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SOLAR PILOT PLANT Phase I

QUARTERLY REPORT No. 3

(Approved)

(CDRL No. 10)

28 October 1976

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HONEYWELL INC.

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28 October 1976

**SOLAR PILOT PLANT
PHASE I**

**QUARTERLY REPORT NO. 3
(April - June 1976)**

(APPROVED)

CDRL Item No. 10

**Energy Resources Center
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FOREWORD

This is the final submittal of Solar Pilot Plant Quarterly Technical Report No. 3 per Contract Data Requirements List Item 10 of ERDA Contract E(04-3)1109. The report has been reviewed by ERDA for technical content and patent clearance, and has been released for normal distribution.

ABSTRACT

Honeywell Inc. is investigating the technical and economic feasibility of generating electricity from solar energy under Energy Research and Development Administration (ERDA) Contract E(04-3)1109. During the report period (1 April through 30 June 1976), detailed designs for the collector, steam generator, and thermal storage subsystem research experiments (SREs) were approved, and the program moved into the hardware stage preparatory to SRE testing later in the year. The program was on schedule at the end of the period.

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SECTION I INTRODUCTION

BACKGROUND

The Energy Research and Development Administration (ERDA) is commissioned to identify and evaluate alternate sources of energy to ensure orderly and timely development of those offering potential for supplementing and/or replacing conventional fuels that will be in increasingly short supply. An alternate source with great potential is solar energy, and one goal of the overall national energy program is to demonstrate the technical and economic feasibility of a central receiver solar power plant for generating electricity. Pursuant to that goal, ERDA, on 1 July 1975, awarded Honeywell Inc. a 2-year contract to develop a preliminary design for a 10-MW(e) proof-of-concept pilot plant.

PROGRAM SCOPE

The program being conducted by Honeywell under ERDA Contract E(04-3)1109 calls for preparing a solar pilot plant baseline design and carrying out research experiments on three key subsystems to obtain data for evaluating the baseline. Because these subsystems (collector, receiver, and thermal storage) and their integration are critical to the success of this portion of the program and to initiation of the next phase [constructing and operating the 10-MW(e) pilot plant], Honeywell is using a team approach to provide a low-risk, cost-effective preliminary design. The team and individual responsibilities are shown in Figure 1.

Figure 1. Honeywell Team for Solar Pilot Plant Program

PROGRAM STATUS

Figure 2 is the program schedule.

Figure 2. Solar Pilot Plant Phase I Schedule

The schedule shows that the detailed designs for all three subsystems were completed during the period, those for the collector and steam generator in May, and that for thermal storage in June. This progress was reported in detail at the Solar Pilot Plant Program Semiannual Review in Washington, D. C., on 1-4 June. That completed the design effort, and the program moved fully into the hardware procurement and fabrication stage preparatory to subsystem testing. Certain aspects of the remainder of the schedule are tight, but the program was on schedule at the end of the report period and is expected to remain so.

Preparation of test hardware will continue during the next quarter. In addition to reporting this progress, the fourth quarterly report will summarize progress during the first 12 months of the program.

SECTION II

SOLAR PILOT PLANT CHARACTERISTICS

CONCEPT

Description

The pilot plant concept generated for this program and refined during the first 12 months now consists of an elliptical field of heliostats that concentrate solar energy through the annulus aperture of a receiver tower, as illustrated in Figure 3.

Figure 3. Solar Pilot Plant Concept, Elliptical Field

The concentrated solar energy is converted to thermal energy by an array of boiler and superheater tubes in the cavity to generate electricity from superheated steam produced in the receiver, or from thermal energy stored by melting a eutectic salt (Figure 4).

Figure 4. Solar Pilot Plant Baseline Schematic

The 10-MW(e) pilot plant is related to a 100-MW(e) capacity plant (based on net power at the winter solstice). The design ensures that data obtained from the pilot plant will be applicable to commercial operations. A comparison is shown in Figure 5. It will be noted that some values have been adjusted since the last report.

Figure 5. Comparison of Commercial and Pilot Plant Parameter

Change to Baseline

Heliostat field layout studies showed a tower-south-of-center, nonuniform field (Figure 6) could efficiently redirect energy to a circular steam generator atop the tower. In this geometry, the heliostat field completely surrounds the tower. The field outer perimeter is elliptic, with an eccentricity of approximately 0.6. This perimeter shape was chosen because heliostat field studies showed tracking efficiency is optimal for elliptic field boundaries.

Figure 6. 360-Degree Heliostat Field Geometry

The heliostat spacing is based on an analysis of shadowing and blocking of adjacent heliostats. The spacing chosen has a minimal amount of shadowing and blocking annual energy losses. The heliostats can be packed relatively dense close to the tower, and spaced farther apart farther out in the field. The spacing also varies somewhat with azimuth position. Heliostats in the south field can be spaced closer together than those in the north or east. The change permitted a reduction in the number of heliostats from 1905 to 1682. Definition of the new field parameters is in progress.

Figure 7 shows the cavity and cavity aperture sized to pilot plant scale.

Figure 7. Receiver and Aperture Dimensions

Figure 8 is a flux map for noon on 21 March. Total power entering the cavity is 52.9 MW, of which 46.2 MW is incident on the cavity walls and 6.7 MW on the cavity ceiling. The map shows peak incident flux will be slightly over 350 kW/m². Other flux maps are being generated to determine power output variance with time of day and year.

Figure 8. Cavity Wall Incident Flux - Noon, 21 March

The flux map (Figure 8) shows that the north side of the cavity interior has very low incident flux on the lower surfaces (less than 6 meters up). This could impact the receiver boiler design in that the north wall may not need boiler tube surface, but could instead be an inactive surface. This would decrease the required boiler mass, and most probably would decrease the cost of the steam generator.

It should be noted that the cavity size shown in Figure 7 is larger than that in the baseline design. The increase in size (diameter) is due to increase in mirror area per heliostat (from 18.6 m² to 40 m² per heliostat) and to the change in tracking error budget from 1 milliradian (1 σ) to 2 milliradians (1 σ) error. For the same size heliostat and tracking error budget, our estimates show that field geometry has little, if any, effect on total aperture area required.

MAJOR SUBSYSTEMS

Major subsystems of the pilot plant are summarized in Table 1. The first three are of primary interest in this phase of the program because practical generation of electricity is dependent on how well they function as a system. Figure 9 shows the subsystem interfaces.

