

Solar Two: A Molten Salt Power Tower Demonstration*

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Abstract

A consortium of United States utility concerns led by the Southern California Edison Company (SCE) is conducting a cooperative project with the U.S. Department of Energy (DOE), Sandia National Laboratories, and industry to convert the 10-MW Solar One Power Tower Pilot Plant to molten nitrate salt technology. The conversion involves installation of a new receiver, a new thermal storage system, and a new steam generator; it utilizes Solar One's heliostat field and turbine generator. Successful operation of the converted plant, called Solar Two, will reduce economic risks in building initial commercial power tower projects and accelerate the commercial acceptance of this promising renewable energy technology. The estimated cost of Solar Two, including its three-year test period, is \$48.5 million. The plant will begin operation in early 1996.

Introduction

A solar power tower plant (sometimes called a solar central receiver plant) uses a field of sun-tracking mirrors, called heliostats, to concentrate sunlight onto a tower-mounted, centrally located receiver, where the thermal energy is collected in a heated fluid. In the past 18 years, a number of component and system experiments have been fielded around the world to demonstrate the engineering feasibility of the power tower concept and to validate its potential.

The 10-MW Solar One Pilot Plant (Figure 1) near Barstow, California, was the largest of the system experiments and established the technical feasibility of the power tower concept. To establish utility confidence in the concept and to minimize technical risks, Solar One used a water/steam receiver coupled directly to the turbine-generator.

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A thermocline oil/rock system provided limited thermal storage. Solar One used 1818 glass-mirrored heliostats to reflect the solar energy to the receiver on the tower.

Solar One started operation in 1982, and its six-year test and power production program proved that the technology operates reliably and has both very low environmental impact and high public acceptance [1].

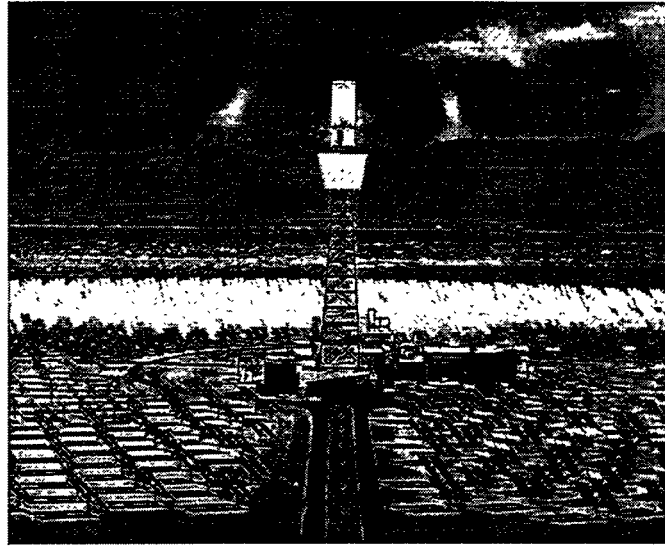


Figure 1. Solar One

There were, however, two key disadvantages to the water/steam system at Solar One. First, the receiver was directly coupled with the turbine, causing the turbine to drop off-line each time a cloud came by, and second, the oil/rock thermal storage system was not efficient because of thermodynamic losses [2,3,4]. After successfully completing its six years of test and operation, Solar One was decommissioned in 1988.

In parallel with Solar One, a series of studies funded by the U.S. Department of Energy and industry examined advanced power tower concepts using single-phase receiver fluids [5,6,7,8], the best of which was a 60% sodium nitrate/40% potassium nitrate molten salt. The primary advantages of molten nitrate salt as the heat transfer fluid for a solar power tower plant include a lower operating pressure and better heat transfer (and thus higher allowable incident flux) than a water/steam receiver. This translates into a smaller, more efficient, and lower cost receiver and support tower. In addition, the relatively inexpensive salt can be stored in large tanks at atmospheric pressure, allowing 1) economic and efficient storage of thermal power collected early in the day for use during peak demand periods; 2) increased plant capacity factor by oversizing of the collector and receiver systems with storage of the excess thermal energy for electricity generation in the evening; 3) isolation of the turbine-generator from solar energy transients; and 4) operation of the turbine at maximum efficiency. If necessary, a molten salt system can be hybridized with fossil fuel in a number of possible configurations to meet demand requirements when the sun is not shining.

A schematic of a molten salt power tower system is shown in Figure 2. During operation, cold (285°C) molten salt is pumped from the cold salt tank through the receiver, where it is heated to 565°C . It then flows by gravity to the hot salt tank, where it is stored until needed for generation of steam to power the turbine. At that time, it is pumped through the steam generator, producing 512°C steam for the electric power generation system before being routed back to the cold tank to begin the cycle again.

