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Review of the Molten Salt Electric Experiment: A Solar Central Receiver Project

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REVIEW OF THE MOLTEN SALT ELECTRIC EXPERIMENT: A SOLAR CENTRAL RECEIVER PROJECT

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ABSTRACT

The Molten Salt Electric Experiment was the first full solar-to-electric central receiver system to use molten nitrate salt as a primary working fluid. The experiment was built and tested at the Central Receiver Test Facility in Albuquerque, New Mexico, between 1982 and 1985. The purpose of the project was to demonstrate the technical feasibility of a molten salt central receiver system.

The Molten Salt Electric Experiment was operated through a year of successful testing; system performance was measured, operating procedures and an effective receiver control algorithm were developed, and personnel from participating electrical utilities and solar industries were trained to operate the system. The testing culminated in a one-month power production campaign to measure daily performance, component reliability, and system availability.

This paper discusses the major accomplishments and some of the more significant problems of the project.

SOLAR THERMAL TECHNOLOGY FOREWORD

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

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

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

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

The work presented in this report was performed as part of the Central Receiver Systems Task and evaluates a full solar-to-electric central receiver system.

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INTRODUCTION

A major goal of the solar central receiver technology program is to develop systems that are economically competitive, reliable, and flexible. Economic analyses performed in the late 1970's (Reference [1]) indicated that central receivers using molten nitrate salts as both the primary heat transfer fluid in the receiver, and as the thermal storage medium, have a cost advantage over other central receiver concepts. One of the important advantages of molten salt central receiver systems is that the thermal storage buffers the end-use from solar transients such as clouds. In addition, this type of storage requires no intermediate heat exchangers because the heat transfer fluid and the thermal storage medium are the same. Hence, there is no temperature degradation through storage

The Molten Salt Electric Experiment (MSEE) was the first full solar-to-electric central receiver system to use molten nitrate salt as a working fluid. The project was built and tested at the Central Receiver Test Facility in Albuquerque, New Mexico, between 1982 and 1985 to demonstrate the technical feasibility of a molten salt central receiver system. The MSEE consisted of two previously tested molten salt subsystems, a 5 MW_t receiver and a two-tank thermal storage system, in addition to a new steam generator, a rebuilt turbine-generator, and other existing equipment.

The Molten Salt Electric Experiment had three goals:

(1) Verify the capability, flexibility, and simplicity of an advanced central receiver concept.

(2) Provide performance information and operating experience on molten salt systems and components for utilities, system designers, component suppliers, and financial institutions.

(3) Establish a test bed for component development and advanced controls.

A consortium of industries with solar technology experience, interested utilities, and the Electric Power Research Institute, was formed to help fund, construct, and operate the experiment. The consortium supplied half of the funding in the form of cash contributions and cost-shared engineering services. The Department of Energy supplied the other half of the funding, plus project management and on-site construction and operations through Sandia National Laboratories. The Department of Energy also made the Central Receiver Test Facility, with its existing heliostat field and receiver tower, available for the experiment.

This paper presents a retrospective overview of the MSEE. We will give a brief description of the project, discussions of the major accomplishments, and a review of the more significant problems.

PROJECT DESCRIPTION

This section describes the MSEE system, lists the participants, and gives a brief history of the project.

System Description

The MSEE has five major subsystems as shown in Figure 1: the receiver, the thermal storage unit, the steam generator, the electric power generator, and the master controller. The MSEE also makes use of the existing Central Receiver Test Facility components and equipment, including the heliostat field, the 200 foot tower, the data acquisition system, the heat rejection and feedwater equipment, and the control room.

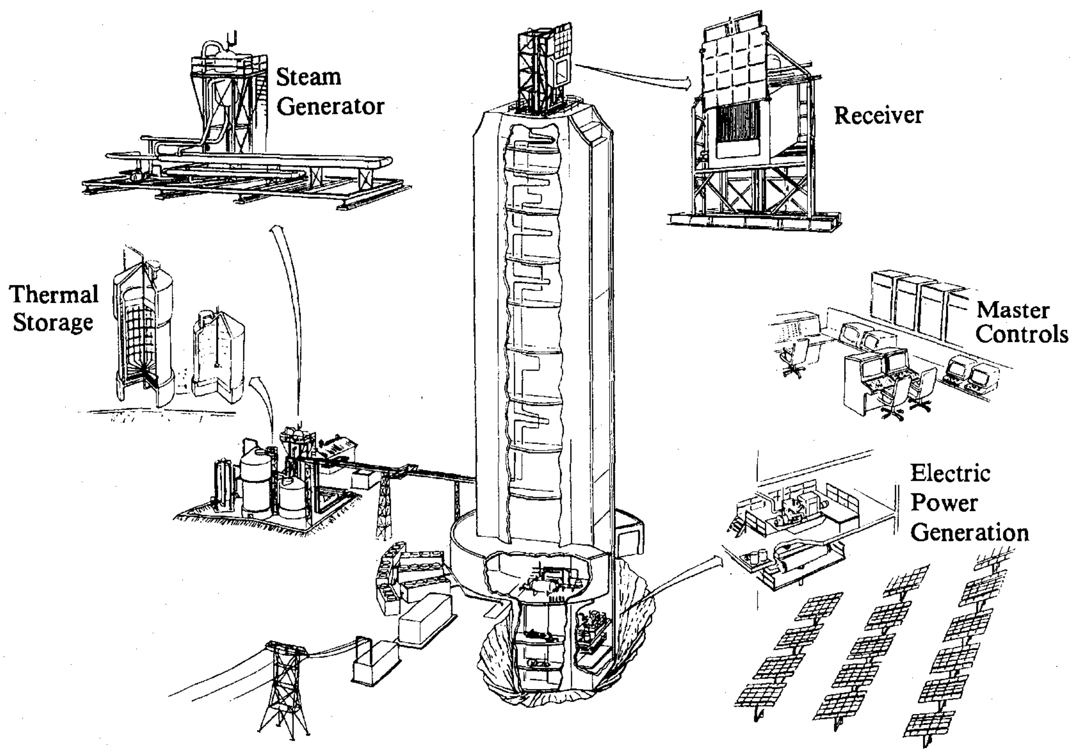


Figure 1. The five subsystems of the MSEE

The *receiver* heats the molten salt from 590°F to 1050°F. Solar flux is concentrated by the heliostat field into the receiver cavity and onto the 11.5-foot by 18-foot absorber panel. The salt flow serpentines up and down through 18 vertical passes of tubes. Each pass consists of sixteen 0.75-inch Incoloy 800 tubes. A salt flow of 97,000 pounds per hour is required for the full-rated capacity of 5 MW_t. The peak flux is 600 kW/m^2. This receiver was previously tested as a stand-alone subsystem at the Central Receiver Test Facility in 1979-80 [2].

