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CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM PHASE 1

CDRL ITEM 10
Second Quarterly
Technical Progress Report

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

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Raymon W. Hallet, Jr. and Robert L. Gervais

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PREFACE

This report is submitted to the Energy Research and Development Administration under Contract E(04-3)-1108 as the formal documentation of CDRL Item 10, Second 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 January 1976 and 31 March 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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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 January 1976 and 31 March 1976 on ERDA Contract No. E(04-3)-1108 are summarized. This is the second 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 detailed definition of the subsystem research experiments and the design of the test articles and test facilities. Summaries of these activities are presented.

Design changes to the 10-MWe pilot plant preliminary design baseline which have occurred during the report period are also 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 January 1976 and 31 March 1976 is summarized in the following sections of this document. This is the second 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 second quarterly report will focus on the preliminary design baseline modifications introduced since the last quarterly report and the conceptual and detailed design activities of the subsystem research experiments.

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 March, 1976, and no major problems are anticipated on program progress during the next reporting period.

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

Following incorporation of customer comments, publication of the final preliminary design baseline report (CDRL 1), and the final SRE conceptual design reports for the collector, receiver and thermal storage subsystems (CDRL items 3, 4 and 5) occurred as requested in January, 1976.

Detail designs of the subsystem research experiments for the collector, receiver, and thermal storage subsystems were completed during the reporting period and were presented and approved at a series of mini-DDR meetings. Oral presentations summarizing all DDR activities were presented to ERDA, Sandia, and Aerospace in March coincident with the publication of the draft DDR reports (CDRL Items 6, 7, and 8).

In response to customer request, a preliminary analysis of 10-MWe pilot plant costs was prepared and submitted to ERDA, Sandia, and Aerospace in March 1976.

Figure 1-2. Summary Master Program Schedule

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Section 2

PILOT PLANT SYSTEM

2.1 REQUIREMENTS AND DESIGN SUMMARY

The pilot plant system remains conceptually unchanged from the system description presented in the first Quarterly Report (January 1976) except in three areas where changes were made to enhance cost, performance, or operational characteristics of the system. These changes involve a revision 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. Since these changes were made as a result of system considerations, they will be presented as part of the pilot plant system discussion, even though the change may influence only one subsystem.

2.1.1 Revised Steam Conditions

Previously reported data on the design steam conditions at key points in the system are presented in the following table:

	<u>Temperature</u>	<u>Pressure</u>
Receiver outlet	477°C (890°F)	10.3 MN/M ² (1,500 psia)
Turbine inlet	471°C (880°F)	10.0 MN/m ² (1,450 psia)

(Industrial turbine heat rate -- 10,220 Btu/kWh at 2.75 in Hg)

These conditions were originally selected to be compatible with the charging side of the thermal storage subsystem and the original baseline utility turbine while ensuring a sufficient degree of design conservatism. With the introduction of the more flexible 10-MWe industrial turbine into the baseline system definition, the above turbine inlet conditions represented a derated condition with a corresponding efficiency penalty. Therefore, an evaluation was carried out to determine the feasibility of upgrading the system steam conditions to match those of the turbine inlet design point [510°C (950°F), 10.1 MN/m²

(1,465 psia)]. The corresponding receiver outlet conditions required to produce the above steam conditions at the turbine inlet are [516°C (960°F), 10.4 MN/m² (1,515 psia)].

The impact of the revised steam conditions on the receiver was determined from the standpoint of increased receiver surface temperature and the resulting effect on receiver tube life. The impact on surface temperature is shown in Figure 2-1, based on a one-dimensional analysis. The solid lines represent the previous baseline fluid and tube surface temperature while the dashed lines represent the modifications introduced by going to a higher outlet temperature. The principal impact occurs in the outlet region of the tube. In this region, the tube temperature is ~ 42°C (75°F) higher than for the previous baseline condition. Moving away from the outlet region, it is seen that the degree of variation between the two wall temperature profiles decreases to the point of ~ 1°C (2°F) in the subcooled liquid and nucleate boiling regions. This variation is due to the slightly lower heat transfer coefficient that occurs on the inside of the tube because of the lower fluid velocity required to produce a higher outlet steam temperature. This reduction in

Figure 2-1. Comparison of Receiver Temperature Profiles (1-D Analysis)

fluid velocity also affects the phasing of events in the boiling process, which is particularly noticeable in the high-temperature film boiling region. Also indicated in Figure 2-1 are the more exact results based on a two-dimensional analysis. These data points indicate a peak tube temperature of 552°C ($1,025^{\circ}\text{F}$).

As in the case of the previous steam conditions, the region of film boiling represents the most critical region from a design standpoint. The two factors that govern tube design are hoop stress and low cycle fatigue, due to the daily cycling of receiver temperature. The impact in going to a higher surface temperature is shown in Figure 2-2, where the PDBR condition refers to the previously reported preliminary design baseline condition and the current condition refers to the new receiver steam conditions under consideration. The data point for the current condition is plotted based on the temperature indicated on the tube cross section in the lower left hand corner. A hot-wall temperature differential, $\Delta T'$, of 50°C (90°F) exists in this region. This value, along with the 552°C ($1,025^{\circ}\text{F}$) hot-wall temperature, locates the current condition data point on the figure.

Figure 2-2. Tube Temperature for Allowable Life and Stress

From a hoop stress standpoint, it is seen that this condition is below the allowable hoop stress limit which is shown as the dashed line at the top of the figure. Therefore, no impact would occur from the hoop stress standpoint in going to a more severe outlet steam condition.

From the standpoint of low cycle fatigue, the value read off the abscissa indicates the minimum acceptable value for cold-wall temperature to provide a 10,000-cycle, 30-year lifetime. The indicated minimum value is 183°C (360°F). By comparison, the actual cold-wall temperature experienced during the most severe operating period is ~ 415°C (780°F), as indicated on the tube cross section shown in the lower right hand corner of the chart. Comparing these values, it is seen that a significant design margin exists between the predicted value and the minimum acceptable value.

The results of the analysis described above indicate that raising the receiver outlet steam conditions to ensure the compatibility of the steam conditions with the turbine design point will not adversely affect the rest of the system. The revised system conditions are summarized in the following table:

	<u>Temperature</u>	<u>Pressure</u>
Receiver outlet	516°C (960°F)	10.4 MN/m ² (1,515 psia)
Turbine inlet	510°C (950°F)	10.1 MN/m ² (1,465 psia)

(Industrial turbine heat rate = 9,807 Btu/kWh at 2.75 in Hg)

In considering the turbine heat rate, it is seen that an improvement of ~ 4 percent will be experienced by going to the revised steam conditions. This change will result in an equivalent reduction of the energy collection elements of the system with a corresponding cost savings. This revised energy collection condition will require 2,290 heliostats.

2.1.2 Receiver Outlet Flow Control and Piping Network

An expanded definition of the receiver outlet equipment was developed to facilitate the operation of the receiver within the overall system, particularly during startup, shutdown, and other highly transient periods. The once-through nature of the receiver produces periods when water will be circulated completely through the receiver; therefore, provisions must be made to ensure

that this water cannot adversely affect other elements of the system. The specific types of adverse effects of concern are the passage of feedwater into the main downcomer, which can cause either quenching of a hot pipe or potentially destructive flashing of the feedwater to steam. In addition, it is highly undesirable to allow feedwater to come to the vicinity of the turbine inlet which would necessitate an emergency shutdown.

The principal additions on the outlet side of the receiver which alleviate this water carryover problem and ensure receiver operational compatibility with the rest of the system are shown in Figure 2-3. The additions center around a receiver-mounted flash tank which is used during periods when water carryover conditions occur along with the required inlet and outlet piping network. Included in the piping network are small-diameter water and steam downcomers which pass down the tower and operate independently from the main steam downcomer. This allows a complete decoupling of the receiver from the rest of the system during critical transient periods such as startup when the balance of the system may be undergoing necessary preheating.

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Figure 2-3. Modifications to Baseline Schematic

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When dry steam is produced at the receiver outlet (which can be determined through a series of thermocouple measurements), the flash tank equipment is removed from the loop and flow in a manner shown in Figure 2-5. The merit of this approach to receiver operation is that it preserves the responsive nature of the once-through receiver concept which is desirable for solar electric applications. On the other hand, the characteristics of a drum boiler can be introduced by activating the flash tank to minimize problems that can occur during transient periods. Also, the fact that the flash tank is rated at $\sim 2.1 \text{ MN/m}^2$ (300 psia) ensures the desired thermal responsiveness of the receiver. By contrast, if the flash tank were incorporated in series with the receiver (performing the function of a steam drum), it would be rated to withstand the full receiver design pressure of 10.4 MN/m^2 (1,515 psia). This would result in a thick-walled device which would impose severe limitations as to the acceptable rate of change in receiver outlet temperature.

2.1.3 Thermal Storage Steam Generator

A change in the design of the thermal storage steam generator was made from a once-through concept to a three-step (preheater, boiler, superheater)

Figure 2-5. Normal Receiver Operation

arrangement to facilitate its operation within the system. The details of the three-step arrangement are shown in Figure 2-6. Supply feedwater first enters the tube shell preheat section where it is heated to near saturation conditions. The hot water then enters the kettle boiler section where liquid level is maintained by means of a level-control valve. Vapor produced in the kettle boiler passes to the tube shell superheater where the desired outlet steam condition is produced. The high-temperature storage fluid on the other hand circulates in a controlled counter flow manner entering the superheater and exiting from the preheater.

The principal reasons for making this change center around water carryover, startup, and operational/control considerations. First, from a water carryover standpoint, the previous once-through concept had no accumulation capability such as exists in the kettle boiler section of the current concept. This means that it is possible during transient periods that feedwater could be carried over to the low-pressure inlet of the turbine. This is of particu-

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Figure 2-6. Thermal Storage Steam Generator

lar concern due to the relatively low heat fluxes experienced in the heat transfer process and the low degree of superheat produced at the outlet of the steam generator.

In considering startup of the steam generator, the previous once-through concept required circulation through an external flash tank during the transitional period going from water to steam at the design point conditions. The current three-step design is self starting in that circulation through an external flash tank is not required.

