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**CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM,
PHASE 1**

**Quarterly Progress Report (Final) for Period Ending
March 31, 1976**

October 1976

Work Performed Under Contract E(04-3)-1110

**Martin Marietta Corporation
Denver, Colorado**

**ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy**

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I. INTRODUCTION

During this period (January 1976 through March 1976), the primary program effort was expended toward the completion of the detail design of the three major research experiments. Also, the Preliminary Pilot Plant Economic Cost Study was completed and submitted to Sandia.

In the Collector Subsystem, the designs for both the twenty-five mirror and the nine-mirror heliostats were completed and released. A contract for the fabrication of the heliostat structure was awarded and the first assembly will be delivered to Martin Marietta, Denver, April 8, 1976. Procurement of the heliostat drive mechanisms proceeded on schedule, with their delivery scheduled for the first week in May. A detailed test plan for the collector research experiment was prepared and reviewed with Sandia. The sensor control electronics breadboard was fabricated, and a series of tests were performed to demonstrate the operational characteristics of the control system.

In the Receiver Subsystem, Foster Wheeler continued with the detail design of the 5 MW research experiment receiver. A preliminary draft of the detailed test plan for the receiver subsystem research experiment was prepared and is now undergoing a final review. A series of incremental detail design reviews were held at Foster Wheeler in order to review and approve the design as it progressed. These reviews were attended by personnel from Sandia-Livermore, Sandia-Albuquerque, and Martin Marietta-Denver.

The detailed design of the Thermal Storage Subsystem continued at Georgia Institute of Technology. Several incremental detail design reviews were held as the design progressed. The design is scheduled to be completed by April 1, 1976. Coordination effort continued with the Georgia Power Company on whose property the experiment will be erected and the tests conducted. Also, during this period, a study of the candidate heat transfer fluids was conducted. It is now planned to select the fluid for the oil stage prior to June 1, 1976.

During this period, Bechtel completed the Preliminary Environmental Analysis for the Pilot Plant, and this report was submitted to Sandia. The optimization studies of the Electrical Power Generation Subsystem were initiated. Bechtel also initiated work on performance data for the Electrical Power Generation Subsystem which will become part of the Martin Pilot Plant Simulation Model.

A major effort was the preparation of the preliminary Cost Analysis for the 10 MWe Central Receiver Solar Thermal Pilot Plant. This task required the development of a cost accounting structure

and a definition of all of the costs associated with the design, construction, checkout, and two-year test of the Pilot Plant. The study was completed and the report submitted to Sandia and ERDA on March 8, 1976.

The following sections discuss the work accomplished during this period in more detail.

II. 10 MW_e PILOT PLANT

A. INTRODUCTION

Based on the conceptual design of the pilot plant, analysis of operational modes have continued and a cost analysis of the pilot plant was performed. The performance characteristics of the pilot plant for a diurnal start from a hot standby were established. The analyses have shown that with the solar energy available, the collector, receiver, and turbine performance characteristics match quite well to provide a startup capability with minimum loss of energy. Analyses of the electrical system were performed for normal operation and for transfer to standby and emergency power. This analysis shows the system design provides for safe operation of the equipment and personnel in the event of loss of power to the plant auxiliary equipment. A cost analysis of the pilot plant was performed, based on the baseline conceptual design. This cost analysis is to be updated toward the end of the program. Inputs for the cost analysis were received from each member of the team which includes Martin Marietta Aerospace, Foster Wheeler Energy Corporation, Georgia Institute of Technology, and Bechtel Corporation.

B. PILOT PLANT DIURNAL START FROM HOT STANDBY

Analyses have been performed to evaluate the pilot plant performance when starting from the overnight hot standby condition. The purpose of this analysis was to assess the imposed system requirement not to exceed 20 minutes for a diurnal start from hot standby to full power. In order to make an assessment of the requirement, several items were defined which include an agreed starting point and what is considered full power. The starting point is defined as the time of sunrise since this is readily achievable, consistent, and measurable. Since full power can be defined in several ways, depending on the point of reference, i.e., turbine rating, pilot plant design point, receiver capability, solar insolation, etc., a composite definition was selected which relates to each of these items. Full power is assumed to be the point at which all available solar insolation is used in generating electrical power (i.e., the collector field is reflecting all solar insolation potentially available to it, the receiver is accepting all the solar insolation available, and the electrical power generation subsystem is converting that thermal power from the receiver to electrical power.)

The analysis involves the performance characteristics of the subsystems and how they interact to establish the pilot plant

performance. This requires first establishing the subsystem inherent constraints and then evaluating their performance under the desired operating conditions so as not to exceed these constraints. The primary constraints for this type of analysis involve temperature limits and rates of change of temperatures. It is important to establish these constraints based on the operational life requirements of the plant and not what is possible on a one time basis.

In addition to the evaluation of the system performance characteristics of operating the turbine-generator, the first thing in the morning, a performance comparison was made to charging the thermal storage as the first operation in the morning.

1. Morning Startup with the Turbine-Generator

a. Analysis Approach - The approach used for the analysis was to capture all available solar insolation, starting at sunrise, and to direct this into the receiver aperture for the generation of steam which, in turn, is provided to the turbine.

The primary receiver constraints for this mode of operation are to maintain acceptable superheater tube metal temperatures. These metal temperatures are a function of the flux on the cavity walls, the energy required to bring the steam drum temperatures up from the overnight conditions and the resultant flowrates in the tubes.

The primary constraints for the turbine are the rates of change of temperatures allowable on a daily basis and still provide the operational life required. Selected starting and loading curves are based on the average metal temperatures. As the shutdown period increases and the average metal temperatures decrease, the minimum allowable time to bring the turbine on line increases. For an overnight condition where the average metal temperatures have cooled to 645 to 811 K (701 to 1000°F), the predicted turbine starting and loading curves are shown in Figure II-1. This curve shows the flowrates and times required to synchronize the turbine and the allowable rate of increase for loading the turbine. The initial steam conditions required for starting the turbine are 3447.5 kPa (500 psig) and 56 K (100°F) of superheat.

Solar insolation data, as a function of time from sunrise, is necessary as input data to perform the analysis. Reliable, accurate data of this type is not readily available. Therefore, solar insolation measurements at Waterton, Colorado, were made

Figure II-1 Predicted Turbine Starting and Loading Curves, Hot Start

— Actual Insolation (Cloud Effects Not Shown if Less than 5 Minutes)
 --- Estimated Insolation

Figure II-2 Direct Solar Insolation, Waterton, Colorado, 01-20-76

for purposes of these analyses and are shown in Figure II-2.

These data were coupled with the performance characteristics of a collector field located at Inyokern, California, for December to establish solar power as a function of time. These conditions represent the maximum rate of increase of solar power into the receiver cavity and provide worst case conditions for this analysis. Table II-1 shows the calculations and system characteristics used to establish the amount of solar power put into the receiver cavity as a function of time. In addition to solar insolation, the effects of tower shadow and the effective

Table II-1 Solar Power Through Receiver Aperture

Solar Power Through Aperture = (Mirror Area)(Effective Cosine)(Solar Insolation)(System Efficiency Factors)

Mirror Area = (1718 Heliostats)(400 ft²/Helio.) = 63,843 m² (687,200 ft²)

Effective Cosine = Average Field Cosine; Shading; Blocking for Inyokern, December 21

Solar Insolation = Data from Waterton, January 20, 1976

System Efficiency Factors = Utilization	0.994
Tower Shadow	0.969 - 1.00
Mirror Reflectivity	0.8565
Tracking	0.982
Optical	0.988
Tower Sway	1.0

cosine of the collector field varies as a function of time, as shown in Figure II-3. The resultant power to the receiver cavity and a comparison plot of the direct solar insolation available is shown in Figure II-4. Based on these input data, computer programs were utilized by Foster Wheeler to model the performance characteristics of the receiver in terms of steam temperatures, pressures, and flowrates and to insure that tube metal temperatures were not exceeded. This data is shown in Figure II-5.

Figure II-3 Effective Cosine and Tower Shadowing

Figure II-4 Morning Startup Power to Receiver

Figure II-5 Morning Startup, Receiver

Figure II-6 Morning Startup, EPGS

b. Performance Characteristics - Utilizing the above data, the receiver performance was matched with the selected starting and loading curves for the turbine to determine the time at which all available solar power will be converted to electrical power. Also determined was the amount of energy lost during this time period, including the heating of piping between the receiver and electrical power generation subsystem and mismatch of steam conditions between the receiver and turbine. This combined data is shown in Figure II-6.

As shown in Figure II-6, the turbine inlet steam remains constant for a period as the tower downcomer and horizontal piping between the receiver and turbine is heated up by the initial steam generated in the receiver. Subsequently, as the steam temperature increases, the turbine requirement for 56 K (100°F) of superheat is satisfied and flow to the turbine is provided for synchronization. For a period of time after synchronization, steam flowrate accepted by the turbine is limited by the turbine starting and loading curves for a start from hot standby.

After approximately 45 minutes from sunrise, the turbine can accept all available steam from the receiver and the definition of full power is satisfied, i.e., all available solar insolation is used in the generation of electrical power.

Figure II-7 summarizes the energy losses for this operational period. The curve "Solar Power to Receiver" is the same data as originally shown in Figure II-4. The "Potential Power to Turbine" is the thermal power in megawatts that the receiver could generate and the turbine could accept if the receiver and turbine were operating under normal operating conditions. The "Actual Power to Turbine" is the thermal power in megawatts that the turbine has accepted for the morning startup operation. The "Potential Electrical Output" is the electrical power that could be generated if the "Potential Power to Turbine" were actually delivered to and accepted by the turbine. The "Actual Electrical Output" is that electrical power delivered during the morning startup operation. The startup losses shown inset in Figure II-7 reflect the losses assigned to the startup operation if considered either as thermal or electrical. These losses are in addition to those that would occur if the plant were in a normal mode of operation. It should be pointed out that the losses are not to be combined, but are the same losses stated two different ways.

Figure II-7 Morning Startup Receiver/EPGS Summary

2. Morning Startup Charging Storage Only

As an alternative mode of operation to the morning startup with the turbine-generator, discussed above, a morning startup operation of charging thermal storage only was analyzed. This mode of operation is intended to provide additional capability from storage prior to starting the turbine-generator. This mode of operation also allows charging thermal storage when the output of the turbine-generator is not required for the first part of the day or for a given day.

a. Analysis Approach - The approach used for this analysis is the same as previously used for the morning startup with the turbine-generator. All of the solar insolation was captured, starting at sunrise, and directed into the receiver cavity. The generated steam was then supplied to the thermal storage rather than the turbine-generator. All of the performance calculations for the collector field and the receiver, previously discussed, also apply here. Likewise, the constraints for the receiver subsystem apply. The constraints for the thermal storage subsystem center around the temperature and pressure of the input steam. The temperature of the charge steam entering the salt stage should be greater than 728 K (850°F) to prevent cooling of the heat exchange since overnight cooldown of this heat exchanger will be minimal. The steam entering the condensing stage has to be greater than 8722 kPa (1265 psia) in order to initiate the flow of oil. These conditions are set in order to insure adequate oil temperatures on the subsequent discharge cycle.

b. Performance Characteristics - The performance characteristics of the receiver for the morning startup were matched to the thermal storage subsystem. Again, the initial steam from the receiver was utilized in heating the tower downcomer and horizontal piping between the receiver and thermal storage subsystem. As shown in Figure II-8, the "Solar Power to Receiver" is the same as previously shown in Figure II-4 and II-7. The "Potential Power to TSS and Potential Stored Power" curve is the same as the "Potential Power to Turbine" curve of Figure II-7. This is true since the collector and receiver performance is the same whether the steam is delivered to thermal storage or the turbine. However, there is an increased delay in the "Actual Power to TSS" as compared to the "Actual Power to Turbine" of Figure II-7. This is due to the temperature and pressure constraints on steam to thermal storage. This delay reflects itself in increased losses, as shown in the inset of Figure II-8, as

Figure II-8. Morning Startup Receiver/TSS Summary

compared to those of a morning startup with the turbine-generator discussed previously. In this case, the thermal losses have been divided into two categories; the first, "unusable steam" is energy which must be dumped to the condenser because it is unacceptable to TSS; the second category, "TSS warm-up steam", is the energy required to heat the TSS to operating temperatures. The total thermal loss is the sum of these two.

3. Summary

The most efficient use of daily energy is a morning startup on the turbine-generator. Table II-2 compares energy loss as either thermal or electrical for a morning startup of the turbine-generator against charging thermal storage first. Percentage loss of daily electrical power for a given Winter day

Table II-2 Morning Startup Loss Summary

	MORNING STARTUP ON T-G	START MORNING BY CHARGING TSS
Potential to User Less Actual Used, MW-hr _{th}	5.33	22.34
Total Equivalent Electrical Loss, MW-hr _e	1.44	5.62
% of Daily Generation*	1.36%	5.32%
Time to Full Power, Min.	45	77
*Daily Generation Calculated for 01-20-76, 105.6 MW-hr _e .		

and time to full power is shown for reference. If the time to full power for a diurnal start from hot standby is defined from sunrise to the point at which all available solar energy is being used in generating electrical power, the specification time should be 50 minutes rather than 20 minutes. It should be noted that during this sunrise period, the combined effect of the solar insolation, collector field, and receiver performance characteristics provide thermal power which closely matches the capability of the turbine-generator.

C. ELECTRICAL SYSTEMS OPERATION INCLUDING STANDBY AND EMERGENCY POWER SOURCES

In the event of loss of the normal source of power to the auxiliary electrical equipment in the power plant, harm to personnel and/or damage to equipment could occur unless backup power sources are provided. Two sources of backup power are provided to preclude this danger. A standby diesel generator is provided to prevent either harm to personnel or damage to equipment if power is lost. In addition, an emergency battery is provided to preclude harm to personnel during the startup period of the diesel generator or if there is a malfunction in the diesel generator. During normal operation, power is provided to the electrical equipment by the power plant itself or the utility grid, depending on the mode of operation.

1. Auxiliary, Standby, and Emergency Loads

The electrical power requirements of the power plant can be categorized into auxiliary, standby, or emergency loads for purposes of defining the requirements of the backup power sources. The auxiliary loads are all power plant loads, including the standby and emergency loads. The auxiliary loads vary depending on the operating mode of the plant. These loads are made up of power requirements from the collector, receiver, thermal storage, electrical power generation and controls subsystems. Table II-3 shows a summary of these load requirements for a typical set of operational modes that the power plant might experience throughout a given day. The power requirements shown for each subsystem are those required to satisfy specific equipment where the total includes a summation of the subsystem requirements plus losses associated with supplying and distributing these load requirements.

Standby loads are those required to place and maintain equipment in a safe condition. These loads are shown in Table II-4, and they also vary with the operational mode of the power plant. These loads are a portion of the auxiliary loads discussed above and are supplied by a standby diesel generator when power to the plant is lost.

