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SOLAR TWO: A SUCCESSFUL POWER TOWER DEMONSTRATION PROJECT

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ABSTRACT

Solar Two, a 10MWe power tower plant in Barstow, California, successfully demonstrated the production of grid electricity at utility-scale with a molten-salt solar power tower. This paper provides an overview of the project, from inception in 1993 to closure in the spring of 1999. Included are discussions of the goals of the Solar Two consortium, the planned-vs.-actual timeline, plant performance, problems encountered, and highlights and successes of the project. The paper concludes with a number of key results of the Solar Two test and evaluation program.

BACKGROUND ON SOLAR TWO

The Solar Two project was a collaborative venture to design, build, test and operate a 10MWe solar power tower plant that utilizes molten salt as its heat transfer and storage medium. Construction on the $56M project began in September of 1994; the final plant operating day was April 8, 1999.

Solar Two built on the success of Solar One, a 10MWe power tower that operated on the same site from 1982 to 1988. Solar One utilized water/steam as its heat transfer medium. The Solar One receiver produced steam that was either sent directly to the turbine or sent to a series of heat exchangers to heat a thermal storage tank containing heat transfer oil, sand and gravel (Baker, 1988, and Radosevich, 1988). Recognizing the shortcomings of a water/steam plant, the Solar Two project was proposed as a demonstration of a power tower utilizing molten salt as both the heat transfer and energy storage medium. The salt chosen was a 60/40 mixture (by weight) of sodium nitrate and potassium nitrate, which has a melting point of approximately 220°C. The use of molten salt allowed the generation of electricity to be uncoupled from the collection of solar energy. This uncoupling solves the major problems inherent in a water/steam system. For example, during periods of intermittent clouds, Solar One would trip offline, whereas Solar Two continued to produce electricity. In addition, Solar Two was able to efficiently produce electricity after sundown. For a utility company with an evening peak demand, this "dispatchability" of power greatly increases the value of power produced.

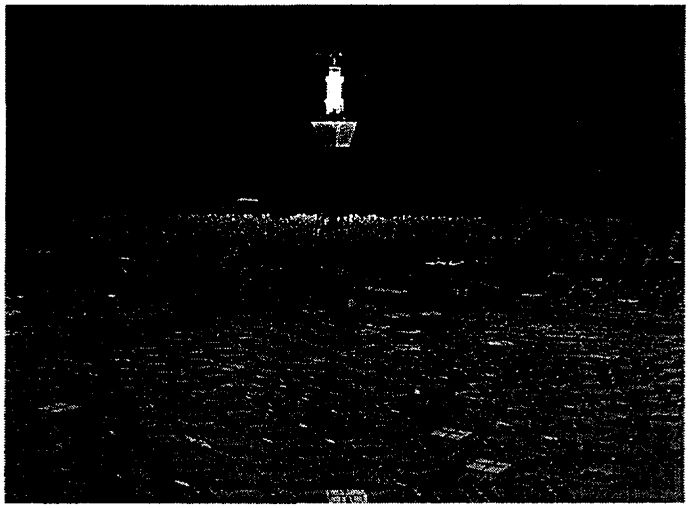

Fig. 1: Aerial view of the Solar Two plant during operation in 1998.

Constructed on the Solar One site near Barstow, California, Solar Two utilized much of the Solar One equipment (heliostats, receiver tower, turbine generator, etc.), but replaced the water-steam heat transfer system with a molten-salt system. The major system replacements were: 1) a new salt-in-tube receiver which accepts cold salt at 290°C and heats it to 565°C; 2) a three-vessel steam generator to heat and

