CONTRACTOR REPORT

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Molten Salt Steam Generator Subsystem Research Experiment

Foster Wheeler

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MOLTEN SALT STEAM GENERATOR SUBSYSTEM RESEARCH EXPERIMENT - EXECUTIVE SUMMARY

PHASE 1 - FINAL REPORT

Sandia Contract 20-9909B

Prepared for

Sandia National Laboratories
Livermore, California

September 1982

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Abstract

This is the Executive Summary of a study conducted for Phase 1 of a two-phase project whose objectives were to develop a reliable, cost-effective molten salt steam generating subsystem for solar thermal plants, minimize uncertainty in capital, operating, and maintenance costs, and demonstrate the ability of molten salt to generate high-pressure, high-temperature steam. The Phase 1 study involved the conceptual design of molten salt steam generating subsystems for a nominal 100-MWe net stand-alone solar central receiver electric generating plant, and a nominal 100-MWe net hybrid fossil-fueled electric power generating plant that is 50 percent repowered by a solar central receiver system. As part of Phase 1, a proposal was prepared for Phase 2, which involves the design, construction, testing and evaluation of a Subsystem Research Experiment of sufficient size to ensure successful operation of the full-size subsystem designed in Phase 1.

Evaluation of several concepts resulted in the selection of a four-component (preheater, evaporator, superheater, reheater), natural circulation, vertically oriented, shell and tube (straight) heat exchanger arrangement. Thermal hydraulic analysis of the system included full and part load performance, circulation requirements, stability, and critical heat flux analysis. Flow-induced tube vibration, tube buckling, fatigue evaluation of tubesheet junctions, steady-state tubesheet analysis, and a simplified transient analysis were included in the structural analysis of the system. Operating modes and system dynamic response to load changes were identified. Auxiliary equipment, fabrication, erection, and maintenance requirements were also defined. Installed capital costs and a project schedule were prepared for each design. The complete Phase 1 final report has been published as SAND82-8179.

Section 1

EXECUTIVE SUMMARY

1.1 STUDY OBJECTIVES

The study conducted by the Foster Wheeler Solar Development Corporation (FWSDC) is Phase 1 of a two-phase project whose objectives are:

- Develop a reliable, cost-effective molten salt steam generating subsystem for solar thermal plants
- Minimize uncertainty in steam generator subsystem capital, operating, and maintenance costs
- Demonstrate the ability of molten salt to generate high-pressure, high-temperature steam.

The Phase 1 study involved the conceptual design of molten salt steam generating subsystems for a nominal 100-MWe net solar central receiving electric generating plant (100-MWe solar stand-alone) and a nominal 100-MWe net fossil-fueled electric power generating plant that is 50 percent repowered by a solar central receiver system (50-MWe hybrid). As part of Phase 1, a proposal was prepared for Phase 2, which will involve the design, construction, testing and evaluation of a Subsystem Research Experiment (SRE) of sufficient size to ensure successful operation of the full-size subsystem designed in Phase 1.

1.2 TECHNICAL APPROACH

To achieve the aforementioned objectives, the Phase 1 study was divided into the following tasks:

Task	Description
1	Review of SGS Definition and Interface Requirements
2	Definition of SGS Requirements
3	SGS Concept Selection
4	SGS Design
5	SGS Cost and Fabrication/Erection Plan
6	SGS SRE and Development Plan
7	Phase 2 Plan and Proposal
8	Project Management

In general, work on each task proceeded in sequential order, except for Task 8, which extended over the entire 10-month project schedule. Because of SNLL's request for submittal of the Phase 2 proposal 1 month ahead of schedule, we based the proposal solely on the 100-MWe solar stand-alone SGS. The 50-MWe hybrid SGS design was completed after the Phase 2 proposal was submitted.

1.3 PROJECT TEAM

The Phase 1 project team consisted of the following companies:

Prime Contractor:	Scope of Work:
Foster Wheeler Solar Development Corporation	Project coordination, concept selection, preliminary thermal design, dynamic modeling, structural analyses, modes of operation
Subcontractors:	
FW Energy Applications, Inc.	Thermal/hydraulic design and analysis, mechanical design
Foster Wheeler Energy Corporation	Fabrication requirements, heat exchanger cost estimate
Foster Wheeler Special Projects Engineering and Construction, Inc.	Maintenance requirements, SRE installation
Gibbs and Hill, Inc.	SGS auxiliary equipment and support structure design and cost estimate, SGS interface requirements, SRE layout
Utility Advisors:	
Arizona Public Service company	Review of subsystem-level requirements
Sierra Pacific Power Company	Review of subsystem-level requirements

1.4 SUMMARY OF RESULTS

1.4.1 Requirements and Specifications

The nominal interface requirements for a 100-MWe solar stand-alone SGS and a 50-MWe hybrid SGS identified by SNLL were refined and used as the basis for preparation of an SGS Requirements and Specification document. The document was written to be site-independent to the greatest extent possible. However, to quantify site-dependent design parameters, we selected Yerington, Nevada, as the location.

