Proceedings of ISEC 2006
ASME International Solar Energy Conference
July 8-13, 2006, Denver, CO

ISEC2006-99005

PERFORMANCE ANALYSIS OF THERMOCLINE ENERGY STORAGE PROPOSED FOR THE 1 MW SAGUARO SOLAR TROUGH PLANT

Gregory J Kolb
Sandia National Laboratories
Solar Systems Department
Albuquerque, NM, 87123 USA
(505) 844-1887(p), (505) 844-7786 (f)
gjkolb@sandia.gov

Vahab Hassani
National Renewable Energy Laboratory

ABSTRACT

The 1 MW Saguaro solar parabolic trough power plant began operation in December 2005. The plant will initially operate without an energy storage system. However, recent studies predict a thermocline-type storage should be the most cost-effective storage concept for solar parabolic troughs power plants. If such a system can be successfully demonstrated at Saguaro, future trough plants will likely adopt this storage technology. A thermocline storage system for Saguaro has been proposed by Department of Energy (DOE) laboratories and the solar industry. In this paper, the time-dependent performance of the proposed storage system was evaluated with a new model of the plant based on the TRNSYS simulation system. Results indicate that the proposed system should work well at Saguaro. The paper describes the TRNSYS model and the engineering insights gleaned from annual performance simulations of the plant.

INTRODUCTION

The 1 MW Saguaro plant, owned by Arizona Public Service (APS), is the first new parabolic trough solar power plant to come on line in 15 years (Figure 1). The plant uses an organic Rankine power cycle (ORC), developed by Ormat Incorporated, with a maximum design-point operating temperature of 300 ^{o}C. This type of power cycle, which is routinely used in geothermal applications, allows smaller solar trough plants to be built and to be operated without need for onsite staff. The APS plant [13] is the first plant to use the new

Fig. 1 The 10,300 m^2 solar plant began delivering 1 MW of electricity to the APS grid on December 27, 2005. The plant is currently operating without energy storage.

Solargenix parabolic trough collector. The trough, which was developed under the DOE USA Trough Initiative,[1] integrates a number of technical improvements in the concentrator, drive and controls that reduce the cost and enhance the performance of the solar field. The plant is also the first application of the receiver tube of the German manufacturer Schott. The Schott

[1] http://www.nrel.gov/csp/usa_trough.html

receiver includes a number of improvements that increase performance and reliability of the heat collection elements. Although relatively small in size, the APS parabolic trough project is playing an important role in the reintroduction of parabolic trough technology into the U.S. power markets. It also helps APS meet the solar-production requirements defined by the state of Arizona's Environmental Portfolio Standard.

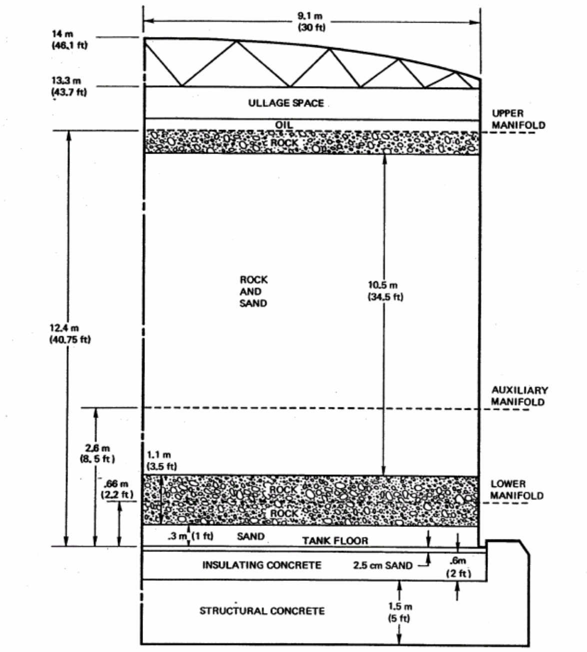

Fig. 2 Solar One's thermocline storage tank

To achieve the long-term economic goals established for trough technology, low cost energy storage must be included in the plant design [1]. Saguaro is currently operating without energy storage. However, APS and the national labs are actively pursuing a possible future retrofit to increase the size of the solar field and to install an energy storage system.