From an operational standpoint, the previous once-through concept required a tight control system to ensure operational compatibility. The three-step steam generator utilizes a simple level-control scheme which operates in a positive and highly stable manner. In addition, discussions with utility representatives indicated a substantial preference on their part for the three-step steam generator concept.

The cost penalty associated with adopting the three-step concept is ~ \$60,000, with the actual cost estimates for the three-step steam generator being \$280,000.

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Section 3
ELECTRICAL POWER GENERATION SUBSYSTEM

3.1 REQUIREMENTS AND DESIGN SUMMARY

The design of the electrical power generation subsystem remains unchanged from that presented in the first Quarterly Report (January 1976) except in the area of operating steam conditions, as discussed in Section 2. Efforts during this quarter have focused on expanding the performance and operational information related to the subsystem.

3.1.1 Turbine Performance

In order to better predict system performance over the entire range of operation, performance characteristics of the industrial turbine were developed for a variety of receiver/thermal storage steam flow ratios with the aid of General Electric. The resulting predictions of gross turbine heat rate are shown in Figure 3-1 for two values of turbine back pressure. As seen from the figure the greatest increase in heat rate occurs near the left side of the curve where receiver steam flow is at or near its maximum value. As the percentage of thermal storage steam increases, the impact on the turbine heat rate decreases, approaching a linear relationship when the thermal storage steam flow exceeds 50 percent of the total flow. The total flowrates used to develop these curves correspond to that required to:

- A. Produce 10 MW of net electrical power during the winter using 100 percent receiver steam.
- B. Produce 7 MW of net electrical power during the winter using 100 percent thermal storage steam.

The approximate total flow rate satisfying these conditions is 13.3 kg/sec (105,000 lb/hr). As the total flow drops off, either because of a reduced net-work demand or reduction in steam availability, additional penalties to heat rate would be assessed while preserving the shape of the curves shown in Figure 3-1.

Figure 3-1. Influence of Steam Source Flow Ratio on Gross Turbine Heat Rate

3.1.2 Operation of the Turbine from Thermal Storage Steam

During periods when the turbine operates exclusively from thermal storage steam, the current design calls for the admission of this steam through a low-pressure port which is downstream from the high-pressure turbine stage. However, since all of the turbine blades are on a common shaft, they continue to spin in the high-pressure stage, thus causing an excessive temperature buildup and possible blade damage in that area due to mechanical dissipation of energy. Therefore, a requirement to cool or maintain temperature control of the high pressure stage exists during this period of operation.

After consulting with General Electric this situation was overcome by connecting the low-pressure admission port to the high-pressure admission port with a bypass line as indicated in Figure 3-2. This bypass line would permit a partial flow to be maintained through the high-pressure stage of the turbine during this period of operation. The blade action in this section would be sufficient to draw ~ 30 percent of the steam flow through the high-pressure

Figure 3-2. Turbine Operation from Thermal Storage

admission port, which would be sufficient to provide the necessary cooling flow. This cooling steam would then pass directly to the low-pressure stage where it would be used for the generation of electricity; therefore, none of the bypass steam would be lost from the turbine.

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Section 4

RECEIVER SUBSYSTEM

The dominant activity during the report period has been the detail design of the SRE tests, the test articles, and test facilities to be used to accomplish the receiver tests.

The detailed designs of the receiver subsystem research experiments and hardware were completed on schedule and accepted by ERDA during the report period. All major procurement activities have begun and the fabrication and installation of test articles and test facilities are proceeding on schedule.

4.1 REQUIREMENTS SUMMARY

The primary mission of the receiver subsystem is to efficiently utilize incident solar radiation from the collector field to create and deliver steam to the electrical generation or thermal storage subsystems. The major hardware assemblies comprising the subsystem are the receiver assembly, the tower, and the riser/downcomer.

The performance requirements for the receiver subsystem continue to be as described in the first quarterly technical progress report (January 1976) with the exception of a minor change in required nominal steady state steam outlet conditions.

In order to more efficiently utilize the industrial turbine chosen for the electrical generation subsystem, nominal receiver steam exit conditions have been revised from 10.4 MN/m^2 (1,500 psia) and 477°C (890°F) to 10.5 MN/m^2 (1,515 psia) and 516°C (960°F). No change in receiver design was necessary to accommodate these revised conditions (Ref Section 2.1.1).

4.2 PILOT PLANT RECEIVER ASSEMBLY DESCRIPTION

The pilot plant receiver assembly is comprised of 24 individual panels, flow control subassembly, the instrumentation subassembly, and supporting structure.

Each panel subassembly includes a tube bundle, manifolds, backup structure, and insulation. The function of the panel subassembly is to efficiently utilize incident thermal energy to convert ingested water into superheated steam and to protect the structure from radiation.

The flow control subassembly includes the control computers, controllers, orifices, valves, filters, and plumbing whose function is to direct and control the flow of water to the various parts of the receiver. This subassembly also provides for cleaning of the receiver by filtering, flushing, and purging.

The instrumentation subassembly includes the sensors and signal conditioning equipment. This subassembly determines the condition of the receiver and utilizes the data to inform the plant operators, master control, and the flow control subassembly.

The structural assembly provides support for the other subassemblies with respect to gravity, wind, and seismic forces. These loads are transmitted by the structural assembly to the tower unit (Figure 4-1).

Figure 4-1. Steel Receiver Tower

Figure 4-2 depicts the pilot plant receiver as it would appear on top of the tower.

Figure 4-2. Receiver Configuration

The detailed design of the pilot plant receiver subsystem remains essentially as described in the first quarterly technical progress report (MDC G6318; January 1976) with the exception of the addition of the tower-mounted flash tank discussed in detail in Section 2.1.2.

4.3 SUBSYSTEM RESEARCH EXPERIMENTS

The receiver subsystem research experiments (SRE) are designed to eliminate any risks inherent in the performance, control, stability, and mechanical integrity of the pilot plant receiver.

The receiver subsystem research experiments are designed to verify the following specific capabilities of the pilot plant receiver design:

- A. Performance – Deliver rated steam over required range of power, and variations thereof.
- B. Cooling Capability – Withstand peak heat flux and heat loads, as well as gradients within a panel.
- C. Stability – Provide stable flow over entire range of power/flow spectrum.
- D. Life – Be capable of operating over 30 years (10,000 cycles).
- E. Structural – Withstand combined wind and seismic loads.
- F. Fouling – Provide capability of maintaining cooling surfaces and restrictions designed into systems corrosion/erosion free when supplied with nominal power plant water.
- G. Clouds – Be capable of reacting to passing cloud cover over collector field with no degradation of subsystem.

4.3.1 SRE Test Plan

The receiver SRE includes test of subassemblies as well as tests of a complete segment of a full scale pilot plant receiver. The lower level tests include tests of single and multiple tube configurations to provide thermal, hydrodynamic, structural, and life data. A summary of the SRE test requirements is provided in Table 4-1.

4.3.1.1 Single-Tube Tests

A single tube identical to pilot plant tubing in dimensions, material and configuration, will be tested in vertical orientation over the ranges of anticipated pilot plant operating conditions using a radiant heat input. Various inlet orifices will be used to determine a lower limit on orificing requirements for stability. Preliminary assessment of absorber integrity and efficiency will be obtained. Abnormal operating conditions also will be explored.

Objectives of the single-tube tests are (1) facility checkout, (2) preliminary demonstration of thermal performance, (3) preliminary demonstration of safe tube operation under nominal conditions, (4) preliminary assessment of emergency operating conditions, and (5) demonstration of flow stability in a single tube.

Table 4-1
RECEIVER TEST REQUIREMENTS

Design Considerations	SRE Test Requirements
Performance	Test single tube to establish initial flow stability and cooling capability.
Cooling capability	Test narrow panel to verify multitube stability, cooling, fouling resistance, and fatigue characteristics over normal and emergency range of pilot plant operating conditions.
Stability	
Fatigue life	
Structural	Test complete pilot plant panel assembly over complete range of operating conditions to demonstrate performance cooling, stability, and structural capability.
Fouling	
Clouds	
	Test panel surface coating under concentrated sunlight conditions.

The configuration for the single-tube tests, as well as the narrow panel tests, is shown in Figure 4-3. Heated water is supplied by the facility high-pressure storage tank and flows through facility shutoff and flow control valves and flowmeter. Pilot plant filter and stop check valve will be used if available in time for the test. The inlet orifices, tubing, and discharge orifice will be of the pilot plant configuration. The relief valve, stop valve, and back pressure regulator will all be facility items for these tests.

The results of the single-tube tests will be the definition of tube wall temperature profiles versus absorbed heat and coolant flow. Stable operating regions in terms of inlet and outlet pressure drops, heat flux values, and coolant flow rates will be defined. The ability of the tubes to function at off-design conditions including higher than nominal heat flux and during emergency shutdown conditions will be demonstrated.

4.3.1.2 Narrow Panel Test

An overall view of the narrow panel is shown in Figure 4-4. This panel consists of five receiver tubes with inlet and outlet manifolds and backup structure that duplicates the configuration of the 70-tube receiver segment panel in many respects.

Figure 4-3. Configuration for Single-Tube and Narrow-Panel Tests

Figure 4-4. Narrow Panel

The tubing material, ID, OD, and heated length are identical to the corresponding parameter on the full panel. The method of supporting the tubing and allowing for thermal expansion is essentially identical for both panels. The manner in which the tubing is joined to the manifolding in the narrow panel is shown in Figure 4-5 and is similar to the manner of joining on the 70-tube panel. As shown in Figure 4-5, the five tubes penetrate the water manifold in two rows, three tubes in one row, two tubes in another row. Each tube contains a flow control restriction and a downstream pressure tap that will be used to monitor flow in each of the five tubes during the SRE. The manifold is drilled, tapped, and plugged with a pipe plug immediately behind each of the five tubes. These plugs allow installation, removal, and inspection of each of the orifices. The two large tubes shown in the manifold in Figure 4-5 are for water inlet and for draining. The bracketry shown partially in the figure provides a support for the water manifold and is attached by a sliding block, which rides along the eye beam rail, to the remainder of the panel. Groups of bosses will be provided at several locations on the five-tube panel to permit monitoring both fluid temperature and pressure at several locations along the panel.

