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Molten Salt Solar-Electric Experiment

Volume 1:
Testing, Operation, and Evaluation

Prepared by
McDonnell Douglas Astronautics Company
Huntington Beach, California

REPORT SUMMARY

SUBJECTS Power system planning and engineering / Advanced delivery system technology

TOPICS

Solar energy
Solar power plants
Technology assessment
Solar-thermal conversion
Digital systems

AUDIENCE R&D engineers / Generation planners

Molten Salt Solar-Electric Experiment

Volumes 1 and 2

The Molten Salt Electric Experiment assembled and tested the first full-system experiment of a solar central receiver plant employing molten nitrate salt as the heat transport fluid and thermal storage medium. This report focuses on the last two phases of the project: testing/operation and evaluation. Overall project data will help utilities evaluate the central receiver concept's technical status, development requirements, and potential as a renewable source of electricity.

BACKGROUND The Molten Salt Electric Experiment (MSEE) employs a central receiver that converts solar energy to electricity, using molten salt and water/steam as the working fluids. The first major power plant installation employing a central receiver was a 10-MWe pilot plant, operated by Southern California Edison, which used water/steam as the thermal transport fluid in the receiver. Subsequent analysis and subsystem research showed the possible advantages of an advanced central receiver concept that uses molten nitrate salt for thermal transport and storage. As a result, EPRI, DOE, and a number of industrial and utility cosponsors decided to assess the concept.

OBJECTIVES To assess the capability, flexibility, and simplicity of the molten salt central receiver system concept; to provide performance information and operating experience; and to create a test-bed for component and system development.

APPROACH The MSEE team constructed and tested a full-system central receiver solar power plant at DOE's Central Receiver Test Facility (CRTF) in New Mexico. The CRTF provided the heliostat field, tower, controls, and heat rejection; the receiver and thermal storage subsystems were constructed from previous subsystem experiments and hardware. A molten salt–heated steam generator was the only equipment developed for the experiment. A refurbished 750-kWe marine turbine completed the plant. An engineering test and evaluation program was conducted. Teams of industry personnel trained to operate the MSEE and its digital control system evaluated the concept from a utility perspective.

RESULTS Results indicate that the molten salt central receiver solar power system is technically feasible and has certain attractive features, but it requires engineering development and performance verification to establish its potential for economical power production. Molten nitrate salt proved to be an effective, inexpensive heat transfer fluid for energy collection and storage. The experiment also showed that molten salt storage can be used to decouple solar energy collection from power production, permitting collection to follow solar availability and power production to follow user demand. Distributed digital controls were highly effective, allowing for the automation of many operating sequences. The high melting temperature, however, of the heat transfer salt (above 430°F) caused problems in maintaining the equipment at temperatures required for startup. This finding raised concern about the ultimate complexity and operating cost of the system. In addition, the nonoptimized design of the power system (because of its utilization of previously existing equipment) makes a meaningful assessment of the potential economic viability of the concept difficult.

Volume 1 of this report describes the test and evaluation program. Volume 2 provides addenda.

EPRI PERSPECTIVE

The MSEE demonstrated that the molten salt central receiver solar power system is technically feasible and shows promise, but it requires further development and performance verification to determine its potential for economic power production. It also demonstrates the particular effectiveness of the digital control system and provides utility personnel and those involved in solar power plant development with a better understanding of the molten salt central receiver concept. However, a definitive assessment of the molten salt central receiver concept awaits further experience with an optimized power system. Related EPRI reports include AP-3285, AP-4608, and GS-6573.

PROJECT

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Molten Salt Solar-Electric Experiment
Volume 1: Testing, Operation, and Evaluation

GS-6577, Volume 1
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ABSTRACT

The Molten Salt Electric Experiment, built at the Department of Energy's Central Receiver Test Facility located in Albuquerque, New Mexico, was 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 experiment was sponsored jointly by the Department of Energy, the Electric Power Research Institute and a consortium of utilities and industry. The main purpose of the project was to make a preliminary, experimental evaluation of this concept's potential as applied to a utility power plant.

In summary, the molten salt central receiver solar power system is technically feasible, and has certain attractive features. It does, however, require engineering development and performance verification in order to establish its potential for economical power production.

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SUMMARY

INTRODUCTION

Research and development programs on solar thermal central receiver systems were initiated in the early 1970s. The first central receiver system in the United States (Solar One) demonstrated the use of water and steam as a heat transfer fluid in the receiver. Subsequent studies and test programs investigated molten salt, liquid sodium, and hot air as heat transfer media. Although all have advantages, molten nitrate salt is a good choice for solar electric power plants with thermal storage.

To prove the technical feasibility of such a system, a full-system power plant called the Molten Salt Electric Experiment (MSEE) was built at the Department of Energy's (DOE) Central Receiver Test Facility (CRTF) located at Kirtland Air Force Base, Albuquerque, New Mexico, with the support of a consortium of utilities, industries, the U.S. Department of Energy, Sandia National Laboratories, and the Electric Power Research Institute (EPRI).

The overall objectives for the MSEE were:

1. To verify capability, flexibility, and simplicity of molten salt central receiver systems.
2. To provide performance information and operating experience.
3. To create a test bed for future component and system development.

This experiment was conducted in the following three phases:

I. Construction and Integration, September 1982-June 1984. This phase included the design, construction, installation, checkout, and verification effort.

II. Testing and Training, June 1984-December 1984. This phase included system characterization tests and the operation and evaluation of the system by utility and industry personnel.

III. Integrated System Operation, January 1985-May 1985. During this phase, the system was operated for maximum energy collection and utilization.

This report documents Phases II and III. Following the integrated system operation test, the receiver was tested in the exposed configuration in June and July 1985 to obtain data for comparison with the cavity configuration. This effort is documented separately. Following the MSEE, the Molten Salt Subsystem Component Test Experiment (MSS/CTE) will be implemented using a model receiver whose performance is to model that of a commercial power plant.

MSEE SYSTEM DESCRIPTION

The MSEE converts solar energy to electricity using molten salt and water/steam as the working fluids. Molten nitrate salt (60 percent $NaNO_3$, 40 percent KNO_3) is the energy collection and storage medium. The energy stored in the molten salt is then transferred to water and steam for use in a conventional Rankine steam cycle to generate electricity. Figure S-1 depicts the system schematic. The receiver, located at the top of the CRTF tower, receives concentrated solar energy from the collector field. Molten salt from the "cold" (570°F) storage tank, located at ground level, is circulated through the receiver and heated to 1,050°F. Salt then flows through a downcomer, and is throttled into the hot salt storage tank. Hot salt from storage is pumped through the steam generator and evaporator and is returned to the cold storage tank. Main steam from the steam generator is used to drive a conventional steam turbine-generator. The electricity generated is supplied into a utility grid network. The system is divided into the following subsystems:

- The Collector Subsystem redirects, concentrates, and focuses solar radiation onto the tower-mounted receiver. This subsystem consists of 221 two-axis tracking heliostats (211 used for MSEE) located north of the receiver tower. Under optimum insolation and heliostat conditions, the heliostat field can concentrate approximately 5.5 megawatts, thermal, onto the receiver.

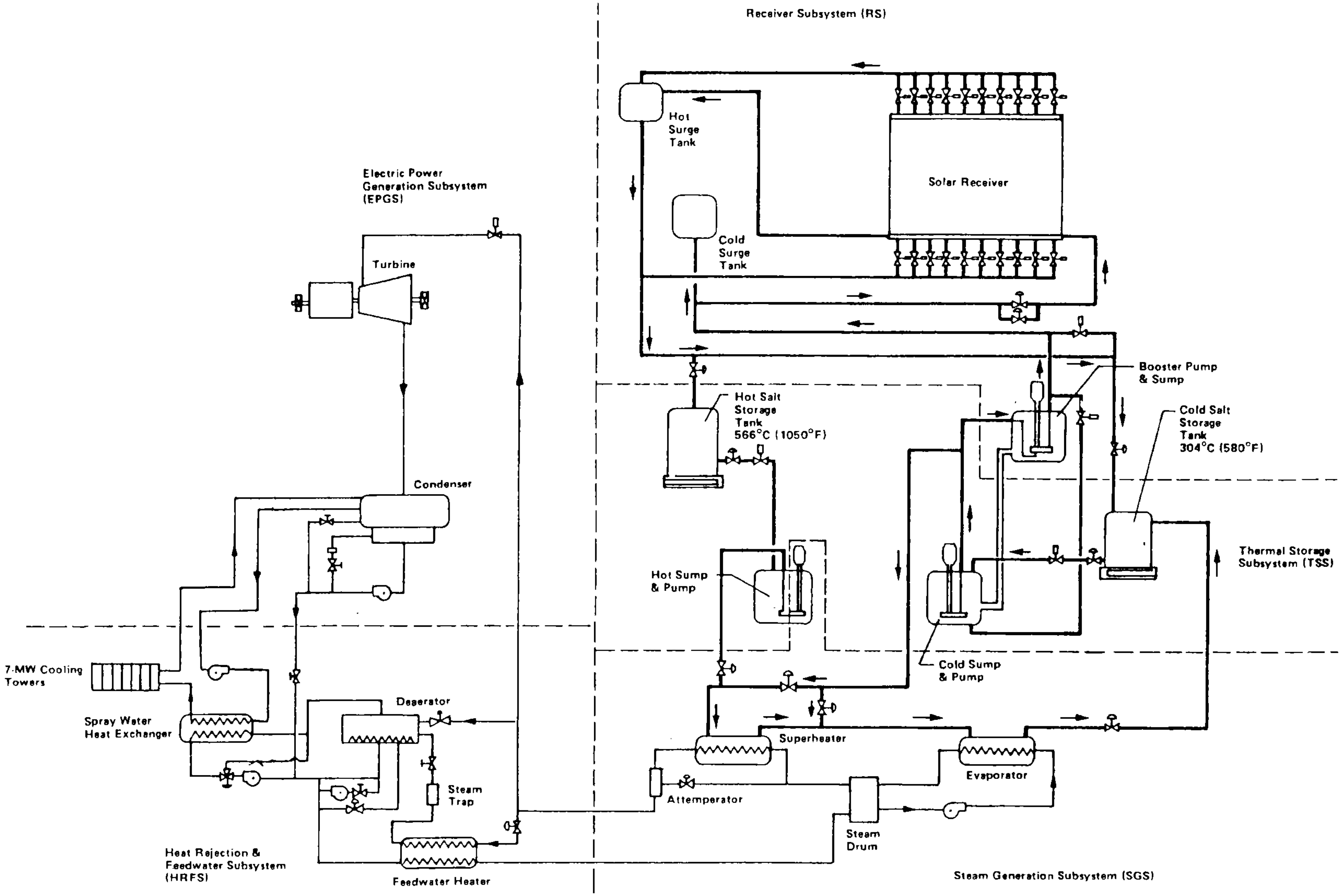

Figure S-1. MSEE System Schematic

- The Receiver Subsystem, located at the top of the CRTF tower, intercepts and absorbs concentrated energy from the heliostat field and transfers this energy to the molten salt. This subsystem consists of the receiver absorber panel, cavity enclosure with one vertical aperture door, insulation, heat tracing, cold surge tank, booster pump, hot surge tank, overflow tank, instrumentation, and control valves.

- The Thermal Storage Subsystem decouples the energy collection process from the energy conversion process. It provides a cold (570°F) salt supply source for the receiver and a hot (1,050°F) salt supply source for the steam generator; it absorbs or supplies the differences in their flow demands. Because the thermal storage capacity is 5.8 megawatt-hours, thermal, there is a limited capacity for "resource shifting." This subsystem includes the hot and cold salt storage tanks, propane-fired salt heater, the cold salt pump, and the hot and cold salt pumps.

- The Steam Generation Subsystem transfers heat from the molten salt to produce superheated steam for the turbine-generator. This subsystem includes an evaporator, steam drum, boiler water recirculation pump, superheater, attemperator, and the hot salt pump.

- The Heat Rejection and Feedwater Subsystem rejects waste heat to the atmosphere, and pressurizes, heats and deaerates the condensate to the final feedwater conditions. This subsystem includes six air cooling towers, circulating water pump, deaerator, spray water heat exchanger, spray water pump, feedwater pump, feedwater heater, demineralizers, chemical feeders, water analyzers, and condensate makeup pump.

- The Electric Power Generation Subsystem converts the enthalpy in the main steam to electricity. This subsystem includes the steam turbine, electric generator, electric power equipment, condenser, condensate pump and storage tank.

- The Master Control Subsystem consists of an EMCON-D2 for primary system control. A Bailey Network 90 system is used to directly control the Steam Generation Subsystem. The Network 90 operation and control functions are directed from the EMCON console through a hardwired interface. Additionally, an Acurex Data Logger collects and displays all the temperature measurements relating to the heat tracing and data instrumentation. The logger also performs certain logical control functions, such as activation of heat trace circuitry and generation of go/no-go signals for the EMCON system. The data acquisition system utilizes both the EMCON-D2 and Hewlett-Packard HP-1000. EMCON collects the data and HP-1000 stores and displays data.

- The Equipment Protection Subsystem is an independent hardwired relay system using dedicated sensors. It is designed to safely shut down the MSEE in the event of any potentially unsafe condition. The relay units are independent of the EMCON and the Network 90 control systems.

PROJECT RESULTS

Results of the MSEE project are summarized in the following tables at the end of this section: Table S-1, Design Configuration Evaluation; Table S-2, Performance; Table S-3, Operational Results; and Table S-4, Component Reliability.

Results of the MSEE test program, as well as other observations on the system, are briefly summarized in the second (MSEE Test Results) column of each table. Many of the problems encountered were due to specific facility limitations; these are described in the third (Discussion) column. Corrective actions taken during the test program are also given in this column. Applicability of the results to commercial systems and design recommendations are given in the fourth column. Recommendations for further testing and development to be accomplished prior to considering commercial installations are given in the last column.

ASSESSMENT OF RESULTS

The MSEE contributed substantially to our knowledge and understanding of both the potential and the problems of a molten salt central receiver solar power plant. An overall assessment of the test program follows:

1. The system has been demonstrated to be technically feasible.
2. Two tank molten salt storage decouples solar energy collection from power production, permitting the collection to follow solar availability and power production to follow user demand.
3. Molten nitrate salt is an effective, inexpensive heat transfer fluid for energy collection and storage.

4. Distributed digital controls were highly effective, and many operating sequences were automated.

5. Thermal and hydraulic performance can be accurately predicted.

6. System startup can be accomplished without excessive loss of collectable solar energy.

7. The high melting point of the nitrate heat transfer salt (430°F to 460°F) poses important design issues while maintaining the temperatures required for startup.

8. Net positive energy production has not been demonstrated, but it is predicted for larger scale installations because parasitics will not increase as rapidly as energy production.

9. Lifetime limitations of components were not measured or observed because of the limited duration of the project.

10. Most components required for this plant are available; further development is required for instrumentation and large-scale salt valves.

In summary, the molten salt central receiver solar power system is technically feasible, and has certain attractive features. It does, however, require engineering development and performance verification in order to establish its potential for economical power production.

RECOMMENDATIONS

Based on this technical assessment, the following needs to be accomplished prior to the construction of commercial molten salt central receivers: development and qualification of certain components; some modifications to the current system configurations; and the development of alternate means of maintaining the system warm for startup.

Specific recommendations follow in five categories:

1. Component Development

   - Develop and qualify, at the full commercial plant scale, pumps, valves, and instrumentation for molten nitrate salt application. All requirements, particularly cyclic operation, should be covered.

- Design and qualify water/steam components for the cyclic operation required in solar plants.

2. Subsystem Tests

   - Build and test, preferably at the CRTF, a model receiver that incorporates the potential improvements identified in this program.

   - Develop and confirm, in a subsystem test, alternative methods of maintaining the system warm overnight. This objective could be combined with those of the model receiver test described in the preceding paragraph.

3. Design

   - Work toward greater design simplicity. Reduce the number of components, particularly the receiver purge and drain valves and temperature monitoring instrumentation.

   - Include the requirement for cyclic operation in all component specifications and loop designs.

   - Design all equipment for the most rapid startup and shutdown.

4. Programmatic

   - Include a quality assurance plan that covers both hardware manufacture and installation.

5. Full-System Test

   - Conduct a large-scale (10 to 30 megawatts electric) system test that incorporates the results of all of the above developments.

TABLE S-1 - DESIGN CONFIGURATION EVALUATION

COMPONENT	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
SYSTEM	System operated as designed.	Most problems were due to the use of certain previously existing equipment.	Design all equipment for cyclic operation.	Test all recommended configuration features in a full system experiment.
RECEIVER	General configuration adequate but complex.	Procedures were modified to operate receiver as designed.	2 surge tank configuration recommended. Try to eliminate purge and drain valves. Consider multi-stage single pump.	
THERMAL STORAGE	2 tank configuration was successful.	Modifications were performed to allow transfer of salt between tanks.	Use 2 tank configuration. Provide for salt transfer between tanks.	
STEAM GENERATION	Functioned over full operating range. Some failures and control difficulties.	All problems can be accommodated by design.	Forced recirculation was qualified for a molten salt steam generator.	
HEAT REJECTION AND FEEDWATER	- - - - -	Configuration not designed to model commercial system.	Use conventional design practice but include cyclic operating requirements.	
ELECTRIC POWER GENERATION	40 year old turbine failed prior to systems test.	Turbine repair not essential to solar technology demonstration. Turbine performance inferred from existing Solar One data.	Use state-of-the-art turbine with extraction ports.	
MASTER CONTROL	Digital control functioned effectively and was well received by utility operators. Limitations due to use of multiple systems and moderate capability.	Used existing equipment (1976 technology).	Use state-of-the-art digital system.	

TABLE S-2 - PERFORMANCE

PERFORMANCE FACTORS	MSEE TEST RESULTS			DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM	RECOMMENDATION FOR FURTHER TESTING
	DESIGN POINT	DAILY	PROJECTED ANNUAL			
COLLECTION EFFICIENCY	0.494	0.362	0.349	Predictions were: 0.563, 0.413 and 0.411.	Analytical Predictions can be used within a reasonable confidence level to estimate efficiencies.	Develop and test subsystem configurations with higher efficiency.
				Test results compared well with predictions (to within 15 percent).	Higher efficiencies are possible.	
				Low heliostat reflectivity (0.805) included in collection efficiency.		
THERMAL EFFICIENCY (Storage and SGS)	0.967	0.960	0.905	Predictions were: 0.993, 0.978 and 0.966.	Same as above.	
STEAM-TO-ELECTRIC CONVERSION EFFICIENCY	0.176			Prediction was 0.240. 0.335 used to calculate output during Integrated System tests based on measured Solar One results adjusted for MSEE steam conditions.	Not applicable.	
PARASITICS	311 KWe	5525 KWHr 24 hr day	1847 MWHr Year	High parasitic power due to small size of installation and non-optimized design.	Parasitic Power is a major factor to consider in commercial plant design.	Test alternative features selected for the commercial system design.
o Trace Heating (%)	19	37	43			
o Salt Pumps (%)	27	17	14	Steam cycle and balance of plant values are based on normalized Solar One results.	Less parasitic power is possible with optimized design at commercial size.	
o Collector Field and Controls (%)	17	12	9			
o SGS Circulation Pump & Heater (%)	2	6	8	Overnight hold standby power requirements contributed substantially to daily and annual parasitics.	Alternative heat sources such as circulating hot salt, should be evaluated for overnight standby.	
o Steam Cycle and Balance of Plant(%)	35	28	26			

TABLE S-3 - OPERATIONAL RESULTS (PAGE 1)

OPERATION	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM	RECOMMENDATION FOR FURTHER TESTING DESIGN
WARM UP - RECEIVER PANEL	Efficient early morning warmup with heliostats demonstrated (50 minutes after flat horizon* sunrise).	Uses only 0.3% of clear day's energy.	Warmup using heliostats is tentatively recommended. Should be compared with overnight salt flow.	Refine and improve warmup patterns.
STARTUP				
Receiver	Rapid receiver startup demonstrated (65 minutes after flat horizon* sunrise).	Minimum loss of useful energy.	Applicable.	Demonstrate for new configurations simulating a commercial design.
	Flexible operations demonstrated - could start SGS first.	Startup can be sequenced according to inventory in thermal storage.	Flexibility is available.	Automated, simultaneous startup with SGS.
	Startup frequently delayed due to "cold" salt components.	Windshielding, new insulation and active trace heater controls reduced frequency of delays.	Would not apply if recommendation of flowing salt for overnight hold is adopted.	Test with selected overnight hold condition.
Steam Generator	55 minute startup demonstrated.	40 minutes is the minimum based on warmup rates.	Startup of commercial size unit could be longer.	Demonstrate most rapid startup.
	Startup sequenced with EPGS.	Turbine startup simulated for integrated system test due to prior turbine failure.	Steam generator and turbine generator subsystems should be designed for simultaneous startup.	Test the automated, integrated startup sequence.
HRFS and EPGS	105 minutes required from pretest to full power.	Excessive startup time due to facility limitations and sequencing with SGS.	Startup of commercial scale unit could be longer. Integrated startup (see above) would reduce this time.	
STEADY STATE	Full system operation was stable and required minimum operator intervention	See discussions under decoupling and automated operation.	MSEE demonstration is applicable to commrcial systems.	

*Actual sunrise over local mountains is 15 minutes later than flat horizon.

TABLE S-3 - OPERATIONAL RESULTS (PAGE 2)

OPERATION	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM	RECOMMENDATION FOR FURTHER TESTING DESIGN
TRANSIENTS	Receiver outlet temperature derated 50°F during partly cloudy conditions.	Receiver controls allowed up to 70°F temperature overshoot with severe cloud transients.	Not applicable if control alogrithm is based on flux measurements. An indirect flux measurement method is preferred to anticipate changes in flow requirements.	Test with recommended control algorithm.
	Receiver turndown ratio limited to 3 to 1.	3 to 1 turndown in specification. Limit imposed in order to increase flow rapidly enough following a cloud transient.	5 to 1 turndown ratio should be used. Design control system to accommodate.	Test with 5 to 1 turndown.
DECOUPLING OF ENERGY COLLECTION AND UTILIZATION	Fully demonstrated.	Allowed flexible startup and operation and permitted all subsystems to operate at maximum effieiency.	Applicable. Storage can be selected for desired duty cycle.	
AUTOMATED OPERATION				
Receiver Loop	Fully automated.	Routinely performed by utility operators.	Applicable.	Test new configurations and control alogrithms.
Steam Generator	Most operations automated.	Manual operations were required for transitions	Full automation can be achieved.	Test fully automated operation.
HRFS and EPGS	Not automated.	Facility and control system limitations prevented automated operation.	Full automation could be achieved.	Test automated operation.
OVERNIGHT HOLD				
Receiver	Drained and maintained warm with trace heaters (except receiver panel). System was frequently "cold" by morning.	Excessive heat loss due to high winds, gaps in insulation, and trace heater failures.	Alternatives to electric trace heating should be investigated.	Test selected approach.
Steam Generator	Salt loop drained and maintained warm with trace heaters.	Electric trace heaters have high parasitic power usage and reliability problems.	See recommendations for receiver.	Test selected approach.
	Electric startup heater used to maintain water temperature above salt freezing point throughout the night.	Cold warmup from ambient would have taken approximately 6 hours.	Not required if overnight salt circulation is used.	
HRFS and EPGS	Restart on daily basis caused various problems.	Much of the equipment was not designed for cyclic operation.	Design for cyclic operation to accommodate daily startup and shutdown.	

TABLE S-4 - COMPONENT RELIABILITY

COMPONENT	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
TRACE HEATERS	More than 25 failures occurred.	Use of redundant heaters and repairs kept system operational.	Install at least dual redundant heaters and keep junctions exposed. Consider alternatives recommended for overnight hold under operations.	Test selected design.
SALT PUMPS	No problems with hot salt pump. High internal leakage in cold pump. Boost pump freeze up and bearing failure.	Vertical cantilever pumps performed well.	Use vertical cantilever pumps. Design for full head requirements.	
SALT VALVES	Problems with internal and external leakage.	Operating procedures revised to accommodate internal leakage. Significant downtime required to fix external leakage.	Design system to accept internal leakage. Add isolation valves.	Develop and test commercial size valves and packing material.
WATER/STEAM EQUIPMENT	Numerous leaks and problems.	Existing equipment used.	Design for cyclic operation. This is a major new requirement for many of the components.	Qualify for cyclic operation
INSTRUMENTATION	Procedures changed to operate with inaccurate readings.	See text, Section 3.	Design to eliminate problems.	Test improved transducers.
MASTER CONTROL	Integration of existing hardware with limited compatibility resulted in numerous problems.	Caused significant downtime.	Include automatic diagnostic system and sufficient spares. Utilize results of ongoing development of digital controls for power plants.	Test system with automatic diagnostics.

Section 1

INTRODUCTION

BACKGROUND

Research and development programs on solar thermal central receiver systems were initiated in the early 1970s. The first central receiver system in the United States (Solar One) demonstrated the use of water and steam as a heat transfer fluid in the receiver. Subsequent studies and test programs investigated molten salt, liquid sodium, and hot air as heat transfer media. Although all have advantages, molten nitrate salt is a good choice for solar power plants with thermal storage.

To prove the technical feasibility of such a system, a full-system power plant called the Molten Salt Electric Experiment (MSEE) was built at the Department of Energy (DOE) Central Receiver Test Facility (CRTF) located at Kirtland Air Force Base, Albuquerque, New Mexico. The CRTF heliostat field concentrates reflected solar energy onto a molten salt cooled solar receiver located on top of the 200-foot CRTF test tower. Molten salt is pumped from a "cold" salt storage tank at ground level up the tower to the solar receiver. There it is heated by concentrated solar energy and then returns to a "hot" salt storage tank at ground level. A hot salt pump delivers salt from the hot tank to a molten salt steam generator. The generator produces steam to power a turbine-generator which, in turn, feeds electricity into the local power grid.

This project was conducted in the following three phases:

I. Construction and Integration, September 1982-June 1984. This phase included the design, construction, installation, checkout, and verification efforts. The results of this phase are documented in References 1, 2, and 3.

II. Testing and Training, June 1984-December 1984. This phase included system characterization tests and the operation and evaluation of the system by utility and industry personnel.

III. Integrated System Operation, January 1985-May 1985. During this phase, the system was operated for maximum energy collection and utilization.

This report documents Phases II and III. Following the integrated system operation test, the receiver was tested in the exposed configuration in June and July 1985 to obtain data for comparison to the cavity configuration. This effort is documented separately.

A consortium consisting of utilities, industries, and EPRI helped construct and support operation of the experiment. The consortium supplied nearly half of the project's funding through cash contributions or donations of engineering services. The balance of project funding was supplied by the DOE, through Sandia National Laboratories.

The Testing and Training and Integrated System Operation efforts were conducted by McDonnell Douglas Astronautics Company (MDAC) under contract to EPRI.

The following organizations participated in the MSEE:

Arizona Public Service Company
Bechtel Power Corporation
Babcock & Wilcox
Black and Veatch Consulting Engineers
U.S. Department of Energy
Electric Power Research Institute
Foster Wheeler Company
Martin Marietta Corporation
McDonnell Douglas Astronautics Company
Olin Chemical Group
Pacific Gas & Electric Company
Public Service Company of New Mexico
Sandia National Laboratories
Southern California Edison Company

OBJECTIVES

The MSEE was the first full-system feasibility demonstration of a solar thermal central receiver electric power plant using molten nitrate salt for energy collection and storage. The test and evaluation program was designed to provide data and experience for use in the design and operation of future commercial scale plants. Operation of the MSEE by utility and industry personnel made a significant contribution to this goal by providing familiarization with the operation of this type of solar power plant. The integrated system operation portion of MSEE demonstrated efficient early morning startup and the capability for energy collection and utilization over a wide range of solar conditions.

MSEE Overall Objectives

The following overall objectives were established for the MSEE project:

1. Verify capability, flexibility, and simplicity of the molten salt central receiver.
2. Provide performance information and operating experience.
3. Create a test bed for future component and system development.

Construction and Integration Specific Objectives

The specific objectives for the construction and integration of MSEE are as follows:

1. Verify that the system operates as an integrated unit.
2. Demonstrate performance in all operating modes.
3. Provide baseline characterization for the system.
4. Develop safe operating procedures for follow-on testing in engineering testing and training operations.
5. Train test personnel to operate the MSEE.
6. Check out the system for all engineering testing and training operating conditions.

Testing and Training General Objectives

The primary objectives were to test and evaluate the MSEE and train operators in the operation of the MSEE and are as follows:

1. Obtain, evaluate, and document performance data for each subsystem and total system interaction sufficient to verify design and identify uncertainties.
2. Define the operating range, flexibility, and limitations of the system as installed.
3. Document performance results and evaluations that may be used for scaleup.
4. Identify and prioritize areas that need additional development.
5. Verify that equipment protection system functions properly in all modes of operation.
6. Provide training and hands-on operating experience for utility and industry personnel.

Specific Goals for Testing and Training

The following specific goals were developed by the MSEE Technical Committee:

1. Demonstrate system performance:

   --At design point operating conditions for all subsystems.
   --Of control concept and subsystem interaction.
   --To evaluate overall performance efficiency.

2. Determine the response of the system to deviations (transients) from design conditions:

   --Naturally occurring, including clouds, and unanticipated outages.

   --Controlled disturbances to determine limits (cold and hot startups, shutdowns, etc.).

3. Develop the appropriate operating strategies to maximize solar energy utilization.

4. Collect thermal/hydraulic and thermal/mechanical design data to support design assumptions and to determine acceptable heatup and cooldown rates of steam generation subsystem.

5. Provide data to evaluate the mechanical reliability of individual components through:

   --Regular inspections (visual and nondestructive).

   --Post-failure examination.

   --A plan for post-test inspections of critical components for corrosion, erosion, wear, cracking, etc.

6. Provide performance data to compare analytical predictions with operational data, and update the control models and the system models where required.

7. Document results and actions via:

   -Interim quarterly presentations covering results, conclusions and action plans.

   --Final MSEE report.

Integrated System Operation Objectives

During this final portion of the MSEE the turbine-generator failed and the system was operated using a computer simulated turbine-generator. The original objectives were as follows:

1. Fully characterize and evaluate the system and subsystem performance of the MSEE.

2. Develop operating procedures and control strategies that are applicable to the design and operation of a utility power plant.

3. Determine the daily system performance characteristics and estimate the annual power output of the MSEE.

4. Determine the thermal losses of the receiver in the cavity configuration with the door open and closed.

Data Team Revised Objectives for Integrated System Operation

Prior to starting the integrated system operation a data team consisting of utility and industry experts was assembled to review the overall objectives and system readiness of this portion of the MSEE.

Two of the original integrated system operation objectives were revised by the data team as follow:

1. Maximize operating time within constraints of test personnel and operate the system through extended transients to obtain data even if parasitics exceed power production.

2. Operate system as utility power plant and identify design, operating, and personnel limitations.

   --Characterize MSEE subsystems.

   --Estimate annual net electrical power output of MSEE based on Solar One electric power generator subsystem efficiency and MSEE steam generation system efficiency.

Rationale for Data Team Revision of Test Objectives

1. MSEE configuration was not designed to maximize net electrical power production; results could be misinterpreted.

2. Personnel resources were not available to maximize electrical power production from sunrise to sunset.

3. Maximizing production of net electricity would limit operation of receiver and steam generator during extended transient periods.

4. Adherence to the original objectives would delay the start of testing and require additional unavailable test personnel.

This report covers the period from April 9, 1984, through May 11, 1985. Construction and integration tests were completed on July 18, 1984. Engineering characterization tests were started on June 13, 1984, and utility training started on September 4, 1984. The test and training program was completed on December 21, 1984. Integrated system operations were conducted from January 2, 1985, through

May 11, 1985, with systems refurbishment from January 2, 1985, through April 12, 1985.

Volume 2 of this report contains various important documents related to the MSEE. These are available from the EPRI Project Manager and include the following:

Addendum A, Phase II Test Plan
Addendum B, Test Procedures
Addendum C, Test Data
Addendum D, Test Conductor's Daily Log
Addendum E, Reliability Audit Report
Addendum F, Master Control Subsystem Display
Addendum G, Receiver Freeze/Thaw Report
Addendum H, Turbine-Generator Failure

An aerial photograph of the MSEE system is shown in Figure 1-1.

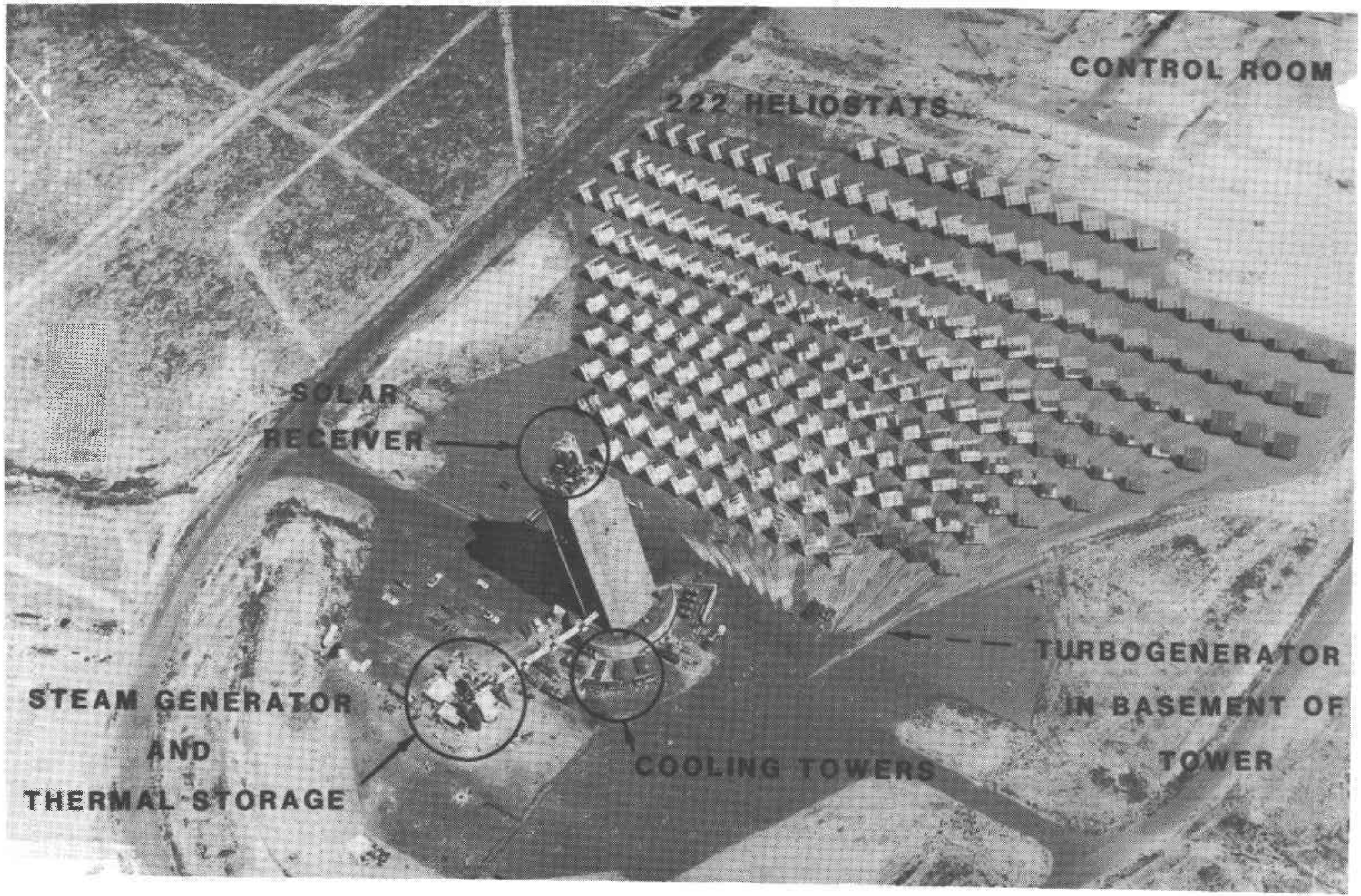

Figure 1-1. Molten Salt Electric Experiment

Section 2

MSEE SYSTEM DESCRIPTION

The MSEE was designed to demonstrate the conversion of solar energy to electricity using molten salt and a water/steam mixture as the working media. Molten nitrate salt is the energy collection and thermal storage medium. The energy stored in the molten salt is then transferred to the water/steam mixture for use in a conventional Rankine steam cycle to generate electricity. Figure 2-1 depicts the system schematic. The receiver, located at the top of the CRTF tower, receives concentrated solar energy from the collector field. Molten salt from the "cold" (570 deg F) storage tank, located at ground level, is pumped up the tower piping and through the receiver and heated to 1050 deg F. Salt then flows through a downcomer, and is throttled into the hot salt storage tank. Hot salt from storage is pumped through the steam generator superheater and evaporator and is returned to the cold storage tank. Main steam from the steam generator is used to drive a conventional steam turbine-generator. Electricity generated is supplied to a utility grid network. The system is divided into the following subsystems:

1. Collector (CS)
2. Receiver (RS)
3. Thermal storage (TSS)
4. Steam generation (SGS)
5. Heat rejection and feedwater (HRFS)
6. Electric power generation (EPGS)
7. Master control (MCS)
8. Equipment protection system (EPS)

Data describing the MSEE system are summarized in Table 2-1. A complete detailed description of the MSEE subsystems is contained in the following subsections.

COLLECTOR SUBSYSTEM

The collector subsystem redirects, concentrates, and focuses solar radiation onto the tower-mounted receiver. This subsystem consists of 221 two-axis tracking

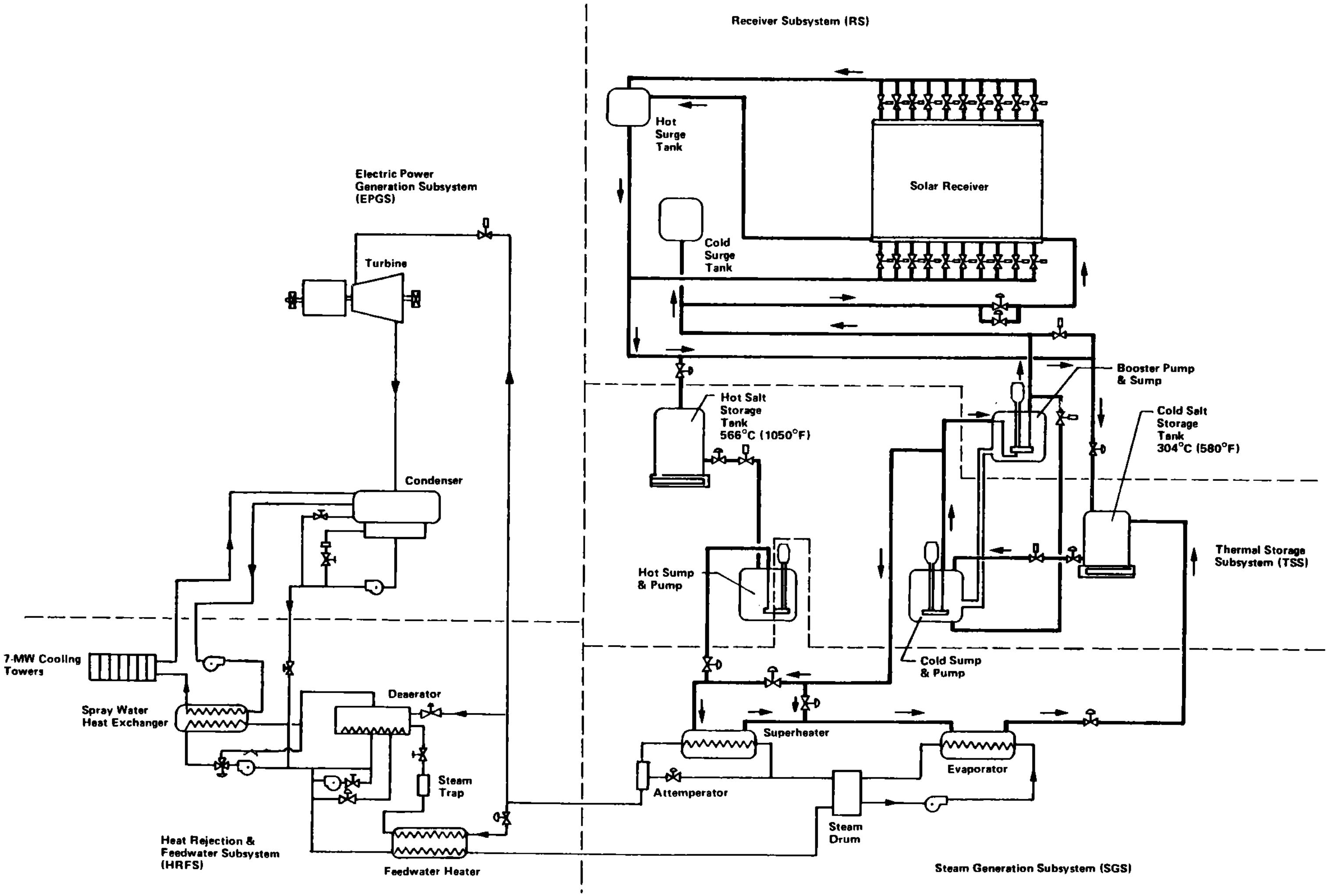

Figure 2-1. MSEE System Schematic

Table 2-1

MSEE DATA

Location -- CRTF, Kirtland Air Force Base, Albuquerque, NM

Heliostat Field -- Existing field of 221 heliostats each with 400 ft^2 of mirror surface.

Tower -- Existing concrete tower, 200 feet high with internal lifting module.

Master Control -- EMCON D-2 distributed digital control system with central consoles; separate equipment protection system.

Receiver -- Refurbished from previous Subsystem Research Experiment designed and built by Martin Marietta.

- Rating: 5 MWth
- Salt temperatures: in - 570 deg F; out - 1050 deg F
- Configuration: cavity with door
- Absorber: Single panel of 3/4-in. Incoloy 800 tubes (18 passes, 16 tubes per pass)
- Peak flux: 630 kW/m^2 (200,000 Btu/hr - ft^2)

Thermal Storage -- Existing from previous Subsystem Research Experiment

- Rating: 5.8 MWth hr when operating between 570 deg F and 1050 deg F
- Type: 2-tank
- \- Hot tank, internal insulation
  \- Cold tank, external insulation

Steam Generator -- Supplied by Babcock and Wilcox

- Type: Forced recirculation
- 2 units: evaporator and superheater (both U-tube, U-shell) with steam drum separator
- Rating: 11,000 lb/hr of steam at 940 deg F and 1100 psi (3.13 MWth)
- Prototypical of commercial design

Turbine-Generator -- GE rebuilt unit

- Marine turbine
- 750 kWe rating (500 kWe under nominal operating conditions)

Heat Rejection and Feedwater System -- Existing at CRTF

- Feedwater treatment only
- 20,000 gallon demineralized water storage
- Dry cooling, 7 MWth apacity
- Spray water heat exchanger to reject heat when turbine not in use or tripped off line

heliostats (211 used for MSEE) located north of the receiver tower (Figure 2-2), and a control system. Under optimum insolation and heliostat conditions, the heliostat field can concentrate approximately 5.5 MW onto the receiver.

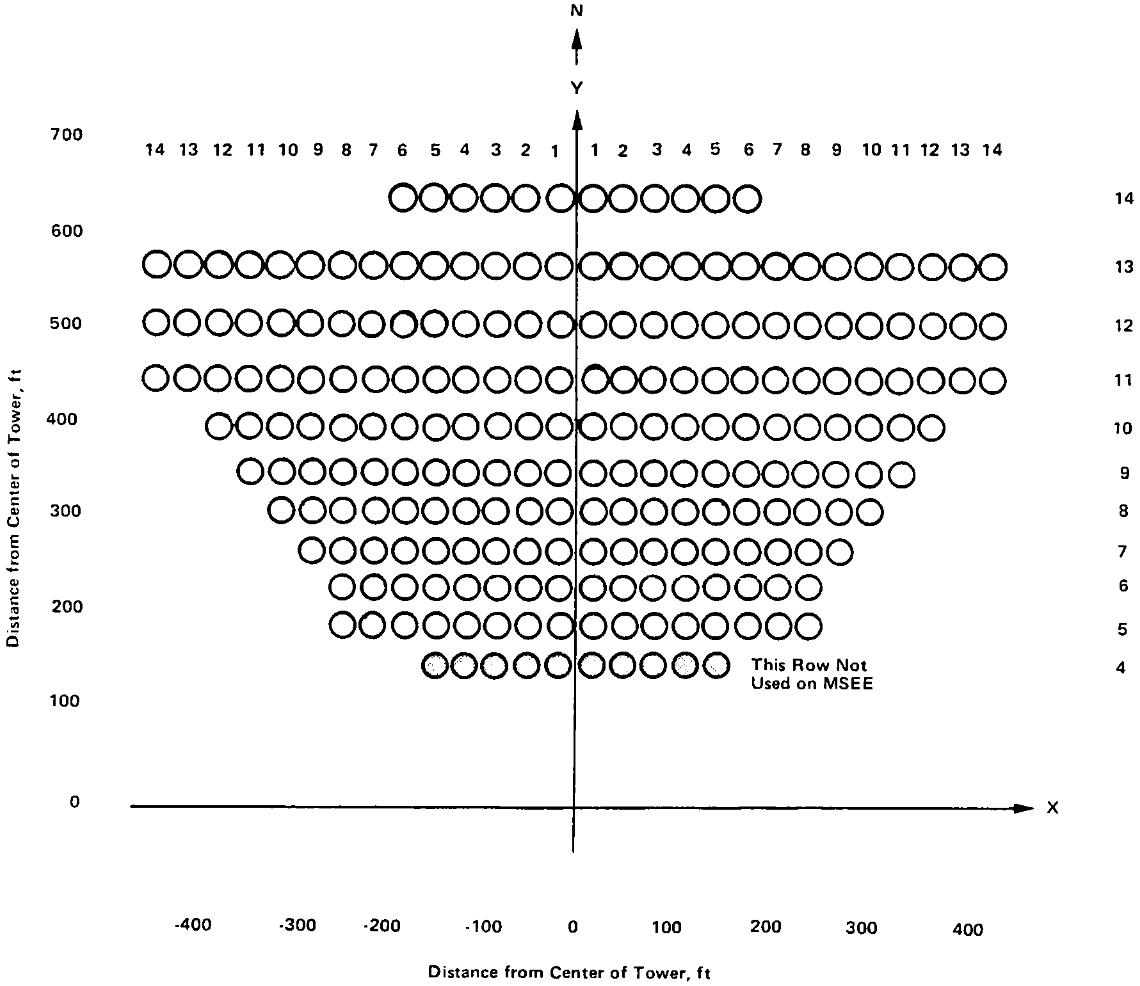

Figure 2-2. General Layout of the Heliostat Array

Each heliostat has 25 individual mirror facets totaling 37.2 m^2 (400 ft^2) of reflective surface. All facets are mounted on a structure and are individually adjusted to provide a concentration ratio of approximately 25 to 1 on the receiver. The structure has motor-driven azimuth and elevation gimbals, which allow it to track the sun during the day.