Efforts by DOE, Sandia National Laboratories, and industry to demonstrate nitrate salt system elements have been very successful. Component tests have included two 5-MW_{th} receivers, a 7-MW_{th} thermal storage system, a 3-MW_{th} steam generator, a pump and valve loop sized for a $190\text{ MW}_{\text{th}}$ receiver, and a series of panel and flow tests to qualify valves and freeze mitigation procedures [8,9,10]. A small, complete system demonstration, the Molten Salt Electric Experiment, used one of the receivers, the thermal storage tanks, the steam generator, and a 750-kW turbine-generator to form a complete nitrate salt system. The size of the experiment was not large enough, however, to demonstrate the economic potential of a commercial facility [11].

The next step needed for commercialization of power tower technology is the design, construction, and operation of a demonstration plant large enough in size to reduce to acceptable levels the risks in building the first commercial plant. Solar Two is this plant.

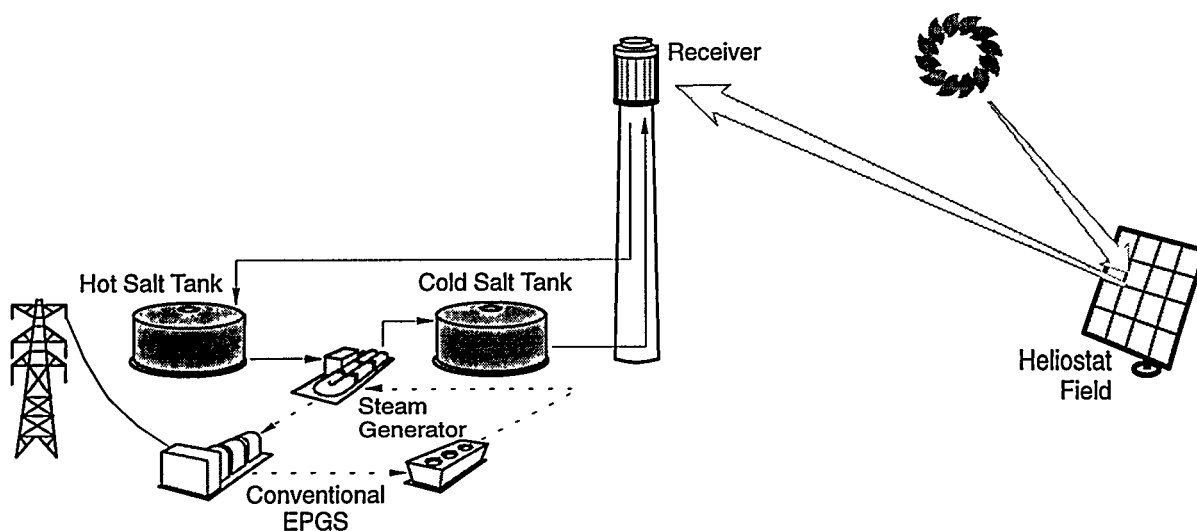


Figure 2. Molten Salt Power Tower Plant Schematic

The Solar Two Project

Solar Two is a utility-led project to promote the commercialization of solar power towers by retrofitting the Solar One pilot plant with a molten salt system. The project is being cost shared by a consortium of utilities and the U. S. Department of Energy. Southern California Edison leads the consortium, whose additional members include the Sacramento Municipal Utility District, Los Angeles Department of Water and Power, Idaho Power, PacifiCorp, Arizona Public Service, Salt River Project, Nevada Power, the Electric Power Research Institute, the California Energy Commission, and the South Coast Air Quality Management District. Major industry contributors to the project include Bechtel Corporation as the Engineer and Construction Manager, Rockwell International as the receiver supplier, and Chilean Nitrate Corporation as the salt supplier. Sandia National Laboratories provides technical support on behalf of DOE.

The project is directed by a Steering Committee (headed by SCE), which sets project policy and objectives and assures the accomplishment of project objectives as permitted by the project resources. In addition, a Technical Advisory Committee headed by Sandia reviews designs and proposals and supports transfer of information to all participants, and a Commercialization Advisory Board headed by Bechtel works to use Solar Two as the stepping stone for the commercialization of power tower plants.

The project schedule includes six phases: nine months for systems engineering and preliminary design; six months for issuing and evaluating major bid packages; one year for final design and equipment fabrication; one year for construction; six months for startup and checkout; and three years for operation (including one year for system test and evaluation and two years of power production to simulate a commercial plant). The project will begin its test and evaluation period at the beginning of 1996 and its power production phase early in 1997. The schedule is summarized in Figure 3.

