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Performance of the Solar Two Central Receiver Power Plant

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Abstract. Solar Two is a utility-led project to promote the commercialization of solar power towers by retrofitting the Solar One pilot plant from a water/steam-based system to a molten salt system. Solar Two is capable of producing 10 MW_e net electricity with enough thermal storage capacity to operate the turbine for three hours after sunset. The plant was turned over to its operations and maintenance contractor in February 1998, marking transition from start-up to the test and evaluation phase. Solar Two has collected as much as 230 MWh thermal and generated as much as 72 MWh_e gross electricity in one day. The plant has demonstrated dispatchability after dark, during clouds, and during sunshine hours. To date, Solar Two has collected thermal energy at a maximum rate of 39 MW_t and generated gross electricity at a maximum rate of 11.1 MW_e. Important lessons have been learned in the areas of heat trace, valve selection, materials of construction, and steam generator design. Testing has begun in a number of areas relating to receiver performance, storage tank performance, salt chemistry, overnight thermal conditioning, electricity dispatching, performance monitoring and evaluation, availability tracking, and receiver controls.

1. INTRODUCTION

Molten-salt solar power towers offer dispatchable solar electricity by virtue of cost-effective thermal energy storage. In the long term, they will be able to provide capacity factors as high as 77%. Currently, 65% is realistic. It is anticipated that power towers could produce electric energy at a cost of 14 cents/kWhr in the year 2000, 5 cents/kWhr by 2010, and 4 cents/kWhr by 2020 [1]. Before they are ready for commercial deployment, however, power towers require demonstration of the reliability of the molten-salt systems and the development of low-cost heliostats. Reliability is

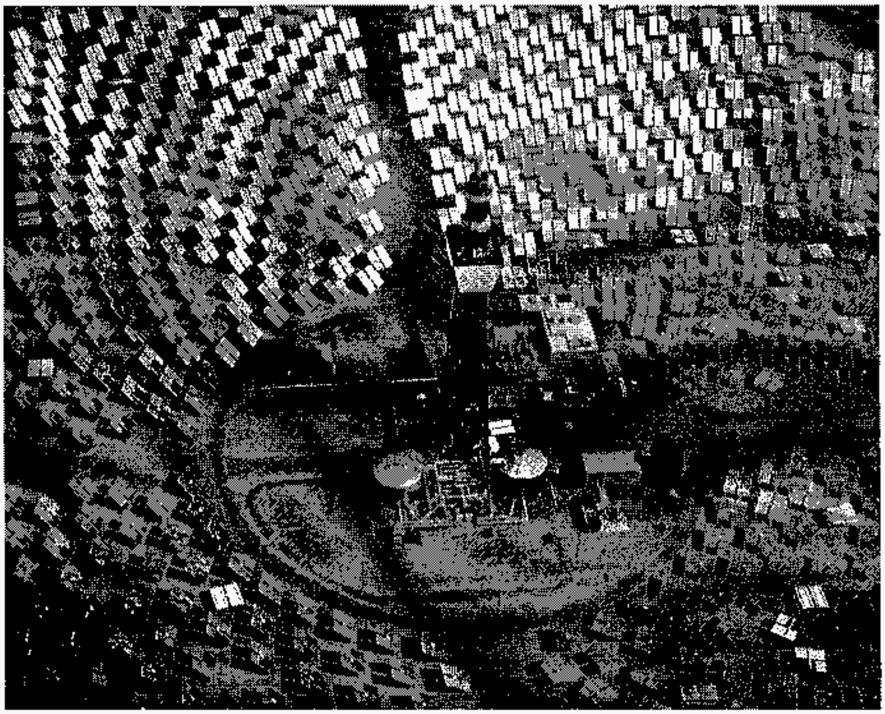

Figure 1. Aerial view of Solar Two.

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currently being demonstrated by the 10 MW_e Solar Two project, Figure 1.

The goals of Solar Two are to validate nitrate salt technology, reduce technical and economic risk, and stimulate the commercialization of the technology. The developmental history and design of Solar Two have been described previously [2-5]. This paper summarizes the status of the project, highlights some of its accomplishments, details some lessons learned, and provides key results from the project's test and evaluation program.

2. ACCOMPLISHMENTS

Solar Two was turned over to the operations and maintenance (O&M) contractor, Energy Services Inc., in February 1998, marking the successful completion of plant acceptance testing and transition to the test and evaluation phase of the project.

