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A Study of Alternative System Conversions for the Solar One Pilot Plant

Systems Evaluation Division

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A STUDY OF ALTERNATIVE SYSTEM CONVERSIONS FOR THE SOLAR ONE PILOT PLANT

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Solar Central Receiver Department
Sandia National Laboratories Livermore
for the
U.S. Department of Energy

ABSTRACT

This report describes a study of alternatives for the conversion of Solar One, the 10 MWe solar thermal central receiver pilot plant near Barstow, California, to an advanced molten salt or liquid sodium central receiver system. These advanced systems offer a potential 25% reduction in the cost of delivered electricity at a utility plant scale. The results of this study indicate that several options exist for reducing the technical and economic risks associated with advanced central receiver systems. For all options studied, startup of the converted plant could begin approximately three years after the project is authorized. Because all of the conversion options have similar technical advantages and have costs in the range of $55-64M, a comparison did not identify a clear choice. Therefore, the electrical utility preferences should play a strong role in selecting the conversion option.

FOREWORD

The research and development described in this report was conducted within the U.S. Department of Energy's (DOE) Solar Thermal Technology Program. The Solar Thermal Technology Program directs efforts to advance solar thermal technologies through research and development of solar thermal materials, components, and subsystems, and through testing and evaluation of solar thermal systems. These efforts are carried out through DOE and its network of national laboratories who work with private industry. Together they have established a goal-directed program for providing technically proven and economically competitve options for incorporation into the Nation's energy supply.

The two primary solar thermal technologies, central receivers and distributed receivers, use various point and line-focus optics to concentrate sunlight onto receivers where the solar energy is absorbed as heat and converted to electricity or used as process heat. In central receiver systems, which this report will consider, fields of heliostats (two-axis tracking mirrors) focus sunlight onto a single receiver mounted on a tower. The concentrated sunlight is transformed into high temperature thermal energy in a circulating working fluid. Receiver temperatures can reach 1500^{o}C.

This report is the result of efforts of staff of the Solar Central Receiver Systems Division, Advanced Systems Department, Sandia National Laboratories Livermore. Mr. Lee Radosevich wrote the draft and final reports and performed the storage system design. Mr. Scott Faas coordinated all the technical tasks of the study and performed the heat transport system design. Mr. James Bartel performed the receiver system design, and Mr. Clay Mavis conducted the heliostat and master control system designs. Mr. Hal Norris aggregated the system cost estimates and Ms. Betty Carrell provided the plant layouts. Ms. Diane Atwood performed the heliostat field computer analyses and Mr. Michael Alley provided the technical editing.

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Overview

The Chairman of the House Science and Technology Committee requested that the Department of Energy (DOE) undertake a study of the potential for converting Solar One, the 10 MWe solar thermal central receiver pilot plant near Barstow, California, to a test facility for advanced concepts. To meet this request, DOE asked Sandia National Laboratories Livermore to study the conversion of Solar One to a 10 MWe or larger molten salt central receiver system or to an alternate advanced system.

This report describes the study of options for the conversion of Solar One to an advanced molten salt or liquid sodium central receiver system. The conversion of Solar One from a first-generation, water/steam system to one of the advanced systems is one approach to reduce technical and economic risks associated with an advanced central receiver technology. Compared to a water/steam system, the advanced systems offer at a utility plant scale a potential 25% reduction in the cost of delivered electricity.

The conversion options were selected to provide important component interaction data on attractive near-term central receiver technologies. The study did not consider options for testing a single component. Although test data on a single component would be a useful basis for future designs, a larger scale system test will eventually be needed to qualify the components for use in a utility-scale plant.

Six options were considered for the system conversion of Solar One. Five of the options are solar stand-alone plants that add combinations of the following equipment: molten salt or liquid sodium receiver, thermal storage, and steam generator; and upgrading of the existing heliostats or the addition of advanced heliostats. The sixth option combines a molten salt receiver, molten salt storage, and steam generator with a fossil-fueled energy source to provide data for hybrid (solar/fossil) operation.

Implementation of a Solar One system conversion requires the following activities: design, construction, startup, and testing and evaluation. If a Decision-to-Proceed is made in October 1985, the converted plant design would begin shortly thereafter. Construction would start in mid FY87, the last year of Solar One's five-year

Operational Test Period, and would be completed in FY88. A thirty-month startup, testing, and evaluation period would be completed in early FY91.

The costs (in 1984 dollars) for the six conversion options range from $55M to $64M. It should be emphasized that the relative cost estimates of the options are more accurate than the absolute values. A conversion of the plant will require purchasing substantial quantities of equipment which has never been built.

The results of this study indicate that several conversion options exist which will reduce the technical and economic risks associated with advanced central receiver systems. The costs of the options are not significantly different, and a comparison of the options did not identify a clear technical choice as to the best alternative. Electrical utility preferences should play a strong role in selecting the conversion option.

Discussion

The technology for the Solar One power plant was selected in 1977. At that time, a water/steam central receiver system was clearly the best choice for Solar One for two reasons: (1) water/steam technology was the most familiar to electric utility firms; and (2) water/steam central receiver technology was the most technically mature technology, having completed a successful design and component testing effort that began in 1975.

Solar One is now into the third year of a five-year Operational Test Period. Many goals have already been achieved: delivery of 10 MWe net from receiver steam, delivery of 7 MWe net from thermal storage, delivery of 28 MWe-hr net (7 MWe net for 4 hours) from thermal storage, and plant operation in all steady-state and transition modes. The successes at Solar One have substantially reduced the technical and economic risks associated with central receiver technology.

In 1978, soon after the design for Solar One had been chosen, the development of advanced technologies for solar central receiver systems began. Conceptual design studies identified molten salt- and liquid sodium-cooled central receiver systems as attractive alternatives to the water/steam technology selected for Solar One. The advanced technology central receiver systems would provide improvements over current technology in the following areas:

(1) improved performance resulting in an overall annual system efficiency of 22% compared to the 13% capability of Solar One technology;

(2) improved storage performance resulting in elimination of the 70% storage output limit of Solar One technology; and

(3) reduction of relatively high electricity production costs of the Solar One technology.

An advanced solar central receiver system at a pilot plant scale and in a utility operating environment would be a significant step in demonstrating these improvements. The conversion of Solar One is one approach for accomplishing testing and evaluation of an advanced technology system at the 10 MWe size. A conversion approach provides a low project cost by maximizing the use of existing equipment and replacing only those elements that are essential for testing and evaluating the advanced technology system.* An assessment of the results would support decisions concerning the construction of a utility-scale plant.

The advanced technologies proposed for a Solar One system conversion use high-temperature receiver heat transfer fluids, such as molten salt or liquid sodium, which also serve as the storage medium. Advantages of these technologies over the water/steam technology are higher cycle efficiencies resulting from the use of a reheat steam cycle and a capability to generate the full plant electrical output when operating from storage.

The advanced technologies also offer economic advantages. An estimate of electricity production costs (levelized in nominal dollars) indicates that a busbar cost of 80 mills/kWe-hr may be achievable at a utility scale** with an advanced technology like molten salt (Reference 1). A busbar cost of 80 mills/kWe-hr in 1980 dollars is equivalent to a cost of about 110 mills/kWe-hr in 1984 dollars. The latter value is the same as the solar thermal program cost target of 110 mills/kWe-hr*** and is thus an encouraging indication that a utility-scale plant using an advanced technology can meet the program cost targets.

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* A converted 10 MWe plant would save at least $25M from the cost of a new plant because it would not require installing a heliostat field, turbine-generator, and support systems.

**A utility-scale plant is nominally 100 MWe in size. Central receiver systems cannot achieve the program cost targets at small plant sizes--for example, 10 MWe.

***Cost targets have been developed that are levelized in both real and nominal dollars. The long-term cost target for central receiver electrical production is 50 mills/kWe-hr in real dollars and 110 mills/kWe-hr in nominal dollars (assuming 7% inflation).

Objectives

The objectives of a Solar One system conversion project, if implemented, would be to:

(1) establish the technical feasibility of an advanced, high-performance, low-cost solar central receiver technology at the 10 MWe scale;

(2) reduce the technical and economic risks associated with an advanced solar central receiver technology; and

(3) identify areas where future central receiver research and development may lead to significant performance improvements and increased capabilities.

To meet these objectives, conversion options are proposed that combine the following features:

(1) convert Solar One to a system with a molten salt or liquid sodium receiver, thermal storage, and steam generator heat exchanger;

(2) upgrade the Solar One heliostats or add advanced heliostats to the existing Solar One heliostat field;

(3) add a fossil-fueled energy source; and

(4) test and evaluate the converted Solar One plant for at least 18 months.

Plant Design

Six options were studied for the conversion of Solar One. Options 1-5 are solar stand-alone plants, while Option 6 is a hybrid (combined solar/fossil) plant. All six options have a 10 MWe plant rating and use system designs that are representative of a utility-scale plant. The design characteristics of each option are presented in Table ES-I.

All options use the Solar One collector and electrical power generating systems, as well as major portions of the plant control and plant support systems. All options also require the installation of new receiver, tower, thermal storage, heat exchangers, controls, and instrumentation. In addition, Option 4 will require the upgrading of heliostats, Option 5 will add advanced heliostats, and Option 6 will require a fossil-fueled energy source.

