

GA-A13926

CONCEPTUAL DESIGN OF A DEMONSTRATION
FIXED-MIRROR SOLAR CONCENTRATOR

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FINAL REPORT

General Atomic Project 2099

May 28, 1976

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1. INTRODUCTION

1.1 GENERAL

The work reported herein was done under a joint program sponsored by Arizona Public Service Company, Southern California Edison Company, and Utah Power and Light Company. The work was proposed by General Atomic Company (GA) on December 18, 1974, and the contract authorizing the work was released on July 1, 1975.

This report presents a conceptual design and discusses the features of a fixed-mirror solar concentrator demonstration prototype unit (FMSC Demo). The FMSC Demo is a length of FMSC typical of what could be used for a solar power plant. The principles of the FMSC are discussed in Ref. 1 and a plant using this concept is discussed in Ref. 2.

The FMSC Demo features a mirror unit, 200-ft long with a 21-ft-wide aperture, and a traversing heat receiver assembly (HRA), suspended from a beam mounted on six support arms.

1.2 PURPOSE OF THE FMSC DEMO

The FMSC Demo is intended to demonstrate with representative hardware the performance of a solar power plant design based on the FMSC concept.

The conceptual design is of a single mirror trough and HRA. The mirror aperture width represents what may be used for a power plant, but of course a plant would comprise many such mirror units. Similarly, although the production and construction methods of parts would be different, the design is typical of a power plant.

The design of an economically viable solar power plant is a continuing effort at GA so the final design of the FMSC Demo differs from the conceptual design presented here.

1.3 THE CONTEXT OF THE FMSC DEMO

The many aspects of FMSC power plants are being studied at GA. The conceptual design of the FMSC Demo uses data and design ideas from related study programs. Among these are:

1. ERDA contracts to explore designs and construction methods for full scale, fully developed n^{th} (production) plants. This study is for organizing and comparing alternative designs and construction techniques of components such as the mirror trough, the HRA, its support and drive system, and the headering systems for the heat transfer fluid. The first phase of this work is reported in Ref. 3.
2. An EPRI-funded effort to develop the method for a system analysis of a 100 MW(e) solar power plant. This computer model will represent the major subsystems of the plant by the use of analytical expressions. The model will be used to make sensitivity studies of performance and cost that will assist in making selections from many design parameters.
3. A hardware-oriented study that is complimentary to the FMSC Demo design is being conducted for the Sandia Corporation. This unit has a smaller mirror aperture width than the FMSC Demo and lends itself to mirror construction from precast concrete sections assembled in the field. After the practicality and size limits of this field technique have been evaluated, it may find wider applications.

Results from these and other studies for particular projects will be factored into the final design of the FMSC Demo. The purpose of the FMSC Demo will be to test and demonstrate solar power plant hardware.

2. THE DESIGN

This section describes two conceptual designs of the FMSC Demo. The designs are based on concrete-mounted mirror strips. General arrangement and details of the alternative designs are shown in Figs. 1 through 13. The designs incorporate some work done for other FMSC contracts and from GA-funded efforts.

2.1 THE MIRROR UNIT OPTICAL DESIGN

The reference design mirror is 200-ft long with a 12-ft radius and an arc of 120 deg. The resulting aperture width is 20.8 ft, which yields a concentration factor (including secondary concentration) of about 50.

The mirror unit is made up of flat mirror strips running the full length of the FMSC Demo. The mirror strips can be mounted on concrete or on pairs of tensioned cables. When concrete-mounted, 89 mirror strips 3-in. wide are arranged around the 120-deg arc. The cable-mounted version uses 67 mirror strips, each 4-in. wide.

2.2 STRUCTURAL DESIGN

The 12-ft-radius mirror, being a typical (but not necessarily optimum) size for a power plant, is an appropriate size for demonstrating the conceptual design. The simple mechanical design can be scaled to a variety of large sizes for anticipated power plant designs.

Two concepts for mounting the mirror strips were selected for further study in the subject design. They are:

1. Mounting the mirror strips in a concrete-lined ditch.
2. Mounting the mirror strips on pairs on tensioned cables.

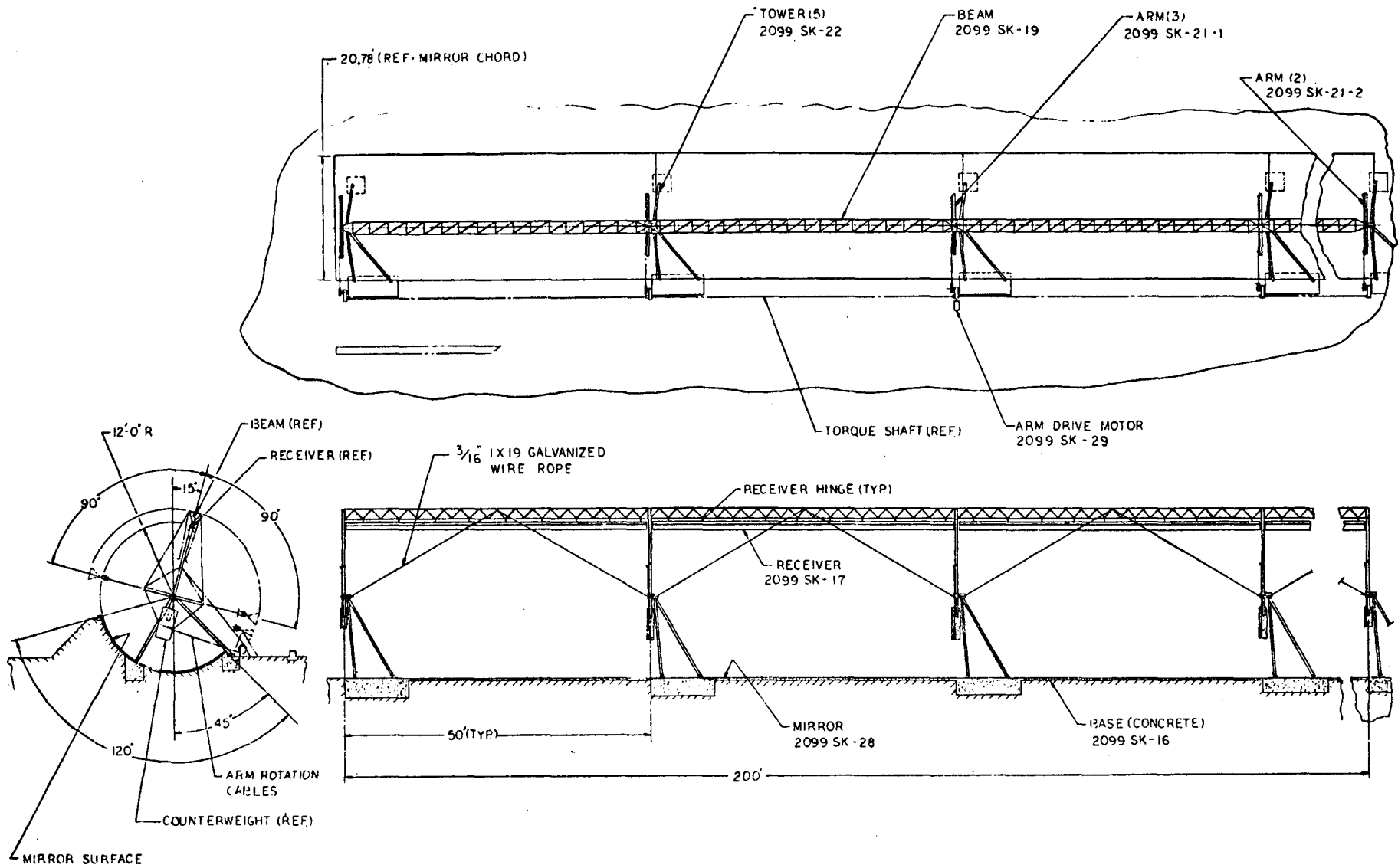


Fig. 1. FMSC Demo with concrete-mounted mirrors

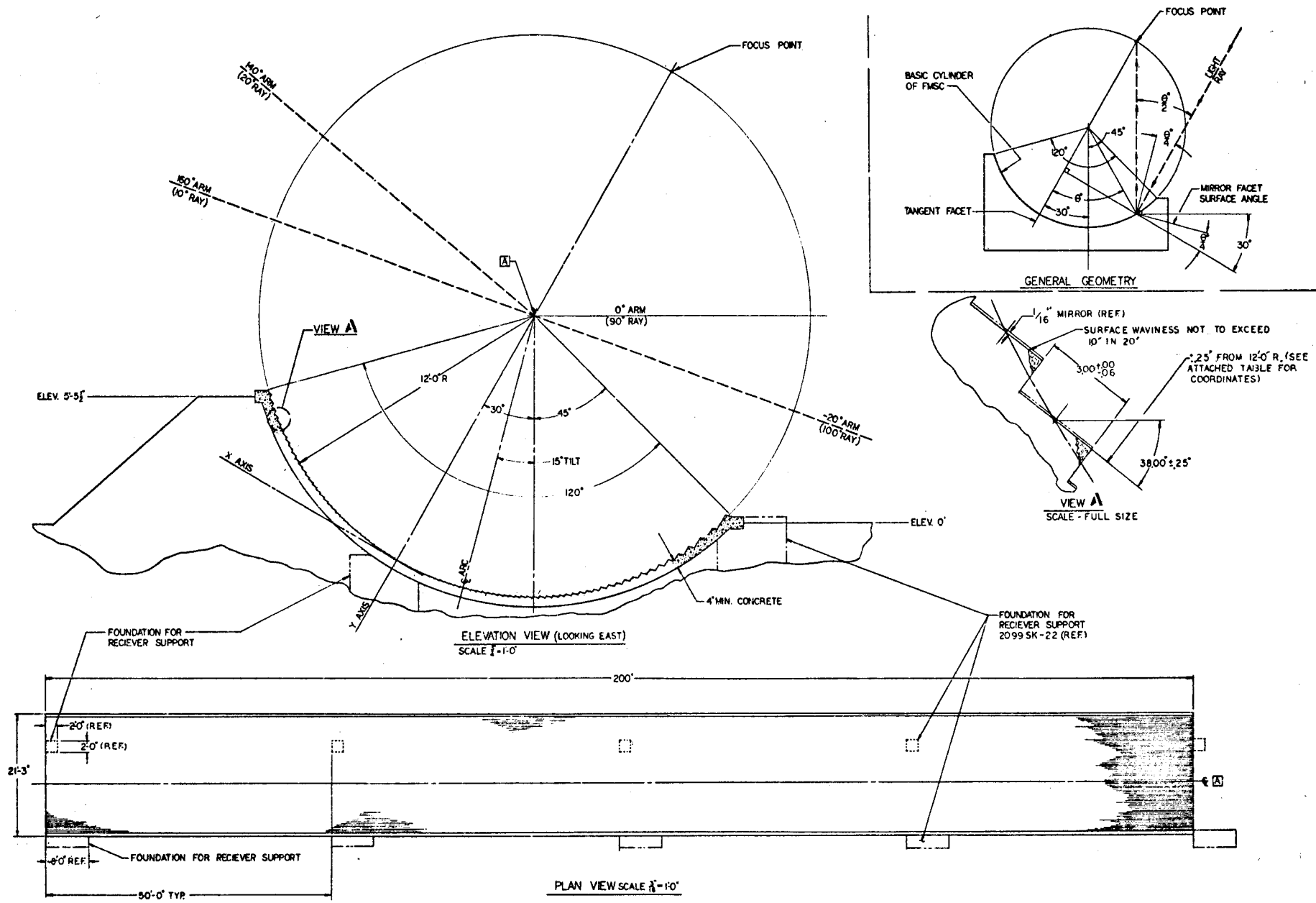


Fig. 2. FMSC Demo concrete-mounted mirror base

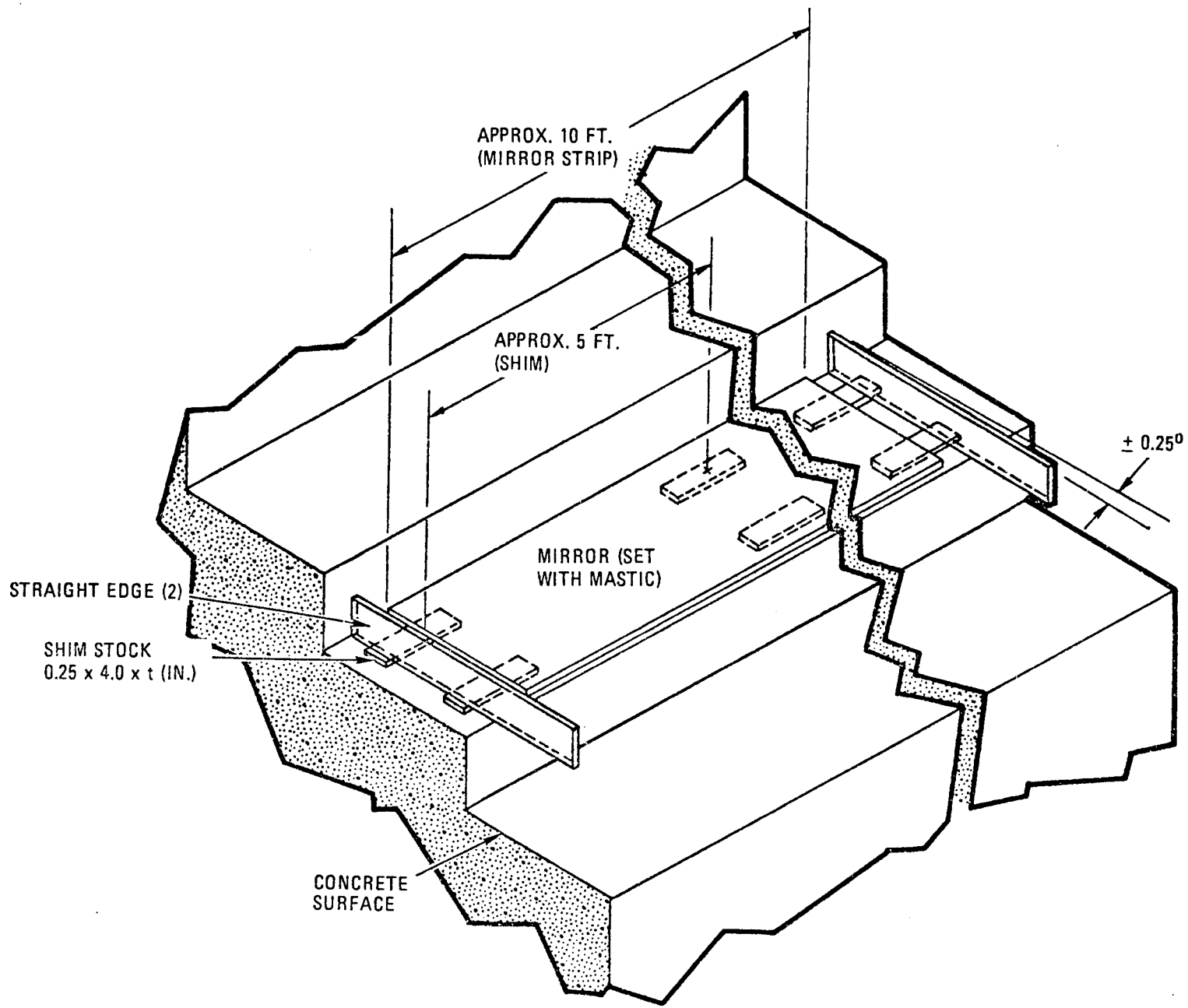


Fig. 3. Shim-aligned concrete-mounted mirrors

