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Molten Salt Electric Experiment (MSEE) — Phase I Report Volume I

Martin Marietta

Prepared by Sandia National Laboratories, Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789.

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SOLAR THERMAL TECHNOLOGY
FOREWORD

The research and development described in this document was conducted within the U.S. Department of Energy's (DOE) Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology, and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar radiation by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 meters in diameter track the sun in two axes and use mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100^{o}C in low-temperature troughs to over 1500^{o}C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories who work with private industry. Together they have established a comprehensive, goal directed program to improve performance and provide technically proven options for eventual incorporation into the Nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to insure a successful program.

The work described in this report falls under Task 11, System Experiments, of the Solar Thermal Technology Program. The report covers the design and construction phases of a demonstration of a central receiver system that uses molten nitrate salt as both the heat transport fluid in the receiver and as a thermal storage medium. The 5 MWt system converts solar energy to sensible heat in molten salt, from there to enthalpy in steam, and finally to mechanical work and electrical energy through a convention steam-driven turbine generator. This work was performed between December 1982 and April 1984. The test and evaluation phase of this project is covered separately in a later report.

FOREWORD

This report is submitted by Martin Marietta Corporation to Sandia Laboratories in accordance with the provisions of Sandia Contract No. 81-7469. This final report consists of the following volumes:

Volume I, Executive Summary and Lessons Learned

Volume II, System Development and Test

Volume III, Appendixes

Volume I is an abbreviated summary of the Phase I activities in the MSEE program, which are described in more detail in Volume II. The section on lessons learned includes a listing and description of important design and operating issues which were encountered in the Molten Salt Electric Experiment (MSEE) that should be considered when designing a larger scale solar power generating facility.

Volume II presents the historical development of the program and a summary of the test activities and results. This volume describes the MSEE by subsystem and the results of actual subsystem and system tests, and compares them to expected test results.

Volume III summarizes the documentation generated to support the MSEE. Copies of key documents were reproduced and included in this volume.

The contract was under the technical direction of Dr. William Delameter of Sandia National Laboratories, Livermore, California. The following organizations have contributed to this work:

Martin Marietta Denver Aerospace	Responsible for receiver refurbishment, the receiver and storage subsystems, and system design and integration of the MSEE. This effort included conducting system analyses, providing specifications, defining subsystem interface requirements, controlling system configuration, designing the master control and instrumentation subsystems, supplying engineering support of the hardware installation, preparing and conducting all subsystemand system-level tests, integrating the efforts of supporting subcontractors, and developing and maintaining the master schedule.
Sandia National Laboratories, Livermore, CA	Project management.

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MOLTEN SALT ELECTRIC EXPERIMENT (MSEE) - PHASE I REPORT VOLUME I

Prepared by
Martin Marietta Aerospace
Denver Aerospace

ABSTRACT

The Molten Salt Electric Experiment (MSEE) conducted at the Central Receiver Test Facility (CRTF) located in Albuquerque, New Mexico, is the first large-scale demonstration in the United States of the technical feasibility of operating a solar central receiver power plant with molten nitrate salt as the receiver heat transfer fluid and thermal storage medium.

This report documents the design, construction, and checkout (Phase I) of the project. This final report consists of three volumes:

Volume I is an abbreviated summary of the Phase I activities in the MSEE program, which are described in more detail in Volume II. The section on lessons learned includes a listing and description of important design and operating issues which were encountered in the Molten Salt Electric Experiment (MSEE) that should be considered when designing a larger scale solar power generating facility.

Volume II presents the historical development of the program and a summary of the test activities and results. This volume describes the MSEE by subsystem and the results of actual subsystem and system tests, and compares them to expected test results.

Volume III summarizes the documentation generated to support the MSEE. Copies of key documents were reproduced and included in this volume.

Sandia National Laboratories Albuquerque, NM	Responsible for constructing the MSEE at the Central Receiver Test Facility (CRTF), providing test and support personnel to conduct the tests, software programming for the control and data acquisition subsystems.
Black and Veatch Consulting Engineers	Design of the civil, mechanical, and electrical portions of the MSEE as directed by Sandia National Laboratories.
Babcock and Wilcox	Design, fabrication, installation, and test support of the steam generating subsystem including the control system.
Public Service Co. of New Mexico	Installation of turbine generator and condenser, electric power generation subsystem (EPGS)/grid interface, EPGS standalone test support.
Olin Chemical Group	Responsible for the Olin molten salt loop experiment and salt chemical analysis.

Other participants in the MSEE include the Arizona Public Service Co., Arizona Solar Energy Commission, Department of Energy (DOE), Electric Power Research Institute, Foster Wheeler Co., McDonnell Douglas Astronautics Co., Pacific Gas and Electric Co., and Southern California Edison Co.

CONTENTS

Figure

Table

1.0 INTRODUCTION

The Molten Salt Electric Experiment (MSEE) conducted at the Central Receiver Test Facility (CRTF) located in Albuquerque, New Mexico, is the first large-scale demonstration in the United States of the technical feasibility of operating a solar central receiver power plant with molten nitrate salt as the receiver heat transfer fluid and thermal storage medium.

The principal advantages of a molten salt receiver system over a water/steam receiver system are: (1) the steam and turbine generators are decoupled from the receiver by a thermal storage subsystem, minimizing the effects of cloud transients on the plant operation, and providing the ability to shift power output for several hours, if needed, to accommodate changes in demand; (2) molten salt from the receiver is used directly as an economical thermal storage fluid; and (3) the molten salt receiver is a simple design using a single-phase heat transfer fluid.

As an intermediate step in the continuing development of molten salt central receiver technology, the experiment was preceded by materials research, receiver subsystem and thermal storage subsystem experiments (Ref 1 and 2), as well as a number of commercial-scale feasibility and preliminary design studies (Ref 3, 4, and 5) funded by the Department of Energy (DOE). Additional studies have been funded in molten salt steam generator and advanced central receiver designs. The MSEE was built around existing CRTF facilities and equipment from the receiver and thermal storage subsystem experiments. It uses the existing heliostat field, heliostat control system, receiver, tower, control computers, site facilities, and personnel at CRTF, and uses surplus equipment for the electric power generation and condenser subsystem. New equipment specifically designed and built for the experiment includes: the steam generator subsystem, piping (including downcomer and riser) and valves connecting the receiver on the top of the tower with the storage subsystem, a molten salt booster pump, and receiver refurbishments, including a new cavity door, cold and hot surge tanks, and a master control subsystem (MCS).

This extensive reliance on existing equipment was necessary to conduct an integrated experiment of this magnitude within available funding. This was accomplished at the expense of constraints imposed by this approach on experiment performance, and on the scaling of the results to commercial applications.

The experiment provides partial modeling of commercial-scale plants, similar to the use of pilot plants in the process industry. Partial modeling means close reproduction or scaling of only certain aspects of the process, while the rest of the "model" remains unscaled or "distorted." For the MSEE, the closely simulated parameters include: the properties and temperature ranges of the salt; the pressures and temperatures of the steam side; heat transfer coefficients; departure from nucleate boiling (DNB) considerations; salt flow, leakage, and freeze control; qualitative equipment design guidelines; and the analytical understanding of systems-level operation and control requirements and implementation. Additionally, the experiment provides familiarization and operational experience with the major subsystems comprising a molten salt solar thermal receiver system, including manual as well as automatic control via the master control subsystem.

On the other hand, the overall efficiency, solar utilization factor, and cost per kilowatt-hour of the MSEE are not expected to accurately reflect the values for projected commercial-scale plants and have not been considered major drivers in designing and executing the experiment.

The experiment is being conducted in three phases: Phase I is a design, construction, installation, checkout, and performance verification effort, and is the subject of this report. Phase II will be an operating effort aimed at evaluating integrated performance under steady-state and transient conditions, and providing operating experience for those utilities and industrial firms interested in solar receiver plants. An optional Phase III for continued testing is under consideration.

The specific objectives (Ref 6) of Phase I as established by the MSEE technical committee are to:

- Verify that the system works,
- Demonstrate performance in all operating modes,
- Provide baseline characterization for the system,
- Develop safe operating procedures for Phase II,
- Train test personnel,
- Check out the system for all Phase II operating conditions.

This report covers the Phase I activities from February 1982 through July 1984, with emphasis on Martin Marietta's responsibilities to the MSEE program. These include systems design and integration; Phase I test conduction; onsite construction support; master control subsystem design/analysis; equipment protection system (EPS) design, installation and checkout; complete subsystem responsibility for the receiver and storage subsystems; and instrumentation and control onsite support. Some of the activities that were not Martin Marietta's primary responsibilities, such as onsite construction, the heat rejection and feedwater subsystem, the electric power generation subsystem, and the status of test activities for the period from April 6 through July 30, 1984 are also covered. Effective April 6, 1984, and based on an agreement by all parties concerned, the systems integration responsibility was transferred from Martin Marietta to McDonnell Douglas Astronautics Company, with Martin Marietta retaining only a support and advisory role for the remainder of Phase I. This transfer of responsibilities was motivated in part by the long delays in the Phase I effort caused by construction and equipment problems. These delays resulted in an overall extension of the Phase I effort by approximately 8 months beyond original schedule, overtaxing the manpower resources originally allocated by Martin Marietta to this program.

During the reporting period, the system design, construction, integration and checkout, including subsystems-level tests of the receiver, thermal storage, steam generator, and associated control systems, as well as the systems-level performance demonstration tests, have been completed. Accordingly, a solid foundation has been established for the operating effort of Phases II and III. This activity is summarized in Section 2. Section 3 discusses lessons learned, emphasizing those aspects of problems encountered, resolutions, and recommendations applicable to commercial-scale molten salt thermal plants. An evaluation of the procurement and construction management approaches used in this experimental program compared to well-established, commercial-scale practices is not within the scope of this report.

Conclusions and recommendations for future work are presented in Section 4. Consistent with the MSEE's role as an intermediate step in the continuing development of molten salt central receiver technology, the recommendations reflect our experience gained not only from the Phase I program, but also from its preceding SRE's.

2.0 SYSTEM DEVELOPMENT AND TEST SUMMARY

2.1 SYSTEM DESCRIPTION

The principal elements of the MSEE are shown in Figure 2-1. Figure 2-2 shows an aerial photograph of the experiment, and Figure 2-3 is a simplified flow schematic of MSEE. The system design parameters are summarized in Table 2-1.

The molten salt is the energy transfer medium from the receiver through the thermal storage to the steam generation subsystem, and water/steam is the energy transfer medium from the steam generation subsystem through the heat rejection and feedwater subsystem (HRFS) to the electric power generation subsystem (EPGS). The receiver is located at the top of the CRTF tower, and receives concentrated solar energy from the collector field. Cold salt at a temperature of 590°F in the cold storage tank located at ground level is pumped up the tower and through the receiver where it is heated to 1050°F. It then flows through a downcomer and is throttled into the hot salt storage tank. Hot salt is pumped from storage through the superheater and evaporator of the steam generation subsystem (SGS), and is returned to the cold storage tank. An additional flow of cold salt is added to the salt line between the superheater and evaporator to reduce the salt temperature entering the evaporator. This allows the use of low alloy steel in the evaporator. Main steam from the steam generator is used to drive a conventional steam turbine generator power plant.

The MSEE system consists of the following seven subsystems, which are described below:

1) Collector,

2) Receiver/Tower,

3) Thermal storage,

4) Steam generation,

5) Electric power generation,

6) Heat rejection and feedwater,

7) Master control.