The overall project cost of \$48.5 million is being shared on a 50/50 basis by DOE and the other project participants. The costs of plant design, construction, and checkout have been

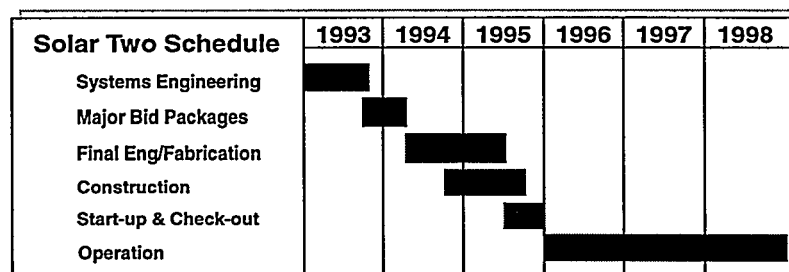


Figure 3. Project Schedule

very close to the originally estimated \$39 million. Operation and maintenance costs for the one-year test and evaluation phase plus the two-year power production phase are projected to be \$9.5 million.

The principal goal of the Solar Two project is to significantly reduce the perceived technical and economic risks associated with building the first commercial projects. To accomplish this goal, the project has established the following objectives:

- Simulate the design, construction, and operation of the first commercial plants.
- Validate the technical characteristics of the nitrate salt receiver and storage technology.
- Improve the accuracy of economic projections for commercial projects by increasing the data base of capital, operating, and maintenance costs.
- Collect, evaluate, and distribute the knowledge gained from the project to United States utilities and the solar industry to foster wider utility interest in commercial plants.
- Stimulate the formation of a commercialization consortium that will facilitate the construction of the initial commercial projects.

Plant Description

The Solar Two project adds a nitrate salt receiver, salt storage system, salt steam generator, and a new master control system to the existing Solar One heliostat field, receiver tower, turbine-generator, and balance-of-plant. Table 1 summarizes features of

Table 1. Summary of Solar Two Features

<u>System</u>	<u>Type</u>	<u>Size or Rating</u>
Collectors	Silvered-glass heliostats	82,700 m ²
	1818 Solar One heliostats	72,500 m ²
	108 new 95-m ² heliostats	10,200 m ²
Receiver	External cylinder, 24 panels	43 MW _{th}
Steam Generator	U-tube, U-shell pre-heater	35 MW _{th}
	Kettle boiler evaporator	
	U-tube, U-shell superheater	
Thermal Storage	Externally insulated hot and cold salt tanks, 900 m ³ each	105 MW _{th} (3 hr)
Turbine	Non-reheat Rankine cycle	10 MW net electric

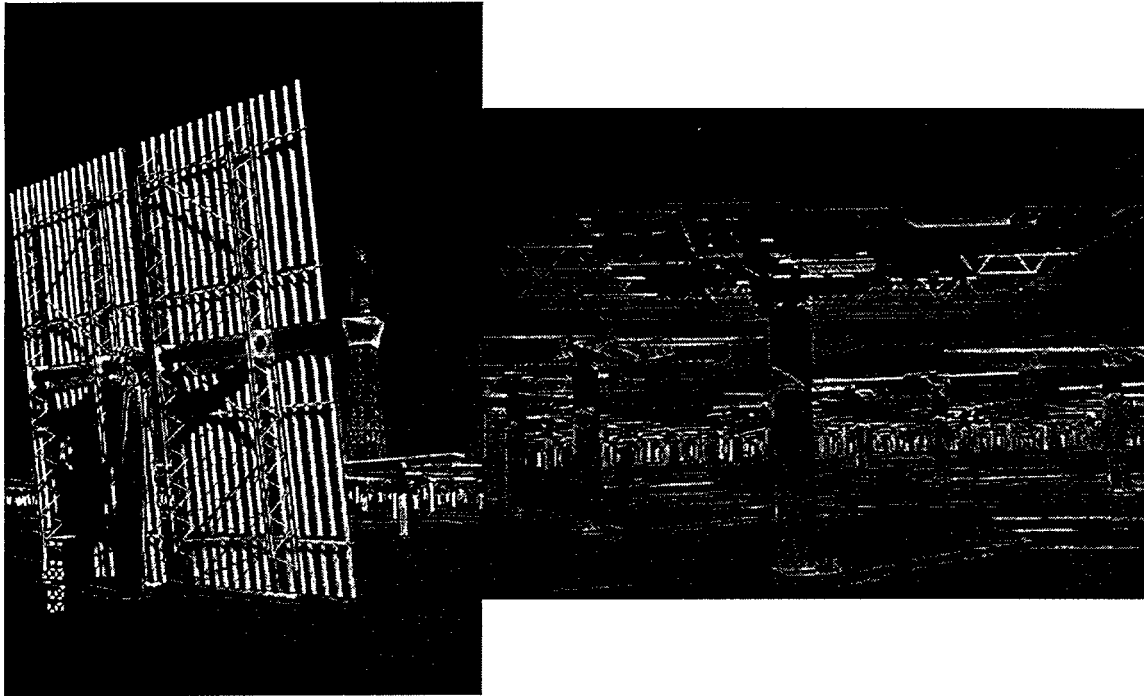


Figure 4. New Heliostats and Facets

the plant. Details are discussed below.