Studies predict a thermocline-type storage should be the most cost-effective storage concept [2]. If such a system can be successfully demonstrated at Saguaro, future trough plants will likely adopt this storage technology.

Nexant Incorporated has proposed a thermocline system for Saguaro that is a scaled-down version of the system demonstrated at the Solar One power tower in the 1980's [3,4]. A thermocline tank is one that uses a single tank to store thermal energy (Figures 2 and 3). A thermal gradient separates the hot from the cold fluid. Low-cost gravel is used to displace the higher-cost heat-transfer fluid (HTF) (a synthetic oil). The gravel as well as buoyant forces helps to maintain the thermal gradient. When the system is charged, cold HTF is drawn from the bottom of the tank, heated by the solar field and returned to the top of the tank. When the tank is discharged, hot HTF is drawn from the top of the tank and cooled as it passes through the ORC power conversion equipment (Figure 4).

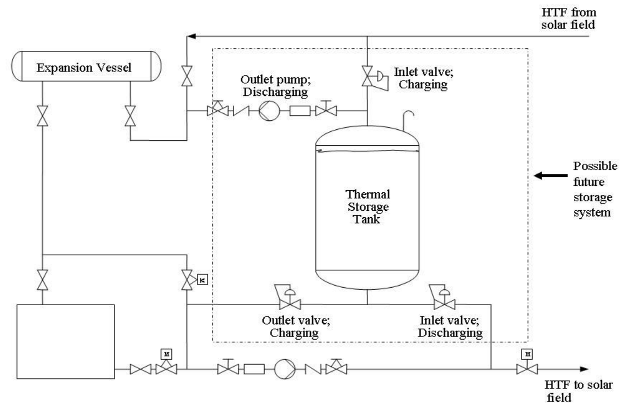

Fig. 3 Proposed integration of thermocline storage tank into Saguaro plant

The proposed system will store 30 MWh of thermal energy. This will allow the ORC to operate at full load for 6 hours after sundown to meet APS's need for electricity during the evening peak period. The analysis presented here evaluates the time-dependent performance of the proposed storage system with the TRNSYS computer code [5].

TRNSYS MODEL OF SAGUARO

Previous TRNSYS models of complete solar power plants with thermocline storage experienced numerical stability problems and/or required excessive computer time (several

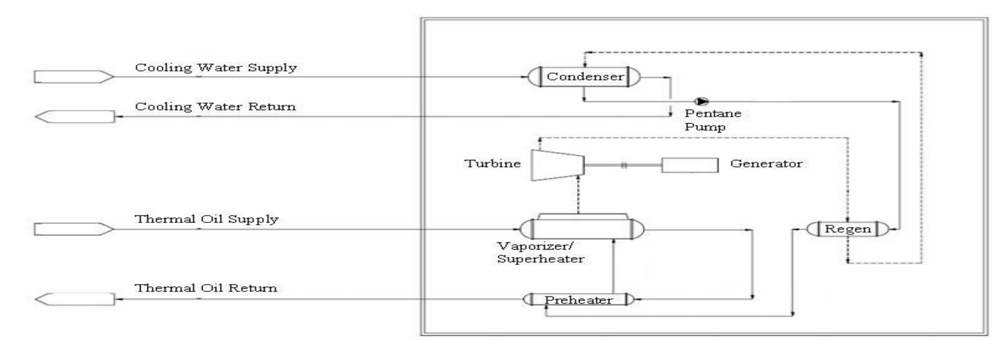

Fig. 4 The 1 MWe ORC at Saguaro is powered by solar-heated oil with a maximum temperature of 300 C^{o}. The ORC working fluid is pentane.

