SAND96-2662C
CONF-961016--1

Solar Power Tower Development: Recent Experiences

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Abstract

Recent experiences with the 10 MW_e Solar Two and the 2.5 MW_t TSA (Technology Program Solar Air Receiver) demonstration plants are reported. The heat transfer fluids used in these solar power towers are molten-nitrate salt and atmospheric air, respectively. Lessons learned and suggested technology improvements for next-generation plants are categorized according to subsystem. The next steps to be taken in the commercialization process for each these new power plant technologies is also presented.

1. Introduction

The 10-MW_e Solar One Pilot Plant, which operated from 1982 to 1988 in Barstow, California, was the largest demonstration of first-generation power tower technology [1]. During operation of Solar One and after its shutdown, significant progress was made in the United States (US) and in Europe on more advanced second-generation power tower designs [2]. 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 US and in Europe use molten salt and atmospheric air, respectively.

Molten-salt power towers are currently preferred by the US because the design is simpler and more efficient than water/steam systems and 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 [3]. In Europe, researchers are pursuing the volumetric-air power tower because it is an inherently simple and efficient design that uses a non-problematic heat transfer fluid system and has the potential to be very reliable. In addition, the volumetric-air plant is easily hybridized with gaseous and liquid fossil fuels. Key features of the second-generation systems are depicted in Figures 1 and 2, for the molten salt and air plants, respectively.

American and European industries have expressed interest in commercializing second-generation technology and have recently constructed demonstration power plants. In the US, a team composed of utility companies, private industry, and government agencies is completing startup of the 10-MW_e Solar Two plant, which was constructed by retrofitting the Solar One with molten-salt technology. In Europe, an industrial consortium has been testing the 2.5 MW_t TSA (PHOEBUS Technology Program Solar Air Receiver) plant near Almeria, Spain since 1993.

This paper will present recent experiences with the Solar Two and TSA demonstration plants. Based on the lessons learned to date, technology improvements will be suggested. The paper

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will close with a discussion of the next steps to be taken in the commercialization process for each these new power plant technologies.

2. Solar Two power tower

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 Two will produce 10 MW net electricity with enough thermal storage to operate the turbine for three hours at full capacity after the sun has set. The goal of Solar Two is to validate nitrate salt technology at a scale that is much larger than tested previously (i.e., 42 MW_t vs. 5 MW_t receiver [5]). This will reduce the technical and economic risk of power towers and is expected to stimulate the commercialization of power tower technology.

2.1 Solar Two plant description

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. Specifications and manufacturers of the major Solar Two equipment are summarized in Table 1 and discussed in the paragraphs that follow.

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. Bechtel also installed all of the salt piping (except piping in the receiver system near the top of the tower), pumps, sumps, instrumentation and controls. In addition, Bechtel is responsible for plant start-up and acceptance testing.

The Solar Two receiver, which is shown in Figure 3, was designed and built by Rockwell International. It is rated to absorb 42 MW of thermal energy at an 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 290 to 570 °C in less than one minute. The salt fed to the receiver is split into two streams. One stream 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 energy storage tanks were fabricated on-site by Pitt-Des Moines. A natural convection air 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 are constructed from stainless steel because of its corrosion resistance in molten-salt at 565 °C [6]. Carbon steel is used for cold-salt containment because of the salt's lower corrosivity at 290 °C [6]. 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. 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 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 Solar Two power plant was officially dedicated on June 5, 1996. Figure 4 is a photograph of the plant in operation. The salt system performs very well, and simultaneous solar energy collection, charging of thermal storage, and production of electricity have been demonstrated. Tuning of the control system to permit fully automatic control and maximum performance are in progress. Once this is complete (anticipated for the end of calendar year 1996), a year of testing will begin. 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.

2.2 Solar Two performance expectations

Table 2 shows estimated peak efficiencies for Solar Two subsystems in comparison to those expected for a 100 MW commercial-scale plant. Due to the non-optimal configuration of the Solar Two plant, we estimate the efficiency will lower than the commercial plant. The reasons are enumerated below:

1. Unlike the 100 MW plant, Solar Two does not use a reheat turbine cycle. Consequently, gross Rankine-cycle efficiency will be revised from 43% to 34%.

2. 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 replacement and major improvements to the existing Solar One heliostat field were kept to a minimum. Consequently, the heliostat field is not state-of-the-art. The heliostats employ an old control strategy and several of the mirrors have experienced degradation due to corrosion (leading to lost surface area and defocusing of heliostat facets). 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 too large for the installed receiver. Consequently, the reflected beams from the heliostats are too large and a significant portion of the beams will not intercept the receiver target. Combining many of the known field problems, we estimate that field efficiency will be below the commercial-plant standard (68% vs. 73%).

3. Since Solar Two is small, uses a less-efficient turbine, and employs some non-optimal balance of plant equipment, it will have a higher parasitic fraction than the commercial plant. This results in lower parasitic efficiency at Solar Two (88% vs. 93%).

One object of the Solar Two Test and Evaluation program is to determine actual system efficiencies to compare against our predictions and to use a guide to refine our prediction tools.

2.3 Solar Two startup experiences

In general, all of Solar Two's salt systems perform well. Some specific observations and startup events for the various subsystems are described below.