Table 1. Solar Pilot Plant Major Subsystems

Parameter	Value
Collector Subsystem:	
Field area	Being determined
Number of heliostats	1682 (C)
Receiver Subsystem:	
Tower height	130 m (C)
Cavity diameter	14.4 m (C)
Cavity height	14 m (C)
Thermal Storage Subsystem:	
Thermal storage capacity	315 MWhr(t)
Total quantity of phase-change material (NaNO ₃ - NaOH)	7.33 x 10 ⁶ kg
Electrical-Generation Subsystem:	
Turbine name-plate capacity	15,000 kW
High-pressure steam turbine inlet conditions	12.4 MPa/510°C (C)
Low-pressure steam turbine conditions	6.5 MPa/307°C

(C) indicates change in value from last report.

Figure 9. Subsystem Interface

Collector Subsystem

The collector subsystem is designed to gather and transmit solar energy using prefocused heliostats (Table 2).

Table 2. Collector Subsystem Characteristics

Parameter	Value
Field area	Being determined
Number of heliostats	1882 (C)
Individual heliostat area	40 m ²
Total heliostat area	67,280 m ² (C)
Peak thermal power into aperture	53 MW
Annual thermal energy into cavity aperture	1.58 x 10 ⁵ MWhr
Net annual thermal energy per unit mirror area	2.01 MWhr/m ² (C)
Net peak power per unit mirror area (thermal)	0.72 kW/m ² (C)

(C) Change from last report.

Receiver Subsystem

The receiver subsystem takes in the solar energy from collector subsystem. Feedwater in the receiver boiler tubes is superheated and piped directly to the electrical generation subsystem and/or to the thermal storage subsystem (Table 3).

Table 3. Receiver Subsystem Characteristics

Parameter	Value
Tower height	130 m (C)
Cavity diameter	14.4 m (C)
Cavity height	14 m (C)
Steam generator housing height	20 m
Steam generator housing diameter:	21 m (C)
Aperture slant height	5.5 m to 7.3 m (C)
Aperture lower diameter	6.3 m (C)
Annulus aperture area	210 m ² (C)
Peak absorbed thermal power	48.3 MW (C)
Peak wall incident thermal power flux	400 kW/m ² (C)
Annual thermal energy absorbed by cavity working fluid	1.35 x 10 ⁵ MWhr (C)

(C) denotes changes from last report.

Thermal Storage Subsystem

The thermal storage subsystem supplies feedwater to the receiver and receives superheated steam during the charge cycle. During the discharge cycle, it receives feedwater from the electrical generation subsystem and discharges steam (Table 4).

Table 4. Thermal Storage Subsystem Characteristics

Parameter	Value
Thermal storage capacity	315 MWhr(t)
Total quantity of phase change materials (NaNO ₃ - NaOH)	7.33×10^6 kg
Maximum thermal power input to storage	31.58 MW
Maximum thermal power output from storage	31.58 MW for 6 hr
Net annual electrical energy produced if storage is charged and discharged daily	3.6×10^4 MWhr (C)
Net annual electrical energy produced if storage is not used	4.1×10^4 MWhr (C)
Outlet stream conditions	6.5 MPa/307°C

(C) denotes changes from last report.

Electrical Generation Subsystem

The electrical generation subsystem receives steam from the receiver boiler tubes and/or thermal storage and pumps back feedwater. It also provides electrical power to the other subsystems and the communication/control center (Table 5).

Table 5. Electrical Generation Subsystem Characteristics

Parameter	Value
Turbine nameplate capacity	15,000 kW
Turbine type	Dual-pressure admission
High-pressure steam turbine inlet conditions	12.4 MPa/510°C (C)
Low-pressure steam turbine inlet conditions	6.5 MPa/307°C
Peak steam flow rate to turbine inlet	80,150 kg/hr

(C) denotes changes from last report.

Subsystems Control

The plant control scheme (Figure 10) is based on providing centralized coordination and control of the subsystems while maximizing utilization of the solar energy collected. Safety is a primary consideration, and adequate protection against dangerous operating conditions is incorporated in the control scheme.

Figure 10. Control Coordination of Plant Subsystems

Plant Layout

The geometry of the pilot plant site plan is changed by placing the receiver tower half south of the centroid of an ellipse, but the underlying principle of respecting functional relationships among plant subsystems is not.

SECTION III

COLLECTOR SUBSYSTEM RESEARCH EXPERIMENT

DESCRIPTION OF SUBSYSTEM

The essential elements of the solar collector subsystem are shown in Figure 11. This baseline features:

- Computed sun tracking and calculation of heliostat commands based on line-of-sight (LOS) vectors to the sun and the tower
- Low-profile, two-axis gimbaled heliostats
- Commands to two motors at each heliostat from the central controller
- Periodic heliostat calibration on a target array on the tower near the receiver (the period will be determined by test)
- Continuous central control of heliostats for flexibility of power plant operation

Figure 11. Collector Subsystem Baseline

OBJECTIVES OF THE EXPERIMENT

The objectives of the collector SRE are to:

- Evaluate heliostat and tracking and control designs
- Assess environmental effects on the heliostat
- Simulate pilot plant daily operation

The end products of the experiment will be:

- Verified and refined testing techniques
- Test results and data
- Correlation with analysis
- Design requirements
- Assembly methods
- Test hardware

STATUS OF THE EXPERIMENT

The detailed design for the collector SRE was presented on 18 May 1976. Formal approval was given after further review of the documentation. The design featured:

- Tilt-tilt heliostat configuration
- Two-speed motor control
- Battery prime power (trickle-charged)
- Hard-line simplex serial data link
- Open-loop real-time command/control

An engineering model was presented as part of the review. The model is undergoing testing and modification to obtain proper performance has begun. The schedule for the remainder of the experimental work is shown in Figure 12.

DESCRIPTION OF THE EXPERIMENT

Table 6 is a summary of collector SRE performance parameters, design goals, and evaluation methods.

Figure 12. Collector SRE Preparation and Test Schedule

Table 6. Collector SRE Performance Parameters and Evaluation Techniques

Parameter	Design Goal	Evaluated By
Tracking performance	2 mr/axis, 1σ	Analysis and test
Redirected energy	95 percent in aperture	Analysis and test
Surface reflectance	>80 percent	Test
Functional performance:		
Slew rates	>0.4 deg/sec	Analysis and test
Angular freedom	---	Analysis and test
Auto tracking	---	Analysis and test
Offset pointing	---	Analysis and test
Initialization	---	Analysis and test
Environmental effects:		
Temperature	4.4 to 54.4°C (40 to 130°F)	Analysis and test
Wind	13.5 m/sec	Analysis and test

Heliostat Configuration

The SRE heliostat under test (Figure 13) is a simple structure designed to provide the following cost and time benefits:

- Ease of mass production
- Ease of transportation
- Ease of assembly (can be done with unskilled labor)
- Ease of field adjustment

Figure 13. SRE Heliostat Configuration

Figure 14 shows the full-scale model in the operational position, and Figure 15 in the stowed position. This configuration is representative of those that will be used in the pilot plant.