The *thermal storage unit* consists of two large tanks, one to store "hot" salt at 1050°F and one for the 590°F "cold" salt. Salt is pumped from the cold tank up the tower, through the receiver, and down the tower where it is stored in the hot tank. Salt from the hot tank is pumped to the steam generator where superheated steam is produced to drive a turbine-generator. The hot tank is a special design to accommodate the corrosive nature of the salt and the high temperature. A corrugated liner, 0.050-inches thick and made of Incoloy 800, contains the salt. The structural load, however, is carried by an outer shell of 0.25-inch carbon steel. To insulate the carbon steel from the high temperature, a 13.5-inch layer of fire brick was installed between the liner and the outer shell. The hot tank is 23.6 feet tall and 12.3 feet in diameter. The cold tank, a conventional design with a carbon steel shell and external insulation, is 15 feet tall and 12.3 feet in diameter. Either tank can hold the full salt inventory of 176,000 pounds or 11,000 gallons. The thermal storage system has a capacity of about 7 MW-hours when fully charged, enough to supply the steam generator at rated conditions for slightly more than 2 hours. This thermal storage system was previously tested at the Central Receiver Test Facility in 1980-81 [3].

The *steam generator* has three major components: a superheater, an evaporator, and a steam drum. Salt from the hot storage tank flows first through the superheater where saturated steam at 567°F and 1200 psi from the steam drum is superheated to 1000°F. Salt leaving the superheater is mixed with cold salt before entering the evaporator. This allows the use of low-alloy, chrome-molydenum steel in the evaporator whereas the superheater requires more expensive 304 stainless steel to withstand salt corrosion at the elevated temperatures. The water/steam is pumped counterflow to the salt, first through the evaporator and then through the superheater. The evaporator has forced-circulation with a recirculation ratio of 7:1 to avoid tube wall dryout at the outlet. A separator in the steam drum allows only saturated steam into the superheater.

Both heat exchangers are U-tube within U-shell designs to accommodate differential thermal expansion. The high-pressure water/steam is in the tubes and the low pressure molten salt is in the shell. At design conditions, the steam generator produces 11,600 pounds/hour of steam at 950°F and 1100 psi and has a rating of 3.1 MW_t. The steam generator design and performance is documented in Reference [4].

The *electric power generator* converts the steam enthalpy into electric power. The turbine-generator accepts 7,800 pounds/hour of steam at 940°F and 1050 psi and produces 750 kW_e at 460 volts, three-phase alternating current. This power is fed to the local power distribution grid. The steam condenses at five inches Hg and 133°F, and the waste heat is rejected through dry cooling towers. The turbine-generator was originally used aboard a Navy ship.

The *master controller* for the MSEE is a distributed digital process controller. This system governs all flow rates, temperatures, and pressures, from operator commands and process data. The heliostat controls are separate from the MSEE controls. The steam generator is controlled separately by another digital controller which receives and executes commands from the master controller. The MSEE controls are supported by a hard-wire relay logic system which automatically provides safe shutdown of the system in the event of an emergency.

The *molten salt* is 60% sodium nitrate and 40% potassium nitrate. Averaged over the working temperature range, the density is 113 lb/ft^3, the heat capacity is 0.37 Btu/lb-°F, and the thermal conductivity is 0.30 Btu/hr-ft-°F. Melting occurs between approximately 430 and 470°F. The heat of fusion is 46.8 Btu/lb.

Project Participants

The MSEE was funded, built, and tested by a consortium consisting of four electric utilities, seven industrial firms, the Electric Power Research Institute, and the U.S. Department of Energy (DOE), listed in Table 1. Sandia National Laboratories managed the project for the DOE.

Table 1. MSEE Participants

Utilities	*Industry*	*Other*
Arizona Public Service	Babcock & Wilcox	Electric Power Research Institute
Pacific Gas & Electric	Bechtel	U. S. Department of Energy
Public Service Company of New Mexico	Black and Veatch	
Southern California Edison	Foster Wheeler	
	Martin Marietta	
	McDonnell Douglas	
	Olin	

The MSEE used a management structure with a Sponsor's Committee, a Technical Committee, and an Executive Committee. Each MSEE participant was represented on both the Sponsor's and the Technical Committees. These committees made programmatic and technical recommendations to the three-man Executive Committee which had one representative from industry, one from the utilities, and a chairman from DOE.

The Executive Committee implemented these recommendations through the DOE project manager, Sandia. This management structure gave each participant a voice in the technical direction of the MSEE, and at the same time served as a focal point and forum for the participants in the development of central receiver molten salt technology. Because of the active participation in the MSEE, each utility or industrial firm had access to the technology first-hand as it evolved.

Project History

System design for the MSEE was begun by Martin Marietta in early 1982. Later that year, Black and Veatch was contracted to perform the piping design and the electric power generation subsystem. In August 1982, DOE gave official approval for the project, and Martin Marietta was chosen to be the system integrator through system checkout. McDonnell Douglas planned and implemented the subsequent system performance evaluation and utility training and operation phase.

Babcock & Wilcox was contracted to supply the steam generator. The steam generator was delivered to the test site in May of 1983, and its checkout was completed that December. A Navy surplus turbine-generator was purchased for the system and delivered to the Central Receiver Test Facility in April 1983.

The receiver was refurbished by Martin Marietta and Sandia with new instrumentation, a new cavity, and new insulation. This refurbishment was completed and the receiver raised to the top of the tower in June 1983. All major construction activities were completed in August 1983, and the design, construction, and checkout of the MSEE through April 1983 was documented by Martin Marietta in Reference [5].

The time allotted for checkout was unreasonably short, and we were unable to meet the original schedule. A series of equipment failures after the completion of construction slowed the checkout testing. Some of the problems were specific to the molten salt solar technology and represent valuable lessons learned; these problems are discussed in this report. Other problems, while no less frustrating, were the result of mistakes or were not related to solar central receiver or molten salt technologies, and will not be discussed here.