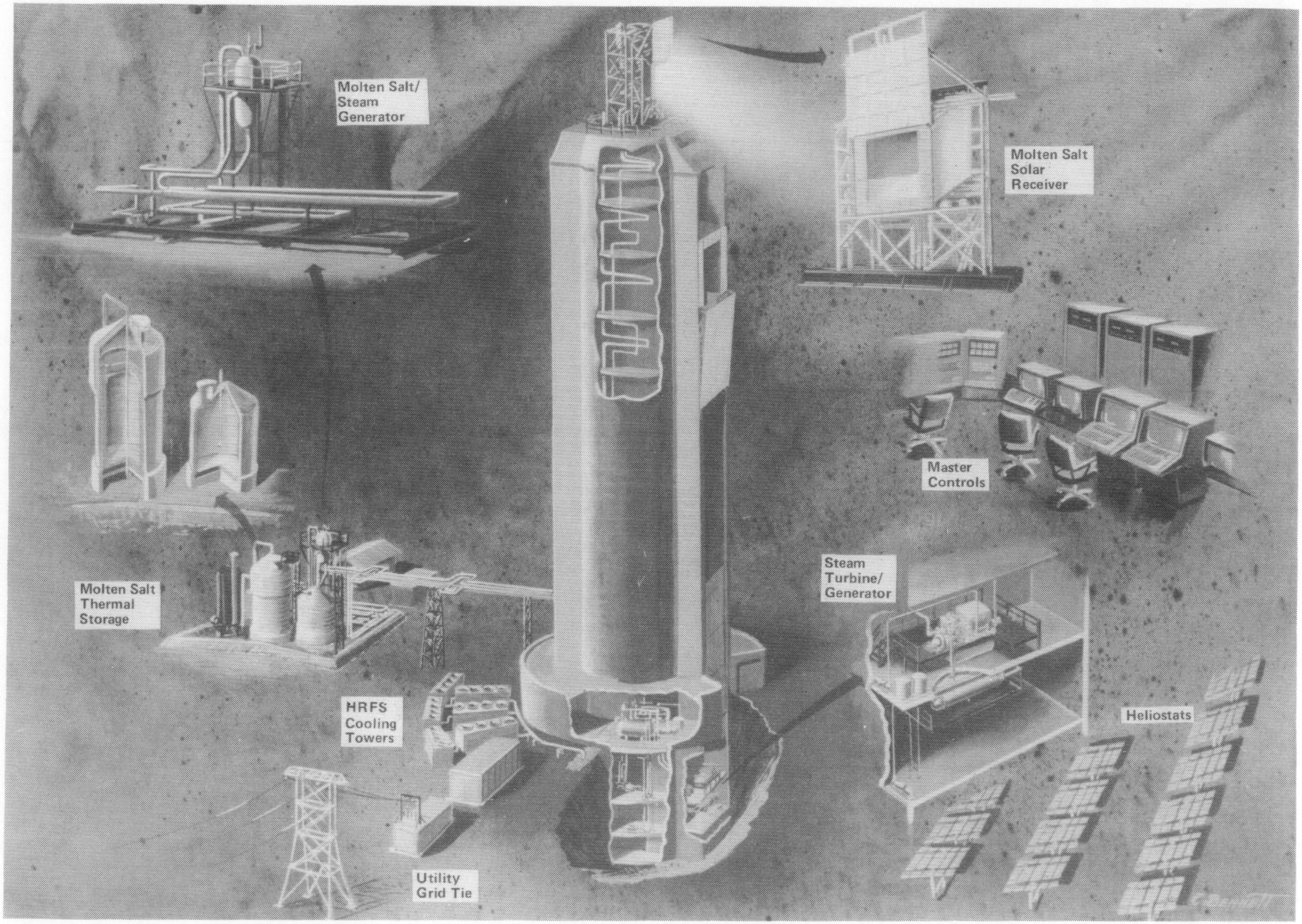

Figure 2-1 Artist's Concept of MSEE

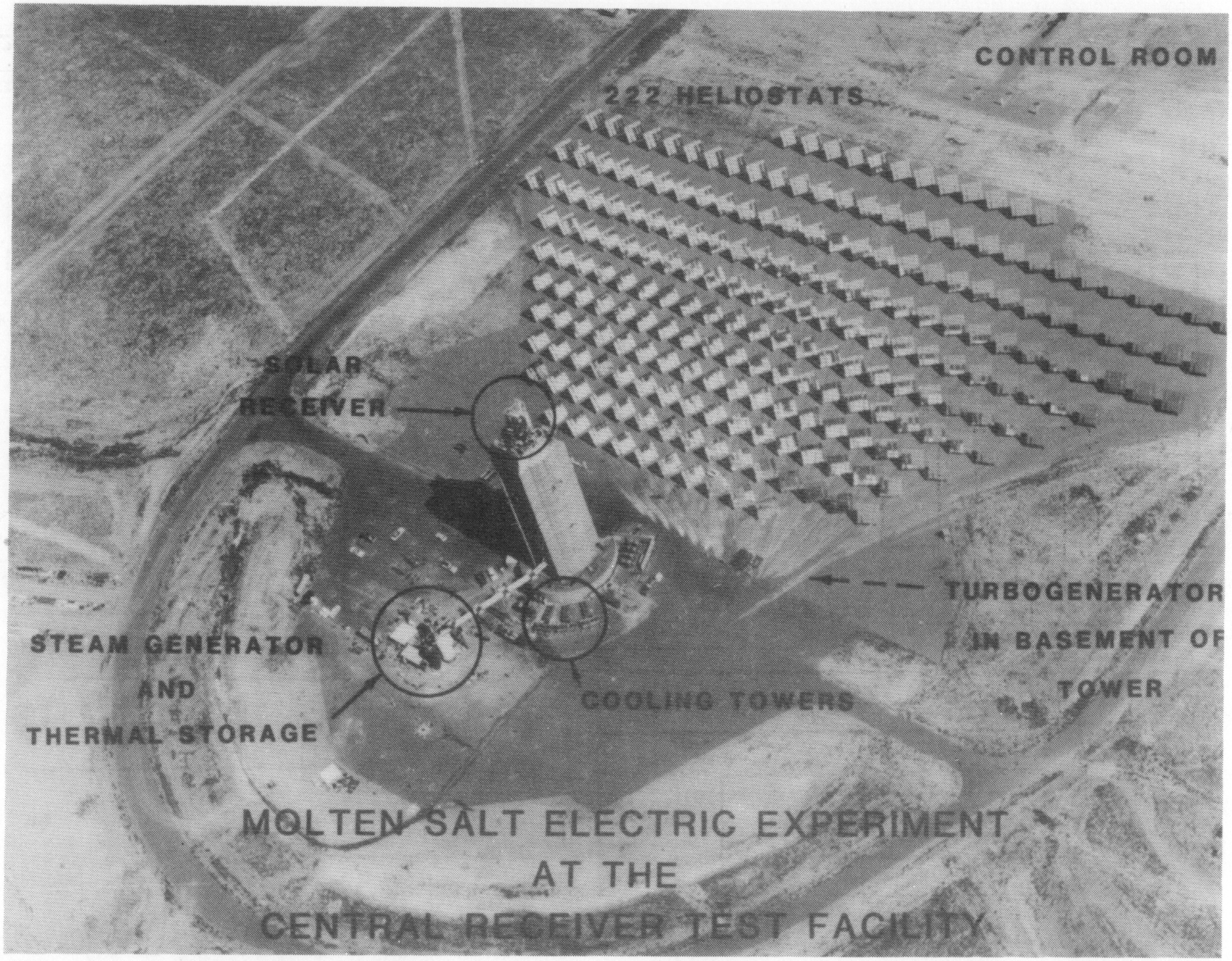

Figure 2-2 Aerial Photograph of MSEE

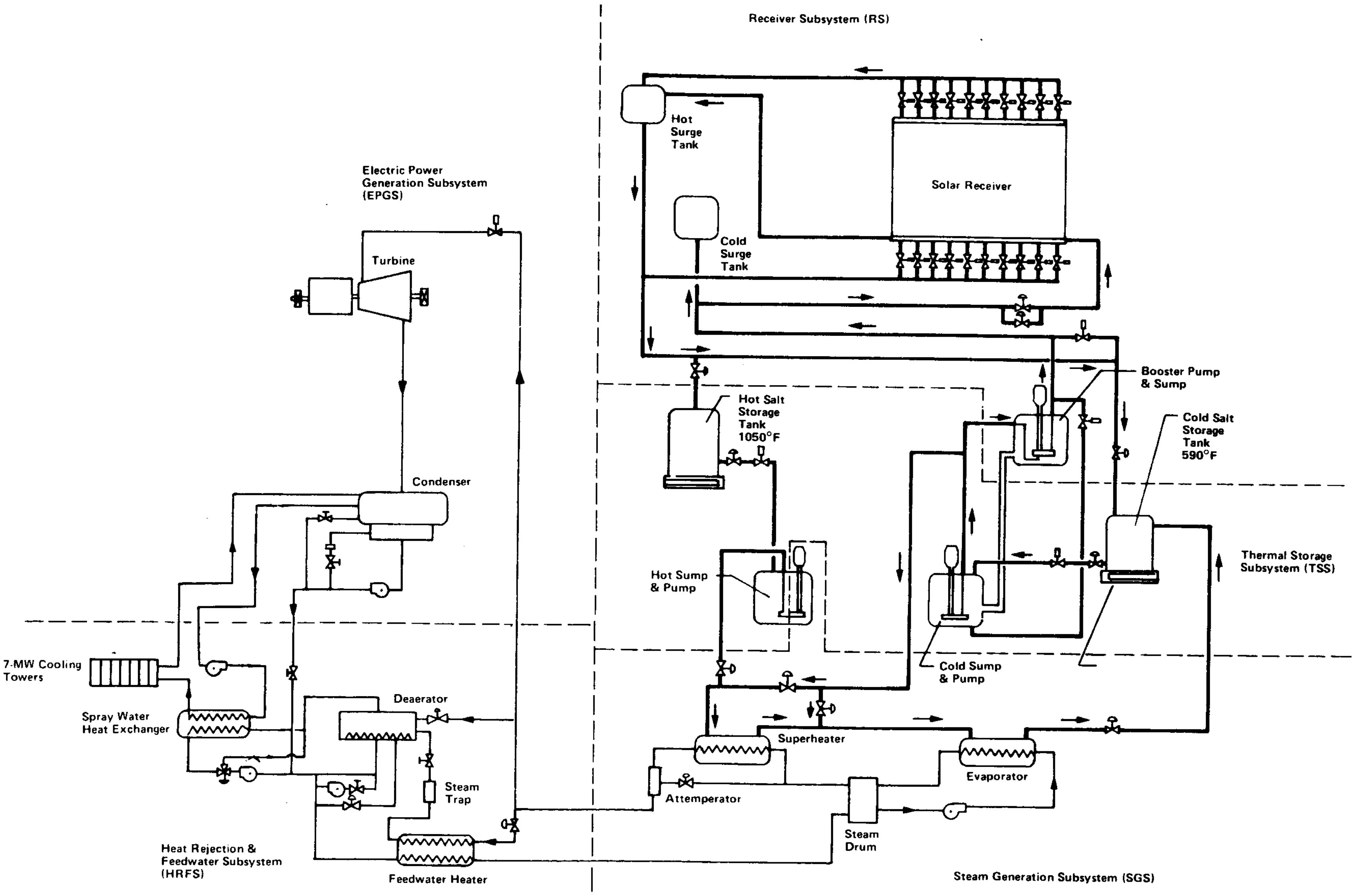

Figure 2-3 MSEE Flow Schematic

Table 2-1 MSEE System Characteristics

Electric Power Generation Subsystem	
Type	Non-Reheat
Turbine-Generator Gross Electrical Power	0.758 MWe
Net Electrical Power	0.413 MWe
Steam Temperature	990°F
Steam Pressure	1050 psig
Steam Flow Rate	7800 lb/h
Feedwater Temperature	401°F
Condenser Pressure	Dry Cooling at 5-in. Hga
Gross Heat Rate	1422 Btu/kWh
Collector Subsystem	
Heliostat Number	211 (Goal: 200 Operational at All Times)
Reflective Surface per Heliostat	400 ft^2
Total Mirror Area	84, 488 ft^2
Total Collected Energy to Receiver	4.79 MW_t
Field Efficiency (Design Point)	61.5%
Receiver Subsystem at Design Point*	
Type	Molten Salt Cooled Single Cavity
Solar Multiple	1.43
Thermal Power at Tower Base	16.3×10^6 Btu/h
Salt Flow Rate	96,867 lb/h
Salt Temperature—In	590°F
Salt Temperature—Out	1050°F
Efficiency	83%
Number of Absorber Panels	18
Number of Control Zones	1
Maximum Heat Flux on Absorber	168,000 Btu/h-ft^2
Absorber Active Surface Area	(207 ft^2)
Thermal Storage Subsystem	
Type	Hot/Cold Tank Pair (Lined Hot Tank)
Capacity	6.49 MWh_t
Salt Quantity	175,000 lb
Cold Salt Tank Shell Height	12 ft
Cold Salt Tank Shell Diameter	12.26 ft
Cold Tank Volume	1420 ft^3
Hot Salt Tank Shell Height	23.6 ft
Hot Salt Tank Shell Diameter	10.0 ft
Hot Tank Volume	1539 ft^3
Cold Tank Temperature	590°F
Hot Salt Temperature	1050°F
Tower Subsystem	
Type	Concrete Cylindrical
Height	200 ft
Base Dimensions—Outside Diameter	51 ft
Top Dimensions—Outside Diameter	43.3 ft
Foundation Diameter	100 ft
Solar Steam Generator Subsystem	
Type	
— Evaporator	U-Tube, U-Shell
— Superheater	U-Tube, U-Shell
Evaporator Circulation Type	Forced
Duty	10.7×10^6 Btu/h
Inlet Salt Temperature	1050°F
Outlet Salt Temperature	590°F
Salt Flow Rate	64,680 lb/h
Attemperator Salt Flow Rate	13,870 lb/h
Steam Flow Rate	11,582 lb/h

*December 21, (Day 355) Solar Noon, 950 W/m^2 Insolation

2.1.1 Collector Subsystem (CS)

The collector subsystem redirects, focuses, and concentrates solar radiation on the tower-mounted receiver. The subsystem shown in Figure 2-2 is an integral part of the CRTF. It consists of 221 two-axis tracking heliostats located north of the receiver tower, and a separate heliostat control system. Under optimum insolation and heliostat conditions, the heliostat field can concentrate approximately 5 MWt on the focal plane. A maximum of 211 heliostats are used on the MSEE program with a goal of having a minimum of 200 heliostats operational at all times.

Each heliostat has 25 individual mirror facets totaling 400 ft^2 of reflective surface. The facets are mounted on a support structure and individually adjusted to provide a concentration ratio of approximately 25 to 1 at the focal point. The support structure has motor-driven azimuth and elevation gimbals to track the sun during the day.

2.1.2 Receiver/Tower Subsystem (RS)

The receiver shown in Figure 2-4 captures the solar flux redirected from the collector field and converts it into the sensible heat in the molten salt. The subsystem consists of the receiver panel, cavity enclosure with a vertical aperture door, hot and cold surge tanks, boost pump, overflow tank, molten salt piping, CRTF tower, flowmeters, thermocouples, pressure transducers, electric heat trace provisions, and control valves. The receiver is located at the top of the CRTF tower.

The receiver's active surface was designed for use in the receiver Subsystem Research Experiment (SRE) to heat 83,000 lb/h of molten salt from 550 to 1050°F with a solar power level at the aperture of 5 MWt.

