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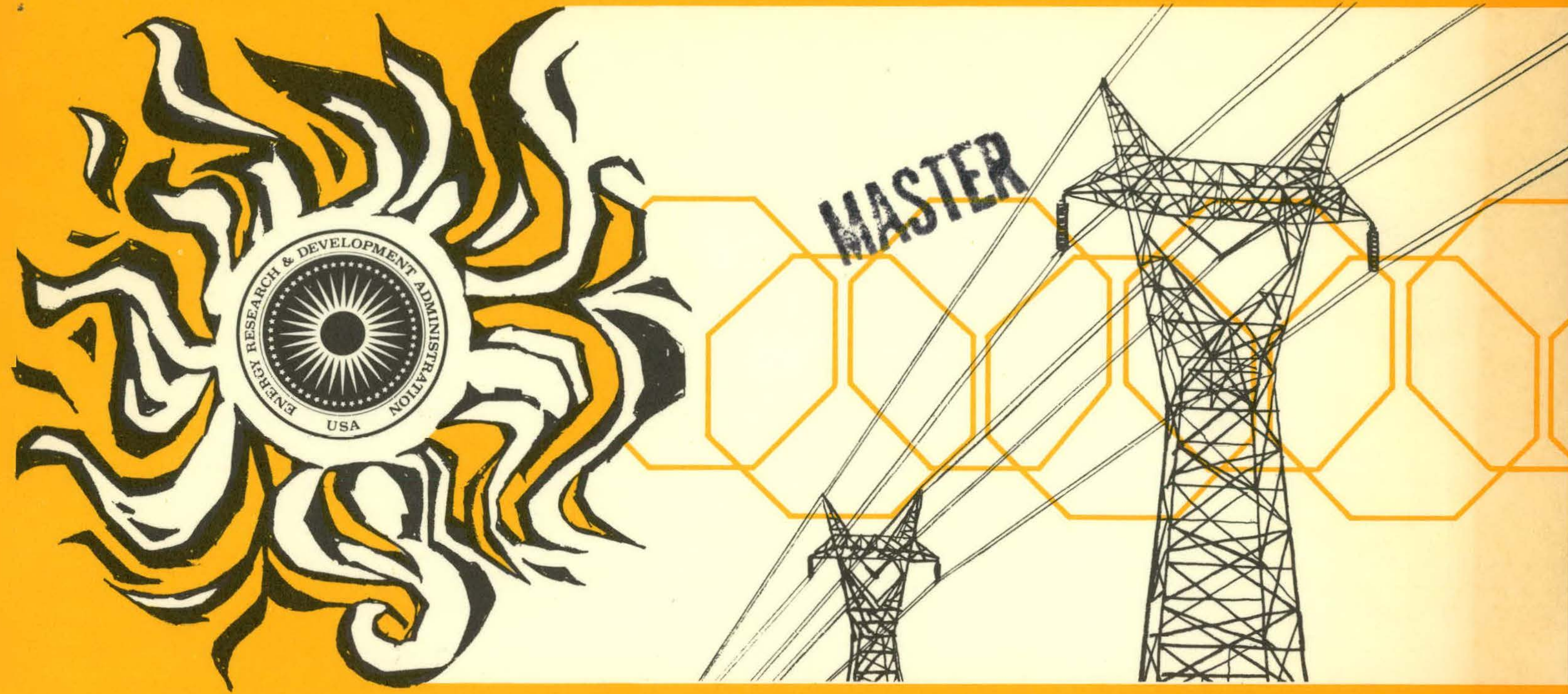

CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM PHASE 1

CDRL ITEM 10
Third Quarterly Technical Progress Report

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

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MDAC □ Rocketdyne □ Sheldahl □ Stearns-Roger □ University of Houston

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CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM, PHASE 1

CDRL ITEM 10. Third Quarterly Technical Progress Report

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PREFACE

This report is submitted to the Energy Research and Development Administration under Contract EY-76-C-03-1108 as the formal documentation of CDRL Item 10, Third Quarterly Technical Progress Report. It summarizes the analysis and design efforts performed on the Phase 1 Central Receiver Solar Thermal Power System Program by the MDAC team between 1 April 1976 and 30 June 1976.

This report was prepared for distribution by ERDA to the technical public under Standard Category UC-62, as contained in Document TID-4500.

Specific efforts performed by the members of the MDAC team were as follows:

- McDonnell Douglas Astronautics Company
  - Commercial System Summary
  - System Integration
  - Collector Subsystem Analysis and Design
  - Thermal Storage Subsystem Integration
- Rocketdyne Division of Rockwell International
  - Receiver Assembly Analysis and Design
  - Thermal Storage Unit Analysis and Design
- Stearns-Roger, Inc.
  - Tower and Riser/Downcomer Analysis and Design
  - Electrical Power Generation Subsystem Analysis and Design
- University of Houston
  - Collector Field Optimization
- Sheldahl, Inc.
  - Heliostat Reflective Surface Development
- West Associates
  - Utility Consultation on Pilot Plant and Commercial System Concepts

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CONTENTS

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ABSTRACT

Results of analysis and design efforts by McDonnell Douglas Astronautics Company (MDAC), Rocketdyne, Stearns-Roger, Inc., Sheldahl, Inc., and the University of Houston between 1 April 1976 and 30 June 1976 on ERDA Contract No. EY-76-C-03-1108 are summarized. This is the third quarterly technical progress report published on the Phase 1 Central Receiver Solar Thermal Power System contract.

The dominant activities during the reporting period have involved the preparation of test facilities for the subsystem research experiments and the fabrication of the test hardware. Summaries of these activities are presented.

Alternative design approaches for the 10-MWe pilot plant system and the current pilot plant project schedule are also presented and described.

Section 1
INTRODUCTION

The status of technical progress on the Phase 1 Central Receiver Solar Thermal Power System contract during the period between 1 April 1976 and 30 June 1976 is summarized in the following sections of this document. This is the third of seven technical progress reports that will be published during Phase 1, with the reporting frequency being quarterly for subsequent issues. A discussion of the program approach and program status follows.

1.1 PROGRAM APPROACH

The objectives of the Central Receiver Solar Thermal Power System Phase 1 contract are to develop a preliminary design of a central receiver pilot plant concept and to define and carry out a series of test programs to verify the critical subsystems contained in the design. The methodology used to accomplish this program is presented in Figure 1-1. Starting with a series of program inputs which include ERDA, utility, and self-imposed constraints along with representative environmental conditions, a preliminary design baseline phase was implemented. In order to provide proper focus to this activity, a commercial plant and related commercial system requirements were initially defined from which the pilot plant preliminary baseline definition and subsystem research experiment requirements could be derived. With the establishment of the preliminary baseline design, program activity continues toward the subsystem research experiment and preliminary design phases. The content of this third quarterly report will focus on the subsystem research experiment activities, particularly the fabrication of the test articles and preparation of the associated test facilities, including installation of the test hardware. Additionally, efforts on system design alternatives for the pilot plant which were active during the current reporting period are also presented.

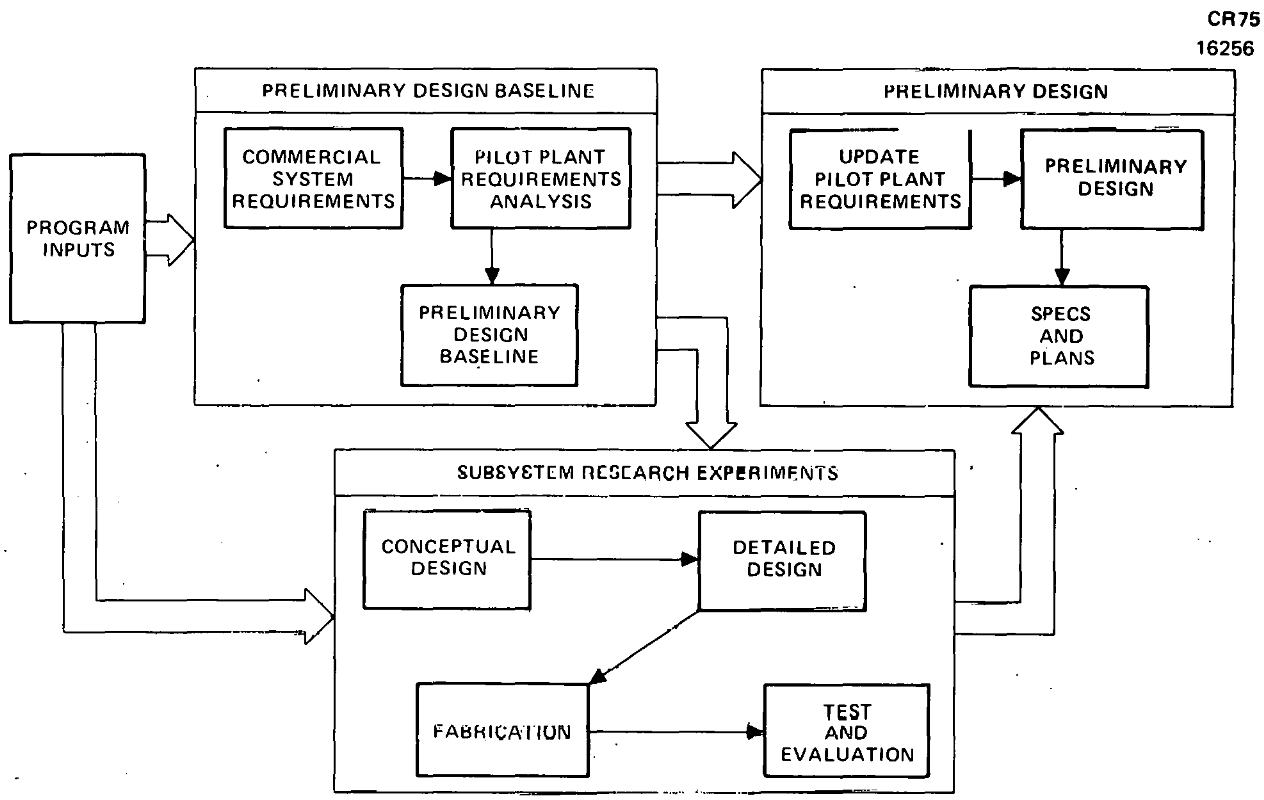

Figure 1-1. Central Receiver, Phase 1, Program Network

1.2 PROGRAM STATUS

The summary schedule of Phase 1 program activities is shown in Figure 1-2. All tasks are being performed on schedule through June, 1976, and no major problems are anticipated on program progress during the next reporting period.

Final versions of the SRE detail design reports for the collector, receiver, and thermal storage subsystems were published in April 1976 following incorporation of customer review comments (CDRL Items 6, 7, and 8).

An updated version of the Program Plan (CDRL Item 9) was published in June 1976. Additionally, a semiannual review of progress on the Phase 1 central receiver effort was held in Washington, DC on June 2 as part of a semiannual review of all solar-thermal-electric effort being funded by ERDA. An oral briefing was presented, and a summary report of progress during the previous six-month period was delivered (CDRL Item 10).

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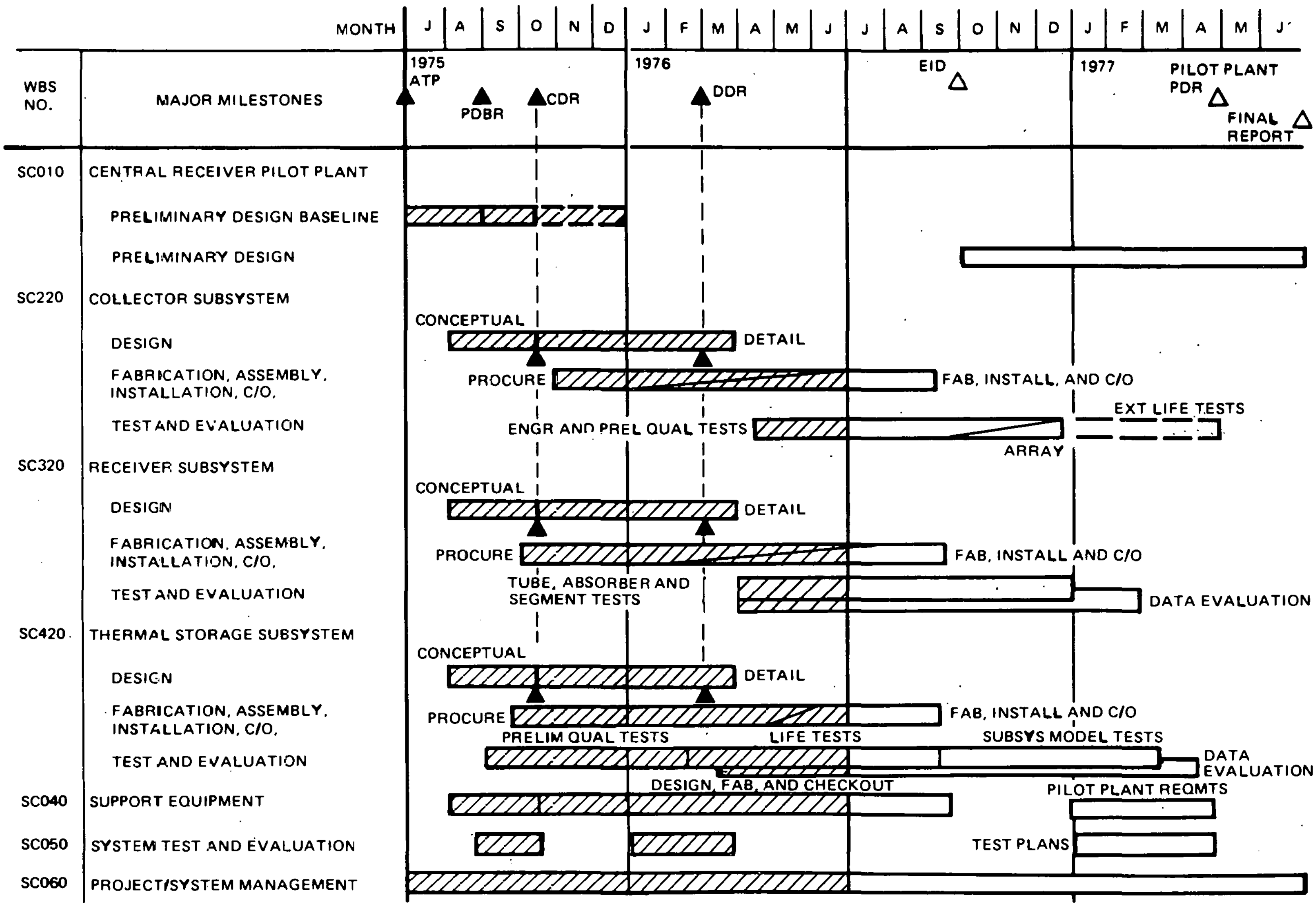

Figure 1-2. Summary Master Program Schedule

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Section 2
PILOT PLANT SYSTEM

The pilot plant system remains conceptually unchanged from the system description presented in the second quarterly report (April 1976), which incorporated revisions of the system steam conditions, an expanded definition of the receiver outlet flow control and piping network, and a change in the steam generator on the discharge side of the thermal storage subsystem from the preliminary design baseline. The principal system efforts during this report period consisted of an analysis of alternative approaches to configuring the pilot plant system and an update of the Phase 2 program schedule, which are summarized in the following paragraphs.

2.1 ALTERNATIVE SYSTEM DESIGNS

The expressed goal of the 10 MWe pilot plant is to establish the technical feasibility of a commercial solar thermal power plant and provide early system economic data. As a result, the approach followed by MDAC to date in defining the pilot plant has been to start with the definition of an optimized 100 MWe commercial system, based on commercial system costing assumptions, and then selectively scale the system down to the 10 MWe power level. During the scaling process, key elements of the commercial system are preserved. These elements include commercial sized heliostats, the operation and control of a full 360° receiver, and a close representation of commercial system heliostat spacing to investigate such issues as optical and aerodynamic interactions and mirror back-side heating, as well as installation, maintenance, and cleaning in a tightly packed heliostat field.

The resulting baseline pilot plant collector field is shown in Figure 2-1. It consists of a trimmed square field 527 meters (1728 feet) on a side with a 95 meter (312 foot) tower located slightly to the south of center. It should be noted that during the scaling process, insufficient energy levels were available on the south side of the receiver. This situation was improved by adding additional heliostats to the south side of the field resulting in the net

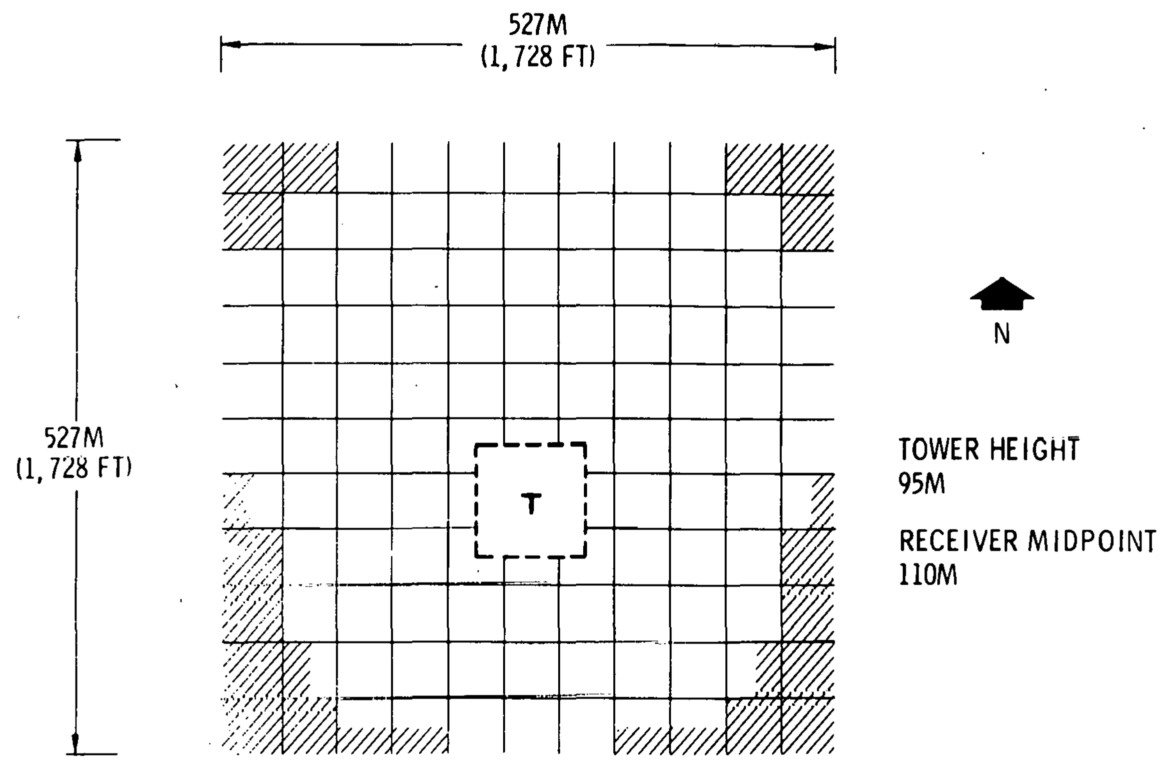

Figure 2-1. Collector Field Layout

movement of the tower more toward the center of the field as compared to the corresponding commercial system. The baseline receiver is composed of 24 independently controlled single pass-to-superheat panels, which is consistent with the commercial system design. The system is capable of producing ~36,700 MWH of electricity on an annual basis.