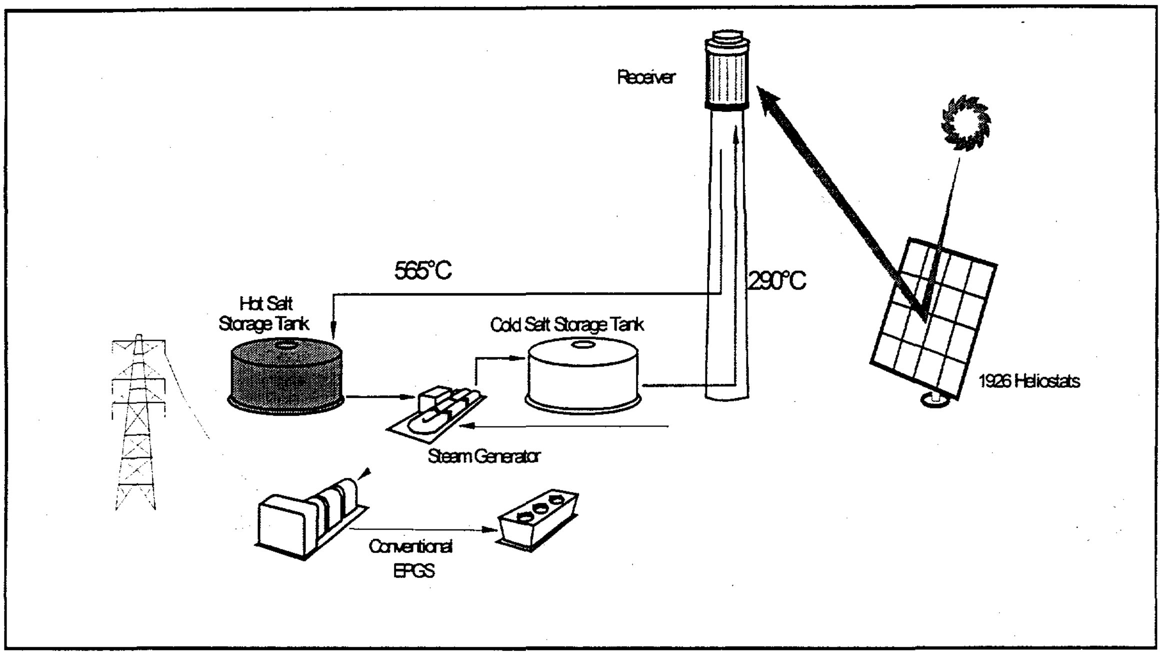

Fig. 2: Solar Two schematic. Molten salt at 290°C is pumped from the cold tank to the receiver where it is heated to 565°C and delivered to the hot storage tank. To make electricity, hot salt is pumped to the steam generator, then returned to the cold tank.

evaporate water and produce superheated steam; 3) one hot and one cold salt storage tank; and 4) salt piping with electric heat trace. To supplement the original 1818 Solar One heliostats, each with 39m^2 of reflective area, 108 heliostats, each with 95m^2, were added to the south half of the field.

Project participants regarded Solar Two as the final necessary step towards commercialization of molten-salt power tower plants. In general, the project sought to reduce the perceived risks of building the first commercial plant. More specifically, the objectives of the Solar Two project were to:

1. Validate the technical characteristics of the nitrate salt receiver, storage system, and steam generator;
2. Improve the accuracy of economic projections for commercial molten-salt power-tower projects by increasing the database of capital, operating, and maintenance costs;
3. Simulate the design, construction, and operation of the first 100 MWe (or larger) power plants;
4. Collect, evaluate, and distribute to U.S. industries and the solar industry the knowledge gained in order to foster wider utility interest in the first commercial projects; and
5. Stimulate the formation of a commercialization consortium to facilitate the financing and construction of the initial commercial projects.

A consortium including utilities and industry joined the U.S. Department of Energy (USDOE) in funding the Solar Two project. Table 1 shows the partners that comprised the Solar Two Consortium. The consortium members formed a Solar Two Steering Committee, chaired by Southern California Edison, to oversee the schedule and budget and to ensure the project was meeting its goals and objectives. A Technical Advisory Committee, chaired by Sandia National Laboratories (Sandia), aided the Steering Committee throughout the project by performing functions such as design review, evaluation of technical issues, and development of the test and evaluation program. The Bechtel Group, Inc. was selected as the Engineer and Construction Manager (E&CM); Energy Services, Inc. (ESI) was selected as the plant's Operations and Maintenance (O&M) contractor. Sandia served as the technical consultant to the USDOE and provided an on-site representative throughout the project's construction, startup, testing and operating phases.