Since the completion of the SRE, the receiver has been refurbished, including instrumentation and control system modifications, minor structural and piping changes, and replacement of the two original cavity doors opening horizontally with a single aperture door opening vertically.

The vertical motion of the door during opening and closing is guided by rails installed behind the aperture insulation for thermal protection. In its closed position, the door protects the internal surfaces of the cavity from inclement weather, and provides thermal isolation of the cavity from the environment. The door is insulated on its cavity side to minimize conduction losses. Placing the insulation on the cavity side only ensures good thermal coupling between the door structure and the ambient environment, thus preventing thermal warpage of the door due to internal heating. This design is not intended to protect the door from external heating at full heliostat field flux levels.

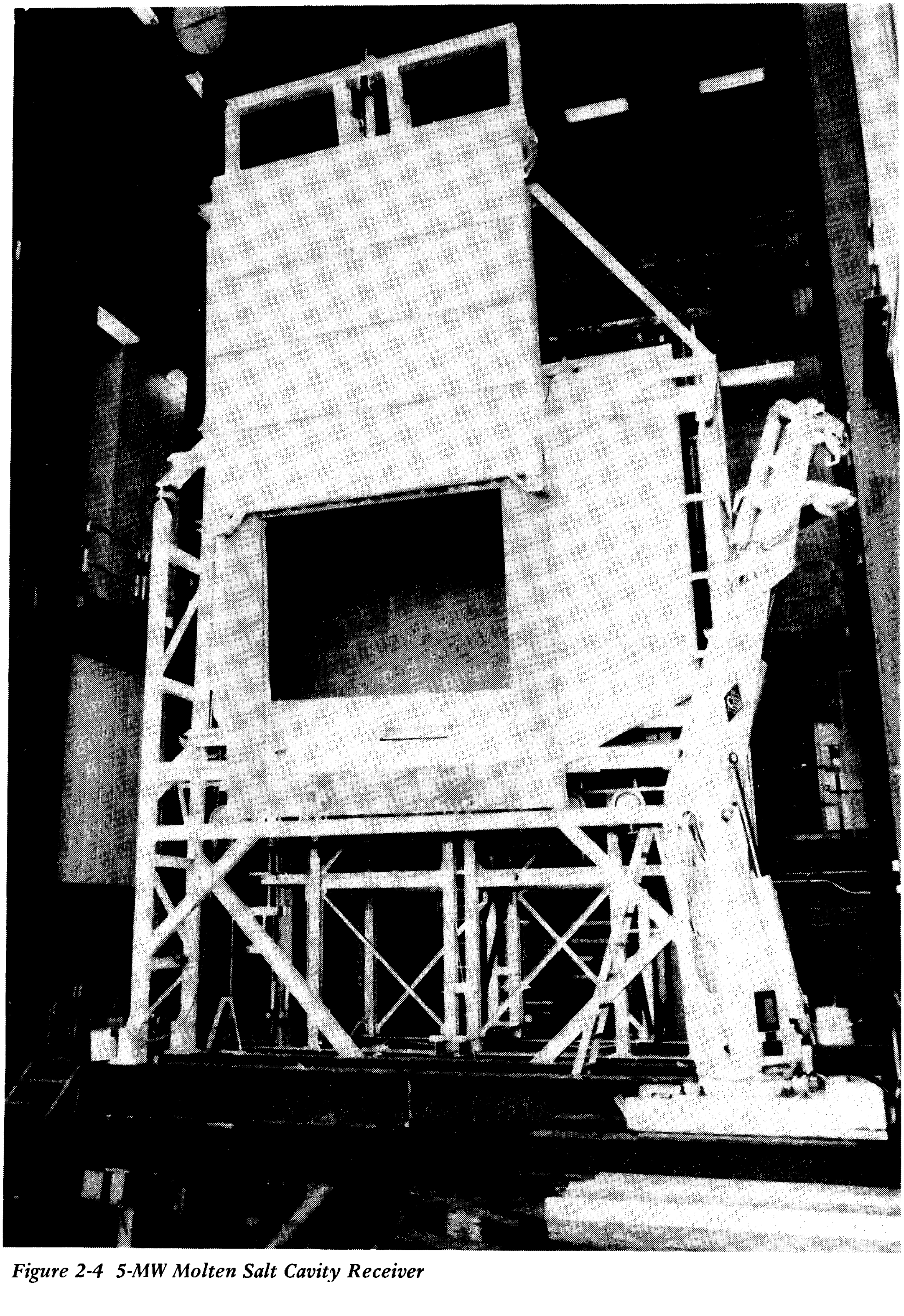

Figure 2-4 5-MW Molten Salt Cavity Receiver

A seal is installed along the outer edges of the door to prevent air flow through the aperture. The door seals against the front face of the aperture insulation. The seal is made of ceramic materials to withstand the potentially high temperatures of the aperture due to flux spillage.

The passive thermal design of the aperture, consisting of structure covered with high-temperature insulation, is a significant departure from the original water-cooled aperture frame used on the SRE.

The receiver active surface consists of 18 vertical passes in series with 16 tubes per pass. The tubes have a 0.75 in. outside diameter and are made of Incoloy 800.

Surge tanks are provided to dampen the effects of transients in the salt flow to and from the receiver, and to provide emergency salt flow through the receiver in the event of a cold salt pump failure. The cold surge tank is pressurized with instrument air to supply the necessary head to force the salt through the receiver in the event of a pump outage, and to provide a surge volume within the tank. The hot surge tank operates at atmospheric pressure, and is vented to an adjacent overflow tank that catches the salt in the event of an inadvertent flow blockage in the downcomer (e.g., a level control problem). The level in the hot surge tank is maintained sufficiently high by a control valve at the bottom of the downcomer to prevent two-phase (liquid salt and air) flow from entering the receiver downcomer piping.

The cold salt boost pump provides the necessary head to get the salt up the tower and through the receiver. The hot salt downcomer can supply salt to either the hot or the cold storage tank. Throttle valves are included in this return line to direct the flow to either of these tanks, depending on the salt temperature.

2.1.3 Thermal Storage Subsystem (TSS)

The thermal storage subsystem (Fig. 2-5) provides cold salt for the receiver for daytime operation, and hot salt for the steam generator for day and early evening operation. The TSS can also furnish a source of thermal energy for overnight freeze protection of the receiver, steam generator, and salt piping and for early morning startup. The TSS has the capacity to store 6.49 MWht of thermal energy. The subsystem includes the hot and cold salt storage tanks, a propane-fired salt heater, a cold salt pump and sump, the hot salt sump, and interconnecting pipes and valves. The hot salt tank's unique design uses internal insulation in conjunction with a waffled Incoloy 800 liner that separates the salt from the internal insulation. The liner transmits the salt pressure loads through the internal insulation into the steel shell, which is made of carbon steel (SA516, grade 70).

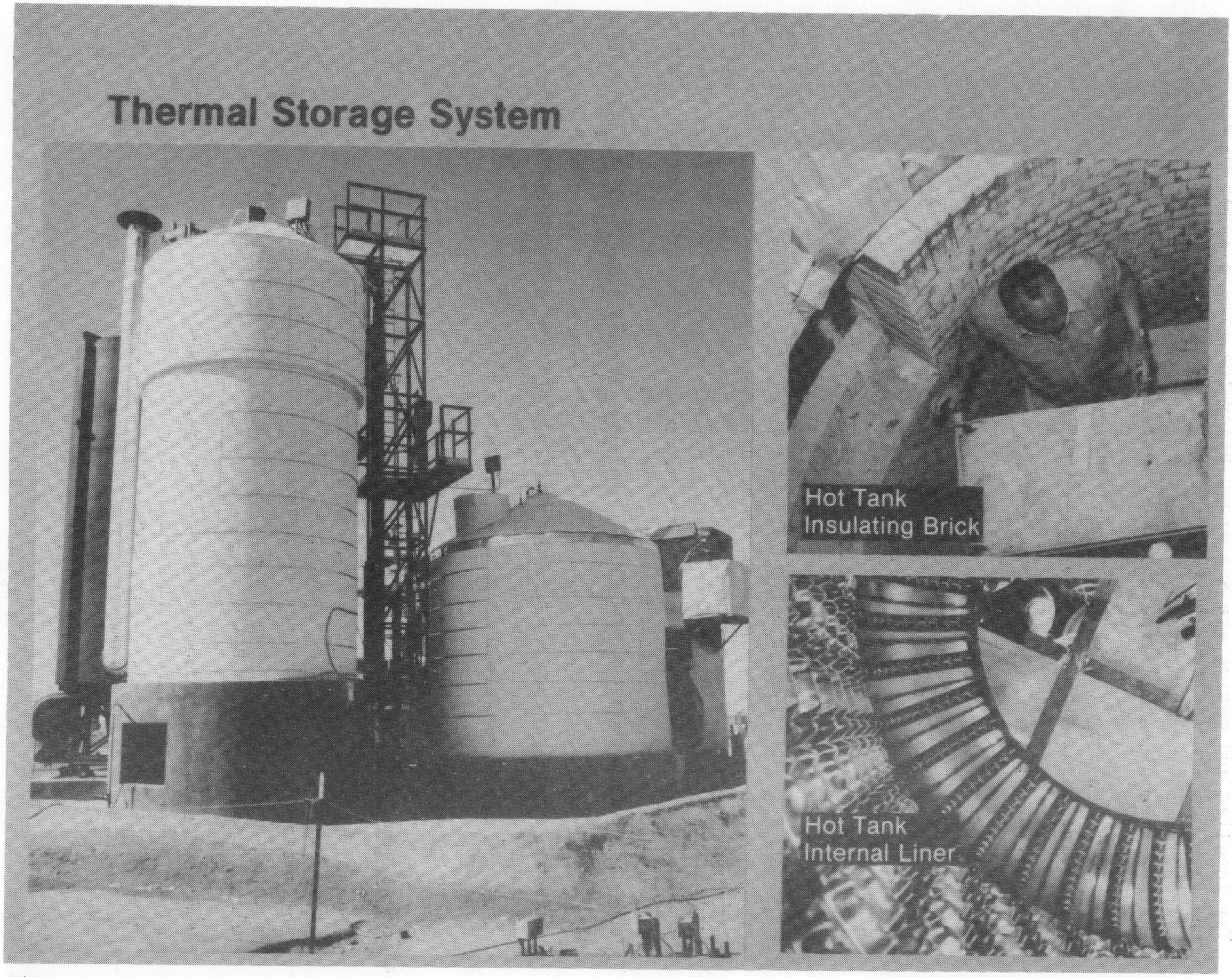

Figure 2-5 Thermal Storage Subsystem

The cold salt tank is similar in design to the hot tank, except that, due to its lower operating temperature, it does not require the internal insulation and liner, and uses conventional external insulation.

The cold salt and hot salt pumps are of vertical cantilever design. The impeller and casing are suspended below the liquid level in a sump; the bearings are located above the liquid level and do not contact the salt. The major advantage of this type of design is that no rubbing seals are required, and there are no bearings in the salt.

The propane heater is used only during checkout as a source of heat when solar insolation is not available or the receiver is not available.

As an integral part of the storage subsystem, the Olin molten salt experiment is designed to investigate the corrosion and erosion effects of hot 1050°F nitrate salt on various iron/nickel alloys under actual thermal cycling conditions. This is done by pumping hot salt through selected tube specimens at various velocities during hot salt pump operation. When the hot salt pump is not in operation, the tubes are allowed to drain and cool. The effects of thermal shock will be evaluated after completing a sufficient number of cycles of hot salt flow followed by cooldown.

Salt samples are collected and analyzed periodically to monitor salt chemistry during the operation of the system. The chemical reactions at high temperatures that could effect the properties of the salt have been evaluated in Reference 1. Of particular concern is the formation of carbonates and hydroxides due to exposure to atmospheric carbon dioxide and water vapor in the ullage spaces of the various salt tanks in the system. Carbonates and hydroxides are detrimental in that they can form precipitates (and fouling) as well as corrosive products in the system. They may require either "scrubbing" of the ullage gases or periodic regeneration of the salt (Ref 1) in commercial scale solar thermal plants. The MSEE data will provide some understanding of the rates of these reactions in a real system. This information will be helpful to the designers of commercial systems in selecting the proper approach to the problem.

2.1.4 Steam Generating Subsystem (SGS)

The SGS is shown in Figure 2-6. It uses hot salt to produce superheated steam for the turbine generator. The subsystem includes an evaporator, steam drum, boiler recirculation pump, superheater, hot salt pump, attemperator, associated piping and valves, instrumentation, and an electric heater for startup.

The evaporator and superheater are U-tube/U-shell type heat exchangers, with low-pressure salt on the shell side and high-pressure water and steam on the tube side. This shell and tube configuration has been selected to minimize thermal stresses due to differential expansion in the tubes and tubesheets.

A conventional steam drum, located above the evaporator, separates water from the saturated steam before the latter enters the superheater. The drum receives feedwater from the feedwater heater. A forced recirculation design has been selected to effectively maintain nucleate boiling in the evaporator. Forced recirculation is also preferred for power plants requiring daily startup and shutdown.

The turbine requires a main steam temperature of 940°F, while the steam outlet temperature from the superheater is 1000°F. The superheater outlet steam is attemperated to 940°F by mixing with a small saturated steam flow from the drum. The salt flow from the superheater to the evaporator is also attemperated, from 906 to 850°F, by mixing with a cold salt flow from the salt pumps. This allows the use of chrome-moly piping and fittings in the evaporator.

SGS warmup is accomplished by isolating the subsystem and preheating the steam drum water with the subsystem's electrical circulation heaters.