Test Site

Testing of the SRE hardware is being conducted at the Honeywell Aerospace Division complex in St. Petersburg, Florida. Figure 16 is the test site plan. Building E-2, which contains the central control and mounts the target arrays, is tall and centrally located. The target areas consist of a photodetector

Figure 14. Heliostat, Operational Position

Figure 15. Heliostat, Stowed Position

Figure 16. Collector SRE Site Plan

array and a photographic reference grid, both capable of being pointed toward the desired test site. Figures 17 and 18 are, respectively, views from the mirror module minimum range test site and the heliostat south test site. The LOS views of the target arrays from the other test sites are equally free of obstructions.

Master Control and Computer

The master control computer for the collector SRE (Figure 19), in the north-east corner of the Building E-2, is operational. The operator commands mode selection for each heliostat individually. The operator can, after entering the appropriate commands, get immediate output from the calibration array. The computer program is written in FORTRAN to facilitate transfer to other computers. Open-loop tracking is measured by comparison with closed-loop commands. This technique ensures good test data and good beam control.

Meteorological Data

Climatronics Corporation has delivered a fully integrated meteorological measuring system. The data obtained will be correlated with the subsystem performance data to give a complete profile of the heliostat array and mirror module characteristics.

Capabilities of the meteorological measuring system are given in Appendix A.

Test Results

Six mirror modules have been built and tested. First the mirror contour was measured and compared with the nominal design value. The modules were then checked at various distances for performance using the optical sensor array and photographic grid to determine spot size, shape, and intensity.

The sensor array is 4.3 x 4.9 m (14 x 16 ft). It contains 224 individual sensor/amplifier packages on a 200-pound aluminum frame. Each sensor is on 1-foot centers and is precisely calibrated. All sensor signals are multiplexed into the central computer and processed to determine centroid. The data are also recorded on magnetic tape for later analysis.

Mirror Contour Measurements -- The data shown in Figure 20 were obtained from two full-scale honeycomb mirror modules. Weights were used to simulate the design wind load, 9.7 kg/m^2 (2 lb/ft^2). These results show that the mirror contour will produce a well-focused and well-formed spot on target under the design wind load.

Figure 17. SRE Mirror Module Minimum Range Test Site
(147-m LOS, 3-deg Az)

Figure 18. SRE Heliostat South Test Site
(314-m LOS, 163-deg Az)

Figure 19. Collector SRE Master Control and Computer

Figure 20. Results of Contour Measurements of Two Mirror Modules Under Design Wind Load

Mirror Module Focusing Tests -- Mirror module focus testing has preceded heliostat testing, as would be expected. Figure 21 shows an actual pattern on the target, and Figure 22 shows computer printouts of two focusing patterns. When a heliostat (with four such mirrors) is brought to focus on the photodetector array, it can develop an intensity level equal to or greater than seven suns. There is ample safety margin because the calibration array is designed to handle an intensity equivalent to 14 suns.

ASSESSMENT OF PROGRESS

There are no major technical problems, and none are foreseen. Minor problems were uncovered in the process of building the first heliostat (e.g., gear box pivot location and high actuator torque), but these are being corrected. Progress to date has been good and on schedule.

Figure 21. Mirror Focusing Pattern on Target Array

```

TIME 9:28: 5
0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 1 1
0 0 0 0 0 0 0 0 0 0 1 1 3 5 3 1
0 0 0 0 0 0 1 0 0 1 3 9 13 11 7 2
0 0 0 0 0 0 0 0 1 3 11 19 20 19 12 5
0 0 0 1 0 1 0 1 2 10 20 29 31 24 13 4
0 1 0 1 0 0 1 1 6 17 29 36 34 25 12 1
1 0 1 0 1 1 1 2 15 29 17 38 31 19 7 1
0 0 1 0 1 1 0 7 16 27 34 25 24 12 2 1
0 0 0 0 0 1 0 7 13 23 25 22 13 5 1 1
0 0 1 0 0 0 0 3 9 14 15 10 3 1 1 0
1 0 0 0 0 0 1 0 2 4 2 1 1 1 1 1
0 0 0 1 0 1 1 1 0 1 1 1 0 1 0 1
0 0 0 0 0 1 1 0 0 1 0 1 0 0 0 0
0 0 1 0 1 1 0 0 1 1 1 0 0 1 1 0

```

DELVER= 0.76 DELHOR= 3.29

```

TIME 9:30: 3
0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 1 0 0 1 0 1 1 0 0 0
0 0 0 0 0 0 0 1 3 4 2 1 0 0 0 1
0 0 0 1 0 1 1 9 13 12 8 3 1 0 0 0
0 0 0 1 0 3 11 18 22 18 12 4 1 1 0 0
1 0 1 1 2 11 20 30 33 26 7 4 0 0 0 1
0 0 1 0 6 17 23 39 39 28 15 1 1 0 0 1
0 0 0 2 7 28 37 43 36 22 9 1 0 0 1 0
0 0 1 5 16 27 37 36 28 15 4 1 0 0 0 0
1 1 0 6 14 21 28 18 15 5 1 0 1 1 0 0
0 0 0 3 9 14 17 12 4 1 1 0 0 1 0 0
0 0 0 1 2 4 3 1 1 1 0 1 0 0 0 0
0 0 1 0 1 1 1 1 0 1 1 0 0 0 1 0

```

DELVER= -1.17 DELHOR= -0.43

Redirected Pattern
Sample 1
Height 9 ft Width 8 ft
Time: 9:28 AM EDST

Redirected Pattern
Sample 2
Height 9 ft Width 8 ft
Time: 9:30 AM EDST

----- 0.1 Sun
————— 0.8 Sun
○ 1.7 Sun

MM3P (SN P01) BEAM ON PHOTODETECTOR ARRAY
RANGE: APPROXIMATELY 500 FT DATE: 13 MAY 1976

Figure 22. Mirror Module Focusing Test Data

SECTION IV

STEAM GENERATOR SUBSYSTEM RESEARCH EXPERIMENT

DESCRIPTION OF SUBSYSTEM

The baseline solar steam generator is a pump-assisted recirculating drum boiler with a helical superheater (Figure 23). Key features are:

- Recirculating drum boiler control to follow the sun during daily startup and shutdown.
- Steam generator heat transfer surface forming a cavity with a high effective absorptivity.
- Pump-assisted circulation, allowing the use of smaller boiler tubes than natural circulation, reducing weight, thermal stress, and seismic loads.
- Flexibility of helical superheater minimizing thermal stress during startup and shutdown, reducing thermal fatigue. Helical flow averages out the effect of heat flux maldistribution and lowers maximum operating temperature, which reduces creep fatigue and corrosion.
- Spray attemperator controlling exit steam temperature during cycle variations in insolation, minimizing thermal cycles on the turbine.

