SAND99-0091C

OVERVIEW OF RECENT RESULTS OF THE SOLAR TWO TEST AND EVALUATIONS PROGRAM

James E. Pacheco

Rockwell Gilbert

Sandia National Labs, 6216
PO Box 5800, MS 0703
Albuquerque, NM 87185-0703
Phone: 505-844-9175
Fax: 505-844-7786

ABSTRACT

The Solar Two project is a collaborative, cost-shared project between eleven US industry and utility partners and the U.S. Department of Energy to validate the molten-salt power tower technology. The Solar Two plant, located east of Barstow, CA, comprises 1926 heliostats, a receiver, a thermal storage system and a steam generator system that use molten nitrate salt as the heat transfer fluid and storage media. The steam generator powers a 10 MWe, conventional Rankine cycle turbine. This paper describes the test plan and evaluations currently in progress at Solar Two and provides some recent results.

PROJECT BACKGROUND AND SYSTEM DESCRIPTION

The 10-MWe Solar One Pilot Plant, which operated from 1982 to 1988 in Barstow, California, was the largest demonstration of first-generation power-tower technology (Radosevich, 1988). During operation of Solar One and after its shutdown, significant progress was made in the United States on more advanced second-generation power tower designs. The primary difference between first- and second-generation systems is the choice of receiver heat-transfer fluid; Solar One used water/steam, and the second-generation systems in the U.S. use molten salt.

The U.S. industries currently prefer molten-salt power towers because the design decouples the solar collection from electricity generation better than water/steam systems and it allows the incorporation of a cost-effective energy storage system. Energy storage allows the solar electricity to be dispatched to the utility grid when the power is needed most which increases the economic value of solar energy. A team composed of utilities, private industry, and government agencies have joined together to demonstrate molten-salt power towers at the 10-MWe Solar Two plant, which was constructed by retrofitting Solar One with molten-salt technology.

Converting Solar One to Solar Two required a new molten-salt heat transfer system (including the receiver, thermal storage, piping, and a steam generator) and a new control system. The Solar One heliostat field, the tower, and the turbine/generator required only minimal modifications. The major Solar Two equipment are described in the paragraphs that follow. A schematic of the plant is shown in Figure 1.

The Bechtel Group, Inc. designed and constructed the new salt system; they developed the plant layout, sized much of the salt handling equipment, and developed specifications for the receiver, storage tanks, steam generation system, and the master control system (Kelly and Singh, 1995). The design was based on experience gained from molten-salt receiver and system experiments conducted at the National Solar Thermal Test Facility (Smith and Chavez, 1992). Bechtel also installed all of the salt piping (except piping in the receiver system), pumps, sumps, instrumentation and controls. In addition, Bechtel was responsible for plant start-up and acceptance testing.

The Solar Two receiver was designed and built by Boeing North American, Inc. It is rated to absorb 42 MW of thermal energy at an

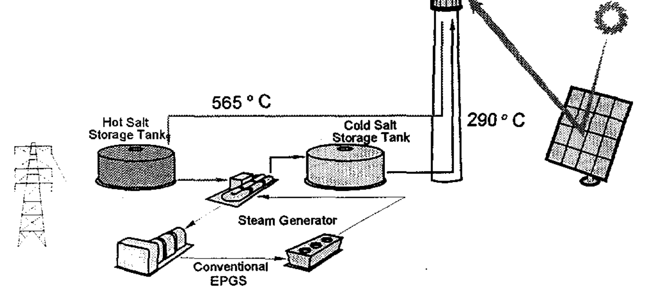

Figure 1. Schematic of a molten-salt power plant. Molten salt is heated to 565°C within a salt-in-tube receiver and pumped to the hot storage tank. After making steam, molten salt at 290°C is returned to the cold tank and pumped back to the receiver.