Steam pressure, steam temperature, drum water level, and the evaporator salt inlet temperature are controlled automatically by a Network 90 control system supplied by the steam generator manufacturer.

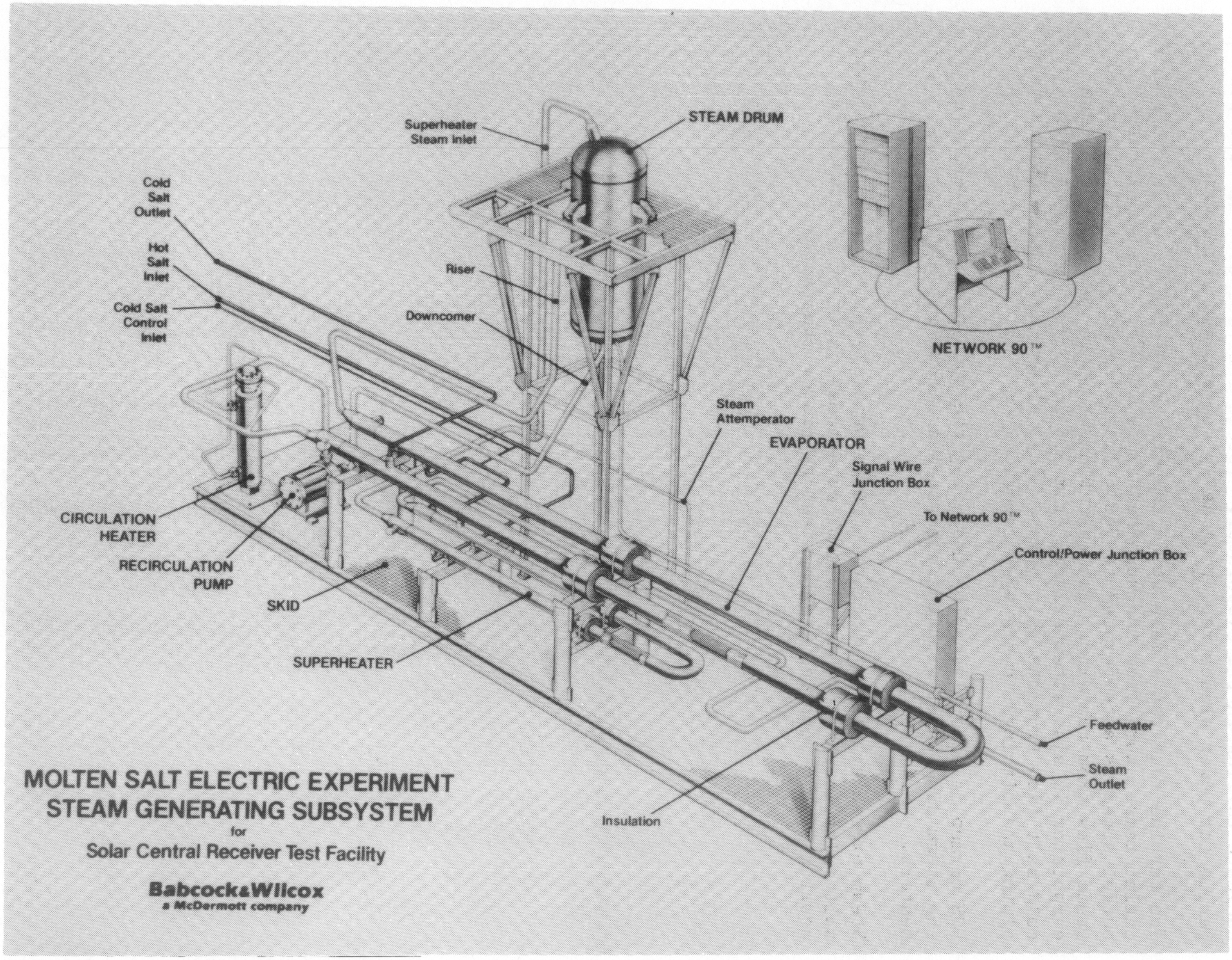

Figure 2-6 Steam Generating Subsystem

2.1.5 Heat Rejection and Feedwater Subsystem (HRFS)

The HRFS serves three main purposes. First, it preheats and deaerates the turbine condensate to the required SGS steam drum feedwater inlet conditions. Second, it pressurizes the condensate-to-feedwater system. Third, it rejects waste heat from the EPGS condenser during normal operation, and from the SGS during transients such as a turbine trip or shutdown or startup. The major components of the HRFS are the cooling towers, cooling water pump, spray water pump, feedwater pump, deaerator/feedwater heater, feedwater heater, demineralizers, makeup storage tank, condensate makeup pump, cycle fill pump, chemical feeders, water analyzers, valves, piping, controls, and instrumentation. These major components, except for the feedwater pump and two interface control valves, were used during previous CRTF tests.

There are two functional operating modes of the HRFS. The first mode is under normal operation when the turbine uses two-thirds of the superheated steam from the SGS and the remaining one-third of the superheated steam is used in the HRFS for deareating and preheating the feedwater. When the turbine is not in operation, all the steam can be directed to the HRFS for heat rejection.

The cooling towers consist of six forced-draft, finned-tube water-toair heat exchangers, originally designed as Freon condensers for refrigeration systems. Designed for previous testing (the 10-MWe pilot plant panel test), the cooling towers have a duty rating of 7 MWt (24×10^6 Btu/h) providing for cooling water from 200 to 160°F by using air at the design point temperature of 94°F. The turbine condenser cooling required for this experiment, however, is only 2.7 MWt (8×10^6 Btu/h), or about one third the original rating. As a result, the cooling towers can provide cooling water temperatures as low as 75°F, at an ambient air temperature of 52°F.

2.1.6 Electric Power Generation Subsystem (EPGS)

The EPGS converts the enthalpy in the main steam flow to electric power. The subsystem includes the turbine generator, electric power equipment, condenser, condensate pump, condenser makeup water storage tank, and lubrication equipment.

The turbine-generator set is rated at 750 kWe and is a skid-mounted unit located at the north end of the receiver tower complex at the 80-ft level (Fig. 2-7). The unit consists of a turbine, stepdown gearbox, generator, and auxiliary equipment. The turbine is a seven-stage, single-flow machine, operating at 17,443 rpm with a shaft power output of approximately 650 kWe with the available condensate conditions.

Main steam conditions are 940°F and 1065 psia. A single-reduction gearbox reduces the turbine shaft speed to the generator speed of 1200 rpm. The generator operates at 480 V, and is cooled by circulating water through air-cooling coils located above the generator. The turbine-generator auxiliaries include a lubricating oil pump, lube oil cooler, air ejection vacuum pump, and mechanical hydraulic governor.

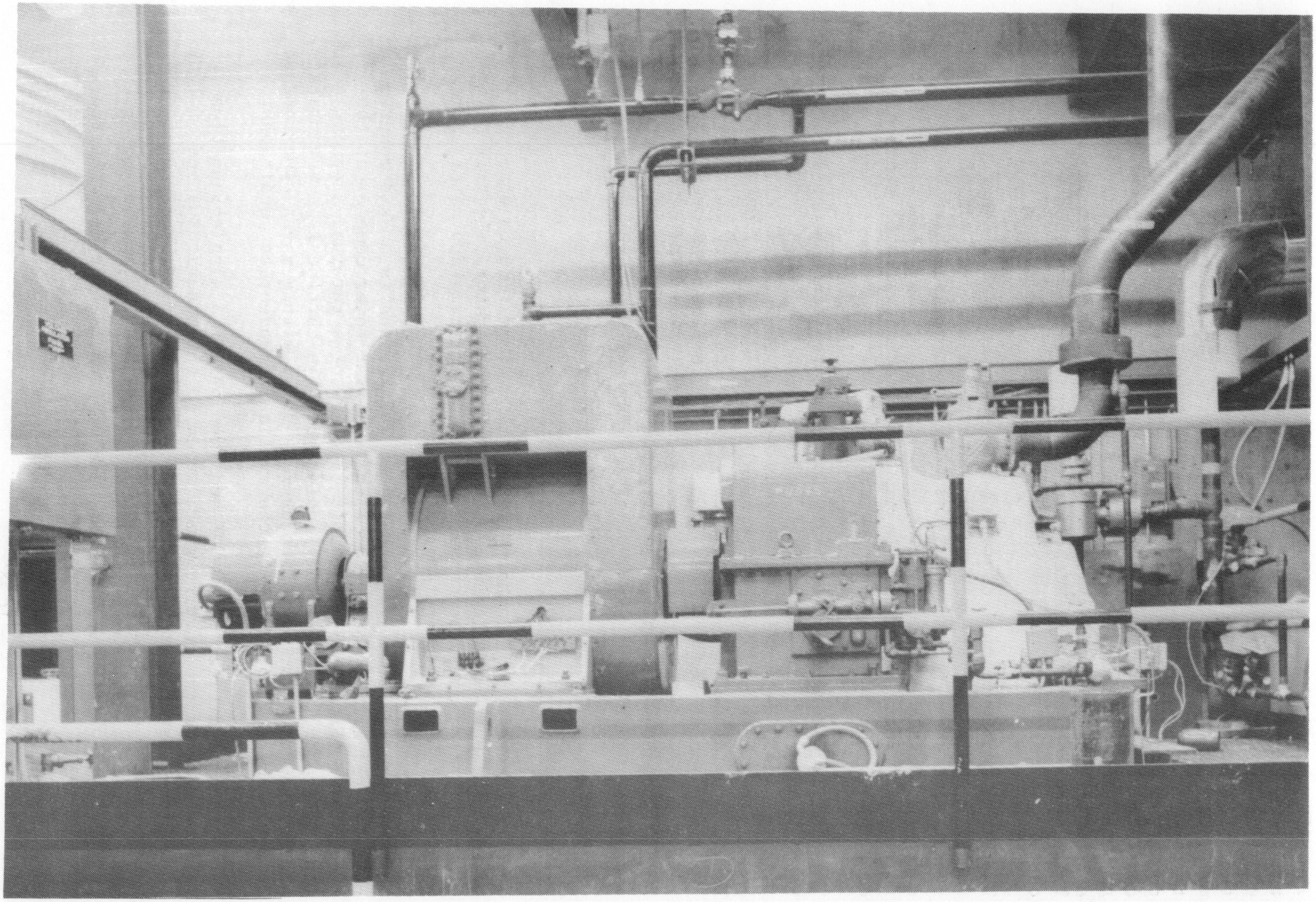

Figure 2-7 Turbine Generator

A shell and tube condenser, supported by a separate frame, is located directly below the turbine. The turbine-generator set is installed in the base of the tower on a floor 20 ft below the ground floor of the tower. The condenser is supported directly below this floor (the ceiling of the 40-ft floor is below ground). Condensate from the hot well of the condenser is transferred to the feedwater heater/deaerator when the water level in a deaerator requires makeup. Otherwise, the condensate is pumped to a storage tank. Condensate from this tank is piped back to the condenser hot well when the hot well level requires water.

2.1.7 Master Control Subsystem (MCS)

The MCS consists of an EMCON-D for system control, a Bailey Network 90 for direct SGS control, an Accurex data system for trace heat control, and an equipment protection system. The equipment protection system is an independent shutdown system composed of hardwired relay units. These relay trip devices will shut down the receiver or the power generation portion of the plant when critical parameters reach preset limit values. The relay units are independent of the EMCON-D and Network 90 control systems. Additionally, an Accurex data logger is used to collect and display all the temperature measurements relating to heat tracing as well as engineering data from the SGS. It also provides closed-loop control for some heating circuits.

The EMCON-D controls the Network 90 and the remainder of the MSEE subsystems. The EMCON-D is a distributed digital control system consisting of two operator consoles (Fig. 2-8), a host computer with its peripheral hardware, a communication control module, and three process control modules distributed among the subsystems. The two EMCON-D operator consoles, and a hard copy unit, are located in the CRTF main control room (Fig. 2-9) presenting graphic information to the operators on the status of the control subsystem. The host computer is a DEC PDP 11/34 unit located in the control room. This computer links the operator with the process control modules (PCM) and analyzes data from the control modules. A printer is also located in the control room to provide a hard copy of specific data, such as valve positions. The peripheral equipment includes two disk drives, an alarm system, and a data analysis system.

A communication control module links the host computer with the three field-located process control modules. Each PCM is a small digital computer capable of monitoring a number of instrumentation points and responding with a number of process control signals. Communication between the control modules and the host computer is accomplished through a series connection of the control modules. This distributed control system reduces the number of instrumentation and control links between the subsystems and control room.

Each PCM consists of a digital computer control unit, a multiplexer, an analog-to-digital converter, and a digital-to-analog converter. Analog signals from the process instrumentation are converted to digital signals, selected in rotation by the multiplexer, and analyzed by the control unit. The module responds with an analog-to-digital control signal, which is sent to the appropriate controller. Each PCM is capable of monitoring 95 analog signals at a total sampling rate of 30 samples per second, and controlling 64 on/off switches.

Figure 2-8 EMCON-D Operator Consoles

Figure 2-9 CRTF Main Control Room

The receiver subsystem PCM modulates the salt flow rate to the receiver to maintain, as closely as possible, a constant outlet temperature of 1050°F. The quasi-feed forward control algorithm estimates the absorbed power by the receiver using temperature measurements along the receiver flow path, and determines the salt flow required to maintain the set-point outlet temperature from a heat balance.