Operational Mode	Collector	Receiver	TSS	EPGS	Controls	Total & Losses, 10%
Receiver Startup	247.2*	25*	1.9	178	6.1	472
Charge TSS	61.9	2	249.2	267	6.1	604
Turbine Startup to Sync	61.9	2	249.2	696	6.1	1046
Turbine Sync to Load	61.9	2	249.2	696	6.1	1115
Generating from Receiver Alone	61.9	2	1.9	913	6.1	1085
Generating from Receiver and Charging TSS	61.9	2	249.2	910	6.1	1329
Generating from Receiver and TSS	61.9	2	249.2	828	6.1	1217
Generating from TSS Alone	247.2*	25*	249.2	735	6.1	1333*
Turbine Planned Load to Trip	0	0	249.2	57	6.1	322
Shutdown and Overnight	0	0	1.9	48	5	57
*Peak						

Table II-3 Auxiliary Power Requirements, kW

Table II-4 Standby Power Requirements

Mode	Collector	Receiver	TSS	EPGS	Controls	Total Incl. Losses
Receiver Startup	247.2 kW for Up to 18 min. to Stow Heliostats	27 kW for 1 min. 25 kW to Close Door, 2 kW to Fix Valves	1.9 kW Sealing Steam Fluid Pump	79.8 kW	3.5 kW	371 kW
Charge TSS						
Turbine Startup to Sync						
Turbine Sync to Load						
Generating from Receiver Alone						
Generating from Receiver & Charging TSS	0 kW, Assumes Heliostats in Stowed Position	0 kW, Assumes Door Closed & Valves Fixed				88 kW
Generating from Receiver & TSS						
Generating from TSS						
Turbine Planned Load to Trip						
Shutdown & Overnight						
Power Required from Emergency Battery (26.5 kW Peak) Cooling Water Pumps Turbine Emergency Oil Pump Controls, Lighting, Beacon PA System Computer Seal Steam						

Emergency loads are required for personnel safety and critical plant loads that require continuous power. These loads are shown in Table II-5 and are a portion of standby loads discussed above. These loads are supplied by an emergency battery in parallel with, but isolated from, the normal sources of power for the auxiliary loads and the standby diesel generator.

Table II-5 Emergency Power Requirements

Power Required from Emergency Battery	
Cooling Water Pumps	} 26.5 kW Peak
Turbine Emergency Oil Pump	
Controls, Lighting, Beacon	
PA System	
Computer	
Seal Steam	

2. Standby and Emergency Power Operation

During normal daily operation, the power plant supplies power required for auxiliary loads and the net power generated is supplied to the utility grid. The utility grid supplies power to the plant auxiliary equipment for morning startup, evening shutdown, and overnight operations. This power is drawn from the utility grid through the main transformer and circuit breaker as shown in Figure II-9. The 13.8 kV switchgear then distributes the power to the two load center units where it is stepped down to 480 v and distributed to the required auxiliary loads.

During morning startup, the main generator is brought up to rated voltage and speed. After it is synchronized with the 13.8 kV main bus, the generator circuit breaker is closed, thereby paralleling the unit with the utility power grid. The generator is then controlled to supply the pilot plant auxiliary loads and transmit net power to the utility grid.

In the event of loss of the utility grid power, the turbine-generator will remain in operation, supplying the pilot plant auxiliary loads until it is manually shutdown or down to a minimum of .12 MW, at which time the turbine will trip off line. If the 13.8 kV bus is lost due to interruption of both the utility grid and main generator, the 1600A load center circuit breakers and nonessential loads circuit breakers trip and automatic starting of the diesel generator will occur.

Any number of events could occur leading up to the starting of the diesel generator. Usage of the diesel generator is more likely to occur during plant startup, shutdown, or overnight operations, since loss of the utility grid will cause loss of the

Figure II-9 Electrical System Block Diagram

13.8 kV switchgear bus. During daytime operations when the main generator is operating, loss of both the utility grid and main generator would be required to lose the 13.8 kV switchgear bus. Several possible causes for loss of the utility grid are storm, earthquake, fire, etc. The output of the generator may be lost for various reasons. Either a turbine trip or generator trip will shutdown the units and can be brought about by any number of mechanical or electrical irregularities.

Immediately upon loss of the 13.8 kV switchgear bus (loss of utility grid tie and main generator output), sensing circuitry detects the power loss; and within 0.5 seconds, signals operate the compressed air line solenoid to start the standby diesel generator. During the diesel generator startup period of about 10 seconds, the emergency battery will supply all loads on the 125 Vdc bus. As the output of the battery charger falls due to the loss of power, the battery immediately takes over and continues an uninterrupted supply of power to the emergency DC loads. Additionally, power to the DC/AC inverter serving the plant computer and public address system will be supplied by the battery. After the 10 seconds and the diesel generator has come up to speed, it will furnish the emergency loads previously supplied by the battery and will also start to recharge the battery. Should the diesel generator fail to start, or should its operation be interrupted, the emergency loads will be supplied by the battery for about 2 hours, after which time the battery will be completely discharged.

Once the diesel generator has started and has been brought on line, it will supply loads up to 375 kW for up to 48 hours. If it is determined that a longer run time will be required, additional fuel will need to be trucked in. Upon resumption of the utility grid power tie, it will be necessary to manually shutdown the diesel generator and reset the 1600 A load center circuit breakers, thereby restoring normally supplied power.

After the standby diesel generator has come up to speed and assumes its standby loads, plant safing actions will begin. If this occurs during normal daytime operating conditions, the turbine-generator, condenser, and feedwater pumps will stop. Using the residual water in the boiler drum, steam will continue to be generated until the heliostats are removed from the receiver cavity. This steam will be vented to the atmosphere since the condenser is not operating. Therefore, the initial sequence to be performed on standby power includes defocusing the heliostats off the receiver aperture and stowing, sealing off the thermal

storage subsystem, closing the receiver doors, and sealing off the receiver subsystem.

D. 10 MWe PILOT PLANT COST ANALYSIS

A report was prepared and delivered that provided a cost analysis of the Central Receiver Solar Thermal Power System 10 MWe Pilot Plant. The design baseline for the plant is that presented in the Preliminary Design Baseline Report and Conceptual Design Report, Volumes I, II, and III, dated December 1975. The cost estimates were provided by a team lead by Martin Marietta Aerospace of Denver, Colorado, who is the integrator for the overall effort and the Collector Subsystem designer. Bechtel Corporation, San Francisco, California, is responsible for the Electric Power Generation Subsystem and the architect-engineer task of the Pilot Plant. Foster Wheeler Energy Corporation, Livingston, New Jersey, is responsible for the Receiver Subsystem and Georgia Institute of Technology, Atlanta, Georgia, is responsible for the Thermal Storage Subsystem.

The format for presenting the cost estimates were provided by Sandia Laboratories, Livermore, California. For estimating purposes, the site location was assumed to be between Phoenix and Yuma, Arizona, and adjacent to the main highway system. The estimate is based on 1975 mid-year average dollars. A three-year program was assumed from go-ahead to plant operation.

In addition to the introduction section, the report consists of four sections. Section 2 provided a summary description of the pilot plant for reference purposes and Section 3 provided a general description of the content of the Work Breakdown Structure provided by Sandia. Section 4 contained the detail investment cost for providing an operational plant, including plant startup. The detail cost estimates were separated into material and labor cost when this information was available. The work breakdown structure provided by Sandia identified cost accounts to the third level and was used for collection of the cost estimates. In general, cost detail was provided to a lower level of detail for the solar peculiar portion of the plant than for the conventional portion of the plant. Cost estimate breakouts below the third level for the solar peculiar portion of the plant were selected based on the respective subsystem design and configuration and are peculiar to the design baseline report discussed above. Section 5 provided cost data for a two year operation test program, a breakout of the design cost for the solar peculiar portion of the plant investment cost and time phasing of the plant investment, and two year

operational test program cost.

In order to provide understanding of the contents of the third level accounts and below, general ground rules were established to define the conventional and the solar peculiar portions of the plant. The conventional portion of the plant, in general, follows the applicable portions of "Guide for Economic Evaluation of Nuclear Reactor Plant Design", USAEC Report Number NUS 531, for the details of these accounts. The solar peculiar accounts for the plant, collector, receiver, and thermal storage, are structured primarily independent of the conventional portion. The following is a general description of the second level cost for both portions of the plant.

MP2000 Land

It is assumed that the land procured is 200 acres, even though the actual area covered is somewhat smaller, and the location is in a relatively remote area between Phoenix and Yuma. Based on this location, only the cost of the land is included, and the requirement for relocations of buildings, utilities, highways, etc., is not required.

MP2100 Structures

Included in this account is the cost of the various structures required to house the conventional portion of the plant and general site improvements including grading, general excavation, landscaping, fences, roads, water wells, and sewage required by the total plant, including the solar peculiar portions. Excavation and backfill associated with installation of the heliostat, receiver tower, and thermal storage foundations are not included.

MP2300 Turbine Plant Equipment

The installed cost of the turbine-generator, air cooled condenser, feedheating and related support systems, turbine-generator controls, makeup and chemical treatments, auxiliaries, cooling systems, piping, etc., for the turbine plant are included. Horizontal piping from the receiver and thermal storage is not included.

MP2400 Electrical Plant Equipment

The switchgear; station service equipment, including standby and emergency power supplies and main substation transformer; control boards for the electrical systems, receiver, thermal storage, and collector; master control computer; and the power, instrumentation, and control wiring from the administration and control building to the receiver, thermal storage, and electrical systems are included here. Not included here is the power, instrumentation, and control wiring for the collector subsystem heliostat field to the administration and control building. The instrumentation and control devices that are located at the collector, receiver, and thermal storage subsystems are not included here.

MP2500 Miscellaneous Plant Equipment

All transportation and lifting equipment, communications, furnishings and fixtures, and weather monitoring equipment, which are of a general nature and are associated with equipment or facilities in more than one of the other accounts, are located here. In reference to NUS-531, however, the well and associated drinking and fire water are located in MP2100, and the air system for the conventional portion of the plant is located in MP2300.

MP2700 Collector Equipment

Included are all costs associated with the installed cost of the collector subsystem, excluding the computer control which is in MP2400 and the general grading of the collector field, roads, and fences which is in MP2100.

MP2800 Receiver Equipment

Included are the installed costs of the cavity receiver, the receiver tower including elevator, foundation, etc., and the tower riser and downcomer piping. Also included is the horizontal piping from the receiver tower to the turbine building.

MP2900 Thermal Storage Equipment

Included are the installed cost of the total thermal storage subsystem and the horizontal piping from the thermal storage subsystem to the turbine and to the base of the receiver tower.

MP3000 Thermal Storage Material

Included is the cost of the molten salt and the hydrocarbon oil storage media. The cost includes delivery to the site and installation in the tanks. The cost of molten salt is included.

MP4000 Spare Parts

In general, the spare parts are those recommended by manufacturers for repair of various components such as pumps, etc. In addition, selected items such as tubes for the receiver, oil and Hitec pumps for the thermal storage, and the equivalent of 10 heliostats for the collector subsystem is provided. The combination of spare parts should support the initial operating period of the pilot plant with replacement parts procured as required.

MP4100 Contingency Allowance

An allowance is included to provide for uncertainties within the estimate detail in quantities, pricing, and labor within the defined scope of work. It is expected that the contingency will be expended during the course of the project. As designs mature, the contingency can be reduced accordingly for the respective confidence level, as the uncertainties discussed above are accounted for and priced accordingly.

MP9000 Indirect Cost

Included are the cost of temporary construction services, facilities and equipment, and cost of overall construction/management services, taxes and insurance, and training and plant startup. Not included is the cost of owners plant operating staff. Included under construction services also are field supervision and engineering cost for the conventional portion of the plant, including the receiver tower and the heliostat foundation. Included under architect and Engineering Services are the related construction/management services for the conventional portion of the plant, and also, the integration management for the total pilot plant, including the solar peculiar portions

III. COLLECTOR SUBSYSTEM

The contents of Section III highlight the detail design and fabrication phases of the Collector Subsystem from January through March 1976.

A. HELIOSTAT DESIGN AND FABRICATION STATUS

1. Structure

The design of the structures for the four SRE heliostats is based upon the results of wind tunnel testing of scale-model heliostats. These results, reported earlier, allowed the optimum sizing of both the reflecting area and structure to minimize cost while not sacrificing performance.

a. 25-Mirror Heliostat Structure - The main features of the structure of the 25-mirror SRE heliostat are shown in Figure III-1. The structure consists of two main assemblies; the first being a yoke assembly constructed of two vertical 0.3 m (12 inch) steel I-beams and a horizontal 0.3 m (12 inch) steel box beam. The second assembly, consisting of a 0.12 m (5.0 inch) diameter shaft with vertical beams, seats into bearings mounted in the upper ends of the yoke. The function of this beam assembly is to support the 25 1.2 x 1.2 m (4 x 4 ft) laminated glass mirrors which form the 37.16 m² (400 ft²) reflective surface.

The detail structural design of the 25-mirror SRE heliostat has been completed and approved. The first unit has been fabricated by Rio Grande Fabricators of Albuquerque, New Mexico, and has been received at Martin Marietta where it is awaiting final assembly. Final fit and assembly checks were performed at Rio Grande to insure compliance to the drawings and specification. As a result of these fit checks, the fabrication of the remaining two 25-mirror heliostats for the SRE experiment has been authorized.

b. 9-Mirror Heliostat Structure - The 9-mirror SRE heliostat, shown in Figure III-2, is similar in design to the three 25-mirror heliostats in that the area of the reflecting surface is 37.16 m² (400 ft²). The primary difference is that the reflecting surface consists of nine 2.0 x 2.0 m (80 x 80 in.) fixed-curvature mirrors in place of the 25 smaller mirrors. The support of these nine mirrors results in a structure of slightly different dimensions, although the material types and sizes remain unchanged.

Figure III-1 25-Mirror Heliostat

Figure III-2 9-Mirror Heliostat

The fabrication drawings and specification for the 9-mirror configuration have been completed and approved. The structure will be fabricated by Rio Grande Fabricators following the completion of the two 25-mirror structures.

2. Reflecting Surfaces

a. Variable-Curvature Mirror - The variable-curvature mirror frames to be used on the three 25-mirror heliostats are advanced versions of the basic ring and bar concept used upon the prototype heliostat. The advanced concept (Figure III-3) employs a technique of focusing by adjusting a center screw only. The necessity for corner adjustments has been eliminated, allowing savings in both fabrication time and material cost.

This advanced center-focus configuration resulted from a series of tests conducted at ranges greater than 32.9 m (108 ft), the distance used for all earlier prototype heliostat testing.

The 75 mirror frames necessary for the SRE experiment are being fabricated by Rio Grande Fabricators. After receipt in Denver, laminated glass mirrors will be bonded to the frames. The mirror assemblies consist of a second-surface mirror with a 3 mm (0.118 in.) thick panel of sheet glass laminated to a 3 mm (0.118 in.) thick base sheet of float glass. The spectral reflectivity of the laminated mirror assembly is approximately 91%, based upon previous testing.

Two types of adhesive are being used to bond the mirrors to the frames. The first adhesive is General Electric RTV 560, as previously used in all experiments. The second adhesive is RTV 108, also manufactured by General Electric. RTV 108 is unique in that a primer coat is not needed as with RTV 560, and that it can be applied with a gun. Providing it can be proven to withstand extended outdoor exposure, RTV 108 is expected to result in considerable cost savings for large scale bonding operations, e.g., the pilot plant.

b. Fixed Curvature Mirrors - Development of the honeycomb-substrate, fixed curvature mirrors has continued. Figure III-4 shows the latest configuration mirror assembly for the 9-mirror heliostat.