DISCLAIMER

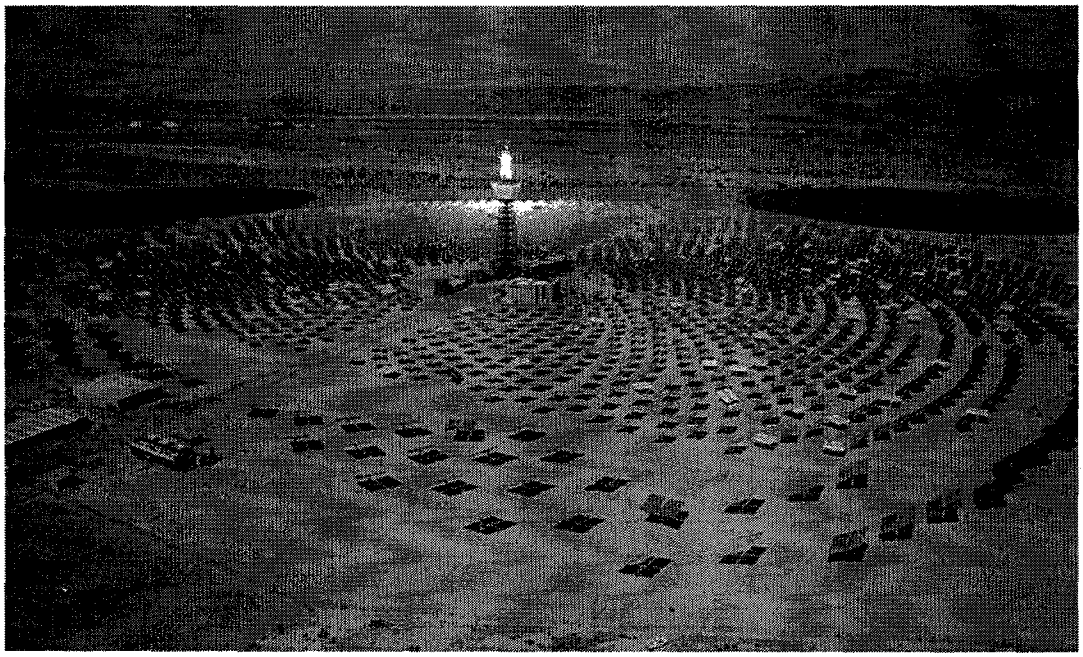

Figure 2. Photograph of the 10 MWe Solar Two power plant in operation.

average solar energy flux of 430 kW/m^2. The receiver consists of 24 panels that form a cylindrical shell around internal piping, instrumentation and salt holding vessels. Each panel consists of 32 thin-walled, stainless steel tubes connected on either end by flow-distributing manifolds called headers. The external surfaces of the tubes are coated with a black Pyromark paint that is robust, resistant to high temperatures and thermal cycling, and absorbs 95% of the incident sunlight. The receiver is designed to rapidly change temperature without being damaged. For example, during a cloud passage, the receiver can safely change from 565 to 290 °C in less than one minute (Kolb and Saluda, 1999). The salt fed to the receiver is split into two flow paths. One circuit enters the north-most west panel and flows west in a serpentine fashion from panel to panel. The other stream enters the north-most east panel and flows east. After six panels, both streams cross over to balance energy collection variations that occur from east to west as a function of time-of-day.

The thermal storage tanks were fabricated on-site by Pitt-Des Moines. All pipes, valves, and vessels for hot salt are constructed from stainless steel because of its corrosion resistance in molten-salt at 565 °C. Lower cost carbon steel is used for cold-salt containment because of the salt's lower corrosivity at 290 °C. Solar Two is designed with a minimum number of gasketed flanges and most instrument transducers, valves, and fittings are welded in place to minimize salt leaks.

The steam generator system (SGS) was constructed by ABB Lummus. It consists of shell-and-tube super- and pre-heaters and a kettle evaporator. Stainless steel cantilever pumps transport salt from the hot sump through the SGS to the cold tank. Salt in the cold tank flow to the cold sump and is pumped with multi-stage centrifugal pumps up the tower to the receiver.

The thermal storage medium consists of 1.5 million kilograms of nitrate salt consisting of 60 wt% $NaNO_3$ and 40 wt% KNO_3, provided by Chilean Nitrate Corporation (New York). This salt melts at 220 °C and is thermally stable to about 600 °C.

The Rankine cycle turbine was refurbished from the Solar One project. It is rated for 12.4 MWe gross generation. It accepts steam from the steam generator at 100 bar and 510 °C.

The original 1818 Martin Marietta heliostats were also reused from Solar One, but the inner 17 rows of heliostats were refocused for the smaller Solar Two receiver. The area of each of these heliostats is 39.1 m^2. Some of the facets had fallen off in the early 1990s and were replaced with facets from a defunct photovoltaic power plant. Also, 108 large area (95 m^2) heliostats were added to the south part of the field to improve the flux profile of the receiver. Figure 2 is a photograph of the Solar Two plant.