From an economic point of view, the pilot plant defined in the above manner does not represent the minimum cost 10 MWe system. This discrepancy occurs because of the more expensive heliostats (relative to the receiver and tower costs) for the pilot plant as compared to the commercial system. The pilot plant heliostats are more expensive because of the lack of high volume, mass production, and installation techniques assumed for the commercial system. As a result, an optimization of a 10 MWe system based on pilot plant cost assumptions would produce a system where the heliostats are more widely spaced and located in regions of highest heliostat performance.

Two optional collector field layouts were considered during this reporting period which have the potential of reducing system costs. The first which is shown in Figure 2-2 is based on a layout designed to maximize annual energy collection per unit investment, based on pilot plant costing assumptions. The result is a field located to the north of the tower (T). From the standpoint of simulation of a commercial system, several compromises occur. First, the receiver no longer contains the full 24 panels (360°) of active receiver surface. As a result, the complete simulation of a commercial system flow control network during all modes of operation would not be possible. The second compromise exists in the collector field due to the use of significantly more expensive heliostats which results in a wider heliostat spacing. The advantage of this configuration over the previously defined scaled commercial system is one of cost.

The second optional collector field considered during this period is shown in Figure 2-3. The objective of this field was to define a minimum cost configuration by optimizing the pilot plant for winter 2 PM (and the mirror image case of winter 10 AM) energy collection and disregarding the perform-

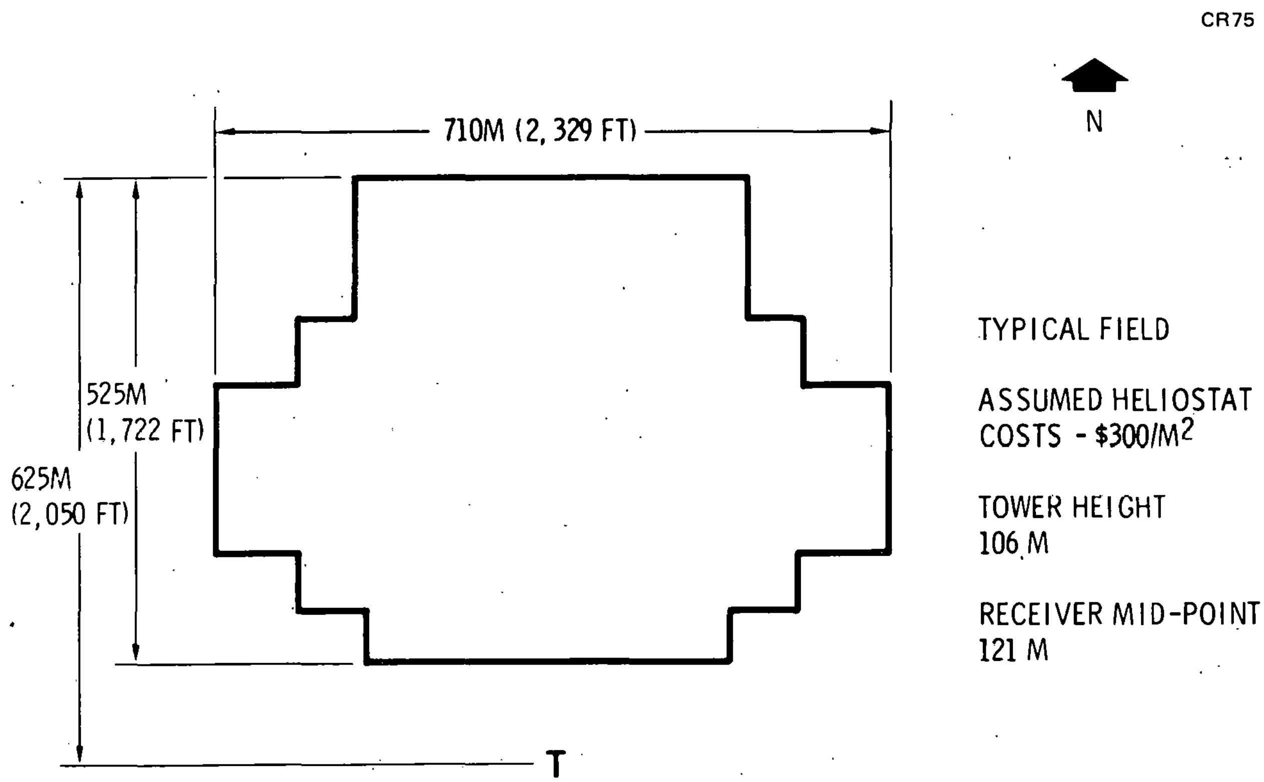

Figure 2-2. Optimum Annual Energy Field Layout

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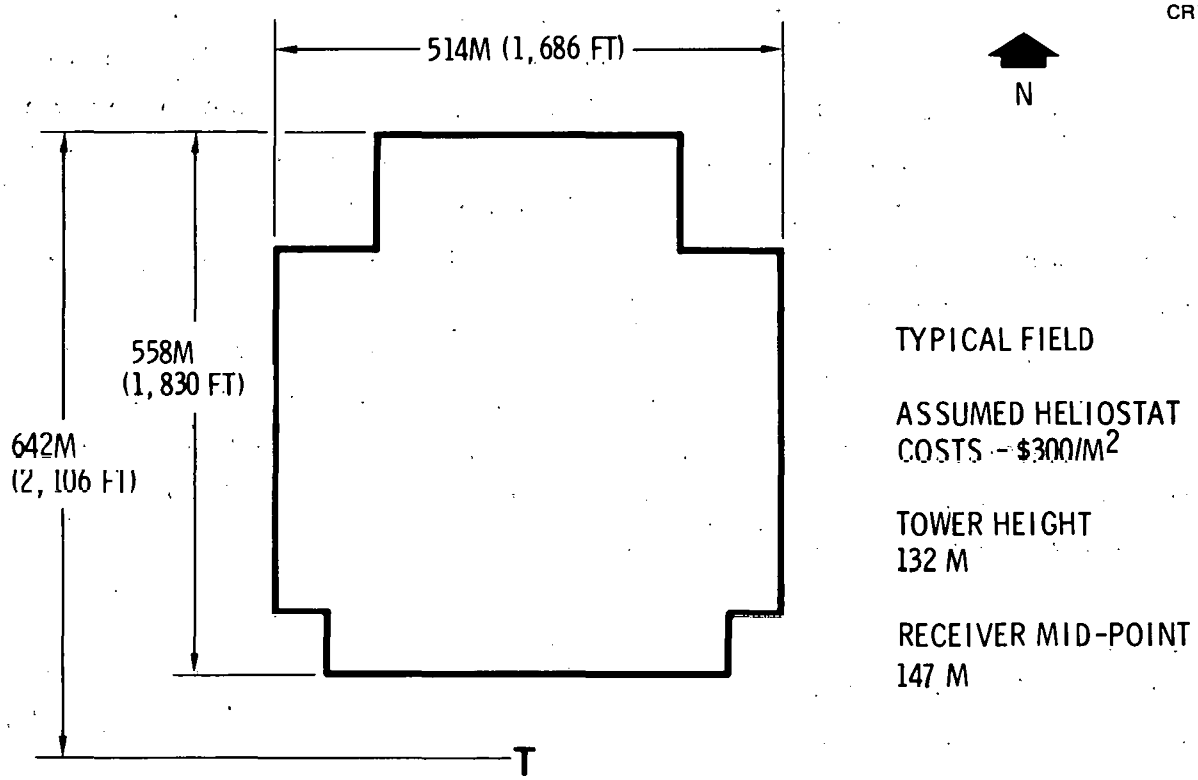

Figure 2-3. Winter Optimum Field Layout

ance during the rest of the year. As in the optimum annual energy option, the layout was based exclusively on pilot plant costing assumptions. The data presented in Figure 2-3 show the impact of the winter optimum design objective. The field tends to be narrower than the previously shown optimum annual energy configuration with a significantly taller receiver tower. This is due to the near due-south nature of the sun and low sun elevation angle associated with the winter 2 PM (and 10 AM) design point. As in the case of the optimum annual energy configuration, a full 360°, 24 active receiver panel simulation would not be possible. Also the collector field spacing is not a good simulation of the anticipated commercial system. The principal advantage of the winter optimum configuration is to minimize the pilot plant cost while producing the desired 10 MW of net electrical power at winter 2 PM.

Before considering the potential cost savings of the optional collector fields in detail, it is useful to investigate their performance on an annual basis. The annual energy characteristics of the two options are given in Figures 2-4 and 2-5 for the optimum annual energy and winter optimum fields, respectively.

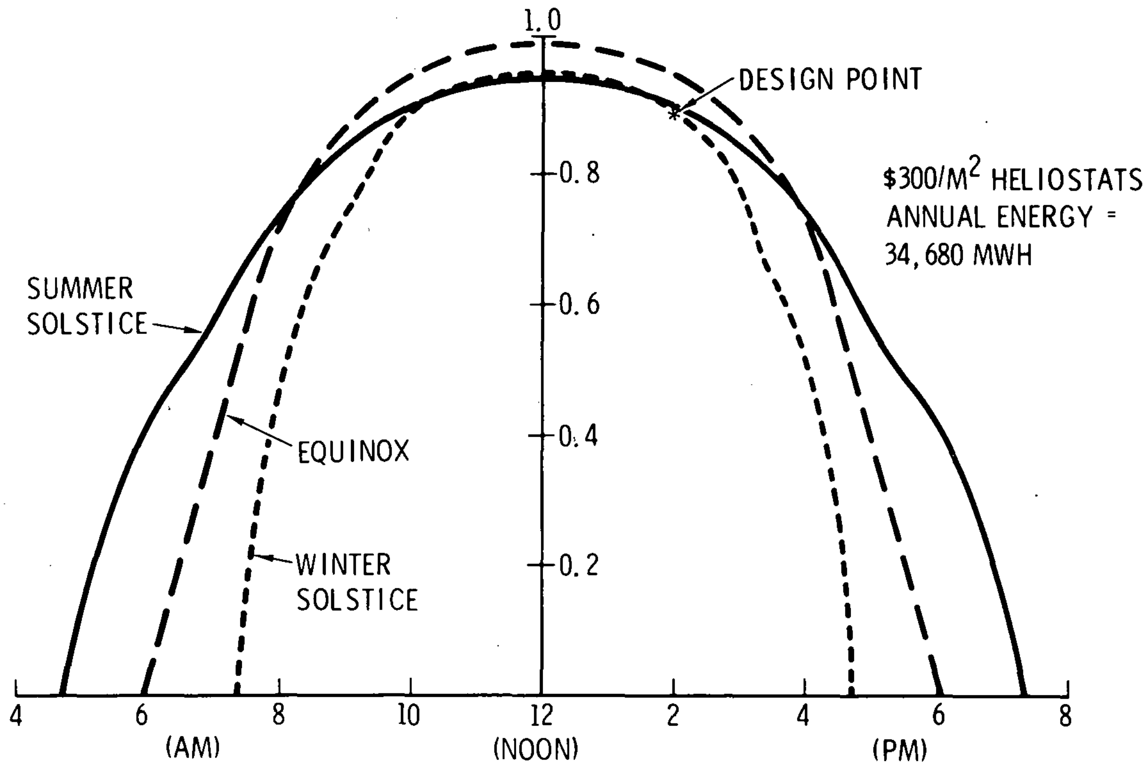

Figure 2-4. Relative Incident Receiver Power (Annual Optimum)

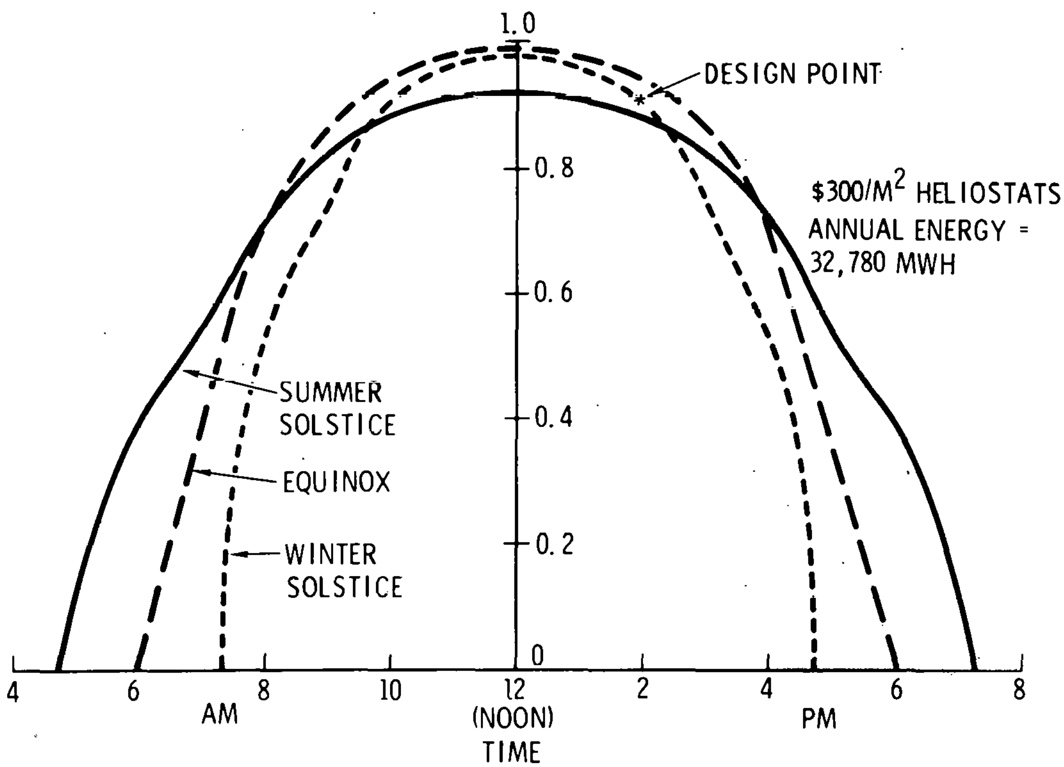

Figure 2-5. Relative Incident Receiver Power (Winter Optimum Layout)

In comparing the two, both from a total annual energy and a detailed daily and hourly variation standpoint, it is noted that only minor differences exist. From an annual energy standpoint, the winter field is capable of producing approximately 5% less electrical energy than the annual optimum field. On a daily and hourly basis, the principal difference occurs in the vicinity of noon where the winter optimum field produces superior performance over the annual optimum configuration during the time of year between the equinoxes and winter solstices (Figure 2-5). The summer noon performance, on the other hand, is degraded from that indicated for the annual optimum case (Figure 2-4).

The potential cost savings associated with compromising the pilot plant from the originally assumed scaled commercial system to either the optimum annual energy or winter optimum configuration is shown in Figures 2-6 and 2-7. Due to uncertainties associated with heliostat costs at the pilot plant level, the study was carried out for three heliostat cost assumptions (200, 300, and 400 $\$/m^2$). The impact on the collector field cost is shown in Figure 2-6. It is seen that the number of heliostats are reduced from the 2,290 associated with the scaled commercial system to the values indicated.

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	HELIOSTAT COST ($\$/m^2$)	NUMBER OF HELIOSTATS	PERCENT HELIOSTAT REDUCTION	Δ COLLECTOR FIELD COST (MILLIONS OF DOLLARS) Δ RELATED TO NO. HELIOSTATS	Δ RELATED TO HELIOSTAT COSTS	TOTAL
OPTIMUM ANNUAL ENERGY	200	2,073	9.5	$-1.32	$-1.25	$-2.57
	300	2,034	11.1	$-2.34	$-0.70	$-3.04
(34,680 MWH PER YEAR	400	2,029	11.3	$-3.18	$+0.08	$-3.10
WINTER OPTIMUM	200	1,881	18.0	$-2.49	$-2.36	$-4.85
	300	1,886	18.5	$-3.87	$-1.16	$-5.03
(32,780 MHS PER YEAR)	400	1,818	20.6	$-5.75	$+0.14	$-5.61
SCALED COMMERCIAL SYSTEM (BASELINE) (36,670 MWH PER YEAR)	390	2,290	0	-	-	-

Figure 2-6. Preliminary Results of System Design Analyses, Collector Field

		NUMBER RECEIVER PANELS	Δ RECEIVER COST (MILLIONS OF DOLLARS)	TOWER HEIGHT (M)	Δ TOWER COST (MILLIONS OF DOLLARS)	Δ SYSTEM COST (MILLIONS OF DOLLARS)
OPTIMUM ANNUAL ENERGY	200 $/m^2$	13	$-2.3	97.4	$+0.05	$-4.82
	300	13	$-2.3	106.2	$+0.24	$-5.10
	400	13	$-2.3	110.8	$+0.35	$-5.05
WINTER OPTIMUM	200 $/m^2$	13	$-2.3	124.3	$+0.70	$-6.45
	300	13	$-2.3	131.6	$+0.90	$-6.43
	400	13	$-2.3	137.9	$+1.08	$-6.83
SCALED COMMERCIAL SYSTEM (BASELINE)		24	0	95	0	0

Figure 2-7. Preliminary Results of System Design Analyses, Receiver/Tower Considerations

The percentage savings in heliostats along with the predicted cost savings are also shown. It is seen that system savings approaching $6 M can be realized for 400 $/m^2$ heliostats in the winter optimum configuration.