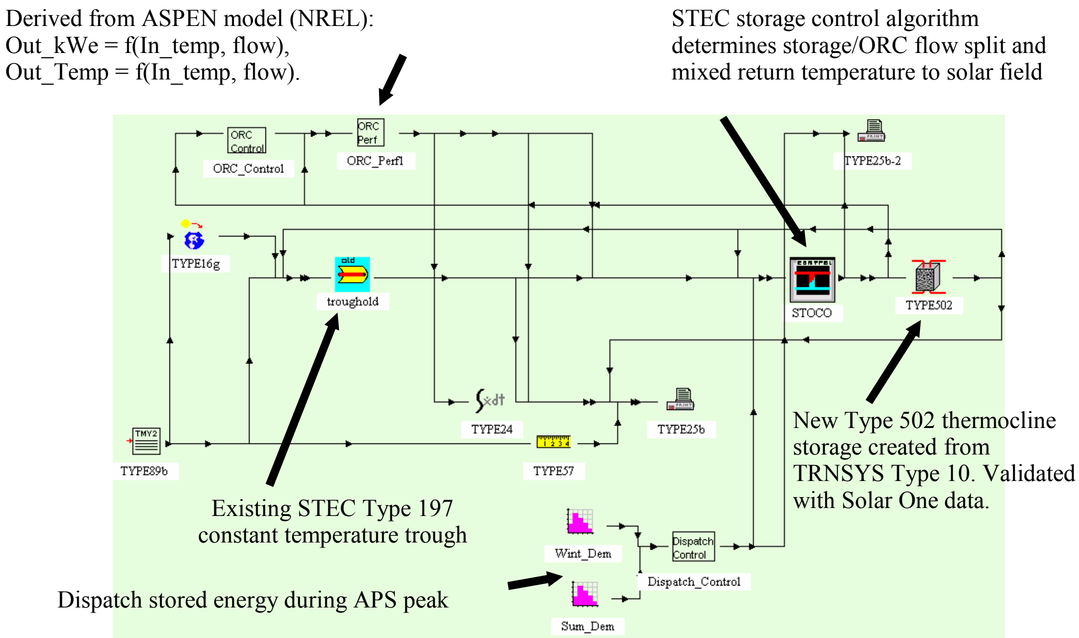

Fig. 5 TRNSYS model of Saguaro with storage

hours to several days) to complete an annual simulation. The problems were believed to be caused by the detailed models of the Rankine equipment (Figure 4) and solar equipment, as well as the short time step required by the differential-equation model of the storage tank [6]. In an effort to solve these problems it was decided to retain the detailed models of the solar equipment and storage tank but to greatly simplify the model for the organic Rankine power block. Using this approach, we were able to complete a stable annual simulation (using 3-minute time steps) in less than 1-minute of computer time.

The TRNSYS model of Saguaro with storage is depicted in Figure 5. It is a combination of standard TRNSYS components, new components developed by the authors, and a library of components (called STEC) developed by the SolarPACES international working group [9][2]. The model input is an hourly insolation and weather file, based on a typical metereological year (TRNSYS component Type 89). The model output (temperatures, flows, turbine power, etc.) is written to standard TRNSYS Type 25 output files. The ORC and storage models merit further discussion.

Rather than a detailed model of all components in the ORC power block, the system was represented by 2 transfer functions; the inputs to the functions were solar-field flow rate and exit temperature, and the outputs were solar-field return temperature and turbine-generator power output. The transfer functions depicted in Figure 6 were developed with a modified version of a previous Aspen[3] simulation model of the ORC [7]. Another transfer function (not shown) was also implemented that relates the effect that wet-bulb temperature has on condenser cooling water temperature and on the turbine power [8].

The basis of the thermocline tank model was the standard TRNSYS Type 10 component. The tank is divided into