Heliostats are operated from the control room by the CRTF collector control system. This control system is separate from the MSEE master control subsystem. The collector control system analyzes heliostat operating commands from a number of programmed test sequences or from the facility heliostat operator. Control signals are distributed to the heliostats to obtain the desired heliostat positions.

RECEIVER SUBSYSTEM

The receiver subsystem, located at the top of the CRTF tower (Figure 2-3), intercepts and absorbs concentrated energy from the heliostat field and transfers this energy to the molten salt. The salt is heated from 570 deg F to 1050 deg F in the receiver. This subsystem consists of the receiver absorber panel, cavity enclosure with a vertical aperture door, insulation, heat tracing, cold surge tank, boost pump, hot surge tank, overflow tank, instrumentation, and control valves.

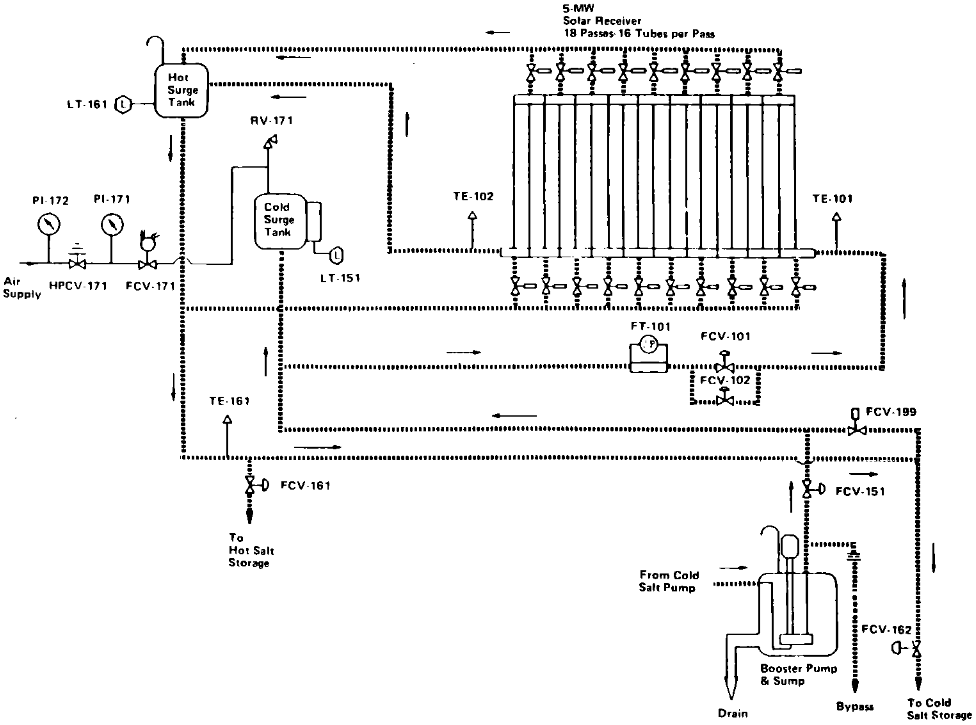

Figure 2-3. Receiver Subsystem Schematic

The receiver absorber is a single flat panel (18 feet x 11.5 feet), with a cavity aperture (9 feet x 9 feet), with 18 serpentine vertical passes having 16 tubes per pass of Incoloy 800 material with 19 mm (0.75 in.) outside diameter x .065 wall. Purge and drain valves for filling and draining are provided for each pair of passes.

The receiver surge tanks are designed to dampen changes in the salt flow rate. In addition, temporary salt flow through the receiver is provided by the pressurized cold surge tank in the event of a cold salt pump outage. The hot surge tank operates at atmospheric pressure; it is vented to an adjacent overflow tank in the event of a control problem in the salt downcomer throttle valve.

Cold salt is pumped through the receiver by a cold salt booster pump that takes its suction from the discharge of the cold salt pump and pumps the salt up the tower.

The hot salt line leaves the hot surge tank and flows through the downcomer to the base of the tower and across the pipe bridge to a control valve, where it is throttled into the hot storage tank. All salt piping is electrically heat traced, insulated with calcium silicate and aluminum sheathing, and properly inclined to ensure complete draining.

The receiver components are listed in Table B-1, Appendix B. Valves are described in Table B-2, Appendix B. Instrumentation is listed in Table B-3, Appendix B. Control loops are described in Table B-4, Appendix B.

THERMAL STORAGE SUBSYSTEM

The thermal storage subsystem (Figure 2-4) decouples the energy collection process from the energy conversion process. It provides a cold (570 deg F) salt supply source for the receiver and a hot (1050 deg F) salt supply source for the steam generator; it absorbs or supplies the differences in their flow demands. Because the thermal storage capacity is 5.8 MWht there is a limited capacity for "resource shifting." In addition, the subsystem can furnish energy to provide thermal conditioning (in lieu of trace heaters) for the receiver, steam generator, and salt piping. This subsystem includes the hot and cold salt storage tanks, propane-fired salt heater, cold salt pump, and cold salt sump.

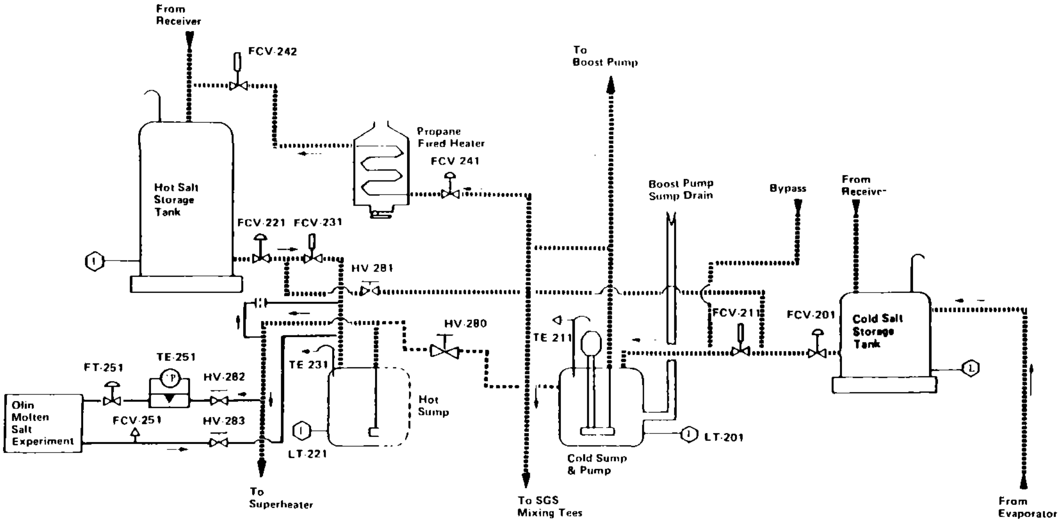

Figure 2-4. Thermal Storage Subsystem Schematic

The salt pumps are of a vertical cantilever design. The impeller and the casing are suspended below the liquid level in a sump. Pump bearings are located above the liquid level and do not contact the salt.

Design of the hot salt tank (10 feet inside diameter x 20.5 feet high) allows the use of carbon steel in the structural portions of the tank. An internal refractory insulation is used to limit the temperature of the walls, roof, and floor. A waffled Incoloy liner separates the salt and the internal insulation. The outside of the tank is insulated in the conventional manner with calcium silicate and aluminum sheathing. Design of the cold salt tank (12.3 feet inside diameter x 12 feet high) is similar to that of the hot tank except that it does not require the internal insulation and liner due to its lower operating temperature. Major components, valves, instrumentation and control loops are described in Tables B-5 through B-8, Appendix B.

STEAM GENERATION SUBSYSTEM

The steam generation subsystem (<u>4</u>) (Figure 2-5) transfers sensible heat from the molten salt to produce superheated steam for the turbine-generator. This subsystem includes an evaporator, steam drum, boiler water recirculation pump, superheater, attemperator, and the hot salt pump.

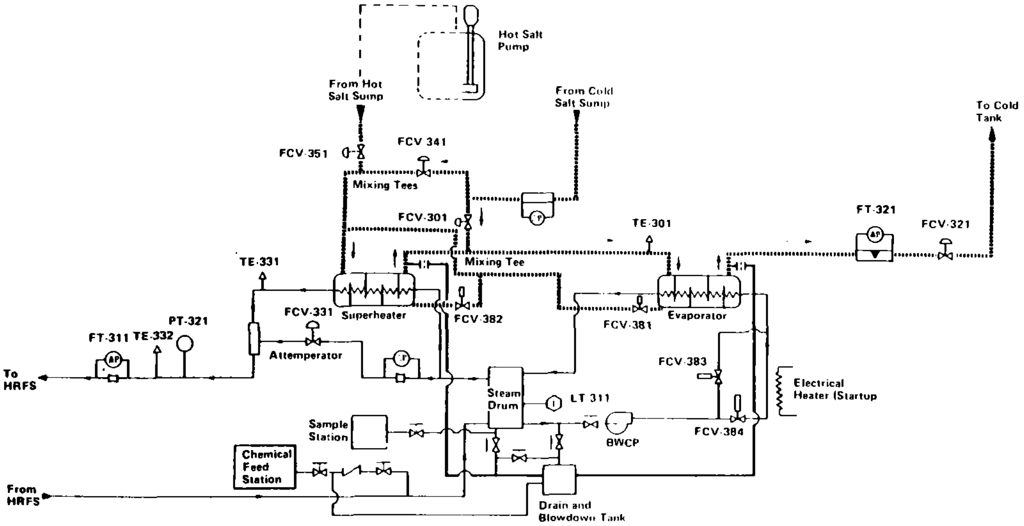

Figure 2-5. Steam Generation Subsystem Schematic

The evaporator and superheater are U-tube, U-shell heat exchangers, with low-pressure salt on the shell side and high-pressure water and steam on the tube side.

A conventional steam drum, operating at 565 deg F and 1200 psi, is located above the evaporator. The steam drum separates the saturated steam from the water and steam mixture exiting the evaporator before the steam enters the superheater. The drum receives feedwater from the feedwater heater.

Outlet steam from the superheater (1000 deg F, 1100 psi, 10529 lb/hr) can be attemperated to 950 deg F (11,582 lb/hr) by mixing it with a small amount of saturated steam (1053 lb/hr) from the drum. Salt flow from the superheater to the evaporator is also attemperated to 850 deg F, when necessary, by mixing it with salt flow from the cold tank. This allows chrome-moly piping and fittings rather than stainless steel to be used in the evaporator.

Major subsystem components, valves, instrumentation, and control loops are described in Tables B-9 through B-12, Appendix B.

HEAT REJECTION AND FEEDWATER SUBSYSTEM

The heat rejection and feedwater subsystem (Figure 2-6) rejects waste heat to the atmosphere, and pressurizes, heats, and deaerates the condensate to the final feedwater conditions. This subsystem includes six air cooling towers, circulating water pump, deaerator, spray water heat exchanger, spray water pump, feedwater pump, feedwater heater, demineralizers, chemical feeders, water analyzers, and condensate makeup pump.

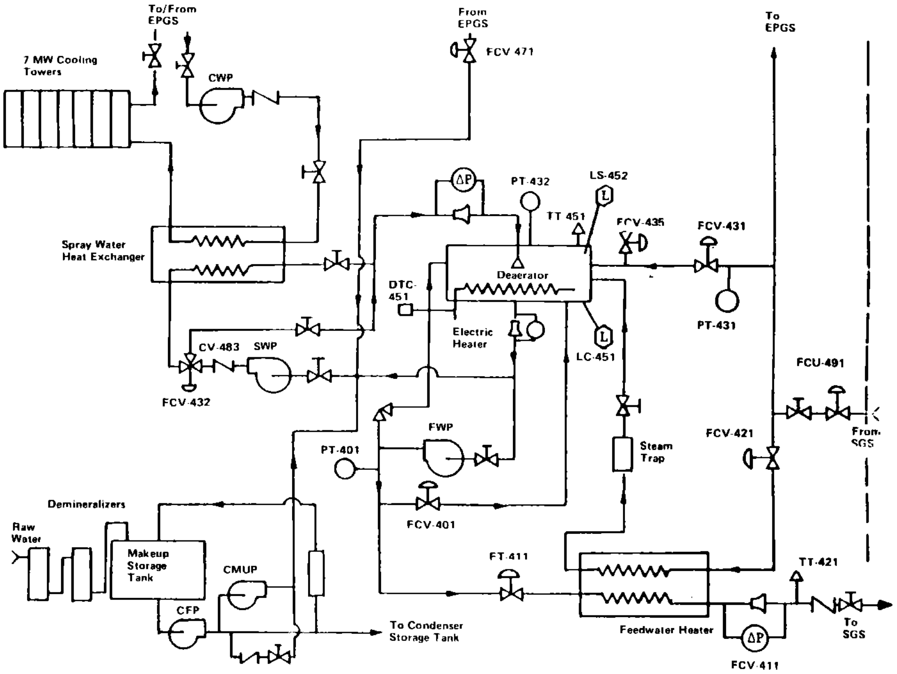

Figure 2-6. Heat Rejection and Feedwater Subsystem Schematic

Turbine condensate is supplied to the deaerator for removal of oxygen and other noncondensable gases and to be preheated before delivery to the feedwater heater. The steam required by the deaerator is supplied by a branch off the SGS main steam line. The deaerator is a horizontal, cylindrical pressure vessel that operates at 250 psia and 400 deg F. It also serves as a desuperheater with the capacity to absorb the full SGS steam output when the EPGS is not operating, or after a turbine-generator trip. When operated as a desuperheater, heat is rejected through the spray water heat exchanger.

Feedwater from the deaerator is heated on the tube side of a feedwater heater as steam from a branch off the SGS main steam line condenses on the shell side. This pressure vessel is a vertical cylindrical design with an internal steam condensing coil.

Major components, valves, instrumentation, and control loops are described in Tables B-13 through B-16, Appendix B.

ELECTRIC POWER GENERATION SUBSYSTEM

The electric power generation subsystem (Figure 2-7) converts the enthalpy in the main steam flow to electricity. This subsystem includes the steam turbine, electric generator, electric power equipment, condenser, condensate pump, and storage tank.

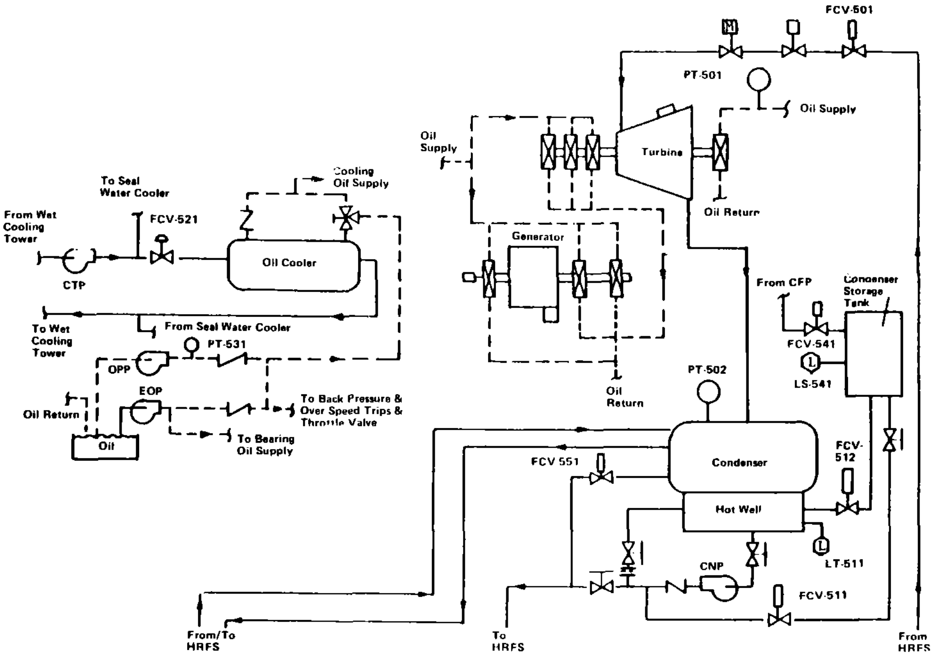

Figure 2-7. Electric Power Generation Subsystem Schematic

A conventional turbine-generator set rated at 750 kW_e and 450 V is skid-mounted below ground level in the tower. The turbine is a seven-stage, single-flow machine without extraction ports, operating at 17,400 rpm. Inlet steam conditions are rated at 940 deg F and 1050 psia. A single-reduction gearbox reduces the turbine shaft speed to the generator speed of 1200 rpm.

A shell-and-tube condenser, supported by a separate frame, is located directly below the turbine. Condensate from the hot well is pumped to the deaerator; the condensate storage tank collects or supplies condensate as required.

Major components of the EPGS, valves, instrumentation, and control loops are described in Tables B-17 through B-20, Appendix B.

MASTER CONTROL SUBSYSTEM

The master control subsystem (Figure 2-8) consists of an EMCON-D2 for primary system control. A Bailey Network 90 system is used to directly control the SGS. The Network 90 operation and control functions are directed from the EMCON console through a hardwired interface. Additionally, an Acurex Data Logger collects and displays all the temperature measurements relating to the heat tracing and data instrumentation. The logger also performs certain logical control functions, such as activation of heat trace circuitry and generation of go/no-go signals for the EMCON system. The data acquisition system utilizes both the EMCON-D2 and the Hewlett-Packard HP-1000. EMCON collects the data, and HP-1000 stores and displays data.

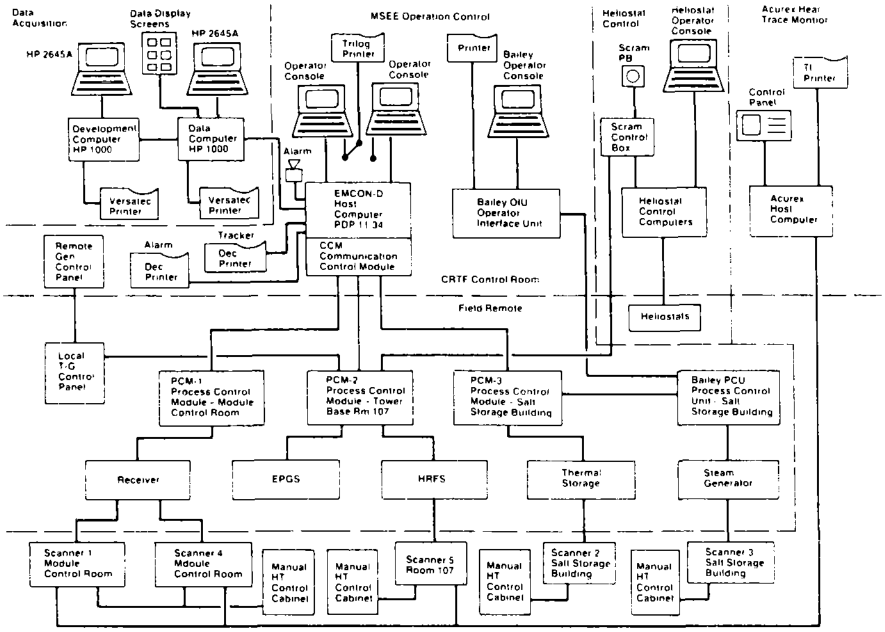

Figure 2-8. Master Control Subsystem Schematic

The EMCON-D2 is a distributed digital control system consisting of two operator consoles, a host computer with its peripheral hardware, a communication control module, and three field-located process control modules (PCM) distributed among the subsystems. The two operator consoles and the host computer (DEC PDP 11/34) are located in the CRTF main control room. This computer links the operator with the PCMs by dispatching control commands and by accepting returning data from the control modules for presentation at the operator consoles. Communications between the process control modules and host computer are directed by the communication control module. This distributed control system reduces the number of instrumentation and control links between the subsystems and the control room. The peripheral equipment includes two disk drives, an alarm system, and a data analysis system.

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 selected in rotation by the multiplexer, converted to digital signals, and analyzed by the control unit. The module responds with an appropriate digital control signal that is passed through the multiplexer and sent to the appropriate controller. Each PCM is capable of monitoring 30 analog signals per second, monitoring 95 thermocouples, generating 20 analog control signals, and controlling over 100 on-off switches.

PCM 1, located below the receiver in the tower elevator, is dedicated to the control of the receiver. PCM 2, located at the base of the tower, controls the heat rejection and electric power generation subsystems. PCM 3, located in the control building adjacent to the salt storage tanks, controls the thermal storage subsystem and commands the Network 90 controlled steam-generation subsystem.

The Bailey Network 90 control system consists of two units: one process control unit (PCU) and one operator interface unit (OIU).

The PCU architecture is based on two key modules, the controller module (COM) and the logic master module (LMM). In combination, these modules provide a mix of both modulating and sequential control functions. The COM can service up to four analog and three digital inputs and two analog and four digital outputs by itself, or an additional four outputs through the use of separate analog output modules (AOM). It also provides A/D and D/A conversion, alarm limit checking and notification, point quality checking, and interlocking. The LMM provides only digital control. The PCU for this subsystem contains nine COM's, one LMM, and four AOM's.

The OIU provides the high-level operator interface for the Network 90 system and consists of a color CRT-based table-top console, with functional keyboard, mass storage device, and console driver electronics. In operation, the unit performs the system information display and control requirements.

The data acquisition system (DAS) utilizes both the EMCON-D2 and an HP-1000. The EMCON collects the data; the HP-1000 stores and displays data. Data collected by the EMCON system is transmitted to the HP-1000 system on a terminal-to-terminal data link. The tag list for the data to be collected is in a file of 180 tags, which are divided into 6 groups of 30 tags. One group of 30 is transmitted every 10 seconds, giving a total update rate of once a minute. The data are then time-tagged with day of the year, hour, minute, and second. Then the data are stored in a data file and/or are displayed on one of six CRTs in a graphical form. The data are transmitted and stored in integer format (not floating point) in engineering units.

Recovery of stored data is accomplished by a separate HP-1000 data development computer having plotting and listing capabilities. These plots are not displayed on a CRT, but are directly generated on the printer/plotter.

The equipment protection subsystem (EPS) is an independent hardwired relay system using dedicated sensors. It is designed to safely shut down the MSEE in the event of any potentially unsafe condition. These relay units are independent of the EMCON and Network 90 control systems. After the EPS safely shuts down the system, operator action is required to shut the system down or to change into any other mode. A detailed list for the EPS, including actions taken by the EPS and actions subsequently to be taken by the operator, is in Appendix D.

Section 3

MSEE OPERATIONS

Martin Marietta served as MSEE system integrator and test conductor from the start of the project in September 1982, through April 6, 1984. The activities during this period are documented in References 1, 2, and 3. McDonnell Douglas assumed the responsibilities of system integrator and test conductor for the MSEE on April 9, 1984, and continued in this role through the completion of the construction and integration testing, the characterization testing, the operator training which ended on December 21, 1984, and the integrated system operations test campaign which ended on May 11, 1985. This section summarizes the 17 construction and integration tests and the 15 characterization and training tests completed by McDonnell Douglas. A summary of the integrated system operations testing, includes facility refurbishment, procedure development, and operations, is also provided.

CONSTRUCTION AND INTEGRATION TEST SUMMARY

Of the original 36 construction and integration tests that were scheduled, MMC completed 11 tests. MDAC completed the remaining 17 tests between April 9, 1984, and July 18, 1984. Details are depicted in Table 3-1. Six of the original tests were deleted: one subsystem test and five system tests. The automatic sequence test of EPGS was deleted due to the slow EMCON update rate. Due to cancellation of the automatic sequence test of the EPGS, the system level automatic sequence test was also cancelled.

The heat rejection feedwater subsystem startup, operation, and shutdown was never automated. This contributed to canceling the system automatic sequence demonstration test and four additional system tests.

Several major milestones in the construction and integration testing were as follows:

1.	Project started	September 1982
2.	Receiver operation	October 1983
3.	Rated steam generation and turbine roll	December 1983

Table 3-1

CONSTRUCTION AND INTEGRATION TEST SUMMARY

		Tests Planned	MMC Completed 4/6/84	MDAC Completed 7/17/84	Combined w/ Integrated System Operations	Deleted
Receiver tests	1	Cold flow	X			
	2	Hot flow	X			
	3	Margin	X			
	4	Manual sequence	X			
	5	Auto sequence	X			
	6	Cloud simulation		X		
Steam generation tests	1	Initial checkout	X			
	2	Hot salt/transient	X			
	3	Diurnal	X			
	4	Load following	X			
	5	Alternate diurnal			X	
	6	FW loss emergency		X		
	7	Salt flow loss		X		
	8	Manual sequence	X			
	9	EMCON	X			
	10	Auto sequence		X		
Electric power generation tests	1	Initial checkout		X		
	2	No load synchronized		X		
	3	Steady state/transient		X		
	4	Load ramping		X		
	5	Hold overnight		X		
	6	Turbine upsets		X		
	7	Margin test		X		
	8	Auto sequence				X
System tests	1	Manual sequence		X		
	2	Auto sequence				X
	3	EPS		X		
	4	25% transient		X		
	5	50% transient		X		
	6	100% transient		X		
	7	Cloud		X		
	8	Extended standby			X	
	9	TSS				X
	10	Solar and TSS				X
	11	Cloud				X
	12	System performance				X

4. Synchronized to grid	April 1984
5. Full system operation	May 1984
6. Checkout completed	June 1984

ENGINEERING TESTS AND TRAINING SUMMARY

Engineering testing was started on June 13, 1984, concurrent with integration testing to take advantage of system availability in performing subsystem tests. These tests are grouped into three categories: engineering tests, training tests, and salt characteristics tests.

Engineering tests were used to generate the test data that evaluated performance and functional capability of the MSEE. Engineering tests are as follows:

1. Receiver loop performance
2. Power production subsystems performance
3. Transient response of receiver loop
4. Overnight thermal conditioning of the receiver
5. Overnight hold conditions for the steam generator
6. Development of optimum operating strategy.

Training tests were used to train utility operator teams and to evaluate the routine operation of MSEE as a utility power plant. Wherever possible, these tests were designed to also provide useful performance information. Training tests were:

1. Receiver loop cold flow
2. Receiver loop operation
3. Receiver operation with simulated (slow cloud)
4. Thermal storage charging with propane heater
5. Steam generator and HRFS operation
6. Operation of full electric loop (TSS through EPGS)
7. System operation from receiver
8. System operation with fossil fuel.

Salt samples were taken throughout the testing and training program by Olin Chemical Group to obtain data on salt properties, stability, and corrosion. There were two characteristics tests:

1. Salt properties and stability
2. Salt corrosion.

Approximately 90% of the scheduled engineering and training testing was completed. Of the six engineering tests, four were completed, one (Test 5) was partially completed, and one (Test 6) was transferred to the integrated system operation test campaign. The optimum operations Test 6 was rescheduled into the integrated system operation testing since this testing was dedicated entirely to a utility type operation. All eight training tests were used during the operator training program, and the two salt characteristics tests were completed. A complete description of each of these tests is included in Appendix C.

The salt characteristics test, performed by the Olin Chemical Group, was successfully completed. All salt samples tested were taken from the cold sump. During 1984, there was no significant change in the concentration of the major components: sodium, potassium, nitrate, and nitrite. The sodium to potassium ratio remained in balance so there was no significant change in the melting and freezing characteristics of the salt. Nitrite levels were as expected for a nitrate salt in a thermally cycled system. Olin's 1984 status report (5) summarized that the salt chemistry remained stable during the MSEE test program.

Additional Tests

Special receiver loss tests were repeated 15 times to accumulate convective loss data during various weather conditions with the cavity door open and with the door closed.

In the heat rejection feedwater subsystem, deaerator loss tests were performed by allowing the deaerator electric heaters to cycle on and off to determine the actual losses. Tests were also performed to determine heat losses due to leakage through the spray water heat exchanger. It was determined that a three-way valve, which diverts water through the spray water heat exchanger when heat rejection is required, was constantly leaking to the heat exchanger. This allowed water to be diverted through the spray water heat exchanger when not required, significantly reducing the steam cycle efficiency. This loss was instrumental in deferring the optimum operations test to integrated system operation testing.

Additional heliostat tests were performed primarily to develop a new receiver warmup pattern. The warmup pattern was developed which limited the panel temperatures to 850 deg F, instead of over 1000 deg F as originally developed. A test was also designed and conducted to evaluate the effect of misaligned heliostats (heliostats whose facet alignment had not been recently upgraded) on the receiver performance. Two specially selected groups of heliostats, one with 50 newly aligned heliostats and one with 50 heliostats awaiting realignment, were used for this test. An aligned heliostat casts a smaller precise image onto a specific area of the receiver, which results in loss of spillage.

PROCEDURE DEVELOPMENT AND OPERATING TIME LINES

Procedures

An iterative process was employed for development of the system operating procedures. Part of the original procedures were developed by Martin Marietta and Sandia National Laboratories; the steam generation subsystem procedures were all new and developed by Babcock & Wilcox. These basic procedures were continually modified and upgraded as additional testing was performed and experience was gained.

Each of the subsystem procedures was subdivided into four basic sections: pretest checklist, operations, post-test checklist, and emergency procedures.

In the pretest checklist, both control room and field checklists were completed with the control room operator and field technicians coordinating their activities by radio. The control room pretest checklist activities consisted of verifying that the temperatures of salt systems were acceptable and that the control system and components were configured for startup. As each of the field technicians in the various subsystems was proceeding through the field checklist the control room personnel verified the proper equipment configuration.

The operations portion of each procedure was controlled from the control room by the console operators, using either the automatic or manual sequences for each of the subsystems. However, during these operations the field technicians were kept aware of critical operations. Subsequent to testing, post-test checklists were completed for each of the subsystems and the control room to secure the equipment. The control room operator then secured the master control system and the remaining control room equipment.

During the construction and integration and testing and training, no integrated system procedures were developed. The system was operated by starting each subsystem sequentially rather than as an integrated system. An optimized integrated system startup procedure was developed and later demonstrated in the integrated system operation.

Operating Timelines

A typical daily timeline for testing and training is outlined in Figure 3-1, which illustrates the times involved in startup operation and shutdown of each subsystem. The receiver, heat rejection, and steam generation subsystems pretest checklists were performed in parallel prior to the startup operations. During the deaerator warmup, and to heat the feedwater to its minimum startup temperature, the receiver panel was warmed up. During the final stages of panel warmup, and subsequent to the deaerator being ready, the steam generation subsystem was filled with cold salt and the electric power generation pretest checklist was completed. The receiver was then automatically filled and serpentine cold flow established through the receiver. If the hot salt tank inventory was low, the receiver was put into a charging mode. If the hot salt tank inventory was high, the receiver was put into a cold flow mode while the steam generation subsystem was ramped into hot flow to deplete the tank of hot salt. Finally, the electric power generation

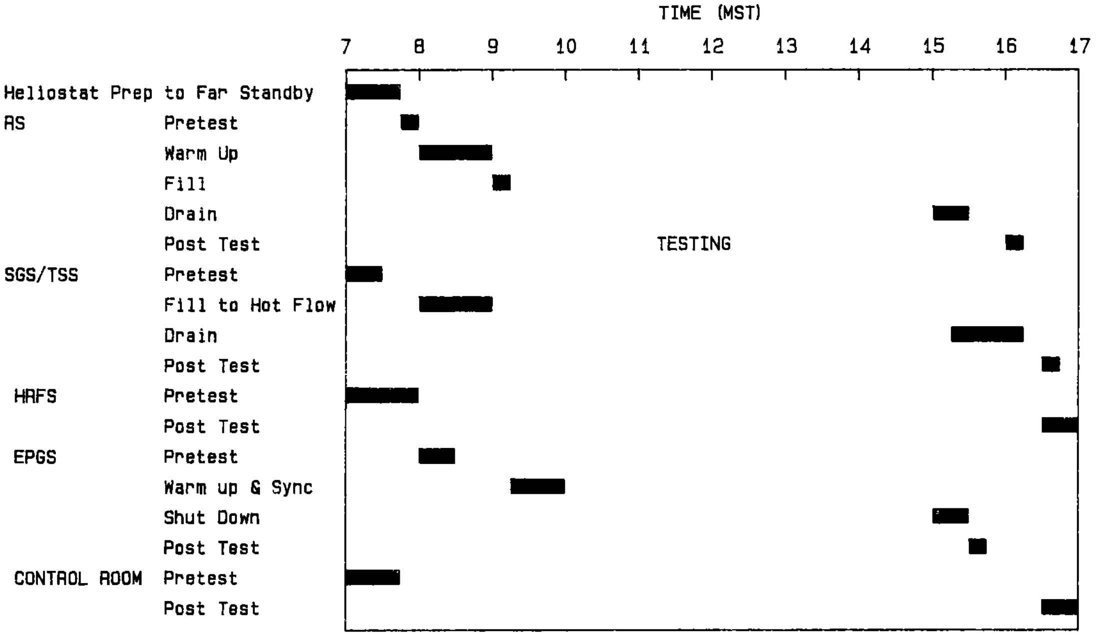

Figure 3-1. Timeline for Characterization Testing

subsystem was started and the turbine-generator synchronized to the grid. Following warmup, the EPGS was ramped to full power. The complete system was up and operating and synchronized to the grid nominally by 10 AM.

During the engineering test and training phase of the program it usually required about three hours to start up the MSEE. During the integrated system operation, the startup was reduced to one hour (a detailed discussion is in Section 4). This three-hour startup was followed with testing activity and two hours to totally shut down and secure the system. The shutdown sequence usually started with the receiver because it could be shut down with the SGS and EPGS operational. The EPGS could be shut down during or immediately following receiver shutdown. The SGS was shut down and drained last. The receiver post-test checklist followed the EPGS with the heat rejection feedwater subsystem, SGS, and control room post-test checklists occurring in parallel. Prior to final securing of the SGS, the steam drum was refilled for diurnal shutdown. The control room then verified the complete system configuration for final securing.

It was seen that a 10-hour work day allowed for 5 hours of testing, or a total of 20 hours of testing in a four-day, 40-hour work week. In contrast, a work week of five 8-hour days allowed only 3 test hours per day or a total of 15 test hours per week. For this reason, a work week consisting of four 10-hour days was employed for test periods.

INTEGRATED SYSTEM OPERATIONS

The integrated system operations were conducted from April 14 to May 11, 1985, seven days a week for a minimum of 12 hours per day. The operations were designed to simulate those of a commercial solar power plant. Prior to actual operations the test facility was refurbished to ensure equipment and component reliability.

The purpose of this integrated system operation was to develop operating procedures and control strategies similar to those that would be employed by an electric utility. Valuable information on annual system performance and methods to reduce parasitic power requirements was obtained.

Facility Preparation

The facility preparation effort was concentrated in five major areas: (1) trace heating elements and insulation, (2) cold salt tank drain line, (3) feedwater pump, (4) cold salt boost pump, and (5) turbine-generator.

A total of 22 trace heating elements were repaired or replaced in the receiver, thermal storage, and steam generation subsystems due to failures of heating elements and inadequate heating in high winds. This problem is discussed in more detail later.

During the testing and training portion of MSEE it was verified that the cold salt tank line that supplied the cold sump was too small. The salt flow from the cold salt tank to the cold salt pump is gravity fed, and there was insufficient flow at cold tank levels below 30%. This did not allow the receiver to be operated at full flow when the cold salt tank was depleted below 30%. The original 3-inch line and valves were replaced by a new 4-inch line with two new salt valves, which corrected the problem.

The main feedwater pump required refurbishment as a result of a major failure that occurred in December 1984. The pump was returned to the vendor and was rebuilt. To improve reliability, the pump flow characteristics were modified to more closely match the MSEE requirements, and a new auxiliary oil pump with interlocks was added.

During checkout of the system, on March 14, 1984, the cold salt boost pump shaft bearing failed. All bearings were successfully replaced prior to startup of the integrated system operation.

The shaft-driven oil pump failed in the turbine-generator just prior to starting the integrated system operation. This eliminated the EPGS subsystem from the integrated system operation. A complete rework, requiring months to complete, would have been necessary. A computer program was written that simulated a commercial turbine-generator using the steam conditions and flow from SGS. Its startup and operation were consistent with that actually demonstrated by the turbine-generator. The simulated power output was calculated and recorded at one-minute intervals.

Operating Sequence and Procedure Development

The development of new procedures for the integrated system operations testing occurred in five areas: (1) heliostat early morning warmup pattern, (2) receiver rapid early morning startup, (3) HRFS rapid early morning startup, (4) SGS rapid early morning startup, and (5) simulated turbine-generator startup.

For the early morning receiver warmup, 50% of the heliostats were utilized and were commanded onto the receiver in two equal groups. Most of the heliostats were aimed away from the middle section of the receiver panel to achieve a more uniform flux distribution.

The system startup sequence was determined by the hot salt tank level. If the tank was less than one-third full, the receiver was started prior to SGS since the available hot salt would not be sufficient to sustain full-power operation. If the hot tank was greater than two-thirds full, the SGS was started prior to the receiver to begin depleting the hot tank and provide the required storage capacity for the full-power operation of the receiver. Heliostats were commanded on the receiver panel when the insolation reached 350 W/m^2 to begin warmup of the panel. At 450 deg F minimum panel temperature, the receiver fill sequence was started. Shutdown was accomplished as previously developed.

The HRFS startup operations were performed during receiver startup. However, to reduce electrical parasitics, the HRFS pumps were not started until just prior to filling the SGS with cold salt. The SGS was then ramped up to hot salt flow at low steam output while the steam lines and simulated turbine were being heated. The resulting low amount of steam was also used to warm up the deaerator and feedwater. Subsequent to synchronizing the simulated turbine-generator to the grid, the SGS steam production was ramped up while simultaneously ramping up the simulated turbine-generator.

Shutdown of the HRFS/SGS/EPGS was started by reducing the SGS steam production while simultaneously reducing the simulated turbine power production and reducing deaerator pressure. The simulated turbine-generator was disconnected from the utility grid at approximately 10% steam flow and 100 psi in the deaerator. The deaerator then absorbed any residual steam. Hot salt flow through the SGS was reduced and transitioned to cold salt flow, and shutdown of the SGS/HRFS was as previously developed.

Operations

The integrated system operations testing was conducted on 28 consecutive days from April 14 to May 11, 1985. Six days per week consisted of 12-hour single-shift days; Wednesday of each week was a 14-hour day with overlapping shifts. This 14-hour schedule allowed for early morning startup and late afternoon shutdown. Availability of trained personnel did not permit full utilization of the system's full daily production capability.

Prior to starting the integrated system operations testing, a data team consisting of experienced industry and utility personnel familiar with the MSEE evaluated the operating procedures, test objectives, and data requirements. This resulted in revisions of the objectives, the data collection plan, and the data reduction plan of the integrated system operations. The data team also reviewed the performance predictions, the system procedures, and the system readiness. During the integrated system operations, the data team reviewed the data and assisted in the data reduction and recommended revisions to the data collection. At the completion of the integrated system operations, the data team assisted in the performance analysis, recommended the data presentation format, assisted in data reduction, recommended system improvements, and assisted in formulating the final report format.

Integrated System Operations Objectives. The four objectives were as follows:

1. Fully characterize and evaluate the system and subsystem performance of the MSEE.

2. Develop operating procedures and control strategies which are applicable to the design and operation of a utility power plant.

3. Determine the daily system performance characteristics and estimate the annual power output of the MSEE.

4. Determine the thermal losses from the receiver.

Revised Objectives. Prior to starting the integrated system operations, the data team revised two of the original objectives as follows:

2. Maximize operating time within constraints of test personnel and operate the system through extended transients to obtain data even if parasitics exceed power production.

3. Operate system as utility power plant and identify design, operating, and personnel limitations.

   --Characterize MSEE subsystems.

   --Estimate annual net electrical power output of MSEE based on Solar One EPGS efficiency and MSEE SGS efficiency.

The rationale for revising the test objectives was as follows:

1. MSEE configuration was not designed to maximize net electrical power production; results could be misinterpreted.

2. Personnel resources were not available to obtain electrical power production from sunrise to sunset.

3. Maximizing production of net electricity would limit operation of receiver and steam generator during extended transient periods.

4. Adherence to the original objectives would delay the start of testing and require additional test personnel who were not available.

Test Personnel Assignments. All of the test personnel used in the primary operations were personnel that were assigned to the CRTF permanently or personnel from utility and industry that were previously trained during the training program. Prior to starting the integrated system operations, all previously trained personnel were exposed to a one-week, on-site refresher course in operating the MSEE. Personnel to operate the MSEE from sunrise to sunset were not available. Therefore two teams were assembled to operate the MSEE 12 hours per day for six days, and overlapping on Wednesday for maximum operations. Figure 3-2 depicts the specific assignments for all the test personnel on both the number 1 and number 2 teams and the backup test personnel required to operate the MSEE during the integrated system operation. This was the minimum personnel required to perform the test.

	#1 (SUN - WED)	#2 (WED - SAT)	BACK - UP
PROCESS CONTROL CONSOLE	EVANS HILL (PG&E 1)	NELSON PINK (PG&E 2)	BARRON
HELIOSTAT CONSOLE	* JOHNSON	VANCE	BROOKS
TOWER (RS/HRFS/EPGS)	* HOLTON	WILLIAMS (PNM)	EGAN (BECHTEL)
SALT STORAGE (TSS/SGS)	GRIEGO FLORA	* MATTHEWS GUNNER (APS 1) MITCHEL (APS 2)	MILLER (SCE)
I&C TECHNICIAN	TUCKER	DUNKIN	* STOMP
COMPUTER SUPPORT	BOWEN	* BOLDT	------
TEST DIRECTOR	SALOFF	* HOLMES	COLEMAN
RESPONSIBLE ENGR	* COUCH	* HOLMES	* OTTS

* SNLA EMPLOYEE
ALL OTHERS ARE MSEE SPONSORS
OR CONTRACT EMPLOYEES

Figure 3-2. Personnel Assignments

Receiver Startup Timeline. For the receiver startup, timeline sunrise is defined as the time when the sun is predicted to rise above the horizon, not the local mountain range at the test site. The receiver warmup started approximately 25 minutes after sunrise due to the wait for the insolation to reach 350 W/m^2. Below 350 W/m^2, the receiver panel temperatures would initially decrease, requiring additional time to complete the warmup process. Refinement of the heliostat warmup pattern would permit an earlier start of the receiver warmup.

Receiver warmup was done approximately 50 minutes after sunrise; maximum power output from the receiver was reached approximately 65 minutes after sunrise. A detailed description and evaluation of the receiver startup and shutdown timelines is in Section 4.

SGS/EPGS Startup Timeline. Selection of the startup sequence of SGS and EPGS was based on the hot salt storage tank level. At lower levels in the hot salt storage tank, the SGS and EPGS were started subsequent to the receiver fill to avoid depleting the hot tank. At higher salt levels in the hot salt storage tank, the SGS and EPGS were started prior to the receiver fill to avoid overfilling the hot salt tank during full-power receiver operation. A detailed description and timeline evaluation is included in Section 4.

Solar Utilization

During the integrated system operations, from April 14 through May 11, 1985, approximately 70% of the available solar energy was delivered to the receiver. Approximately 11% of the available 30% of solar energy was lost due to unscheduled downtime. Weather-related losses amounted to approximately 10%. Miscellaneous reasons caused the remaining 9% of the losses. A complete detailed evaluation of the solar utilization is discussed in Section 4.

OPERATIONAL PROBLEMS

Thermal Conditioning and Environmental Protection

In order for salt to flow through lines and components, thermal conditioning is required to maintain the lines and components above the freezing temperature of salt. On MSEE this was done by using electrical trace heaters attached to the lines and components. Failures in these electrical trace heaters used to thermal condition the salt lines and components were a major contributor to downtime throughout the MSEE. More than 20 primary and backup trace heater failures were experienced in both the receiver and thermal storage subsystems. An example of the repair complexity is depicted in Figure 3-3. This trace heater failure occurred in the thermal storage subsystem.

Additional test time was lost because of equipment temperatures dropping below the freezing point of salt due to winds and inadequate shielding and insulation. This was primarily evident in the receiver subsystem. The severity and location of the problems varied with the wind velocity and direction, and with air temperature.

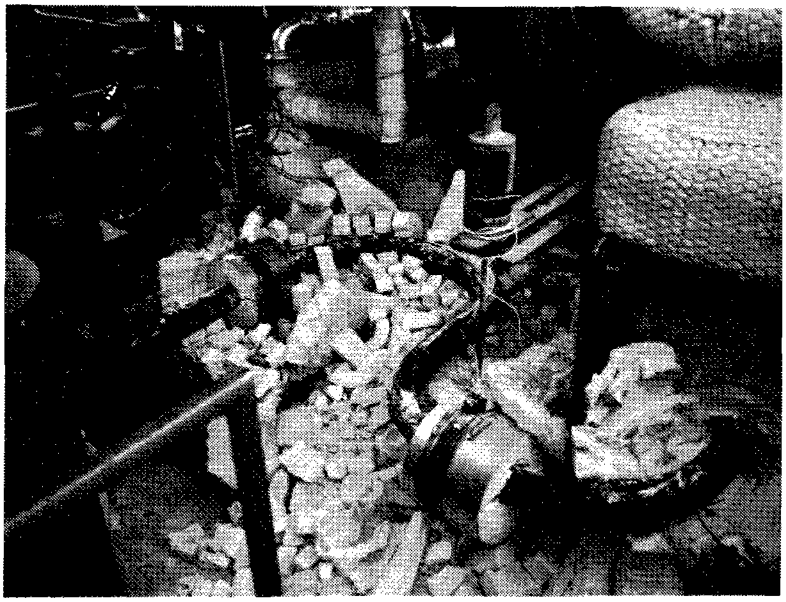

Figure 3-3. Thermal Storage Trace Heater Repair

Component Reliability

Numerous hardware problems were experienced during the testing and training phase. A large number of the component failures can be attributed to minimum redundancy and the use of existing hardware. A majority of these problems were of the typical power plant nature and would be reduced during the normal maintenance program.