Solar Two has collected as much as 230 MWh_t and generated as much as 72 MWh_e gross electricity in one day. Also, Solar Two has demonstrated dispatchability after dark, during clouds, and throughout the day. To date, Solar Two has collected thermal energy at a maximum rate of 39 MW_t and generated electric energy at a maximum rate of 11.1 MW_e. Operation so far has demonstrated that Solar Two is meeting its objective of reducing risk by identifying and resolving various technical problems. The plant is doing everything it was intended to do: collect solar energy efficiently, store energy efficiently, and generate dispatchable electricity.

3. LESSONS LEARNED

Solar Two faced some challenging problems during its startup period which began in the fall of 1995 and ended in February 1998. However, the project has encountered no technology showstoppers. The major problems were incorrect application of heat trace, a ruptured tube in the evaporator system, failure of ball valves in molten-salt service, and stress-corrosion cracking in the receiver and the stainless steel salt piping. As these problems surfaced, the engineering team made up of Bechtel Corporation, Energy Services, Southern California Edison, Sun•Lab[2], and Boeing systematically reviewed the appropriate components and subsystems and made the necessary installation modifications, design changes, and upgrades. Some of the more important lessons are discussed below.

3.1 Electric trace heating

The nitrate salt in the plant is a mixture of 60 percent by weight sodium nitrate and 40 percent potassium nitrate. The nominal melting temperature is 210 °C; thus, electric heat trace cable must be used to 1) preheat the equipment prior to filling with salt, and 2) maintain the temperature of salt-filled equipment above 260 °C when the plant is not in operation. The initial approach to heat tracing the piping and valves was to place the pipe and valve bodies in a common circuit. To prevent the temperature of the valve body from lagging the temperature of the adjacent pipe during the preheat period, multiple loops of heat trace cable were installed on the valve bodies. The lengths of the cables in each circuit were determined by the heat trace vendor. The cables were fabricated in a factory, and shipped to the site for installation by the general contractor.

Major problems with the heat tracing became apparent during startup. The lengths of the cables intended for each valve were inconsistent with the dimensions of the valve bodies, and most circuits had a surplus of cable. The extra cable was installed on the adjacent pipe in short double or triple loops, resulting in nonuniform power densities. Depending on where the control temperature indicator was located on the pipe, some regions near the extra heat trace were subject to extreme overheating (> 650 °C) while areas away from the extra heat trace were often too cold (< 150 °C).

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[2] Sun•Lab refers to the collective efforts of Sandia National Laboratories and the National Renewable Energy Laboratory toward the development of Concentrating Solar Power technologies.

The detrimental effects of the nonuniform heat trace installation surfaced in June of 1996, when a tube in the receiver overheated and ruptured. Scale produced by excessive temperatures in the carbon steel and low-alloy piping accumulated in one of the receiver tubes, and blocked the cooling flow.

The heat trace design was revised and much of the plant heat tracing was replaced. This eliminated the local regions of high and low pipe temperatures. The new heat trace can maintain the temperature of a valve body within 1 °C of the set point for an indefinite period. In addition, set point temperatures for the valves in hot salt service can be safely maintained at values as high as 480 °C; this significantly reduces the effects of temperature changes during plant startup.

3.2 Steam Generator

The steam generator system consists of a preheater, a kettle evaporator, and a superheater. Its design was based on the following feedwater temperatures: 121 °C during auxiliary steam production; 146 °C at the minimum feedwater flow rate of 13,600 kg/hr; and 206 °C at the maximum flow rate of 51,800 kg/hr. The minimum feedwater temperatures were to be established by 1) using saturated water from the deaerator at a temperature of 121 °C, 2) recirculating saturated water from the evaporator to mix with the feedwater at the inlet to the preheater, and 3) using the extraction feedwater heaters.

Achieving these feedwater temperatures proved to be impossible. First, the feedwater entered the evaporator through a distribution sparger along the bottom of the shell, adjacent, unfortunately, to the suction nozzles for the recirculation pumps. As a result, the coldest feedwater in the evaporator was recirculated to the inlet of the preheater.

Because of this and other design problems, the temperature of the salt entering the preheater was often above the saturation temperature of the feedwater, and periodic batch boiling of stagnant water likely occurred in the preheater tubes. More seriously, a combination of low feedwater temperatures, low flow rates, and poor recirculation established a temperature gradient in the evaporator water inventory of perhaps 220°C. Salt would freeze in the bottom rows of tubes, and then thaw when the extraction feedwater heaters were placed in service. Repeated freeze and thaw cycles ruptured an evaporator tube in November of 1996.