108 “new” heliostats (approximately 10,000 m² of mirrors) have been added to the south side of the collector field. The additional reflective area provides a flux distribution representative of a commercial receiver, eliminates the excessive morning start times common to Solar One, and provides additional energy for charging the thermal storage system. The added heliostats are not truly new, but rather utilize flat glass panels mounted on heliostat-like tracking structures. Both the glass panels and tracking structures were salvaged from decommissioned photovoltaic facilities. Except for the glass being flat (as opposed to being contoured to the focal length of the heliostat), these 95-m² heliostats are very similar to heliostats previously manufactured by ARCO Solar and Advanced Thermal Systems (manufacturers of the tracking structures). Additional flat glass facets were used to replace approximately 300 missing or damaged facets on the original Solar One heliostats. Figure 4 illustrates the heliostat and facet construction and modifications.

A 43-MW_{th} external, cylindrical nitrate salt receiver replaces the Solar One water/steam receiver. The Solar Two receiver is 5.1 m in diameter, 6.2 m tall, and receives an average flux over 0.4 MW_{th}/m² from the heliostat field. It uses 24 panels of 32 tubes each, terminated in headers at each end. The tubes, made of 316 stainless

steel, have an inside diameter of 2.06 cm and a wall thickness of 0.12 cm. Molten salt enters the receiver at 285°C, flows in a serpentine path in two parallel control zones through the receiver, and exits the receiver at 565°C. The receiver was designed and manufactured by Rockwell International. Figure 5 shows the installation of the new Solar Two receiver.

A nitrate salt thermal storage system has replaced Solar One's oil/rock thermocline unit. Sized for 3 hours of full turbine output, the storage system uses separate cold (285°C) and hot (565°C) salt tanks. The system will demonstrate the decoupling of solar energy collection from electric energy generation, the potential to meet a utility evening peak demand, and the dispatch characteristics of a commercial plant. The tanks, designed and erected by Pitt-Des Moines, Inc., are externally insulated and utilize air to passively cool the foundations to meet soil load-bearing constraints. The cold tank is

11.6 m in diameter, 7.8 m tall and is constructed of carbon steel; the hot tank is 11.6 m inside diameter, 8.4 m tall, and is constructed of stainless steel. Approximately 1600 tonnes of salt are used in the system. Salt flows from the cold and hot nitrate salt storage tanks by gravity to two sump vessels (receiver sump and steam generator sump, respectively) in which the main nitrate salt pumps are mounted. The receiver sump is a 4.3-m diameter, 2.9-m tall hemispherical-head vessel. The steam generator sump is a 4.3-m diameter, 2.4-m tall flat-head vessel. The sump vessels also