Figure 4-5. Five-Tube Panel Water Manifold

The narrow panel will be oriented vertically and tested in a manner similar to the single-tube. These tests, by including inter-tube stability characteristics, will better define orificing and control valve requirements. Further definition of absorber integrity and performance will be obtained including the effects of flow reduction in a single tube. Verification of vertical expansion capability, the adequacy of the panel restraint (to warping), and the tube-to-tube weld integrity will be obtained. The basics of panel fabrication and transportation will be demonstrated.

The objectives of the narrow-panel test are to (1) demonstrate thermal performance of the absorber, (2) verify safe operation and wall temperatures consistent with 30-year life under pilot-plant operating conditions, (3) demonstrate flow stability in a multiple-tube panel, (4) provide a preliminary demonstration of fabrication techniques, (5) verify the adequacy of the backup structure with respect to restraint and thermal expansion capability, and (6) evaluate emergency shutdown procedures.

The results of these tests will include wall temperature and bulk fluid temperature profiles versus the absorbed heat and flow. Correlations between bulk fluid temperature and wall temperature and heat flux will also be obtained. Uniformity of flow between the tubes as well as stability of flow and orificing requirements will be generated. The relationship between absorbed heat, incident heat, and coolant flow rate will be correlated. The thermal expansion characteristics of the panel will be mapped for the various operating conditions. The ability of the panel to function in the steady-state mode with one tube completely blocked will be demonstrated. The ability to accomplish an emergency shutdown in the event of water failure will be demonstrated, including the effect of an additional delay in defocusing of the heliostats.

4.3.1.3 Solar Absorptance Test

The solar absorptance panel consists of a block of Incoloy with water coolant ports provided. Water coolant is used to maintain the surface of the Incoloy block, which is exposed to concentrated solar radiation, at a temperature of 540°C (1,012°F). The block will be coated with S-31 and pyromark paints.

The objective of the absorptivity surface test is to determine the effect of high-intensity solar insolation on panel surface absorptivity.

The absorptive surface panel will be shipped to the White Sands Solar Furnace Test Facility where the sample will be irradiated with concentrated solar energy to produce a heat flux level of 0.3 MW/m^2 ($0.18 \text{ BTU/in}^2/\text{sec}$) for a period of approximately 3 months. After this period of exposure, the surface will be returned to the Rockwell Thermodynamics Laboratory where the exposed and the unexposed areas will be tested to determine the solar absorption coefficient. In this manner, any degradation of the absorptivity of the tube surfaces will be detected.

4.3.1.4 Receiver Segment Test

The SRE receiver unit segment is identical to the absorber panel planned for use in the pilot plant. An overall view of the panel is shown in Figure 4-6. The panel consists of 70 tubes which have a heated length of 17m (56 ft). The tubes are folded over at the top and bottom to protect the manifolds from the concentrated solar radiation. The width of the panel is 0.9m (35 in). In order that the width of the manifolds not exceed this dimension (to facilitate installation and removal of the panels in the pilot plant), the eight tubes at each side of the panel are bent in and doubled over, resulting in the tube-to-manifold configuration shown in Figure 4-7. The similarity in configuration between the full panel manifold and the narrow panel manifold is evident with provisions for pipe tap plugs opposite each of the tube inlets in the manifold and water inlet and drain fittings also provided.

The manner in which the tubes are joined to the manifolds is illustrated in Figure 4-8. Dimensions are typical of the steam manifold, but the method is similar for both steam and water manifolds. The tube is inserted into the hole in the manifold and roller expanded to firm contact with the manifold. A seal weld is placed around the tube on the inside surface of the manifold (only one-half of the manifold being in place at this time) and the tube again expanded by roller into the manifold wall. This joint is a standard boiler configuration joint and has been proven to be very reliable.

Figure 4-6. SRE Receiver Panel

Figure 4-7. Absorber Water Manifold

Figure 4-8. Steam Manifold Tube Joint

The provisions for thermal expansion of the panel are shown in Figure 4-9. At numerous axial stations, several of the tubes have pairs of small clips welded to them, as shown in the upper view of Figure 4-9. These clips allow lateral expansion of the panel by sliding along the hat-shaped beam. The hat-shaped beam in turn is fastened to a sliding block which traverses along the eye beams to permit axial expansion of the panel. The panel is fastened to the two eye beams only at the top of the assembly and grows freely downward and longitudinally during the expansion and contraction.

Objectives of the receiver segment test are to (1) demonstrate pilot plant absorber fabricability, weight, and transportability; (2) verify pilot plant receiver performance including compatibility with thermal storage and electrical power generating subsystem interfaces, operation at safe wall temperature with design pressure drop, and efficient transfer of incident thermal energy to produce steam; (3) verify control and stability of a pilot plant segment including steady-state stability and accuracy, stability and accuracy during start and shutdown sequences, stability and safety during

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Figure 4-9. Thermal Expansion Provisions

cloud cover transients, component dynamic characteristics, and response to standard control signals; and (4) verify thermal stress and expansion provisions.

The test hardware configuration is shown in Figure 4-10. Water enters the test hardware through the shedding vortex flowmeter (FM-1) then through the water throttle control valve (TV-1) which is used to control the water flow rate in accordance with outputs from (1) the three steam temperature transducers (TX-3, TX-4, and TX-5); (2) the water flowmeter; or (3) the valve position indicator (DX-1). After flowing through the filter (F-1) and the water stop check valve (SC-2) the water enters the receiver panel through the 70 inlet orifices and is converted to steam. The steam flows through the single-outlet orifice (O-2) and through the outlet stop valve (MV-4) and is returned to the facility flash tank. The safety relief valve (SR-1) is also a pilot plant component as is the water drain valve (MV-2). Other pilot plant instrumentation points are noted in Figure 4-10.

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Figure 4-10. SRE Receiver Pilot Plant Segment Schematic

Several tests will be conducted initially to determine optimum start sequences and the effects of various conditions during the start sequence for a southern panel. For example, the influence of the lower holding value of backpressure on flow stability during the start will be determined. These start sequences will terminate in steady-state conditions which produce derated steam at minimum southern flux.

Subsequent to the start-sequence test, tests will be conducted at one-half and at full southern heat flux to produce both derated and rated steam conditions at nominal interface conditions. Then will follow a series of 12 tests wherein the interface conditions are perturbed to determine the effect on receiver operating conditions. The interface conditions that will be perturbed are the inlet and outlet pressures and the inlet temperature.

The panel will be orificed as a northern panel based on the results of the narrow-panel test and the above test program will be repeated. Thus, operation of the full pilot plant segment will be characterized at the extremes in operating conditions expected; namely, the northern and southern panel operating conditions.

Following these tests, cloud simulation transient testing will be conducted. Cloud transients will be simulated simply by turning off and turning on the power to the facility heater. The transient resulting from this operation is expected to take approximately one-half minute to undergo the major portion of the power ramp. Tests will first be conducted with the panel orificed as a southern panel and undergoing transients from the minimum and maximum values of heat flux expected upon those panels. The panel will then be reorificed as a northern panel and transients from the maximum to minimum northern heat flux to the cloud passage will be simulated.

4.3.2 Test Support Equipment and Facilities

The majority of the testing (single tube, narrow panel, and receiver segment) will be conducted at the Rockwell B-1 Thermodynamics Laboratory. The special equipment required to support these tests consists of heater arrays to simulate solar energy (Figure 4-11) and a flash-tank assembly to simulate the bypass valve and flash tank of the pilot plant receiver.

Figure 4-11. SRE Panel Installation

The absorptive surface tests will be conducted at the White Sands Solar Furnace Test Facility. The existing heliostats at the White Sands facility will concentrate the solar energy to simulate the function of the pilot-plant heliostats.

The receiver SRE digital data acquisition facility at the B-1 thermodynamics lab is shown in Figure 4-12. The system includes multiplexers and analog digital converters, a double tape unit for recording the incoming data together with a programmer for organizing and formatting data. Two separate analog digital converters with visual displays are shown in the center of the lower right hand photograph. These can be used for monitoring real-time data or tape outputs for playback of two channels of taped data. Two video display units are also available as is a printing unit shown to the left in the lower figure. The vertical unit in the upper photograph includes a programmer for converting the data into engineering units and a tape recorder for storing the engineering data. Digital (numerical on paper) printout equipment is shown in the foreground of the upper figure. Card printout is also available.

96 DATA CHANNELS
DIGITAL DISPLAY

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VIDEO DISPLAY
GRAPHIC PRINTOUT
DIGITAL PRINTOUT

Figure 4-12. Digital Data Acquisition Facility

4.4 OVERALL SCHEDULE

The overall schedule for the receiver subsystem research experiments is shown in Figure 4-13. Fabrication of the single-tube test article is complete. Completion of the five-tube narrow panel is well along and completion on schedule is anticipated.

The initiation of single-tube and multitube testing has been delayed due to test facility interferences. However, those problems have been resolved and no impact on the initiation of full segment testing is anticipated.

Figure 4-13. Overall Receiver SRE Schedule

Section 5

THERMAL STORAGE SUBSYSTEM

The detailed design of the thermal storage subsystem research experiments and the test hardware were completed on schedule during the report period.

Following a procurement competition the contract for the model thermal storage tank was awarded and fabrication was begun. Construction and refurbishment activities have begun at the subsystem test site. Prequalification tests of the candidate heat transfer fluids continue to yield favorable results.

5.1 REQUIREMENTS SUMMARY

The primary operational requirement of the Thermal Storage Subsystem (TSS) is to extend the solar plant's electrical generating capacity into periods of low or no insolation. The second major requirement is to buffer the electrical generating subsystem from short term variations in insolation.

The specific performance requirements for the TSS have not changed during the report period and continue to be as described in the first quarterly technical progress report (MDC G6318; January 1976).

5.2 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).

Figure 5-1. Thermal Storage Subsystem

Figure 5-2 is a schematic diagram of the pilot plant thermal storage subsystem, showing all major components, lines, and major control concepts. Table 5-1 summarizes the principal characteristics of the subsystem and major components. As shown in Figure 5-2, the subsystem can be considered in three major parts: (1) central thermal storage unit, (2) thermal charging loop, and (3) heat-extraction loop. In the charging loop, energy is removed from the receiver steam and stored in the thermal storage unit tank. A commercial petroleum-base, heat-transfer fluid (Caloria HT-43) is used to permit economical ambient pressure storage in the tank. The extraction loop utilizes the fluid to remove energy from the storage unit and produces steam for turbo-generator operation and/or other power plant applications.