Figure 2 presents the overall system schematic for the Solar Two plant. Additional system details are available elsewhere (Pacheco, 1999).

Table 1: The Solar Two Consortium

Participants	***Contributors***
Arizona Public Service Company	Chilean Nitrate (A New York Company)
Bechtel Corporation	Nevada Power Company
California Energy Commission	South Coast Air Quality Management District
Electric Power Research Institute	
	Industrial Cost Share
Idaho Power Company	ABB Lummus
Los Angeles Department of Water and Power	Goulds Pumps
	General Process Controls
PacificCorp	Pitt-Des Moines
Sacramento Municipal Utility District	Raychem
	Boeing (Rockwell International Corp.)
Salt River Project	The Industrial Company
Southern California Edison Company	
U.S. Department of Energy	

SOLAR TWO TIMELINE

The Solar Two project was organized into six phases: 1) Systems Engineering; 2) Major Procurements; 3) Detailed Engineering; 4) Construction; 5) Startup, Checkout and Acceptance Testing; and 6) Operation. Table 2 presents the six phases along with both the planned and actual starting period for each phase. Dates for several key milestones are also included in the table.

DELAYS DURING STARTUP

The project met the planned schedule through the start of construction (Phase 4) and was within one month of the schedule at the end of the nearly one-year construction phase. However, significant delays occurred during Phase 5 (Startup, Checkout and Acceptance Testing). The following paragraphs present, in chronological order, some of the most significant sources of delays during the startup phase.

Table 2: Solar Two Project Phases and Milestones

Phase	*Planned Start*	*Actual Start*
1: Systems Engineering	**June 1993**	**January 1993**
2: Major Procurements	**October 1993**	**October 1993**
3: Detailed Engineering	**March 1994**	**March 1994**
4: Construction	**October 1994**	**September 1994**
5: Startup, Checkout & Acceptance Testing	**July 1995**	**August 1995**
First electricity to grid	October 1995	April 1996
Dedication	---	June 5, 1996
Acceptance Testing	November 1995	November 1997
6: Operation	**January 1996**	**February 1998**
Test & Evaluation	January 1996	Concurrent with power production
Operate for Power Production	January 1997	March 1998
Shutdown	**December 1998**	**April 8, 1999**

Delays in Completion of the Solar Two Receiver (March–June 1995)

Springtime winds at the site caused delays in installation of the receiver panels. Each of the 24 panels that comprise the Solar Two receiver had to be hoisted up the side of the 82-meter receiver tower, moved radially inward, bolted into place, and welded into the connecting piping. Raising the panels was impractical if the winds were not calm. In addition, maintaining purge gas for welding the receiver piping proved difficult in moderate winds.

Unexpected Need to Thermally Treat the Nitrate Salt (August–December 1995)

In performing small-scale tests on the nitrate salt delivered to the Solar two project, Sandia discovered that impurities in the salt led to chemical reactions in the salt. To drive these reactions to completion, the salt needed to be thermally treated prior to use in the plant. Plant personnel also found that the salt, delivered as small beads ("prills"), had absorbed moisture and clumped together. Additional material handling and heating equipment had to be temporarily installed at the site to crush the salt, melt it, then heat it for thermal treatment.

Delays Due to Improper Installation of Heat Trace on Salt Piping (June–October 1996)

Electric heat trace cables were used to maintain piping above salt freezing temperatures. The heat trace also served to reduce pipe stresses by preheating piping systems prior to flowing hot salt. The cables were inadvertently not installed uniformly along the length of much of the salt piping. This non-uniformity caused the portions of the piping with the most heat trace to be heated excessively while regions with less heat trace were just approaching design setpoint temperatures. The elevated temperatures lead to rapid corrosion of some of the carbon steel piping used for the cold salt systems. Corrosion products spalled off inside ground-level piping, became entrained in the salt, and caused pluggage in receiver tubes. A single receiver tube failed in June of 1996 during receiver operation. The tube was plugged with corrosion products and consequently starved of adequate salt flow. The tube ruptured from excessive temperatures due to the high solar flux, low-flow condition. An aqueous chemical solution was subsequently used to flush the piping systems and remove the corrosion products. Delays occurred as construction personnel replaced much of the heat trace cable and performed this unplanned chemical flush.