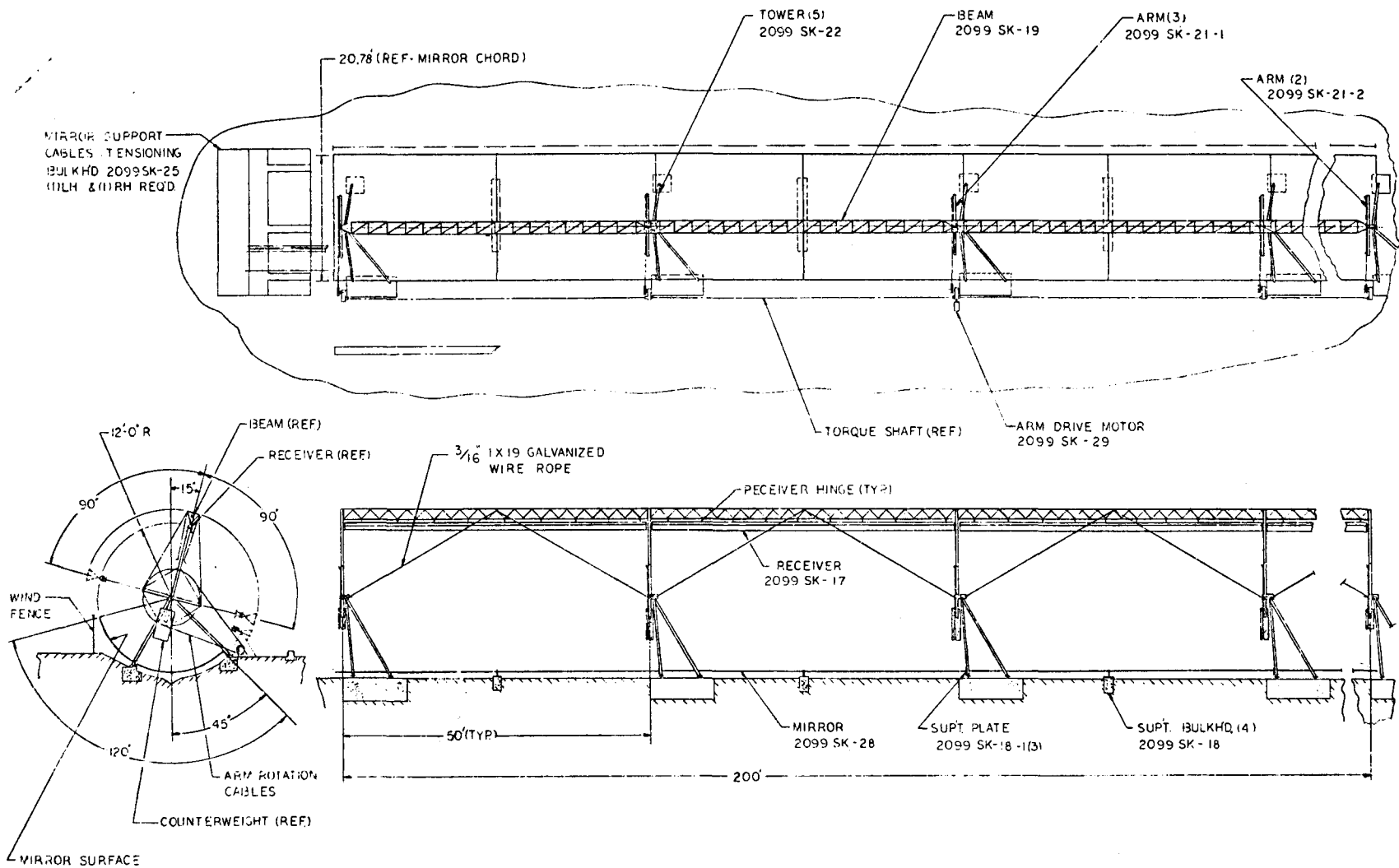


Fig. 4. FMSC Demo with cable-mounted mirrors

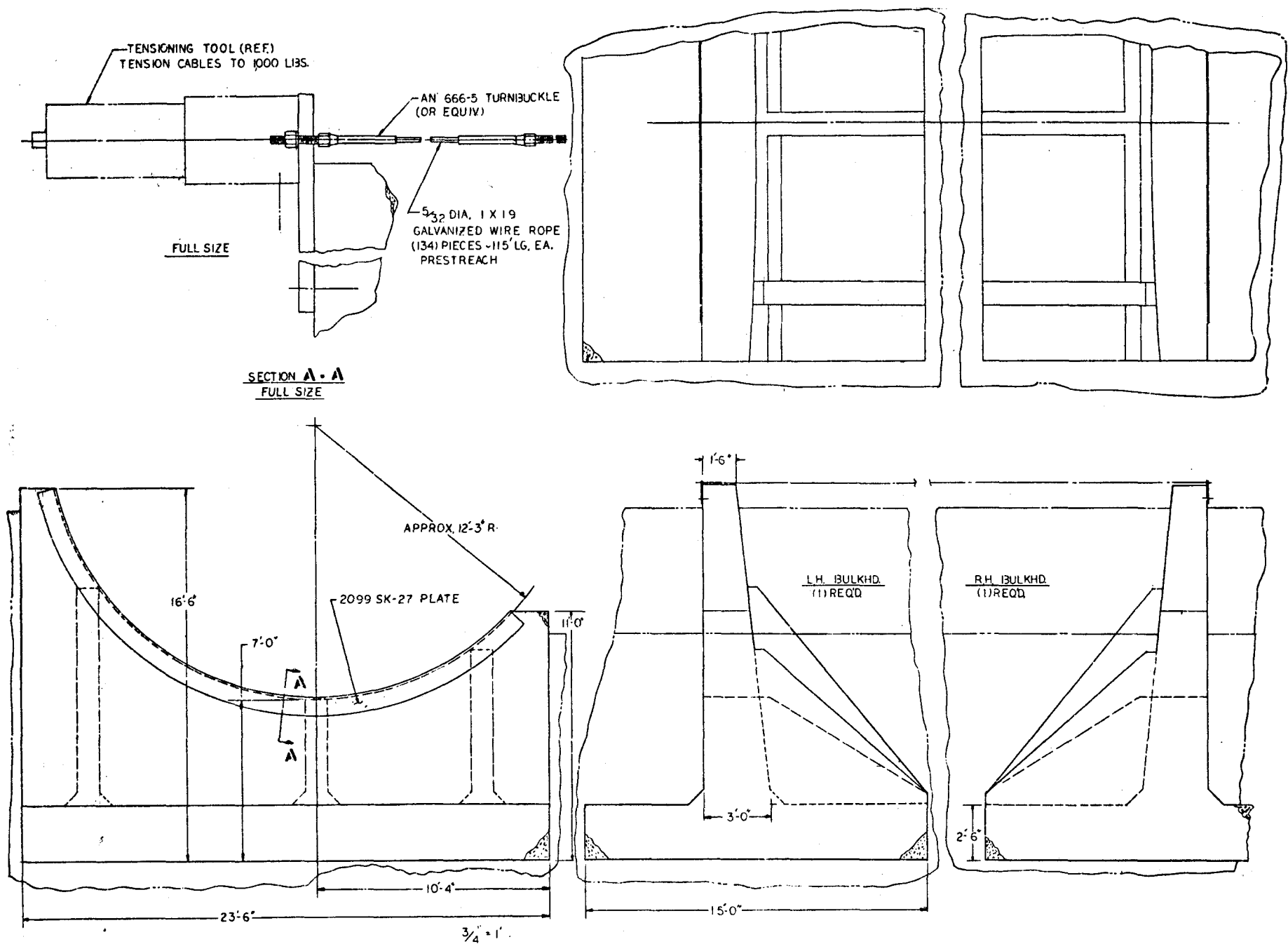


Fig. 5. FMSC Demo cable-tensioning end

Fig. 6. FMSC Demo cable support

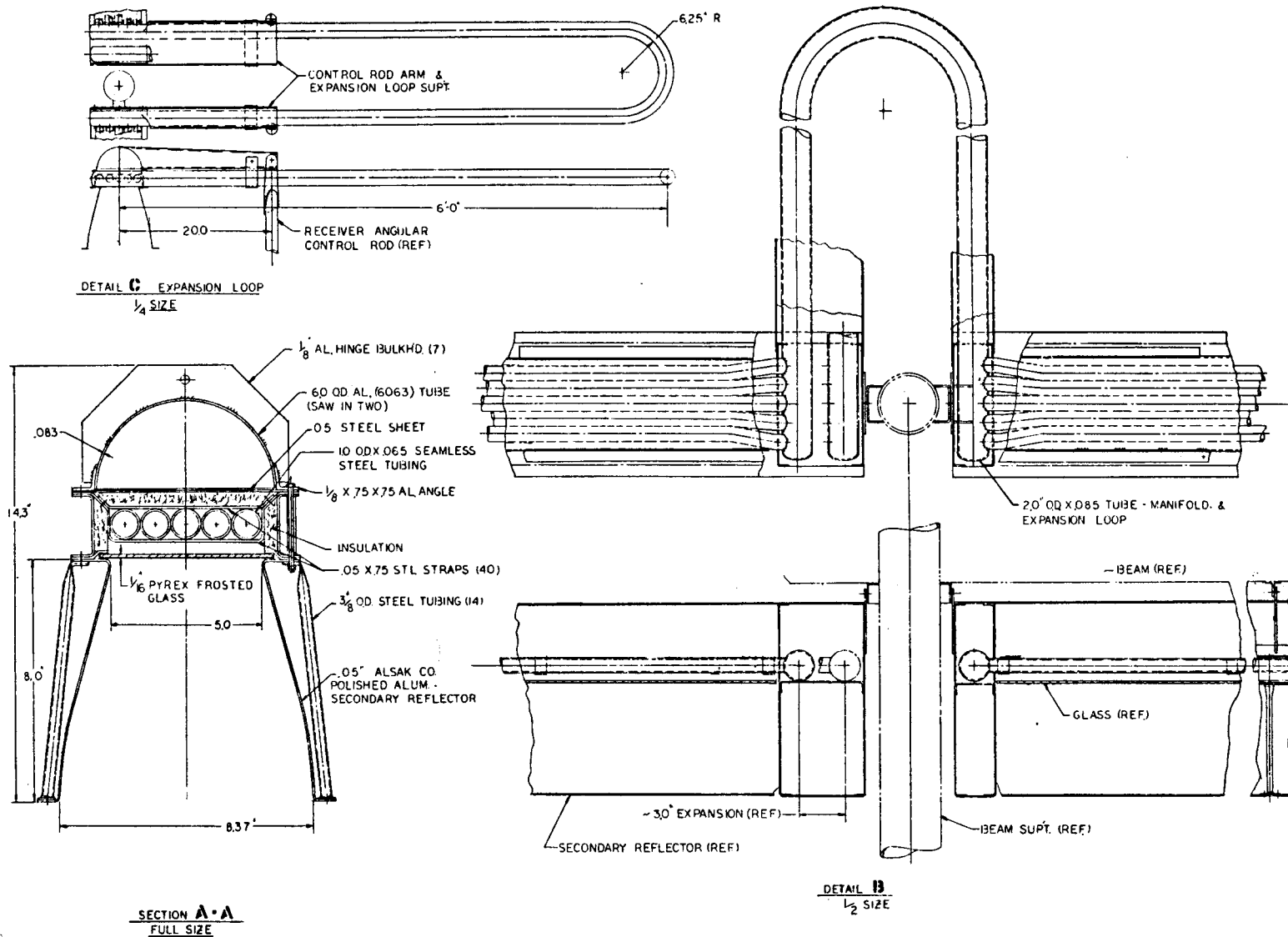


Fig. 8. FMSC Demo HRA

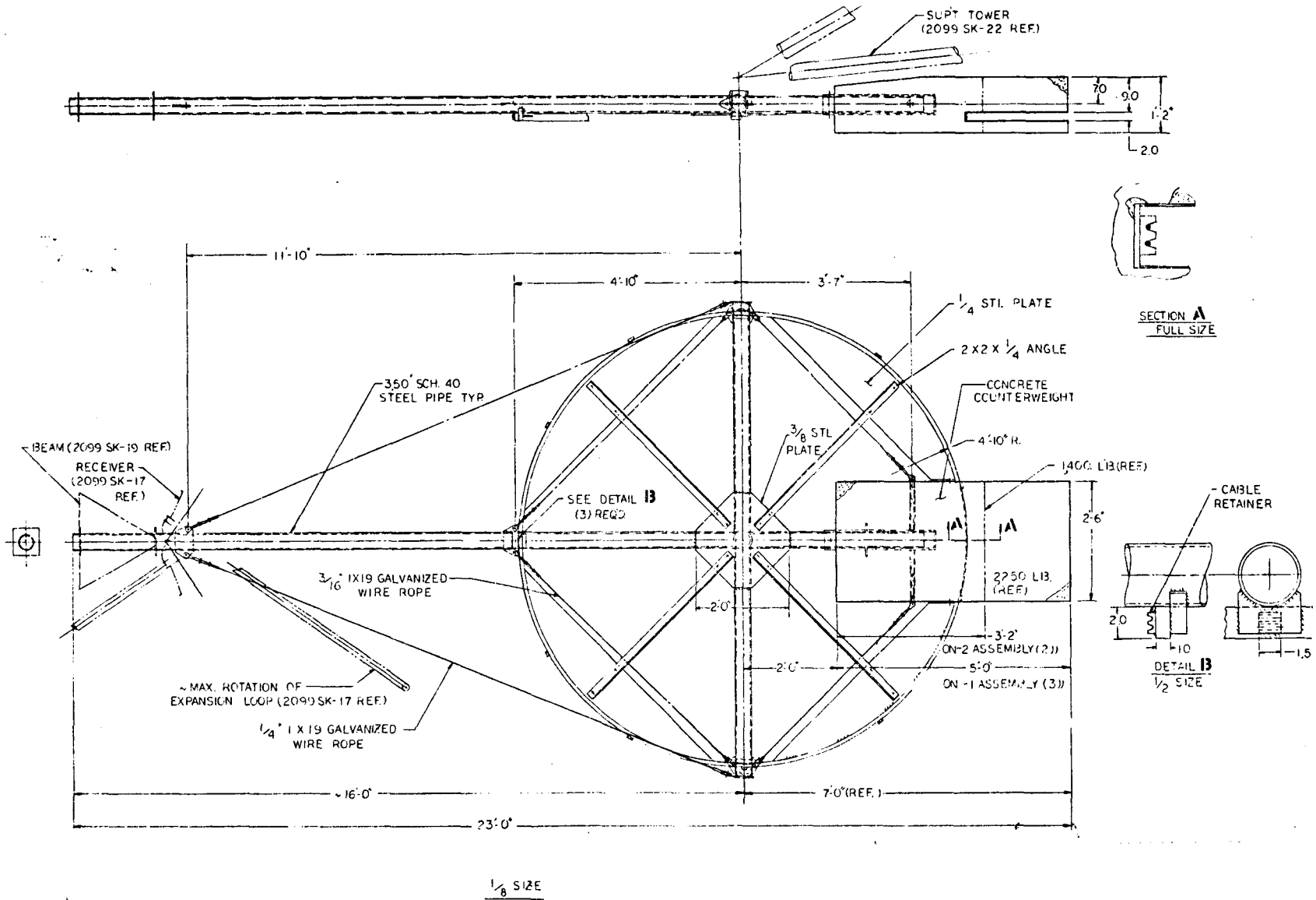
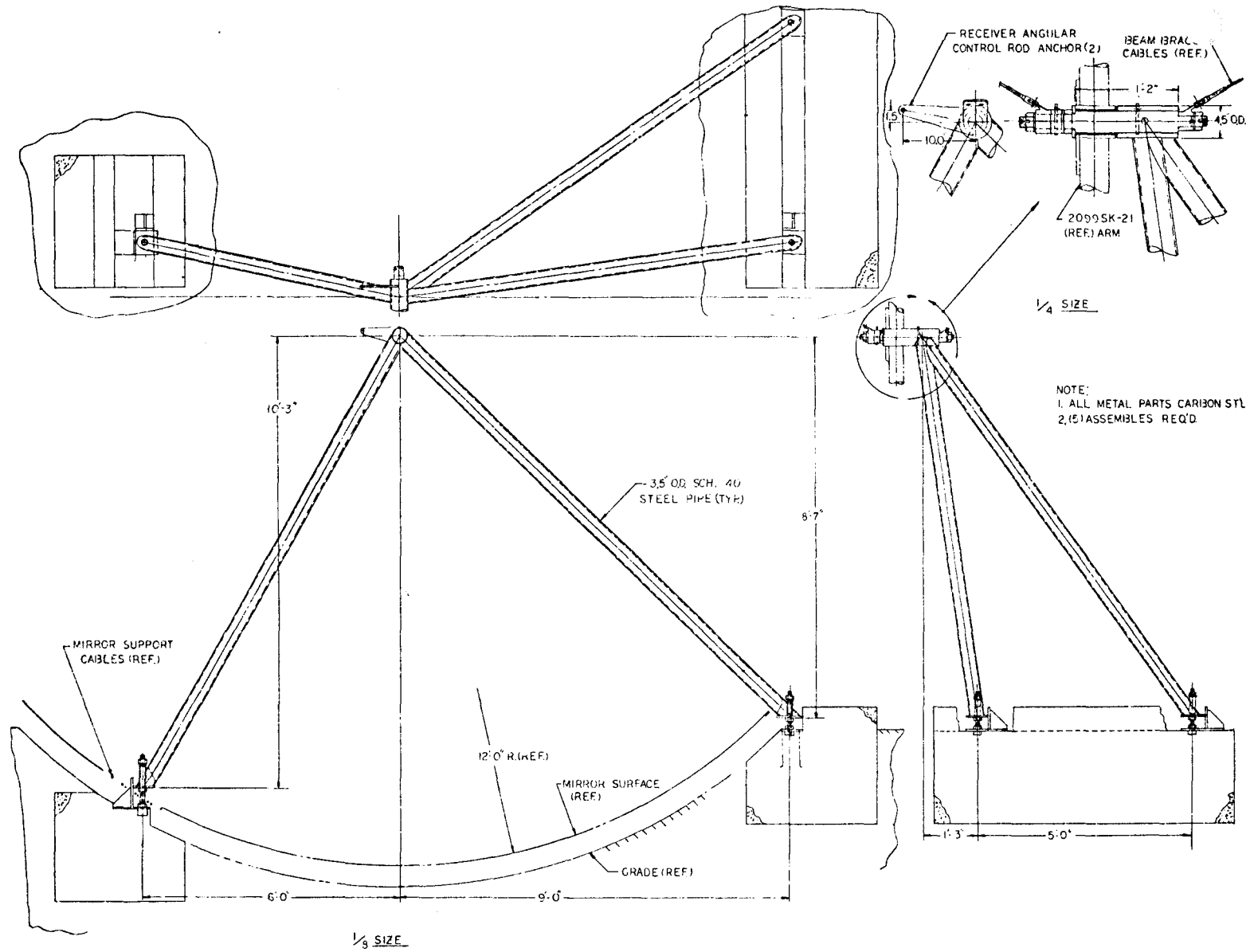