The detail design of the pilot plant TSS remains essentially as described in the first quarterly technical progress report (MDC G6318; January 1976) with the exception of the change in steam generator design discussed below and in Section 2.1.3.

Figure 5-2. Pilot Plant Thermal Storage Subsystem Schematic

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 ⁶ kg (10,600 ton) crushed granite rock, 1.18 x 10 ⁶ l (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 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.

5.2.1 Steam Generator

The pilot plant TSS steam generator converts the thermal energy stored in the TSS heat transfer fluid to superheated steam to supply the electrical generation subsystem during periods of low, intermittent, or no solar insolation. The steam generator is required to function in two basic operational modes. First, during late afternoon periods when solar insolation is reasonably steady but yet too low to provide sufficient energy to generate the nominal 10-MWe electrical output and also permit turbine steam extraction for adequate feedwater heating, the TSS steam generator will provide the steam to the electrical generation subsystem high-pressure feedwater heater. Second, during periods of intermittent solar insolation (clouds) or extended operation with no insolation, the steam generator will provide sufficient steam to the turbogenerator to produce 7 MWe.

As part of the continual effort to keep pilot-plant costs as low as possible, the TSS steam generator was originally designed as a single-pass oil-in-shell steam generator. However, subsequent analyses have indicated that due to the duty requirements of the steam generator and the relatively low pressure and low differential temperature conditions in which it must operate, a drum type, oil-in-tube design would be more appropriate, even at slightly higher cost.

The pilot plant baseline design will therefore incorporate two drum type steam generator assemblies with separate preheater and superheater sections. (Figure 5-3).

5.3 SUBSYSTEM RESEARCH EXPERIMENTS

The thermal storage subsystem research experiments (SRE) are designed to minimize any risk inherent in the pilot plant design by establishing a firm technical data base in each design area. Fortunately, the TSS concept has a sound base of commercial experience. Most of the equipment, materials, flow loops, and controls include commercial components that are available; therefore, unique features of this program requiring development are minimized.

Figure 5-3. Thermal Storage Steam Generator

These assessments indicate that the primary tests for the SRE should involve large-scale thermocline establishment, high temperature stability of candidate heat transfer fluids in contact with rock and metallic surfaces, and tank stresses induced by interaction with the rock bed.

5.3.1 SRE Requirements

Requirements for the SRE tests are summarized in Table 5-2. The SRE program consists of two series of tests: (1) prequalification tests and (2) model subsystem tests.

5.3.2 SRE Prequalification Tests

Thermal stability and compatibility tests are designed on a laboratory scale to demonstrate the fluid characteristics when subjected to long-term exposure to operating temperatures. The tests are being conducted on three commercially available fluids which may be capable of meeting the requirements of the TSS. Exxon Caloria HT43, Monsanto Therminol 55, and Monsanto Therminol 66.

Table 5-2
THERMAL STORAGE TEST REQUIREMENTS

Design Consideration	SRE Test Requirement
Heat-transfer fluid thermal stability	Duration tests at maximum operating temperatures, 288 to 316°C (550 to 600°F).
Heat-transfer fluid compatibility	Duration tests with fluids exposed to subsystem materials.
Heat exchanger surface fouling	Duration tests with fluid exposed to hot metal surfaces.
Subsystem operating characteristics	4-MWhth thermal storage unit test with charging and extraction fluid velocities identical to pilot-plant conditions.
Rock bed/tank interactions	Strain measurements during SRE subsystem tests.

The objectives of the fluid thermal stability and compatibility tests are to (1) determine the ability of the heat transfer fluids Caloria HT43 (formerly Humbletherm 500), Therminol 55 and Therminol 66 to function stably at 288 to 316°C (550 to 600°F) for extended periods of time; (2) assess the high-temperature, long-term compatibility of these heat transfer fluids with rock and materials of construction (stainless steel, carbon steel) which will be in contact with fluid in the thermal storage unit; and (3) determine the rate and extent of fouling of heat transfer surfaces by Caloria HT43 and Therminol 66.

5.3.2.1 Stability Testing

Stability tests of the heat transfer fluids are being conducted at 288, 302, and 316°C (550, 575, and 600°F) in the presence and absence of rock aggregate, stainless steel, and carbon steel. The tests are carried out at atmospheric pressure under a nitrogen gas atmosphere. (Figure 5-4).

The loss of fluid from each of the flasks over the heating time was determined from weighings before and after heating. Kinematic viscosity of the fluids was measured with a viscosimeter to further assess the effect of heating on the fluid.

Figure 5-4. Fluid Thermal Stability and Compatibility Setup

In actual pilot plant or commercial plant cycles, the fluid will range in temperature from 218 to 302°C (425 to 575°F) or from 232 to 316°C (450 to 600°F), respectively. Using an estimate of the temperature-time profile in a typical cycle (7-hours heating, 1-hour hold at top temperature, 6-hours cooling, 10-hours at bottom temperature) and data on the thermal stability of Caloria HT43, one day (24 hours) at 316°C (600°F) would produce the same thermal decomposition that would result from about 15.4 days of pilot-plant operation or from 6.4 days of commercial plant operation. Therefore, the present 4,600-hour testing period corresponds to about 8.1 years of pilot plant operation.

Using the test data and the temperature dependence derived from the data, estimates were made of the expected weight loss for each of the three fluids with both pilot plant and commercial plant cycles. These values are given in the top half of Table 5-3. The bottom half of this table translates these makeup requirements into relative costs, using the latest costs supplied by the manufacturers (\$1.02/gal for Caloria HT43, \$1.60/gal for Therminol 55,

Table 5-3
COMPARISON OF FLUID MAKEUP COSTS

Fluid	Caloria HT43	Therminol 55	Therminol 66
Estimated weight loss (percent/year)			
Pilot plant (218 to 302°C)	6.0	19.7	3.0
Commercial plant (232 to 316°C)	14.5	47.6	7.4
Relative cost of makeup fluid			
Pilot plant (218 to 302°C)	1.0	5.2	2.7
Commercial plant (237 to 316°C)	3.1	16.1	8.7

and \$5.70/gal for Therminol 66). It can be seen that either weight loss or cost of makeup fluid makes Therminol 55 unattractive. Therminol 66 has the lowest weight loss of the three fluids, but its higher price would result in higher fluid makeup cost than for the baseline fluid, Caloria HT43.

5.3.2.2 Heat Exchanger Surface Fouling Tests

Surface fouling from degradation of the heat transfer fluid is most likely to occur at the points of highest surface temperatures. Examination of the fluid flow loops shows that the highest temperatures occur in the thermal storage heater. The potential impact of fouling, if it should occur, would be greater for the heater than for many other portions of the subsystem; e. g., fouling of the piping or heat storage media (rocks) would have little impact. Continuing attention will be given to evaluating the possibility of fouling in other portions of the fluid circulation loops and, if such fouling seems possible, to evaluate whether it would have significant impact on the subsystem operation.

Tests are being performed to determine the extent and rate of fouling of electric heaters immersed in the heat transfer fluids as a function of the surface temperature of the heater for two fluids; Caloria HT43 and Therminol 66.

Each apparatus for the surface fouling tests (see Figure 5-5) consists of 180-watt electric heating element, sheathed with 304 stainless steel, immersed in a pool of the heat transfer fluid contained in a 10-cm (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, which is maintained constant. The ullage space at the top of the cap contains nitrogen.

Six fouling tests are being conducted, three with Caloria HT43 and three with Therminol 66. The surface temperatures of the electrical heaters are controlled at 316, 329, and 343°C (600, 625, and 650°F). The manufacturer's recommended maximum film temperatures are 360°C (680°F) for Caloria HT43 and 374°C (705°F) for Therminol 66.

Visual examination, still and motion photography, and measurement of the change with time in power supplied to the heater to maintain the surface

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Figure 5-5. Surface Fouling Test Setup

temperature at a constant value are being used to detect the presence of a surface film. The weight per unit area of foulant (if any) will be determined at the conclusion of a test by removing the deposit from a known area and weighing it. The tests are approaching a 2,600-hour duration. This is equivalent to about 4.6 years of pilot plant operation.

Preliminary conclusions from the heated surface fouling tests are that (1) there is no indication of an increase in thermal resistance due to fouling of heated surfaces, (2) higher wall temperatures do not measurably increase fouling in a natural convection regime, and (3) increasing the velocity past a surface tends to decrease fouling. It is important to note that the temperatures of the tests bracket the temperatures anticipated for pilot plant and commercial plant thermal storage heaters. In both cases, the maximum temperature of the incoming steam is 343°C (650°F); the maximum fluid-side metal temperatures will be slightly lower.

5.3.3 SRE Model Subsystem Tests

5.3.3.1 Test Objectives

The basic objectives of the thermal storage SRE model system tests are to:

- A. Evaluate charging and extraction capabilities of a scalable TSU.
- B. Obtain performance of the TSU over all ranges of equivalent operating conditions in the pilot plant.
- C. Demonstrate stable operation for high, low, intermittent, and no insolation conditions.
- D. Demonstrate changeover capabilities from one operating mode to another and emergency response modes.
- E. Develop requirements and techniques for treating the heat transfer fluid to permit 30-year lifetime with makeup.
- F. Determine the additional strain on container walls from tank/rock interaction during repeated thermal cycling.