To correct the problems, the following modifications were made:

1) The feedwater bypass line around the preheater was removed, ensuring a continuous flow of feedwater through the preheater and <u>hot</u> feed water to the evaporator.
2) The feedwater sparger system in the evaporator was redesigned to eliminate thermal stratification.
3) The tube bundle in the evaporator was replaced to eliminate damaged tubes.
4) A larger recirculation water pump was added to increase the flow rate of saturated water to the preheater.
5) A startup feedwater heater was added between the first-point extraction feedwater heater and the preheater to insure adequate feedwater temperature during startup.

The modifications have proven successful. Transient feedwater flow rates up to 31,800 kg/hr during turbine synchronization have been accommodated without the feedwater temperature to the preheater falling below 210 °C. In addition, the temperature of the feedwater entering the evaporator is always 271 °C or above, and the temperature gradients within the evaporator inventory are now less than 2.2 °C.

3.3 Valves

Ball valves were selected for isolation service in both hot and cold salt in preference to gate valves. The shaft on a ball valve only needs to rotate 90 degrees to move the valve between the open and closed positions. In contrast, the stem on a gate valve must translate through the packing a nominal distance equal to the pipe diameter. Ball valves were chosen because if solid salt were to form in a valve packing, rotation of the stem of a ball valve should cause less damage to the packing than translation of the stem of a gate valve.

In practice, the ball valves were found to be generally unacceptable. In 80 percent of the valves, a combination of clearances could not be obtained which allowed the valve to both move freely between the open and close positions, and to be free from internal leakage. In addition, the 10.2-, 15.2-, and 20.3-cm valves used three-piece valve bodies sealed with two ring-type joints. In 20 percent of the valves, the daily temperature cycles produced external leakages in as little as 10 operating cycles.

Conventional globe valves were selected for control service in both hot and cold salt. In general, the valves have performed well and are free of external leaks. However, the extended bonnets on the valves in hot salt service must be tall enough to maintain the packing below its upper limit of 316 °C. Above this temperature, the Teflon® washers in the packing decompose, which releases fluorine gas and chemically attacks the stainless steel valve stem. The weakened material is subject to scoring, which causes erratic operation of the valves. As major problems are encountered with ball valves at Solar Two, they are replaced on a case-by-case basis.

3.4 Nitrate Salt Piping Materials

The project used ASTM A106 Grade B carbon steel for the cold salt piping. Some of the lines suffered severe corrosion damage due exclusively to the incorrect application of heat trace cable. The corrosion rate on the balance of the piping was no greater than expected. Therefore, mild steel is appropriate for cold salt piping, provided care is used in the design and application of its heat tracing.

The project used primarily AISI Type 304/304H stainless steel, with a minimum carbon content of 0.04 percent, for the hot salt piping. Limited portions of the piping, and essentially all of the fittings, were fabricated with Type 316H and Type 347 materials.

Late in 1997, a crack developed in the stagnant leg of a 304H tee in the hot salt piping. A destructive examination of the crack showed that intergranular stress corrosion cracking (SCC) was a principal contributor to the failure. All of the requirements for this type of corrosion were present:

1) Susceptible Material. When the material is heated to temperatures in excess of 540 °C for periods of more than a few hours, or to higher temperatures for shorter times (e.g., during welding), the chromium and the carbon in the steel react to form chromium carbide at grain boundaries. The depletion of some of the chromium leaves the stainless steel sensitive to chemical attack along the grain boundaries.
2) Tensile Stresses. To weld the cap to the tee, the temperature of both must be raised to the melting point of the steel. As the weld region cools and shrinks, significant residual tensile stresses remain in and adjacent to the weld.
3) Chloride Ions. The nitrate salt from Chilean Nitrate Corporation contains approximately one-third of one percent by weight of chlorides, in accordance with project specifications.
4) Water. The fitting was removed from the pipe in the summer of 1996, and stored on a pallet adjacent to the steam generator. Moisture was free to enter the pipe from both rain and evening condensation.

In the next central receiver project, it is unlikely that moisture can always be excluded from the hot salt piping; as a minimum, the lines will be open to the atmosphere for valve and pump maintenance. To prevent a repetition of this corrosion phenomenon, the hot salt piping should be constructed from a material less susceptible to stress corrosion cracking (e.g., 304L, 347, 321).

