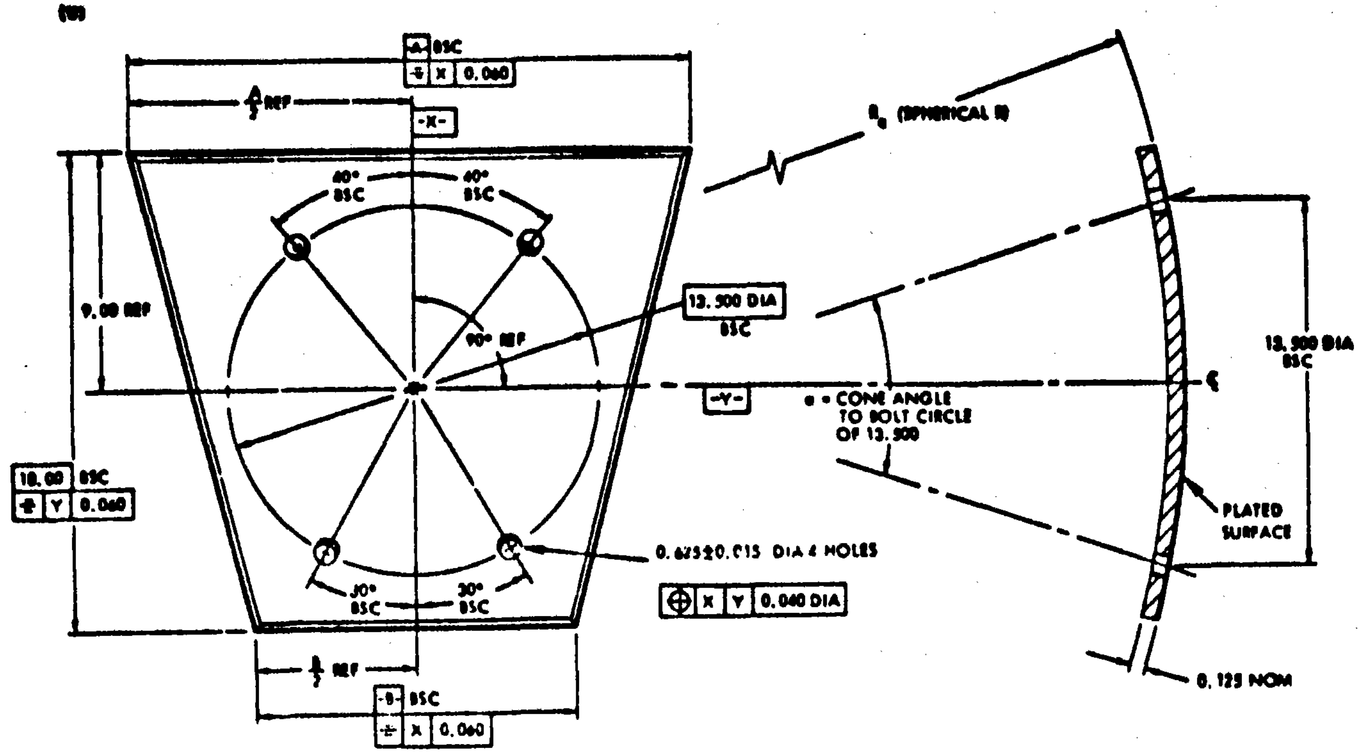


FIGURE 3-8. Mirror Assembly Details

(U)



-NO	R_C ±10 In.	A ±0.030 REF	A/2	B ±0.030 REF	B/2	α°	ALTERNATIVE R_C	
							$R_{C\,MIN}$	$R_{C\,MAX}$
-1	250 In.	18.806	9.403	8.858	4.429	3.094	236.3	246.3
-2	250 In.	13.573	6.786	8.796	4.398	3.094	239.3	249.3
-3	250 In.	17.958	8.979	13.197	6.598	3.094	246.0	256.0
-4	250 In.	14.755	7.377	11.687	5.843	3.094	256.0	267.6
-5	295 In.	17.554	8.777	14.519	7.259	2.622	267.6	285.0
-6	295 In.	15.166	7.583	12.952	6.476	2.622	285.0	304.8
-7	295 In.	17.178	8.589	15.014	7.507	2.622	304.8	328.8

NOTE: ALL DIMS SHOWN ARE TO R_c (PLATED SURFACE) AND ARE PARALLEL TO ℄
ALL DIMS IN INCHES

FIGURE 3-9. Mirror Segment Details

UNCLASSIFIED

UNCLASSIFIED

3.1.4.1.5 Concentrator Assembly

The trusses, the support rings and the hub were assembled prior to shipment to Sandia to ensure fit and structural alignment. The concentrator was then disassembled and shipped to Sandia for reassembly and installation on the collector pedestal. The concentrator structure incorporates pickup points for use during field erection. At this time, mirror mounting brackets are bolted to the corresponding support ring mirror pads using the two pre-drilled bolt holes. The mirrors are then assembled on the mounting bracket using elastomeric grommets, and stainless steel bushings, bolts and washers. Individual mirrors may be replaced without removing adjacent mirror segments and the mirrors may be installed either before or after the concentrator is installed on the pedestal.

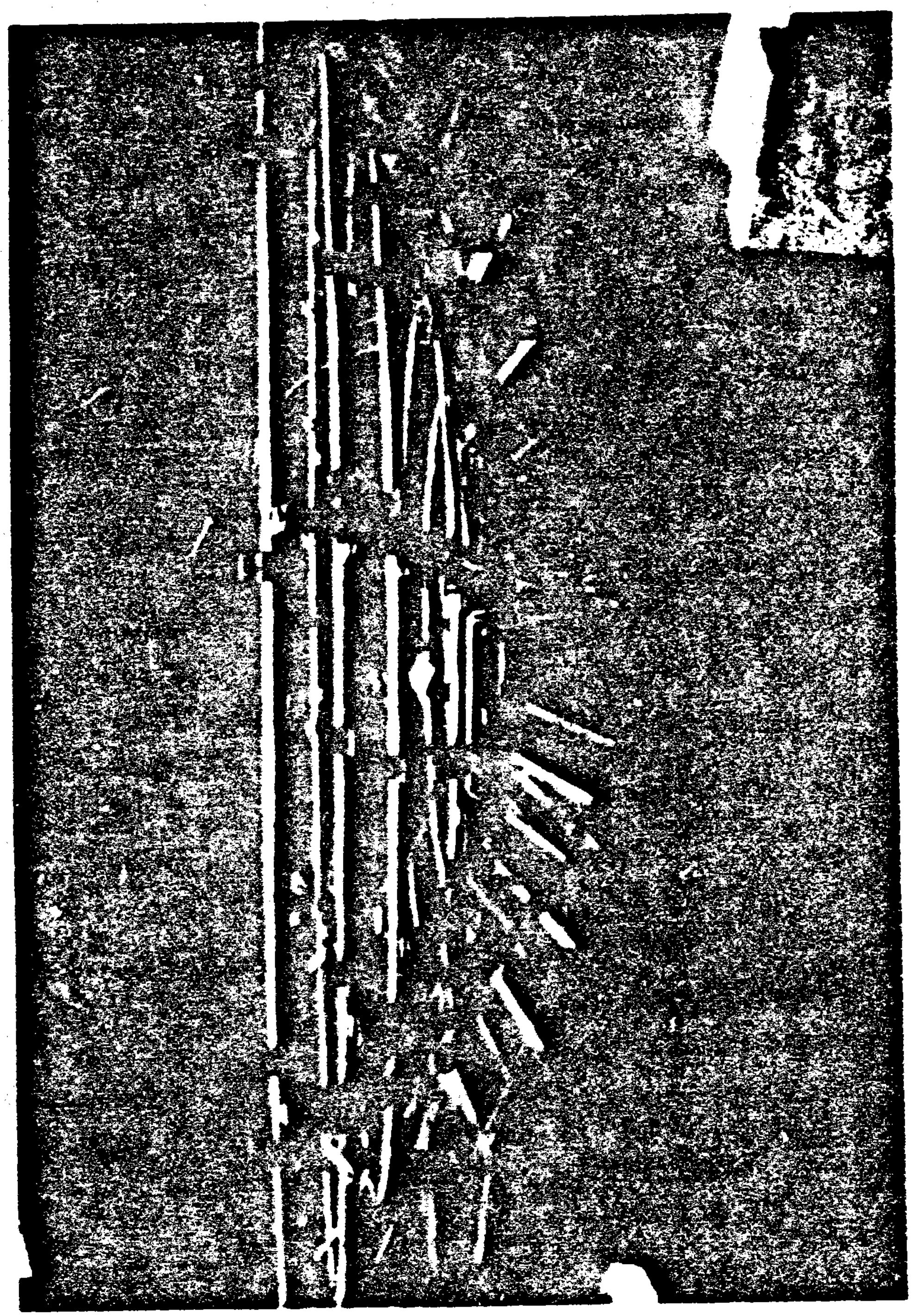
3.1.4.2 Concentrator Fabrication

Concentrator fabrication was subcontracted to Motor Machine, Co., Edison New Jersey. Figures 3-10 through 3-14 show various components and assemblies, the photographs taken at Motor Machine during fabrication. Figure 3-15 shows an artist's rendition of the support members attached to the rear of the trusses to resist side loads. Castings shown in Figure 3-11 were supplied by Raytheon to the subcontractor.

The concentrator fabrication and assembly sequence was:

a) Fabricate the trusses, rings and elevation hub.

b) Attach the appropriate castings to the trusses and rings, and machine for flatness and orthogonality.



CN-6-5325 #9A

FIGURE 3-10. Concentrator Assembly

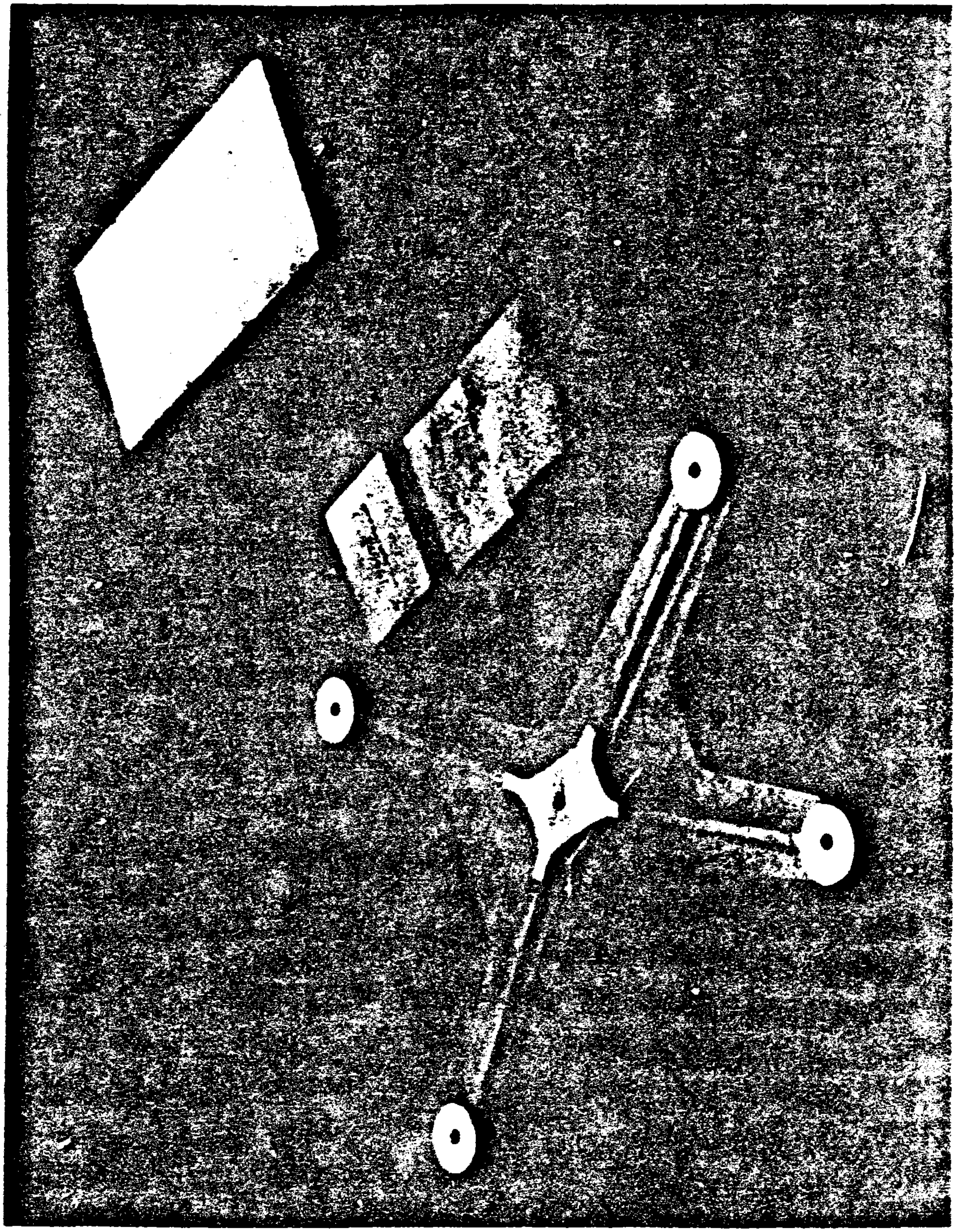


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FIGURE 3-11. Concentrator Castings

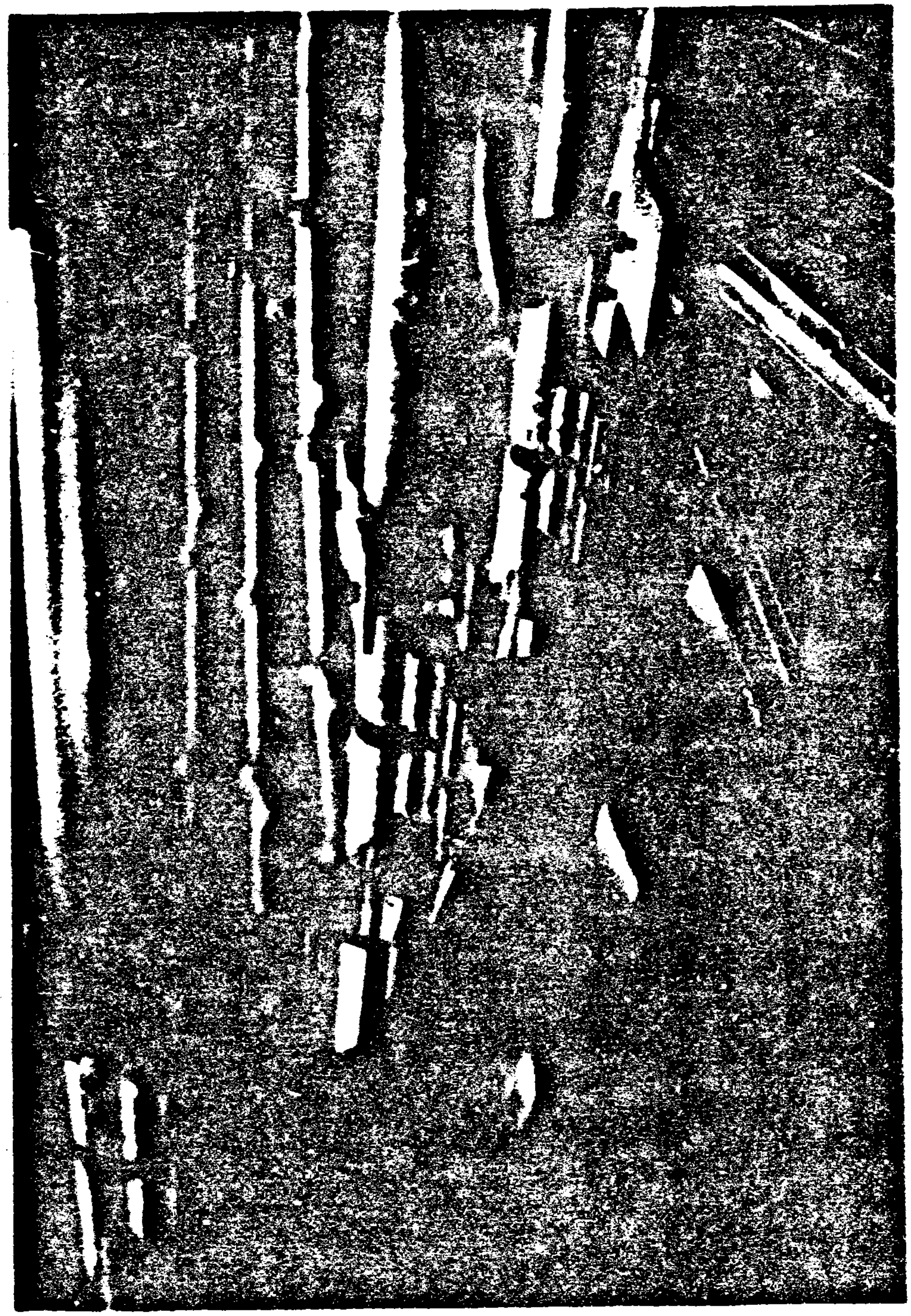

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FIGURE 3-12. Truss/Ring Attachment

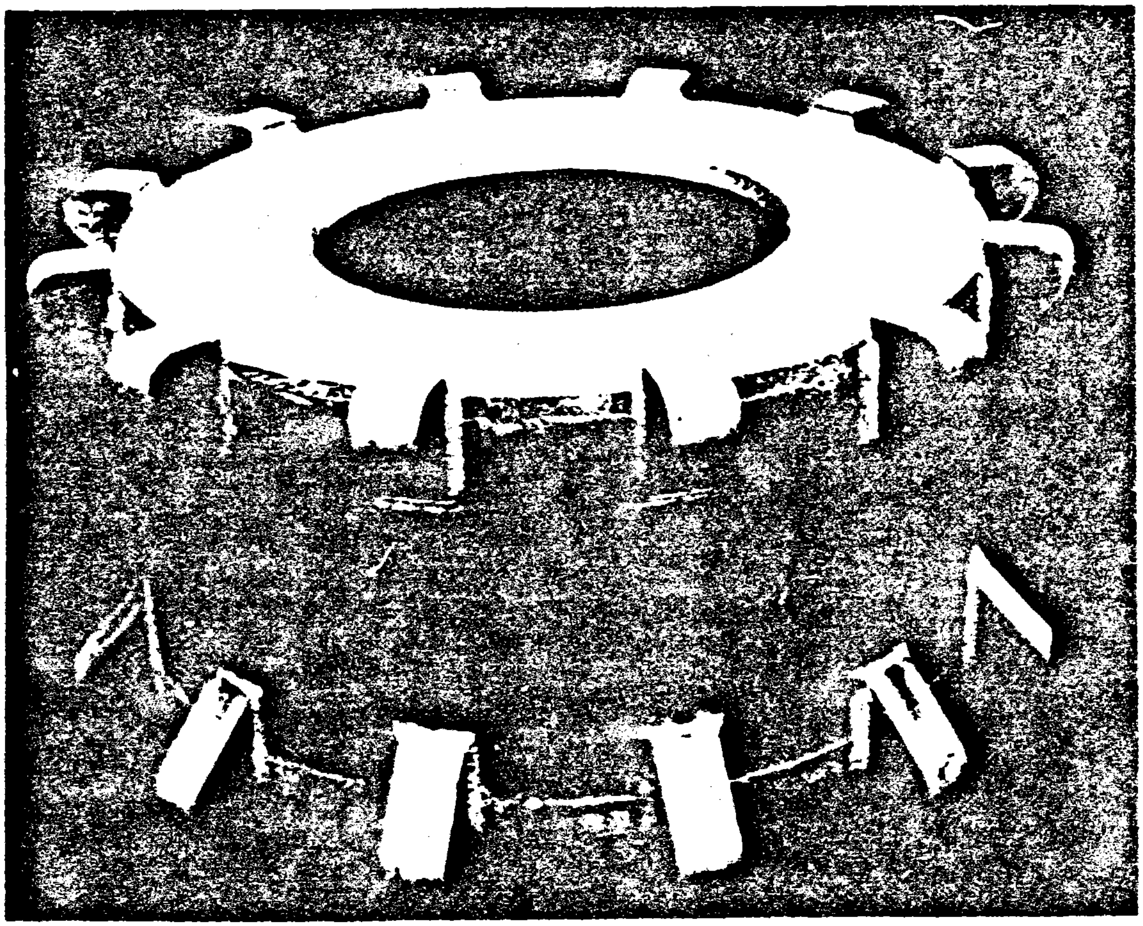

FIGURE 3-13. Hub Before Machining

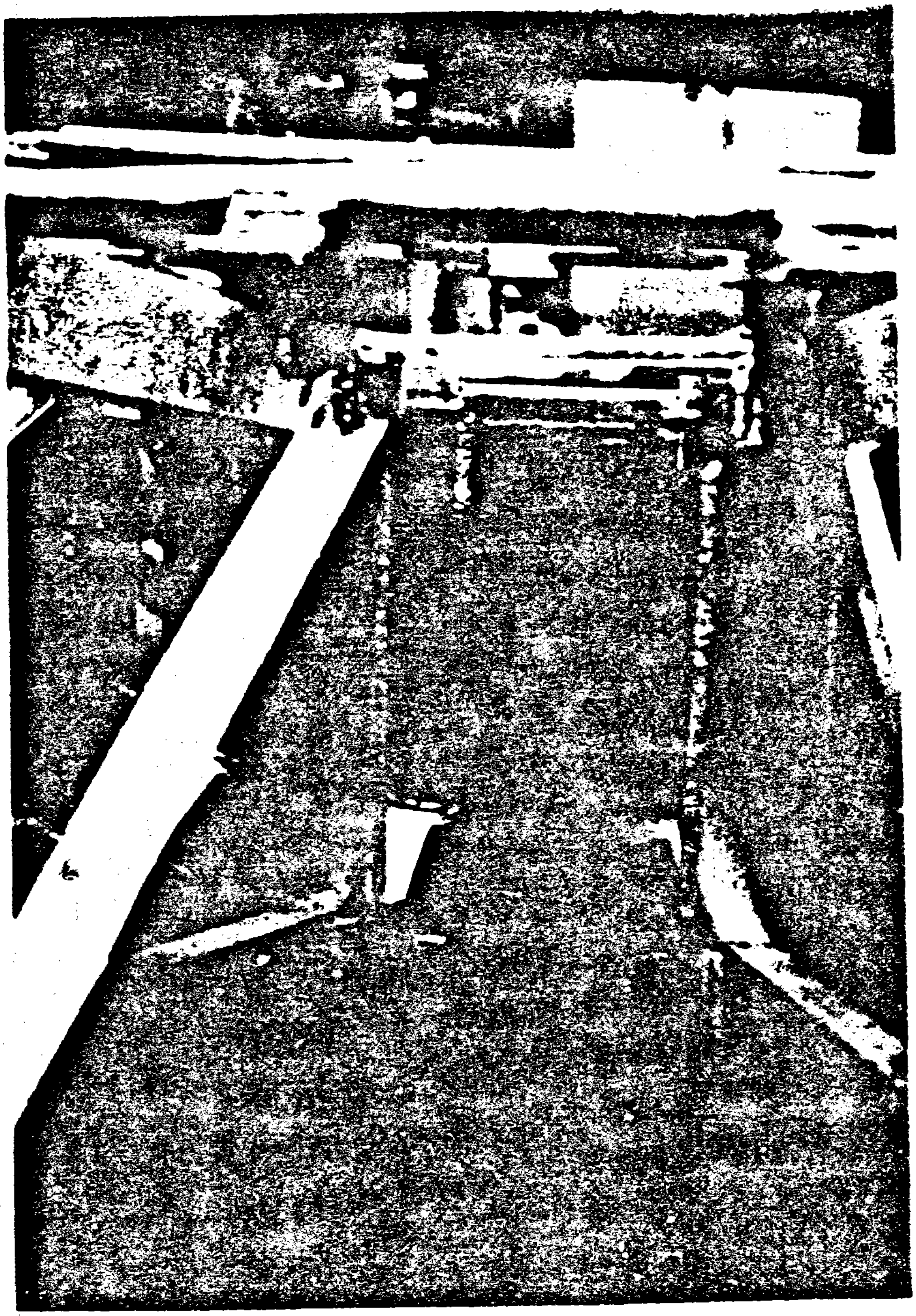

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FIGURE 3-14. Hub/Truss Attachment

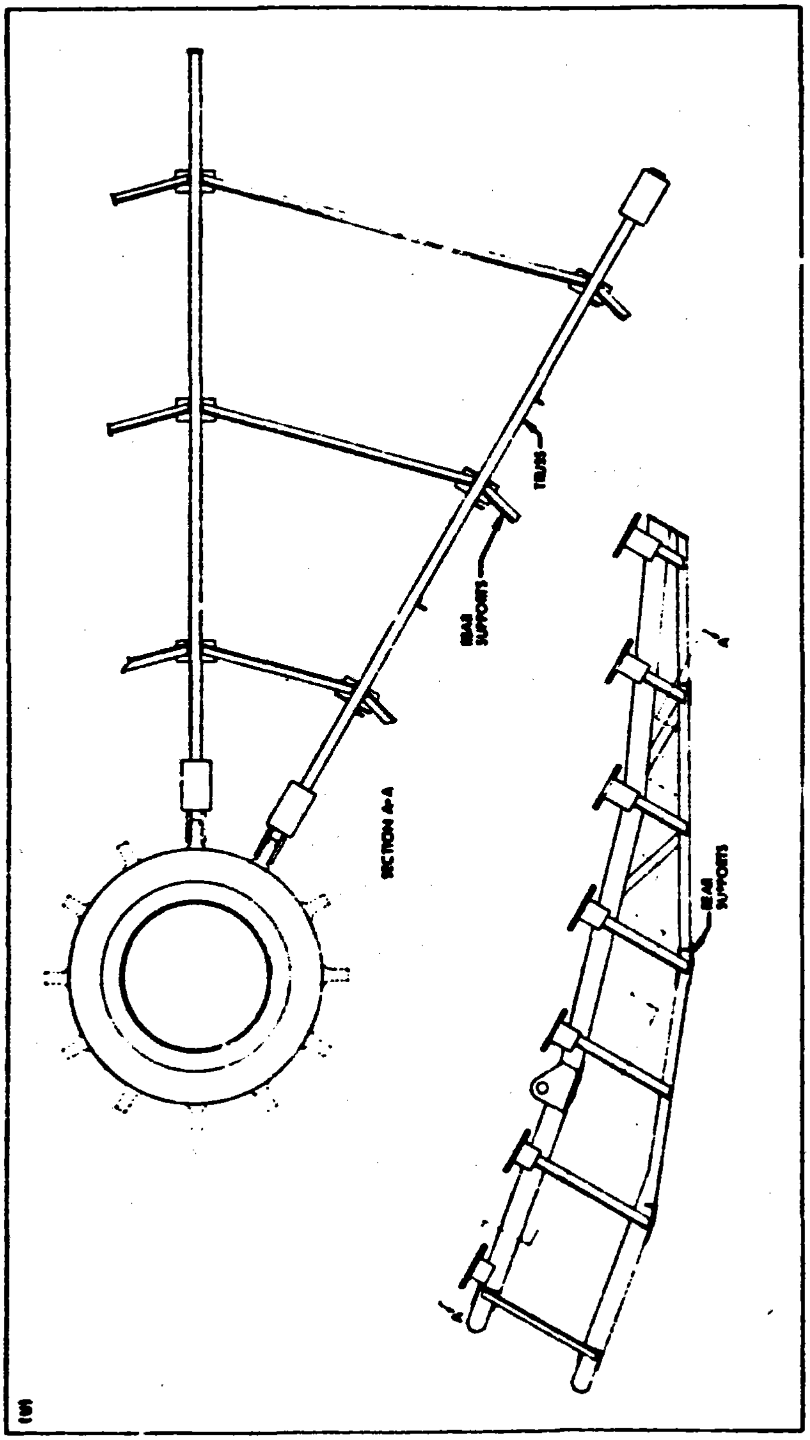


FIGURE 3-15. Truss Support System

c) Assemble the trusses to the hub.

d) Position and attach the rings to the trusses. (The 3 inner rings are complete, comprising 360 degrees of arc. Outer rings are split [180 degrees each] for shipping purposes.

e) Set-up the mirror support pads on the rings at appropriate angles, and tack weld in place.

f) Machine mirror mounting brackets.

g) Attach the truss supports in place.

h) Disassemble for shipping.

The entire process went very well, especially considering the fact that this was the first such concentrator of that type built. The single most critical fabrication process was attaching the mirror support pads to the rings at the correct angle. Angular tolerance on this process was originally specified at ±15 min. arc, equivalent to approximately 4.4 mr. The original design for the collector hypothesized the machining of these angles after the pads had been rough set and positioned on the ring. Vendors that responded to the concentrator fabrication request for quote that possessed requisite machining capability were very high in their total cost estimates (there was however, no indication that the desired procedure was responsible for the higher cost estimates). Therefore, the fabrication approach was changed to finish machining the pads off-ring, and accurately attaching and welding them at the desired angle. This change resulted in a great reliance on the welding process not disturbing the set angle, which constituted a large unknown. Prior planning in the manufacturing techniques had foreseen some of these potential difficulties, and the design incorporated the ability to make numerous adjustments in the final mirror positioning, either by adjusting the mirror support bracket backface by cutting at an angle, or by shimming the space between the support bracket and the machined pad, or by adjusting the support bracket at the four mirror mount points.

The detailed approach toward mounting the machined pad was to set the pad at the proper angle ±8" of arc using a sine bar and machinist's level. Tack welds were then applied at four corner locations along the semi-circular pad/ring interface. Full welding along the arcs at the ends then completed the attachment.

The initial pad attachments were set up and tacked, with the results generally being that the tacking operation introduced a 6 min. rotation in the casting, and the full weld introduced a 20 min. rotation. The rotation direction could be selected by locating the initial application of heat, and first experiments, eight total, resulted in all pads being within specification. However, the production tacking and welding of the remaining 220 pads yielded rotations exceeding specification. This was caused by excessive filler material and heat application. As a result, the mirror mounting castings were selectively machined as discussed below, which utilized their correctability for providing an accurate mirror mounting surface. There is general agreement among those who were engaged in the fabrication program that the potential is there for accurately and inexpensively manufacturing large scale concentrators using approaches similar to those described herein. A reasonable amount of weld development, process specification and special tooling (none was used) could bring the as-manufactured concentrator into specification without selective machining of mirror mounting castings. In addition, the concept of final angle machining on the ring could prove to be the most accurate and least expensive approach. The inherent capability of the process and the available tooling is approximately 1 min. of arc. These concepts might be pursued as part of a larger manufacturing process development program that could precede substantial quantity manufacturing of the concentrator.

3.1.4.3 Mirror Mounting Angle Adjustment

The tilt angle of all of the machined pads on all of the rings were measured with a "sine bar". The value of the tilt of each casting is given in Table 3-7, in minutes of arc, with sign convention and further definitions shown in Figure 3-16 and 3-17.