The stand-alone and hybrid SGS's were designed to generate main and reheat steam for a nominal 100-MWe net steam turbine-generator. For the purpose of defining SGS performance requirements over the operating load range, the Sierra Pacific Power Company Fort Churchill Unit 1 turbine-generator was selected. The turbine "valves wide open" (VWO) steam flow requirements that each SGS design must satisfy are as follows:

	100-MWe Solar Stand-Alone, kg/s (lb/h)	50-MWe Hybrid kg/s (lb/h)
Superheated steam [541°C (1005°F) and 13.48 MPa gage (1955 lb/in²g)]	96.1 (762,900)	48.1 (381,400)
Reheat steam [541°C (1005°F) and 2.86 MPa gage (415 lb/in²g)]	83.2 (660,300)	41.6 (330,150)

The heat source for the SGS is hot, molten salt stored in a thermal storage tank at 566°C (1050°F). To compensate for heat losses in the salt piping between thermal storage and the SGS, and to provide a design margin, an inlet salt temperature of 563°C (1045°F) was selected. A salt exit temperature of 293°C (560°F) was selected to provide a reasonable pinch-point temperature difference [7.3°C (13.1°F)].

1.4.2 Concept Selection

We identified 29 selection criteria for evaluation of candidate SGS concepts. Combinations of the following parameters were considered:

Surface Arrangements:

- Straight Tube
- Hockey Stick
- Helical Coil
- Bayonet Tube
- Involute Tube (serpentine)
- U-Tube (common tubesheet)
- U-Tube (U-shaped shell)
- U-Tube (involute)

Circulation Methods:

- Benson Once-Through
- Sulzer Once-Through
- Natural Circulation
- Forced recirculation

Orientation:

- Horizontal
- Vertical

Qualitative and preliminary quantitative evaluation of the candidate configurations resulted in selection of a four-component (preheater, evaporator, superheater, and reheater) straight-tube, vertical, natural-circulation arrangement as the concept that best satisfies the selection criteria.

Based on a review of available molten salt corrosion data, the following materials were selected for component fabrication:

Component	Material
Preheater	Carbon Steel
Evaporator	1-1/4%Cr-1/2%Mo
Superheater	Type 304 Stainless Steel
Reheater	Type 304 Stainless Steel

1.4.3 SGS Design

The physical arrangement of the 100-MWe solar stand-alone SGS and 50-MWe hybrid SGS are essentially the same except for the variations in size resulting from the difference in thermal rating. The equipment arrangement for the 100-MWe solar stand-alone SGS is illustrated in Figure 1.1. The process flow diagrams for the 100-MWe solar stand-alone SGS and the 50-MWe hybrid SGS are shown in Figures 1.2 and 1.3.

Hot molten salt entering the system at 563°C (1045°F) flows in parallel through the superheater and reheater, combines, and passes in series through the evaporator and preheater; cold salt leaves the preheater at approximately 293°C (560°F). All heat exchangers are oriented vertically with all heated steam/water flowing upward. The preheater, superheater, and reheater are counterflow; the evaporator is parallel flow to improve natural circulation. An integral vertical steam drum is mounted atop the evaporator. A drum water recirculation pump is provided to maintain the feedwater at a temperature above the salt freezing point [221°C (430°F)] during start-up and part-load operation.