Control of the thermal storage subsystem involves operation of the two salt downcomer flow control valves, cold salt pumps, salt storage tanks and piping, heat tracing, and the propane-fired salt heater. The downcomer throttling valves are controlled by the receiver control system to maintain a constant level in the receiver hot surge tank. Salt equipment heat trace temperatures are monitored continuously by the Accurex data logger. If required, the propane-fired salt heater is operated manually during subsystem checkouts. Automatic control of the HRFS and EPGS involves controlling the steam and condensate flows to the feedwater heater/deaerator, steam flow to the feedwater heater, and operating the cooling water, spray water condensate, and feedwater pumps. The EPGS condenser temperature, level, and pressure are monitored by the master control system. The feedwater heater/deaerator temperature and the saturation temperature corresponding to the feedwater heater/deaerator pressure are maintained by controlling the steam flow from the main steam header. The final feedwater temperature is maintained by controlling the main steam flow to the feedwater heater.

Automatic control of the steam generation subsystem primarily involves the control of steam pressure, steam temperature, drum water level, and the evaporator salt inlet temperature through the Network 90 control system. The water level in the drum is controlled by modulating the control valve downstream of the feedwater pump. Control of the main steam pressure is accomplished by modulating the salt flow control valve downstream of the evaporator. Steam temperature is controlled using an attemperator to mix steam from the steam drum with the output of the superheater. The evaporator salt inlet temperature is controlled by monitoring the inlet salt temperature and modulating the cold salt control valve at the mixing tee between the superheater and evaporator.

2.2 APPROACH

The experiment was assembled using subsystems in different stages of development. The receiver and thermal storage were built and tested as separate experiments, and their established performance ratings and characteristics, together with those of the existing field at CRTF, formed the basis of the overall performance rating of the experiment. The molten salt steam generator was designed and built with a thermal rating sufficient to supply steam for a 750 kWe turbine-generator and compatible with the supply of molten salt-sensible heat from the first three subsystems. Electric power is generated by a previously used shipboard turbine generator. Other existing equipment used included the HRFS and the EMCON-D control system. Other new equipment included the cold and hot surge tanks, downcomer, riser, control valves, and a boost pump connecting the thermal storage with the receiver subsystem, and the piping connecting the steam generator with the thermal storage and heat rejection subsystems.

2.2.1 Documentation

The principal elements of the systems integration effort are indicated by the documentation tree shown on Figure 2-10. The system specification provides a complete definition of the experiment, including a method for evaluating its performance. Five principal modes of operation have been specified:

1) Warm standby - circulating salt; system ready to begin operation.

2) Shutdown - no salt in system.

3) Charging storage with solar - no electric power production.

4) Electric power from storage only - no collection of solar energy.

5) Charge storage and electric power production - full operation of system.

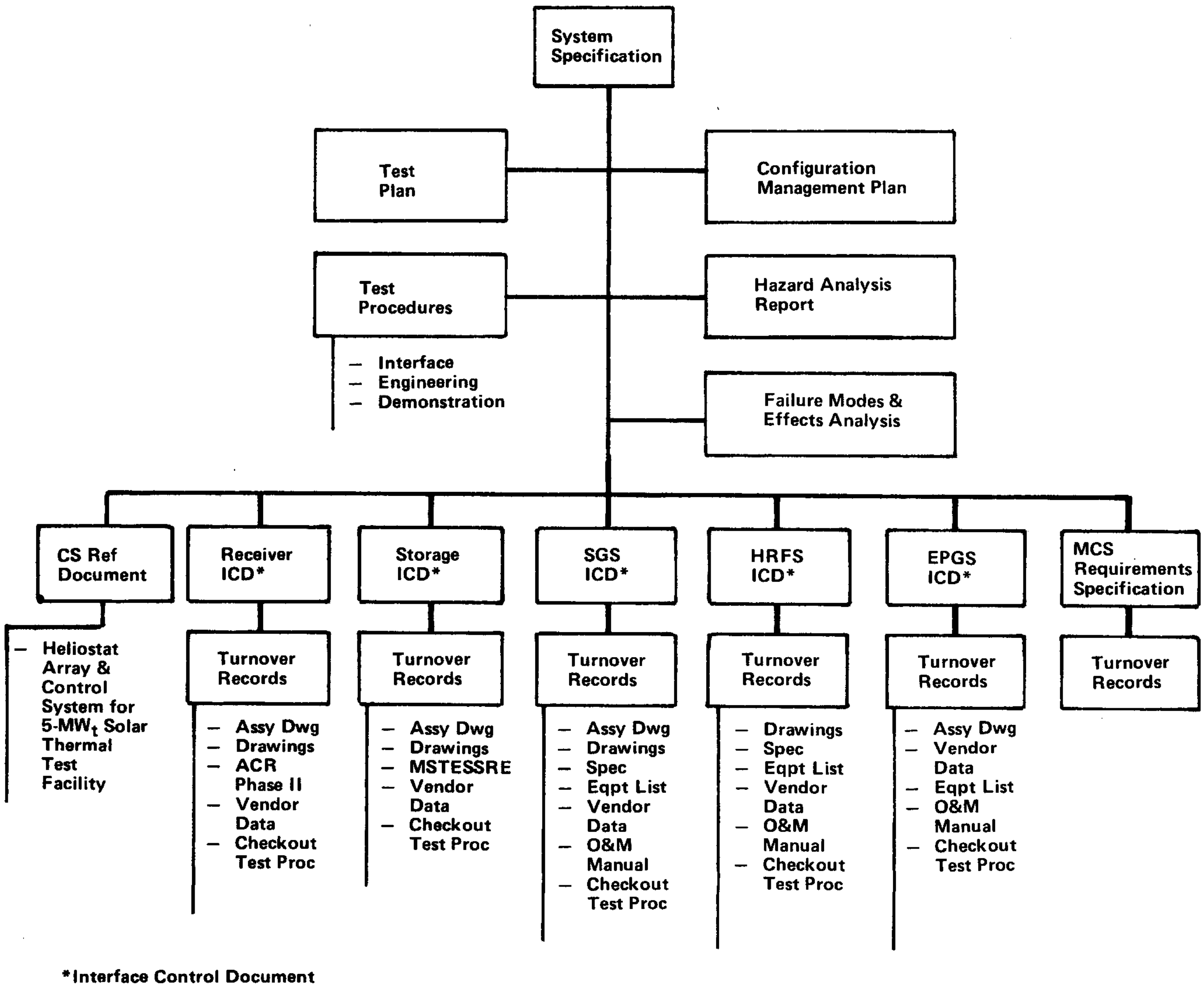

Figure 2-10 MSEE Documentation Tree

The test plan defines the specific tests to be conducted. The Phase I testing was specified at three major levels: (1) standalone checkouts, (2) subsystem tests, and (3) total system tests. The first was accomplished by analyses, visual inspection, and interface instrumentation. Subsystem tests were conducted to verify flow, temperature, and pressure requirements, and to evaluate subsystem and control response to transients. Total system tests are used to develop the system as a whole, refine normal operating procedures, and perform system demonstration and verification tests. The overall approach to the test schedule was to put the highest priority on testing the new elements of the system. However, the plan provides alternative sequences to work around delays resulting from equipment failures or construction problems.

The test procedures provided step-by-step sequences for checkout, startup, operation, and testing of individual modes. The configuration management plan provided a method of control and documentation of the as-built, as-tested configuration of the MSEE. The interface control documents (ICD) define the interfaces among the various subsystems. The master control subsystem requirements specification defines the complete MCS and its interaction with the various subsystems of the MSEE. The hazards analysis provides a systematic identification of hazards and qualitative safety analysis of the MSEE in all modes of operation. The failure modes and effects analysis (FMEA) identifies single-point failure modes in the major subsystems of the MSEE with the exception of the collector subsystem.

2.2.2 System Performance

An MSEE system performance analysis was conducted to predict the overall rating and efficiency of the experiment under simulated commercial type operation. The principal results are shown on Figures 2-11 through 2-14. The first three of these are stairstep diagrams for the design point, performance day, and yearly performance, respectively. The design point was selected as solar noon on December 21, 1983 (Day 355) corresponding to maximum collector field efficiency, and using an insolation level of 950 W/m^2. The performance day was somewhat arbitrarily selected to be Day 142, coinciding with the planned performance test on May 21, 1984. The annual performance estimates were based on the Albuquerque typical meteorological year (TMY), and were accomplished using a modified Solar Thermal Electric Annual Energy Calculator (STEAEC) model.

Figure 2-14 shows the receiver power diagram associated with the performance day stair step of Figure 2-12. The solid line on this figure represents the power available to the receiver from the collector field, and the dashed line shows the power that can be used by the receiver using available salt flow from the cold storage tank. The salt flow is constrained by the size of the line and the valves between the cold tank and the sump. The total time span, including pretest and posttest activities, associated with this power profile is approximately 13 hours. The overall efficiency of the experiment is but a fraction of what is to be expected from a commercial-scale plant. This is due in part to the relatively small scale of the experiment (e.g., large percentage of parasitics) and in part to the fact that the experiment was put together using existing subsystems without an opportunity for systemsor subsystems-level optimization.