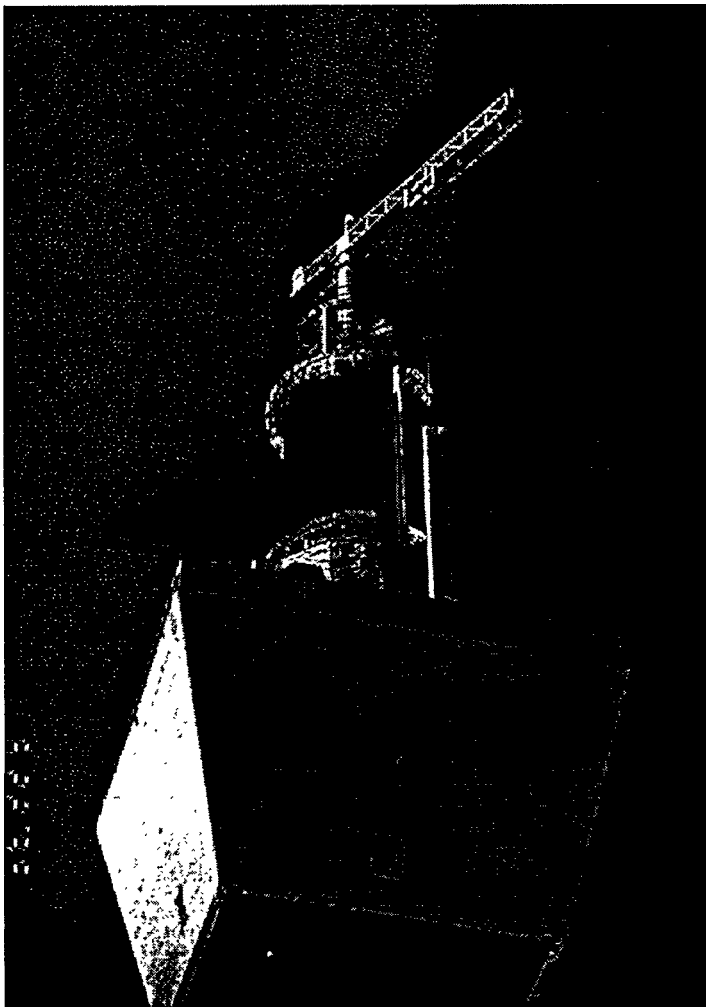


Figure 5. Installation of Final Receiver Panel

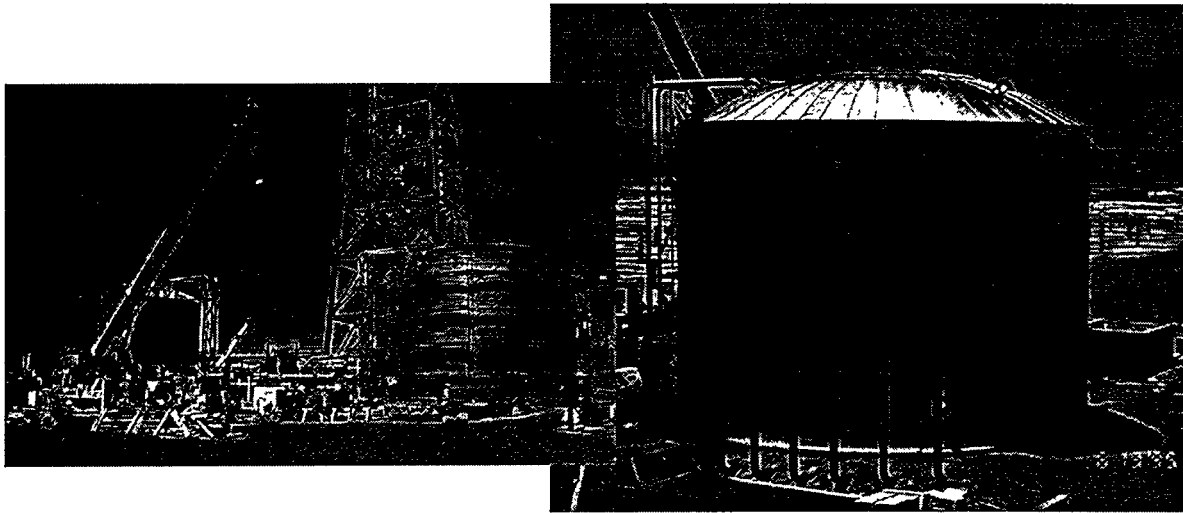


Figure 6. Tank Construction and Nearly Complete Hot Tank

serve as low points in the system to drain salt from all associated piping systems. Cold salt is pumped from the receiver sump to the receiver by two multistage, vertical turbine pumps. Hot salt is pumped from the steam generator sump to the steam generator by two vertical cantilever pumps. The receiver pumps are 50% rated capacity with both pumps required to operate the receiver. The two steam generator pumps are 100% rated due to the limited size ranges available for the required flow, temperature, and pressure conditions, and to provide redundancy. (The project design approach has been to use commercially available equipment to the maximum extent possible and avoid developing special equipment.) In addition to the main pumps, a nitrate salt mixer pump uses cold salt to attenuate the hot salt streams to the steam generator and for the production of auxiliary steam. Figure 6 illustrates tank construction and the nearly completed hot tank.

A 35-MW_{th} steam generator has been added to convert the thermal energy in the nitrate salt to 512°C/6.8-MPa steam for the turbine-generator. The steam generator, designed and supplied by ABB Lummus, consists of a U-tube/U-shell preheater, a kettle-boiler evaporator, and a U-tube/U-shell superheater. Figure 7 shows steam generator hardware early in the installation process.

Modifications and additions to the plant's control system have been made to replace equipment no longer supported by the original suppliers and to integrate the existing and new heliostats under one heliostat array controller. The plant control system consists of five subsystems which coordinate process system control through all states and transitions in response to operator commands and system alarms, integrate the

control of the heliostat field with the receiver through the operator control system and the heliostat array controller, and in addition support data acquisition and communications. The Master Control System is a distributed process control system supplied by Fisher Rosemount with an interlock logic system