Synchronization of the turbine-generator to the utility grid was accomplished in April 1984, and the full system was operated simultaneously for the first time in May. Checkout testing of the full system was completed and performance testing was begun in July 1984. In the Autumn of 1984, teams of electric utility operators and solar industry engineers were trained to run the MSEE during six 3-week sessions.

The system was shut down for refurbishment between January and March, 1985, in preparation for a one-month power production campaign. The refurbishment included the replacement of a large number of trace heaters in the receiver. The start of the power production campaign was delayed by a failure of the cold salt boost pump in March and threatened by the loss of the turbine-generator in April. The MSEE participants decided to proceed with the power production campaign without the turbine-generator. It was necessary to calculate an estimated electric power output based on the steam flow from the steam generator.

The power production campaign was run from mid-April to mid-May 1985. The system was operated at all time possible in an attempt to maximize the energy output. The purpose of this test was to assess the availability of the system and to develop operating procedures typical of a power plant rather than a test facility. The testing activities from April 1983 through May 1985 are documented in Reference [6].

In the final MSEE test, the receiver was reconfigured and tested as an external receiver in June and July 1985. This test, documented in Reference [7], demonstrated the feasibility of an external molten salt receiver, and produced thermal performance data for comparison of an external with a cavity receiver.

ACCOMPLISHMENTS

The most important result of the Molten Salt Electric Experiment was demonstrating the technical feasibility of a molten salt power plant. The following discussion covers six important accomplishments of the MSEE that contributed to this result.

Full System Operation

Individual subsystems of a molten salt solar power plant had been tested since 1980, but these subsystems had never been operated as part of a solar power plant. In the MSEE, the receiver was combined with a thermal storage unit, a steam generator, a turbine-generator, and feedwater and heat rejection equipment to generate electricity from solar energy. This was the first central receiver system in the United States to generate electricity using a working fluid other than water/steam.

The advantage of a molten salt central receiver system is the ability to isolate the end use from solar transients through the thermal storage system. Figure 2 shows that the electric power output from the turbine-generator is steady, despite variations in solar energy input. This permits uninterrupted power production and allows the turbine-generator to operate at its design point and therefore at higher efficiencies – major improvements over water/steam systems.

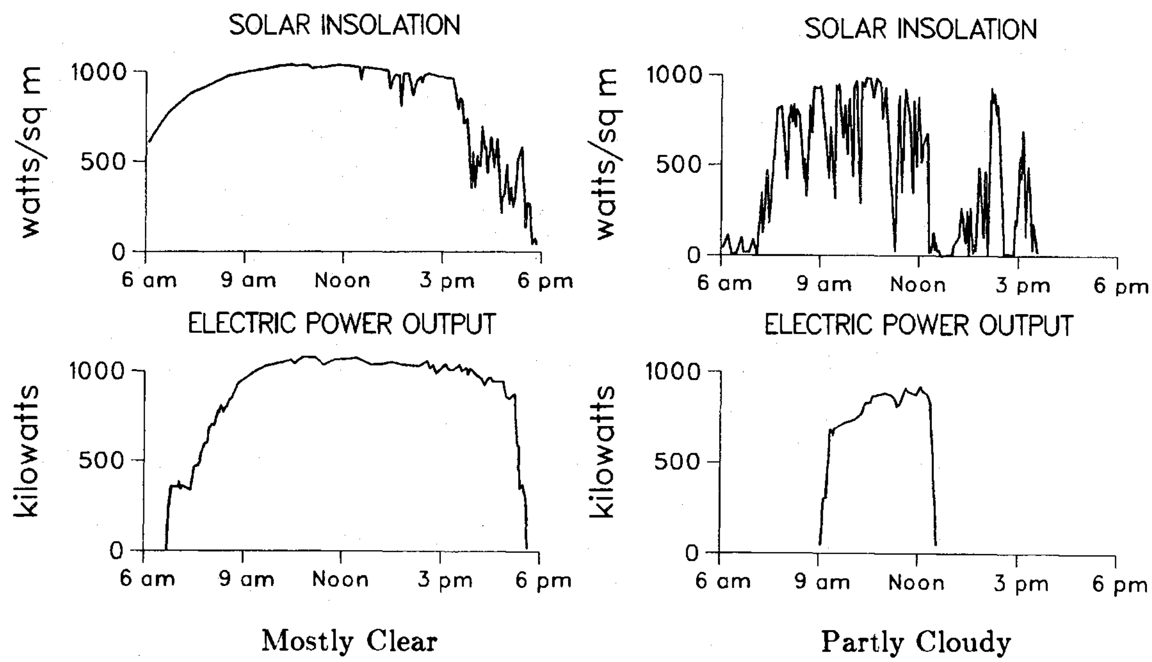


Figure 2. Examples of solar insolation and MSEE electric power output in clear and partly cloudy weather

In April 1984, the turbine generator was synchronized to the power distribution grid. This was the first time in this country that electric power had been produced with a solar central receiver using a working fluid other than water/steam.

The MSEE "Power Production Campaign" simulated operation of a solar power plant as it would be operated by a utility. The objective was to collect as much solar energy as possible, starting the receiver at sunrise and continuing as long into the day as possible.

The Power Production Campaign provided two important results. First, system availability was measured as a function of weather and equipment downtime. Figure 3 shows representative results – percent of available solar energy delivered to the receiver. The available solar energy includes brief interludes of sunlight during otherwise cloudy days. However, since the plant was not always operating, this energy is recorded as a weather related loss. Other contributors to lost available solar energy include scheduled and unscheduled startups and shut-downs, equipment failures, reduced power operation, and delays in recoveries from cloud transients. System availability is a key parameter in annual performance calculations.