TABLE ES-I
DESIGN CHARACTERISTICS OF SOLAR ONE AND SOLAR ONE SYSTEM CONVERSION OPTIONS

DESIGN CHARACTERISTIC	SOLAR ONE	SOLAR ONE CONVERSION OPTION					
		1	2	3	4	5	6
Plant Type	Stand-Alone	Stand-Alone	Stand-Alone	Stand-Alone	Stand-Alone	Stand-Alone	Hybrid
Plant Net Output	10 MWe	10 MWe	10 MWe	10 MWe	10 MWe	10 MWe	10 MWe
Receiver Technology and Output Temperature	Water/Steam Cylindrical 516°C	Salt Flat Plate 574°C	Sodium Flat Plate 574°C	Sodium Flat Plate 593°C	Salt Flat Plate 574°C	Salt Flat Plate 574°C	Salt Flat Plate 574°C
Existing Heliostat Area	71,130 m2	71,130 m2	71,130 m2	71,130 m2	71,130 m2	71,130 m2	71,130 m2
Upgraded or Added Heliostat Area	N.A.	N.A.	N.A.	N.A.	39,000 m2 (Upgraded)	15,000 m2 (Added)	N.A.
Total Heliostat Area	71,130 m2	71,130 m2	71,130 m2	71,130 m2	71,130 m2	86,130 m2	71,130 m2
Field Configuration	Surround	North	North	North	North	North	North
Tower Height	79 m	128 m	128 m	128 m	128 m	128 m	128 m
Storage Technology and Operating Temperature Range	Oil/Rock Thermocline 218-302°C	Salt Two Tank 277-566°C	Sodium Two Tank 277-566°C	Salt Two Tank 277-566°C	Salt Two Tank 277-566°C	Salt Two Tank 277-566°C	Salt Two Tank 277-566°C
Fossil Heater Technology	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	Salt Heater

N.A. – Not Applicable

The design point (2 p.m. winter solstice) thermal efficiency of the converted plant is only slightly less than the present Solar One plant, because Solar One's heliostats are not optimally located for the converted plant's north field configuration. As a result, the converted plant and Solar One would have a comparable annual electrical energy output. The installation of 100 advanced heliostats (Option 5) and a larger receiver would boost the converted plant output by 25%.

The difference in annual output between Solar One's water/steam technology and molten salt (or liquid sodium) technology would be significant on a utility scale. The use of a reheat steam Rankine cycle, along with an optimized field layout and advanced technology components, could potentially increase the annual plant output of a molten salt or liquid sodium system by almost 40% over a utility-scale plant that uses water/steam technology.

Schedule

The schedule for a Solar One system conversion is predicated on using DOE procurement procedures and a Decision-to-Proceed date of October 1985. Because of the location of the various system elements, conversion construction activities could be initiated early, with little interference with Solar One's on-going power production testing. Preliminary design would begin in October 1986, and construction would start in April 1987, four months before the end of Solar One's power production testing. Construction would be completed for all options in June 1988. A one-year startup period would be followed by an 18 month testing and evaluation period. The testing and evaluation would be completed in December 1990.

Resource Requirements

The resource requirements for converting Solar One are shown for each option in Table ES-II. The required funding is displayed in real (constant) 1984 dollars (no escalation). In 1984 dollars the costs range from a high of $64M for Option 4 to a low of $55M for Option 1.

The required funding includes the total design, construction, and startup costs. No cost sharing was assumed in deriving the total costs. The costs do not include funding for a DOE project office, technical support groups (e.g., DOE national laboratories), and operating and maintenance staffing needs for the period from the end of the Solar One Power Production Phase to the end of the converted Solar One testing and evaluation period.

TABLE ES-II
SOLAR ONE SYSTEM CONVERSION RESOURCE
REQUIREMENTS IN 1984 DOLLARS

SOLAR ONE CONVERSION OPTION	SYSTEM	REQUIRED RESOURCES ($M)
1	Molten Salt Stand—Alone	55
2	Liquid Sodium Stand—Alone	61
3	Liquid Sodium Receiver/Molten Salt Storage Stand—Alone	57
4	Molten Salt Stand—Alone With Upgraded Heliostats	64
5	Molten Salt Stand—Alone With Added Heliostats	61
6	Molten Salt Hybrid With Salt Heater	62

Assessment of the Conversion Options

The results of this study indicate that several options exist for reducing the technical and economic risks associated with advanced central receiver systems. The costs of the options are not significantly different, and a comparison of the options did not identify a clear technical choice as to the best alternative. Electrical utility preferences should play a strong role in selecting the conversion option. If a successful plant at a power level of 10 MWe will provide sufficient data to effect a utility decision to construct a utility-scale plant without government subsidy, then any one of the options might become very attractive. If the utilities indicate that a larger experiment is needed prior to construction of a utility-scale plant, then none of the options may be appropriate.

The selection of a Solar One conversion option will hinge strongly on three factors: (1) plant configuration (stand-alone or hybrid); (2) capability for evaluating advanced heliostat designs; and (3) heat transfer fluid.

The addition of a fossil-fueled energy source to a utility-scale central receiver plant is a very attractive modification. A hybrid plant could maximize the use of plant equipment and personnel, provide a high plant capacity factor, and assure plant operation even if the solar equipment is not operational.

The inclusion of 50-100 advanced, large-area heliostats will give an industrial firm the opportunity to learn about the manufacture of a new design and obtain the results of actual field performance. This number of new heliostats should be sufficient to guarantee realistic manufacturing procedures and provide statistically significant numbers for operations and maintenance evaluation.

Finally, utility preferences for a heat transfer fluid are an important consideration, because the cost, safety, and handling characteristics of liquid sodium and molten salt are somewhat different. In particular, a system which uses two working fluids--that is, a sodium receiver and molten salt storage--requires careful scrutiny. Such a system is complicated by the need to transfer heat from one fluid to the other and the need to provide a handling and service capability for two different fluids. The costs to solve these complications may reduce any potential cost advantages of this system over a single fluid system.

1.0 INTRODUCTION

The Chairman of the House Science and Technology Committee requested that the Department of Energy (DOE) undertake a study of the potential for converting Solar One, the 10 MWe solar thermal central receiver pilot plant near Barstow, California, to a test facility for advanced concepts. To meet this request, DOE asked Sandia National Laboratories Livermore to study the conversion of Solar One to a 10 MWe or larger molten salt central receiver system or to an alternate advanced system.

Solar One (see Figure 1) uses a large number of computer-guided tracking mirrors, called heliostats, to reflect the sun's energy onto a receiver mounted on top of a tower. The receiver absorbs the solar energy in water that is boiled and converted to high-pressure steam. This steam powers a turbine-generator for the production of electrical energy. Steam from the receiver can also be diverted to thermal storage for use when insufficient sunlight is available for solar operation. Solar One can supply ten megawatts of electrical power to the Southern California Edison (SCE) grid, making it the world's largest solar electric generating plant.

Technology development for Solar One was initiated in 1975. Conceptual designs of utility- and pilot- scale plants were completed by three industrial firms, while a fourth firm completed a collector system design. Component experiments at a reduced scale were performed for each of the plant's major systems: the collector, receiver, and thermal storage systems. Based on the results of these studies, the glass/metal heliostat, single-pass-to-superheat water/steam receiver, and oil/rock thermocline storage technologies were selected for incorporation into Solar One.

In 1978 the Department of Energy (DOE) and the Associates* entered into a Cooperative Agreement to design, construct, and operate Solar One. Construction of Solar One was completed in 1981, and the plant is now undergoing a five-year Operational Test Period. The Operational Test Period consists of a two-year Experimental Test and Evaluation Phase followed by a three-year Power Production Phase.

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*Southern California Edison, Los Angeles Department of Water and Power, and the California Energy Commission

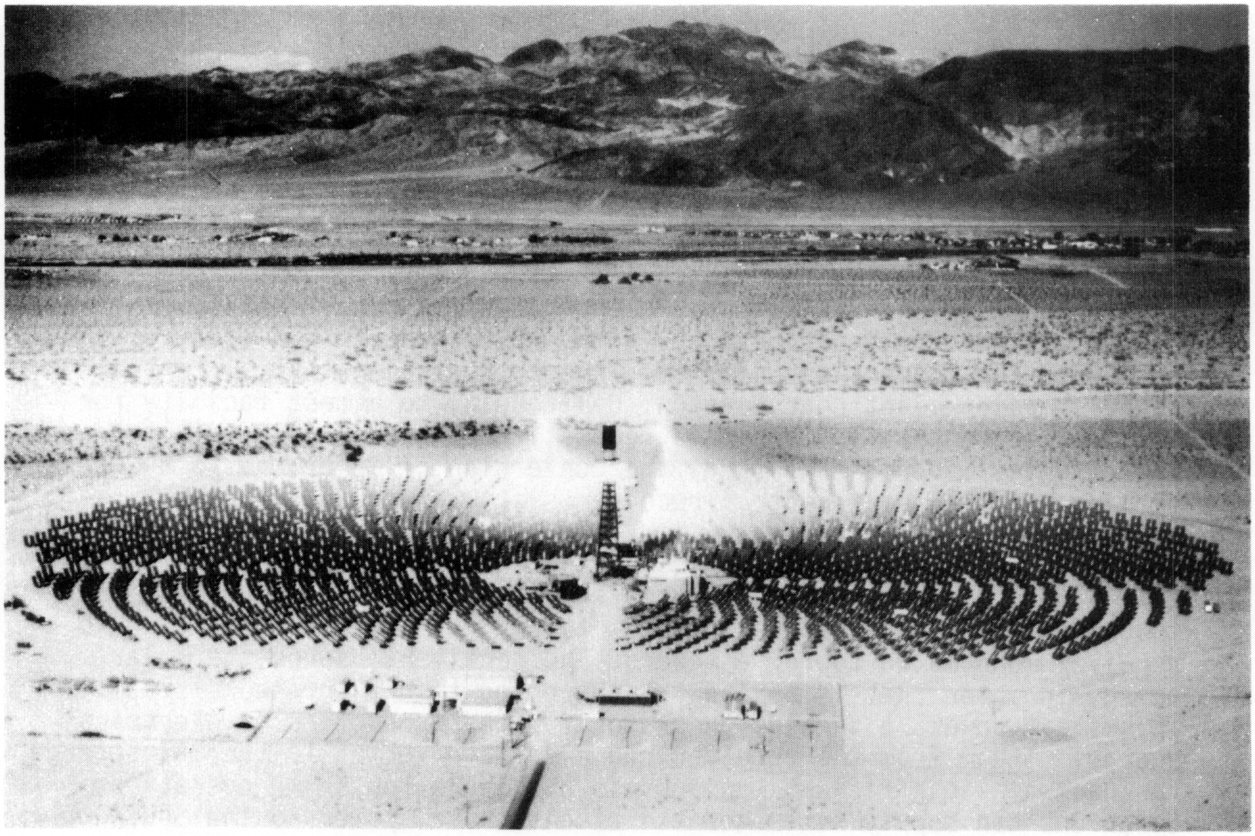


Figure 1. Solar One: 10 MWe Solar Thermal Central Receiver Pilot Plant Near Barstow, California

The Experimental Test and Evaluation Phase, which began in mid-1982, is complete. During this phase the plant was successfully operated in all its steady-state and transition modes, and the plant's system and component performance was evaluated. The Power Production Phase, which began in August 1984, will primarily demonstrate the operational capability of Solar One to reliably supply electrical power.