Further component development is needed to account for the effects of thermal cycling and salt exposure on functional reliability of components and leakage through components. Continued component development such as full-scale salt pumps and valves are scheduled to be tested in MSS/CTE.

Receiver Temperature Control

A cloud transient experienced when the receiver was operating at its nominal salt outlet temperature of 1050 deg F often resulted in a potentially damaging temperature overshoot. The overshoot caused an automatic removal of the heliostat beams from the receiver. To avoid this during the testing and training program, the receiver was normally operated at an outlet temperature setpoint of 1000 deg F; temperature was reduced to an even lower setpoint (925 deg F) when cloud transients caused receiver flow to drop below 35,000 pounds per hour. During the integrated system operation, the receiver was operated manually during clear days between 1030 and 1040 deg F. During transients, the receiver was operated automatically at 975 deg F. An evaluation of the receiver control algorithm is included in Section 4.

Receiver Freeze-Up

In June 1984, a salt freeze occurred in the receiver. Upon attempting the receiver startup, a salt blockage in the receiver prevented serpentine flow through the receiver. This salt blockage was caused by a substantial drop in lower header temperatures between the time they were checked in the pretest procedures, approximately 9 AM, and the time of actual fill, approximately 12 noon. Attempts were made throughout the day to free the blockage, but were hindered by intermittent clouds. After the final afternoon shutdown, salt in the receiver absorber tubes above the blocked header froze because warmup heliostats were removed. The receiver was left with all purge and drain valves open to allow drainage of salt from any lower header that thawed overnight by the trace heating. The lower header temperatures did reach nearly 500 deg F by 10 PM (salt melting temperature is 430 deg F). However, by this time, the salt in the blocked receiver tubes was frozen at temperatures between 100 and 200 deg F.

Subsequent investigations established that six receiver panels were filled with frozen salt. Several methods for thawing the frozen panels were considered. Melting from the top using heliostats with concentrated beams was selected. Additional thermocouples were installed to help guide the melting operation, and the frozen panels were successfully thawed. Subsequent operation and inspection showed no apparent damage to the receiver. However, it is not known if any tube material yielding occurred during the thawing. The basic cause of the receiver freeze-up was the cooling of the lower headers between completion of the morning checklist and actual startup. The startup procedures were revised to require checking all temperatures of salt lines and components within 15 minutes of receiver fill. This prevented any recurrence of the freeze-up.

SGS Recirculation Pump

The design point circulation ratio of the steam generator subsystem (SGS) is 4.5 to 5.0. However, circulation ratios of 3.3 and 3.4 were typically obtained. Also, the circulation water pump was drawing high current, up to 8.2 amps, and tripping out on high temperatures. The last occurrence was on April 12, 1984. Subsequent tests determined that the circulation pump was wired incorrectly, causing the pump to run backward. The wiring was corrected and the circulation ratio increased, ranging from 10.7 to 11.2, with the motor drawing only 7.0 amps.

Turbine-Generator Failure

Just prior to integrated system operations testing, the shaft-driven oil pump failed, causing extensive damage to the turbine. The turbine-generator was not used during these operations. A complete evaluation of the failure is in Appendix H, Volume 2.

RELIABILITY AUDIT

As a result of the large number of component problems, an extensive reliability audit of the MSEE was conducted in May and June 1984 by MDAC and the CRTF staff. An in-depth review was held with the representatives of MMC, B&W, B&V, and PNM. The objective of the audit was to recommend a maintenance program to achieve the following MSEE system availability targets:

50% for the engineering test program

75% for utility operator training

A detailed listing was made of every component of the MSEE, including all instrumentation. Individual interviews were conducted with all members of the CRTF staff associated with MSEE and with the major equipment suppliers. In addition, suggestions on how to improve equipment availability were solicited.

A detailed review of the reliability of each MSEE subsystem was then conducted and potential improvements were discussed.

A set of recommendations to improve the reliability of MSEE was prepared by the CRTF staff, then reviewed and agreed upon by MDAC.

The reliability recommendations were implemented according to the following priority list:

1. CRTF utilities
2. Steam generator
3. Thermal storage and propane heater
4. Heat rejection and feedwater
5. Receiver
6. Turbine-generator

7. Master control, data, and EPS
8. Heliostats.

Spare parts and scheduled maintenance became major issues in improving system availability. A complete spare parts list was prepared with inputs from all the field technicians and the responsible engineers at the CRTF. These spare parts were then purchased and stocked at the CRTF. A scheduled maintenance program was established which used the available spare parts to repair equipment as required to improve system availability. The first major scheduled maintenance period was in mid-August for two weeks just prior to the start of utility training in September 1984.

Windshields were systematically erected around all portions of the receiver piping and valves to reduce heat loss and the resulting low temperatures of molten salt piping and components. The windshield effort was completed at the end of September 1984. Figures 3-4 through 3-7 depict the receiver prior to and subsequent to the installation.

Both EMCON and Network 90 were reprogrammed with many safety interlocks incorporated to safely shut down the system prior to tripping EPS. Overrides were then used to reconfigure the system to normal operations.

Utility personnel were available to assist in startup and operations of the MSEE and to recommend operational improvements to protect equipment. The primary startup operations improvements occurred in the turbine-generator area. The utilities recommended a local startup that was more precisely controlled with the local readout of gauges. This allowed a more gentle startup of the turbine-generator and reduced the vibration originally experienced during startup. Input from the utility personnel enhanced the CRTF knowledge in operating the MSEE as a power plant.

Figure 3-4. Exposed Receiver (South Side)

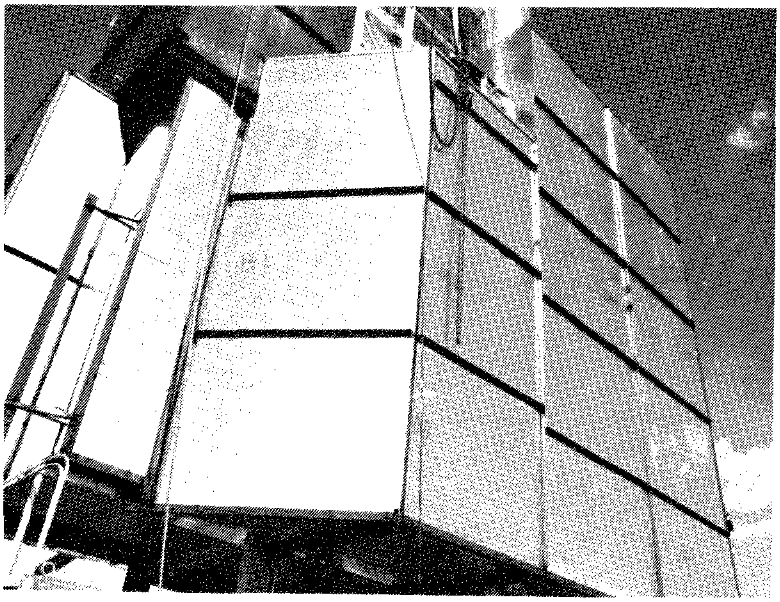

Figure 3-5. Enclosed (With Windshield) Receiver (Southwest Side)

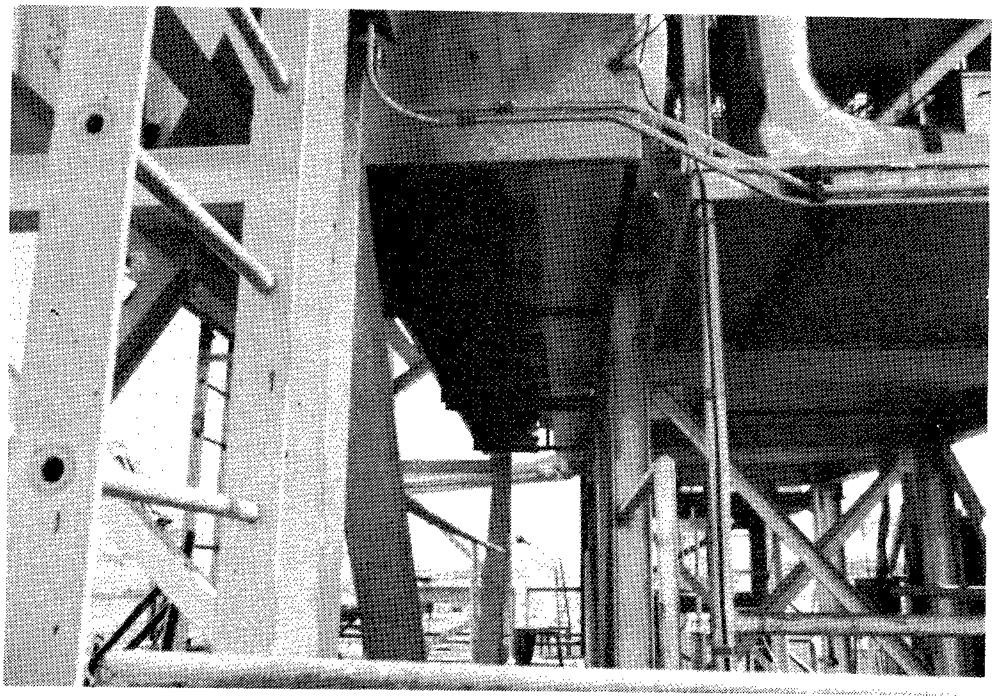

Figure 3-6. Exposed Receiver Drain Valves

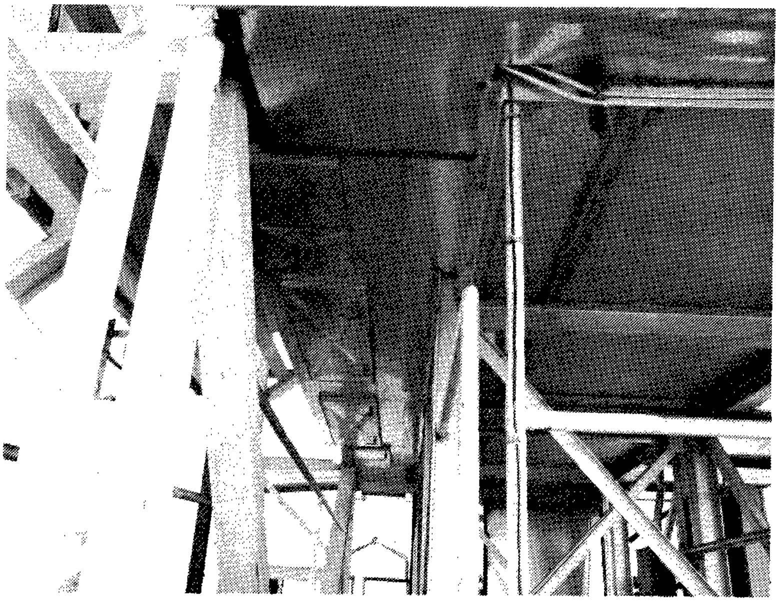

Figure 3-7. Enclosed (With Windshield) Receiver Drain Valves

Section 4

EVALUATION OF TEST RESULTS

Included in this section is the evaluation of the engineering data collected from June 13, 1984, through May 11, 1985. Within this 11-month period, the four months from August through November 1984 were dedicated to the training of utility operators. For the four months from December through March,the system was shut down while being prepared for the integrated system operations test campaign. The most significant engineering data was collected during June and July 1984 and April and May 1985. The period of the integrated system operation test campaign, April 14 through May 11, 1985, provided the most valuable engineering data.

The system performance is evaluated first in this section. The performance was evaluated under four conditions: (1) solar noon operation, (2) clear day operation, (3) partly cloudy day operation, and (4) the full month of the integrated system test. Also included is an annual performance projection. Where appropriate, the performance of the MSEE is compared to that predicted for a commercial size plant.

Following the performance evaluation are the results of receiver thermal loss tests, receiver transient response tests, overnight thermal conditioning tests, and salt sampling tests.

SOLAR NOON AND CLEAR DAY SYSTEM PERFORMANCE

Energy Collection

The MSEE was implemented at a test facility not designed to optimize performance. Improvements in heliostat reflectivity and improvements in the receiver geometry would reduce losses significantly through higher thermal efficiency and greater interception of incident radiation. The design and scale of the MSEE receiver results in a disproportionate amount of both external and internal spillage on inactive surfaces. Furthermore, parasitic load requirements will be a significantly smaller fraction of the gross output for the larger plant.

The energy collection portion of the MSEE consists of the collector subsystem (includes heliostats) and the receiver loop. The receiver loop begins at the cold salt storage tank, continues through the cold salt pump, boost pump, and receiver, and ends at the hot salt storage tank.

Solar Noon Energy Collection. The solar noon energy collection efficiency for the MSEE is lowest on June 21 (summer solstice) and highest late in February and early October. This variation in the collection efficiency is due to the cosine, shadowing, and blocking losses associated with the heliostats. The solar noon efficiency as a function of the day of the year is shown in Figure 4-1.

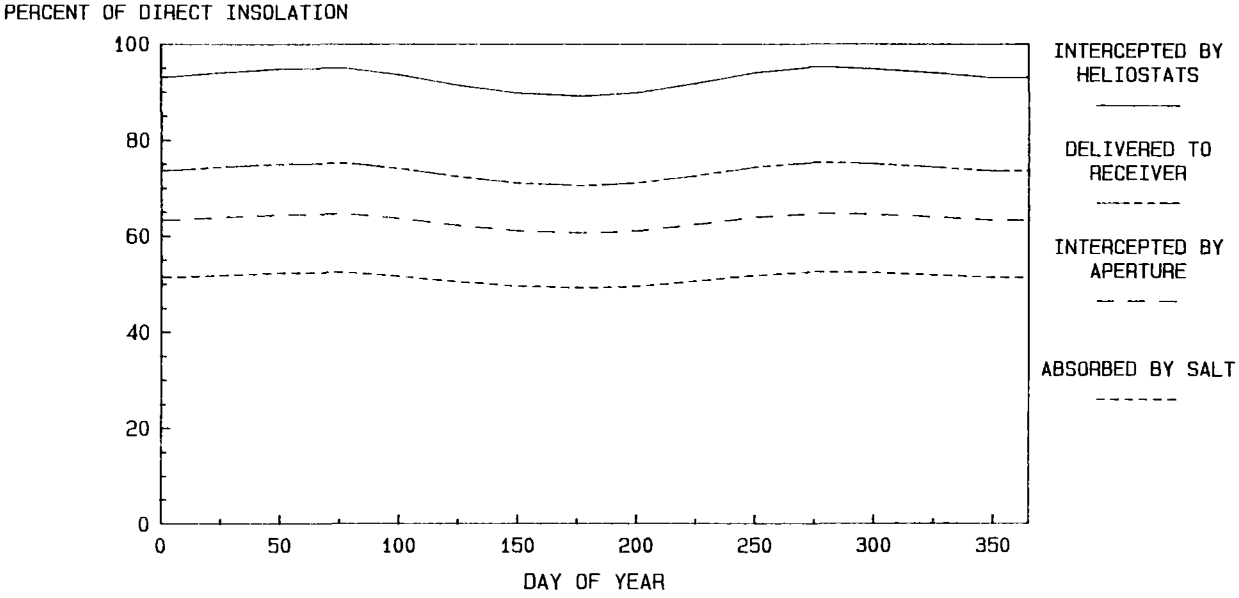

Figure 4-1. Solar Noon Energy Collection Versus Day of Year

The direct insolation in Figure 4-1 is that which would be intercepted if all the heliostats were normal to the sun. The percentage of the direct insolation actually intercepted when the heliostats are targeted on the receiver (upper curve on Figure 4-1) ranges from 89% to 95% as a result of cosine, shadowing, and blocking losses. These losses were calculated by the HELIOS computer code. The HELIOS computer code is a mathematical model that simulates the solar flux-density pattern on a target from a field of reflecting heliostats. It follows the incident solar radiation from the sun through the system and includes all the pertinent factors related to incident flux and total power which influence the performance of a receiver. The basic outputs of the code are the flux-density pattern at a grid of points on a surface and the integral (power) over this surface. The angular distribution of sun rays for the incident radiation of a heliostat is modified by convolution to determine the effects of sun-tracking errors, surface slope errors and surface reflectance. The percentage intercepted by the heliostats is further reduced by the mirror reflectivity (80.5%) and the atmospheric transmittance (98.3%) resulting in 70% to 75% of the direct insolation being delivered to the receiver. The absence of instrumentation to directly measure the power input to the receiver prevents the accurate determination of spillage; however, the average spillage at solar noon has been estimated at 14.1% using HELIOS. With this estimate of the spillage, it is calculated that 60% to 65% of the direct insolation is intercepted by the receiver aperture. The lowest curve on Figure 4-1, the percent of direct insolation absorbed by the salt, is based on extensive test data collected during the integrated system test. This direct insolation absorbed by the salt is the only curve on Figure 4-1 that is derived from test data. Using the 14.1% estimate for spillage, the receiver efficiency (absorbed by salt divided by intercepted by aperture) is calculated to be 81.5% at the solar noon power levels. However, as a percentage of direct insolation, 49% to 53% is absorbed by the salt at solar noon, depending on the day of the year as depicted on the lowest curve.

For a typical late April day at solar noon, the MSEE energy collection will exhibit the efficiencies shown by Figure 4-2. The collector subsystem efficiencies are for April 24. The receiver-related efficiencies are averages from actual solar noon performance data gathered on 12 days, from April 14 through May 11. All efficiencies, except those represented by the shaded bars, were accurately calculated or measured. These efficiencies apply to receiver outlet temperatures of 1000 to 1050 deg F, inlet temperatures of 560 to 580 deg F, and the use of a single heliostat aim point approximately 3 feet in front of the aperture plane. Although not verified during testing, analysis has indicated that the large spillage losses could be reduced by almost half through the use of an optimized, multiple aim point, aiming strategy (2).

Referring to Figure 4-2, the total direct power is that which would be intercepted by all 211 heliostats normal to the sun. Typically, about 206 of the 211 heliostats were operational. The reduction for cosine, shadowing, and blocking was calculated by HELIOS. The reflectivity was sampled on four representative heliostats. The atmospheric attenuation was based on the average heliostat to receiver distance, the elevation of Albuquerque, and 40-mile visibility, to determine the power delivered to the receiver. The power intercepted by the cavity aperture was estimated by HELIOS. The cavity/receiver reflectivity was calculated

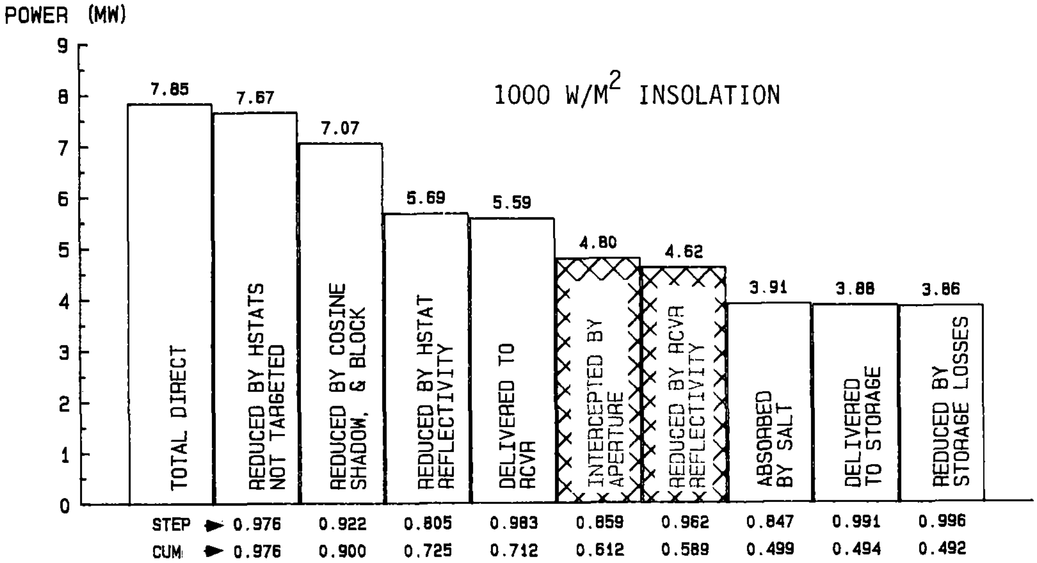

Figure 4-2. Solar Noon Energy Collection Efficiencies (April 24)

from the cavity geometry, surface optical properties, and flux density distributions inside the cavity (2). The receiver convection, conduction, and radiation losses are represented in the step from receiver reflectivity loss to the power absorbed by the salt. The power absorbed by the salt was measured using the most recent Sandia specified value for the specific heat as a function of temperature (0.363 Btu/lb F for the average temperature), the salt mass flow rate, and the temperature rise across the receiver.

Assuming that the estimated spillage is accurate, the measured receiver input-output efficiency of 0.815 (0.962 receiver absorbtivity X 0.847 thermal efficiency) is in good agreement with the Subsystem Research Experiment (SRE) results presented in the Alternate Central Receiver (ACR) Phase II Report (6) after appropriate adjustments are made. The adjustments are required due to modifications in the aperture, which reduced reflection losses from an estimated 6.0% to 3.8%, and to account for the revision in the specific heat from 0.377 to 0.363 Btu/lb F. With these adjustments the input-output efficiency, based on the SRE test results, is approximated by the expression:

$$\eta_{IO} = 0.845 - 0.1403/P_I \qquad \text{(Adjusted SRE input-output efficiency)}$$

where P_I is the input power in MW.

For the 5.04-MW input from Figure 4-2, the expected receiver input-output efficiency, based on the adjusted SRE results, is 0.817. Good agreement between the SRE and the MSEE test results has not always been the case during the MSEE test program. During the early months of the MSEE testing more than 50% of the 211 heliostats were awaiting realignment of the 25 individual mirror facets to correct inaccuracies. The facet misalignments resulted from an approximate visual alignment technique employed during 1982 and 1983. This large number of unaligned heliostats contributed to an increase in the incident flux spillage over that associated with the SRE testing. The increased spillage degraded the apparent receiver performance and introduced error into the estimation of the flux intercepted by the receiver aperture.

Special tests were conducted during the MSEE testing to evaluate the effect of the misaligned heliostats. Receiver performance with aligned heliostats was compared to the performance with a like number of unaligned heliostats. The testing revealed that the receiver output was approximately 10% less with the misaligned heliostats than with optimally aligned heliosatats. The test results agreed with performance improvements exhibited during the ongoing heliostat realignment process. By May 15, 1985, 85% of the heliostats had been realigned and the receiver thermal output had increased by almost 5% over the output at the start of the MSEE testing.

Clear Full Day Energy Collection. Again the integrated system test provided valuable test data to evaluate the full day energy collection. Prior to the integrated system test, early morning startups had never been performed. The early morning startups provided some of the most significant test results of the entire MSEE test program. The ability to perform routine rapid startups was demonstrated. These rapid startups showed that the collectable energy lost during the startup period was limited to less than 1% of the total energy collected on a clear day.

Figure 4-3 shows actual energy collection power levels for April 24. With the exception of the period after 17:00 when clouds developed, this was one of the clearest days during the integrated system test campaign with the insolation reaching 1050 W/m^2 near solar noon. On this particular day the receiver was not collecting maximum energy until 100 minutes after sunrise due to early morning maintenance that was required on the receiver. Some of the more rapid startups demonstrated that the receiver can be collecting maximum energy 60 minutes after sunrise.

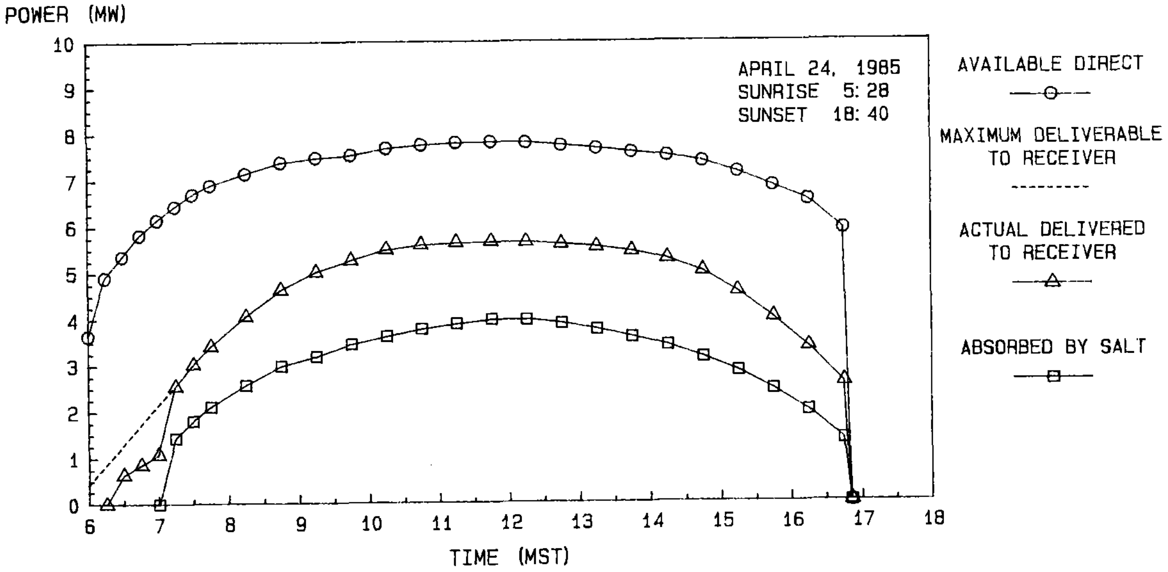

Figure 4-3. Clear Day Energy Collection Power Levels

The integration of the power levels of Figure 4-3 gives the following:

	MWh
Available direct solar energy	77.5
Maximum energy deliverable to receiver	48.3
Actual energy delivered to receiver (Does not include warmup of receiver panel)	46.9
Absorbed by salt	30.3

The available direct solar energy is based on the actual number of operational heliostats. The maximum energy deliverable to the receiver assumes all available heliostats are focused on the receiver at all times. Included in the actual energy delivered to the receiver is the spillage external to the cavity, which is estimated at 8.9 MWh. The receiver thermal output for this day was the highest single-day output achieved during the integrated system test.

The receiver thermal performance for the range of power levels exhibited on April 24 is shown in Figure 4-4. The power levels correspond to all available heliostats targeted, and the power variation is that which occurs with the time of day. The highest power levels correspond to those near solar noon and the lowest power levels correspond to those in the early morning.

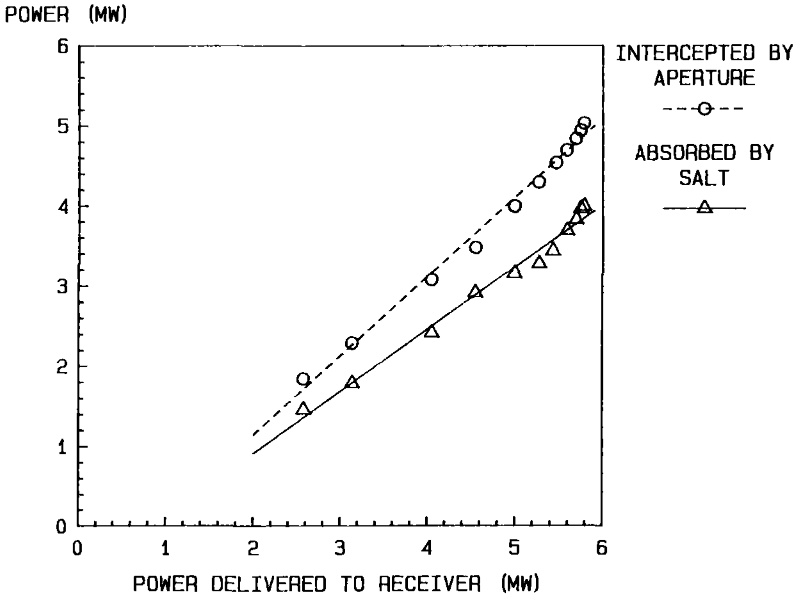

Figure 4-4. Receiver Input-Output Performance

Averaging the results of seven clear and mostly clear days during the integrated system test yields the energy collection efficiencies shown by Figure 4-5. The total direct energy is the average measured values. The collector subsystem efficiencies correspond to April 24 and the receiver-related efficiencies are averages for the eight clear and mostly clear days of operation. The efficiencies were determined in a manner similar to that described for solar noon, but on an energy rather than power basis. As with solar noon, assuming that the HELIOS spillage loss estimate is accurate, the receiver efficiencies are in good agreement with the adjusted receiver SRE results. The efficiencies are also consistent with the MSEE predictions. The receiver input-output efficiency of 0.802 (0.962 receiver absorbtivity X 0.834 thermal efficiency) is within 1% of its expected value.

The efficiencies shown in Figure 4-5 is based on the receiver operating at maximum energy collection levels from one hour after sunrise until one hour before sunset. The collectable energy lost during the periods in which the receiver is not operating (primarily during startup) is a major performance issue. The following discussion of the receiver startup and shutdown losses will show that these losses are small. As for the startup and shutdown of the energy conversion subsystems, with the exception of the boiler, the operations for a cycling commercial central

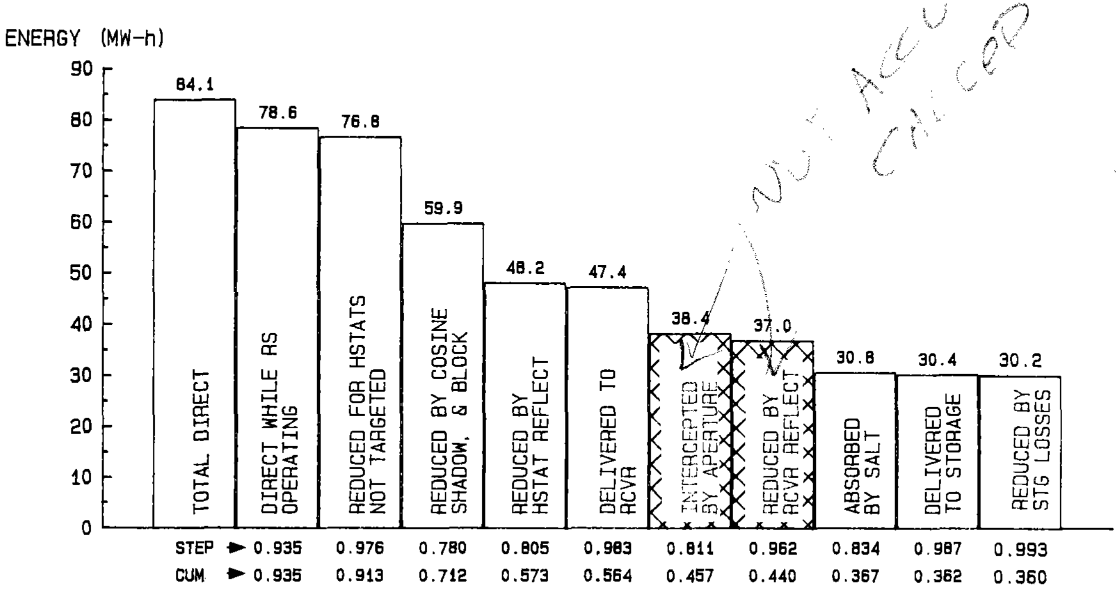

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Figure 4-5. Clear Day Energy Collection Efficiencies

receiver system would essentially duplicate those of a conventional daily cycling fossil generating station.

<u>Startup and Shutdown</u>. One of the advantages of a molten salt and direct storage central receiver system over a direct coupled water and steam receiver is that the receiver can achieve useful maximum energy collection levels more rapidly. For the direct coupled water and steam receiver, the time required to reach useful maximum energy collection levels is greater due to the limitations associated with the startup of the energy conversion subsystems. The molten salt and direct storage system, on the other hand, can be brought up to maximum collection levels in a matter of minutes after the receiver is filled with salt.

Figure 4-6 shows an actual startup timeline for the energy collection process. This timeline was followed on May 8 during the integrated system test. The power levels during this startup are shown in Figure 4-7. The energy deliverable to the receiver remains at zero until 17 minutes after sunrise while the CRTF is in the mountain shadow. The warmup of the dry receiver panel begins at 23 minutes after sunrise, when the insolation reaches approximately 350 W/m^2. The warmup extends until 50 minutes after sunrise, when the panel temperatures are all above the salt freezing temperature of 430 deg F. With further development of the heliostat aiming strategy (using more heliostats), the warmup process could begin earlier. At 50 minutes after sunrise the receiver fill sequence starts. It requires 10

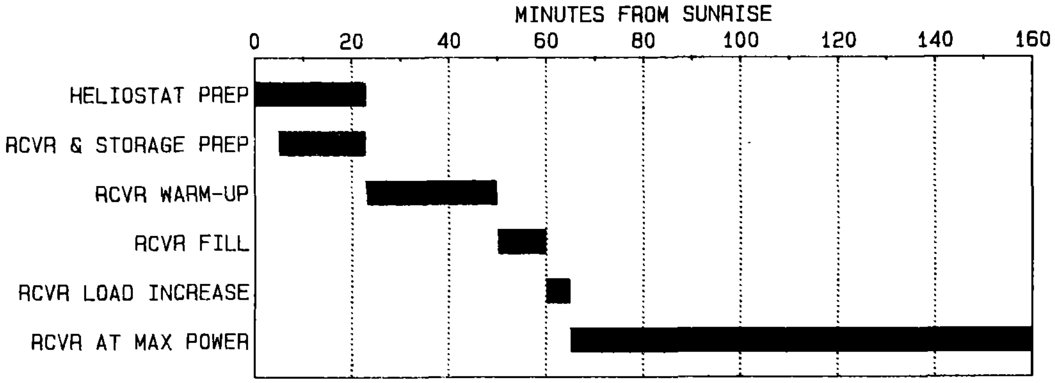


Figure 4-6. Receiver Startup Timeline

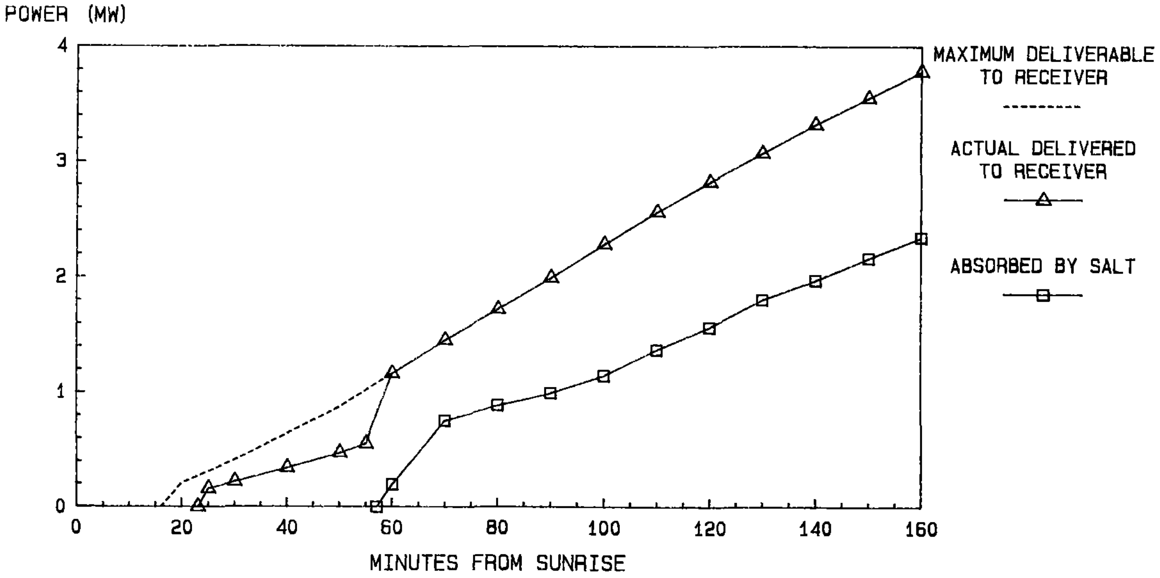


Figure 4-7. Early Morning Energy Collection Power Levels

minutes to complete. At 60 minutes after sunrise the receiver is in serpentine flow and all available heliostats are targeted on the receiver. By 65 minutes after sunrise the receiver thermal output has stabilized at a level consistent with the maximum power being delivered to the receiver. This startup sequence is routinely achievable and could even be shortened with further development of the panel warmup strategy. The integration of the available direct power and the maximum power deliverable to the receiver, from sunrise until maximum energy collection 65 minutes after sunrise, is given in Table 4-1. Also included in this table is an estimate of the energy that could have been collected if the energy

Table 4-1

SOLAR ENERGY USAGE DURING RECEIVER STARTUP

	Thermal Energy (MWh)	Percent of Clear Day Total
Available direct solar energy	2.9	3.5
Maximum energy deliverable to receiver	0.35	0.7
Collectable energy lost during startup	0.18	0.6

collection had begun with the first available insolation. Each of the energies of Table 4-1 are also expressed as a percentage of their typical late April or early May clear day total.

Although the direct energy usage during the receiver startup appears somewhat significant at 3.5% of the daily total direct, the collectable energy which could have been absorbed if the receiver had been operating during the startup period is actually only 0.6% of the daily total energy collected. The collectable energy lost is low due to the high cosine, shadowing, and blocking losses in the heliostat field in the first hour after sunrise.

At the start of maximum energy collection, the receiver is normally operated at its minimum flow rate to maximize the outlet salt temperature. For a molten salt receiver, the minimum flow rate is established by the point at which the transition to laminar salt flow in the receiver tubes occurs. The minimum flow rate must be sufficiently above this transition point to assure that turbulent flow in the receiver is maintained. For the MSEE receiver the minimum flow rate is approximately 20% of full flow. However, operation at this flow rate was not possible due to flow instrumentation limitations that would not permit adequate flow control at less than 30% of full flow. This limitation resulted in lower outlet temperatures after startup, delaying the output of the rated 1050 deg F salt.

Figure 4-8 shows typical outlet salt temperatures, both actual and what would be achievable if the flow rate could be lowered to its minimum, for the first 160 minutes after sunrise. The temperatures correspond to the power levels of Figure 4-7. As indicated, an outlet salt temperature of just over 900 deg F is achievable shortly after the receiver startup. An outlet temperature of 900 deg F is considered the minimum acceptable for continuous delivery to the hot storage tank. The lower initial outlet temperature did not significantly reduce the overall system performance because energy delivered to the cold tank is retained as useful energy in the system.

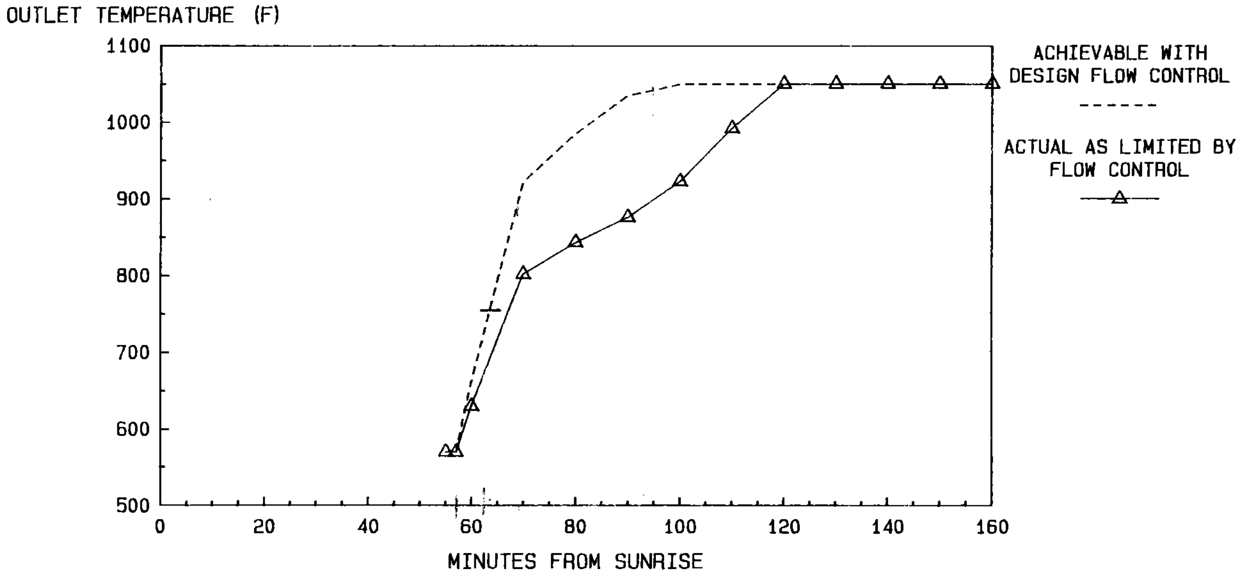


Figure 4-8. Receiver Early Morning Outlet Temperature

On a typical clear day, the receiver shutdown and drain would normally be initiated whenever the outlet temperature falls below 900 deg F. Since the receiver output is symmetrical about solar noon, the temperatures of Figure 4-8 also apply to the 160 minutes prior to sunset on a clear day. With the termination of energy collection occurring approximately one hour before sunset, the energy levels associated with the period after shutdown are identical to those listed in Table 4-1.

With the start of maximum energy collection occurring one hour after sunrise and continuing until one hour before sunset, the energy collected is only 1.2% less than what could be collected with continuous operation from sunrise to sunset. This 1.2% loss in the collectable energy applies to clear day operation during late

April and early May. The loss percentage would be slightly higher near the winter solstice and slightly lower near the summer solstice. These results indicate that the losses attributed to the daily startup and shutdown do not significantly reduce the overall energy collection performance of the MSEE receiver.

Energy Conversion

The energy conversion portion of the MSEE system includes the steam generation subsystem, the heat rejection and feedwater subsystem, and the electric power generation subsystem. The energy conversion performance of the MSEE is not representative of a commercial plant. This is due to the relatively small scale of the experiment and its unoptimized design. The small scale and unoptimized design results in lower efficiencies throughout the system and, as a fraction of gross plant output, a much greater parasitic electric load than would be expected from a commercial plant. There was no opportunity to optimize the complete system because the system was designed to utilize existing subsystems and many salvaged components.

For clear day operation, the primary advantage of a molten salt and direct storage system over a direct coupled (e.g., Solar One) system is that it allows the energy conversion subsystems to operate at or near rated conditions (and peak efficiency) throughout the day rather than only near solar noon. This advantage was demonstrated during the MSEE test program. During the integrated system test, the energy conversion subsystems were operated at full load most of the time. The storage tanks were absorbing or supplying the difference between the thermal output of the receiver and the thermal input to the steam generator.

Steady-State Energy Conversion. Since the energy conversion portion of the system is decoupled from the energy collection portion, its performance can be evaluated independently. Typical full load operating conditions for the steam generation subsystem are shown in Figure 4-9. Full load refers to operating with the main salt flow control valve 100% open such that the salt flow rate through the steam generator is at its maximum.

Referring to Figure 4-9, off-rated operating conditions were primarily the result of lower than rated hot salt and feedwater temperatures. With the receiver typically operating at 1030 to 1040 deg F, rather than the rated outlet temperature of 1050 deg F, the hot salt available for delivery to the steam generator ranges from 1010 to 1020 deg F. This low hot salt inlet temperature leads to a lower superheater salt outlet temperature, and the required flow of cold salt at the

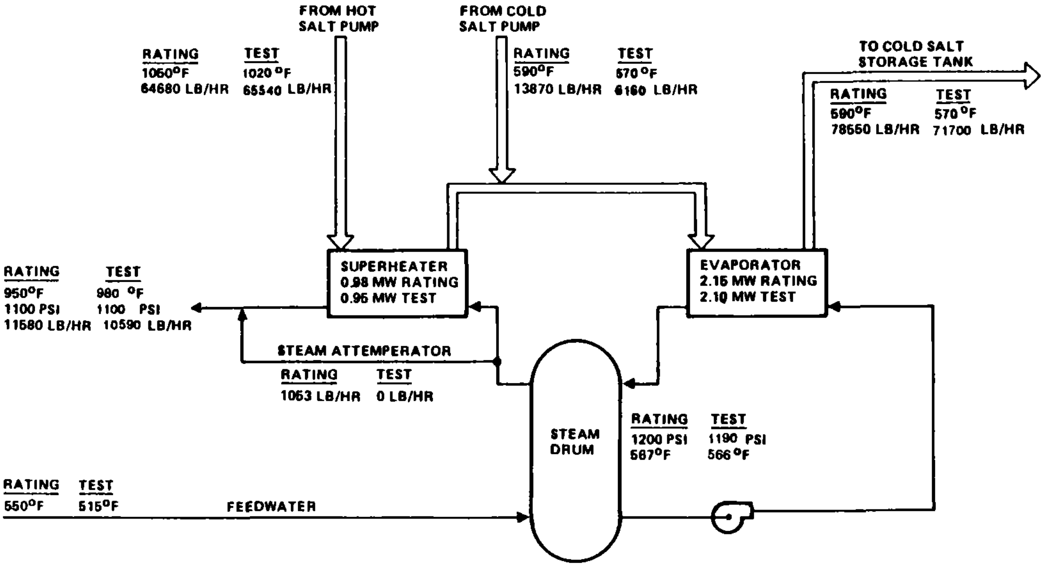


Figure 4-9. SGS Full Load Operation Conditions

attemperator between the superheater and evaporator is lower as a result (6,160 lb/hr rather than the rated flow of 13,900 lb/hr). This attemperation cools the salt entering the evaporator to 850 deg F as limited by its 2 1/4 Cr-1 Mo construction. The lower than rated evaporator outlet salt temperature is primarily the result of the additional load on the evaporator due to a lower-than-rated feedwater temperature.