5.3.3.2 Test Hardware

The thermal storage model subsystem consists of a heat transfer fluid heater, steam generator, thermal storage unit, two fluid circulation pumps, ullage maintenance unit, fluid maintenance unit, and associated controls, valves, and sensors (Table 5-4). The heat transfer fluid heater and steam

Table 5-4
SRE MODEL SUBSYSTEM DESCRIPTION

Assembly	Description
Thermal storage unit	Cylindrical tank, axis vertical, installed above ground; 3.2m (10.5-ft) dia by 13.3m (43.7-ft) high; contains 210,000 kg (231 tons) of crushed granite rock and 24,400 liters (6,430 gal) of Caloria HT43 heat transfer fluid. Fluid temperature range up to 316°C (600°F). Fabricated of structural steel with exterior insulation on all surfaces.
Thermal storage heater	Direct-fired fluid heater, capable of 316°C (600°F) fluid outlet and 1-MWth heat generation rate, provided by facility.
Steam generator	Submerged-coil generator; 3.4 MN/m ² (500 psia) maximum steam pressure and 1-MWth heat absorption rate, provided by facility.
Fluid charging loop pump (P1)	Centrifugal, high temperature. Up to 4.3 kg/sec (9.5 lb/sec), 0.69 MN/m ² (100 psi), 15 kW (20 hp) pump shaft power.
Fluid extraction loop pump (P2)	Same as P1
Fluid maintenance unit	Parallel filters. Batch and side-stream
Ullage maintenance unit	Relief valve, pressure regulator, nitrogen supply

generator are existing units at Rocketdyne's Santa Susana Field Laboratory that are part of a large steam ejector system used for altitude drawdown for a large liquid rocket engine program (Figure 5-6).

The facility was designed to generate steam by use of a heat transfer fluid heated to 316°C (600°F) by the fluid heater.

A basic flow schematic of the subsystem for the SRE is given in Figure 5-7, and the major assembly and subassemblies characteristics are summarized in Table 5-5. The SRE model subsystem has the same three major constituents as the pilot plant and commercial thermal storage system; central thermal storage unit (TSU), charging loop, and the energy extraction loop.

Figure 5-6. SRE Model Subsystem Test Installation

Figure 5-7. Thermal Storage SRE Subsystem Schematic

Table 5-5
SRE THERMAL STORAGE UNIT DESCRIPTION

Scalable size

4-MWhth capacity	107,000 liters (28,300 gal) volume
1-MW functional operating rate	209,000 kg (231 ton) rock/sand
5-MW maximum design rate	24,400 liter s (6,430 gal) Caloria HT43

Structural

ASTM A537-70 Grade B steel
Fabricated to ASME Section VIII
Div 2 standards
Basic design API code

Foundation

Low-density insulating concrete – 70% reduction in conductivity

Insulation

Owens-Corning intermediate hardboard (Fiberglas)
0.38-mm (0.015-in) aluminum weather cover

Instrumentation

70 thermocouples for measuring performance and heat loss
20 strain gages for measuring rock/wall interaction stress

During thermal charging cool fluid will leave the TSU through the lower manifold and circulate through the charging pump, fluid heater, flow control and back into the TSU through the upper manifold. During heat extraction, the hot fluid will leave the TSU through the upper manifold and circulate through the extraction pump, steam generator, flow control, and back into the TSU through the lower manifold.

Thermal Storage Unit (TSU)

The TSU is a welded steel storage tank with overall interior dimensions of 3.2m (10.5 ft) diameter by 13.3m (43.7 ft) high (Figure 5-8 and Table 5-5). The vessel will be filled to a height of approximately 12.5m (41.0 ft) with granite rock of approximately 10-mm (0.4 in) and sand approximately 1.5-mm (0.06 in) diameter. The tank top will be removable for installation of the rock and the fluid distribution manifolds. The fluid distribution manifolds will be located near the top and at the bottom of the tank and will provide uniform flow through the rock during the charging and heat extraction cycles. The exterior of the vessel will be covered with insulating material to minimize heat losses during tests and provide a maximum amount of energy recovery during heat extraction.

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Figure 5-8. Model Subsystem - TSU

Instrumentation will include (1) temperature probes located throughout the bed for thermocline definition, (2) strain gages located in the lower portion of the tank to determine the stress on the tank wall resulting from the thermal cycling, and (3) temperature surveys through the rock bed, tank wall, and foundation to determine heat losses during inactive as well as active periods (Figures 5-9 and 5-10).

Structural analysis conducted during the preliminary design portion of the program indicated that available commercial design and fabrication codes include (1) API Standard 650, Welded Steel Tanks for Oil Storage, and (2) Section VIII of the ASME Pressure Vessel Code.

Investigation of these codes during the detailed design indicated that the API Standard 650 was most appropriate for the proposed SRE tank design as well as the pilot plant TSU tank design since these are both basically gravity head vessels.

The ASME Unfired Pressure Vessel Code is primarily intended for pressure vessels where stored gas or liquids exert an ullage pressure on the tank of 103 kN/m^2 (15 psi) gage or higher.

The selected design approach for the SRE TSU tank was based primarily on three considerations: (1) use of design criteria and test results that could be applied to the pilot plant, (2) a design that would ensure safety of operation and fit within the overall operational safety requirements of the Rocketdyne SSFL for experimental units, and (3) provide test results that would allow correlation and verification of the soil mechanics analysis concerning the rock/tank stress interactions.

The application of these criteria led to the following selected design and fabrication approach for the SRE TSU tank.

- A. Design the basic tank configuration to API Standard 650 (flat bottom and top with tapered wall).
- B. Use ASME unfired pressure vessel code, Section VIII, Division 2, for structural material strength at elevated temperature and manufacturing standards.
- C. Install adequate strain gage instrumentation to ensure correlation and verification of the rock/tank stress interaction.

Figure 5-9. Thermal Storage Unit Temperature Sensors (all Sensors Iron-Constantan)

Figure 5-10. Strain Gage Locations – Thermal Storage Unit

The TSU material selected is A537-70, Grade B (ASTM designation), SA537, Class 2 (ASME designation). The allowable design stress for this material listed in the API Standard 650, Appendix K, is 204 MN/m^2 (29,600 psi). Because API Standard 650 does not allow for a reduction in strength at elevated temperatures, the ASME code (Section VIII, Division 2) values were used which results in an allowable design stress of 182 MN/m^2 (26,400 psi). An allowable design stress of 179 MN/m^2 (26,000 psi) was used for establishing course thicknesses based on the API gravity head design approach. The required wall thicknesses calculated for the various tank wall courses vary from 5.36 mm (0.211 in) at the lower course to 4.76 mm (0.1875 in) (API minimum gage) in courses 3 to 11. Wall thickness selected for construction is 6.35 mm (0.250 in) which is the next highest gage standard for commercial steel. The bottom course thickness was imposed on all courses from the bottom to the top to simplify the construction of the SRE TSU as well as to provide adequate rigidity for movement of the tank during transportation.

TSU Fluid Distribution Manifolds

The fluid distribution manifolds near the top and at the bottom of the tank distribute and collect the hot and cold fluid from the system and provide uniform flow distribution across the tank cross-sectional area.

The concept selected for the SRE TSU tank is shown in Figure 5-11. This design resulted from the requirements listed below.

- A. Provide uniform superficial velocity profile.
- B. Inflow and outflow mode.
- C. Take full system pressure.
- D. Avoid plugging with solids.
- E. $\Delta P = 25$ to 50 percent of bed ΔP .
- F. Low in cost.

The resulting design utilized standard pipe of low cost welded construction with 1,164 1.5-mm (0.06-in) diameter drilled holes. The design utilizes 10 cm (4-in) schedule 40 carbon steel pipe for the main manifold and 7.6 cm (3 in) schedule 40 carbon steel pipe for the branch manifolds. Hole size was based on (1) providing the pressure drop through the manifold of 25 to 50 percent of the estimated bed pressure drop for stability and uniform flow and

Figure 5-11. TSU Fluid Distribution Manifolds – Bottom and Top Identical

(2) a hole size small enough to avoid ingestion in the manifold of the small size solid particles which might otherwise result ultimately in clogging and disruption of the fluid flow through the manifold. Investigation of this problem in similar applications such as sand filters for water purification indicates that operation can be achieved for many years without a problem of ingestion of solids material in the inlet and outlet fluid manifolds.

Further consideration indicates that the design operating region of the bed is conducive to minimum solids deposition inside the manifold. First, induced solids transport by fluid motion is expected to be minimal because of the very low fluid velocity in the bed (maximum of 12m [40 ft] per hour). Second, the bed will be packed so that the lower portion will contain only the larger size particles that cannot migrate through the holes and will not be picked up by the fluid because of the low fluid velocities. Third, the hole pattern selected for the manifolds is canted downward at a 30° angle to avoid migration of the particles into the holes if the particles were nearby, as might occur if the holes were directed upward. In addition, the con-

siderably higher fluid velocity in the manifold network (compared to the bed) ensures that particles swept into the manifold will be transported through the system and removed by the fluid maintenance unit.

TSU Foundation

The foundation support for the TSU is a relatively conventional concrete pad with steel reinforcing bars. The concrete foundation must have adequate strength to support the tank plus rock as well as minimize heat loss from the TSU. Investigation indicates that a wide variety of commercially available concrete can be utilized to support the TSU. Data from the American Concrete Institute and the Portland Cement Association indicate that the concrete strength and thermal conductivity are directly related to the density of the concrete. Conventional concrete used in normal building construction has a specific gravity of approximately 2.2 to 2.4 g/cc (140 to 150 lb/cu ft) with a thermal conductivity on the order of 1.4 to 1.7 W/m-K (10 to 12 Btu-in/hr-sq ft-°F). Decrease in the density by use of lightweight aggregate provides a marked reduction in conductivity with a small decrease in compressive strength.

The concrete selected for the thermal storage unit has a density of 1.48 g/cc (92 lb/cu ft) with a corresponding reduction in thermal conductivity to approximately one-fourth that of standard concrete.

Heat Transfer Fluid Heater

For the warmup and charging modes a fuel oil fired combustion heater of 1 MWth capacity and 316°C (600°F) upper temperature limit (previously used for steam generator water heating) will be used to heat the fluid to 302°C (575°F) maximum temperature. The heater is of the continuous forced circulation, modulating, tube type, with fully automatic controls.

Fluid outlet temperature is controlled by a device which compares measured and preset heater outlet temperatures, and consequently calls for more or less fuel, or even shuts off the burner. Together with the adjustments of fuel flow, an efficient fuel/air ratio is maintained throughout the entire modulating range to avoid excess fuel consumption and air-polluting products due to off-design combustion. In the event the fluid pressure becomes

dangerously low or high (perhaps due to a leak or an obstruction in the line), a differential pressure switch will shut down the burner to prevent an overheated condition.