The tilt angle rotation (error) varies from -31 minutes (Ring 2) to +51 minutes (Ring 6). Minuses denote a rotation array from the absorber toward the sun. The specification on the mirror tilt was ±15 minutes. The tilt angle can be corrected by machining an equal and opposite tilt on the mirror mounting bracket. Four alternatives were investigated to reduce the error within the constraint of reasonable cost impact.

a) Machine all of the brackets with no rotation correction. This would minimize the set-up time for machining the brackets but would result in the largest error -31 min. to +51 min. The mean error of the 228 mirrors is 8.7 min. and the standard deviation of the error variation is 19.1 min. The error is unacceptable.

b) Machine all the brackets of each ring to the mean rotation of that ring. There would be seven separate brackets. This would leave 26 mirror tilt angles out of specification (Ring 1-0, Ring 2-1, Ring 3-3, Ring 4-1, Ring 5-10, Ring 6-5, Ring 7-6). The error would vary from -28 min. to +25 min. with a standard deviation of 9.4 min. The error is large, but the number of machine set-ups is also large.

c) Machine three bracket configurations, one with a 30 min. rotation correction, one with no correction and one with +30 min. correction (see Figure 3-17). All but three of the mirrors can

TABLE 3-7

SHEET NO. 2 : TITLE: Pad/Bracket Data

RING NO. 1 TILT ANGEL REQUIREMENT 3°27' ±0°15'

PAD	PAD ROTATION (FROM IDEAL) ARC MINUTES	BRACKET TYPE USED	RESULTING ROTATION (FROM IDEAL) ARC MINUTES
1	-19	A	+11
2	-26	A	+4
3	-15	B	-15
4	-7	B	-7
5	-15	B	-15
6	-23	A	+7
7	-16	A	+14
8	-22	A	+8
9	-10	B	-10
10	-15	B	-15
11	-20	A	+10
12	-12	B	-12

TABLE 3-7 (CONT.)

SHEET NO. 3 : TITLE:

RING NO. 2 TILT ANGEL REQUIREMENT 7°31' ±0°15'

PAD	PAD ROTATION (FROM IDEAL)	BRACKET TYPE USED	RESULTING ROTATION (FROM IDEAL)
	ARC MINUTES		ARC MINUTES
1	-12	B	-12
2	-7	B	-7
3	-16	A	+14
4	-9	B	-9
5	+5	B	+5
6	-12	B	-12
7	-9	B	-9
8	-6	B	-6
9	-6	B	-6
10	-10	B	-10
11	0	B	0
12	-10	B	-10
13	-8	B	-8
14	-4	B	-4
15	-6	B	-6
16	-3	B	-3
17	-9	B	-9
18	-19	A	+11
19	-16	A	+14
20	+4	B	+4
21	-9	B	-9
22	-15	B	-15
23	-15	B	-15
24	-30	A	0

TABLE 3-7 (CONT.)

SHEET NO. 4 : TITLE:

RING NO. 3 TILT ANGEL REQUIREMENT 11°31' +0°15'

PAD	PAD ROTATION (FROM IDEAL)	BRACKET TYPE USED	RESULTING ROTATION (FROM IDEAL)
	ARC MINUTES		ARC MINUTES
1	-6	B	-6
2	-29	A	+1
3	+3	B	+3
4	-10	B	-10
5	-23	A	+7
6	-8	B	-8
7	-12	B	-12
8	-20	A	+10
9	-22	A	+8
10	-7	B	-7
11	-16	A	+14
12	-6	B	-6
13	-3	B	-3
14	-16	A	+14
15	-10	B	-10
16	-6	B	-6
17	-5	B	-5
18	-4	B	-5
19	-18	A	+12
20	-22	A	+8
21	-10	B	-10
22	-17	A	+13
23	-28	A	+2
24	+2	B	+2

TABLE 3-7 (CONT.)

SHEET NO. 5 : TITLE:

RING NO. 4 TILT ANGEL REQUIREMENT 15°27' ±0°15'

PAD	PAD ROTATION (FROM IDEAL)	BRACKET TYPE USED	RESULTING ROTATION (FROM IDEAL)
	ARC MINUTES		ARC MINUTES
1	-1	B	1
2	-3	B	-3
3	-7	B	-7
4	-10	B	-10
5	+10	B	+10
6	+20	C	-10
7	-3	B	-3
8	+2	B	+2
9	-8	B	-8
10	-7	B	-7
11	+5	B	+5
12	-3	B	-3
13	-14	B	-14
14	+7	B	+7
15	+6	B	+6
16	-12	B	-12
17	-8	B	-8
18	-3	B	-3
19	+3	B	+3
20	-8	B	-8
21	-4	B	-4
22	-6	B	-6
23	-9	B	-9
24	-10	B	-10
25	-3	B	-3

TABLE 3-7 (CONT.)

SHEET NO. 6 : TITLE:

RING NO. 4 TILT ANGEL REQUIREMENT 15°27' ±0°15'

PAD	PAD ROTATION (FROM IDEAL) ARC MINUTES	BRACKET TYPE USED	RESULTING ROTATION (FROM IDEAL) ARC MINUTES
26	-4	B	-4
27	-10	B	-10
28	-9	B	-9
29	-14	B	-14
30	-12	B	-12
31	-6	B	-6
32	-18	A	+12
33	-3	B	-3
34	-6	B	-6
35	-8	B	-8
36	0	B	0

TABLE 3-7 (CONT.)

SHEET NO. 7 : TITLE:

RING NO. 5 TILT ANGEL REQUIREMENT 19°11' ±0°15'

PAD	PAD ROTATION (FROM IDEAL) ARC MINUTES	BRACKET TYPE USED	RESULTING ROTATION (FROM IDEAL) ARC MINUTES
1	+45	C	+15
2	+36	C	+6
3	+30	C	0
4	+30	C	0
5	+43	C	+13
6	+30	C	0
7	+31	C	+1
8	+36	C	+6
9	+38	C	+8
10	0	B	0
11	+8	B	+8
12	+8	B	+8
13	+9	B	+9
14	+8	B	+9
15	+8	B	+8
16	+19	C	-11
17	+17	C	-13
18	+10	B	+10
19	+6	B	+6
20	+8	B	+8
21	+8	B	+8
22	+8	B	+8
23	+16	C	-14
24	+15	B	+15
25	+10	B	+10

TABLE 3-7 (CONT.)

SHEET NO. 8 : TITLE:

RING NO. 5 TILT ANGEL REQUIREMENT 19°11' ±0°15'

PAD	PAD ROTATION (FROM IDEAL)	BRACKET TYPE USED	RESULTING ROTATION (FROM IDEAL)
	ARC MINUTES		ARC MINUTES
26	+3	B	+3
27	+38	C	+8
28	+22	C	-8
29	+25	C	-5
30	+32	C	+2
31	+17	C	-13
32	+38	C	+8
33	+23	C	-7
34	+25	C	-5
35	+28	C	-2
36	+23	C	-7

TABLE 3-7 (CONT.)

SHEET NO. 9 : TITLE:

RING NO. 6 TILT ANGEL REQUIREMENT 22°43' ±0°15'

PAD	PAD ROTATION (FROM IDEAL)	BRACKET TYPE USED	RESULTING ROTATION (FROM IDEAL)
	ARC MINUTES		ARC MINUTES
1	+26	C	-4
2	+14	B	+14
3	+29	C	-1
4	+23	C	-7
5	+30	C	0
6	+28	C	-2
7	+41	C	+11
8	+29	C	-1
9	+23	C	-7
10	+26	C	-4
11	+38	C	+8
12	+15	C	-15
13	+21	C	-9
14	+28	C	-2
15	+35	C	+5
16	+19	C	-11
17	+26	C	-4
18	+38	C	+8
19	+32	C	+2
20	+21	C	[illegible]
21	+30	C	0
22	+31	C	+1
23	+42	C	+12
24	+36	C	+6
25	+24	C	-6

TABLE 3-7 (CONT.)

SHEET NO. 10 : TITLE:

RING NO. 6 TILT ANGEL REQUIREMENT 22°43' ±0°15'

PAD	PAD ROTATION (FROM IDEAL)	BRACKET TYPE USED	RESULTING ROTATION (FROM IDEAL)
	ARC MINUTES		ARC MINUTES
26	+27	C	-3
27	+30	C	0
28	+23	C	-7
29	+26	C	-4
30	+36	C	+6
31	+25	C	-5
32	+32	C	+2
33	+10	B	+10
34	+32	C	+32
35	+30	C	0
36	+23	C	-7
37	+30	C	0
38	+17	C	-13
39	+26	C	-4
40	+23	C	-7
41	+17	C	-13
42	+28	C	-2
43	+27	C	-3
44	+28	C	-2
45	+25	C	-5
46	+35	C	+5
47	+48	C	+18
48	+49	C	+19

TABLE 3-7 (CONT.)

SHEET NO. 11 : TITLE:

RING NO. 7 TILT ANGEL REQUIREMENT 26°02' ±0°15'

PAD	PAD ROTATION (FROM IDEAL)	BRACKET TYPE USED	RESULTING ROTATION (FROM IDEAL)
	ARC MINUTES		ARC MINUTES
1	+15	B	+15
2	+22	C	-8
3	+10	B	+10
4	-3	B	-3
5	+17	C	-13
6	+2	B	+2
7	+15	C	-15
8	+9	B	+9
9	+3	B	+3
10	+24	C	-6
11	+16	C	-14
12	+15	C	-15
13	+24	C	-6
14	+26	C	-4
15	+34	C	+4
16	+10	B	+10
17	+19	C	-11
18	+11	B	+11
19	+17	C	-13
20	+19	C	-11
21	+19	C	-11
22	+19	C	-11
23	+27	C	-3
24	+18	C	-12
25	+7	B	+7

TABLE 3-7 (CONT.)

SHEET NO. 12 : TITLE:

RING NO. 7 TILT ANGEL REQUIREMENT 26°02' ±0°15'

PAD	PAD ROTATION (FROM IDEAL) ARC MINUTES	BRACKET TYPE USED	RESULTING ROTATION (FROM IDEAL) ARC MINUTES
26	+19	C	-11
27	-11	B	-11
28	+10	B	+10
29	+8	B	+8
30	+15	B	+15
31	+22	C	-8
32	-3	B	-3
33	+8	B	+8
34	+24	C	-6
35	+12	B	+12
36	+3	B	+3
37	+17	C	-12
38	+21	C	-9
39	+23	C	-7
40	+21	C	-9
41	+9	B	+9
42	+23	C	-7
43	+31	C	+1
44	+15	B	+15
45	+8	B	+8
46	+21	C	-9
47	+34	C	+4
48	+12	B	+12

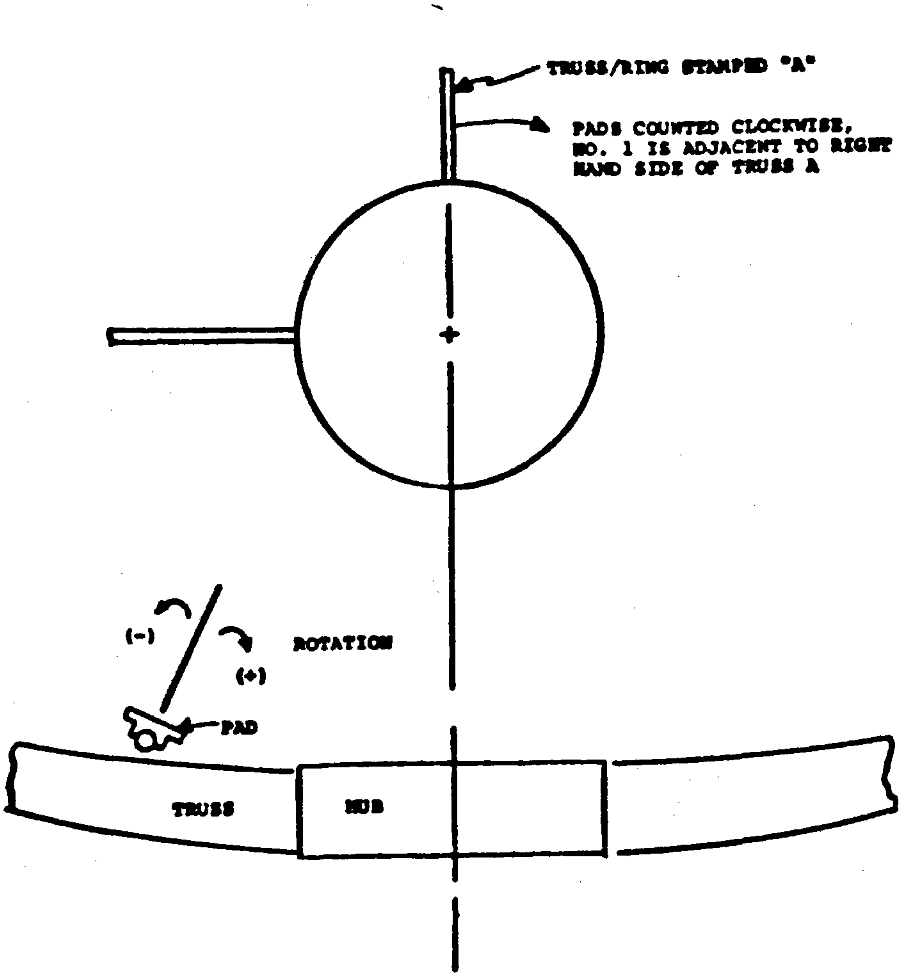
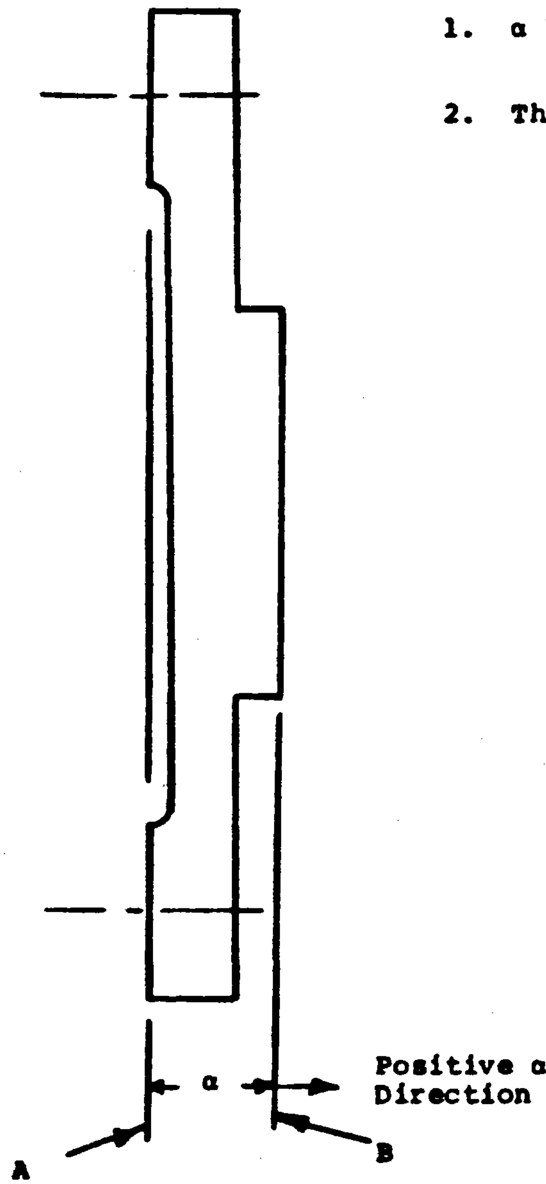


FIGURE 3-16. Pad Numbering and Sign Convention



NOTES:

1. α ≡ Angle between planes
   A and B

2. Three casting types as follows:

   "A", α = −0°30' ±0°1'

   "B", α = 0 ±0°1'

   "C", α = +0°30' ±0°1'

FIGURE 3-17. Mirror Support Bracket Aligment Machining be brought into specification by using the proper mirror support casting. The error ranges from -15 min. to +21 min. with a standard deviation of 8.8 min.

d) Machine each mirror support casting to correct each mirror angle. The resulting rotation error is the accuracy of the measurement and the machining capability. This would result in no interchangeable parts for the mirror support brackets. This approach is the most expensive of the four and the result is an "overkill" in regard to this one system error.

The third approach was implemented. If the mirror radius of curvature problem had been known at the time, another selection, such as (d) might have been made. However, the data used in the selection process proved useful by indicating the amount of adjustment required at each mirror to exactly align the mirror with the aperture centerline, thereby making the use of out-of-specification mirrors feasible.

3.1.5 Absorber Design and Fabrication

3.1.5.1 Design

Figure 3-18 depicts the absorber mounted on its support post. The post, a standard aluminum tube, is welded to a support plate, via gussets, and is bolted to the dish hub. Therminol-66 lines occupy the interior of the post along with absorber instrumentation lines. The fluid lines terminate in a flexible hose that is ultimately attached to the elevation hose assembly, allowing elevation motion on the part of the dish. The hoses have union type connections, allowing easy assembly/disassembly and accommodating fluid line expansion/contraction.

The energy absorber, Figure 3-19, is the cavity type described in prior sections. The absorber is supported on the

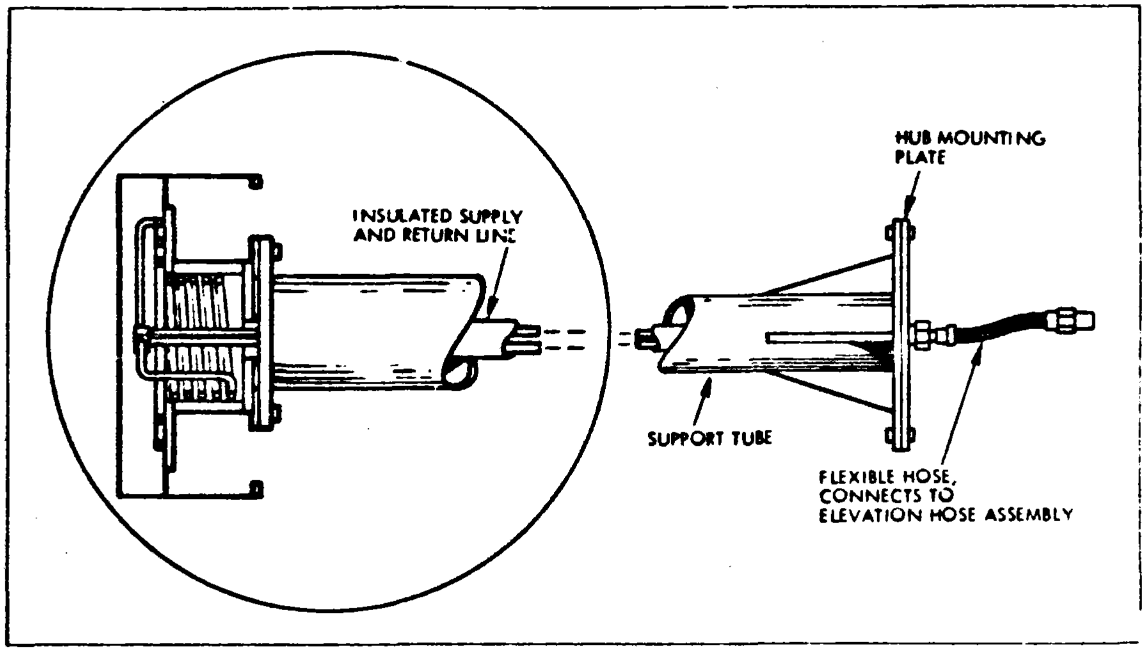


FIGURE 3-18. Absorber Support System

center post with insulating gaskets that limit heat flow to the post. The input aperture annulus is achieved by placing stainless steel plates, inner and outer, into the larger aperture formed by the absorbing surfaces and surrounding covers. The aperture plates are removable with the absorber in place for experimentation purposes; increasing or decreasing the aperture size will impact the absorber collection and conversion efficiency. Fluid connections are made to the post lines with the top cover removed. The entering fluid flows to the top of the absorber (near the cover) where the connection is made, and then returns to the base of the absorber, thereby achieving the maximum cooling capability at the point of maximum heat flux. The fluid then flows in a spiral along the cylindrical section, to the disc or "hat brim" section, and then it returns to the support fluid lines.

(U)

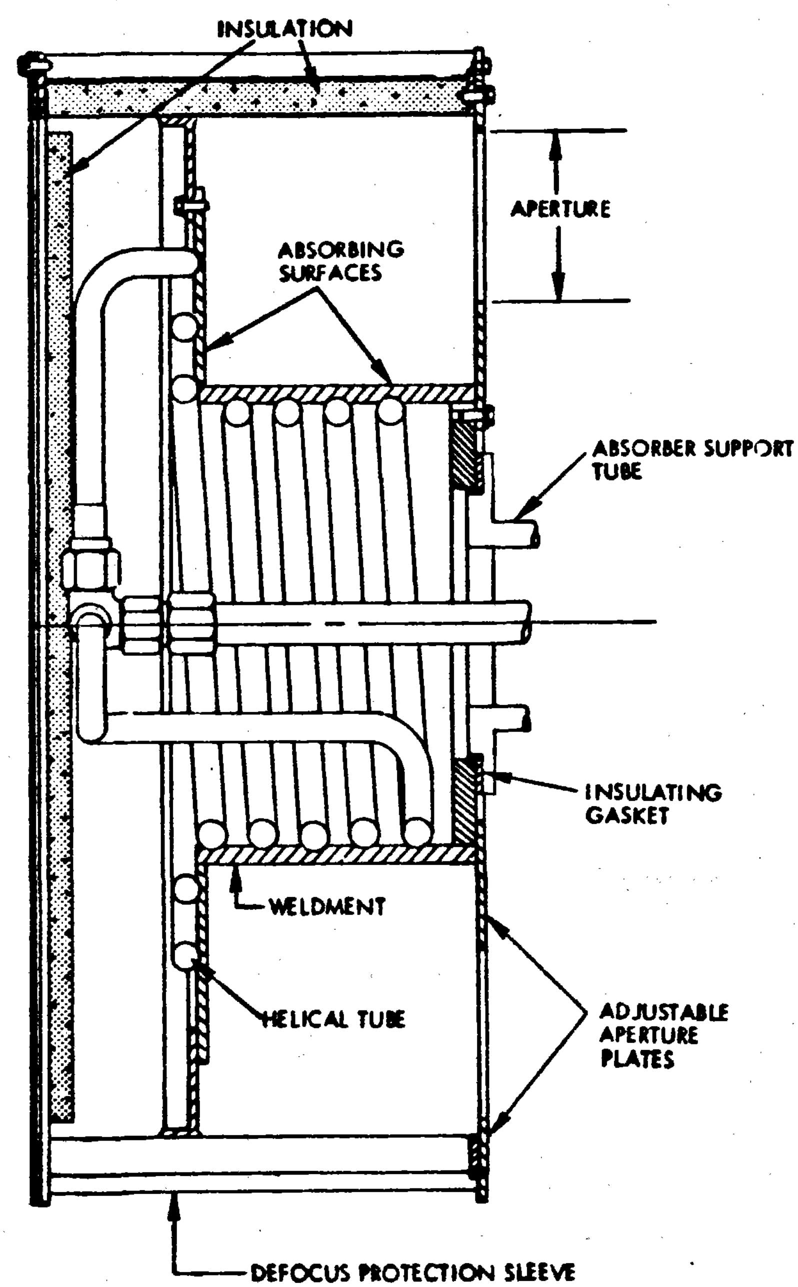


FIGURE 3-19. Energy Absorber

Figure 3-20 shows typical energy incidence curves used to design the absorber during earlier program phases. The curves are shown in terms of magnification factors, which can be interpreted in terms of "suns".

Figure 3-21 shows the results of thermal analyses of the absorber design. The input energy is 0.95 kW/m^2 times the aforementioned magnification factors and the fluid flow is 15g/min. The Therminol-66 temperature increases 25°F from 573°F to 598°F with the assumed input and fluid flow rate. Material compatibility tests and tests on the selective coating indicate that the materials can handle the expected temperatures.

3.1.5.2 Absorber Fabrication

Figures 3-22 and 3-23 depict the absorber prior to brazing the zirconium-copper tube to the weldment. At the stage shown a groove had been cut in the weldment, into which the tube was fitted, the object being to increase the braze contact area. During the braze process, the tube holding fixture did not function properly, causing the tube to leave the groove and become brazed haphazardly along approximately 1/2 of its length at the post end. Attempts to unbraze the components were unsuccessful. A fix was accomplished that consisted of additional torch brazing with Sil-Phos (Hardy & Harmon Co.), to provide up to 1/2 the previously desired braze/tube/weldment contact area along the tube. The absorber was originally brazed with BT alloy which melts at 1100°F. The expectation - later confirmed - was that the BT alloy would form a dam, allowing the Sil-Phos to form a fillet sufficient to perform its thermal task. A thermal analysis confirmed that the effect of reduced braze area was minimal, considering the overall conductance of the copper system.

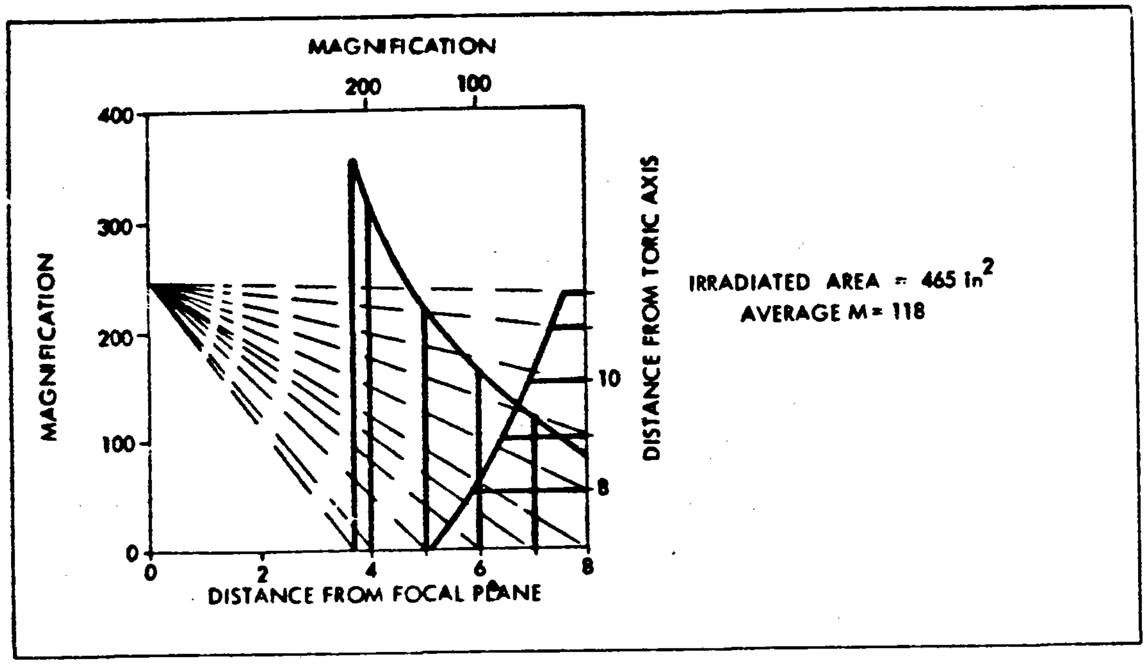


FIGURE 3-20. Absorber Incident Energy Pattern

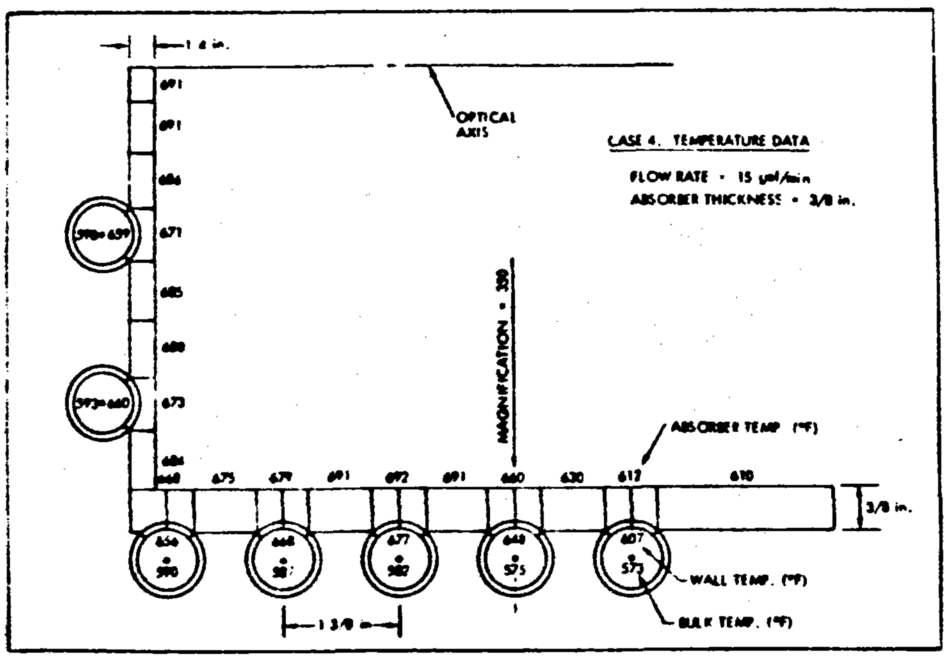
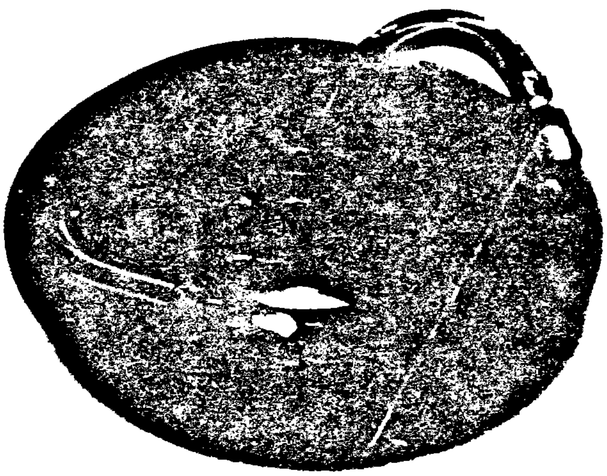
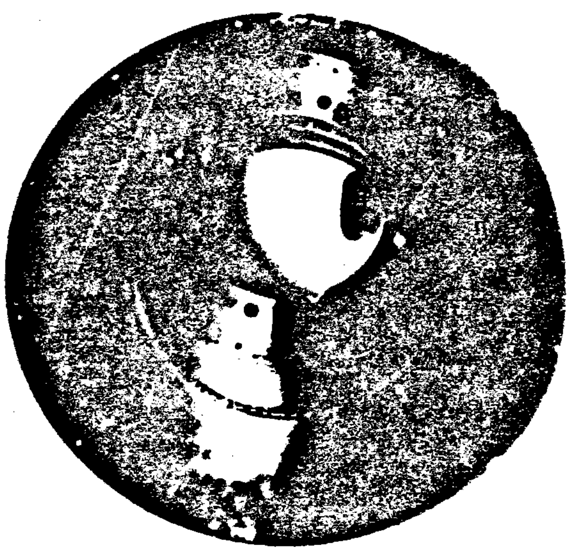


FIGURE 3-21. Absorber Temperature Data



CN-6-5147

FIGURE 3-22. Absorber Weldment and Tube, Top View



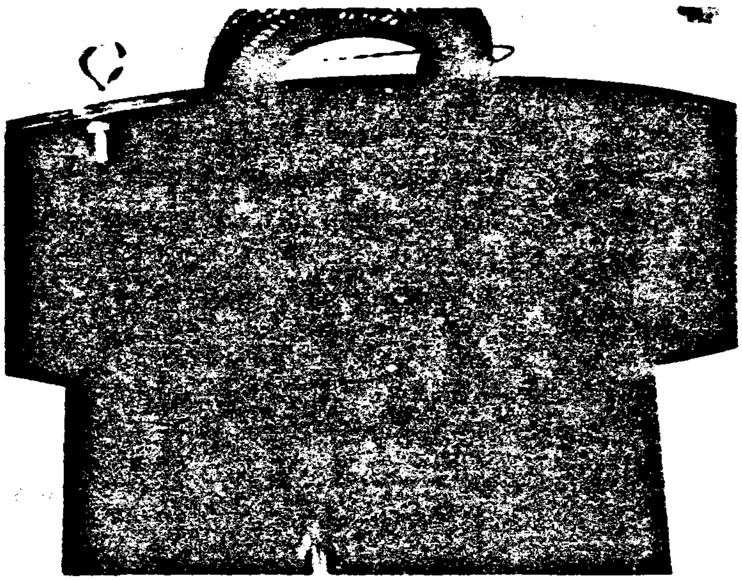
CN-6-5146

FIGURE 3-23. Absorber Weldment and Tube, Bottom View

After brazing, and pressure testing at 750 psig at room temperature, the absorber was shipped to Highland Plating Company, Los Angeles, Calif., for application of the black chrome selective coating. The experience of others has been that the black chrome process is somewhat inconsistent although very high quality test pieces had been produced by Highland during a preceeding program. Sandia Laboratories provided portable Gier-Dunkle equipment and technical support to determine solar absorptivity and 300°C emittance at Highland, verifying that the process was producing the desired $\alpha = 0.92$, and $\epsilon = 0.3$. After a few "learning" type experiments with the absorber and the Highland designed anode, the absorber was plated and measured $\alpha = 0.97/0.98$, $\epsilon = 0.34/0.39$. These results were considered excellent, and with the absorber design being cavity like, very nearly 100 percent of the impinging solar energy will be absorbed. Figure 3-24 shows the absorber as plated. The bright spots are copper plugs containing thermocouples inserted after plating. Figure 3-25 is a view of the thermocouple patch panel, which also shows the melted effect of the Sil-Phos brazing fix. The wire ties on the flexible hoses are for restraint during shipping.