Evaporator Tube Failure and Subsequent Evaporator Modification (November 1996–October 1997)

As designed, the Solar Two steam generator consisted of a preheater, an evaporator of kettle-boiler design, and a superheater. Salt flowed on the tube side of the evaporator. In November of 1996, a single evaporator tube failed during operation of the steam generator. Examination of the failed evaporator tube indicated that it had ruptured after undergoing a number of freeze-thaw cycles. The evaporator was sent to the manufacturer for modification. The evaporator was re-installed, system modifications completed, and the steam generator startup procedure revised before the plant returned to operation. During this outage, plant personnel installed a 3 MWth salt cooler provided by Sandia. This air-cooled system allowed some limited operation of the receiver system while steam generator repairs continued.

Stress Corrosion Cracking (August 1997)

A number of receiver tubes developed slow leaks due to intergranular stress corrosion cracking. It is believed that this cracking was accelerated by 1) contact with water as a result of flushing the piping system with an aqueous chemical solution (described above) and 2) contact with ambient moisture drawn into the receiver tubes as they cooled at the conclusion of daily operation. The leaking tubes were replaced, a dry-air purge system was installed, and the plant returned to operation.

IMPACT OF STARTUP DELAYS ON THE REMAINDER OF THE PROJECT

The original Solar Two schedule (see Table 2) called for completion of Phase 5 (Startup, Checkout, and Acceptance Testing) by the end of December 1995. After acceptance of the plant by ESI, the Operations and Maintenance contractor, test and evaluation activities were scheduled for one full year (all of 1996). The plant would then enter a two-year power production period, after which the plant would shut down. The Solar Two consortium had provided funding based on this schedule.

In reality, the protracted startup period, with its attendant costs, meant the project would not meet its schedule and was in jeopardy of not meeting its goals and objectives within the available funding. To address the problem, the Steering Committee adopted a modified approach, wherein Test and Evaluation goals and power production goals were to be met concurrently. On February 18, 1998, the plant was turned over from Bechtel's startup group to ESI operating staff. Starting with this turnover, one month of operation was to be devoted to conducting any tests that required an abnormal plant configuration or abnormal operating parameters. (For example, receiver efficiency testing was performed during this period since it required operating at 50% flow with only 50% of the heliostat field tracking the receiver.) After this period, the plant was to be run in a power production mode. In this mode, anytime the plant was operational, test objectives were being met by collecting and archiving extensive data and operational (power production) objectives were met by accumulating hours of full plant operation and operator experience. This approach worked well: during this abbreviated operational phase, the plant collected a wealth of test data while setting a number of operational records.

KEY RESULTS OF THE TEST AND EVALUATION PHASE

Sandia is compiling the final results of the Solar Two Test and Evaluation program. The following sections describe key results from tests on the receiver efficiency, steam generation and electric power generation system characterization, thermal storage, dispatchability, and plant performance. The primary objectives of these tests were to characterize each major subsystem relative to design predictions and to characterize the overall plant performance.

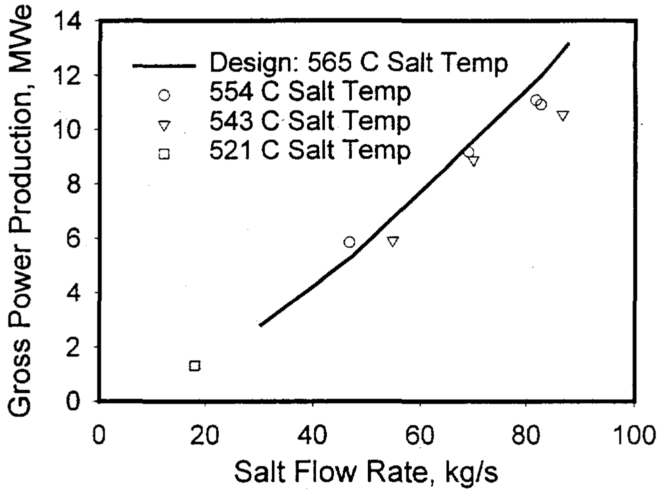

Fig. 3: ***Measured and design gross electrical power output versus salt flow rate.***