Since the receiver and tower are also involved in the costs of energy collection, it is necessary to investigate the impacts of these factors on possible system cost savings. The results of these factors are shown in Figure 2-7. Considering first the receiver, the optimum receiver configuration for both of the optional fields contains 13 active panels with the remaining 11 being replaced by dummy panels. The resulting savings in receiver costs are estimated to be $2.3 M which may be optimistic since it assumes a 100% savings associated with the removal of the 11 active panels. In reality, the inclusion of dummy panels, as well as possible preheat panels at the extreme boundaries of the remaining 13 active panels, can significantly influence the indicated receiver savings. From the standpoint of tower height, the two optional fields result in taller towers than the scaled commercial system. As a result, a positive increment (increase) to system cost is introduced into the study. The net effect of the collector field, receiver, and tower cost impacts are shown at the extreme right of Figure 2-7. It is seen that estimated cost savings in excess of $7 M are predicted for the 400 $\$/m^2$ heliostats used in a winter optimum collector field layout. As indicated in these two figures, the results indicated are preliminary in nature. This is partially a result of uncertainties related to receiver cost savings, as previously discussed, and impacts on tower costs associated with detailed designs corresponding to particular seismic conditions which will be known once a site is selected.

The definition and evaluation of alternate system configurations which do not excessively compromise the development nature of the pilot plant is continuing at a low level of activity. These system definitions will be retained and utilized in the event pilot plant costs become of overriding concern at the expense of developmental issues. It should be noted that the flexibility implicit in the external receiver (24 independently controlled, single pass-to-superheat panels) permits a wide latitude in system design options with only a minimum impact on receiver design and system operation.

2.2 PHASE 2 PROGRAMMATICS

The major features of the preliminary pilot plant program definition effort, which was accomplished to provide schedule information for the pilot plant program budgetary cost estimates in first quarter of 1976, have been revised to reflect the major program milestones furnished to MDAC by Sandia in May. A current pilot plant project schedule, as shown in Figure 2-8, was formulated based on the following milestones:

- A&E ATP - November 15, 1977
- All other contractor ATP's - January 1, 1978
- Initial site activities - October 1, 1978
- Initiation of subsystem installation - April 1, 1979
- Initiation of integrated subsystem c/o - July 1, 1980
- Start of 2-year system test operations - December 15, 1980

The revised schedule appears to provide a reasonable time frame for each of the project activities, thus reducing the risk factor associated with the earlier, shorter schedule. The initiation of site activities on October 1 of

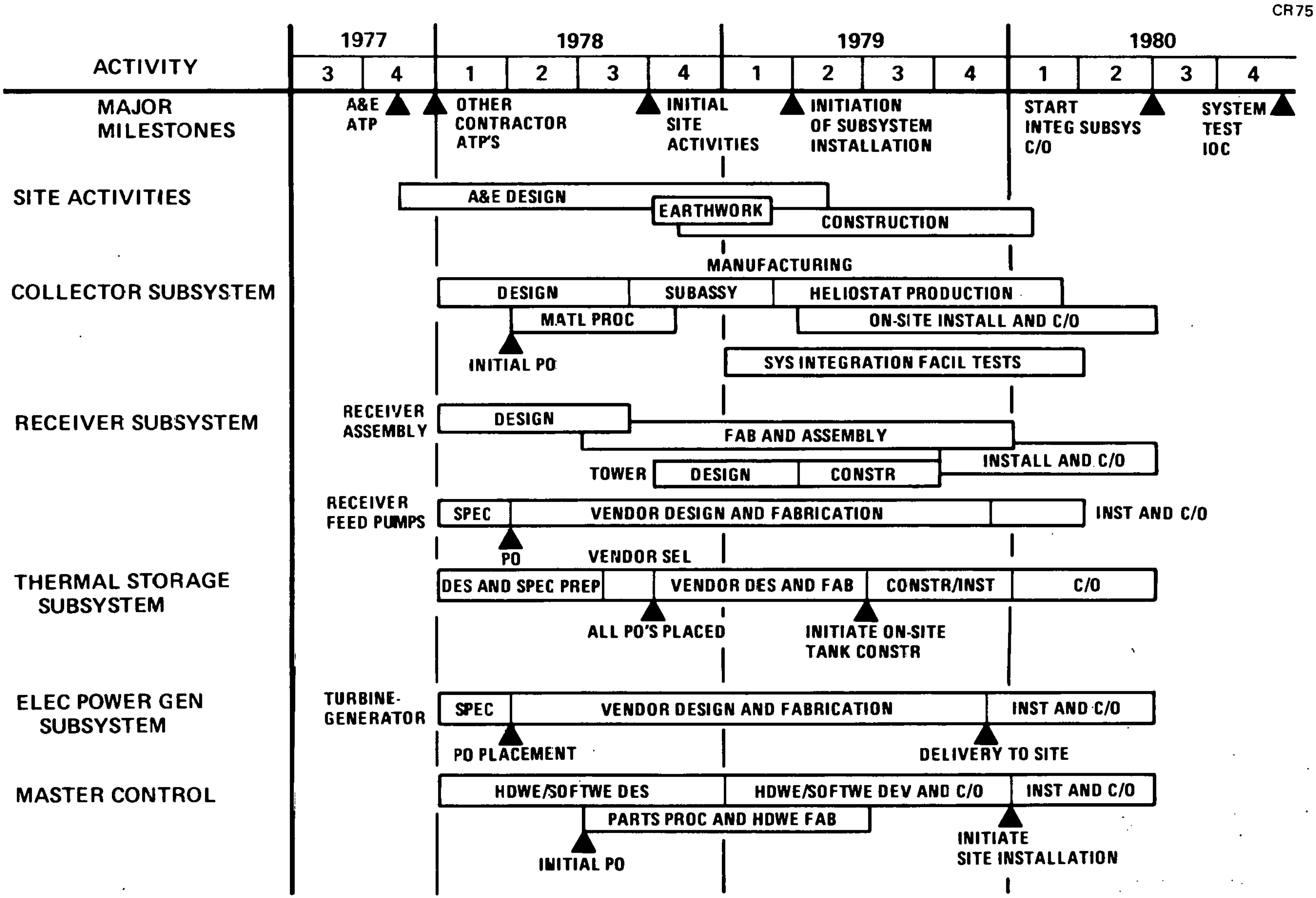


Figure 2-8. Current Pilot Plant Project Schedule

1978, as compared to an original schedule for January 15, 1979, provides considerable relief in that the tower construction, heliostat foundation installation, and turbine building construction can be accomplished in a timely manner for allowing initiation of receiver installation, heliostat installation, and turbine-generator installation. Additionally, deferral of initial integrated subsystem checkout from January 15, 1980 to July 1, 1980 allows sufficient time for installation of appropriate subsystem hardware. This revised schedule also allows all long-lead time item procurement activities to be deferred until the program ATP's occur, while still meeting hardware availability dates required.

Section 3

COLLECTOR SUBSYSTEM

3.1 DESIGN SUMMARY

The collector design is illustrated in Figure 3-1. The heliostat is designed to meet a 3 miliradian slope error in winds up to 11.6 m/s (26 mph) at any orientation and to survive winds up to 46.5 m/s (104 mph) in a stowed position. The complete collector is designed to survive temperatures from -30°C (-20°F) to 60°C (140°F) and meet performance specifications from 0°C (32°F) to 40°C (104°F). The heliostat is designed for 0.33 g's seismic loads, hail up to 25 mm (1 inch) diameter, blowing dust at 10^{-3} kg/m^3 at 14 m/s (31 mph), ice loads up to 50 mm (2 inches) and snow loads up to 0.3 m (12 inches).

The reflective surface is a mirror made from 6.35 mm (1/4 inch) float glass

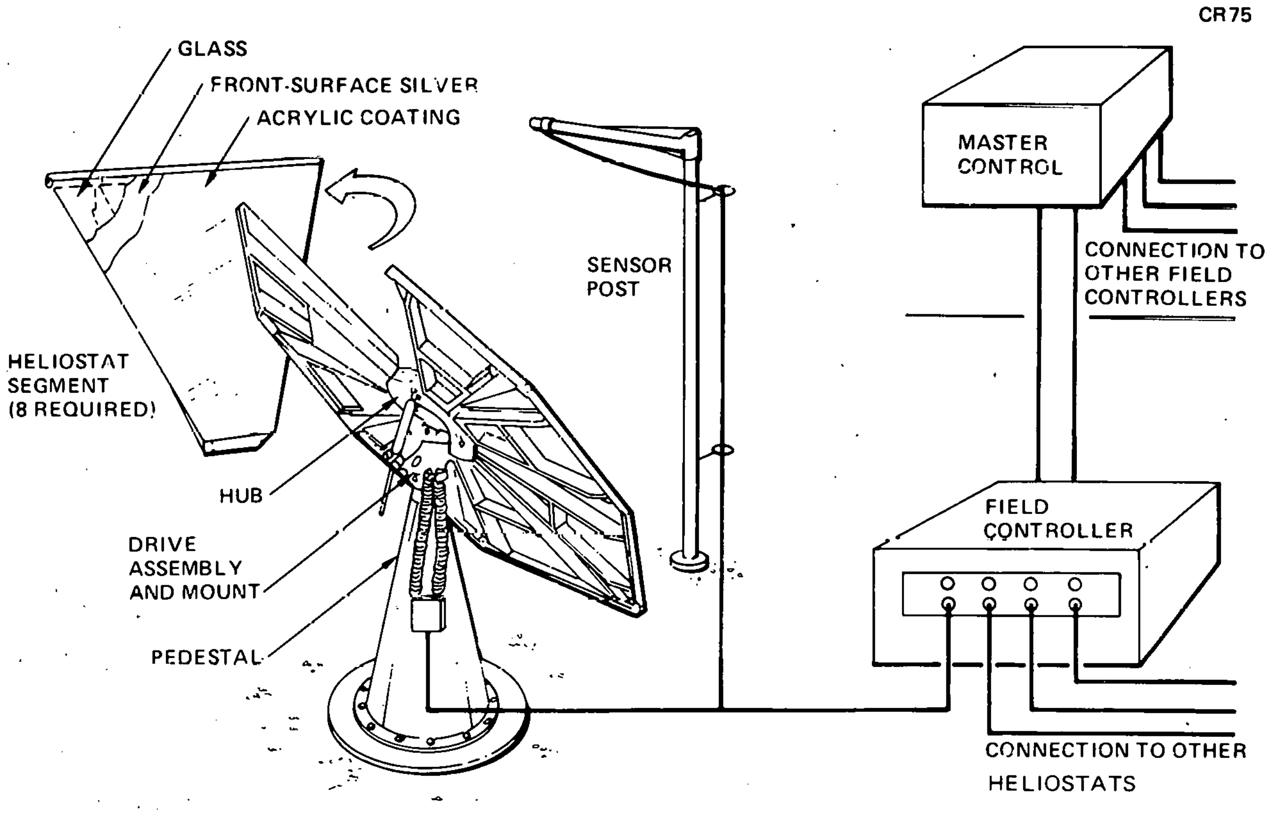


Figure 3-1. Collector Subsystem

with a chemically deposited silver front surface reflector, protected by a thin layer of acrylic. The reflectivity of mirrors made in the first run at a commercial mirror plant showed a specular reflectivity from 0.88 to 0.90. The reflective surface is supported by a steel channel beam frame. Eight trapezoidal mirror segments are bolted to a central hub to form the complete reflector.

The reflector is mounted on an elevation/azimuth drive unit which is in turn supported by a central pedestal. The drive unit employs a linear machine screw jack for elevation motion and a rotary drive with a 242:1 harmonic drive output stage for azimuthal rotation. Both drive axes employ 230 volt, 3-phase AC motors for drive unit actuation. The drive unit incorporates position potentiometers to provide for closed loop commanded steering and provide data for error signal conversion from beam sensor axes to gimbal axes.

A separate pole mounted beam sensor provides tracking error data for closed loop feedback control during normal tracking.

Control signals are generated by a field controller which provides control on a time-sharing basis for 24 heliostats. The field controller multiplexes the heliostat controls sensor data and converts these data to proportional error signals. A 3-phase AC power bus provides alternate cycles of clockwise and counterclockwise motor power and is connected to the drive motors to provide the correct proportional control motor rotation.

The field controller is slaved to the master control to provide coarse tracking data and to direct the field controller to normal tracking or commanded steering.

3.2 SRE FABRICATION

Hardware is nearing completion for the Collector Subsystems Research Experiments. The schedule for SRE hardware production is summarized in Figure 3-2. Reflective surfaces were successfully produced in a trial run on April 18 and a subsequent production run on May 16. A typical reflective surface is shown in Figure 3-3. Also shown is the reflector support structure bonded to the reflective surface. Some of the details of the support structure

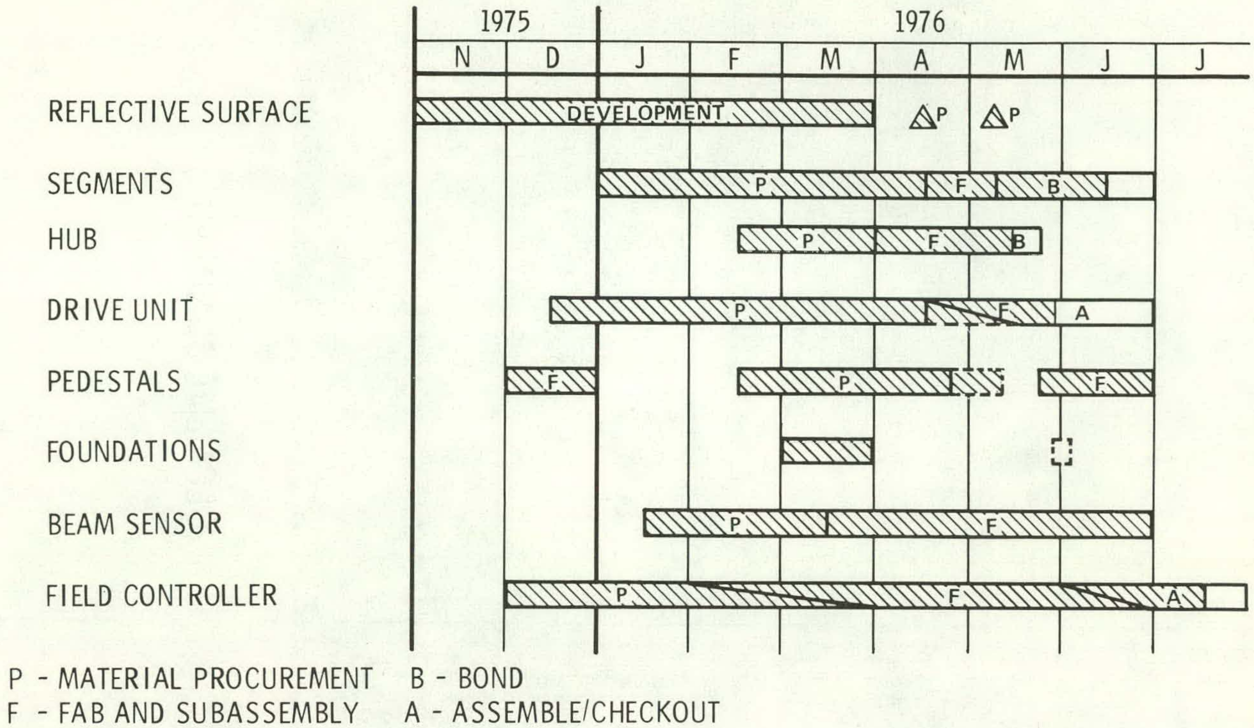


Figure 3-2. Collector SRE Hardware Production

can be seen in Figure 3-3. The main channel beams are stabilized by a cross beam near midspan. The square box beam at the outboard edge of the mirror protects it and provides additional support for the reflector. The attach fittings at the inboard end of the main beams can also be seen.

A partially assembled reflector hub is shown in Figure 3-4. The tee frame which supports the drive unit attach points is seen in the open bottom side of the hub. The interior is painted to prevent corrosion, and the hub is then closed to complete the structure.