The mirror assembly measures 2.0 x 2.0 m (80 x 80 in.) in size and consists of a series of layers of glass, glass cloth, impregnated paper honeycomb, and aluminum sheeting. A detail

Figure III-3
Adjustable, Center-Focus Mirror Frame Showing Simplified Construction

Figure III-4
*Exploded View of Honeycomb
Substrate, Fixed-Curvature Mirror*

discussion of the materials and assembly process are contained in Paragraph III-C.

Two mirror assemblies with paper honeycomb cores have been fabricated; the first mirror serving as a tooling check. After several minor modifications to the tooling, a second mirror was fabricated and is currently awaiting testing.

Although strong supportive data from other governmental agencies exists to indicate that the paper core will satisfy the long-life requirements for the mirror, attempts will be made to develop an aluminum core mirror assembly as a backup. It is currently planned that five paper core mirrors and four aluminum core mirrors will be fabricated for the 9-mirror SRE heliostat.

3. Drive Mechanism

A direct gear drive mechanism has been designed and is currently being produced by the Morse Chain Division of Borg Warner Corporation. A total of four sets of azimuth and elevation drive units are being procured for the SRE experiment, with delivery of the first set expected on May 12, 1976.

Table III-1 presents the final performance requirements for the drive mechanism. The bending moments and aerodynamic torques were derived from the heliostat wind tunnel tests.

Figure III-5 shows a cutaway view of the azimuth drive mechanism. Several features are important to note. The worm gear is driven either in tracking or in slew by one of two tandem-mounted motors. Motion is transferred through the drive train to the large 0.3 m (12 in.) diameter bull gear which is centered on the main drive shaft. The drive speeds for the heliostat are 13.4 rad/hr (755 deg/hr) for slew and 1.5 rad/hr (89 deg/hr) for tracking.

For the SRE experiment, absolute position is indicated by a potentiometer. The design also permits a 13-bit disc encoder to be mounted to the main drive shaft. Both the potentiometer and encoder are covered by a housing for environmental protection.

The heavy cast housing of the azimuth drive has been designed to also act as the main support and interface with the foundation.

The elevation drive mechanism is identical to the azimuth drive except for a more streamlined housing. Two tandem-mounted motors are used to provide slewing and tracking speeds. A potentiometer

Table III-1

Performance Requirement for Heliostat Drive Mechanism

Base Bending Moment (Azimuth) at 22.3 m/s (50 mph)	456.39 kg-m (39,600 lb)
Aerodynamic Torque at 22.3 m/s (50 mph)(Slew Only)	673.06 kg-m (58,400 in-lb)
Aerodynamic Torque at 13.5 m/s (30 mph)(Max Tracking Torques)	242.02 kg-m (21,000 in-lb)
Aerodynamic Lift at 22.3 m/s (50 mph):	
Positive	634.2 kg (1400 lb)
Negative	634.2 kg (1400 lb)
Slew Speed	13.4 rad/hr (755 deg/hr)
Tracking Speed, Azimuth	1.5 rad/hr (89 deg/hr)
Angular Displacement of Heliostat at Azimuth	$\pm 1.91 \pm 0.09$ rad ($\pm 110 \pm 5$ deg)
Angular Displacement of Heliostat, Elevation	-4.71 ± 0.09 rad (-270 ± 5 deg)
Tracking Increment	1 arc-min
Weight to be Supported	2718 kg (6000 lb)
Drive Must be Irreversible (Cannot be Back-Driven)

Figure III-5

Cutaway View of Azimuth Drive Mechanism

is used to provide the absolute position. Like the azimuth drive, a 13-bit disc encoder may be mounted on the main shaft, if necessary.

Fail safe protection in the SRE heliostats is limited to four modes. The first is provided for by two pair of micro-switches located in each drive mechanism. Their function is to limit the clockwise or counter clockwise rotation of the drive mechanism to within certain specified angles. For the SRE, these angular limits are $\pm 135^{\circ}$.

If the SRE heliostat attempts to move beyond these limits, one of the first pair will break the motor circuit, causing the heliostat to stop. If this switch malfunctions, redundancy is provided by the second set of limit switches. Once a limit switch breaks the motor circuit, all control signals will be ignored except for an executive command to reverse and drive back toward the center position.

The second fail-safe mode incorporated in the SRE is the synthetic track offset, which upon operator command, offsets the heliostat beam above the receiver (calorimeter) several degrees while continuing to track in azimuth.

The remaining two fail-safe modes for the SRE are emergency stop and emergency stow. The emergency stop is controlled from the control center. The emergency stow mode can be activated from either the calorimeter or the control center.

4. Control Elements

The elements of the control subsystem for the heliostats have been breadboarded and tested.

The control subsystem consists of six elements as shown in Figure III-6, i.e., the control and display (C&D) panel, executive control computer, data bus interface electronics, sensor interface electronics, motor control electronics, and fine-tracking sensor. The status and operation of each of these elements is described below.

The C&D panel is undergoing final checkout prior to its integration to the executive control computer. The function of the C&D panel is to provide for the operator an efficient means of controlling and determining the status of the heliostats. This function could be performed by the teletypewriter, but control and status determination would be much less efficient. The panel indicates the response of each heliostat as it is commanded and displays a verification of position as indicated by the potentiometers.

Figure III-6 Functional Schematic of Heliostat Control System

The computer has been received, installed, and checked out by a factory representative. Various control and data reduction programs are being compiled at present. When the compilation and debugging phases have been completed, the computer will be integrated with the C&D panel.

The data bus interface electronics actually consist of a number of subelements. A data bus transmitter is located at the computer terminal. Coded commands from the computer are sent over the data bus lines by the transmitter and received at each heliostat. A heliostat will only respond if the command is preceded by the designator for that heliostat.

Signals received and accepted by a heliostat are decoded in the heliostat electronic control box, and the proper commands sent to the motors. A verification signal indicating that the command has been received is transmitted back to the control center where it is displayed.

The data bus interface electronics have been breadboarded and tested by means of a simulator. Commands were sent by the transmitter over a 914 m (3000 ft) data bus and were successfully received by the data receiver.

The complete digital decoding and motor control circuits in the heliostat electronics control box have been breadboarded and successfully tested. The experimental units for the four heliostats are being fabricated at present.

In practice, the computer will calculate the approximate location of the sun, and knowing the position of the target (calorimeter), will command the heliostats to drive to positions where the reflected solar beam illuminates the target.

At this point, the heliostat can be commanded to the fine track mode. In this mode, the tracking function is performed by a tower-mounted sensor inline between the heliostat and target. The sensor, which consists of two solar cell bridges, detects the deviation of the reflected beam as the sun moves and generates an error signal which activates the tracking motors. The heliostat is then driven to a position where the reflected beam is on target.

Absolute position is determined at all times by the potentiometer on each drive mechanism and is transmitted back to the executive control computer. Here, the positioning of the heliostat is verified by the computer and the results of the verification displayed on the C&D panel.

Figure III-7 Pictorial View of Calorimeter

B. CALORIMETER DESIGN AND FABRICATION STATUS

1. Basic Structure

A pictorial view of the calorimeter is shown in Figure III-7. The most notable feature is the large receiving surface which measures 7.3 x 7.3 m (24.0 x 24.0 ft). The receiving surface is large enough to take the full image from a heliostat positioned at a slant range of 502.9 m (1650 ft), the greatest distance that will be achieved in the subsystem research experiment.

The receiving surface consists of 53 vertical finned tubes, coated with Martin Black, a coating with an absorptivity in excess of 99%. During operation, 150 ℓ /min (40 gal/min) will be pumped through the tubes to absorb the received heat. When all four SRE heliostats are operating, the surface will receive a flux of nearly 19 suns.

To protect the calorimeter or receiving surface from high winds and environmental damage, a large supporting structure of I-beams and steel pipe is used. The supporting structure, which is 8.5 m (28 ft) square, is designed to withstand a wind load of 44.7 m/s (100 mi/hr). The receiving surface is protected by two cable-driven steel doors.

Behind the large structure which supports and protects the receiving surface, a 6.1 m (20 ft) long operations trailer is located. This trailer contains all of the plumbing and electrical controls, as well as the instrumentation necessary to monitor test operations. The data resulting from a test is transmitted real-time to the executive control computer, where the performance calculations for each test are made.

2. Calorimeter Operation

The basic operation of the calorimeter is described in the functional schematic of Figure III-8. Water is pumped upward through the vertical finned tubes of the receiving surface. The water temperature is measured at the entrance to the inlet manifold. The heated water flows through the outlet manifold through a mixing chamber where the water temperature is again recorded. At each temperature measuring point, two sensors record the temperatures automatically. An independent check on the inlet and outlet water temperatures can be made with a thermometer located at each temperature sensor position.

After leaving the mixing chamber, the water flows into a weigh tank where the weight of the water used in each run is recorded. The water is then drained to the dump tank, leaving the weigh tank free for additional runs. From the dump tank, water is continually pumped to the storage tank by the return pump, passing through a water chiller en route to cool the water.

Figure III-8 Functional Schematic of Calorimeter

The data, which includes the inlet and outlet temperatures, the start and stop times of the test, and the solar flux incident upon the heliostat are recorded and transmitted to the executive control computer where the results are calculated.

During all tests, the operator in the calorimeter trailer has voice communications with the operator in the control room, allowing the immediate detection of any problems with a test. Additionally, the operator of the calorimeter trailer has the ability to command all heliostats to a stow position in case of an emergency.

3. Calorimeter Assembly Status

The concrete foundation and main support structure for the receiving surface have been completed. Currently, the remainder of the supporting structure and the doors are being fabricated. Coating of the finned tubes with the Martin Black finish has been started.

C. FIXED CURVATURE MIRROR DEVELOPMENT

The basic structure of the fixed-curvature mirror was described earlier in Paragraph A.2.b. and is shown in Figure III-4. Figure III-9 shows some additional details of the fabrication product and the first prototype mirror. Figure III-9(a) shows the fabrication tool under construction. The tool consists of a series of concentric rings, each ring decreasing in thickness as its size increases. Designed to produce a mirror with a focal length of 401 m (1314 ft), the tool has a maximum displacement of 1.346 mm (0.053 in.) at the center.

The mirror is placed face down and centered on the tool. The layers of glass cloth, resin, paper honeycomb and aluminum are added sequentially until the entire sandwich is completed. Weights are then applied evenly over the back of the mirror assembly to form the sandwich to the desired shape until the resin hardens.

Figure III-9d shows the mirror, first layer of glass cloth and one of the two sheets of honeycomb that form the core in place on the tool. A wooden frame surrounding the tool provides temporary support and alignment for the assembly. Excess glass cloth from the first layer is shown draped over the wooden frame; this excess cloth is later coated with resin and wrapped around the edges of the honeycomb, forming a sealed, protective edge for the mirror.

(a) Preliminary Test of 2.0x
2.0 m (80x80 in.) Mirror

(b) Image of First 80x80-in.
on Target at 346 m
(1135 ft)

(c) Fabrication Tool for
2.0x2.0 m Mirror

(d) Paper Honeycomb and
Fiberglass Structure in
Place on Fabrication

Figure III-9
Fabrication and Test of Prototype Honeycomb Substrate Mirror

The completed mirror assembly is shown in Figure III-9a. Although formal testing is currently being conducted to determine image quality, the results of a preliminary test are shown in Figure III-9b. The image from the mirror is shown projected on a target at a range of 346 m (1135 ft); the image diameter is approximately 3.4 m (11 ft).

To date, two fixed-curvature mirrors have been fabricated; both with commercial, impregnated paper honeycomb cores. The first mirror provided a tooling check and determined how great an allowance should be made for "springback" in the assembly after the completed mirror was removed from the tool. After testing of this prototype mirror, minor changes were incorporated into the tool, after which a second mirror was made (Figure III-9a). Testing of this mirror is currently underway.

Although treated paper honeycomb has been determined to be the least expensive core material, its ability to withstand the external environment for 15 to 30 years, even when sealed inside a fiberglass shell, has been questioned.

The U.S. Forest Service, as well as several commercial firms, has demonstrated that impregnated paper honeycomb, when properly sealed, can withstand external exposure for at least 20 years without noticeable degradation.

In an attempt to collect comparative data, up to four mirror assemblies will be fabricated using commercial grade aluminum honeycomb for the core material. The honeycomb is fabricated from 3031 aluminum, with 7.62 cm (3 in.) thickness and a cell size of 1.9 cm (0.75 in.). Since commercial grades come in 1.2 x 2.4 m (4 x 8 ft) sheets, two sheets are needed to fabricate one core.

The mirrors used for these experiments have been standard second-surface silvered float glass with a 6 mm thickness. The weight of a single 2.0 x 2.0 m (80 x 80 in.) mirror is approximately 73 kg (160 lbs). For this size mirror, a thickness of 6 mm is the thinnest that can be manufactured by industry today.

The use of thinner glass could result in both lower cost and weight and in greater ease of handling. Since glass of 3 mm thickness or less is available in smaller sizes, a mirror fabricated from four small pieces could achieve the required results.

A small experimental assembly consisting of four small 0.3 x 0.3 m (1.0 x 1.0 ft) mirrors has been fabricated. The overall size of the mirror is 0.6 x 0.6 m (2.0 x 2.0 ft) and is formed on a 3.8 cm (1.5 in.) paper honeycomb core. This small assembly will be checked for both image quality and producibility.

D. BREADBOARD TESTING OF HELIOSTAT CONTROL UNIT ELEMENTS

1. Fine-Tracking Sensor

The sensitivity of the fine-tracking sensor was determined during a test (Figure III-10). The prototype sensor was mounted on the end of a sine bar 2.54 m (100 in.) long, and was illuminated by an artificial light source whose intensity could be varied from 0.1 to 1.0 suns. The sine bar was moved in angular increments of 0.29 mrad (1 arc-min) and the response was plotted over a range of +2.9 mrad (+10 arc-min) to -2.9 mrad (-10 arc-min) at three solar intensities.

Figure III-11 shows the electrical output of the fine-tracking sensor as a function of the angular displacement, or error. For an error of ± 0.29 mrad (± 1.0 arc-min), which is the required sensitivity, the logic must be able to detect output voltages as low as 100 millivolts, when operating under normal or 1 sun conditions. The sensitivity increases as the solar intensity decreases, e.g., at 0.1 sun, an output voltage of 100 millivolts corresponds to an error of 0.15 mrad (0.5 arc-min).

2. Breadboard Testing of Executive Control and Fine-Tracking Electronics

The complete system has been breadboarded and checked out with the exception of the computer and C&D panel. The components, including a fine-tracking sensor and drive motors, were interconnected in the laboratory.

The executive control section was first checked by introducing simulated computer commands into the data bus interface electronics and verifying the response of the drive motors. These tests proved successful in all respects.

The fine-tracking control section was checked in a similar manner by illuminating the sensor with an artificial light source. The sensor was mounted on the sine bar apparatus described earlier to allow an accurate error to be introduced. The motors responded to all fine-tracking control modes, as expected.

Figure III-10
Prototype Fine-Tracking Sensor Test Setup

Figure III-11
Sensitivity of Prototype Fine-Tracking Sensor

The complete system, including the C&D panel will be given a final verification as soon as the computer programs have been compiled and debugged. This verification will be performed before installation of any part of the system in the field.

E. SAFETY PLAN

A safety plan (SK-SRE-05750) covering all aspects of construction and operation of both the heliostat field and calorimeter has been approved by MMC engineering and safety personnel. This plan has been designated as required reading for all personnel who will be present during the construction, installation, or test phases of the subsystem research experiment.