The rated feedwater temperature is 550 deg F. It was necessary to reduce this temperature to prevent steam drum level instabilities that were observed during load changes with the 550 deg F feedwater. The drum level instabilities were due to drum pressure variations, which resulted in drum pressure less than the saturation pressure for the incoming feedwater. This allowed flashing of incoming feedwater and resulted in level swell. It was determined that a 520 deg F temperature setpoint for the feedwater heater (thermal losses result in the temperature dropping to 515 deg F at the SGS skid) would assure that the water entering the steam drum remained subcooled during load changes, and thus prevent drum level instabilities.

The steam attemperator, although fully operable, was not required during operation with lower than the rated 1050 deg F superheater inlet salt temperature. Without attemperation, the main steam temperature of 980 deg F was acceptable since it did not exceed turbine throttle steam temperature limitations. The possible elimination of the steam attemperator in future designs is discussed in the SGS design evaluation.

The off-rated operating temperatures reduced the SGS thermal output capacity by 6%. They also resulted in approximately the same reduction in the gross steady-state electric power generating capacity.

Typical full load efficiencies for the complete energy conversion process are given in Figure 4-10. The thermal power extracted from storage, delivered to the steam generation subsystem, and added to the steam cycle are all averages based on extended periods of operation. The cumulative efficiency from the thermal power extracted from storage through the power added to the water and steam loop represents the thermal losses associated with the transfer of energy from the molten salt to the water and steam. These losses would not be incurred in a direct coupled system; however, these losses are relatively small for the MSEE, and the loss fraction would be even less for a commercial plant. In addition, since the molten salt and direct storage system permits continuous operation of the turbine-generator at rated output, this penalty is offset by higher steam cycle efficiencies. This loss offset is not apparent in the efficiencies shown in Figure 4-10; it will be examined later in the discussion of the full day energy conversion.

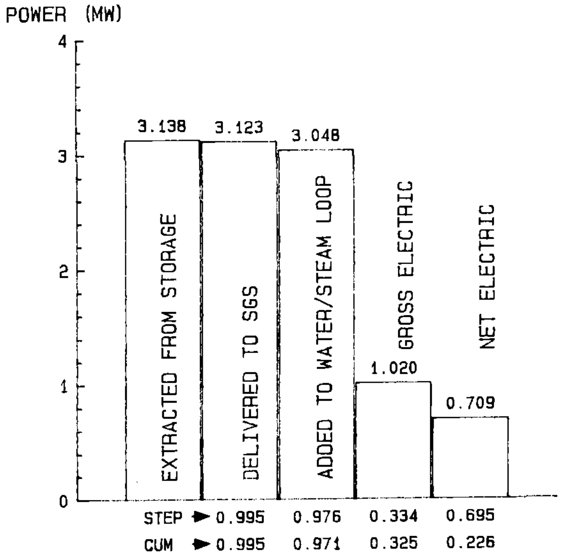


Figure 4-10. Steady-State Energy Conversion Efficiencies

The gross and net electric outputs shown in Figure 4-10 are simulated values based on the actual thermal output of the MSEE steam generator, and the actual performance of the Solar One turbine-generator with appropriate adjustments, the heat rates shown in Figure 4-11, and a combination of measured and calculated electric parasitic loads. The simulation of the electric output was required due to the failure of the turbine oil pump, which prevented the operation of the turbine-generator. This failure occurred prior to the integrated system test; however, the operation of the turbine-generator was not required in order to meet the test objectives. The turbine-generator met its primary objectives prior to its failure by demonstrating compatibility with the startup and operation of the steam generation subsystem and by demonstrating stable electric output from the steam generated by the molten salt.

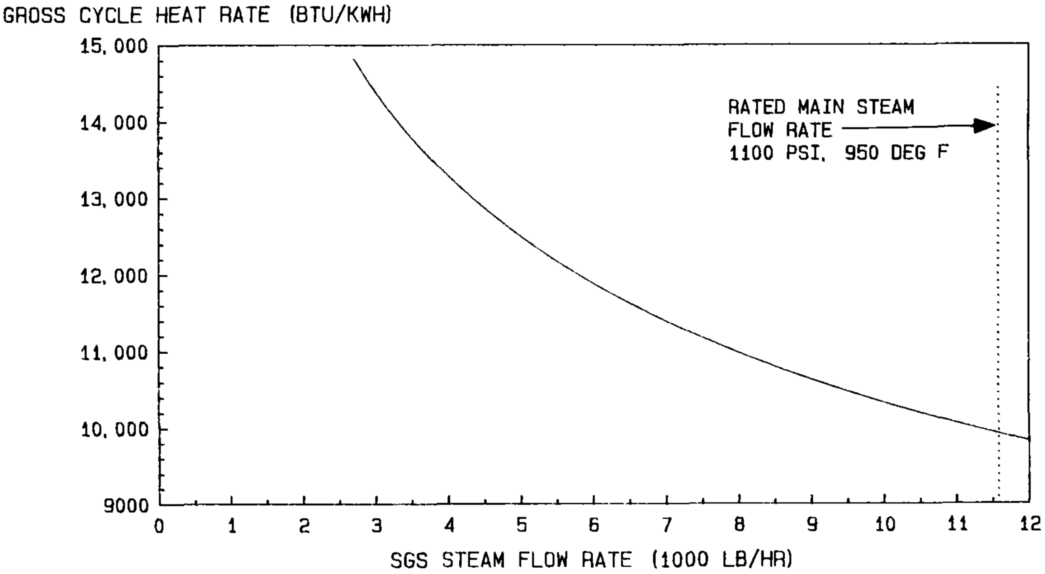


Figure 4-11. Gross Steam Cycle Heat Rate

The heat rates of Figure 4-11 are based on the actual performance of the Solar One turbine-generator with appropriate adjustments to compensate for the lower MSEE steam pressure and higher steam temperature. The determination of these heat rates is presented in detail in Appendix E along with their comparison to actual MSEE heat rates exhibited prior to the turbine-generator failure. The actual MSEE heat rates serve little purpose in this performance evaluation. The MSEE steam cycle through the heat rejection feedwater subsystem and the electric power generation subsystem, which includes the turbine-generator, is extremely inefficient.

Consequently, the simulation of the actual MSEE electrical output would be misleading.

From Figure 4-11, the gross steady-state steam cycle heat rate for the full load steam flow rate (10,600 lb/hr) is 10,270 Btu/kWh. Adjusting this heat rate to correct for the higher than rated main steam temperature (980 deg F instead of 950 deg F) gives a heat rate of 10,220 Btu/kWh. The heat rate adjustments for off-rated steam conditions are discussed in Appendix E. This adjusted heat rate corresponds to the gross steam cycle efficiency of 0.334 shown in Figure 4-10.

The gross electric output is reduced by the plant parasitic load to arrive at the net plant electric output. The parasitic electric loads are listed in Table 4-2. All the values in Table 4-2, except the steam cycle and balance of plant, are actual measured loads. The steam cycle and balance of plant parasitics are based on actual Solar One values that have been scaled for MSEE application. The actual MSEE steam cycle and balance of plant parasitic loads were not used because they were unrepresentatively large and the results would be misleading. A listing of the actual steam cycle parasitic loads is included in Appendix E.

The above approach to evaluating the energy conversion gives the most realistic appraisal of the capabilities of a very small scale molten salt electric plant. The only performance characteristics not actually exhibited by the MSEE are those for the steam cycle. This approach does not reduce the validity or value of the evaluation since the steam cycle performance is not a source of uncertainty in the design of future plants.

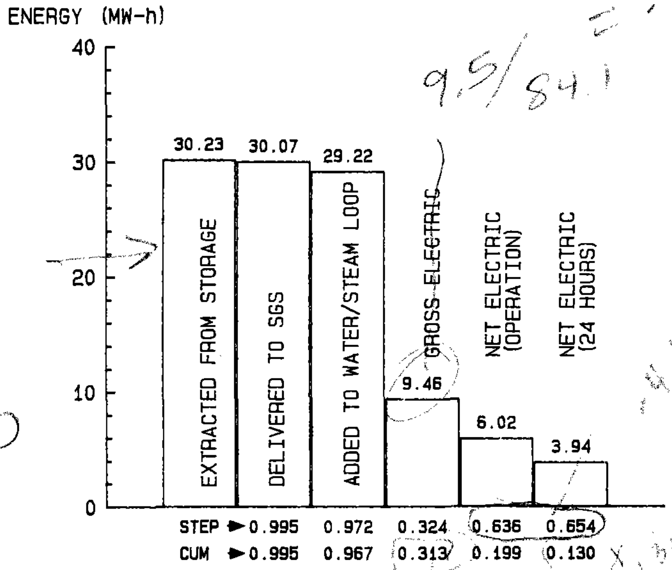
<u>Clear Day Energy Conversion</u>. The approach to the clear day energy conversion performance evaluation was similar to the steady-state energy conversion discussed above, but on a total daily energy rather than power basis. As with the steady-state performance, the electric output was simulated based on the measured SGS thermal output and the heat rates of Figure 4-10. When appropriate, the heat rates shown in Figure 4-11 were adjusted for off-rated steam pressure and/or temperature.

Figure 4-12 shows the clear day energy conversion efficiencies corresponding to the energy collection performance represented by Figure 4-5. The comparison of the clear day efficiencies shown in Figure 4-12 to the steady-state efficiencies shown in Figure 4-10 indicates the conversion effectiveness characteristic of the molten salt and direct storage system. The clear day gross steam cycle efficiency of 0.324 is only slightly less than the 0.334 steady-state efficiency. The high clear

Table 4-2

ELECTRIC PARASITICS - CLEAR DAY

	Steady State Power (kW)	X	Duty Cycle (Hr/Day)	=	Daily Energy (kWh/Day)
Operation					
Salt pumps					
Cold salt	45.4		11.2		508
Booster	33.2		11.2		372
Hot salt	6.1		10.5		64
	84.7				944
Trace heaters					
Receiver	13.4		11.2		150
Thermal storage	24.5		11.2		274
Downcomer and riser	17.0		11.2		190
Steam generator	5.7		10.5		60
	60.6				674
Collector field and controls	52		12.2		634
SGS circulation pump	4.6		10.5		48
Steam cycle and balance of plant	109		10.5		1,145
Operation total	310.9				3,445
Standby					
Trace heaters					
Receiver	27.2		12.8		348
Thermal storage	33.0		12.8		422
Downcomer and riser	29.8		12.8		381
Steam generator	16.9		13.5		228
	106.9				1,379
SGS circulation heaters	17.3		13.5		234
SGS circulation pump	4.6		13.5		62
Balance of plant	30		13.5		405
Standby total	158.8				2,080
Grand Total					5,525



from Fig 4-5

9.5/84.1 = .113

.41 = parasitic η

x .36 = .047 Daily η

Figure 4-12. Clear Day Energy Conversion Efficiencies

high for such a small turbine

day efficiency (relative to steady state) is due to the operation at or near rated load conditions throughout the day and the minimal losses associated with its startup.

Subtracting the parasitic electric loads from the gross electric gives the net electric shown in Figure 4-12. The net electric is given for both the period when the system is operating and on a 24-hour basis. The itemized parasitic energies are included with the parasitic powers listed in Table 4-2. A substantial reduction in the trace heater electric consumption is achievable and will be discussed with the monthly performance evaluation.

The clear day energy conversion performance results indicate that a molten salt and direct storage system is capable of efficiently converting the thermal energy stored in molten salt into electricity.

Startup of Energy Conversion. The molten salt/direct storage system provides the capability to shift the energy conversion period from the energy collection period, within the limits of the available storage capacity. This feature results in a rather meaningless comparison of the energy conversion startup timeline to the receiver startup or sunrise. For completeness, however, Figure 4-13 shows two typical startup timelines for the energy conversion process. The early startup corresponds to that when the hot salt storage tank is more than two-thirds full and

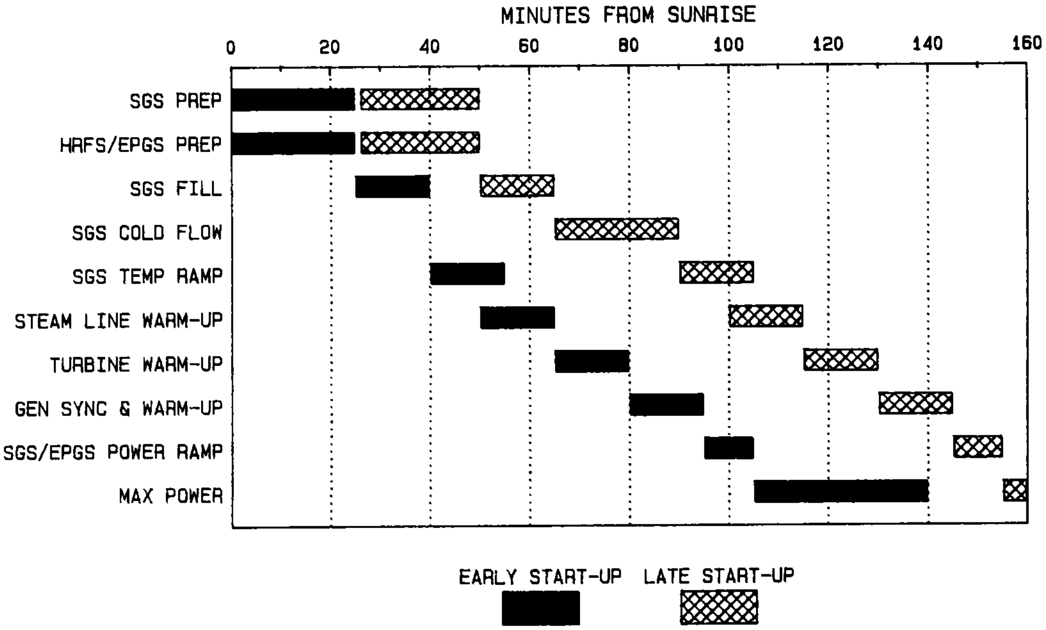


Figure 4-13. Energy Conversion Startup Timeline

the late startup corresponds to that when the storage tank is less than one-third full. Exact adherence to these timelines is not required for performance optimization. As long as the receiver is operated at its maximum energy collection level and the energy conversion process operates continuously at its maximum output, overall performance will be similar regardless of when the energy conversion process startup begins.

Startup power levels for the energy conversion process are shown in Figure 4-14. The energy required to start up the energy conversion process (represented by the area under the SGS thermal input curve for the first 40 minutes) amounts to 0.52 MWh or approximately 1.7% of the total energy delivered to the SGS on a clear day. Thus, energy usage during the startup of the energy conversion process is relatively low. In addition, only a small fraction of this energy is rejected during the startup. The steam generated during the startup is used primarily to heat the steam lines as rapidly as possible. Even then most of the energy remaining is used to heat the feedwater rather than being rejected as waste heat. This is accomplished by reducing the steam output as shown by the large dip in Figure 4-14. Small amounts of steam are required at this time while the turbine is going through warmup for 15 minutes. After the generator synchronization, any

1% for
100 MW for
SG + TURB

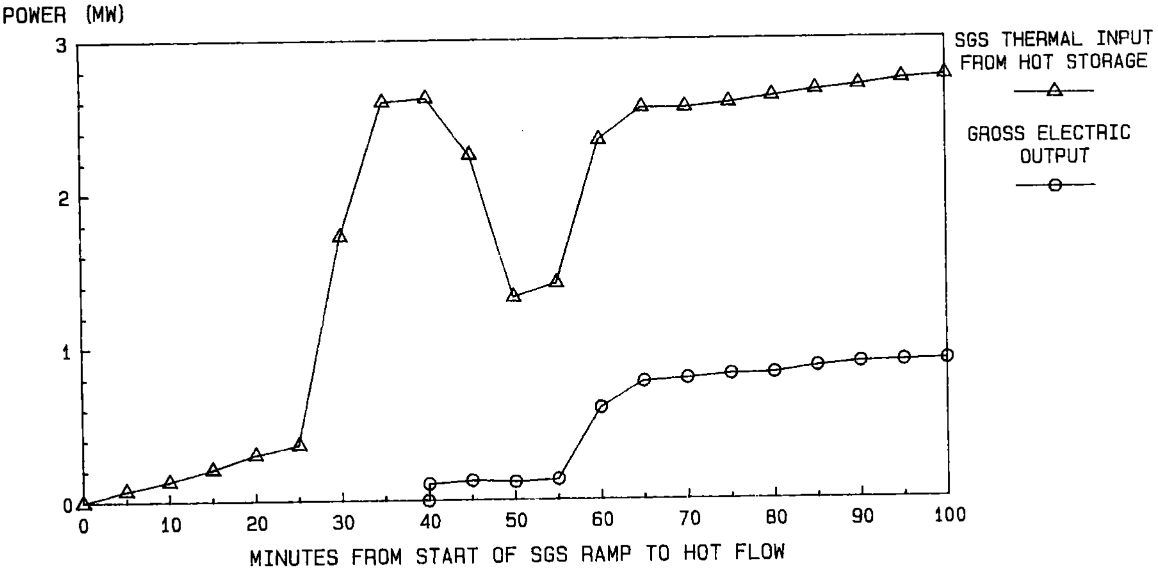


Figure 4-14. Energy Conversion Startup Power Levels

excess steam produced while the steam generator and turbine-generator loads are being adjusted is rejected to the deaerator to preheat the feedwater.

Thermal Storage Capacity. The total thermal storage capacity, based on the quantity of salt in the system during the MSEE test program, is approximately 6 MWh. Since the sumps are fed by gravity from the storage tanks, the tanks have minimum operating levels in order to provide the head to supply salt to the sumps at a rate which meets the receiver and SGS demands.

The MSEE was originally constructed with an undersized line feeding the cold sump from the cold salt storage tank. This undersized line severely limited the full utilization of the storage capacity and forced the reduction in the receiver energy collection rate during peak collection periods. The undersized line was replaced in January 1985 in preparation for the integrated system test to alleviate the flow limitations it presented. With the new line, both the energy collection and energy conversion subsystems could be operated at full capacity as long as neither storage tank contained less than approximately 15% of the total salt inventory. Considering these minimum tank levels, the MSEE available storage capacity is approximately 4.2 MWh.

The available storage capacity of 4.2 MWh allows the energy collection process to continue by itself for a maximum of about one hour at peak collection levels. On the energy conversion side of the system, its operation by itself can be sustained at full load for a maximum of about 1.4 hours.

During clear day operation with energy collection and conversion occurring simultaneously, the thermal storage subsystem absorbs or supplies the differences between the thermal collection and conversion rates. Figure 4-15 shows the relationship between the energy collection rate, energy conversion rate, and the energy in storage for April 28. As indicated, the stored energy varies through most of the available range. This wide variation in the stored energy illustrates that the MSEE storage capacity is adequate and not excessive.

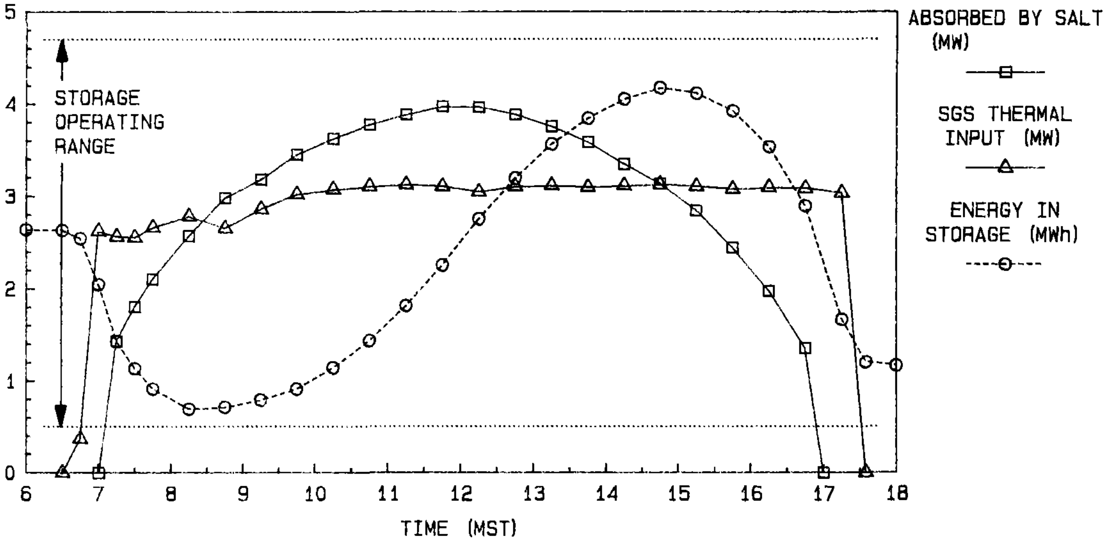


Figure 4-15. Thermal Storage Energy Variation

PARTLY CLOUDY DAY SYSTEM PERFORMANCE

A major advantage of the molten salt and direct storage system over the water and steam direct coupled system is its ability to effectively operate under partly cloudy conditions. The MSEE successfully demonstrated this capability by exhibiting efficient energy collection and stable energy conversion during widely varying solar conditions.

The normalized energy collection efficiencies for the 28 days of the integrated system test, shown in Figure 4-16, illustrates the energy collection effectiveness of the MSEE under less than ideal solar conditions. Disregarding the five days in which the receiver was not operated and the seven days of low solar utilization resulting from operating complications gives the correlation indicated by the straight line in Figure 4-16.

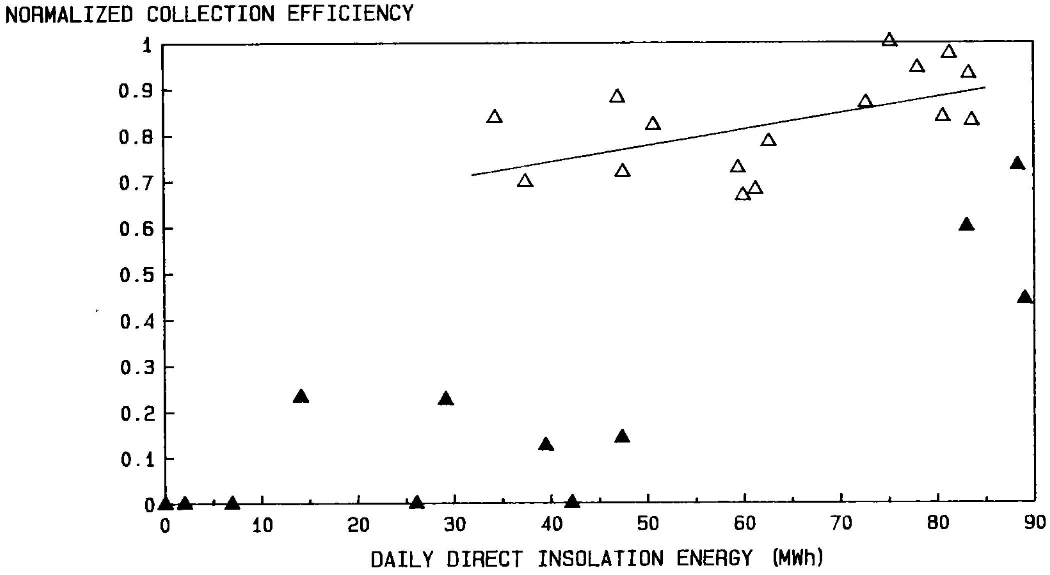


Figure 4-16. Normalized Energy Collection Efficiencies For 28 Days

The startup, operation, and shutdown of the energy conversion process are essentially the same, regardless of the solar conditions. However, the operating schedule must be adjusted to compensate for variable energy collection rates.

Figures 4-17 through 4-19 show the system response to wide variation in insolation. Each of these figures illustrates that useful energy can be collected during variable solar conditions and that the electric output is independent (within storage limits) of the insolation level. This was the first data on MSEE to clearly demonstrate the thermal storage buffering. Figure 4-17 shows that steady-state electricity (bottom curve) was generated throughout the day when solar conditions varied due to clouds of short duration (top curve). The middle curve shows the salt flow through the receiver varied with the transient insolation.

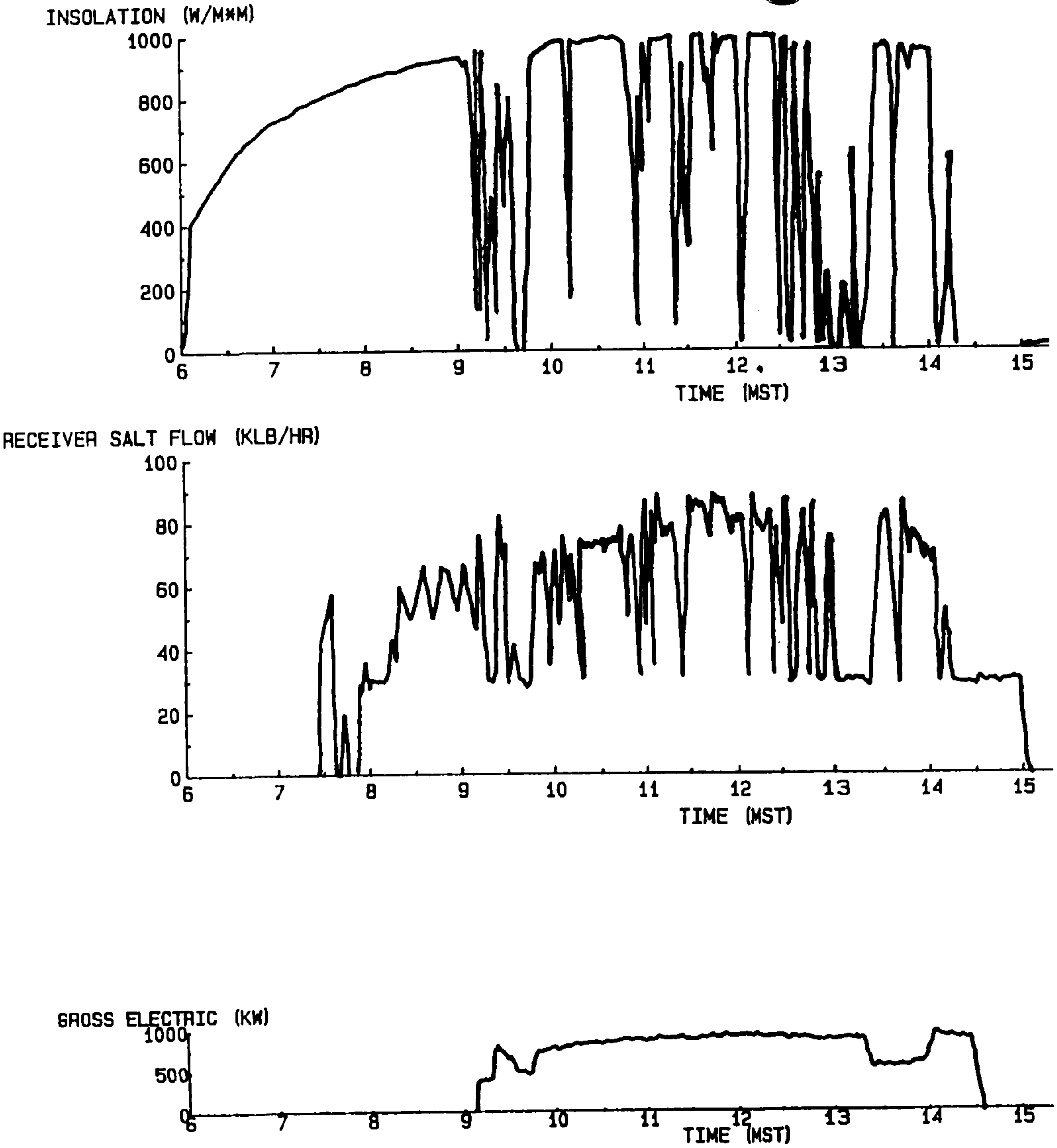


Figure 4-17. System Performance During Variable Solar Conditions, April 18, 1985

Figure 4-18 shows that steady electricity (bottom curve) was generated throughout the day and particularly the later part of the day when solar conditions deteriorated and was finally nonexistent. Generation of electricity was terminated when storage was depleted or when the scheduled test day ended.

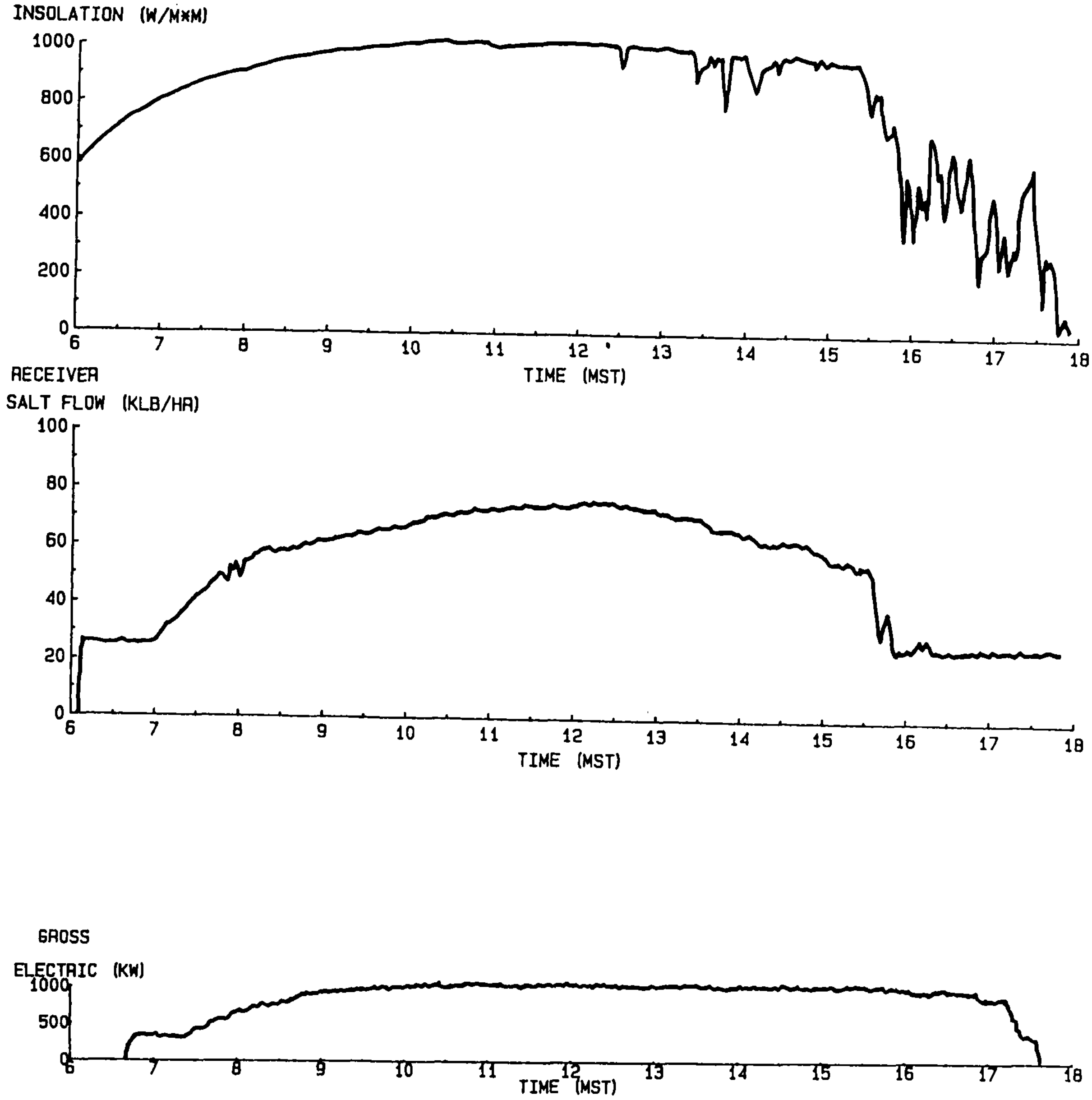


Figure 4-18. System Performance During Variable Solar Conditions, May 8, 1985

Figure 4-19 shows that steady electricity (bottom curve) was generated during varied solar coditions. This was terminated when solar conditions deteriorated and the receiver was not able to produce useful hot salt. The receiver flow rate (middle curve) shows the salt flow after 12 noon was at minimum flow rate until shutdown except for a brief period between 2 and 3 PM.

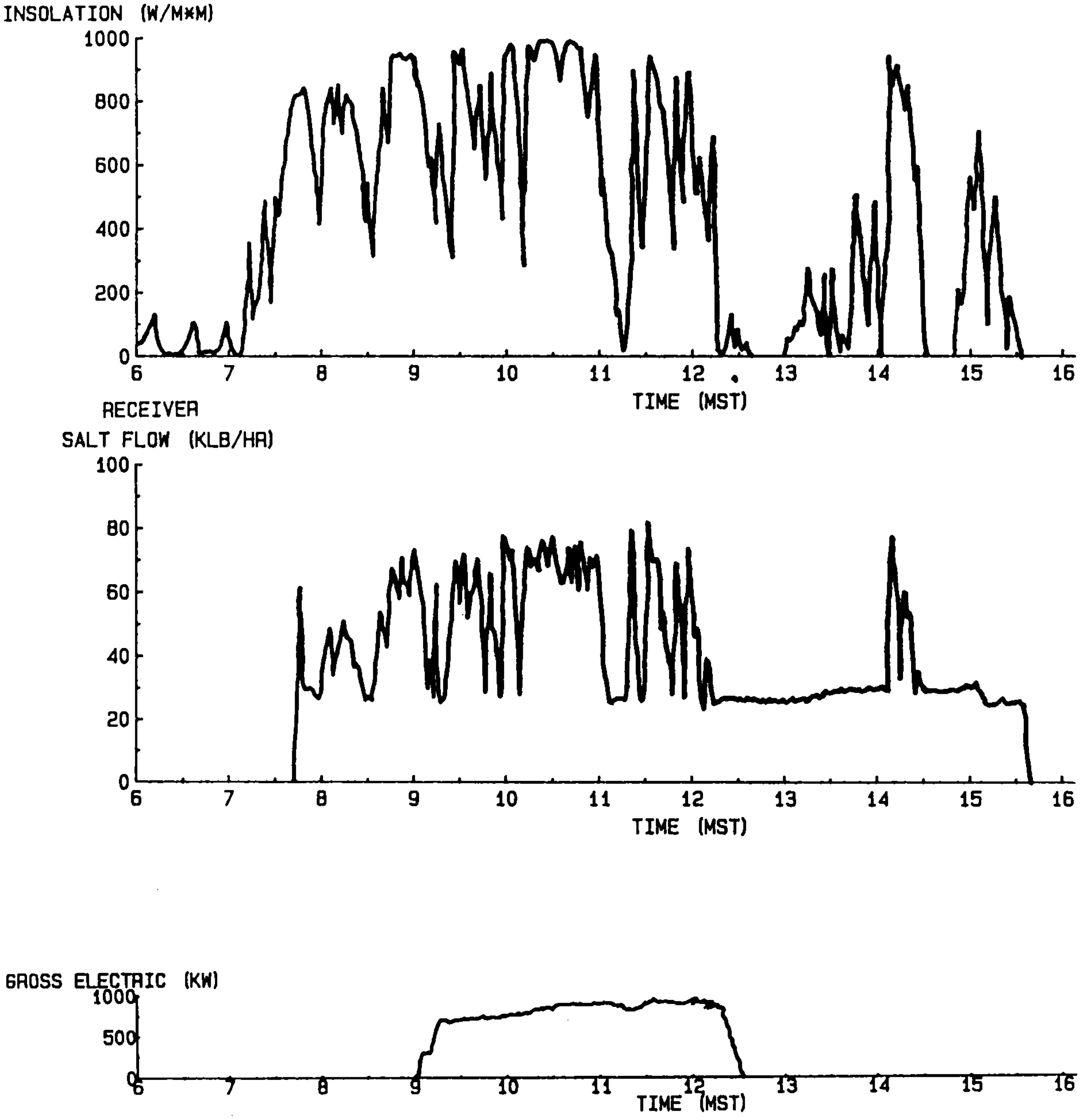


Figure 4-19. System Performance During Variable Solar Conditions, May 9, 1985

MONTHLY PERFORMANCE

The 28-day integrated system operations test provided comprehensive performance data for the system evaluation. The system was operated through a wide range of solar conditions typical of those which would be encountered during the operation of a commercial plant. Appendix F contains key operating data for each of the 28 days of the test campaign. These data include available direct energy, energy delivered to receiver, energy delivered to SGS, gross electric production, and net electric production. Also included are the hours of daylight for each day, to hours synchronized (simulated) to the grid.

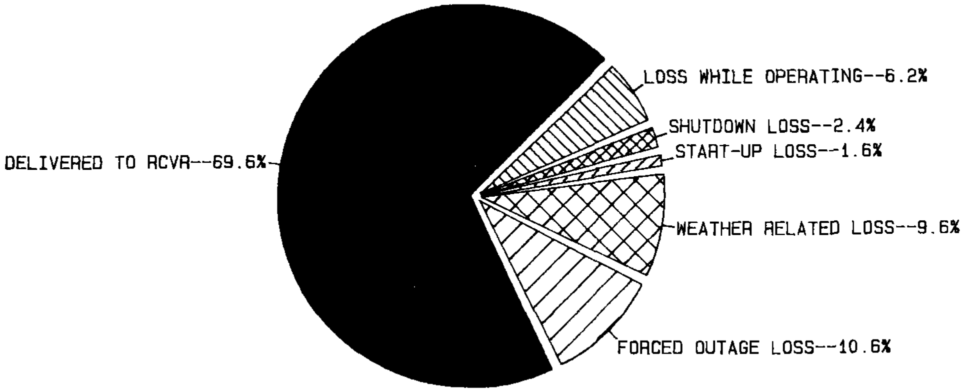
Energy Collection

The sky condition for the 28 days of the test campaign can be classified as follows:

Mostly sunny days, 10
Partly cloudy days, 14
Mostly cloudy days, 4

The average daily direct solar availability during the test was 6.7 kWh/m^2. This average was below the historical Albuquerque average of 7.6 kWh/m (7).

Solar Utilization. The utilization of the total solar energy deliverable to the receiver for the 28 days is shown in Figure 4-20. The total energy deliverable to the receiver (100%) was that which would be delivered if all heliostats were targeted on the receiver during all daylight hours, regardless of the system's operating status. The fraction actually delivered to the receiver (69.6%) was that delivered during periods of energy collection. The loss while operating (6.2%) represents energy not delivered to the receiver during periods while it was operating and available for energy collection. This loss was primarily due to periods of reduced power operation and delays in bringing the heliostats back on target after extended periods of cloud cover.



DISTRIBUTION OF TOTAL ENERGY
DELIVERABLE TO RECEIVER

Figure 4-20. Solar Utilization For 28 Days

The startup loss (1.6%), shown in Figure 4-20, represents energy not delivered to the receiver from sunrise until the scheduled completion of the startup process. The shutdown loss (2.4%) represents energy not delivered to the receiver from the scheduled shutdown until sunset. The shutdown loss was higher than the startup loss; this was due to the work schedule, which forced the system shutdown 30 to 90 minutes early on many days.

The weather related loss (9.6%), shown in Figure 4-20, represents energy not delivered to the receiver during days or periods in which it was not operated due to adverse weather conditions. The weather related loss was accumulated primarily during periods of sunshine when the overall solar availability was judged as being insufficient to justify the operation of the system and during periods when the receiver could not be operated due to insufficient solar availability to complete the startup process. Only a small fraction of the weather-related loss was due to high winds. The operation of the system was demonstrated during wind speeds of 40 to 45 mph. The forced outage loss (10.6%) represents energy lost due to operating complications and equipment outages. Most of this loss was accumulated during the one day in which the steam generation subsystem was unavailable due to a trace heater failure and during startup delays.

Figure 4-21 shows a histogram of the receiver startup frequency as a function of the elapsed time from sunrise until full power operation. During the integrated system operation test campaign the startup process was normally scheduled for

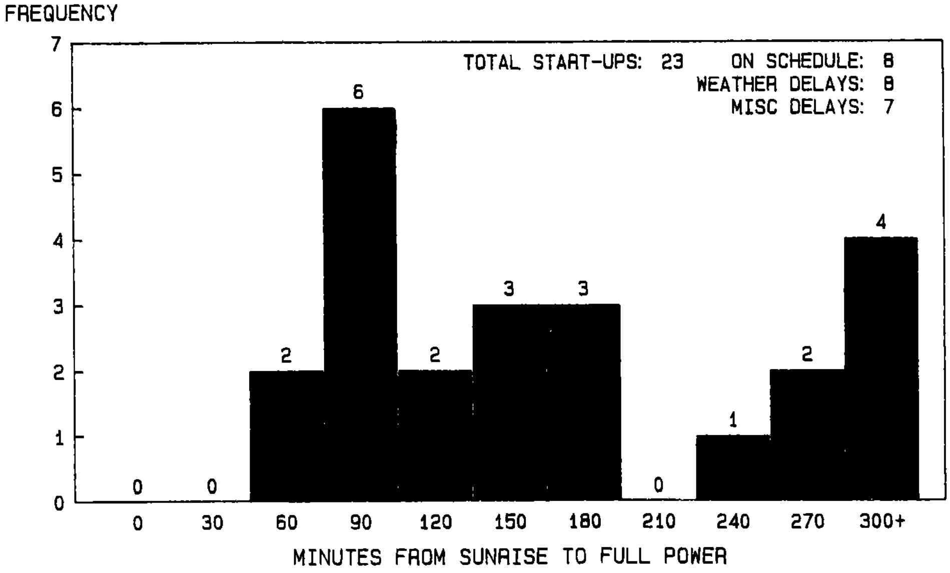


Figure 4-21. Receiver Startup Histogram

completion 90 minutes after sunrise. Although it was demonstrated that the startup process could be completed within 60 minutes of sunrise, 90 minutes was scheduled to accommodate the proficiency levels of the utility operators. There was no indication, however, that the startup process could not be routinely completed within 60 minutes after gaining a few additional weeks of operating experience.

Disregarding the delays due to weather, Figure 4-21 shows that the startup of the energy collection process was completed on schedule more than 50% of the time. The delays not related to weather consisted of three occurrences of salt blockages, a problem which was later eliminated with trace heater control modifications, and four occurrences of cold components due to inadequate thermal protection. The frequency of startup delays is considered unique to the MSEE.

The integrated system operation test was successful in demonstrating that a molten salt central receiver is capable of effective solar utilization.

Energy Collection Performance. The receiver was operated on 23 of the 28 days of the integrated system operation test campaign, as shown in the following summary:

Total daylight hours	373
Hours above 400 W/m^2 insolation	213
Hours of receiver salt flow	169
Hours of receiver outlet > 900 deg F	130
Hours of propane operation	0

The energy collection efficiencies for the 28 days of the test campaign are shown in Figure 4-22. In addition to the efficiency improvements discussed with the solar noon and clear day performance, substantial improvements would be expected in a commercial system as a result of increasing the period of operation for the energy collection process.

Comparing the 28-day energy collection efficiencies to the corresponding clear day efficiencies (Figure 4-5) illustrates the overall effectiveness of molten salt as an energy collection and storage medium. Disregarding the loss due to the period of time in which the receiver was not operating, the remaining efficiencies are similar to their corresponding clear day values. Most significant is the energy absorbed by the salt which, as a fraction of the energy intercepted by the aperture, was only slightly less than its clear day value. This performance is

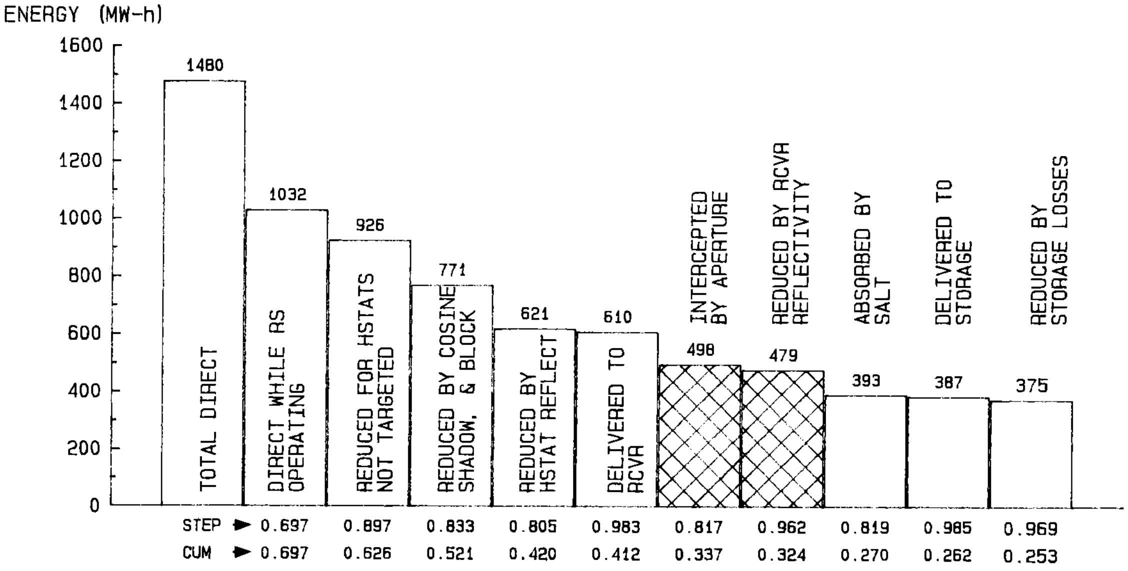


Figure 4-22. 28-Day Energy Collection Efficiencies

remarkable, considering that only 10 of the 23 days of operation represented by these efficiencies were classified as mostly sunny. Also, recall that the solar availability for the 28 days was below average.

These results of the integrated system operation test campaign indicate that a molten salt and direct storage system can efficiently collect energy during less than ideal solar conditions. This performance is the result of the capability of a molten salt receiver to almost instantly begin collecting useful energy (although at lower temperatures initially) after periods of cloud cover. In addition, the lower initial receiver outlet temperature was determined to not adversely affect the energy conversion performance since low-temperature energy is added to the cold salt storage tank.