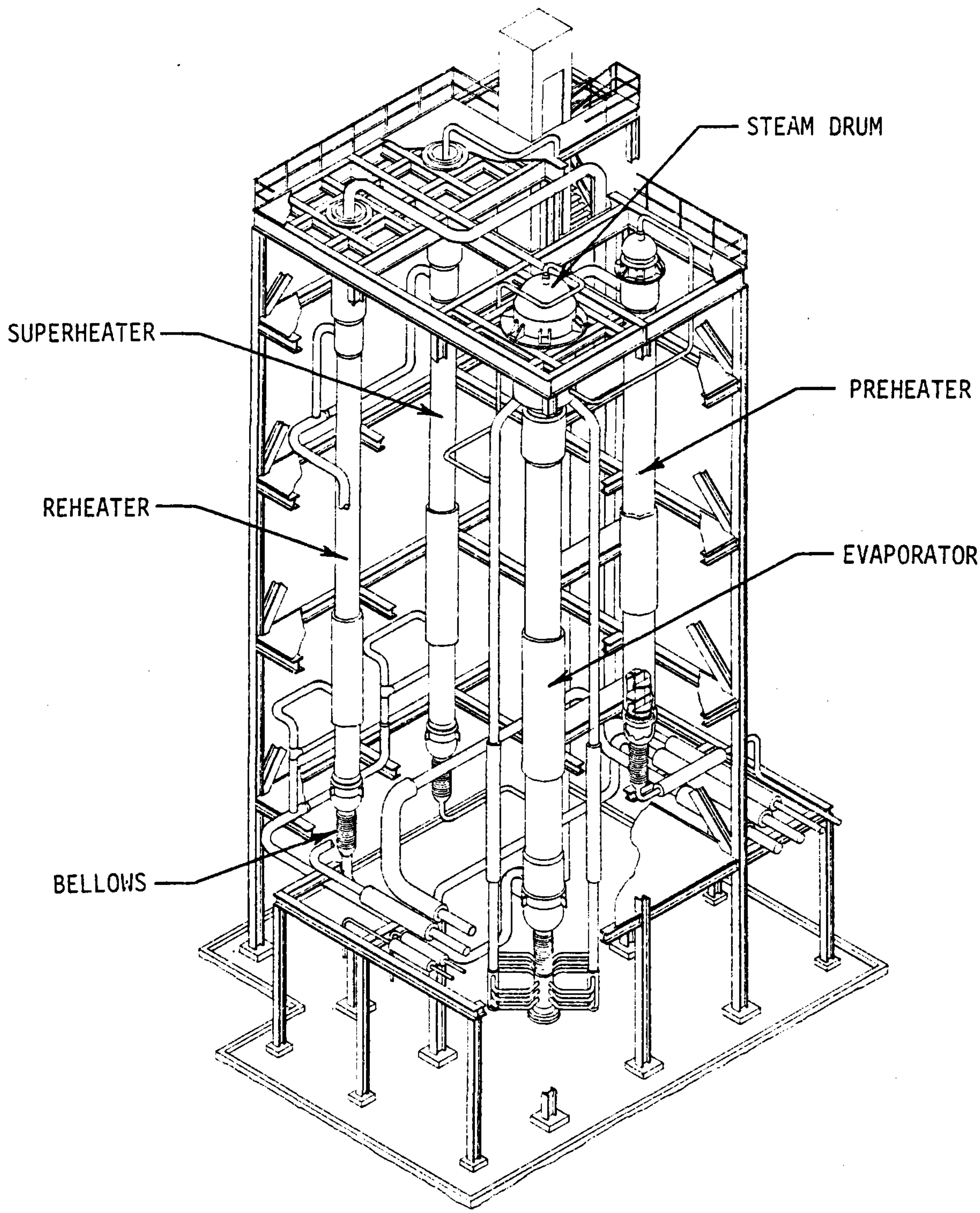


Figure 1.1 SGS Isometric View--100-MWe Solar Stand-Alone SGS

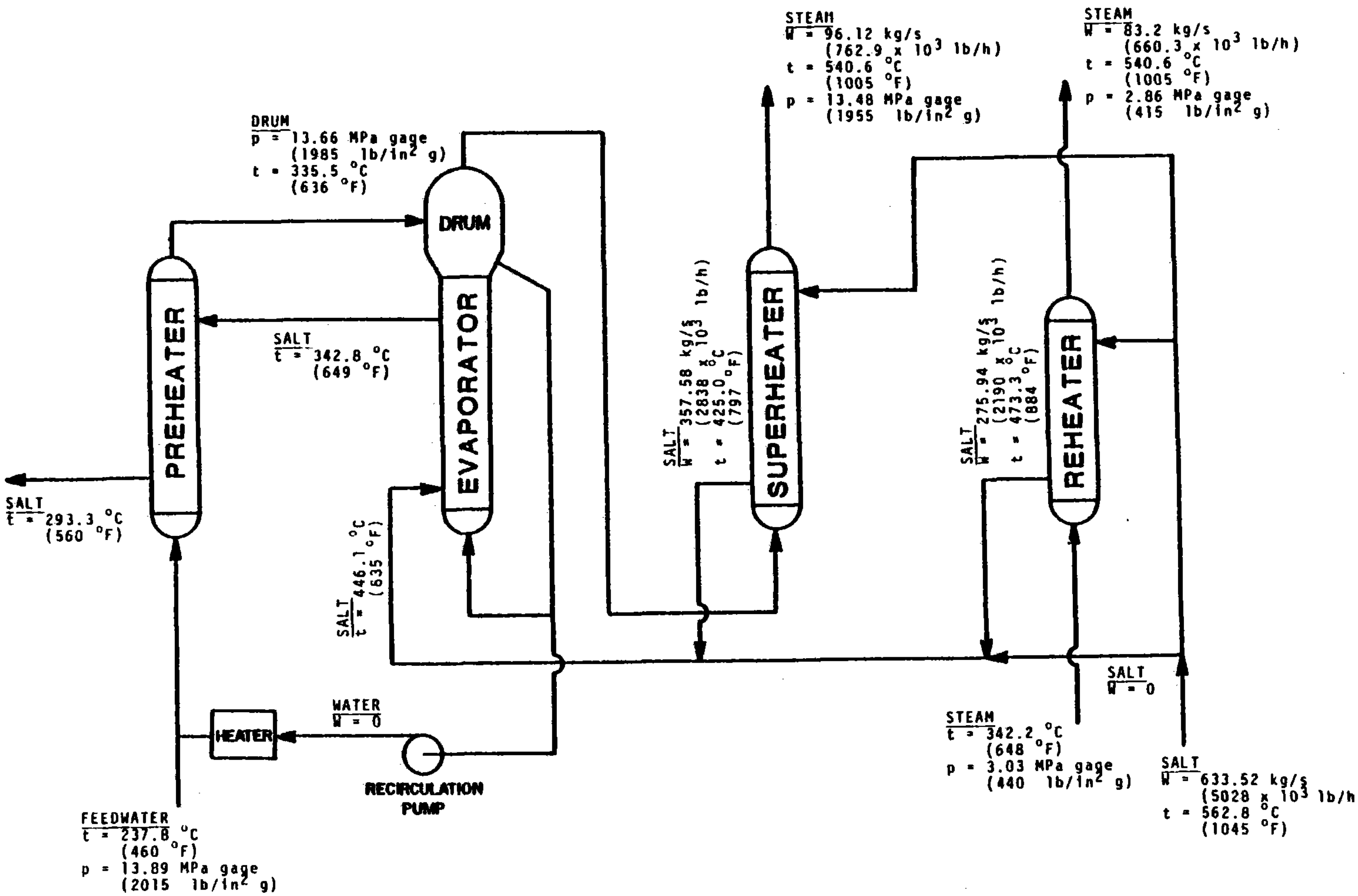


Figure 1.2 Process Flow Diagram--100-MWe Solar Stand-Alone SGS

