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Solar Central Receiver Technology: The Solar Two Project

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ABSTRACT

Solar Two will be the world's largest operating solar central receiver power plant. It is expected to begin operating in April, 1996; it is currently undergoing start-up and checkout. The plant will use sunlight reflected from 1926 sun-tracking mirrors to heat molten nitrate salt flowing in a heat exchanger (receiver) that sits atop a 200 foot tower. The heated salt will be stored in a tank for use, when needed, to generate superheated steam for producing electricity with a conventional Rankine-cycle turbine/generator. The purpose of the project is to validate molten-salt solar central receiver technology and to reduce the perceived risks associated with the first full-scale commercial plants. Already, much has been learned during the project including the effects of trace contaminants in the salt and the large effect of wind on the receiver. There is also much that remains to be learned. This report describes the technical status of the Solar Two project including a summary of lessons learned to date.

MOLTEN-SALT POWER TOWERS

Molten-salt solar power towers (central receiver power plants) produce utility electric power from solar energy with a system that decouples solar energy collection from electricity generation. This is achieved through the use of molten nitrate salt as the heat transfer and thermal energy storage medium. Electricity can be generated from stored thermal energy and dispatched whenever needed, even at night and during periods of cloudy weather.

In a molten-salt solar power tower, sunlight is concentrated by heliostats (mirrors that continuously track the sun) onto a central receiver (a high-tech heat exchanger) that sits atop a tower. Molten salt at 290 °C is pumped from a 'cold' storage tank, through the receiver where it is heated to 560 °C, and then into a 'hot' tank for storage. When the grid load dispatcher decides electricity is needed from the plant, hot salt is pumped to a steam generating system that produces superheated steam for a turbine/generator. The salt is then returned to the cold tank where it is stored and eventually reheated in the receiver to complete the cycle. Figure 1 shows a schematic diagram of the primary flow paths in a molten-salt solar power plant.

The heliostat field which surrounds the tower is laid out to optimize annual performance; the collector field, salt storage capacity, and the receiver are also optimized for the needs of the utility. In a typical installation, the rate of solar energy collection exceeds the maximum rate of energy consumption by the turbine. Storage tanks can be designed with enough capacity to power a turbine at full output for up to twelve hours, and much longer at reduced output. Consequently, the thermal storage system can be charged while the plant produces electricity at full capacity.

The receiver is comprised of 24 panels of thin-walled metal tubes through which salt flows in a serpentine path. The panels form a cylindrical shell surrounding associated piping, structural supports and control equipment. The external surfaces of the tubes are

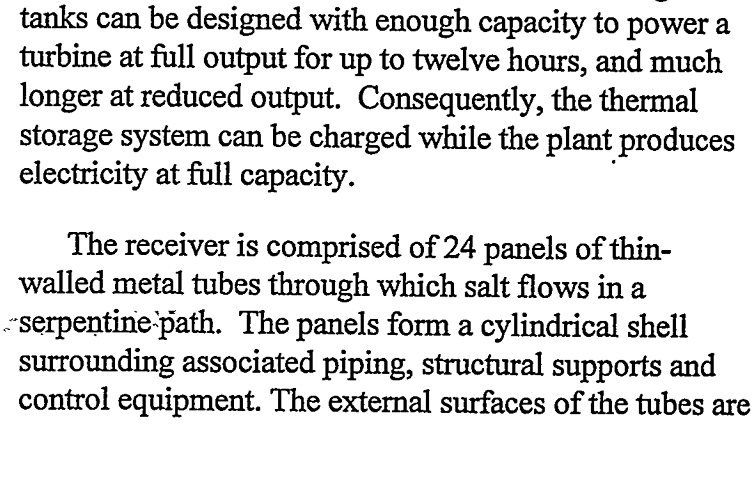

Figure 1. Schematic diagram of a molten-salt solar central receiver power plant.