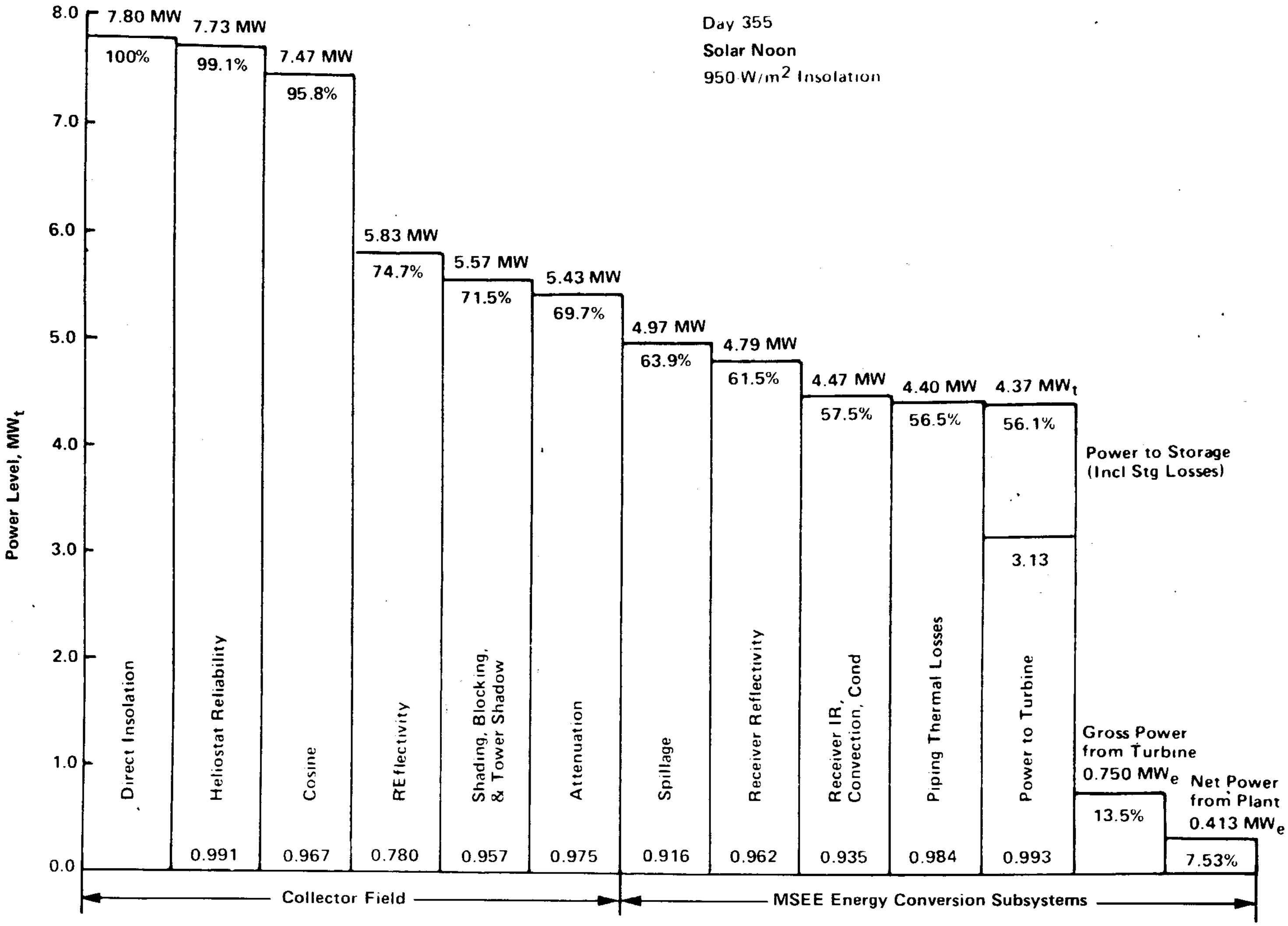

Figure 2-11 Calculated Design Point Stairstep Efficiencies

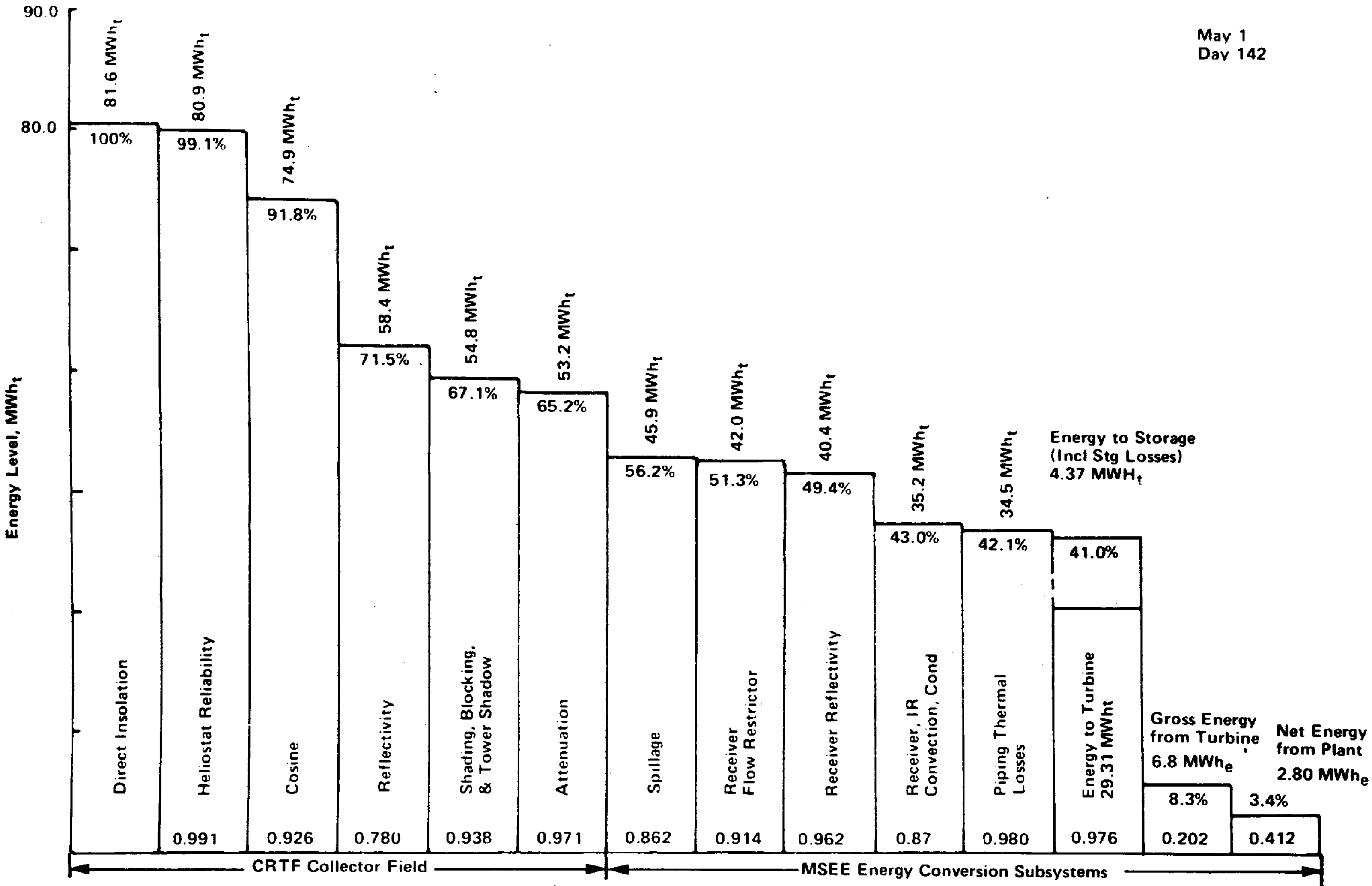

Figure 2-12 Calculated Performance Day Test Stairstep

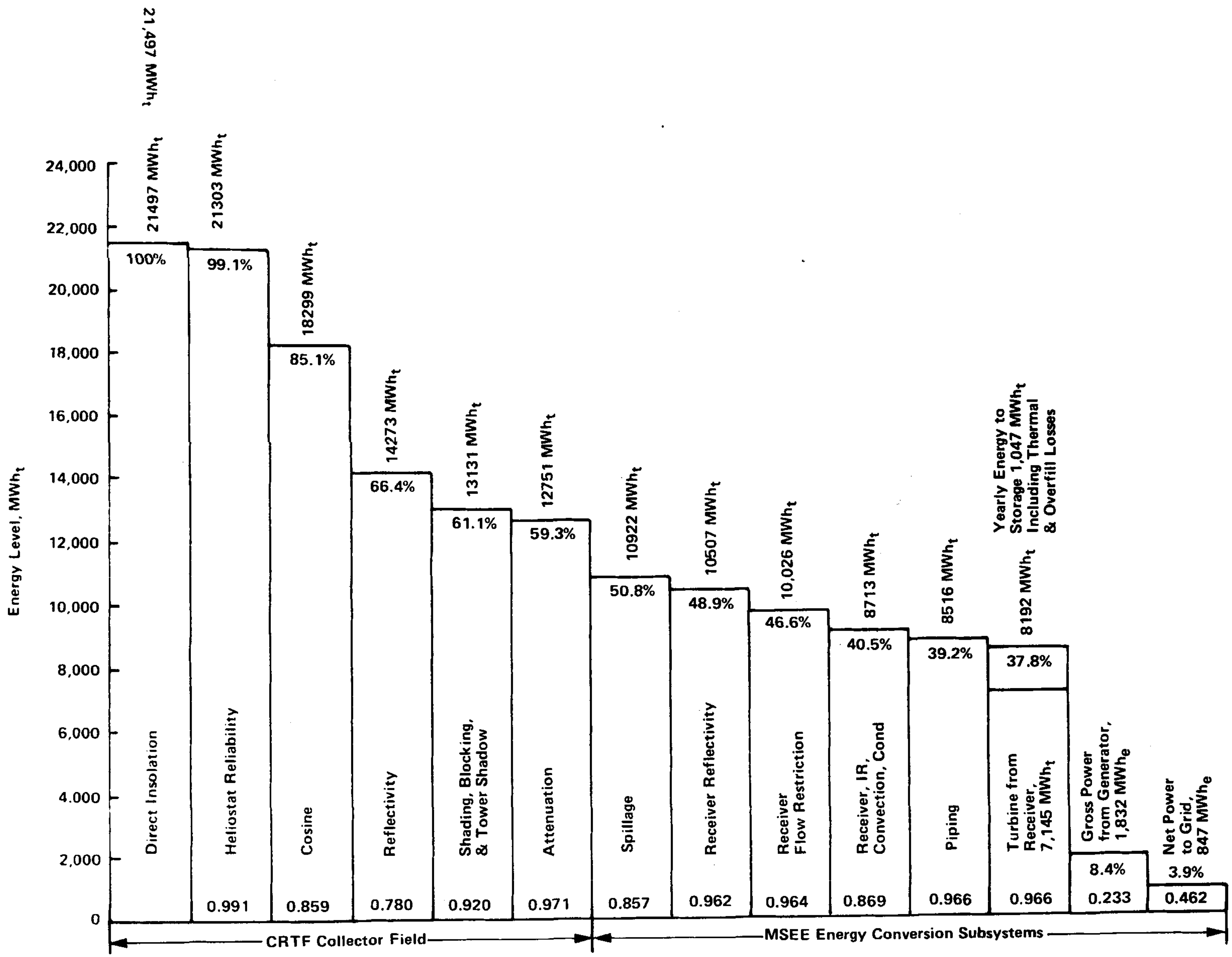

Figure 2-13 Calculated Annual Energy Stairstep

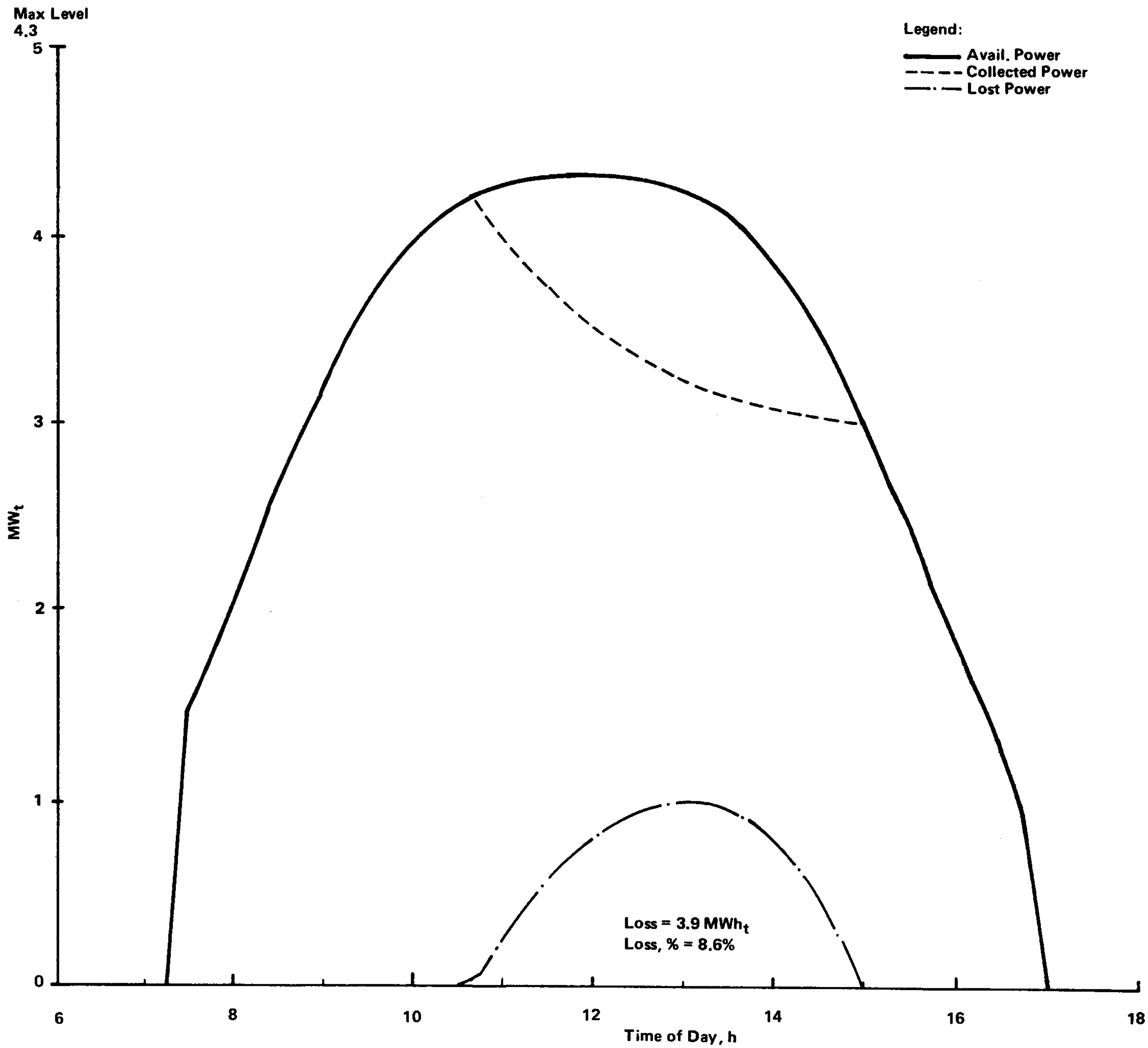

Figure 2-14 Receiver Power Diagram for System Performance Test

2.3 PHASE I PROGRAM HISTORY AND STATUS

The Phase I program history and status are summarized in Tables 2-2, 2-3, and 2-4. Table 2-2 shows the program milestones completed during the reporting period. The original test plan placed the highest priority on steam generator testing, followed by receiver and turbine generator testing. The actual priorities, however, were dictated by the availability of equipment, and required that the original operating procedures be altered accordingly.

Table 2-3 lists the major problems encountered during checkout testing on a subsystem basis, with the resulting downtimes in test days as well as percentages of the total. Table 2-4 lists the tests completed during Phase I. These do not include all of the tests originally planned, some of which have been either deleted or rescheduled for Phase II as a result of a recent restructuring of the MSEE program.

Table 2-2 MSEE Phase I Project Milestones

Date	Milestone
February 1982	Black & Veatch Design Contrast
June 1982	Receiver Refurbishment Contrast
September 1982	Babcock & Wilcox Steam Generator Contract
January 1983	Martin Marietta Systems Integrator Contract
January 1983	Construction at CRTF Begins
May 1983	Raise Receiver to Top of Tower
May 1983	Steam Generator Onsite
September 1983	Salt Flow through Receiver
October 1983	1050°F Salt to Storage from Receiver
October 1983	Automatic Control of Receiver
December 1983	Rated Steam Production
December 1983	Turbine Roll
April 1984	McDonnell Douglas Assumes System Integration Role
April 1984	Synchronize to Grid
June 1984	First-Rated Turbine Output
July 1984	End of Phase I/Begin Phase II
	Turbine Synchronized to Grid

Table 2-3
Problems Encountered during Testing (7/26/83 through 4/6/84)

Subsystem	Problem	Approximate Downtime Test Days	Percent
Receiver	Heat Trace Problems	16	
	Valve Leakage Causing Hot Tank Inlet Freezeup	5	
	Salt Overtemperature (Greater than 398°C [750°F])	5	
	Salt Plug in Downcomer	3	
	Boost Pump	14	
	Total RS:	43	16.8
Thermal Storage	Corroded Bellows	3	
	Valve Seats/Gaskets	5	
	Total TSS:	8	3.1
Steam Generator	Circulation Heater Burnout	30	
	BWCP Motor Burnout	23	
	BWCP Bearing Failure	13	
	Circulation Heater Replacemen	5	
	Overnight Hold	4	
	Salt Valve Repair	4	
	Control Hardware	6	
	Heater Rupture	36	
	Total SGS:	121	47.3
EPGS	Attempted Sychronization	13	
	Total EPGS:	13	5.1
Facility	Circuit Breaker	6	
	Wiring Problem	4	
	Heliostats Unavailable	2	
	Power Outages	1	
	Computer	4	
	Feedwater Pump	3	
	Spray Water Heat Exchanger	4	
	Total Facility:	24	9.4
Other	Installation of Hot Sump Bypass	3	
	Weather	23	
	Maintenance	12	
	Procedure Dev Following Receiver Salt Spill	9	
	Total Miscellaneous:	47	18.3
	Grand Total:	256	100.0

Table 2-4 Phase I Tests Completed Through July 18, 1984

Receiver Integrated Testing

- Cold Salt Flow with Transients
- Hot Salt Flow with Transients
- Cold Salt Flow Margin Test
- Manual Sequence Demonstration
- Automatic Sequence Demonstration
- Cloud Simulation

Steam Generation Acceptance Testing

- Initial Control Loop Checkout
- Hot Salt Flows with Transients
- Diurnal Standby (No Salt Flow)—Hold Overnight
- Load Following—10%/minute
- Feedwater Loss Safe Shutdown
- Salt Flow Loss Safe Shutdown
- Manual Sequence Demonstration
- Retest under MCS Control

Electric Power Generation Testing

- Vibration/Bearing Test (10 to 100%)
- No-Load Generator Grid Synchronization
- Steady-State Loads with Transients
- Load Variations (5 & 10%/Minute)
- Turbine Upsets
- Margin Load Test

Total System Engineering Development

- 30% Load Performance with Transients
- 60% Load Performance with Transients
- 100% Load Performance with Transients
- Simulated Cloud Operation
- Manual Sequence Demonstration

System Demonstration & Verification Testing

- "Warm Standby" Operation
- Thermal Stroage Operation
- Solar & Thermal Storage Operation
- Cloud Performance (Partial Solar)

2.4 TEST RESULTS

Receiver and steam generator test data, with comparisons to predictions (where applicable), are summarized in Table 2-5.