Although many goals have already been achieved in testing the first-generation, water/steam system of Solar One, the system has performance limitations and is relatively expensive to build, even in large-scale production. Advanced central receiver technology offers the potential for higher performance and lower costs. Conversion of Solar One to incorporate this advanced central receiver technology would provide data to verify these potential improvements.

The conversion of Solar One to incorporate advanced central receiver technology would require a modification to the existing Cooperative Agreement. The agreement presently requires that, at the end of the Power Production Phase in 1987, the Department of Energy--at its own expense--must remove the "Solar Facilities" and restore the plant site to its original condition. The agreement also provides that DOE with the prior written permission of the Associates may abandon the Solar Facilities in place. To cover restoration, a total of $360,000 has already been obligated under the agreement. This is the estimated amount that would be required over and above the salvage value of the Solar Facilities.

This report describes a study of alternatives for the conversion of Solar One to an advanced central receiver system. In the next section, the rationale for the conversion of Solar One and the rationale for selection of molten salt or liquid sodium technology for the conversion are presented. Section 3 discusses the objectives of a conversion project, while Section 4 describes several design options for conversion of the plant. The schedule and cost for each option are presented in Sections 5 and 6, respectively. Section 7 assesses the capabilities of each option to meet the conversion project objectives and describes the factors governing a utility selection.

2.0 DISCUSSION

2.1 Limits of Current Technology

Solar One consists of seven major systems: the collector, receiver, thermal storage, plant control, beam characterization, electrical power generating, and plant support systems (see Figure 2). The heliostats in the collector system reflect the solar energy onto the receiver, which is mounted on a central tower. The receiver absorbs the solar energy in water that is boiled and converted to high-pressure steam. This steam powers a turbine-generator for the generation of electrical energy. Steam from the receiver, in excess of the energy required for the generation of 10 MWe net power to the utility grid, is diverted to thermal storage for use when output from the receiver is less than that needed for rated electrical power. Thermal storage also provides steam for keeping selected portions of the plant warm during nonoperating hours.

The technology for the Solar One power plant was selected in 1977. At that time, a water/steam central receiver system was clearly the best choice for Solar One for two reasons: (1) water/steam technology was the most familiar to electric utility firms; and (2) water/steam central receiver technology was the most technically mature technology, having completed a successful design and component testing effort that began in 1975.

Solar One is now into the third year of its five-year Operational Test Period. Completion of the Operational Test Period is a significant milestone in the development of water/steam central receiver technology. As a consequence of this testing, the technical feasibility of a first-generation central receiver system will be established. Many goals have already been achieved: delivery of 10 MWe net from receiver steam, delivery of 7 MWe net from thermal storage, delivery of 28 MWe-hr net (7 MWe net for 4 hours) from thermal storage, and plant operation in all steady-state and transition modes. The successes at Solar One have substantially reduced the technical and economic risks associated with central receiver technology.

The development of advanced technologies for solar central receiver systems began in 1978, soon after the design for Solar One had been chosen. Conceptual design studies identified molten salt-cooled and

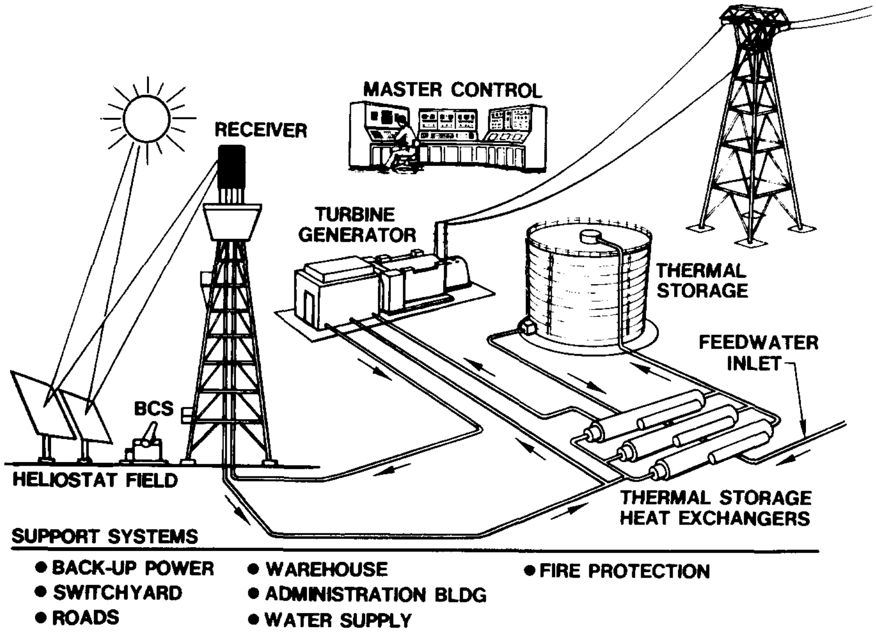


Figure 2. Solar One System Schematic

liquid sodium-cooled central receiver systems as attractive alternatives to the first-generation water/steam technology selected for Solar One. The advanced technology central receiver systems would provide improvements over current technology in the following areas:

(1) improved performance resulting in an overall annual system efficiency of 22%, compared to the 13% capability of Solar One technology;*

(2) improved storage performance resulting in elimination of the 70% storage output limit of Solar One technology; and

(3) reduction of relatively high electricity production costs of the Solar One technology.

An advanced solar central receiver system at a pilot plant scale and in a utility operating environment would be a significant step in demonstrating these improvements. A conversion of Solar One is one approach for accomplishing testing and evaluation of an advanced technology system. A Solar One conversion permits the evaluation of key component interactions in an operating system and at a cost that would be comparable to the cost of a Solar One receiver-only experiment. The

*This improvement in system performance is predicated on the use of advanced heliostat, receiver, and thermal storage designs and the use of a reheat steam turbine.

costs of a Solar One receiver-only test would be similar to a Solar One conversion because a receiver experiment would require most of the major equipment of a converted system including receiver, pumps, piping, storage tanks (to contain the receiver heat transfer fluid), and steam generator or air heat exchanger (to dissipate heat from the receiver heat transfer fluid).

A Solar One conversion provides a low project cost by maximizing the use of existing equipment and replacing only those elements that are essential for testing and evaluating the advanced technology system. A converted 10 MWe plant would save at least $25M from the cost of a new plant, because it would not require installing a heliostat field, turbine-generator, and support systems.

Also, a Solar One conversion can provide a thermal power of 40-50 MW, thus assuring that the advanced technology components and system will be tested at a relatively large scale. The capability of the Central Receiver Test Facility (CRTF) in Albuquerque, New Mexico, is 5 MWt, a level which is far too low to test even a single full-scale panel of a utility-scale receiver. Increasing the power level at the CRTF is a possibility, but a major expansion would be required and significant increases in heliostat field power would be necessary.

A Solar One conversion will also permit a direct comparison of water/steam and advanced technology (i.e., molten salt or liquid sodium) system performance. Finally, a Solar One conversion will permit the operation and evaluation of an advanced technology system in a utility operating environment. An assessment of the results would help support decisions concerning the construction of a utility-scale plant.

2.2 Advanced Technology Selection

The attractiveness of molten salt-cooled and liquid sodium-cooled central receiver technologies and thus their selection for a Solar One system conversion are based on technical and economic considerations.

Technical Factors

The advanced technologies use high-temperature receiver heat transfer fluids, such as molten salt or liquid sodium, which also serve as the storage medium. Advantages of these technologies over the water/steam technology are higher cycle efficiencies resulting from the use of a reheat steam cycle and a capability to generate the full plant electrical output when operating from storage. A $NaNO_3$-KNO_3 salt mixture appears attractive because of its low cost, high energy density, and potentially high operating temperature (566°C or 1050°F). Liquid sodium also provides this high operating temperature capability and is an excellent heat transfer medium.

The development of both technologies is well under way. Material studies have been performed to establish the physical properties and long-term stability and corrosion potential of nitrate salts at elevated temperatures. A molten salt-cooled receiver prototype has been built and tested at the CRTF. The designs of molten salt steam generators and advanced molten salt receivers have been completed. An advanced storage concept, in which molten salt is contained in an internally insulated tank, was also tested at the CRTF.

A central receiver electric system, using molten salt technology, has been integrated into the CRTF. The experiment, named Molten Salt Electric Experiment (MSEE), uses a molten salt-cooled central receiver and molten salt storage system, previously built and tested, with the CRTF heliostat field, a steam generator heat exchanger, and a steam turbine to generate 0.75 MWe of electric power. Testing of this experiment, which is cost-shared (50/50) by DOE and several private firms (Electric Power Research Institute, utilities, and industrial suppliers), will be completed in 1985.

Additional experiments are also planned at the CRTF to proof-test individual components of an advanced molten salt system. A receiver experiment will employ a cavity configuration and will evaluate three different panel designs. Other experiments include two fluid loops that will test full-scale pumps and valves at temperatures of 277°C (530°F) and 566°C (1050°F), the lower and upper operating temperature limits of several proposed molten salt system designs.

The designs of liquid sodium-cooled receivers have been completed, and a liquid sodium-cooled receiver prototype was built and tested at the CRTF. Liquid sodium technology that is applicable to solar central receiver systems has been developed under DOE's nuclear reactor program.

A liquid sodium experiment of comparable size to the MSEE is being performed under the auspices of the International Energy Agency, Small Solar Power Systems (IEA/SSPS) Project. The U.S. is one of nine IEA member countries participating in this project, which is located near Almeria, Spain. The experiment uses a liquid sodium-cooled central receiver, liquid sodium storage system, heliostat field, steam generator heat exchanger, and a steam engine to generate 0.5 MWe of electrical power. Testing and evaluation were completed at the end of 1984.