2.3.1 Receiver

Although it is too early to report receiver thermal efficiency, the receiver appears to operate reliably and is robust. Also, it easily handles its rated flow of 100 kg/s. A few receiver startup occurrences are worth mentioning:

In one instance, a heat-trace inadequacy in a receiver drain line resulted in a salt-freeze in two interconnected panels. Once the drain line was cleared, a procedure that involved using solar energy to heat the panels progressively from bottom to top resulted in safe, rapid thawing and draining. This systematic approach was needed because salt grows in volume as it melts. Constrained melting such as might occur if the center of the panels were heated while the ends remained cool could severely damage the receiver tubes [7]. Since the panels were thawed, they have been operated through many thermal cycles and hours of salt flow with no sign of degradation.

In another episode, a tube ruptured while the receiver was on sun. Salt flow to the tube was obstructed causing a lack of cooling which resulted in a pressure failure as the extreme temperature weakened the stainless steel. A post-mortem analysis on the plant revealed that flow in the tube had been blocked by debris that had accumulated in the receiver. The debris originated in the cold salt carbon-steel piping in areas that were experiencing excessive temperatures due to inadequacies in the heat-tracing system. This localized overheating in the piping caused accelerated corrosion. Corrosion scale spalled off the piping and migrated to the receiver where larger pieces accumulated and caused receiver tube blockage. Since the problem was discovered, the salt systems and receiver were flushed to remove the scale, the tube was replaced, and the heat-tracing problem was solved. An important observation resulting from the tube failure was the ease with which individual receiver tubes can be replaced.

A technical development that 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 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 was unable to achieve desired temperatures on the windward side of the receiver due to convective losses. 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.

2.3.2 Salt systems, heliostats, and master control system

The salt systems have, in general, experienced few problems with the exception of the heat trace problem that caused the receiver tube failure. The thermal storage tanks function as expected with heat loss rates very close to prediction. Tank preheat and fill with molten salt proceeded without incident and tank growth measurements indicated that the tank expanded freely with no indications of binding. The 11.6 m diameter hot tank grew by 80 mm in diameter after it was fully charged with salt and heated to 430 °C.

The salt pumps have functioned nearly flawlessly as has the steam generator. As discussed previously, the heliostat field does not represent state-of-the-art technology and this has led to some problems with the field.

Despite the overall good performance of the salt systems, a few recommendations can be made at this time that will improve the next plant.

- Make all salt piping out of stainless steel and forgo the use of mild steel for cold-salt piping systems. Using stainless steel pipe throughout the plant will increase plant cost by an insignificant amount and it is much more resistant to corrosion in molten salt and hence can withstand a wider temperature range. Thus, it is more forgiving to control and installation problems related to the heat trace. This also makes the plant more versatile.
- Avoid the use of thin-walled schedule 10 piping which was used in much of the Solar Two hot-salt systems. The thin-walled piping was selected because of cost and because it can be heated more rapidly than thicker material. However, it is difficult to work, often arrives bent or dented, and has a lower corrosion tolerance. The time to work the thinner material easily overrides any cost benefit. Furthermore, startup time depends on the heat-up rate of other components and is independent of piping heat-up since piping can endure thermal shock [7].

3. TSA power tower

Small-scale experiments, in the mid-to-late 1980's, proved the concept of a volumetric receiver using wire-mesh materials [8]. Receiver outlet temperatures of 780°C at peak flux densities of 1 MW/m2 (average 0,35MW/m2) were obtained in these early tests. From 1988 onward, a wire-knit structure was used as absorber material, replacing the original wire-mesh, thus improving absorber performance and durability. Encouraging results from the new material convinced German industry to found the PHOEBUS consortium. In 1990, the PHOEBUS IB feasibility study [9] demonstrated the technical and economical viability of a 30 MW_e volumetric power tower for Jordan (i.e., the PHOEBUS plant). In preparation for the PHOEBUS plant, a European industrial consortium teamed with government organizations to build the much larger TSA plant during the early 1990's [10]. The TSA plant was dedicated in early 1993.

3.1 TSA Plant Description

The TSA plant consists of the CESA-1 heliostat field, a 2.5 MW_t volumetric receiver, a 2.2 MW_t once-through steam generator, and a 1 MWh thermocline alumina-pebble heat-storage module.

Air flow is circulated and controlled by two blowers and dampers, air ducts, and a PC-based control system. An overview of the major components is given in Table 3.

3.2 TSA Startup Experiences

Construction and startup went according to plan with the startup phase occurring even faster than anticipated [11,12]. The system has performed well; it has been operated for approximately 1000 hours up to now without severe problems or outages. Some specific observations and startup events for the various subsystems are described below.

3.2.1 Receiver, heliostats, and control

When insolation exceeds 300W/m^2, the heliostats are focused sequentially in groups onto the receiver. This is performed using command batch files for the heliostat field. Operating the TSA plant quickly became routine work for the PSA (Plataforma Solar de Almeria) operations team. The design air outlet temperature of 700°C is routinely achieved with an average flux density of over 300kW/m^2 and a peak flux of 800kW/m^2 (see Figures 5 and 6).

During the early phases of plant operation, it was the heliostat field operator's task to keep the flux (i.e. the temperature) distribution on the absorber within the desired range; this is necessary to achieve a good thermal efficiency for the receiver. The operator attempted to accomplish this by modifying the coordinates of heliostat aimpoints and adjusting the number of heliostats allocated to the different aim points. A five aimpoint strategy was (and still is) used. Using this manual method, the operator was able to maintain the temperature distribution within 50 °C of the desired profile. Consequently, improvements were needed in the area of control automation, since a commercial plant must run automatically.