F. TEST PLAN

A verification plan (SK-SRE-05650) has been written and submitted to ERDA for comment and/or approval. The plan establishes and documents the verification requirements associated with the components, subassemblies and assemblies which make up the hardware and software activities of the Subsystem Research Experiments.

Three types of verification will be employed. First, verification by analysis when it can be shown by generally accepted analytical techniques that the components, subassemblies or assembly can meet or exceed requirements. This method will be the most commonly used one to demonstrate the ability of components to meet environmental requirements.

Verification by similarity will be used when it can be shown that a component, subassembly, or assembly is identical or substantially similar in design, manufacturing, and quality to a previously verified component, subassembly, or assembly.

Verification by test will be used only when either analysis or similarity cannot satisfy the requirements. Additionally, environmental exposures will be limited to those natural environments existing at the SRE test site, with no formal environmental exposures planned for this phase of the 10 MWe program. Any data collected during the ERDA/Sandia 5 MWth Solar Thermal Test Facility test program which is applicable to the Subsystem Research Experiment will be utilized.

A verification matrix has been established which is based upon the design criteria for the collector subsystem for the 10 MWe pilot plant. All of these design criteria will not be verified during this phase of the program. It is, however, the intent of this program to perform the requirement verification to the maximum extent possible.

The verification testing for the Subsystem Research Experiment consists of four parts, as described below.

1. Component Testing

The SRE component testing will be primarily limited to functional performance types of testing. This testing is to provide assurance that the subject component is capable of performing all defined design functional parameters within the limits specified. In addition to the testing described in the following paragraphs, the components performance will be periodically checked and inspected during usage as a part of the SRE.

The SRE components fall primarily into two categories. These are electrical and mechanical/structural. The SRE components covered by this plan are as follows:

a. Electrical

- 1) Sensor assembly;
- 2) Heliostat electronics control box;
- 3) Position potentiometers;
- 4) Limit switches;
- 5) Drive motors;
- 6) Cabling.

b. Mechanical/Structural

- 1) Drive mechanisms;
- 2) Mirrors;
- 3) Yoke assembly;

4) Mirror support assembly;

5) Sensor tower.

2. Subassembly and Assembly Testing

The SRE Subassembly and Assembly level of testing will be primarily directed toward activation of the SRE Test Facility. This testing will essentially be of a functional performance nature which includes both laboratory and field site testing. The test program is designed to perform an incremental in-process type of testing which will lead to an orderly build-up and activation of the collector subsystem research experiment. This series of tests falls into two primary categories, i.e., those directed toward the control electronics and heliostat structural assembly.

3. Subsystem Testing

This phase of testing will demonstrate the collector subsystem's capability to deliver the predicted solar thermal energy to the receiver and to perform in all operational mode.

The testing accomplished during this phase will primarily be directed toward collector efficiency and tracking accuracy of individual and groups of heliostats. In addition, empirical performance data will be collected during critical periods of the solar year, such as summer solstice, equinox, and winter solstice. Further, operation of the experiment as a subsystem will provide the necessary data to establish preliminary design requirements, support equipment requirements, operational and emergency procedures. The test program consists of three increments, these being as follows:

a. Control System Performance Verification

b. Collector Performance Verification

c. Subsystem Performance Verification

4. Special Engineering Tests

The special engineering tests are designed to evaluate such things as degradation of mirror surfaces as an effect of environmental exposures, effects of wind and thermal loading on heliostat and fine-tracking assembly structures, effects of critical solar angles (early morning and late afternoon) on the fine-

tracking assembly and techniques of pointing and focusing of heliostat mirrors.

G. MILESTONES - MARCH THROUGH JUNE 1976

During this period, the following major milestones are expected to be achieved:

- o Installation and activation of the first 25-mirror SRE heliostat - May 18, 1976.
- o Delivery of the remaining two 25-mirror SRE heliostats to MMC - May 15, 1976.
- o Delivery of the single 9-mirror SRE heliostat to MMC - June 15, 1976.
- o Fabrication and checkout of large calorimeter - June 1, 1976.
- o Monitoring of 25-mirror heliostat performance with calorimeter during summer solstice period.

IV. RESEARCH EXPERIMENT RECEIVER TEST SUPPORT EQUIPMENT

The Research Experiment Receiver test support equipment being designed and fabricated by MMC consists of two major subassemblies, a mechanical equipment module and a test control console. The mechanical equipment module performs feedwater pumping, steam, and water pressure regulation and thermal conditioning functions. The test control console provides remote control functions for operation of the receiver and mechanical equipment module.

A. MECHANICAL EQUIPMENT MODULE (MEM)

The MEM is shown schematically in Figure IV-1. The major elements include a feedwater pump, feedwater heater, and condensate subcooler. Note that the condenser, hotwell and related components are to be supplied by Sandia Laboratories and are not included in the MEM. Sandia is also providing the boiler feedwater treatment module, not shown.

The feedwater pump (P-1) is a reciprocating positive displacement device. An automatic controller with remote adjustable set point and override capability operates a bypass valve (FPP) to maintain the desired receiver feedwater inlet pressure. The subcooler cools the condensate from 438 K (328°F) coming out of the condenser hotwell to below 380 K (225°F), which is the upper limit of pump tolerance. Receiver steam output pressure is maintained by an automatic controller with remote adjustable set-point and override capability, which operates valve PCV-1. The feedwater heater is designed to increase the feedwater temperature to the desired level of 480 K (405°F), while simultaneously removing much of the superheat from the receiver output steam. Four remote operated valves (TCV-1, TCV-2, TCV-3, and TCV-4) control the operation of the feedwater heater.

Figures IV-2 and IV-3 are conceptual plan and side view sketches of the MEM. Detail design of the module is now well underway, and some simplifying modifications have been implemented which are not evident in the figures. Notably, the variable speed drive and the feedwater pump shutoff valve (V-1) have been eliminated. Also, taps are being provided between the subcooler and feedwater pump to bypass water to the treatment module.

Most of the components (pump, motor, and valves) and materials for the MEM have been ordered. Detailed drawings will be complete by the end of May, and fabrication will be initiated by the first week in June.

Figure IV-1 5 MW_t Research Receiver Support Equipment Module

5 MW_t RESEARCH RECEIVER TEST SYSTEM

Figure IV-2 Equipment Module Concept Plan View

Figure IV-3 Equipment Module

B. TEST CONTROL CONSOLE (TCC)

The test control console will be the focal point for remote operation of the receiver and mechanical equipment module. The TCC will include set-point and override controls for all automatic valves, actuation controls for remote operated manual valves, an emergency shutoff switch for the infra-red heater system, and a limited number of real time visual data indicators necessary for safe operation of the test system. A preliminary functional summary of the console is presented in Table IV-1. Finalization of specific components to be included in the TCC is now underway.

TABLE IV-1 5 MW TEST CONTROL FUNCTION REQUIREMENTS

A. REAL-TIME VISUAL DATA READOUTS

- 1) STEAM DRUM PRESSURE
- 2) SUPERHEATER OUTLET PRESSURE
- 3) SUPERHEATER OUTLET TEMPERATURE
- 4) FEEDWATER TEMPERATURE TO BOILER
- 5) LIQUID LEVEL IN BOILER DRUM
- 6) FLOW MEASUREMENT AT SUBCOOLER
- 7) FLOW MEASUREMENT AT FEED PUMP RECIRCULATION LINE
- 8) FLOW MEASUREMENT AT HIGH PRESSURE HEAT EXCHANGER

B. CONTROL FUNCTIONS

- 1) BACKPRESSURE CONTROL VALVE (PCV-1) SET POINT OR OVERRIDE
- 2) FEED PUMP RECIRCULATION VALVE (FPP) SET POINT OR OVERRIDE
- 3) TEMPERATURE CONTROL VALVES (TCV 1, 2, 3 & 4)
- 4) PUMP SWITCH ON/OFF
- 5) MAKEUP WATER VALVE ON/OFF
- 6) POWER ON/OFF
- 7) EMERGENCY SWITCH

SECTION V _
RECEIVER SUBSYSTEM

BY:

J. F. COX
T. V. NARAYANAN
S. F. WU
R. J. ZOSCHAK

FOSTER WHEELER ENERGY
C O R P O R A T I O N

JOHN BLIZARD RESEARCH CENTER
12 PEACH TREE HILL ROAD
LIVINGSTON, NEW JERSEY 07039

V. RECEIVER SUBSYSTEM DESIGN

A. PILOT PLANT RECEIVER START-UP ANALYSIS

The effort on the pilot plant receiver preliminary design during the past three months has been concentrated on the study of start-up transients. The computer program for thermal/hydraulic transient analysis has been revised to include more options for performing different types of start-up calculations. The receiver transient operation modes analyzed were hot start-up after overnight shutdown, restart after cloud passage and cold start-up from ambient condition. In the following sections, the controlling parameters and assumptions for these start-up modes will be indentified, the general method and procedure used in the study will be briefly described, and, for each mode, the cases analyzed will be summarized and the pertinent results presented.

1. Description of Start-up Transients

a. Hot Start-up - This is a diurnal morning start-up of the receiver after overnight shutdown. Since the insulation of the receiver cavity is designed to limit the drop in saturation temperature to 83 K (150°F) during a 12-hour shutdown period, the receiver can be restarted each morning from a relatively hot standby state. In order to utilize all available insolation during the start-up period, it is desirable to bring up the receiver with the full solar energy input anticipated for any day of the year, or, in a simple phrase, "start-up with the sun". This would minimize the control functions required for the collector subsystem, but incur more operational restraints on the receiver subsystem. Among all the parameters affecting a hot start-up transient, the most important and governing one is the rate of increase of drum pressure. The faster pressure is raised, the greater is the portion of the heat input stored as thermal capacitance of the receiver and the smaller is the rate of steam generation. Hence, with full solar flux directed indiscriminately toward the boiler and superheater surfaces, the rate of pressure increase has to be limited so that acceptable temperature and stress levels can be maintained during the transient for all receiver components.

b. Restart after Cloud Passage - The receiver, which was operating at the normal load condition before being shutdown due to cloud cover, is required to restart as soon as the cloud disappears. To cover the most critical condition, the instant

that this restart begins is assumed to be at 1200 on winter solstice, the time of maximum solar flux. Since the receiver is expected to be started up from its full pressure condition, the rate of increase of incident energy to the receiver becomes the dominant parameter for this type of restart. Although the solar energy to the receiver can conceivably be brought up from zero to the peak intensity in 1/2 minute by the collector subsystem, as predicted by Martin Marietta, it is very doubtful that such a rapid rate can be accepted by the receiver.

c. Cold Start-up - This mode of operation is anticipated when the receiver is first put into operation or is started after a duration of shutdown longer than 72 hours. The receiver is assumed to be at the ambient condition before being brought up. Starting from this condition, the receiver cannot absorb the fully concentrated solar energy without overheating its components, especially during the early period of start-up when there is no steam being generated. The incident energy to the receiver has to be greatly reduced by de-focusing the heliostats. After the receiver begins to steam, the incident energy intensity can be increased gradually, accompanied by a gradual increase in drum pressure. Therefore, the rates of increase of both incident energy and drum pressure play the governing roles in this type of start-up.

2. Method of Analysis

The study of start-up transients involved the development of a computer program for transient overall receiver heat balance calculation and the use of an existing program for local tube temperature and stress evaluation. The simulation models used in conjunction with these two programs are shown in Figure V-1.

A detailed description of the computer program and the simulation model developed for the overall thermal/hydraulic calculation was given in Section V.A.4 of Quarterly Report No. 1 of this project. Since then, this program has been modified to handle all three types of start-up transients. Another important feature added to the program is the calculation of feedwater temperature during a transient period from its relationship with the turbine flow. Because of the time delay caused by the system fluid capacity, it is a complicated procedure to correlate a relationship between the receiver steam flow rate, turbine flow rate and the temperature of feedwater entering the receiver at any instant of the transient. In revising the program, efforts were made to predict a reasonably correct feedwater temperature without adding too many

(a) OVERALL RECEIVER HEAT BALANCE MODEL

(b) TUBE WALL TEMPERATURE DISTRIBUTION MODEL

Figure V-1 Analytical Models for Start-up Transient Study

iteration loops in the program. This added feature is reflected in the model (Figure V-1a) by inclusion of the electrical power generation subsystem (EPGS) as a whole. The output of this program gives predicted pressures, steam flow, attemperator spray flows, steam temperatures, average tube wall temperatures and average superheater steam film coefficients during a transient period.

For each case of transient analysis, the overall heat balance program was first run with an assumed drum pressure ramping rate, or an increasing rate of incident energy, or both, depending on the type of start-up. After the computer output of this program was examined, the critical locations on the superheater passes were selected for more detailed analysis. This detailed temperature distribution analysis was performed using the program ANSYS with a two-dimensional tube wall model as shown in Figure V-1b. This finite element model was modified from the one previously used for steady-state calculation. All input and boundary conditions were changed to functions of time and provisions were also added to the model to include the radiant heat exchange between the tube surface and its surroundings. The front face of the tube was connected to a time-dependent temperature boundary representing the average temperature of all uncooled, interior cavity surfaces, and the rear face of the tube to another boundary representing the average temperature of the boiler walls. Optional radiation connections were also provided between tube inside surface nodes. This option was employed only for the early part of cold start-up runs when there was no steam flow inside the superheater tubes. The program output of this tube model was then used to check whether at any instant of the start-up period, the wall temperature and front-to-rear face temperature difference of the superheater tubes exceeded their respective design limits or not. If so, a slower start-up rate was programmed in the next run.

3. Summary of Cases Analyzed and Results

a. Hot Start-up - Three typical sunrise-to-noon solar input rate curves were used for morning hot restart studies. The first one approximated those of spring and fall equinoxes based on Inyokern 1963 insolation data. The second one was a rate identical to that of winter solstice based on the same data source. The third one also represented a winter solstice rate, but was derived by Martin Marietta from the insolation data they collected at Waterton, Colorado, on January 20, 1976. The time for the receiver to reach its full drum pressure from

hot standby condition was first assumed to be 30 minutes, but was extended to 1 hour after the former time was found to be unacceptably short.