The MSEE and IEA/SSPS experiments represent the first system-level development steps along the evolutionary path to mature large-scale plants using advanced central receiver technologies.* At the low thermal power levels achieved in these experiments (less than 5 MWt), many component designs were not representative of utility-scale components since the intent was to prove the concept rather than to simulate utility-scale designs. Therefore, the next step in the

* The 2.5 MWe French Themis power plant is a second, small-scale molten salt system experiment that is under test.

development of these technologies is an experiment, much larger in size, that can be scaled to a full-sized power plant. Either molten salt or liquid sodium technology could be used based on a similar level of technical maturity.

Economic Factors

A comparison of electricity production costs for several central receiver technologies is shown in Figure 3 (derived from Reference 1). The busbar energy cost (levelized in nominal dollars) using different heat transport fluids is shown for a 100 MWe plant as a function of capacity factor.* Results are displayed for three working fluids: water/steam, liquid sodium, and molten nitrate salt. The water/steam curve is a utility-scale version of the Solar One single-pass-to-superheat design. Both a single line and a band are shown for liquid sodium. The line corresponds to the cost of an all-sodium system--that is, one which

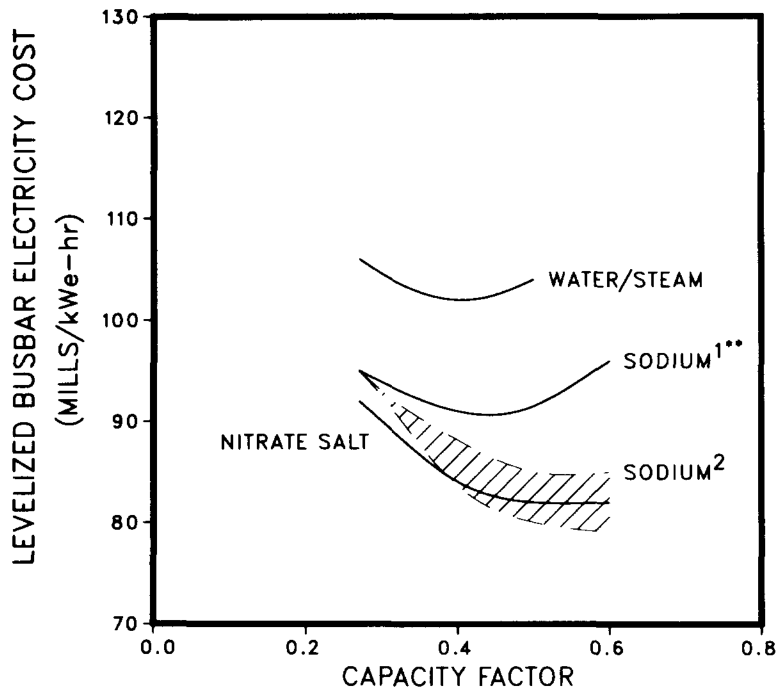


Figure 3. Central Receiver Technology Comparison for the Production of Electricity

*Capacity Factor: Annual energy production divided by the energy that would have been generated if the plant had operated at its rated power for the entire year. Capacity factors of about 0.42, 0.54, and 0.63 can be achieved with 3, 6, and 9 hours of storage capacity, respectively. See Reference 1 for further discussion.

**Sodium[1] - Sodium receiver with sodium storage
Sodium[2] - Sodium receiver with low-cost storage

uses a liquid sodium-cooled receiver and liquid sodium storage. The band represents the costs that might be achieved by using a liquid sodium-cooled receiver with a low-cost storage system, such as molten salt or air/rock. A band of costs is shown due to uncertainties in the costs of a combined system. The assumed collector system cost is $\$97/m^2$ ($\$9/ft^2$) in 1980 dollars.

The results indicate that a busbar cost of 80 mills/kWe-hr may be achievable with a molten salt system or a combined liquid sodium/molten salt system. A busbar cost of 80 mills/kWe-hr in 1980 dollars is equivalent to a cost of about 110 mills/kWe-hr in 1984 dollars. The latter value is the same as the solar thermal program cost target of 110 mills/kWe-hr* and is thus an encouraging indication that a utility-scale plant using an advanced technology can meet the program cost targets.

For relatively low capacity factors (25%)--that is, systems with little storage--the busbar costs of molten salt and all-liquid sodium systems are comparable and are about 10% less than the water/steam system. For larger capacity factors, a molten salt system or a combined liquid sodium/molten salt system has the lowest busbar cost, with an even larger cost differential (about 25%) between them and the water/steam system. A qualitative discussion of the cost differences between these technologies is given below.

The all-sodium system is projected to be more expensive than the nitrate salt system at larger capacity factors because the density of sodium is about half that of salt and its heat capacity is about 25% less. This comparison implies a need for larger sodium heat transport piping and thermal energy storage tanks. In addition, sodium costs more than the nitrate salt mixture. For systems with storage greater than two hours, this combination produces a significant cost difference. By combining a sodium receiver with molten salt or other low-cost storage, this cost difference can essentially be eliminated at larger capacity factors. However, no such combination has been built and tested.

Water/steam systems should be more expensive than nitrate salt or sodium systems because heavy wall tubing must be used in the receiver to contain the steam pressure, while thin wall tubing is used in a salt or sodium receiver. The greater mass of the pressure-containing parts for the water/steam system results in a greater receiver cost. Water/steam systems also have a thermodynamic (and therefore, cost) penalty compared with salt or sodium when thermal energy goes through storage, because of the phase changes between steam and water.

*Cost targets have been developed that are levelized in both real and nominal dollars. The long-term cost target for central receiver electrical production is 50 mills/kWe-hr in real dollars and 110 mills/kWe-hr in nominal dollars (assuming 7% inflation).

No options using an air working fluid were considered because the air/Brayton systems studied to date have had high electricity costs. For air-cooled systems, the low heat transfer coefficient of air requires that the heat-absorbing area of the receiver be large. The receiver runs at a higher temperature than that for nitrate salt or water/steam with a greater radiative loss. This loss requires more heliostats to compensate for the thermal loss. The large size of the receiver and the need for materials compatible with high temperatures also increase the costs. In order to achieve high thermal-to-electric efficiencies, the air-Brayton cycle must be recuperated or coupled with a steam-Rankine bottoming cycle. For these reasons, the overall electric power generating system cost exceeds that of the Rankine turbine plus steam generator and associated equipment (Reference 1).

Another plant configuration, the addition of a fossil-fueled energy source to a molten salt or liquid sodium central receiver plant, could also result in favorable energy costs similar to those shown in Figure 3. Low energy costs result because the plant can generate significantly more energy with only a small increase in capital costs. In addition, the plant's output can be easily matched to the system load of a utility grid, thereby obviating the need (and cost) for a backup plant. Previous studies--for example, Reference 2--have shown a hybrid plant to be an attractive plant option.

3.0 OBJECTIVES

The objectives of a Solar One system conversion project, if implemented, would be to:

(1) establish the technical feasibility of an advanced, high-performance, low-cost solar central receiver technology at the 10 MWe scale;

(2) reduce the technical and economic risks associated with an advanced solar central receiver technology; and

(3) identify areas where future central receiver research and development may lead to significant performance improvements and increased capabilities.

To meet these objectives, conversion options are proposed that combine the following features:

(1) convert Solar One to a system with a molten salt or liquid sodium receiver, thermal storage, and steam generator heat exchanger;

(2) upgrade the Solar One heliostats or add advanced heliostats to the existing Solar One heliostat field;

(3) add a fossil-fueled energy source; and

(4) test and evaluate the converted Solar One plant for at least 18 months.

4.0 PLANT DESIGN

A central receiver system can be configured as either a stand-alone or hybrid plant. A stand-alone plant operates on solar energy alone with no on-site, fossil-fueled back-up power system. A hybrid plant has both a solar energy collection system and a fossil-fueled back-up system, allowing it to operate on solar energy alone, fossil energy alone, or both. Either configuration can also have a storage system.

In this section the characteristics of Solar One, a 10 MWe stand-alone plant, are described first. Next, converted plant designs are described that employ an advanced central receiver technology in either a stand-alone or hybrid plant configuration.

4.1 Solar One Plant Design

Collector System

The collector system consists of 1,818 heliostats and a control system. Each heliostat has 39.13 m^2 (421 ft^2) reflective area, and the total field reflector area is 71,130 m^2 (765,700 ft^2). The control system consists of a microprocessor controller in each heliostat, a field controller for control of groups of up to 32 heliostats, and a central computer called the heliostat array controller.

Receiver System

The receiver system consists of an external single-pass-to-superheat boiler, pumps, piping, wiring, and controls necessary to provide the required amount of steam to the turbine. The receiver is designed to produce 516°C (960°F) steam at 10.1 MPa (1,465 psia). The receiver is 7 m (23 ft) in diameter and 13.7 m (45 ft) high with a total surface area of 302 m^2 (3,252 ft^2). The top of the receiver is about 90 m (300 ft) above ground level.

Thermal Storage System

The thermal storage system consists of a tank, heat exchangers, pumps, valves, piping, and controls required for operation and monitoring. The storage tank is 13.7 m (45 ft) high and 18.3 m (60 ft) in diameter. The tank is filled with rock, sand, and thermal oil. When fully charged, the mixture has a temperature of 302°C (575°F). When the system is discharging, the oil is pumped through a heat exchanger to produce 277°C (530°F) steam at 2.8 MPa (400 psia), for delivery to the turbine. The net rated electrical capacity of the plant operating on thermal storage is 28 MWe-hr or 7 MWe for four hours.

Plant Control System

The plant control system consists of equipment that provides for plant control from a centralized control room. It supplies overall coordinated supervisory control to individual system controls; it also supplies data collection and display functions.

Beam Characterization System

The beam characterization consists of tower-mounted targets, video cameras, heat flux sensors, and supporting and display equipment. The system aligns heliostats, updates the heliostat tracking equation, and detects heliostat anomalies.

Electrical Power Generating System

The electrical power generating system consists of the turbine-generator, rated at 12.5 MWe, and associated support functions, such as feedwater chemistry, uninterruptible power supply, condenser, and cooling and lubrication systems.