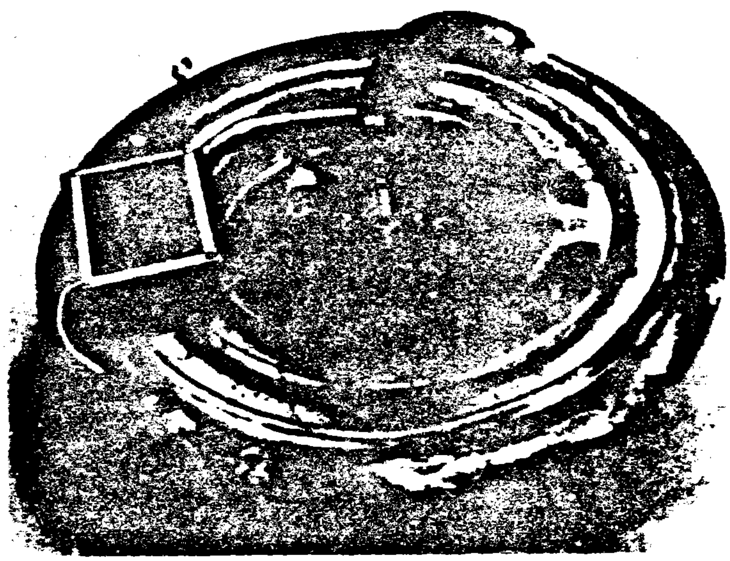
3.1.5.3 Effect of Emergency Defocus on Absorber System

The center-supported absorber approach was selected over rim or intermediate support to minimize shadowing and blocking effects, and to minimize piping runs. That decision resulted in a ring focus, and ultimately the modified cavity-type absorber design fabricated. A system requirement is that the collector be capable of surviving a utility power loss during operation, which could stop fluid flow. Analysis indicated that the most efficient approach toward attaining the required survivability is to equip the collector with an emergency power supply to drive the collector away from the solar line-of-sight when utility power fails. This results in a



CN-6-5360

FIGURE 3-24. Absorber After Plating



CN-6-5357

FIGURE 3-25. Absorber Instrumentation Patch Panel gradual blurring of the ring focus as the line-of-sight error increases, and displacement of the focus along the absorber cover and the center support post. (The same effect would be realized for any absorber support scheme. The deliberate beam spreading caused by ring focusing may lead to a less severe problem than more classical point concentrators face).

At a stage in the program where the detailed mechanical designs of all items were available a computerized ray-trace investigated the effects of defocussing on the absorber cover and support post. The analysis considered actual solar and collector dimensions and line-of-sight errors ranging from 0 to 20 degrees. The errors were presumed to occur along one axis, although in fact the emergency defocus system is designed to drive both axes away from alignment. The defocus drive rates requirements are specified as to provide a minimum of 4 deg./min LOS error worst case. Figure 3-26 summarizes the solar intensity on affected components during defocus.

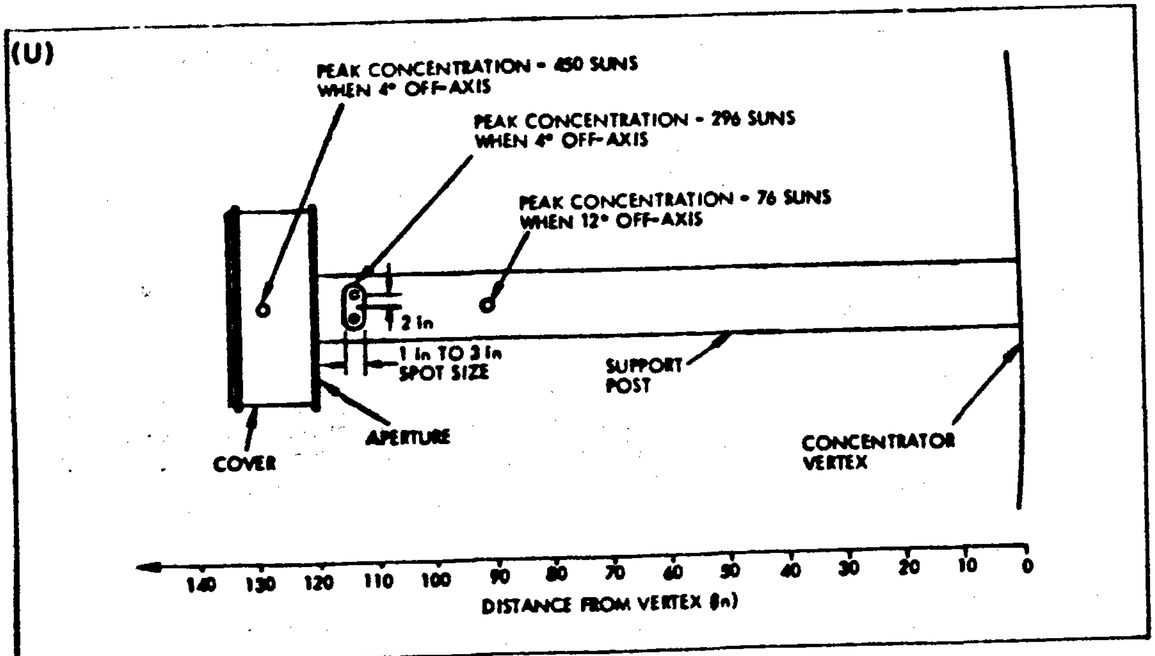


FIGURE 3-26. Peak Concentration Locations During Start-Up or Shutdown

The magnitude of the radiation on locations such as the cover was surprisingly large, and resulted in some equipment redesign.

The possible protection schemes for the support post and absorber cover consist of at least:

a) Ablative coatings and high temperature insulators.

b) Reflective coatings.

c) High temperature insulating systems.

The first of these could consist of materials such as silicone rubbers or asbestos, to name two commonly available. They could be used and re-used if, in the case of silicone rubber, a hard, insulating char is formed as does occur with some RTV's. These were a viable candidate, although they were not selected.

Reflective coatings were rejected on the basis that long term, high reflectance metal systems were not likely to be obtained, at least at minimum cost.

The third option was selected, in the form of wrapping the cover and post with a loose fitting stainless steel sleeve such as shown on Figure 3-19. The sleeves were assumed to have high thermal absorptance, which resulted in analytical temperature predictions of 2000°F at some locales. The resultant energy transfer is by radiation to the protected members and the ambient, convection to the ambient, and conduction across an air gap to the protected members. This intercepting of the intense beam and its subsequent redistribution is sufficent to limit support post and cover temperature rises to 200°F and 830°F, respectively.

An additional factor was considered in the analysis, represented by the intensity levels at 10 degrees off axis and beyond. These intensities could be achieved over a long term, for instance when the collector is stowed (vertical optical axis) on a typical summer day. At noon the misalignment would be 12 deg. of arc, at Albuquerque, and spot motion would be determined by the solar rate, an order of magnitude less than the defocus rate. Under these conditions the absorber cover is not illuminated, but the protected post, experiencing 76 suns, reaches a local temperature of 730°F.

In this case the problem solutions were easily implemented, and were relatively inexpensive. Future designs should consider optimizing angular relationships between the defocussed radiation and absorber external surfaces to limit the problem. Collectors that edge support the absorber could have their drive controllers designed to prevent defocussed beam impingment on the supports. In combination with these, the selection of a stow position must include consideration of stray radiation effects on the absorber supports, particularly if center supports are being used.

3.2 Mount Design and Fabrication

The concentrator mount shown in Figure 3-27, 3-28 and 3-29, supports the concentrator and contains the azimuth and elevation drive system. The artists concept is shown without the protective panels at the azimuth mount base.

3.2.1 Azimuth Assembly

The azimuth assembly provides both the supporting structure and the elevation/azimuth drive system for the concentrator assembly. Included is the supply and return piping for the absorber, consisting of hard piping, an elevation hose wrap and the azimuth hose wrap. Azimuth Drive system protective covers enclose the base.

3.2.1.1 Pedestal

The azimuth pedestal assembly is a steel quadraped with vertical post supported at its apex by two bearings. This post is rotated by the azimuth chain drive system, attached to the base of this post (Figure 3-30). Attached to the top of the yoke

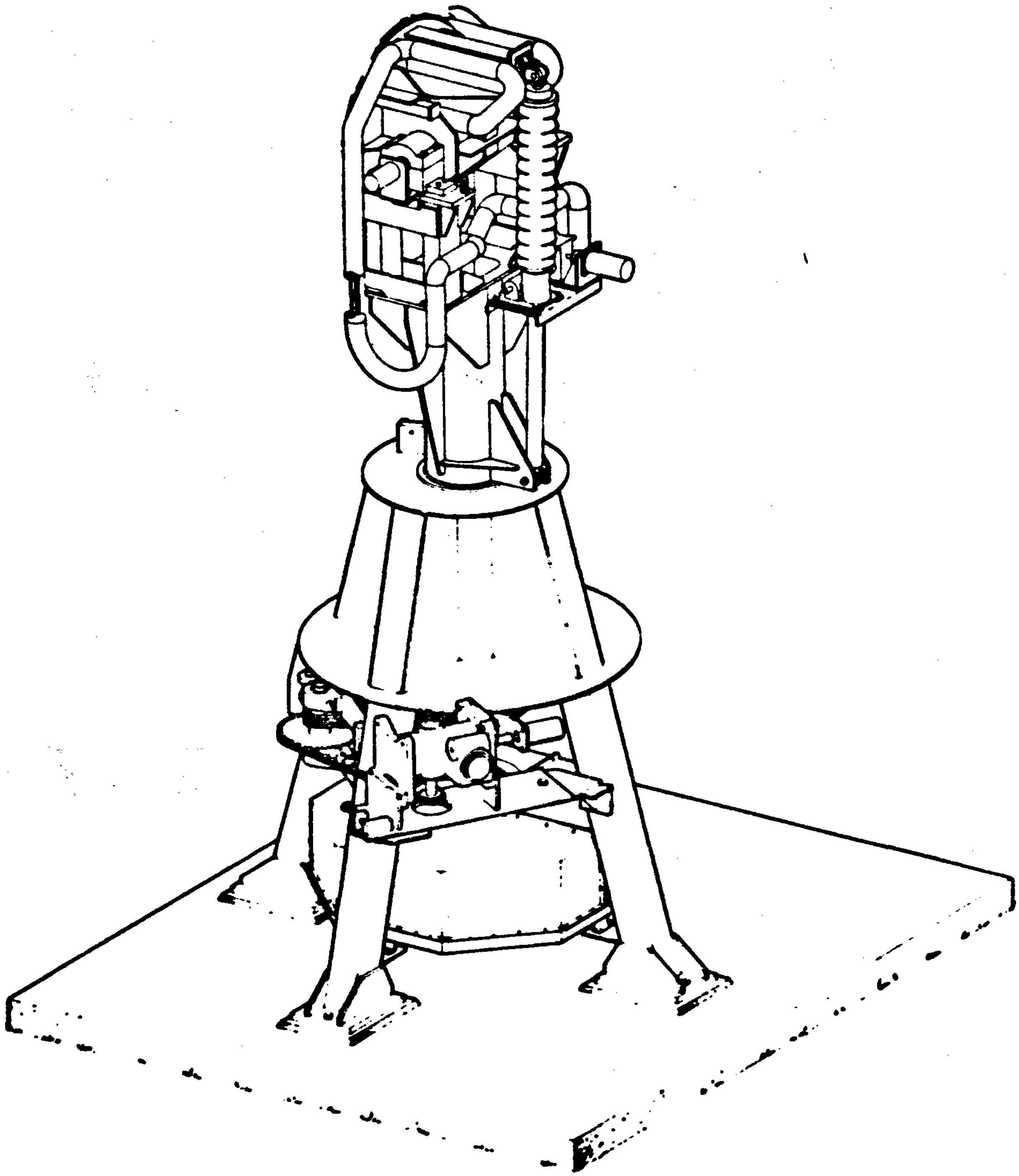


FIGURE 3-27. Collector Mount, Artist's Concept

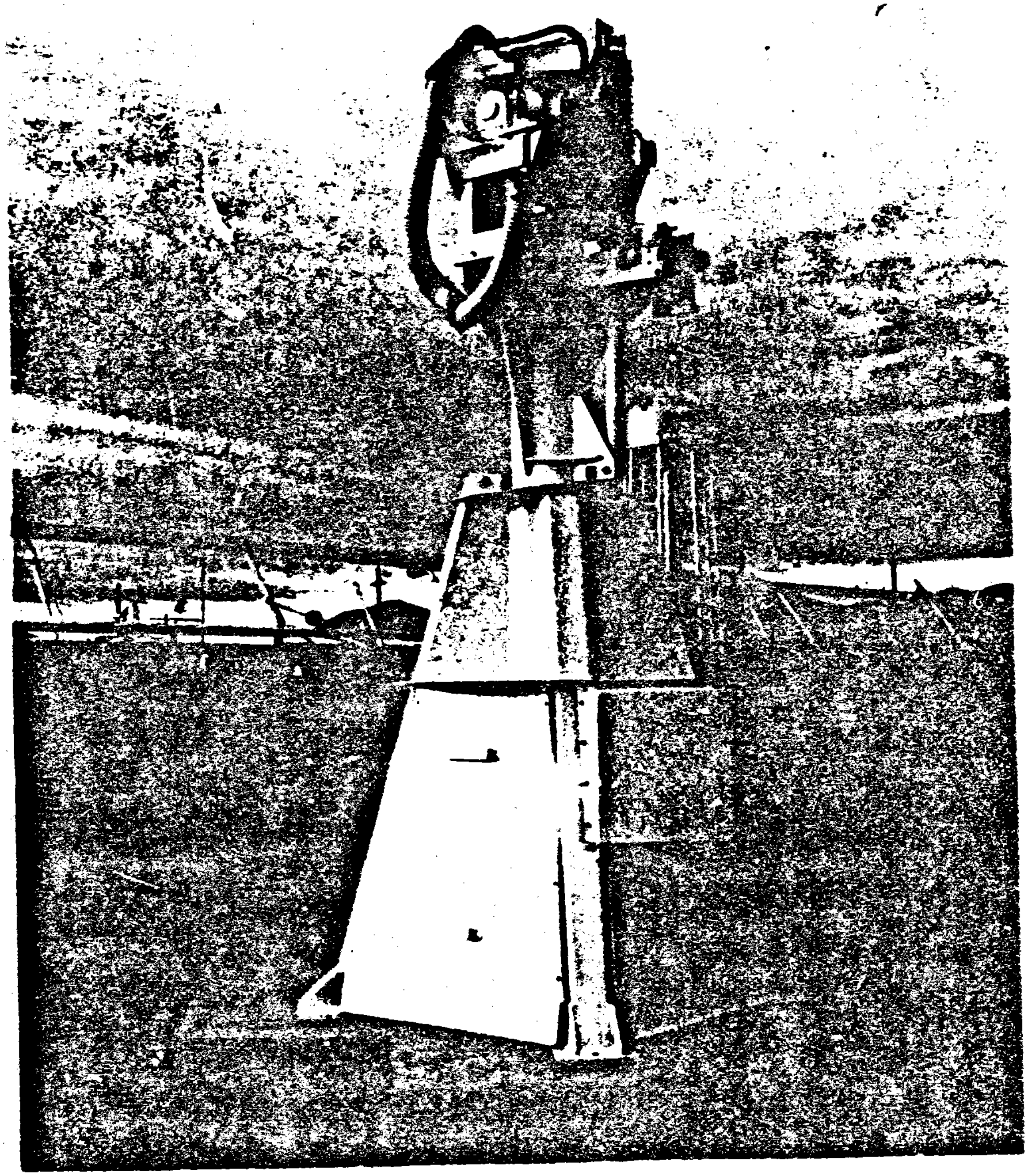


FIGURE 3-28. Collector Mount Rear View

FIGURE 3-29. Collector Mount Front View

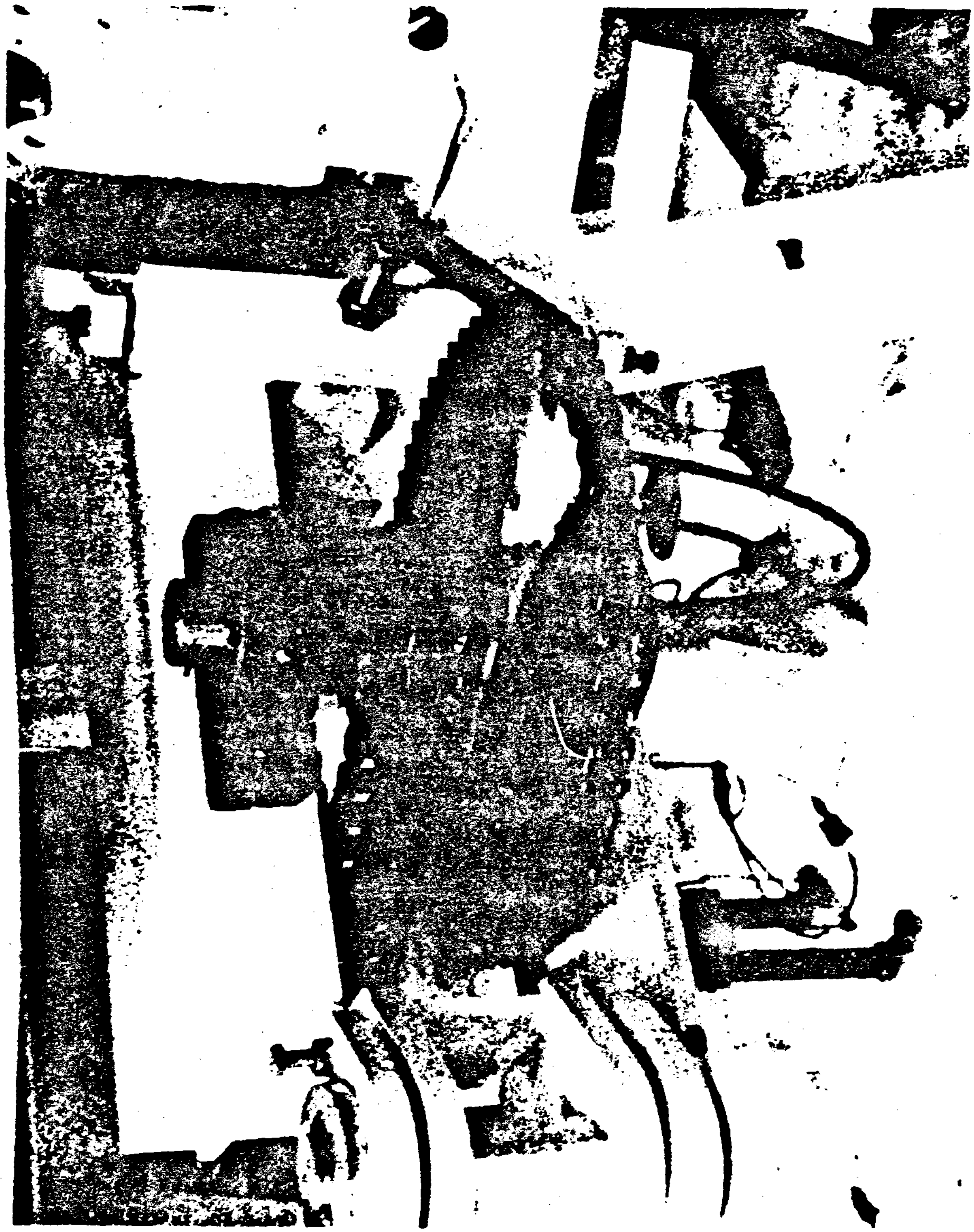


FIGURE 3-30. Azimuth Chain Drive

assembly is a horizontal shaft supported by two pillow block bearings (Figure 3-31). The elevation hub mount is attached to this shaft and the elevation drive is connected between it and the azimuth yoke (Figure 3-32).

The azimuth pedestal assembly is a 2200 lb. structural steel weldment comprising of four (4) 6.0 in. sq. x .50 in. wall tubular legs spaced 49 inches apart. They taper toward the center as they rise to a height of 85 inches. At the center, a 38 inch long x 16.50 inch dia. x .50 inch wall tube is welded vertically with support gussets to the tubular legs. The tube is machined at both ends to accept the azimuth bearings and seals. Below the bottom of the tube, plates and brackets are welded to the legs to mount the azimuth drive systems sprockets and reducer. Near the base of the pedestal, 4 gussets are welded to the legs to mount the azimuth hose wrap. One leveling bolt (1.0 inch dia. x 6 inches long) is installed at the foot of each leg. After leveling, each leg is welded to the foundation plates.

3.2.1.2 <u>Yoke</u>

The azimuth yoke assembly is a carbon steel weldment weighing 1200 lbs comprised of a vertical tube and a yoke structure welded to the top of the tube. The vertical tube was fabricated with two pieces of 13.38 inch O.D. MT-1026 carbon steel tubing, with the lower piece having a wall thickness of 1.0 inch to allow for machining the azimuth bearing seats and seals. A plate was welded into the bottom of the tube and machined for mounting the chain drive sprocket, the encoder drive shaft and the azimuth piping clamps. At the middle of the tube, a support bracket is welded to attach the bottom of the elevation ball screw drive. Two vertical posts, comprised of box channels, are welded to a gusseted platform welded to the top of the tube. This is the elevation axis bearing mount.

This large weldment contains most of the accurate machining required for the reflector mount. The elevation bearing

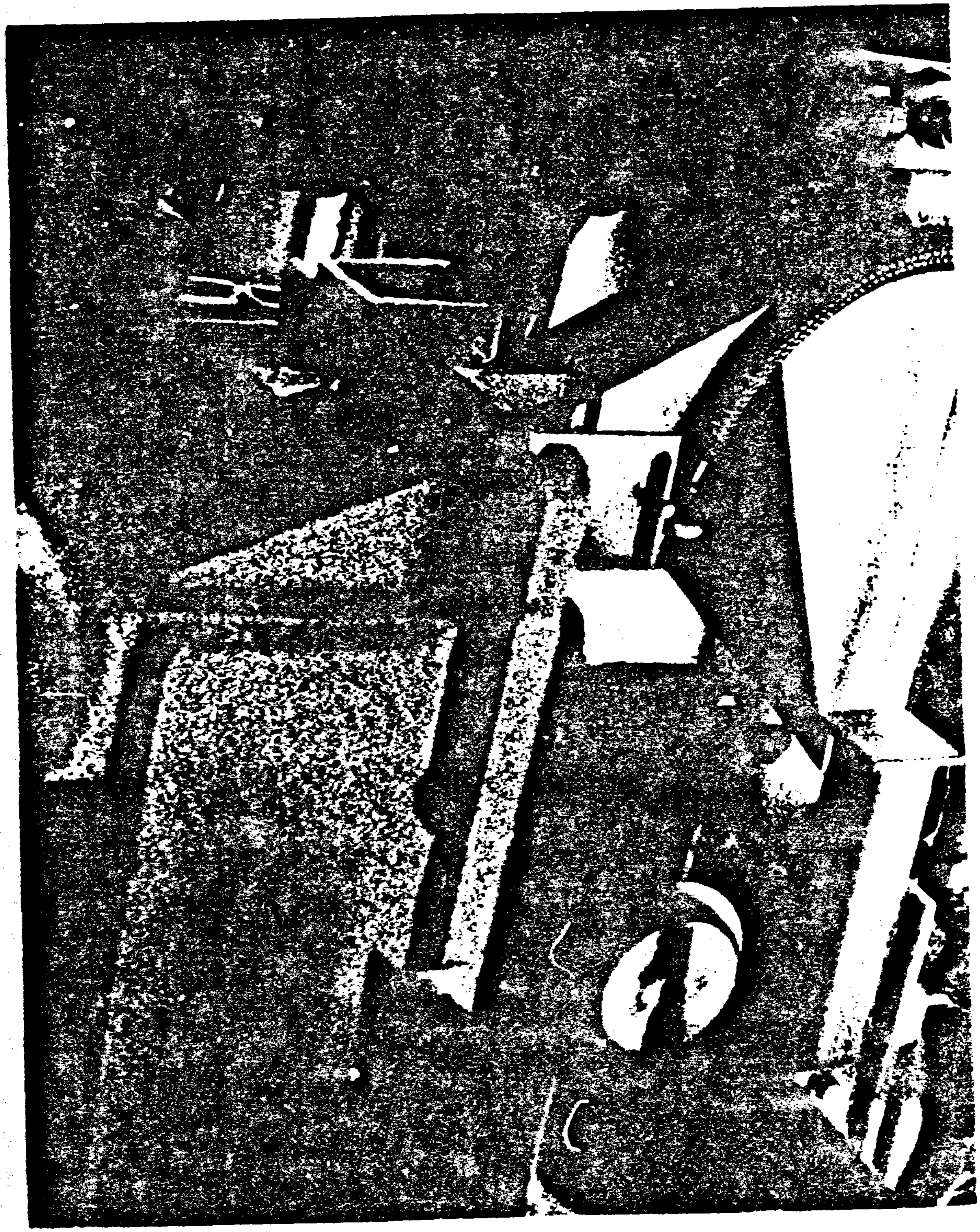


FIGURE 3-31. Elevation Drive Shaft Bearings

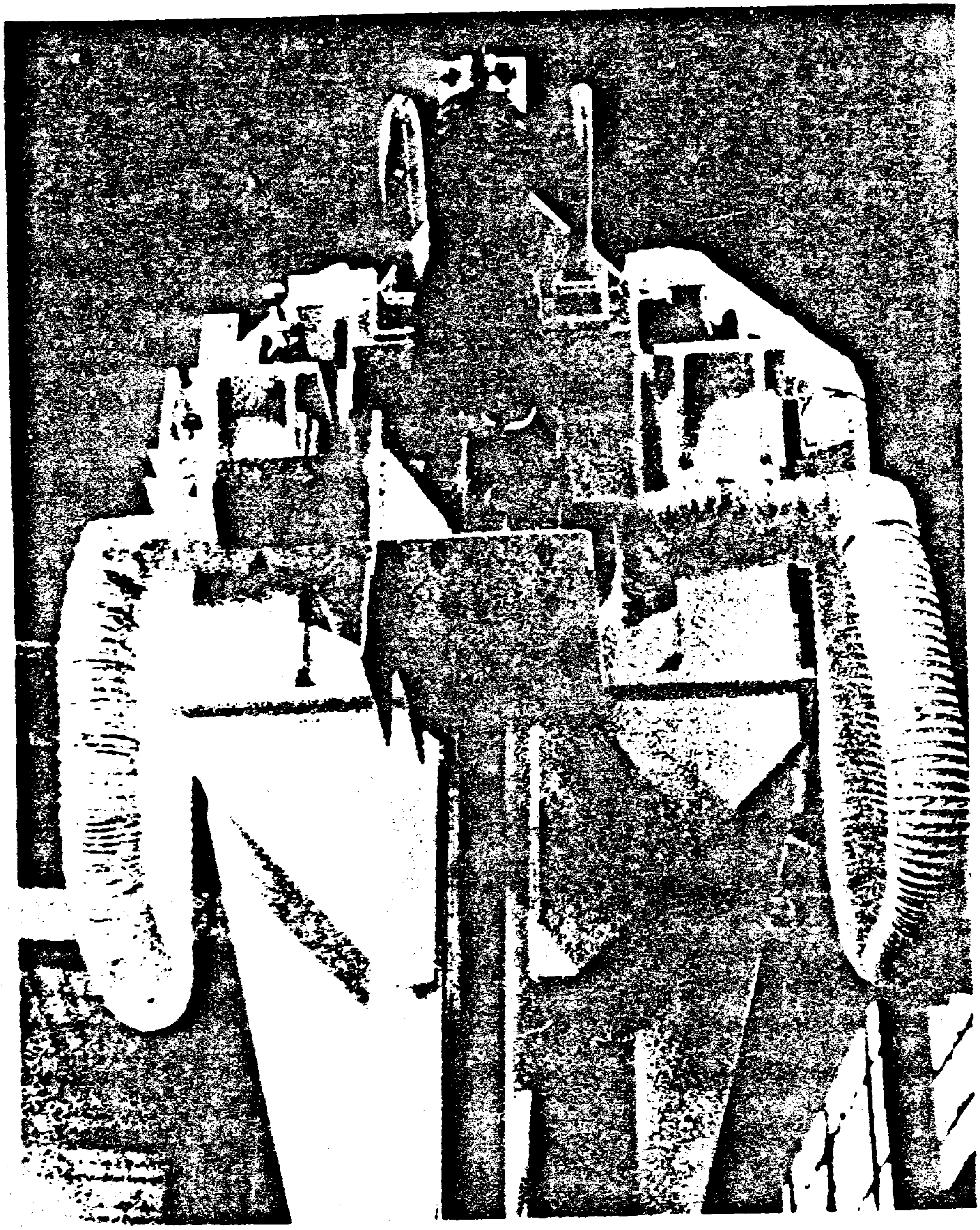


FIGURE 3-32. Elevation Drive System

mounting surfaces are machined flat, orthagonal and concentric to the azimuth bearing seats. This provides a flat plane by which to level the azimuth pedestal as an assembly during installations. There were no significant fabrication problems encountered in welding or machining this assembly.

3.2.1.3 Piping

The azimuth piping assembly is the supply and return piping which is installed through the center of the yoke assembly. It interfaces with the azimuth hose wrap at the bottom and the elevation flex hoses and piping at the top.