Fig. 9. FMSC Demo HRA support beam

Fig. 10. FMSC Demo beam support tower



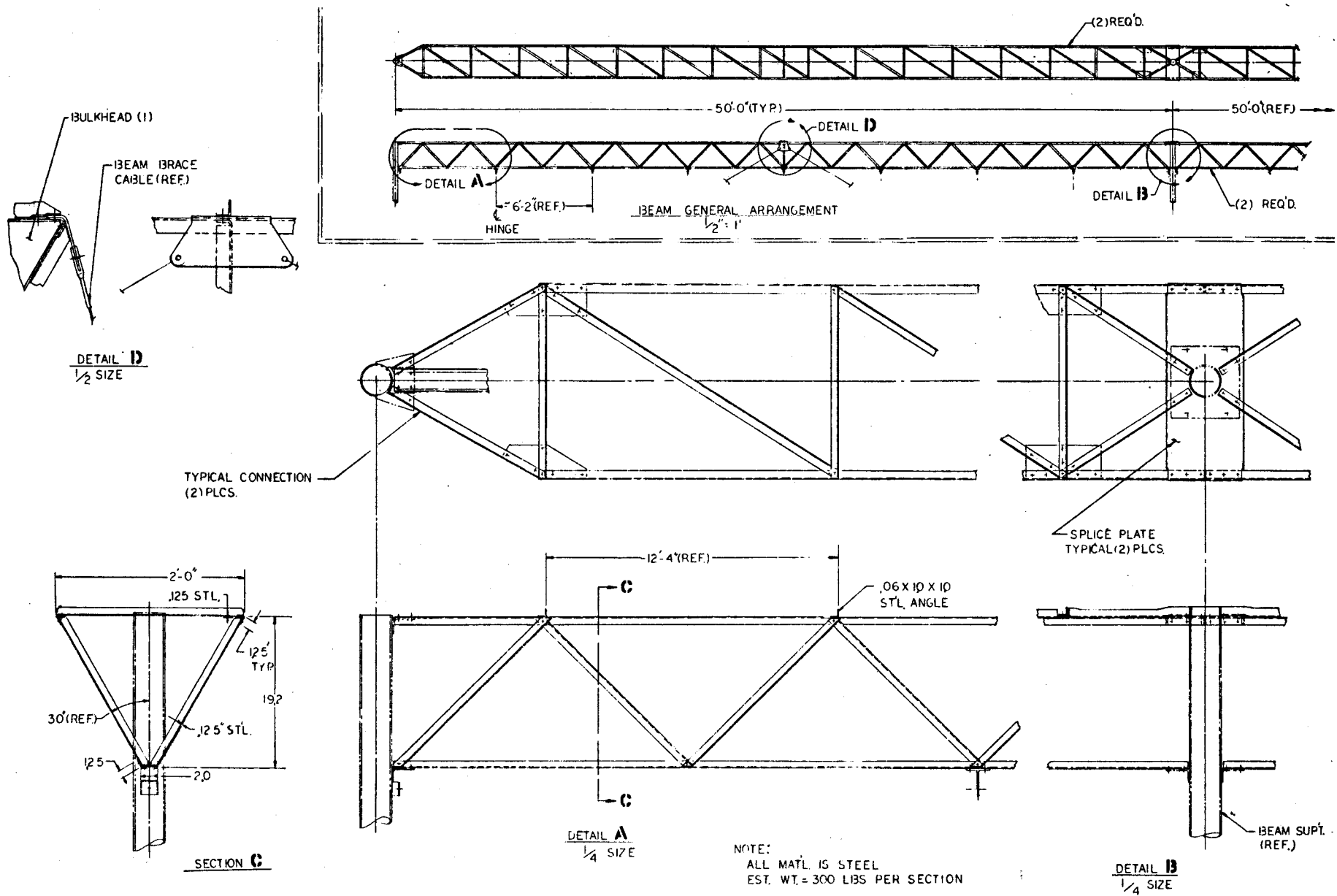


Fig. 11. FMSC Demo HRA beam support

SOLAR CONCENTRATOR GENERAL ARRANGEMENT
SCALE $\frac{3}{16}'' = 1'$

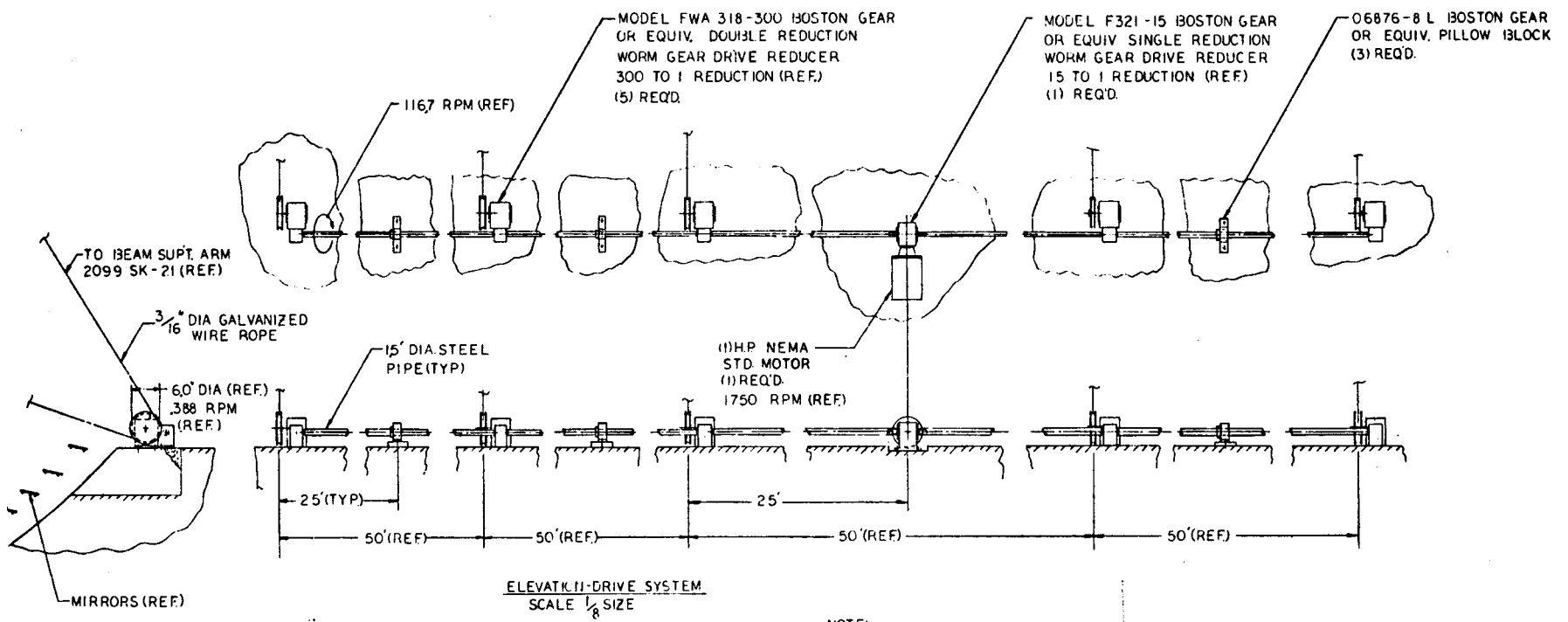
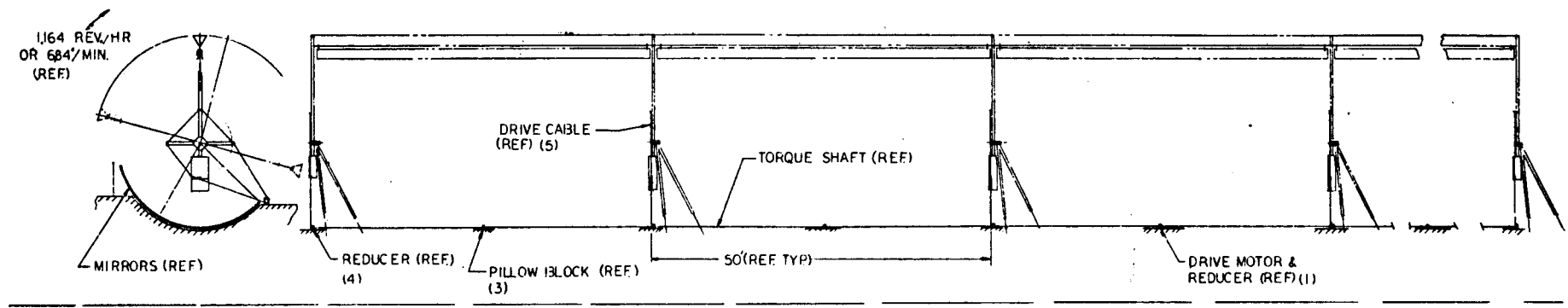
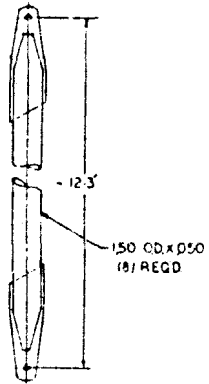
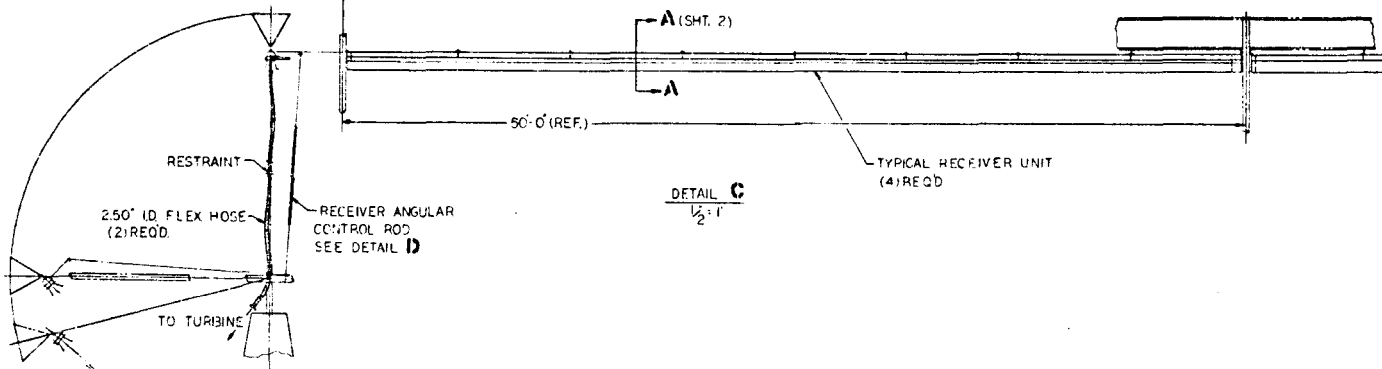
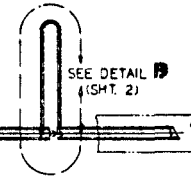
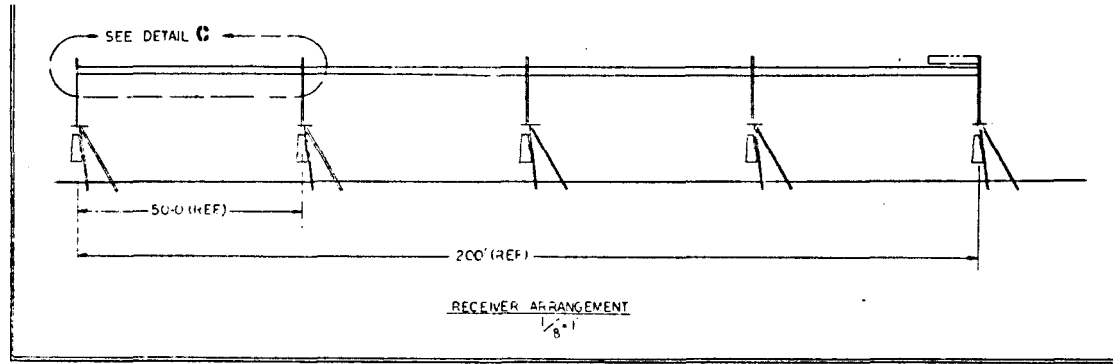


Fig. 12. FMSC Demo beam rotation actuator

Fig. 13. FMSC Demo receiver



DETAIL D
1/2 SIZE



Both concepts have inherent advantages, but they also have disadvantages that have not yet been resolved. The concrete-lined ditch makes a stable bed for the mirror strips, but questions of large-scale production methods and long-term earth stability have not yet been adequately addressed. Mounting the mirror strips on pairs of tensioned cables promises to be economic, but the method cannot be adopted until more is known about their stability and strength during crosswinds. The design criteria are to limit torsional oscillation to 0.25 deg in 25-mph winds and to survive 100-mph winds.

2.2.1 Concrete-Mounted Mirror Strips

The general arrangement of the FMSC Demo using concrete-mounted mirror strips is shown in Fig. 1. A plan view and cross section of the concrete-lined trough is shown in Fig. 2. The 3-in.-wide mirror strips mount directly on steps in the 4-in.-thick concrete liner. The mirror strips, in lengths of about 10 ft, are displayed on a 120-deg arc of a basically cylindrical surface of 12-ft radius.

2.2.1.1 Construction Techniques. General Atomic is studying what the best construction technique for a full-scale plant, one that will allow accurate mirror strip placement for the minimum cost, will be. For the concrete-mounted mirror version of the one-of-a-kind FMSC Demo, we plan to use the construction and mirror mounting technique described below.

A cut-and-fill procedure will be used to excavate a trench. Material from the trench will be used to build up the north side of the trench. The treatment of the ground and fill material during this operation will depend on the soil composition. It is likely that the fill material used to build up the north side of the trench will be compacted and stabilized by mixing with cement or fly ash (to form a soil cement).

Foundation footing ditches for the HRA support tripods will then be excavated and a final cut made to form the cylindrical profile of the trench. A metal form to produce the steps in the concrete for mirror mounting will be placed over a 10-ft length of the trench and aligned to normal civil

engineering standards of 1/8 in. in 10 ft. Concrete is pumped into the cavity between the floor of the trench and the form. After setting the concrete, the form is moved over another section of the trench and the procedure is repeated.

Two forms probably will be adequate to make the 200-ft FMSC Demo mirror bed. By alternately moving one form while the other remains in place for concrete setting, construction time can be reduced.

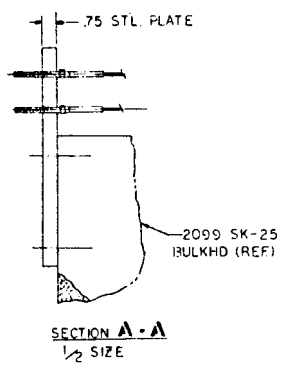
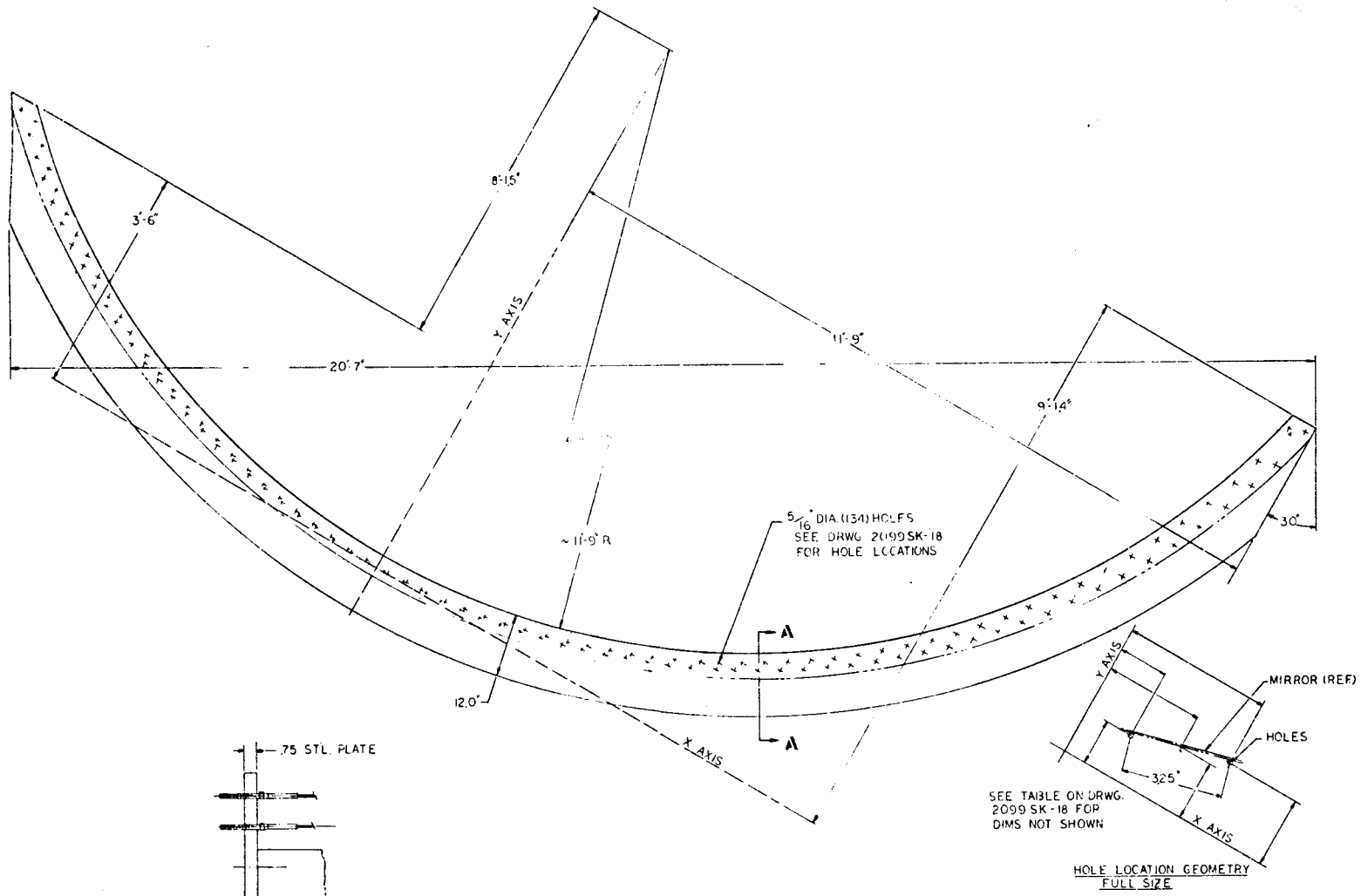
2.2.1.2 Placing Mirror Strips on Concrete. After the concrete bed is set and the forms removed, the flashes and form-parting marks are ground off. The concrete surfaces are then accurate to 1/4 in. in 10 ft, which is satisfactory for mirror placement. The concrete step surfaces are not, however, expected to be within $\pm 1/4$ deg tolerance along their long axes, which is required for mirror positioning. The required angular accuracy of mirror placement will be achieved as follows.

At 5-ft intervals along each step in the concrete, pairs of shim strips will be placed as shown in Fig. 3. One of each pair is placed along the edge of the step and the other near the riser. The shim thicknesses will be selected so that straight edges placed on them transverse to the step length are aligned to the required angular tolerance. A mastic will then be applied to the concrete between the shims, mirror strips applied, and weighted down over the shim stock until the mastic sets.

2.2.2 Cable-Mounted Mirror Strips

Figure 4 shows a general arrangement of the FMSC Demo with the alternative method of mounting the mirror strips on pairs of tensioned cables. The cables run the full length of the prototype and are anchored at each end to massive concrete cable tensioning bulkheads as shown in Fig. 5. At 25-ft intervals the cable is supported by sheetmetal bulkheads as shown in Figs. 6 and 14. The mirror strips mount on the cables by clips such as those shown in Fig. 7.

Fig. 14. FMSC Demo anchor cable plate.



2 PIECES REQD.

A simple experimental program was undertaken at GA to determine the best combination of cable type, size and tension, mirror thickness, distance between cable support bulkheads, and mirror attachment methods. The design presented is based on 1/10 in.-thick glass mirrors clipped to 5/32-in. diam cables, tensioned to 1000-lb force, and supported at 25-ft intervals.

2.3 HEAT RECEIVER ASSEMBLY (HRA)

2.3.1 Thermal Performance

The HRA shown in Fig. 8 was designed to maximize the amount of solar radiation transferred to the heat transfer fluid and minimize thermal losses from reradiation and convection. The heat transfer fluid is carried in five side-by-side pipes to increase the pipe surface area presented to the incoming light. The pipes are insulated on three sides to reduce heat losses and the remaining side is covered with frosted glass plate. The glass allows sunlight to enter the receiver, while reducing convective heat loss from the pipes. Frosted glass reduces reflective losses. The pipes are coated with a selective black chrome to increase their performance by reducing their thermal emissivity.

A secondary concentrator increases the concentrating ability and efficiency of the system. Secondary reflector surfaces increase the secondary concentration factor to approximately 1.6.

2.3.2 Mechanical Design

This is a compound parabolic concentrator designed by A. Rabl in cooperation with R. Winston. The glass, secondary reflectors, and heat receiver pipes fasten to a sheetmetal box framework. This box is insulated to minimize heat loss from the back side of the heat receiver tubes. Narrow steel support straps spaced along the pipes position the pipes within the box while allowing for reflective differential expansion. To minimize conduction heat loss, the mounting straps may require thermal isolation where they are attached to the sides of the box.

2.4 HRA SUPPORT

Each HRA is 50-ft long and is suspended from a support beam and main rotating arm. At each end of the HRA, the heat receiver pipes are welded to a 2-in.-diam manifold. The coolant mixes in the manifold as it flows through a loop, giving a uniform temperature entering the next heat receiver pipe downstream. With coolant mixing every 50 ft, hot spots in the heat receiver pipes are almost eliminated. Mild steel pipes could expand almost 3 in. in a 50-ft section when exposed to 700°F temperature differential. The present design uses a 6-ft long U-shaped expansion loop to take up the thermal expansion. Alternatively, a double loop or a coil, which might take up less space, could be used. Expansion bellows and flexible metal hoses were also considered but were discarded because they were more expensive and less reliable than simple expansion loops.