During the latest testing phase, an advanced control algorithm has been implemented in the CESA-I heliostat field master control, allowing fully automatic field operation. This new approach maintains absorber temperatures within 35 °C of the desired value. Outlet air temperatures from the absorber are used as input to a closed-loop control scheme. Implementation of the control algorithm has simplified the operation of the TSA plant. Nevertheless, additional control improvements are currently being investigated by DLR (Deutsche Forschungsanstalt fur Luft- und Raumfahrt) and PSA.

Receiver efficiency decreases with increasing air outlet temperature, (i.e. absorber temperature), due to rising radiation losses. Excessive beam spillage, caused by a non-optimal heliostat/receiver optical geometry, has resulted in high rim loads (>200kW/m2) and therefore elevated reflection and radiation losses of the air return cone. The high rim load has caused the cone to oxidize and darken, which exacerbates the losses. These effects are irrelevant for a 30 MW_e PHOEBUS plant since the optical geometry of the heliostats and receiver will be optimized to reduce beam spillage to an acceptable level[1].

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[1] For PHOEBUS a different type of (large area) heliostat will be used, therefore no conclusions can be drawn for PHOEBUS from the behavior of the CESA-1 field. PHOEBUS-Type heliostat tests are currently being performed at PSA (see the paper elsewhere in these proceedings concerning the ASM150 stressed membrane heliostat).

Two air return configurations were tested which were shown to significantly influence efficiency. Configuration 1 with an air return cone exhibited better results and is therefore still being used..

3.2.2 Thermal storage

It was the primary goal of the TSA storage test to evaluate the storing / discharging behavior of the storage system. Storage capacity of 1 MWh, allowing for approximately 30 minutes of discharging under nominal conditions, is relatively small compared to the original PHOEBUS concept (3-4h). Operating TSA showed that constant steam production with design steam parameters and quality can be reached and maintained during times of varying insolation (cloud transients), using the heat storage system as a buffer. However, for the sake of cost reduction, future volumetric receiver plants will replace thermal storage with a fossil-fired duct burner.

3.3.3 Air transport system

Except for very few initial blower trips during startup and the initial test phase, there have been no further problems encountered with the blowers and their controllers. Nevertheless, for a future PHOEBUS plant, redundant blowers and a very reliable UPS (uninterruptable power supply) are recommended. Dampers have proved to be very reliable.

3.3.4 Master control system

Overall process control is performed by the PC-based commercial digital control system (DCS) "Genesis". On two PCs, process data coming from eight Schlumberger Isolated Measurement Pods (IMPs), are displayed on graphic user interfaces. The main screens show the TSA plant, receiver sections, a front view of the absorber and the storage system. One PC is used for data acquisition only, the second for operator interaction using the keyboard and a pointing device. This state-of-the-art control system proved to be very appropriate for testing, allowing the display of trends, visual alarm statususing color codes and flashing displays. Operation is intuitive. Nevertheless, it was never meant to be a small-scale PHOEBUS plant control, but an off-the-shelf solution for testing and evaluation.

3.2.5 Plant reliability

Forced plant shutdowns have been caused by blower trips, power failures and absorber overloading due to wrong aimpoint modifications in manual mode. The latter problem has been eliminated since implementation of the automatic heliostat field control algorithm (spring 1996).

During the initial test campaign in 1993, there were 15 days of outages due to technical problems. Since that time, plant availability has been almost 100% when called upon for service. For example, in the first 9 months of 1996, only two forced shutdowns occurred: one because of a grid failure, the other due to a flow-meter problem. The heliostat field has also proved to be reliable, although heliostat offset corrections must be performed on a regular basis. As mentioned above, PSA together with DLR Cologne are conducting a joint effort to automate heliostat offset correction.

4. Conclusions and future prospects

4.1 Conclusions regarding Solar Two

The Solar Two project is making great strides towards is objective of validating molten-salt power tower technology at the utility scale. Knowledge gained during startup regarding receiver tube replacement, receiver panel thawing, 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. As the plant enters its routine operation phase, data will be collected regarding plant performance, reliability, etc., that will help identify further design and O&M improvements for future molten-salt power towers.

A US industrial consortium, led by Bechtel National Inc. and Rockwell International, has been formed to develop future commercial-scale projects. Based on insights and data obtained from Solar Two, this team plans to offer a fixed-price bid to the Solar Enterprise Zone project by mid 1997. This goal of the first phase of this project is to deploy 100 MW of solar power in southern Nevada, USA.

4.2 Conclusions regarding TSA

Due to the good experiences with the TSA and the ASM150 PHOEBUS heliostat, the German power station contractor L.&C. Steinmüller, a member of the PHOEBUS consortium, is now offering a turn-key 30MW_e PHOEBUS Power Tower.

Acknowledgments

The Solar Two project is supported by: 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, with additional industrial cost share from ABB Lummus, Goulde Pumps, General Process Controls, Pitt-Des Moines, Raychem, Rockwell International, and the Industrial Company. The work at Sandia National Laboratories is supported by the U.S. Department of Energy under contract DEAC0494AL85000.