It is fabricated of 1.0 IPS black iron pipe and socket weld elbows. The feed and return pipes are welded together with spacers to increase its torsional stiffness. It is then wrapped with two inches Carborundum Co., 8 lbs/ft^3 ceramic fibre "dura-blanket" insulation. This assembly was pressure tested with water to 2000 psig.

The assembly is bolted to the yoke assembly and it is allowed to thermally expand downward 0.6 inch into the hose wrap assembly. As the piping passes through the bottom of the yoke a rectangular slip joint is provided which will torsionally support the pipes during the rotational wrapping of the flex lines in the azimuth hose wrap.

Due to manufacturing tolerances of the yoke assembly, pedestal assembly, and pipe assembly, the pipe assembly bracket which bolts to the yoke was cut to fit after the piping was temporarily installed and the inlet/outlet elbows were positioned to the proper height for the azimuth hose wrap. This did prove to be an effective method to achieve the end results without imposing extra cost for tight tolerance. There were no significant problems in fabricating or installing this assembly.

3.2.1.4 Drive

The azimuth drive consists of the motor, reducer, chains, sprockets and the adjusting plates and supports required to install it into the pedestal.

The Superior Electric Co., Slo-Syn No. M112-FJ25 stepping motor, is attached to the Morse Co. No. 50W-DV800 reducer input shaft with a Morse Co. Debrin No. N41.4 FB coupling and supported by a bracket attached to the reducer. This reducer is a nonbackdriving type which eliminates the necessity of providing a brake or stow lock pins. The reducer is mounted on a movable plate to allow for adjusting the chain tension. A 15 tooth, 1" pitch sprocket is attached to the reducer output shaft. It is connected with a single strand 1" pitch, heavy series Morse Co. chain to an idler sprocket assembly. The idler sprocket assembly consists of a combination 1" pitch 60 tooth sprocket and a double 1 1/4" pitch 13 tooth sprocket, mounted on a center shaft supported by two SKF Co., SYR series pillow block bearings. The bearings are mounted on an adjustable support which attaches to the azimuth pedestal. A double 1 1/4" pitch heavy series Morse chain is attached to a sprocket assembly which is bolted to the bottom of the azimuth yoke.

3.2.1.5 Hose Wrap

The hose wrap assembly is located within the base of the pedestal assembly. It provides the flexible feed and return plumbing to accommodate the collector azimuth rotation. The housing is insulated to limit heat loss.

The assembly consists of a split stainless steeel platform, two split circular aluminum plates, two flexible metal hoses, a four section insulated outer housing, rigid 1 inch piping and valves, and a circular "Transite" cap. The assembly is fabricated in sections to allow for installation within the pedestal legs and to allow access to the flexible hoses for maintenance.

The site piping interface is a 1 inch male 37° JIC flared fitting, Parker Hannifin Co. No. 16-FTX-5. Adjacent to the interface joint, a Vogt Co. No. 12121, 1 inch globe valve is installed in the feed and return piping. On the return line, prior to the globe valve, a Teledyne-Farris, No. HTF-2745T safety relief valve is installed. The pressure setting is 110 psig and it vents through a female 1/2 inch NPT hole.

The two Anaconda Co. 1.0 inch type BWL-21-1 braided stainless steel flex lines attach to the right angle male 37° JIC flared fitting of the azimuth piping, which protrudes down into thenose wrap assembly.

3.2.2 Elevation Assembly

The elevation assembly consists of the elevation hub mount, the elevation drive, and other subsidiary hardware.

3.2.2.1 Hub Mount

The elevation hub mount is the steel weldment whose function is to provide the structure for the elevation axis rotation. The 3.50 inch elevation axis shaft passes through and is pinned to the center horizontal tube. A 34.375 dia. flat plate with dowel pins and bolt holes is provided to attach the reflector assembly.

3.2.2.2 Drive

The elevation drive consists of a Duff-Norton Co. ball screw jack, Model 2801 modified, with clevises, and Torrington Co., No. 8SF14 spherical bearing attached to the top of the screw and the bottom of the screw housing. The bearings allow for minor mis-alignment during the 90 degree elevation. The jack input shaft is connected to a Morse Co., No. 18W-T, 25-1 worm drive reducer with a Morse Co. Delring No. W416FB chain coupling. The reducer input shaft is connected to the Superior Electric Co., Slo-Syn No. M112-FJ25 stepping motor with a Morse Co., Delrin No. N414FB chain coupling. The reducer and motor is attached to a platform bolted to the jack base. The reducer is a non-back drive unit which eliminates the need for a brake or stow lock pins.

3.2.3 Elevation Hose Wrap

The elevation hose wrap consists of a 1.0 inch dia. stainless steel braded Anaconda Co. flex metal hose with 37° JIC flared ends, 5'11" long. The hose was spiral wrapped 1.0 inch thick with Carborundum Co. 8 lb/ft^3 ceramic "Durablanket" insulation and jacketed with a white vinal spiral hose. As the reflector is rotated from 0° horizontal to 90° vertical, the flex line loop rises and wraps on a 90 degree curved support plate. A separate loop is provided on each side of the assembly for the feed and return piping. The piping is attached to the absorber port piping through 2'9" long 1.0 inch dia stainless steel braded Anaconda Co., flex hoses with 37° JIC flared ends. These flex lines allow for thermal expansion of and accessibility to connect the piping at site installation. Micro-Switch type LSA limit switches are provided to prevent 0° to 90° rotational overtravel causing the bolting of the Duff-Norton ball screw jack. Mechanical stops are provided in the even to switch failure.

3.3 Mount Assembly

3.3.1 Assembly Yoke and Pedestal

a) The upper bearing seal, Chicago Rawhide Co. No. 1325540 was slipped onto the azimuth yoke and pushed to the top of the machined surface.

b) The upper Tinkin Co. bearing cone, No. LL758744 was pressed on the yoke.

c) The upper bearing cap, No. LL758715 was pressed into the top of the pedestal.

d) The yoke was lowered down into the pedestal and the lower bearing and seal were installed, after packing the bearing with AMOCO "h" industrial grease.

e) The tapered bearing retainer (lower) was positioned and the 70 tooth chain drive sprocket assembly weldment was bolted to the yoke and the three .750 inch dia. torsional shear pins were installed.

f) The upper bearing was repacked with "h" industrial grease and the seal pressed down into place.

g) The bearings were preloaded by tightening the tapered ring bolts and the starting torque was measured to determine proper fit.

3.3.2 Installation of the Azimuth Drive System

a) The idler, 13 tooth idler sprocket was aligned to the 70 tooth yoke sprocket and the 1 1/4" pitch chain was installed.

b) The reducer was mounted and welded to its adjustable plate after its sprocket was aligned to the 60 tooth idler sprocket. The 1" pitch chain was installed.

c) The 1 1/4" and 1" pitch chains were preloaded to 1650 lbs and 415 lbs respectively.

3.3.3 Azimuth Piping

The azimuth piping assembly was installed and insulation was added where it protrudes through the bottom of the yoke.

3.3.4 Elevation Assembly

a) The elevation hub mount with the 3.50 inch dia. shaft installed, was fitted to the Tarrington FSAF-22518A pillow block bearing and then aligned and bolted to the top of the yoke.

b) The elevation ball screw was assembled and the elevation hub mount was rotated 90 degrees, after insuring proper alignment the bolted clevis bracket on the hub mount was welded.

c) The piping and brackets of the elevation support and drive were installed and the elevation hose wrap was installed.

d) The azimuth and elevation limit switches were installed.

3.3.5 Covers

The covers were installed.

4.0 Collector Controls Investigations

4.1 Background

Raytheon designed and constructed a point concentration collector for installation in the Solar Collector Test Facility (SCTF) at Sandia Albuquerque.

The SCTF would supply circulating heat transfer fluid, data acquisition, collector foundation, and a HP 2116 computer programmed per Raytheon requirements to control the collector. Raytheon's responsibilities included control system and interface definition and collector foundation design. A block diagram of the contracted system is shown in Figure 4-1.

During the course of the program it became obvious that the scheduled installation of the collector at the SCTF would conflict with other test activities, and that relatively high energy spots could strike a nearby building should a large collector pointing error occur during test. The solution to these problems was to relocate the collector to a designated Industrial Research Area, to the North of the SCTF. However, this location has no provision for collector control, data acquisition, or fluid circulation.

A previously planned study activity into three collector field control and instrumentation requirements was then coupled with single collector similar activities to define these parameters for each system, as reported in this section.

4.2 Approach

The relocation to the Raytheon Industrial Research Area, Figure 4-2, placed the collector in the region designated for

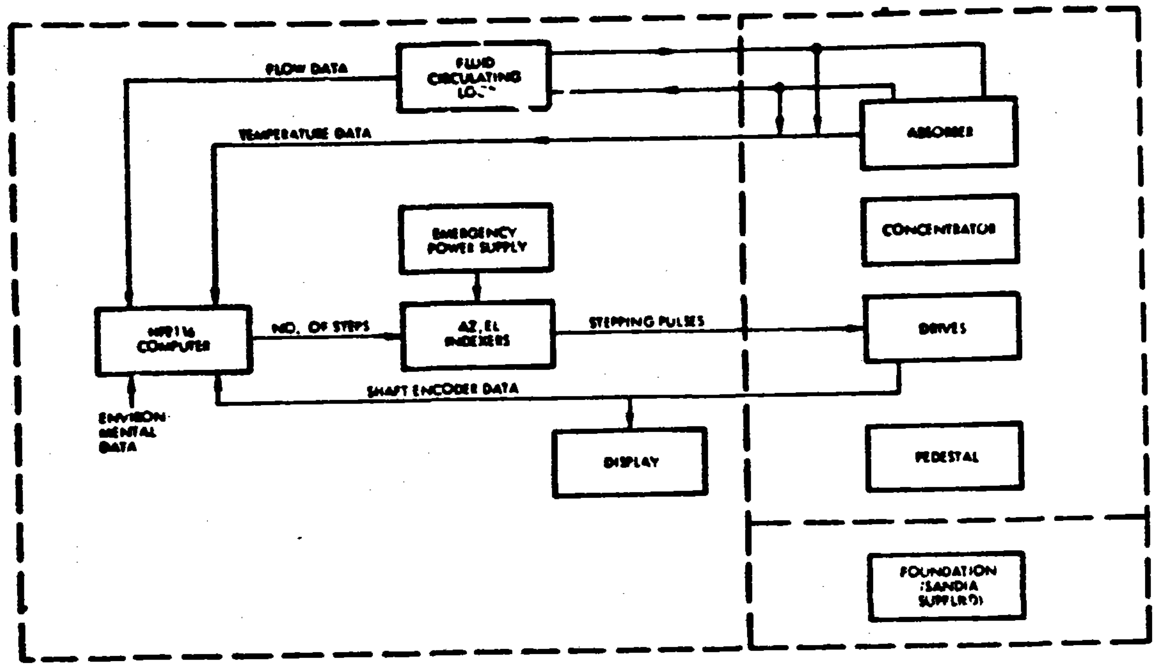


FIGURE 4-1. Solar Collector Test Facility Block Diagram

Raytheon's use during a following program in which an entire collector sybsystem would be constructed and tested. The full subsystem has been described briefly elsewhere as a three or four collector field with computer control, Local Control Panel, Fluid Circulating Loop and Data Acquisition System. The approach taken in this study was to determine requirements for these equipments and hopefully build-in capability in the single collector version thereof, to minimize redesign when additional collectors are installed. Thus, for example, computer requirements are for up to four collectors, and the Local Control Panel has a select switch to display data from shaft encoders from four collectors, rather than just the one set being installed now.

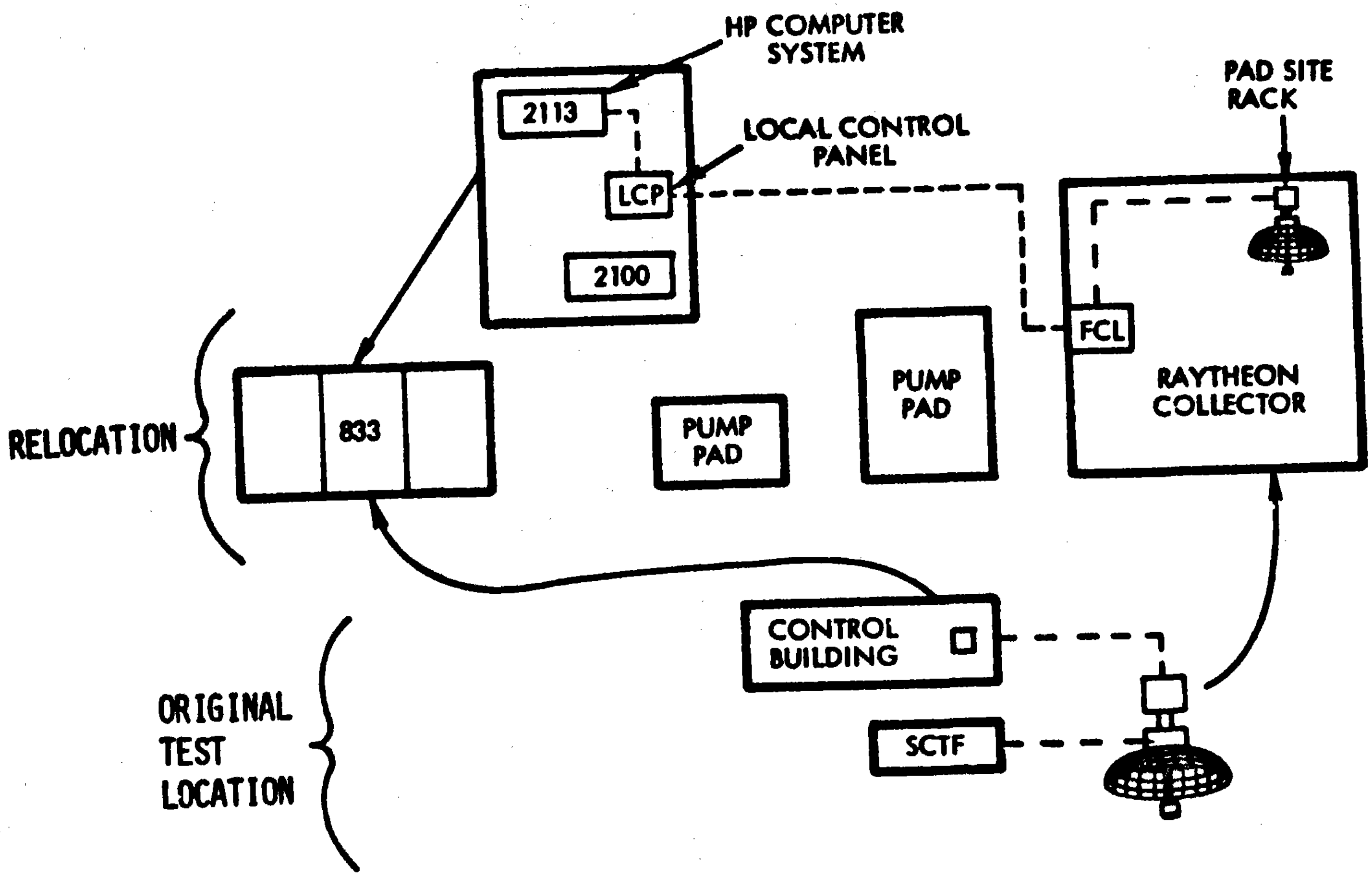


FIGURE 4-2. Geographical Layout

The System Block Diagram is shown in Figure 4-3. The following sections describe the approach taken in each of the major equipment areas.

4.2.1 Local Control Panel

The Local Control Panel (Figure 4-4) is composed of six sections; Encoder Display and Power Supply section; Collector Control and Monitor section; Azimuth Indexer section; Elevation Indexer section; Fluid Control and Monitor section; Low Level Analog to Digital Data Acquisition section.

These six sections are incorporated into a standard rack, with a fan section which supplies cooling air to the individual units.

4.2.1.1 Encoder Display

The Encoder Dsiplay section contains two digital indicators which display Azimuth and Elevation positions to 0.01 degrees, the conversion electronics to convert the binary Encoder signals for display, the line receives necessary to accommodate the length of cable between the Encoders and the display unit, the output buffer amplifiers which interface with the computer.

4.2.1.2 Collector Control and Monitoring Section

The Collector Control and monitoring panel (Figure 4-5) contains the switches and indicators which are necessary to transfer control of the collector mount between the computer and the manual mode of the Azimuth and Elevation Indexers to control ac power to the system, and to provide an emergency stow capability. In addition, the panel has the capacity to switch the encoder display to any of four incoming encoder signals, should this be necessary in the future.

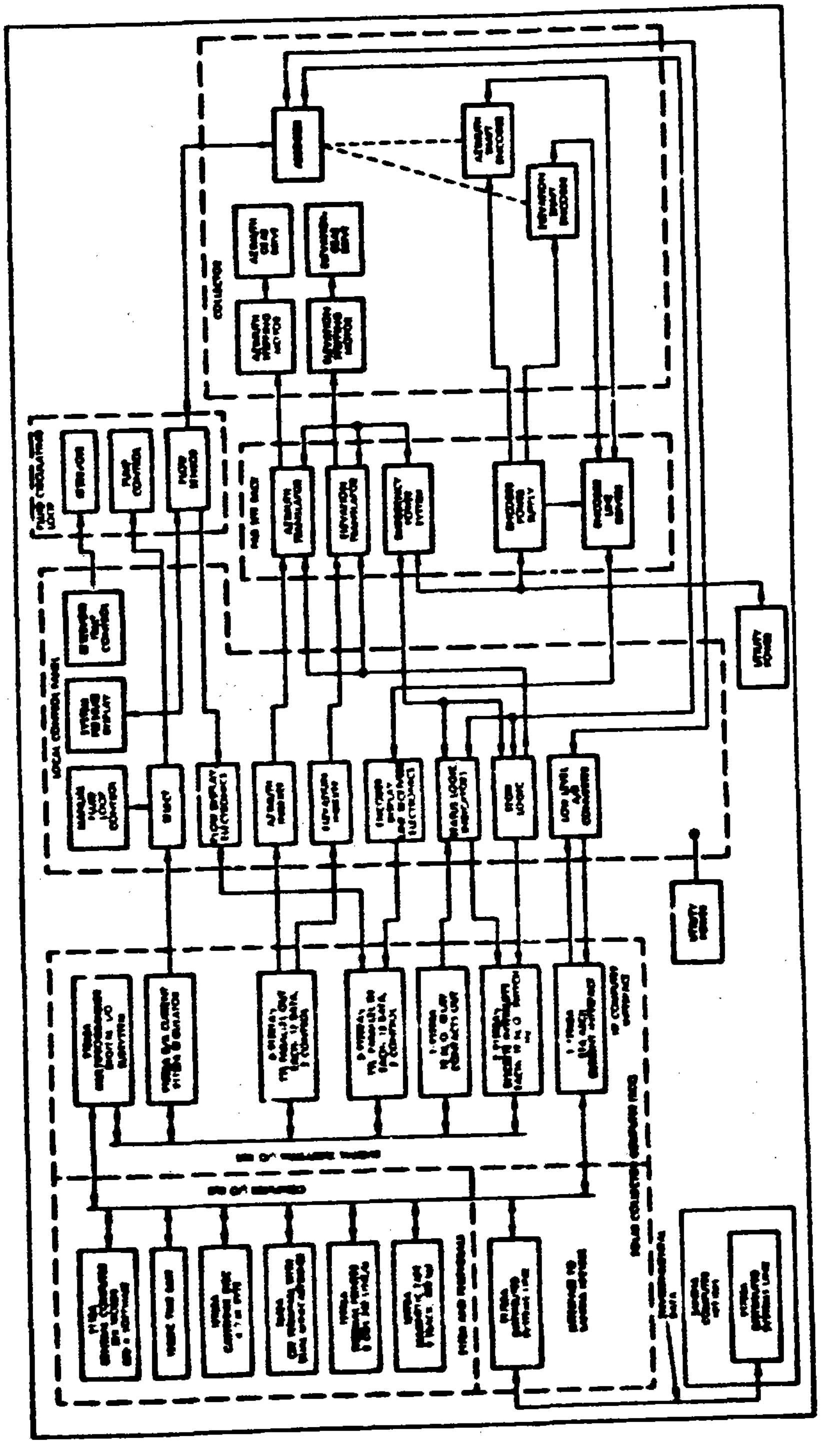


FIGURE 4-3. Controls Systems Block Diagram

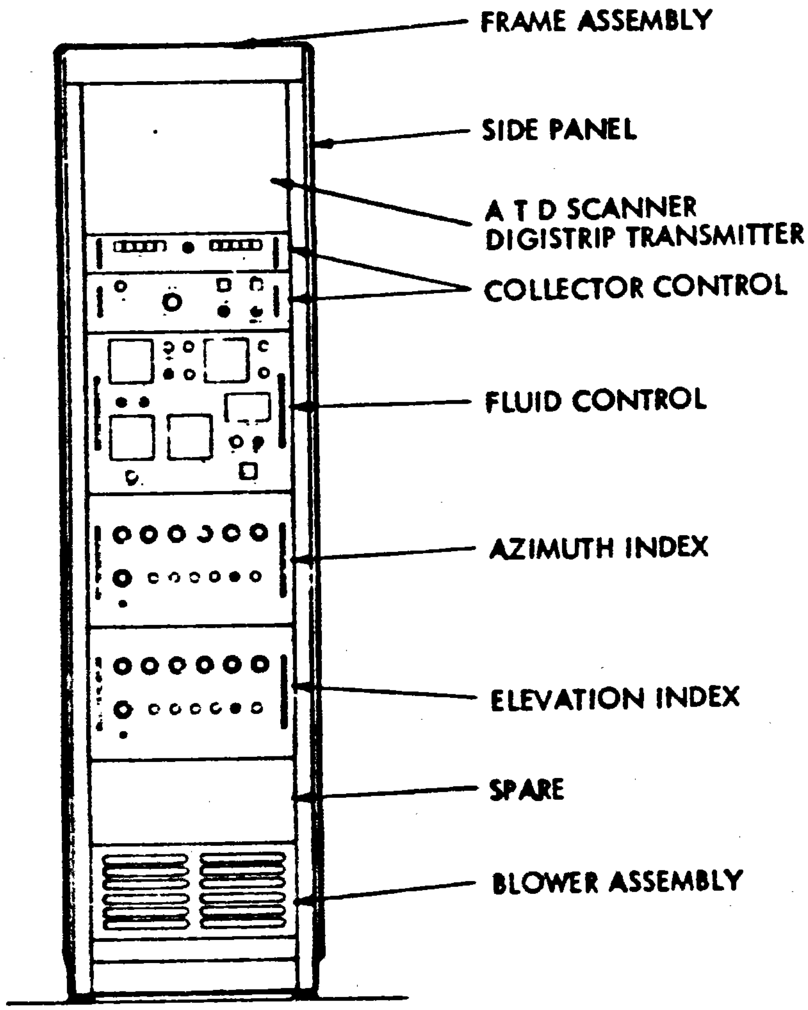


FIGURE 4-4. Local Control Panel Layout

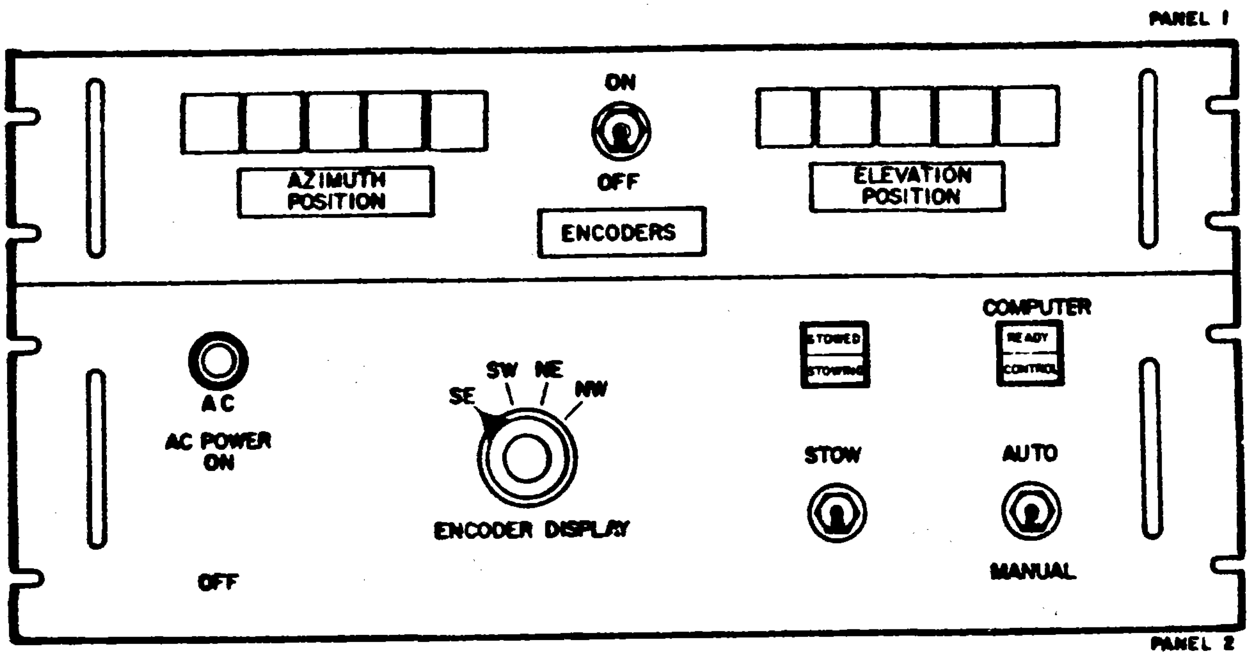


FIGURE 4-5 - Collector Control Panel

4.2.1.3 Fluid Control and Monitoring Section

The Fluid Control and monitoring section (Figure 4-6) contains the switches and indicators necessary to monitor and control the functioning of the Fluid Loop. (See Section 5).

Absorber temperature and fluid Outlet temperature are displayed on digital indicators, with the Absorber temperature section having the capability of being expanded to four collectors.

Reservoir temperature is indicated and controlled by the Reservoir Temperature Controller. Switches are incorporated to allow the proportionally controlled application of heat to the reservoir, and to manually or automatically control the heat exchanger action. An indicator denotes power being applied to the heat exchanger solenoid.

Pump outlet pressure is indicated on a digital indicator, and high and low pressure indicator lights are controlled by this module. These pressure lights have adjustable set points.

Position of the system diverter valve, which will indicate whether flow is internal to the field, or is being delivered to the Sandia reservoirs, is shown by a split indicator on this panel.

System flow, in gallons per minute, is displayed on a digital indicator. An Automatic/Manual switch allows transfer of fluid loop control between the Computer, and a manually adjustable pump speed control which is located on the panel.

4.2.1.4 Azimuth and Elevation Indexer Sections

The Azimuth and Elevation Indexer sections (Figure 4-7) control the pulses to the stepping motor drivers. Number of pulses to be driven is input into the Indexers by the computer in Automatic mode or by front panel rotary switches

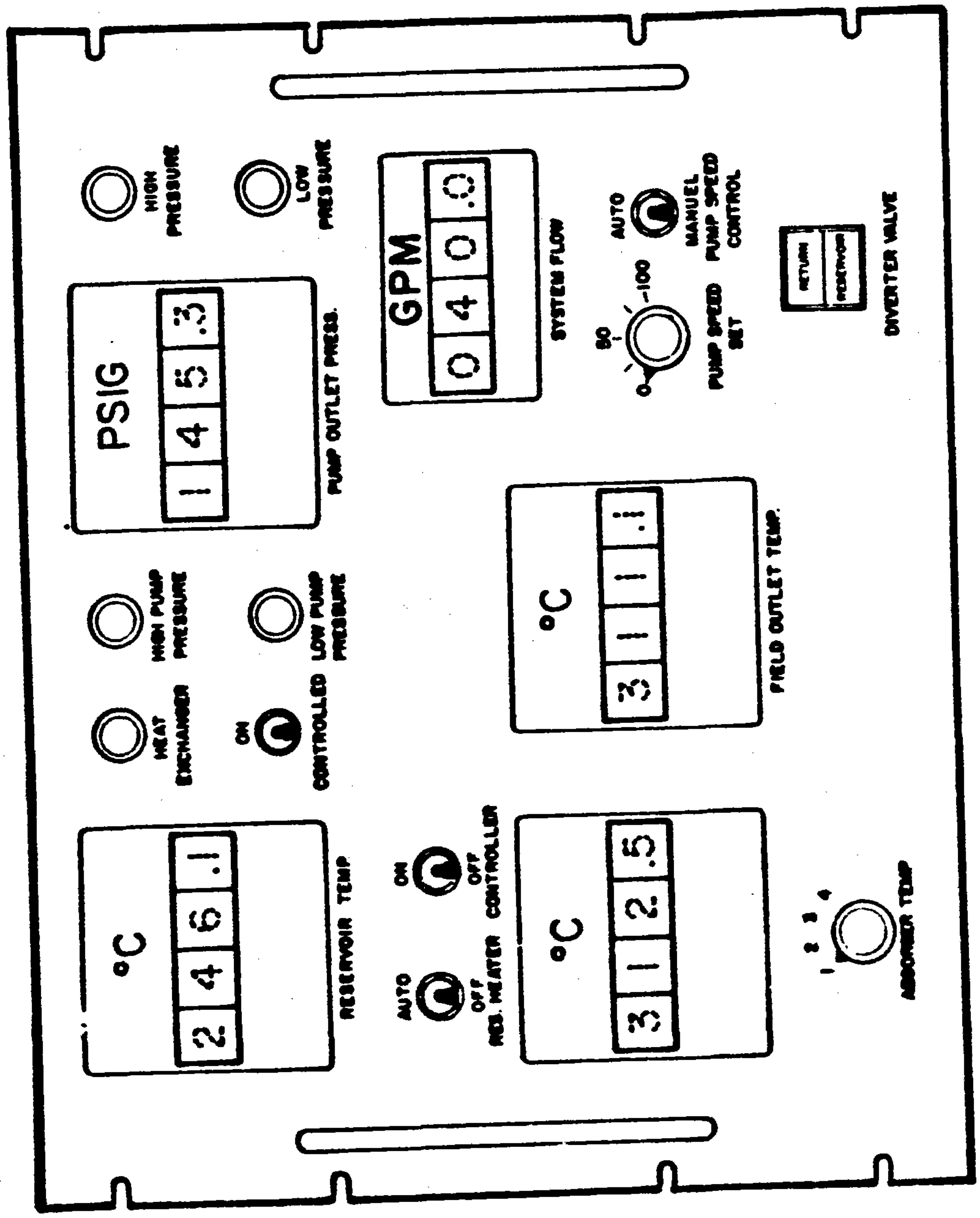


FIGURE 4-6. Fluid Control Panel

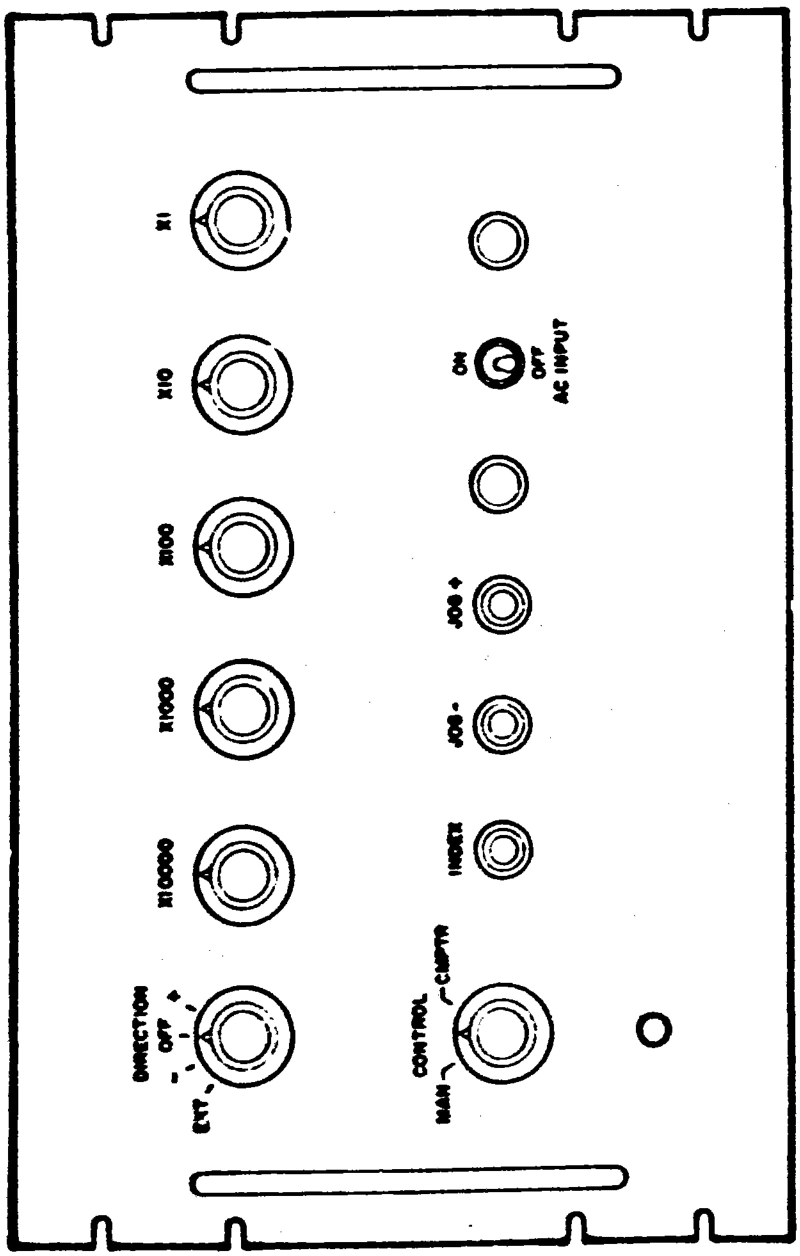


FIGURE 4-7. LCP Indexers

in manual mode. Selection of mode is accomplished by a front panel switch.