Energy Conversion

The 28-day integrated system operation test campaign included the operation of the energy conversion process on 20 days. Of the eight days in which the energy conversion process was not operated, seven were a direct result of the solar availability and only one was due to a forced outage. The following summarizes the time periods relating to the energy conversion process for the 28 days:

Hours of steam production	
Total	142
Above 80% of rating	105
Above 60% of rating	123
Hours connected to grid (simulated)	135

The hours connected to the electric grid, although simulated, are consistent with the actual turbine-generator start-up and operation demonstrated before its failure. The hours connected to the electric grid relative to the hours of steam production illustrates that the system can be started up rapidly.

Figure 4-23 shows the simulated periods of electric power generation and the solar conditions for each of the days during the test campaign. The period from 6:00 through 18:00 has been divided into three-hour intervals for classification of the solar conditions. Intervals classified as clear are those in which the direct insolation was greater than 400 W/m^2 for more than 95% of the time. Intervals classified as partly cloudy are those in which the direct insolation was greater than 400 W/m^2 for 25% to 95% of the time. Mostly cloudy intervals are those in which the direct insolation was greater than 400 W/m^2 for less than 25% of the time. The periods of electric power production overlapping with periods of partly or mostly cloudy solar conditions illustrates the advantage provided by the direct storage feature.

The energy conversion efficiencies for the 28 days of the test campaign are shown in Figure 4-24. In addition to the demonstrated performance, Figure 4-24 shows five adjustments to the net simulated electric output that would have improved the plant performance.

Comparing the 28-day energy conversion efficiencies to the corresponding clear day efficiencies (Figure 4-12) shows that the thermal storage losses were not excessive relative to the clear day operation and that the thermal to gross electric efficiency dropped only slightly. However, the net electric output was significantly less, as a fraction of gross, for the 28 days.

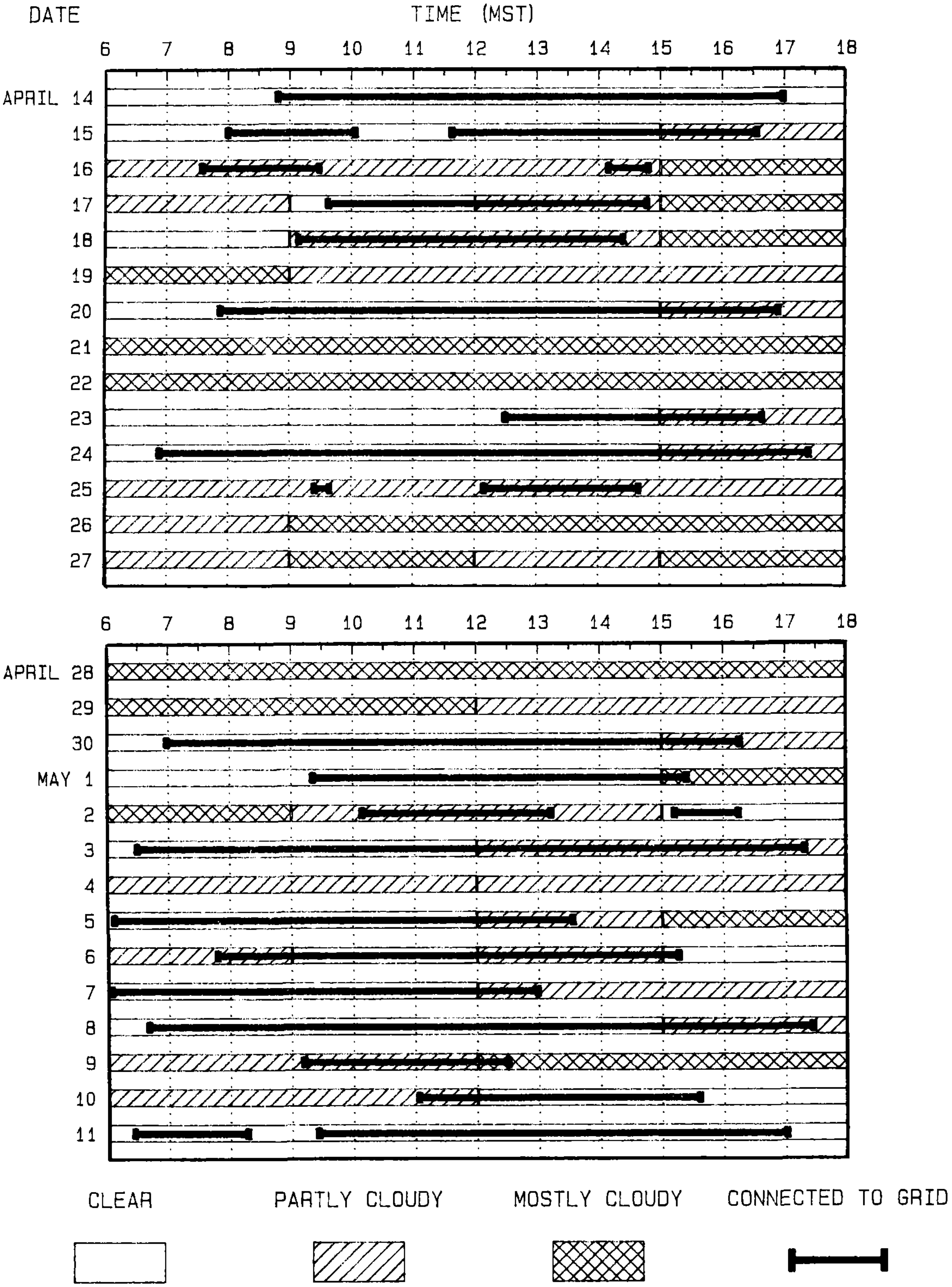


Figure 4-23. Periods of Electric Power Generation

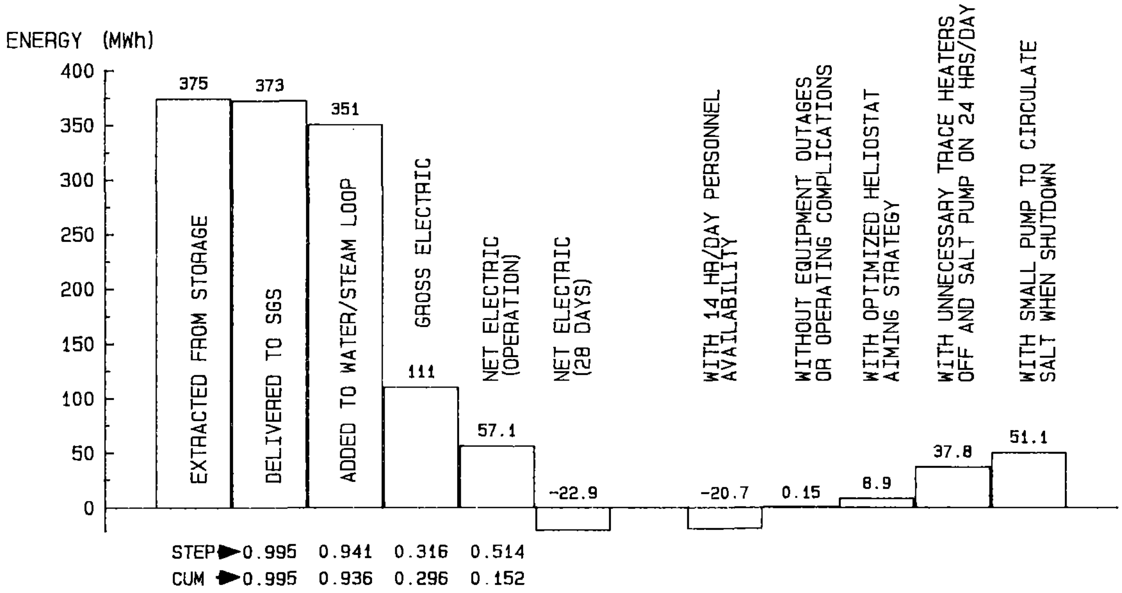


Figure 4-24. 28-Day Conversion Efficiencies

The low net electric output was expected of the MSEE due to its unoptimized design, small scale, and an operating strategy which was intended to maximize energy collection rather than net electric output. This operating strategy resulted in higher parasitic electric loads; however, it provided more complete energy collection data. The electric parasitics for the 28 days are summarized in Table 4-3. The determination of the parasitics follows that described for the solar noon and clear day operation.

As indicated by the adjustments to the net electric output shown in Figure 4-24, without the early shutdown required due to the work schedule, and if equipment outages and operating complications had not occurred, the net electric output would have increased to near zero. Additional improvements in the net electric output would be realized if an optimized heliostat aiming strategy, using multiple aim points, had been used and if the excessive electric parasitic associated with trace heating was reduced. The gains resulting from such a reduction in parasitics are indicated by the last two adjustments in Figure 4-24. The reduction in the trace heating parasitic results from supplying most of the energy required for thermal conditioning with stored thermal energy rather than electrical energy. The only areas requiring electric trace heating after salt flow is established would be drained or stagnant salt lines and some valves with bellows seals. All other electric trace heaters could be turned off.

Table 4-3

ELECTRIC PARASITICS - 28 DAYS

	kWh
Operation	
Salt pumps	15,150
Trace heaters	10,810
Collector field and controls	10,610
SGS circulation pump	700
Steam cycle and balance of plant	16,680
Total	53,950
Standby	
Trace heaters	52,960
SGS circulation heaters	8,980
SGS circulation pump	2,390
Balance of plant	15,570
Total	79,900

The above results indicate that positive net electric output is achievable on the MSEE scale, even with the below-average solar availability of the 28-day integrated system operation test campaign. Relative to a commercial scale plant, however, the MSEE performance capability is poor and is not directly scaleable. Therefore, the MSEE efficiencies throughout the system will be compared to those expected of a commercial scale system in the following annual performance projection.

ANNUAL PERFORMANCE PROJECTION

The 28-day integrated system operation test campaign provided plant performance data over a wide range of operating conditions. This performance data has been utilized in projecting the plant's annual performance. The projected efficiencies, from direct insolation through net electric output, are shown in Figure 4-25. These efficiencies are based on typical meteorological year (TMY) insolation data and do not include allowances for plant outages.

The projected annual electric parasitics are listed in Table 4-4. As previously discussed, the total electrical parasitic loads could be significantly reduced by using stored thermal energy in place of operating electric trace heaters.

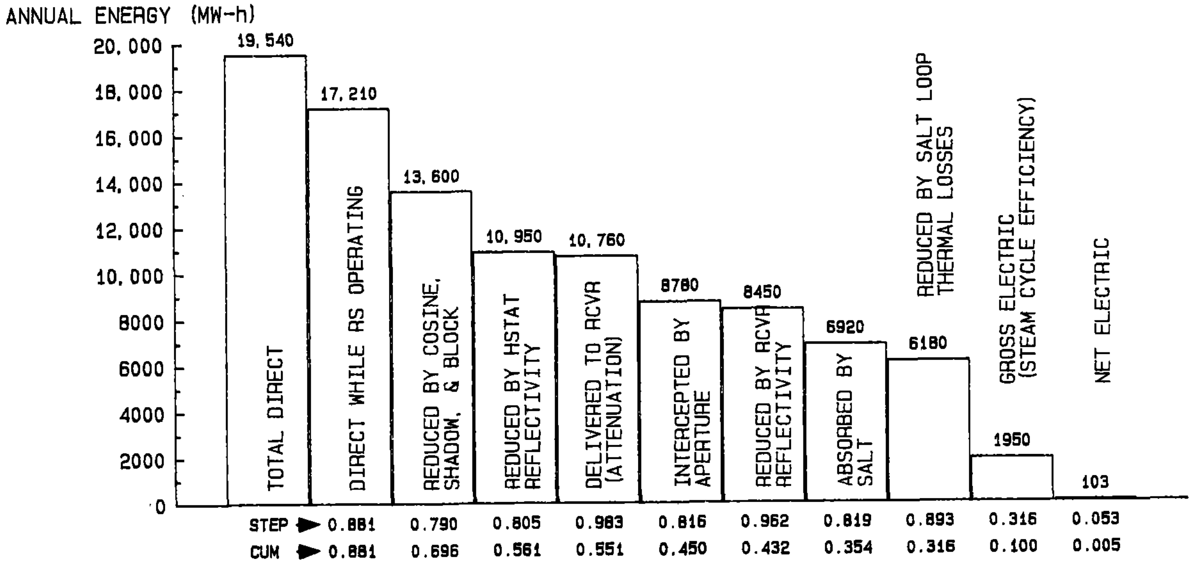


Figure 4-25. MSEE Projected Annual Efficiencies

Table 4-4

ELECTRIC PARASITICS - ANNUAL

	kWh
Operation	
Salt pumps	258,100
Trace heaters	184,000
Collector field and controls	174,000
SGS circulation pump	12,000
Steam cycle and balance of plant	283,800
Total	912,300
Standby	
Trace heaters	615,200
SGS circulation heaters	106,500
SGS circulation pump	28,300
Balance of plant	184,700
Total	934,700

Figure 4-26 shows the predicted typical efficiencies of a 100 MW_e molten salt central receiver system with a north heliostat field and cavity receiver (8). The comparison of these efficiencies to the projected annual MSEE efficiencies (Figure 4-25) shows where substantial efficiency improvements would occur in a large-scale commercial plant.

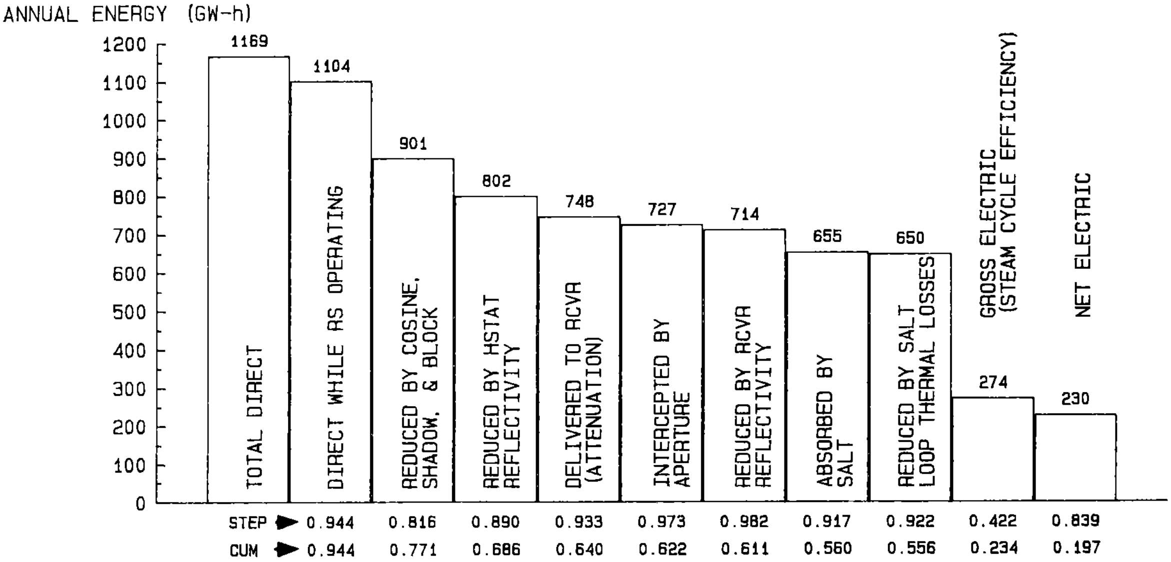


Figure 4-26. Solar 100 Predicted Annual Efficiencies

The MSEE test program was not intended to validate the performance predictions for a commercial plant. However, there was no evidence to indicate that the predicted performance for a commercial plant could not be achieved.

RECEIVER THERMAL LOSS TESTS

The determination of the actual thermal losses associated with the receiver is essential for the verification and refinement of methods for estimating these losses. Tests were performed to measure the thermal losses for various wind conditions and absorber panel temperatures with the cavity door both open and closed. These tests were all conducted with the receiver in cold flow (no solar input).

The testing consisted of establishing a constant flow rate through the receiver, followed by a period of time sufficient to allow the inlet and outlet temperatures to stabilize. Each test case was allowed to continue a minimum of 15 minutes after the temperatures had stabilized. The total energy loss from the receiver was then calculated by:

$$Q_t = \dot{m}C_p \, [T_i - T_o]$$

where:

Q_t = total thermal loss
C_p = specific heat of salt
T_i = salt inlet temperature
T_o = salt outlet temperature
$\dot{m}$ = mass flow rate of salt

The specific heat of the salt was calculated at the average receiver temperature using the relation given in Reference 9.

$$C_p \text{ (Btu/lb-deg F)} = 0.345 + 2.28 \times 10^{-5} \, T_{avg} \text{ (deg F)}$$

The loss test results are listed in Table 4-5. Included in this table are the total loss, the radiation loss, and the convection loss. The radiation emission loss was calculated by:

$$Q_r = \sigma\varepsilon \, A_a \, [T_r^4 - T_{sky}^4]$$

Where:

σ = Stefan-Boltzmann constant
ε = effective emittance of cavity
A_a = aperture area of cavity
T_r = average receiver absorber temperature = $(T_o + T_i)/2$

For the effective emittance of the cavity, a value of 0.86 was used. This was the value given in the ACR Phase II Report (6) and was determined by assuming diffuse radiation and that the interior cavity walls act as reradiating surfaces. The aperture area was 80.6 ft^2, and the sky temperature was assumed to be 30 deg F less than the ambient air temperature (T_a).

Table 4-5

RECEIVER THERMAL LOSS TEST RESULTS

Test Date	Wind Speed (MPH)	Wind Direction (from)	T_a (°F)	T_i (°F)	T_o (°F)	$\dot{m}$(klb/hr)	Q_t (kBtu/hr)	Q_t (kW)	Q_r (kBtu/hr)	Q_r (kW)	Q_c (kBtu/hr)	Q_c (kW)
Cavity Door Closed												
10/2/84	5	S	68	623	619	33.3	84	25				
10/18/84	20	NW	43	598	583	33.9	182	53				
10/19/84	9	S	48	630	622	33.9	97	29				
12/7/84	8	SW	45	677	670	41.7	105	31				
Cavity Door Open												
9/17/84	12	NW	72	630	602	29.0	291	85	151	44	140	41
10/18/84	15	NW	43	591	559	33.9	388	113	131	39	257	74
10/18/84	20	NW	43	595	551	33.9	534	157	129	38	405	119
12/10/84	6	S	42	671	639	33.5	386	113	177	52	209	61
12/17/84	5	S	32	725	688	34.0	454	133	215	63	239	70
12/17/84	5	S	32	613	594	43.5	298	87	140	41	158	46

The conduction loss through the insulation on the back side of the absorber panel was reported in Reference 6 as less than 4% of the total receiver loss. Therefore, this loss was neglected and the convection loss was calculated by subtracting the emitted radiation from the total receiver loss.

$$Q_c = Q_t - Q_r$$

Figure 4-27 shows the total thermal loss for the various cases as a function of wind speed. This figure illustrates the loss sensitivity to both the panel temperature and the wind speed.

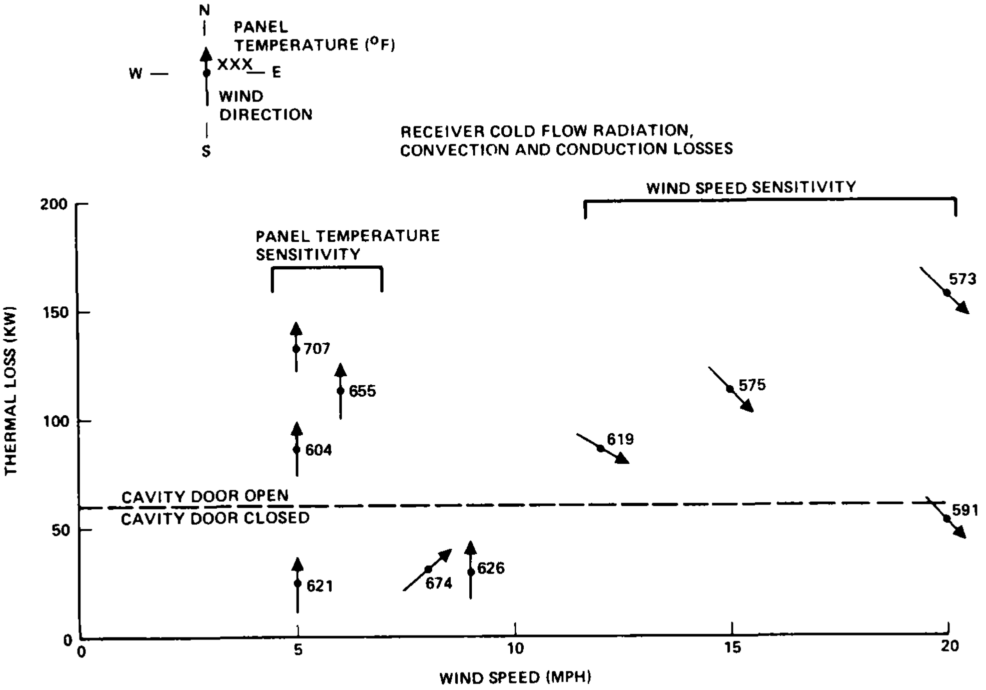


Figure 4-27. Receiver Thermal Losses

The uncertainties associated with the measurements used in calculating the total loss are estimated at 1700 lb/hr for the flow rate and 4 deg F for the temperature difference $T_i - T_o$. Considering these uncertainties, the uncertainty in the calculated total loss is less than 15% for all of the open cavity door cases except the second case of December 17, 1984, which is 26%. The wind speeds were constant for each test case and were measured at the north end of the heliostat field. A tower-top anemometer was not available.

RECEIVER TRANSIENT RESPONSE

The receiver must respond to variations in solar flux to maintain the outlet salt temperature within tolerable limits and to protect the structural integrity of the receiver. For the MSEE receiver, the response to variations in solar flux, such as those due to cloud passages, is governed by a quasi-feed-forward control algorithm. The control algorithm regulates the receiver outlet temperature through flow modulation. It estimates the absorbed power during flux variations by monitoring the temperature changes across each of the receiver's passes and the salt flow rate. This estimation of the absorbed power is then used to compute the flow required to achieve the desired outlet temperature.

The receiver transient response testing consisted of the simulation of cloud passages by controlling the rate at which heliostat beams were brought on target. Tests were conducted for various power ramp rates, temperature set points, and minimum flow limits. The test results were used to determine operating constraints and develop operating procedures and limits for sun tracking through cloud passages.

The power levels and ramp rates were progressively more severe for the simulation of cloud passages. Details of these ramp rates are included in Volume 2, Addendum A. Initial testing at lower power levels and slow ramp rates indicated that the control algorithm could not adequately control the receiver outlet temperature within the high limit of 1080 deg F while tracking through cloud passages at full power with the 1050 deg F rated set point. Figure 4-28 shows the salt flow rate and temperature response for a relatively slow (compared to actual cloud passage) 35-second ramp to a 75% power level. As shown by Figure 4-28, the temperature exceeded the set point by 50 deg F. Further testing showed that temperature overshoots of 60 deg F to 70 deg F were characteristic of the response to actual cloud passages with 100% of the heliostat field on target. Figure 4-29 shows this response to cloud passages. As indicated, the 1020 deg F setpoint required the heliostats to be defocused upon reacquiring the sun to avoid exceeding the receiver temperature limit of 1080 deg F.

Due to the control algorithm limitations, it was not possible to operate the receiver at the rated 1050 deg F outlet temperature during partly cloudy conditions unless the flow rate was controlled manually. It was determined that 1000 deg F was the maximum temperature set point for the control algorithm during partly cloudy conditions. In order to operate at the 1000 deg F set point, it was also necessary to provide an additional temperature margin for the most severe transients through an automatic set point reduction to 975 deg F, which occurred when the minimum flow

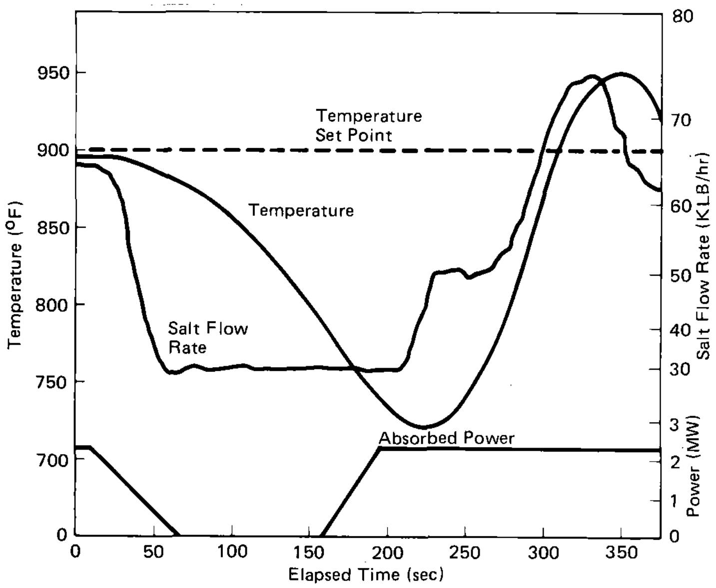
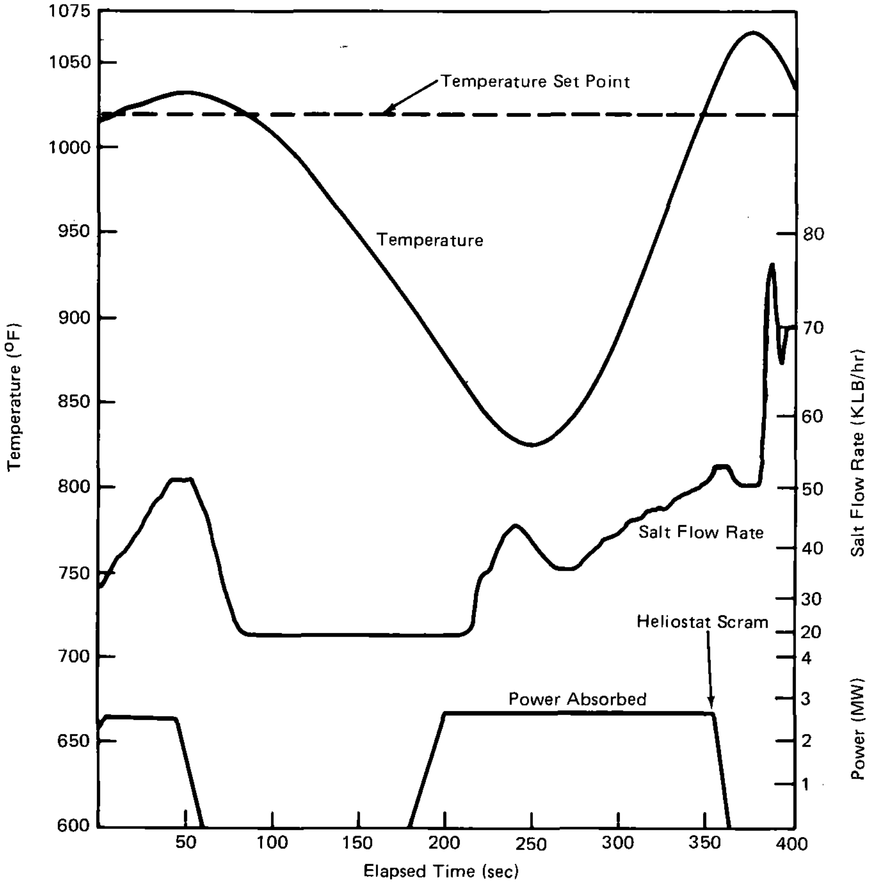


Figure 4-28. Receiver Transient Response - Simulated Cloud Passage



Start Time
14:04

Temperature
Set Point
1020°F

Heliostats
on Target
100%

Figure 4-29. Receiver Transient Response - Actual Cloud Passage limit was approached. After reacquiring the sun, and temperature stability was reached, the temperature set point would then be manually increased to its normal operation point of 1000 deg F.

The relatively large temperature overshoots are due to the control algorithm. The control algorithm was good in theory, but in practice it lacked the accuracy and response necessary to give tight temperature control of the receiver. In using measured flow for the mass heat balance calculation, inaccuracies in the flow measurement propagate through the calculations. Control problems are also caused by the slow control system update rate (2 seconds), thermal response rate, and the long transport delays.

The controllability of the receiver could be improved by the use of flux gauges (or other instruments for sensing the solar input directly) in the control algorithm. Flux gauges would be much more responsive to transients and would reduce the sensitivity to errors in the flow measuring device. However, survivability of gauges has been a problem in the past.

The control algorithm limitations, although preventing the receiver operation at rated temperature during partly cloudy conditions, did not adversely affect the energy collection performance of the MSEE. If anything, the collection efficiency improved slightly as a result of lower thermal losses at the reduced operating temperatures. The impact of the lower temperature operation was more significant on the energy conversion process. The lower temperature salt reduced the steam generation capacity by approximately 6%, which in turn resulted in a lower turbine-generator efficiency. However, since the steam generated with 1050 deg F salt required attemperation to obtain the rated 950 deg F steam temperature the rated main steam enthalpy could still be maintained. The steam attemperation and its overall effect on performance is discussed in more detail in Section 5.

OVERNIGHT THERMAL CONDITIONING

The feasibility of using the cold surge tank to pulse salt through the receiver and maintain the receiver in a filled, warm condition overnight was examined. Testing indicated that under mild wind conditions (5 to 8 mph) the salt supplied from the initially fully pressurized surge tank could keep the receiver above salt freezing temperature for 40 minutes before being depleted. For the testing the surge tank was filled with 670 deg F salt. The flow was pulsed as required to maintain all receiver panel temperatures above 600 deg F with the cavity door closed and no external sources of heat. During the tests, the surge tank salt supply valve was fully closed except when the surge tank required replenishment. The MSEE design would not allow the pumps to be shut off between periods of surge tank replenishment because air would be trapped in the lines upon restarting the pumps. Therefore, pulsing salt to provide overnight thermal conditioning of the MSEE receiver has no advantage over maintaining a continuous flow through the receiver.

For future receivers, if thermal conditioning is to be provided by keeping the receiver filled, it appears that a continuous flow approach would have advantages over pulsing. Whether the continuous flow is provided by a smaller circulation pump or by replenishment-depletion cycles of a surge tank, the flow requirement would be less than with pulsing because isolated cold spots are eliminated. With salt pulsing, isolated cold spots can require moving large quantities of salt, much of which is at acceptable temperatures, in order to remove a slug of cold salt. In addition, the expected performance must be carefully evaluated to determine if there is really any advantage to maintaining the receiver warm overnight. In the case of the MSEE cavity receiver, the thermal energy required to maintain it warm overnight is approximately twice that which can be gained by starting the energy collection process with the first available insolation. Therefore, although more efficient than electrical heating, this method of thermal conditioning provides no performance benefits.

The conclusion that there is no performance benefit in maintaining the receiver in a warm standby mode overnight does not imply that the system should be completely drained at the end of each day. There are definite performance advantages to circulating salt throughout the remainder of the system, bypassing the receiver, which would allow most trace heaters to be turned off. The only areas where trace heaters could not be turned off are on dry or stagnant lines and on some valves with bellows seals. The potential performance benefits are significant. The trace heater electrical loads when the system is drained, and the loads for only essential heaters when salt is circulating are as follows:

	Trace Heater Electric Load (kW)	
	System Drained	Salt Circulating
Receiver loop	57.0	21.00
Thermal storage	33.0	2.6
Steam generator loop	16.9	2.3
Total	106.9	25.9

Under two conditions, the system electric requirements for thermal conditioning could be reduced by 20%, from 106.9 kW to an electric equivalent of 85.3 kW: (1) by utilizing the cold salt pump alone to provide circulation, and (2) by assuming that 80% of the 45.4 kW electric required to operate the pump is recovered as thermal input to the salt through kinetic heating and throttling. The electric equivalent is based on a thermal to electric conversion efficiency of 0.33 to determine the electric value of the thermal energy supplied by storage; it also includes the pump load. Substantial additional gains could be realized by the installation of a small-capacity pump to circulate the salt rather than using the oversized primary salt pump. With such a pump, the equivalent electric requirement for thermal conditioning could be reduced to 59.6 kW.

SALT PERFORMANCE

The Olin Chemical Group's summary report of the analytical results of the MSEE salt sampling reveals there were no major changes in the salt performance during 1984 (5).

There was virtually no change in the percentage concentration of the major components - sodium (15.27 to 16.23), potassium (16.52 to 14.92), nitrate (65.9 to 73.6), and nitrite (1.12 to 1-17). The sodium-to-potassium ratio was in balance so there was no major change in the melting and freezing characteristics of the salt. Nitrite levels were what would be expected for a nitrate salt that is in a thermally cycled system.

Besides nitrates and nitrites, other anions analyzed were oxides (i.e., hydroxide/oxide), carbonates, chlorides and sulfates. Oxide concentration levels started the year at less than 1 ppm and rose to about 9 ppm in November. It appears there may be a buildup of oxide, but the apparent rate and current levels are acceptable for a 30-year life cycle. More sampling and analysis is required to determine if there is indeed an oxide buildup, and to better define the rate. Carbonate concentration also started the year at less than 1 ppm. The carbonate levels held at about 60 ppm, which is well below its solubility of about 2500 ppm at 550 deg F. The chloride analysis gave a scattered trend, but since the high of 40 ppm is well below the 1800 ppm specification and no new sources of chloride will be introduced, there is no cause for concern or comment. The highest sulfate measured, 1751 ppm, is lower than the 2025 ppm specification.

The cations studied included chromium, nickel, iron, molybdenum, magnesium, aluminum, and calcium. Chromium concentration increased from 4 ppm to 6.5 ppm during 1984. The rate of chromium increase should decrease as surfaces of the MSEE equipment are passivated. The levels of chromium are considered good and are well below the solubility limit. Iron and nickel levels were stable during 1984. However, since iron and nickel are likely saturated in the salt at about 4 ppm, the analytical results are not a good indicator for the corrosion rate. Salts of iron and nickel may have precipitated and settled in equipment and therefore were not included in the sample.

In summary, the 1984 analytical results show that the MSEE salt performed well. There were no changes in its characteristics, and all chemical species remained at acceptable levels.

Section 5

DESIGN EVALUATION

The objectives of the design evaluation are to:

1. Present the experimentally determined range of operability of the MSEE.
2. Evaluate design assumptions.
3. Identify deficiencies and limitations associated with the design and recommend design improvements.

The design evaluation has been categorized by system configuration, system control, subsystem design, system maintainability, and trace heating and thermal protection.

SYSTEM CONFIGURATION

The system configuration met the functional objective of demonstrating the technical feasibility of a molten salt system. There were no inherent system level configuration design deficiencies identified. Design deficiencies were all at the subsystem or component level.

Some of the key operational limits of the system are listed in Table 5-1.

The range of operability of the receiver permitted its operation down to 1.0 MW output while maintaining a minimum flow of 30,000 lb/hr and 900 deg F outlet temperature. For the turbine-generator, stable operation was demonstrated down to less than 100 kW_e gross output with acceptable steam generator following during rated load changes of 10% of full load per minute.

Although the basic system configuration was verified, many specific components were identified which contributed to the overall inefficient operation of the MSEE. These components include a feedwater pump (highest single parasitic load) with an electrical load over 50% greater than an optimized pump, the use of dry cooling towers rather than wet, and electrical trace heaters whose parasitic load could be

Table 5-1

OPERATIONAL LIMITS

	Maximum As Tested	As Designed
Receiver flow rate, 1000 lb/hr (pump capacity)	93	97
Receiver thermal output, MW	4.02	5*
SGS total salt flow rate, 1000 lb/hr (1050 deg F hot salt)	80	79
SGS thermal input, MW (1050 deg F hot salt)	3.35	3.17
Gross generator output, kW (steady state, 1050 deg F SGS supply salt)	600 (actual) 1100 (simulated)	750
Gross generator output, kW (non steady state)	900 (actual)	
Net plant output, kW (steady state, 1050 deg F SGS supply salt)	104 (actual)	413

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*This is the design point output and is not directly comparable to the test output due to different input conditions.

significantly reduced by optimized control or largely eliminated with the utilization of stored thermal energy. Many other components also contributed toward the system inefficiencies.

The partial effect of the MSEE inefficiencies is evident in comparing the actual electric output to the simulated output in Table 5-1. The simulated output is that which could be reasonably expected with efficiency improvements in the steam cycle. The simulated electric corresponds to that discussed in Section 4.

Unoptimized components were used because of their availability or cost. Their use did not detract from the value of the experiment.

SYSTEM CONTROL

The digital control system demonstrated its advantages over analog control and was well accepted by the utility operators who participated in the operator training program. Among its demonstrated advantages were:

- The flexibility permitted in the utilization of incoming data.
- The ease with which control loops could be configured.
- The ability to readily change the tuning parameters associated with the control loops.
- The capability for automatic sequence programming.
- The accessibility of a large amount of operational information.

Although the control system had many features not available with an analog control system, a single state-of-the-art digital control system with at least four display screens would have been superior. The control system deficiencies were primarily the result of using two separate control systems (EMCON and Bailey Network 90) and only two EMCON consoles.

The use of two control systems contributed to operating complexities and reduced system availability, and resulted in greater possibilities for operator errors. In addition, it created maintenance and programming difficulties since support personnel thoroughly versed in both control systems were not readily available.

With the availability of only two EMCON control consoles, the system's operation status was less than adequate. This created and/or contributed to emergency situations since the detailed status of only portions of the system were available at any one time.

The control system also proved inadequate for complete remote operation of the turbine-generator. The inadequacy was primarily due to the slow EMCON update rate (5 seconds) on critical generator instrumentation, including the power factor and the kilowatt load. Due to this limitation, the remote operation of the turbine-generator was restricted to load adjustments.

A lack of instrumentation in many key areas limited the thoroughness of the system performance evaluation. Key measurements not available through the data acquisition system included:

- Turbine steam flow rate
- Turbine exhaust temperature
- Hot well temperature
- Cooling water flow rate
- Cold sump outlet temperature

Instrumentation has since been added for the turbine exhaust and hot well temperatures. There are many other areas, although less important, where additional instrumentation would have been desirable. For example, more thermocouple probes in the various salt lines would have been useful for both the performance evaluation and for providing additional operating status information to the operators.

Although there was room for substantial improvements in the control system, its limitations had minimal impact on the completion of the primary objectives of the program.

SUBSYSTEM DESIGN

Receiver Subsystem

Since the receiver itself was thoroughly evaluated as part of the previous alternate central receiver (ACR) test program, this evaluation will focus primarily on areas relating to its operation as part of an integrated system. The reader is referred to Reference 1 for the results of the ACR test program.

The maximum salt flow rate of 93,000 lb/hr, although slightly less than the 96,000 lb/hr design flow rate, was adequate for all steady-state operating conditions during MSEE testing. However, the 93,000 lb/hr flow rate originally could not always be sustained because of the undersized line supplying the cold sump. As salt is added to the hot storage tank and the level in the cold storage tank falls, the maximum flow rate to the sump decreases. Consequently, when the required flow rate for the receiver exceeded the rate at which the sump could be replenished, the receiver had to be operated at reduced power levels. This problem was later alleviated with the replacement of the line supplying the cold sump.

The boost pump discharge, cold surge tank, and receiver inlet pressures are shown as a function of flow rate in Figure 5-1. The cold surge tank level (and consequently its pressure) was originally designed to be controlled to a constant value through modulation of the boost pump discharge throttle valve (FCV-151). This control, and the external pressurization of the cold surge tank, was determined to be unnecessary. Throughout most of the MSEE testing, the receiver was operated with FCV-151 in its full open position, allowing the cold surge tank pressure to vary with the flow rate as shown in Figure 5-1.

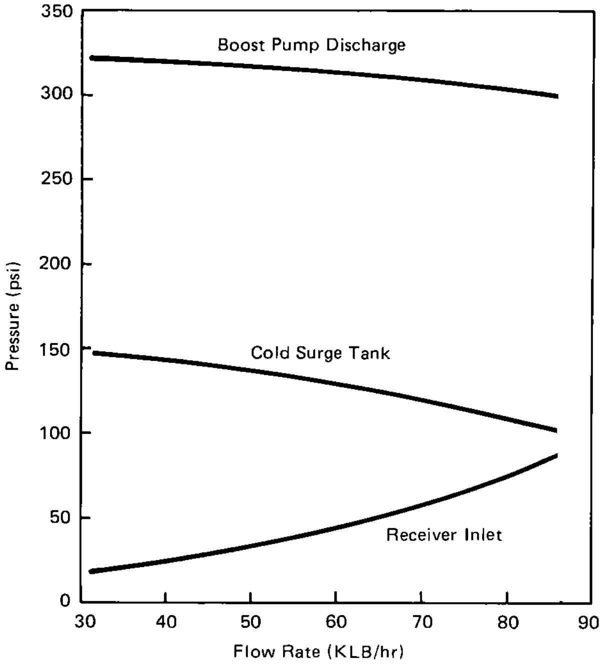

Figure 5-1. Receiver Subsystem Operating Pressures

The function of the cold surge tank to maintain flow through the receiver in the event of a pump outage was verified. With the equipment protection system monitoring the pump pressure and sending the signal to defocus the heliostats upon sensing a low pressure, an adequate margin of cooling is available for all operating levels.

The basic receiver design satisfied the project objectives. However, since it was one of the first of its kind and was designed primarily to demonstrate technical feasibility rather than high performance, its design is not representative of a commercial receiver. There are numerous areas for design improvements that are being addressed with the follow-on test program (MSS/CTE) being conducted at the CRTF.

Thermal Storage Subsystem

As with the receiver, the thermal storage subsystem was tested and evaluated as part of a separate research experiment (10). Therefore, the following discussion will be limited to those areas relating to its operation as part of the integrated MSEE system.

The size of the thermal storage subsystem (see Section 4) restricted the amount of resource shifting that could be demonstrated. Therefore, the thermal storage subsystem functioned mainly as a buffer between the energy collection and energy conversion sides of the system. To the extent that hot salt was available in storage, receiver transients remained invisible to the energy conversion process, and with proper scheduling the storage capacity allowed continuous full load operation.

The major operational problems with the thermal storage subsystem were associated with the limited capacity of the hot and cold sumps. The requirement for high sump levels to provide sufficient suction head to start the pumps left little margin before their overflow. Because of the high sump levels, an emergency shutdown and the resultant salt drainback to the sumps or the leakage of salt internally through the control valves could easily result in salt spillage.

For future designs the sumps should be provided with automatic high level dumps. Also, if the subsystem is sized for more resource shifting, valving should be provided to permit the draining of either the receiver or the steam generator without shutting down the complete system.

It is recognized that the cold salt booster pump was added in series with the existing primary cold salt pump to eliminate the expense of a single full-capacity pump. However, the additional pump complicated the system operation and reduced the system availability; such a configuration should be avoided in future designs.

The addition of a small salt circulation pump should be evaluated for future designs. Such a pump could be used to maintain a minimum salt flow through the system when the plant is in a standby mode, allowing many electric trace heaters to be turned off. It was also determined that supplemental heating of the storage tanks and sumps was not required with daily operation. Therefore, electric heaters in these areas should be provided with active rather than passive control.

Steam Generator

The steam generation subsystem was designed specifically for the MSEE. Its design, construction, operation, and component level performance evaluation are documented in Reference 4. From a performance standpoint, the subsystem design satisfied requirements. Its operation was demonstrated at rated conditions and also at a thermal input level 6% above rating. In its automatic steam pressure control mode, the steam generator demonstrated successful following of turbine-generator rated load changes of 75 kW/min over the range from 100 kW to full load.

Although the steam generator performed acceptably during operation, its design could be improved with the elimination of the following:

- Limited accessibility for maintenance
- Instabilities during startup
- Inability to sustain warm diurnal shutdown mode
- Inadequate freeze protection
- Deficient steam drum blowdown capabilities
- Unnecessary steam attemperator

The compactness of the subsystem, although more thermally efficient, limited the accessibility for maintenance. Future designs should allow for easier accessibility for component repair and replacement.

The instabilities during startup were primarily due to inadequate control of the low feedwater and main steam flow rates. Without adequate control of these flow rates, a loss of the steam drum level control results. For future designs, the low flow rates during startup should be considered when selecting valve trims, and/or a small bypass line and valve should be provided.

The inability of the steam generator to sustain the warm diurnal shutdown caused many delays in its startup. The problem was due to the overnight loss of level in the steam drum, through leakage, and the resultant shutdown of the circulation pump and heaters. With the circulation pump and heaters off, the subsystem would cool to unacceptable levels for immediate startup the next day. After refilling the system, a period of two to three hours was typically required for the temperatures to reach acceptable startup levels. For future designs, an automatic steam drum makeup system should be considered and the subsystem should be designed to minimize leakages during diurnal shutdown.

Inadequate freeze protection resulted in frozen water and steam lines when subfreezing overnight temperatures were experienced. Future designs should thoroughly address the area of freeze protection.

The manual valving provided for steam drum blowdown was deficient in that it offered poor blowdown control and would not permit a desirable continuous blowdown. This area should be improved in future designs by the use of remote actuating valves.

The design could be simplified with the elimination of the steam attemperator. It was determined that the main steam temperature can be adequately controlled within turbine-generator limits by adjusting the receiver outlet temperature. This method of control also results in more efficient operation since the receiver is not operated at a higher than necessary temperature.

The salt attemperator, which cools the salt exiting the superheater to 850 deg F (evaporator material limit) before it enters the evaporator, was determined not to adversely affect the plant performance. However, the attemperator did add to the complexity of the subsystem design and operation. Eliminating the salt attemperator would have required that the evaporator be constructed of stainless steel. For future systems, the added material and fabrication costs related to the stainless steel should be evaluated against the resultant design and operation simplifications to determine if the elimination of the attemperator can be justified. Performance gains are not a key issue in the elimination of the salt attemperator since 850 deg F salt is entirely adequate for the evaporation process.

Although there were areas for improvement in the steam generation subsystem, its basic design was verified. As a first-of-its-kind design, its operation and performance were acceptable and it was capable of operating at design conditions. In future designs, simplicity of design and operation should be important considerations in any steam generator design.

Heat Rejection and Feedwater Subsystem

The HRFS was an existing subsystem adapted to the MSEE. The subsystem met all functional requirements but only after the removal of the impulse device from the steam trap between the feedwater heater and the deaerator (T-484).

The subsystem as built would not provide adequate feedwater heating due to insufficient steam and water flow through the feedwater heater as limited by the steam trap. After removal of the steam trap's impulse device, rated feedwater temperature was achievable.