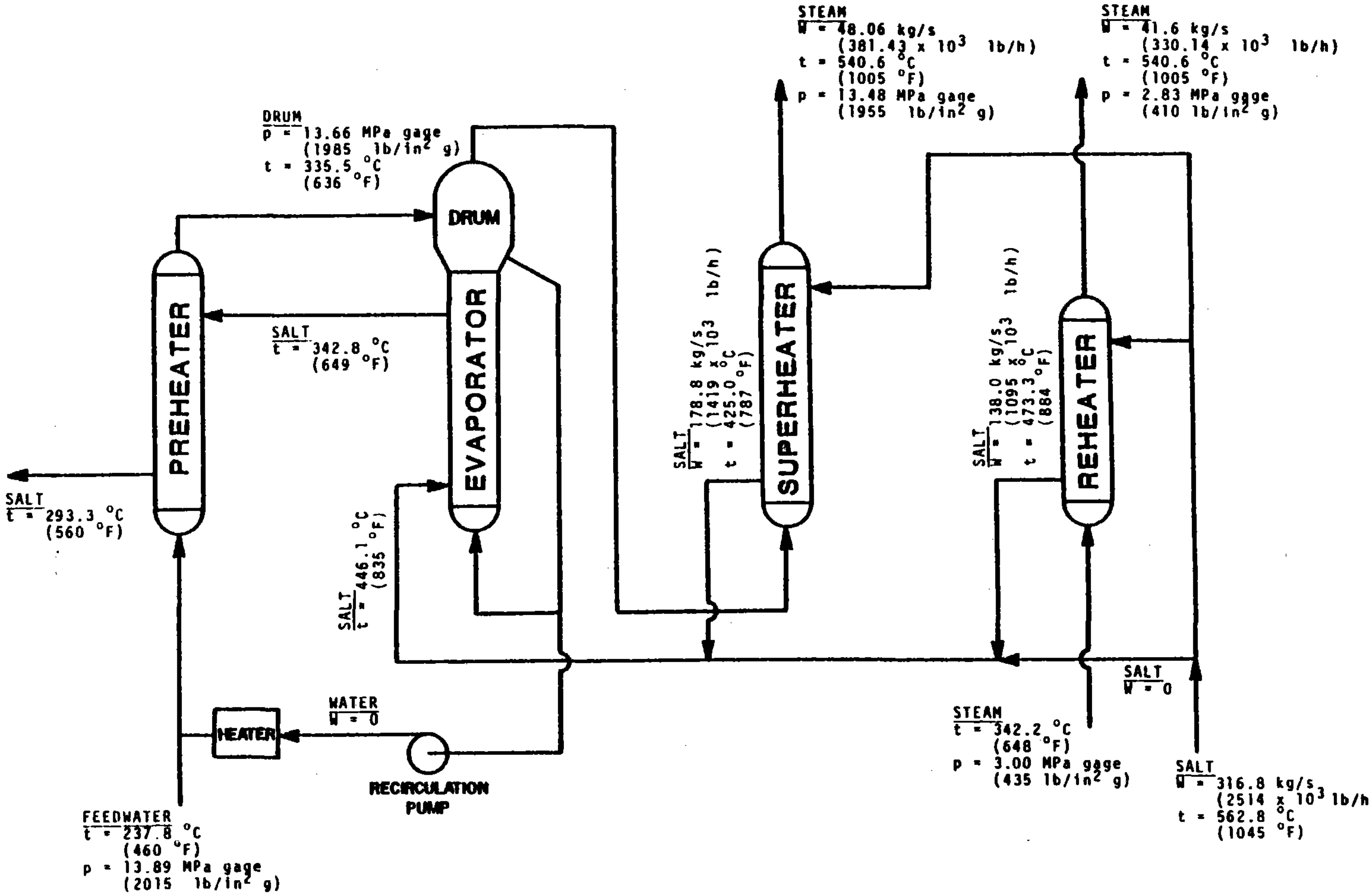


Figure 1.3 Process Flow Diagram--50-MWe Hybrid SGS

A cold salt recirculation pump is also provided to control the salt temperature entering the subsystem during unit start-up and shutdown.