Proper acceleration and deceleration of the motors is provided in the indexer which functions as a pulse generator. Due to the output requirements of minimal impedance in the motor control lines, the output drive lines are not utilized to directly drive the motors, but are routed to buffer amplifier drivers located in the Pad Site Rack.

During emergency stow conditions, the indexers are programmed into a free running mode, utilizing the "Jog" commands, to drive the collector to the limit switch positions. The "Jog" commands can also be addressed from front panel switches to manually position the collector for maintenance or test purposes.

4.2.1.5 Data Acquisition Section

The Data Acquisition section consists of a low level analog signal to coded digital signal module, which has the capability of accepting linear or thermocouple signals transmitted over long lengths of wire, and generating digital output signals of 0.1 degree Fahrenheit resolution.

Cold junction compensation of the thermocouple signals is accomplished by generating a signal equivalent to the temperature of the terminal point of the thermocouple wires, and outputting this signal to the computer where the compensation is handled in software manipulation.

4.2.1.6 Rack

The Local Control Panel consists of a standard 19 in. rack 88.62 in. maximum in height, composed of the following hardware:

1) Standard 19 in. Amco frame
2) Three standard panel two sides, one rear

3) Louvered top panel
4) Blower assembly
5) Four levelers

The LCP will be fitted with a blower assembly located at the bottom of the rack to circulate room air upward through the equipment and exhaust out the louvered top panel.

4.2.2 Computer System

The System block diagram, shown earlier, shows the relationship of the principal subsystems of the Solar Collector System. The computer systems interface is with the Manual operating panel. The system should be configured such that the Solar Collector Subsystem, the Fluid Circulating Subsystem and the system sensor readings can be operated manually independent of the computer system. This provides the capability to perform checkout of these subsystems before the computer is operational. The control panel is contiguous with the computer system which is remote from the collector subsystem. The instrumentation of the control panel is remotely programmable by the computer; and when placed in the computer control mode will be used for data conversion and mount control.

The system may be placed in the computer control mode or manual mode at the control panel. In the computer mode the interface with the operator will be via the CRT Terminal. The operation of the system in the computer mode is controlled by software functionally described herein.

4.2.2.1 Solar Collector Computer Hardware

It is proposed that the automatic control, instrument monitoring and data recording of the Solar Collector System be implemented by a Solar Collector Computer (SCC) whose configuration is based upon the HP1000 Model 31 and other HP accessories as shown in Figure 4-8.

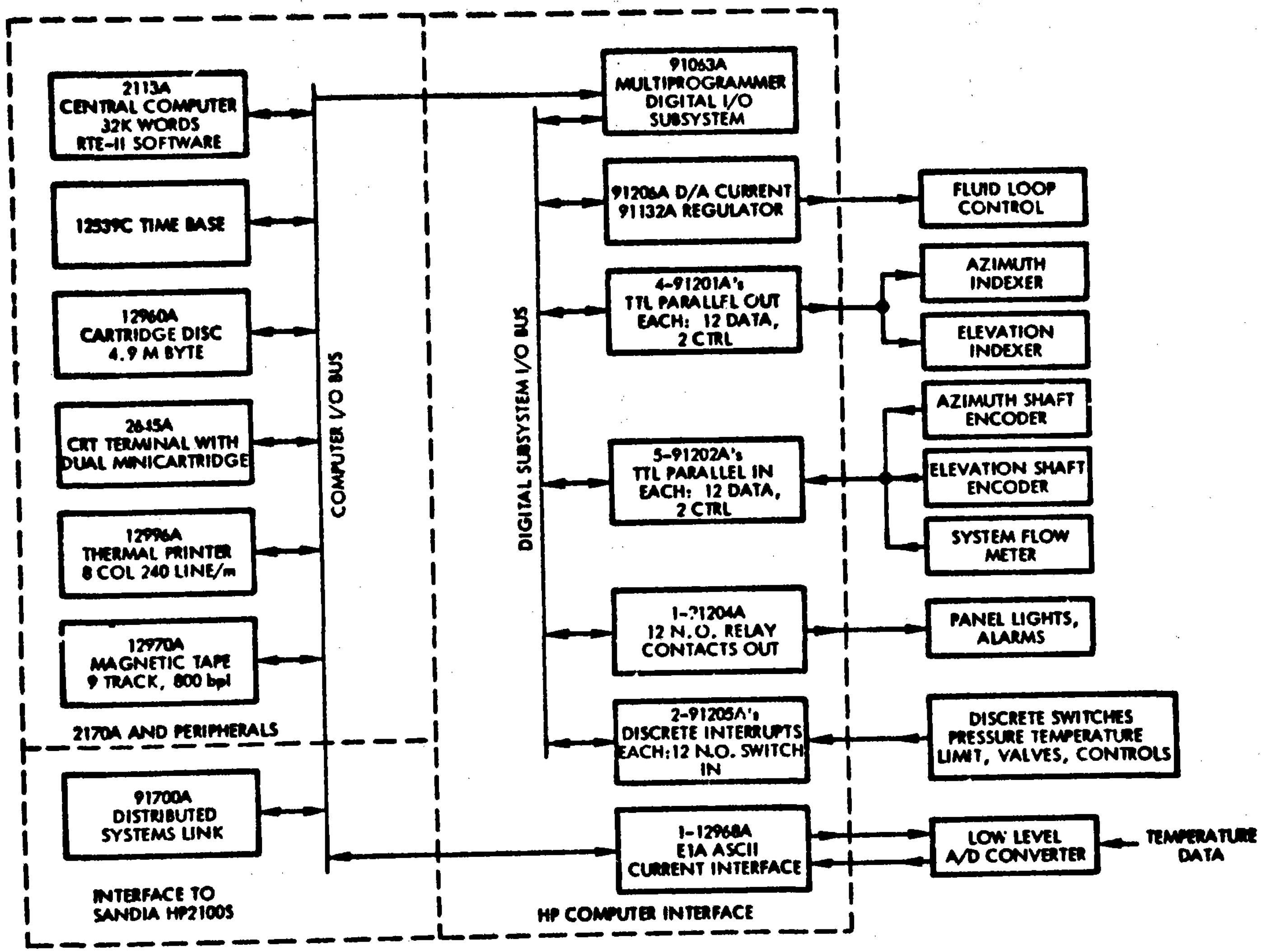


FIGURE 4-8. Collector/Computer Interface

The Solar Collector Computer has three principal hardware parts:

1) The base configuration of HP2170A together with accessory peripherals

2) The interface to the Sandia facility (HP2100S)

3) The interfaces to the controllers and instrumentation of the Solar Collector System.

4.2.2.1.1 The Base Computer and Peripherals

The base HP2170A Computer System consists of:

1) A Central Computer, the HP2113A with 128 base set instructions, 14 I/O channels, space for 10 memory modules, and ROM loaders for the disc and punched tape reader (in our case used only for HP maintenance). The 2170A peripherals and the accessory peripherals use 7 of the I/O channels, leaving 7 for the configuration of the System Interfaces, of which 3 are allocated leaving 4 spares for contingency. The 2113A also includes:

   a) Memory Controller and 32K words of Semiconductor memory (2102B in two modules)
   b) Dual-Channel Port Controller (12897B)
   c) Memory Protect (12892B)
   d) Power Fail Recovery System (12991A)
   e) CRT Terminal Loader ROM (12992C)
   f) Time Base Generator (12539C)
   g) Firmware Accessory Board (13304A)

2) Fast-access Program and Data Storage for the RTE-II software operating system via a 4.9 M byte cartridge disc subsystem (12960A). This disc, and as a result the HP2170A configuration, was

selected for its compatability with the Sandia HP2100S Computer Facility.

3) A System Console, which consists of CRT Display station, a keyboard and dual Mini-Cartridge tape transports (HP2645A). The Display has a screen size of 5 x 10 in., a capacity of 24 lines of 80 columns, and a set of 128 upper/lower case Roman characters. The Keyboard provides the full set of ASCII character keys, 8 special function keys, a 10 key numeric pad and 18 additional control and editing keys. The system console terminal also contains two Mini-cartridge tape transports with a read/write speed of 10 ips, search/rewind of 60 ips and a total storage capacity of 110K bytes/cartridge.

Two additional peripherals have been added to the base HP2170A. These are as follows:

1) Hard copy, via a 240LPM Thermal Printer (12996A), to facilitate programming and report generation.

2) Bulk storage, via a Magnetic Tape Subsystem (HP12970A) to facilitate the transfer of programs developed on other computers.

4.2.2.1.2 <u>The Sandia 2100S Interface</u>

The SCC configuration includes part of the Hewlett Packard network central communications package which supports program-to-program communication between RTE-II based HP1000 or 21MX Computer Systems. Both systems, the Sandia HP2100S facility and the HP2170A, must be equipped with the 91700A Network Central Communications Package.

4.2.2.1.3 <u>Local Control Panel Interface</u>

All computer interfaces to the Solar Collector System are via the Local Control Panel. This configuration is based upon the requirement that this first solar collector have 100 percent manual control and direct readout of all system parameters. The computer, when so directed, becomes simply an overriding real time controller and data logger.

The system has been configured so that all interfaces between the Solar Collector Computer and the Local Control Panel may be implemented via standard Hewlett Packard instrumentation techniques. Figure 4-8 shows the components used for the HP Computer Interface. A more detailed description of the interface parameters in the SCC interface is shown in Table 4-1.

All collector control and sensor data interfacing is through the Control Panel. The interface to the panel consists of the items listed below.

<u>Inputs</u>

1) <u>Shaft Encoder (2)</u>

   Two shaft encoders (Az and El) are input to the computer, each of which is Negative 2's complement 15 bits

2) <u>Discretes</u>

   Twenty-four bits of discrete switch closure data and input to the computer. Change of any of these discretes cuases a computer interrupt to be generated.

   - 4 bits, dish travel limit switches (two, each axes)
   - 1 bit, fluid diverter valve position
   - 19 bits, control panel switches and others to be determined

3) <u>Kaye Instrument Sensor Scanner</u>

   A sensor scanner is connected to the computer by way of a TTY interface. It provides for the A/D

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TABLE 4-1

SCC INTERFACE

Item	Solar Collector Computer	Lines	Manual Control Panel
1	91206A Digital-to-Analog Current Converter (69370A) Input 12 bit digital, Output 0 to 20.475 mA at up to 10.5 V. Requires: 91132A Voltage Regulator	1 →	Pump Speed Control: 4-20 mA Input requirement 0-16 mA to be added to 4 mA 0-16 mA → (+) → (+) → Pump Motor CKTS; Bias 4 mA; Manual 4-20 mA
2	4-91201A Digital Output Cards Option 001 provides positive true TTL Data Output: 12 bits CTRL: Gate Output, Flag input	48 → DATA 8 ← CTRL	Indexer Commands Two axis each requiring Step count = (5 BCD), 20 lines Cmds: Direction, Index, Reset = 3 lines CTRL: Strobe, Busy. Levels = TTL
3	3-91202A Direct Digital Input Cards, with negative-true TTL Data Input: 12 bits CTRL: Gate Output, Flag Input	36 ← DATA 6 ← CTRL	Shaft Encoders (Az and El) Two axis each requiring Position Data = 15 (bits) lines CTRL: Hold = 1 line Levels = Negative TTL Spares Lines: 6 data, 2 CTRL
3	2-91202A As above except Option 002 provides positive-true TTL	24 ← DATA 4 → CTRL	Pump Flow via DUM output Precision: 3 1/2 Digits = 14 lines CTRL: Hold = 1 line. Levels = TTL Spare Lines: 10 data, 2 CTRL
4	91204A Relay Output Card Capacity: 12 normally open contact pairs Ratings: 100 V, 1.0 A, 20 W Life: 10^8 operations	12 →	Discrete Control Actions • Dish Selection = 4 lines • Indexer Automatic = 1 line • Indicator lights & spares = 7 lines Life at 1/s operations > 5 years
5	2-91205A Event Sense Interrupt Cards, Capacity: 12 bits Data Input: Integrated 10 ms "1" State: Contact open > 1 mΩ "0" State: Contact closed < 100 Ω Interrupt state bit selectable	← 24	Discrete Interrupt Switches • Dish Limit Switches = 4 lines • Indexer Status = 4 lines • Diverter Value = 1 line • Discrete Control Switches < 15 Note: Monitor Switches without interrupt via spares of Item (3)
6	1-12968A Current Loop Interface EIA compatible, character mode	→ ←	Low Level Sensors read via Kaye Instruments A/D Scanner Interfaces via EIA Current Loop 24 Individually addressable channels

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conversion and reading of 24 sensors. The sensors are

- 10 Type J Thermocouples from the Absorber
- 6 Type T Thermocouples fluid temperature
- 8 spare channels, type T

4) Flow Sensor

A DVM is connected to the computer to provide digital (BCD) measurement of the output flow rate of the Fluid system.

Outputs

1) Fluid Pump Control

The computer system outputs a 4 to 20 mA signal for control of the pump speed for the Fluid Circulation System.

2) Indexers (2)

Two Stepping Motor Indexers are controlled by the computer. One for Azimuth and one for Elevation of the Collector Dish. Each will generate the commanded number of steps in BCD Format for incremental stepping motor control. These are programmed either manually or with the computer.

3) Discretes

The computer system provides the output of 12 discrete relay contacts. These are used as the following:

- 4 select individual mounts for connection to the Indexer busses (2)
- 8 for lights on the control panel

4) Kaye Instruments Sensor Scanner Programming

Sensor selection may be programmed either manually or automatically from the computer.

4.2.2.2 Software Functional Description

The Software is divided by tasks running under RTE-II Real Time Executive. The tasks are:

1) Collector Mount Control
2) Designate Generation
3) Fluid Loop Control
4) Data Acquisition and Recording
5) Sensor data status Monitoring
6) Operator Interaction

The tasks are scheduled on a real time and priority basis. Sensor input, control calculation and control outputs are performed on a nominal 1 s frame rate.

4.2.2.2.1 Collector Mount Control Task

Two Indexers on the control panel provide stepping pulses to stepping motors on the AZ and EL axis of the mounts for movement of the dishes. Each mount is selectable by the computer providing for individual control or ganged control. The Indexers can be operated from their front panel or remotely by the computers. Four Limit switches (two on each axis) are read to the computer for sensing travel limits. The processing of this task depends on the mode which is selected by the operator.

1) Mount Mode Logic

The operator from the Terminal Keyboard shall be able to select the following mount modes for one or more mounts.

a) Initialize Mount Mode

The Initialize Mode will cause the program to initialize the position that it keeps for the mount to either operator input AZ and EL positions to the Limit switch positions, or to the shaft encoder read outs.

b) <u>STOW Mount Mode</u>

The Stow Mount Mode will cause the program to move the mount (s) to its predetermined stow position.

c) <u>SLEW Mount Mode</u>

The Slew Mount Mode will cause the program to move the mount in the direction and axis requested.

d) <u>Position Mount Mode</u>

The Position Mount Mode will cause the program to move the mount to the operator entered position.

e) <u>Designate Mount Mode</u>

The Designate Mount Mode will cause the program to move the mount to the position generated by the designate task. This is the mode for open loop tracking of the sun.

f) <u>STOP Mount Mode</u>

The Stop Mount Mode will cause the program to stop moving the mount until one of the above modes is reentered by the operator.

2) <u>Mount Misalignment Correction</u>

The program will correct the requested mount position for mount misalignment.

3) <u>Indexer (s) Increment Generation</u>

The mount movement shall be performed by sending to the Indexer(s) the delta number of steps between the mounts position and the requested position. The delta is limited to the number of steps that can be generated before the next up date period. The mount position is then updated by the number of steps sent the indexer. The program shall control each mount individually by the time multiplexing the Indexer (s) between mounts.

The number of steps per degree for AZ is 9440. The movement in Elevation requires a coordinate transformation to calculate the number of steps per degree.

4) Indexer Command Generation

The program will convert the number of steps to BCD for output to the indexer along with appropriate indexer control and mount selection discretes. The data will be output on a periodic frame basis.

4.2.2.2.2 Designate Generation Task

The program generates designate pointing angles for solar tracking from ephermeris data as a function of initialization data and real time. The operator has the capability to override real time to determine look angles for any particular time of day. The time to move the collector from the present position to the designate position is always calculated and displayed for planning purposes.

4.2.2.2.3 Fluid Loop Control Task

The Fluid Loop control hardware consists of a D/A current generator for pump speed control and temperature sensors (thermocouples) for feedback.

The operator should be able to select the following modes for control of the Fluid Circulation System.

1) Fluid Circulator Manual Mode

   In this mode the operator can enter the percent of full pump speed that he may desire and the program will generate the appropriate control output to the pump.

2) Fluid Circulator Auto Mode

   In the auto mode the program controls the temperature range of the fluid by controlling the speed of the circulator pump. Parameters of the thermal control equation will be alterable by the operator.

4.2.2.2.4 Data Acquisition and Recording Task

The program performs data acquisition for control calculation, display and post processing and analysis. The sensor data defined earlier is collected at a 1 s rate and where appropriate converted to engineering units. Inputs from the Sandia 2100S are acquired using a "Mail Box" technique. The 2100S loads up to 10 parameters (in engineering units) into the 2131A memory. All acquired parameters are part of the programs data base, updated at the frame rate.

At the operators command the program writes data records to the Mag tape. The data contains the time of day and up to 100 parameters from the programs data base. The data recording rate is operator selectable from every frame to every n frames.

4.2.2.2.5 Sensor Data Status Monitoring Task

The program provides out of limit checking of sensor data. The upper and lower limits will be modifiable by the operator. When a parameter is out of limit it is displayed on the CRT.

4.2.2.2.6 Operator Interaction Task

The program generates an operator display of operational parameters on the CRT. In addition, selected discrete parameters can be outputted to the Local Control Panel for indicator lights. The operator is able to display and change all parameters in the programs data base. Up to 19 control discrete commands to the program from the Local Control Panel are provided. All other operate inputs are by the CRT terminal keyboard.

4.2.3 Pad Site Rack

The Pad Site Rack, Figure 4-9, located in the proximity of the collector is composed of five sections; Azimuth Translator section; Elevation Translator section; Encoder Power Supply section; Inverter section; Battery section.

4.2.3.1 Azimuth and Elevation Translators

The Azimuth and Elevation Translators accept the pulse input from the Azimuth and Elevation Indexers located in the Local Control Panel, and generate signals of the correct voltage current, and phasing to drive the Azimuth and Elevation Stepping Motors in the prescribed manner. The translator must be located near the stepper-motors, as they require a maximum of 50 mΩ line resistance.

4.2.3.2 Encoder Power Supply Section

The Encoder Power Supply section contains the power supplies, electronics and line drivers necessary to transmit encoder information to the receivers in the Encoder section of the local Control Panel. These line drivers and receivers and the remote power supply were necessitated by

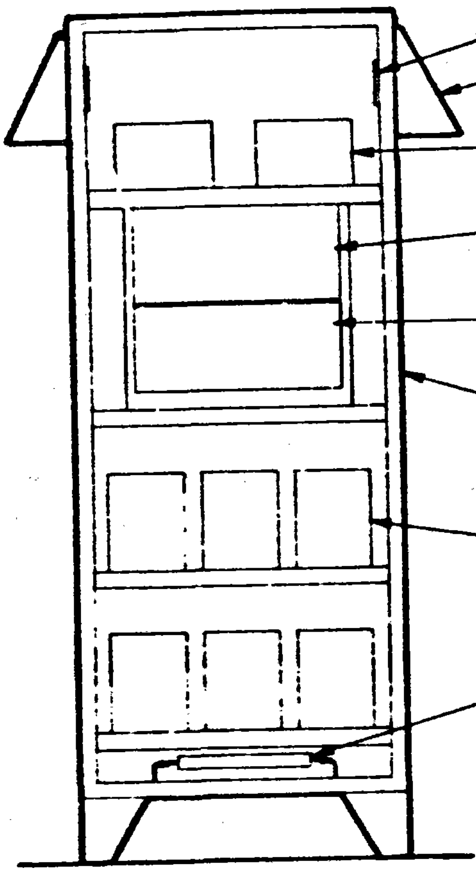

FIGURE 4-9. Pad Site Rack

the increase in distance between the Local Control Panel and the encoders.

4.2.3.3 Inverter Section

The inverter section accepts the utility AC input, and converts it into DC to charge the emergency battery pack, and regulated AC to power the Azimuth and Elevation translator modules. Logic and switches internal to the inverter control the input source between the utility AC input and the Battery DC input to provide sufficient capacity and reaction time to drive the collector system to stow upon loss of utility AC power.

A contact closure is generated in the inverter and routed to the computer and local control panel, when the inverter switches to the emergency battery power.

4.2.3.4 Battery Pack

The Battery Pack section consists of six 12V batteries which have sufficient capability to power the collector drive system for upwards of 30 min., thus providing the power for emergency stow procedures on loss of AC power.

4.2.3.5 Rack

The Pad Site Rack is a prefabricated enclosure with a hinged door for access. The enclosure will be NEMA4 rated (weatherproof). The Enclosure Assembly will contain the following hardware:

a) Internal mounting racks,

b) Inlet air heater,

c) Inlet air dust filter,

d) Floor stand legs,

e) Two blower assemblies,

f) Two exhaust hood assemblies.

4.2.3.6 Interconnections

Figure 4-10 diagrams the interconnections between the equipments. Table 4-2 indicates the functions carried in each cable group.

TABLE 4-2

CONTROL SYSTEM INTERCONNECTING CABLE

Cable	Routing	Functions
1	HP 2100 S to HP 2113 (I/O Modules)	Environmental Data Other Data
2	HP 2113 to LCP	Indexer Control Shaft Encoder Data Parameter Data Discrete Signals Spares
3	LCP to Bldg 833 Terminal Board Bldg 833 T.B. to Field T.B.	Translator Control Encoder Data Limit Switch Signals Parameter Data Hexter, Pump Control Spares
4	Field T.B. to PSR	Translator Control Encoder Data Limit Switch Signals Prime Power Parameter Data Spares
5	PSR to Collector	Encoder Data Encoder Power Motor Power Limit Switch Data Temperature Data Spares

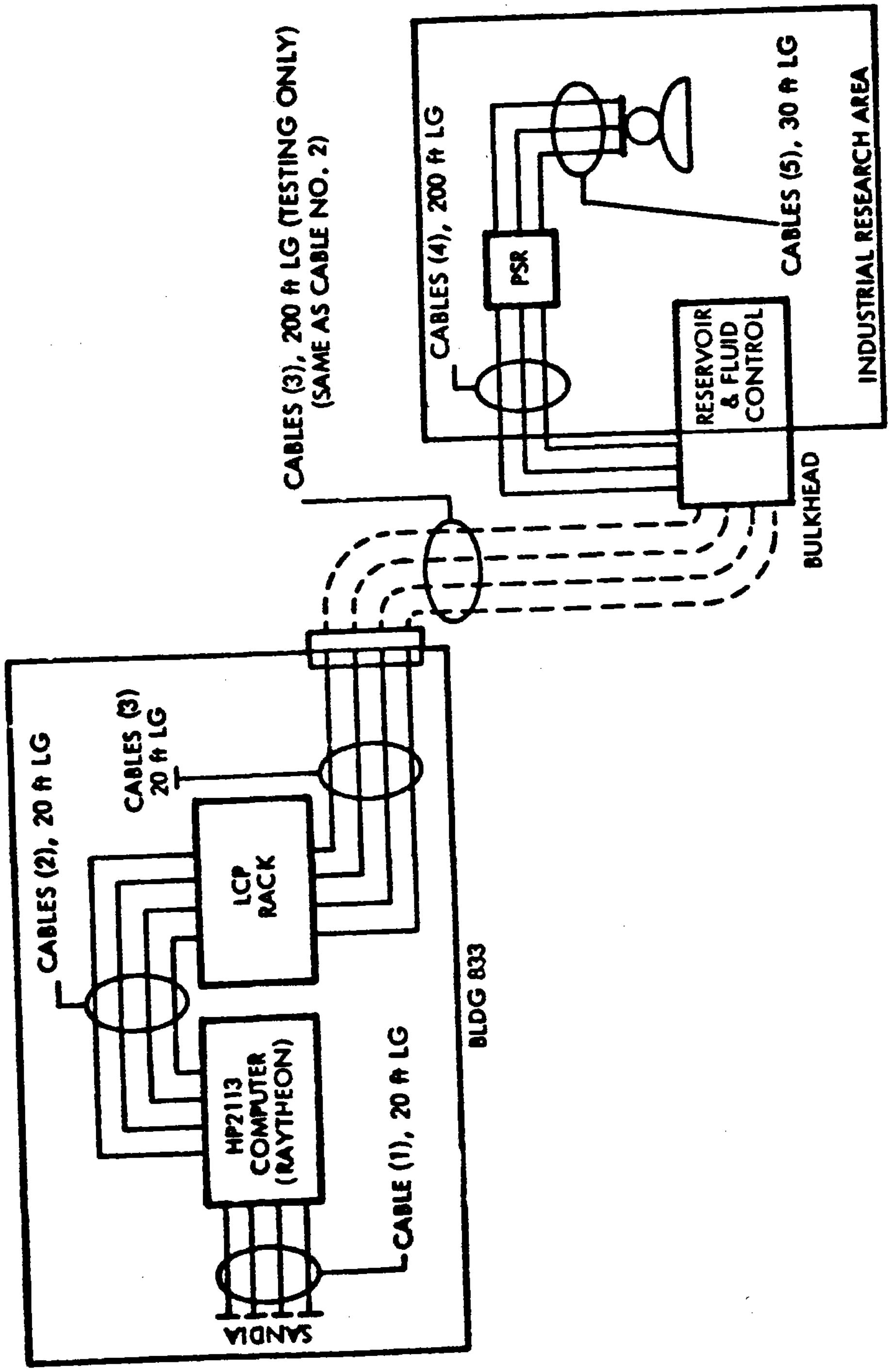

FIGURE 4-10. Interconnections Wiring Diagram

5.0 Fluid Circulating Loop

Raytheon's task for the FCL was to determine key system requirements and to support Sandia's design and fabrication of the FCL. A hydraulic schematic of a full field systems as currently envisioned is shown on Figure 5-1. Key FCL functions and parameter set points are controllable from the LCP and the computer. Interface data is assumed applicable to a junction box in Building 833.

5.1 Operation

Supply fluid is taken from Sandia at the field edge with a temperature between 463 and 486°F depending on the season. The fluid pump then delivers fluid to the collector(s), controlling the temperature of the return fluid back to Sandia at 592 ±5°F. This system must be adaptable to test operation with the single prototype collector and automatic multiple operation with collectors for later phases. In order to provide this flexibility reservoir contains both electric heating elements and a cooling water heat exchange similar to the SCTF loops. Therminol 66 is pumped from the Sandia storage tank by use of a fixed speed pump actuated through a level sensor in the reservoir. The capacity of the reservoir will be sufficient to accept 120 L (31.7 gal) of fluid at ambient temperature during startup and to stabilize fluid temperature during other transient conditions.