The TSA project is supported by: Deutsche Forschungsanstalt fur Luft- und Raumfahrt e. V. (DLR), Plataforma Solar de Almeria (PSA) and the Industrial Consortium: L. & C. Steinmüller, Fichtner Development Engineering and Didier M+P Energietechnik. The project was financed by the Industrial Consortium, German Federal Ministry of Research and Development, Ministry of Economics of the Sate of Baden-Württemberg, Pacific Gas & Electric Company (USA), and in kind contributions borne by PSA.

References

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

2. Becker, M., and P. Klimas (editors), J. Chavez, G. Kolb, and W. Meinecke (authors), *Second Generation Central Receiver Technologies - A Status Report,* ©1993 Verlag C. F. Mulller GmbH, Karlsruhe, Germany, ISBN 3-7880-7482-5.

3. Kolb, G. J., "Economic Evaluation of Solar-only and Hybrid Power Towers Using Molten Salt Technology", *Proceedings of the 8th International Symposium on Solar Thermal Concentrating Technologies,* October 6-11, 1996, Cologne, Germany, elsewhere in these proceedings.

4. Chavez, J., Klimas, P., DeLaquil, P., and Skowronski, M., "The Solar Two Power Tower Project", *Proceedings of the 6th International Symposium on Solar Thermal Concentrating Technologies*, Mojacar, Spain, September 28 - October 2, 1992, ISBN 84-7834-163-3.

5a. Martin Marietta Corporation, *Molten Salt Electric Experiment (MSEE) - Phase 1 Report,* SAND85-8175, Sandia National Laboratories, August 1985.

5b. Smith, D. C. (author) and J. M. Chavez (editor), *A Final Report on the Phase 1 Testing of a Molten-Salt Cavity Receiver,* SAND87-2290, May 1992.

6. Goods, S., Bradshaw, R. Prairie, M., and Chavez, J., *Corrosion of Stainless and Carbon Steels in Molten Mixtures of Industrial Nitrates*, SAND94-8211, Sandia National Laboratories, 1994.

7. Pacheco, J.E., Ralph, M.E., Chavez, J.M., Dunkin, S.R., Rush, E.E., Ghanbari, C.M., and Matthews, M.W., *Results of Molten Salt Panel and Component Experiments for Solar Central Receivers: Cold Fill, Freeze/Thaw, Thermal Cycling and Shock, and Instrumentation Tests,* SAND94-2525, Sandia National Laboratories, 1995.

8. Fricker, H. W., *Report of the Wire Pack Volumetric Receiver Tests Performed at PSA, Spain in 1987 and 1988,* SSPS Technical Report No. 2/89

9. FICHTNER Development Engineering, *PHOEBUS, a 30 MWe Solar Tower Power Plant for Jordan*, Phase 1B Feasibility Study - Volume 1: Main Results, Stuttgart, Germany, 1990.

10. TSA Consortium, *PHOEBUS: A Solar Tower Plant with Volumetric Air Receiver - Post-Feasibility Study 1C*, Germany, 1994.

11. Haeger, M. et al., "Operational Experiences with the Experimental Set-Up of a 2,5MWth Volumetric Air Receiver (TSA) at the Plataforma Solar de Almeria", 1994.

12. Haeger, M. et al, "Phoebus Technology Program Solar Air Receiver (TSA): Experimental Setup for TSA at the CESA Test Facility of the Plataforma Solar de Almeria (PSA)", *Proceedings of the Joint ASME Solar Engineering Conference,* 1994.

13. L. & C. Steinmueller GmbH, 1996, "PHOEBUS Solar Power Tower", Gummersbach, Germany

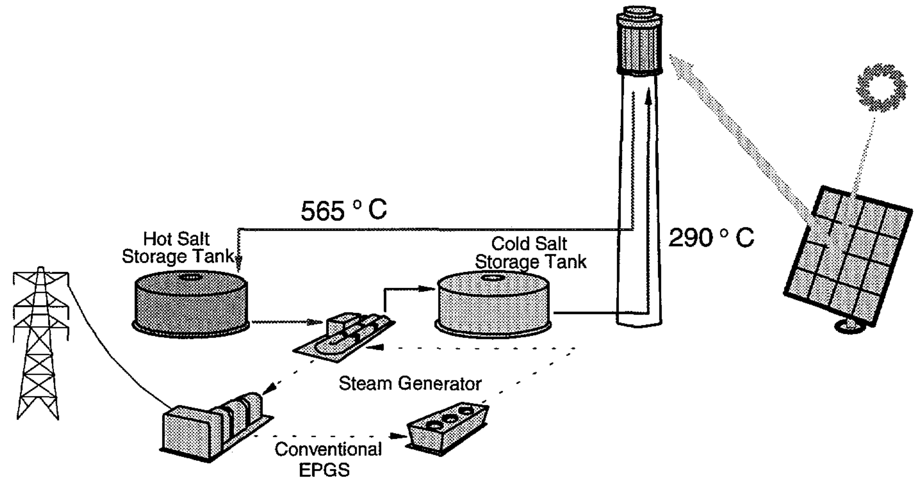

Figure 1 Schematic of a molten-salt power plant. Molten salt is heated to 565°C within a tubular-type receiver and pumped to the hot storage tank. After making steam, molten salt at 290°C is returned to the cold tank and pumped back to the receiver.