OBJECTIVE OF THE EXPERIMENT

The objective of the steam generator SRE is to provide data relating to high-risk technological issues of the pilot plant steam generator. These issues arise from two unique aspects of the solar thermal power concept, and are answered on the design level as described above. The two aspects are:

- The steam generator will be subjected to a very large number of stress cycles during its 30-year design life. In addition to the normal solar diurnal cycle, the energy source will be interrupted by clouds and the necessity to stow the heliostats in high winds.
- The steam generator is located atop a tower where wind and seismic loads can be more severe than at ground level.

The SRE configuration is based upon the design requirement to accommodate the thermal cycle and seismic issues. Limited test operation will not permit extensive verification.

Figure 23. Pilot Plant Steam Generator

While the SRE steam generator has only 1/10th the capacity of the proposed pilot plant version, the test data from the former must be directly applicable to the latter. To accomplish this, two requirements must be met:

- The physical arrangement and flow circuitry of the SRE and pilot plant steam generators must be the same so the same design procedures can be used.
- The SRE and pilot plant boiler and superheater tubes must operate at the same stress levels and temperatures and be subjected to the same thermal cycling since they are the most highly stressed components.

Table 7 compares these features in the SRE and pilot plant steam generators.

Table 7. SRE/Pilot Plant Steam Generator Comparison

Item	Parameter	SRE	Pilot Plant
Physical arrangement	Flow Circuit	Pump-assisted drum boiler	Same
	Cavity: Height/diameter ratio Surface absorbtance Effective absorbtance	1.2 > .8 > .93	0.97
Boiler and superheater tube	Boiler tubes: OD Minimum wall Material Operating pressure Fluid temperature Maximum metal temperature heat flux	2.223 cm 0.376 cm SA-210 grade AICF 123 bars 328°C 382°C	Same
	Superheater tubes: OD Minimum wall Length Material Operating pressure Fluid temperature Maximum metal temperature heat flux	2.54 cm 0.419 cm 38 m SA-213-T-22 109 to 123 bars 328°C to 513°C 588°C	Same
Transient response	Boiler section transit time	Same	
	Superheater transit time	Same	

STATUS OF THE EXPERIMENT

The detailed design for the steam generator and test SRE was presented on 6 May 1976 and approved after further review of the documentation.

Most of the subassemblies have been released to production. Several long-leadtime items, such as control valves, recirculating pump, and attemperator, are not required until on-site erection of the experiment hardware on the test site in the September-December time frame. All other valves are on order, with promised delivery dates that are compatible with the schedule (Figure 24). Fabrication of the solar simulator is about a week behind schedule, which does not constitute a serious problem at this point.

During the next quarter, procurement and fabrication activities will continue, with assembly starting in September.

Figure 24. Steam Generator SRE Schedule

DESCRIPTION OF THE EXPERIMENT

Physical Arrangement

Figure 25 shows the physical arrangement of the SRE steam generator as it will be installed at the test site.

Figure 26 shows the steam generator arrangement at the test site.

Support Structure

The SRE steam generator supports are three box beams. Three support legs flanged to these beams are removed for shipment. (The structure will be fabricated elsewhere and transported to the site by truck.) Appendix B illustrates the erection sequence for the SRE steam generator structure.

The interconnecting piping and headers are located between the structure and heat transfer surface. The boiler and superheater headers are hung from the structure by supports that allow for thermal expansion. The interconnecting pipes do not require support. The downcomer, recirculating line, feedwater line, attemperator feedwater line, and the main steam line are placed adjacent to the supporting box beams.

Flow Circuit

Figure 27 is a flow circuit diagram.

Feedwater from the Northern States Power Plant (test site) system is piped into the steam generator drum at 227°C (440°F). Water flows through a downcomer at about 315°C (600°F) and is pumped through the recirculation line to the boiler section, where steam generation occurs. The saturated steam-water mixture flows through the risers to the steam drum at 328°C (622°F).

Moisture-free steam from the drum flows through the saturated steam lines to the first-stage superheater where it is heated to 476°C (800°F). Steam exiting the first-stage superheater passes through the spray attemperator where additional feedwater (at 227°F) is injected as required to control steam exit temperature.

Under nominal conditions, the attemperated steam enters the second-stage superheater at about 410°C (770°F) where it is heated to 513°C (955°F).

The steam exits through the main steam line and, after pressure reduction to near atmospheric, is discharged to the power plant condenser cooling water circuit.

Figure 25. Arrangement of SRE Steam Generator

Solar Simulator

The solar simulator will provide controlled radiant heat for the steam generator SRE tests.

The solar simulator (Figure 28) has four components: a control console, power controllers, radiant array, and a bottom heat shield for the steam generator. Power to the four controllers is supplied from the substation through forty-eight 500-MCM cables. The power controllers regulate the lamp power input in response to their respective control voltages from the console.

The radiant array is a mounting fixture for 1512 General Electric Q6 MT/3/CL/HT quartz-iodine heat lamps. The lamps are divided into twelve 2.35-m- (92.6-in.) high facets forming a right-circular cylinder whose diameter is 1.4 m (55.1 in.). The facet cylinder is divided into four equal power dissipating zones consisting of six consecutive half-length facets.

Stress Analysis

The SRE steam generator stress analysis was made to verify that the subsystem meets ASME code requirements, and that the pressure components are structurally adequate and properly supported. Tools used in the analysis were:

- Section I code criteria
- Existing fossil power generation design technology

The results for the pressure components and support structure are summarized in Tables 8, 9, and 10.

In summary, it was found that the boiler section has a fatigue life in excess of 10^6 cycles (combined pressure-thermal stresses). A fatigue life of 10^5 cycles is predicted at the inlet of the first-stage superheater. It is expected that the results of the inelastic analysis will show that secondary thermal stresses do not make a significant contribution to creep damage of the tubes.

A finite element model of the support structure was used to analyze stresses from deadweight loads, earthquake loads, and wind loads. Reaction forces and moments transferred to the support structure by the steam generator components at the various support points were placed at the corresponding nodal locations on the finite-element model. The resulting stress state in the structural members was compared with failure criteria of the AISC.