The entire HRA is suspended from the support beam along its length by pivots, as shown in Figs. 1, 8, and 9. The pivots allow for a total of about 110 deg of angular rotation of the assembly relative to the support beam. For maximum sunlight collection, the assembly must rotate so that the centerline axis of the secondary reflector points at about the midpoint of the mirror arc at every operating position of the rotating arm. For every 2 deg of arm rotation the HRA should rotate only 1 deg. A satisfactory approximation of this motion is shown by the angular control rod and heat receiver rotation arm in Figs. 8 and 13. The top end of the control rod attaches to a pivot point at the outboard end of the rotation arm. The bottom end pivots near the center of the mirror surface arc. This causes the HRA to rotate about 1 deg about its pivot for every 2 deg of rotation of the main arm about the mirror arc centerline. At main arm positions far from the neutral point, the motion becomes more curved. This desired motion can be obtained by choosing the position of the fixed pivot point and the length of the control arm.

Wind loading on the HRA is an important design consideration. The assembly is fully operable in winds up to 30 mph, above which a storm condition is assumed to exist, prohibiting solar concentration. The assembly

is movable in wind speeds of 50 to 60 mph but need not meet sun-tracking requirements. About about 60 mph, the assembly will be feathered to a stationary position near the ground. Feathered it will survive in winds of 100 to 120 mph. The exact wind design speeds will depend upon site location and more detailed design considerations. Wind loads on the assembly could reach 15 to 20 lb/ft² of frontal area at wind speeds of 60 mph. These loads tend to make the assembly rotate about its pivot point, as can be visualized from Fig. 8. This torsion is resisted by the force of the HRA angular control arm upon the rotation arm. The HRA framework box is designed to withstand the resulting torsion. In addition, the secondary reflectors and the heat receiver angular control rod and arms are designed for these wind loads.

Most of the basic design is quite similar to the full-scale plant being designed under an ERDA contract, but it should be noted that the prototype uses a 12-ft- rather than a 20-ft-radius mirror.

2.4.1 The Support Beam

The HRA suspension shown in Fig. 1 consists of a steel support beam formed as a triangulated truss. Its concept is similar to that of an open-web steel roof joist. As shown in Fig. 11, this beam consists of three trusses joined along their chords to form a triangular shape in end view. This shape gives good beam strength and deflection characteristics in all directions of load application, with relatively low weight and cost.

The beam ends are fastened to the end of the long pipe of the main rotating arm, which is described in Section 2.4.3. The HRA is suspended from the bottom of the beam on pivots mounted periodically along the beam. Deflection limits severely restrict the allowable span of the support. It must be extremely straight between towers to keep the heat receiver pipe accurately aligned along the focus line. An open-web steel joist appears to be the lightest and least expensive beam available. For a given beam geometry and unit loading, beam deflection increases as the fourth power

of the span. The dead weight of the beam alone is a critical factor. For these reasons, the beam span is limited to between 50 and 60 ft for an economical design; spans much greater than 100 ft are impractical.

For preliminary design purposes, a standard steel floor or roof joist was used, although this may not be the most efficient joist for this condition of high loading. A 24H7 joist, 24 in. deep and weighing 11.5 lb per linear foot, was selected. Three such joists can, in concept, be redesigned and formed as previously described into a triangular section in end view. If a single common joist chord is used at each apex, a triangular-section joist weighing about 25 lb per linear ft can be made. This joist would cost about \$10/ft, based on \$0.40 per lb. This represents a reasonable cost of about \$0.50 ft² of mirror aperture. This beam design requires further detailed work.

2.4.2 Heat Receiver Support Towers

As discussed, the main support beam and HRA are positioned about the surface of the mirror cylinder by a large rotating arm having its center of rotation at a bearing supported by the tower at the mirror arc center. The tower and rotating arm are shown in Figs. 9 and 10. The support tower shown consists of a tripod formed on three pieces of pipe anchored in the ground, giving stability in all directions. The main bearing for the rotating arm is mounted at the apex of the tripod as shown in Fig. 10. With the tower designed as a tripod, the legs are loaded primarily not as beams but as columns. This greatly reduces both the size of the tower members and the tower cost.

2.4.3 Heat Receiver Rotating Arm

The main rotating arm, which positions the HRA, is shown in Fig. 9. This arm rotates about the center of the mirror arc in a bearing mounted to the apex in a cruciform. The pipes are stabilized in this position by wires connecting adjacent pipe ends, forming a triangulated, rotating structure.

This concept was chosen for much the same reasons that pipes were selected for the tower design. The cruciform design permits the overhanging load of the HRA and support beam to be carried through the rotating arm without inducing bending moments in the arm members. Guy wires react all loads into column forces in the pipes. The short pipes are about 2.5 in. in diameter, and the long pipe is about 3.5 in. in diameter in a noncounter-weighted design. By eliminating bending stresses, the size, weight, and cost of the arm members are greatly reduced.

The beam supporting the HRA is fastened to the end of the long pipe of the cruciform as shown in Figs. 9 and 11. The counterweight is at the opposite end. The counterweight is carefully attached and guyed to avoid inducing bending moments in the cruciform members. The counterweight in the prototype keeps the arm balanced in any position. This stability is needed because of the frequent testing, debugging, disassembly, and assembly of various parts such as drives and heat receiver pipes. For a full-scale plant, it is not yet clear whether the additional complexity and cost of the counterweight design are justified.

2.4.4 Rotating Arm Drive

The arm is rotated by cables as shown in Fig. 1. The cables are guyed around the short arms of the cruciform and terminated near the midpoint of the long pipe. The cables thus exert a pull at the extremities of the cruciform, putting only column loads, and not bending stresses, into the rotating arm members. In addition, by pulling a point of large radius, they reduce the arm rotation cable tensions and minimize the winch loads. Figure 12 shows an arm drive motor and a torque shaft (not yet designed in detail) running the full 200-ft length of the prototype. This mechanical system assures coupling of all the rotating arms and eliminates the need to electronically synchronize the motions of the arms.

Wind forces with a component in an axial direction along the mirror arc centerline will tend to load the rotating arm in this direction. If unrestrained, this side load on the long pipe of the cruciform will induce

bending stresses and column buckling failure in the pipe. Thus, diagonal guy wires are placed as shown in Fig. 1. The wires run from the rotating-arm-bearing centerline diagonally to a point at the midspan of the HRA support beam. The triangulated wires thus take the moderate end loads placed on HRA.

2.4.5 HRA Flexible End Connections

The duct connecting the HRA to the fixed headering system must accommodate two operational motions and differential expansion movements. The assembly rotates over a range of about 90 deg on each side of the traverse arm centerline. The traverse arm moves over a range of about 180 deg relative to the fixed headering system. The paths of motions are illustrated in Fig. 15.

Flexible metal hose at each end of the heat receiver pipe eliminates the disadvantage of sliding surface joints and hermetically seals the heat transfer fluid system. These hoses have been proved in service under a wide range of operation conditions. They are very reliable provided their minimum radius of bend is generous. In operation, they are not subjected to torque.

Tests were made on a specimen of 2-1/2 in. i.d. braided metal hose in a rig simulating the design shown in Fig. 15, plus another configuration. A 4-ft-long hose accommodated angular movements over a range of 210 deg (as in Fig. 15) with internal pressures of zero and 400 psig. For long life, a 6-ft length would be used for this application. Figure 16 shows the tests in progress. The lower photograph shows a test condition with the radius of bend below the minimum recommended; this gave the hose a permanent set. The specimen later withstood a proof-pressure test of 400 psig, which is five times the maximum working pressure.

A further development is to use one continuous hose from the HRA to the headering system, eliminating two flanged joints. Whether a single hose or a pair of hoses is used at each end of the HRA is mainly a cost

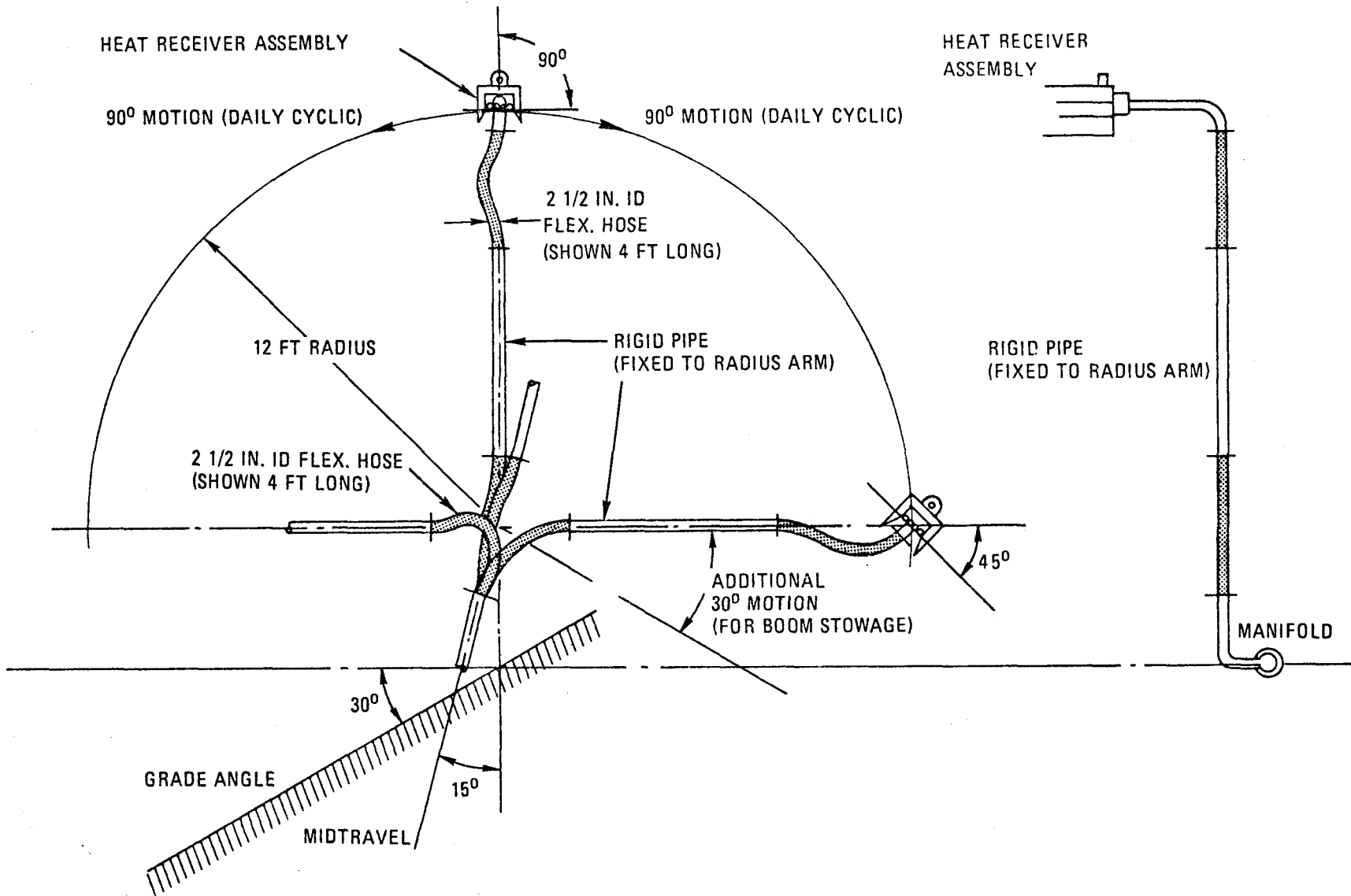


Fig. 15. Motion of HRA

Fig. 16. Flexible metal hose test arrangement



consideration. A sketch of a single hose connecting the HRA to the headering system is shown in Fig. 17 and a model of this design is shown in Fig. 18. This model demonstrated the large-bend radii of the hose in any operating position. The hose is guided at its midlength by a loose-fitting yoke.

2.5 BALANCE OF PLANT

2.5.1 Heat Transfer Fluid Circuit

The heat transfer fluid circuit is shown diagrammatically in Fig. 19. It operates at pressures between zero and the few psig caused by circuit flow resistance. The circuit is hermetically sealed, so leakages will be negligible.

The heat transfer fluid is a commercial organic fluid. It is heated to about 650°F in the HRA and from there is ducted to a cooler and cooled to about 350°F. The fluid then proceeds via a surge tank and a flow-measuring orifice to a pump that circulates the fluid back to the HRA. The bypass loop around the heat exchanger allows for warm-up. The flexible metal hoses at each end of the HRA accommodate the HRA motion relative to its support arms and the support arms relative to the fixed ducting.

The cooler is a commercial once-through fan-cooled oil-to-air heat exchanger. From the cooler, the fluid passes through a 40-gal. surge/expansion/header tank, which incorporates a pressure relief valve, and a standard ASME flat-plate flow-measuring orifice.

The fluid then enters a single-stage circulation pump. The standard process pump handles fluid at up to 650°F, which allows it to operate during a transient if the oil cooler is bypassed and the heat receiver is at maximum temperature.