The elevation azimuth drive unit schematic is shown in Figure 3-5. The harmonic drive is seen as the output stage of the azimuth drive. The linear actuator is shown in its retracted position. The two drive motors employ motor mounted gear heads with a 30:1 reduction ratio. The major drive unit components are shown in Figure 3-6. The housing on the left is a built-up structure which simulates the deep-draw-pressed structure of the pilot plant design. The components shown are the linear actuator (top), the drive motors (left), the bellows boot which encloses the extended linear

REFLECTIVE SURFACE

SEGMENT BONDING

Figure 3-3. Reflective Surface and Segment

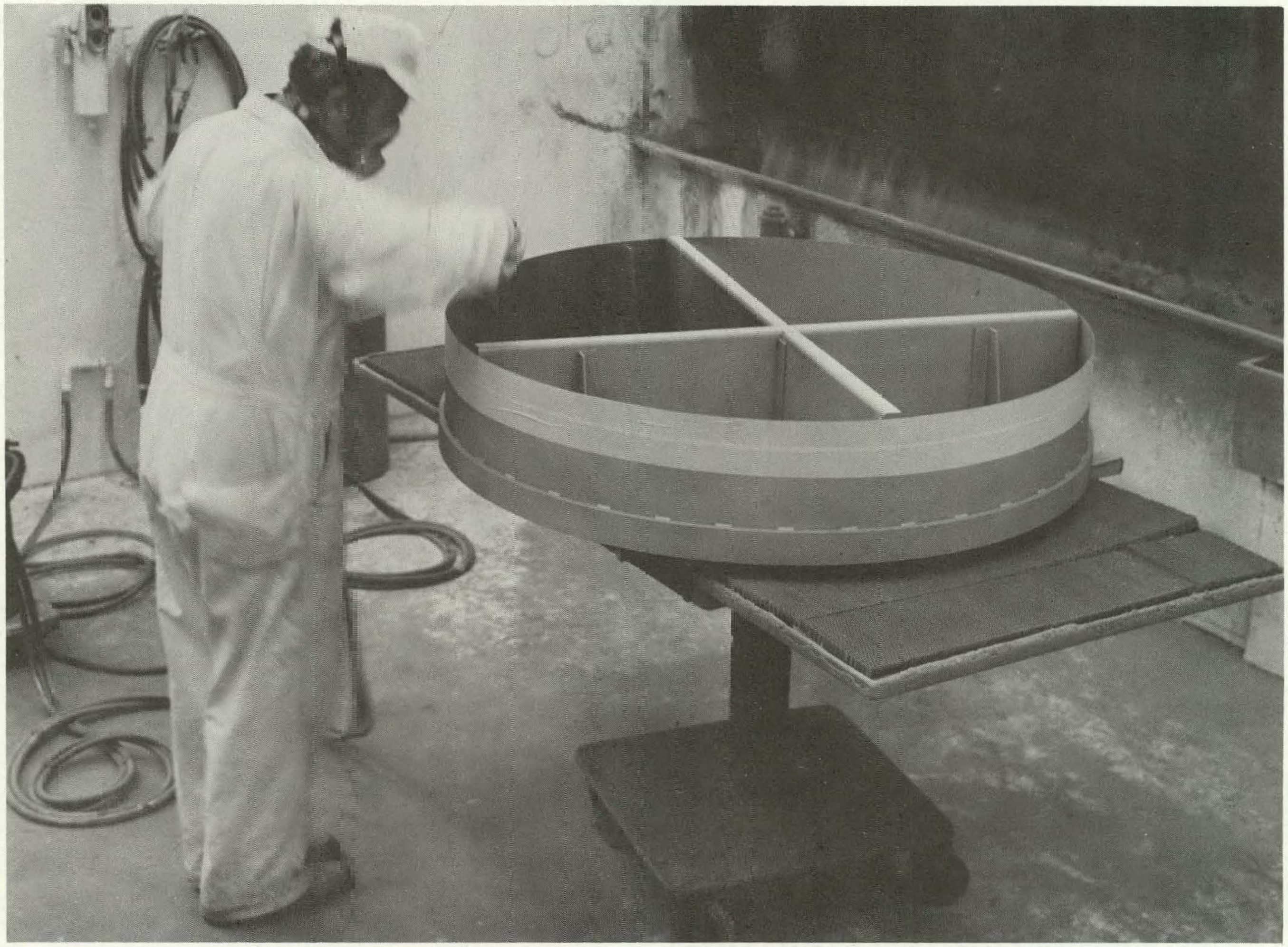


Figure 3-4. Hub

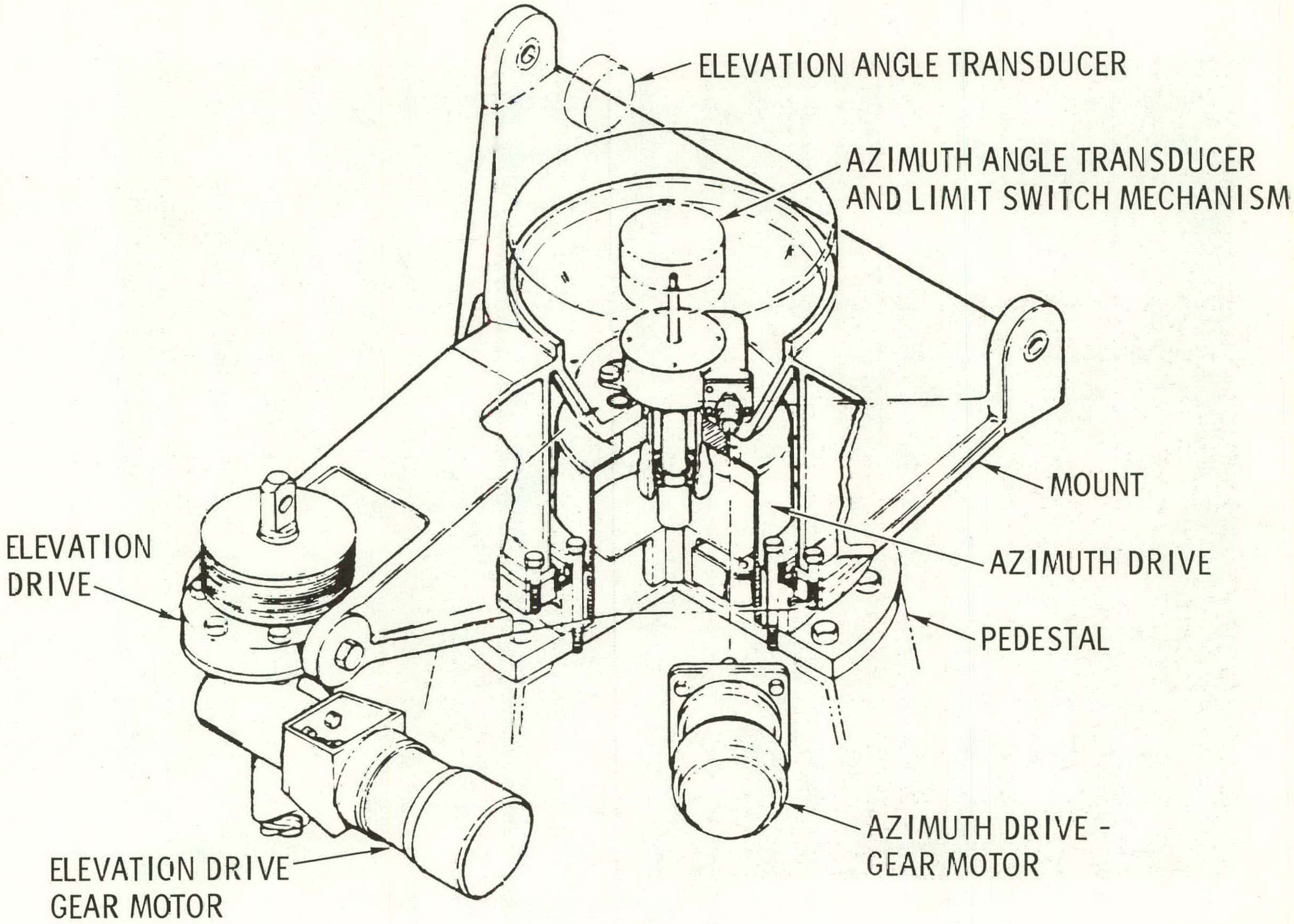
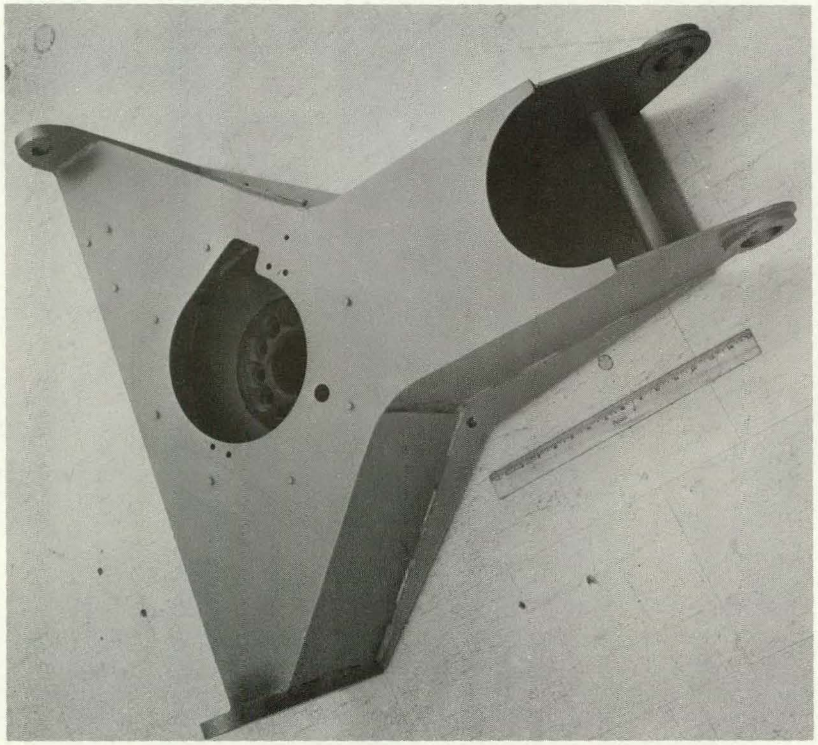


Figure 3-5. Elevation – Azimuth Drive Unit



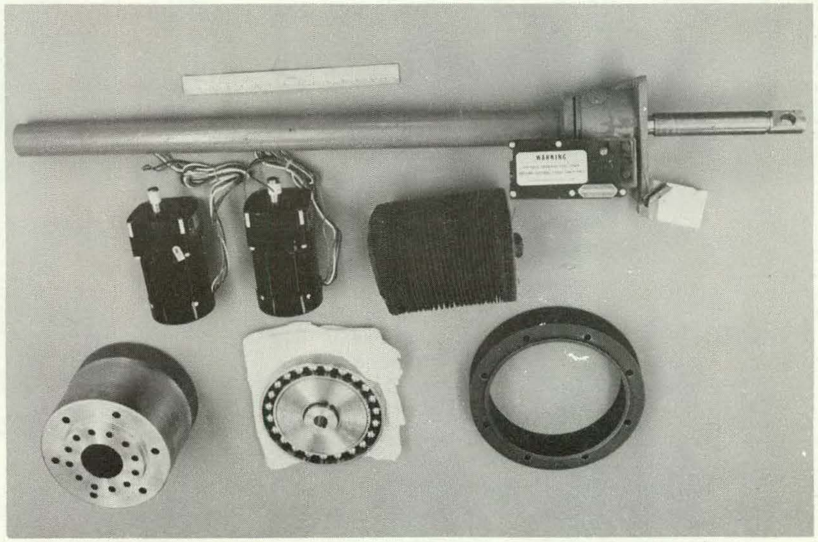


Figure 3-6. Drive Unit Hardware

actuator (right), and the flex spline, wave generator, and circular spline from left to right across the bottom. The first two drive units have been completely assembled and subassembly is complete on the remaining units.

Beam sensor fabrication is essentially complete, pending completion of checkout tests on the initial units. The beam sensor poles were fabricated in December 1975.

The partially assembled field controller and interface set are shown in Figure 3-7. The interface set (left) contains a key board for program development and checkout, as well as a paper type reader for program input. The controller interface, microprocessor and motor controller will be rack-mounted in the instrumentation van during tests of the heliostat.

3.3 SRE TESTING

The Collector SRE test program is just beginning at the end of June. The first test scheduled is structural static test. A complete heliostat has been assembled in the MDAC Structures Laboratory at Huntington Beach. The final stage of assembly of the reflector segments to the hub and drive unit is shown in Figure 3-8. Seven of the eight segments have already been assembled onto the hub. The eighth segment is being positioned onto a dolly preparatory to being rolled into place for attachment to the hub. The reflector is being assembled on the trailer which will subsequently support the mobile heliostat during the heliostat array tests at Naval Weapons Center. After assembly, the reflector and drive unit are lifted by a crane onto the pedestal and bolted in place.

The structural static test will verify the operational deflections of the reflective surface under combined wind and gravity loading and the survival strength under maximum wind conditions. A subsequent vibrational test will determine vibrational frequencies and damping characteristics of the lower frequency vibrational modes.

The second test to be conducted is a development test on the collector controls system. Early phases of this testing were begun ahead of schedule on the partially assembled field controller to verify internal interfaces. The field controller and a complete heliostat will be set up in the MDAC Solar

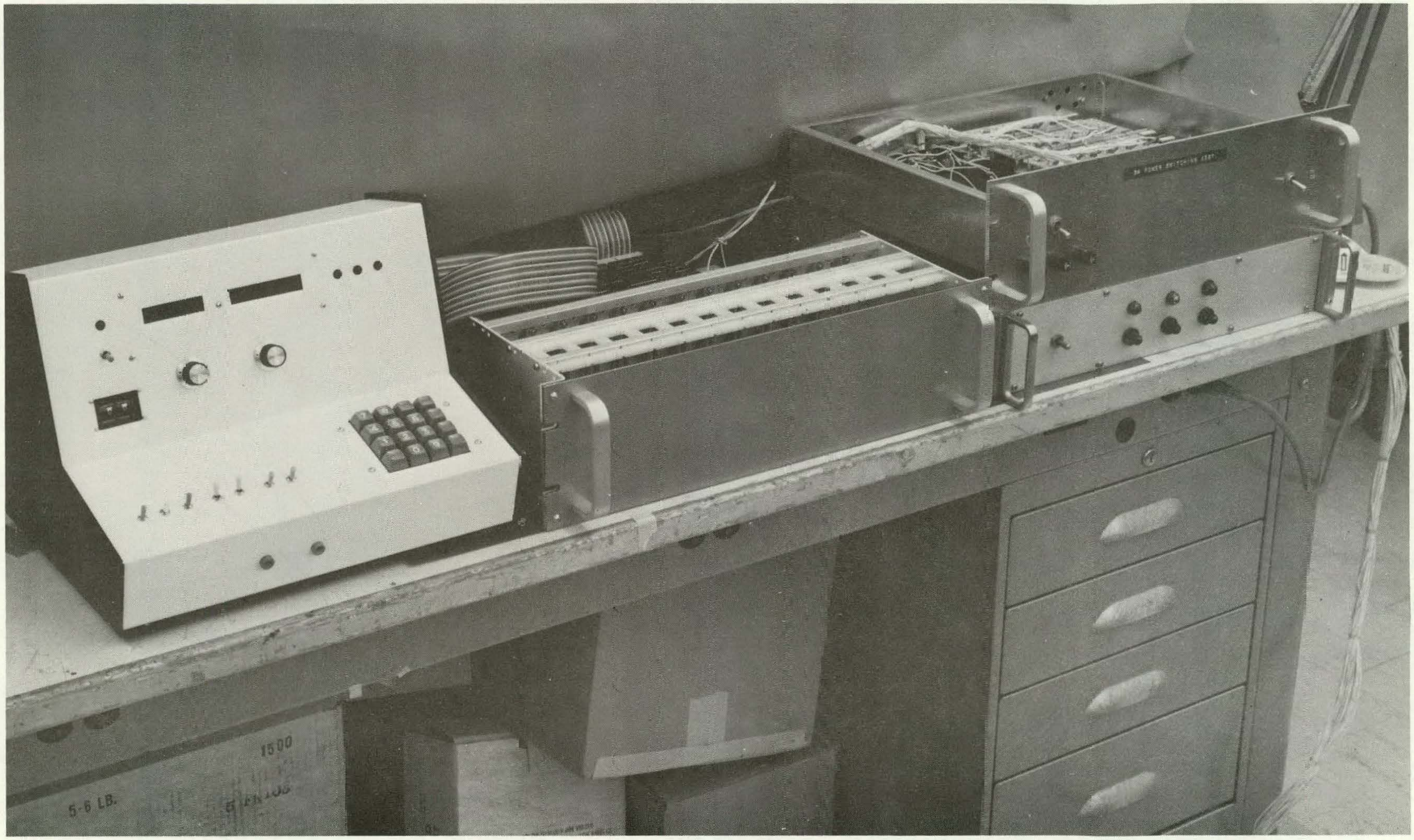


Figure 3-7. Field Controller

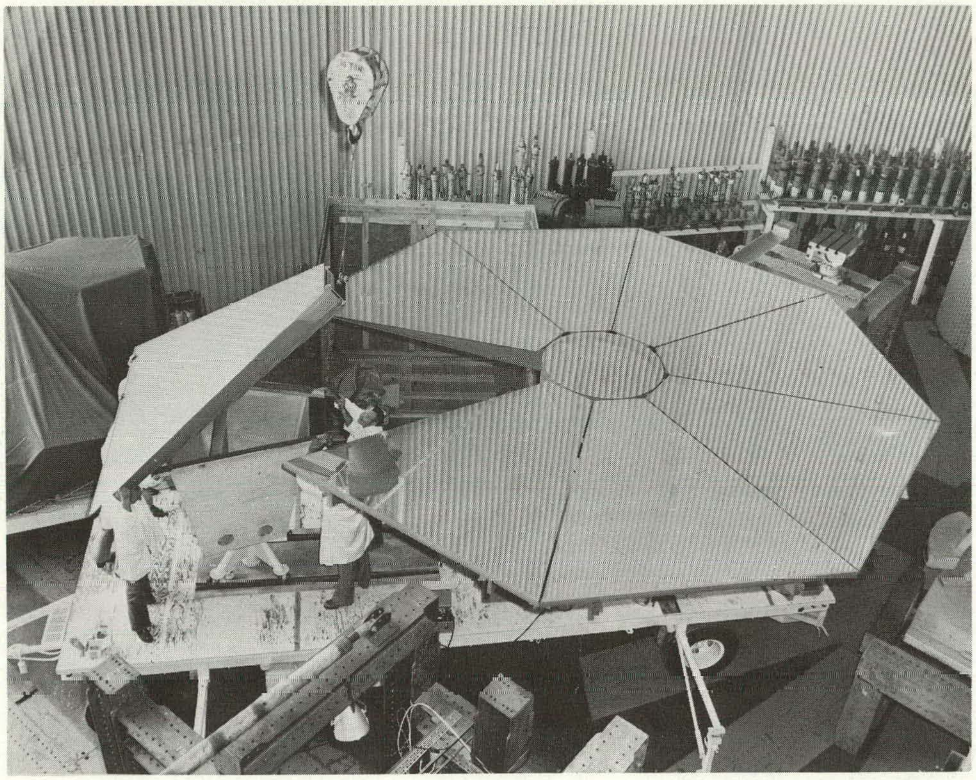


Figure 3-8. Structural Static Test Heliostat

Integration Laboratory at Huntington Beach, and the complete functioning of the collector will be checked out, including tracking performance, controls interfaces, and collector operating modes.

In parallel with, and subsequent to, the above tests, a series of environmental/preliminary qualification tests and life tests will be conducted on critical components of the heliostat. These tests will be conducted primarily at facilities at MDAC, Huntington Beach. These tests will verify the design adequacy of the drive unit, the controls sensors, the reflector structure, and adhesive bond and the reflective surface.

The tests will culminate in a subsystem level test at the Naval Weapons Center, Randsburg Wash test site, China Lake, California. The primary test objectives are: to demonstrate simultaneous tracking of multiple heliostats; demonstrate tracking at positions of extreme range, tracking angles, and tracking rates; demonstrate multiple heliostat characteristics, including beam overlap/shading & blocking, and to a limited degree, array aerodynamic effects; to measure beam power and distribution; and to gain data on assembly, operations and maintenance procedures.

The site plan schematic of Figure 3-9 shows the array test arrangement at Randsburg Wash. The twin range towers are used to suspend an elevated target from 250 to 300 feet above the ground. An emplaced array of heliostats is used to obtain data for multiple heliostat operation. Mobile heliostat locations are indicated at positions of long range, severe tracking angles and high tracking rates.

3.4 OVERALL SRE SCHEDULE

The Collector SRE schedule is shown in Figure 3-10. The schedule calls for the structural and environmental/preliminary qualification tests to begin in late June and the controls development tests to begin the first of July. The test program appears to be on schedule and no delays are anticipated.