Steam Generator

The steam generator to be used served previously to produce a high flowrate of steam as an ejector fluid in an altitude test facility. The steam generator is essentially a pool boiler with submerged coils through which the hot heat transfer fluid flows. Convective heat transfer from the fluid to the water at lower temperature provides the heat for evaporation. The net generation of steam is controlled by setting an ullage vent control valve at a desired pressure. When the ullage pressure reaches the set value, the vent valve opens and steam is flashed via suitable piping to a blowdown stack.

The steel steam generator vessel is ASME coded, of nominal 110,000-liter (30,000-gallon) capacity, holding 100,000 kg (220,000 lb) of water and rated at $3,445 \text{ kN/m}^2$ (500 psig) and 343°C (650°F). With overall dimensions 3.05m (10-ft) ID by 18.3m (60-ft) long, the vessel contains 33.6m^3 (362 ft^3) of heat transfer area provided by 8 U-shaped coils in parallel, each a 32.3m (106 ft) length of 1-inch Schedule 40 pipe (42-mm OD, 35-mm ID) through which the fluid flows.

Ullage Maintenance Unit

The ullage maintenance subsystem provides a controlled pressure, oxygen free gas space over the surface of the fluid in the TSU using gaseous nitrogen.

Gaseous nitrogen is supplied through a staged regulation system from the facility bulk high-pressure supply lines. In addition, an emergency standby supply using K bottles is incorporated into the system to assure that possible service interrupt would not jeopardize the quality of the heat transfer fluid. During thermal charging the ullage volume will be decreasing and mixed nitrogen and fluid vapors will be discharged to the atmosphere with a back pressure regulator through a water cooled heat exchanger to trap condensed vapors for laboratory examination.

During heat extraction the ullage volume will be decreasing and gaseous nitrogen will enter through a regulator set for approximately 13.8 kN/m^2 (2 psig).

Fluid Maintenance Unit

Maintenance of the fluid for satisfactory operation over the relatively short SRE test period (compared to the 30-year pilot plant operational life) requires only removal of entrapped solids. Filtering is necessary only on the charging circuit (fluid discharging from the TSU through the lower manifold). Entrapment of particles larger than 80 microns will be accomplished with two parallel-mounted, full-flow filters between the TSU lower manifold and the charging pump.

Each 80-micron filter has full flow capacity allowing one to be cleaned or on standby if necessary without interrupting operations. Charging flow will always occur with a minimum of one filter in the line. A second 5- to 10-micron filter will be installed as a bypass around the charging pump to sample the fluid for small particle entrapment. This filter will be used intermittently. An estimate will be made of total entrapped solids based upon the duration and flowrate when the filter is in operation.

Data Acquisition System

The data acquisition system includes all elements and components necessary to sense, retrieve, and record all temperatures, pressures, flows, and strains necessary for complete evaluation of the model subsystem. These components include power supplies, sensors, calibration consoles, recorder, read-out, instruction, and translation equipment.

The data acquisition system is shown schematically in Figure 5-12. Consideration of various approaches (pen recorders, multipoint recorders, magnetic tape with high-speed multiplexing) led to this selection of the data logger as the basis for the data acquisition system.

The data logger selected, Doric Model 220, provides a high degree of accuracy with a multiplexing speed (20-sec sweep for 100 channels) adequate for the relatively slow transient characteristic of the solar thermal system.

Figure 5-12. Data Acquisition System

Access to the data will include a printed tape (decimal with selected units), punched tape (to be processed with a program in the Rocketdyne Central Data Processing System) and visual display (selected by front panel switching control).

5.3.3.3 Test Plan

The test plan is structured to provide the basic information necessary to verify the pilot plant design and operation. Operations and data analysis will establish the following characteristics.

- A. TSU performance map (steady-state operation).
- B. Start/stop and changeover characteristics.
 1. Time to energy availability.
 2. Energy output for various hold times.
 3. Control error band and thermal lag.
 4. Emergency shutdown.
 5. Warmup.

- C. Response to rapid energy changes (nonsteady state).
- D. Steady-state temperature control.
- E. Heat losses.
- F. Fluid stability and particulate measurements.
- G. Tank/bed structural loads.

Initially, testing will establish system characteristics for accurate control and operation during the subsequent charging and extraction cycles. The heater, steam generator, and all control elements will be operated and characteristics will be documented. During this period, the TSU will be heated to approximately 93°C (200°F).

The next test will condition the TSU bed by heating it slowly through 100°C (212°F) to remove the remaining water. The exact heating rate will depend on the degree of outgassing. Continuing this test, further heating will condition the bed and tank to the minimum pilot plant operating temperature of 218°C (425°F).

After bed conditioning, the remaining tests will be concerned with determining all functional characteristics to meet program objectives stated earlier.

Charging and heat extraction rates will be varied from the 0.1- to 1-MWth range with transient characteristics noted and measured for each start and stop. Significant charging and extraction periods at fixed steady-state rates will establish heat storage and extraction capability for correlation with the basic analysis.

5.4 OVERALL TEST SCHEDULE

The overall test schedule is shown in Figure 5-13. Prequalification tests were initiated in the first month of the contract and have been continuing (currently as life tests). The tests will continue for a period adequate to predict fluid life and general refurbishment requirements. Prequalification tests were initiated in July with fluid stability and material compatibility tests. These samples have accumulated up to 4,600 hours of test time (for the longest duration sample).

Figure 5-13. TSS SRE Test Program Schedule

Surface fouling tests were initiated in December 1975 and have accumulated about 2,600 hours for the longest exposed samples.

The model subsystem tests are scheduled to begin in mid-September after approximately one month of subsystem activation. Activation will include making the final instrumentation connections, filling the system with heat transfer fluid, activating the pumps and controls for proper operation, and familiarization with system operation. Prior to activation, the construction of the model subsystem will involve installation of the insulation on the external portion of the thermal storage unit and connecting the top to the tank, installation of thermocouples on the walls and in the bed of the TSU, and filling the TSU with the solids material.

The status of the program at the writing of this report is that all major material and fabrication items have been ordered, and it is expected that installation of these items will begin in mid-April and be completed by mid-August, immediately prior to the activation period.

Section 6

COLLECTOR SUBSYSTEM

The collector detailed design has been completed, procurement of materials for fabrication of the SRE collector is 95 percent complete, and detail fabrication and subassembly are in progress. Detailed test plans for all SRE tests are completed.

In this section the detailed design is described for each major component or subassembly, followed by a summary description of the SRE test plans.

6.1 DESIGN SUMMARY

6.1.1 Reflective Surface Description

The base for the reflective surface is 6.35-mm (1/4 in.) commercial float glass. The glass may have any iron content, and need not be free of cosmetic defects. Hence, the basic glass should be cheaper than the selected glass used for second surface mirrors. Defects which affect the long-term strength of the glass should be avoided.

The silver should be laid down in about an 800Å thickness layer to provide optimum reflectance. A primer coating of a base polymer of 5-micron (0.2-mil) thickness is laid over the silver and cured. Then a top polymer coating of 26-micron (1.0-mil) thickness is laid on and cured.

The resulting coating has a high reflectivity (about 0.90) and a high degree of specularity. As the coating is to be applied in a commercial silvering facility, the result should be an excellent representation of the pilot plant and commercial reflective surface as presently defined.

6.1.2 Reflector Support Structure Description

The SRE units use a reflector hub assembly that simulates the pilot plant design and a reflector segment design that is identical to the pilot plant design exception for detail design of the inboard attach fittings.

In the hub assembly the deep drawn upper and lower shells are simulated by spot-welded sheet and angle assemblies which essentially duplicate the pilot plant design (Figure 6-1). The upper and lower face sheets are cut circular from sheet and stiffened by angle stiffeners rather than by formed beads. The outer cylindrical shell and the cross channels are formed from flat sheet. The upper and lower rings are made from structural angles and machined, after assembly, to the required dimensions. The internal support fittings and the outer support fittings are machined from bar stock. The lower skin, outer cylindrical shell, cross channels, lower ring, angle stiffeners, and internal fittings are assembled and joined by spot welding. The upper skin, upper ring, and angle stiffeners are assembled as a unit, then joined to the lower assembly. The final assembly of the hub is made by joining the upper skin to the cross channels by means of rosette welds or rivets. Fusion welding is used to attach the upper ring to the cylinder. After assembly, the outer cylindrical surface of the rings is machined circular and perpendicular to the machined top surface. The key slot is machined parallel with the upper surface to provide accurate alignment for the reflector segments which bolt to the hub in field assembly. The attachment holes for the segments are drilled for an interchangeable clearance fit with respect to the segment hole pattern.

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Figure 6-1. Reflector Hub Assembly

The SRE reflector segment assembly is the same as for the pilot plant except for the beam attach fittings which are made from welded angle and bar stock to avoid the lead time required for a forging (Figure 6-2). The ends of the fittings must be machined perpendicular to the reflector surface and the index pins installed parallel to the reflector surface. The attach holes are located for interchangeable clearance fit with respect to the hub assembly. The frame assembly is assembled flat within 1.52 mm (0.060 in.) to control bond thickness between the glass reflector and support structure. Plastic spacers are used between the steel frame and the glass plate to limit the minimum bond line thickness to 1.27 mm (0.050 in.).

6.1.3 Drive Unit Hardware Description

Each heliostat incorporates azimuth and elevation drive mechanisms to produce movement of the reflective surface about its axes of rotation. The drive mechanisms are comprised of motors, drive trains, position feedback transducers, limit switches, reflector-support bearings, and structural housings. The azimuth drive train is shown schematically in Figure 6-3. The input 230V, 3-phase, 42 frame, 4-pole AC torque motor drives an integral

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Figure 6-2. Reflector Segment

Figure 6-3. Azimuth Drive Schematic

30:1 gearhead, whose output shaft is coupled to a 15:1 worm reduction. The worm reduction in turn is connected to the wave generator of a 242:1 harmonic drive, whose output produces reflector motion about the azimuth axis. The worm gear reduction is required to prevent back driving of the drive train under high external loads.

Figure 6-4 is a schematic representation of the elevation drive train which employs the same motor-gearhead as the azimuth train in the interest of commonality. The motor-gearhead is attached to a linear screw-jack having a 6:1 worm input and an output reduction through the acme-type screw of 9.52 mm (0.375 in.) per revolution. The antibackdrive nature of the screw jack prevents back driving and excessive power consumption under high external loads. In addition, the screw jack is capable of holding the reflector in the stowed position with power removed, provided that the aerodynamically induced vibration environment is not excessive.