The oil cooler can be isolated by inlet and outlet valves. Another valve is fitted to the cooler bypass line, which is normally closed but

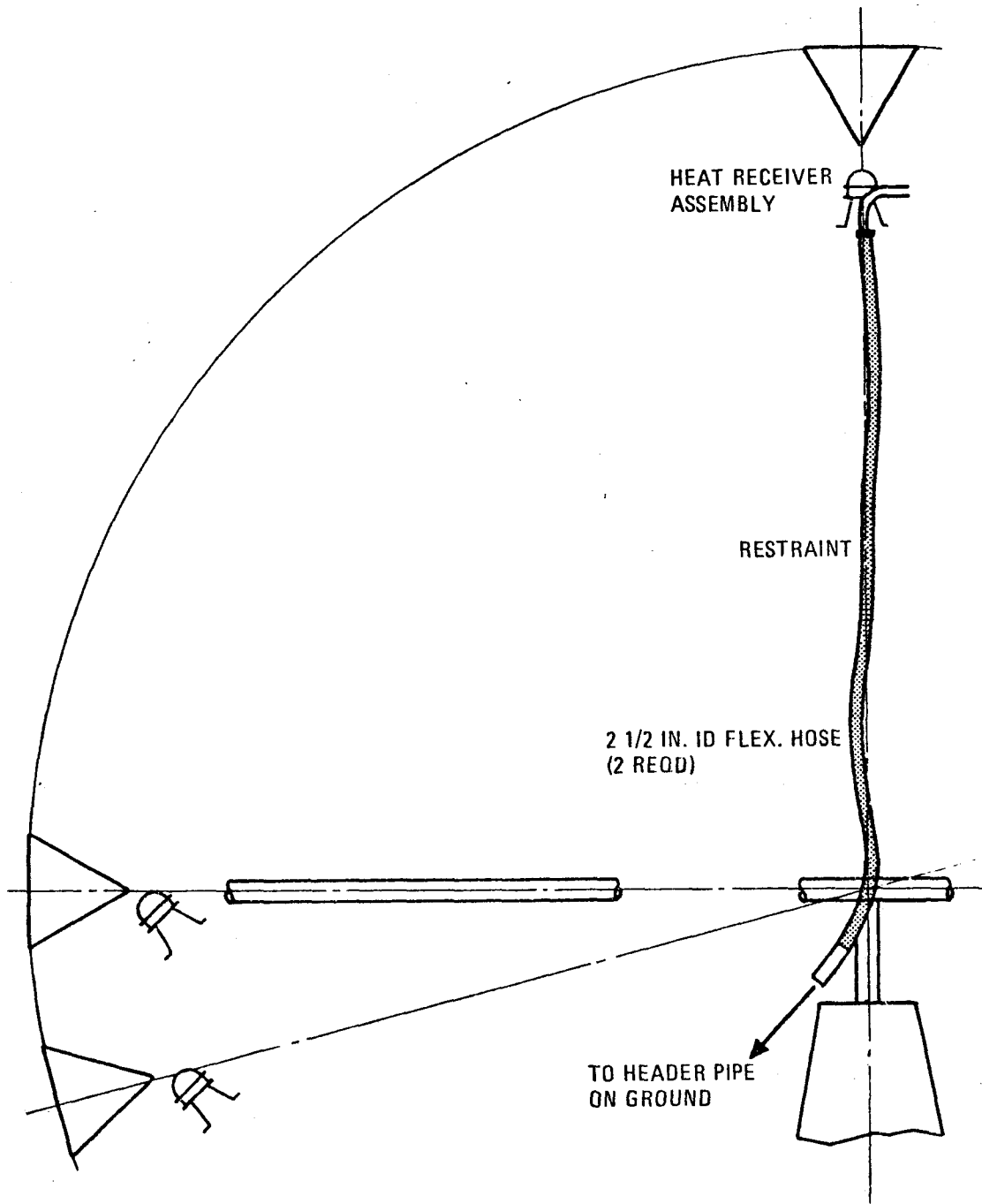
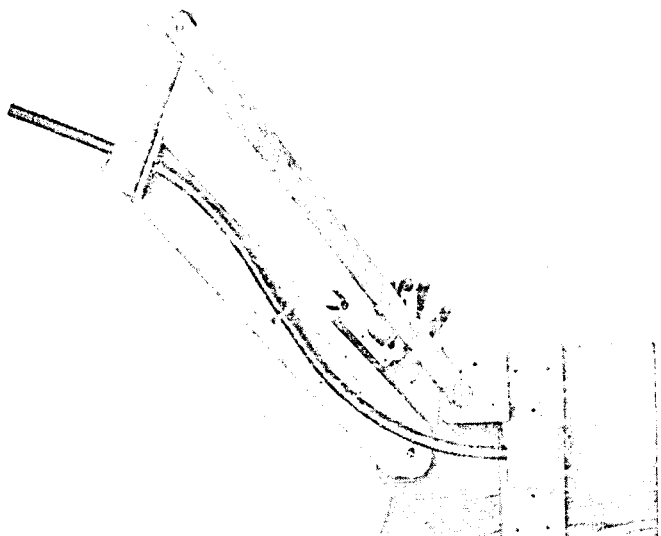
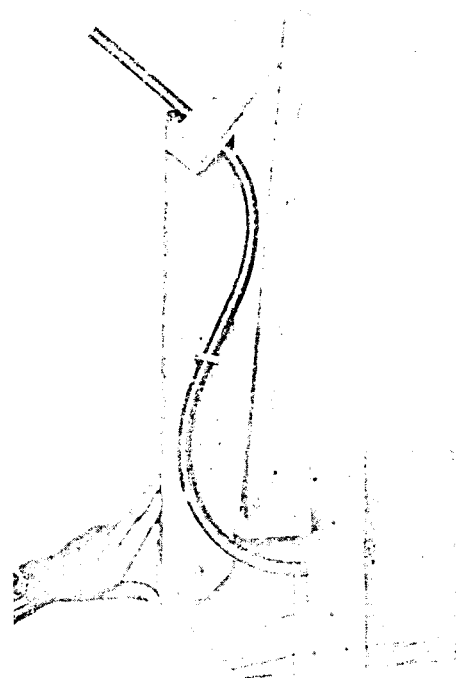
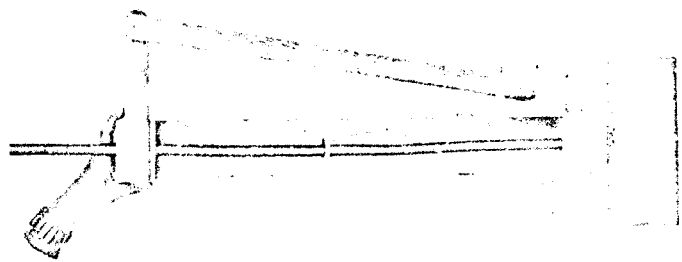


Fig. 17. Flexible hose from the HRA to headering system

Fig. 18. Flexible hose from HRA to headering system model



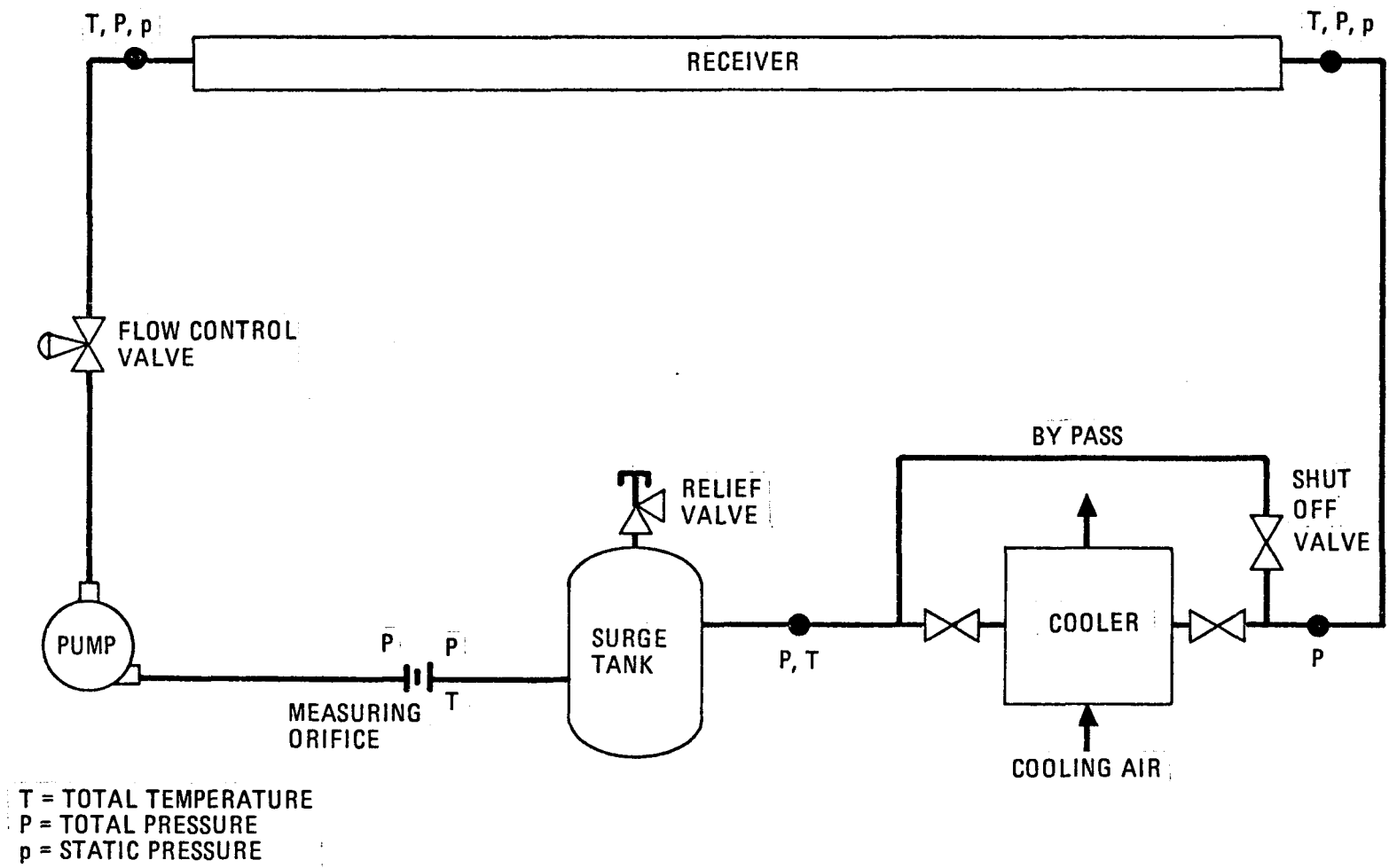


Fig. 19. Fluid system instrumentation

is opened before isolating the cooler. All three valves are standard manually operated equipment. A manually controlled flow control valve is fitted in the HRA inlet line.

The fixed ducting of the heat transfer fluid circuit is made from standard process piping and pipe fittings and mounted on local footings.

2.5.2 Heat Transfer Fluid Instrumentation

Instrumentation is designed to be simple and flexible, being composed of standard probes and wall taps. It is comprehensive enough to permit the measurement of the unit's performance and designed for easy change and augmentation to investigate particular phenomena or parts of the fluid system.

Temperature will be measured with thermocouples. Pressures will be measured with standard wall static taps, total and static pressure probes, and yawmeters. The probes will be held in standard bosses welded onto the ducting to permit easy adjustment and change. Flow will be measured using a standard ASME flat-plate orifice. A multipoint recorder will be used for taking data on long-duration or standard testing. A typical arrangement of instrumentation in the circuit is shown in Fig. 19.

3. COST ESTIMATE

A preliminary cost estimate of the conceptual design is given in Appendix A.

4. DESIGN ALTERNATIVES

Design studies at GA for the economical manufacture of the FMSC is a continuing effort. The FMSC Demo conceptual design is the best of several component design ideas that evolved from the study period reported. Several designs of components studied but not incorporated in the conceptual design are described and discussed in this section.

4.1 THE MIRROR UNIT

Several techniques for manufacturing and mounting the mirror elements were investigated. The basic task is to accurately position the 4-in. wide mirror strips and hold them stable in winds of up to 25 mph while operating and to ensure that they survive winds of up to 100 mph. The positional accuracy of the mirror elements is significantly affected by twisting, and torsional rigidity of the mounting system is therefore important. A design was established that holds the mirror strips along their longitudinal axes to 0.25 deg of their nominal angle.

Five concepts for mounting the mirror strips were considered. They were:

1. Mirror strips on pairs of tensioned cables.
2. Mirror strips in a concrete-lined trench.
3. Mirror strips on preformed concrete modules.
4. Mirror unit of strips of preformed aluminum bonded together.
5. Mirror strips on prealigned formers grouted into the ground.

All mirror designs except those with concrete or some other solid-bed mounting could be built above or below grade. It appears that the capital costs of the manufacturing machinery would be greatest for the

concrete or other solid-bed configuration, but the cost-per-unit would of course decrease with production of a full-scale power unit. All designs discussed except the wire-mounted mirrors and the mirrors on prealigned grouted formers are free of aerodynamic flutter and instability; construction methods that make them stable, however, create drainage problems.

4.1.1 Mounting Mirror Strips on Pairs of Tensioned Cables

The main apparent disadvantage of the wire-mounted mirror system was that its flexibility would make it difficult to limit torsional motion to 0.25 deg and to achieve survival in 100-mph crosswinds from aerodynamic loads. The advantage of the wire-mounted mirror system is that tensioned wires are very straight and contain minimum material, which is a major factor in the cost. Thus, the system deserved further investigation.

When considering wind loads, the mirror system can be considered to be a cascade of airfoils in a variable and turbulent flow field. This does not lend itself to analysis, so a flow test program was designed to give information on aerodynamic stability of loads on the mirror elements. This test program will be reconsidered in the next phase of the design work and implemented if the cable-mounted mirror concept remains a main contender. A preliminary analysis was made of a single-mirror element in a free-stream crosswind. Although the analysis was relatively crude and of a simplified model, it supplied useful data to get an idea of the magnitude of problems with aerodynamic loading and flutter. Results indicated that tensioned wire-mounted mirror strips could satisfy stability and strength requirements if they are supported at about 10-ft intervals.

Experiments have been conducted at GA with glass mirror strips 4-in. wide and of three thicknesses (0.092, 0.130, and 0.250 in.) mounted on pairs of tensioned cables. These have indicated that torsional rigidity is considerably enhanced if the mirror strips overlay the cable support frames along the cable span.

Tests show that 5/32-in. diam 1x19 cables up to 100 ft long, supported at 25-ft intervals and tensioned to 1000 lb, can hold the mirror firm in crosswinds of up to 8 mph. The mirrors have survived seasonal Southern California wind storms (about 40 mph gusts) with no apparent damage. Significant flutter occurs at the center of a span when wind speeds reach the 10- to 20-mph range, which results in image broadening. This has not been quantitatively evaluated. In the range of conditions tested thus far, the single-strength (0.092-in. thick) commercially available mirrors appear to be the best.

A so-far unresolved problem is cables that stretch with time. This has manifested itself as a reduction of cable tension from 1000 to about 600 lb in about 4 weeks. Tension reduction from 1000 to about 900 lb appears to be acceptable. Other cables, including 1x7 work-hardened guy wire, reportedly have very little creep.

4.1.2 Mirror Strips Mounted on Concrete or Other Solid Bed

Concrete can be commercially laid to a tolerance of $\pm 1/4$ -in. in 10-ft lengths, but local waviness is much greater than 1 in 480 (1/8 deg). To set a 4-in. chord mirror to the required $\pm 1/4$ deg about its long axis, the surface waviness must be less than 0.017 in. in 4 in. It appears that even with the best commercial practice this angular tolerance cannot be achieved on the concrete surface, so the mirror must be mounted on a filler material and held accurately until it sets. An alternate method would be to hold the mirror strips accurately and pump the concrete lining behind them.