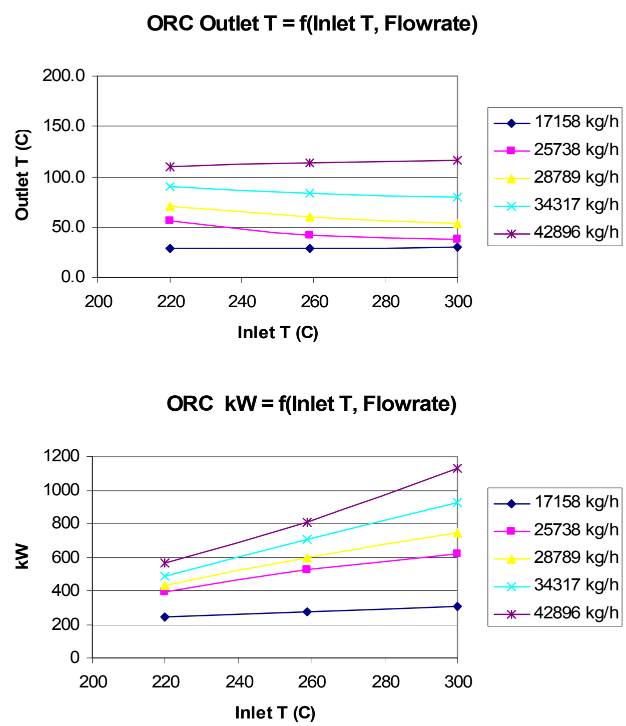

Fig. 6 ORC transfer functions developed by ASPEN

several equally-sized control volumes (23 stacked cylinders used here) and a first-order differential equation describes the energy balance of each. The Type 10 component is improved relative to a previous model of a thermocline tank [10]. The previous model did not allow thermal conduction between

[2] The mathematical models for the TRNSYS components are fully described in [5] and [9].
[3] Aspen Plus® is a steady-state simulation language developed by Aspen Technology, Inc., Cambridge, Massachusetts.

control volumes or for thermal losses through the walls of the tank; the TRNSYS Type 10 includes these effects. However during validation of this model with performance data obtained from the Solar One system it became apparent that a few modifications to the FORTRAN code were necessary to obtain agreement with the data. In particular, it was necessary to add thermal losses from the roof and floor of the tank, as well as the thermal inertia caused by the massive concrete foundation. These changes led to generally good agreement with Solar One data recorded during a discharge test [11] and during a multi-day cool down of the tank [12], as depicted in Figure 7. The thermocline within the storage tank is clearly visible, hot zone on top of cold zone with a thermal gradient in between. It can be seen that the slope of the thermal gradient predicted by TRNSYS during the discharge test is not quite as steep as the actual data. The reason for this difference is unknown. The validated model, labeled Type 502 in Figure 5, was scaled down to the size defined by Nexant and integrated within a TRNSYS model of the entire power plant.

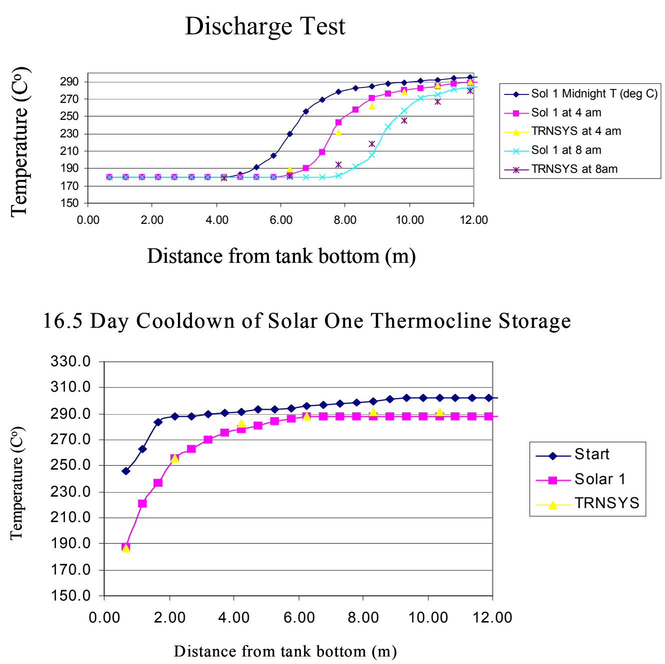

Fig. 7 The cool down test was performed in November 1982. There was no flow into or out of the tank during the test. The TRNSYS model was given the Solar One initial conditions (Start). After 16.5 days we compare the temperature profiles. The discharge test was performed June 28, 1983. The flow remained constant during the 8 hr test. The TRNSYS model was given the Solar One initial conditions (Midnight). We compare the temperature profiles 4 and 8 hrs later. Test data has been corrected for flowmeter errors identified during the test.