Table 2-5 Test Results Summary

Performance Parameter	Predicted	Measured
Receiver Input	5.0 MWt	5.25 MWt (Max SRE)
Receiver Output		4.71 MWt (Max SRE)
Salt Flow to Receiver	10.98 kg/s (Max Required)	12.00 kg/s
Steam Generator Outlet Temp	510°C (950°F)	509°C (948°F)
Steam Generator Outlet Pressure	75.8 MPa	74.4 MPa
Steam Generator Steam Flow	1.46 kg/s	1.33 kg/s
Hot Tank Heat Loss at 677°C (1050°F)	17.24 kW	17.45 kW
Cold Tank Heat Loss at 310°C (590°F)	6.20 kW	8.38 kW
Cold Tank Salt Level Height Reqd for 10.9 kg/s Outflow	0.92 m	1.09 m
Riser Velocity Head Loss	142	142-200
Downcomer Velocity Head Loss	100	100-133
Pump Head for Riser at Max Flow	121 m	119-121 m
Total Parasitic Loss		66 kWe

3.0 LESSONS LEARNED

An important MSEE objective is to inform potential users of the molten salt solar technology of the lessons learned. The heat rejection and feedwater subsystem (HRFS) and electric power generation subsystem (EPGS) hardware is unique to the MSEE experiment. Although several significant problems occurred in these subsystems, they are not applicable to future salt systems, consequently, these problems are not discussed. A detailed report will be written for the steam generator subsystem by Babcock and Wilcox (B&W).

3.1 CONTROL AND DATA ACQUISITION SYSTEM

The most important lessons learned concerning the control and data acquisition system were:

1) Requirements definition, hardware selection, and computer programming should be done by one organization.

   On this program, Martin Marietta was responsible for defining control and data acquisition system requirements. CRTF defined the hardware and performed the computer programming. This division of responsibilities created some interface problems. Also some problems occurred with the requirements specification not being perfectly clear, and an incomplete lack of understanding of the requirements by CRTF personnel.

2) Control and data acquisition system requirements should be defined before a system is selected to implement those requirements.

   The EMCON D-2 system was selected before the control and data acquisition system requirements were defined because the EMCON D-2 system was available from another program. This imposed limitations on the control system in several areas, e.g., the sampling rate capability is low, and the amount of logic available for automatic sequencing is limited.

3) A single system should be used for control and data acquisitions, instead of three systems (EMCON D-2, Bailey Network 90, and the Accurex).

   During the test program, the interface between the EMCON D-2 system and the Bailey Network 90 system occasionally caused problems. For example, operators were confused about which system was controlling a valve and what the actual valve position was. Also, using multiple systems reduced system reliability; failures in either the EMCON D-2 or the Bailey Network 90 system could (and did at times) prevent testing of the steam generator.

4) More than two operator consoles are needed during checkout.

The EMCON D-2 system had only two operator consoles. During check-out, three or four should have been provided to allow the operators to monitor more closely the instrumentation in the several subsystems.

5) Alarms should be used more effectively during checkout.

The alarms were active for most of the checkout time period. Many alarms were showing up at all times, and so the alarms did not get the operators' attention as much as they should have. It was late in the checkout time period before the alarms were enabled only at the appropriate point in the startup sequence. If this had been done sooner, it could have helped the operators to be aware of an actual alarm condition (and could have prevented some incidents such as salt spills that resulted in delays in the test program).

6) The Equipment Protection System (EPS) should be connected and used earlier in the checkout phase.

The EPS was not installed and connected until near the end of the test program. If it had been installed and used earlier, it could have tripped the plant and prevented some conditions that delayed the test program (e.g., salt spills).

7) Great care must be used to avoid time delays in critical feedback control loops.

In spite of an awareness of the problems that time delays can cause, the initial installation of the thermocouples used in the receiver control algorithm introduced time delays that had a serious detrimental effect on receiver control.

8) Automatic sequences cannot be defined until manual sequences are run and checked out.

Flow charts were prepared for automatic control sequences before MSEE checkout was begun. Such flow charts can be used to obtain an estimate of the amount of logic required, but the actual sequences changed significantly as a result of going through the manual startup and shutdown sequences.

9) Redundancy should be used in the control and data acquisition system hardware.

At times a single failure in either the EMCON D-2 system or the Bailey Network 90 system shut down test operations. The use of dual redundancy could have improved system availability.

10) A better data recording system is needed.

In cases such as salt spills, the data recorded were inadequate for analyzing the failure. A higher data-rate capability should be provided for recording test data, and a sequence-of-events recording capability should be included in the system for postfailure analysis.

3.2 VALVES

We encountered many problems with valves. It is important to pay attention to details in the design, analysis, fabrication, installation, and checkout of all valves--especially salt valves.

The molten salt valves used in the system include globe valves with bellows stem seals from both Kieley and Mueller (K&M) and from Valtek as well as rotary valves from Valtek.

1) Molten salt systems should be designed to allow for leakage through the valves without causing spillage or damage to the system.

   The valves were required to meet the ANSI Class 4 leakage requirement (0.004% of max flow). However, most valves leak internally (through the seat) at a rate higher than 0.004%. When this happens with salt, it is very important to either contain the leakage or to pump it to storage tanks where it can be contained. External leakage of the salt causes problems. We recommend that systems be designed based on the assumption that there will be some internal leakage and that the system should be able to accept the leakage by containing the salt in the sumps or storage tanks so that it does not spill or damage the insulation or pump packings.

2) Proper detailed design, material selection, and quality control are vital to obtaining a reliable bellows stem seal in molten salt valves.

   Bellows type seals appear to be the only acceptable sealing method for globe valves for molten salt service. Limited testing at Martin Marietta indicated that conventional packing will not seal against molten salt in globe valves, although it works in rotary valves.

   Recommended for medium- and high-temperature service are 316 stainless steel and Inconel 625, respectively. Severe corrosion leading to bellows failure was experienced in an MSEE isolation valve where 347 stainless steel was inadvertently used as the bellows material.

The bellows should be of single-ply, seamless or butt-welded construction, with sufficient wall thickness to allow for corrosion. (Material certification should be required for the bellows material.) Multi-ply and/or lap-welded construction is conducive to accelerated corrosion due to entrapment of salt between the layers, as indicated by the failure analysis of the isolation valve mentioned above.

3) The operation of molten salt valves below the freezing point must be avoided to prevent damage to the stem seals.

   It is difficult to completely drain molten salt from the bellows seal. When the salt was frozen between the bellows convolutions, very high stress occurred that caused bellows failures.

4) The Kieley and Mueller valve design used in the MSEE is not recommended for use as control valves in molten salt systems.

   The Kieley and Mueller valves have several serious design problems and are not recommended in salt systems as control valves. They may be acceptable as isolation valves. These valves have small diameter stems (1/2-in. dia), which resulted in severe vibration problems. Also, the shafts were easily bent by using the hand wheel for manual closing and the seats were threaded into the body, making them difficult to remove (stainless steel galling).

5) A detailed thermal analysis of salt valves is required to predict and control temperatures of the valves.

   It is difficult to maintain valve temperature requirements using a standard valve yoke design. The required insulation tends to interfere with positioners and limit switches. Also, the valve temperature tends to be sensitive to wind speed. We believe it is important to work very closely with the valve manufacturer during design. A detailed thermal computer model should be developed to assure that the valve temperature can be maintained with a reasonable amount of trace heating over the expected range of ambient temperatures and wind speeds. It would be desirable to lengthen the yoke to reduce the heat leak and allow adequate room for the insulation, positioner, and switches. It is also desirable to add wind shields. However, because they could interfere with maintenance and adjustments, extending the yoke appears to be a better solution.

   The use of a separate heater on each valve with its own active control adds complexity and cost. However, it should prevent cold temperatures.

6) Valve position indicators were poor quality.

   The position indicators and hardware associated with them were designed as an add-on to the Valtek valves. The brackets supplied would bend, resulting in false readings on the indicators. Eventually they broke. If position indicators are to be relied on for accuracy, more consideration must be given by the manufacturer to their design and method of attachment. The limit switches supplied with the Valtek valves have a dead band from 5 to 25% of the valve stroke. They cannot be relied on when determining the open or closed position of a valve. More accurate limit switches are available and should be considered.

7) The Valtek valve positioner is too sensitive and must be redesigned to reliably control the valve position.

8) Valve assembly must be carefully monitored particularly when it is done in the field.

   Valtek requires disassembly of its valves in order to weld the valve body into the line. As a result, the valves had to be reassembled in the field. Even though this was done by their field engineer, serious errors were made. Some valves were reassembled with the seats installed backwards. The seat in the Valtek valve is machined to fit either way; however, the seal between the seat and the body works only when the seat is installed properly. The result was internal leakage. Closer monitoring of valve reassembly is needed. The need to disassemble the valve for field welding should be investigated.

9) A careful status of the valves during fabrication should be maintained to ensure the delivery date is met.

   Significant problems were encountered with procurement delays for the Valtek valves. When the status was determined near the time of valve delivery, it was found that they were far behind the original schedule. Similar problems were encountered with the Kieley and Mueller valves on the receiver SRE program.

3.3 PUMPS

All three pumps used in the MSEE were of a vertical cantilever design with no bearing or seals in the molten salt. This is our recommended design for molten salt service.

1) Hot Pump - The hot pump performed well and did not present any problems.

2) Cold Pump - During drainback, the pump spins backwards. The supplier was concerned that the impeller nut might be loosened. We solved this problem by changing the procedures so that a minimum of reverse spin was encountered during drainback.

3) Boost Pump - Adequate deflectors and drain holes must be provided in a vertical pump to prevent damage and leakage from the shaft packing.

We had problems freezing the shaft of the boost pump at the packing. It was not possible to get enough trace heating on the packing to keep it above the freezing point because of the pump design. The problem was initially overcome by combinations of "bumping" the pump after shutdown and heating the packing with a torch. Eventually the leakage became excessive. It became necessary to disassemble the pump and add deflectors and more drain holes. The impeller seal had been damaged by rubbing. This was probably caused by shaft bending due to heating the packing area with the torch.

3.4 TRACE HEATING

Reliable trace heating requires a detailed thermal analysis, a long life cable design, and careful installation of the cable and insulation.

1) Heat Trace Cable Design - Considerable progress has been made in heat trace cable design on the MSEE program, but more work should be done. There were nine failures in the system consisting of 216 cables with a total length of 8000 ft.

   The heat trace cable used is a sealed unit with an Inconel 600 sheath and MgO insulation. Of the nine failures, four were in the transition (nichrome to copper) braze joint and five were in the cable. A possible cause for failure in the transition joints was the use of a wrong electrical isolator: most of our cables are single-wire cables, but the electrical isolator was designed for two wires. This resulted in some additional stress in the wire. The actual cause of failures is not known and requires further investigation.

2) Installation - Our installation approach used two cables (one a built-in spare) covered with steel foil, calcium silicate insulation, and passive control. This system generally performed quite well on lines, and on most valves.

   We had some thermal problems with valves exposed to wind especially on the receiver. This problem can be solved by a combination of adding wind shields, using extended yokes on the valves (as discussed earlier), and the use of active control.

   The temperatures were erratic when passive control was used. The calcium silicate insulation originally used was installed by cutting out the inside surfaces, and its geometry was not very well controlled. All of these valves were completely reinsulated later using a fibrous material and put on active control.

3) Maintenance - The cables and transition joints should be made as accessible as possible.

The transition joints on the purge valves are extremely difficult to get to for repair. All insulation on the drain and purge valves is sealed using a nonremovable mudding process. It would be better to use a removable aluminum sheathing.

3.5 STEAM GENERATOR

The steam generator performance was good, but failures of the immersion heater, recirculation pump, and leakage resulted in large system test delays.