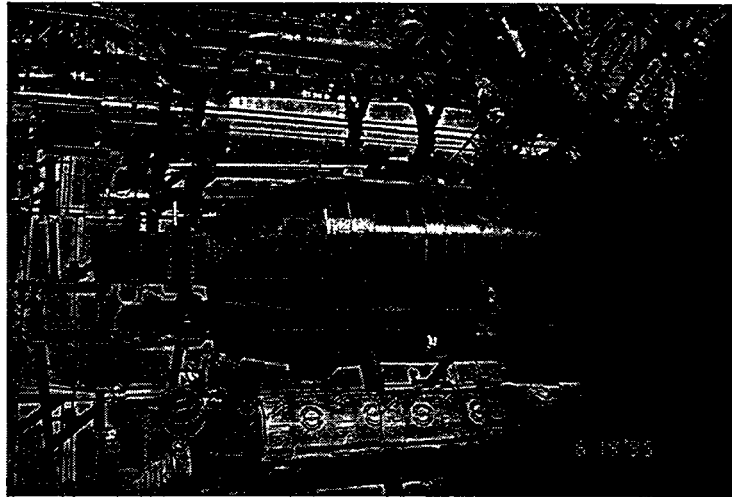


Figure 7. Steam Generator Vessels

(programmable logic controllers (PLCs)) supplied by Modicon. These two systems comprise the man-machine interface and the primary plant process controls. Three other systems, the Heliostat Array Controller (HAC), Operational Control System (OCS), and the Data Acquisition System (DAS) are configured on DEC Alpha hardware and "Setcim" software for the overall project archive database. The HAC and OCS comprise the primary software interfaces between the heliostats and receiver. In conjunction with the HAC and OCS, the University of Houston has developed two software algorithms which configure the heliostat field for daily warm-up and provide a real time look-ahead to protect the receiver from over-temperature. The DAS records and archives all process and discrete data at specified time intervals ranging from one second to one minute. The primary control systems are redundant and have "hot" failover capability to protect the plant. The Solar Two Beam Characterization System (BCS) replaces the Solar One BCS with a stand-alone system for periodically checking heliostat alignment and flux patterns.

An inherent design feature of nitrate salt technology is the electric heat tracing required for piping and components to prevent salt freezing (at approximately 240°C) in any pipe or component. The process electric heat tracing (EHT) system was designed and manufactured by Raychem. The primary function of the EHT is to warm-up and control the nitrate salt piping systems and equipment to prevent thermal shock and to maintain filled systems above the salt freezing temperature. The system consists of redundant stainless steel-sheathed MgO-insulated resistance heating elements (both single and dual elements). The 250 individual EHT zones are controlled by Chromalox

solid state temperature controllers and allow for remote set-point adjustments and multiple system configurations to accommodate the various plant operating states and transitions. The test and evaluation phase of Solar Two will evaluate operational strategies to minimize the parasitic load imposed by operation of electric heat trace.

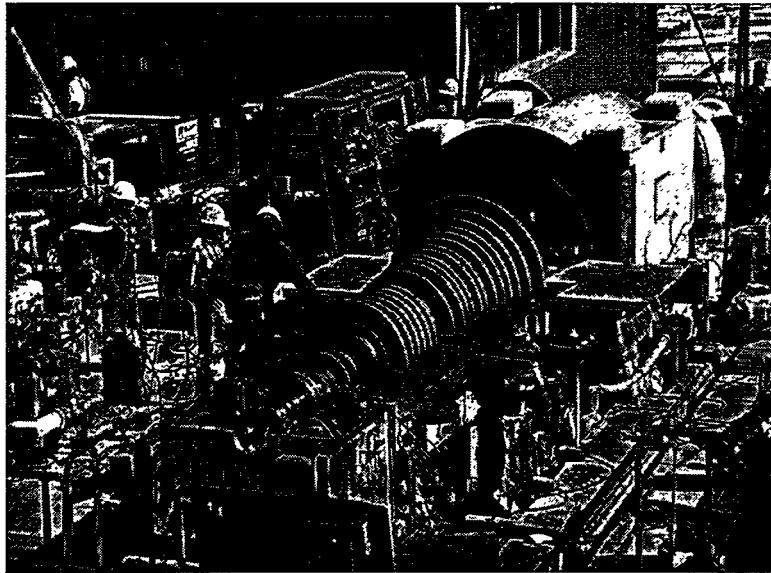


Figure 8. Refurbishment of Solar Two Turbine

The turbine and associated equipment was originally supplied by General Electric as a part of the Solar One Project. The unit is rated at 12.5 MW gross electrical output at 8.4-kPa condenser back pressure and throttle steam inlet conditions of 510°C, 10 MPa, and a flow rate of 50,000 kg/hr. The air-cooled generator is rated at 14,230 kVA, which supplies 13.8 kV electric power to the 13.8-to-33-kV main transformer and onto SCE's 33-kV distribution system. The turbine is configured with four extraction points for feedwater heating. Feedwater heating is accomplished using a conventional train design where condensate is forwarded from the condenser through the fourth-point low pressure heater, the deaerator (third-point heater), and then through the high pressure (first- and second-point) heaters. Feedwater is forwarded to the steam generator for main steam production as described earlier. The turbine, generator, condenser, feedwater train, and auxiliary systems were all refurbished for reuse by the Solar Two Project, reducing project costs substantially. Figure 8 shows reassembly of the refurbished turbine.