Final main steam temperature is controlled by a valve at the superheater outlet which controls the salt flow rate through the superheater. Saturated steam from the steam drum is bypassed to the superheater outlet for emergency control. Reheat steam temperature is controlled by a valve at the reheater outlet which controls the salt flow rate through the reheater. A spray attemperator is located at the reheater steam inlet for emergency control. The quantity of steam generated is determined by the salt flow rate and temperature entering the evaporator. A salt line which bypasses hot salt around the superheater and reheater to the evaporator is used for this purpose.

The heat exchangers are single pass shell-and-tube exchangers, each with a floating head and double segmental baffles. The 100-MWe units have bellows welded to the lower shell head and the steam/water inlet nozzle which permits differential expansion between the tube bundle and shell. The smaller diameter 50-MWe preheater, superheater, and reheater have the bellows designed in the exchanger shell. The 50-MWe evaporator is similar to the 100-MWe design. The evaporator on both units have a pair of external downcomer pipes and flexible feeders which direct water from the steam drum to the evaporator inlet. The loops in the feeder pipes permit differential growth between the downcomers and the evaporator.

A shroud at the salt inlet to each unit surrounds the tube bundle. The slots in the shroud uniformly distribute salt over the tube bundle. Tie-rods attached to the upper tubesheet support the double segmental baffles, which function as tube-support plates to suppress fibration and buckling. Heat-transfer tubes are welded to the face of each tubesheet using a fillet-type welding technique. Each unit is vertically hung from either a support skirt (superheater, reheater) or lugs (on preheater upper tubesheet; on evaporator, drum shell).

The vertical steam drum, which is designed as an integral part of the evaporator, is equipped with spiral arm separators and box type chevron driers to provide dry saturated steam. Feedwater enters the steam drum through a circular distribution pipe positioned below the drum water level. A blowdown line is provided to control impurity concentration levels in the evaporator water.

Electric trace heaters are provided on the heat exchanger shells as well as on all interconnecting salt piping. The trace heaters are sized to preheat and maintain the salt piping and heat exchanger shells at approximately 288°C (550°F). The heat exchangers and all interconnecting piping are insulated with calcium silicate and covered with aluminum lagging.

Safety valves are located on the steam drum, superheater outlet, reheater inlet, reheater outlet, and preheater outlet. Pressure-relief devices are located in the inlet and outlet salt piping of each heat exchanger to prevent over-pressurization of the shell in the event of a tube rupture. A salt drain system is provided to drain the salt from each heat exchanger and the associated interconnecting pipes in 120 minutes. The salt is drained by gravity into a sump tank equipped with a pump which directs the salt to the cold storage tank.

Table 1.1 summarizes significant heat exchanger design features for the 100-MWe solar stand-alone SGS and 50-MWe hybrid SGS; Table 1.2, significant results of the thermal/hydraulic, structural, and subsystem level analyses.

1.4.4 Shop Fabrication and Field Fabrication/Erections Plan

The straight tube heat exchanger design selected for molten salt steam generation is such that standard "state-of-the-art" fabrication techniques can be used. A step-by-step fabrication sequence including all significant fabrication and inspection operations were identified for both the 100-MWe solar stand-alone SGS and 50-MWe hybrid SGS heat exchangers.

Field fabrication and erection of each SGS can be accomplished using standard civil, mechanical, and electrical installation procedures. A schedule that identifies the interrelationships and time periods required for each major installation step was prepared.

1.4.5 Cost Estimates and Schedules

The installed SGS capital costs based on first quarter 1982 dollars are:

	100-MWe Solar Stand-Alone SGS ($)	50-MWe Hybrid SGS ($)
Heat exchangers	3,614,100	2,480,900
Auxiliary systems and equipment	2,994,000	1,942,700
Structure	522,000	475,000
Instrumentation and controls	2,400,000	2,166,000
Subtotal	9,530,100	7,064,000
Contingency at 20 percent of Subtotal	1,906,000	1,412,900
Home office costs	1,715,400	1,271,600
Construction management	914,900	678,200
Total Cost	14,066,400	10,427,300
Fee at 8 percent of Total Cost	1,125,300	834,200
Sell Price	15,191,700	11,261,500