For any large installation it has been estimated that to dig mirror ditches and line the inside surfaces with 3 in. of concrete by conventional methods cost about $\$1/\text{ft}^2$. Therefore, if the mirrors can be mounted as suggested for a cost of $\$.50/\text{ft}^2$, the solid-bed mounting is feasible. The cross section of the concrete-lined mirror bed is shown in Fig. 2.

4.1.3 Mirror Strips Mounted on Preformed Concrete Modules

The concrete would be poured into an inverted mold of the stepped section of the mirror surface. The mirror strip mounting surfaces would be accurate enough to eliminate having to jig-hold the mirror strips while the filler material set. A variant of this technique would be to place the mirror strips face-down in the mold and pour the concrete over them. When the concrete sets the section would be turned over in the mold and then the mold removed. Sections would probably be cast with integral mounting feet and flanges for joining to adjacent sections. Size will probably limit this technique of mirror trough manufacture. An economic comparison with other techniques will be desirable. This approach is presently being explored on subcontract with Sandia under their total-energy ERDA contract.

4.1.4 Mirror Unit Made with Glued Strips of Preformed Aluminum

This is also a modular construction, in which the preformed strips of about 30-ft length would be assembled on a jig. After removal from the jig, the mirror unit would be externally braced to maintain its shape accurately and then joined to its neighboring unit. Preliminary estimates show that material and structural costs of this scheme are too high, but lower-cost materials and a simpler structure could reduce the cost to a desirable level.

4.1.5 Mounting Mirrors on Prealigned Formers Grouted into the Ground

In this technique, accurately stamped formers are aligned by being suspended from two or more wires. When aligned, they are grouted into the earth. The mirror strips would then be mounted either directly or by using bearers on the preformed surfaces of the formers.

The spacing of the formers would depend on the design of the mirror strips and their mounting method. The viability of this mirror mounting technique is closely related to the design of the mirror strips themselves.

4.2 HEAT RECEIVER OPTICAL THERMAL DESIGN

From preliminary work, it was decided to analyze the performance of three configurations, all having secondary concentrators.

The first design is a glass-enclosed pipe partially covered with insulation as shown in Fig. 20. The second and third designs consist of a row of parallel pipes covered on the top and sides with insulation and on the bottom with glass. The second design has one glass plate; the third has two. Figure 20 illustrates and defines these designs.

A computer model of each design was written, the results of which are presented in Figs. 21, 22, and 23. The notation used is as follows:

Symbols

- α - absorptivity
- γ - transmissivity
- ϵ - emissivity
- ρ - reflectivity

Subscripts

- G - glass
- S - short wavelengths
- L - long wavelengths
- P - pipe

At high temperature, the two-plate glass system gave slightly better efficiency. At intermediate temperatures, the one-plate glass system was better. Since the extra glass in the two-plate glass system would increase the complexity of the heat receiver, it was rejected. The one-plate glass