During the third quarter of 1976, the structural and vibrational tests will be completed, as will the controls development tests. The environmental/ preliminary qualification tests will be well underway. Life tests will be begun. Assembly of the emplaced heliostats for the array tests should be completed and the array tests ready to begin.

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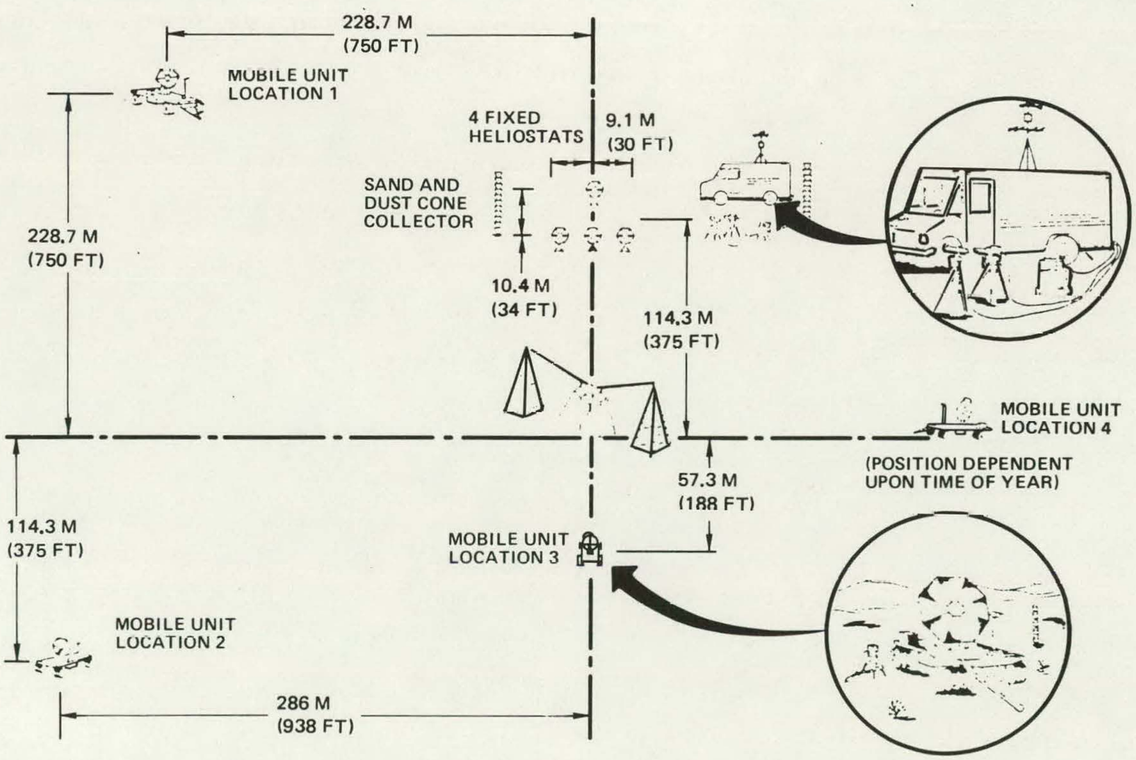

Figure 3-9. Heliostat Array Test Locations

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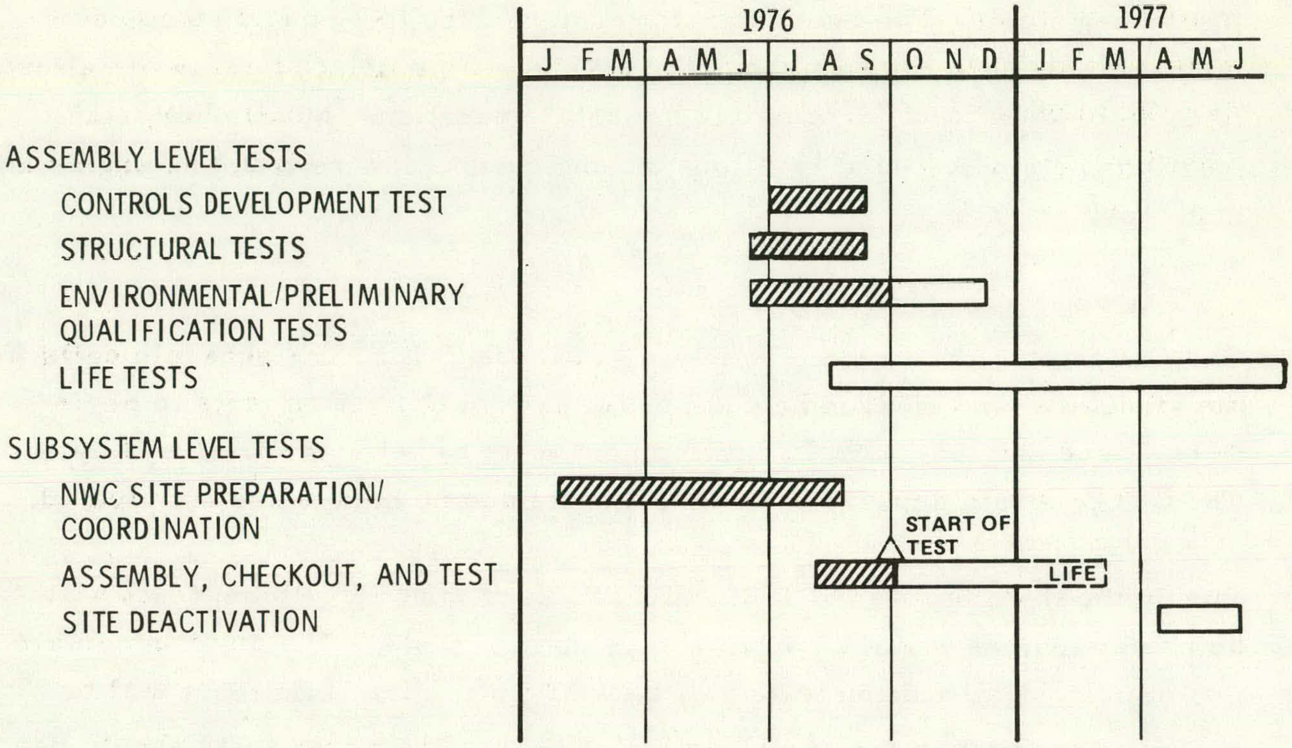


Figure 3-10. Collector SRE Test Schedule

Section 4
RECEIVER SUBSYSTEM

Fabrication of the subsystem research experiment (SRE) test hardware and test facilities and initiation of the single tube tests at the B-1 facility have been the primary activities during the report period.

The fabrication of the single tube test article and its installation into the test facility have been completed and the progress on the 5 tube and 70 tube receiver panels remain on schedule.

Buildup of the B-1 test facility for the single tube tests was completed and single tube test article installation was accomplished during the latter part of June.

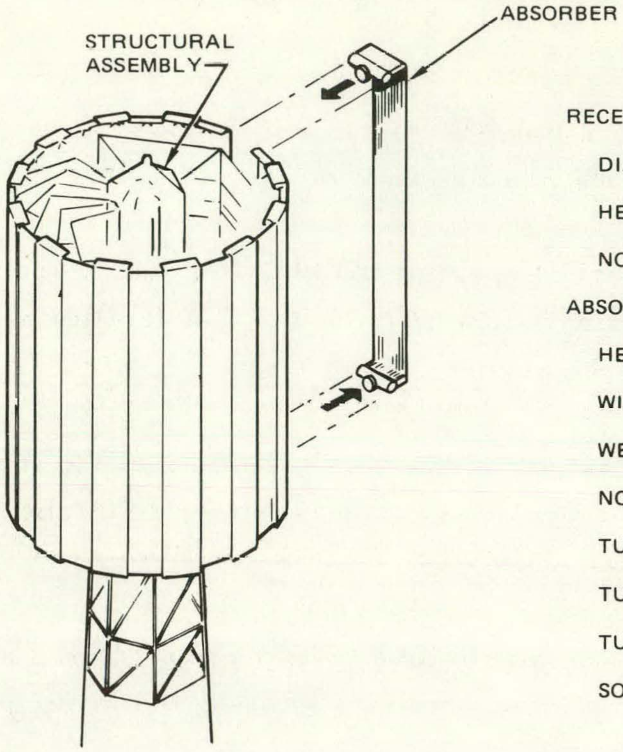
4.1 DESIGN SUMMARY

4.1.1 Baseline Design

Although the design of the baseline pilot plant receiver subsystem remains essentially as described in the previous technical progress reports, and summarized in Figure 4-1, continuing system analyses have indicated several cost-saving modifications which have been incorporated.

Recent structural analyses have shown that the lower end panel support bracketry could be eliminated. This modification has been incorporated into the design along with a more easily fabricated version of the transverse beam assembly.

The pilot plant receiver design originally called for S-31 paint on the surface of the receiver panels to enhance the absorption of solar insolation. The continuing pursuit of innovations to reduce pilot plant costs recently revealed an absorptive coating which has significant cost and operational advantages over S-31.



RECEIVER UNIT ASSEMBLY	
DIA	7.0M (23 FT)
HEIGHT	24.4M (80 FT)
NO. OF ABSORBER PANELS	24
ABSORBER PANEL	
HEIGHT	17.1M (56 FT)
WIDTH	1M (3.3 FT)
WEIGHT	1,816 KG (4,000 LB)
NO. OF TUBES	70
TUBE OD	1.27 CM (0.5 IN)
TUBE ID	0.68 CM (0.269 IN)
TUBE MATERIAL	INCOLOY 800
SOLAR SURFACE COATING	PYROMARK

Figure 4-1. Receiver Configuration

The candidate coating has the trade name "Pyromark" and is manufactured by the Tempil Corporation, 2901 Hamilton Blvd., South Plainfield, New Jersey 07080. Pryomark has been in commercial use for various applications for many years, including extensive use at the Rockwell Thermodynamics Laboratory.

Simultaneous absorptivity comparisons by TRW, Inc., of two samples of each paint showed a broadband solar absorptance of 0.954 for Pyromark and 0.935 for S-31. The greater absorptance of Pyromark will produce significant savings in pilot plant collector field cost.

Tubes of Incoloy 800 painted with both S-31 and Pyromark and cured according to manufacturer's specifications have been thermally cycles between 138°C (280°F) and 607°C (1125°F) to simulate receiver operation for one year. The test apparatus, shown in Figure 4-2, consisted of uncooled, electrically heated tubes. Approximately five percent of the S-31 paint was lost by flaking off during 300 cycles. Initial pyromark samples experienced approximately a two

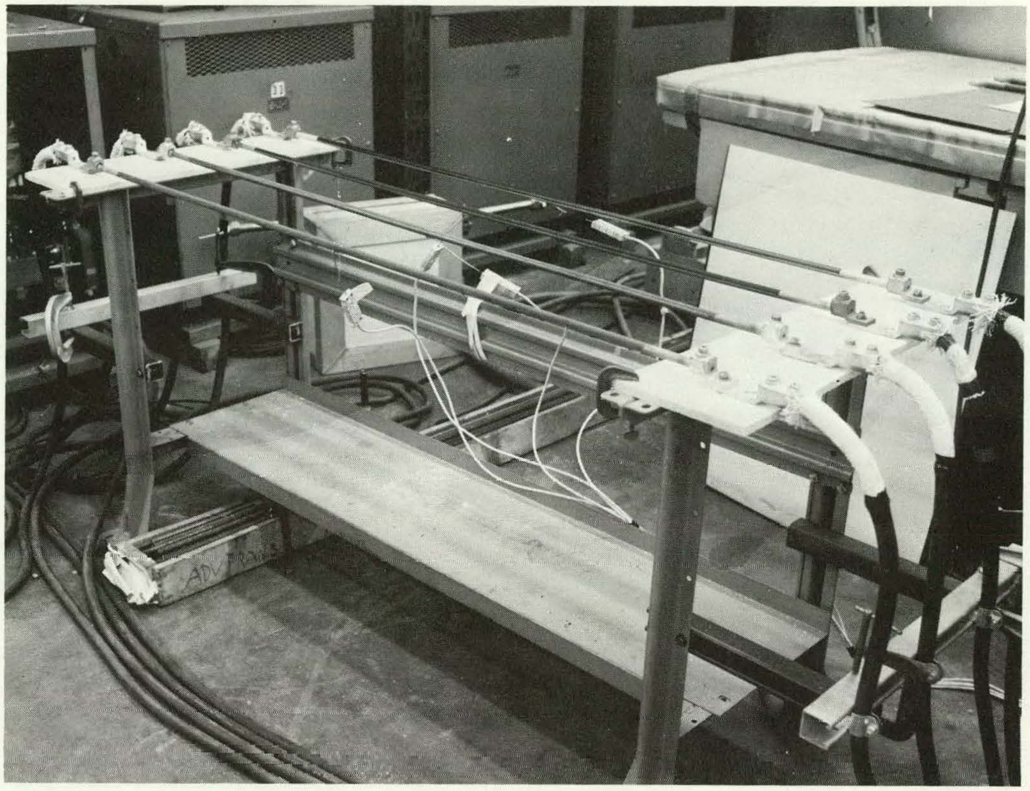


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Figure 4-2. Thermal Cycling Test Fixture

percent loss over 300 cycles. However, where the Pyromark was applied within six hours following grit blasting, no deterioration was detected after 318 thermal cycles. (Figure 4-3.) All samples were subjected to overly severe water spray during the tests with no apparent effect on either paint.

The initial application and curing process for Pyromark also offers significant manufacturing and operational advantages over that required for S-31. Although both paints require elevated temperature curing at 316-538°C (600-1000°F) to assure maximum durability, Pyromark is considerably easier to handle, since it will air dry while S-31 will not. This feature of Pyromark offers the potential of eliminating the necessity for 18.3m (60 ft) paint curing ovens during manufacturing and permitting initial coating and subsequent refurbishment on the receiver tower with elevated curing provided by heliostat directed insolation.

Consideration of the above data has resulted in the selection of Pyromark as the baseline material to provide a high solar absorptivity for the solar

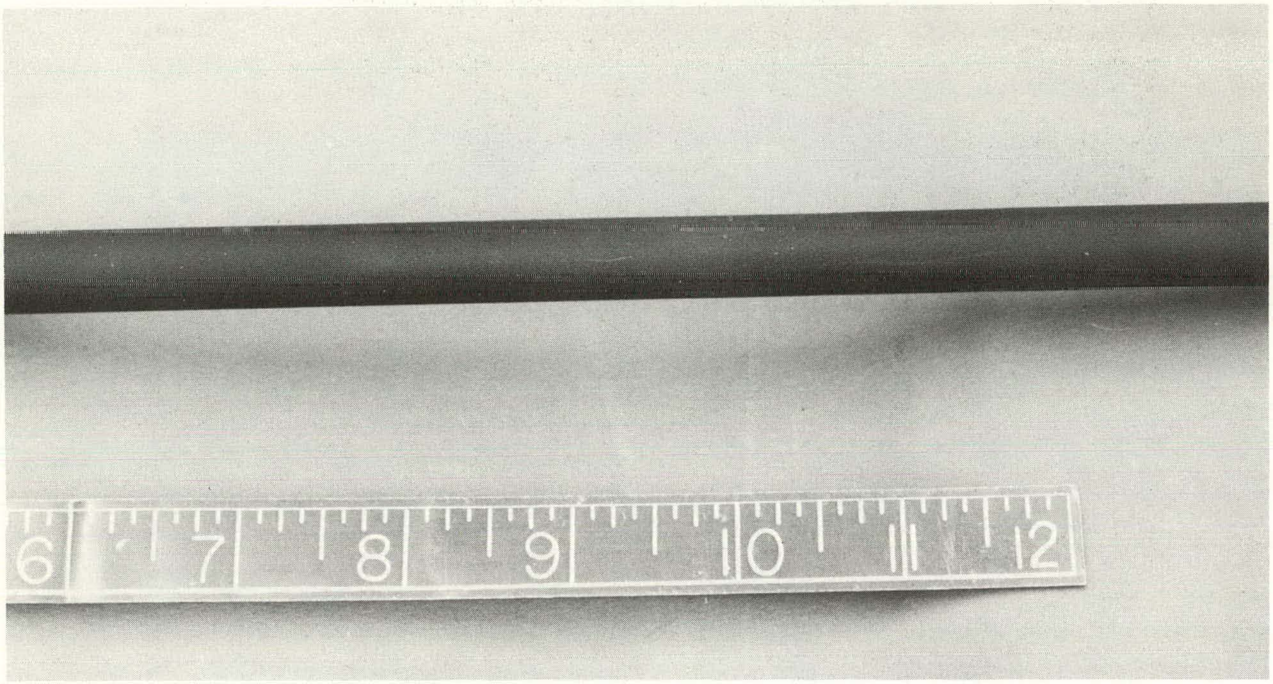

Figure 4-3. Pyromark After 318 Cycles

receiver. All SRE hardware will be painted with this material. The absorptivity sample to be evaluated at White Sands will be painted with both Pryomark and S-31.

4.1.2 Preliminary Design Analysis

In an investigation of methods to reduce heat losses from the baseline receiver configuration, preliminary analysis of a modified receiver using a north heliostat field was conducted during the report period with thermal input data furnished by the University of Houston. Peak heat flux for this heliostat configuration is 2 times that for the baseline. The receiver has 11-13 panels which are the same size as those on the baseline receiver. The northern 7 panels are boiler/superheaters while the 2-3 panels on the eastern and western extremes are preheaters. Water from the riser is split by a diverter valve to the eastern and western preheaters. After passing through the preheaters in series on each side, the preheated water is combined in a manifold common to the boiler/superheater panels which are in parallel as in the baseline design. The diverter valve regulates eastern and western flows so that the preheater outlet temperatures are equal even though eastern and western preheater thermal inputs vary considerably. This is necessary to prevent boiling in the preheaters.

The results of the preliminary analyses indicate that the required control ranges for the diverter valve and the boiler valves are reasonable if throttlable pumps are used. The tubes on the panel with peak heat flux will operate at about 649°C (1200°F) and will have to be evaluated in more detail to assure compatibility with safety and life requirements. An instantaneous loss of water would result in 1093°C (2000°F) tube temperature in about 1/2 minute under maximum flux conditions.

Gradients are much more severe than on the baseline receiver. The panel producing rated steam at 516°C (960°F) as an average output under maximum gradient conditions would be producing steam at >732°C (1350°F) on its hottest side which implies unacceptable wall temperatures. The panel temperature gradient is also unacceptable for the required life. These gradients occur on the extreme eastern and western boiler panels. Selectively orificing of each tube (or groups of tubes) on these two panels would eliminate the problem. Gradients are less severe on adjacent panels but have not yet been evaluated.