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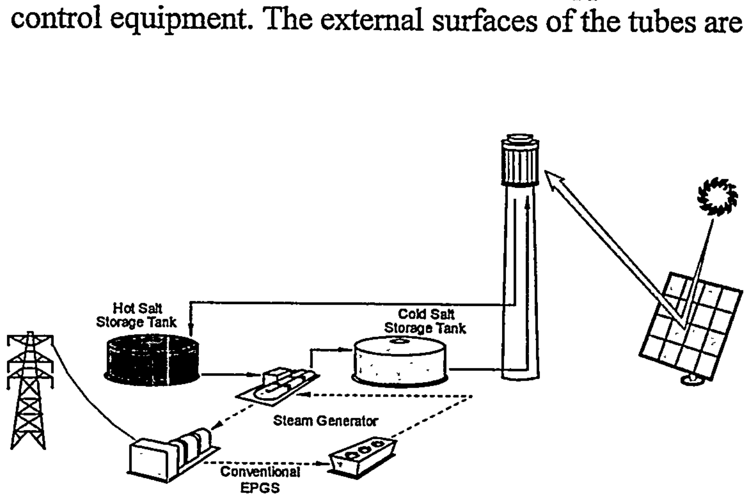

Figure 1. Schematic diagram of a molten-salt solar central receiver power plant.

coated with a black Pyromark™ ceramic-like material that is robust, resistant to high temperatures and thermal cycles, and exhibits an absorptivity such that 95% of the incident sunlight is absorbed. The receiver is designed to accept a maximum amount of solar energy in a minimum area to reduce heat losses due to convection and radiation.

The salt storage medium is a mixture of 60 percent sodium nitrate and 40 percent potassium nitrate. This nearly eutectic mixture melts at 220 °C and is kept molten at 290 °C in the 'cold' storage tank. Molten salt is used because it is inexpensive and provides for efficient storage (99% on an annual basis); it is liquid at atmospheric pressure and its operating temperatures match the needs of modern high-pressure and high-temperature steam turbines. Although it is an oxidizer, it is nonflammable and nontoxic. Nevertheless, molten salt can be tricky to handle; it has very low viscosity (like water) and wets metal surfaces extremely well.

An important element in the successful implementation of molten-salt technology was the identification of system components that are compatible with molten salt. Several years of research and development at the National Solar Thermal Test Facility has resulted in the successful identification of pumps, valves, valve packing, and gasket materials that will withstand molten salt [1-3]. As a direct result of this experience with salt systems, Solar Two is designed with a minimum number of gasketed flanges and most instrument transducers, valves, and fittings are welded in place.

SOLAR TWO

General Description

To encourage the development of molten-salt power towers, a consortium of utilities led by Southern California Edison has joined with the United States Department of Energy to retrofit the Solar One plant from a water/steam-based system to a molten salt system [4]. Solar One was the first large-scale power tower. It operated from 1982-1988 and successfully demonstrated the feasibiltity of central-receiver technology. Solar Two will be the world's largest molten salt solar central receiver electricity generating station, producing 10 MW electricity with enough thermal storage to operate the turbine for three hours at full capacity after the sun has set. The goals of Solar Two are to validate nitrate salt technology, to reduce the technical and economic risk of power towers, and to stimulate the commercialization of central-receiver 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 Solar Two receiver was designed and built by Rockwell International. Advanced design features including laser welding, sophisticated tube-nozzle-header connections that reduce thermal stresses, tube clips that facilitate tube expansion and contraction, and non-contact solar flux measuring devices insure that the receiver can rapidly change temperature without being damaged. During cloud passage, for example, the receiver can safely withstand a temperature change from 290 °C to 560 °C in less than one minute.