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 other measurements. The test allows the heat loss to be determined by operating the receiver at full and half power by removing and putting back on every other heliostat sequentially and keeping the salt outlet temperature constant. This procedure is described further in (Pacheco, Gilbert, 1999).

The tests were conducted during high (> 3 km/h) and low wind speeds (≤3 km/h). At full power, the receiver efficiency was found to be a weak function of wind velocity, being 88% with low wind velocities and 86% in wind speeds of 23 km/h. These data agreed well with results from the calculated (modeled) efficiency at low wind speeds and were actually slightly higher than predicted at high wind speeds.

Steam Generation / Electric Power Generation System Characterization

The purpose of the Steam Generation/Electric Power Generation System Characterization Test was to measure the steam generation system (SGS) and electric power generation system (EPGS) performance over a range of power loads and two inlet salt temperatures. Testing was done under steady-state conditions where the unit was held at the required conditions for a minimum of two hours, but typically three to eight hours. For the steady-state operations test, the SGS and the EPGS were operated together to measure the gross thermal conversion efficiency at the various loading conditions.

Figure 3 shows the gross electrical power output plotted against salt flow rate for three different salt inlet temperatures to the steam generator. Also shown in the figure are the design values calculated by Bechtel during the design phase of the project. In a new plant, a state-of-the-art turbine with reheat capability would be used, dramatically improving the conversion efficiency (greater than 40% for a modern turbine versus 34% for the Solar Two turbine).

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. The system was unable to reach the design gross turbine output for several reasons, including salt inlet temperature degradation (due to leak-through in salt valves), increased feedwater temperatures necessitated by SGS design issues, and fouling in the SGS. After these tests, in August 1998, the flange on the preheater was removed and the tubes were found to be fouled and plugged. After cleaning, the performance improved dramatically, yielding a gross turbine output of 11.6 MW_e, much closer to the design point. The water chemistry was monitored more closely after the cleaning and adjusted to reduce the rate of scaling on the water side of the SGS.

Thermal Storage System Performance

The thermal storage system provides a reservoir of hot salt that the steam generator and electric power generation systems use to dispatch electricity. The efficiency of the thermal storage system is a direct result of its thermal losses. To measure the thermal storage performance, we quantified the thermal losses of the hot tank, cold tank, steam generator sump, and receiver sump and compared the values to predictions. We also determined the actual thermal capacity of the thermal storage system based on the operating temperatures and delivered salt inventory.

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 mass of salt in the vessel, an estimate of the heat loss can be made. Another method is to have the heaters energized and regulate 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. Both methods were employed.

A summary of the measured and design thermal losses is shown in Table 3. The thermal losses for the tanks and sumps are similar to the design values except for the steam generator sump. The losses for the steam generator sump were higher than predicted possibly because the insulation degraded over the course of the project. Salt had leaked out of the sump and into the insulation on the sump which significantly affected its insulating properties.

The usable capacity of the thermal storage system (energy that could be sent to the steam generator) was estimated to be 107 MWh. The thermal storage system was designed to deliver thermal energy at full-rated duty of the steam generator for three hours at the rated hot and cold salt temperatures of 565°C and 290°C, respectively. (The design included a 12% capacity margin.) The amount of salt in the system was estimated to be 1380 tonnes, which was somewhat less than the design-specified 1490 tonnes, because approximately 100 tonnes of salt were not delivered to the site. In addition, the maximum attainable hot salt temperature from thermal storage delivered to the steam generation system was typically 554°C. Despite the slightly lower-than-specified salt inventory and decreased hot-salt temperature, the storage system still had the capacity to deliver the full-rated steam generator duty for three hours (35.5 MW x 3 h=106.5 MWh) with no capacity margin.