Table 1.1 Heat Exchanger Design Summary

	100-MWe Solar Stand-Alone				50-MWe Hybrid			
	Preheater	Evaporator	Superheater	Reheater	Preheater	Evaporator	Superheater	Reheater
Shell I.D., m (ft)	1.30 (4.10)	1.64 (5.38)	0.91 (3.00)	0.85 (2.80)	0.78 (2.57)	1.00 (3.30)	0.58 (1.93)	0.64 (2.08)
Tube Length, m (ft)	17.5 (57.3)	18.1 (59.5)	18.3 (60.0)	18.9 (62.0)	16.8 (55.0)	18.3 (60.0)	16.8 (55.0)	18.6 (61.0)
Height, m (ft)	20.9 (68.7)	28.0 (91.8)	23.5 (77.1)	24.0 (78.8)	18.2 (59.7)	26.6 (87.3)	18.9 (62.2)	20.7 (67.8)
Tube O.D., mm (in.)	15.9 (0.63)	25.4 (1.0)	15.9 (0.63)	25.4 (1.0)	15.9 (0.63)	25.4 (1.0)	15.9 (0.63)	25.4 (1.0)
Tube MW, mm (in.)	1.47 (0.058)	2.1 (0.083)	1.65 (0.065)	1.24 (0.049)	1.47 (0.058)	2.1 (0.083)	1.65 (0.065)	1.24 (0.049)
Number of Tubes	2325	1359	1049	458	997	629	529	229
Actual Heat Transfer Surface, $10^3 m^2$ ($10^3 ft^2$)	2.03 (21.8)	1.97 (21.2)	0.96 (10.3)	0.69 (7.4)	0.83 (9.0)	0.92 (9.9)	0.44 (4.8)	0.34 (3.7)
Tube Material	CS	1-1/4%Cr-1/2%Mo	304SS	304SS	CS	1-1/4%Cr-1/2%Mo	304SS	304SS
Design Margin, %	15.1	17.64	10.5	9.8	13.1	16.8	9.1	9.5
Dry Weight, $10^3 kg$ ($10^3 lb$)	54.0 (119.0)	122.0 (269.0)	28.5 (62.8)	20.9 (46.0)	18.1 (40.0)	67.1 (148.0)	12.2 (27.0)	10.9 (24.0)
Filled Weight, $10^3 kg$ ($10^3 lb$)	84.8 (187.0)	166.6 (367.2)	44.9 (99.0)	33.1 (73.0)	30.4 (67.0)	104.9 (231.2)	18.1 (40.0)	18.6 (41.0)
Steam Drum I.D., m (ft)	---	2.1 (6.9)	---	---	---	1.5 (5.0)	---	---
Chevron Driers	---	19	---	---	---	10	---	---
Separator Arms	---	27	---	---	---	16	---	---

Table 1.2 Significant Analysis Results

Analysis	Significant Results
Thermal/Hydraulic:	
• Uncertainty	Tube length (i.e., heat transfer surface) was increased to account for uncertainties in heat transfer coefficients, tube material thermal conductivity, variations in wall thickness, and inactive regions. Design margins are listed in Table 1.1. Number of tubes (3%) was increased to account for possibility of tube plugging.
• Circulation	Evaporator, downcomers, feeders, drum internals sized for 4:1 circulation ratio.
• Full- and Part-Load Performance	Variation in steam/water/salt temperature pressure, and flow rate over the operating load range (25 to 100%) were identified.
• Stability	Static (Ledinegg) and dynamic (Nyquist) stability curves plotted for the evaporator indicated that the steam/water flow is stable.
• Critical Heat Flux	The Atomics International and Westinghouse critical heat flux correlations indicate that DNB and/or dryout will not be experienced in the evaporator.
Structural:	
• Fatigue	Allowable temperature variations and ramp rates were determined by steady-state and transient analysis of the tubesheet-shell and tubesheet-head junction for the cyclic nature of SGS operation.
• Buckling	Analysis of a plugged tube (most severe condition) indicated that the baffle spacing is less than the critical buckling length and buckling should not occur.
• Flow-Induced Vibration	The analysis shows that tube vibration and fluid elastic whirling are not significant. The baffle damage and collision damage numbers are significantly below the allowable limit of 1.0.
Subsystem Level:	
• Modes of Operation	Procedures for cold start-up, cold shutdown, diurnal start-up, diurnal shutdown, warm standby, start-up from warm standby, shutdown to cold conditions, and emergency shutdown were identified.
• Dynamic Model	The mathematical model of the SGS for evaluation of response to load changes revealed that in addition to proportional and integral controls, feed-forward and derivative controls are required for quick, stable response; one percent salt flow through the bypass line is required at 100 percent load for pressure control; an evaporator/preheater bypass line under pressure control is required to minimize pressure surges during emergency conditions.

Interest during design, fabrication, and construction, state and local taxes, escalation, and owner's costs were not included.

The time period from start of design to the end of preoperational testing is 32 months for the 100-MWe solar stand-alone SGS and 29-months for the 50-MWe hybrid SGS. The schedule for both units are included in Figure 1.4.