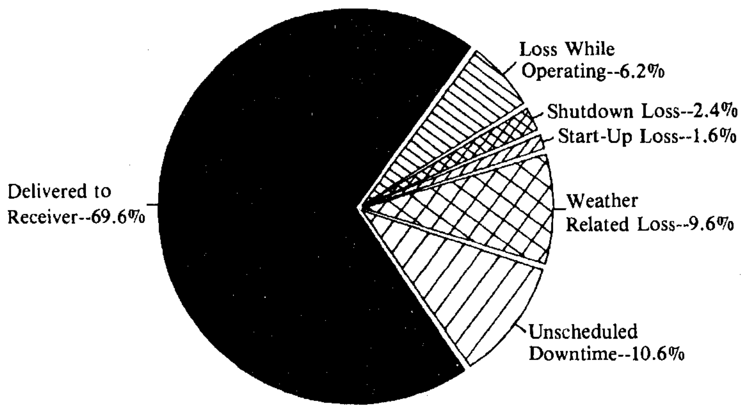


Figure 3. Results of the MSEE Power Production Campaign: percent available solar energy delivered to the receiver

As much as the Power Production Campaign simulated standard utility practices, equipment downtime does not directly extrapolate to a commercial plant. Both equipment redundancies and maintenance schedules will be quite different in a commercial plant than what was available for the MSEE. Nevertheless, the data is valuable in a qualitative sense.

The second important result of the Power Production Campaign was operational experience, both for the solar power plant as a whole and specifically for molten salt. Unique operational requirements of molten salt stem from its high freezing temperature (470°F). Freezing should be avoided, especially in the receiver tubes, because the salt expands when it melts. To prevent freezing, the receiver absorber panel is heated prior to introducing salt, and all pipes and valves are trace heated and insulated.

Overall, the MSEE showed that a full molten salt central receiver system can be built and operated. No major technical hurdles stand in the way of commercialization. Problems were encountered and areas requiring further component development were identified. Since the MSEE was conducted with the active participation of the central receiver community, the technology was made readily available to those who will one day commercialize it.

Development of Receiver Controls

Two versions of a receiver control scheme were used in the MSEE. The original version used receiver back surface thermocouples to anticipate changes in salt outlet temperature. The control response was burdened by large, slow thermocouples. The thermocouple response time needs to be on the order of 1 to 2 seconds rather than the 8 to 10 seconds of the original three-eighths inch thermocouple. Smaller diameter thermocouples were installed, after which the algorithm was able to control the steady state outlet salt temperature to 1050°F.

However, these back surface temperature measurements were still too slow to respond to flux changes during cloud transients. Figure 4 shows receiver response to a cloud. With a steady set point, the receiver outlet temperature overshoots to an unacceptable level of 1100°F. We altered the control scheme to operate through cloud transients using an automatic set point reduction. The overshoot seen in Figure 4 is acceptable when the set point is reduced before the cloud passes.

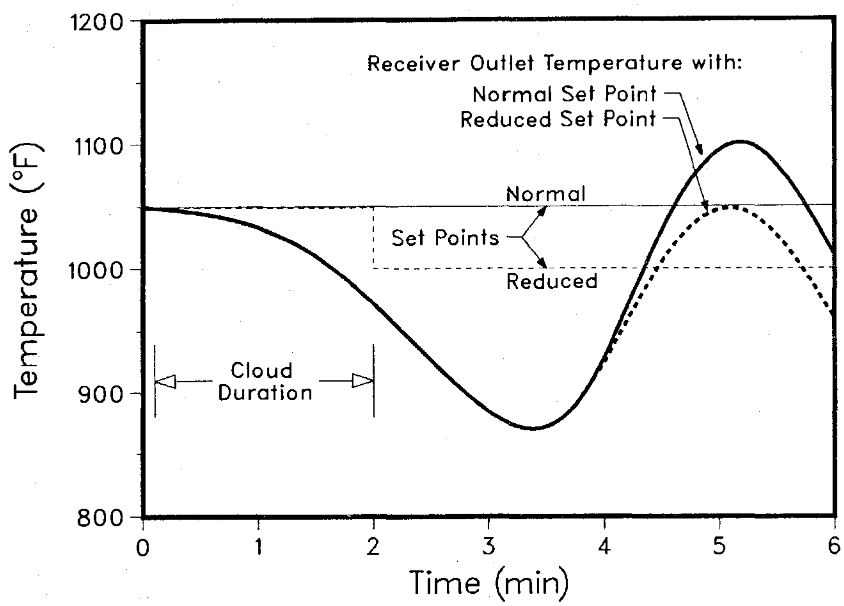


Figure 4. MSEE receiver response to a cloud transient, with and without set point reduction

Control difficulty for this receiver stems from molten salt's long residence time in the receiver and a slow computer update rate. The outlet salt thermocouple does not sense the inlet salt until approximately two minutes after the salt enters the receiver. Tight receiver control, without temperature overshoot, requires some kind of flux indicator, either direct or indirect. A flux signal, updated at least every second, should be fed into the control algorithm to anticipate changes in salt flow requirements. This method of feed forward control is best accomplished using a direct flux sensor. Future control algorithms for a molten salt receiver must consider flux sensors and fast computer update rates.

Development of Operating Procedures

Efficient receiver operating procedures were developed during MSEE testing, including fast early morning startup, operation through cloud transients, use of molten salt rather than electrical heat trace for overnight conditioning, and the thawing of a receiver plugged with frozen salt.

Early morning startup – If no overnight conditioning is used, the receiver panel is drained at the end of each day of operation. Before introducing salt the next morning, the panel must be heated to temperatures above the freezing point of salt. Heliostats are used to warm the receiver since the receiver panel is not trace heated. Typically, warm-up takes 60 minutes from sunrise.* The collectable energy lost during sunrise startup of the MSEE receiver is less than 1% of the energy collected on a clear day.

Since it is de-coupled from energy collection through thermal storage, electric power generation can begin immediately after startup. Rated salt outlet temperature (1050°F) is achievable within 100 minutes of sunrise.

The time required to start up plays an important role in annual performance of solar central receivers. Figure 5 shows a receiver startup timeline, identifying the tasks required to bring the receiver from its cold, drained state to operating at full power. The minimum insolation required for warm-up is reached 7 minutes after actual sunrise, or 22 minutes after theoretical sunrise at the Central Receiver Test Facility.