TEST AND EVALUATIONS OVERVIEW

The objectives of the Solar Two Test and Evaluation (T&E) program are to gather data and information, and perform analyses to:

1. Validate the technical characteristics (reliability, annual net electric performance, environmental impact, and capability for dispatch) of the nitrate salt receiver, storage system, and steam generator technologies.
2. Improve the accuracy of economic projections for commercial projects by increasing the database of capital, operating, and maintenance costs.
3. Distribute information to U.S. utilities and the solar industry to foster wider interest in the first commercial plants.

Originally, the T&E program was planned to run for a period of one year after final plant acceptance (Bechtel, 1995). During this period, the entire plant and the operations and maintenance (O&M) crew were to be devoted exclusively to T&E with no emphasis on power production goals. However, the startup and acceptance phase of the project took much longer than expected. Consequently, the T&E phase was integrated into the power production phase and

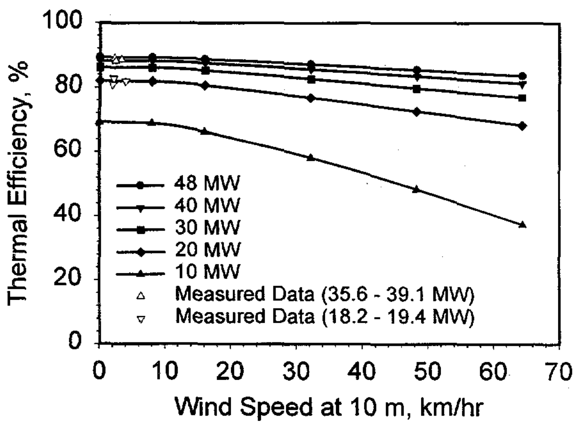

Figure 3. Receiver efficiency as a function of wind speed (various incident powers along with measured data). The model assumes the receiver absorptivity is 0.95, the inlet and outlet salt temperatures are 290 °C and 565 °C, respectively.

reorganized. Special tests that required the plant to be in a non-standard configuration were accommodated during power production, then the plant was returned to normal operation. Because of the compressed project schedule, the test plan was revised. Some tests were eliminated, others combined and re-scoped to fit into the new objectives. The following sections describe recent results from tests on the receiver efficiency, steam generator and electric power generation system characterization, thermal losses of major equipment, dispatchability, and plant performance. The primary objectives of these tests were to characterize each major subsystem relative to design performance and to characterize the overall plant performance relative to predicted performance.

RECEIVER EFFICIENCY TEST

The primary objective of the receiver efficiency test was to map the receiver efficiency as a function of operating temperature and wind speed. The 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.

Since the incident power cannot be measured directly on this size of receiver, the efficiency has to be obtained by eliminating incident power from the heat balance equation and by estimating the thermal losses from known measurements. The power-on method is designed for this type of measurement (Baker, 1988).

The heliostat field is divided into two groups of equal numbers of heliostats, symmetrically dispersed about the receiver. Group 1 contains every other heliostat. Group 2 contains the heliostats not in Group 1. The test is conducted symmetrically about solar noon between 11:00 AM and 1:00 PM solar time to minimize cosine effects of the heliostat field.

The receiver is operated at full power (both groups) with the outlet temperature fixed (e.g., 565°C ±14°C) during period A that runs between 11:00 AM and 11:30 AM (solar time). Then, for period B, group 2 heliostats (half the field) are removed (put in standby) and the flow is adjusted so the same outlet temperature is achieved. This period runs between 11:30 AM and 12:00 PM. At 12:00 PM, period C starts. The flow is increased and the full field tracks the receiver again. The flow rate is again adjusted to maintain the same outlet temperature as for the previous periods. At 12:30 PM, period D begins. Group 1 heliostats are removed. The flow rate is adjusted to maintain the desired salt outlet temperature. The test ends at 1:00 PM.

By dividing the heliostat field into two symmetric groups, the power on the receiver can be halved independent of field cleanliness, mirror corrosion, and to some extent heliostat availability.

The following assumption is made: under steady-state conditions with constant inlet and outlet salt temperatures and wind velocities, the temperature distributions on the receiver surface and throughout the receiver are independent of power level. Therefore, the thermal losses, $L_{thermal}$, are independent of the incident power and are a function of the absorbed power.