Plant Support System

The plant support system consists of site structures, buildings and facilities, and facility services. Site structures include the receiver support tower, pipe racks, and equipment foundations required for component support. Major buildings and facilities include an administration building, turbine-generator and control building, warehouse, pump house, weather monitoring equipment, and visitor's center. Facility services include support systems such as raw water, fire protection, demineralized water, cooling water, nitrogen, compressed air, liquid waste, oil supply, and lightning protection.

4.2 Converted Plant Designs

Conversion Options

Six options were studied for the conversion of Solar One. Options 1-5 are stand-alone plants, while Option 6 is a hybrid (solar/fossil) plant. All options provide a capability for the evaluation of an advanced technology system at a plant size that is representative of a utility plant design.

Options 1-5 offer the potential for establishing technical feasibility and reducing the risk of operating a stand-alone, advanced central receiver system at a utility-plant scale. These first five options permit the evaluation of molten salt technology, liquid sodium technology, or a combination of the two technologies. These options also permit the evaluation of advanced mirror module designs or advanced heliostat designs. Option 6, a hybrid plant, will establish technical feasibility and significantly reduce the risk of operating an advanced central receiver system at a utility-plant scale. A hybrid system is attractive because it can maximize the use of plant equipment and personnel, provide a high plant capacity factor, and assure plant operation even if the solar equipment is not operational. A hybrid option is presented that offers a simple approach for integrating the solar and fossil-fueled energy sources.

All options use the Solar One collector and electrical power generating systems, as well as major portions of the plant control and plant support systems. Option 1 (see Figure 4) provides for the conversion of Solar One with a molten salt-cooled receiver system, molten salt thermal storage system, salt steam generator system, new tower, upgraded beam characterization system, and upgraded plant control system.

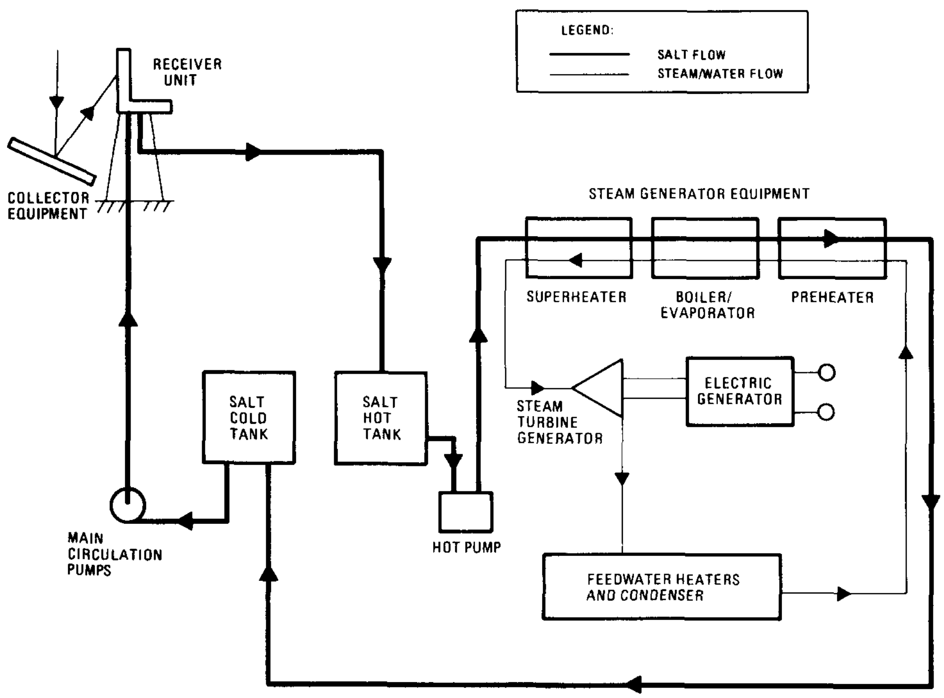


Figure 4. Molten Salt Stand-alone System (Options 1, 4, and 5)

Option 2 (see Figure 5) is similar to Option 1 but substitutes liquid sodium technology for molten salt technology. Option 3 (see Figure 6) combines features of both molten salt and liquid sodium technologies; it includes a liquid sodium-cooled receiver system, molten salt thermal storage system, sodium-to-salt heat exchanger system, and salt steam generator system. Both Options 4 and 5 use molten salt technology like Option 1 (see Figure 4); however, they also provide for the upgrading or expansion of the heliostat field: Option 4 replaces the corroded* and low-reflectivity mirror modules of the existing Solar One heliostat field, while Option 5 provides for a moderate (21%) expansion of the reflector area using advanced heliostat technology.

Option 6 is similar to Option 1 except for the addition of a fossil-fueled energy source. This option (see Figure 7) uses a salt heater as the fossil-fueled energy source for hybrid operation. The plant has a rating of 10 MWe, when operating from solar energy, fossil energy, or combined solar and fossil energy.

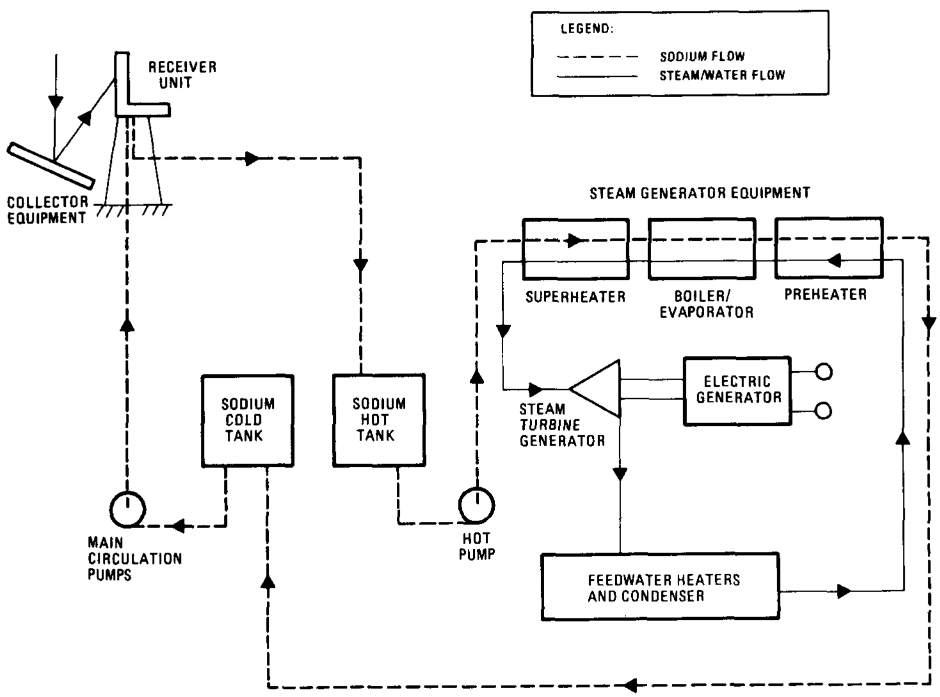


Figure 5. Liquid Sodium Stand-alone System (Option 2)

*Mirror corrosion surveys taken in 1983 and 1984 revealed corrosion areas of 0.016% and 0.029% of the total mirror reflective area, respectively. Therefore, mirror corrosion is expected to be an insignificant problem during the course of a Solar One conversion project.

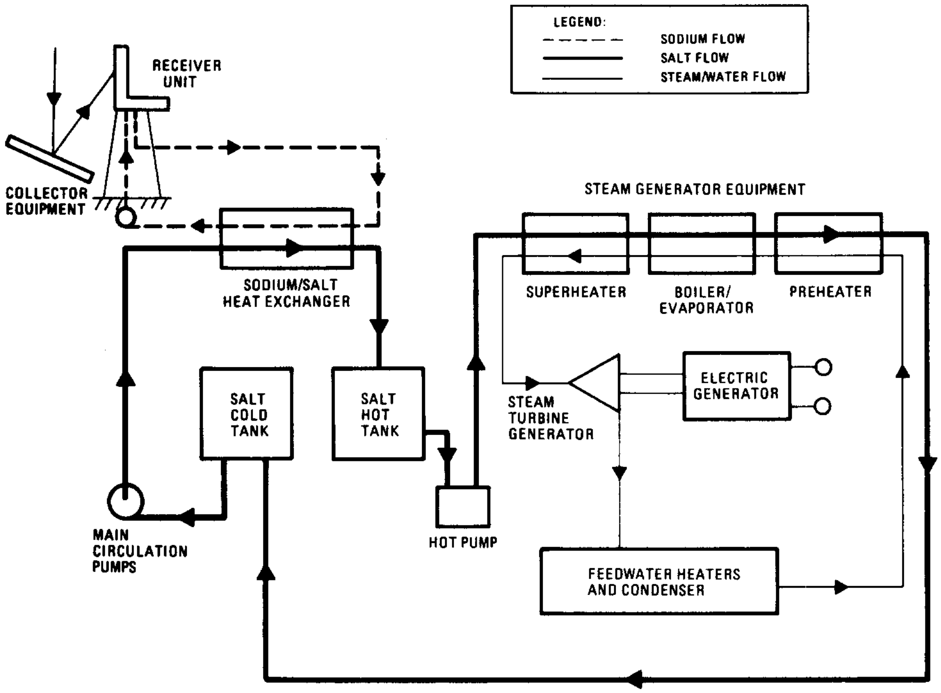


Figure 6. Liquid Sodium Receiver and Molten Salt Storage Stand-alone System (Option 3)