SIMULATION OF ANNUAL PERFORMANCE

The TRNSYS model was used to estimate the annual performance of Saguaro given the Phoenix TMY2 hourly insolation and weather file[4]. Simulations of the plant with and without storage were performed.

Since Saguaro will initially be operated without storage, a model of this configuration has near-term relevance. The TRNSYS model without storage is a subset of the components listed in Figure 5. The tank model (Type 502), storage control (STOCO), and the energy dispatch controller are removed. In addition, the solar trough model (Type 197) is modified to allow constant-flow operation rather than constant outlet temperature; with storage included in the design, constant temperature is needed to maintain the tank thermocline, but without storage, a simpler control strategy is warranted in which the HTF pumps run at a constant flow and outlet temperature is allowed to float. The annual turbine output predicted by TRNSYS is 2000 MWh; this is equivalent to an annual solar-to-electric efficiency of 7.8% and capacity factor of 23%[5]. This estimate is very close to the independent estimate by the plant builder, SolarGenix. An insight gleaned from the analysis is that annual output can be improved through monthly or seasonal changes in the HTF flow rate. As stated above, the plant operates at constant flow throughout the year (42300 kg/hr). On winter days, with relatively poor solar intercept by the troughs, this can lead to HTF temperatures that are much lower than the design point temperature of 300°C. Low temperatures delay startup and cause early trips of the ORC (need 190 °C) and reduces the output from the turbine after startup. The problem is depicted in Figure 8. The problem can be mitigated by changing the flow rate to more closely match the solar power intercepted by the troughs such that the peak operating temperature during the day achieves the 300 °C design point required by the ORC. Thus, flows in winter months would be set to a lower value than flows in the summer.

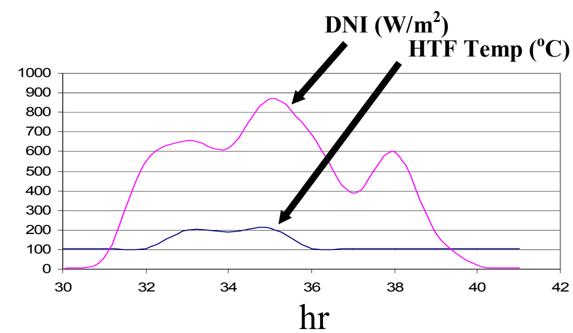

Fig. 8 TRNSYS prediction of solar field outlet temperature on January 2nd given constant-flow operation. The outlet temperature is higher than the ORC startup temperature of 190 °C for only a few hours.

[4] Typical Meteorological Year (TMY) 2 files can be downloaded from the NREL website. The annual direct normal insolation (DNI) for Phoenix is 2.5 MWh/m^2.

[5] Annual efficiencies and capacity factors do not include losses due to plant parasitics or equipment unavailability. 7.8% = 2000 MWh/(2.5 MWh/m^2 * 10300 m^2). Annual capacity factor: 23% = 2000 MWh/(1 MW * 8760h). Saguaro's efficiency (7.8%) is lower than standard SEGS plants (14%) because the efficiency of the power block is less, i.e., 20% for ORC vs. 37% for steam Rankine.

In the TRNSYS model with storage it is assumed that the solar field will be expanded from the current size of 10300 m^2 to 18800 m^2. During daytime the solar field directly powers the ORC, as before, but excess energy collected by the solar field is stored in the thermocline for later delivery to the ORC after sunset. The annual turbine output predicted by TRNSYS is 3690 MWh; this is equivalent to an annual efficiency of 7.9% and capacity factor of 42%. The annual efficiency of the plant with storage is predicted to be very similar to plant without storage. An insight gleaned from the analysis is that the storage size proposed by NEXANT is nearly optimal and only small improvements in annual energy production are possible through design and operation changes. For example, if storage volume is increased by 50% to avoid the discard of excess thermal energy collected by the solar field, annual output only increases by 60 MWh. A second change investigated with the TRNSYS model was to increase the temperature when tank charging ceases from the proposed value of 225 ^oC to 250 ^oC. During tank charging, 300 ^oC oil from the solar field enters the top of the tank and much cooler oil exits the bottom of the tank and returns to the solar field. As the tank becomes fully charged, the oil exiting the bottom starts to rise. The original proposal suggested that oil exit temperature should be limited to 225 ^oC when the tank is fully charged. However, the TRNSYS simulation indicates that relaxing this restriction to 250 ^oC will increase annual electricity production by only 20 MWh. And finally, if we combine an increase in storage of ~20% with a 250 ^oC setpoint, the total improvement is only 60 MWh, the same as the first design variation of increasing the storage volume by 50%. As such, we conclude the original size of storage proposed by NEXANT is nearly optimal.