With constant thermal losses, the thermal loss can then be found by eliminating the incident power from the heat balance equation and determined only in terms of the absorbed power and receiver absorptivity, α. The efficiency can be expressed as:

$$\eta = \frac{\overline{P}_{abs}}{\overline{P}_{inc}} = \frac{\overline{P}_{abs}}{\dfrac{\overline{P}_{abs} + \overline{L}_{thermal}}{\alpha}} = \frac{\alpha}{1 + \dfrac{\overline{L}_{thermal}}{\overline{P}_{abs}}}$$

On September 29, 30, and October 1, 1997, the power-on method was used to measure receiver efficiency. For these tests, the outlet salt temperature was set to 552 °C instead of 565 °C because there was some concern that the outlet temperature would overshoot the set point when the receiver went through a severe transient. It turns out that the control system responded well and did not overshoot its set point. Performing the test at the de-rated outlet temperature of 552 °C results in measured efficiencies about ½ percentage point higher than what would be seen at 565 °C. At full power (34 MW–absorbed) the receiver efficiency was measured to be 88% with low wind velocities (<8 km/h). These data agree well with results from the calculated (modeled) efficiency as a function of wind speed as shown in Figure 3.

STEAM GENERATION / ELECTRIC POWER GENERATION SYSTEM CHARACTERIZATION

The Steam Generation / EPGS Characterization Test was intended to measure the steam generator system (SGS) and electric power generation system (EPGS) performance over a range of power loads and two inlet salt temperatures as described in Table 1. All the sub-tests, except the first, deviated from normal plant operation. Testing was done under steady-state conditions where the unit was held at that state for a minimum of two hours, but typically three to eight hours.

For the steady state operations test, the steam generator system and the electric power generation system were operated together to measure the gross thermal conversion efficiency at the various loading conditions.

We were not able to achieve the desired 565 °C salt at the inlet to the steam generator because, in addition to thermal losses, some of the molten salt valves in the receiver and steam generator system leaked causing cold salt to be mixed with hot salt. Although the receiver outlet temperature was set to 565 °C in the first set of tests and 575 °C, in the second, the salt entering the steam generator was typically about 21 °C cooler due to attemperation from the leaky valves and thermal losses. Also, at low salt flow rates, the operating procedure dictated that the cold mixer pump be turned on which further decreasing the inlet salt temperature by 27 °C.

In Figure 4, the measured gross turbine electrical output is plotted as a function of salt flow rate along with the heat balance values

Table 1: Desired and Actual Steady State Operation Loading Conditions.

Test No.	Hot Salt Temperature (Desired / Actual), °C	Salt Outlet Flow, % Full, kg/s (Desired / Actual) based on tank level changes	Steam Pressure, MPa	Steam Temp. (Desired/ Actual), °C	Actual Gross Electrical Output, kWe
1	565 / 544	100% (82.5 / 86.4)	10.1	538 / 532	10570
2	565 / 544	80% (66.0 / 69.8)	10.1	538 / 534	8880
3	565 / 542	60% (49.5 / 54.8)	10.1	538 / 536	5900
4	565 / 516	40% (33.0 / 18.0)	10.1	538 / 513	1310
5	575 / 557	100% (82.5 / 82.5)	10.1	546 / 542	10930
6	575 / 553	80% (66.0 /69.0)	10.1	546 / 542	9170
7	575 / 551	60% (49.5 / 46.7)	10.1	546 / 543	5830
8	575 / 525	40% (33.0 / 18.0)	10.1	546 / 522	1300

calculated by Bechtel during the design phase of the project. The measurements agree well with design estimates. The gross cycle efficiency (gross electrical power output divided by thermal power input provided by the salt to the steam generator system) is plotted against salt flow rate in Figure 5. Also shown is the design calculated gross cycle efficiency. Again, the measurements agree well with the design calculations. The inlet salt temperature has only a slight effect on both the efficiency and gross power output.