4.2 SRE FABRICATION

Single Tubes

Early in the report period, two single tubes were formed, prepared for orifices, and grit blasted. Bosses for pressure and fluid temperature measurements were added and the tubes were shipped to the Rockwell Thermodynamics Laboratory.

One of the single tubes has been painted with Pyromark, instrumented, and provided with sliding feet to accommodate thermal expansion as shown in Figure 4-4. The single tube has since been installed into the test facility and testing has begun as discussed in Section 4.3.

5 Tube Panel

Fabrication of the 5-tube panel is nearly complete. Completion of this panel has been delayed primarily so that the major effort could be placed on

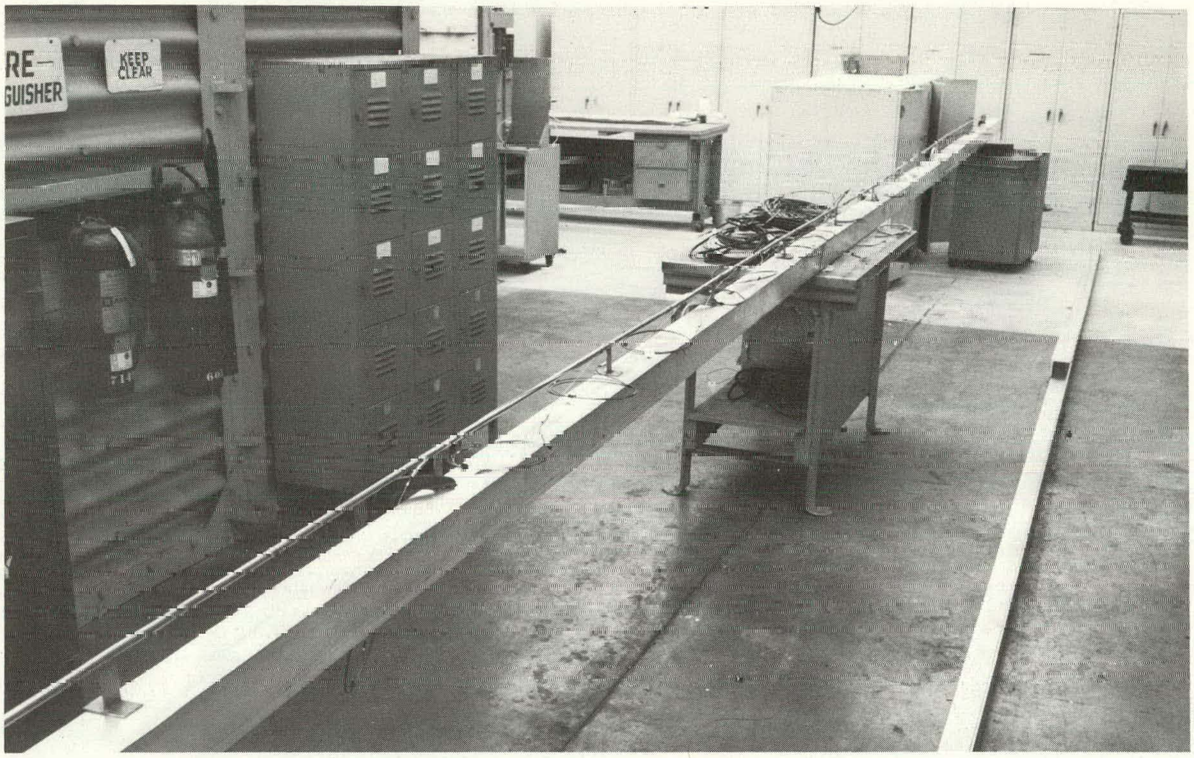

Figure 4-4. Single Tube Instrumented and With Sliding Feet

keeping the 70-tube panel on schedule since the test facility is not yet ready to accept the 5-tube panel. All welding has been completed and inspected (tubes, manifolds, pipes, structure) except for the stop valves required to define the limits of the boiler. All subassemblies for the backup structure have been completed. Final assembly, hydrotest, and ASME acceptance is expected during the week of 9 July.

One of the big features of the fabrication process is the seam welding between tubes that provides a light-tight seal such that no structure or functional components located within the receiver will be damaged. This weld is performed at 100 cm/min (40 in/min) on an automatically tracked welding table developed for this program. Figure 4-5 shows the tack-welded tubes in the final stage of preparation for the seam weld. Shown in Figure 4-6 is the welding in progress. The MIG weld head tracks with a wheel which rolls in the tube interstices while the weld wire feeds automatically concurrent with an inert purge which blankets the general area. An excellent quality weld was obtained, the uniformity of which can be seen in Figure 4-7. Fourteen panels

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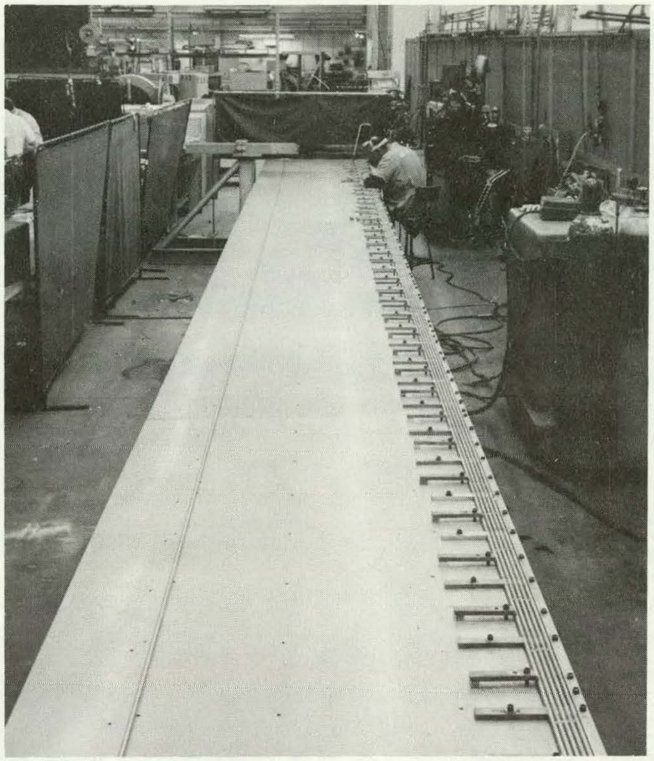

Figure 4-5. Narrow Panel Tube Bundle

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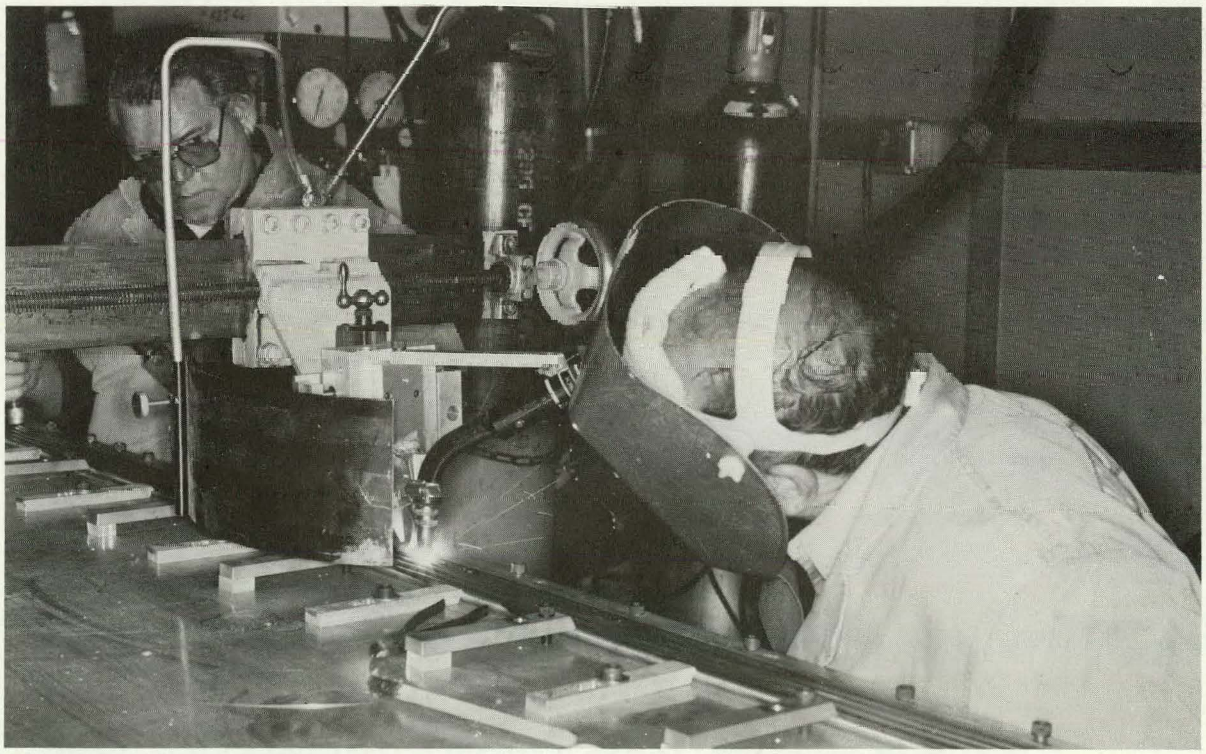

Figure 4-6. Automatic Welding of Five-Tube Panel

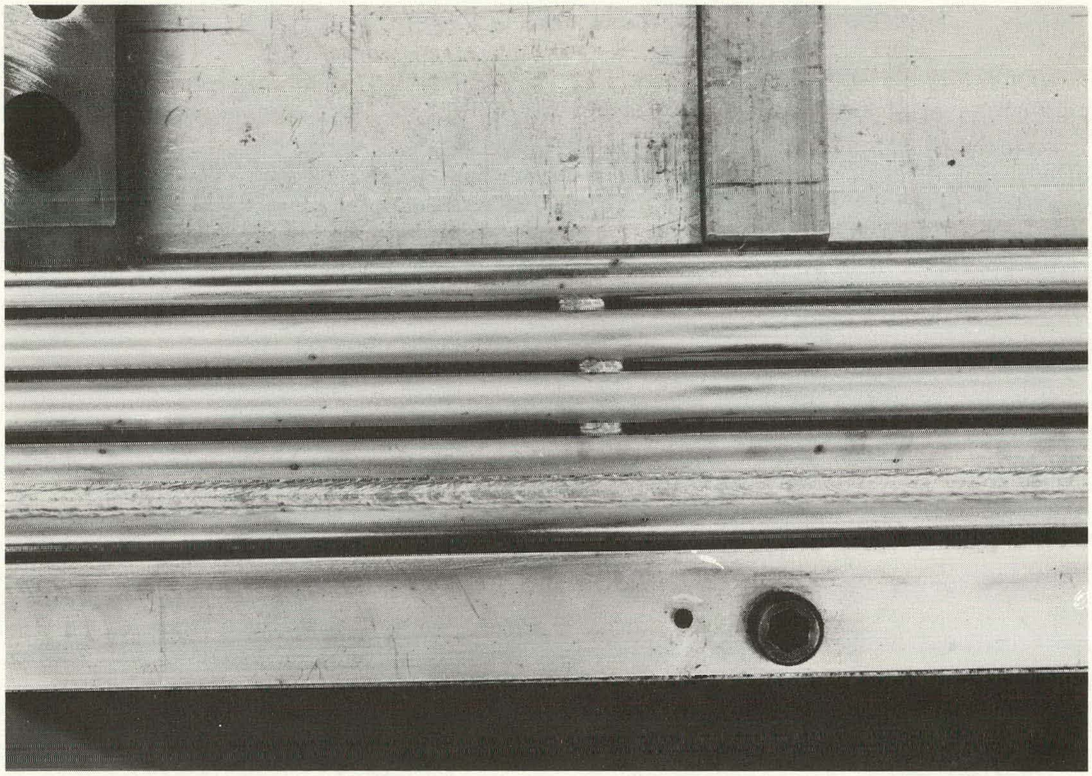

Figure 4-7. Tack Welds and First Weld Pass on Five-Tube Panel

of five tubes each will be joined together in an identical manner to form the full scale pilot plant panel.

Another important feature of the panel is the manifold (or header) which either provides water to or extracts steam from the tubes. A completed manifold for the narrow panel is shown in Figure 4-8. Prominent therein are the tack welds used to hold the parts prior to the root pass weld of the end caps, and the drilled and tapped holes wherein the tubes will fit.

Satisfactory tube-to-manifold rolled joints have been demonstrated for the 5- and 70-tube panels by fabricating a sample joint and pulling until the tube failed outside the joint area. Six samples were tested in this manner before the process was certified for the panel.

The single rail backup structure has been fabricated. The sliding members have been coated with a baked dry lubricant which is predicted to last for the specified life of the Pilot Plant. Instrumentation bosses and clips for attachment of the backup structure have been welded to the back of the tube bundle.

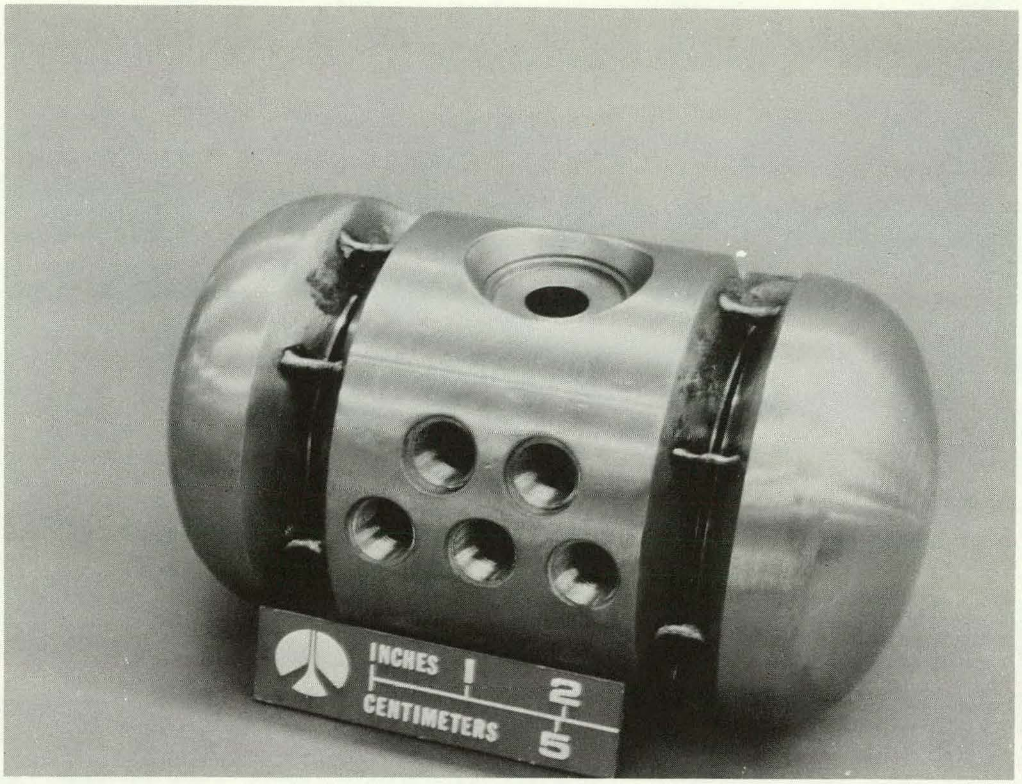

Figure 4-8. Narrow Panel Manifold

70 Tube Panel

All tubes for the 70-tube panel have been cut and formed. Half of the tubes have been tack welded in preparation for the automatic tube welding operation. The water and steam manifolds have been machined (Figure 4-9) and the end caps welded to the half of each manifold which receives the tubes. The scheduled completion date for the 70-tube panel has been advanced from 1 October to 3 September in order to further assure completion of testing on schedule.

Absorptivity Test Article

The absorptivity sample to be tested at the White Sands Solar Furnace has been designed and fabricated. The sample consists of a 2.36 x 3.18 x 20 cm (0.93 x 1.25 x 8 in.) bar which is water cooled by a single 0.74 cm (0.29 inch) diameter passage located 1.9 cm (0.75 in.) below the heated 2.36x20 cm (0.93 x 8 in.) surface. The bar has been grit blasted and will be painted on the heated and unheated surfaces with S-31 and Pyromark paints. Four thermocouples will be installed to measure the heated surface temperature.

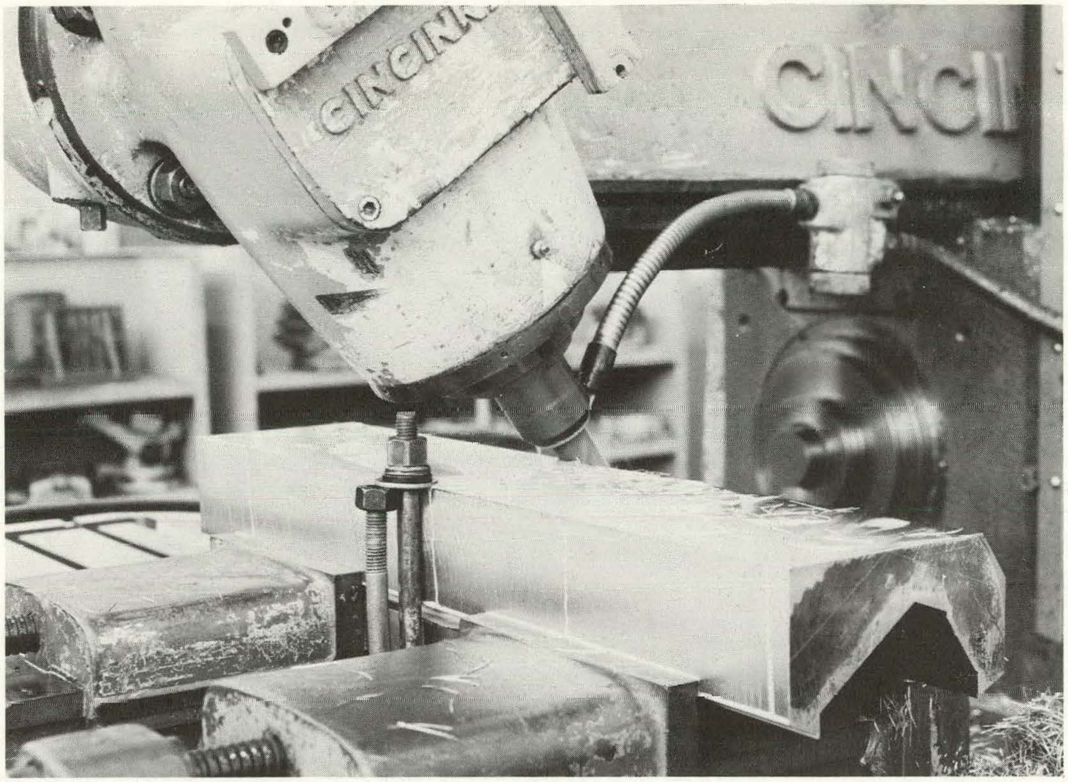

Figure 4-9. Machining Water Manifold for 70-Tube Panel

4.3 SRE TESTING

The primary effort in the testing area has been devoted to preparation of the test facility for the single and five tube panel tests.