The transition from schematic to mechanical representation of the drive unit is facilitated by Figure 6-5, which shows the arrangement of the various elements comprising both drive trains. In addition, this figure shows the bolted

Figure 6-4. Elevation Drive Schematic

Figure 6-5. Elevation-Azimuth Drive Unit

interface between the drive unit and support pedestal, and the two elevation support bearings and elevation actuator rod end which comprise the three-point interface between the drive unit and the reflector substrate. The drive unit structure is simulated for SRE by flat-plate elements cut to shape and joined by fusion welding (Figure 6-6). This method of construction simulates the deep drawn parts baselined for the pilot plant. The turret bearing seat, input drive shaft bearing seat, and upper harmonic drive mounting seat are machined parallel and concentric after welding to achieve alignment for the harmonic drive unit. The horizontal elevation axis uses self aligning ball bushings to avoid close tolerance hole alignment.

6.1.4 Pedestal/Foundation Description

The pedestal/foundation for SRE is similar to that for the pilot plant (Figure 6-7). The pedestal is comprised of a steel cone with attach angles at the top and bottom with eight bolt holes in each for attachment to the drive unit and the foundation. The foundation for SRE is circular and buried to a depth of 23 cm (9 in.) below grade with the base on the slab 40.6 cm (16 in.) below grade line. The base of the foundation is a flat slab 17.8 cm (7 in.) thick and 2.13m (84 in.) in diameter, reinforced with 9.5 mm (3/8-in.) diameter reinforcing rods. After the cone is attached to the foundation, the interior of the cone is filled with soil or sand to provide mass to resist overturning moments.

6.1.5 Sensor Post Description

The SRE sensor post is the same as for the pilot plant. It provides support for the tracking beam sensor which must be positioned along the line of sight to the receiver from the center of each reflector. The post consists of a 6.1m (20 ft) steel pole set in a concrete foundation with its top 5.8m (19 ft) above ground. Due to the fact that the sensors must be mounted on the line of sight to the receiver, the poles near the base of the tower will have booms extending at a 45° angle from the top to position the sensor over the reflector. The basic straight pole will accommodate 63 percent of the field. Booms 1.27m (50 in.) long are required for 28 percent of the field while booms 2.80m (110 in.) long are required for 9 percent of the field. For the SRE fixed array, the maximum receiver target elevation angle will be about 35°, which will require the 1.27m (50 in.) boom.

Figure 6-6. SRE HelioStat Mount/Actuator Structure

Figure 6-7. Pedestal Foundation Assembly

The foundation for the pole is a steel reinforced concrete block which is sized to hold the pole stable against the maximum wind loads. The sensor pole for the mobile unit will be bolted to the bed of the trailer and be a telescoping straight pole to allow lowering the sensor for adjustment and servicing. The poles will be coated with a heat reflective paint to minimize thermal distortion. A typical sensor post/foundation is shown in Figure 6-8.

6.1.6 Control Sensors Description

6.1.6.1 Heliostat Electronics

The major electrical components associated with the heliostat are:

- A. Three-phase 42 frame, 230 VAC drive motors in a torque motor configuration with return side switching.
- B. A three-turn azimuth position potentiometer.
- C. A one-turn elevation position potentiometer.

Figure 6-8. Sensor Post/Foundation

- D. Limit switches for azimuth and elevation.
- E. A heliostat interface box mounted on the heliostat pedestal to connect to the field controller cabling. This box also provides a plug-in interface with the heliostat manual control unit.

6.1.6.2 Beam Sensor

Figure 6-9 is a block diagram of the beam sensor. The beam sensor is packaged in a 2 by 2 by 4-in. extruded aluminum tube. All of the detectors and associated electronic circuitry are mounted on a thick film substrate with adequate environmental protective coating so that the overall housing does not require an environmental seal. A red optical filter (Schott Optical Company RG630) is used to attenuate ultraviolet background noise to improve tracking performance. An integral low pass filter (1/4 Hz) is used to attenuate transient movement of the beam sensor pole.

Figure 6-9. Beam Sensor Block Diagram

6.1.7 Field Controller Description

The SRE field controller (FC) performs the operations associated with power-ing and controlling the heliostat in the various operational modes. Although there are also many housekeeping-type operations the major areas of concern are:

- A. Initialization.
- B. Simulated master control/heliostat communication.
- C. Data acquisition.
- D. Calculation of coordinate conversion constants.
- E. Command position (synthetic) tracking.
- F. Beam sensor tracking.

A block diagram of the field controller is shown in Figure 6-10.

6.1.7.1 Power Interface. The FC requires a power source capable of delivering 240-VAC, 3-phase, 60-Hz power at 20A, and 120-VAC, single-phase, 60-Hz power at 5A. The FC will present a power factor load to the

Figure 6-10. Collector Controls Block Diagram

source which may range from 0.3 to 1.0 for the 3-phase source and 0.8 to 1.0 for the single-phase source.

6.1.7.2 Processor. The high-speed processor used in the FC is implemented with standard integrated circuits for low cost and maximum availability of replacement parts to assure maintainability over many years of operation.

6.1.7.3 Data Acquisition. A two-stage multiplexer system is used. Five heliostat data channels feed into an 8-channel multiplexer, with a separate multiplexer for each heliostat. A second level of multiplexing is used to switch the data channels into the 8-bit analog-to-digital (A/D) converter. The 8-bit A/D provides 0.4 percent accuracy over an input range of ± 10 VDC (78.4 MV/bit). The use of a high-level data system prevents noise problems by increasing the available signal-to-noise ratio.

6.1.7.4 AC Servo Loop Selection. The AC servo system was developed to provide a highly reliable, easily maintained and economic field controller.

Single- and two-phase AC motors were rejected primarily because of their lower efficiencies, poor low-speed performance, and undesirable starting characteristics. The standard three-phase AC motor with slightly modified torque/speed characteristics was selected because it could be operated in a low-speed mode without mechanical brushes or slip rings and could be reversed easily by electrically interchanging any two of the three motor circuits. High motor efficiency during low-speed operation was verified by test.

6.1.7.5 AC Power Bus. The three-phase AC power bus concept was developed as a unique approach to reduce FC component count and increase reliability. The bus concept permits the same power triacs to be used for electrically reversing all of the heliostat motors while still providing proportional control to all motors. The power bus provides 1/4-sec duration alternate clockwise and counterclockwise phase sequence power cycles separated by a single-cycle null.

6.1.7.6 AC Motor Control. The output of the beam sensor horizontal and vertical error channels is acted on by the processor to calculate a magnitude command for driving the reflected beam back to null. This command is normalized for solar intensity to maintain constant servo loop gain and is then quantitized to determine the number and phase sequence of 60-Hz AC cycles which must be applied to the azimuth and elevation motors. The number and phase sequence of the required AC cycles is loaded into the motor control RAM as a binary word where it is compared with the output of the power bus subperiod decrement counter. Whenever the correct phase polarity and the number of AC cycles remaining in the 1/4-sec period is equal to or less than the contents of the motor control RAM, the appropriate heliostat motor is turned on. The motor remains connected to the power bus until the null period at which time all of the triacs in the power bus and motor control circuits are allowed to turn off, thus disconnecting the motors from the power bus. If the heliostat motor requires more than the 6 AC cycles available for the proportional range, the motor will be connected for the full 14 AC cycles of required phase sequence once a second. During position command (synthetic) tracking, the proportional feature is not used, and the motor operates in a true bang-bang mode (either 28 AC cycles or none at all).

During emergency shutdown the three-phase power bus is locked in the desired phase sequence and all azimuth motors are connected, resulting in a 100 percent duty cycle with maximum available torque and speed.

6.1.8 Simulated Master Control Description

For SRE the primary purpose of the simulated master control is to provide the commands and data to the field controller to allow functional operation comparable to the pilot plant. The simulated master control will also provide an operator interface to the collector controls to simply test the operations at NWC.

The simulated master control provides position commands resulting from solutions of the equations governing coarse tracking of the heliostats. These calculations provide synthetic track and commands to the field controller.

The simulated master control provides the operator capability to send commands to or request data from the field controller via the teletypewriter and to display data on the CRT for the following commands.

Sun Acquisition — The operator will enter the identification of the heliostats to acquire the sun, azimuth angle of heliostat from receiver, elevation angle of receiver from heliostat, latitude of location, number of hours after midnight, and number of days after spring equinox. SMC will initiate sun acquisition.

Synthetic Track — When sun acquisition has been initiated a separate operator command will initiate the synthetic track update process. At the three-minute interval SMC will solve the sun acquisition equations, convert the gimbal angle data to the field controller compatible format, and transmit the commands to the field controller.

Heliostat Position Command — When the operator enters the identification of the heliostat to be commanded, the desired elevation angle and the desired azimuth angle, the heliostat position command algorithm will convert the angle data to the format compatible with the field controller and transmit the commands to the field controller.

Stowage – When the operator enters the identification of the heliostats to be stowed, the stowage algorithm will generate and transmit commands to the field controller to drive each elevation gimbal to the 90° or horizontal position.

Emergency Defocus – For SRE the emergency defocus operation is TBD. The emergency defocus requirements will be defined when the safety aspects of the NWC test operations have been analyzed.

Heliostat Status – When the operator enters the heliostat identification and initiates the display process, the following parameters will be displayed.

- A. Beam sensor vertical error.
- B. Beam sensor horizontal error.
- C. Beam sensor insolation.
- D. Elevation gimbal position.
- E. Azimuth gimbal position.

The algorithms will access or generate the data required.

Heliostat Array Status – At the operator's request, SMC will simultaneously display the elevation and gimbal axis positions for all five heliostats. The algorithm will access or generate the data required.

Selected Display – The operator enters the identification of 1 to 20 data parameters. The selected display algorithm will generate the required data and display these data with periodic, automatic update if required.

6.2 TEST PLAN SUMMARY

MDAC has planned a comprehensive set of tests to demonstrate the functioning of the collector subsystem and to demonstrate the adequacy of the design through environmental and lifetime testing.