At full flow (82.5 kg/s) and at the design inlet and outlet salt temperatures of 565 and 290°C, respectively, the steam generator was designed to transfer 35.5 MW_t for a gross turbine output of 12 MW_e. We were unable to reach the design gross turbine output for several reasons. First, since some cold salt bypasses isolation valves down stream of the receiver, the inlet salt temperature to the steam generator was degraded. The highest salt temperature going into the steam generator was approximately 557 °C. Second, the original design of the steam generator was based on a feedwater temperature coming into the preheater at 201°C, which is below the salt freezing point, causing the evaporator tube bundle to experience several freeze thaw cycles. The steam generator was modified to recirculate saturated water from bottom of the evaporator to the inlet of the preheat to assure that feedwater below the salt freezing point never enters the preheater or evaporator during startup or normal operation. The effect of the recirculation is the preheater has less potential to transfer heat from the salt to the feedwater since the feedwater temperature is higher than design. Another reason we were unable to achieve the design gross turbine output was the preheater performance appeared to be degrading over time which showed up as a gradual increase in the outlet salt temperature of the steam generator. Table 2 shows the heat exchanger effectiveness for the preheater, evaporator, and superheater. The effectiveness is defined as the ratio of the actual heat transferred to the maximum possible for the actual flows and inlet and outlet temperatures of salt and water. It is apparent that the preheater effectiveness was low. After these tests, in August 1998, the flange on the preheater was removed and the tubes were found to have fouling and plugging. After cleaning, the performance improved dramatically, yielding a record gross turbine output of 11.6 MW_e.

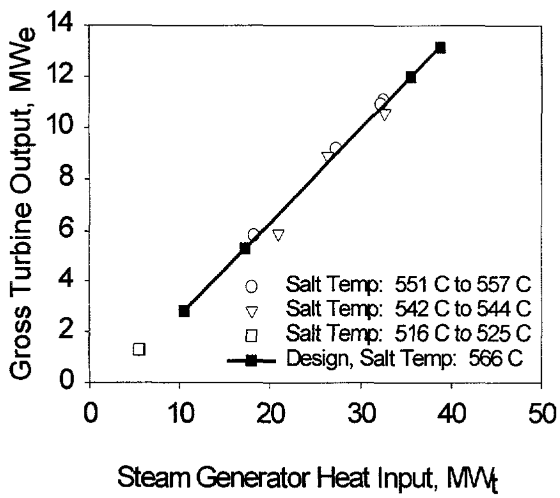

Figure 4. Measured and calculated (design) gross turbine electrical output as a function of heat input to the steam generator.

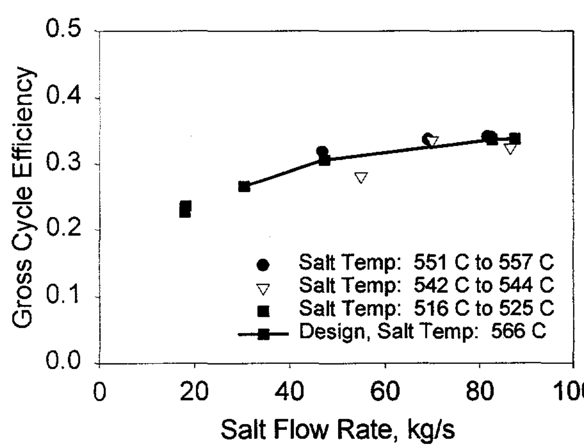

Figure 5. Measured and design gross cycle efficiency versus salt flow rate.

Table 2. Preheater, Evaporator and Superheater Effectiveness

Salt Flow, kg/s	Salt Temp, C	Preheater Effectiveness	Evaporator Effectiveness	Superheater Effectiveness
47	551	0.42	0.75	0.98
55	542	0.45	0.75	0.98
69	553	0.47	0.74	0.96
70	544	0.48	0.74	0.97
82	557	0.46	0.73	0.96
83	557	0.40	0.74	0.95
87	544	0.47	0.74	0.96

Table 3. Measured and Actual Thermal Losses of Major Equipment

Major Equipment	Calculated Thermal Loss, kW	Measured Thermal Loss, kW
Hot Tank	98	102
Cold Tank	45	44
Steam Generator Sump	14	29
Receiver Sump	13	9.5

THERMAL LOSSES

The objectives of the thermal losses test were to quantify the thermal losses of major equipment throughout the plant and to compare the values to estimated values. The major pieces of equipment evaluated were the hot tank, cold tank, steam generator sump, and receiver sump. There are two methods of measuring the thermal losses in the tanks and sumps. One method is to turn off all auxiliary heaters and track the rate of decay of the average tank or sump temperature. By knowing the salt level, and thus the volume of salt in the vessel, an estimate of the heat loss can be made. Another method is to have the heaters energized and regulating the inventory at a set temperature. Once the vessel is at steady state, the power consumption of the heaters is measured over a long period of time. The electrical power consumption is assumed to be equal to the heat loss.