Figure 28. Solar Simulator Configuration

Table 8. Boiler Section Stress Analysis Summary

Source	Failure Mode	Failure Criteria	Criteria Met
Internal pressure	Ductile rupture	Section I	Yes
Internal pressure + deadweight	Ductile rupture	Section III	Yes
Thermal cycling	Fatigue	Section III	Yes

The diagram illustrates the components of a boiler section. On the left, a vertical assembly of membrane panels is shown, with labels for 'MEMBRANE PANEL' and 'BOILER MEMBRANE PANEL'. To the right, a U-shaped header assembly is depicted, with the top part labeled 'OUTLET HEADER' and the bottom part labeled 'INLET HEADER'. Further to the right, a cross-sectional view of the 'BOILER CAVITY' is shown, highlighting the 'MEMBRANE PANELS' that form its walls.

Table 9. Superheater Stress Analysis Summary

Source	Failure Mode	Failure Criteria	Criteria Met
Internal pressure	Ductile rupture and creep rupture	Section I	Yes
Internal pressure + deadweight	Ductile rupture and creep rupture	Code case 1592	Yes
Thermal cycling	Fatigue	Code case 1331	Yes
All sources	Creep-fatigue	Code case 1592	*

The diagram shows a superheater coil, which is a circular structure composed of multiple turns of pipe. The coil is depicted with a perspective view, showing its three-dimensional form and the arrangement of the piping segments.

*Not required for Section I compliance. Complex calculations are beyond program scope.

Table 10. Support Structure Stress Analysis Summary

Load Case	Maximum Stresses, MPa (psi)			
	Normal	Shear	Torsion	Bending
Deadweight	10.3 (1,500)	3.4 (500)	4.8 (700)	46.9 (6,800)
Earthquake*	18.6 (2,700)	12.4 (1800)	6.2 (900)	149.6 (21,700)
Wind**	13.1 (1,900)	16.5 (2400)	11.7 (1700)	136.5 (19,800)
AISC Allowable***	103.5 (15,000)	$\Sigma = 107.6$ (15,600)		161.3 (23,400)

SOURCES CONTRIBUTING TO STRESS

- DEADWEIGHT
- EARTHQUAKE
- WIND

* 0.14-g-level earthquake.

** 193-km/hr (120-mph) wind at 61-m (200-ft) elevation.

*** ASTM A500-72 Grade A. Minimum yield strength of 269 MPa (39,000 psi)

DNB Limit for Boiler Section

Departure from nucleate boiling (DNB) occurs when the heat transfer mechanism in the tube changes from nucleate boiling to film boiling. The resultant increase in tube temperature can cause tube failure. The safe operating conditions are the range of absorbed heat fluxes and quantities below and to the left of the DNB limit for a given set of parameters. Figure 29 shows the DNB limit curve and safety margins under typical SRE steam generator operating conditions.

Figure 29. DNB Limit for SRE Steam Generator Boiler Section

ASSESSMENT OF PROGRESS

The procurement and fabrication of SRE steam generator components and test site preparation have proceeded on schedule. The remainder of the schedule is tight, and any setback or delay could have a significant effect.

Testing planned for the steam generator and results expected are:

- Tests:
 - Pretest checkout
 - Steady-state performance
 - Transient performance
 - Recirculation rate evaluation
 - DNB limit determination
- Results:
 - Heat balance data
 - Transient response data
 - DNB limit definition
 - Optimum recirculation rate

SECTION V

THERMAL STORAGE SUBSYSTEM RESEARCH EXPERIMENT

1

DESCRIPTION OF SUBSYSTEM

The thermal storage subsystem uses an $\text{NaNO}_3/\text{NaOH}$ phase change mixture to store thermal energy. Energy to charge the salt is obtained as heat-of-condensation from steam supplied by the steam generator (receiver) subsystem. The banks of tubes located at the bottom of the storage tank condense the steam. Heat is transferred to the salt by natural convection. The heat energy in the tank is discharged by circulating feedwater through the vaporizer tubes at the top of the tank. The vapor generated is collected in a steam drum where saturated steam is withdrawn on demand by the turbine. The superheater provides 50°F rise in temperature above saturation to meet turbine admission requirements. Material buildup on the tubes caused by the solidifying salt is removed mechanically.

Figure 30 shows the thermal storage arrangement for the pilot plant. Figure 31 is a flow diagram for the subsystem.

OBJECTIVE OF THE EXPERIMENT

The thermal storage SRE is designed to give maximum information relative to the design, performance, and operating parameters of the proposed pilot plant configuration. Pilot plant and SRE parameters are compared in Table 11.

STATUS OF THE EXPERIMENT

The detailed design for the thermal storage SRE was presented on 22 June 1976 and tentatively approved pending formal review of the documentation.

Vendors have been selected for the steam drum, traps, and desuperheater. The condenser and vaporizer units have been detailed for procurement and offered for bids. Details of the control modes and logic have been completed, including ample provision for operator warning and safety. A design freeze was imposed on thermal storage/test interfaces on 18 June.

The schedule for the remainder of the SRE effort is shown in Figure 32. Like the schedule for the steam generator, it is tight.

Figure 30. Pilot Plant Arrangement - Thermal Storage

Figure 31. Thermal Storage Subsystem Flow Diagram

Table 11. Pilot Plant/SRE Thermal Storage Requirements

	Pilot Plant	SRE
Design	<ul style="list-style-type: none"> • 315 MWhr(t) main storage capacity • Salt PCM - NaNO_3 - NaOH • 235 modular exchangers housed in 5 cylindrical storage tanks • Self-regulating control system • Ground-level storage 	<ul style="list-style-type: none"> • 1.34 MWhr(t) storage capacity • Same salt PCM - NaNO_3 - NaOH • Single PP modular exchanger in a rectangular tank • Same control system • Above-ground storage with insulation/variable heat loss control system
Performance	<ul style="list-style-type: none"> • Deliver 7 MW(e) net or 31.58 MW(t) discharge rate - 6 hours • 6.5 MPa/307°C discharge cycle • 12 MPa/510°C charge cycle • 31.58 MW(t) charge rate • Heat loss < 0.35%/hr 	<ul style="list-style-type: none"> • 134 kW(t) discharge rate - 6 hours • Same discharge cycle • Same charge cycle • 134 kW(t) charge rate - 6 hours • Variable heat loss

Figure 32. Thermal Storage SRE Preparation and Test Schedule

DESCRIPTION OF THE EXPERIMENT

Thermal Storage Unit

The detailed thermal storage unit is essentially as described in the second Quarterly Technical Report. It is a full-size heat exchange module. The cube-shaped tank (Figure 33) is 2.53 m high by 2.56 m wide and long (8.3 x 8.4 x 8.4 ft). It will hold 27,915 kg (61,540 lb) of molten salt, sufficient to provide 1.34 MWh(t) of latent heat of fusion.