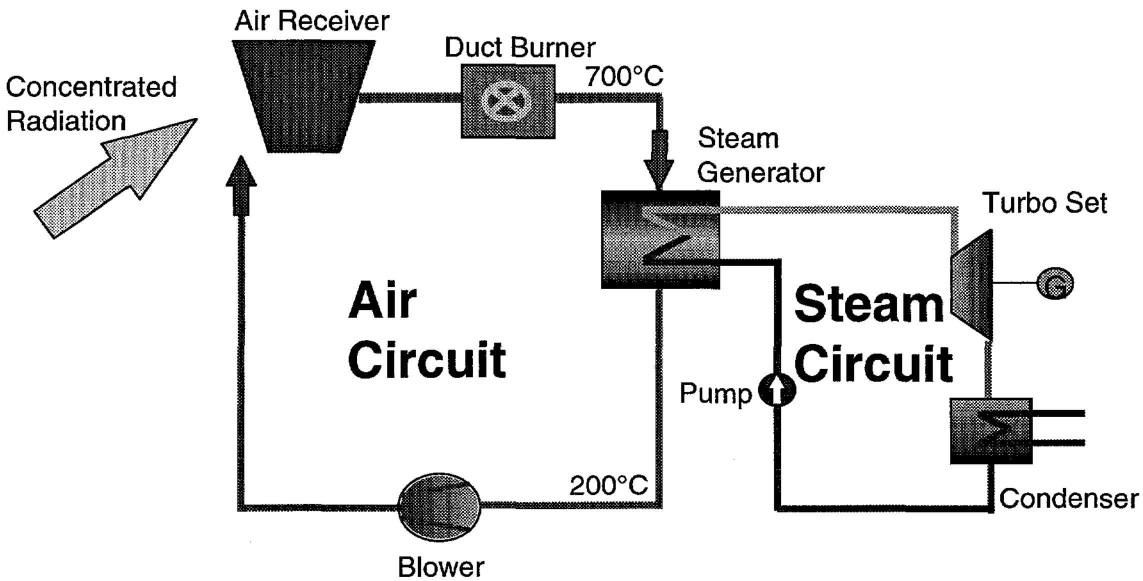

Figure 2 Schematic of atmospheric-air power plants [13]. Air is heated to 700°C within volumetric-type wire-knit receiver and blowers move the air directly to the steam generator. (In the baseline design, a fossil-fired duct burner provides heat to the steam generator during periods when solar is unvailable.) After making steam, warm air at 200°C is mixed with atmospheric air and reintroduced to the receiver inlet.

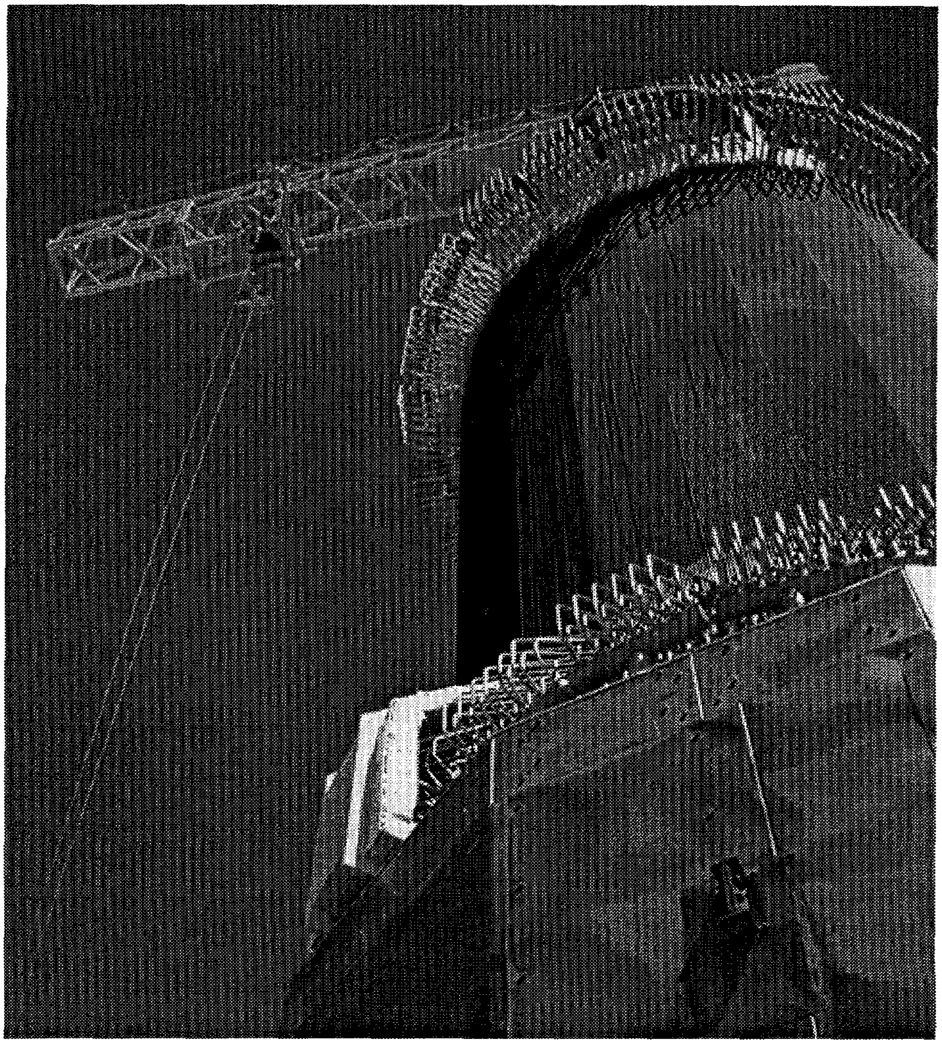

Figure 3 The Solar Two receiver during installation. Pictured are individual panels, upper and lower headers, and a lower header oven.