CONCLUSIONS AND FUTURE WORK

A TRNSYS model of the 1 MW Saguaro solar trough plant has been developed. The model is capable of predicting the time-dependent flows and temperatures within the solar field and proposed thermocline storage system, as well as the power produced by the organic Rankine cycle power block. Analysis conducted with the model indicates that the proposed thermocline energy storage system should work well and only small annual performance improvements are possible through changes to its design and operation.

The Saguaro plant began operation in late December, 2005. Actual performance data from the plant in the non-storage configuration is now becoming available. The non-storage version of the TRNSYS model will be validated with the actual data. Following validation, the TRNSYS analysis of the plant with the proposed thermocline storage system will be updated and the analysis will help APS and DOE decide whether energy storage should be pursued at Saguaro in the future.

ACKNOWLEDGMENTS

Nate Blair (NREL) provided frequent and invaluable advice on the quirks of TRNSYS. With his help the beauty of the code was revealed.

REFERENCES

1. Sargent and Lundy, *Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts*, SL-5641, May 2003. http://www.nrel.gov/csp/pdfs/34440.pdf
2. Price, Hank, E. Lupfert, D. Kearney, E. Zarza, G. Cohen, R. Gee, and R. Mahoney, "Advances in Parabolic Trough Solar Power Technology," *Journal of Solar Energy Engineering,* Vol. 124, pp. 109-125, May 2002.
3. Kelly, Bruce, "Arizona Public Service Solar Power Plant Saguaro Power Plant Thermal Storage Design Options," Nexant under contract to NREL, 2004, internal report.
4. Kelly, Bruce, "Technical Specification for the Thermocline Thermal Storage Tank, Arizona Public Service Saguaro Project, Rev. 0," Nexant under contract to NREL, October, 1, 2004, internal report.
5. University of Wisconsin, Solar Energy Laboratory, *TRNSYS Version 15.3 with IISiBat,* March 18, 2003.
6. Personal communication with Nathan Blair (NREL) and Peter Schwarzboezl (German Aerospace Center (DLR) Institut of Technical Thermodynamics), Spring 2005.
7. Price, Hank and Vahab Hassani, *Modular Trough Power Plant Cycle and Systems Analysis,* National Renewable Energy Laboratory, NREL/TP-550-31240, January 2002.
8. Natural Energy Engineering, *Technical Description 1 MW APS Solar Trough Power Plant Project,* Document No.: SOL002-01-SD-8-01, Rev. 3, internal report.
9. SolarPACES, *Solar Thermal Electric Components (STEC), version 2.2.,* http://www.solarpaces.org/STEC.HTM
10. Pacheco, J., S. Showalter, and W. Kolb, "Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants," *Journal of Solar Energy Engineering,* Vol. 124, pp. 1-7, May 2002.
11. McDonnell Douglas Astronautics Company, *10 MWe Solar Thermal Central Receiver Pilot Plant Mode 5 (Test 1150) and Mode 6 (Test 1160) Test Report,* SAND86-8175, contractor report, June 1986.
12. Faas, S. E., L. Thorne, E. Fuchs, and N. Gilbertsen, *10 MWe Solar Thermal Central Receiver Pilot Plant: Thermal Storage Subsystem Evaluation – Final Report,* Sandia National Laboratories, SAND86-8212, June 1986.
13. Canada, Scott, D. A. Brosseau and H. Price, "Design and Construction of the APS 1-MWE Parabolic Trough Power Plant," *Proceedings of the ISEC2006,* July 8-13, 2006, Denver, CO.