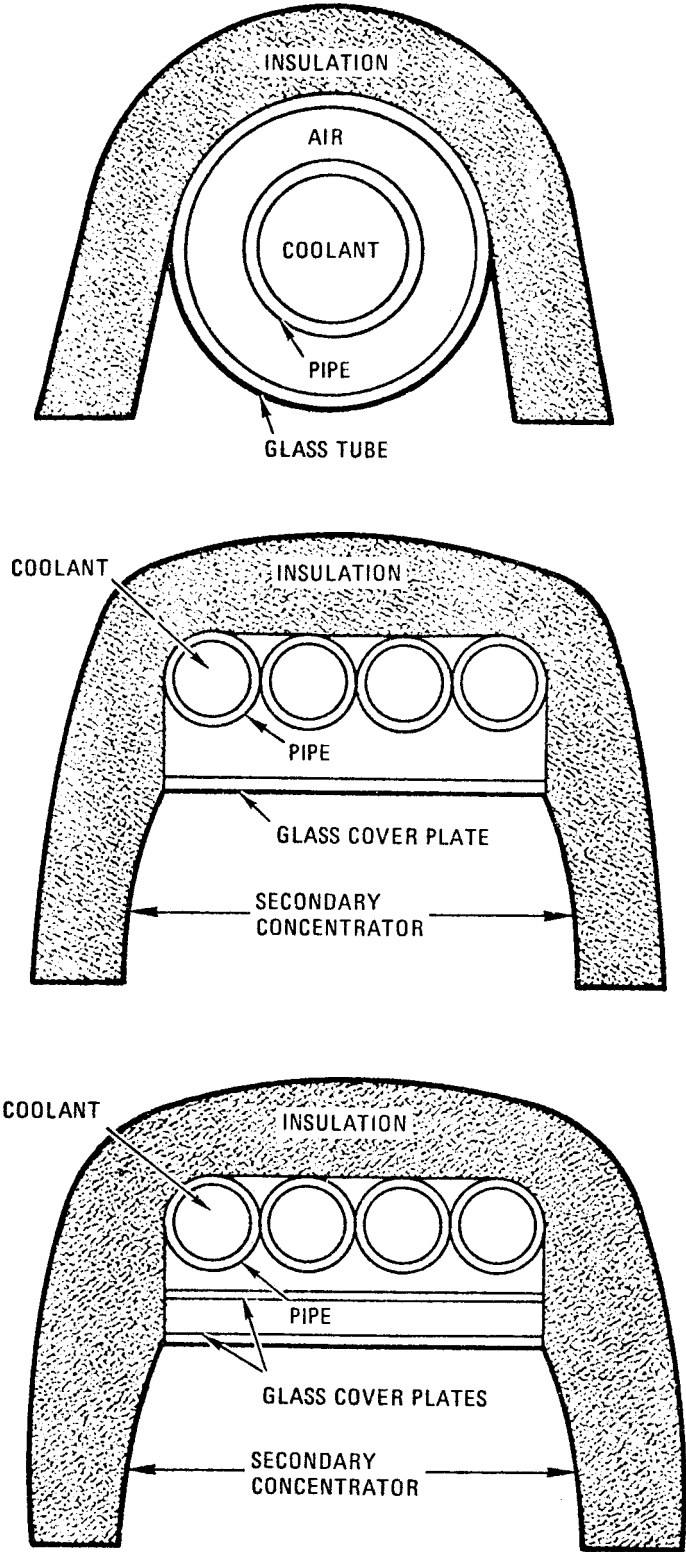


Fig. 20. Section view of three HRA designs

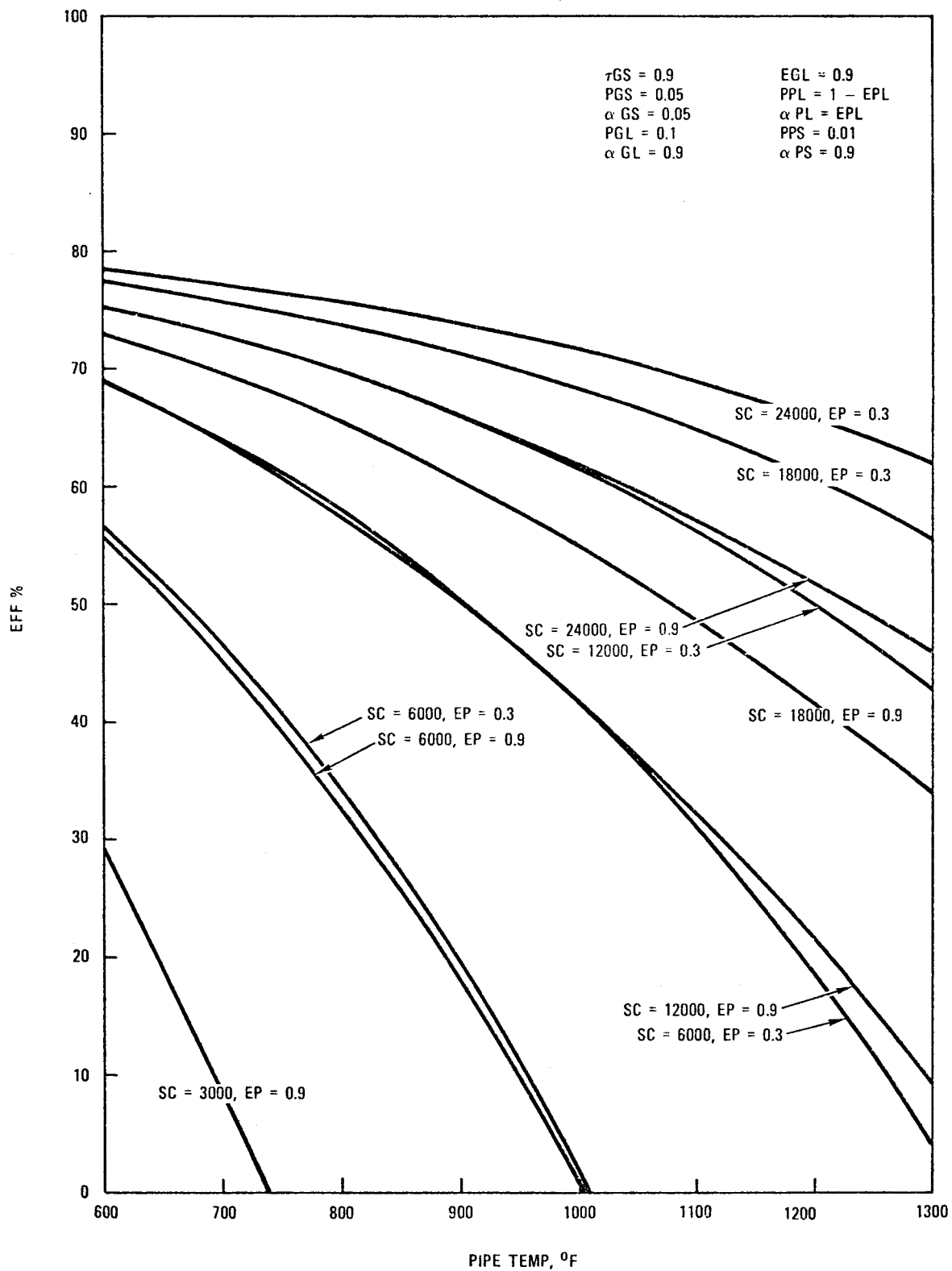


Fig. 21. Glass enclosed pipe solar collector

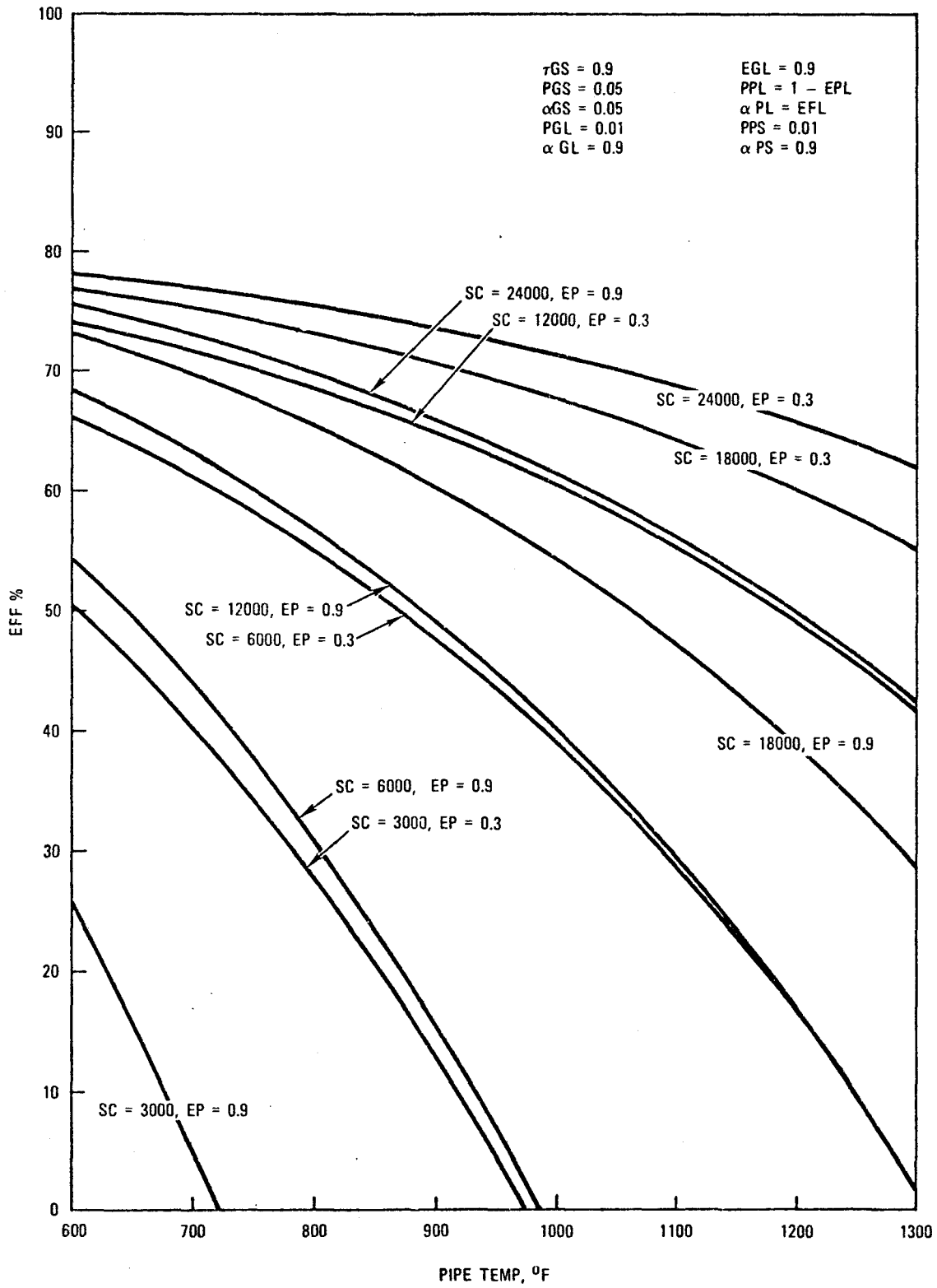


Fig. 22. One flat plate solar collector

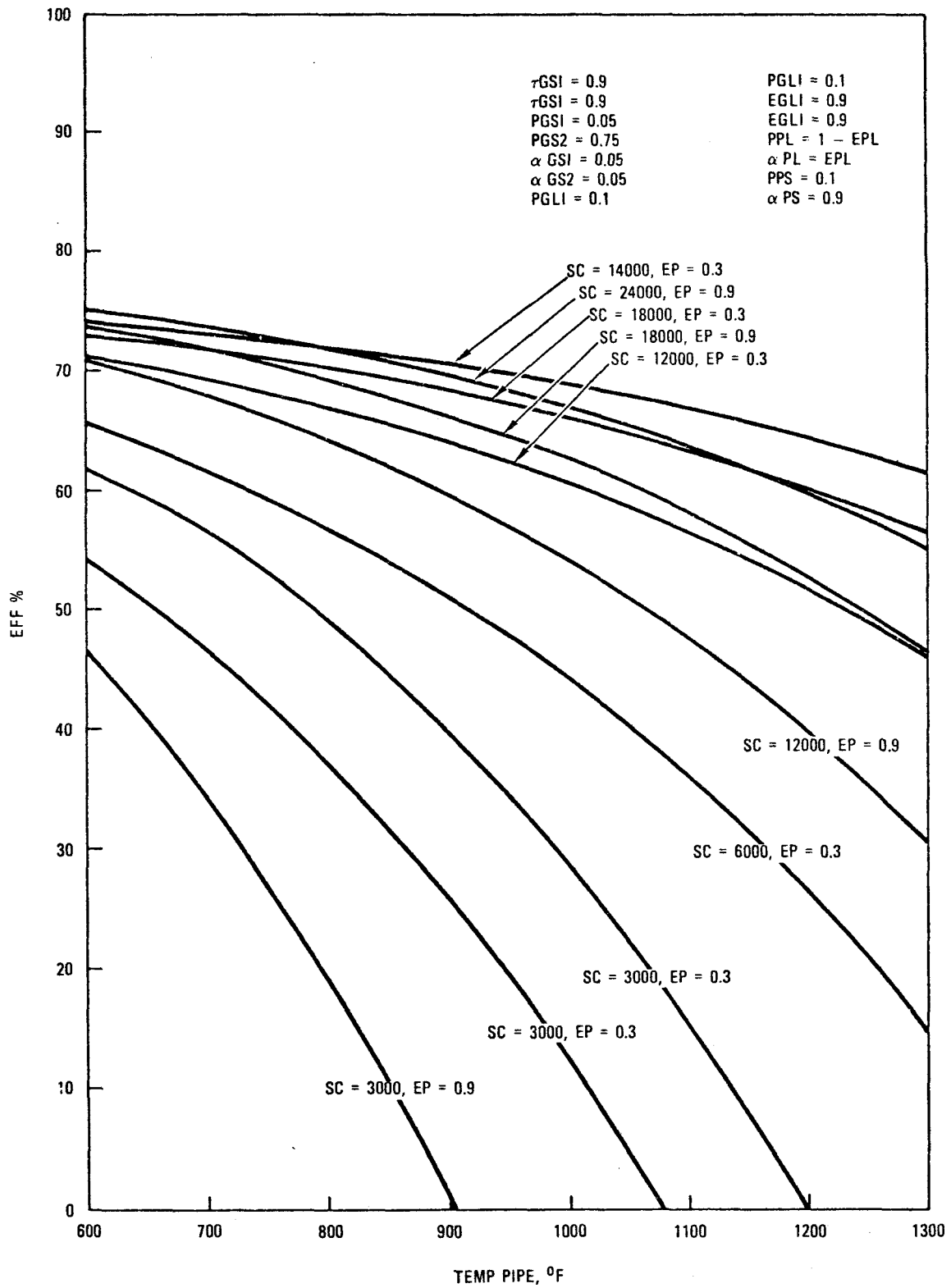


Fig. 23. Two flat plate solar collector

system and the glass-enclosed pipe system compare closely in terms of efficiency and economy, but if the glass-enclosed pipe were sized for the contemplated heat-transfer fluid, it would be incompatible with the optical characteristics of the FMSC. For these reasons, it was decided to adopt the one-plate glass system in the HRA design used for the FMSC Demo (see Figs. 8 and 20).

The computer models of these systems include reradiation between the glass and pipe, and heat losses from the combined effects of convection and radiation. System properties were assumed to remain constant in all but the glass-enclosed pipe model where the thermal conductivity of the air in the air gap was allowed to vary with temperature.

The reference design HRA has pipes coated with black chrome or an equivalent coating, giving an emissivity (ϵ) of 0.3. The maximum efficiency of the unit is 65%.

4.3 HRA SUPPORT

The preferred design of the HRA suspension is shown in Fig. 1 and described in Section 2.4.1. It consists of a steel support beam formed as a triangulated truss. The preferred designs of the support towers and rotating arms are steel columns with guy wires, shown in Figs. 9 and 10, for stabilization.

Alternative heat receiver supports, towers, and rotating arm designs are discussed below. The mechanical design study of the complete support system included problems of thermal expansion, insulation, wind loads, and pointing the receiver.

An HRA suspension system with a very tightly stretched axial cable passing through the ends of the main rotating arms was analyzed. The HRA is hung from the cable. The concept has the potential advantage that few mechanical systems have -- natural straight-line accuracy and alignment of

a tightly tensioned steel wire or cable. This system could solve the heat receiver pipe alignment problem previously discussed. The rotating arms are spaced every 50 to 100 ft to support and position the cable. As the arms rotate in synchronization, the entire cable and HRA move to track the line of mirror focus. The arms support only the vertical loads of the cable and HRA but do not take the tension loads of the stretched cable. At each end of a long mirror trough is a very rigid rotating arm. The cable is fastened to the end of this arm and then runs angularly back to a stationary anchor point located on the mirror centerline. The tensioned cable suspension system has several problems. Loads on the end anchors and end rotating arms are quite high, perhaps 300,000 lb or more. Thus, end anchor and end rotating arm costs are important. Cable span between rotating arms is limited for reasons similar to those for the steel joist design. Cable sag increases disproportionately with span, and practical spans are limited to less than 100 ft. The weight of the cable alone causes significant sag. Another problem is that a malfunction at any point or at any arm along the cable can have severe effects all along the mirror trough. Adverse interactions are probably far more severe for this concept than for the steel joist design.

Supporting the HRA by a suspension-bridge design with sagging curved cables was also considered. Several curved cables would support the assembly in all positions of orientation. A complex cable support at each rotating arm would be needed. Also, the inherent alignment accuracy of the system is probably inadequate. Alignment accuracy is affected by the alternating load orientation and by slight tension differences between top and bottom cables. As in the other systems, sag requirements limit allowable spans between towers. An alternative to the suspension bridge would be several straight guy wires running from points along the HRA angularly up to supports mounted at the four places spaced out from the end of the rotating arm. Such supports are complicated, and the system is difficult to align accurately.

4.4 MAIN ROTATING ARM DESIGN

The main rotating arm, which positions the HRA, is shown in Fig. 9 and is described in Section 2.4.3. Several other HRA rotating mechanisms were also considered.

A single radius arm acting as a beam was excessively large, heavy, and costly.

A system using large bicycle-type wheels to position the HRA was also considered. Each wheel diameter would equal the mirror arc diameter. The wheels would rotate about the mirror arc centerline on rollers fixed at points on the mirror arc. An HRA would be attached to the periphery of each wheel, with a counterweight attached to the opposite side. These wheels would be located 50 to 100 ft apart. By rotating the wheels simultaneously with a common drive mounted on the ground, the desired motion of the HRA theoretically could be achieved. While this concept eliminates the tower, it is complex and probably expensive; it would interfere with the mirror surface and pose special end connector problems. This approach was not analyzed in detail.

Another concept uses a single long pipe with one end pivoted on the ground somewhere near the mirror arc. The other end of the pipe is moved in a plane perpendicular to the mirror trough centerline by cables in a manner similar to that of shipboard cranes. The HRA is fastened to a sliding mount that rides up and down the pipe. By accurate control of both the rotational motion of the pipe and the relative sliding position of the HRA, the assembly theoretically can traverse the circular arc of the locus of the FMSC focus. This concept seems simple in that the tower is eliminated, and only guy wires and a single pipe loaded as a column are involved. However, it is complicated by the sliding carriage and by the requirement for complex and accurate two-dimensional control. In addition, the pipe is rather long, and the geometry of positioning the controlling guy wires is complicated by the wide range of movement of the HRA.

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1. Russell, J. L., Jr., E. P. DePlomb, and R. K. Bansal, "Principles of the Fixed Mirror Solar Concentrator," General Atomic Company Report GA-A12902, May 31, 1976.
2. Russell, J. L., Jr., "Investigation of a Central Station Solar Power Plant," General Atomic Company Report GA-A12759, August 31, 1973.
3. Potthoff, R., et al., "Investigation of a Central Station Solar Power Plant," Final Report, U.S. Energy Research and Development Administration, General Atomic Company Report GA-A13821, February 26, 1976.

APPENDIX A
COST DEVELOPMENT REPORT
SOLAR DEMONSTRATION UNIT

COST EFFECTIVE DATE JANUARY 1976

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GENERAL ATOMIC PRIVATE DATA

SOLAR POWER DEMONSTRATION UNIT

CONCEPTUAL COST ESTIMATE

GENERAL

This estimate represents a preliminary investigation of a first-of-a-kind Solar Power Demonstration Unit and is subject to many of the uncertainties inherent in a conceptual estimate of a project at this stage of its development.

The estimate reflects the present plant design and the cost of constructing this plant on the assumed site.

ESTIMATE BASIS

The preliminary drawings and sketches provided for the estimates were issued for that purpose and reflect only a feasible plant and not an optimized design.

The basis for the Demonstration Plant estimate is described below:

- Civil and structural quantities were developed from engineering drawings and sketches for the following items: concrete, formwork and structural steel. Items such as rebar and embedded metal were evaluated based on engineering judgment or upon information from other projects. Building services, such as HVAC, plumbing, and fire protection were assumed not required. Site preparation dollars were allowed for a flat site for which clear and grub and minimal grading is required.
- Pipe quantities for the plant systems were developed from P&ID's and equipment general arrangement drawings. Small pipe quantities were evaluated to satisfy the indicated requirements of the various systems.

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- Electrical single line diagrams were used for major systems; however, bulk quantities were evaluated based on other projects and this project's specific layout, areas, and volumes.
- Mechanical equipment is based on equipment lists provided by GA engineering.
- Labor pricing reflects current wage agreements and rates for the Los Angeles area.
- Basic installation unit rates for bulk materials were developed from Cost Engineering Construction Estimating Standards.
- Plant construction is on a one-shift basis with casual overtime.
- Construction equipment costs are based on rental equipment.
- State taxes are included for all materials and equipment at the present rate.
- Distributable manual labor was developed on relationships to direct labor using current experience on construction projects.

Contingency

Contingency is included to provide the most probable estimate of costs of the project as presently indicated by the engineering information prepared for, and included in, this report. Contingency is not to provide for changes in scope, site conditions, escalation, schedule, labor availability, revisions in regulatory agency requirements, force majeure, or project features not shown or described in this report.

Exclusions

The Engineering, Procurement, and Construction exclusions are as follows:

- General Atomic's Home Office Costs
- Medical First Aid Services

GENERAL ATOMIC PRIVATE DATA

- Access road to the site boundary
- Transportation (craft)
- Land, interest during construction, and other owner's costs
- Building Services (HVAC, Plumbing, etc.)
- Cost of construction water and power

PRICING BASIS

Mechanical Equipment. Some preliminary quotes were obtained for large pumps, condensers, heat exchangers, and cooling towers. The balance of the equipment was priced using historical information and quotes received for various current estimates.

Electrical Equipment. Electrical equipment was priced using price book information.

Bulk Materials

Concrete material pricing reflects an estimate for local supply and delivery. Miscellaneous iron and steel, rebar, and concrete materials are priced according to Construction Estimate Guide Standards.

Bulk electrical, piping, and instrumentation materials reflect current information on similar construction projects.

Manual Labor

Wage rates were developed from labor bulletins obtained from the Means Labor Rates Publications. Fringe benefits are included in the wage rates. Present-day wage rates are those in effect on Jan 1, 1976.

Nonmanual Labor

Nonmanual labor manhours were developed from historical information with an allowance to reflect the first-of-a-kind feature of this project.

GENERAL ATOMIC
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Construction Equipment and Tools

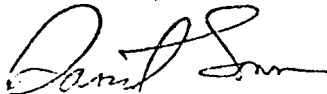
Equipment is priced on a rental basis using an equipment schedule reviewed with the construction department. Small tools costs are based on dollars per direct manhour.

Engineering and Home Office Costs

The Engineering and Home Office estimate is based on construction experience.

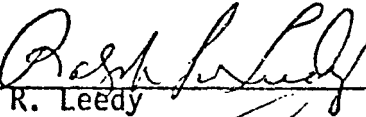
Engineering manhours exclude preproject engineering and assume that the plant criteria remain fixed after construct award.

Estimate Prepared By:



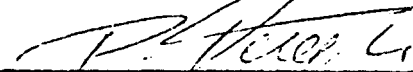
D. Sonn Cognizant Estimator

Approved By:



R. Leedy

Approved By:



P. Vergne

SOLAR POWER DEMONSTRATION UNIT
CONCEPTUAL COST ESTIMATE SUMMARY

	<u>Concrete Mounted Mirror Concept</u>	<u>Cable Mounted Mirror Concept</u>
<u>Direct Costs</u>		
Site Work	6.3	4.0
Civil		
Concentrator Bed	69.7	40.0
Other	9.4	
Mechanical - Receiver	109.5	208.0
Process Equipment	<u>60.8</u>	<u>61.0</u>
Subtotal Directs	255.7	313.0
Contingency	<u>54.6</u>	<u>62.0</u>
<u>Total Directs</u>	<u>310.3</u>	<u>375.0</u>
 <u>Indirect Costs</u>		
Bonds Ins	2.0	2.0
Non Payroll Tax	14.8	19.9
Field Indirect Costs	88.6	88.6
Home Office Eng. Services	18.0	18.0
Fee on Construction	<u>35.0</u>	<u>40.0</u>
<u>Total Construction Costs</u>	<u>468.7</u>	<u>543.5</u>