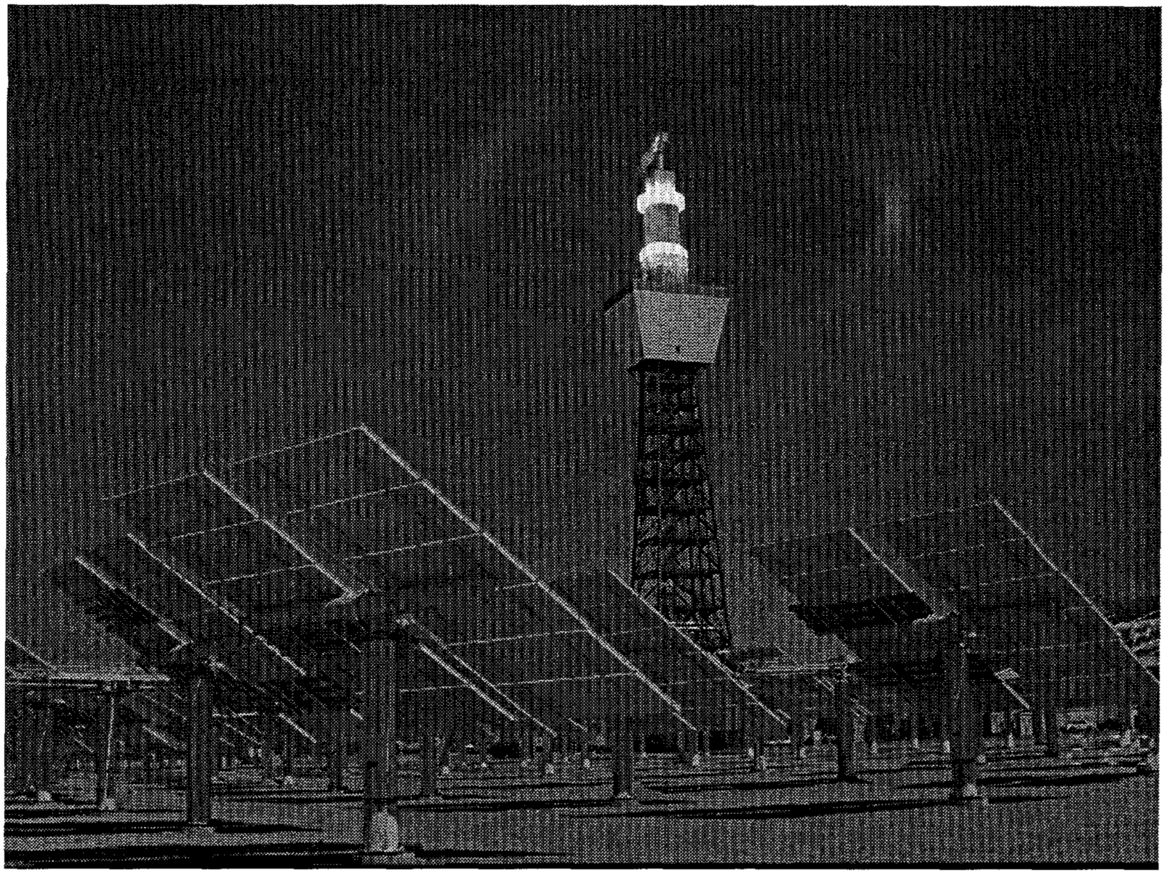

Figure 4 The Solar Two power plant in operation. A fraction of heliostats are focused at their standby aimpoints, the rest are heating salt in the receiver.