Because the rate of increase of solar energy to receiver is fastest at winter solstice, start-up on this day is more critical than on any other day of the year. The results of an acceptable winter solstice hot start-up are shown in Figures V-2 and V-3. The energy input rate for this case was based on the Waterton, Colorado data. The drum pressure was assumed at 3620 kPa (525 psig) after overnight shutdown and was programmed for rise to full pressure of 9343 kPa (1355 psig) one hour from sunrise as depicted in Figure V-2. Feedwater temperature was assumed to stay at 367 K (200°F) until the steam generated by the receiver met the minimum turbine start conditions. Thereafter, it followed the transient relationship between feedwater temperature and turbine flow rate, including the time delay caused by the system fluid capacity. Its transient profile is shown in Figure V-3. Also shown in this figure are the predicted steam temperatures at the inlet and outlet of each superheater section. Detailed tube wall temperature calculations were performed for superheater tubes in passes 4B and 5B, which were judged to be the critical locations during this transient. The front (maximum) and the rear (minimum) face temperatures of these two locations are shown in Figures V-4 and V-5. It can be found from these figures that, during the whole start-up period, the maximum superheater tube temperature is below 922 K (1200°F) and the front-to-rear tube temperature difference is less than that predicted for steady state.

b. Restart after Cloud Passage - Four cases of this type of rapid restart were analyzed. The heat energy incident on the receiver after cloud passage was assumed to increase linearly from 0 to 52.3 MWt (winter solstice noon peak) in 1/2, 5, 15 and 20 minutes, respectively, for these four cases. The receiver was assumed to be brought up from a drum pressure of 9136 kPa (1325 psig) and a feedwater temperature of 475 K (395°F). From the results of these computer runs, the case with a heat-increasing period of 20 minutes was found acceptable to the receiver. The key parameters of this transient case are shown in Figure V-6.

c. Cold Start-Up - Only one preliminary case was analyzed. The receiver was assumed to be at ambient conditions of 0 kPa (0 psig) and 289 K (60°F) at the beginning of the transient. The drum pressure was programmed for rise to full pressure

Figure V-2 Predicted Pressures and Flow Rates for an Acceptable Hot Start-up Transient

Figure V-3 Predicted Feedwater and Steam Temperatures for an Acceptable Hot Start-up Transient

Figure V-4 Tube Wall Temperatures of Superheater Pass 4B during a Hot Start-up Transient

Figure V-5 Tube Wall Temperatures of Superheater Pass 5B during a Hot Start-up Transient

Figure V-6 Key Transient Parameters of an Acceptable Restart after Cloud Passage

Figure V-7 Key Transient Parameters of a Cold Start-up (Preliminary Analysis)

4 hours and 40 minutes from sunrise. The energy incident on the receiver was assumed to ramp up, in six hours, from 0 to the value at 1300 on the winter solstice, gradually in the early stage of the transient and more rapidly during the later portion. Before the drum and boiler section reach the saturation temperature, the peak heat flux input to any point on the superheater was limited to 31.5 KW/m^2 ($10,000 \text{ Btu/hr-ft}^2$). The feedwater temperature was assumed to remain at 289K (60°F) until it could be related to turbine flow. The results of this study are shown in Figure V-7. As indicated in the figure, it takes 68 minutes from sunrise for the drum and boiler section to reach the saturation temperature of 373 K (212°F). During this non-steaming heat-up period, the maximum superheater tube temperature was found to be below 811 K (1000°F). However, as soon as steam generation begins, the already heated superheater tubes would be chilled by relatively low temperature steam. The potential problems associated with this have yet to be analyzed.

B. RESEARCH EXPERIMENT RECEIVER

1. Conceptual Design

For better mechanical arrangement, minor revisions were made to the boiler circuitry. These revisions included addition of one tube to the side wall screen, adjustment of the number of tubes in the rear wall and right side wall panels, and the elimination of one feeder and two riser.

The conceptual design of the two attemperators was completed and the design information was released for mechanical detailing. Each attemperator consists of a 168.3 mm (6.625 in.) O.D. header, a thermal liner, a spray nozzle assembly, a venturi section and a thermowell. The venturi section is installed adjacent to and downstream of the spray nozzle. The venturi type attemperator provides better mixing of the steam and spray water, especially at low steam flow conditions, than the disc type which was proposed before. In an effort to cut costs of the experimental receiver, the second-stage attemperator and its associated controls were eliminated. This was justified after reviewing the results of start-up transients computed for the pilot plant receiver. Of all three types of start-ups, only hot start-up in the morning required use of the second-stage attemperator for a brief period of 6 minutes, as shown in Figure V-2. In testing the experimental receiver, the lack of the second-stage attemperator can be compensated for by increasing the time taken to raise drum pressure.

Table V-1 Instrumentation List for I.R. Testing of 5 Mw
Experimental Receiver

Parameter to be Measured	Sensing Range	Quantity	Type of Sensor (Manufacturer)	Output Signal Range
1. Temperature	0- 700°F	40	Thermocouples "K"	0-15.2 mv
	0-1000°F	110	"	0-22.3 mv
	0-1300°F	20	"	0-29.3 mv
	0-2000°F	10	"	0-44.9 mv
	0- 350°F(ΔT)	15	"	0- 7.2 mv
2. Pressure Differential (For Flow and Density Measurements)	0-20" H ₂ O	6	D. P. Cell (Taylor Instrument)	4-20 ma
3. Heat Flux	0-220,000 Btu/hr-ft ²	3	Water-cooled Calorimeter (HY-CAL Engr)	0-10 mv
	0-220,000	7	Calorimeter (HY-CAL Engr)	0-10 mv
4. Strain	$\pm 1000\mu\epsilon$	7	Resistance Strain Gage (Ailtech, SG-420)	± 10 mv
5. Deflection	± 1 in.	3	LVDT (Columbia)	± 5 v D.C. @ 5 ma
6. Drum & Steam Outlet Press.	0-3000 psi	2	Pressure Transmitter (Leeds & Northrup)	4-20 ma.
7. S.H. Outlet Temp.	0-1200°F	1	Temperature Transmitter (Leeds & Northrup)	4-20 ma.
8. Drum Water Level	0-30"	1	Level Transmitter (Leeds & Northrup)	4-20 ma.
9. Feedwater, S.H. Steam and Spray Flowrates	0-20,000#/hr	2	Flow Transmitter (Leeds & Northrup)	4-20 ma.
	0-3000#/hr	1		

2. Instrumentation and Test Plan

The instruments to be used in testing the experimental receiver were selected and are listed in Table V-1. Items 6 through 9 in the table are required for the receiver steam temperature and feedwater regulating control systems. The other items are for various testing purposes. The locations of the key parameters to be measured on the receiver are shown in Figures V-8, V-9, and V-10. The temperature sensing points on the waterwalls and superheater are shown in Figures V-8 and V-9 respectively. In addition, temperatures at the inlet and the outlet of each superheater pass and temperatures of the superheater header drain lines will be measured outside the heated zones. Thermocouples will also be installed on the uncooled, interior cavity surfaces at selected locations. Two types of flow meters, namely, venturi and Ravese pitot, will be used in measuring flow rates inside the downcomers and selected feeders. The drum and superheater outlet pressures will be measured and their signals will be displayed on the control panel. Additional pressure taps will also be provided on selected superheater headers. Radiant heat flux meters will be used to sense the incident heat flux on the boiler walls. Ten critical locations marked by "H" in Figure V-8 were chosen for this measurement. The strains in the boiler and superheater tubes will be measured using weldable high temperature resistance strain gages. The gages will be spot welded to the rear face of each tube. The use of capacitance gages is not warranted in view of the substantial development work needed to obtain any meaningful results. The residual strain measurements will be made by Image Transfer Technique developed at Foster Wheeler Energy Corporation. The locations of these strain measurements are shown in Figures V-8 and V-10. Because of the difficulties involved in high temperature strain measurement it was decided to use LVDT's (Linear Variable Differential Transformers) to measure the deflections of superheater tubes at the selected points. The locations of these points are identified by the letter "D" in Figure V-10. These devices will only be installed at the three locations along the second tube from the top of superheater pass 2A for IR testing. Provisions have been made for installing three more LVDT's for subsequent testing in the solar test facility.

A test plan for the research experimental receiver has been drafted. This test plan was expanded from the preliminary test plan and test system requirements as presented in Section V-B of Quarterly Report No. 1 of this project. More detailed descriptions were added to the test plan with regard to the instrumentation and sensing locations as outlined above, the types

- LEGEND**
1. Feedwater Pipe	6. Side Boiler Tubes
2. Steam Drum	7. Rear Boiler Tubes
3. Downcomer	8. Side Screen Tubes
4. Lower Header	9. Corner Screen Tubes
5. Feeder	10. Upper Header
11. Riser	

INSTRUMENTATION LEGEND:

F = Flow Measurement	R = Resistance Strain Gage
H = Heat Flux Meter	S = Residual Strain Measurement
P = Pressure Measurement	T = Thermocouple

Figure V-8 Instrumentation Locations on the Boiler Circuitry

Figure V-9 Locations on the Superheater for Temperature and Pressure Measurement

Figure V-10 Locations on the Superheater for Strain and Deflection Measurements

and conditions of the tests to be performed, data logging systems, test personnel and scheduling.

Steam sampling and steam purity checks have been deleted from the test plan because the advanced state of development, and hence reliability, of steam purification equipment (drum internals), coupled with the use of high purity water in the boiler, preclude the need for them.

3. Detail Design, Procurement and Fabrication

The current status of the receiver design is illustrated in Figure V-11, which shows the sectional side elevation of the receiver, and Figure V-12 which shows Section B-B of Figure V-11. These two views are excerpted from the general arrangement drawings, which are 95% complete as of this writing.

When the general arrangement drawings were sufficiently complete, a review of schedule for the remaining Research Receiver effort was performed. It was determined that the field erection will take longer to complete than the three months originally allocated. Therefore, in order to maintain the planned test schedule, the erection start date has been moved ahead to 1 July 1976 from the original 1 September date. Schedules for supporting design and shop fabrication efforts were revised to accommodate the shift in erection schedule.

CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM (PHASE I)

Quarterly Report

SECTION VI

THERMAL STORAGE SUBSYSTEM

Authors:

Steve H. Bomar, Jr.

Ralph F. Altman

John H. Murphy

John E. Myers

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Engineering Experiment Station
Georgia Institute of Technology

VI. THERMAL STORAGE SUBSYSTEM

A. INTRODUCTION

Georgia Tech's primary area of responsibility within the Martin Marietta Pilot Plant team is the Thermal Storage Subsystem. During this reporting period, January 1 to March 31, 1976, program effort has been concentrated on (1) detailed design of the Thermal Storage Subsystem Research Experiment, (2) specification and procurement of components for the Research Experiment, (3) preparation of a preliminary test plan for the Research Experiment, and (4) compilation of cost data for the Pilot Plant Thermal Storage Subsystem in support of a Pilot Plant economic analysis.

Overall progress during the quarter can be summarized as follows:

1. Thermal Storage Subsystem Research Experiment

- o Specification packages have been prepared and design reviews conducted for tanks, valves, controls and recording instruments, and pumps.
- o Bids have been reviewed and orders placed for heat exchangers, tanks, controls and instrumentation, and HITEC pumps; an order is in process for valves.
- o Agreement has been reached with the Georgia Power Company on all details associated with conducting the Research Experiment at Plant Yates; a contract has been executed between the Company and Georgia Tech.
- o The Research Experiment design has been thoroughly reviewed with the objective of eliminating unnecessary components and substituting existing hardware where possible, without compromising the value of the data which will be obtained.
- o The Plant Yates site has been surveyed and updated layout drawings prepared.
- o Drawing formats have been selected and a complete list of drawings has been prepared.
- o Calculations in support of piping drawings have been completed and drawings for the steam, HITEC, and oil systems are in process; minor revisions may be necessary if process equipment details, such as nozzle mountings, are changed.
- o Analysis of supporting structures for the HITEC stage is complete; preliminary analysis has been done for the oil stage.

- o The heat exchanger supplier is proceeding with his detailed design; Georgia Tech and Martin Marietta engineers are maintaining close liaison to obtain concurrence with the heat exchanger design and assure proper matching at interfaces.
- o A preliminary test plan has been written.

2. Other Program Activities

- o A Quarterly Program Review was conducted at the Martin Marietta Corporation plant in Denver on February 12-13, 1976.
- o Pilot Plant economic analysis data were supplied for the Thermal Storage Subsystem; these were integrated by Martin Marietta into an economic analysis package representing the complete Pilot Plant and furnished to ERDA and its designated recipients.

B. DESIGN OF THE THERMAL STORAGE SUBSYSTEM RESEARCH EXPERIMENT

The major program effort this quarter has been the detailed design of the Research Experiment, including specification and procurement of equipment to be furnished by subcontractors. The system has been subdivided into sections corresponding to equipment types, such as heat exchangers, tanks, valves, pumps, and controls and instrumentation. The design approach is to handle the longest-lead equipment items first, followed by the next longest, etc., then to establish interconnecting piping arrangements as soon as equipment interfaces are known, and finally to establish structural designs. Details of the current status of the design are described in the following sections.

1. Baseline Heat and Mass Balance

The heat and mass balance for the Research Experiment operating at the maximum design power level during discharging is shown in Figure VI-1. High pressure feedwater (3260 kg/hr, 7187 lb/hr) is fed into the tube side of the preheater heat exchanger where energy is extracted from the oil storage fluid flowing in the shell side of the exchanger. This exchanger raises the temperature of the feedwater from 505 K (450° F) to 524 K (485° F), slightly below the saturation temperature of the water. The preheater transfers 84.3 kWt (287,480 Btu/hr) from the hot oil to the water.

The preheated high pressure water then goes into the thermal syphon boiler (thermal syphon circulation system not shown in Figure VI-1) where the water is heated to saturation temperature and boiled. The high pressure boiling water is on the tube side of the heat exchanger. During this operation 1.54 MWt (5.26×10^6 Btu/hr) is transferred from the oil to the water. Thus, the total heat rate required from the oil is 1.62 MWt (5.55×10^6 Btu/hr), including both the preheater and boiler.

Figure VI-1. Discharging Heat Balance for Thermal Storage Subsystem Research Experiment.

Figure VI-2. Charging Heat Balance for Thermal Storage Subsystem Research Experiment.

The saturated steam now goes to the tube side of the superheating heat exchanger. Hot molten salt is on the shell side of this heat exchanger. This exchanger extracts 0.373 MWt ($1.2 \times 10^6 \text{ Btu/hr}$) from the hot salt and adds it to the steam as superheat.

Thus, the research experiment delivers a 2.0 MWt ($6.82 \times 10^6 \text{ Btu/hr}$) energy rate. This energy is divided such that 18.6 percent of the energy comes from the salt and 81.4 percent comes from the oil. The energy split between the oil and salt system is a constraint on the thermal storage system during charging. The charging control system must ensure that 18.6 percent of the energy being stored is stored in the salt.

Figure VI-2 illustrates the heat and mass balance for the Research Experiment operating at the maximum design power level during charging. High pressure, high temperature superheated steam first enters a spray desuperheater where its temperature is reduced from 783 K (950° F) to 747 K (930° F) by the injection of water. This operation is conducted for the purpose of avoiding thermal decomposition of the molten salt in the subsequent heat exchanger and increases the steam flow rate from 3247 kg/hr (7159 lb/hr) to 3284 kg/hr (7241 lb/hr). Superheated steam at 747 K (930° F) then enters the tube side of the desuperheating heat exchanger, where energy is transferred into the molten salt heat storage medium flowing in the shell side of the exchanger.

Superheated steam exits the desuperheating heat exchanger at 626 K (667° F). This exit steam temperature is controllable and the temperature at which it is set determines how much energy is stored in the oil and how much energy is stored in the salt. If the steam exit temperature is increased, less energy will be stored in the salt. If the temperature is decreased, more energy will be stored in the salt. With an exit temperature 626 K (667° F), 0.370 MWt ($1.26 \times 10^6 \text{ Btu/hr}$) is being stored in the salt.

The superheat steam next goes into another spray desuperheater which reduces the steam temperature from 626 K (667° F) to 600 K (620° F) and increases the steam flowrate from 3284 kg/hr (7240.8 lb/hr) to 3452 kg/hr (7609.7 lb/hr).

The temperature reduction is done to protect the oil in the condensing heat exchanger from being overheated. This superheated steam now enters the condenser (tube side) where the remaining superheat and the latent heat are removed. This heat is transferred to oil on the shell side of the heat exchanger. This heat exchanger transfers 1.486 MWt ($5.069 \times 10^6 \text{ Btu/hr}$) from the steam to the oil.