A summary of the measured and calculated thermal losses is shown in Table 3. The thermal loss for the tanks and sumps are about what was calculated except for the hot sump. The losses for the steam generator sump were higher than predicted possibly because the insulation may have degraded significantly since it was installed. Salt has leaked out of the sump and into the insulation on the sump which significantly affects its insulating properties.

DISPATCHABILITY TEST

The objective the dispatchability test was to demonstrate the ability to dispatch electricity during the day, evening and night – independent of energy collection. The plant was designed to operate at full turbine output for three hours after shutdown. However, since the heliostat field has degraded both in availability, optical quality and tracking accuracy, the rate of collection was lower than design. Even though the collection was lower than design, we were still able to demonstrate dispatchability. Figure 6 shows the receiver thermal collection and turbine output for September 30, 1998 along with

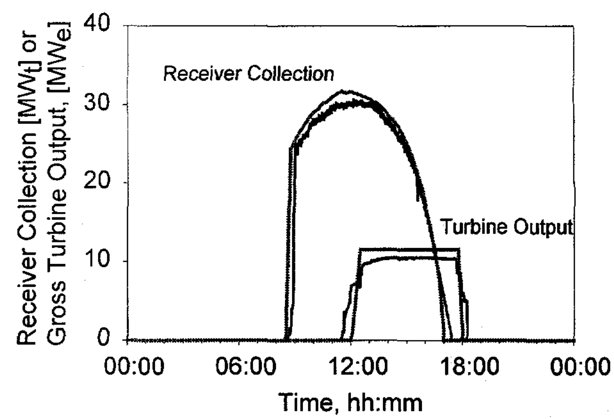

Figure 6. Measured receiver thermal collection and turbine output (lower curves) for September 30, 1998 along with predicted collection and turbine output (upper curves) from a SOLERGY model under similar conditions.

predicted collection and turbine outputs from the SOLERGY model (Stoddard, 1987) under similar conditions. Note how electricity is produced after collection stops and into the evening.

In one test in particular, the objective was to generate uninterrupted grid-connected electricity for as long as possible. To conduct this test, the steam generator and electric power generation system were operated with the receiver such that by the end of the day the hot salt tank was full. The operators derated the turbine such that the inventory of salt would last through the night and into the morning until the receiver could be started. This test was conducted in June and July of 1998. During one stretch, with the help of the operation and maintenance crew from Energy Services, Inc. and Southern California Edison, the plant produced electricity 24 hours-a-day for a week (153 hours total) by using stored energy at night and recharging the inventory during the day.

OVERALL PLANT PERFORMANCE

A measurement of the performance of a solar power plant is how well it can collect energy relative to what is predicted. The daily thermal collection is a function not only of the incident energy, but of several factors including the plant availability, heliostat field availability, mirror cleanliness, heliostat facet optical quality, corrosion, delamination, canting (Stone and Jones 1999), heliostat tracking quality, and wind effects (Hale, et. al, 1999). Figure 7 shows the daily thermal energy collected as a function of daily incident insolation for typical high performance days. The figure also includes two curve fits of SOLERGY data: one for 98% heliostat field availability and 95% mirror cleanliness and another for 90% heliostat field availability and 90% cleanliness. Since the heliostat field has not been fully available (typically between 90-94%) and since the field output has degraded with time, the Solar Two performance closely resembles the 90% field availability/90% cleanliness curve.

Another measure of the plant performance is how well the daily energy that is sent to the steam generator is converted into electrical energy. This data is shown in Figure 8. A certain amount of energy is required to startup the steam generator system and keep system warm at night and on cloudy days.