1.4.6 Subsystem Research Experiment (SRE)

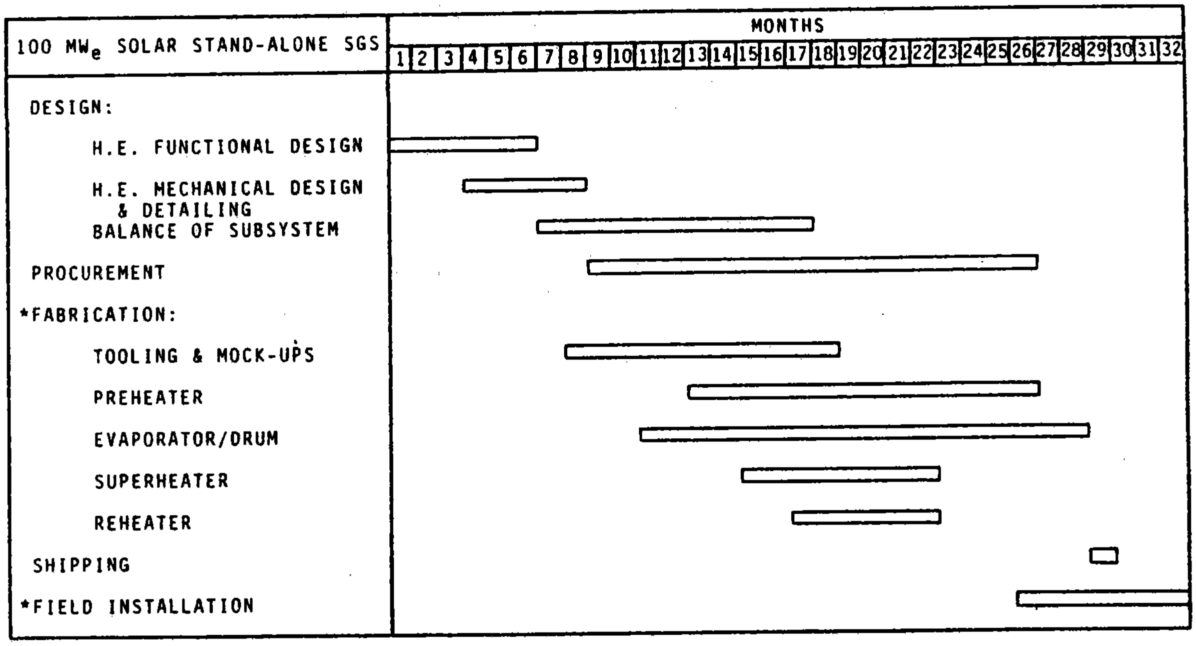
As part of Phase 1 a proposal was prepared for the design, construction, testing, and evaluation of a SRE of sufficient scale to ensure successful operation of the full-size subsystem designed in Phase 1. The objectives of the SRE specified by SNLL are as follows:

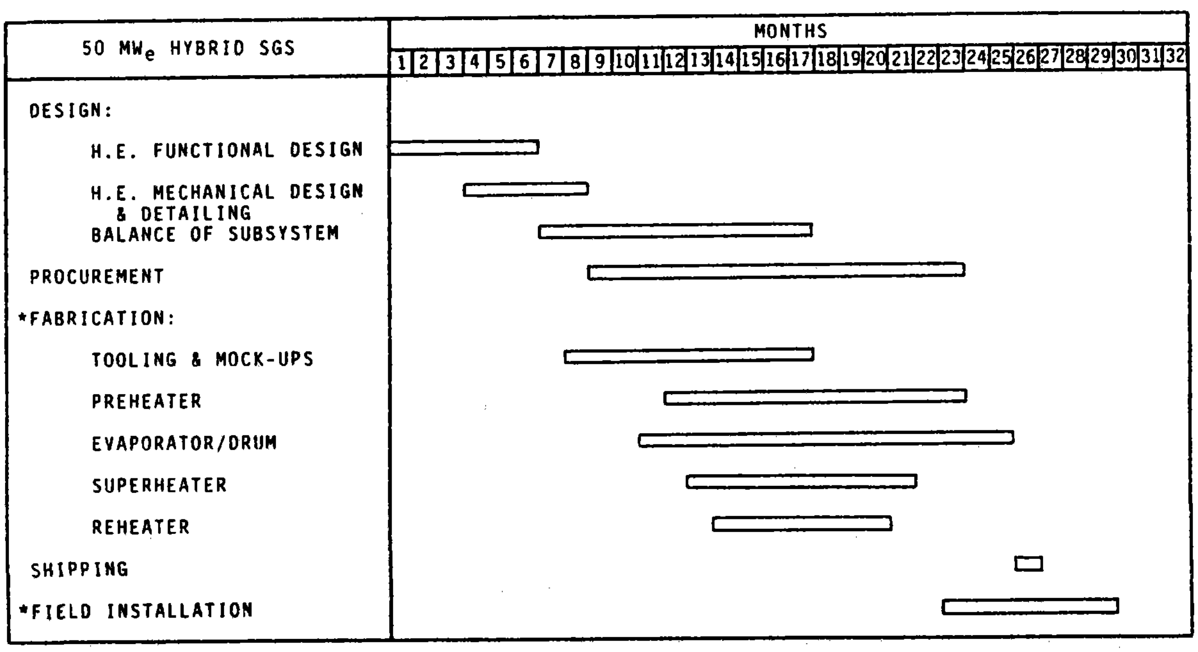
- Demonstrate the ability to design, construct, and operate a molten salt steam generator for generating high-pressure [13.48 MPa gage (1955 lb/in²g)], high-temperature [541°C (1005°F)] steam for power generation
- Resolve all critical design fabricating, performance, operating, and cost-estimating uncertainties associated with the full-scale SGS designs developed during Phase 1
- Provide a molten salt steam generator that can be utilized for a future full-system experiment (FSE).