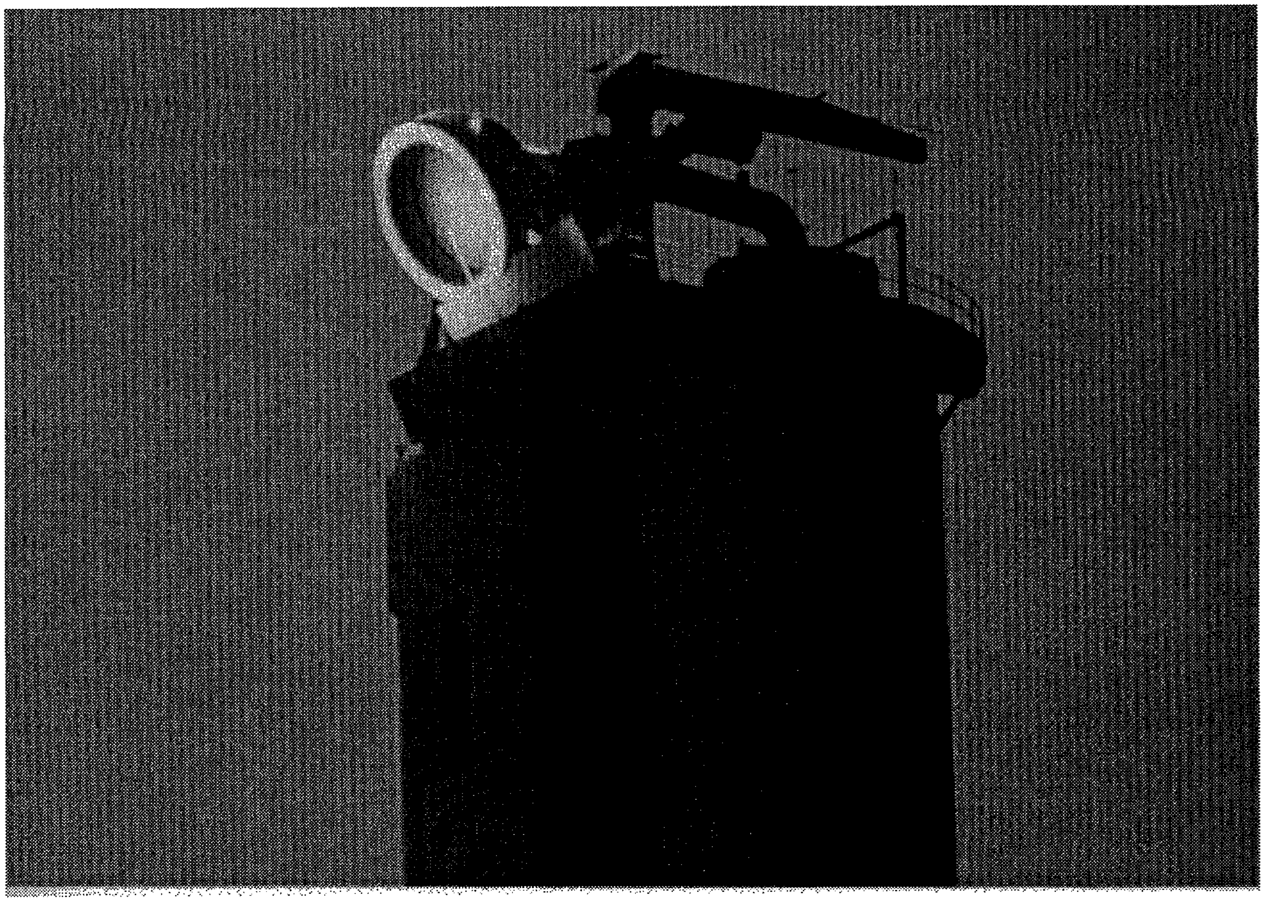

Figure 5 Closeup of the TSA receiver in operation.

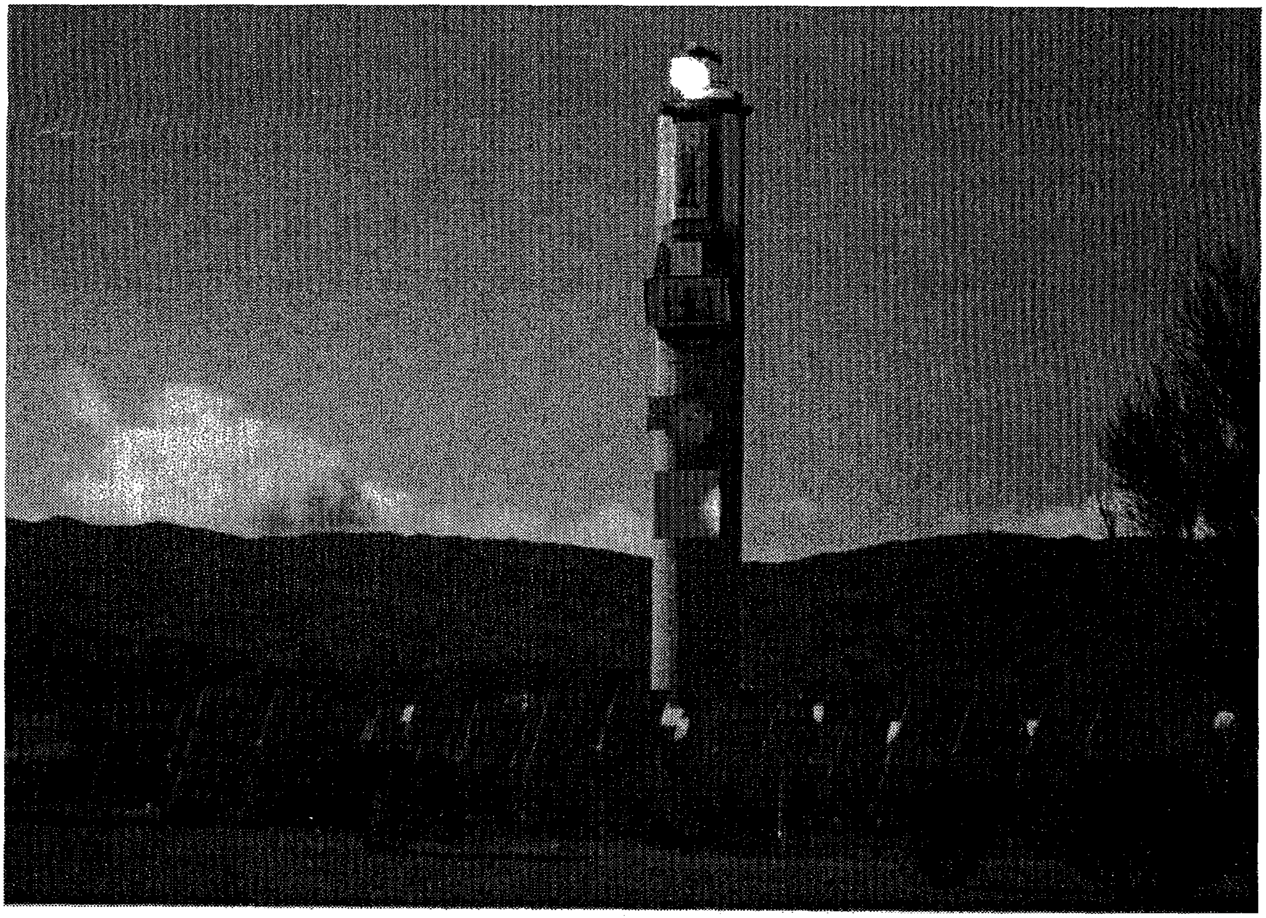

Figure 6 The TSA plant in Almeria, Spain.