The tank will be made of mild steel, Type A285, Grade B, because the salts appear not to attack it (corrosion less than 0.02 mm/yr). It is also weldable and available in a wide variety of shapes.

Phase Change Material

The phase change material selected, NaNO_3 and NaOH in a 99/1 percent by weight mixture, meets the requirement that the salt composition form a slurry during the freezing process. This is illustrated in Figure 34, which shows that the composition of the liquid changes as the NaNO_3 solidifies, and that the solidus temperature is well below the steam boiling temperature. The crystallizing material is always in equilibrium with the surrounding liquid and a slurry is maintained.

The relationship of phase change material composition to vaporizer scraper torque is illustrated in Figure 35. The calcium and potassium nitrates were less effective than the sodium nitrate because they formed solid solutions with the ternary eutectic. The vaporizer ΔT is the temperature drop from the bulk salt melt to the outside tube wall temperature.

Design limits of the external scraper latent heat salt storage system based on the $\text{NaNO}_3/\text{NaOH}$ composition are summarized in Table 12. The first two limits have been observed in the engineering model. The third is an extrapolated value.

Specific Test Goals

The thermal storage SRE is designed to collect quantitative engineering data adequate to specify the thermal storage subsystem for the pilot plant. Specific test goals are those shown in Figure 36. The tests will be carried out according to the schedule in Figure 37.

Figure 33. Thermal Storage Tank

Figure 34. NaNO₃ - NaOH Phase Diagram

Figure 35. Vaporizer Scraper Stall Torque as a Function of Composition

Table 12. Design Limits Based on $\text{NaNO}_3/\text{NaOH}$ Phase Change Material

Experimental Result	Physical Hypothesis	Resulting Numerical Design Limits	Controlling Physical Parameters
Quick, hard freeze-up ①	Tube wall temperature below solidus temperature	Tube wall temperature $> 246^\circ\text{C}$ (475°F)	Vaporizer pressure
Low-energy recovery; uniform thick layer on tank top ②	Particles cannot settle out fast enough	Top tank heat flux limited to $\sim 20 \text{ kW/m}^2$ (6500 Btu/hr-ft^2)	Top tank tube spacing
Low-energy recovery; thick fluid cylinder trapped around scraper ③	Very high pipe heat flux too large for particle removal	Pipe heat flux $> 50 \text{ kW/m}^2$ ($> 15,000 \text{ Btu/hr-ft}^2$)	Boiler pressure

Figure 36. Thermal Storage Test Goals

Figure 37. Thermal Storage Test Schedule

The data obtained will be presented graphically when possible. Graphic presentations will include:

1) Vaporizer data plots:

- a) Heat flux versus saturation pressure
- b) Heat flux versus scraper speed
- c) Heat flux versus percent discharge
- d) Heat flux versus exit quality
- e) Heat flux versus entrance temperature
- f) Scraper torque versus heat flux
- g) Scraper torque versus speed
- h) Scraper torque versus percent discharge
- i) Maximum percent discharge versus discharge rate
- j) Scraper power versus heat flux
- k) Pressure drop versus recirculation rate
- l) Heat rate versus recirculation rate

2) Condenser data plots:

- a) Heat flux versus saturation pressure
- b) Heat flux versus percent charge
- c) Heat flux versus type of steam trap
- d) Heat flux versus salt freezing history
- e) Heat flux versus percent charge while discharging
- f) Heat flux versus percent charge after extended settling time
- g) Condenser effectiveness versus distance along condenser

3) Salt temperature movement data:

a) Discharge:

- i) Temperature profiles versus time during discharge
- ii) Temperature profiles versus time after a complete discharge
- iii) Temperature profiles versus time after a partial discharge

b) Charging:

- i) Temperature profile versus time while charging immediately following a full discharge
- ii) Temperature profiles versus time while charging after an extended settling time
- iii) Temperature profiles versus time for various charging rates

c) Charging while discharging:

- i) Temperature profiles for charge while discharge as a function of charge rate
- ii) Temperature profile for charge while discharge as a function of percent charged.

Figure 38 illustrates the types of graphic information expected. Scales were left off to avoid the appearance of anticipating actual results.

Since the data obtained will be crucial to the pilot plant design, an instrumentation error analysis was made to ensure that the values obtained will afford the necessary degrees of accuracy. The analysis is presented in Appendix C.

ASSESSMENT OF PROGRESS

Substantial progress was made during the report period. The thermal storage conceptual design was completed and detailed, and the hardware procurement effort was accelerated. This is especially significant because the thermal storage subsystem concept has less basis in conventional usages and precedents than the other subsystems. Over 30 separate heat exchange tests were conducted on the engineering model. Each test required 2 to 6 hours of test time. The results confirm the validity of the concept and ensure achievement of the expected SRE performance.

Figure 38. Types of Test Results Expected
(Sheet 1 of 3)

Figure 38. Types of Test Results Expected
(Sheet 2 of 3)

Figure 38. Types of Test Results Expected
(Sheet 3 of 3)

SECTION VI

ELECTRICAL GENERATION AND PLANT INTEGRATION

ELECTRICAL GENERATION SUBSYSTEM

The electrical generation subsystem is being designed to generate electrical power using a water/steam cycle with the thermal energy being supplied by solar radiation, either directly through the receiver or indirectly through the thermal storage subsystem. The operating modes are listed in Table 13.

Table 13. Solar Power Plant Steady-State Operating Modes

Subsystem	Steady-State Mode					
	A	B	C	D	E	F
Receiver	On	On	On	Off	On	Off
Turbine	On (Receiver steam)	On (Receiver steam)	On (Receiver and storage steam)	On (Storage steam)	Off Off	Off Off
Storage	Holding	Charging	Discharging	Discharging	Charging	Holding

Work being done under this heading includes:

- Performance requirements and operational analysis
- Mechanical design
- Electrical design
- Structural design
- Control and instrumentation
- Plant and support services

Items addressed primarily during this report period were performance requirements and operational analysis, structural design, and control and instrumentation.

Early in the period, an outline control philosophy document was completed and problem areas were identified. A computer program was developed to determine the air-cooled condenser size and performance tradeoffs, and tower and base foundation parameters were determined.