Dispatchability Test

The objective of the dispatchability test was to demonstrate the ability to dispatch electricity during the day, evening and night – independent of energy collection. Solar Two repeatedly met this objective. The plant routinely generated power during partly cloudy conditions, demonstrating the uncoupling of electricity production from solar energy collection. The plant also routinely generated power after receiver shutdown in the evening. The plant was designed to operate at full turbine output for three hours, utilizing the energy stored in the hot salt. Utilizing its three-hour, full-power storage capacity, and reducing the salt flow to the steam generator, the plant also demonstrated the ability to generate electricity for extended periods, including round-the-clock electricity generation.

The objective of one series of tests 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 input (to about 8 MWt) such that the inventory of salt would last through the night and into the morning, when the receiver could be restarted. This test was conducted in June and July of 1998. During one stretch, the plant produced electricity 24 hours-a-day for nearly a week (153 hours total) by using stored energy at night and recharging the inventory during the day.

Overall Plant Performance

One of the key performance goals of Solar Two was to demonstrate a 15% overall peak efficiency. The overall peak efficiency can be broken down into efficiencies of each major step in the conversion from sunlight to grid-connected electricity as shown in Table 4. The table shows the project goals, along with what was achieved at Solar Two and what would be expected in a commercial plant with im-

Table 3: Design 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

Table 4: Solar Two Peak Efficiencies (Goal and Achieved) Along with Values Expected for a Commercial Plant

Parameter	*Solar Two Goal*	*Solar Two Achieved (July 4, 1998)*	*Commercial Plant Predictions*
A. Mirror Reflectivity	90%	90%	94%
B. Field Efficiency	69%	61%	74%
C. Field Availability	98%	94%	99%
D. Mirror Cleanliness	95%	95%	95%
E. Receiver	87%	88%	87%
F. Storage	99%	99%	>99%
G. Overall Collection (Product of Above)	50%	43%	57%
H. EPGS	34%	34%	43%
I. Parasitics	88%	87%	93%
J. Overall Peak Efficiency (G*H*I)	15%	13%	23%

provements implemented into the design. The project efficiency goals were meant to be achieved in the third year of operation, after the two-year test and evaluation phase, during which the optimum operating conditions were to be determined. As stated earlier, project delays severely compressed the testing schedule. Consequently, Solar Two was not fully optimized. The shortfalls in the actual peak performance can be attributed primarily to the under-performance of the heliostat field (caused by low availability, excessive corrosion, delamination of the facets, poor canting, and high tracking errors of the old Solar One heliostat technology).

The daily plant performance is a function not only of the incident energy, but also on several factors including the plant availability, heliostat field availability, mirror cleanliness, heliostat optical performance, and wind effects. We were able to meet the performance goals of conversion of thermal energy to electrical energy and parasitic power consumption. We also approached the daily collection goals. A discussion of the daily collection, gross power production and parasitic energy consumption is described by Pacheco, et al (2000).

CONCLUSION

The Solar Two project successfully demonstrated the potential for molten-salt power towers to deliver bulk, dispatchable electricity to the power grid. Solar Two built on the system and component testing that had been accomplished previously, integrating them into a successful large-scale demonstration project. Typical of large-scale demonstration projects, Solar Two had to overcome startup problems. In so doing, the project provided invaluable lessons on what works and what doesn't work. The project concluded with a wealth of data needed by the project sponsors and future designers and investors who will design, fund, and build the first commercial power tower plants.

Commercial molten-salt power tower plants will have two distinct advantages over Solar Two. First, they will be able to draw on the lessons learned during each phase of Solar Two. For example, a strong quality control program during construction would avoid heat trace installation errors. Second, a commercial plant would not be a retrofit of an outdated power tower plant. Although reusing the Solar One site and much of its equipment afforded Solar Two considerable savings in capital costs, it also imposed restraints and penalties on performance. A good example is the heliostat field, where mirror corrosion, missing mirror facets, and obsolete hardware and controls degraded daily plant performance. A commercial plant would use new mirrors with new hardware and modern controls.

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