The dry cooling towers provided sufficient cooling to attain the rated 5-inch Hg absolute backpressure in the condenser for all test conditions. During early MSEE testing, the rated condenser backpressure was not achievable due to excessive condenser vacuum losses through the turbine steam seal suction lines. Rated backpressure was achieved by restricting the vacuum draw through the suction lines.

Design changes that would improve the HRFS include the following:

- Replace the three-way diverting valve (FCV-432), which is of a type prone to leakage, with a valve or valves that would provide a positive seal against leakage through the spray water heat exchanger.
- Provide a means for gradually preheating the feedwater pump with the warm deaerator water prior to pump startup.

Obviously, future systems should not use main steam for feedwater heating.

The unique design of the HRFS, which allowed the deaerator to be used as a steam dump, proved to be beneficial by minimizing thermal losses during startup. Most of the steam generated during the line warmup process is rejected to the deaerator, where it preheats the feedwater, rather than being rejected as waste heat. This capability should be evaluated for possible incorporation in future plants.

Electric Power Generation Subsystem

The EPGS consisted mainly of conventional and proven components. As a result, it operated basically as expected prior to the turbine-generator failure. The limitations associated with the subsystem were primarily due to control and instrumentation deficiencies. These deficiencies necessitated local startup and generator synchronization.

Prior to the turbine-generator failure, its operation was demonstrated at the rated 750 kW full load gross generator output; however, this power level could not be maintained for more than approximately 5 minutes since it required the diversion of steam normally supplied to the HRFS. EPGS operation at 20% above the rated 750 kW output was also demonstrated.

The limited subsystem instrumentation prevented the accurate determination of the turbine-generator performance, especially at partial loads.

Consequently, the turbine-generator design performance for the various load conditions probably represents its actual operation better than what could be indirectly calculated. Based upon the design performance at the rated 0.8 power factor, the turbine-generator steam flow rates and efficiencies for 1050 psi, 940 deg F throttle steam, and 5-inch Hg absolute condenser backpressure are as follow:

	Generator Load Fraction			
	25%	50%	75%	100%
Steam flow rate (100 lb/hr)	29.0	45.2	61.7	78.0
Gross efficiency (%)	16.1	20.7	22.8	24.0
Generator output (kW)	188	375	563	750

System Maintainability

For system maintainability, the need was demonstrated for improved accessibility and an improved preventive maintenance program.

The limited accessibility in many areas of the system resulted in excessive delays when maintenance or repairs were required. Trace heater repairs or replacements and steam generator maintenance were especially difficult due to limited accessibility. Future designs should allow for the replacement of any trace heaters (unless their reliability is substantially improved) with a minimum of complications. In addition, each subsystem should be designed such that individual components are accessible with minimum delays. Examples of components where accessibility was restricted include the boiler water circulation pump and many other steam generator components, receiver valves, and receiver panel instrumentation. In cases where it may be impractical to provide easy accessibility to components subject to failure, such as in the case of the thermocouples on the receiver back tubes, redundant components should be provided.

The MSEE preventive maintenance program, although good in its intentions, did not benefit the project to its full potential. The limited benefit resulted from the lack of personnel available to perform the preventive maintenance. In order to maintain the total system integrity, future projects must establish, implement, and strictly adhere to a preventive maintenance program in order to maximize the system reliability.

With improved accessibility and proper preventive maintenance, the overall maintainability and availability of future systems would be greatly enhanced over that of the MSEE. In addition, component redundancy similar to that provided in conventional power plants should be incorporated into any commercial designs.

Heat Tracing and Thermal Protection

Monthly system downtime forced by heat tracing and thermal protection related problems ranged from 3% to 50% for the period from April 1984 through December 1984. The system unavailability due to deficiencies in these areas emphasizes the need for improvements.

The reader is referred to the Sandia Report, Electric Heating for High Temperature Heat Transport Fluids, (11) which reviews the experience with trace heating and thermal protection for the MSEE and other projects (10). The recommendations of this report are summarized in Table 5-2.

Table 5-2

SUMMARY OF RECOMMENDATIONS FOR HEAT TRACING MOLTEN SALT HEAT TRANSPORT SYSTEMS

Design

- Thermal
  - --Provide heat input of 125% of the highest possible calculated heat loss.
  - --Provide separate heaters on valves and other components.
- Electrical
  - --Select element with a derated power output to operate at 50% of design voltage.
- Maintenance
  - --Design for ease of replacement or repair of each element.
  - --Install spare elements prior to insulating.

Heating Element Selection

- Select tubular or MI cable heaters based on a reliability/cost study using ETEC heater failure rates as the reliability criteria.
- Use band, ring, or strip elements or Inconel-sheathed MI cable on irregular shaped components.
- Do not use immersion heaters in salt.

Installation

- Attach heater elements at one-foot intervals.
- Cover elements with stainless steel foil.
- Locate welded hot-to-cold junctions of heater elements on the component. Locate outside the insulation if MI cable with brazed joints is used.

Controls

- Use active, proportional voltage control system on all areas that experience environmental changes.
- Install spare, welded-on, thermocouples for each control zone.
- Provide a separate control circuit for each component or heater zone.

Insulation

- Block air convection around the pipe or component with ceramic blanket insulation.
- Preformed block insulation should be used as the outer insulating layer on straight runs of pipe only.
- Ceramic blanket layers should be used for irregular shapes.
- Wind shields are required for valves and non-pipe components.

Section 6

OPERATOR TRAINING PROGRAM

In addition to system characterization testing, a major part of MSEE testing and training was dedicated to the training of utility and industry personnel.

The operator training program consisted of two-week and three-week courses of instruction in the operation of the MSEE. The primary objectives of the program included the following:

1. Train utility and industry personnel in the hands-on operation of the MSEE.
2. Disseminate information and experience relating to the operation of a molten salt central receiver solar power plant.
3. Familiarize the participants with a distributed digital control system.
4. Obtain feedback on the training methods and course structure.
5. Obtain an evaluation of the system design and operation.

To create a more effective training program, a trial team was given classroom instruction and trained in actual operations of the MSEE in early August 1984 for a two-week period. This resulted in a partial reorganization of the course material and greatly enhanced the effectiveness of the training program. During the training program, engineering tests were performed and useful engineering test data was obtained to be used in the overall evaluation of the MSEE.

There were 20 participants in the training program: 13 from utilities, five from industry, one EPRI consultant, and one from IEE-Mexico. Twelve of the personnel were power plant operators and eight were engineers. A total of six classes were conducted (including the trial team in August) with five regular classes starting in early September 1984 and ending in early December 1984.

COURSE STRUCTURE

The trial team class was conducted in August 1984 over a two-week period, followed by three three-week classes consisting of utility operators, and concluding with two two-week classes with a mixture of personnel. A systems operations training manual was supplied to each of the trainees before the start of the course. This allowed them to become familiar with the overall training program and MSEE before arriving on site. The training course used the subsystem approach starting with the master control subsystem and ending with integrated system operation. The time was effectively divided between classroom, field tours, and control room operations to increase the interest and attentiveness of the trainees. Flexibility was incorporated into the course organization to allow for the minor maintenance of equipment and adverse weather conditions, and the interest and ability of the trainees.

Integrated system startup and shutdown operations were performed during most of the final week of the three-week training course. In the two-week training session, the final two days of the second week were devoted to integrated system operations. A listing of the participants and a detailed schedule is in Appendix H.

TRAINING AND OPERATING SESSIONS

Day 1 of the operator training program was begun with a CRTF and MSEE orientation. Past solar projects were reviewed, leading to Solar One and the current MSEE project. The orientation concluded with an overall facility safety briefing with particular emphasis on the MSEE safety concerns.

An overview of the MSEE system was discussed in the conference room using a large piping and instrumentation drawing. This was discussed in general terms with the trainees until a moderate understanding was achieved. The trainees were then given a facility tour to familiarize them with the overall layout of all the subsystems and large equipment. The tour areas included the heliostat field, the thermal storage area, the steam generation subsystem, the heat rejection feedwater subsystem, the electric power generation subsystem, and the receiver subsystem. On the return trip to the control room, other CRTF projects were pointed out to the trainees, including the dish, parabolic trough, and furnace projects.

Following the hardware tour, the subsystem level instruction began with the master control subsystem. In the classroom the subsystem was described and its operation was discussed. When the trainees sufficiently understood the master control subsystem, they were taken into the control room to perform console exercises. These exercises were primarily used to familiarize the trainees with the EMCON keyboard. The trainees would locate specific keys, systematically call up different control groups for the various subsystems, call up a subsystem graphics and system graphics, print data from the console, and get a complete view of the console operation. Finally, the Accurex computer which controls the trace heaters was demonstrated to the trainees.

Day 2 of the training and operating sessions was devoted to the receiver and thermal storage subsystems. The subsystems were first discussed in the conference room using the piping and instrumentation drawing. This discussion was followed by a detailed field tour to familiarize the trainees with the equipment including the location of all salt lines, valves, pumps, and all major components. The piping and instrumentation drawing was reviewed on the site with the equipment allowing the trainees to correlate the actual locations of each specific piece of equipment.

Subsequent to this field tour, the trainees were exposed to the control and operations of the receiver and thermal storage subsystems. Prior to actually operating any of the equipment, pre-operational console exercises were performed in the control room. These exercises included checks of the salt lines and valve temperatures on the Accurex computer, checks of the equipment configuration, and familiarization with the various controls.

A pump and valve exercise followed which consisted of the actual operation of each type of valve and the pumping of salt from the cold sump back to the cold storage tank. This exercise was repeated by each trainee at the console until complete familiarization and understanding was achieved.

Days 3, 4, and 5 were devoted to classroom discussions of and actual operation of the receiver subsystem. During procedure reviews each trainee participated by explaining specific steps in the procedures and discussing the operating sequences using the piping and instrumentation drawing in the classroom. After demonstrating adequate understanding of the procedures, each trainee was allowed to fill and drain the receiver using the automatic sequences. This procedure was performed as often as required until each trainee became confident in the operations. Cold salt flow operations were conducted, changing the salt flow rate as required to allow each trainee to observe the reaction of the equipment. The receiver operations terminated with charging the hot salt storage tank completely with hot salt. Following the equipment operations, a performance calculation was done by each trainee to complete their understanding of the complete receiver subsystem.

In all operations, the trainees were not required to respond to equipment emergencies. CRTF personnel stood by in the control room at all times and intervened during emergencies with the trainees only observing the operations.

Days 6 and 7 were devoted to the steam generation subsystem. As with previous subsystems, the complete system description was given in the conference room, followed by a field tour for equipment familiarization, a review of the control and operations, and pre-operational console exercises. Upon completion of the pre-operational console exercises, the steam generation subsystem procedures were reviewed in detail.

Because of the slow response in the steam generator during the fill operation, the trainees were allowed to fill and drain the steam generator manually rather than using the automated sequences. This manual approach enhanced the trainees' understanding of the complete operation. Following the cold salt flow fill and drain sequences, each trainee was allowed to ramp the steam generator to a hot salt flow using both manual and automatic sequences.

Day 8 was scheduled for the propane heater and the steam generator; however, this day was typically rescheduled to a day with poor solar availability. The propane heater control and operations review was followed by a detailed procedure review of the propane heater operation. The trainees then proceeded to charge the hot tank with hot salt using the propane heater instead of the receiver. After completely charging the hot tank, the propane heater was shut down and the steam generator was operated using the hot salt previously generated. Prior to any training operations, the CRTF personnel configured the equipment to allow the trainees to complete the scheduled activities. For example, if the hot tank had to be drained through the steam generator to provide additional cold salt for training operations, this was accomplished by the CRTF personnel while the trainees were in the classroom. During control room activities the trainees were in direct radio contact with the field technicians coordinating all the required operations to perform the required task.

Days 9 and 10 were devoted to the electric power generation subsystem. Less time was required to become familiar with this subsystem due to the familiarity with normal power plant operations. The digital control system was thoroughly discussed and the control and operations reviewed. Subsequent to the complete procedure review, a local startup was performed by the CRTF personnel with the trainees only observing. This was conducted to allow the trainees to be exposed more thoroughly to the solar portion of the MSEE. Following the local startup of the turbine, the trainees returned to the control room and operated the steam generator and the turbine system from the control room consoles. Performance calculations were also performed subsequent to shutdown of the operation.

At the beginning of the third week, days 11, 12, and 13 were completely dedicated to integrated system operation and to synchronizing the generator to the grid. All subsystems were thoroughly discussed with the trainees relative to their integrated operation. The order of subsystem startups was discussed, allowing the trainees to understand the proper sequence. Procedures were again reviewed which consisted of subsystem procedures being sequenced in proper order to obtain a final system operation. The trainees were then allowed to start up, operate, and shut down the complete system daily. This included synchronizing the turbine-generator to the utility grid and ramping up the generator to the maximum power output.

The morning of day 14 was dedicated to operating the steam generator and turbine-generator subsystems from the storage tanks. This included synchronizing to the utility grid and ramping the turbine-generator for maximum power output. Following the shutdown of daily operations, a training class debriefing was conducted. This included an oral and written debriefing and evaluation of the training class and the MSEE project. In preparation for the Solar One tour, a Solar One briefing was conducted. This briefing included a review of the control strategy and the state-of-the-art control system used at Solar One. Day 15 was dedicated entirely to the Solar One trip. The team arrived at the Solar One site before sunrise and was given a complete description of the control system. Each team observed an early morning startup and complete operation of the Solar One facility. Detailed discussions were conducted as required to meet each trainee's desires. The trip was concluded by a detailed tour of the facility that included the control room, the computer room, and all the external equipment.

ACCOMPLISHMENTS

Each of the participants was provided with actual hands-on experience in operating a molten salt central receiver power plant. This was the first such training in the United States on an advanced salt central receiver system. Each participant was also provided experience with distributed digital control systems. Feedback of the training methods and the MSEE design and operation was obtained from each participant.

TRAINING PROGRAM EVALUATION

The training program met all of its objectives. The general consensus among the trainees was that the training program provided a valuable and worthwhile experience. The training class debriefing included a written evaluation by the trainees of the training course, the subsystem design and operation, and the control system.

The trainees evaluated the training course favorably in all areas. The overall curriculum and methodology was judged appropriate for the utility operations; however, a four-week course would have been preferable over the three-week course in order to improve the operators' proficiency. Industry personnel, such as engineers or designers, whose objective would not be proficient console operation but rather to evaluate the system, could be effectively exposed to the system in a three- to five-day course. The training material required for an accelerated course for engineers and designers is available and would only have to be condensed and organized to meet the specific needs of such a course.

The responses also indicated an overall acceptance of digital control among the utility operators. From the operator's viewpoint, all felt that digital controls should be utilized in future plants, both conventional and solar. The single negative response relating to the operation of the control console was that the alphabet keypad was not laid out like a typewriter.

A detailed evaluation is listed in Appendix I.

Section 7

TECHNICAL ASSESSMENT AND RECOMMENDATIONS

PROJECT RESULTS

Results of the Molten Salt Electric Experiment (MSEE) project are summarized in four categories in the following tabulation:

- Design Configuration, pages 1 to 6
- Performance, page 7
- Operations, pages 8 to 10
- Reliability of Components, pages 11 and 12.

Results of the MSEE test program, as well as other observations on the system, are briefly summarized in the second column of the table. Many of the problems encountered were due to specific facility limitations. These problems and the corrective actions taken during the test program, are described in the Discussion column. Applicability of the results to commercial systems and design recommendations are given in the fourth column. Recommendations for further testing and the development to be accomplished prior to considering commercial installations are given in the last column.

TECHNICAL ASSESSMENT

The MSEE contributed substantially to our knowledge and understanding of the potential and problems of a molten salt, central receiver solar power plant. An overall assessment of this technology is as follows:

1. The system has been demonstrated to be technically feasible. Many of the problems encountered were caused by facility limitations or by specific design features of the MSEE itself. Despite these problems, the plant could be operated effectively. Salt freezing during the experiment was handled with no significant damage to the system.

2. The thermal storage configuration effectively decouples solar energy collection from power production. This allows the collection function to effectively follow solar availability and power production to follow user demand.

3. Molten nitrate salt is an effective, low-cost heat transfer fluid for energy collection and storage. No degradation in salt properties was observed over the limited duration of the MSEE operation.

4. Distributed digital controls were highly effective. Many operating sequences were automated. Further automation will be possible which will allow operation of future plants and little operator requirements.

5. Thermal and hydraulic performance can be predicted with good accuracy.

6. Reasonably rapid startup can be accomplished without excessive loss of collectable solar energy.

7. The high melting point of the nitrate heat transfer salt (430 to 460 deg F) creates substantial problems in maintaining the temperatures required for startup. The main problems are associated with:

   - Trace heating
   - Insulation
   - Wind protection
   - Extensive instrumentation for temperature monitoring
   - High parasitic power
   - General system complexity

   Any future technology development program should include improved solutions to these problems.

8. Net positive power production has not been demonstrated; it is predicted for larger installations. The major parasitic power loads and approaches to their reduction have been identified.

9. Lifetime limitations were not measured or observed because of the limited duration of the project.

10. Most components required for this plant are available. Further development is required for salt valves and instrumentation and to improve reliability, particularly during cyclic operation.

In summary, the molten salt, central receiver solar power system is technically feasible, and has certain attractive features but requires substantial development to establish its potential for economical power production.

RECOMMENDATIONS

Based on the foregoing technical assessment, development and qualification of components, modifications to the system configuration, and alternative means of maintaining the system warm for startup should be accomplished. These should all be verified in a large-scale full-system test prior to commitment to any commercial program.

Specific recommendations follow in five categories:

1. Component Development

   - Develop and qualify, at the full commercial plant scale, pumps, valves, and instrumentation for molten nitrate salt application. All requirements, including particularly cyclic operation, should be covered.

- Design and qualify water and steam components for the cyclic operation required in solar plants.

2. Subsystem Tests

- Build and test, preferably at the CRTF, a model receiver that incorporates the potential improvements identified in this program.

- Develop and confirm in a subsystem test alterative methods of maintaining the system warm overnight. This objective could be combined with those of the model receiver test described in the preceding paragraph.

3. Design

- Achieve greater design simplicity. Reduce the number of components, particularly the receiver purge and drain valves and temperature monitoring instrumentation.

- Include the requirement for cyclic operation in all component specifications and loop designs.

- Design all equipment for the most rapid startup and shutdown.

4. Programmatic

- Include an adequate quality assurance plan that covers both hardware manufacture and installation.

5. Full-System Test

- Conduct a large-scale (10 to 30 megawatts electric) system test that incorporates the results of all of the above developments.

MSEE PROJECT RESULTS - (Page 1)

EVALUATION OF MSEE DESIGN CONFIGURATION

SUBSYSTEM FEATURE	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
SYSTEM				Test all recommended configuration features in a full system experiment. This recommendation applies to all of the features discussed on pages 1-6 of this table.
Equipment Layout	Steam generator separated from HRFS and turbine by over 150 ft. High thermal losses and control lags resulted.	Due to use of existing equipment and facilities.	Locate subsystems as close as practical.	
Salt Loop Issues				
o. Insulation	Large temperature variations observed on valves, headers, and complex bends. Inspection revealed that solid calcium silicate insulation had deteriorated to powder due to thermal cycling.	Retrofitted soft insulation and conformal lagging on complex bends and components	Use soft insulation and conformal lagging.	
o. Wind Protection	Large temperature variations on components exposed to winds.	Added wind shielding that reduced temperature variations.	Provide wind shields in original design.	
o. Trace Heater Control	Passive control resulted in large temperature variations and substantial downtime.	Changed from passive to active control -- limited to 2 control zones.	Use active control of trace heaters with multiple control zones for different thermal loss rates or applications.	
o. Instrumentation - Thermocouples	Insufficient number to monitor salt lines for startup. Freezeup and delays resulted.	Temperature criterion used for startup was increased to reduce the frequency of salt freezing.	Provide sufficient number of thermocouples.	
- Pressure Transducers	Not provided for hot pump discharge.		Provide.	

MSEE PROJECT RESULTS - (Page 2)

EVALUATION OF MSEE DESIGN CONFIGURATION

SUBSYSTEM FEATURE	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
o. Isolation Valves	Leaks occurred thru control valves that were used as isolation valves.	Caused salt freezing and delays.	Install isolation valves on upstream side of all control valves.	
Water/Steam Loop Issues	Numerous leaks --particularly with threaded fittings.	Due to cyclic operation.	Design for cyclic operation. This is a crucial requirement and is treated again on page 11 under reliability of components.	
RECEIVER SUBSYSTEM				
Surge Tanks	Effectively buffered hydraulic surges in receiver flow.		Two surge tank configuration recommended.	
o. Cold Tank	Also provided source of emergency coolant for the receiver.	Inability to vent tank complicated shutdown.	Provide controlled vent in cold tank.	
	Procedures developed which did not require level control.	Operated with level control bypassed.	Can eliminate level control feature.	
o. Hot Tank	Several overflows occurred.	Procedures modified and level sensor used to eliminate problem.	Use larger tank; use level sensor for high salt level protection.	
Boost Pump	Pump in series with cold pump complicated operation and caused forced outages.	Added to existing pump to provide head needed by the receiver.	Use one cold salt pump for full head.	
Flow Control Valves	Two parallel valves functioned well.		Use two parallel valves.	
Riser Shutoff Valve Fail Position	Fail in open position.	This limited emergency flow through receiver; not serious problem in MSEE due to rapid heliostat slewoff.	Provide fail closed configuration.	

MSEE PROJECT RESULTS - (Page 3)

EVALUATION OF MSEE DESIGN CONFIGURATION

SUBSYSTEM FEATURE	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
Purge Valves and Drain Valves	Fill without use of purge valves accomplished.	Receiver fill by flooding functioned well. However, purge and drain valves are a cost and complexity issue.	Possible elimination of purge valves or both purge and drain valves.	Test serpentive fill (by pump) and drain (by gas purge) without using valves. Provide controlled melting provisions for the residual salt in the purge drain case.
Cavity Door	Functioned well. Seal not highly effective.	Very effective seal desired for overnight hold.	Retain Cavity Door. Improve seal capability.	
Protection Against Beam Spillage	Receiver instrumentation damaged by beam spillage.	Caused damage to door drive mechanism.	Provide protection	
THERMAL STORAGE SUBSYSTEM				
Two Tank Configuration	Successful.		Use this configuration.	
Immersion Heaters In Storage Tanks	Cold tank heater functioned as designed.	Conditioned hot tank using solar or fossil fuel.	Do not use immersion heaters in hot salt tank due to corrosion problems.	
	Hot tank heater had previously failed.	Transferred salt to cold tank for extended shutdown.		
Sumps - Bypass Loop	Orifice flow restrictor used in bypass loop to prevent deadheading the pump.	Requires larger salt pump.	Use shutoff valve in place of orifice.	
Transfer of Salt Between Tanks	Originally flowed salt through SGS to transfer from hot to cold tank.	Installed transfer line from hot sump to cold sump.	Provide transfer line from hot sump to cold tank and from cold sump to hot tank.	
Fossil-Fired Heater	Manual operation.	Automatic operation would be simpler and safer.	Provide automatic temperature control loop with a flow meter.	

MSEE PROJECT RESULTS - (Page 4)

EVALUATION OF MSEE DESIGN CONFIGURATION

SUBSYSTEM FEATURE	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
STEAM GENERATION SUBSYSTEM				
Forced Recirculation	Functional over full operating range.		Forced recirculation qualified but was not compared with natural recirculation.	
Superheater/Evaporator Materials	Use of low alloy steel in evaporator required mixing cold salt prior to entering evaporator.		Trade study needed on evaporator material vs. the provision of a seprate cold pump for salt attemperation.	
Burst Disks on Superheater & Evaporator	Burst upon being subjected to pump discharge pressure.	Margin not allowed for burst disk tolerance.	Include tolerances in design.	
Steam Drum	Steam drum level difficult to control.	Revised operating procedure.	Provide revised control loop.	
	Manual blowdown required.	Caused poor water quality and hazardous operation.	Provide automatic blow down.	
Electric Startup Heater	Maintained water/steam temperatures overnight above salt melting point.	Failed several units.	Eliminate. Provide function with salt circulation or fossil heating	
Steam Attemperator	Used to reduce steam outlet temperature.	Required to match steam from SGS (1000°F) to allowable turbine inlet (950°F).	Eliminate. Not required for fine temperature control.	
Equipment Layout	Maintenance extremely difficult due to limited access.	Delayed scheduled testing.	Consider access for maintenance in equipment layout.	
HEAT REJECTION AND FEEDWATER SUBSYSTEM				
Deaerator	Used to reject heat from SGS for startup and turbine out conditions.	Existing equipment employed.	Reject heat to the condensor.	

MSEE PROJECT RESULTS - (Page 5)

EVALUATION OF MSEE DESIGN CONFIGURATION

SUBSYSTEM FEATURE	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
Feedwater Heater	Heated with bypasss steam from steam generator.	No extraction ports on turbine.	Use extraction steam from turbine.	
Spraywater Heat Exchanger	Used to remove heat from deaerator.	Valves leaked.	Eliminate.	
Water Treatment	Manual water treatment and sampling resulted in variation in water quality.	Existing equipment used.	Provide inline water treatment with automatic controls	
Feedwater Pump	Failed due to corrosion of cooling coils.	Oversized. Poor water quality.	Design for all requirements including cyclic operation.	
	Cavitated.	No meter for net pump suction head (NPSH).		
ELECTRIC POWER GENERATION SUBSYSTEM				
Turbine	Various problems. Failed prior to integrated system tests in 1985.	Refurbished, 40 year old.	Use state-of-the-art turbine with extraction ports.	
o Steam Seals	Non-functional.	High back pressure.		
o Oil Pump	Manual pump used for startup.	Installed electric oil pump.		
Generator Exciter	Dynamic exciter did not work.	Replaced with static solid-state exciter.	Use static exciter.	
MASTER CONTROL SUBSYSTEM				
Digital Control	Functioned effectively.	Utility operators accepted system and were impressed with its capability.	Use digital controls.	
Multiple Systems	Problems due to communications between systems.	Multiple control systems used because of existing equipment and dedicated SGS control system.	Use single control system for the full plant.	

MSEE PROJECT RESULTS - (Page 6)

EVALUATION OF MSEE DESIGN CONFIGURATION

SUBSYSTEM FEATURE	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
MASTER CONTROL SUBSYSTEM (Continued)				
Capability	Update rates of approximately 10 seconds limited control's response.	Used existing equipment (1976 technology).	Use state-of-the art system and provide update rates at 1 - 2 sec.	
Consoles	Two viewing/control consoles.	Limited control and system visibility.	Provide at least 4 consoles.	
Heliostat Control	Not integrated into master control.	Required separate operator.	Integrated control recommended.	
EQUIPMENT PROTECTION SUBSYSTEM	Function adequately.	Limited Instrumentation available.	Expand capability and have available during checkout and startup.	

MSSE PROJECT RESULTS - (Page 7)

PERFORMANCE

PERFORMANCE FACTORS	MSEE TEST RESULTS			DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
	DESIGN POINT	DAILY	PROJECTED ANNUAL			
COLLECTION EFFICIENCY	0.494	0.362	0.349	Predictions were: 0.563, 0.413 and 0.411.	Analytical Predictions can be used within the confidence level determined.	Test configurations with higher efficiency.
				Test results compared well with predictions (to within 15 percent).	Higher efficiencies are possible.	
				Low heliostat reflectivity (0.805) included in collection efficiency.		
THERMAL EFFICIENCY (Storage and SGS)	0.967	0.960	0.905	Predictions were: 0.993 0.978 and 0.966	Same as above	
CONVERSION EFFICIENCY	0.176			Prediction was 0.240. 0.335 used for Integrated System tests based on measured Solar I results adjusted for MSEE steam conditions.	Not applicable.	
PARASITICS	311 KWe	5525 KWHr 24 hr day	1547 MWHr Year	High parasitic power due to small size of installation and non-optimized design.	Parasitic Power is a major factor to consider in commercial plant design.	Test alternative features selected for the commercial system design.
o Trace Heating	(60)	(2053)	(799)			
o Salt Pumps	(85)	(944)	(258)	Steam cycle and balance of plant values are based on normalized solar I results.	Less parasitic power is possible with optimized design at commercial size.	
o Collector Field and Controls	(52)	(634)	(174)			
o SGS Circulation Pump & Heater	(5)	(344)	(147)	Overnight hold standby power requirements contributed substantially to daily and annual parasitics.	Alternative heat sources such as circulating hot salt, should be evaluated for overnight hold.	
o Steam Cycle and Balance of Plant	(109)	(1550)	(469)			

OPERATIONS

OPERATION	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
WARM UP				
Receiver Panel	Efficient early morning warmup with heliostats demonstrated (50 minutes after sunrise).	Uses only 0.3% of clear day's energy.	Warmup using heliostats is tentatively recommended. Should be compared with overnight salt flow with well insulated and sealed receiver cavity.	Refine and improve warmup patterns.
Balance of Salt System	Maintained warm overnight using trace heat.	See overnight hold discussion below.	See recommendations under overnight hold below.	None.
START UP				
Receiver config- purge	Rapid receiver startup demonstrated (65 minutes after sunrise).	Minimum loss of useful energy.	Applicable.	Demonstrate for new urations simulating a commercial design and with serpentine flow if the or purge and drain valves can be eliminated.
	Flexible operations demonstrated -- could start SGS first.	Startup can be sequenced according to inventory in thermal storage.	Flexibility is available.	Automated, simultaneous startup with SGS.
	Startup frequently delayed due to "cold" salt components.	Windshielding, new insulation and active trace heater controls reduced frequency of delays.	Would not apply if recommendation of flowing salt for overnight hold is adopted.	Test with selected overnight hold condition.
Steam Generator	55 minute startup demonstrated.	40 minutes is the minimum based on warmup rates.	Startup of commercial size unit could be longer. Consider the allowable warmup rates in component design.	Demonstrate most rapid startup.
	Startup sequenced with EPGS.	Turbine startup simulated for integrated system test due to prior turbine failure.	Automated startup integrated with turbine warmup and startup should be specified.	Test the automated, integrated startup sequence.

MSEE PROJECT RESULTS - (Page 9)

OPERATIONS

OPERATION	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
HRFS and EPGS	105 minutes required from pretest to full power.	Excessive startup time due to facility limitations and sequencing with SGS.	Startup of commercial scale unit could be longer. Integrated startup (see above) would reduce this time. Consider daily startup requirement in subsystem and component specifications and design.	
STEADY STATE	Full system operation was stable and required minimum operator intervention.	See discussions under decoupling and automated operation.	Demonstrated for commercial system.	
TRANSIENTS	Receiver outlet temperature derated 50°F during partly cloudy conditions.	Receiver controls allowed up to 70°F temperature overshoot with severe cloud transients.	Not applicable if control algorithm is based on flux measurements. An indirect method is preferred.	Test with recommended control algorithm.
	Receiver turndown ratio limited to 3 to 1.	5 to 1 turndown in specification. Limit imposed in order to increase flow rapidly enough following a cloud transient.	5 to 1 turndown ratio should be used. Design control system to accommodate.	Test with 5 to 1 turndown.
DECOUPLING OF ENERGY COLLECTION AND UTILIZATION	Fully demonstrated.	Allowed flexible startup and operation of all subsystems. Permitted all subsystems to operate at maximum efficiency.	Applicable Storage can be selected for desired duty cycle.	
AUTOMATED OPERATION				
Receiver Loop	Fully automated.	Routinely performed by utility operators.	Applicable.	Test for new configurations.
Steam Generator	Most operations automated.	Manual operations were required for transitions during startup and shutdown.	Full automation can be achieved.	Test fully automated operation.

MSEE PROJECT RESULTS - (Page 10)

OPERATIONS

OPERATION	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
HRFS and EPGS	Not automated.	facility and control system limitations prevented automated operation.	Full automation could be achieved.	Test automated operation.
OVERNIGHT HOLD				
Receiver	Drained and maintained warm with trace heaters (except receiver panel). System was frequently "cold" by morning.	Excessive heat loss during high winds and trace heater failures resulted in 31% outage at the beginning of Phase II. Wind shields reduced this to 15% by the end of Phase II.	Electric trace heating is questionable.	Test selected approach.
		Salt circulation recommended as a more efficient and reliable overnight hold method.	Recommend that salt circulation be used for overnight hold and either steam tracing or hot air be evaluated for initial and periodic warmup.	
Steam Generator	Salt loop drained and maintained warm with trace heaters.	Electric trace heaters have high parasitic power usage and reliability problems.	See recommendations for receiver.	Test selected configuration.
	Electric startup heater used to maintain water temperature above salt freezing point throughout the night.	Warmup from ambient would have taken approximately 6 hours.	Not required for recommended approach.	
	Recirculation pump had to run on a 24 hour duty cycle.	Pump not designed for cyclic operation.	Design for cyclic operation to accommodate daily startup and shutdown.	
HRFS and EPGS	Restart on daily basis caused various problems.	Much of the equipment was not designed for cyclic operation.	Design for cyclic operation to accommodate daily startup and shutdown.	

MSEE PROJECT RESULTS - (Page 11)

RELIABILITY OF COMPONENTS

COMPONENT	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
TRACE HEATERS	More than 25 failures occurred.	Use of redundant heaters and repairs kept system operational.	Install at least dual redundant heaters and keep junctions exposed.	Test selected design.
		Location of hot/cold junctions made repair difficult.	Use strip heaters on tanks and band heaters on instruments. Consider alternatives recommended for overnight hold under operations.	
SALT PUMPS	No problems with hot salt pump.	Vertical cantilever pumps performed well.	Use vertical cantilever pumps.	
	High internal leakage in cold pump.	Did not cause downtime.		
	Boost pump freeze up and bearing failure.	Modified procedures and prevented salt from entering packing.	Single pump recommended.	
SALT VALVES	Problems with internal and external leakage.	Operating procedures revised to accommodate internal leakage. Significant downtime required to fix external leakage.	Design system to accept internal leakage. Add isolation valves.	Develop and test commercial size valves and packing material.
			Employ valve types and materials selected from further testing.	
			Have quality assurance program.	
WATER/STEAM EQUIPMENT	Numerous leaks and problems.	Existing equipment used.	Design for cyclic operation. This is a major new requirement for many of the components.	Qualify for cyclic operation.
INSTRUMENTATION	Receiver salt flow transmitters diaphram distorted.	Replaced & heated with band heaters.	Use band heaters.	
	HRFS water flow transmitters not functional.	Operated without transmitters.	Provide reliable flow transmitters.	

MSEE PROJECT RESULTS - (Page 12)

RELIABILITY OF COMPONENTS

COMPONENT	MSEE TEST RESULTS	DISCUSSION	APPLICATION TO COMMERCIAL SYSTEM DESIGN	RECOMMENDATION FOR FURTHER TESTING
INSTRUMENTATION (continued)				
	SGS steam flow transmitter was erratic.	Required repeated evacuation of air from the transmitter.	Design to eliminate problems.	
	Surge tank level transmitters erratic.	Procedures changed to operate with inaccurate readings.	Develop improved transducers for salt use.	Test improved transducers.
	Numerous thermocouples failed.	Replaced or operated without thermocouple.	Provide extra thermocouples as spares.	
	Microswitches and valve position indicators required frequent adjustment.	Added complexity to operations and control.	Design & install for more reliable operation.	
MASTER CONTROL	Numerous hardware problems.	Caused significant downtime.	Include automatic diagnostic system and sufficient spares. Utilize results of ongoing development of digital controls for power plants.	Test system with automatic diagnostics.

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2. <u>Molten Salt Electric Experiment - Phase I Report</u>. Volume II, System Development and Test. Denver, CO: Martin Marietta Aerospace, September 1984. MCR-84-548-2.

3. <u>Molten Salt Electric Experiment - Phase I</u>. Volume III, Appendices. Denver, CO: Martin Marietta Aerospace, September 1984. MCR-84-548-3.

4. <u>Molten Salt Electric Experiment Steam Generating Subsystem</u>. Barberton, OH: Babcock & Wilcox, August 1, 1984. B&W 700-0027-45-3.

5. A. B. Quakenbush. "MSEE Salt Sampling, 1984 Status Report." Memorandum, January 11, 1985. Olin Chemicals Group, Lake Charles, LA.

6. <u>Alternate Central Receiver Power System, Phase II</u>. Volume II, Molten Salt Receiver. Denver, CO: Martin Marietta Corporation, May 1981. MCR 81-1707.

7. <u>Fundamentals of Solar Radiation</u>. Albuquerque, NM: Sandia National Laboratories. SAND79-0490.

8. C. M. Finch. "Central Receiver Uncertainties and Options. <u>EPRI Solar Thermal Workshop on Technical Problems and Issues</u>, 1985.

9. D. B. Dawson. "Revised Physical Property Values for Molten Nitrate Salts." Memorandum, April 26, 1982. Sandia National Laboratories, Div. 8453.

10. <u>Molten Salt Thermal Energy Storage Subsystem Research Experiment</u>. Denver, CO: Martin Marietta Aerospace, September 1982. MCR-82-1722.

11. J. T. Holmes. <u>Electric Heating for High Temperature Heat Transport Fluids</u>. Albuquerque, NM: Sandia National Laboratories. SAND 85-0379.

APPENDIX A

CONSTRUCTION/INTEGRATION TESTING LESSONS LEARNED

An important part of MSEE to potential users was the lessons learned. The MSEE portion of lessons learned while under the responsibility of Martin Marietta were not included in detail as they were covered in a separate report. The following summarizes the MSEE lessons learned and conclusions from Martin Marietta's report.

CONTROL AND DATA ACQUISITION SYSTEM

1. Requirements definition, hardware selection, and computer programing should be done by one organization.
2. Control and data acquisition system requirements should be defined before a system is selected to implement those requirements.
3. A single system should be used for control and data acquisitions, instead of three systems (EMCON D-2, Bailey Network 90, and the Acurex).
4. More than two operator consoles are needed during checkout.
5. Alarms should be used more effectively during checkout.
6. The equipment protection system (EPS) should be connected and used earlier in the checkout phase.
7. Great care must be used to avoid time delays in critical feedback control loops.
8. Automatic sequences cannot be defined until manual sequences are run and checked out.
9. Redundancy should be used in the control and data acquisition system hardware.
10. A better data recording system is needed.

VALVES

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

1. Molten salt systems should be designed to allow for leakage through the valves without causing spillage or damage to the system.
2. Proper detailed design, material selection, and quality control are vital to obtaining a reliable bellows stem seal in molten salt valves.

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

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

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

6. Valve position indicators were poor quality.

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.

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

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 backward. 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.

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 9 failures in the system consisting of 216 cables with a total length of 8000 ft.

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.

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

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 overtemperature 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 destroys 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 SGS.

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 Acurex.

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

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.

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 by contaminants.

INSTRUMENTATION

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

TEST PLANS AND PROCEDURES

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

CONSTRUCTION

Three lessons learned during construction were:

1. The 316L 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 affected the inert gas purge required. Prefabrication of welding should be done as much as possible.

CONCLUSIONS

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 ft 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 many 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 freesing 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 water-cooled aperture frame on the receiver SRE.

6. During the checkout of the MSEE models in HELIOS, TRASYS, and DOMAIN computer programs, 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.

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.

APPENDIX B

SUBSYSTEM COMPONENTS AND INSTRUMENTATION LISTS

This appendix provides a detailed listing of the major components of each subsystem (RS, TSS, SGS, HRFS, and EPGS) with a description, function, and nominal operating conditions for each component. It also provides a listing of the remotely operated valves, by tag name, manufacturer, size, type, function, and location. A detailed instrumentation listing is provided by tag name, description, range, alarm levels, and location. Lastly, the control loops are listed with set points, inputs and outputs. The piping and instrumentation drawing is provided to assist in locating the components and instruments.