The primary controller is a variable speed pump which delivers Therminol from the reservoir to the collector (field) with a flowrate between 0.5 to 15 gal/min that is proportional to the net energy collected. Absorber and fluid temperature sensors at the inlet and outlet of the field (collector) provide signals from which the computer calculates the energy collected, and subsequent

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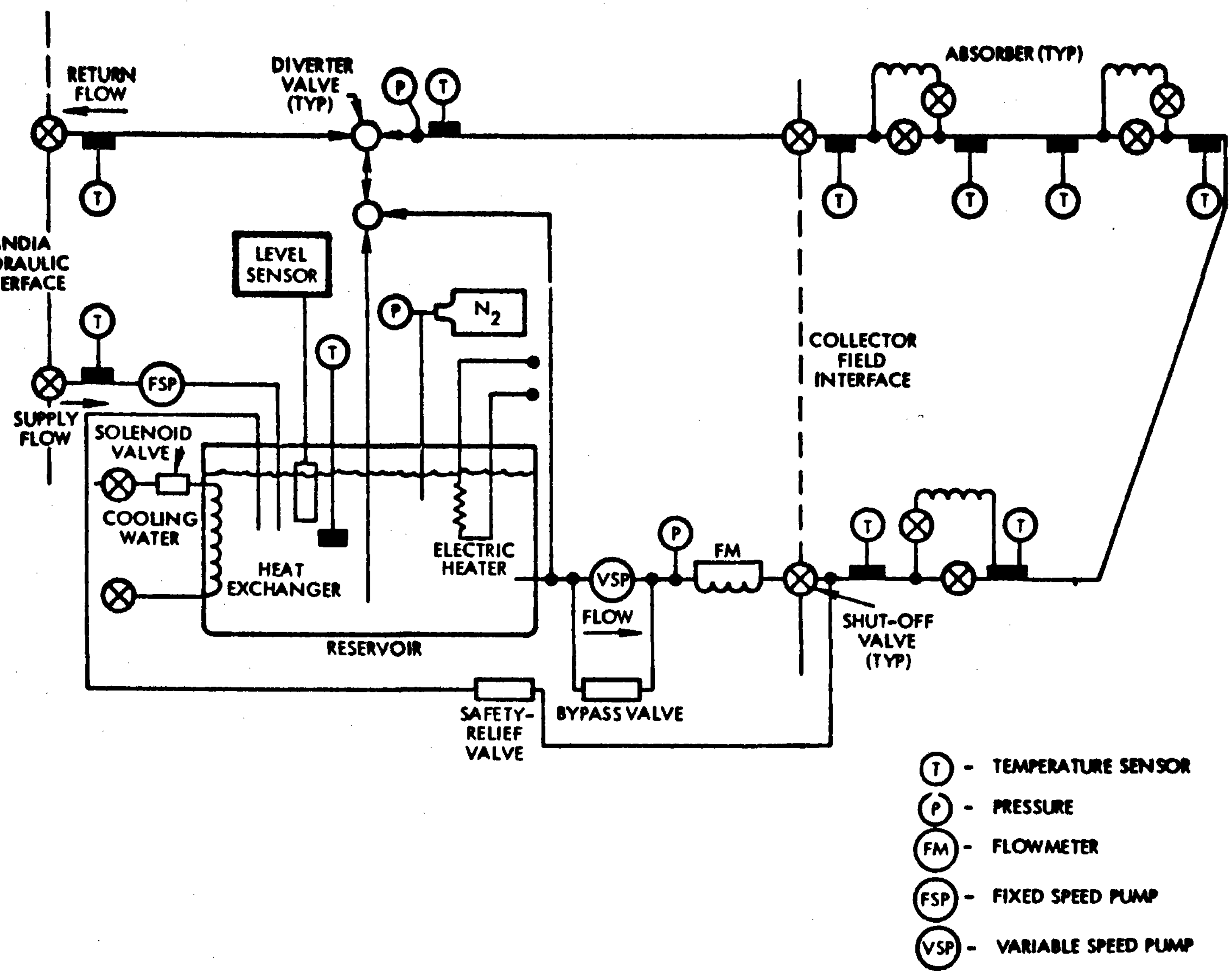

FIGURE 5-1. Fluid Circulating Loop Schematic

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required pump speed. Manual speed control will also be available as desired at the local control panel.

A diverter-type valve allows return flow-to Sandia only when the Therminol temperature is within specification (592 ±5°F). Otherwise, the fluid is diverted back to the reservoir. Flow would continue in this closed loop until either sufficient energy is absorbed to bring the temperature up to specification, or energy is rejected through the heat exchange reducing the fluid temperature. Eventual operation will require the use of an additional diverter valve to divert fluid around the reservoir back to the collector field. This would be necessary during certain periods of low insolation when the return fluid temperature is below specification. Otherwise the closed loop operation could result in an excessive reservoir temperature and hence system over-temperature should the full insolation return. These valves will be controlled by temperature controllers with setpoints at the desired return and reservoir fluid temperatures respectively.

Operation of the electric heater and the heat exchanger in the reservoir is through a temperature controller, when selected. Both can also be activated manually at the local control panel. In order to assist in manual operation as well as to provide system monitoring, the local control panel will include remote display of the reservoir temperature, pump discharge pressure, fluid flowrate through the collector(s), fluid temperatures returned from the collector(s), collector absorber temperature(s), and the status of the heat exchanger, high/low pressure, and the diverter valve position.

The system will have a pump bypass valve for cold start-up when the therminol in the system is very viscous, causing greater than normal pump discharge pressure. Mixing of hot make-up flow from the reservoir will increase as the fluid in the system is heated (viscous heating) until the discharge pressure drops below the valve set point. A safety relief valve vented back to the reservoir will provide protection from over-pressure at any time. A nitrogen blanket of approximately 10 psig is provided at the reservoir to minimize oxidation of the hot therminol.

The transient characteristics of the system at an ambient temperature of approximately 20°F are such that the absorber need not be defocused during startup with the insolation associated with a normal sunrise.

The requirements for a single collector test system is shown on Figure 5-2.

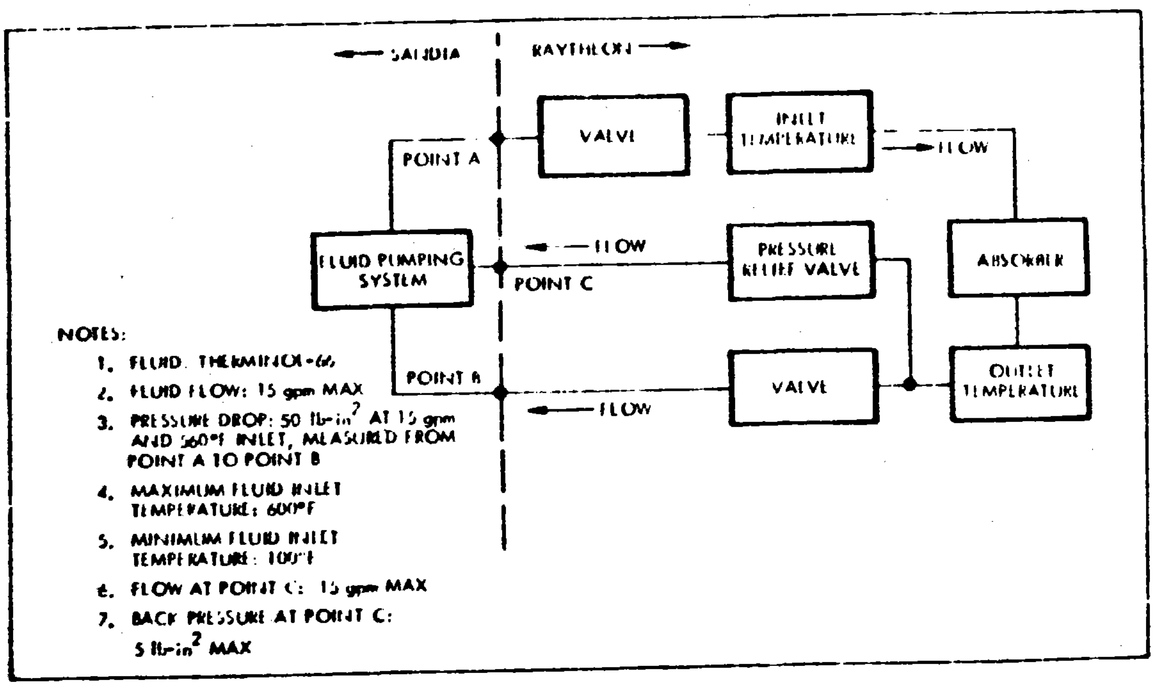

FIGURE 5-2. Fluid Circulating System Block Diagram, Requirements

Appendix A

Personnel Safety Considerations

In order to determine the potential hazard to personnel during non-operating modes, an optical analysis was performed to determine the solar images that would result from the sun at a 45 degree azimuth and 30 degree elevation orientation relative to a zero elevation position of the mount. The equations for solar reflection and spot size are derived in Appendix C.

The direction cosine of the incident rays are:

$$a_1 = -\cos E \cos \Delta Az = -.61237$$

$$b_1 = -\sin E = -.50000$$

$$c_1 = \cos E \sin \Delta Az = .61237$$

The direction cosines of the normal to the center of the mirrors are

$$a_{n_i} = \cos \theta_i$$

$$b_{n_i} = -\sin \theta_i \cos \psi$$

$$c_{n_i} = -\sin \theta_i \sin \psi$$

where θ_i = tilt of the i^{th} ring

ψ = angle around the center post.

The parametric equations of the reflected rays are

$$x_2 = x_i + a_2 t$$

$$y_2 = r_i \cos \psi + b_2 t$$

$$z_2 = r_i \sin \psi + c_2 t$$

where x_i = position of the i^{th} ring

r_i = radius of the i^{th} ring

a_2, b_2, c_2 = direction cosine of the reflected ray

t = parameter = distance from point of incidence.

At some horizontal plane, $y = y_o$ and

$$t = \frac{y_o - r_i \cos \psi}{b_2}$$

and

$$x_2 = x_i + \frac{a_2}{b_2} (y_o - r_i \cos \psi)$$

$$z_2 = r_i \sin \quad + \frac{c_2}{b_2} (y_o - r_i \cos \psi)$$

The direction cosine for the reflected rays are given in Appendix C as:

$$a_2 = a_1 - 2a_n(a_1 a_n + b_1 b_n + c_1 c_n)$$

$$b_2 = b_1 - 2b_n(a_1 a_n + b_1 b_n + c_1 c_n)$$

$$c_2 = c_1 - 2c_n(a_1 a_n + b_1 b_n + c_1 c_n)$$

The angle of incidence is

$$I = \cos^{-1}[a_1 a_n + b_1 b_n + c_1 c_n]$$

The size of the spot from a mirror in a plane normal to the ray reflected from the center of the mirror is

$$S_1 = \left| r \left(\cos I - \frac{2L}{R} \right) \right| + \xi L$$

$$S_2 = r \quad 1 - \frac{2L \cos I}{R} \quad + \xi L$$

where r = dimension of the mirror = 18 inches

ξ = angular extent of sun = .009 mrad.

L = distance mirror to spot

R = radius of curvature of the mirror

S_1, S_2 = solar image dimension

The magnification is taken to be the area of the mirror divided by the area of the spot or

$$M = \frac{r^2}{S_1 S_2}$$

The values of x_i, r_i and θ_i for the solar collector are given in Table A-1.

TABLE A-1

COLLECTOR GEOMETRIC DATA

RING NO.	x_1 (Inches)	r_1 (Inches)	θ_i (Arc Deg.)
1	.437	26.483	3.452
2	3.052	43.387	7.512
3	6.828	60.142	11.522
4	11.745	76.789	15.450
5	17.653	92.953	19.171
6	24.560	108.896	22.717
7	32.345	124.452	26.032

The solar images in a plane 8 ft. below the center of the mount were determined. Figure A-1 shows the lines through the center of each spot for each ring. Ring 6 and Ring 7 extend below the plane that was chosen. Therefore, the lines for Rings 6 and 7 terminate at the intersection of the plane and the collector.

For Rings 5, 6 and 7 some of the mirrors reflect the solar energy almost horizontal. The resulting image locations are far from the collector as is seen in the upper right hand section of Figure A-1. Some of the solar reflections will be incident upon other mirrors. Double reflections were not analyzed and these reflections are shown in the upper left hand section of Figure A-1 as if the collector was transparent to these reflections.

Figure B-1 is a plot of the incidence angles on the mirrors. The incidence angle for the mirror that reflect the solar image to the hot spot in Figure A-2 is about 50 degrees. The distance from the mirrors to the hot spot is about 200 inches. The mirror radius of curvature varies from 250 to 300 inches. The magnification varies from 5 to 7 for each mirror and the reflection from more than 10 mirrors are concentrated in a few square ft. region at the hot spot.

The incidence angle on the mirrors for the reflections that fall far from the collector are about 30 degrees. The distance is about 350 inches and the radius of curvature is about 350 inches. The magnification is about 1.0.

Although only one case was analyzed, some general conclusions can be drawn. First, if the mount is at a zero elevation angle and the sun is within 60 degrees of the azimuth of the collector, there will be a hot spot, greater than 30 suns, within 20 feet of the center of the collector. Secondly, at these close distances to the collector, it is erroneous to assume that the concentration of the spot on the ground is the same as the concentration of the spots five feet from the ground. Third, a magnification of one sun will occur within 30 ft. from the center of the collector.

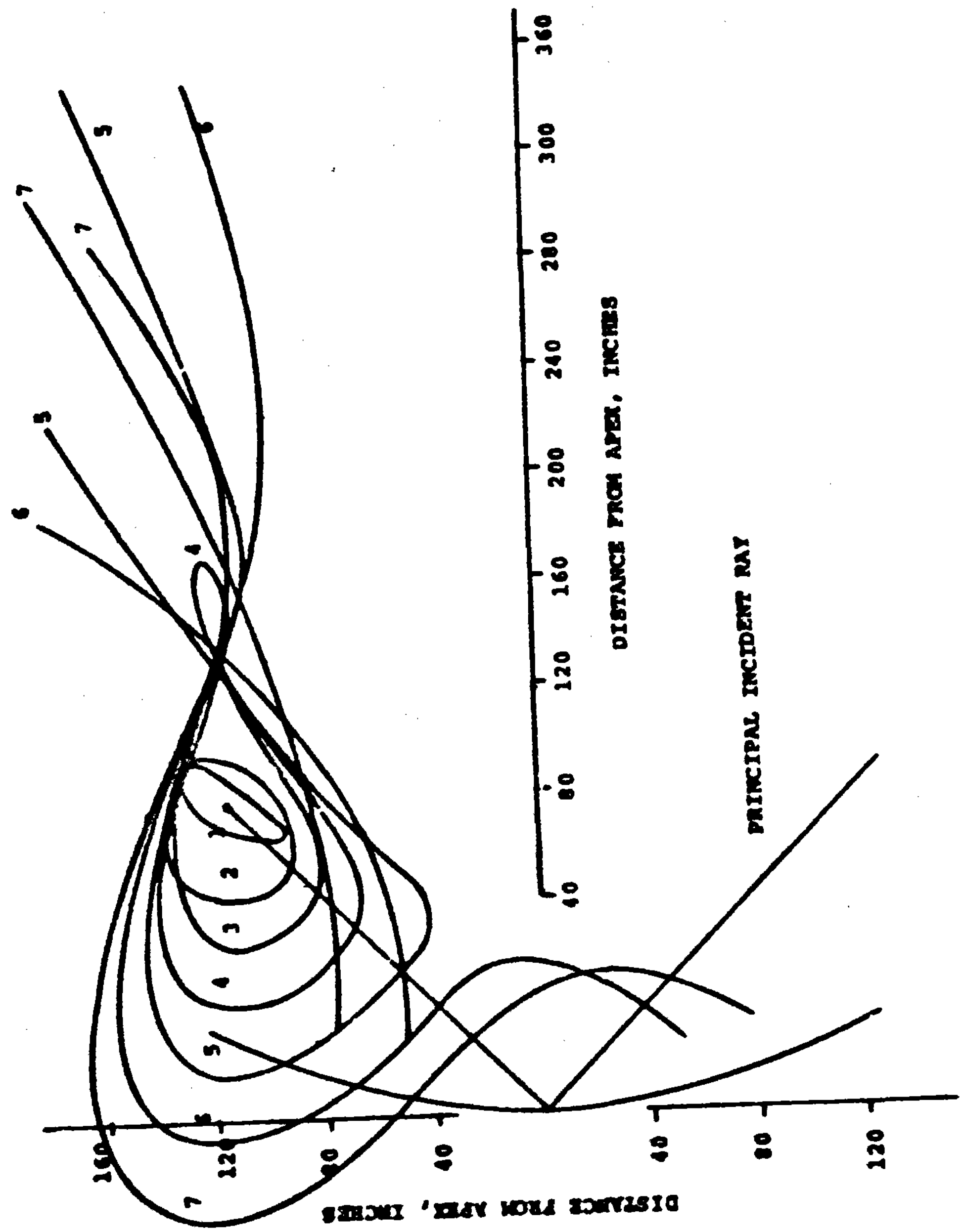

FIGURE A-1. Stray Radiation Pattern

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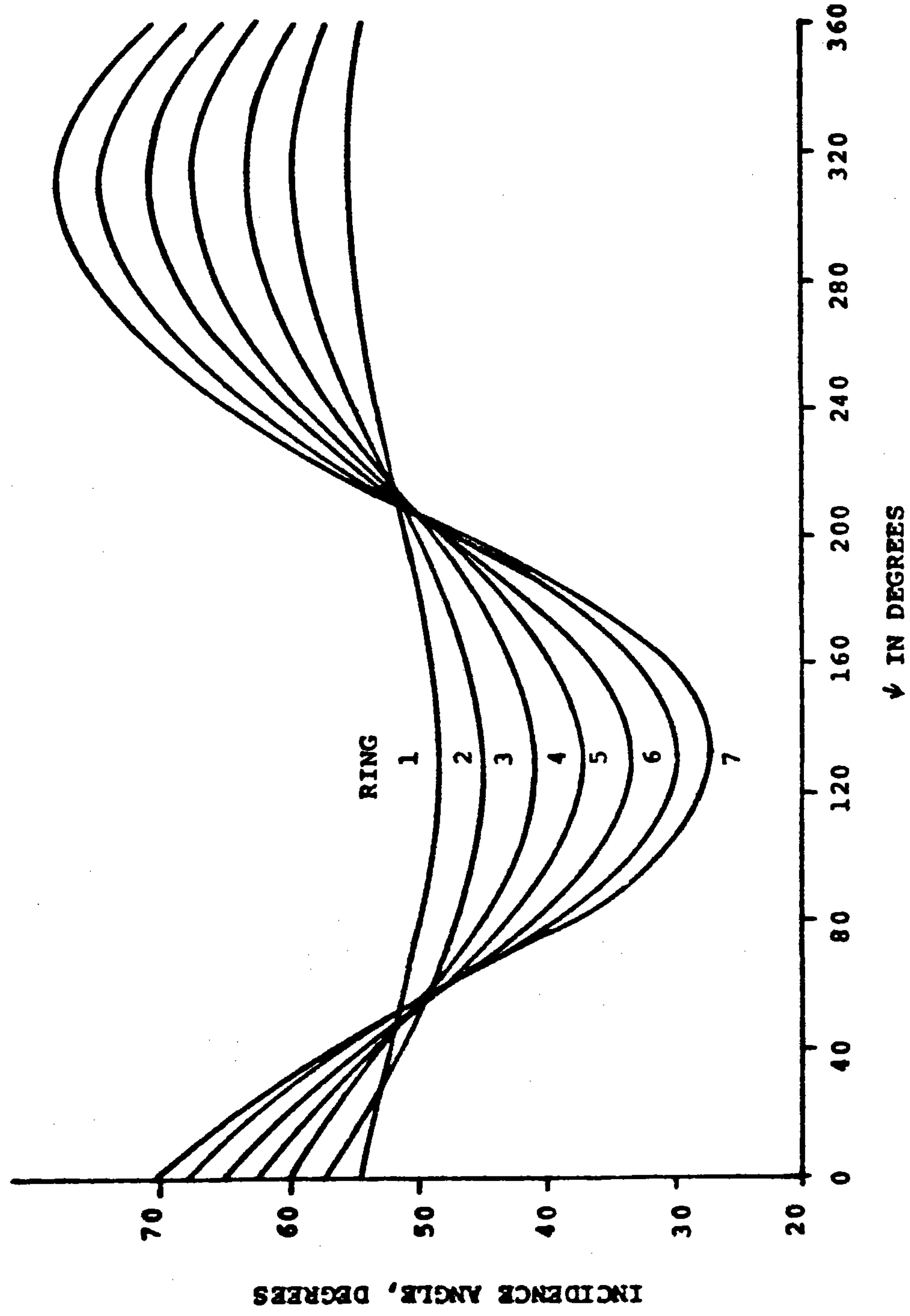

FIGURE A-2. Mirror Incidence Angles

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Because of the above considerations it is recommended:

a) Construct fences 32 ft. and 20 ft. away from the mount to warn personnel of the danger zone.

b) Make the entrance through the fence on the north side and supply dark glasses for personnel at the entrance.

c) Never work on the collector with the azimuth angle of the sun less than 90 degrees from the azimuth angle of the mount.

Appendix B

Error Analysis

An error analysis was performed on the Solar Collector to determine the size and location of the solar image in the absorber aperture. It is assumed that high spatial frequency errors give rise to spreading of the image; while low spatial frequency errors give rise to image location errors. Examples of high spatial frequency errors are:

a) Deviations from a spherical mirror,

b) Errors in radius of curvature,

c) Errors in mirror alignment.

Low spatial frequency errors are system pointing errors. For a system that uses open loop pointing (i.e., determine what the gimbal angle should be for a perfect system and command those gimbal angles) the error sources are:

a) Error in determining required gimbal angles,

b) Error in implementing commanded gimbal angle,

c) Error in North alignment,

d) Verticality error,

e) Elevation axis non-orthogonality to the azimuth axis,

f) Tracking line non-orthogonality to the elevation axis.

The temporal frequency of the errors can also be high or low. The effect of a high temporal frequency error is to effectively spread the image. A temporal frequency is considered to be high if the period is short relative to the thermal time constants of the absorber and of areas that can absorb spurious radiation. For the purpose of this analysis, it will be assumed that all errors are relatively static.

The total elevation and traverse tracking errors can be expressed as:

$$\varepsilon_E = \Delta E + \varepsilon_1 + \varepsilon_5 \sin A - \varepsilon_6 \cos A$$

$$\varepsilon_T = \Delta A \cos E + \varepsilon_2 - \varepsilon_3 \sin E + \varepsilon_4 \cos E$$

where ε_E = Total elevation angle error

ε_T = Total traverse angle error

ΔE = Elevation gimbal angle error

ΔA = Azimuth gimbal angle error

$\varepsilon_1, \varepsilon_2$ = Non-orthogohality of tracking line to the elevation axis

$\varepsilon_3, \varepsilon_4$ = Non-orthogonality of the elevation axis to the aximuth axis

$\varepsilon_5, \varepsilon_6$ = Verticality errors

A = Azimuth angle

E = Elevation angle

The gimbal angle errors include the errors in the determination of the required angles and the errors in implementing the commanded angles. North alignment, and errors in the knowledge of time, tracker location and ephemeris data are considered to be errors in the determination of the required angles.

The tracking errors are listed in Table B-1.

The radial spot size in the absorbing aperture of the solar image for each ring of mirrors is given in Table B-2.

TABLE B-1

TRACKING ERRORS

ERROR	MAGNITUDE (μrad)	
ΔE		
Time	100	
Computation	100	
Ephemeris	100	
Encoder Accuracy	200	
Encoder Zero Set	300	
Backlash & Stiction	300	
Wind Load Torque	300	
RSS		583
ΔAz		
Time	300	
Computation	100	
Ephemeris	100	
Encoder Accuracy	200	
Encoder Zero Set	300	
Error in North	1000	
Backlash & Stiction	300	
Wind Load Torque	300	
RSS		1192
ε_1		
Non-Compensated Post Droop	2000	
Mirror Average Misalignment	300	
Absorber Positioning	100	
RSS		2025

TABLE B-1 (Cont.)

ε_2			
	Mirror Average Misalignment	300	
	Absorber Positioning	100	
	∴ RSS		316
ε_3	Gimbal Axes Non-Orthogonality	2000	
ε_4		2000	
ε_5	Verticality	2000	
ε_6		2000	

$$\varepsilon_E(RSS) = [(\Delta E)^2 + (\varepsilon_1)^2 + (\varepsilon_5 \sin A)^2 + (\varepsilon_6 \cos A)^2]^{1/2} = 2905\ \mu rad$$

$$\varepsilon_T(RSS) = [(\Delta A \cos E)^2 + (\varepsilon_2)^2 + (\varepsilon_3 \sin E)^2 + (\varepsilon_4 \cos E)^2]^{1/2}$$

$$= 2272\ \mu rad$$

TABLE B-2

APERTURE SPOT SIZE, RADIAL DIRECTION

RING NO.	SPOT SIZE (inches)	NO. MIRRORS
1	1.092	12
2	1.128	24
3	1.204	24
4	1.334	36
5	1.498	36
6	1.746	48
7	2.083	48

The mirrors are not perfect spherical sections. The errors are in the errors in the radius of curvature* and the deviations from a spherical surface. (The fact that spherical sections rather than parabolic sections are used, resulting in spherical abberations, is negligible relative to the other errors).

The angular errors in the reflection at a point can be expressed as

$$\theta_\varepsilon = 2\Delta_1 - (2n-1)\Delta_2$$

where n = index of refraction

Δ_1 = slope errors

Δ_2 = rate of change of thickness

The parameter of interest is the root mean square (rms) error over the face of the mirror. The error parameters are independent and therefore their combined effect can be estimated by an RSS process of the individual effects. The rms values of Δ_1 and Δ_2 are estimated to be 2 mrad and 1 mrad respectively, resulting in an rms value of 4.5 mrad for θ_ε. The rms effect of all of the mirrors considering the incidence angle of the rays at the absorber aperture is 5.9 mrad. The effective rms angular spreading resulting from radius of curvature errors is 2.9 mrad resulting in a total mirror error of 6.6 mrad rms.

The mirrors are mounted on a casting with four bolts. If the position of the four surfaces are considered to be independent random variables the rms tilt of the mirror is

$$\text{mirror tilt} = \frac{\sigma_x}{d}$$

* The desired radii were used in the analysis, neglecting the problem discussed earlier.

where σ_x = rms displacement of bolt location

d = bolt separation

For σ_x = .015 inch, d = 13.5 inches, a doubling effect due to reflection and a multiplier of 1.322 to account for the varying incidence angles of the rays from the different mirrors, the angular spreading of the image due to mirror support machining error is 2.9 mrad.

Each mirror is tilted by an angle that depends upon the mirror's position. Each of these angles will be separately machined relative to a reference plane. The specified tolerance is 2.2 mrad rms. The resulting error in the image spreading is 5.8 mrad.

The total mirror distortion effect for a point sun is shown in Table B-3.

TABLE B-3

MIRROR DISTORTION, POINT SUN

ERROR	RMS ANGLE (mrad)	RMS SIZE (inches)
mirror slope	5.9	.708
mirror radius	2.9	.348
mirror support	2.9	.348
mirror tilt	5.8	.696
RSS	9.2	1.110

That is, a point sun would result in an image, in the annular aperture of the absorber, that is Gaussian shaped with a "one sigma" value of 1.11 inches due to mirror errors. The real sun (9 mrad) with perfect mirrors would produce an image that is more uniform than the Gaussian shape and has a total spread of 2.088 inches. Since each mirror moves and distorts the solar image independently from the other mirrors, the total image size and shape is the convolution of the above two image size and shapes. The convolution process can be approximated by assuming the 2.088 inch dimension of the solar image with perfect mirrors in a "±2 sigma" value of a random Gaussian distribution. The total solar image would then be Gaussian with a "one sigma" value of 1.2 inches. Figure B-1 shows percentage of the total energy that will be in the aperture as a function of the aperture size. The SCS design uses a 5 inch aperture resulting in 96.5 percent of the energy going into the absorber.

The pointing error of 2.9 mrad in elevation and 2.2 mrad in traverse are considered to be "two sigma" values. If one were to consider pointing error to be a high temporal frequency phenomenon, the "one sigma" additional image spreading is 0.18 inch. This would increase the image size by only one percent and have negligible effects.

However pointing error is low temporal frequency phenomenon. This will result in a slight increase in the total energy splashed on the aperture plate. This is shown in Figure 3-6.

The system drawings have been generated with due regard to the desires to minimize errors within manufacturing capabilities and cost/schedule constraints. Reviewing these drawings with respect to the error analysis yields the following comparisons:

a) Verticality (ε_5, ε_6)

Fabrication drawings specify dimensions (verified by inspection) that yield verticality errors ±0.8 mr vs assumed ±2 mr.

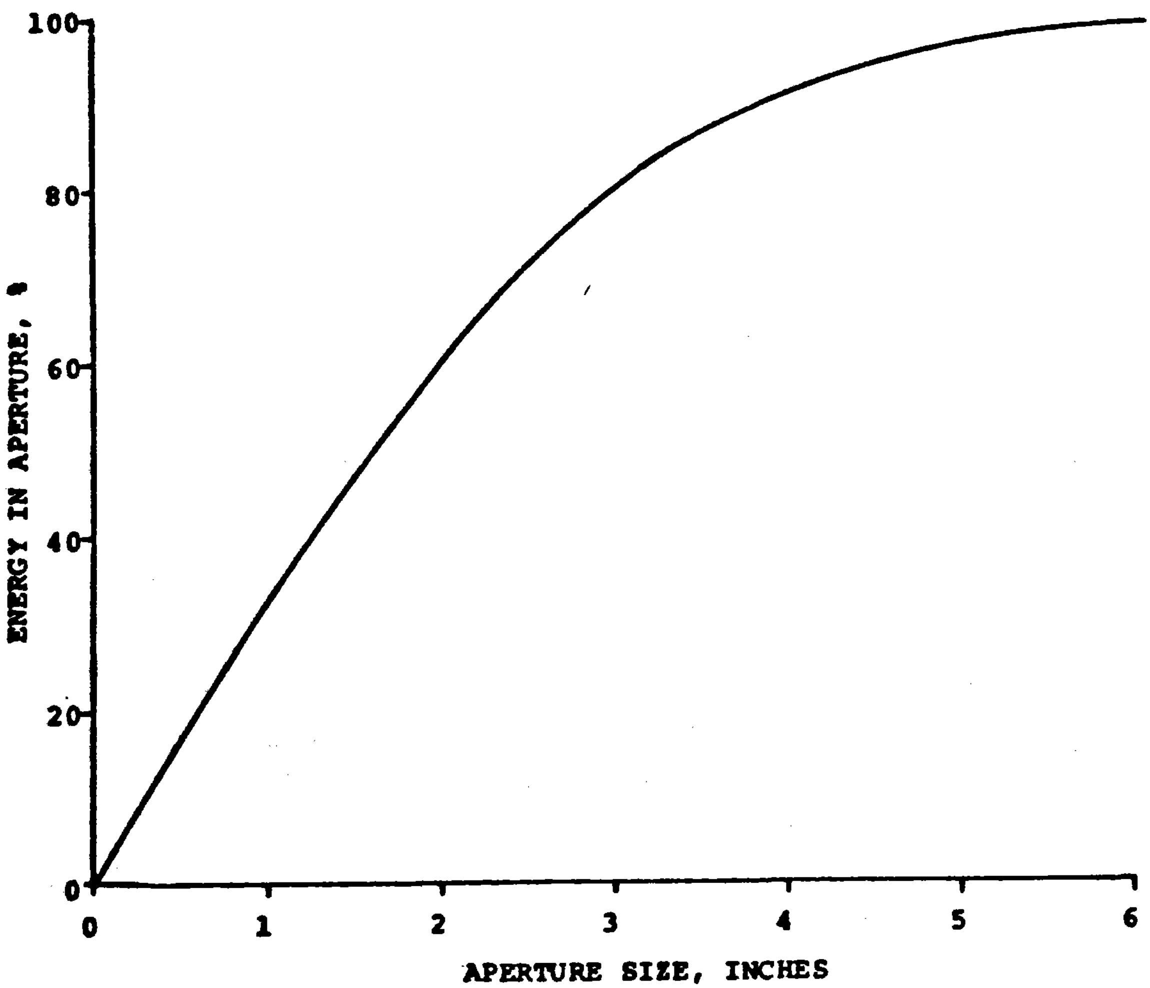

FIGURE B-1. Energy Acceptance Vs. Aperture Size

b) Gimbal Axis Non-Orthogonality (ε_3, ε_4)

Fabrication drawings specify dimensions (verified by inspection) that yield non-orthogonality errors ±0.9 mr vs. assumed ±2 mr.

c) Post Droop, Mirror Misalignments and Absorber Positioning Errors (ε_1, ε_2)

Drawings indicate values that result in ε_1, ε_2 errors of ±1.1 mr vs. ±2 mr (ε_1) and ±3 mr (ε_2).

This comparison indicates that the energy conversion efficiency intent as stated by the error analysis was transferred in a reasonable manner to the system design. Actual determination of the degree of success of the design and manufacturing process will be determined by the test series planned by Sandia during the evaluation phase.