Table 1. Characteristics of the major equipment comprising the Solar Two plant.

Component	Characteristics
Tower	Modified slightly for Solar Two 85 m to top of the receiver

Heliostats	1818 original Solar One Martin Marietta Heliostats
	    39.1 m^2 each
	    Baseline reflectivity is 90%
	108 new Lugo heliostats
	    95.1 m^2 each
	    Baseline reflectivity is 93%
	Surround Field
	Total reflective surface - 81,400 m^2

Receiver	Designed and constructed by Rockwell International Power rating - 42.2 MW_t Design salt flow rate - 100 kg/s Average solar flux - 430 suns (430 kW/m^2) Peak solar flux of 800 suns - (800 kW/m^2) Salt temperature in - 290 °C Salt temperature out - 565 °C Number of panels - 24 Number of tubes per panel - 32 Height - 6.1 m Diameter - 5.1 m Tube O.D. - 2.06 cm Tube material - 316H stainless steel

Thermal Storage System	Designed and constructed by Pitt Des Moines
	Number of tanks - 2
	Volume - 875,000 L each
	    Stainless steel hot tank
	    Carbon steel cold tank

	Thermal storage capacity - 110 $MWhr_t$ (three hours at rated turbine output) Hot-tank temperature - 565 °C Cold-tank temperature - 290 °C
Salt Transport System	Designed and constructed by Bechtel Group, Inc. Receiver pumps - Two, nine-stage turbine pumps Rated at 50% of design flow each 52 kg/s each 244 m dynamic head 187 kW variable speed drives Steam generator pumps - Two, single-stage cantilever pumps Rated at 100% of design flow each 88 kg/s each 64 m dynamic head 150 kW variable speed drives Stainless steel piping for hot salt pipes Carbon steel piping for cold salt pipes Heat trace - Dual element, mineral-insulated cable on all salt lines
Salt Inventory	Provided by Chilean Nitrate Corporation Inventory - 1.5 million kilograms Composition - 60 wt% $NaNO_3$ and 40 wt % KNO_3 Melting point - 220 °C
Steam Generator System	Designed and constructed by ABB Lummus Nominal power rating - 35 MW_t Superheater design - salt-in-shell Boiler design - salt-in-tube kettle Preheater design - salt-in-shell Steam conditions - 100 bar, 540 °C Salt flow rate - 83 kg/s
Turbine/ Generator	Refurbished Solar One General Electric system Gross power rating - 12 MW_e

Table 2. Estimated peak efficiencies for the Solar Two subsystems in comparison to those expected for a commercial solar-only plant.

	Solar Two	Commercial Plant
Mirror Reflectivity	90%	94%
Field efficiency	68%	73%
Mirror cleanliness	95%	95%
Receiver	87%	87%
Storage	99%	>99%
EPGS	34%	43%
Parasitics	88%	93%
Overall Peak Efficiency	15%	23%

Table 3. Characteristics of the major equipment comprising the TSA Plant

Component	Characteristics
Tower	CESA-1 Tower 86 m above ground to receiver
Heliostats	160 to 180 Heliostats, manufactured by Aisenel 40 m^2 each, recently refurbished North Field Total reflective surface - 6,400 to 7200 m^2
Receiver	Designed and constructed by L & C Steinmuller Power rating - 2.5 MW_t Air flow rate - 4.1 kg/s Average solar flux - 300 suns (300 kW/m^2) Peak solar flux of 800 suns - (800 kW/m^2) Air temperature in - 150 °C Air temperature out - 700 °C Aperture Diameter - 3.4 m Absorber tilt angle - 30 ° Absorber Diameter - 3 m

Thermal Storage System	Designed and constructed by Didier M+P Energietechnik Number of tanks - 1 Thermocline type Media - 18 t of alumina pebbles Internally insulated tank Thermal storage capacity - 1 $MWhr_t$ with 30° C temperature drop (30 minutes) Storage temperature - 325 to 680 °C
Air Transport System	Designed and constructed by Fichtner Development Engineering and L&C Steinmuller Receiver Blower - centrifugal type Rated at 100% of design flow 4.1 kg/s 4500 Pa rated pressure drop Variable speed motor Steam Generator Blower - centrifugal type Rated at 100% of design flow 3.4 kg/s 5450 Pa rated pressure drop Variable speed motor Internally insulated ducting made of low-temperature steel alloys
Steam Generator System	Designed and constructed by L&C Steinmuller Monotube, once-through boiler of the Benson type Nominal/maximum power rating - 1.84 MW_t/ 2.2 MW_t Steam conditions - 45 bar, 340 °C
Turbine/ Generator	None