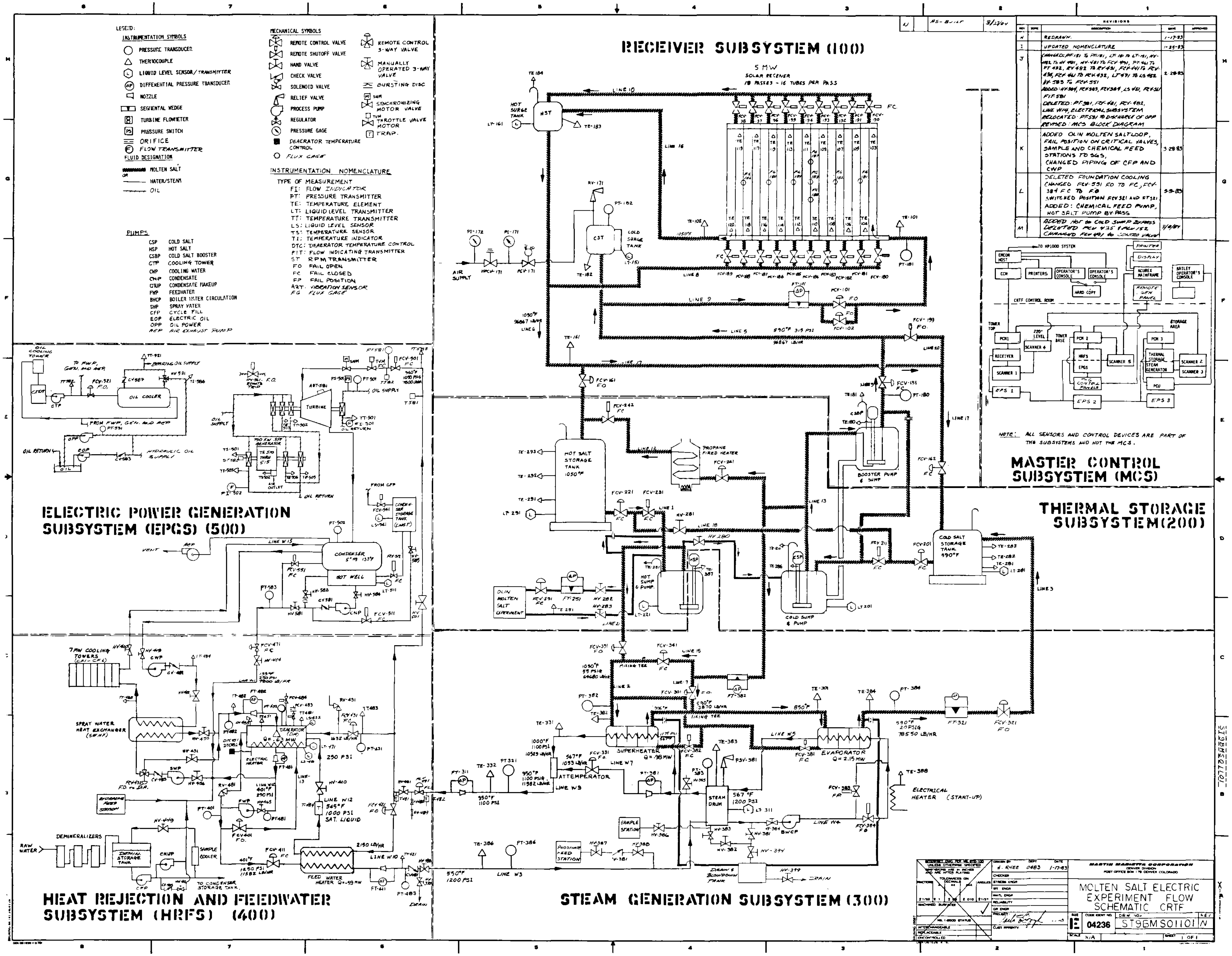

RECEIVER SUBSYSTEM (100)
5 MW
SOLAR RECEIVER
18 PASSES - 16 TUBES PER PASS
THERMAL STORAGE SUBSYSTEM (200)
STEAM GENERATION SUBSYSTEM (300)
HEAT REJECTION AND FEEDWATER SUBSYSTEM (HRFS) (400)
ELECTRIC POWER GENERATION SUBSYSTEM (EPGS) (500)
MASTER CONTROL SUBSYSTEM (MCS)
NOTE: ALL SENSORS AND CONTROL DEVICES ARE PART OF THE SUBSYSTEMS AND NOT THE MCS.
LEGEND:
INSTRUMENTATION SYMBOLS
PRESSURE TRANSDUCER
THERMOCOUPLE
LIQUID LEVEL SENSOR/TRANSMITTER
DIFFERENTIAL PRESSURE TRANSDUCER
NOZZLE
SEGMENTAL WEDGE
TURBINE FLOWMETER
PRESSURE SWITCH
ORIFICE
FLOW TRANSMITTER
FLUID DESIGNATION
MOLTEN SALT
WATER/STEAM
OIL
MECHANICAL SYMBOLS
REMOTE CONTROL VALVE
REMOTE SHUTOFF VALVE
HAND VALVE
CHECK VALVE
SOLENOID VALVE
RELIEF VALVE
PROCESS PUMP
REGULATOR
PRESSURE GAGE
DEAERATOR TEMPERATURE CONTROL
FLUX GAGE
REMOTE CONTROL 3-WAY VALVE
MANUALLY OPERATED 3-WAY VALVE
BURSTING DISC
SWM SYNCHRONIZING MOTOR VALVE
TVM THROTTLE VALVE MOTOR
TRAP.
INSTRUMENTATION NOMENCLATURE
TYPE OF MEASUREMENT
FI: FLOW INDICATOR
PT: PRESSURE TRANSMITTER
TE: TEMPERATURE ELEMENT
LT: LIQUID LEVEL TRANSMITTER
TT: TEMPERATURE TRANSMITTER
LS: LIQUID LEVEL SENSOR
TS: TEMPERATURE SENSOR
TI: TEMPERATURE INDICATOR
DTC: DEAERATOR TEMPERATURE CONTROL
FIT: FLOW INDICATING TRANSMITTER
ST RPM TRANSMITTER
FO FAIL OPEN
FC FAIL CLOSED
FP FAIL POSITION
ART. VIBRATION SENSOR
FG FLUX GAGE
PUMPS
CSP COLD SALT
HSP HOT SALT
CSBP COLD SALT BOOSTER
CTP COOLING TOWER
CWP COOLING WATER
CNP CONDENSATE
CMUP CONDENSATE MAKEUP
FWP FEEDWATER
BWCP BOILER WATER CIRCULATION
SWP SPRAY WATER
CFP CYCLE FILL
EOP ELECTRIC OIL
OPP OIL POWER
AEP AIR EXHAUST PUMP
HOT SURGE TANK
HST
COLD SURGE TANK
CST
AIR SUPPLY
LINE 10
LINE 16
LINE 8
LINE 9
LINE 5
LINE 6
LINE 17
LINE 20
1050°F
590°F 315 PSI 96867 LB/HR
HOT SALT STORAGE TANK 1050°F
PROPANE FIRED HEATER
BOOSTER PUMP & SUMP
COLD SALT STORAGE TANK 590°F
HOT SUMP & PUMP
COLD SUMP & PUMP
OLIN MOLTEN SALT EXPERIMENT
MIXING TEE
SUPERHEATER Q = .98 MW
EVAPORATOR Q = 2.15 MW
ATTEMPERATOR
STEAM DRUM
SAMPLE STATION
PHOSPHATE FEED STATION
DRAIN & BLOWDOWN TANK
ELECTRICAL HEATER (START-UP)
LINE W3
LINE W4
LINE W5
LINE W7
LINE W9
550°F 1200 PSI
950°F 1100 PSI
TURBINE
CONDENSER
HOT WELL
OIL COOLER
750 KW SYN GENERATOR
COMPENSATE STORAGE TANK (CMST)
7 MW COOLING TOWERS
SPRAY WATER HEAT EXCHANGER (SWHX)
DEAERATOR Q = .63 MW
ELECTRIC HEATER
FEED WATER HEATER Q = .49 MW
DEMINERALIZERS
RAW WATER
DEMIN. STORAGE TANK
SAMPLE COOLER
HYDRAZINE FEED STATION
TO CONDENSER STORAGE TANK
LINE W10
LINE W12
545°F 1000 PSI SAT. LIQUID
250 PSI
TO HP1000 SYSTEM
EMCON HOST
CCM
PRINTERS
OPERATOR'S CONSOLE
HARD COPY
PRINTER
DISPLAY
ACUREX MAINFRAME
BAILEY OPERATOR'S CONSOLE
REMOTE GEN PANEL
CRTF CONTROL ROOM
TOWER TOP
TOWER BASE
STORAGE AREA
RECEIVER
SCANNER
THERMAL STORAGE STEAM GENERATOR
EPGS
HRFS
CONTROL PANELS
EPS
N AS-BUILT 3/22/84
REVISIONS
H REDRAWN. 1-17-83
I UPDATED NOMENCLATURE 1-25-83
J CHANGED: PT-151 TO PT-181, LT-181 TO LT-151, HV-482 TO HV 481, HV-481 TO FCV-491, PT-461 TO PT 432, RV 482 TO RV 431, FCV-441 TO FCV-436, FCV 461 TO FCV 432, LT 471 TO LS 462, HV-583 TO FCV-551; ADDED: HV 384, FCV 383, FCV 384, LS 451, FCV-561, FIT-581; DELETED: PT-381, FCV-481, FCV-482, LINE W14, ELECTRICAL SUBSYSTEM; RELOCATED: PT-531 TO DISCHARGE OF OPP; REVISED: MCS BLOCK DIAGRAM 2-28-83
K ADDED OLIN MOLTEN SALT LOOP, FAIL POSITION ON CRITICAL VALVES, SAMPLE AND CHEMICAL FEED STATIONS TO SGS, CHANGED PIPING OF CFP AND CWP 3-28-83
L DELETED FOUNDATION COOLING; CHANGED FCV-551 FO TO FC, FCV-384 FC TO FO; SWITCHED POSITION FCV 321 AND FT 321; ADDED: CHEMICAL FEED PUMP, HOT SALT PUMP BY-PASS 5-5-83
M ADDED HOT to COLD SUMP BYPASS; DELETED FCV 435 & FCV 152; CHANGED FCV 491 to CONTROL VALVE 3/8/84
DRAWN BY H. RHEE 0483 1-17-83
MARTIN MARIETTA CORPORATION
DENVER DIVISION
POST OFFICE BOX 179 DENVER COLORADO
MOLTEN SALT ELECTRIC EXPERIMENT FLOW SCHEMATIC CRTF
SIZE E
CODE IDENT NO. 04236
DRW NO. ST9BMS01101
REV N
SCALE N/A
SHEET 1 OF 1

Table B-1

RECEIVER SUBSYSTEM COMPONENTS

Component	Description	Function	Nominal Operating Condition
Receiver	- 18 ft wide x 13 ft high panel - 18 serpentine passes Incoloy 800 tubes - 16 tubes per pass - 3/4 in. dia. tubes	- Heat molten salt with solar energy from heliostat field	- 590°F inlet salt - 1050°F outlet salt - 96,867 lb/hr - 5 MW rating
Cold salt booster sump	- Carbon steel cylindrical tank	- Reservoir for cold salt pump	- 590°F salt - Atmospheric pressure
Cold salt booster pump	- Vertical cantilever type	- Supply additional head to outlet of cold salt pump to provide salt circulation through receiver	- 590°F salt - 96,867 lb/hr
Cold surge tank	- Carbon steel cylindrical tank - 3 ft. dia. - 7 ft. high	- Dampen changes in salt flow rate - Provide emergency salt flow through receiver until solar flux can be removed in the event of pump outage	- Pressurized to 125 psi
Hot surge tank	- Stainless steel cylindrical tank - 2 ft. dia. - 7 ft. high	- Dampen changes in salt flow rate	- Atmospheric pressure

Table B-2

RECEIVER SUBSYSTEM REMOTE OPERATED VALVES

VALVE	MANUFACTURER	SIZE	TYPE	FAIL POSITION	FUNCTION	LOCATION
FCV-101 FCV-102	Valtek	2"	CV	FO	Receiver Flow Control	Near Receiver Lower West Corner
FCV-151	Valtek	2"	CV	FC	Receiver Fill Control Cold Surge Level Control	Above Hot Tank
FCV-161	Valtek	2"	CV	FO	Hot Surge Tank Level Control	Above Hot Tank
FCV-162	Valtek	2"	CV	FC	Hot Surge Tank Level Control (Receiver)	Above Hot Tank
FCV-180 thru FCV-189	Kieley-Mueller	1 1/2"	SV	FC	Receiver Fill and Drain	Below Receiver
FCV-190 thru FCV-198	Kieley-Mueller	1 1/2"	SV	FC	Receiver Purge	Above Receiver
FCV-199	Kieley-Mueller	2"	SV	FC	Allow Downcomer Backflow During Receiver Fill and Permit Drainage to Cold Storage Tank During Shutdown	Above Hot Tank

CV - Control Valve
SV - Shutoff Valve
FO - Fail Open
FC - Fail Close

Table B-3
RECEIVER SUBSYSTEM INSTRUMENTATION

Identifier	Description	Control Module	Display Range	Alarm Levels		Dimension	Sampling Period (sec
				High	Low		
	Boost Pump						
PT-180	Discharge pressure	PCM 3	0-400	350	275	PSI	2
TE-180	Bearing temp	PCM 3	0-500	190		°F	10
TE-181	Sump vent temp	PCM 3	0-1200	350		°F	10
	Hot surge tank						
LT-161	Level	PCM 3	0-100	70	15	inch	2
TE-183	Salt temp	PCM 1	0-1200	1070	500	°F	10
TE-184	Vent temp	PCM 1	0-1200	400		°F	10
	Cold surge tank						
LT-151	Level	PCM 1	0-100	90	10	inch	10
TE-182	Salt temp	PCM 1	0-1200	750	500	°F	10
PT-182	Pressure	PCM 1	0-200	180	10	PSI	10
TE-161	Downcomer outlet temp	PCM 3	0-1200	1070	500	°F	2
Sun	Solar insolation	PCM 3	0-1000			W/M^2	5

Table B-3

RECEIVER SUBSYSTEM INSTRUMENTATION

Identifier	Description	Control Module	Display Range	Alarm Levels		Dimension	Sampling Period (sec)
				High	Low		
	Receiver						
PT-181	Inlet pressure	PCM 1	0-200	125	10	PSI	10
FT-101	Salt flow rate	PCM 1	0-100	100		KLB/hr	
TE-101	Salt inlet temp	PCM 1	0-1200	650	500	°F	2
TE-102	Salt outlet temp	PCM 1	0-1200	1060	500	°F	2
TE-103	Back tube-pass #1 outlet	PCM 1	0-1200	640	500	°F	2
TE-104	Back tube-pass #2 outlet	PCM 1	0-1200	665	500	°F	2
TE-105	Back tube-pass #3 outlet	PCM 1	0-1200	690	500	°F	2
TE-106	Back tube-pass #4 outlet	PCM 1	0-1200	720	500	°F	2
TE-107	Back tube-pass #5 outlet	PCM 1	0-1200	750	500	°F	2
TE-108	Back tube-pass #6 outlet	PCM 1	0-1200	780	500	°F	2
TE-109	Back tube-pass #7 outlet	PCM 1	0-1200	810	500	°F	2
TE-110	Back tube-pass #8 outlet	PCM 1	0-1200	835	500	°F	2
TE-111	Back tube-pass #9 outlet	PCM 1	0-1200	865	500	°F	2
TE-112	Back tube-pass #10 outlet	PCM 1	0-1200	890	500	°F	2
TE-113	Back tube-pass #11 outlet	PCM 1	0-1200	920	500	°F	2

Table B-3

RECEIVER SUBSYSTEM INSTRUMENTATION

Identifier	Description	Control Module	Display Range	Alarm Levels		Dimension	Sampling Period (sec)
				High	Low		
	Receiver (cont.)						
TE-114	Back tube-pass #11 outlet	PCM 1	0-1200	950	500	°F	2
TE-115	Back tube-pass #12 outlet	PCM 1	0-1200	975	500	°F	2
TE-116	Back tube-pass #13 outlet	PCM 1	0-1200	990	500	°F	2
TE-117	Back tube-pass #14 outlet	PCM 1	0-1200	1010	500	°F	2
TE-118	Back tube-pass #15 outlet	PCM 1	0-1200	1030	500	°F	2
TE-119	Back tube-pass #16 outlet	PCM 1	0-1200	1050	500	°F	2
TE-120	Back tube-pass #17 outlet	PCM 1	0-1200	1070	500	°F	2
TE-131	Back tube-pass #1 upper	PCM 1	0-1200	645	500	°F	10
TE-132	Back tube-pass #5 upper	PCM 1	0-1200	745	500	°F	10
TE-133	Back tube-pass #8 upper	PCM 1	0-1200	815	500	°F	10
TE-134	Back tube-pass #11 upper	PCM 1	0-1200	915	500	°F	10
TE-135	Back tube-pass #14 upper	PCM 1	0-1200	980	500	°F	10
TE-136	Back tube-pass #17 upper	PCM 1	0-1200	1045	500	°F	10
TE-137	Back tube-pass #2 middle	PCM 1	0-1200	680	500	°F	10

Table B-3

RECEIVER SUBSYSTEM INSTRUMENTATION

Identifier	Description	Control Module	Display Range	Alarm Levels		Dimension	Sampling Period (sec)
				High	Low		
	Receiver (cont.)						
TE-138	Back tube-pass #6 middle	PCM 1	0-1200	735	500	°F	10
TE-139	Back tube-pass #8 middle	PCM 1	0-1200	825	500	°F	10
TE-140	Back tube-pass #11 middle	PCM 1	0-1200	905	500	°F	10
TE-141	Back tube-pass #14 middle	PCM 1	0-1200	990	500	°F	10
TE-142	Back tube-pass #17 middle	PCM 1	0-1200	1045	500	°F	10
TE-143	Back tube-pass #1 bottom	PCM 1	0-1200	660	500	°F	10
TE-144	Back tube-pass #5 bottom	PCM 1	0-1200	725	500	°F	10
TE-145	Back tube-pass #8 bottom	PCM 1	0-1200	830	500	°F	10
TE-146	Back tube-pass #11 bottom	PCM 1	0-1200	895	500	°F	10
TE-147	Back tube-pass #14 bottom	PCM 1	0-1200	985	500	°F	10
TE-148	Back tube-pass #17 bottom	PCM 1	0-1200	1035	500	°F	10
TE-185	Header-pass #2 outlet	PCM 1	0-1200	665	500	°F	10
TE-186	Header-pass #3 outlet	PCM 1	0-1200	690	500	°F	10

Table B-3
RECEIVER SUBSYSTEM INSTRUMENTATION

Identifier	Description	Control Module	Display Range	Alarm Levels		Dimension	Sampling Period (sec)
				High	Low		
	Receiver (cont.)						
TE-187	Header-pass #4 outlet	PCM 1	0-1200	720	500	°F	10
TE-188	Header-pass #5 outlet	PCM 1	0-1200	750	500	°F	10
TE-189	Header-pass #6 outlet	PCM 1	0-1200	780	500	°F	10
TE-190	Header-pass #7 outlet	PCM 1	0-1200	810	500	°F	10
TE-191	Header-pass #8 outlet	PCM 1	0-1200	835	500	°F	10
TE-192	Header-pass #9 outlet	PCM 1	0-1200	865	500	°F	10
TE-193	Header-pass #12 outlet	PCM 1	0-1200	950	500	°F	10
TE-194	Header-pass #13 outlet	PCM 1	0-1200	975	500	°F	10
TE-195	Header-pass #14 outlet	PCM 1	0-1200	990	500	°F	10
TE-196	Header-pass #15 outlet	PCM 1	0-1200	1010	500	°F	10
TE-197	Header-pass #16 outlet	PCM 1	0-1200	1030	500	°F	10
TE-198	Header-pass #17 outlet	PCM 1	0-1200	1050	500	°F	10

Table B-4
RECEIVER SUBSYSTEM CONTROL LOOPS

Controlled Variable	Mode	Set Point	Controller Inputs	Controller Output
Receiver salt flow	Constant flow (start-up & shutdown with receiver control algorithm off scan	30 KLB/hr FD-101	Flow set point (FD-101) Measured flow (FT-101)	FCV-101/102 position
	Constant Outlet Temperature (Receiver control algorithm on)	1000°F SP. SALT	Temperature set point (SP. SALT) Outlet temperature (TE-102) Inlet temperature (TE-101) Salt flow (FT-101) Receiver back tube temperatures (TE-103 thru TE-120)	FCV-101/102 position
Hot surge tank level	Operation	20 in FCV-161 FCV-162	Surge tank level (LT-161) Level set point	FCV-161 or FCV-162 position (selection based on salt temperature)
Receiving storage tank selection	Operation	750°F	Downcomer salt temperature (TE-161)	TE-161 < 750°F Cold storage tank selected TE-161 > 750°F Hot storage tank selected
Cold surge tank level	Operation	~85" LT-151	Cold surge tank level (LT-151) Level set point	FCV-151 position

Table B-5
THERMAL STORAGE SUBSYSTEM COMPONENTS

Component	Description	Function	Nominal Operating Condition
Cold salt storage tank	- Carbon steel cylindrical tank - 12.3 ft. dia. - 12.3 ft. high - 15 in fibrous external insulation	- Cold salt storage	- 590°F salt
Hot salt storage tank	- Carbon steel cylindrical shell - 12.3 ft. dia. stainless steel liner - 23.6 ft. high - 13-1/2 in. insulating firebrick between shell and liner - 2 in. fibrous external insulation	- Hot salt storage	- 1050°F salt - Approx. 7 MW_t hr storage capacity
Cold salt sump	- Carbon steel cylindrical tank - 59 in. dia. - 66 in. deep	- Pump reservoir	- 590°F salt - Atmospheric pressure
Cold salt pump	- Vertical cantilever type - 60 H.P. driver	- Pump salt from cold storage tank to cold salt booster pump, SGS, or propane heater	- 590°F salt - 96,867 lb/hr

Table B-5

THERMAL STORAGE SUBSYSTEM COMPONENTS

Component	Description	Function	Nominal Operating Condition
Hot salt sump	- Stainless steel cylindrical tank - 48 in. dia. - 49 in. deep	- Reservoir for hot salt pump	- 1050°F salt - Atmospheric pressure
Hot salt pump	- Vertical cantilever type - 7-1/2 HP driver	- Provide hot salt circulation through STS	- 1050°F salt - 64,680 lb/hr
Propane heater	- 3 MW propane fired heater - 9 ft. dia. shell - 24 ft. high - One stainless steel heating coil, 2.12 in. dia., 1640 ft. long	- Provide auxiliary salt heating capability	- 59,900 lb/hr salt - 590°F inlet - 1050°F outlet

Table B-6

THERMAL STORAGE SUBSYSTEM REMOTE OPERATED VALVES

VALVE	MANUFACTURER	SIZE	TYPE	FAIL POSITION	FUNCTION	LOCATION
FCV-201	Valtek	3"	CV	FC	Cold Sump Level Control	Cold Storage Tank Base South Side
FCV-211	Kieley-Mueller	3"	SV	FC	Cold Sump Isolation	Pump House North Side West End
FCV-221	Valtek	3"	CV	FC	Hot Sump Level Control	Hot Storage Tank Southwest Side
FCV-231	Kieley-Mueller	3"	SV	FC	Hot Sump Isolation	Outside Pumphouse Northeast Corner
FCV-241	Valtek	2"	CV	FC	Propane Heater Flow Control	Line to Propane Heater East of FCV-231
FCV-242	Valtek	1 1/2"	SV	FC	Propane Heater Isolation	Top of Hot Tank

Table B-7

THERMAL STORAGE SUBSYSTEM INSTRUMENTATION

Identifier	Description	Control Module	Display Range	Alarm Levels		Dimension	Sampling Period (sec)
				High	Low		
	Cold Storage Tank						
LT-281	Level	PCM 3	0-150	134	15	inch	10
TE-281	Lower temp	PCM 3	0-1200	700	500	°F	10
TE-282	Middle temp	PCM 3	0-1200	700	500	°F	10
TE-283	Upper temp	PCM 3	0-1200	700	500	°F	10
	Hot storage tank						
LT-291	Level	PCM 3	0-200	190	10	inch	10
TE-291	Lower temp	PCM 3	0-1200	1070	500	°F	10
TE-292	Middle temp	PCM 3	0-1200	1070	500	°F	10
TE-293	Upper temp	PCM 3	0-1200	1070	500	°F	10
	Cold salt pump						
LT-201	Sump level	PCM 3	0-60	60	15	inch	2
TE-286	Bearing temp	PCM 3	0-500	190		°F	10
TE-211	Vent temp	PCM 3	0-1200	400		°F	2
	Hot Salt Pump						
LT-221	Sump level	PCM 3	0-48	41	15	inch	2
TE-231	Vent temp	PCM 3	0-1200	400		°F	2

Table B-8

THERMAL STORAGE SUBSYSTEM CONTROL LOOPS

Controlled Variable	Mode	Set Point	Controller Inputs	Controller Output
Cold sump level	Operation	23 in FCV-201 (45 in fill)	Sump level (LT-201) Level set point	FCV-201 position - Flow from cold storage tank
Hot sump level	Operation	20 in FCV-221	Sump level (LT-221) Level set point	FCV-221 position - Flow from hot storage tank

Table B-9

STEAM GENERATION SUBSYSTEM COMPONENTS

Component	Description	Function	Nominal Operating Condition
Evaporator	- U-tube/U-shell counterflow heat exchanger - 8 in. dia. chrome - moly shell (salt) - 27 chrome-moly tubes 0.875 in. dia. 68 ft avg. length (water)	- Evaporate subcooled water to produce saturated steam/water mixture	- 850°F salt inlet - 590°F salt outlet - 78,550 lb/hr salt flow rate - Subcooled water inlet - 567°F, 1200 psi saturated steam/water outlet - 2.15 MW rating
Superheater	- U-tube/U-shell counterflow heat exchanger - 6 in. dia. stainless steel shell (salt) - 23 stainless steel tubes 0.500 in. dia. 33 ft. avg. length (steam)	- Heat saturated steam to superheat condition	- 1050°F salt inlet - 906°F salt outlet - 64,680 lb/hr salt flow rate - 567°F 1175 psi saturated steam inlet - 1000°F. 1100 psi superheated vapor outlet - 10,530 lb/hr steam flow rate - 0.98 MW rating
Steam Drum	- Cylindrical pressure vessel with elliptical heads - 24 in ID - 6 ft 10 in overall height - 2 in thick carbon steel - Contains primary cyclone steam separator and primary & secondary steam scrubbers	- Separate steam/water mixture exiting evaporator - Supply saturated steam to superheater - Provide feedwater surge volume	- 567°F - 1200 psi

Table B-9

STEAM GENERATION SUBSYSTEM COMPONENTS

Component	Description	Function	Nominal Operating Condition
Boiler water circulation pump	- Canned centrifugal type - 5 HP driver	- Provide circulation of subcooled water from the steam drum to evaporator. Maintain high recirculation rate over full range of operating conditions.	- 560°F - 119 GPM - 111 ft. head
Start-up heater	- Chamber type electric heater - 3 40-kW heating elements - 2 15-kW heating elements	- Raise temperature and pressure of water during cold start-up to avoid salt freeze-up in evaporator - Heat boiler water to maintain temperature and pressure of water/steam system during diurnal hold	- 150 kW during start-up - Cycled during diurnal hold - Bypassed during normal operation
Steam attemperator	- Mixing tee	- Mix saturated steam from steam drum with superheated steam from superheater to control steam delivery temperature to turbine	- 1053 lb/hr dry saturated steam at 567°F - 10,529 lb/hr superheated steam at 1000°F 1100 psi - 11,582 lb/hr delivery steam at 950°F 1100 psi
Salt attemperator (evaporator inlet)	- Mixing tee	- Mix cold salt with superheater outlet salt to limit evaporator inlet salt temperature to 850°F because of Cr-Mo construction	- 64,680 lb/hr at 906°F - 13,870 lb/hr at 590°F - 78,550 lb/hr at 850°F supplied to evaporator

Table B-9

STEAM GENERATION SUBSYSTEM COMPONENTS

Component	Description	Function	Nominal Operating Condition
Salt start-up attemperator (superheater inlet)	- Mixing tee	- Mix cold salt with hot salt from hot tank to provide a controlled temperature increase of salt entering superheater during start-up	- Full flow of cold salt at start-up - No cold salt flow during operation
Heat tracing	- Electrical heating element - Inconel sheath	- Maintain heat exchangers and salt piping above the freezing point of salt - Provide freeze protection of feedwater piping and instrumentation during shutdown	- Temperature monitored by thermocouples - Cycle as required

Table B-10

SGS REMOTE OPERATED VALVES

VALVE	MANUFACTURER	SIZE	TYPE	FAIL POSITION	FUNCTION	LOCATION
FCV-301	Valtek	1"	CV	FO	Evaporator Salt Temperature Control and Cold Salt Fill	SGS Skid West Side South End
FCV-321	Valtek	2"	CV	FO	Main Salt Flow Control	SGS Skid South End
FCV-331	Fisher	1"	CV	FO	Steam Attemperator Temperature Control	SGS Skid North Side Steam Drum
FCV-341	Valtek	1"	CV	FC	Main Salt Fill	SGS Skid West Side Middle
FCV-351	Valtek	2"	CV	FO	Hot Salt Flow Control	Outside Pumphouse Northeast Corner
FCV-381	Kieley-Mueller	1"	SV	FC	Evaporator Salt Drain	SGS Skid West Side Middle
FCV-382	Kieley-Mueller	1"	SV	FC	Superheater Salt Drain	SGS Skid West Side Below Steam Drum
FCV-383	Dresser	4"	SV	FO	Evaporator Water Supply	SGS Skid Southeast Corner
FCV-384	Valtek	2"	SV	FO	Start-up Heater Supply	SGS Skid Below FCV-383

Table B-11

SGS INSTRUMENTATION

Identifier	Description	Control Module	Display Range	Alarm Levels High	Alarm Levels Low	Dimension	Sampling Period (sec)
	Feedwater						
PT-386	Pressure	PCM-3/ Bailey	0-1500	1500		PSI	5
TE-386	Temp	PCM-3/ Bailey	0-750	575	500	°F	10
	Steam Drum						
PT-383	Pressure	PCM-3/ Bailey	0-1500	1250	950	PSI	5
TE-383	Fluid temp	PCM-3/ Bailey	0-750	575	500	°F	10
LT-311	Fluid level	PCM-3/ Bailey	-17 to +23	4	-4	inch	2
	Evaporator						
TE-301	Salt inlet temp	PCM-3/ Bailey	0-1200	880	500	°F	2
TE-384	Salt outlet temp	PCM-3/ Bailey	0-1200	640	500	°F	2
PT-384	Salt outlet pressure	PCM-3/ Bailey	0-200			PSI	5
FT-321	Salt flow rate	PCM-3/ Bailey	0-100			KLB/hr	2

Table B-11

SGS INSTRUMENTATION

Identifier	Description	Control Module	Display Range	Alarm Levels High	Alarm Levels Low	Dimension	Sampling Period (sec)
	Superheater						
PT-382	Salt inlet pressure	PCM-3/ Bailey	0-200	100		PSI	5
TE-382	Salt inlet temp	PCM-3/ Bailey	0-1200	1070	500	°F	5
TE-331	Steam outlet temp	PCM-3 Bailey	0-1200		910	°F	2
FT-381	Attemperator steam flow	PCM-3/ Bailey	0-2500			lb/hr	5
FT-382	SGS Cold Salt Supply	PCM-3/ Bailey	0-16			KLB/hr	5
	Steam Delivery						
PT-321	Pressure	PCM-3/ Bailey	0-1500	1150	950	PSI	2
TE-332	Temp	PCM-3/ Bailey	0-1200	990	910	°F	2
FT-311	Flow rate	PCM-3/ Bailey	0-100	12.6	3.2	KLB/hr	2
TE-387	Hot Salt Pump Bearing	PCM-3	0-500	190		°F	10
TE-388	Start-up Heater 5 Element Temp	PCM-3/ Bailey	0-1200	1100	500	°F	10

Table B-12

SGS CONTROL LOOPS

Controlled Variable	Mode	Set Point	Controller Inputs	Controller Output
Steam delivery pressure	SGS start-up	1000 psig FCV-491	Delivery pressure (PT-321) pressure set point	FCV-491 position - SGS steam flow
	Boiler following	1100 psig SP. SP	Delivery pressure (PT-321) Pressure set point (SP. SP) Steam flow (FT-311) Salt flow (FT-321)	FCV-321 position - SGS main salt flow
Steam delivery temperature	Operation	950°F SP. ST	Delivery temperature (TE-332) Temperature set point (SP. ST)	FCV-331 position - Steam attemperator flow
Steam drum level	Operation	0 in SP. DL	Drum level (LT-311) Level set point (SP. DL) Feedwater flow (FT-411) Steam flow (FT-311)	FCV-411 position - Feedwater flow
Evaporator salt inlet temperature	Operation	850°F SP. EST	Inlet temperature (TE-301) Temperature set point (SP. EST)	FCV-301 position - Cold salt flow
Boiler water temperature	Diurnal Shutdown	~520°F	Circulation heater outlet temperature (TE-388)	Electric immersion heater elements on/off

Table B-13

HEAT REJECTION AND FEEDWATER SUBSYSTEM COMPONENTS

Component	Description	Function	Nominal Operating Condition
Feedwater heater	- Shell and coiled tube counterflow heat exchanger - 35 in ID 2.5 in thick carbon steel shell (feedwater) - 4 ft 8 in overall height - 30 coiled tubes 0.500 in. dia. 43 ft long (steam)	- Raise feedwater temperature to SGS inlet condition	- 950°F superheated steam inlet - 545°F saturated liquid outlet - 2150 lb/hr steam flow rate - 401°F feedwater inlet - 550°F feedwater outlet - 11,582 lb/hr feedwater flow rate - 0.59 MW heat transfer
Deaerator	- Horizontal tank - 5 ft ID - 12 ft long - Contains 15 submerged mixing nozzles, 1 overhead spray nozzle, 2 147-kW electric immersion heaters	- Degasify condensate - Heat condensate for delivery to feedwater heater - Provide alternate steam dump when turbine is not operating	- 401°F - 250 psi - 0.63 MW heat transfer
Spray water heat exchanger	- Shell and tube heat exchanger - 24 in. dia. shell	- Reject excess heat from deaerator when utilized as alternate steam dump	- No flow from deaerator during normal operation

Table B-13

HEAT REJECTION AND FEEDWATER SUBSYSTEM COMPONENTS

Component	Description	Function	Nominal Operating Condition
Feedwater pump	- High speed centrifugal type - 18,770 pump RPM - 150 HP driver	- Provide high pressure feedwater to the steam generator (through the feedwater heater)	- Inlet: 250 psi, 401°F water - 1450 psi head (mfg rating) - 60 GPM (mfg rating)
Spray water pump	- Vertical turbine type - 3 stage - 7-1/2 HP driver	- Provide circulation from deaerator to spray water heat exchanger and/or its bypass and return to deaerator overhead spray nozzle	- 401°F - 26 psi head (mfg rating) - 300 GPM (mfg rating)
Cooling water pump	- Centrifugal type - 40 HP driver	- Provide glycol/water circulation for spray water heat exchanger - cooling tower - condenser circuit	- 132°F glycol/water - 40 psi head - 1200 GPM
Cooling towers	- 6 units - Forced draft, finned-tube, glycol/water-to-air heat exchangers	- Reject waste heat to atmosphere	- 94°F air - 132°F glycol/water inlet - 120°F glycol/water outlet - 2.4 MW heat rejection

Table B-14

HRFS REMOTE OPERATED VALVES

VALVE	MANUFACTURER	SIZE	TYPE	FAIL POSITION	FUNCTION	LOCATION
FCV-401	Fisher	2"	CV	FO	Feedwater Pump Pressure Control	Southwest of Deaerator
FCV-411	Kieley-Mueller	2"	CV	FC	Feedwater Flow Control	SGS Skid Northeast
FCV-421	Kieley-Mueller	2"	CV	FO	Feedwater Heater Temperature Control	Above Feedwater Heater
FCV-431	Kieley-Mueller	2"	CV	FC	Main Steam Pressure Control	Southwest of Deaerator
FCV-432	Kieley-Mueller	3"-3 way	CV	To SWHX	Deaerator Pressure Control	Between Deaerator and Spray Water Heat Exchanger
FCV-471	Valtek	1"	CV	FC	Condensate Control to Deaerator	Above North Door to Spray Water Pump Room
FCV-483	Atkomatic	1"	SV	--	Deaerator Vent Block	Above Deaerator
FCV-484	Atkomatic	1/4"	SV	--	Deaerator Vent Bypass	Above Deaerator
FCV-485	ASCO	2"	SV	--	Demineralized Water Storage Tank Fill	Above Culligan Beds
FCV-491	Kieley-Mueller	2"	CV	FC	SGS Steam Delivery Control During Start-Up	North End of SGS Skid

Table B-15

HRFS INSTRUMENTATION

IDENTIFIER	DESCRIPTION	CONTROL MODULE	DISPLAY RANGE	ALARM LEVELS		DIMENSION	SAMPLING PERIOD (sec)
				HIGH	LOW		
	Main Steam						
PT-431	Pressure	PCM 2	0-1500	1200	900	PSI	2
TE-483	Temp	PCM 2	0-1200	990	850	Inch	10
	Deaerator						
PT-432	Pressure	PCM 2	0-400	250	200	PSI	2
TE-451	Fluid Temp	PCM 2	0-500	400	300	°F	2
TE-481	Steam Temp	PCM 2	0-500	400	300	°F	10
LT-471	Fluid Level	PCM 2	0-30	30	10	Inch	2
	Spray Water						
PT-482	Pressure	PCM 2	0-400	300	200	PSI	5
FT-482	Flow Rate	PCM 2	0-160			KLB/hr	5
TE-482	Temp	PCM 2	0-500	445		°F	10
FT-481	Feed/Spray Water Flow Rate	PCM 2	0-160			KLB/hr	5
	Feedwater						
PT-481	FWP Supply Pressure	PCM 2	0-400		170	PSI	5
PT-401	FWP Discharge Pressure	PCM 2	0-1500	1400	900	PSI	2
PT-484	FWP Coolant Pressure	PCM 2	0-100			PSI	5
PT-483	FWH Outlet Pressure	PCM 2	0-1500	1230	1180	PSI	5
FT-411	Flow Rate	PCM 2/	0-160 Bailey			KLB/hr	2
FT-421	FWH Outlet Temp	PCM 2	0-750	600	400	°F	2
	Cooling Water						
TE-484	SWHX Inlet Temp	PCM 2	0-500	130		°F	10
TE-486	Tower Outlet Temp	PCM 2/	0-500	110	32	°F	10

Table B-16

HRFS CONTROL LOOPS

Controlled Variable	Mode	Set Point	Controller Inputs	Controller Output
Feedwater temp.	Operation	540°F FCV-421	Feedwater temperature (TE-421) Temperature set point	FCV-421 position - Feedwater heater Steam supply flow
Feedwater pressure	Operation	1250 psig FCV-401	Feedwater pressure (PT-401) Pressure set point	FCV-401 position - FWP recirculation flow
Steam delivery pressure	Manual salt flow GSTAT off	1080 psig PT-431	Delivery pressure (PT-431) Pressure set point	FCV-431 position - Deaerator steam dump
Deaerator pressure	Operation - Desuperheating GSTAT off	233 psig PT-432	Deaerator pressure (PT-432) Pressure set point	FCV-432 position - Deaerator dump to SWMX
	Boiler following GSTAT on	233 psig PT-432	Deaerator pressure (PT-432) Pressure set point	FCV-431 position - Deaerator steam supply
Deaerator temp.	Start-up	390°F DTC 451 DTC 452	Deaerator temperature (TE-451) Temperature set point	DTC-451/452 on/off - Electric heater control
Deaerator level	Operation	15 in FY-472 (14 in backup during turbine operation)	Deaerator level (LT-471) Level set point	FY-472 condensate - Makeup pump stroke position
	Turbine Operation	15 in FCV-471	Deaerator level (LT-471) Level set point	FCV-471 position - Turbine condensate return from hot well

Table B-17

ELECTRIC POWER GENERATION SUBSYSTEM COMPONENTS

Component	Description	Function	Nominal Operating Condition
Turbine	- Axial flow condensing type - 7 stage	- Expand steam to drive electric generator	- 940°F 1050 psig throttle steam - 133°F 2.5 psia exhaust steam - 7800 lb/hr steam flow - 17,443 RPM - 1000 HP
Electric generator	- AC generator - 450 volt, 3 phase - 1200 RPM - Solid state excitor	- Generate electric power	- 750 kW_e (rating) - 600 kW_e (maximum in MSEE) - 0.8 power factor rating
Condenser	- Crossflow shell and tube heat exchanger - Rectangular shell (condensate) - 438 tubes, 5/8-in. dia. 7-1/2 ft long (glycol/water coolant) - Cylindrical hot well	- Condense turbine exhaust steam - Provide turbine exhaust vacuum	- 2.5 psia saturated steam inlet - 133°F condensate outlet - 7800 lb/hr steam/water flow - 1200 GPM glycol/water coolant flow
Condensate pump	- Turbine type - 2 stage - 20 HP driver	- Pump condensate from hot well to deaerator	- 133°F water - 260 psi head (mfg rating) - 18 GPM (mfg rating)

Table B-17

ELECTRIC POWER GENERATION SUBSYSTEM COMPONENTS

Component	Description	Function	Nominal Operating Condition
Air exhaust pump	- Nash vacuum pump - 5 HP driver	- Provide condenser vacuum	- 5 in Hg condenser pressure (ABS) - 75 CFM (mfg. rating)
Electric oil pump	- Viking gear pump	- Provide bearing oil pressure during turbine start-up and shutdown	- Off during operation (Turbine driven pump provides oil pressure)
Cooling tower pump	-Aurora centrifugal pump	- Provide coolant circulation through oil cooler	- 35 psi head (mfg. rating) - 120 GPM (mfg. rating)
Wet cooling tower	-Fan forced wet cooler -1/2 HP fan motor	- Reject oil coolant heat	- 110°F coolant outlet temp

Table B-18

EPGS REMOTE OPERATED VALVES

VALVES	MANUFACTURER	SIZE	TYPE	FAIL POSITION	FUNCTION	LOCATION
FCV-501	Valtek	2"	SV	FC	Turbine Steam Isolation	TWR Level 80 North Turbine Northeast Corner
FCV-511	Asco	1/2"	SV	FC	Hotwell Overflow	TWR Level 60 North Condenser Platform Northwest
FCV-512	Asco	3/4"	SV	FC	Hotwell Make-up	TWR Level 80 Northeast Condensate Storage Tank
FCV-521	Masoneilan	2"	CV	FO	Oil Cooler Water Flow Control	TWR Level 80 North Turbine/Generator Overhead
FCV-541	Asco	3/4"	SV	FC	Condenser Storage Tank Make-up	TWR Level 80 Northeast Condensate Storage Tank
FCV-551	Asco	1/2"	SV	FC	Condenser Recirculation	TWR Level 60 North Condenser Platform Northwest
TVM	GE w/auma Actuator	1 1/2"	CV	FC	Turbine Steam Supply Throttle	Turbine North Side
SNM	GE	--	CV	--	Turbine Sync Speed Control	Turbine Center
Fcv-561	ASCO	1/2"	SV	FO	Close throttle valve in emergency trip (dumps hydraulic oil)	Turbine

Table B-19

EPGS INSTRUMENTATION

IDENTIFIER	DESCRIPTION	CONTROL MODULE	DISPLAY RANGE	ALARM LEVELS HIGH	ALARM LEVELS LOW	DIMENSION	SAMPLING PERIOD (sec)
	Turbine						
PT-581	Steam Supply Pressure	PCM 2	0-1500		800	PSI	5
PT-582	Steam Seal Pressure	PCM 2	0-1500			PSI	5
TT-583	Steam Supply Temp	PCM 2	0-1200	990	800	°F	5
TT-501	Outboard Bearing Oil Temp	PCM 2	0-500	170	110	°F	5
TT-502	Inboard Bearing Oil Temp	PCM 2	0-500	170	110	°F	5
TE-503	Gear Outboard Bearing Oil Temp	PCM 2	0-500	170	110	°F	5
AZT-581	Vibration	PCM 2	0-100 (0-5g)	100		PCT	5
	Generator						
JT-581	Power	PCM 2	0-960			kw	5
ET-581	Voltage	PCM 2	0-600	480	450	Volt	5
IT-581	Current	PCM 2	0-1200			Amp	5
PFT-581	Power Factor	PCM 2	0-1.0	1.0	0.85	PCT	5
VT-581	VARS	PCM 2	0-960			KVA	5
ST-582	Speed	PCM 2	0-1500	1270		rpm	5
ST-581	Frequency	PCM 2	0-100 (55-65 HZ)	60	40	PCT	5
TT-510	Stator Winding 1 Temp	PCM 2	0-500	260		°F	5
TT-511	Stator Winding 2 Temp	PCM 2	0-500	260		°F	5
TT-512	Stator Winding 3 Temp	PCM 2	0-500	260		°F	5
TT-513	Stator Winding 4 Temp	PCM 2	0-500	260		°F	5
TT-514	Stator Winding 5 Temp	PCM 2	0-500	260		°F	5
TT-515	Stator Winding 6 Temp	PCM 2	0-500	260		°F	5
TE-508	Cooling Air Outlet Temp	PCM 2	0-500	100		°F	5
TT-507	Outboard Beearing Oil	PCM 2	0-500	170	110	°F	5
TE-505	Gear Outboard Bearing Oil Temp	PCM 2	0-500	170	110	°F	5
TE-506	Gear Inboard Bearing Oil Temp	PCM 2	0-500	170	110	°F	5
PT-502	Condenser Pressure	PCM 2	0-30	15		In Hg	5
PT-583	Condensate Pump Discharge Pressure	PCM 2	0-400	300	240	PSI	5
LT-511	Hot Well Level	PCM 2	0-15	16	8	Inch	2
TE-582	Cooling Tower Pump Discharge Temp	PCM 2	0-500	100	40	°F	5
PT-531	Oil Pump Discharge Pressure	PDM 2	0-200	100	55	PSI	5
TT-521	Bearing Oil Supply Temp	PCM 2	0-500	140	100	°F	2
PT-501	Bearing Oil Supply Press.	PCM 2	0-50	40	10	PSI	5

Table B-20

EPGS CONTROL LOOPS

Controlled Variable	Mode	Set Point	Controller Inputs	Controller Output
Condenser hot well level	Remote operation (TCP. MS on) (EN.HLC on)	9 in min 14 in max	Hot well level (LT-511)	FCV-512 open/close - makeup FCV-511 open/close - dump
Condensate storage tank level	Operation	12 in min 30 in max	Storage tank level (LS-541)	FCV-541 open/close - supply from cycle fill pump FCV-542 open/close - CMUP Stand pipe air overpressure
Turbine/generator oil temperature	Remote operation	125°F FCV-521	Oil temperature (TT-521)	FCV-521 position - cooling water flow

APPENDIX C

ENGINEERING TESTS/TRAINING

This testing was started on June 13, 1984, and completed December 21, 1984. These tests are grouped into four categories.

Part A tests were used to generate the test data to be used to evaluate performance and functional capability of the MSEE.

Part B contained training tests which were used to train utility operator teams.

Part C contained those tests that were performed to evaluate the routine operation of MSEE as a utility power plant. They were used to produce extended performance information using the operating strategy developed in Part A tests. These tests were conducted by the utility operator teams.

Part D tests were conducted throughout by Olin Chemical Group to obtain data on salt properties, stability, and corrosion. These engineering/training tests are listed below:

Part A - MSEE Characterization
1 Receiver Loop Performance
2 Power Production Subsystems Performance
3 Transient Response of Receiver Loop
4 Overnight Thermal Conditioning of the Receiver
5 Overnight Hold Conditions for the Steam Generator
6 Development of Optimum Operating Strategy

Part B - Training Tests
7 Receiver Loop Cold Flow
8 Receiver Loop Operation
9 Receiver Operation with Simulated (slow cloud)
10 Thermal Storage Charging with Propane Heater
11 Steam Generator and HRFS Operation
12 Operation of Full Electric Loop (TSS through EPGS)

Part C - Operation as a Utility Power Plant

13 System Operation from Receiver
14 System Operation with Fossil Fuel

Part D - Salt Characteristics

15 Salt Properties and Stability
16 Salf Corrosion

The purpose for Test #1, Receiver Loop Performance, was to calibrate the receiver flow meter and receiver inlet and outlet thermocouples, run the receiver loop in cold flow conditions, and run the receiver at various power levels with TSS, SGS, and HRFS operating. The main objectives were to determine receiver thermal loss rates at two temperatures determine steady state performance for full and part load operation, and verify receiver subsystem controllability under full and part load conditions. The success criteria for this test was successful operation of the receiver throughout all tests, instruments to stay within calibration throughout test, and specified data collected and recorded.

The purpose for Test #2, Power Production Subsystems Performance, was to run the steam generator and turbine generator at full and partial loads. The main objectives were to determine steady state performance for full and partial load operation and to determine system responses and controllability at partial flow conditions. Success criteria were successful operation of the system at full and partial load, acceptable controls behavior, and collection and recording of specified data.

The purpose for Test #3, Transient Response of Receiver Loop, was to operate the receiver loop through progressively faster ramp increases in power. The main objectives were to develop a map of system response to flux transients, verify controls response to fast transients and adjust controllers if required, develop limits of some tracking through cloud passage, and to develop minimum receiver startup time. Success criteria were the successful determination of maximum transient capability of the receiver, data system operational throughout tests, and specified data recorded and controllability of receiver during flux transients.

The purpose for Test # 4, Overnight Thermal Conditioning of Filled Receiver, was to maintain filled receiver warm with the door closed by pulsing salt flow through the receiver from the cold surge tank and replenishing cold surge tank level when required with the salt pump. The main objective was to determine the most efficient operations to maintain the receiver in the field warm condition overnight. Success criteria were salt filled receiver maintained warm in a simulated overnight hold condition and specified data collected and recorded.

The purpose for Test # 5, Overnight Hold Conditions for SGS, was to hold the SGS warm and filled with salt in a diurnal shutdown condition. The main objective was to compare diurnal hold using salt for thermal input with the baseline electric heater. The success criteria was maintained warm diurnal shutdown condition for at least 6 hours using pulsed salt flow and collected specified data for comparison with baseline case.

The purpose for Test # 6, Optimum Strategy Development, was to operate full MSEE to collect maximum net energy within the operating constraints identified in the previous five tests. The main objectives were to develop operating strategies which maximize net power output and develop data to be used to specify requirements for plant configuration components and controls which would improve net plant output. The success criteria were developed optimum operating strategy and obtained data for improvement of plant output.

The purpose for Test # 7, Receiver Cold Flow, was to use warmup heliostats on the receiver and flow cold salt through the receiver back to the cold salt storage tank. The main objectives were to verify operation of receiver loop equipment, controls, and EPS, to confirm that surge tank provides emergency coolant to the receiver under all conditions, to confirm procedures to accomplish startup, shutdown, and emergency shutdown and to confirm operation and interfaces of data system. Success criteria were successful operation of equipment and controls, safe shutdown by EPS, and data system operational.

The purpose for Test # 8, Receiver Steady State Operation, was to focus heliostats on the receiver and heat salt from the cold tank through the receiver and return it to the hot salt storage tank. The main objectives were to verify operation of receiver loop equipment, controls, and EMCON alarms at related receiver outlet temperature, and to confirm automatic switchover of TSS storage tanks accepting receiver outlet flow. Success criteria were successful operation of equipment and controls, successful automatic switchover of cold salt tank flow into hot salt tank flow and confirmed functioning of receiver outlet temperature alarm.

The purpose of Test # 9, Receiver Operation with Simulated Slow Cloud, was during receiver loop operation, ramp heliostats off the receiver and back on. The main objectives were to verify system operation through simulated cloud passage and confirm control stability through transients. Success criteria were successful operation of equipment and maintains control stability through transient conditions.

The purpose of Test # 10, Thermal Storage Charging with Propane Heater, was to charge the hot salt tank with hot salt using the propane heater. The main objective was to verify operation of the propane heater loop to provide hot salt to TSS hot tank. Success criteria were successful operation of propane heater and controls, salt flow from cold tank through heater to hot tank, and data system operational.