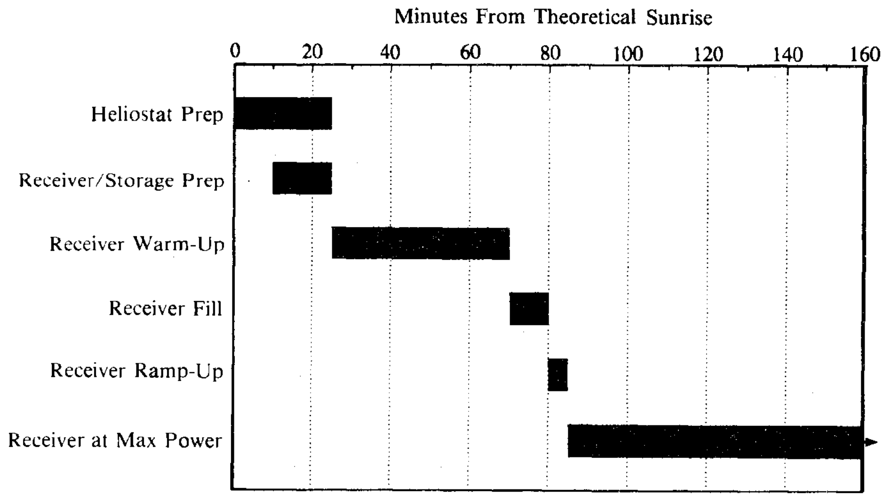


Figure 5. MSEE receiver startup timeline

Cloud Transient Operation – Efficient receiver operation during cloud transients is achieved by keeping the receiver warm and ready to collect energy. This is accomplished by circulating cold salt through the receiver. However, this stand-by mode will not always be the most economical operating strategy. At some point it will become more economical to drain the receiver and save on pumping costs and receiver thermal losses rather than to remain in cold flow waiting for the sun to return.

* All times in this report are referenced to "theoretical" sunrise, which is the time the sun would rise over a flat horizon. At the test facility, mountains in the east cause the sun to appear approximately 16 minutes after "theoretical" sunrise.

The disadvantage of draining the receiver is that the receiver is not available to collect intermittent solar energy during partly cloudy weather. When the receiver is drained, it requires between fifteen and thirty minutes of uninterrupted solar energy to re-start. Meanwhile, the receiver kept in a stand-by mode with circulating salt would be collecting energy. Also, heat trace parasitics are lower when salt is flowing, because most heat trace is turned off.

To determine the economics of cold flow stand-by, graphs such as shown in Figure 6 can be developed. This graph shows the number of hours that cold flow can be economically maintained before thermal losses from the salt exceed the energy that would be collected when the sun returns. Numerical values are not presented in this figure because the thermal losses and electrical parasitics for the MSEE are not representative of a commercial central receiver plant, either small or large scale.

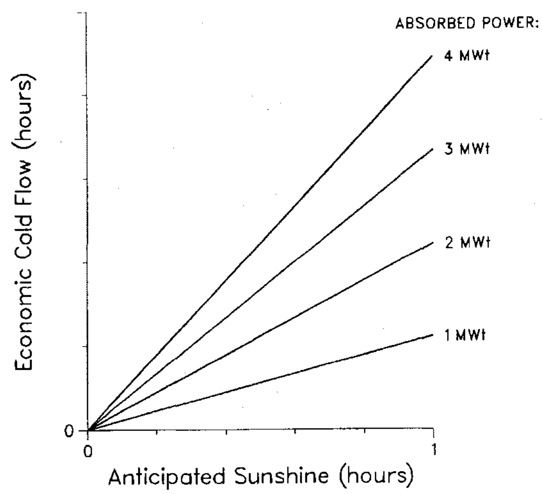


Figure 6. Hours of economic receiver cold flow versus anticipated sunshine

Additional graphs which account for the energy cost of draining and restarting the receiver are necessary to determine when to drain the receiver. This type of graph would show the number of hours of cold flow that offset the energy lost in restart. The energy lost in restart will vary with time of day and weather conditions and is equal to the product of the time required to preheat the panel and the anticipated incident power.

Graphs such as these, coupled with a knowledge of local weather patterns, would be very helpful in deciding when to maintain cold flow and when to drain the receiver.

The important distinction between the economics of circulating salt during cloud transients and for overnight conditioning is the quality of solar energy available when energy collection resumes. The trade-off for overnight conditioning occurs in the early morning when the insolation and therefore potential absorbed power is very low. The recovery from cloud transients, however, usually occurs when the incident power is relatively high, above 3 MW_t.

Overnight conditioning – Even though the energy lost from sunrise warm-up of the

MSEE receiver is a small fraction of the clear day total, the lost energy must be weighed against the energy used to keep the receiver warm overnight. In the case of a commercial receiver, it may be more economical to keep the receiver warm overnight and begin collecting energy at sunrise, rather than 60 minutes later.

A benefit of overnight conditioning is reduced trace heating. When the receiver is drained every night, all pipes and valves in contact with salt must be trace heated. However, once hot salt is flowing, trace heating is not required. Overnight conditioning using molten salt allows most trace heating to be turned off. (Trace heaters on bellows valves must remain on to prevent freezing salt in the bellows.) The penalties of overnight conditioning are the cost of pumping the salt and the thermal energy lost from the salt.

Overnight conditioning using salt circulating through the receiver is not economical for the MSEE. This does not mean a commercial, optimized system would not benefit from overnight conditioning. A small auxiliary salt circulation pump and a loop by-passing the receiver might make overnight conditioning economical as well as practical for commercial receivers.

Salt Freeze– An important operational tool was developed when the receiver inadvertently plugged with frozen salt due to a procedural error. Using a small number of heliostats to heat the receiver tubes, we demonstrated that the frozen salt could be thawed and the receiver safely unplugged. This important result showed that frozen salt in the receiver is not a catastrophic event and the receiver can be cleared using straightforward procedures.

Summary of Operational Experience – Fast early morning startup was demonstrated by warming the receiver to operating temperature with heliostats while the sun is coming up. Comparing sunrise warmup to overnight salt flow, this receiver was more economical in the sunrise warmup mode. Commercial receivers may operate more efficiently using overnight salt flow.

Optimum procedures can be developed to determine how much solar energy need to be collected to justify losses from cold flow operation. Cold flow operation has the advantage of being ready to collect intermittent solar energy between clouds, rather than requiring uninterupted solar energy to pre-heat the drained receiver.

These test results show that the molten salt system is operationally flexible. Efficient and economical operating procedures have been demonstrated. In addition, the experience of thawing a frozen receiver, coupled with data from the cold receiver fill test discussed previously, indicates the receiver can be operated closer to the freezing point of salt than previously thought. Less cautious operation during cloud transients and morning startup may be possible, allowing for greater annual energy collection.