The condensate now enters the subcooling heat exchanger (tube side) where it is subcooled from 572 K (569.3° F) to 545 K (521.7° F) and in the process transfers 125 kWt ($0.461 \times 10^6 \text{ Btu/hr}$) to the oil (shell side).

During charging the Research Experiment is capable of storing 1.99 MWt (6.782×10^6 Btu/hr) of which the required 18.6 percent is stored in the salt with the remainder stored in the oil.

2. Storage Tank Temperature Stability

A stability analysis of the fluid reservoir temperatures has been accomplished to investigate the effect of tank heat losses on the storage fluid temperatures after repeated cycles of charging and discharging. The study was done on both the oil and salt systems; however, the results of only the salt system investigation are shown here since the two systems behave similarly and the same conclusions apply in both cases. The temperature of the salt in the hot reservoir is established by the steam charging rate and the salt temperature in the cool reservoir. Figure VI-3 shows a family of curves representing hot tank storage temperatures as functions of cool tank storage temperatures for a 2 MWt charging rate and various steam inlet temperatures.

The cool tank temperature is established by the discharging rate and the hot tank temperature. Figure VI-3 shows one curve representing the cool tank temperature as a function of the hot tank temperature for a 2 MWt discharging rate.

Examination of the curves in Figure VI-3 permits several conclusions to be drawn regarding the behavior of the system. For example, if one assumes that the system has just been discharged and that the cold salt storage temperature has some value, say 565 K (557° F), and further assumes that the overnight temperature decay is 6 K (10° F), then the cold fluid temperature at the beginning of the charging operation will be 559 K (547° F). For a steam inlet temperature of 772 K (930° F), which is the nominal charging condition, the hot fluid temperature will become 739 K (870° F). Immediate discharge leads to a cold fluid temperature of 565 K (557° F), the starting value. Thus, the complete cycle has led to the original starting point, illustrating that the system can be operated in a stable manner. Similar examples lead to the observation that at nominal operating conditions (as shown in Figures VI-1 and VI-2) the system will tend to move toward the lower intersection of the thermal discharge line and the 772 K (930° F) steam input temperature line.

With this sort of performance, the hot and cool tank temperatures are inherently stable, and will not display a steady degradation with repeated cycling.

3. Research Experiment Equipment

The Thermal Storage Subsystem Research Experiment will be erected at the Georgia Power Company's Plant Yates, about 50 miles southwest of Atlanta.

Figure VI-3. Storage Tank Temperature Relationships for HITEC Stage.

Figure VI-4. Perspective View of Equipment in Thermal Storage Subsystem Research Experiment, excluding Supporting Structures.

a. Description of the Research Experiment - A preliminary perspective view of the major items of Research Experiment equipment is shown in Figure VI-4. The supporting structures and trees in the foreground have been omitted, but the drawing illustrates the orientations and relative sizes of the heat exchangers and tanks. The site is a triangular-shaped plot of land approximately one-half acre in area, located immediately northwest of Unit Number 1 at Plant Yates. An updated layout drawing of the arrangement of the Research Experiment at this site is shown in Figure VI-5; it is surrounded on two sides by roadways and on one side by a pipe trestle and earth embankment. The experiment will occupy about one-third acre adjacent to the trestle. The site is substantially level and a recent survey with test drillings has confirmed that it is suitable for the experiment. The high-pressure steam and water lines from the Georgia Power Company will be supported on the pipe trestle extending north from Unit Number 1. The vantage point in Figure VI-4 is located near the intersection of the roadway and trestle in Figure VI-5.

An updated schematic of the Research Experiment is shown in Figure VI-6. Both a layout drawing and a schematic were shown in the First Quarterly Report; the newer ones published here are similar to the old ones, but reflect the most recent revisions which have been adopted during the detailed design. During the charging mode of operation, superheated steam is received from the Georgia Power Company, as indicated on the right side of the schematic, desuperheated in the heat exchanger HE1, condensed in the heat exchanger HE2, subcooled in the heat exchanger HE3, and the subcooled water is discharged to the silencer S1. The energy removed from the steam in HE1 raises the temperature of a molten salt storage medium which is flowing in the circuit from the cooler salt reservoir T2, through HE1, to the hotter salt reservoir T1. The energy removed from the steam in HE2 and HE3 is used to raise the temperature of a hydrocarbon oil storage medium flowing in the circuit from the cooler oil reservoir T4, through HE3 and HE2, to the hotter oil reservoir T3.

During the discharging mode of operation, all stream flows in the system are reversed and the energy contained in the two storage media is used to convert feedwater into superheated steam. High pressure feedwater is received from the Georgia Power Company, preheated in HE3, evaporated in HE2, superheated in HE1, and discharged to the silencer. Water can be injected at the spray desuperheaters DS1 and DS2 to moderate steam temperatures and oil can be bypassed around HE3 to balance heat loads.

The Georgia Power Company will supply superheated steam and high pressure water during charging of the Research Experiment and high pressure feedwater during discharging. The flow rates and temperature and pressure conditions are shown in Figures VI-1 and VI-2. The Georgia Power Company will also supply electrical power, plant service water, potable water, and a sewer leading to the plant drain system. Other details of the interfaces with the Georgia Power Company are given in the First Quarterly Report.

Figure VI-5. Ground Layout of Thermal Storage Subsystem Research Experiment Site.

Figure VI-6. Schematic of Thermal Storage Subsystem Research Experiment.

b. Heat Exchangers - The heat exchangers are required to perform dual functions since the same units are used in the charging and discharging modes of operation. This requirement is especially important in HE2, which in the charging mode works as a condenser whose water level is maintained near the bottom of the vessel and in the discharging mode works as an evaporator whose water level is maintained at the top of the vessel. A subcontract has been placed with THERMXCHANGER, Inc. of Oakland, California to design and build the heat exchangers, with collaboration on design by Georgia Tech and Martin Marietta.

The thermal design of all three heat exchangers is complete. HE1 will consist of two tube-in-shell bundles mounted horizontally and operated in series, as shown on the right side of Figure VI-4. Each unit will contain 60 U-tubes with a diameter of 0.01905 m (3/4 in.) The shells will be 0.3556 m (14 in.) in diameter and 3.048 m (10 ft) long. The total outside surface area of both units is 4.38 m^2 (471 ft^2). Both the salt and the steam will undergo approximately half of their total temperature changes in each unit. The thermal stresses in these series connected units, particularly the stresses in the heads and tube sheets, will be lower than the stresses in a single unit used for the same operation. The HE1 assembly will be elevated above the level of the HITEC tanks so that the molten salt can be drained by gravity into the tanks. HE2 will be a single tube-in-shell bundle mounted vertically, as shown on the left side of Figure VI-4. The top head of the heat exchanger will serve as the separator during discharge, and a downcomer leading from the top head to the bottom head will be used so that the heat exchanger will operate as a natural circulation boiler. The shell will be 0.508 m (20 in.) in diameter by 7.3152 m (24 ft) long and will contain 305 tubes that are 0.01905 m (3/4 in.) in diameter. The shell of HE2 will have an expansion joint to accommodate the differential thermal expansion between the tubes and the shell. HE3 will be a small tube-in-shell bundle for subcooling or preheating liquid water, and is located behind HE2 in Figure VI-4. This unit will contain 30 U-tubes that are 0.01905 m (3/4 in.) in diameter. The shell will be 0.254 m (10 in.) in diameter and 3.6576 m (12 ft) long. Data for the three heat exchangers are summarized in Table VI-1.

c. Storage Media Tanks - The salt and oil storage media tanks are shown in Figure VI-7. Both types are cylindrical tanks with ASME flanged and dished heads; two tanks, a hot and a cool reservoir, are required in the Research Experiment for each storage fluid.

The molten salt tanks have a length to diameter ratio of approximately one, which minimizes the surface to volume ratio and thus the heat losses for a given volume. A steam coil will be provided to allow the temperature of the molten salt to be maintained safely above the melting point (415 K , 288° F) during prolonged periods of shutdown. Three thermocouple wells are provided so that the presence of thermoclines can be detected if they exist

Figure VI-7. Design of Tanks for Thermal Storage Media.

TABLE VI-1

TENTATIVE HEAT EXCHANGER PARAMETERS FOR RESEARCH EXPERIMENT

Parameter	HE1	HE2	HE3
Heat exchange area m ² (ft ²)	43.8 (471)	326.1 (3510)	33.2 (357)
Mat'ls & const.	carbon steel; two-tube pass, two-shell pass; two identical units in series; 0.01905 m tubes	carbon steel; vertical vaporizer/condenser; 0.01905 m (3/4 in.) tubes	carbon steel; two-tube pass, two-shell pass; 0.01905 m (3/4 in.) tubes
Shell diameter m (in.)	0.3556 (14)	0.508 (20)	0.254 (10)
Shell length m (ft)	3.048 (10)	7.3152 (24)	3.6576 (12)

and a HITEC pump is located inside each tank (pumps are described more fully in a subsequent section of this report). The HITEC level sensor will be a flowing nitrogen manometer rather than a conventional "delta P" cell, in order to avoid freezing of the salt in the cell.

The diameter of the oil tanks was selected to permit their transport by truck or rail car after shop fabrication, and the length was then fixed by the volume of fluid which must be contained. They incorporate conventional design with thermocouple wells and "delta P" level sensors.

A contract for the fabrication and delivery of the four storage tanks has been placed with J. J. Finnigan Industries, Inc., of Duluth, Georgia. A summary of the storage tank specifications is given in Table VI-2.

d. Storage Media Pumps - The storage media pumps are required to circulate the two storage fluids through their respective circuits from one tank, through the heat exchanger(s), to the other tank. They must operate at the elevated temperatures of the fluids and must be capable of being sealed against leakage.

As shown in Figure VI-7, a HITEC pump is provided in each storage tank. The drive motor is mounted outside the tank and the pump is

TABLE VI-2

SUMMARY OF STORAGE TANK SPECIFICATIONS

Specification	HITEC Tanks	Oil Tanks
Must contain	HITEC: 6,636 kg (14,629 lbs)	heat transfer oil (Thermia 33 typical); 59,380 kg (130,910 lbs)
Normal & maximum operating temps.	722 K (840 ^o F); 755 K (900 ^o F)	570 K (567 ^o F); 580 K (585 ^o F)
Normal operating pressure	14 kPa (2 psig)	14 kPa (2 psig)
Material & const.	carbon steel, welded with ASME flanged & dished heads; vertical mounting	carbon steel, welded with ASME flanged & dished heads; vertical mounting
Dimensions	1.83 m (6 ft) OD; 2.06 m (6.75 ft) high plus pump motor; 4.6 m ³ (162 ft ³) volume	3.66 m (12 ft) OD; 9.30 m (30.5 ft) high; 90.6 m ³ (3,200 ft ³) volume
Insulation	mineral wool and fiber- glass; 13 cm (5 in.) thick	mineral wool and fiber- glass; 13 cm (5 in.) thick

submerged in the liquid near the bottom of the vessel. This design was selected because no shaft seals are available which can withstand the combination of temperature and corrosive environment existing in this application. For a Pilot Plant HITEC pumping system, with a 30-year lifetime, a cantilevered pump would be employed. Cantilevered pumps have no submerged bearings, and a shaft about 2 meters (6 ft) long is the maximum practical length. In the Pilot Plant the HITEC pumps would be mounted in pressurized sumps, in which nitrogen would be used to force the salt level to a height within reach of the pump. The HITEC pumps in the Research Experiment do not require a pressurized sump. Also, they are not cantilevered pumps since they are equipped with submerged bearings; the use of pumps with bearings represents a significant cost saving and is an acceptable alternative because of the limited operating life of the experiment.

The HITEC pumps have been ordered from Lawrence Pump and Engine Company in Lawrence, Massachusetts. It is anticipated that the oil pump will be purchased from Dean Brothers Pumps, Inc. of Indianapolis, Indiana.

e. Piping and Valves - All piping and pipe components are being designed to meet the requirements of the American National Standards Institute (ANSI) Code for Power Piping, B31.1. This code specifies requirements for allowable materials, stress analysis, fabrication, construction, inspection and testing. Design requirements and the conditions of available steam and feedwater have dictated the pipe pressure loading. Occasional loading of wind and earthquake have been evaluated using ANSI A58.1, building code requirements for minimum design loads in buildings and other structures.

Pipe sizes in the system were initially established with an effort to minimize the pipe size while maintaining pressure drops within acceptable limits and velocities of the various fluids in the range of industrial practice. Pipe schedule (wall thickness) were then determined based on Code allowable pressure stresses.

A pipe run layout is made with the aid of hand calculations for establishing proper support and flexibility of the run. It is necessary to maintain support reactions and all nozzle loadings on prescribed limits. Several published handbooks are available for performing the necessary hand calculations. The primary handbook used has been Piping Design and Engineering, fourth ed. published by ITT Grinnell Corp. This handbook contains valuable data on the properties of pipe and piping components, tables and charts for piping thermal flexibility analysis and procedures for determining location and type of pipe supports.

The adequacy of a pipe run is finally determined by a computer analysis using the computer program PIPESD (pipe static and dynamic analysis). PIPESD is a computer program available on Control Data Corporation Cybernet. The program performs a complete structural analysis of a piping system and evaluates the B31.1 stress requirements for sustained, thermal and occasional loadings. The program is accessed from the local Control Data Corporation terminal to the main computer center in Houston, Texas.

Various pipe runs in the system were identified and designated as subassemblies for the purpose of design and analysis. To date design of the following pipe runs has been completed. Summary sketches have been prepared showing each pipe run with hanger and support locations, hanger and support loadings and loadings on HE and tank nozzles where applicable. Data pertaining to these designs are given in Table VI-3.

1. Main steam line from Georgia Power interface to a fixed support point at end of trestle.
2. Main steam line from fixed support point at end of trestle to HE1. This line contains valves SC1, FCV5, flow sensor FRS1, and desuperheater DS1.

TABLE VI-3

RESEARCH EXPERIMENT PIPING SIZE AND SCHEDULE TABLE

<u>Pipe Run</u>	<u>Design Pressure</u> (psig)	<u>Design Temperature</u> (°F)	<u>Standard Pipe Size</u>	<u>Material</u>
1	1420	985	2½ - Sch. 80	ASME A335-P11
2	1420	985	2½ - Sch. 80	ASME A335-P11
	735	985	2 - Sch. 40	ASME A335-P11
			1 - Sch. 80	ASME A335-P11
			3/4 - Sch. 10	ASME A312-TP304H
3	735	985	1½ - Sch. 40	ASME A335-P11
4	735	985	1¼ - Sch. 40	ASME A335-P11
5	50	865	1¼ - Sch. 40	ASME A335-P11
6	50	865	1¼ - Sch. 40	ASME A335-P11
7	1250	450	1¼ - Sch. 40	ASME A106-B
8	1250	450	1¼ - Sch. 40	ASME A106-B
9	50	585	4 - Sch. 40	ASME A 53-B
10	50	585	4 - Sch. 40	ASME A 53-B
11	65	570	4 - Sch. 40	ASME A 53-B
12	1400	570	1¼ - Sch. 40	ASME A106-B

HITEC steam heat and trace lines from main steam line to fixed support points on HE1 support structure. These lines contain valves BPV1, BVP2 and BVP4.