The purpose for Test # 11, Steam Generator and HRFS Steady State Operations, was to use hot salt from TSS hot tank to generate steam using SGS and reject heat through HRFS. The main objectives were to verify operation of SGS using hot salt from TSS, verify operation of HRFS, to provide feedwater to SGS, and to reject heat, to verify controls of these operations, to verify that EPS functions and safes the system, to confirm procedures to accomplish startup, shutdown, and emergency shutdown, and to confirm operation and interfaces of data system. Success criteria were successful operation of equipment and controls, safe shutdown by EPS and data system operational.

The purpose for Test # 12, Operation of Full Electric Loop, was to use hot salt from TSS to generate steam and flow steam through EGPS at various loads to generate electricity. The main objectives were to verify operation of turbine using steam from SGS, heat rejection through HRFS, and all auxiliary circuits, to verify synchronization of turbine generator with utility grid, to confirm procedures for all operations including emergency shutdown, and to confirm operation at 110% of rated output. Success criteria were successful operation of equipment and control, and data system operational.

The purpose for Test # 13, System Steady State Operation Using Receiver, was with all subsystems operational and integrated, use full heliostat field to develop rated power in the receiver and use this hot salt to produce electricity. The main objectives were to confirm operation of full system to normal startup, steady state and shutdown operations, to confirm subsystem interactions and interfaces, to verify MCS interlock automatic procedures, and to confirm utility type operations. Success criteria were successful operation of all subsystems and data system operational.

The purpose for Test # 14, Hybrid Operation Using Propane Heater, was with all subsystems operational and integrated except no insolation for the receiver, use the propane heater to generate hot salt to the hot tank and use this hot salt to produce electricity. The main objectives were to confirm operation of full system through normal startup, steady state, and shutdown operations, to confirm subsystem interactions and interfaces, and to verify MCS interlock automatic procedures. Success criteria were successful operation of all subsystems and data subsystem operational.

The purpose for Test # 15, Salt Properties and Stability, was during the MSEE, molten salt will be sampled and analyzed to determine if the composition of the molten salt has been altered. Both hot salt (900 to 1000°F) and cold salt (590°F) samples will be analyzed on a monthly basis. The main objectives were to determine if the salt composition has been altered, i.e., sodium-potassium ratio changed, to determine if new components are building up in the salt, i.e. corrosion products, and to determine if new components are being formed in the salt, i.e. carbonates and hydroxide. This test was performed by Olin Chemical.

The purpose for Test # 16, Salt Corrosion, was to place the corrosion loop in the salt loop to provide corrosion data of various metal alloys in molten salt service. The corrosion rates of the metal alloys with hot salt (900 to 1000°F) was tested. The main objectives were to determine the corrosion rate of various metal alloys in hot molten salt service, to determine the effects of thermal cycling on the corrosion rate of the metal alloys, and to determine the effects of the molten salt velocity on the corrosion rate of the metal alloys. This test was also performed by Olin Chemical.

APPENDIX D

EQUIPMENT PROTECTION SYSTEM TRIPS

The MSEE was equipped with an Emergency Protection Subsystem. This would safely shut down each subsystem (RS, SGS, EPGS, and MCS) and then require operator intervention to secure each subsystem. This appendix provides a listing of the emergency trips, the condition causing the trip, the instrument identifier and level of trip and the actions required to safely shut down each subsystem. The action required lists the actions taken by the EPS, process control computer, as well as actions required by the console operator.

Turbine-Generator Trips

Trips built into the turbine/generator are given on Table D-5. Definitions and guidelines are given below.

A. Definitions

1. Turbine Trip - Immediate turbine steam shutoff - manual or auto.
2. Turbine Shutdown - Gradual turbine steam shutoff - manual.
3. Generator Trip - Generator circuit breaker opened - manual or auto.

B. Steam reactions to trips

1. Anticipated - Steam control amintained manually or auto.
2. Upset - Reliance on auto steam control - SGS salt flow will stop and HRFS will attempt to desuperheat steam. Probable HRFS and SGS safety valve lifting if upset is uncontrolled.

C. Trip interlocks

1. A generator breaker trip always initiates a turbine SVC trip (auxiliary relay 32x closes FCV-501) and an EPST TR-586 (32x).

2. A generator breaker trip always initiates a turbine T.V. reset (auxiliary relay 32x resets T.V. closed) w/ZT-581 '0'% open.

3. A turbine T.V. reset and an EPS 2 & 3 reset will reopen FCV-501 unless manually closed (or tripped).

D. All auto trips should be carefully reviewed - determine the cause of the trip and correct the problem before resuming operations.

E. Fail-safe follow-through guidelines
These guidelines present items of concern to fail-safe the EPGS upon a major component failure, after a trip that did not function, or to back up an auto trip. Intimate familiarity with these guidelines is mandatory before EPGS operation to insure safe operation, both from a personnel and equipment standpoint.

1. Three items are of major concern to fail-safe the EPGS and MSEE operating systems:

   a. Steam over-pressurization

   b. Turbine trip

   c. Generator trip

Table D-1

EQUIPMENT PROTECTION SYSTEM RECEIVER SUBSYSTEM TRIPS

Trip Identifier	Trip Condition	Insrrument IdentiferR	Trip Level	Action Required
--	Operator Manual Trip	--	N/A	EPS - Defocus Heliostats
TR-181	Receiver Salt Outlet Temp High	TE-102A	1080°F	Operator - Control Receiver From The EMCON Console
TR-184	Receiver Tube Temp High During Hot Salt Production	TE-140A and TE-102A	925°F »750°F	
TR-187	Loss of Receiver Door Open Signal	ZSHDR	Contact Open	
TR-182	Boost Pump Pressure Low During Hot Salt Production	PT-180A and TE-102A	250 PSIG »750°F	EPS - Defocus Heliostats - Close FCV-151 After Time Delay
TR-183	Receiver Salt Inlet Pressure Low During Hot Salt Production	PT-181A and TE-102A	8 PSIG »750°F	Operator - Shutdown Receiver from EMCON Console
TR-185	Hot Surge Tank Level High	LT-161A or TE-184A	80 In 300°F	EPS - Defocus Heliostats - Close FCV-101 and FCV-102 After Time Delay Operator - Shutdown Receiver From EMCON Console

Table D-1

EQUIPMENT PROTECTION SYSTEM RECEIVER SUBSYSTEM TRIPS (Continued)

Trip Identifier	Trip Condition	Instrument Identifer	Trip Level	Action Required
TR-186	Boost Pump Sump Level High	TE-181A	400°F	EPS - Defocus Heliostats - Time Delay - Close FCV-151 - Turn Off Cold Salt Boost Pump EMCON (Automatic) - Maintain Control of Receiver and HRFS Operator - Shut Down the Plant From the EMCON Console
TR-281	Hot Salt Sump Level High	LT-221A or TE-231A	40 In 300°F	EPS - Close Sump Isolation Valve FCV-231 Operator - Allow Time for Hot Salt Pump Operations To Bring Sump Level Down - Shut down SGS, HRFS, and EPGS From EMCON Console
TR-282	Cold Salt Sump Level High	LT-201A or TE-211A	55 In 350°F	EPS - Close Sump Isolation Valve FCV-211 - Defocus Heliostats Operator - Allow Time for Cold Salt Pump Operations To Bring Sump Level Down - Shut down the Plant From The EMCON Console

Table D-2

EQUIPMENT PROTECTION SYSTEM SGS TRIPS

Trip Identifier	Trip Condition	Instrument Identifer	Trip Level	Action Required
TR-381	Steam Drum Level Low	LT-311A	-10 In	EPS - Close FCV-501 - Open Generator Circuit Breaker - Turn Off FWP (Drum Level High only) EMCON (Automatic) - Dump Steam To Deaerator - Maintain Control of HRFS Network 90 - Shut Off Salt Flow (Close FCV-301, 341, and 351) - Turn Off BWCP (Drum Level Low only) Operator - Shut Down SGS, HRFS, and EPGS From EMCON Console
TR-383	Steam Drum Level High and Water Hot	LT-311A and TE-383A	+17 In »250°F	
TR-382	Boiler Water Circulation Pump Failure	Motor Current Sensor	Off	EPS - Close FCV-501 - Open Generator Circuit Breaker EMCON (automatic) - Dump Steam to Deaerator - Maintain control of HRFS Network 90 - Shut Off Salt Flow (Close FCV-501, 341, and 351)

Table D-3

EQUIPMENT PROTECTION SYSTEM EPGS TRIPS

Trip Identifier	Trip Condition	Instrument Identifer	Trip Level	Action Required
				Operator - Shut down SGS, HRFS, and EPGS from EMCON console
	Turbine Overspeed	OST	1320 RPM Generator	EPS - Close FCV-501 Open Generator Circuit Breaker
	Turbine Back Pressure High	TBPT	5 PSIG	
TR-584	Generator Bearing Temp High	TS-501A	180°F	EMCON (Automatic) - Dump Steam to Deaerator - Maintain Control of HRFS
TR-585	Generator Cooling Air Temp High	TS-502A	122°F	Operator - Control System From EMCON Console - Reduce Steam Flow
TR-586	Generator Circuit Breaker Trip	-Manual - -Overcurrent -Ground Fault		Shut Down If Necessary
TR-587	Turbine Vibration High	AZT-581	5g	
TR-588	Steam Energy Low	TE-332 or PT-581A	750°F 770 PSI	
TR-583	Turbine Oil Pressure	PS-501A (LUBE) or PS-531A (HYDR)	6 PSI 50 PSI	
TR-582	Manual T/G Emergency Trip	Control Room PB	Operator Initiate	

Table D-4

EQUIPMENT PROTECTION SYSTEM MASTER CONTROL SUBSYSTEM TRIPS

Trip Condition	Action Required
PCM 1 Microcomputer Failure - Loss of Receiver Displays - Loss of Salt Auto Flow Control	EPS - Defocus Heliostats - Close FCV-151 After Time Delay
- Loss of Cold Surge Tank Auto Level Control	Operator - Control Receiver from PCM 1 - Drain Receiver If Necessary
PCM 2 Microcomputer Failure - Loss of HRFS and EPGS Displays - Loss of Feedback Control Loops	EPS - Turn Off Hot Salt Pump - Close FCV-301, FCV-341, and FCV-351 - Turn Off FWP - Close FCV-501 and FCV-491 After Steam Pressure Drops - Open Generator Circuit Breaker - Turn Off Condensate Pump
	Operator - Shut Down SGS From Console - Shut Down HRFS and EPGS From PCM 2
PCM 3 Microcomputer Failure - Loss of TSS Displays - Loss of Feedback Control Loops - Loss of SGS Displays	EPS - Defocus Heliostats - Time Delay - Close FCV-211 - Close FCV-231 - Turn Off Hot and Cold Salt Pumps - Turn Off Cold Salt Boost Pump - Close FCV-151 - Close FCV-501 - Open Generator Circuit Breaker
	EMCON (Automatic) - Dump Steam To Deaerator - Maintain Control of HRFS
	Network 90 (Automatic) - Interlocks Will Close FCV-301, FCV-341, and FCV-351
	Operator - Shut Down SGS From Network 90 Console - Shut Down Receiver, HRFS, and EPGS from EMCON Console

Table D-4

EQUIPMENT PROTECTION SYSTEM MASTER CONTROL SUBSYSTEM TRIPS (Continued)

Trip Condition	Action Required
Simultaneous Failure of PCM 1, 2, and 3 Microcomputers - Loss of All Subsystem Control	EPS - Defocus Heliostats - Time Delay - Close FCV-211 - Close FCV-231 - Turn Off Hot and Cold Salt Pumps - Turn Off Cold Salt Boost Pump - Close FCV-151 - Turn off FWP - Close FCV-501 and FCV-491 After Steam Pressure Drops - Open Generator Circuit Breaker - Turn Off Condensate Pump Operator - Shut Down the Subsystems From PCM 1, 2, and 3 and Network 90
CCM Microcomputer Failure - Loss of PCM/Host Computer Communication Lin - Loss of Console Displays - Loss of Console Control Capability - Loss of Sequencing Operations Involving More Than One PCM	
Operator Remote Manual Trip	
EMCON Host Computer Failure	PCMs and CCM Continue To Operate and Control The Plant Operator - Shut Down The Subsystems From PCM 1, 2, and 3

Table D-5

TURBINE-GENERATOR TRIP LIST

Mode	Description	Initiation
Manual	MGBT - Manual generator breaker trip	Breaker switch opened at local or remote generator control panel
Manual	ET - Emergency trip	ET "on" at EMCON console or local trip button actuated
Manual/auto	SVC - Stop valve closure	Close FCV-501
Manual/auto	OST - Overspeed trip	Local OST button
Manual	MTVC - Manual throttle valve closure	Close throttle valve (TVM)
Auto	GBT - Generator breaker trip	a. Reverse power b. Ground fault c. Overcurrent

Table D-5

2. Steam system reactions to turbine trips:
    a. Over-pressurization
    b. Possible HRFS/D-D & SGS/steam drum safety valve lifting
    c. Desuperheating by HRFS/FCV-431 switchover to steam control to dump steam to D/D
    d. FCV-432 D/D heat dump through SWHX and dry cooling tower
3. Turbine tripping is redundant-designed and may be fully utilized with these four trips:
    a. Actuate ET emergency trip FCV-561 (oil trip)
    b. Open generator breaker with breaker C.S. (electric trip)
    c. Actuate EPS T-G trip button from control room (EPS backup)
    d. Manually close throttle valve with hand wheel (manual)
4. Turbine-generator trip verification:
    a. ST-582 speed decreasing
    b. PT-532 hydraulic oil pressure decreasing (T.V. trip)
    c. PT-581 steam pressure drops to zero (FCV-501 trip)
    d. Generator breaker open - green light on

<u>NOTE</u>

EOP operation is not mandatory upon a turbine trip since the shaft driven oil pump provides adequate oil flow for turbine coast down.

5. Generator trips are redundant-designed with turbine trips. Be aware that:
    a. EPGS UPS provides emergency backup C/B trip power
    b. Exciter voltage shutdown local disconnect switch shuts down all of the generator electrical power.

APPENDIX E

SIMULATION OF ELECTRIC POWER AND COMPARISON TO ACTUAL PERFORMANCE

Prior to the April 1984 integrated system operation test campaign, the turbine-generator internal oil pump failed. Since the steam cycle performance of future plants can be accurately predicted and since the MSEE steam cycle performance was of limited significance, it was decided to continue with the test campaign using a simulated electric output rather than delaying the test program until the turbine-generator could be repaired. The turbine-generator operation earlier in the test program satisfied its primary objective of demonstrating complete compatibility with the steam generation subsystem operation.

The simulation of the electric output was based upon the actual steam generator thermal output. This output was calculated from the actual main steam and feedwater enthalpies and the main steam flow rate. By applying the appropriate heat rate to this thermal output, the simulated gross electric power output was determined.

The heat rates applied to the steam generator thermal output were derived from the actual performance of the Solar One steam cycle on June 21, 1984. The actual previously demonstrated MSEE heat rates were not used because of the extreme inefficiencies unique to the MSEE. The heat rates for the simulation were derived by adjusting the Solar One heat rates at various points on the load curve to determine the heat rate curve for MSEE (Figure 4-11). The heat rates were adjusted as in the following examples:

1. Temperature Correction. The MSEE operates nominally at 950 F main steam temperature compared to 835 F for Solar One at noon on June 21, 1984. From J. F. Lee "Theory and Design of Steam Gas Turbines," McGraw-Hill, 1954, an increase of 1 F in main steam temperature decreases the heat rate by 1.53 Btu/kWh. Applying this correction to the heat rate of 10,300 Btu/kWh exhibited by Solar One gives a value for MSEE of 10,120 Btu/kWh.

2. Pressure Correction. The MSEE operates nominally at 1100 psig compared to 1346 psig for Solar One at noon on June 21, 1984. From the reference used above, it can be inferred that for each 1 psi decrease in main steam pressure the heat rate increases by

0.625 Btu/kWh. Applying this correction to the heat rate determined in 1. above yields an MSEE heat rate of 10,270 Btu/kWh.

3. <u>Feedwater Temperature Correction.</u> The MSEE operates with a final feedwater temperature of nominally 520 F compared to 368 F for Solar One at noon on June 21, 1984. To correct for this temperature difference, it was assumed that the MSEE steam cycle was equipped with an additional feedwater heater, fed by main steam and using a pumped-forward drain system. This additional feedwater heater had the effect of reducing the flow of main steam available for the turbine-generator.

The heat rates to use for the MSEE were derived such that the load fraction from Solar One corresponded to the same fraction of rated load for the MSEE. The heat rates were also adjusted accordingly whenever off-rated steam temperatures or pressures existed.

The following table compares the actual steam cycle operation prior to the turbine-generator failure to the "improved" steam cycle derived from Solar One for the rated SGS output.

	Actual MSEE	"Improved" MSEE
Gross Cycle Heat Rate (Btu/kWh)	19,400	10,200
Generator Nameplate Gross (kW)	750	1,100
Steam Cycle Parasitics (kW)	332	109

The 750 kW actual nameplate gross generator output was never achieved in steady state due to the excessive thermal losses resulting from leaking valves in the heat rejection and feedwater subsystem and other inefficiencies. Various operating conditions are shown in Figure F-1. In comparison, a gross electric output of 1,100 kW would be achievable at the rated (and demonstrated) steam generator thermal output if the steam cycle utilized modern and properly operating equipment.

Comparing the steam cycle parasitics in the above table reveals the extreme load associated with the MSEE as designed. The actual steam cycle parasitic load consists of the following:

	Power (kW)
Cooling Water Pump	39.9
Spray Water Pump	8.5
Feedwater Pump	147.0
Condensate Make-up Pump	2.8
Cycle Fill Pump	1.5
Dry Cooling Tower Fans	93.0
Shunt Exciter	9.0
Condensate Pump	19.7
Air Exhaust Pump	4.4
Wet Cooling Tower Pump	5.2
Wet Cooling Tower Fan	0.8
Total	331.8

In contrast, an efficient steam cycle would have a parasitic load that is a fraction of that for the MSEE. The Solar One actual parasitic load was scaled down proportionally to arrive at the 109 kW used in calculating the simulated net electric output. The 109 kW also includes the scaled balance of plant parasitic load.

The 30 kW balance of plant parasitic load applied during the periods when the plant was at standby (see Section 4) was also derived by scaling actual Solar One values.

The steam cycle performance and its related parasitics loads are not a major source of uncertainty in the design and operation of future plants. Consequently, the simulation of its performance, excluding the steam generation subsystem, using reasonable performance factors results in a more meaningful representation of the MSEE. In all other areas of the system, only the actual demonstrated operation was used for its characterization.

Case

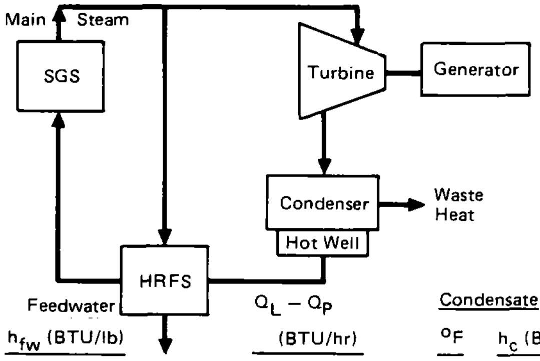
1. – As Tested
2. – No Leak Through Spray Water Diverting Valve
3. – Rated Conditions

Main Steam

	M_m (KB/hr)	PSIG	°F	h_m (BTU/lb)
1.	10.9	1000	965	1485
2.	10.9	1000	965	1485
3.	11.6	1100	950	1473

Throttle Steam

	M_m (KB/hr)	PSIG	°F	h_t (BTU/hr)
1.	6.20	870	930	1470
2.	7.60	870	930	1470
3.	7.80	1050	940	1469



Electric Output (KW)

1. 545
2. 640
3. 750

Feedwater

	°F	h_{fw} (BTU/lb)
1.	520	515
2.	520	515
3.	550	550

$Q_L - Q_P$

	(BTU/hr)
1.	1.79×10^6
2.	0.23×10^6
3.	–

Condensate

	°F	h_c (BTU/lb)
1.	110	78
2.	110	78
3.	133	101

Exhaust

	PSIA	°F
1.	1.96	146
2.	1.96	146
3.	2.46	133

Figure E-1. Steam Cycle Operating Conditions

APPENDIX F

INTEGRATED SYSTEM OPERATION DAILY OPERATING DATA

This appendix provides a listing of the key data for the 28 day integrated system test. Day 104 was April 14, 1985 (start of operation) and day 131 was May 11, 1985 (completion of operation). This data was obtained during a wide range of solar conditions which could be typical during operation of a commercial plant. The data starts with the available direct energy, to net electricity produced, to hours synchronized to the grid. Because of the turbine-generator failure, the electricity produced and the hours synchronized to the grid were simulated by a computer using actual steam conditions from the steam generator.

MSEE OPERATION SUMMARY

INTEGRATED SYSTEM OPERATION TEST CAMPAIGN

	Energy (MWh)								
Day	Direct Energy	Delivered to RS	Absorbed by Salt	In Storage Before Start-up	In Storage After Shutdown	Delivered to SGS	Added to Steam Cycle (After Sync)	Gross Electric	24-Hr Net
104	80.60	37.68	25.80	0.76	1.22	24.92	22.71	7.47	3.05
105	83.07	28.42	18.99	1.07	3.93	15.76	13.81	4.35	(0.10)
106	39.38	3.18	1.89	3.66	0.94	4.04	2.56	0.65	(2.82)
107	47.47	18.37	13.07	0.75	1.15	12.03	10.38	3.22	(0.70)
108	47.06	23.30	15.86	0.94	1.00	14.98	12.82	4.12	0.12
109	42.10	0	0	-	-	0	0	0	(2.80)
110	75.17	42.77	28.78	0.55	1.43	27.43	25.02	8.22	3.79
111	0	0	0	1.11	-	0	0	0	(2.80)
112	6.88	0	0	-	-	0	0	0	(2.80)
113	89.03	23.14	15.08	0.38	3.00	11.78	10.64	3.45	(0.66)
114	81.26	46.48	30.31	2.64	1.23	31.60	29.44	9.69	5.36
115	37.35	16.13	9.96	0.96	1.38	8.78	6.88	2.21	(1.86)
116	14.04	2.71	1.25	1.12	1.87	0	0	0	(2.80)
117	26.04	0	0	-	1.54	0	0	0	(2.80)
118	0	0	0	1.37	-	0	0	0	(2.80)
119	29.06	4.44	2.49	1.02	3.23	0	0	0	(3.10)
120	83.64	41.54	26.51	2.92	3.10	26.17	24.66	8.02	3.63
121	61.16	24.42	15.92	2.73	1.00	17.48	16.45	5.37	1.43
122	50.70	24.99	15.94	0.81	4.46	11.34	10.21	3.28	(0.64)
123	78.03	42.76	28.20	4.22	1.48	31.08	29.38	9.59	4.91
124	47.28	4.01	2.54	1.30	3.54	0	0	0	(3.00)
125	62.63	28.97	18.81	3.25	1.12	20.26	19.44	6.30	2.18
126	72.67	38.20	24.10	0.91	4.04	20.39	19.23	6.22	1.91
127	59.87	25.36	15.26	3.76	1.68	16.77	15.38	4.84	0.67
128	83.34	44.02	29.63	1.48	0.84	29.91	28.67	9.32	4.58
129	34.30	18.55	10.96	0.71	1.79	9.18	8.13	2.61	(1.26)
130	59.40	26.97	16.50	1.50	3.97	12.92	11.85	3.85	0.45
131	88.32	38.89	24.69	3.64	1.51	26.34	24.03	7.75	3.26
Month Total	1479.85	605.30	392.54			373.16	341.69	110.53	

MSEE OPERATION SUMMARY

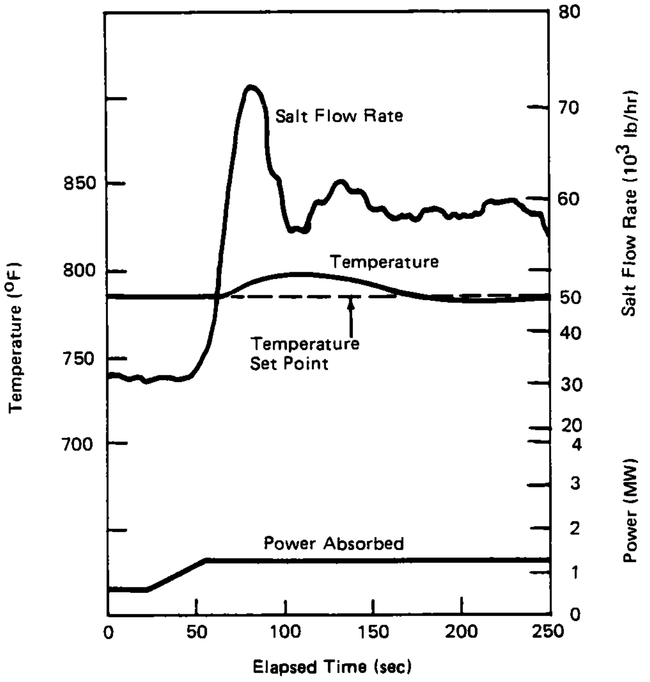
INTEGRATED SYSTEM OPERATION TEST CAMPAIGN

	Hours							
Day	Daylight	> 400 W/m^2 Insolation	RS Salt Flow	RS Outlet > 900 F	All Heliostats Targeted	Any Heliostats Targeted	Steam Production	Connected To Grid (Simulated)
104	12.85	11.83	8.70	7.70	6.80	8.23	8.70	8.22
105	12.89	11.38	8.53	6.63	5.05	7.37	6.87	6.55
106	12.93	5.60	2.18	0.73	0.97	1.06	3.09	2.65
107	12.96	7.93	7.10	3.97	3.78	5.77	5.52	5.18
108	13.00	6.68	6.97	4.65	5.01	6.38	5.95	5.28
109	13.03	5.68	0	0	0	0	0	0
110	13.07	10.38	9.50	8.95	8.57	9.37	9.54	9.08
111	13.10	0	0	0	0	0	0	0
112	13.14	.93	0	0	0	0	0	0
113	13.17	11.75	5.60	4.81	1.77	4.99	4.37	4.13
114	13.20	10.95	9.88	9.66	9.68	9.88	10.80	10.57
115	13.24	5.73	8.56	3.11	6.10	6.33	2.78	2.55
116	13.27	2.34	4.35	0.28	2.11	2.47	0	0
117	13.30	3.78	0	0	0	0	0	0
118	13.34	0	0	0	0	0	0	0
119	13.37	4.32	2.62	1.15	1.22	1.53	0	0
120	13.40	11.96	9.05	8.82	8.85	8.97	9.69	9.38
121	13.43	8.99	6.58	4.75	5.55	5.68	6.34	6.07
122	13.47	7.83	7.58	5.38	5.73	7.05	4.55	4.18
123	13.50	11.68	10.48	9.75	10.62	10.65	11.19	10.87
124	13.53	7.55	1.70	0.93	0.95	0.98	0	0
125	13.56	8.65	7.53	6.23	6.20	6.67	7.79	7.48
126	13.59	10.80	9.52	8.47	8.97	9.23	7.87	7.50
127	13.62	9.47	8.27	6.07	7.68	8.42	7.24	6.67
128	13.65	11.36	11.70	9.36	11.35	11.46	11.05	10.78
129	13.68	4.97	7.76	3.83	5.73	6.08	3.78	3.33
130	13.71	9.40	6.27	5.68	5.97	6.07	4.79	4.55
131	13.73	12.36	8.66	7.95	8.33	8.38	10.19	9.67
Month Total	372.91	212.59	169.09	128.86	136.99	153.02	142.10	134.69

APPENDIX G

ADDITIONAL RECEIVER TRANSIENT RESPONSE TESTS

Figures G-1 through G-5 show the receiver transient response to additional simulated cloud passage tests (see Section 4). Included in these figures are the power level, the temperature setpoint, the salt flow rate, and the outlet temperature. The temperature and flow rate instrumentation were slightly different for the various cases. For Figures G-1 through G-3, the temperature plotted was the slower responding back tube temperature near the receiver outlet. In figures after G-3, the faster responding thermocouple probe at the receiver outlet was used to measure the temperature. The flow rate instrumentation differed in that the flow rate plotted in Figures G-1 through G-3 was measured by the wedge type flow meter FT-101 and, upon the failure of the flow meter, the flow rate for subsequent tests was based on the receiver inlet pressure. The pressure versus flow rate relationship was developed by measuring the rate of change in the cold sump level while it was isolated from the storage tank.



Day 179

Start Time
13:47:55

Temperature
Set Point

785°F

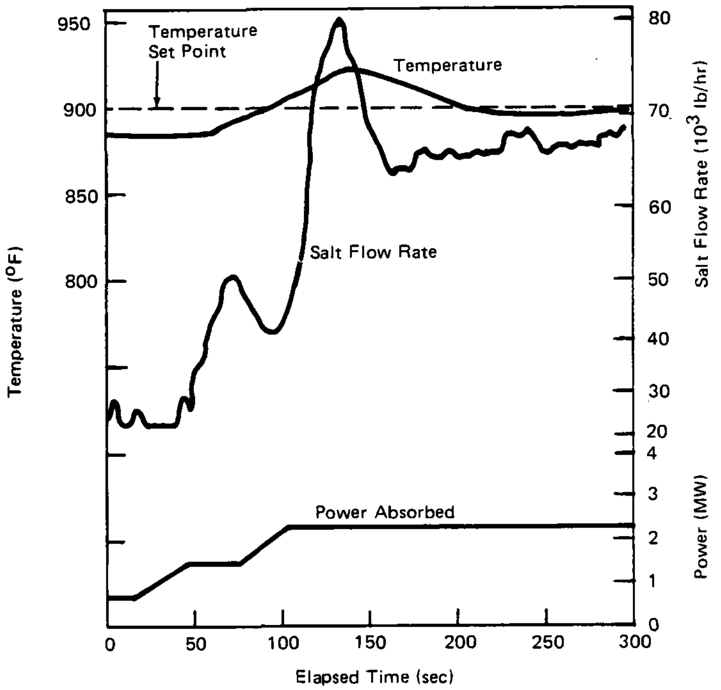
Heliostats on
Target

Initial – 25%

Final – 50%

Steps – 1

Figure G-1. Receiver Transient Response - Simulated Cloud Passage



Day 180

Start Time
13:22:30

Temperature
Set Point

900°F

Heliostats on
Target

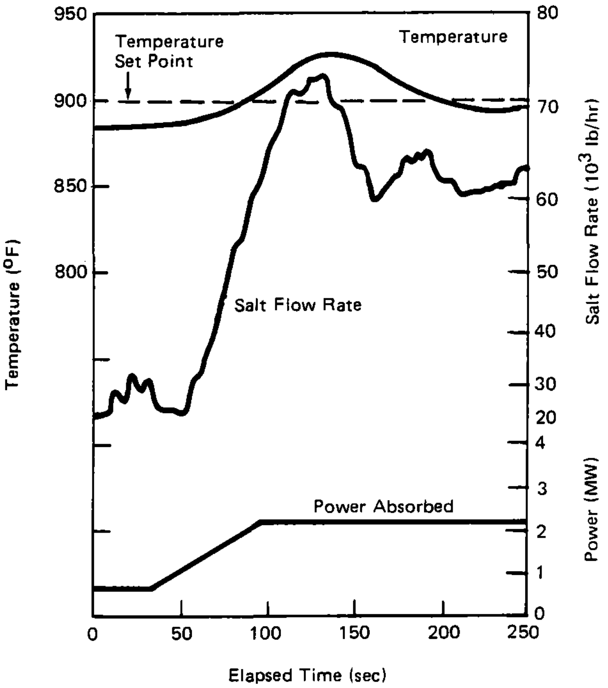
Initial – 25%

Final – 75%

Steps – 2

Increment – 60 sec

Figure G-2. Receiver Transient Response - Simulated Cloud Passage



Day 180

Start Time
14:15:50

Temperature
Set Point
900°F

Heliostats on Target
Initial – 25%
Final – 75%
Steps – 1

Figure G-3. Receiver Transient Response - Simulated Cloud Passage

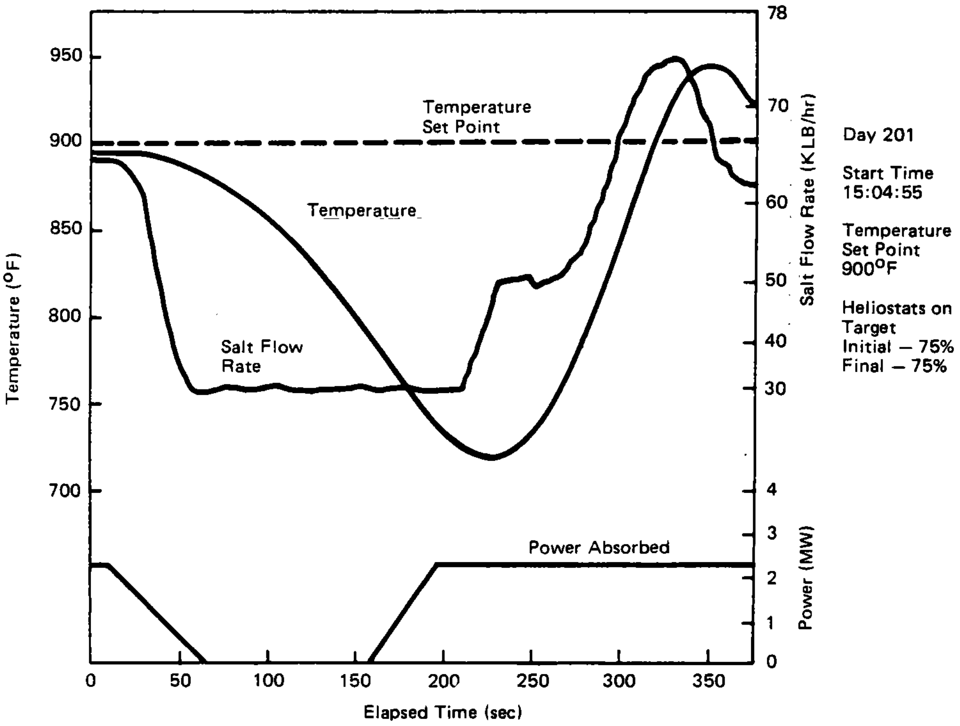


Figure G-4. Receiver Transient Response - Simulated Cloud Passage

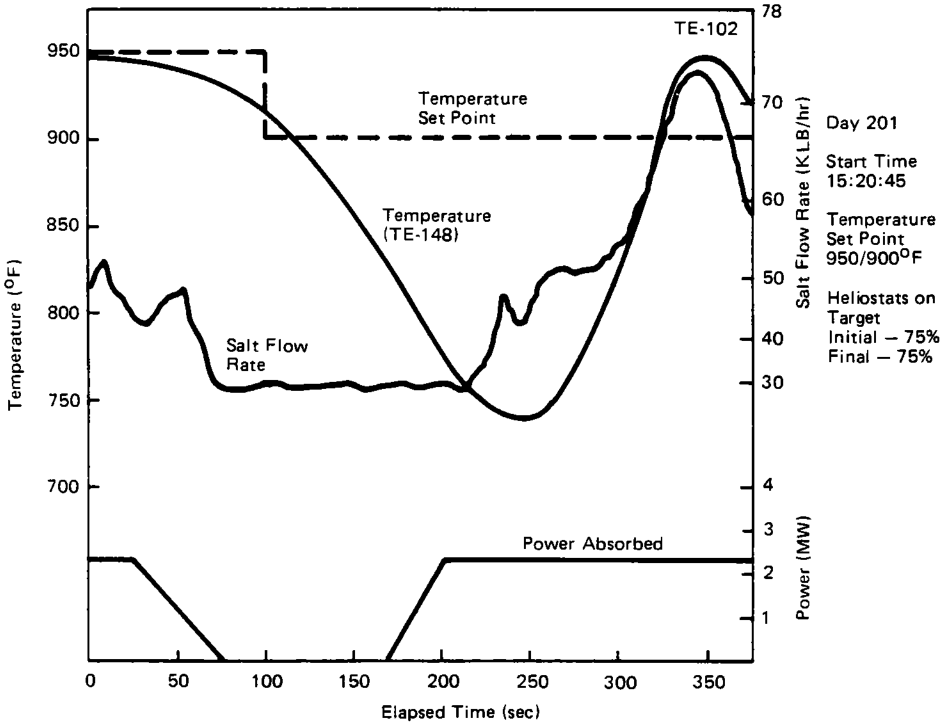


Figure G-5. Receiver Transient Response - Simulated Cloud Passage

APPENDIX H

OPERATOR TRAINING PROGRAM

PROGRAM SCHEDULE AND PARTICIPANTS

The training began in early August 1984 with a trial team made up of solar industry personnel. The purpose of the trial team was to critique the training methods and materials. The course was then partially reorganized, based on the feedback obtained, to enhance the effectiveness of the training program. The training program continued through early December 1984.

The schedule and participants for the training program was as follows:

- Trial Team (August 6-17)
  - Ed Bialkin, Foster Wheeler
  - Gerry Coleman, MDAC
  - Richard Cummings, EPRI Consultant
  - Chuck Lopez, SCE
  - John Swank, B&W
- PNM Team (September 4-21)
  - Dave Lister
  - Mike Napoleone
  - Dick Thayer
  - Earl Williams
- APS Team (September 24 - October 12)
  - Joe Gunner
  - Jim Mitchell
  - Charles Dyer
- PG&E Team (October 15 - November 2)
  - Fenwick Hill
  - William Pink
  - George Nichols
- Composite Team 1 (November 5 - November 16)
  - Robert Dawkins, Georgia Power
  - Carlos Venegas, IEE Mexico
- Composite Team 2 (November 26 - December 6)
  - Fred Krause, Georgia Power
  - Phil Reed, B&W
  - John Harder, B&V

The following was a typical three week schedule for the training program.

WEEK #1

Monday -- Orientation and Master Control Subsystem

8:00	Introduction -- Conference Room
9:00	CRTF Projects Review and Safety Briefing -- Conference Room
9:30	Break
9:45	MSEE System Overview -- Conference Room
10:00	Tour of MSEE -- Field and Control Room
11:30	Discussion and Questions -- Conference Room
12:00	Master Control Subsystem -- Conference Room
1:00	Console Operation -- Control Room
4:00	Complete

Tuesday -- Receiver and Thermal Storage Subsystems

8:00	Subsystem Description -- Conference Room
9:00	Tour of Receiver and Thermal Storage Subsystems -- Tower and Field
10:00	Control Loops and Instrumentation -- Conference Room
11:00	Operation, Alarms and Trips -- Conference Room
12:00	Console Instruction -- Control Room
2:00	Training - Receiver Loop Operation -- Conference Room
	Check Lists
	Procedures
4:00	Complete

Wednesday -- Receiver Operations

8:00 Training - Receiver Loop Operation -- Conference Room
Receiver Start-up Using Simulation -- Control Room
11:00 Test on Receiver Loop Start-up and Operation -- Conference Room
12:00 Receiver Cold Flow -- Control Room
4:00 Complete

Thursday -- Receiver Operation

8:00 Receiver Steady State Operation
4:00 Complete

Friday -- Receiver Loop Operation

8:00 Receiver Cold Flow -- Control Room
10:00 Receiver Operation with Simulated Clouds
Control Room
4:00 Complete

WEEK #2

Monday -- Steam Generation Subsystem

8:00 Subsystem Description -- Conference Room
9:00 Tour of Steam Generator and HRFS Subsystems -- Field
10:00 Control Loops and Instrumentation -- Conference Room
11:00 Operation and Equipment Protection System Trips -- Conference Room
12:00 Console Instruction (individually in Control Room

2:00 Training - Steam Generator Operation -- Conference Room

Check Lists
Procedures
4:00 Complete

Tuesday -- Steam Generator Operation

8:00	Training -- Steam Generator Operation -- Conference Room
11:00	Test on Steam Generator Start-up and Operation -- Conference Room
12:00	Steam Generation Operation -- Control Room
4:00	Complete

Wednesday -- Charge Thermal Storage with Propane Heater, Operate Steam Generator

8:00	Thermal Storage Charging with Propane Heater -- Control Room
12:00	Steam Generator Operation -- Control Room
4:00	Complete

Thursday -- Electric Power Generator Subsystem

8:00	Subsystem Description -- Conference Room
9:00	Tour of EPGS and HRFS -- Field
10:00	Control Loops and Instrumentation -- Conference Room
11:00	Operation and Trips -- Conference Room
12:00	Training - EPGS Operation - Conference Room
4:00	Complete

Friday -- Operation of EPGS

8:00	Operation of Full Electric Loop -- Control Room and field Teams will rotate between Control Room and Turbine Room in A.M. and P.M.
4:00	Complete

WEEK #3

Monday -- System Operation

8:00	Discussion of System Operation -- Conference Room
10:00	System Steady State Operation -- Control Room and field Rotate groups between locations
4:00	Complete

Tuesday -- System Operation

8:00	System Steady State Operation EPGS Steady State Performance Rotate groups between Control Room and field
4:00	Complete

Wednesday -- System Operation

8:00	System Steady State Operation EPGS Steady State Performance Rotate groups between Control Room and field
4:00	Complete

Thursday -- System Operation and Debriefing

8:00	System Steady State Operation -- Control Room and field
12:00	Debriefing -- Conference Room
2:00	Briefing on Solar One
4:00	Complete

Friday -- Tour of Solar One

System Operation

Controls

APPENDIX I

TRAINING PROGRAM EVALUATION

Materials Provided	Strongly Agree	Agree	Disagree	Strongly Disagree
The materials supplied in advance of class provided a useful introduction to the MSEE.	7	4		
The materials accurately described the MSEE system.	6	5		
The materials matched the system's actual operation.	5	6		
The materials were useful throughout the training.	8	3		
I intend to keep the materials and expect them to be a useful reference in the future.	9	2		
Instructor Performance				
The instructor was knowledgable in all areas covered	11			
The instructor was well prepared for the classes.	11			
The instructor matched the pace of the course to the needs of the students.	8	3		
The instructor was available to answer questions whenever required.	11			
The instruction was effective in accomplishing the training goals.	10	1		
Student Performance				
I was able to participate meaningfully in classroom sessions, console exercises and system operation.	7	4		
I understand the design and operation of the MSEE reasonably well.	7	4		
I feel qualified to operate the MSEE.	3	8		

	Strongly Agree	Agree	Disagree	Strongly Disagree
I would feel qualified to operate other plants with digital controls following a similar training program.	4	7		
I think this training program will be useful in my career.	8	3		

Organization of Training Course	Send Less Time	About Same Time	Spend More Time
Classroom sessions on individual subsystem		10	1
Field tours for subsystem familiarization		7	4
Console training exercises		8	3
Organized reviews of operating procedures and check lists		10	1
Self study of operating procedures and check lists	1	8	2
Tests on subsystem operation		11	
Subsystem operation from the console		5	6
Subsystem check lists and operation in the field		7	4
Subsystem data analysis exercises		9	
Full system operation		1	10

Suggestions for Improvement

How would you change the training program?

a) The advance materials supplied
   -- No changes

b) The classroom sessions
   -- No changes

c) The console sessions
   -- More explanation why equipment in configured as is.

d) The actual subsystem and system operation
   -- More time for system operations.

The trainees evaluated the training course favorably in all areas. The overall curriculum and methodology was judged appropriate for the utility operators: however, a four week course would have been preferable over the three week course in order to improve the operators proficiency. Industry personnel, such as engineers or designers, whose objective would not be proficient console operation but rather to evaluate the system could be effectively exposed to the system in a three to five day course. The training material required for an accelerated course for engineers and designers is available and would only have to be condensed and organized to meet the specific needs of such a course.

System Design and Operation

The composite response of the utility operators to the written evaluation questions pertaining to the subsystem design and operation was as follows.

System Performance	Strongly Agree	Agree	Disagree	Strongly Disagree
The system as a whole performed well.	4	6		
The following subsystems performed well:				
a) Receiver	7	3		
b) Thermal storage	7	3		
c) Steam generator	6	4		
d) HRFS	5	4	1	
e) EPGS	6	4		
f) Master Control	5	4		

How would you change the system design?

a) The receiver subsystem
  - -- Improve trace heaters
  - -- Complete wind shielding
  - -- Add More local instrumentation

b) Thermal storage
  - -- Improve trace heaters
  - -- Increase storage capacity
  - -- Add more instrumentation

c) The steam generator
  - -- Improve maintenance accessibility
  - -- Increase steam drum size
  - -- Provide continued blowdown capability for steam drum

d) HRFS
  - -- Improve water treatment
  - -- Use wet cooling towers

e) EPGS
  - -- No changes identified

f) Master Control
  - -- Add at least 2 more control consoles
  - -- Change alphabet keyboard to typewriter layout

How would you change system operation?

a) The receiver loop
  - -- No significant changes identified

b) The Steam Generator
  - -- No significant changes identified

c) Electric Power Generation
  - -- No significant changes identified

How does the operation of MSEE compare with the operation of a conventional fossil power plant?

-- MSEE has less redundancy

Do you think that molten salt is a preferred candidate for a solar power plant? Explain

-- Yes because of storage capability

The general response was positive regarding the system design and operation. The single less favorable response to the heat rejection and feedwater system performance was only because of the leakage through the three-way spray water diverting valve.

Digital Control System

The composite response of the utility operators to the written evaluation questions pertaining to the digital control system was as follows.

Control System	Strongly Agree	Agree	Disagree	Strongly Disagree
The master control console's graphic displays of the system's status and operation were very useful for system control.	7	4		
The master control console was as easy to learn and operate as conventional power plant controls. (Assume that you had no previous training on either.)	4	6	1	
I would recommend a distributed digital control system for my company's new power plants.	6	4		

Control System

Explain why a digital control system would or would not be of use to your company on future plants.

-- Would be of use
-- Easier to control
-- Quicker response
-- Expanded capabilities

The responses indicated an overall acceptance of digital control among the utility operators. From the operator's viewpoint, all felt that digital controls should be utilized in future plants, both conventional and solar. The single negative response relating to the operation of the control console was only because the alphabet keypad was not layed out like that of a typewriter. This keyboard reduced the speed at which letters could be located.