1) Thermal/Hydraulic Performance - The SGS performed as predicted. The heat exchanger area and configuration provided the required heat transfer at the expected pressure drops.

2) Design Approach - The U-tube, U-shell design approach with forced circulation performed reliably over the limited operating time. No internal leakage of the water/steam into the salt was detected and the performance requirements were met.

3) Immersion Heater Design - It is important to provide a properly located sheath over-temperature kill to prevent catastrophic failure. The temperature sensor must be located at the highest point so that loss of water will result in heater shutoff before it overheats and either blows up the vessel or fails the heater.

4) Recirculation Pump - In a canned-type pump design, it is important to make sure that proper cooling is provided and that the pump rotation is correct. Other types of pumps should be considered, particularly for larger systems.

5) Water/Steam Leakage - Leakage in a small system is difficult to control. Very small leakage rates can result in a significant loss of drum level, which automatically cuts off the heater in order to prevent burnout. This may cause a significant delay in the next day's warmup sequence of the SGS.

   Mechanical joints should be minimized in the SGS design. We would expect the leakage problem to be less severe in larger systems.

6) Freeze Protection - Freeze protection must be provided on all lines which can trap water including pressure and level sensor lines.

7) Computer Control - We believe that a single distributed digital control system should be used. In the MSEE the Bailey Network 90 was used in addition to the EMCON and Accurex.

8) Transient Steam Flow Control - A steam control valve capable of controlling at low flow rates is needed near the SGS outlet.

Babcock and Wilcox is preparing a separate report on the steam generator which will present more detail on that subsystem.

3.6 RECEIVER DOOR AND APERTURE

The receiver door and passive aperture design has performed as expected. The limited test time so far on the MSEE did not permit a thorough evaluation of the effectiveness of the door seal. Testing should be performed to assess the advantages and/or requirements for a cavity receiver design and the operational necessity of a cavity door.

3.7 SALT SYSTEM CLEANING

All salt lines should be thoroughly flushed with water (chemical cleaning not required). Also, the design of the outlets at the side of tanks should prevent fouling of valves due to contaminants.

During the reporting period, there have been three malfunctions of valves due to solid contaminants. Two of these could have been avoided using a more complete line water flush. The third could have been avoided using a tank side or raised outlet instead of a bottom outlet.

3.8 INSTRUMENTATION

Proper response of transducers and heat tracing of pressure-sensing diaphragms are necessary to meet instrumentation requirements.

Wired-down 1/8-in. diameter sheathed thermocouples used on the receiver had time constants that were much too long for receiver control. These were replaced with 1/16-in. diameter welded-on sheathed thermocouples. Taylor transmitters were found to have inadequate response, and were replaced with Rosemount transmitters. The bubbler type level sensors used in the sumps and hot surge tank worked very well.

3.9 TEST PLANS AND PROCEDURES

Early coordination of test plans and procedures with all contractors involved will minimize test problems.

The MSEE Test Plan was written by Martin Marietta during the first months after they were brought under contract. This plan outlined the specific tests to be conducted in Phase I, test objectives for each test, test prerequisites, responsibility of each participant in the MSEE test program, test priorities, test sequence, and schedule. This plan was distributed in draft form and was reviewed by the program manager for comments. The comments were incorporated and formed the outline for the test procedures.

The MSEE test procedures were then written as detailed steps to perform the planned tests. After the initial draft of each subsystem test procedures were completed, a meeting was held to review the procedures. This meeting was held at CRTF and included the participating contractors responsible for subsystem design, construction, and checkout. These meetings provided valuable information in refining the procedure as well as improving everyone's understanding of the subsystem interactions. The lesson learned was to conduct these test procedure review meetings with all participating subcontractors early in the program. This will benefit all participants with a better understanding of the hardware capabilities.

3.10 CONSTRUCTION

Three lessons learned during construction were:

1) The 316 L stainless steel pipe is commonly used in place of 316 stainless steel, but does not meet the codes at elevated temperatures. This problem of improper substitution of material required a considerable amount of analysis to prove adequate safety of the downcomer.

2) Inadequate access to pipe welds caused problems in making acceptable quality welds.

3) Winds resulted in considerable delay in welding because it effected the inert gas purge required. Prefabrication of welding should be done as much as possible.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The principal objectives of Phase I have been met including system design, equipment modifications and assembly, subsystem checkout, and system performance verification tests. The MSEE is now ready for Phase II operations.

The Phase I tests have demonstrated (for the first time in the U.S.) the technical feasibility of operating a solar central receiver power plant using molten nitrate salt as the receiver heat transfer fluid and thermal storage medium. Specific conclusions related to the continuing development of molten salt central receiver technology are given below.

1) The system hydraulics performed as predicted. Over 400 feet of piping, a salt boost pump, a new boiler feed pump, a riser and downcomer, surge tanks and valves were required to interconnect the receiver, thermal storage, steam generator, and EPGS.

2) There have been numerous problems encountered with salt valves, indicating the need for improvement in the design of valves for commercial systems. We also believe that it is important to design the system to accommodate small valve leaks, since it appears improbable that internal leakage in molten salt valves can be completely eliminated.

3) Vertical cantilever pumps with no bearings or seals in contact with the salt proved to be reliable. Care must be exercised in the design to minimize salt leakage and freezing at the shaft packing.

4) Most of the trace heating on MSEE performed well. Passive control proved to be adequate on lines. Significant problems were encountered with the trace heating of valves, indicating the need for development and design improvement in this area.

5) The passive thermal design of the aperture proved to be a viable and simpler alternative to the previously used water-cooled aperture frame on the receiver SRE.

6) During checkout of the MSEE models in HELIOS, TRASYS, and DOMAIN computer programs, it has become evident that the calculated flux density distributions can be closely matched with measurements (obtained during the SRE program) by adjusting a single-input parameter: the effective intercept angle of the sun. Since the optimum heliostat aiming strategy of a given solar thermal plant is also a strong function of this parameter, this observation could potentially lead to a rather simple in-the-field procedure for flux adjustments using reaiming of heliostats on the basis of a limited number of flux measurements. Such a procedure has been proposed in Reference 5, (Vol II, pp 5-40 and 5-41).

7) Within the constraints imposed by the use of existing hardware, the Master Control Subsystem (MCS) performed satisfactorily, demonstrating the technical feasibility of using a distributed digital control system to operate a molten salt central receiver power plant. The equipment protection system (EPS) is a valuable independent backup to the MCS.

8) Chemical analyses conducted by Olin indicated no significant accumulation of carbonates or hydroxides in the salt during its total usage including the storage SRE (starting January 1982) and the MSEE Phase I operations. Although encouraging, these data are based on limited exposure to high temperatures (above 700°F), and the analyses will be continued through the remainder of the program in order to obtain more data.

4.2 RECOMMENDATIONS

The following list of recommended R&D has been derived from our experience with MSEE Phase I and its preceding SREs. The items are listed in priority.

1) Full-Scale Molten Salt Component Design and Durability Tests

   Vertical cantilever type pump designs should be considered especially for the hot salt pump. They avoid problems associated with bearings and seals in contact with the salt, which may contain large amounts of particulate contaminants including metals and metallic oxides.

   Globe valve packing development appears to have limited probability of success. There are a number of different types of bellow seal designs that should be considered including welded types.

   Close cooperation with component designers is required, particularly in disciplines in which the component suppliers are weak, such as thermal, material compatibility, and creep-fatigue problems.

2) Receiver Reliability Enhancement

   Tube Durability - Reliable techniques for predicting tube life are lacking. The analytical methods are controversial. The use of a suitable element test to evaluate "worst case" and average tubes should be considered. In view of tube and panel replacement techniques under consideration in receiver design, the life criteria should be reevaluated. For example, the 30-year requirement might be applied only to the average tube, with a shorter life (e.g., 5 years) permitted for the "worst case" situation.

Tube Heat Flux and Temperature Measurement - The measurement of actual tube temperature and flux distributions is required to verify and supplement analytical predictions, and to take the necessary corrective action if over-temperatures are indicated. We feel that it is possible to design an optical system to examine the various parts of the spectrum to determine the temperature and flux distributions. A 1/4 in. resolution on tubes may be required because of the steep temperature gradients. Non-Lambertian emission of the panels and other skewed heating effects must be considered when designing and locating the instruments.

Receiver Cold Start - The feasibility of starting a molten salt receiver without the use of warmup heliostats or keeping the entire cavity warm should be investigated. Such a technique would minimize startup times and possibly eliminate the need for a cavity door.

Preliminary analyses indicate that such an approach would be feasible on commercial receivers using 1-1/2 to 2.0 in. tubes, but would be marginal for the MSEE receiver's 3/4 in. tubes. The following tests are recommended:

a) Run salt through a full-scale tube without preheating, simulating realistic initial temperatures and flow rates. Determine extent of freezing by pressure drop measurements.

b) Install heaters in the MSEE cavity; conduct cold start tests at successively lower temperatures starting with a 500°F cavity; and determine amount of blockage due to freezing by pressure drop measurements.

Receiver Tube and Panel Replacement - Commercial receivers should be designed so that either individual tubes or panels can be replaced in a timely and cost-effective manner. In order to facilitate this approach, tube-to-tube welding and other attachments to the tubes should be minimized. The running of continuous welds between tubes preferred by boiler manufacturers is not recommended because of the following reasons: (a) no gas seal is required as in a boiler (for protection of the structure from corrosive gases); (b) tube replacement is made difficult by continuous welding; (c) the gap between tubes must be kept small to avoid high local temperature and thermal stresses; (d) continuous welding results in a large weld-affected zone; and (e) the process requires expensive tooling.

Optimize Receiver Operation - A study should be conducted to determine the tradeoff between energy collected, and the corresponding reduction in creep-fatigue life, during cloud transient operation. The results may indicate the desirability of shutting down during cloud transients imposing a large number of fatigue cycles; or, alternatively, survival modes of operation involving lower than design salt outlet temperatures.

Elimination of the Cavity Door - This would lead to a simpler cavity design, hence a more reliable system. However, the elimination of the door is contingent on the development of cold start techniques mentioned previously, and on the acceptability of eliminating the protection from inclement weather provided by the door.

3) Hot Storage Tank Reliability Enhancement

The internally insulated hot tank appears to be a reasonably economical design approach for large commercial storage tanks. To assure the reliability of this design, element tests should be conducted to: (a) assess the impact of creep-fatigue, and (b) to develop reliable means of leak detection.

4) Receiver Control Verification and Improvement

Control technology development towards the ultimate goal of unmanned operation of molten salt central receiver power plants should be continued, using the MSEE as a test bed. The receiver analytical model and the control algorithm should be verified by comparison with test data obtained under a variety of cloud transients; the model and algorithm should be improved as required, and the improvement verified by tests.

5) Receiver Fast Start

As an alternative to receiver cold start discussed above, a receiver fast-start procedure should be developed by maintaining the receiver in "hot standby" condition during the night by flowing salt through the panels with the door closed. Fast start could commerce at 10% available power with 20% flow, followed by heliostat rampup and automatic control.

6) Trace Heater Durability and Optimization

Consideration should be given to the following to improve trace heater design and performance: (a) control of heat paths through the thermal insulation/isolation of the heat traced item by the use of detailed thermal analyses and installation control (uneven distribution of heat flow to the environment can increase sensitivity of temperature to winds); (b) de-rate the heaters to improve their reliability; (c) during installation, assure access to the transition sections for repair; (d) avoid bonding heaters down, since reliable bonds are difficult to maintain with the geometries involved, and at molten salt temperatures; (e) proportional controllers should be considered for active control to minimize fatigue in the wires, especially at junctions; (f) enforce rigid quality control of manufacturing, installation, and insulation processes and procedures.

7) Freeze/Thaw Damage

Freezing problems have been encountered in every molten salt system Martin Marietta Corporation has operated. A common method of removing the frozen salt from the system is by thawing by using an external heat source. Since salt expands upon melting, this procedure can result in damaging the system if care is not exercised to ensure that the thawing proceeds along the interface between the frozen salt and the liquid in the rest of the system. A preliminary investigation has indicated that damage in steel tubes or pipes will be in the form of plastic deformation resulting in a decrease in the creep-fatigue life of the system, or eventual rupture upon repeated freeze-thaw cycles. It is recommended that this investigation be continued to characterize the conditions leading to damage, in order to develop safe thawing procedures.

8) Freezing Transients

An analytical and experimental program should be conducted to evaluate and characterize freezing transients in salt systems. This investigation should be conducted in part to support receiver cold start and fast start technique development, and in part to minimize or eliminate heat trace requirements in some salt systems.

9) Recommended Test Items for Phases II and III of MSEE

Verify effectiveness of multiple aim points in reducing peak fluxes on the receiver panels, by comparing test data with analyses.

Evaluate door thermal performance by conducting heat balance tests on the cavity with the door closed.

Continue systematic gathering of data pertaining to parasitic losses; determine how they scale to commercial systems, and how they can be minimized.

Determine the feasibility of eliminating level control from the cold surge tank by operating it as a "blow-down" tank. This would simplify the system.

Determine earliest startup time using the heliostat warmup technique.

Conduct in situ convection tests at various power levels using the technique developed during the receiver SRE and reported in Reference 7.

Conduct tests, as required, to support Items 2, 4, 5, 6 and 8 above.

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6) Conference Memorandum, MSEE Technical Committee Meeting Minutes of August 23, 1983.

7) K.S. Beninga and T. Buna; "In Situ Evaluation of Convection Losses in Molten Salt Receivers." Presented at the 1984 Annual Meeting of the ASES, Anaheim, CA.

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