3. HITEC tanks heat inlet lines from fixed support point on HE1 support structure to top of HITEC tanks.
4. HITEC tank heat outlet lines from bottom of HITEC tanks to fixed support point in field.
5. HITEC line from tank 1 to HE1.
6. HITEC line from tank 2 to HE1.
7. Main feedwater line from Georgia Power Company interface to a fixed support point at end of trestle.
8. Main feedwater line from fixed support point on trestle to HE1 and branch line to fixed support in field leading to silencer.

This line contains valves FWV1, FCV8 and FCV9.

9. Oil line from oil tanks to oil pump inlet. Lines from pump outlet to HE2 and HE3 supply lines. HE2 and HE3 supply and return lines, one running to HE3 and one running to field fixed support point. These lines contain valves FCV2, FRV9, FRV10, FRV11, FRV12, FRV13 and FRV14.

10. Oil line from field fixed support point to HE2.

11. Oil line from HE2 to HE3 including bypass line to pump supply line.

These lines include valves FCV11 and FRV 15.

12. Water line from HE2 to HE3.

f. Insulation - All of the insulation thicknesses for the Research Experiment have been chosen. The insulation thicknesses were dictated by heat loss requirements and material selection was governed by economic, safety and temperature requirements.

The Research Experiment system must be capable of discharging a total amount of 1.6 MWhr of thermal energy into steam at a maximum rate of 2.0 MWth. Both the oil stage and the HITEC stage have an excess capacity of 10 percent so that, with no heat loss, a total amount of 1.76 MWhr of heat energy can be stored. The insulation thicknesses have been chosen so that the Research Experiment can be operated for a period of approximately 5 hours before the 10 percent excess heat stored will be consumed through heat loss to the surroundings. Table VI-4 gives a summary of the heat loss from the various components.

TABLE VI-4
COMPONENT HEAT LOSS

<u>Component</u>	<u>Percent Heat Loss Rate</u> (%/hr)
HITEC Tanks	1.26
HITEC Pipes	0.44
HITEC Heat Exchangers	0.28
Oil Tanks	1.05
Oil Lines	0.31
Oil Heat Exchangers	0.78

The numbers in the table are the percents of heat loss from the respective stage in one hour. For example, 1.26 percent of the heat stored in the salt will be lost through the salt tank walls during every hour of operation. For both the salt and the oil stages the heat loss from the tanks is approximately equal to the heat loss from the piping and heat exchangers. The five hour period of operation will allow 1.6 MWhr of thermal energy to be delivered to the steam for all discharge rates down to the minimum rate of 0.4 MWth. However, a complete discharge at the minimum rate will take 4 hours so the Research Experiment will have to be charged in less than an hour and immediately discharged in order for 1.6 MWhrth to be delivered at the minimum rate.

A summary of the insulation types and thicknesses is given in Table VI-5. Calcium silicate will be used on the steam, feed-water and HITEC lines, but will not be used on the oil lines or tanks. Calcium silicate is porous and if any oil were to leak into this insulation, a severe fire hazard would result. Instead, foam glass, which is impervious to oil will be used.

g. System Control and Instrumentation - The control logic for the Research Experiment is identical to that anticipated in the Pilot Plant. All control functions will be accomplished by state-of-the-art controllers in order to minimize start-up difficulties which might be expected with a centralized control and data processing system. A total of 40 process sensors will be incorporated

TABLE VI-5
INSULATION MATERIALS

Component	Thickness	Material
Main Steam Line	0.0889 m (3-1/2 in.)	calcium silicate
Feedwater and Steam Trace Lines	0.0254 m (1 in.)	calcium silicate
HITEC Lines	0.0762 m (3 in.)	calcium silicate
HITEC Tanks	0.0635 m (2.5 in.)	mineral wool
	0.0635 m (2.5 in.)	fiberglass
HE1	0.0508 m (2 in.)	mineral wool
	0.0254 m (1 in.)	fiberglass
Oil Lines	0.1016 m (4 in.)	foam glass
Oil Tanks	0.0254 m (1 in.)	mineral wool
	0.1016 m (4 in.)	fiberglass
HE2 and HE3	0.1016m (4 in.)	(material not yet selected)

into the experiment, including 23 temperature sensors, 9 flow rate sensors, 6 liquid level sensors, and 2 pressure sensors. These are integrated into 6 charging control circuits and 5 discharging control circuits, which will automatically be called into operation when the system is switched onto one of the two possible operating modes. The sensors and control loops are indicated on the system schematic shown in Figure VI-6. Hard copy records (strip chart recordings) of each sensor output will be made in order to preserve permanent records of raw performance data.

Three overall control modes are anticipated: CHARGE, STANDBY, and DISCHARGE. The control configurations vary depending upon which mode is currently being used; for example, when storage is being charged the liquid level in the condensing-evaporating heat exchanger is controlled by flow control valve FCV8 and when storage is being discharged that liquid level is controlled by three-element feedwater controller TEFWC1.

During the charging mode of operation, the input steam flow rate must simulate the variable flow rate characteristic anticipated in a solar thermal Pilot Plant. This will be accomplished by manual adjustment of the set point on a controller operating flow control valve FCV5. All other controls will then respond in the normal manner to maintain stable system operation.

During the discharging mode of operation, the output steam flow rate must follow the variable characteristic anticipated for a turbine in the load-following mode. This will be accomplished by manual adjustment of the set point on a controller operating flow control valve FCV6. All other controls will then respond automatically, as before.

All control loops will have a manual override capability to permit an operator to perform special operations, such as bleeding pressure from the system. (During operation, the pressure is normally controlled by the oil flow rate in heat exchanger HE2.) The basic control logic for the Thermal Storage Subsystem was described in the First Quarterly Report. The entire control and instrumentation system package is to be supplied by the Martin Marietta Corporation in Denver, Colorado.

4. Preliminary Test Plan

A Preliminary Test Plan for the Thermal Storage Subsystem Research Experiment was published on March 8, 1976. This plan describes the test objectives, test site and interfaces, instrumentation, control and the planned test sequences; a final test plan will be published in June 1976.

a. Primary Objectives - These objectives must be accomplished during the test program in order to demonstrate feasibility of the thermal storage concept and identify design changes for the Pilot Plant Preliminary Design:

- 1) Demonstrate that the Research Experiment hardware is capable of charging thermal energy into the liquid storage media at the desired system temperatures, pressures and rates by desuperheating and condensing the charging steam.
- 2) Demonstrate that the Research Experiment hardware is capable of discharging thermal energy from the liquid storage media at the desired system temperatures, pressures and rates by evaporating and superheating the feedwater.
- 3) Demonstrate that the Research Experiment hardware can be controlled to maintain the required operating conditions while following a variable input steam rate during charging and a variable output steam rate during discharging. Demonstrate that the control system can operate successfully during the transients associated with switching from one operating mode to another, and fast start-up or shutdown.

- 4) Demonstrate that the process equipment designs (heat exchangers, tanks and interconnecting piping) can tolerate anticipated thermal and pressure transients without structural failure.
- 5) Develop and demonstrate a procedure for initial charging of the Pilot Plant Thermal Storage Subsystem.

b. Secondary Objectives - These additional objectives will be met in the course of the test program:

- 1) Develop control and operating experience with a Thermal Storage Subsystem of the planned design.
- 2) Experimentally establish system heat losses and their effect on the storage system efficiency.
- 3) Identify design deficiencies and corrections to be incorporated into the Pilot Plant Preliminary Design.
- 4) Evaluate the modes and rates of storage media degradation during operation at the design conditions.

c. Preliminary System Tests - A series of preliminary system tests will be conducted for the purpose of system checkout and troubleshooting; these tests precede the performance test sequence. The preliminary tests performed by Georgia Tech will consist of:

- 1) Checkout of individual control circuits.
- 2) Flow testing.
- 3) Initial system start-up and checkout of the control system.

The control system checkout involves verification of correct operation of all controls using simulated input signals. The flow tests involve pumping of the storage fluids through their respective circuits. The oil stage will be flow tested and operated alone, before the molten salt stage is brought to operating temperature. During flow testing of the oil stage, a simulated control input will be used to represent the steam pressure in the heat exchanger HE2 which controls oil flow rate. Initial start-up and checkout will involve bringing the storage media to operating temperature and performing very basic charging and discharging operations to acquire familiarity with the system's control characteristics.

d. Performance Test Sequence - This sequence represents the tests which are intended to demonstrate the technical feasibility and to establish the performance capabilities of the thermal storage system concept. A brief outline of the performance tests is:

- 1) Constant rate charging and discharging operations in which the entire Thermal Storage Subsystem Research Experiment is completely charged and discharged at 50, 100, and 20 percent of the design steam flow rates.
- 2) Transient charging and discharging operations in which the Research Experiment is run in modes which simulate steady changes in power level and power level changes which follow anticipated Pilot Plant conditions.

During the performance test sequence, operating mode reversals and repeating of runs will be accomplished in order to demonstrate the capacity of the system to respond to the demands of other Pilot Plant subsystems.

5. Schedule

The master schedule for the Research Experiment is contained in Table VI-5. The major activities that were in progress or were completed during the period covered by this report include:

- 1) Negotiation of the Georgia Power Company Contract.
- 2) Negotiation of Georgia Tech - Martin Marietta Corporation Contract.
- 3) Detail design of the Research Experiment.
- 4) Component procurement.
- 5) Preparation of preliminary test plan.

The negotiation of the Georgia Power Company Contract has been completed and the contract has been executed by the Company and Georgia Tech.

The Georgia Tech - Martin Marietta Corporation Contract was signed on January 16, 1976. Orders for the following major system components were placed during this report period:

- 1) Heat Exchangers
- 2) Storage Media Tanks
- 3) HITEC pumps
- 4) All Valves
- 5) A system instrumentation and controls package.

The vendors and a description of the components are given in their respective report sections. A summary of the preliminary test plan is also included in this report.

TABLE VI-6

MASTER SCHEDULE FOR THE RESEARCH EXPERIMENT

Engineering Experiment Station
Georgia Institute of Technology

Date 2/2/76 Rev. Ltr. A

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The major areas of effort for the next quarterly report period are continued detail design, component procurement, final test plan generation and production of the construction subcontract specifications. The design of the oil piping and steam and feed-water piping will be completed. The support structures for the HITEC heat exchanger and the vertical oil heat exchanger will be designed. The installation drawing will be completed. A components list that includes piping and hanger identification will be completed. All components, except those supplied by the construction subcontractor will be ordered. No significant schedule changes are anticipated.

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VII. ELECTRIC POWER GENERATION SUBSYSTEM AND
BALANCE OF PLANT

A. SUMMARY OF PROJECT WORK TO-DATE

Bechtel has participated in the conceptual design of the Central Receiver Solar Thermal Pilot Plant since contract inception in June 1975.

Bechtel responsibility includes design and estimate of the Electrical Power Generation Subsystem (EPGS), site development, buildings, tower for receiver, interconnecting piping (except to thermal storage), foundations for heliostats and sensors; external wiring and power supply for the Collector Subsystem, Thermal Storage Subsystem (TSS) consultation, environmental study and auxiliary systems comprising the balance of plant.

Optimization of the EPGS conceptual design was initiated late in 1975 and will continue through September 1976.

The conceptual design was completed in 1975 and results were reported in Summary Progress Report in January 1976. This effort was in three phases for the EPGS: turbine selection, cycle studies, and heat rejection system selection. A General Electric admission turbine with automatic extraction was selected after evaluation of three turbine types. The EPGS cycle arrangement for the pilot plant includes four stages of feedwater heating and two feedwater pumps in series to feed storage or receiver without throttling losses when pumping to storage. No reheat was included due to economic disadvantages. A dry condenser heat rejection system was selected in accordance with Martin Marietta Corporation (MMC) criteria to permit pilot plant location in an arid area.

The Bechtel balance of plant items include other tasks than the EPGS. BOP conceptual design resulted in selection of a cost effective circular mat type heliostat foundation after consideration of eight alternative concepts. A reinforced concrete receiver tower was selected after comparison with guyed steel and free-standing steel tower concepts. The concrete tower showed advantages in cost as well as in seismic and wind load design considerations. Other BOP efforts resulted in; a non site specific general plant arrangement, riser and downcomer piping concepts, and an environmental analysis.

B. PROJECT WORK DURING QUARTERLY PERIOD JANUARY 1, 1976
THROUGH MARCH 31, 1976

During this contract period, two major task milestones were met: The Preliminary Environmental Impact Identification and Siting Criteria Report, and the Balance of Plant Conceptual Cost Estimate were submitted. Optimization effort for the EPGS initiated in the previous quarter was continued and a more specific plan for the remainder of this effort was developed. Consultation on the Thermal Storage Subsystem design was continued, and effort in support of the MMC computer simulation model was initiated. Figure VII-1 illustrates the tasks accomplished as well as the Interim Schedule for the optimization period of the contract.

FIGURE VII-1 CRSTPP BECHTEL INTERIM SCHEDULE

1. Preliminary Environmental Impact Identification and Siting Criteria

a. Introduction - The conceptual design of the pilot plant was reviewed to identify the major environmental impacts and to develop siting criteria aimed at mitigating these impacts. The results of this task effort which were presented fully in Bechtel Report, "Preliminary Environmental Impact Identification and Siting Criteria" dated January 1976, and are summarized in Tables VII-1 and VII-2, are briefly discussed in this section in terms of impacts to the physical and chemical, biological, and the social environments.

A site which has an avoidance characteristic in Table VII-2 should be removed from consideration because regulatory agencies or the public would not be expected to give approval for construction and operation of the plant. A site which has one or several characteristics in the downgrading category is environmentally less desirable than one without these characteristics, but need not be eliminated from consideration.

b. Impacts to the Physical and Chemical Environment

Topography - The pilot plant occupies a total area of about 393,000 m² (97 acres). Construction of the plant will require clearing and grading to create the design profile and drainage for the facilities. This will modify the area's topography. By selecting a site that is relatively flat, large-scale topographic changes can be avoided. The topographic feature of the site should also be assessed in terms of aesthetics. Undesirable visibility of the plant from nearby residences or roads should be minimized. (See Section 1.d., Social Environment.)

Soils - Soils in the site area will be disturbed during construction and will be partially covered or shaded by the constructed facilities. This will cause a change in the land surface characteristics and result in the disruption of the natural heating and cooling cycles. The natural interaction between the soils and the atmospheric environment will be changed and their function as a biologic substrate will be curtailed. Sites having highly productive soils from a commercial fertility or an ecological perspective should be downgraded. Also, highly erodible and unstable soils are unsuitable both from an environmental and from an engineering perspective, and should be avoided.