As directed by SNLL, our proposed field tests are compatible with the CRTF equipment and are limited to the thermal capacity of the thermal storage SRE.

Specific areas that will be investigated in the SRE to meet the aforementioned objectives are:

- Demonstrate the performance of the various heat exchangers and correlate it with analytical predictions. This will include:
  - Thermal duty
  - Pressure drop
  - Shell-side heat-transfer coefficient
  - Steam/water-side flow distribution
  - Evaporator circulation
  - Tube-side flow stability
  - Absence of departure from nucleate boiling (DNB)





*See Appendix D for Details.

Figure 1.4 SGS Schedules

- Demonstrate the behavior of the SRE control system and correlate it with the computer predictions obtained from the control system dynamic computer model
- Verify procedures established to start up and shut down the SGS during normal and emergency operating conditions
- Demonstrate the ability to design against tube vibration
- Demonstrate the absence of gross structural deformations
- Demonstrate the compatibility of materials of construction with the molten salt.

Although a molten salt SGS for a high-temperature, high-pressure reheat power cycle has never been designed, fabricated, and operated, it is our assessment (based on our design, fabrication, and testing of similar heat exchangers in the past) that there are no critical design or fabrication uncertainties that must be resolved. However, since the proposed operating procedures have never been demonstrated, we believe that an SRE is needed primarily to demonstrate the ability to operate a molten salt steam generator designed for high-temperature, high-pressure applications. Therefore, our proposed SRE is oriented toward a complete subsystem rather than individual components and contains all essential features of the full-size subsystem.

To meet the objectives of the Phase 2 program, we propose an SRE and a simpler, less-expensive alternative SRE. Both will be designed to be compatible with an FSE and with other necessary equipment at the CRTF.

<u>Proposed SRE</u>. The proposed SRE SGS, like the full-scale 100- and 50-MWe subsystems, has four heat exchangers--preheater, natural-circulation evaporator, superheater, and reheater. All heat exchangers are oriented vertically with all heated steam/water flowing upward. The preheater, superheater, and reheater are

counterflow; the evaporator is parallel flow to improve natural circulation. The proposed SRE SGS is designed to generate 1.57 kg/s (12,500 lb/h) superheated steam at 541°C (1005°F) and 13.5 MPa gage (1955 lb/in²g), and 0.68 kg/s (5413 lb/h) simulated reheat steam at 541°C (1005°F) and 2.9 MPa gage (425 lb/in²g).

The proposed SRE includes 11 test series to demonstrate subsystem-level as well as component-level features of the full-scale SGS. Subsystem-level aspects of the SRE involve demonstration of all operating modes of the full-scale system to show that the individual components can be operated as an integrated system in a safe and stable manner. Component-level aspects of the SRE involve monitoring each heat exchanger for specific data that will verify the ability of developed analytical methods to predict heat exchanger performance characteristics.

Subsystem-level testing will include demonstration of the following operating modes:

- Cold start-up
- Full- and part-load steady-state operation
- Load changes
- Diurnal shutdown
- Diurnal start-up
- Shutdown to warm standby
- Warm standby
- Start-up from warm standby
- Shutdown to cold conditions
- Emergency shutdown

While demonstrating the SRE SGS operating modes, data will also be obtained to evaluate component-level considerations such as the following:

- Salt-side film coefficients
- Dynamic flow stability of evaporator
- Absence of DNB/dryout in the evaporator

- Superheater flow stability
- Fouling
- Ambient heat losses
- Absence of tube vibration
- Absence of gross structural deformation
- Tubesheet temperature response to load change.

The estimated cost for the proposed SRE is $1,999,424. The time period from start of SRE designs to completion of data evaluation would be 24 months.

Alternative SRE. The alternative SRE reduces the SRE cost 21 percent, shortens the SRE schedule from 24 months to 21 months, and still includes 9 of the 11 test series planned for the proposed SRE.

The alternative SRE SGS includes only the evaporator and superheater; the preheater and reheater are eliminated. The superheater is identical to the superheater in the proposed SRE. The evaporator is also essentially the same as the proposed SRE evaporator except for increased pressure-part thickness.

Elimination of the superheater and reheater means that the following full-scale SGS features cannot be demonstrated:

- Evaporator drum-water recirculation to preheater inlet
- Use of main steam to preheat reheater
- Establishing main steam flow to reheater before admission of salt to reheater on start-up
- Control response of superheater/reheater bypass combination
- Demonstration of emergency shutdown procedures for complete subsystem.

We do not believe that these omissions pose serious development risks.

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