Appendix C

Basic Equations for Optical Ray Trace Analysis

The purpose of this analysis is to derive the equations for reflective ray trace analysis. Ray trace analysis is then used to determine the spot size resulting from each spherical mirror.

Let the direction cosines of the incoming ray be a_1, b_1, and c_1. Let the direction cosines of the normal to the surface be a_n, b_n, c_n. Then the direction cosines of the reflected rays are:

$$a_2 = a_1 - 2a_n(a_1a_n + b_1b_n + c_1c_n)$$

$$b_2 = b_1 - 2b_n(a_1a_n + b_1b_n + c_1c_n)$$

$$c_2 = c_1 - wc_n\ (a_1a_n + b_1b_n + c_1c_n)$$

The sign convention is shown in Figure C-1.

If the point of reflection is x_o, y_o, z_o, then the parametric equations of the reflected ray are

$$x_2 = x_o + a_2t$$

$$y_2 = y_o + b_2t$$

$$z_2 = z_o + c_2t$$

where t = parameter.

C.1 Reflections from a Spherical Surface

The geometry for the problem is shown in Figure C-2. The equation for the spherical mirror is

$$(x-R)^2 + y^2 + z^2 = R^2$$

where R = radius of sphere.

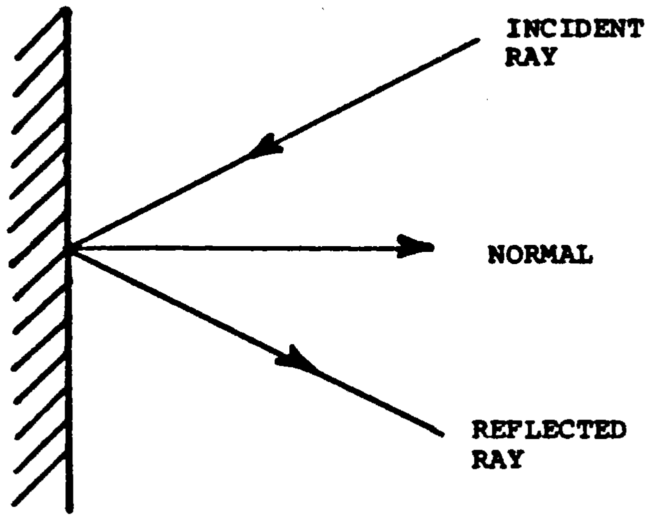

FIGURE C-1. Ray Trace Sign Convection

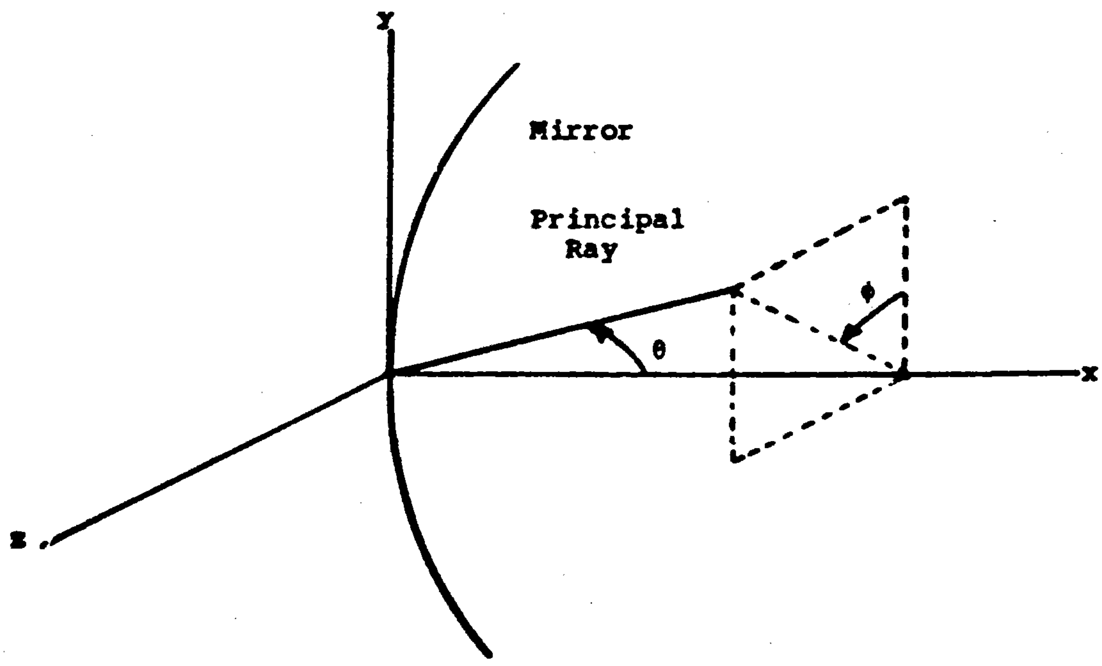

FIGURE C-2. Spherical Surface Reflection Geometry

The direction cosines of the incident ray are:

$$a_1 = -\cos\theta$$

$$b_1 = -\sin\theta\cos\phi$$

$$c_1 = -\sin\theta\sin\phi$$

The direction cosines of the normal are

$$a_n = \left[1 - \frac{r^2}{R^2}\right]^{1/2}$$

$$b_n = -\frac{r}{R}\cos\psi$$

$$c_n = -\frac{r}{R}\sin\psi$$

where

$$r = (y_o^2 + z_o^2)^{1/2}$$

$$\psi = \tan^{-1}\frac{z_o}{y_o}$$

y_o, z_o = point of reflection

Therefore the direction cosines of the reflected ray are:

$$a_2 = -\cos\theta - 2\left(1-\frac{r^2}{R^2}\right)^{1/2}\left[-\left(1-\frac{r^2}{R^2}\right)^{1/2}\cos\theta + \frac{r}{R}\sin\theta\cos(\psi-\phi)\right]$$

$$b_2 = -\sin\theta\cos\phi + \frac{2r}{R}\cos\psi\left[-\left(1-\frac{r^2}{R^2}\right)^{1/2}\cos\theta + \frac{r}{R}\sin\theta\cos(\psi-\phi)\right]$$

$$c_2 = -\sin\theta\sin\phi + \frac{2r}{R}\sin\psi\left[-\left(1-\frac{r^2}{R^2}\right)^{1/2}\cos\theta + \frac{r}{R}\sin\theta\cos(\psi-\phi)\right]$$

The parametric equations for the reflected ray are

$$x_2 = \left[R\ 1 - \left(1-\frac{r^2}{R^2}\right)^{1/2}\right] + a_2 t$$

$$y_2 = r\cos\psi + b_2 t$$

$$z_2 = r\sin\psi + c_2 t$$

For the principal ray $r=o$ and

$$a_2 = \cos\theta$$

$$b_2 = -\sin\theta\cos\phi$$

$$c_2 = -\sin\theta\sin\phi$$

The parametric equations of the reflection of the principal ray are

$$x_2 = t\cos\theta$$

$$y_2 = -t\sin\theta\cos\phi$$

$$z_2 = -t\sin\theta\sin\phi$$

Let

$$\begin{vmatrix} x_2' \\ y_2' \\ z_2' \end{vmatrix} = \begin{vmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{vmatrix} \cdot \begin{vmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{vmatrix} \cdot \begin{vmatrix} x_2 \\ y_2 \\ z_2 \end{vmatrix}$$

(Note y_2' is in the plane of the principal ray and the principal normal).

or

$$x_2' = x_2 \cos\theta - y_2 \sin\theta \cos\phi - z_2 \sin\theta \sin\phi$$

$$y_2' = x_2 \sin\theta + y_2 \cos\theta \cos\phi + z_2 \cos\theta \sin\phi$$

$$z_2' = -y_2 \sin\phi + z_2 \cos\phi$$

Then the parametric equations of the principal ray are

$$x_2' = t$$

$$y_2' = 0$$

$$z_2' = 0$$

The parametric equations for the general ray are

$$x_2' = R\left[1-\left(1-\frac{r^2}{R^2}\right)^{1/2}\right]\cos\theta - r\sin\theta\cos(\psi-\phi)$$
$$+ t\left\{1-\frac{2r^2}{R^2}\left[1 - \sin^2\theta \sin^2(\psi-\phi)\right]\right\}$$

$$y_2' = R\left[1-\left(1-\frac{r^2}{R^2}\right)^{1/2}\right]\sin\theta + r\cos\theta\cos(\psi-\phi)$$
$$-t\left\{\frac{2r}{R}\left(1-\frac{r^2}{R^2}\right)^{1/2}\cos(\psi-\phi)\right.$$
$$\left.+\frac{2r^2}{R^2}\sin\theta\cos\theta\sin^2(\psi-\phi)\right\}$$

$$z_2' = r\sin(\psi-\phi) - t\left\{\frac{2r}{R}\left(1-\frac{r^2}{R^2}\right)^{1/2}\cos\theta\sin(\psi-\phi)\right.$$
$$\left.-\frac{2r^2}{R^2}\sin\theta\sin(\psi-\phi)\cos(\psi-\phi)\right\}$$

For $\frac{r}{R} << 1$

$$a^2 = \cos\theta - \frac{2r}{R}\sin\theta\cos(\psi-\phi)$$
$$b_2 = -\sin\theta\cos\phi - \frac{2r}{R}\cos\theta\cos\psi$$
$$c_2 = -\sin\theta\sin\phi - \frac{2r}{R}\cos\theta\sin\psi$$

$$x_2 = t\left[\cos\theta - \frac{2r}{R}\sin\theta\cos(\psi-\phi)\right]$$
$$y_2 = r\cos\psi - t\left[\sin\theta\cos\phi + \frac{2r}{R}\cos\theta\cos\psi\right]$$
$$z_2 = r\sin\psi - t\left[\sin\theta\sin\phi + \frac{2r}{R}\cos\theta\sin\psi\right]$$

For small variations in θ and ϕ

$$\Delta x_2 + \frac{dx_2}{a\theta}\Delta\theta + \frac{dx_2}{a\phi}\Delta\phi = t\Big[\cos\theta - \frac{2r}{R}\sin\theta\cos(\psi-\phi)$$

$$-\Delta\theta\sin\theta - \frac{2r}{R}\Delta\theta\cos\theta\cos(\psi-\phi)$$

$$-\frac{2r}{R}\Delta\phi\sin\theta\sin(\psi-\phi)\Big]$$

$$\Delta y_2 + \frac{dy_2}{a\theta}\Delta\theta + \frac{dy_2}{a\phi}\Delta\phi = r\cos\psi - t\Big[\sin\theta\cos\phi + \frac{2r}{R}\cos\theta\cos\psi$$

$$+\Delta\theta\cos\theta\cos\phi$$

$$-\frac{2r}{R}\Delta\theta\sin\theta\cos\psi$$

$$+\Delta\phi\sin\theta\sin\phi\Big]$$

$$\Delta z_2 + \frac{dz_2}{a\theta}\Delta\theta + \frac{dz_2}{a\phi}\Delta\phi = r\sin\psi$$

$$-t\Big[\sin\theta\sin\phi + \frac{2r}{R}\cos\theta\sin\psi$$

$$+\Delta\theta\cos\theta\sin\phi - \frac{2r}{R}\Delta\theta\sin\theta\sin\psi$$

$$+\Delta\phi\sin\theta\cos\phi\Big]$$

Therefore the parametric equation of the reflected ray considering small variations of θ and ϕ are ($\Delta\theta = \xi\cos\eta$, $\Delta\phi\sin\theta = \xi\sin\eta$ and $\phi = 0$)

$$x_2' = r \cos\psi \sin\theta + t$$

$$y_2' - r \cos\psi \cos\theta - t\left[\xi \cos \eta + \frac{2r}{R} \cos\psi\right]$$

$$z_2' = r \sin\psi - t\left[\frac{2r}{R} \cos\theta \sin\psi + \xi \sin\eta\right]$$

The equation of the spot at $x_2' = L$ is

$$\frac{(y_2' + \xi L \cos\eta)^2}{(r \cos\theta - \frac{2rL}{R})^2} + \frac{(z_2' + \xi L \sin\eta)^2}{(r - \frac{2rL}{R} \cos\theta)^2} = 1$$

The area of the spot is approximately

$$A = \pi\left[\left|r \cos\theta - \frac{2rL}{R}\right| + \xi L\right]\left[\left|r - \frac{2rL}{R} \cos\theta\right| + \xi L\right]$$

The minimum spot size in the y_2' direction occurs at

$$L = \frac{R}{2} \cos\theta$$

Specification No. MP 778340B
Date: 1 November 1977

Appendix D

Mirror Purchase Specification

1. SCOPE

1.1 This specification establishes the requirements for manufacture, and acceptance of the solar collector mirror critical item.

2. APPLICABLE DOCUMENTS

None

3. REQUIREMENTS

3.1 Item definition. The spherical mirror segments will be fabricated, coated, inspected and tested for use in a Solar Concentrator. The wavelength range is the transmitted solar spectrum through the atmosphere, which extends from approximately 350 to 2000 nanometers. The convex surface and all edges of each curved glass segment shall be coated with a silver reflective film overlaid with protective films of copper and paint. The copper and paint films are required to minimize deterioration of the silver as a high reflective coating during handling and against the outdoor environment in the southwestern United States.

3.2 Characteristics.

3.2.1 Performance.

3.2.1.1 Specular reflectance. The finished coated mirror segments shall have a specular reflectance of not less than (nlt) 92 percent for combined front and rear reflections when measured on a witness sample of the same material at an angle of incidence between 0 and 45 degrees at any wavelength in the range from 400 to 2000 nanometers.

3.3 Design and construction.

3.3.1 Fabrication process. The mirror segments shall be fabricated from SCHOTT-DESAG B-270 water-white, ophthalmic crown, draw sheet glass, double strength with a thickness of 3.25 $\pm$ 0.2 millimeters. Physical characteristics of this glass are summarized in 6.3. The mirror segments shall be fabricated as specified in 3.3.2, 3.3.3 and Figure D-1.

3.3.2 Standards of manufacture.

3.3.2.1 Fabrication. The fabrication requirements for each segment are as follows:

a. Surface accuracy. Plus or minus 4 milliradians maximum slope error from best fit sphere.

b. Tolerance on radius of curvature. Plus or minus 10 inches, or the radius of curvature for each ring shall fall between the values of $R_{C\ MIN}$ and $R_{C\ MAX}$ of Figure D-1.

c. Annealing. Each mirror segment shall be annealed after bending.

d. Cutting. Each mirror segment shall be cut to dimensions and tolerances specified in Figure D-1.

(U)

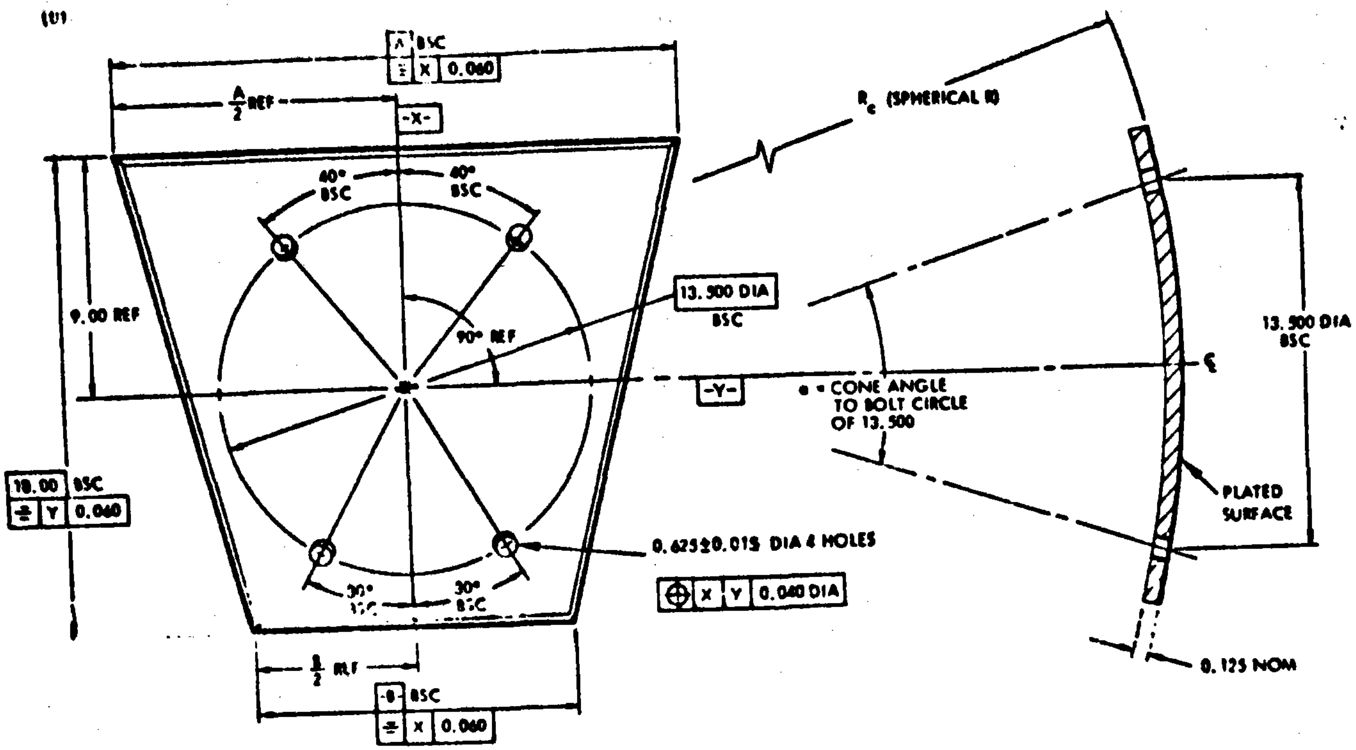

FIGURE D-1. Mirror Segment Details

-NO	R_C ±10 In.	A ±0.030 REF	A/2	B ±0.030 REF	B/2	α°	ALTERNATIVE R_C R_C MIN	R_C MAX
-1	250 In.	18.806	9.403	8.858	4.429	3.094	236.3	246.3
-2	250 in.	13.573	6.786	8.796	4.398	3.094	239.3	249.3
-3	250 In.	17.958	8.979	13.197	6.598	3.094	246.0	256.0
-4	250 In.	14.755	7.377	11.687	5.843	3.094	256.0	267.6
-5	295 In.	17.554	8.777	14.519	7.259	2.622	267.6	285.0
-6	295 In.	15.166	7.583	12.952	6.476	2.622	285.0	304.8
-7	295 In.	17.178	8.589	15.014	7.507	2.622	304.8	328.8

NOTE: ALL DIMS SHOWN ARE TO R_c (PLATED SURFACE) AND ARE PARALLEL TO ℄
ALL DIMS IN INCHES

e. Draw lines. Each mirror segment shall be cut with the draw lines oriented within 5 degrees of parallelism with its axis of symmetry.

f. Mounting holes. Shall be as specified in Figure D-1.

g. Cracks. No cracks that are visible to the unaided eye are permitted as a result of the fabrication operations

h. Edges. All edges to be ground to remove sharp corners and splinters.

3.3.2.2 Coatings. Each curved glass segment shall have been manufactured, inspected, and tested prior to the coating process in accordance with this specification. The glass segment shall be coated over its entire convex area and on all edges with a silver reflective film overlaid with protective films of copper and paint.

3.3.2.2.1 Coating Process. The coating process producing the rear surface, protected silver finish shall cause no impairment to the glass segment. All steps in the coating procedure shall be accompanied by a cleaning operation in accordance with best commercial practice.

a. Silver Film. The reflective film shall be chemically deposited, high quality silver. There shall be no visible discontinuities or blemishes that affect the life of the coating or the specular reflectance as specified in 3.2.1.1.

b. Copper film. The silver film shall be protected from corrosion by a film of chemically deposited high quality copper. The copper film shall be free from holes, discontinuities or blemishes as determined by visual inspection.

c. Paint films. The copper film shall be protected from corrosion and damage during handling by a film of high quality primer paint. The primer paint shall be overcoated with a film of high quality protective enamel paint. The primer and enamel paints shall be applied in accordance with best commercial practice for maximum durability.

3.3.3 Workmanship. All details of workmanship shall be of the highest grade consistent with the intention of this specification.

4. QUALITY ASSURANCE PROVISIONS.

4.1 General. Prior to shipment to Raytheon, the completed mirror segments shall be inspected and tested to determine compliance with the requirements specified herein.

4.1.1 Responsibility for inspection. The mirror fabrication and coating vendor is responsible for the performance of all inspections and tests.

4.2 Quality conformance inspection.

4.2.1 Fabrication process. The mirror segments shall be inspected to determine compliance with the requirements specified in 3.3.1.

4.2.2 Cracks and edges. The mirror segments shall be inspected for cracks and proper edges to determine compliance with the requirements specified in 3.3.2.1 g and 3.3.2.1 h.

4.2.3 Coating. The mirror segment shall be inspected during process for coating quality to determine compliance with the requirements specified in 3.3.2.2, 3.3.2.2.1 a, b and c.

4.3 Test methods and procedures.

4.3.1 Surface accuracy. The surface accuracy of the convex surface of all mirror segments shall be measured prior to the cutting, drilling, and silvering operations. The surface accuracy shall be determined from a total of nine spherometer measurements at points defined in Figure D-2. The spherometer shall be centered at each of these points and the three outer legs of the spherometer shall form a reference circle whose diameter is not less than 3 inches or greater than 4 inches. The ratio of the maximum difference between the radius of curvature measurements at each point to the average measurement for the nine points shall not exceed 25% which meets the requirement in 3.3.2.1 a.

4.3.2 Radius of curvature. The radius of curvature of the convex surface of all mirror segments shall be measured prior to the cutting, drilling, and silvering operations. The radius of curvature shall be determined from a total of nine spherometer

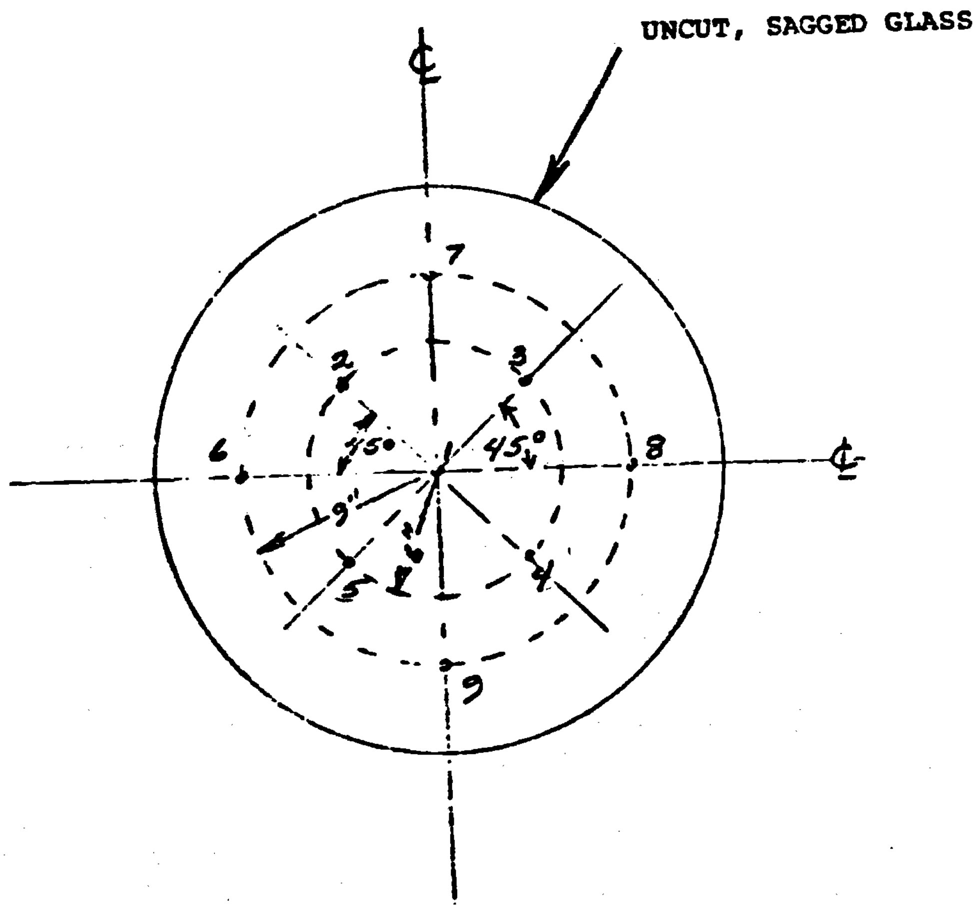

FIGURE D-2. Location of Spherometer Measurement Points measurements as defined in 4.3.1. The radius of curvature for the mirror segment shall be the average of the nine measurements and shall be marked on the mirror segment for reference. The variation in the radius of curvature from one segment to another shall not exceed the requirement in 3.3.2.1 b. The radius of curvature of each segment shall be noted, and reported to Raytheon prior to cutting and drilling.

4.3.3 Mechanical dimensions. The mirror segment dimensions and mounting hole locations shall be measured with the appropriate tools. These mechanical dimension measurements shall be as specified in 3.3.2.1 d and f, and 3.3.1.

4.3.4 Draw lines. The angular orientation of the draw lines with respect to the axis of symmetry of the mirror shall be measured with an appropriate tool. These draw line measurements shall be as specified in 3.3.2.1 e.

4.3.5 Reflectance. The reflectance of the finished mirror segment shall be determined by measuring a witness sample with photometric equipment presently used at SCHOTT-DESAG. The field-of-view of the photometer, or receiver, shall not exceed one degree and its relative aperture as measured from the mirror surface shall not be less than f/50 so that non-specular reflections, such as wide and narrow angle scatter are rejected by the reflectance measurement set-up. The reflectance of the finish mirror segment shall be measured at a wavelength between 400 to 700 manometers for at least five points on the surface, which will include the center and each corner. Reflectance measurements shall be performed on a sampling of at least 5 percent of the mirror segments from each coating run. The specular reflectance requirement shall be as specified in 3.2.1.1.

5. PREPARATION FOR DELIVERY

5.1 Cleaning and handling. Each finished mirror segment shall be cleaned and handled in accordance with the best commercial practice.

5.2 Packaging. Each mirror segment shall be wrapped in soft tissue, overwrapped with cushioning material, and than secured with tape. The packaged mirror segments shall be packed to afford protection against damage during direct shipment from the vendor's facility to Raytheon Company, Bedford, Massachusetts.

6. NOTES

6.1 Intended use. The mirror segments covered by this specification shall be used in a concave solar concentrator that provides maximum collection efficiency.

6.2 Definitions. Words, terms, and expressions used in this specification which are peculiar to the general field of optics are defined in Specification MIL-STD-1241, Optical Terms and Definitions.

6.3 Glass physical properties. The nominal physical properties of the water-white crown glass for the solar concentrator mirrors covered by this specification are summarized as follows:

Chemical properties

% $Fe_2O_3 \leq 0.01$

Mechanical properties

Young's modulus (0°C):	$10.5x10^6$PSI
Rigidity modulus (0°C):	$4.3x10^6$PSI
Poisson's ratio:	0.21
Hardness:	490 Knopp
Density	2.46 gm/cc
Expansion Coefficient (0°-300°C):	$8.7x10^{-6}$/°C

Optical properties

Index of refraction (nd):	1.510
V-value:	63.5
Homogeneity:	$\pm$ $2x10^{-5}$ maximum variation of nd.

Absorption coefficients:

λ(nm)	$B(cm^{-1})$
300	2.41
350	0.032

Absorption coefficients: (continued)

400	0.0077
500	0.0060
600	0.0046
800	0.0040
1000	0.0040
1500	0.0040
2000	0.0050

Viscosity data

Strain Point	505°C
Anneal Point	548°C
Softening Point	730°C
Flow Point	920°C

Appendix E

Schott Mirror Data

DEUTSCHE UHRGLASFABRIK GMBH

GRÜNENPLAN

[illegible] Postfach 100 3223 Delligsen 2

3223 Delligsen 2
Fernruf: Delligsen (0 51 87) 7 80 61
Telex: 92 960 [illegible]
Drahtwort: Uhrglasfabrik Grünenplan
Bahnstation: Alfeld (Leine)

Raytheon Company
Missile Systems Division
Hartwell Road

Bedford, Mass. 01730

Attn. Mr. R. Schumm

Ihre Zeichen	Ihre Nachricht vom	Unsere Zeichen	Datum
		VUU/LSp	25.11.77

Solar Collector mirrors - order T 3015

Dear Mr. Schumm,

We refer to our telex of 23.11.77 and enclose the complete list as promised. One copy is also sent to Mr. W.G. Wash.

Yours faithfully

Deutsche Uhrglasfabrik
G.m.b.H.

Encl.