	PROJECT COMPONENTS				
	ENVIRONMENTAL CHARACTERISTICS	COLLECTOR SUBSYSTEM	RECEIVER SUBSYSTEM	THERMAL STORAGE SUBSYSTEM	ELECTRICAL POWER GENERATION SUBSYSTEM
PHYSICAL AND CHEMICAL	TOPOGRAPHY	<ul style="list-style-type: none"> Alterations due to installation of heliostats and roads 	<ul style="list-style-type: none"> Minor alterations due to receiver tower installation 	<ul style="list-style-type: none"> Minor alterations due to installation of equipment and spill retention pond 	<ul style="list-style-type: none"> Minor alterations due to equipment installation
	SOILS	<ul style="list-style-type: none"> Potential erosion from rainwater Disturbance of soils during construction Disruption of existing heating and cooling cycles Quality degradation if solvents are used for mirror washing 	<ul style="list-style-type: none"> Removal of soil in foundation area 	<ul style="list-style-type: none"> Removal of soil in tank and pond area Potential damage from major spills 	<ul style="list-style-type: none"> Removal of soil in foundation area
	SURFACE WATER HYDROLOGY AND QUALITY	<ul style="list-style-type: none"> Altered surface drainage patterns Turbidity as a result of erosion Degradation if solvents are used for mirror washing 	<ul style="list-style-type: none"> No major impacts anticipated 	<ul style="list-style-type: none"> Potential damage from major spills during operation or thermal storage fluid delivery 	<ul style="list-style-type: none"> No major impacts anticipated
	GROUND WATER HYDROLOGY AND QUALITY	<ul style="list-style-type: none"> Slight potential for interference with ground water recharge Quality will be degraded if solvents are used for mirror washing if they enter the ground water system Potential ground water drawdown for water supply 	<ul style="list-style-type: none"> Potential ground water drawdown for make-up water supply 	<ul style="list-style-type: none"> Potential damage from major spills Potential ground water drawdown for make-up water supply 	<ul style="list-style-type: none"> Potential ground water drawdown for water supply
	METEOROLOGY AND AIR QUALITY	<ul style="list-style-type: none"> Alterations to local microclimate, including temperature and air circulation patterns Air quality temporarily affected by dust generated during construction 	<ul style="list-style-type: none"> Air quality temporarily affected by dust generated during construction 	<ul style="list-style-type: none"> No major impacts anticipated during normal operation Potential temporary air quality degradation if major spills occur Air quality temporarily affected by dust generated during construction 	<ul style="list-style-type: none"> Minor emissions from operation of standby generator Cooling tower waste heat of about 25 MWt Air quality temporarily affected by dust generated during construction
	NOISE	<ul style="list-style-type: none"> Minor contribution to local noise levels due to vehicles 	<ul style="list-style-type: none"> Minor contribution to local noise levels due to fluid flows 	<ul style="list-style-type: none"> Minor contribution to local noise levels due to equipment 	<ul style="list-style-type: none"> Minor contribution to local noise level due to equipment
	TERRESTRIAL ECOLOGY	<ul style="list-style-type: none"> Removal of up to 330,000 square meters of habitat Retardation or prevention of normal revegetation 	<ul style="list-style-type: none"> Preemption of terrestrial habitat Interference with flocks of migrating birds - collision with tower or mortality from heat is expected 	<ul style="list-style-type: none"> Preemption of terrestrial habitat Potential damage from major spills 	<ul style="list-style-type: none"> Preemption of terrestrial habitat
BIOLOGICAL	AQUATIC ECOLOGY	<ul style="list-style-type: none"> Potential impact if solvents are used for mirror washing 	<ul style="list-style-type: none"> No major impacts anticipated 	<ul style="list-style-type: none"> Potential damage from major spills 	<ul style="list-style-type: none"> No major impact anticipated
	LAND USE	<ul style="list-style-type: none"> Preemption of 330,000 square meters of land 	<ul style="list-style-type: none"> Preemption of a small section of land 	<ul style="list-style-type: none"> Preemption of a small section of land 	<ul style="list-style-type: none"> Preemption of a small section of land
SOCIAL	AESTHETICS	<ul style="list-style-type: none"> In flat area, highly visible 	<ul style="list-style-type: none"> In flat area, highly visible 	<ul style="list-style-type: none"> In flat area, highly visible 	<ul style="list-style-type: none"> In flat area, highly visible
	SCIENTIFIC/CULTURAL	<ul style="list-style-type: none"> Potential impact on scientific/cultural resources 	<ul style="list-style-type: none"> Potential impact on scientific/cultural resources 	<ul style="list-style-type: none"> Potential impact on natural scenic and cultural resources 	<ul style="list-style-type: none"> Potential impact on scientific/cultural resources

SUMMARY OF ENVIRONMENTAL IMPACTS

TABLE VII-1

	SITING CRITERIA ENVIRONMENTAL CHARACTERISTICS	DOWNGRADING FACTORS	AVOIDANCE FACTORS
PHYSICAL AND CHEMICAL	TOPOGRAPHY	<ul style="list-style-type: none"> • Extensive topographical modification 	<ul style="list-style-type: none"> • No applicable criteria
	SOILS	<ul style="list-style-type: none"> • Highly productive soils from a commercial fertility or an ecological perspective 	<ul style="list-style-type: none"> • Highly erodable or unstable soils
	SURFACE WATER HYDROLOGY AND QUALITY	<ul style="list-style-type: none"> • Changes in surface drainage patterns, resulting in increases or decreases of flow to the detriment of human or ecological use • Temporary deterioration of quality to the detriment of human or ecological use 	<ul style="list-style-type: none"> • Long-term deterioration of quality to the detriment of human or ecological use
	GROUND WATER HYDROLOGY AND QUALITY	<ul style="list-style-type: none"> • Removal of ground water resources from other existing beneficial uses 	<ul style="list-style-type: none"> • Reduction of ground water quality below limits acceptable for other beneficial uses, particularly human consumption
	METEOROLOGY AND AIR QUALITY	<ul style="list-style-type: none"> • No applicable criteria 	<ul style="list-style-type: none"> • No applicable criteria
	NOISE	<ul style="list-style-type: none"> • No applicable criteria 	<ul style="list-style-type: none"> • No applicable criteria
BIOLOGICAL	TERRESTRIAL ECOLOGY	<ul style="list-style-type: none"> • Recreationally or commercially important, on a regional basis, wildlife species • Adjacent important wildlife populations whose success would be affected • Vegetation species critical to the food base of important wildlife 	<ul style="list-style-type: none"> • Wildlife, vegetation or habitats which are threatened or endangered
	AQUATIC ECOLOGY	<ul style="list-style-type: none"> • Recreationally or commercially important, on a regional basis, aquatic species and habitats • Adjacent important aquatic populations and habitats whose success would be affected 	<ul style="list-style-type: none"> • Aquatic species or habitats which are threatened or endangered
SOCIAL	LAND USE	<ul style="list-style-type: none"> • Incompatible with present or future land use • Dislocation of any residences and business 	<ul style="list-style-type: none"> • Existing heavily utilized recreation activities or commercially important agriculture • Hazards to the pilot plant, e.g., airports • Dislocation to the detriment of community structure
	AESTHETICS	<ul style="list-style-type: none"> • Highly visible or reflections visible from road or residences 	<ul style="list-style-type: none"> • Highly prized scenic vistas
	SCIENTIFIC/CULTURAL	<ul style="list-style-type: none"> • Adjacent scientific, cultural, or archaeological features which would be adversely affected 	<ul style="list-style-type: none"> • Known scientific, cultural or archaeological features on site

SUMMARY OF ENVIRONMENTAL IMPACT
SITING CRITERIA

Surface Water Hydrology and Quality - Site clearance and preparation will result in an alteration of the surface runoff pattern and soil erosion. Potential contamination of surface water due to accidental spills of thermal storage fluids or the use of chemicals in the washing of heliostats is also a concern. Although this type of impact is not expected to be significant for a site with low rainfall and minimum interface with surface water, engineering measures are available to minimize these impacts. These involve the method of surfacing the collector field and a judicious design of a drainage system.

Ground Water Hydrology and Quality - Should the plant be located in a ground water recharge area, recharge to the aquifer system could be reduced. Plant chemicals (e.g. thermal storage fluid, heliostat washing detergent, or solvent) may also find their way to the aquifer. Withdrawal of ground water for plant make-up will remove water from other existing beneficial uses. These impacts can be minimized by a careful site selection with full cognizance of the site hydrology. Since the plant uses a dry-cooling heat rejection system, the water use of the plant is only $9.1 \times 10^{-4} \text{ m}^3/\text{s}$ (15 gal/min).

Meteorology and Air Quality - A portion of the total insolation incident on the site will be diverted for energy conversion resulting in a net energy export from the site. This will cause a localized waste heat rejection of about 25 MW at the design point of the plant and local microclimate will be affected. Air quality will be affected temporarily because of dust during construction. Occasional operation for short duration of the standby generator will result in a minor amount of air pollutants. However, these effects are deemed to be insignificant, and sites need not be evaluated for meteorology and air quality characteristics from an environmental impact perspective.

Noise - Operation of the plant will not result in a significant elevation of the noise level of the site. However, specific noise regulations are highly dependent on local jurisdiction and should be carefully evaluated in the site selection process.

c. Biological Environment

Terrestrial Ecology - The type of biological communities and their sensitivity to disturbance varies with location. The Southwest U.S. is characterized by desert or arid grasslands, woodlands, or chaparral. Biological communities in this area are relatively stable and hardy ecologically. However, once this environment and balance is disturbed, recovery is also relatively slow. If construction or operation at the site would directly or indirectly affect the success of the wildlife, (especially those that are recreationally or commercially important) the site should be downgraded. Sites containing vegetation critical to the food base of important wildlife species or habitats of species that are threatened or endangered should be avoided.

Of special concern is the potential for flocks of migratory birds to collide with the receiver tower or die of exposure to the focused solar beams. Since the Southwest lies within major flyways of migratory birds, it does not appear possible to totally avoid migratory pathways for all species of birds. However, sites should be evaluated for position in pathways of rare and protected birds and for large concentrations of other birds.

Aquatic Biology - Aquatic biology in the Southwest is primarily limited to surface water bodies such as the Colorado River or the Rio Grande River. Some portions of the deserts, however, are typified by small pools, usually brackish, which support a number of rare endemic fish species. The criteria for evaluating a site based on aquatic ecology are much the same as those for terrestrial ecology. Sites supporting recreationally or domestically important aquatic species and habitats should be downgraded and sites that support or contribute to the success of aquatic species and habitats that are threatened or endangered should be avoided.

d. Social Environment

Land Use - The plant requires a large parcel of land and existing land use must be preempted. To minimize this impact, sites where the plant would be incompatible with present or future land use should be downgraded.

Sites which currently support heavily utilized recreation activities or commercially important agriculture should be avoided. Siting should also avoid potential hazard to the plant such as airports, and certain types of industry and defense establishments.

Sites which require a number of dislocations of residences, business establishments, or other human activities to the detriment of existing community structures should be avoided.

Aesthetics - The pilot plant design assumes a flat site. For this reason, the conspicuousness of the receiver tower, the extensive reflective nature of the collector field and the general industrial appearance of the plant may impact on the aesthetics of scenery and broad uninterrupted panoramas. Therefore, sites where the plant would be prominent in highly prized scenic vistas should be avoided. Sites where the facility would be highly visible from nearby roads or residences should be downgraded.

Scientific/Cultural - The selected site may contain archaeological resources or have cultural, historical, or scientific significance. An example of a culturally significant area would be one held sacred by Indian tradition. Historical significance could arise from events which occurred in Indian history or the expansion of the United States into the West. Scientific values could lie in paleontological or rare habitat resources. Construction of the plant could destroy or remove access to the archaeological artifacts, and cultural, historic, or scientific values would be lost.

Sites containing known archaeological, cultural or scientific features should be avoided. A candidate site should be downgraded if it is situated near or adjacent to a known historical/archaeological site, and use of the candidate site would adversely affect the historical/archaeological feature.

2. Optimization of EPGS

a. General - During 1975, work was initiated to further refine Bechtel estimates of EPGS auxiliary power requirements. Subsequently, a definition of major optimization sub-tasks being performed in 1976 has been developed. Table VII-5 provides a summary of these optimization sub-tasks.

Using Bechtel internal computer codes adapted to meet the needs of this project, a modified heat balance for use in analyzing the 10MWe Pilot Plant or larger scale units is being prepared. This program will significantly enhance the Bechtel analytical capability and result in a better optimized baseline design at the start of preliminary design. The schedule for optimization tasks is partially dependent upon this heat balance program as reflected in Figure VII-2.

Table VII-3 EPGS Optimization Sub-Tasks

<u>Sub-Task Subject</u>	<u>Trade Study Factors</u>
Feedwater Heaters	Number of heaters, type, cost plant efficiency, operating and control flexibility, off peak performance.
Pump Types	Drain size, line traps, loop seal, cost. FW and condensate pump types, performance, special requirements.
Plant Control	Heliostat Defocus speed and quantity, receiver heat output, change of operating mode, system efficiency, cost.
Startup Control	Turbine temperature limits, bypass flow, mode of operation, complexity, cost.
Condenser Fan Control	Off peak requirements, variable speed fans, failure mode opera- tion, cost, ambient temperature, turbine discharge pressure.
Line and Valve Size	Extraction lines, bypass control, desuperheaters, downcomer, system efficiency, cost.
EPGS System	Physical layout, interface of subsystem components, cost.
EPGS Operation	Ambient temperature, start from TSS, integrated power, revised admission conditions.

FIGURE VII-2 CRSTPP EPGS OPTIMIZATION SCHEDULE

b. Auxiliary Power Requirements - Auxiliary power requirements were calculated for the EPGS for all designated modes of operation at the design point ambient condition. Table VII-6 presents the results for two operational modes; from receiver only, and from storage only. The principal difference in auxiliary power requirements is the elimination of the High Pressure Feedwater Pumps when operating from storage only. Figure VII-3 shows auxiliary power requirements for all modes of operation during a typical operating day. Changes in power required for pumps were calculated from flow rate and pressure head values corresponding to the operating modes and there does not appear to be significant opportunity to improve these pump power requirements. Figure VII-4 illustrates the location of certain design point positions on pump performance curves if it is assumed that centrifugal pumps will be available for HP FW pumps. If positive displacement pumps are required, curve shape will change. Referring to Table VII-6, the cooling system fans stand out as the auxiliary power requirement where the most benefit could be obtained from power reductions. Condenser fan power for receiver only and storage only operation are 60%, and 74%, respectively, of the total auxiliary power requirement. Using Figure VII-3, together with turbine and condenser performance curves, estimates can be made of the increase in KWH output from the system which could be obtained for specific reductions in total auxiliary power. This information will be utilized during the optimization study of condenser performance to evaluate payback of revised condenser control options.

TABLE VII-4

EPGS AUXILIARY POWER REQUIREMENTS, kW

EPGS	STEAM SOURCE	
	RECEIVER	STORAGE
TURBINE LUBE AND CONTROL OIL SYSTEM	12.0	12.0
COOLING SYSTEM FANS	546.0	546.0
VACUUM PUMP	6.0	6.0
CONDENSATE PUMP	7.5	6.5
BOOSTER PUMP	67.0	60.0
FEEDWATER PUMP, LP	26.0	24.0
FEEDWATER PUMP, HP	168.0	-
CHEMICAL INJECTION	0.5	0.5
AIR COMPRESSOR (22 kW @ .5 SF)	11.0	11.0
FIRE JOCKEY PUMP	2.5	2.5
POTABLE WATER PUMP	1.5	1.5
MAKEUP WATER (DEEPWELL) PUMP	5.0	5.0
SANITARY WATER PUMP	0.8	0.8
COOLING WATER PUMP	11.0	11.0
HVAC	20.0	20.0
LIGHTING	4.0	4.0
CONTROL POWER	10.0	10.0
AIR PLANE BEACON	4.0	4.0
MISC.	10.0	10.0
TOTAL	912.8	734.8

CRSTPP AUXILIARY POWER REQUIREMENTS
EPGS TYPICAL DAY PERFORMANCE PROFILE
AMBIENT CONDITIONS WINTER SOLSTICE DESIGN POINT

FIGURE VII-3

FIGURE VII-4 PUMP CURVES