The receiver test articles will be tested in the vertical position using graphite strip heaters to irradiate the panel. It was originally planned to accomplish the single and 5 tube tests in the large test tower required for the 70 tube receiver panel tests. However in order to expedite testing of the single and 5 tube hardware, a smaller (about 1 foot square) tower which can be readily erected and lowered for servicing has been constructed which contains the test article and the heater/reflector assembly. (Figures 4-10 and 4-11.)

The small tower has been located on the same foundation upon which the tower for the full receiver segment will be placed.

Fabrication of the larger tower for the full receiver segment tests is also proceeding. The tower will be preassembled in three twenty-foot sections

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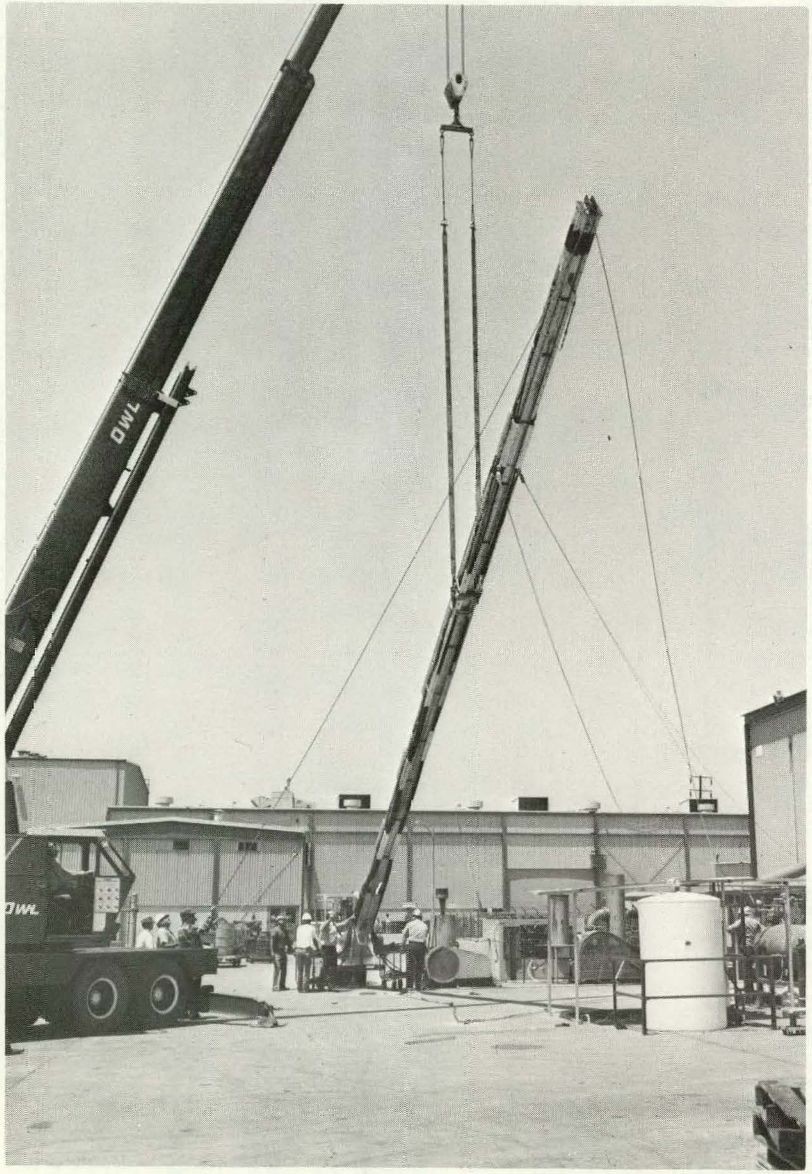

Figure 4-10. Small Test Tower Installation

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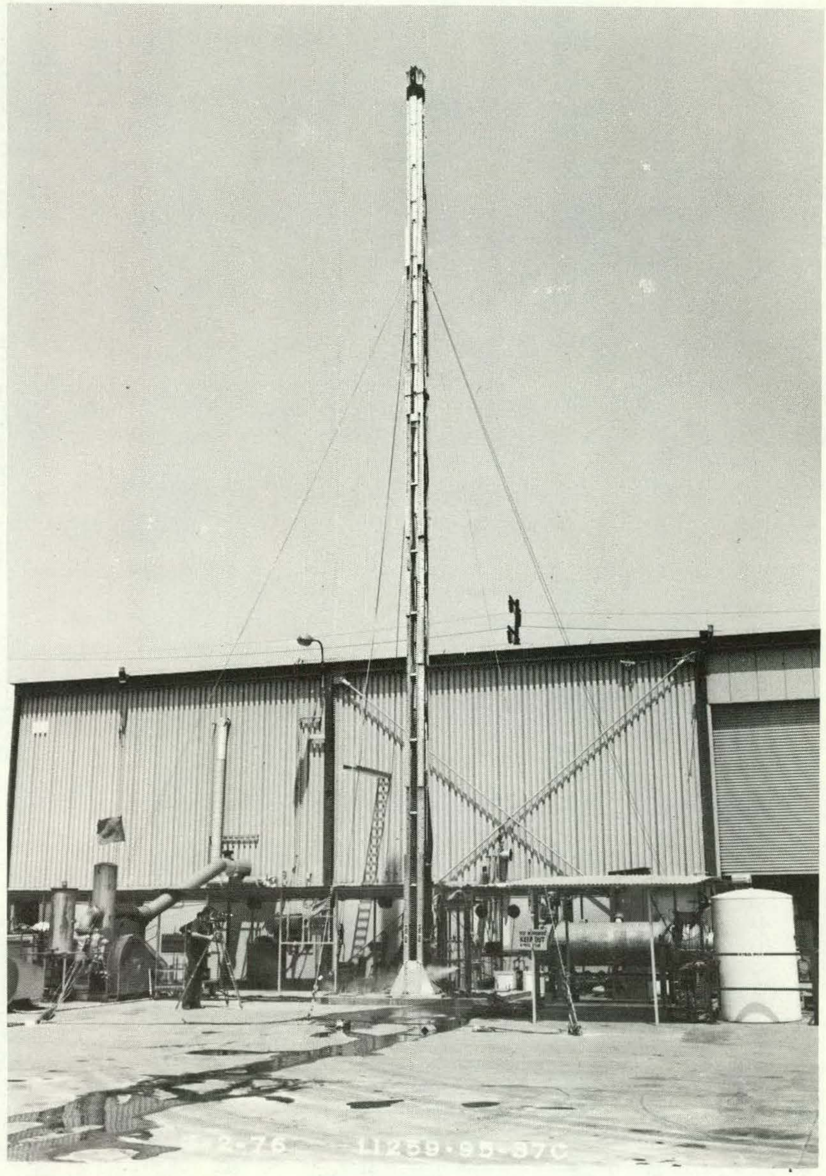

Figure 4-11. Small Test Tower Installed

and subsequently assembled on the foundation. The area in which the tower is being assembled is shown in Figure 4-12.

Fabrication of the plumbing, which will contain in-line heaters to preheat the water to 163 or 204°C (325 or 400°F) is also complete. A facility valve will be used to manually control the back pressure at the exit of the test hardware.

To allay concern over plugging of orifices in the panels, a panel orifice having a minimum diameter of 0.076 cm (0.030 in.) was placed in the recirculating boiler water system and flowed continuously for 340 hours. No detectable variation in flow characteristics (ΔP) was observed. The orifices to be used in the panels will have a minimum diameter of 0.127 cm (0.050 in.).

Single tube testing activities thus far have consisted of only "shake-down" runs conducted without simulating solar heat but flowing hot water through the tube to demonstrate expansion capabilities and checkout instrumentation (Figure 4-13). An upcoming test will be conducted with the radiant heaters providing the maximum southern heat flux profile but with subcooled outlet conditions obtained by not preheating the water and by flowing more than the rated flow. The purpose of this test is an in-place calibration of the heat flux profile using tube temperature instrumentation to determine the enthalpy rise of the fluid as it passes through the heat flux profile.

Some delay has been experienced in the testing of the effects of concentrated solar energy on the absorptance surface at the White Sands Solar Furnace. The delay is caused by a misunderstanding of the channels through which the funding of the facility was to be accomplished and by uncertainty as to whether adequate instrumentation capability could be provided by the facility. It is anticipated that both these problems will be resolved during the next report period. Detailed test requirements have been sent to White Sands.

4.4 OVERALL SRE SCHEDULE

The schedule for completion of fabrication and the test program are shown in Figure 4-14. As noted, the single tube tests have just begun with start of the narrow panel test due to be initiated approximately 1 month later. Completion of the Pilot Plant panel and initiation of the corresponding test program is expected by October 1.

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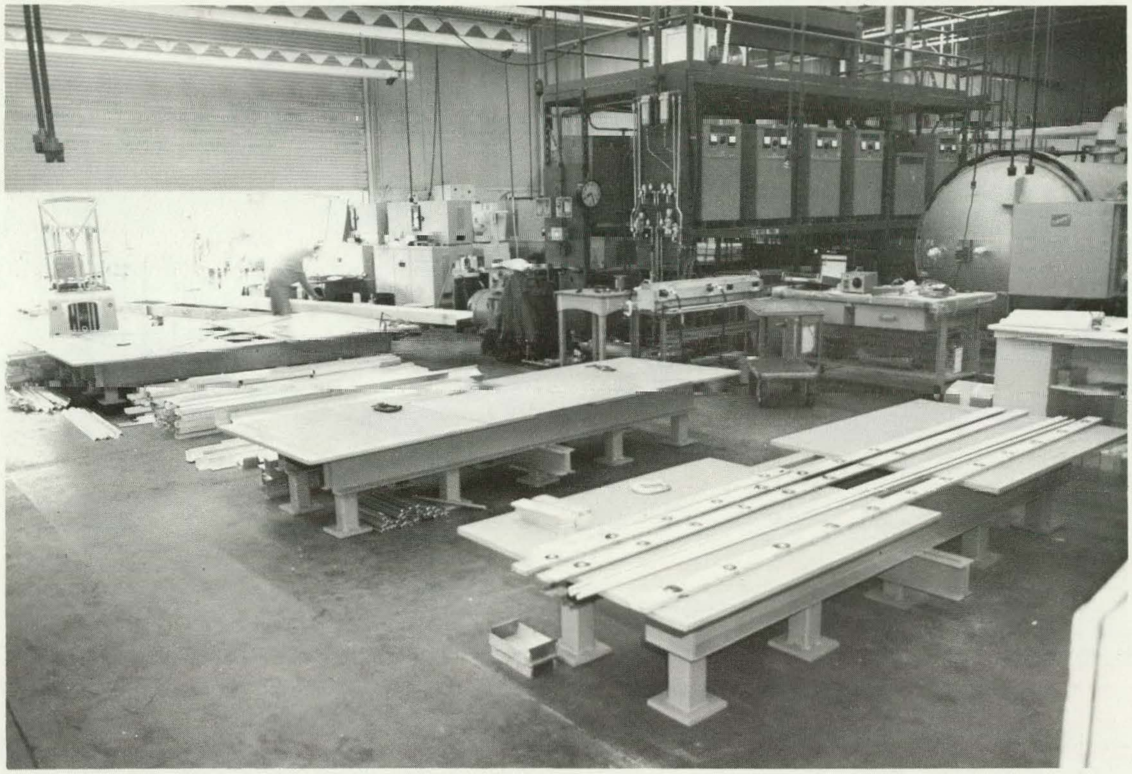

Figure 4-12. Tower Assembly Area

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Figure 4-13. Single-Tube Testing in Progress

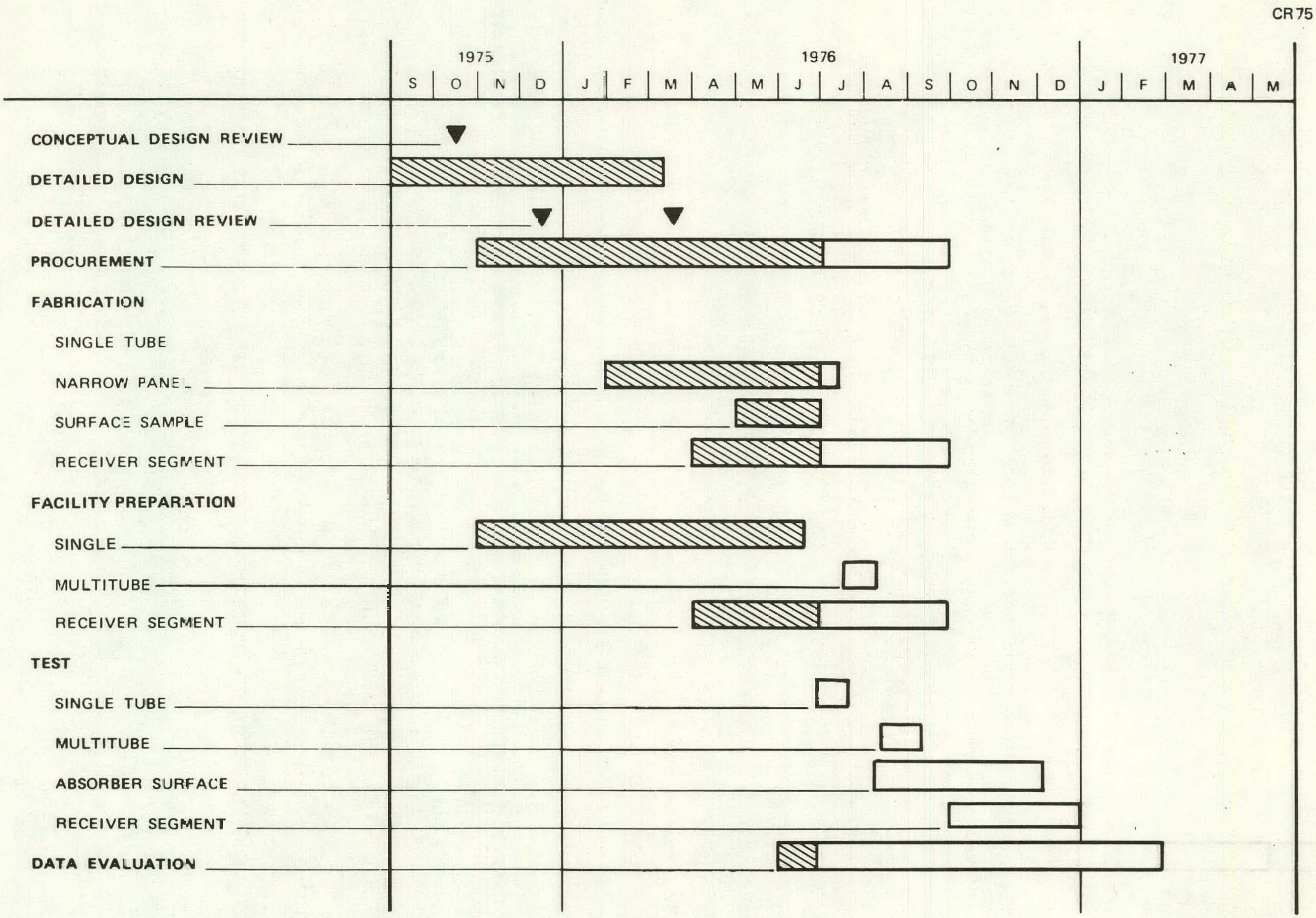

Figure 4-14. Overall Receiver SRE Schedule

Section 5
THERMAL STORAGE SUBSYSTEM

The majority of activities during the report period have involved the fabrication and installation of the subsystem research experiment (SRE) thermal storage tank and the supporting test hardware at the Santa Susana test site.

All major SRE test components have been received, modified or fabricated. The civil/structural work on the test facility is complete. Installation of the thermal storage tank is complete and installation of the remaining components, piping, and instrumentation is proceeding on schedule.

Prequalification tests of the candidate heat transfer fluids continue to yield favorable results.

5.1 DESIGN SUMMARY

The 10-MWe pilot plant TSS employs sensible-heat storage using dual liquid and solid media for the heat storage in a single tank, with the thermocline principle applied to provide high-temperature, extractable energy independent of the total energy stored.

In the cyclical operation, heating of the bed (charging) is achieved by removing 236°C (425°F) temperature fluid from the bottom of the bed, heating it in a heat exchanger with steam from the receiver, and returning 302°C (575°F) fluid to the top of the tank. The fluid flow is reversed for heat extraction (Figure 5-1). Table 5-1 summarizes the principal characteristics of the subsystem and major components.

The detail design of the pilot plant TSS remains essentially as described in the previous quarterly technical progress reports (MDC G6318, January, 1976; MDC G6382, April, 1976) with no changes occurring during the report period.