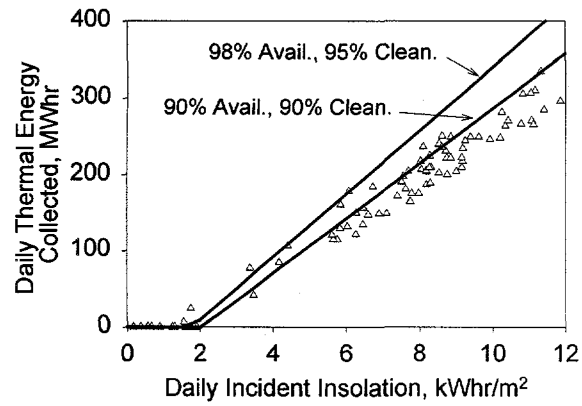

Figure 7. Measured daily thermal energy collected versus daily incident insolation for high performance days along with SOLERGY predicted curves: 98% heliostat availability / 95% mirror cleanliness (upper line) and 90% heliostat availability / 90% mirror cleanliness (lower line).

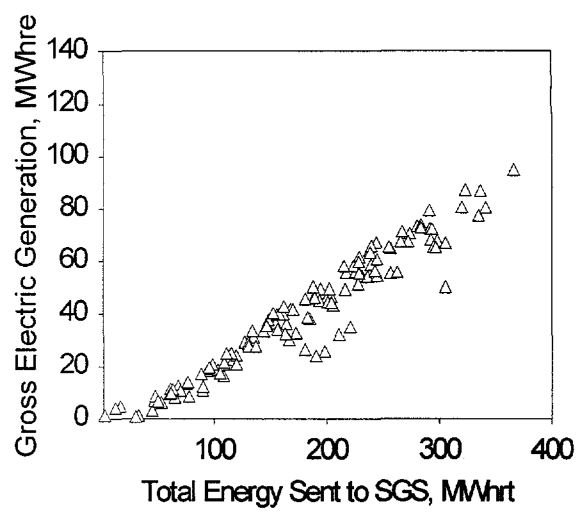

Figure 8. Measured daily gross electrical output versus daily energy sent to the steam generator system.

CONCLUSIONS

The Solar Two Test and Evaluation program has successfully quantified the performance of the receiver, steam generator system, electric power generation system, and heliostat field on instantaneous and daily basis. Monthly system performance and availability data is being collected that will help characterize the full potential of this technology and bring it to the next step of development – a 30 MWe or large power tower.

ACKNOWLEDGEMENT

Solar Two is funded by a consortium consisting of the following partners: *Participants:* Arizona Public Service, Bechtel Corp., California Energy Commission, Electric Power Research Institute, Idaho Power Co., Los Angeles Dept. of Water and Power, PacifiCorp, Sacramento Municipal Utility District, Salt River Project, Southern California Edison Co. *Contributors:* Chilean Nitrate (of New York), Nevada Power Co., South Coast Air Quality Management District, and *Government Partner:* U.S. Dept. of Energy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

REFERENCES

Baker, A. F., 1988, *10 MWe Solar Thermal Central Receiver Pilot Plant Receiver Performance Final Report*, Sandia National Laboratories, SAND88-8000.

Bechtel, *Solar Two Project Test and Evaluation Plan*, Bechtel Document 3PS-G-003, Revision 0, 5/11/95.

Hale, M. J., Kolb, G., Price, H., April 1999, "Solar Two Performance Evaluation", 1999 ASME International Solar Energy Conference, Maui, HI.

Kelly, B., Singh, M., 1995, "Summary of the Final Design for the 10 MWe Solar Two Central Receiver Project," Solar Engineering: 1995, ASME, Vol. 1, p. 575.

Kolb, G., Saluda, D., April 1999, "Solar Two Control System", 1999 ASME International Solar Energy Conference, Maui, HI.

Smith, D. C., Chavez, J. M., May 1992, *A Final Report on the Phase I Testing of a Molten-Salt Cavity Receiver, Vol. II – The Main Report*, Sandia National Laboratories, SAND87-2290.

Stoddard, M. C., et. al., 1987, *SOLERGY – A Computer Code for Calculating the Annual Energy from Central Receiver Power Plants*, Sandia National Laboratories, Livermore, CA, SAND86-8060.

Stone, K., Jones, S., April 1999, "Analysis of Solar Two Heliostat Tracking Error Sources", 1999 ASME International Solar Energy Conference, Maui, HI.

Radosevich, L. G., March 1988, *Final Report on the Power Production Phase of the 10 MWe Solar Thermal Central Receiver Pilot Plant*, Sandia National Laboratories, SAND87-8022.