The energy storage system for Solar Two consists of two 875,000 liter storage tanks, which were fabricated on-site by Pitt-Des Moines. The tanks are externally insulated and constructed of stainless steel and carbon steel for hot and cold salt, respectively. A natural convection cooling system is used in the foundation of each tank to minimize overheating and excessive dehydration of the underlying soil. All pipes, valves, and vessels for hot salt were constructed from stainless steel because of its corrosion resistance in the molten-salt environment [5]. The cold-salt system is made from mild carbon steel. The steam generator system (SGS), which was constructed by ABB Lummus, consists of a shell-and-tube superheater, a kettle boiler, and a shell-and-tube preheater. Stainless steel cantilever pumps transport salt from the hot-tank-pump sump through the SGS to the cold tank. Salt in the cold tank is pumped with multi-stage centrifugal pumps up the 80 m tower to the receiver.

As of this writing, the construction of Solar Two is complete and the plant will begin producing grid power in the spring of 1996. Once the plant is successfully operating, one year will be spent testing and evaluating its performance in detail. Twenty-two tests have been developed to characterize and optimize the plant and its individual components. Of particular interest will be test results related to the plant efficiency, its operability, the parasitic power requirements, the plant's response to cloud transients, the receiver efficiency and robustness, and the efficiency of molten-salt storage. After the year-long test and evaluation period, the plant will be operated in a standard, power-production mode for an additional two years.

Technical Status

Important information has already been gained during construction and start-up of Solar Two. Illustrative examples are described below.

As-received, the entire salt inventory was contaminated with 600 mg/kg magnesium in the form of $Mg(NO_3)_2$. When heated above about 450 °C, this contaminant decomposes to form $MgO_{(s)}$, oxygen and oxides of nitrogen. The MgO settles innocuously to the bottom of the salt storage tanks but gas generation and NO_x removal were a problem. The original plan for salt melting involved the use of an external, gas-fired heater to melt the salt and heat it to around 290 °C for transfer to the cold salt storage tank. In this plan, the first time the salt would experience high temperatures would be in the receiver.

For fear that gas generation in the receiver might cause air locks and receiver tube burnout, and to avoid the need for environmental control equipment on top of the tower, the project team decided to off-gas the salt before ever sending it up the tower. Consequently, the salt was melted as originally planned, but placed in the hot storage tank, which had been retrofitted with an external recirculation heater to thermally precondition the entire 1.5 million kilogram salt inventory. This took about two months and resulted in the acceptable dissolved magnesium concentration of 1 mg/kg. Future applications of molten salt technology should consider economic trade-offs related to salt purity and possibly include thermal preconditioning in the initial design.

One of the 22 tests that comprise the Solar Two Test and Evaluation plan started during the salt melting/ thermal preconditioning operation. This first test "Storage Tank Thermal Stresses" will quantify the effect of thermal stresses on the tank wall and bottom joint caused by filling, draining, and daily thermal cycling. For example, the hot tank is expected to experience daily temperature transients of approximately 60 °C due to startup and shutdown of the receiver. The test involves measuring strains and temperatures on the tank surface to determine if stresses fall within acceptable limits.

On October 10, 1995, the empty hot tank was preheated to 340 °C with a propane fired heater in preparation for being charged with molten salt. The salt was subsequently melted and thermally preconditioned as described above. Tank growth at four locations was monitored during these operations to determine if it expanded freely. The 11.6 m diameter tank grew by 80 mm in diameter after it was fully charged with salt and heated to 430 °C. Figure 2 shows tank growth as a function of temperature for the four locations. The tank expanded freely and there were no indications of binding. Strain measurements on the tank wall from this period are still being analyzed, but we expect that the tank is behaving well within its design specifications.