[illegible]

measuring points:		1	2	3	4	5	6	7	8	9	average value
value of measuring:	1	5435	5435	5950	5682	5682	5952	6944	5952	6250	5920
	2	5952	5952	5682	5435	6250	7350	6944	7353	6944	6429
	3	5435	5952	6579	5682	5435	6250	7353	6944	6579	6245
	4	5952	5435	5682	5682	5682	6250	6250	5682	5682	5811
	5	6250	6250	6580	5682	6250	6250	7350	6580	6944	6460
	6	6250	6250	6250	6250	5952	6944	7350	6250	5952	6383
	7	6250	6250	5952	5435	6250	6250	7350	6944	6944	6403
	8	6590	6250	6580	6250	6250	6250	6250	5950	7350	6413
	9	6250	6250	6940	6250	6580	6580	6940	6580	7350	6636
	10	5680	5950	6250	6250	6250	6250	6940	6250	6940	6307
	11	6250	6250	5950	6250	6940	6580	6580	6250	7350	6489
	12	6580	5950	5950	5950	5950	6580	6250	6250	6580	6227
	13	6250	5680	5680	5950	6250	6940	6580	6940	6580	6317
	14	5950	5435	5580	5580	5950	6250	6580	5950	6940	6024
	15	6580	6940	6250	5580	6250	6940	6580	6250	6940	6479
	16	5950	5950	5440	5440	6250	6580	6250	7810	7350	6336
	17	6250	5950	5680	5950	6580	6580	6580	7350	6940	6429
	18	6940	5680	5950	6250	5950	6940	6250	6580	7810	6483
	19	5950	5950	5950	5950	5680	6580	6940	6580	6580	6240
	20	6580	5950	5950	6250	5950	6940	5680	6250	7810	6373
	21	6940	6250	6250	6250	6250	6250	7350	6940	7350	6648
	22	5440	5680	5680	5440	5950	6580	6580	7350	6580	6142
	23	5440	6250	6580	5950	6250	6940	8930	6250	7350	6660
	24	5680	5950	6580	5950	5440	6250	6580	7810	6580	6313
	25	5950	5950	7810	7350	6580	8330	8930	8930	8930	7640
	26	5950	5440	5680	5440	5950	6250	6580	6580	6580	6050
	27	5950	5950	5440	5440	6940	7810	6940	5950	8330	6528
	28	6940	6940	5950	5440	7350	8330	8330	6250	7350	6987
	29	6250	6590	5680	5440	6580	7350	6580	7350	7810	6626
	30	6250	5680	5440	5440	5680	6250	6940	6580	6580	6093
	31	6580	6250	5680	5440	6250	7810	6590	7810	7350	6640
	32	6940	5980	5680	5440	5950	6580	6940	6580	5950	6227
	33	6580	5680	5950	5680	5440	6580	6580	6580	5950	6113
	34	6250	5440	6250	5950	5950	6940	6940	7350	7350	6491
	35	6250	5440	6250	5950	5950	6250	6940	7350	7350	6414
	36	6580	6250	6580	6250	5680	6580	7350	6940	6580	6532
	37	6250	5440	6250	6940	5680	6580	7350	8930	7350	6752
	38	6580	5440	5440	5950	5680	6250	6250	6580	6580	6083

39	6940	6940	7810	6580	5680	6750	8930	7810	7810	7194
40	6940	6250	5680	6580	8930	7810	7350	6940	8930	7268
41	6590	5950	6940	6250	5950	6580	8330	7350	6940	6764
42	6250	6580	5950	5680	6944	7350	7350	6580	8330	6779
43	6940	6250	6580	5950	5430	7350	7350	6250	5950	6450
44	7350	6940	5680	5680	7350	7350	6580	6940	7810	6853
45	6250	5950	7350	6250	5680	6580	8330	6940	6250	6620
46	6250	5680	6250	6940	5680	6940	6940	7350	6580	6512
47	6250	6250	7350	6580	5950	6940	8330	6580	6580	6757
48	6250	6940	5950	5680	6940	8330	7350	6580	7350	6819
49	6580	5950	5950	5950	5950	6250	6940	7810	6580	6440
50	5950	5440	6250	6580	6250	6250	7350	7810	7810	6632
51	6580	6250	6580	6250	6250	6580	7350	7810	6580	6692
52	6250	5950	6580	6250	6250	6580	7810	6940	6940	6617
53	7140	6250	5680	6250	6250	6580	7350	7350	6250	6567
54	6250	6250	6580	5440	5680	6250	8330	6940	6940	6518
55	6250	5440	5680	6580	5440	5680	6580	7580	7810	6338
56	6410	6250	6410	5680	5950	5810	8620	7350	5950	6492
57	6940	6940	6250	6580	6580	6250	6580	7350	6580	6672
58	6940	5950	6100	5680	6100	6250	6250	6250	6250	6197
59	5950	5520	5680	5680	5560	5950	5950	6580	5680	5839
60	7350	6940	5440	5560	6940	7350	5680	5680	7560	6500
61	6760	5435	5950	6580	6940	6940	6250	6250	8330	6604
62	5950	5950	5560	5810	7810	6580	6940	6940	7140	6520
63	6250	6250	5950	6250	6250	6250	6940	7350	6940	6492
64	6760	7350	6250	5950	6580	7810	7810	6250	6410	6797
65	7140	7350	6250	5950	7350	8330	7580	6580	7350	7098
66	6250	6250	6760	6250	5950	6940	7810	5950	5950	6457
67	6250	6940	6250	5680	6250	6760	7810	6250	6250	6493
68	6250	5680	6250	6580	6580	6580	6760	5950	8330	6551
69	6580	6940	6580	6410	6250	6410	7140	7350	6410	6674
70	6250	6250	5440	6250	7350	6250	6760	6580	8330	6607
71	6250	5950	6940	6250	6580	6940	8330	5950	7350	6727
72	8330	6580	5680	5680	6580	7140	7350	6250	8060	6850
73	5440	5950	5680	5950	5680	6250	6580	6580	8930	6338
74	5680	6250	6940	5680	6250	7810	8930	6580	8930	7006
75	7810	5440	6580	6940	6250	6580	7350	5950	5680	6509
76	6250	6250	5950	6250	5950	7350	6940	7580	6580	6567
77	5440	5440	6580	7350	5950	5950	7810	6250	7810	6509
78	5950	5680	5950	5680	5680	7810	7350	5950	6580	6292
79	5950	6250	5440	5440	5440	6940	6940	6250	6250	6100
80	5680	6250	5440	5440	6250	6940	5440	5950	6940	6037

81	5440	6250	5950	5680	6580	6940	5950	6580	7350	6302
82	5680	5950	5680	5680	5440	6940	6580	6580	5950	6053
83	5560	5680	5440	5680	6250	7350	6250	5680	6250	6016
84	5440	5680	6250	5440	5440	6250	6940	5950	6580	5997
85	5440	5950	5680	5680	5440	5950	6940	5950	6250	5920
86	5440	7810	5950	5950	6250	7350	8930	7350	8930	7107
87	5950	5680	5660	5950	6250	5680	7810	6580	7350	6326
88	6250	6250	5950	6250	5680	6580	8340	6940	7810	6672
89	5680	6250	5950	5440	5950	7340	7810	7350	7350	6969
90	5680	5950	7350	5680	5680	6250	8330	8060	8330	68[illegible]2
91	5440	5950	6580	7580	5680	5440	6330	6250	8330	6620
92	5680	6250	5680	5950	6250	6250	7350	6580	7350	6371
93	5950	5950	6250	6250	5950	6940	6580	6580	7580	6448
94	6250	5950	5950	6580	6940	7[illegible]0	7810	7350	8330	6997
95	5680	5810	6760	6250	5950	6580	8330	7810	6940	6679
96	6250	5680	6250	5950	6250	7810	7350	7810	6940	6699
97	6250	5680	6580	6940	6250	6580	6940	8620	7810	6850
98	5950	5680	5950	5950	5950	6580	7810	6580	7810	6473
99	6250	5950	6250	5950	5950	6250	7810	6580	7350	6482
100	6250	5950	5810	5950	6940	7810	7810	7350	7810	6853
101	6580	6580	6250	6250	6250	6580	7350	8930	7350	6902
102	6580	5680	6940	5950	6580	6940	8330	8620	7810	7048
103	5950	6250	5680	6250	6250	7350	6250	6580	7140	6411
104	5950	5680	6940	5950	6580	6580	7810	76[illegible]0	7810	6790
105	5950	5950	5950	5950	5680	6250	6410	6760	6580	6164
106	5680	5440	5950	5440	6580	6940	6940	5950	6250	6130
107	5440	6940	6250	5950	7810	6940	8330	7350	6940	6883
108	5440	6940	6580	6580	7350	8330	8930	7810	8620	7398
109	8930	8620	8330	7810	7350	6250	6250	6580	7810	7548
110	7350	8330	7350	6250	8330	7350	8930	8330	7580	7756
111	7350	6250	6250	7350	6940	6940	6250	7350	6940	6847
112	5950	6580	7810	7350	7810	6940	8330	8330	8330	7492
113	5950	5950	6580	6940	6250	6580	6580	6760	7580	6574
114	5950	5950	5950	6940	6940	6580	7350	6760	7810	6692
115	5440	5950	6250	5950	5440	7140	7140	8330	6940	650[illegible]
116	5440	5950	6940	5950	5950	6940	7810	8330	7810	6791
117	5440	7350	5680	5950	7350	6940	7350	6580	8330	6774
118	5950	5950	5950	5950	6250	7810	6580	7350	7810	6622
119	5680	6940	5950	5950	5950	6940	7350	6940	6580	6476
120	5680	6250	6580	5560	6250	8620	7810	6940	6250	6660

121	5440	6580	5810	5810	6250	8330	8330	6580	6250	6598
122	5680	6580	5950	5680	6940	7350	8330	6940	6760	6690
123	5440	6250	6250	5950	5950	7810	7810	7810	6760	6670
124	5560	5950	6250	6580	5560	7810	7810	6940	6580	6560
125	5560	5680	6250	5950	5680	6760	8930	8330	7810	6772
126	6940	6250	7810	7580	6250	6760	8930	7350	7350	7247
127	5440	6580	7350	6250	6940	6940	7810	7810	7810	6992
128	5810	5810	5810	5440	5950	6940	7810	7810	7350	6526
129	5810	5950	6250	6100	6250	8330	6940	7350	7350	6703
130	5950	6250	6100	5950	6100	6940	6760	7140	6940	6459
131	5950	5950	6580	6940	6250	6940	6940	8930	8930	7046
132	6100	5950	7810	7140	5440	6580	7350	6940	7350	6740
133	5680	6580	5950	6250	7350	7350	8330	6940	7810	6910
134	5680	5950	6940	5950	5950	6580	7350	7810	8330	6727
135	5680	6580	7350	8330	6250	7350	8330	7350	8330	7283
136	5950	7350	7350	6940	6760	6580	8930	8330	7350	7282
137	5810	6250	6250	6940	6760	6580	6940	8930	6760	6802
138	6580	6250	7350	7810	7350	6940	7350	8330	8330	7366
139	5680	5950	6940	6760	6410	6580	6760	7810	7810	6744
140	5810	5680	6410	6250	5680	7350	6940	7140	6760	6447
141	6940	6250	6940	6580	6250	7350	7350	6760	7810	6914
142	6580	5950	6250	6410	6580	6580	6580	6940	7350	6580
143	6940	6250	7350	7350	6250	6940	7350	7140	7350	6991
144	5680	5950	6250	7810	5440	5950	6940	8930	6940	6654
145	5560	5680	6940	5950	5950	6760	7810	6580	6250	6387
146	5950	6100	6100	6250	5950	6940	6760	6940	7140	6459
147	6100	6250	5950	6940	6580	7350	6250	6940	6940	6589
148	6100	5950	6940	7350	5680	5950	7810	8930	6250	6773
149	6580	6940	6100	5680	6580	8930	7580	6580	7350	6924
150	6250	5440	6250	6580	6250	6940	6940	7810	7350	6646
151	6250	7810	5950	5810	6940	7810	7350	6580	7810	6923
152	5950	5950	6760	7350	5950	7140	6760	8330	6940	6792
153	5950	5440	6760	7140	5950	6250	6940	7350	7350	6570
154	5950	7350	6250	5560	8330	8060	8330	6250	7810	7099
155	6940	5560	7350	8930	6940	6580	7350	6410	8060	7124
156	6100	6760	5950	5680	7350	8330	7580	6250	7810	6868
157	6580	5810	5950	7580	6940	6100	7810	8930	8930	7181
158	5680	7810	5950	6100	7580	6580	7810	6250	7810	6841
159	6940	6580	6250	6580	8330	6940	8330	6940	7810	7189
160	5950	6940	6250	5440	8620	7350	7810	6580	8930	7097

161	6760	5950	7350	7810	5950	6250	8930	8330	8330	7296
162	7140	5950	7580	6940	5950	6250	8930	7810	8330	7209
163	5680	6580	6250	6100	7350	8330	8930	6580	8330	7126
164	5560	6250	6940	7810	5440	5680	8930	7810	7810	6914
165	6940	7810	5680	6250	6940	6940	7810	6940	8330	7071
166	6250	5810	6580	6410	5950	5810	7350	7810	8330	6700
167	6760	6760	6580	5440	7350	6940	8930	7140	8330	7137
168	5950	5560	5950	7580	6250	6580	7350	8330	7350	6767
169	6940	6250	6250	6760	5950	8330	7580	8330	7810	7133
170	6580	6250	6100	5440	5810	6410	6760	8620	5560	6392
171	6100	5950	5680	5810	5950	7140	7350	8930	6940	6650
172	5440	7140	6100	5680	6940	8330	8930	5950	8330	6982
173	5950	6940	6250	5810	5810	8060	8930	6580	7140	6830
174	5680	5680	6940	6580	6250	5680	8330	8930	8930	7000
175	5210	6580	5950	5810	5950	7810	8620	6410	7580	6658
176	6250	6250	5950	7810	6100	6250	8620	9620	8330	7242
177	5810	5810	5680	6580	5810	6940	7350	10420	8330	6970
178	5950	5950	5950	5950	6250	9620	7350	6940	7350	6812
179	5680	5680	5560	6580	6100	7350	6940	9620	8620	6903
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181	5950	6250	7580	7140	6940	6940	9620	6580	10420	7491
182	6580	6580	6100	6940	6100	6410	8330	8930	9620	7288
183	6250	5560	8060	6580	6580	6580	8930	9250	9620	7490
184	6580	11360	6250	6940	6940	6760	8930	6940	7810	7612
185	6100	5950	7350	7810	5950	6580	10000	6940	7810	7166
186	6580	6940	5950	5810	8930	7810	8930	6250	9620	7424
187	5440	5950	8330	5950	5440	6250	9620	8330	6940	6917
188	6250	6940	7810	7810	5950	6250	10870	8620	7810	7590
189	6410	6250	7810	7350	6250	5440	9620	6940	7350	7047
190	5560	6580	6580	5950	7350	10420	10000	8330	8930	7744
191	6940	6250	7810	5950	6250	6580	10420	6580	6940	7080
192	6250	6580	5810	5000	7140	8330	7140	6760	8330	6816
193	7810	5440	6940	7350	6940	7140	7140	10420	7350	7392
194	7350	8930	6410	7350	8930	11360	7810	7350	8330	8202
195	7810	8930	8330	7350	6760	7810	8930	11360	6580	8207
196	7350	7810	8330	10420	6580	8330	10000	9620	7350	8421
197	5950	7350	11360	7350	8330	7810	9620	9620	9620	8557
198	5680	8330	6580	7140	9620	15630	8330	9250	13890	9383
199	8330	8620	9620	8930	7350	7810	7810	14710	8930	9123
200	6250	7350	10420	8620	8930	8330	10870	11360	13890	9558

201	8060	10420	7350	10420	10420	10420	8930	7810	10420	9361
202	6940	10420	17860	13890	15630	11360	13890	27780	17860	15070
203	6940	6940	12500	8330	9620	8930	9620	10420	13890	9688
204	6580	9620	13890	10000	11360	8330	27780	10000	10000	11951
205	5680	8930	8060	7810	12500	13890	9620	10420	10420	9703
206	5810	8330	8930	8930	14710	11360	12500	15630	16670	11430
207	5680	7350	9620	9250	6940	10420	9250	16670	11360	9616
208	5440	7350	6760	6250	8330	10420	7810	8620	6940	7547
209	5950	9620	10420	12500	10000	7810	11360	9620	15630	10323
210	5950	6760	7140	7350	6940	7350	9620	8930	8930	7663
211	5440	7810	7350	6940	9620	10420	10000	8930	10420	8548
212	5560	7140	5950	5440	7350	9620	7810	7810	8330	7223
213	5680	8330	6760	5680	8330	10420	8930	7810	8930	7874
214	5320	5950	7350	6940	6250	8330	7810	11360	8930	7582
215	5560	6100	5320	6250	6250	7350	6940	7350	7350	6497
216	6250	5680	6760	6580	5320	5810	7810	6940	7580	6526
217	5680	6580	6580	5440	6940	8330	7810	6940	7810	6901
218	7350	7810	8060	6940	9250	7810	7810	7810	10870	8190
219	5810	5810	7580	7580	5680	6940	9620	9620	8330	7441
220	5560	5320	6580	6580	5320	6410	8330	7810	7350	6584
221	5680	6760	5680	5210	7350	9620	8330	6760	8330	7080
222	5140	6250	5680	5210	6410	8330	6940	6940	7350	6506
223	6580	6580	7350	6580	6250	7350	7580	12500	7350	7569
224	5810	5950	6580	7350	5950	7350	9620	10870	8930	7601
225	6100	6760	6250	5950	6940	8930	8330	8330	10420	7557
226	5950	8330	6940	6580	8330	13890	14700	9620	13890	9803
227	6580	9620	7810	6250	8930	17870	13890	6250	12500	9967
228	5440	8930	7140	6940	9620	15630	12500	7810	10870	9431
229	7350	6580	7350	8930	6940	6940	9615	7140	10420	7918
230	7350	6250	10420	9250	8330	7580	11360	11360	12500	9378
231	5560	6580	6250	6250	7350	7350	11360	8330	12500	7948
232	7350	6250	10870	9620	6580	7350	11360	10000	10420	8867
233	6250	8060	6250	6580	7350	8930	10420	6940	9620	7822
234	6250	6250	9620	7350	6580	6580	9620	10420	10420	8121
235	7350	7580	9620	6940	6250	7810	15630	10420	10420	9113
236	6940	7810	10420	10870	8940	7810	13890	8330	10870	9542
237	6580	7350	7810	7350	6580	6940	8930	10420	12500	8273
238	6580	8930	6250	7140	7810	8930	9620	7350	9620	8026
239	6250	6250	6940	5950	7140	11360	8620	7350	8330	7577
240	5950	7350	7810	8930	7580	11360	11360	6760	13890	8999

241	6100	7810	10420	7580	7350	7140	12500	7810	11360	8674
242	5680	7810	6940	7810	7810	7810	9620	7810	12500	8199
243	7810	13890	6940	7350	10870	8930	12500	6940	12500	9748
244	5950	6940	8330	8330	5950	5680	10420	10000	9620	7913
245	5680	6250	7810	7140	6250	7580	8930	10870	7350	7540
246	5560	6940	5950	5210	6940	7810	10000	5680	8930	7002
247	6250	6580	7810	6580	5680	6250	5950	9620	7350	6897
248	5440	6250	6580	6250	6940	8930	6940	6940	7810	6898
249	8330	6580	7810	6250	6250	6250	8930	6580	6580	7062
250	8930	8930	8760	6940	8330	10420	7810	7810	7140	8341
251	8930	10420	6940	11360	12500	13890	9620	9620	9250	10281
252	6940	7810	8930	8930	8330	6940	9620	8330	7350	8131
253	7350	7580	9620	7140	7810	8930	9620	7810	6940	8089
254	6250	7580	8330	8330	10000	9250	14710	11360	12500	9812
255	6250	8330	7140	6940	7140	7350	9620	6100	7580	7383
256	5680	9620	7810	6940	8330	10420	13890	8330	9250	8919
257	5950	6250	5440	5210	6580	7350	7140	6250	7140	6368
258	5810	6250	6410	5810	6940	9620	7810	6410	6760	6869
259	5810	6760	6250	6250	6580	10870	7810	6940	8930	7356
260	5950	5210	6250	5950	5810	6250	7810	9620	6940	6643
261	6580	6580	6940	6250	5950	7810	9620	7820	6580	7126
262	5950	6580	7580	6250	5950	6250	12500	6940	11360	7707
263	5320	5680	7140	6250	6250	5950	10420	7570	7810	6932
264	5950	6940	7140	6250	6940	11360	9620	6250	7140	7510
265	5440	6250	5950	5430	6940	7580	8330	6250	7580	6639
266	5440	5680	6760	5950	6250	5950	7810	7350	7810	6556
267	5680	5950	5950	7140	5320	6250	8930	7350	8620	6799
268	5950	5680	6940	5950	6250	6940	9620	7140	8930	7044
269	5810	5440	5950	5680	6580	10420	7350	7140	6580	6772
270	6250	5950	7810	7350	6250	6940	8330	7350	9615	7316
271	5680	5950	5680	5210	5440	6250	6250	6250	5950	5851
272	5440	5210	5210	5440	5210	6250	5320	6250	5680	5557
273	5320	5210	5210	5210	5210	8060	5680	5810	5000	5634
274	5440	5210	5560	5950	5210	5950	6250	6760	6250	5842
275	5440	5440	5950	5680	5440	6580	5950	6940	6250	5963
276	5210	5320	5680	5680	5210	6580	6580	6940	5950	5997
277	5440	5210	5440	5440	5440	5680	6250	6580	6250	5748
278	5440	5000	5950	5000	5000	6250	6940	7350	5210	5793
279	5680	5210	6250	5950	5680	6250	6250	7810	6250	6148
280	5440	5560	6250	6250	5000	5680	6940	8330	6250	6189

281	5440	5560	6940	5210	6250	7810	7140	6250	5950	6283
282	5560	5440	5210	5560	5440	5440	5440	6250	6940	5698
283	5680	6250	6250	5210	5680	6250	6580	6580	5680	6018
284	5320	5950	6580	5810	5680	6250	7140	6580	7350	6296
285	5440	5440	5440	5680	5540	6250	6250	5440	7350	5870
286	5210	5560	6250	6250	6250	6250	6580	6940	7350	6293
287	5440	6250	5950	5560	6250	5950	5950	6580	6940	6097
288	5680	5950	5950	5440	5680	5680	6940	5950	6580	5983
289	6100	5950	6580	5210	5680	6280	7350	5210	6580	6104
290	5320	6580	6250	5680	5320	5950	7350	5950	6940	6149
291	6100	5950	6250	6250	5440	5440	8330	6580	6940	6364
292	5680	5440	5950	5680	5550	5680	6940	7350	6580	6094
293	5440	5440	5000	5680	5950	6580	5680	5440	7810	5891
294	5680	5440	5000	5210	5000	5440	6250	6580	5950	5617
295	5210	5210	5440	5210	5000	5440	6760	6250	6580	5678
296	5440	5440	5210	5440	5440	6250	8330	6580	6580	6079
297	5440	5000	5320	5210	5000	6250	6250	6250	5680	5600
298	5210	5210	5000	5440	5440	6250	5950	6250	6940	5743
299	4810	5000	5000	5440	5680	6940	6250	5680	6940	5749
300	5000	5440	5440	5210	5210	6250	7350	6580	5950	5826
301	5100	6250	5950	5440	5440	7350	8330	6580	6250	6299
302	5440	5560	5950	5210	5000	5950	7580	8330	6250	6141
303	5440	5000	5000	5440	6250	7810	6940	6760	7810	6272
304	5560	5440	5210	5440	5680	6760	6250	6580	6580	5944
305	5680	5210	5000	5950	5680	5950	5950	6250	7350	5891
306	5210	5950	5000	5680	6250	6250	6940	5950	7350	6064
307	5210	5440	5680	5440	5000	5950	6580	8330	6580	6023
308	5000	5440	5950	6250	5680	5210	6760	6940	7350	6064
309	5210	5950	6250	5440	5680	7350	7350	5950	6940	6236
310	10120	7810	6580	6580	6940	6250	5950	7810	6250	7177
311	5520	5950	6580	5440	5440	5950	8930	6250	6580	6293
312	6580	7350	6250	5810	6580	8930	9620	6580	8330	7337
313	6250	5560	5950	5210	4810	5950	6250	5680	5440	5678
314	6250	5860	5210	6250	6940	6580	6250	7350	8330	6558
315	6250	5950	7810	6250	5680	6580	12500	8330	6250	7289
316	6580	5440	6940	7810	5950	6250	7810	11360	7580	7302
317	6250	5950	8330	6580	5320	6580	9620	7810	6250	6966
318	6580	6940	5680	5680	7810	8330	6940	6940	9620	7169
319	7810	5680	7350	6580	5210	5950	8930	6940	6580	6781
320	9620	6580	6580	6250	6580	6580	8330	8330	7140	7332

321	10420	6580	6580	6250	6250	6250	7810	7810	6940	7210
322	7810	6250	5680	5950	8330	9620	6760	5950	9620	7330
323	6940	5680	5440	5000	5440	5680	7140	5950	5950	5913
324	6250	5000	5950	5810	5000	5950	7350	6940	7350	6178
325	5950	5950	5210	5680	5950	6250	7810	5810	12500	6790
326	5950	6250	7810	7350	6580	7350	9620	8930	13890	8192
327	5440	5950	7350	7810	7560	8330	11360	7350	X	X

361	6250	6250	6250	6580	7350	9620	9620	9620	9620	7907
362	6250	6250	7810	7810	6250	6250	7810	7810	6250	6943
363	6250	6250	6250	6940	6250	8330	9620	9620	9620	7681
364	5680	5950	7810	7810	6580	8330	8930	8930	7810	7537
365	6250	7350	6940	6250	6940	10420	9620	8930	8930	7959
366	6250	6580	6250	6580	6940	8330	8330	8330	8330	7324
367	6250	6250	6250	6580	6250	8330	6940	8330	8930	7123
368	6250	6250	6250	6250	6250	6940	8330	8930	7350	6978
369	6250	6250	6250	6250	6250	8330	9620	8330	9620	7498
370	6250	6250	6250	6940	6250	6580	8330	9620	8330	7200
371	5950	5950	6940	6580	6580	7810	9620	9620	9620	7630
372	6250	6250	5950	7350	6580	7350	8330	8930	9620	7401
373	6250	6940	6580	6250	8330	9620	9620	8930	8330	7872
374	6940	6250	9620	6940	6250	6250	8330	8330	7350	7362
375	6250	6250	6250	6250	6250	8330	6940	6940	7350	6757
376	6250	6250	6250	6250	6250	6580	7350	7810	7350	6704
377	5680	6250	6250	6250	5680	7350	10420	9620	7810	7257
378	6250	5680	6250	6250	5950	6580	8330	8930	8330	6950
379	7350	9620	7810	6940	9620	9620	9620	9620	9620	8869
380	5680	6940	6940	6250	6580	7350	9620	9620	8930	7546
381	6250	9620	9620	8330	6940	8930	12500	8930	10420	9060
382	6250	9620	8930	8330	7810	9620	10420	9620	9620	8913
383	6250	5950	6580	6580	6940	6940	7810	8330	8930	7146
384	6250	6940	8330	6940	7350	7810	9620	9620	8330	7910
385	7350	8930	10420	10420	7350	8930	10420	17860	10420	10233
386	6250	5950	6580	6580	6580	6940	7810	9620	9620	7326
387	6250	5950	5950	5950	5440	5680	7350	6250	6250	6119
388	6250	5680	5680	5680	5680	6250	7350	6250	6940	6196
389	6250	5950	5950	6250	6250	6940	7810	6250	6940	6510
390	6250	5950	5950	6250	6250	6250	6940	7350	7350	6504
391	6250	6250	6580	6250	6250	6250	8930	7350	8330	6938
392	6250	6250	6580	6250	6250	6250	8330	7350	7810	6813
393	6250	6250	6580	5950	5950	6940	8330	8330	8330	6990
394	6250	6250	6250	5950	5950	7810	8330	8330	7350	6941
395	7350	8330	8330	9620	7350	9620	9620	8930	8330	8609
396	6250	6250	6580	6580	6250	7810	8330	8330	8330	7190
397	6250	5950	5950	6250	6940	6940	7810	9620	8930	7182
398	6250	6250	6250	5680	7350	8930	8330	7350	9620	7334
399	6250	6250	6250	6580	6580	8930	8930	9620	9620	7668
400	6580	6250	6250	6250	5210	6250	6580	8930	6940	6582

measuring no. :	1	2	3	4	5	6	7	8	9	average value
value of measuring:										
328	6760	7350	8330	8330	6410	9620	8930	9620	9620	8330
329	6410	8930	8930	8930	9620	9620	9620	8930	8930	8880
330	6940	9620	9620	9620	9620	8330	8930	8930	8330	8882
331	6580	8930	6580	6940	8330	8930	9250	8930	9620	8232
332	6580	6940	8330	8330	7350	8930	8930	9615	9620	8292
333	6580	8930	7350	6940	9620	9620	8930	7350	9620	8327
334	10000	6580	8330	8930	6940	8330	6940	6940	6940	7770
335	6940	8930	8330	7350	9250	9620	8930	8930	9620	8656
336	6940	9620	9620	9620	8930	8330	9620	9620	10000	9144
337	7810	6940	9620	8330	8930	8930	8930	9620	8930	8671
338	6940	9620	9620	8930	8930	8930	9620	8930	9620	9016
339	8330	9620	7350	9620	8930	9620	8930	7810	9620	8870
340	6580	6250	6250	6250	6250	6250	6250	6250	7810	6460
341	6250	7350	8930	8330	8330	8330	8930	8930	8930	8257
342	9250	8330	9620	8930	7350	7350	7810	9620	8930	8577
343	6250	8330	6250	6940	9620	9620	8330	8930	8930	8133
344	6250	7350	9620	7350	8330	7350	8930	8930	9620	8192
345	6250	6580	5950	6250	6250	8930	8330	7350	6580	6941
346	6250	6250	6580	6250	6580	7810	8930	9620	6940	7246
347	6250	6250	6940	6580	6250	6940	7810	7810	8330	7018
348	6250	6250	6250	7350	6250	6250	6940	8930	6940	6823
349	6250	6250	6250	6250	6250	8330	6940	6940	6940	6711
350	6250	6250	6940	6940	6250	6250	8330	8330	6250	6866
351	7810	6250	9620	8930	8330	7350	9620	9620	9620	8572
352	7810	7350	8930	6250	6580	7350	9620	9620	9620	8126
353	7350	9620	6940	7350	9620	7810	9620	7350	8930	8288
354	6580	6580	6250	6250	6250	8930	8930	6250	8330	7150
355	6250	6250	6250	6250	6250	7810	7810	8930	7810	7068
356	6250	6250	7350	7810	6580	7810	9620	9620	9620	7079
357	6250	6250	6250	7350	6940	7350	7350	8930	9620	7879
358	6250	6580	7810	7810	7350	8330	8330	9620	9620	7967
359	6250	6250	6250	6250	6250	7350	6940	6250	6940	6526
360	6250	6580	7810	6580	6250	7810	9620	7810	8930	7516

DEUTSCHE UHRGLASFABRIK GMBH

DEUTSCHE UHRGLASFABRIK GMBH Postfach 100 3223 Delligsen 2

Schott Optical Glass Inc.
York Avenue

Duryea, Pennsylvania 18642

USA

Attn. Mr. W.G.Wash

SCHOTT DURYEA
FEB 13 1978
ANSWERED | FILE

3223 Delligsen 2
Fernruf: Delligsen (0 51 87) 7 50 61
Telex 92 950 dewug d
Drahtwort: Uhrglasfabrik Grünenplan
Bahnstation: Alfeld (Leine)

Ihre Zeichen | Ihre Nachricht vom | Unsere Zeichen VUU/LSp | Datum 6.2.78

Solar Collector Mirrors - Order T 3015

Dear Mr. Wash,

With reference to our today's telex please find enclosed the complete list for the following 96 bend glasses measured on 9 points to your convenience. One copy is sent to Mr. Schuma as well.

Yours faithfully

Deutsche Uhrglasfabrik
G.m.b.H.

i.A. Krause

Encl.

401	6580	6580	6250	6250	6940	10420	7810	6580	8330	7304
402	6580	6940	6250	6250	6250	6250	6940	6250	6580	6477
403	6250	6250	6250	6250	6250	6580	6940	6580	6580	6437
404	6250	6250	6250	6250	6250	8330	6250	6250	6250	6481
405	6250	6250	6580	6940	7350	8330	6940	6940	7350	6992
406	6940	6250	6580	6940	7560	9620	7810	6580	6940	7247
407	6250	6940	7350	6580	6580	7810	7812	7140	6250	6968
408	6250	8330	6250	6940	7350	7140	8930	6940	8330	7384
409	6940	6250	6250	7350	6410	7810	6250	8930	7350	7060
410	6940	6250	6250	7350	6250	8330	6250	8930	7350	7100
411	6250	6250	6250	6250	7140	8330	7810	7350	7140	6974
412	6250	6760	6250	6580	6940	6940	6940	9620	8330	7179
413	6940	7350	6250	6250	7350	9620	7810	6940	8330	7427
414	6250	6250	6250	6250	6580	9620	6940	6250	7350	6860
415	6580	6940	6250	6250	6940	8930	7140	6580	6580	6910
416	6250	6250	6940	6580	6250	6940	7350	7810	7350	6858
417	6580	6250	6250	6580	7350	7810	7350	6250	9620	7116
418	6250	6250	6940	7350	7350	7810	7350	7350	8930	7287
419	6580	6250	6250	6580	7350	9250	6940	6940	7140	7031
420	6250	6580	6250	6580	6250	7350	6940	7350	7140	6743
421	5000	6250	6250	5000	6250	11360	8330	7350	8330	7124
422	6250	6250	6250	6580	6250	9620	9620	6250	8330	7267
423	6250	6940	6940	6940	6940	9620	8330	7350	7350	7407
424	6250	6250	6250	6250	6250	9620	7350	9620	9620	7496

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