PREPARATION FOR SRE TESTS

A substantial effort was directed to supporting the SRE steam generator and thermal storage test preparations. This consisted of identifying necessary modifications to the NSP Riverside Plant (test site) facilities and ensuring that the subsystem interfaces with the facilities are compatible. Meetings were held in April to resolve interface requirement questions and in June to check and freeze the plant modification design.

SECTION VII

PROGRAM DOCUMENTATION

In addition to this report, the Solar Pilot Plant Program was documented by the following CDRL items during the second quarter of 1976:

- Steam Generator SRE Detailed Design Report, 6 May --
CDRL Item 7
- Collector SRE Detailed Design Report, 18 May --
CDRL Item 6
- Thermal Storage SRE Conceptual Design Report (Approved),
17 May -- CDRL Item 5
- Thermal Storage SRE Detailed Design Report, 22 June --
CDRL Item 8

The steam generator and collector DDRs are being amended preparatory to final distribution.

The next Quarterly Technical Report, covering the third quarter of 1976 and summarizing the first year of the program will be issued on 15 November.

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APPENDIX A

METEOROLOGICAL DATA MEASURING CAPABILITY,
COLLECTOR SRE

- **Wind Speed:**

Range: 0 to 44.7 m/sec (0 to 100 mph)

or

0 to 22.35 m/sec (0 to 50 mph)

Accuracy: System ± 0.5 mph or 2 percent

Distance constant: 2.44 m max. (8 ft)

- **Wind Direction:**

Range: 0 to 540 deg

Accuracy: ± 2 percent system

Distance constant: 2.44 m max. (8 ft)

Damping ratio: 0.4 to 0.6

- Temperature No. 1 - Ambient:

Range: -34 to +50°C

Accuracy: $\pm 0.2^{\circ}\text{C}$

Linearity: $\pm 0.2^{\circ}\text{C}$

● Temperature No. 2 - Structure:

Range: 0 to 100°C

Accuracy: $\pm 0.2^{\circ}\text{C}$

Linearity: $\pm 0.2^{\circ}\text{C}$

● Temperature No. 3 - Structure:

Range: 0 to 100°C

Accuracy: $\pm 0.2^{\circ}\text{C}$

Linearity: $\pm 0.2^{\circ}\text{C}$

- Temperature No. 4 - Differential Structure:

Range: $\pm 10^{\circ}\text{C}$ from temperature probe No. 3

Accuracy: ± 5 percent of Δt

- Solar Radiation:

Sensor type: Eppley Normal Incidence Pyroheliometer

Field of view: $5^{\circ}43'30''$

Sensitivity: 8 mV/W-m^2 approx.

Temperature: ± 1 percent over ambient temperature range
 -20 to $+40^{\circ}\text{C}$ dependence

Linearity: ± 0.5 percent from 0 to 2800 W-m^2

Response time: 1 sec (1/e signal)

- Barometric Pressure:

Range: 9.14 to 1066 mb

Linearity: ± 0.3 percent

Sensitivity: 0.2 percent

Hysteresis: With 0.2 percent

Repeatability: Within 0.2 percent

Operating temperature range: -340°C to 82°C

Temperature error: ± 0.0045 percent/ $^{\circ}\text{C}$ max.

The pyroheliometer is installed on an equatorial mount to track the sun. Data from the weather station are transmitted to the processor via a Frequency Shift Keying (FSK) modem and are stored on magnetic tape.

The research experiment weather station test setup is shown in Figure A-1.

Figure A-2 defines the actual signal interconnects within the experimental setup.

Figure A-1. Research Equipment Weather Station Test Setup

Figure A-2. Experimental Test Program -- Environmental Sensor Interfaces

APPENDIX B
STEAM GENERATOR SRE ERECTION PROCEDURE

<u>Step No.</u>	<u>Description</u>
1.	Bolt the three leg subassemblies of support structure to basement floor. The bolting pattern for this subassembly is the same as leg bolt pattern. Subassemblies to be held vertical using temporary supports. (Figure B-1)
2.	Bolt drum support structure in place and align subassemblies prior to Step 3. (Figure B-2)
3.	Tack weld tie support members in place and recheck alignment. Apply final structural weld to tie support members. (Figure B-3)
4.	Unbolt the three leg subassemblies from floor mounting and raise assembled structure enough to move entire assembly to south end of turbine pit opening (temporary position). Raise each support leg and bolt same to basement floor. When all three legs are set, raise assembled structure and set on legs and secure bolted flange at 16-ft elevation. (Figure B-4)
5.	Unbolt and remove drum support structure and lower the boiler section to temporary position on timber blocking on basement floor. (Figure B-5)
6.	Lay timber blocking on top of boiler section and individually lower superheater sections -- first and second to temporary position. (Figure B-6)
7.	Install ceiling support and drum support structure. (Figure B-7)
8.	Raise second-stage superheater into position and hang from lugs provided on ceiling support structure. (Figure B-8)
9.	Install hanger brackets for first-stage superheater and raise superheater section. Install hangers. (Figure B-9)
10.	Install hanger brackets for boiler section and raise boiler section. Install hangers. (Figure B-9)
11.	Install steam drum on drum support structure. (Figure B-10)
12.	Install roof segment insulated panels and bolt in place. (Figure B-10)

<u>Step No.</u>	<u>Description</u>
13.	Field weld risers, saturated steam lines, downcomer, main steam line, feedwater line, and recirculation lines and attemperator. (Figure B-10)
14.	Set recirculating pump and couple to supply and discharge lines.
15.	Make electrical, instrumentation, and miscellaneous piping connections as required.

Figure B-1. Step 1 - Bolt Subassembly
to Floor

Figure B-2. Step 2 - Bolt Drum Support Structure
in Place

Figure B-3. Step 3 - Weld Tie Support Members in Place

Figure B-4. Step 4 - Raise Structure and Install Logs

Figure B-5. Step 5 - Remove Dram Support Structure,
Lower Boiler Section to Temporary Position

Figure B-6. Step 6 - Individually Lower Superheater Sections to Temporary Position

Figure B-7. Step 7 - Install Ceiling Support and Drum Support Structure

Figure B-8. Step 8 - Raise Second-Stage Superheater into Position and Install Brackets and Hangars

Figure B-9. Steps 9 and 10 - Raise First-Stage Superheater and Boiler Section into Position and Install Brackets and Hangars

Figure B-10. Steps 11, 12 and 13 - Install Drum, Attenuator, and Piping

APPENDIX C

INSTRUMENTATION ERROR ANALYSIS

Preliminary calculations have been made which demonstrate that the SRE/TS instrumentation will permit an accurate heat balance to be made.