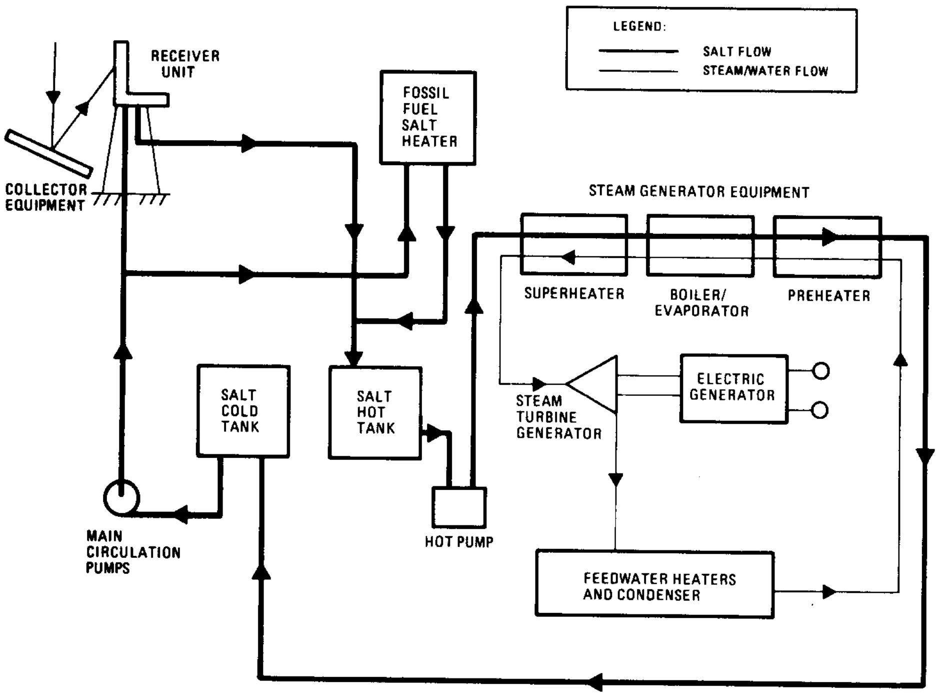


Figure 7. Molten Salt Hybrid System with Fossil Fuel Salt Heater (Option 6)

All options except Option 3 are similar in technical complexity. Option 3 is more complex because it uses two heat transfer fluid loops and requires an, as yet untested, sodium-to-salt heat exchanger. The design characteristics of each option are presented in Table I and are described below.

Converted Plant Configuration

All conversion options use a north field plant configuration with a new tower and receiver positioned at the south end of the existing heliostat field (see Figures 8 and 9). Construction of a new south tower was selected over the conversion of the existing one. A south tower will maximize use of the existing heliostat field since the new receiver will be a flat plate design rather than an external cylinder or multi-cavity design. Tower cost is not a dominant factor in the cost of the conversion project. As an example, for Option 1, it is estimated that the foundation, concrete tower, an enclosure for controls, a crane, an elevator, and a service platform would cost about $5.3M for design and construction. If the existing tower is used, the present receiver, piping, and equipment would have to be removed and modifications made to adapt the tower to a new receiver and piping system. Thus the reduction in cost of the project would be considerably less than $5.3M.

The new storage tanks, steam generator, and fossil energy source (optional) are located in the existing core area and are connected to the tower riser and downcomer by means of piping positioned adjacent to the south access road. For Option 5, added heliostats will be placed at the periphery of the existing heliostat field as indicated by the shaded area in Figure 8.

If a conversion project is authorized, the converted plant configuration will be studied further as the first step of preliminary design. Design issues, such as tower location, receiver design, storage capacity, and solar/fossil integration will be examined to assure that they are the most representative of a utility-scale plant. Revisions in the plant configuration resulting from examining these design issues would not have a major impact on project cost.

Converted Plant System Characteristics

The conversion of Solar One, depending on the option selected, requires the installation of the following major items: receiver, tower, thermal storage, heat exchangers, fossil-fueled energy source, heliostats or mirrors modules, controls, and instrumentation.

Receiver (all options)--A flat-plate receiver, either molten salt-cooled (all options except 2 and 3) or liquid sodium-cooled (Options 2 and 3) is mounted on a tower located south of the heliostat field (see, for example, Reference 3). During operation,

TABLE I
DESIGN CHARACTERISTICS OF SOLAR ONE AND SOLAR ONE SYSTEM CONVERSION OPTIONS

DESIGN CHARACTERISTIC	SOLAR ONE	SOLAR ONE CONVERSION OPTION					
		1	2	3	4	5	6
Plant Type	Stand-Alone	Stand-Alone	Stand-Alone	Stand-Alone	Stand-Alone	Stand-Alone	Hybrid
Plant Net Output	10 MWe	10 MWe	10 MWe	10 MWe	10 MWe	10 MWe	10 MWe
Receiver Technology and Output Temperature	Water/Steam Cylindrical 516°C	Salt Flat Plate 574°C	Sodium Flat Plate 574°C	Sodium Flat Plate 593°C	Salt Flat Plate 574°C	Salt Flat Plate 574°C	Salt Flat Plate 574°C
Receiver Output Power	35.9 MWt	32.8 MWt	30.6 MWt	30.6 MWt	33.5 MWt	41.0 MWt	32.8 MWt
Existing Heliostat Area	71,130 m2	71,130 m2	71,130 m2	71,130 m2	71,130 m2	71,130 m2	71,130 m2
Upgraded or Added Heliostat Area	N.A.	N.A.	N.A.	N.A.	39,000 m2 (Upgraded)	15,000 m2 (Added)	N.A.
Total Heliostat Area	71,130 m2	71,130 m2	71,130 m2	71,130 m2	71,130 m2	86,130 m2	71,130 m2
Field Configuration	Surround	North	North	North	North	North	North
Tower Height	79 m	128 m	128 m	128 m	128 m	128 m	128 m
Storage Technology and Operating Temperature Range	Oil/Rock Thermocline 218-302°C	Salt Two Tank 277-566°C	Sodium Two Tank 277-566°C	Salt Two Tank 277-566°C	Salt Two Tank 277-566°C	Salt Two Tank 277-566°C	Salt Two Tank 277-566°C
Storage Capacity	182 MWt-hr	160 MWt-hr	160 MWt-hr	160 MWt-hr	160 MWt-hr	160 MWt-hr	90 MWt-hr
Fossil Heater Tech. and Output Power	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	Salt Heater 35 MWt
Steam Generator Power Rating	N.A.	35 MWt	35 MWt	35 MWt	35 MWt	35 MWt	35 MWt
Intermediate Heat Exchanger Power Rating	N.A.	N.A.	N.A.	30.6 MWt	N.A.	N.A.	N.A.