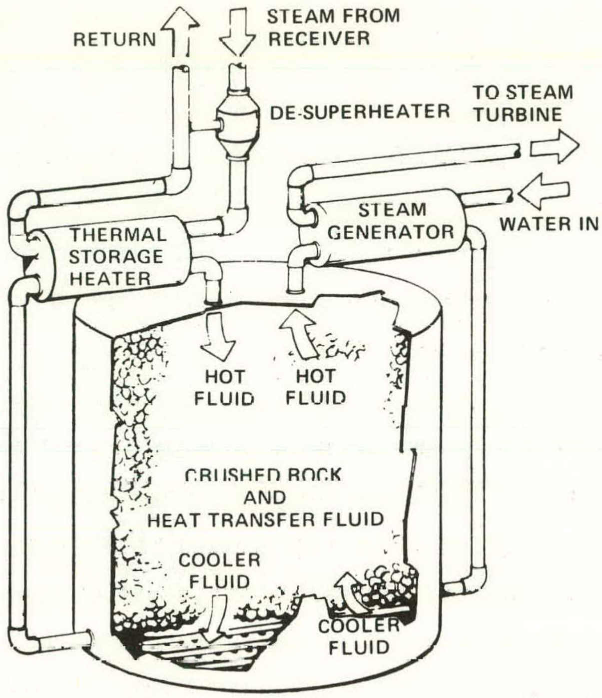

Figure 5-1. Thermal Storage Subsystem

Table 5-1

PILOT PLANT THERMAL STORAGE SUBSYSTEM DESCRIPTION

Assembly	Description
Thermal storage unit	Cylindrical tank, axis vertical, above ground 19.4m (63.7 ft) ID, 17.3m (56.8 ft) high; 9.59 x 10^6kg (10,600 ton) crushed granite rock, 1.18 x 10^6 liters (312,000 gal) of Caloria HT-43; ASTM A537 structural steel.
Thermal storage heater	U-tube, baffled counterflow exchanger, two-pass shell, carbon steel construction.
Steam generator	Drum type, oil-in-tube heat exchanger with separate preheater, boiler, and superheater sections; carbon steel construction.
Desuperheater	Direct contact, water injection type.
Fluid charging/extraction loop pumps	Centrifugal, high temperature.
Fluid maintenance unit	Filtration and vacuum distillation.
Ullage maintenance unit	Storage and control of gaseous nitrogen ullage gas.

5.2 SRE FABRICATION

Fabrication of the SRE thermal storage tank was begun by a commercial tank fabricator early in the report period in accordance with previously approved detailed drawings (Figure 5-2). The tank was constructed by rolling and welding courses of the same structural steel (ASTM 537-70, Grade B) planned for the pilot plant. Tensile pull tests of weld specimens using various weld rods indicated that all welds would meet or exceed design strength properties of the steel.

Cutting of the 1/4-inch plate for the shell fabrication revealed severe laminations in the first of eight sheets. Although laminations do not compromise tensile strength it was determined that thermal cycling could possibly produce local buckling and subsequent growth of the laminated region through a low cycle fatigue mechanism. During heating and cooling severe loads resulting from the high stress concentration at the "infinitely small" radius at the boundary of the laminations could promote propagation

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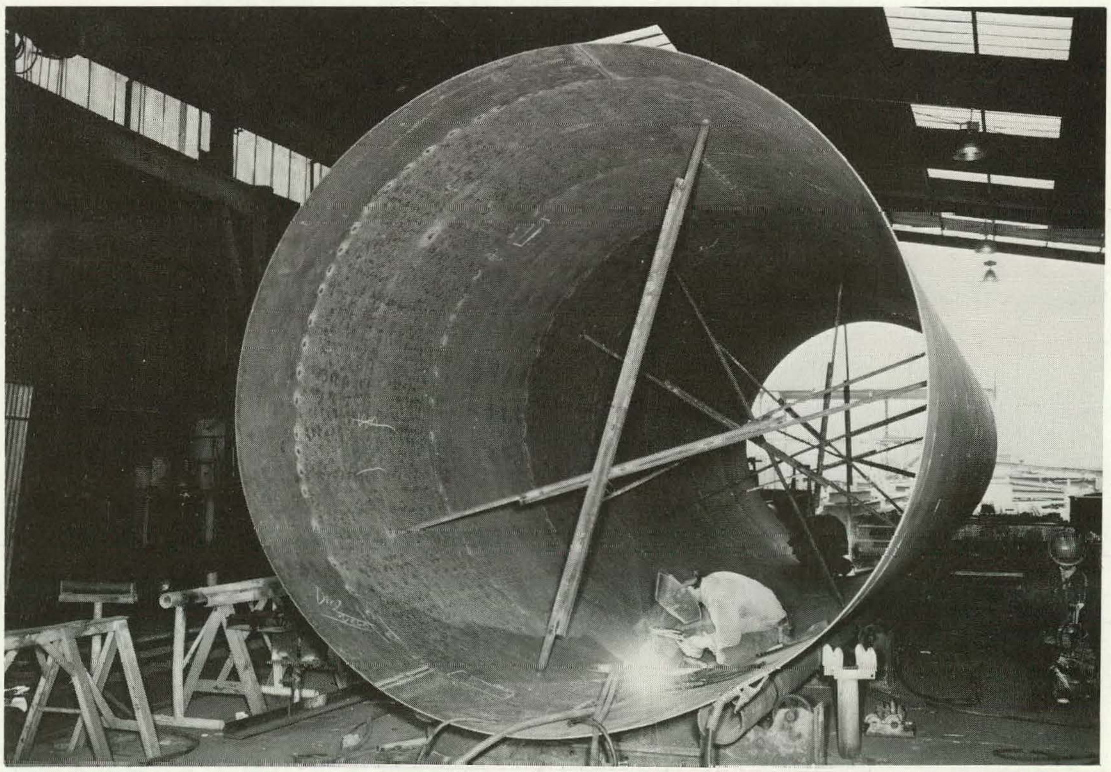

Figure 5-2. Thermal Storage Unit Fabrication

of the separated region. Consequently all eight plates were ultrasonically inspected with the result that two more laminated sections were identified. However, these were relatively small in total area and there was adequate nonlaminated material to proceed with tank construction as planned.

The basic TSU tank was completed and delivered to the Santa Susana test site in early June (Figures 5-3 and 5-4.) The TSU has since been installed, pressure checked, and is now being connected to the fluid circulation pumps and the remaining portions of the system by the piping contractor. Piping fabrication and assembly is proceeding on schedule.

Fluid heater refurbishment and modifications have been completed. Checkout of the heater has indicated that the heater should operate as intended.

The data logger has arrived and is in the process of installation and checkout.

5.3 SRE TESTING

Heat Transfer Fluid Prequalification and Extended Life Tests

Prequalification laboratory tests are continuing to measure the high temperature thermal stability, material compatibility, and surface fouling of selected heat transfer fluids for extended periods of time. The tests will provide information on the rate of fluid replenishment required, the change of viscosity, the percent of high boiling material, and the rate of fouling of heat transfer surfaces as a function of temperature and time. The effect of the presence of materials likely to be used in the energy storage subsystem, e.g., rocks, stainless steel, and carbon steel, on these properties is being determined. At present 13 fluid samples of fluid are immersed in the constant temperature baths at 288, 302, 316, and 343°C (550, 575, 600, and 650°F) with and without exposure to rock and metal.

The fluid stability tests initially set up for the molten salt baths are approaching the 3300 hour mark while two HT-43 tests initially begun in electric mantles, and later transferred to the salt baths, have passed the 5400 hour mark. Several test specimens have been terminated since the beginning of the program. Extremely high weight loss rates were measured

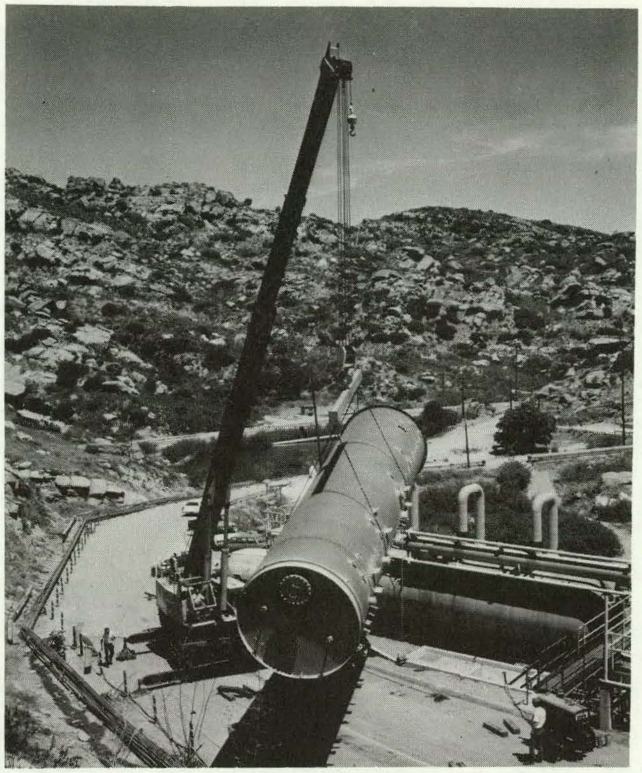

Figure 5-3. SRE Thermal Storage Tank at the Test Site

for Therminol 55, verifying an earlier result obtained with Therminol 55 fluid from another batch. As a consequence, all Therminol 55 tests were terminated. In addition, the test of Therminol 66 with rock and metal at 343°C (650°F) was discontinued because of high weight loss. Another sample of Therminol 66 with solids was prepared and is being subjected to 650°F to check the results obtained from the previous test.

All of the kinematic viscosity measurements taken at the latest 1000-hour interval in the salt bath show an increase. Although all fluids had undergone an initial decrease in viscosity the trend has now been reversed and some heat transfer fluid samples are more viscous than the fresh fluid.

Six fouling tests are continuing. Therminal 66 and Caloria HT43 are being subjected to metal surface temperatures of 316, 329, and 343°C (600, 625, and 650°F), simulating the thermal storage heater heat transfer surface (the highest temperature surface to which the fluid will be exposed). The apparatus for the surface fouling tests consists of a 180-watt electrical heating element, sheathed with 304 stainless steel, immersed in a pool of the heat transfer

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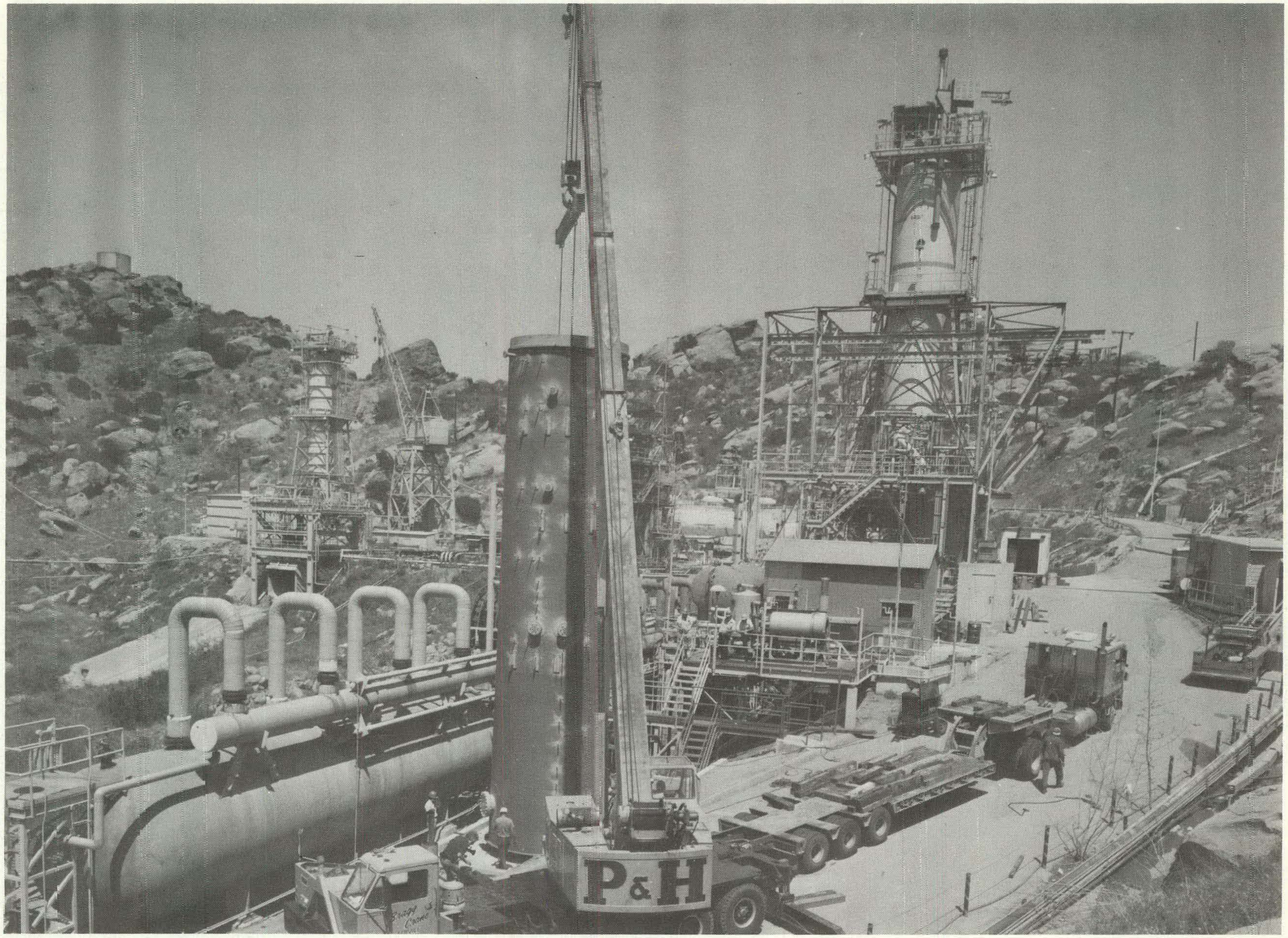

Figure 5-4. SRE Thermal Storage Tank Installation

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fluid contained in a 4-inch diameter glass pipe cap bolted to a stainless steel plate. Heat transfer from the electric heater to the fluid occurs by natural convection. Thermocouples spot welded to the heater surface are used to monitor the surface temperature. The power required to maintain a constant heater surface temperature is being monitored as a function of time to detect the formation and buildup of a fouling film.

The Caloria HT43 heaters initially developed small patches of gummy deposits. However, no significant change in heat transfer accompanied the formation of the deposits. It has been noted that the deposits, especially those on the 316°C (600°F) heater, were not as extensive after 2000 to 2500 hours as they were after about 235 hours. A fouling test with fresh Caloria HT43 subjected to a heater surface temperature of 316°C (600°F) was recently set up as a repeat of the earlier 316°C (600°F) test that showed an early rapid formation of a gummy surface deposit which later disappeared. After 360 hours the repeat experiment also revealed the formation of gummy deposit on the heater surface. Again no reduction in heat transfer was noted. Fouling tests conducted with Caloria HT43 at heater surface temperatures of 329 and 343°C (625 and 650°F) have passed the 3050- and 3580-hour mark respectively with little or no indication of a fouling deposit while samples of Therminol 66 at 329 and 343°C (625 and 650°F) have undergone over 4700 hours of testing without any visible indication of surface fouling.

5.4 OVERALL SRE SCHEDULE

The overall SRE schedule is shown in Figure 5-5. All prequalification tests are proceeding on schedule and are providing excellent results. The fabrication and installation of the SRE thermal storage tank and all other major components are proceeding without difficulty. Construction work at the test site should be completed as originally scheduled by August 15, 1976, permitting activation testing to begin, followed by initiation of SRE tests on September 15, 1976.

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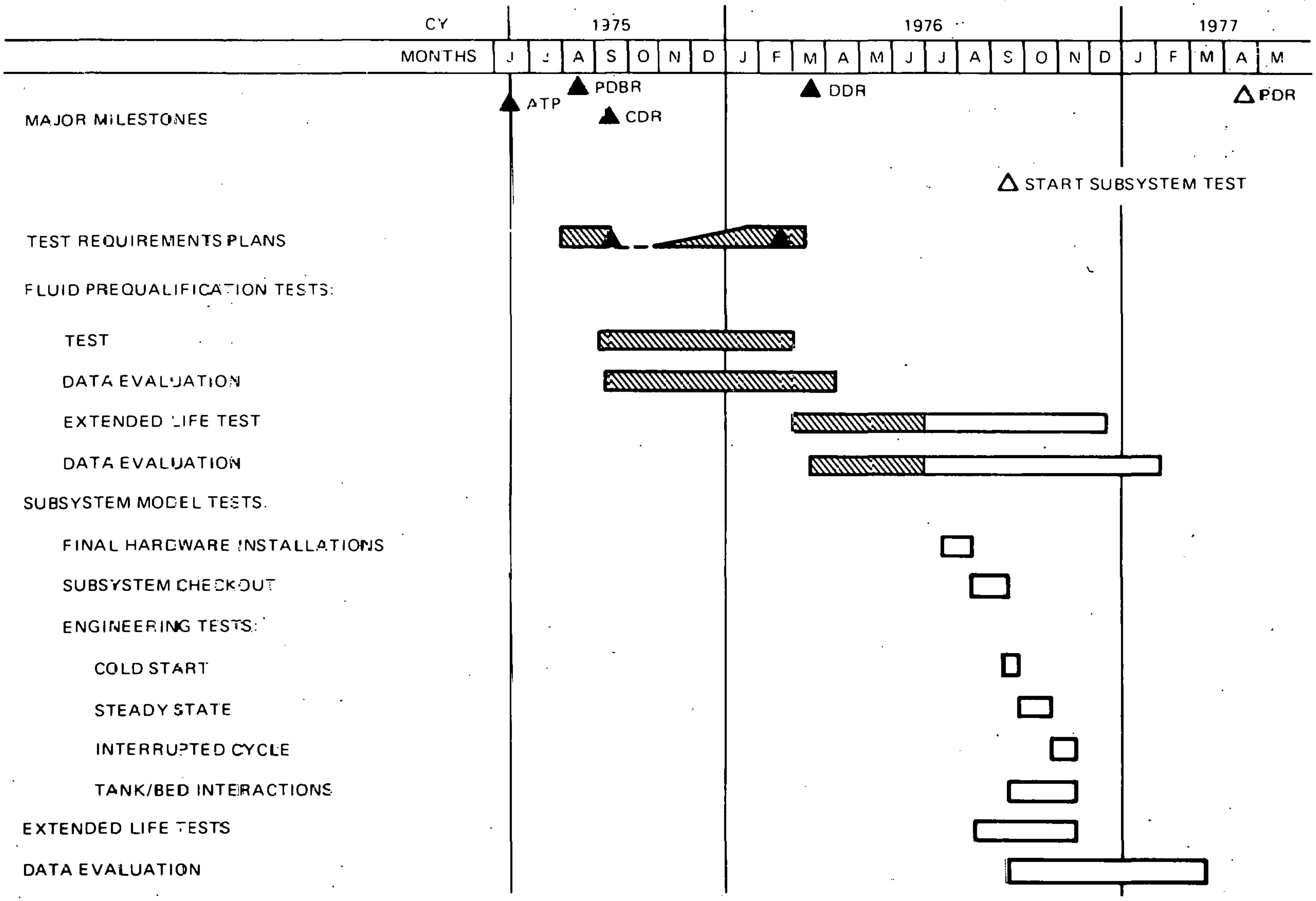

Figure 5-5. TSS SRE Test Program Schedule

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