Nine assembly, subassembly, and component tests are planned. A controls development test will be conducted to verify the field hardware and software, interfaces, and operational performance. The hardware to be verified

includes the three-phase AC reversing power bus, the output three-phase AC switching, and the input multiplexing. Software to be verified includes interface logic, microprograms, and master control simulation software. The interfaces to be verified include the field controller-simulated master control interface, the control sensors-field controller interfaces, and the drive motor-field controller interfaces. Operational performance will be monitored to verify the heliostat operating modes of normal tracking, commanded steering, and manual control.

Heliostat structural tests will be conducted to determine reflective surface deflections under operational wind loads and verify heliostat survival strength under simulated maximum wind loads. The deflection data will be used to verify predictions of reflective surface slope error distributions for operational conditions. Strain gages will monitor strain (hence stress) under severe loading conditions to verify the adequacy of the design for severe storm survival.

Heliostat vibrational mode surveys will be conducted to determine vibrational modes, mode shapes, frequencies, and damping rates for the fundamental vibration modes. The data will be used to verify calculations predicting stability against flutter, oscillations from turbulence and vortex shedding, and seismic loading. Vibrational frequencies will be demonstrated to be sufficiently high to prevent coupling with the controls systems.

The drive unit and control sensors will be subjected to environmental tests including high and low temperatures, dust, rain, icing, static loads, and temperature shock. The environmental test methods are adapted from MIL-STD-810B. The high- and low-temperature and thermal shock tests will ensure that the drive unit is able to operate throughout the range of temperature conditions typical of a desert environment. The dust tests will ensure that dust will not penetrate into critical drive unit components and cause undue wear. The rain tests will determine whether rain will penetrate the drive unit and cause rust or corrosion. The icing tests will show whether ice accumulates in such a manner as to inhibit operation of the drive unit or damage components.

Adhesive bonding tests will be conducted to verify the fast-cure adhesive to be used in the pilot plant. The tests will verify high- and low-temperature properties, adhesion, and lifetime under accelerated ultraviolet exposure. The SRE adhesive has been previously verified under Company-sponsored tests.

Simulated hail impact tests will be conducted on the reflective surface. These tests will demonstrate that the reflective surface is able to survive the hail environment typical of a desert environment. Damage to the protective coating and the glass substrate will be determined.

The drive unit and controls sensors functional/lifetime tests will be conducted to obtain supporting data to verify the operational integrity under conditions simulating the operational lifetime. Complete, real-time tests would require an excessive testing time. Therefore, the principles of accelerated gear life testing will be employed to provide a quick, inexpensive verification of predicted year life.

Life tests will also be conducted on a reflector segment. The objective is to determine the integrity of the reflector bondline between the reflective surface and its structural support. Cyclic loading will be applied to a segment under conditions of high and low temperatures and humidity. The effects of environment and loads on reflective surface flatness will also be monitored.

The reflective surface will also be subjected to dust erosion tests to determine the expected degradation over the lifetime of the pilot plant. Tests will be conducted in a standard dust exposure facility and in laboratory-scale tests. The laboratory tests will be conducted to gain insight into the physics of dust corrosion. The tests in the standard dust facility will be conducted to verify scaling laws on the effect of the external flow field on dust corrosion.

The test program will culminate in a subsystem-level heliostat array test. Four heliostats will be permanently emplaced to the north of a tower-mounted target. A fifth heliostat will be mounted on a trailer to be moved to the positions involving extreme tracking angles. The objectives of the array tests are to (1) determine reflective surface performance, including beam flux distribution, reflective surface flatness, surface reflectivity with exposure and cleaning, and effects of backlighting and shadowing; (2) determine col-

lector tracking performance, including beam pointing accuracy, control loop stability, operation with varying insolation, multiple heliostat control, and severe field position tracking; (3) determine nontracking and off nominal performance, including sun acquisition, safe stow, synthetic tracking, and emergency defocus; (4) determine environmental effects on the reflective surface; (5) determine wind effects on the reflector; (6) collect extended life data; (7) obtain operational data, including timelines, manpower, and environmental impact; and (8) verify selected operations and maintenance procedures, including beam sensor alignment, use of the digital image radiometer, inspection and maintenance requirements, and heliostat operational timelines.

The planned tests will utilize hardware as similar to the pilot plant and commercial hardware as possible, consistent with the low production volume. These tests will verify the pilot plant design to the extent that development testing will be required in Phase 2 only to verify design changes which result from the SRE tests and preliminary design changes.

The overall collector SRE schedule is presented by Figure 6-11. All tasks remain on schedule.

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Figure 6-11. Collector SRE Schedule

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1	FEDERAL POWER COMMISSION, HILL (HQAP)	1	NATIONAL SCIENCE FOUNDATION, RES. APPLIC. (HQAP)
1	FEDERAL POWER COMMISSION, LIBRARY (HQAP)	5	NATIONAL SCIENCE FOUNDATION, ST DIV., ALERT
1	FEDERAL TRADE COMMISSION, WEISSBRODT	25	NATIONAL TECHNICAL INFORMATION SERVICE (COMM)
1	FOSTER WHEELER CORPORATION, ZOSCHAK (HQAP)	1	NAVY ANNAPOLIS LABORATORY
1	GENERAL ATOMIC COMPANY, RUSSELL (HQAP)	1	NAVY ENGINEERING COMMAND
1	GENERAL DYNAMICS, ASER (HQAP)	1	NAVY OFFICE OF NAVAL RESEARCH - CODE 473
1	GENERAL ELECTRIC CO., LA (HQAP)	1	NAVY ORDNANCE STATION
1	GENERAL ELECTRIC CO., PLEASANTON (ERDA)	1	NAVY WEAPONS CENTER
1	GENERAL ELECTRIC CO., SUNNYVALE (ERDA)	1	NAVY WEAPONS CENTER, CODE 45
1	GENERAL SERVICES ADM., PROFESSIONAL SER. DIV.	1	NEVADA POWER CO. (HQAP)
1	GENERAL SERVICES ADM., PUBLIC BLDGS. SER.	1	NEW YORK STATE ATOMIC AND SPACE DEV. AUTH. (HQAP)
1	GEOLOGICAL SURVEY, DENVER (ERDA)	1	NRC DIV. OF RSR
1	GEORGIA INSTITUTE OF TECHNOLOGY, HTML (HQAP)	1	NRC LIBRARY
1	GOODYEAR ATOMIC CORPORATION (ERDA)	2	OAK RIDGE ASSOCIATED UNIVERSITIES (ERDA)
1	HELIO INC. (HQAP)	3	OAK RIDGE NATIONAL LAB. (ERDA)
1	HONEYWELL SYSTEMS AND RES. CTR., POWELL (ERDA)	1	OAK RIDGE NATIONAL LAB., ROSENTHAL (ERDA)
1	HONEYWELL SYSTEMS AND RES. CTR., SCHMIDT (ERDA)	1	OFFICE OF PLANNING AND DEV (HEW)
1	IDAH0 NUCLEAR ENERGY DEV. (HQAP)	1	OFFICE OF THE GOVERNOR, OR (HQAP)
1	IDAH0 POWER CO. (HQAP)	1	PACIFIC GAS AND ELECTRIC, BO (HQAP)
2	LAWRENCE BERKELEY LAB. (ERDA)	1	PASADENA WATER AND POWER CO. (HQAP)
1	LAWRENCE BERKELEY LAB., WAHLIG (ERDA)	1	PENNSYLVANIA POWER AND LIGHT CO., PFEIFFER (HQAP)
2	LAWRENCE LIVERMORE LAB. (ERDA)	1	PHILADELPHIA ELECTRIC COMPANY, LIBRARY (HQAP)
1	LIBRARY OF CONGRESS	1	PHILADELPHIA ELECTRIC COMPANY, RESEARCH (HQAP)
1	PORT OF LOS ANGELES (HQAP)	1	SOUTHERN CALIFORNIA EDISON CO., THILKER (HQAP)
1	PORTLAND GENERAL ELECTRIC, HELM (HQAP)	1	SOUTHERN CALIFORNIA GAS CO., WILSON (HQAP)
1	POSTAL SERVICE, MAINTENANCE MGT.	1	STANFORD RESEARCH INSTITUTE, KINDERMAN (ERDA)
1	PUBLIC SERVICE CO., NM (HQAP)	1	SYSTEMS GROUP OF TRW, INC (ERDA)
1	PUBLIC SERVICE ELECTRIC AND GAS, R AND D (HQAP)	1	SYSTEMS SCIENCE AND SOFTWARE (DRA)
1	PUBLIC SERVICE OF COLORADO, WSCC (HQAP)	1	TENNESSEE VALLEY AUTHORITY
1	ROCKWELL INTERNATIONAL (HQAP)	1	TUCSON GAS AND ELECTRIC CO. (HQAP)
1	SACRAMENTO MUNICIPAL UTILITY DISTRICT, SP (HQAP)	1	UNIVERSITY OF ARIZONA, USC (HQAP)
1	SAN ANTONIO CITY PUBLIC SERVICE (HQAP)	1	UNIVERSITY OF HOUSTON, DEPT. OF PHYSICS (HQAP)
1	SAN DIEGO GAS AND ELECTRIC CO. (HQAP)	1	UNIVERSITY OF HOUSTON, SOLAR ENRGY LAB (HQAP)
1	SANDIA LABORATORIES, BRUMLEVE (ERDA)	1	UNIVERSITY OF MARYLAND, DEPT. OF MECH. ENG. (HQAP)
1	SANDIA LABORATORIES, SELVAGE (ERDA)	1	UNIVERSITY OF MINNESOTA, HEAT TRANSFER LAB. (HQAP)
1	SANDIA LABORATORIES, SKINROOD (ERDA)	1	UNIVERSITY OF MINNESOTA, JORDAN (HQAP)
1	SANDIA LABORATORIES, STROMBERG (ERDA)	1	UNIVERSITY OF PENNSYLVANIA, DENTON (HQAP)
1	SECRETARY OF DEFENSE OFFICE, PENTAGON	1	UNIVERSITY OF WISCONSIN, CHEM. ENG. (HQAP)
1	SHELDahl INC., ANDERSON (HQAP)	1	UTAH POWER AND LIGHT CO. (HQAP)
1	SHELDahl INC., STRICKLEY (HQAP)	1	WESTINGHOUSE ELECTRIC CORP., HAUSER (HQAP)
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