N.A. - Not Applicable

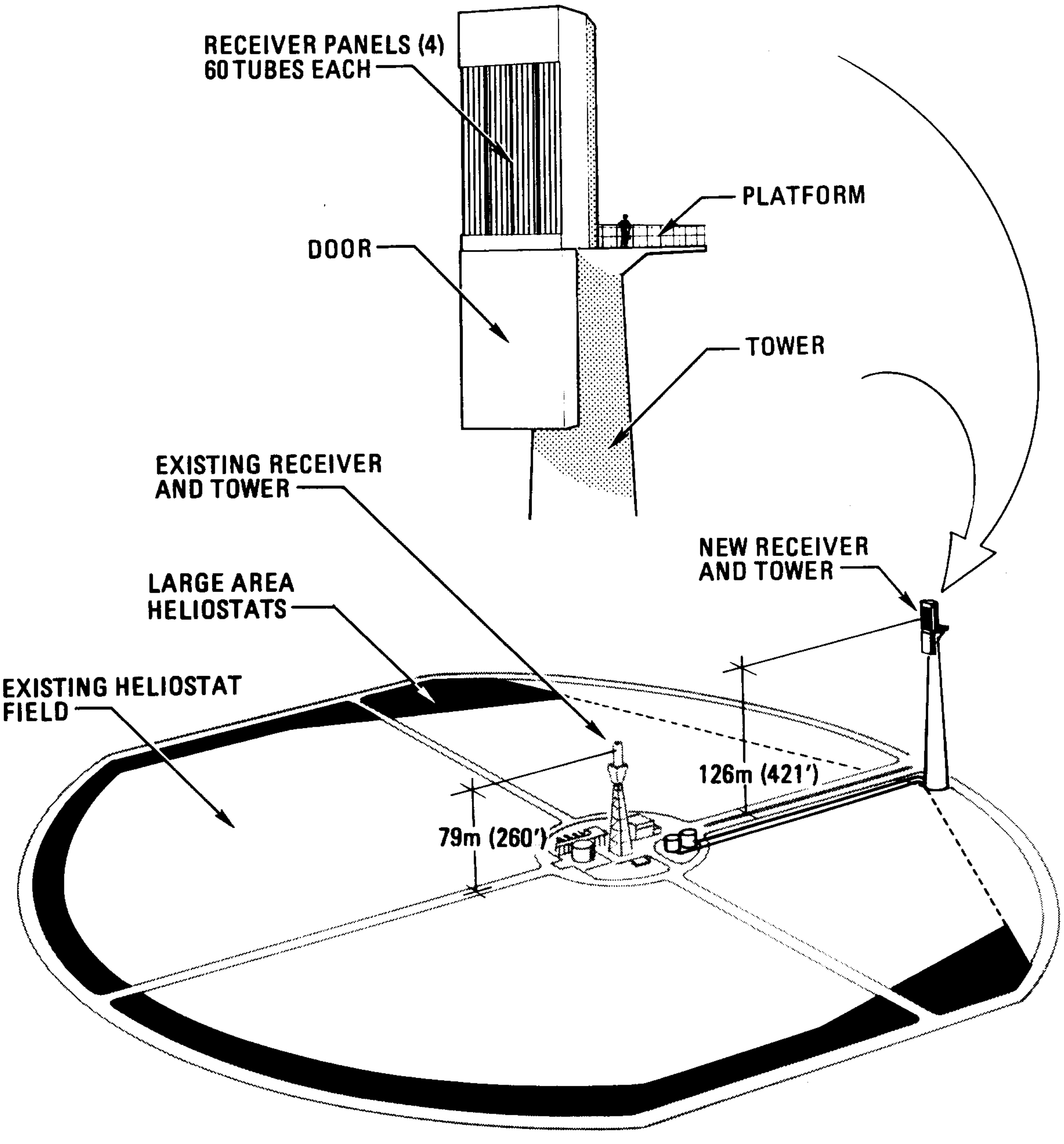


Figure 8. Solar One System Conversion: Typical Field Layout

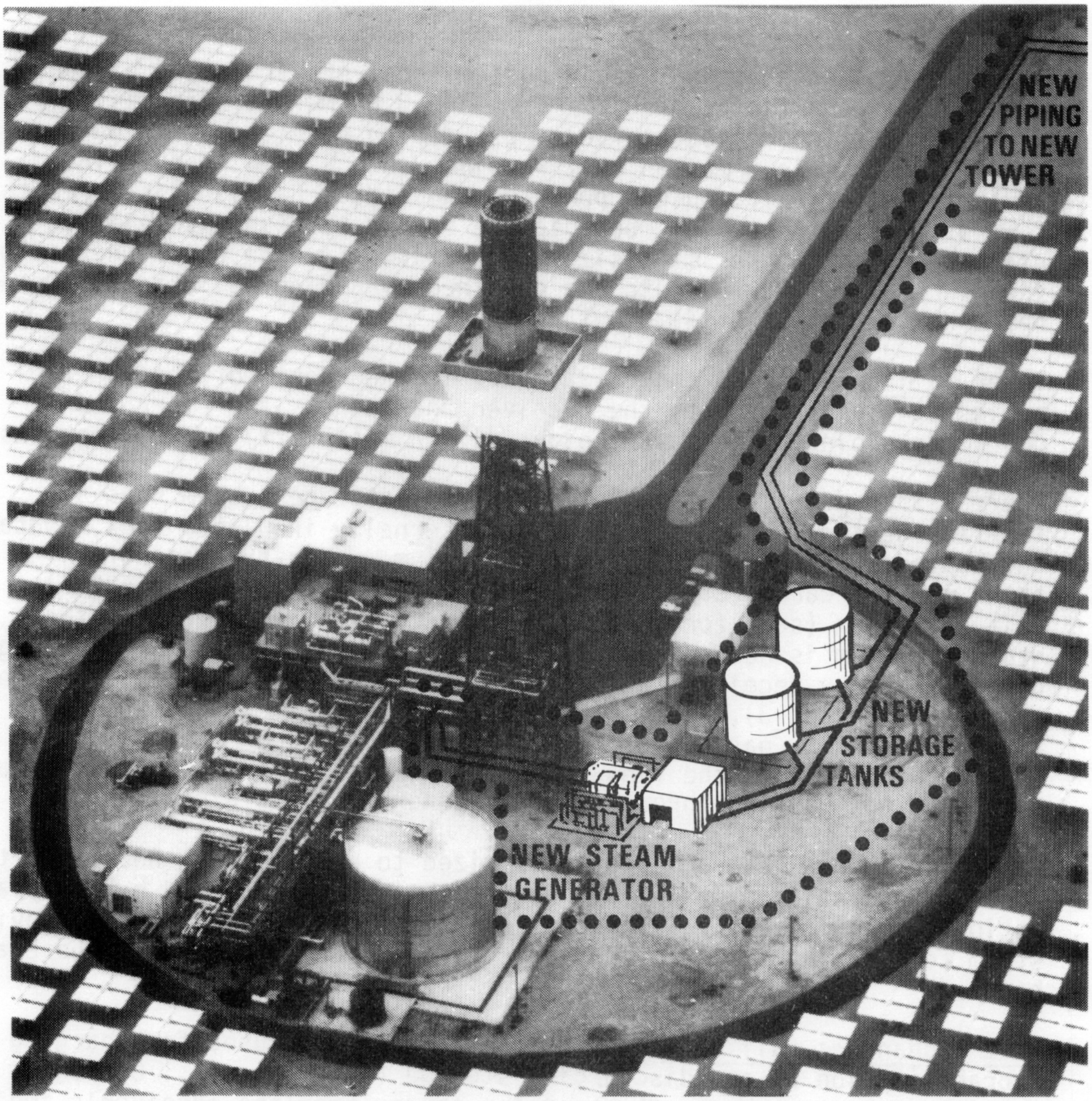


Figure 9. Solar One System Conversion: Typical Core Area Arrangement

molten salt or liquid sodium at 277°C (530°F) is pumped through the riser pipe to the receiver where it is heated in tubes to 574°C or 1065°F (all options except 3) or 593°C or 1100°F (Option 3).* The heated fluid returns to the ground through a downcomer. An insulating door, positioned in front of the receiver surface, minimizes heat losses when the receiver is not in service.

The molten salt and liquid sodium receivers are sized based on average incident fluxes of 0.27 MW/m^2 and 0.60 MW/m^2, respectively. With the existing heliostat field, the design receiver power output is about 32.8 MWt for a molten salt receiver and 30.6 MWt for a liquid sodium receiver. The output power of the sodium receiver is lower than that of the salt receiver, because the sodium receiver is relatively small compared to the image size which exists for the Solar One heliostat field. Higher power outputs are obtained by adding heliostats: Option 5 has a design output of 41.0 MWt.

Tower (all options)--A concrete tower, located south of the heliostat field, supports the receiver and anchors the riser and downcomer piping. The tower height is 128 m (421 ft) for all options.

Thermal Storage (all options)--The thermal storage system uses a two-tank design. The first tank, an internally insulated tank, contains the heated (566°C or 1050°F) salt or sodium, while the second tank, made of carbon steel, contains the unheated (277°C or 530°F) salt or sodium (see, for example, Reference 4). In operation, the storage medium is heated by removing it from the colder tank, heating it directly in the receiver (all options except 3) or indirectly in a heat exchanger (Option 3), and returning it to the hotter tank. The salt can also be heated by passing it through a fossil-fueled heater (Option 6). For heat extraction, the flow from the tanks is reversed, with the salt or sodium now passing through a steam generator heat exchanger.

The thermal storage system is sized to provide four hours and two hours of operation at rated output for the stand-alone and hybrid plant options, respectively. Sufficient capacity is also included to provide steam for keeping selected portions of the plant warm during nonoperating hours.

Heat Exchangers (all options)--Heat exchangers are used for charging storage (Option 3) and discharging storage (all options). Option 3 requires a heat exchanger to transfer energy from the receiver's sodium working fluid to the salt storage medium. All options require a steam generator heat exchanger to transfer energy from the storage medium to the water/steam working fluid used for power generation.

*The increase in receiver outlet temperature for Option 3 is necessary for heating the molten salt to 574°C (1065°F) in the intermediate heat exchanger.

The heat exchangers are sized to match either the outputs of the solar and fossil-fueled energy sources or the power requirements of the steam turbine. Thus, in Option 3 both the sodium-to-salt heat exchanger power rating and the receiver output power rating are equal to 30.6 MWt. Finally, the steam generator heat exchangers have a rating of 35 MWt for all options.

Fossil-Fueled Energy Source (Option 6)--Option 6 offers a simple approach for integrating the solar and fossil-fueled energy sources in a hybrid plant. The option employs a salt heater in parallel with the solar receiver to provide a back-up energy source (see, for example, Reference 2). The salt heater for Option 6 is sized for a design output of 35 MWt, the same rating as the salt steam generator.

Heliostats (all options)--All options provide for the recanting of the existing heliostat mirror modules to reduce spillage losses off the new receiver. Option 4 replaces the corroded and low-reflectivity mirror modules in the existing heliostat field with high-reflectivity (94%) mirror modules. The replacement of 12,000 modules increases the average field reflectivity from 90% to about 92%.

Option 5 augments the existing heliostat field by adding a moderate number, 100, of advanced large-area heliostats. These heliostats, 150 m^2 in area, are almost four times the size of the Solar One heliostats.

Controls and Instrumentation (all options)--Installation of a new receiver, thermal storage, steam generator, and other systems dictates a need for a control and instrumentation system to operate and acquire data from these systems. Existing hardware and software for the Solar One plant will be used to the greatest possible extent. However, upgrades are also planned to assure that the converted plant operates with state-of-the-art technology. For example, an upgraded, fast beam characterization system and an upgraded plant automation system will be added. A new diagnostic and maintenance record system will collect, analyze, and display data, providing the plant operator work-around information and maintenance order inputs. The diagnostic system will reduce the time to locate a problem and thus the number of maintenance personnel.

Converted Plant Performance

The design point (2 p.m., winter solstice) thermal efficiency of the converted plant is slightly less than the present Solar One plant due to differences in the individual efficiency factors. Figure 10 and Table II show the comparison for Solar One and Conversion Option 1. The converted plant has fewer usable heliostats because, in a north field configuration, several heliostats are blocked by the existing tower. Thus, the incident insolation on the converted field is less since it is proportional to the number of usable heliostats. The cosine factor for the converted plant's north field is greater than the cosine factor for Solar One's surrounding field due to a more favorable sun/reflector/receiver geometry. Heliostat reflectivity is the same for both configurations. Blocking and shadowing losses are greater for the north field converted plant because the heliostat locations are optimized for a surrounding field configuration. Atmospheric attenuation losses are greater for the converted plant since the heliostats are, on the average, at a greater distance from the receiver than those of the Solar One plant. Spillage losses are also greater for the converted plant because the heliostat mirror module canting is not optimized for a north field configuration. The receiver absorptance factor for both plants is the same, while radiation and convection losses are less for the converted plant. The latter results from a smaller receiver surface area (about one-half the area of Solar One's receiver) that more than compensates for a slightly greater surface temperature.

As a result of these efficiency differences, the thermal energy captured by all options except Option 5 is only slightly less than Solar One so that the converted plant and Solar One would have comparable electrical energy outputs. The installation of 100 advanced heliostats (Option 5) would boost the converted plant output by 25%.