Demonstration of a Prototype Steam Generator

The MSEE was a proving ground for a molten salt steam generator subsystem, shown in Figure 7. Designed and built by Babcock & Wilcox for the MSEE, the steam generator is prototypical of a commercial design. The receiver and the thermal storage system for the MSEE each had been operated prior to the MSEE. The steam generator was the one solar-unique subsystem of the MSEE to be tested for the first time. The requirements of overnight shutdown and heat tracing on all elements containing salt were unique solar related design features.

The steam generator operated with very few problems. The U-tube and U-shell design with forced circulation was verified to operate at design conditions. Steam production followed turbine load changes of 75 kW/minute over the entire turbine range of 100 to 750 kW_e. Reference [4] discusses the steam generator design and verification in detail.

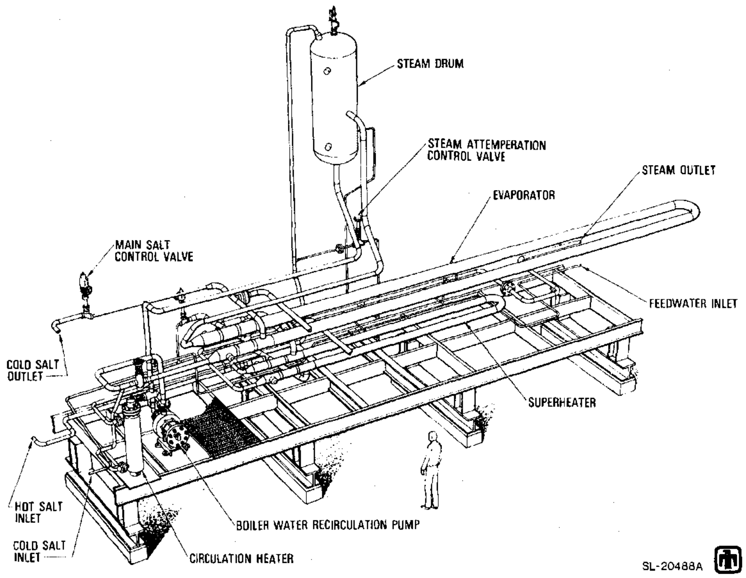


Figure 7. The MSEE steam generator

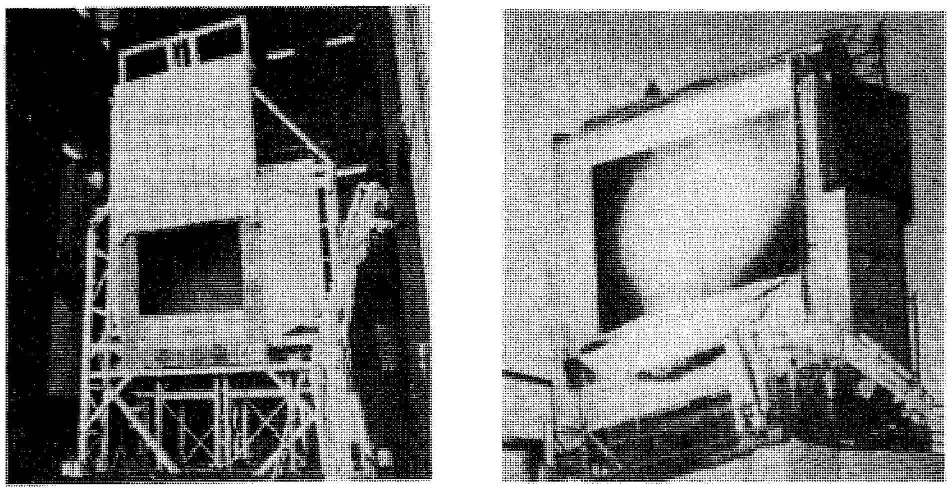
Two steam generator design changes were proposed based on our experience. First, an automatic steam drum make-up system would be helpful. Leaks in the system caused the circulation pump and heaters to turn off overnight, delaying system startup the next morning. Second, test engineers agreed that both the steam and salt attemperators could be eliminated, resulting in simplified design and operation. They believed that both of these attemperator functions can be performed through control of the hot salt temperature.

Demonstration of a Molten Salt External Receiver

The MSEE receiver is unique in that it is capable of being operated as a cavity or an external receiver. In the cavity configuration, the flat absorbing surface is surrounded by an insulated shroud as shown in Figure 8. An external, or billboard configuration is achieved by removing the shroud, exposing the absorbing panel directly to the environment.

The MSEE receiver was tested in the cavity configuration for the majority of the program. In June 1985, the cavity was removed and the receiver tested for five weeks as an external receiver. Before this time, an external molten salt receiver had never been operated. Originally there was concern that receiver losses would be too great to start up and operate in high winds. We were also interested in comparing the external receiver performance—both operational and thermal—to the cavity.

The external receiver was operated without problems in all weather conditions. Based on our experience, we do not foresee any conditions which would constitute a risk of freezing the salt. The external receiver was easier to warm up than the cavity because the solar



Cavity External

Figure 8. The MSEE receiver in a cavity and an external configuration

flux does not have to be focused through the cavity aperture and therefore more uniform flux on the absorbing surface is possible. This results in a shorter startup time. However, during extended cloud cover, a cavity receiver would be kept operational longer because the door can be closed to reduce thermal losses.

As expected, the point-in-time thermal performance of the MSEE cavity receiver was marginally better than the external receiver, due mostly to larger radiation losses from the external receiver. However, the more important comparison between cavity and external receivers must be based on annual performance, which cannot be directly extrapolated from the MSEE data. Nevertheless, the results provide an important reference point for future receiver designers.

Four demonstration tests were performed on the external receiver. These tests were considered somewhat risky in that each could potentially damage the receiver. Therefore, they were performed when all the other testing had been completed. Otherwise, these tests could have just as well been performed with the receiver in the cavity configuration.

The most significant demonstration test results were from the cold receiver fill and the serpentine fill. Cold receiver fill was qualitatively successful with receiver temperatures as low as 240°F using 650°F inlet salt. Results from the serpentine fill test show that it may be possible to fill the receiver in a serpentine, rather than conventional flood fashion, thereby reducing the number of purge valves. Both of these tests demonstrate potential cost savings and simplified operations for commercial receivers.