Solar Two has been designed to demonstrate as many operating features of a commercial plant as possible. The heliostat and receiver systems, along with the thermal storage system, form a solar loop which collects and stores thermal energy. The steam generation and electric power generation systems, along with the thermal storage system, form a second (power generation) loop which converts the stored thermal energy into electricity. The thermal storage system provides a common interface between the

two loops, which operate independently. For a typical operating day at Solar Two, the solar loop will be activated at sunrise with the bulk of the nitrate salt inventory in the cold tank. The loop will operate several hours to charge the thermal storage system using the hot salt storage tank. Once sufficient hot salt is available, the power generation loop will be started. Both loops will then operate during the afternoon. The solar loop will be shut down at sunset while the power generation loop will continue to operate into the early evening (or perhaps delayed until morning if needed), as long as hot salt is available. To demonstrate dispatchability, the power generation loop will also occasionally be operated for longer periods at reduced power output.

Plant Evaluation

The best measure of the performance of a solar thermal system is its annual efficiency, defined as the net annual electricity produced by the plant divided by the annual amount of direct-normal insolation falling upon the mirror field. Examples of the factors included in annual efficiency are energy losses due to dirty mirrors, equipment failures, Rankine-cycle losses, and parasitic energy use by auxiliary equipment such as pumps and electric heat trace.

The annual efficiency for a 100-MW solar-only plant has been estimated to be approximately 15% [5,6,12]. However, due to the small size and non-optimal configuration of Solar Two, we estimate its annual efficiency will be in the 8 to 10% range [13]. The reasons the annual efficiency will be lower than the 100-MW commercial system are:

- A primary objective of the Solar Two project is to evaluate nitrate salt technology, not heliostat technology or performance. With the Solar Two project being cost-driven, heliostat additions and improvements to the existing Solar One heliostat field were kept to a minimum. Consequently, the heliostat field is not state-of-the-art. The Solar One heliostats employ an old control strategy, and the mirrors have experienced degradation due to corrosion. Also, the reflectance of these older mirrors is below today's standard (90% vs. 94%). (Reflectance, corrosion, and controls are not problems with current heliostat technology.) In addition, the 108 new heliostats added to the field, though inexpensive, are relatively large for the receiver being installed. Consequently, the reflected beams from these heliostats are somewhat too large, and a portion of the beams will not intercept the receiver.

Combining all these effects, we expect a field performance of about 90% of the performance of a commercial plant.

- Unlike the 100-MW plant, Solar Two does not use a reheat turbine cycle. Consequently, gross Rankine-cycle efficiency will be reduced from 42.5% to 33%.
- Some of the Rankine-cycle equipment is old, and other sections do not employ the equipment redundancy that is expected in the 100-MW plant. Plant availability is thus expected to be 88% rather than the 91% expected for a commercial plant.
- Since Solar Two is only 10 MW with about a 20% capacity factor, parasitic electricity use will be a much greater fraction of the total gross generation than for a 100-MW commercial plant with a 40% capacity factor. Parasitic energy use at Solar Two is expected to be 20 to 25% of the total gross generation; for a commercial plant, parasitics are predicted to be about 10%.

Peak plant efficiency is not expected to be achieved at Solar Two until its third year of operation, after startup problems with this new technology have been solved and the test and evaluation phase has optimized plant operations.

Current plans for the project's test and evaluation phase include 21 tests and eight sets of evaluations. The first several tests are designed as plant familiarization activities. The next series of tests will determine the plant's operational and performance characteristics, while the final test series will seek to optimize the plant. The eight plant evaluations will analyze specific aspects of plant operation and performance, such as availability, efficiency, parasitic losses, and operability and maintainability. Documentation resulting from the test and evaluation phase will include test reports and reports associated with each of the eight evaluations. Test and evaluation activities will be staffed by lead engineers from the project's utility participants, with support from Sandia and the National Renewable Energy Laboratory as needed.

The project will address the perceived technical and economic risks associated with building the first commercial plants in the following manner:

Plant Design-Point Performance. The largest uncertainties in design point performance are the receiver optical and thermal losses, since the heliostat characteristics and thermal performances in the balance of the plant are reasonably well

understood. Data from field performance and receiver thermal loss measurements during the one-year test and evaluation period will be available to corroborate or refine performance models.