To perform heat flow and heat storage calculations, four types of information must be known: pressure, temperature, mass flow rate, and quality. The heat is all transported, neglecting heat loss terms, across system boundaries by water or steam flow: thus, steady-state energy balances are made by summing fluid enthalpy fluxes.

Measurement error analysis starts with consideration of the inaccuracies in the primary sensors. Table C-1 lists the basic instrument types and their accuracies. In most cases, the data acquisition system contributes as much to the overall error in a reading as does the basic sensor.

Table C-1. Discharge Steam Enthalpy Summary

Instrument	Range	Output Signal	Error
Pressure transducer	0 to 1500 psi	4 to 20 mA	Max. $\pm 0.2\%$ of span Typical $\pm 0.1\%$ of span
Pressure transducer	P > 1500	4 to 20 mA	Max. $\pm 0.5\%$ of span Typical $\pm 0.35\%$ of span
Differential pressure	---	4 to 20 mA	Max. $\pm 0.35\%$ of span Typical 0.25% of span
Venturi tubes	---	---	$\pm 0.5\%$ of full scale
Thermocouples ANSI Type K premium grade	0 to 2300°F	mV	$\pm 0.38\%$ of reading
Data acquisition system, HP-9611	± 10 mV	---	$\pm 0.33\%$ of full scale
	± 20 mV	---	$\pm 0.28\%$ of full scale
	± 20 mA	---	$\pm 0.39\%$ of full scale

Steam quality will not be measured in this experiment, but will be calculated where necessary. The steam drum supplier guarantees a discharge steam quality of better than 99.5 percent, which is greater than can be measured with most instruments. The vaporizer discharge line steam quality can be calculated by performing an energy balance around the steam drum.

In mass flow measurements, three errors must be included in the measurement error: calibration error of the venturi, pressure transducer error, and data acquisition system error. Determination of the fluid density error should also be included, particularly where vapor flow is being measured. To get a better view of the effect the total instrumentation error has on enthalpy determination, four design-state points were chosen and the error envelopes plotted on steam charts.

The steam charts plot lines of constant pressure and constant temperature as functions of specific volume and enthalpy. Figure C-1 shows the region of uncertainty in enthalpy determination for the feedwater at the design point. For the feedwater, the temperature measurement uncertainty accounts for most of the uncertainty in enthalpy, because enthalpy is not a strong function of pressure for a liquid.

Figure C-1. Feedwater Enthalpy Determination

Figure C-2 shows the discharge steam enthalpy determination around the design point. To better show the small region interest, an enlargement was made (Figure C-3). Because the lines of constant pressure and temperature intersect at oblique angles, it would not be intuitively obvious without the diagram which points constitute the extreme maximum and minimum values of uncertainty in enthalpy determination. This particular point is interesting in that three properties are required to define the enthalpy range. Figure C-4 shows the design-point conditions for the condenser inlet. Due to the inherent requirement for a few degrees of superheat in the desuperheater discharge, the saturation vapor line is used as the lower limit for the enthalpy range.

Figure C-2. Discharge Steam Enthalpy Determination

Figure C-3. Discharge Steam Enthalpy Determination

Figure C-4. Condenser Inlet Enthalpy Determination

The condenser outlet enthalpy range is shown in Figure C-5. If the steam traps are working properly, the discharge condensate should be very nearly all saturated water, with little live steam lost. The fluid is compressed liquid; like the feedwater, its enthalpy is largely a function of temperature, with little dependence upon pressure.

Table C-2 summarizes the graphical results. To calculate an enthalpy flux, the enthalpy of each fluid stream must be multiplied by the fluid flow rate which has its own error in measurement. The errors in flow measurement add to the errors in enthalpy determination to give the maximum range of error in enthalpy flux or heat flux determination.

Table C-3 gives the range of errors that the heat flux determination may take on when operating at the design conditions. The lower block lists the largest error that is expected in determination of energy flux to or from storage. These error intervals represent the sum of errors resulting from several independent measurements of pressure temperature and flow rate. It is highly unlikely that all of the errors will add in the same direction to produce the maximum errors calculated in Table C-3.

Figure C-5. Condenser Outlet Enthalpy Determination

Table C-2. Enthalpy Determination

System Location	Design Conditions	Enthalpy	Indeterminant Range
Discharge steam	6.48 MPa/281°C (940 psia/537°F)	2779.1 kJ/kg (1194.8 Btu/lb)	2773 to 2796 kJ/kg (1192 to 1202 Btu/lb)
Feedwater	10.0 MPa/204°C (1450 psia/400°F)	876 kJ/kg (376.5 Btu/lb)	869 to 883 kJ/kg (373.5 to 379.7 Btu/lb)
Condenser inlet	12.32 MPa/326.7°C (1787 psia/620°F)	2682 kJ/kg (1153.2 Btu/lb)	2681 to 2697 kJ/kg (1152.5 to 1159.5 Btu/lb)
Condensate outlet	12.14 MPa/325.5°C (1760 psia/617.9°F)	1497 kJ/kg (643.7 Btu/lb)	1483 to 1500 kJ/kg (637.0 to 646.0 Btu/lb)
Vaporizer inlet	6.86 MPa/284.4°C (995 psia/502.4°F)	1141.6 kJ/kg (490.8 Btu/lb)	1132.5 to 1150.7 kJ/kg (486.9 to 494.7 Btu/lb)
Vaporizer outlet	6.53 MPa/281°C (946.9 psia/538°F)	Calculated from energy balance	---

Table C-3. Enthalpy Changes Across the Thermal Storage System

System	Nominal H	Min. H	Max. H	Percentage Error
Vaporizer	1903 kJ/kg (818.3 Btu/lb)	1889 kJ/kg (812.3 Btu/lb)	1927 kJ/kg (828.5 Btu/lb)	-0.7% to +1.2%
Condenser	1185 kJ/kg (509.5 Btu/lb)	1180.4 kJ/kg (507.5 Btu/lb)	1214 kJ/kg (521.9 Btu/lb)	-0.4% to +2.4%
Mass flow rate:				
<ul style="list-style-type: none"> Discharge steam: 272 ± 5.6 kg/hr = ±2.1% 600 ± 12.3 lb/hr Condensate: 412 ± 7.3 kg/hr = ±1.8% 908 ± 16 lb/hr 				
Total heat flux determination error:				
<ul style="list-style-type: none"> Vaporizer: -2.8% to +3.3% Condenser: -2.2% to +4.2% 				