Utility Operator Training Program

In August 1984, we began a program to train utility personnel to operate the MSEE. In six, three-week classes, teams of engineers and power plant operators gained hands-on experience in running a solar central receiver power plant. By the end of the class each team member was capable of operating the entire system from the control console.

The response of the team members was very positive. Feedback from the classes emphasized the simplicity and flexibility of the distributed digital control system. The operators favored digital controls over conventional analog controls for future plants. Training the utility operators demonstrated to the solar community that the operation of a molten salt solar plant does not require engineering personnel; rather, such a plant can be run by operating technicians.

PROBLEMS

Several problems arose during the construction and testing of the MSEE. From these problems valuable lessons were learned, advancing the technology and lowering the technical risk of building future commercial solar power plants. Five problems important to central receiver technology are discussed here.

Heat Trace and Insulation

Electrical trace heaters were used in the MSEE to keep hot components such as valve actuators and instrumentation, and to preheat piping to avoid thermal shock at system startup. Heat trace was a major cause of delays and lost test time in the MSEE. Most problems were due to improperly designed and installed heat trace and insulation.

The major problem area was trace heater burnouts. A large number of heater cables and connectors failed during the MSEE, and considerable effort was spent repairing the failures and investigating the causes. Figure 9 is a photograph showing the extensive labor required to repair a burned out cable. A report has been written to document this issue [8]. In this report, a thorough review of the heat trace technology developed for liquid sodium in the nuclear industry is recommended.

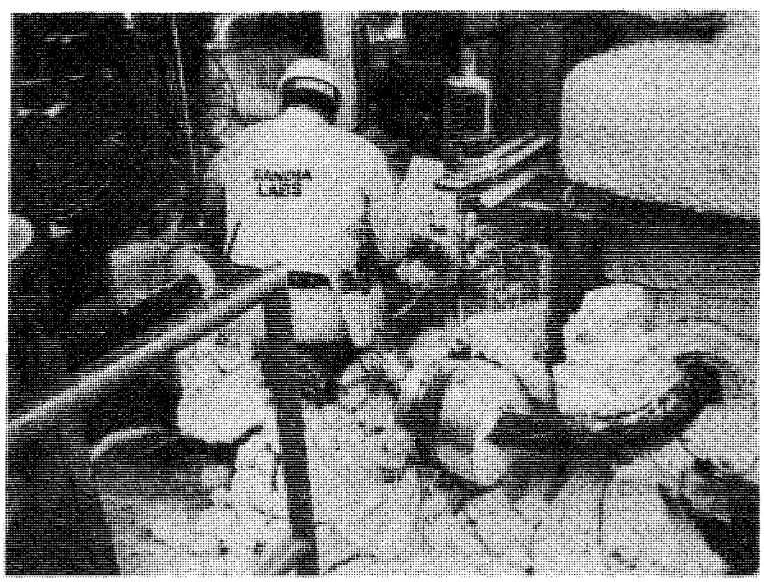


Figure 9. Repair of a burned out heat trace cable

Another problem resulted from the original design philosophy, which was to match the heat trace power density (watts per linear foot of pipe) to the heat loss through the insulation. This "passive control" design did not work. On cold, windy days, the temperature of many portions of the piping fell below the freezing point of salt, and salt could not be introduced for fear of it freezing. Additional insulation could not be added because the pipes would then overheat on hot days. A better approach is to over-design the power density and regulate the electric power to the trace heaters to control the pipe temperatures.

There were also problems with the insulation. Gaps in the insulation allowed convective air flow both from the outside and along interior gaps parallel to the pipe, resulting in high heat losses. The design solution is to use soft blanket insulation around complex shapes, such as elbows and valves, and to apply rigid insulation to straight pipe sections with rigorous attention to correct procedures. The insulation also became wet, due to improper or damaged weather shielding. This resulted in lower thermal resistance and higher heat losses. Sheet metal siding was eventually installed on the entire receiver to give protection from both rain and wind.

All of these problems were due to a lack of understanding of the importance of heat trace and insulation design issues. In future molten salt solar plants, these design issues must be understood, and the design of heat trace and insulation must be given proper consideration and integrated into the early stages of the system design. The emphasis of heat trace design should be on reliability rather than initial cost, as this will minimize the cost in the long run.

Instrumentation

The MSEE experienced numerous problems with instrumentation. Many of these problems were common to all projects of an experimental nature and are not of specific interest here. Some problems, however, were peculiar to the design and operation of a molten salt central receiver and deserve to be reviewed. Most of these are related either to high temperatures, the requirement to keep the salt from freezing, or both.

Pressure transducers are used for both pressure measurements and flow measurements (flow is determined by measuring the pressure drop across a wedge or a venturi). Pressure transducers must be isolated from salt because of the salt's corrosive nature, but at the same time they must be able to sense pressure variations. This is accomplished with a fluid coupling through a diaphragm or bellows. Problems occurred when the fluid coupling mechanisms overheated and when the temperature was not kept above the freezing point of salt. Solid salt formed within the coupling, and the diaphragms or bellows were damaged when actuated.

A general source of instrumentation trouble was high temperature. The instruments must not only be able to survive the extreme temperatures, but must also be temperature compensated to give accurate data.

The receiver is a particularly difficult area to instrument. The front surface of the receiver is subjected to an extremely harsh environment, making flux measurements difficult. Keeping thermocouples attached to the receiver tube panels is also challenging because of thermal cycling. Finally, the receiver is enclosed with windshielding to minimize thermal losses, but the windshielding causes an "oven effect" after a few hours of receiver operation and results in very high temperatures. In summary, instrumentation that can operate reliably in high temperatures is required.

Another problem arises from in-line instrumentation which must be removed periodically for recalibration to insure accurate readings. These instruments can be removed most easily if they are held with flanges in the piping. However, molten salt has a tendency to leak through flanges, and welded joints are preferred. When in-line instrumentation is welded in place, a routine recalibration requires the welds to be cut for removal, and rewelded for replacement. This turns a routine maintenance item into a time-consuming task.

In summary, many improvements in instrumentation methods have been made for molten salt technology over the last few years. However, the special design conditions associated with molten salt must be considered if instrumentation problems are to be avoided.

Pumps and Valves

A major concern for the MSEE was the use of commercially available pumps and valves for molten salt applications. Previous test experience at the Central Receiver Test Facility identified salt valves as a potential source of trouble. Furthermore, a new high-head salt pump was added to the existing hot salt pump and cold salt pump, and its reliability was a concern.