The receiver tubes, which are made of 316H stainless steel, also suffered from stress corrosion cracking. In August of 1997, a number of minor leaks were discovered on several of the tube crowns. Destructive examinations identified intergranular stress corrosion cracking, starting from the inside of the tubes, as the source of the leaks. The liquid water required for this corrosion phenomenon came from either 1) an aqueous flush of the receiver system to remove the scale generated from the initial heat tracing problems, or 2) moisture from the air condensing in the tubes at night. Replacing the corroded tubes eliminated the leaks, and moisture is now excluded from the receiver each night by a continuous flow of dry air. The receiver has been run for several hundred hours since these changes were made without occurrence of new leaks due to SCC.

Because of the limitations of stainless steel, the receiver vendor, in cooperation with Sun♦Lab, has conducted material tests to determine the mechanical properties of several advanced alloys. A suitable material was found, and a prototype panel was fabricated and installed on the Solar Two receiver. Since its installation in December 1997, the new panel has performed well.

4. TEST AND EVALUATION

Sun♦Lab is responsible for Solar Two testing, which consists of 14 specific elements:

1. Develop a performance map for the steam generator and turbine/generator systems. Validate an existing thermodynamic model for the steam generator.
2. Verify performance of the receiver control algorithm for simulated cloud transients. Tune controls for optimum response.
3. Develop heliostat aiming patterns which minimize startup times for various times of day, seasons, and wind conditions.
4. Measure receiver efficiency as a function of operating temperature and wind conditions.
5. Develop a receiver loop performance map as a function of incident power, wind conditions, receiver operating temperature, time of day, and season.
6. Measure the thermal losses from the plant equipment and piping.
7. Measure and reduce electric power consumption throughout the plant.
8. Determine the impact of rain on the startup readiness of the receiver.
9. Determine the impact of high winds on the drain time of the receiver.
10. Develop energy conservation strategies for overnight shutdown.
11. Operate as a utility plant producing maximum net output while characterizing overall performance.
12. Demonstrate dispatchability.
13. Measure chemical composition of salt periodically. Conduct metallographic examination of corrosion samples.
14. Measure the displacements and stresses in the storage tank wall and bottom joint.

The central theme in the test and evaluation (T&E) plan is the performance of tests concurrent with routine power production. A major advantage of this structure where most of the tests essentially run all of the time is that data are obtained for all four seasons of the year over a wide range of weather conditions. To date, progress has been made in a number of areas including receiver efficiency, parasitic power reduction, overnight thermal conditioning, dispatchability, corrosion and salt chemistry, and storage tank characterization. Some of the more significant results are summarized in the sections that follow.

4.1 Receiver Efficiency

The major goal of the receiver efficiency test is to map the receiver efficiency as a function of operating temperature and wind speed. Receiver efficiency, η, is defined as the ratio of the average power absorbed by the working fluid, P_{abs}, to the average power incident on the receiver, P_{inc}, evaluated over a defined period under steady-state conditions.

$$\eta = \frac{\overline{P}\text{abs}}{\overline{P}\text{inc}} \qquad (1)$$

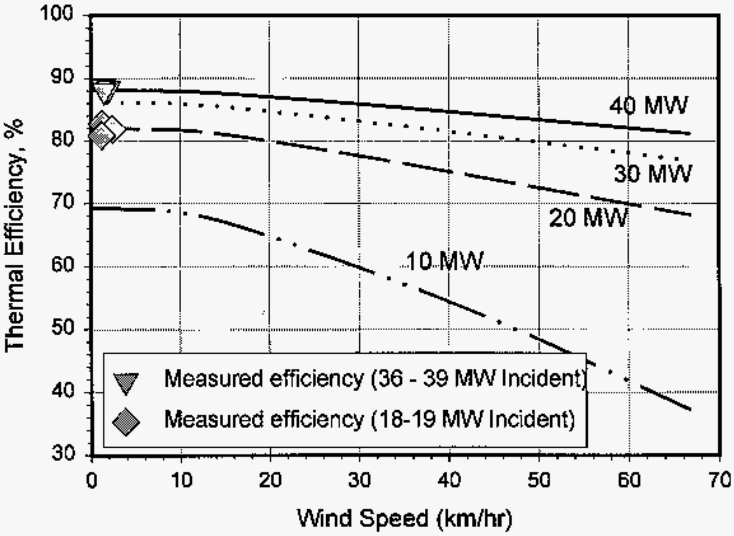

Figure 2: Measured and simulated receiver efficiency as a function of incident power.

In Figure 2, results from tests on September 29, 30, and October 1, 1997 are compared with simulations from a model of the thermal performance of the receiver. This model was used to estimate efficiency at the test conditions [7] and accounts for losses due to reflection, radiation, convection, and conduction. It employs the mixed convection correlation proposed by Stoddard [8]. The results of the model fall within 1% of the receiver manufacturer's predictions (not shown) and agree very well with our test results. At design conditions, the receiver performs with a thermal efficiency near 89%.