Annual Performance. Annual plant performance is estimated with the SOLERGY computer code, which uses equipment performance characteristics and site weather data to calculate energy flows throughout the year. Although the accuracy of the code has been corroborated by comparing the annual performance of the Solar One plant with computer projections [4], the two-year power production phase of the Solar Two project will provide an opportunity to verify the accuracy of the code for nitrate salt systems and to increase confidence in projections for commercial projects.

Plant Availability. During its three-year power production phase, the Solar One pilot plant had annual availabilities above 80%, and during its last year under SCE operation, an availability of 96% [3]. Commercial central receiver plants require an availability of 90% to achieve predicted energy cost goals. The three-year operation of Solar Two will provide the required data for high confidence in commercial plant projections.

Annual Operation and Maintenance Cost. O&M expenses for the Solar One plant are well understood, and projections of O&M expenses for the Solar Two and commercial projects are believed (based in part on extensive data from commercial parabolic trough plants) to be accurate. However, operation of the Solar Two project will provide an opportunity to corroborate the projections for Solar Two and to increase confidence in the estimates for commercial projects.

Equipment Prices and Warranties. This is one of the largest risks. Suppliers of the equipment for the initial commercial projects will be required to provide competitive bids and performance warranties. The Solar Two project will provide an opportunity for vendors to design, fabricate, and test equipment at a size within a factor of 3 of the physical size required for the first commercial project. For example, the height of the 10-MW Solar Two receiver is 6.2 m, compared to 19 m for a typical 100-MW plant. This experience, and a summary of the non-proprietary information and lessons learned, will be distributed to the power tower community and will reduce the uncertainties in providing equipment for the first commercial projects. The reduced risks, together with competitive bids, will help to minimize equipment prices for the initial projects.

System Performance Guarantees. To finance construction of initial 100-MW commercial projects, a limited annual performance guarantee will likely be required to minimize risk to the investors. Successful operation of the Solar Two project will reduce the system performance uncertainties and allow a guarantee to be offered.

Commercialization Plan

A plan for the commercialization of the technology has been developed by project participants and encompasses three phases.

As part of the first phase, the R&D Consortium for the Solar Two project has been formed and is proceeding with design, construction, and operation of the plant to provide the necessary data and confidence in the technology required to proceed with initial commercial plants.

During the second phase, a Commercialization Consortium will likely be formed from an industry joint venture establishing the terms for constructing the initial plants, with utility companies providing commitments for the initial plant orders and investment groups providing debt and equity financing. The key to reducing the plant capital cost to levels that will be acceptable to investors is to establish a steady demand for the most expensive items in the plants, specifically, the heliostats. One potential approach is to develop commitment agreements among one or more investors and interested utilities to build a minimum of three projects as the initial plants.

As currently envisioned, the initial plants could be deployed within the U.S. Solar Enterprise Zone [14] or within developing nations such as Mexico, India, or Morocco. Assuming the full plan for the Solar Enterprise Zone is implemented, 1000 MW of solar thermal and photovoltaic technology will be deployed in southern Nevada over a seven-year period commencing in the late 1990's. Currently, the plan calls for 200 MW of power towers. This amount of power could be supplied by one or more power towers in either solar-only or solar-fossil hybrid configurations. The decision regarding the best approach will be made over the next few years. Low interest money and tax credit and equalization measures are being actively sought by the non-profit Corporation for Solar Technology and Alternative Resources (CSTAR) to bring the cost of electricity from these initial plants within a cost-competitive range. A request for proposals for the first 100 MW was issued in June, 1995.

Besides the Solar Enterprise Zone, an avenue for deploying the initial power towers exists through a program sponsored by the World Bank's Global Environmental Facility (GEF). The GEF provides grant money to develop technologies that reduce global warming. To qualify for up to \$50 million in grant money, a project must be deployed in a developing country. The grant money is used to bring the cost of electricity from the solar project within a competitive range. Recently, the GEF has expressed considerable interest in funding a number of solar thermal projects.

During the third phase, the rights, expertise, and know-how developed by the industry joint venture through construction of the initial plants would be converted into one or more alliances, partnerships, or other ventures to develop, construct, and operate follow-on large-scale projects. Utility and investor participants in the Commercialization Consortium could be part owners and investors in the new entity or entities, which would compete within whatever market structures exist for the construction of new generating capacity by United States utilities and internationally. We anticipate that levelized electricity costs from these higher-volume production facilities will drop to or near the costs of competing fossil technologies.

Conclusions

The Solar Two project is well defined and timely. It is the first step in a process recommended to commercialize the technology [4,5]; it enjoys strong financial support from DOE and utilities in the western United States; and it is well timed to meet the world's needs for large-scale renewable energy generation early in the next century. Its successful completion will enable implementation of plans for commercial power tower development throughout the world.

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