Valves for the MSEE were specified with bellows seals, such as shown in Figure 10, to prevent external leakage of salt around the actuator stem. Standard valves with packed seals were not used because a packing material that could withstand salt at the required temperatures had not been identified. Bellows seals are commonly used in valve sizes up to four inches for applications involving high temperatures. In spite of our design approach, several salt leaks occurred. These leaks resulted from either operational errors or from hardware that was not consistent with design specifications. Salt leakage also damaged instrumentation, heat trace cables, wiring, and insulation, increasing the system down time.

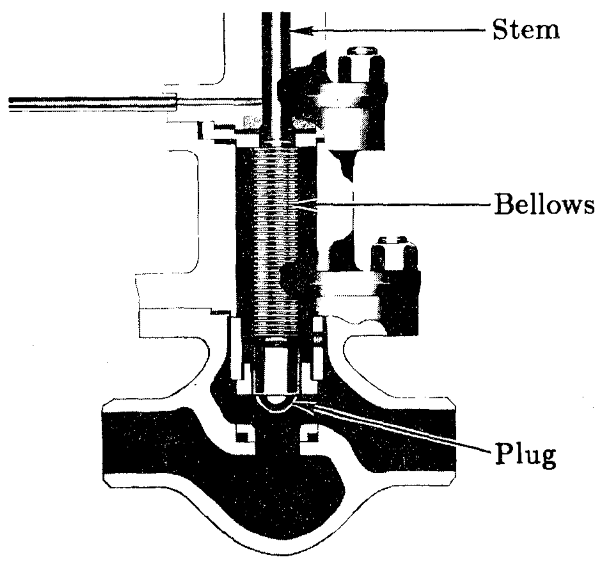


Figure 10. Typical bellows-sealed valve used for molten salt applications in the MSEE

A second problem with MSEE valves was internal salt leakage through valves. Internal leakage was particularly troublesome in the isolation valves. As an example, leakage occurred through the isolation valves in the gravity feed piping between the salt storage tanks and the pump sumps. As a result, it was necessary to run the pumps periodically to reduce the sump level.

These valve problems underscore the need for a development program for economical, reliable molten salt valves coupled with revised system designs that minimize the dependence on valves.

The three molten salt pumps in the MSEE operated with reasonable reliability. However, there were enough problems requiring downtime and repair to forewarn of potential problems with molten salt pumps in commercial solar plants. Many of the problems were related to two properties of nitrate salts. First, the high degree of "wettability" of the liquid results in salt creeping up the impeller shaft into the seals and bearings. Second, the extreme hardness of the salt when frozen makes it very difficult to restart cold pumps with salt frozen around the impeller shaft seal.

For hot salt applications at 1050°F, the corrosive nature of the salt dictates a "cantilever pump" design with the bearings out of the salt. Commercial solar plant requirements will extend the capabilities of existing cantilever pumps and require either the use of multiple pumps staged in series, or the use of other types such as the vertical turbine pump. The experience with MSEE salt pumps underscores the need for demonstration existing, or developing new, types of pumps for commercial solar central receiver plants.

Parasitic Losses

Parasitic losses for the MSEE were a major contributor to low net performance of the system. High parasitics were due to two factors. First, the MSEE is a relatively small system, and thermal losses are a large percentage of the system power rating. Second, the MSEE was not designed to simulate commercial system performance. The experiment contains many inefficient components which greatly increase the parasitic losses.

The net result is that the MSEE parasitic losses were greater than the gross energy output of the system. This result can be misleading without understanding the experiment's background. As the MSEE data correctly points out, small systems suffer a greater penalty from parasitic and thermal losses than do large systems. However, there is nothing in the MSEE test results that lead us to doubt the high efficiencies anticipated for commercial solar power plants.

Component Reliability

The MSEE had a number of equipment failures during system installation and checkout. This gave the impression that there might be some inherent design problems with either molten salt as a working fluid or with solar thermal plants in general, which is not the case.

The MSEE was a complex system with hundreds of components, the failure of any one of which would shut the system down because there was no redundancy in the design. For example, a commercial plant would typically use three half-capacity pumps in parallel for a particular function. If one of these pumps were to fail, the other two would be used while the third was repaired. In contrast, the MSEE used single pumps. A failure shut down the system until repairs could be made. Similar examples are numerous. As a result, the component problems associated with the MSEE startup were exaggerated.

The MSEE also had a shortage of spare parts during the checkout phase of the project. Spares, which should have been on-site, were procured as needed. This resulted in longer than necessary shutdowns. Therefore, a reliability review was held and a list of spare parts was recommended to be kept on hand. After a period of "infant mortality" and with a better inventory of spares on hand, the reliability of the system improved tremendously.

Thermal cycling must be carefully considred during the design of a solar thermal power plant. Most conventional power plants are run almost continuously, except for maintenance, to maximize the payback on capital equipment. This is not possible for solar thermal plants; both cloud passage and nightly shutdown result in thermal cycling of the equipment. Problems associated with thermal cycling were encountered on the MSEE and other solar thermal projects. Special attention must be given to this design issue in all solar applications.

CONCLUSIONS

The Molten Salt Electric Experiment accomplished its primary goal—demonstrating the feasibility of a full solar-to-electric central receiver system using molten nitrate salt as a primary working fluid. The MSEE served as the focal point for molten salt central receiver development between 1982 and 1985. A large group of industry and electric utility participants received hands-on experience in the design, operation, and performance verification of the hardware.

The MSEE significantly advanced the technology of molten salt central receivers. Receiver controls were improved to accommodate cloud transients. Operating procedures were developed for rapid and efficient early morning startup. An external molten salt receiver was demonstrated and compared to a cavity configuration. A prototypical molten salt steam generator was designed, built, and successfully operated as part of the system. Techniques for designing and installing trace heaters and insulation were greatly improved. Extensive experience with molten salt pumps and valves operating under actual service conditions was obtained.

Furthermore, the MSEE demonstrated to central receiver designers and potential users that the system has the inherent flexibility to be operated as a power plant. Rapid startup, operation through cloud transients, load shifting of electric power production, and uniform power output buffered from solar transients were all demonstrated.

Finally, the MSEE gave a status report on the state of molten salt central receiver technology to the solar community and served as a benchmark from which the next steps in technology development can be defined.

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