4.2 Coupon Corrosion and salt chemistry

Tests have been started to determine the long-term chemical behavior of the molten salt and its effect on containment materials. Four corrosion chambers were installed in various locations throughout the salt piping; each chamber contains many coupons of different alloys for periodic extraction and metallurgical examination. The composition of the salt and its melting point have been tracked since the salt was introduced into service. Figure 3 shows how salt melting point has evolved since the salt was added to the plant. Salt composition and impurity levels are nominal. However, the salt melting point has been trending down over the last 20 months, from about 207 °C, initially, to about 202 °C now. We currently have no explanation for this trend, but it appears to be tapering off. Examination of corrosion specimens and analysis of salt composition and melting point will continue throughout the T&E program.

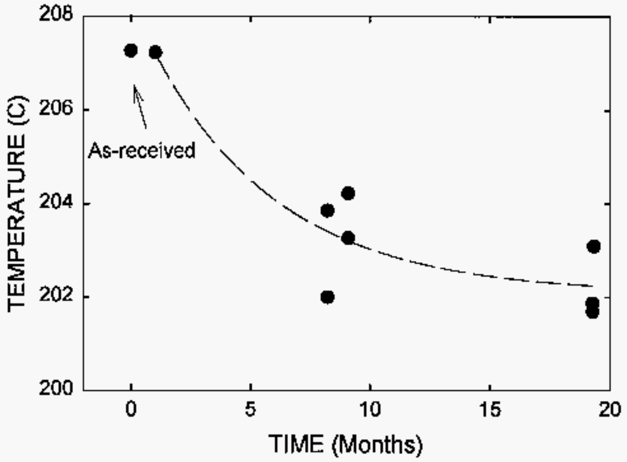

Figure 3: The melting point history for the Solar Two Salt.

4.3 Dispatchability

Dispatchability has been demonstrated on numerous occasion at Solar Two. Electricity generation after dark, after clouds rolled in, and during sunshine hours has proved the versatility of the molten-salt power tower technology. Figure 4 illustrates dispatchability at half power for over two hours after sunset and for over four hours after receiver shut down.

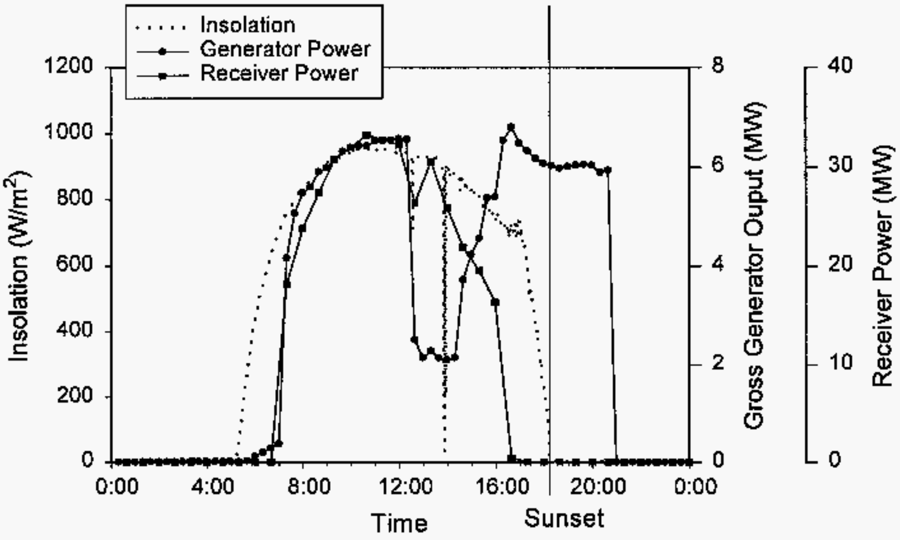

Figure 4: Illustration of electricity dispatching after sunset, April 22, 1998. Electric energy was dispatched for 4.5 hrs after the receiver was shut down and for about 2.5 hrs after sunset.

5. CONCLUSIONS

Solar Two is meeting its objective of mitigating risk by surfacing problems that are subsequently corrected through improved design, better equipment, and superior operating procedures. The project is proving viable the concept of dispatchable electricity from a molten-salt power tower plant. Operations are currently scheduled to continue at least through 1999. By then, we anticipate that the technology will be validated through testing and demonstrated reliable operation.

6. ACKNOWLEDGMENTS

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