Another technical development that has surfaced during startup is the large effect of wind on the receiver temperature during preheat operations. Before the receiver is flood filled with salt each morning to begin operation, it must first be heated to approximately 290 °C to reduce thermal shock and to insure that salt will not freeze in the tubes. This preheating is achieved by focusing a selected subset of the heliostat field onto the receiver to achieve a uniform temperature distribution both vertically and circumferentially. The master control computer uses an algorithm called the dynamic

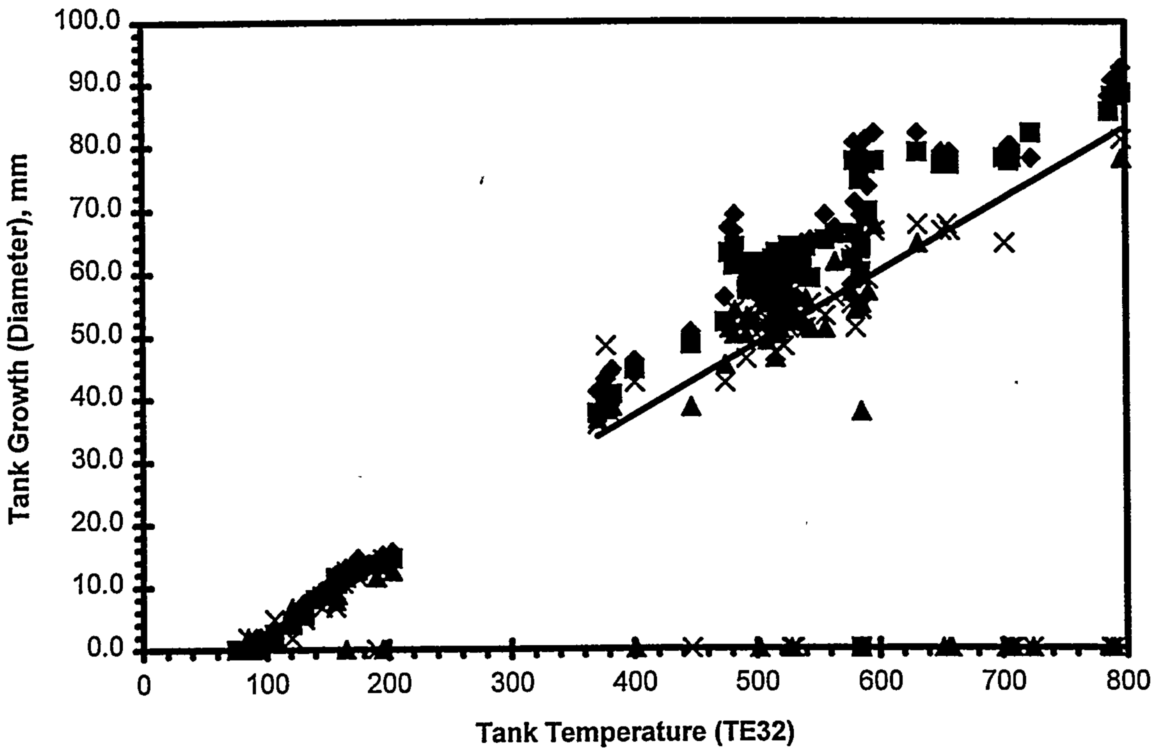

Figure 2. Hot tank growth as a function of tank temperature during initial preheat and fill.

aim point system (DAPS) to calculate which heliostats should be focused where on the receiver for different times of day and days of the year. Unfortunately, this open-loop calculation has been unable to achieve desired temperatures on the southwest quadrant of the receiver due, primarily, to convective losses caused by wind. To overcome this problem, a feedback control system has been incorporated into the DAPS code that is based on receiver back-wall tube temperatures. The system now reliably preheats the receiver in a uniform manner.

These are but a few examples of the type of information that has already been gained during the construction and startup of Solar Two. Much more will be learned in the days and months ahead.

CONCLUSION

In conclusion, the Solar Two project is progressing well and is well on its way to validating molten-salt central receiver technology at the utility scale. Lessons that have already been learned regarding salt impurities, tank growth, and receiver preheat strategies illustrate that the project is beginning to meet one of its primary objectives - identifying problems and solutions that will result in reduced risk for construction of the first commercial molten-salt solar power tower plants.

ACKNOWLEDGMENTS

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