SOLAR ONE & SOLAR ONE CONVERSION OPTION 1

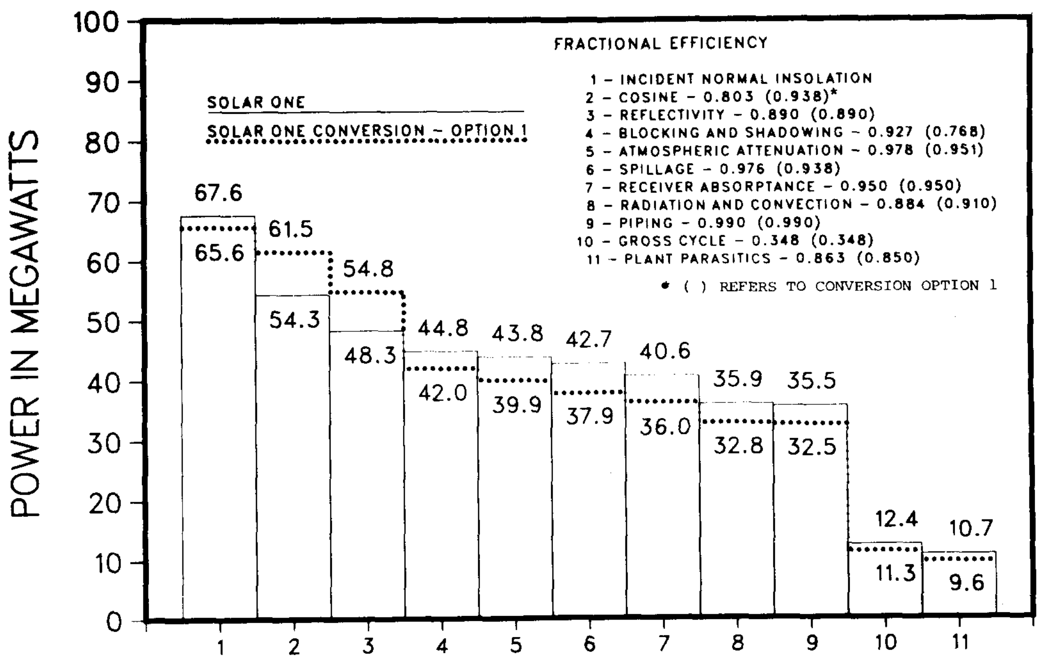


Figure 10. Solar One and Solar One Conversion Option 1 "Waterfall Efficiency" Chart (2 p.m., Winter Solstice)

TABLE II
COMPARISON OF SOLAR ONE AND SOLAR ONE
CONVERSION OPTION 1 THERMAL PERFORMANCE
(2 P.M., WINTER SOLSTICE)

ITEM	SOLAR ONE EFFICIENCY (FRACTION)	SOLAR ONE POWER (MWt)	SOLAR ONE CONVERSION OPTION 1 EFFICIENCY (FRACTION)	SOLAR ONE CONVERSION OPTION 1 POWER (MWt)
Incident Normal Insolation*		67.6		65.6
Cosine	0.803	54.3	0.938	61.5
Reflectivity	0.890	48.3	0.890	54.8
Blocking and Shadowing	0.927	44.8	0.767	42.0
Atmospheric Attenuation	0.978	43.8	0.951	39.9
Spillage	0.976	42.7	0.949	37.9
Receiver Absorptance	0.950	40.6	0.950	36.0
Radiation and Convection	0.884	35.9	0.910	32.8

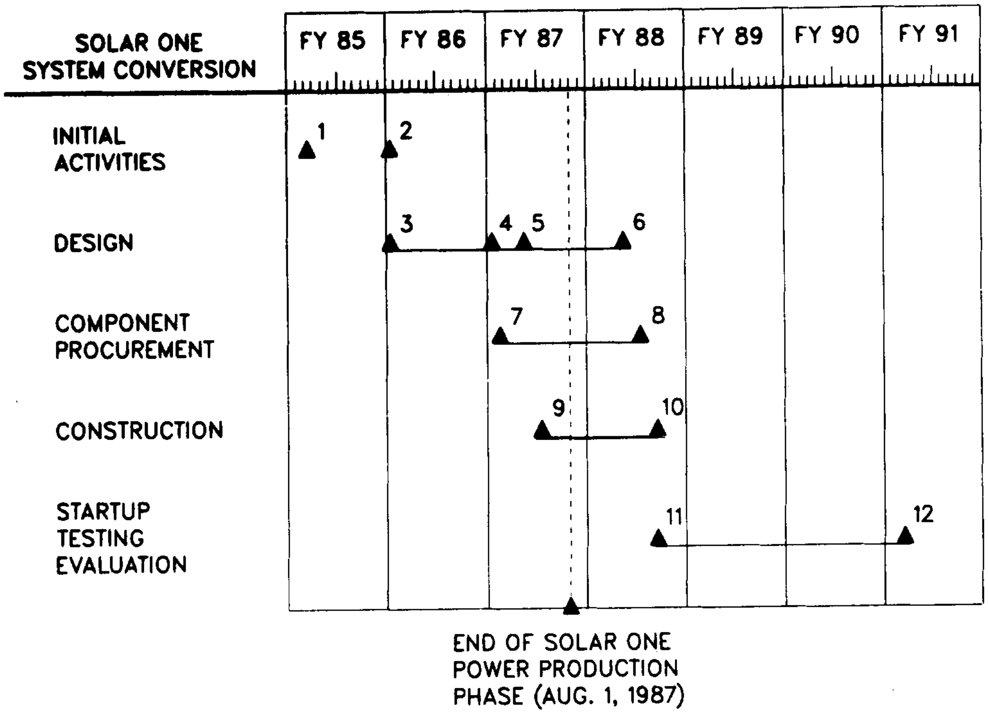
* The incident power values are based on an insolation value of 950 w/m2 and 1,818 and 1,764 usable heliostats for the Solar One and Solar One converted plant configurations, respectively.

The difference in annual output between Solar One's water/steam technology and molten salt (or liquid sodium) technology would be significant on a utility scale. The reason is that the latter technologies can be integrated effectively with the high-efficiency, reheat steam Rankine cycles used in utility-scale power plants. The same integration is much more difficult and costly to perform using water/steam technology, thus limiting its use to the less efficient, non-reheat, steam Rankine cycles. The use of a reheat steam Rankine cycle, along with an optimized field layout and advanced technology components, could potentially increase the annual plant output of a molten salt or liquid sodium system by almost 40% over a utility-scale plant that uses water/steam technology.

5.0 SCHEDULE

The schedule for a Solar One conversion, which is applicable to all options, is shown in Figure 11. Because of the location of the various system elements, conversion construction activities can be initiated early, prior to the completion of the Solar One Power Production Phase. Activities can proceed in parallel, with little interference with Solar One's on-going power production testing. All construction activities will be planned and coordinated with SCE and are subject to the concurrence of SCE and its utility partners.

The schedule is predicated on using DOE procurement procedures and a Decision-to-Proceed date of October 1985. Preliminary design will begin in October 1986, and construction will start in April 1987, four months before the end of Solar One's power production testing. Construction will be completed in June 1988. A one-year startup period is planned and will be followed by an 18 month testing and evaluation period. The testing and evaluation will be completed in December 1990. The time period from the start of Preliminary Design to the end of testing and evaluation is 52 months. A detailed list of tasks to carry out a Solar One Conversion project is given in Appendix A.



Milestone	Date
1. Submit report	Dec. 1984
2. Project authorized	Oct. 1985
3. Begin conceptual design	Oct. 1985
4. Begin preliminary design	Oct. 1986
5. End preliminary design – start final design	Feb. 1987
6. End final design	Feb. 1988
7. Begin component procurement	Nov. 1986
8. End component procurement	Apr. 1988
9. Begin field construction	Apr. 1987
10. End field construction	Jun. 1988
11. Begin startup, test, and evaluation	Jun. 1988
12. End startup, test, and evaluation	Dec. 1990

Figure 11. Solar One System Conversion Project Schedule

6.0 RESOURCE REQUIREMENTS

The resource requirements for converting Solar One are shown for each option on a year-by-year basis in Table III. The required funding is displayed in real (constant) 1984 dollars (no escalation).

The required funding includes the total design, construction, and startup costs. The costs do not include funding for a DOE project office, technical support groups (e.g., DOE national laboratories), and operating and maintenance staffing needs from the end of the Solar One Power Production Phase to the end of the converted Solar One testing and evaluation period. In 1984 dollars the costs range from a high of $64M for Option 4 to a low of $55M for Option 1.

TABLE III
SOLAR ONE SYSTEM CONVERSION RESOURCE
REQUIREMENTS IN 1984 DOLLARS

	REQUIRED RESOURCES					
	FY 85	FY 86	FY 87	FY 88	FY 89	TOTAL
Option 1	0	4	35	16	0	55
Option 2	0	4	41	16	0	61
Option 3	0	4	37	16	0	57
Option 4	0	4	44	16	0	64
Option 5	0	4	41	16	0	61
Option 6	0	4	42	16	0	62

The cost estimates include 15% of direct and indirect costs as contingency. The cost of equipment, materials, labor, and subcontracts was estimated by scaling previous designs and costs whenever possible. It should be emphasized that the relative cost estimates of the options are more accurate than the absolute values. A conversion of the plant will require substantial quantities of equipment which has never been built, and considerable uncertainty exists in doing estimates without drawings and specifications.

The costs of other options, similar to the six options studied here, can be derived from Appendix B. For example, the cost to evaluate an advanced heliostat design (Option 5) was developed by adding heliostats to Option 1. A similar cost could be developed by starting with Options 2, 3, 4, or 6. The incremental costs for adding 100 advanced heliostats, including a larger receiver, is $6M.

7.0 ASSESSMENT OF THE CONVERSION OPTIONS

7.1 Technical Capabilities of Options

The six options studied have the same project schedule and do not differ significantly in costs. The costs in 1984 dollars range from a high of $64M for Option 4 to a low of $55M for Option 1. Although the option costs are subject to some uncertainties, changes in plant configuration which might occur during design are not expected to affect them greatly. For example, using the existing plant tower and reducing the storage capacity from four hours to one hour would have a small impact on the project costs (less than $5M). At the start of design, the plant configuration would be reviewed to select the most cost-effective configuration.

Constructing and operating an advanced central receiver system on a utility-scale presents many technical and economic risks. Each of the presented conversion options would provide data on the technical feasibility, system performance, and component performance of an advanced central receiver system. This data could significantly reduce the technical and economic risks of operating such a system on a utility scale.

A key area is the component interaction in an operating system that is representative of a utility-scale plant. All options can provide data on component interaction that will determine the technical feasibility and system performance of an advanced central receiver stand-alone system. This capability also applies to the hybrid plant option, because the hybrid plant can be operated in either a stand-alone or hybrid configuration.

Furthermore, all options can provide data for scaling thermal storage to a utility-scale plant. Storage tank fabrication techniques for the smaller-sized plants are judged to be no different than those used for utility-scale plants. The main difference in storage scaling pertains to the startup and control characteristics of the storage systems. As storage capacity is reduced, the size and, in particular, the number of storage tanks is reduced. A larger storage capacity option will therefore be more representative of the more complex, multi-tank storage system that would be used in a utility-scale plant.

All options will provide data for the scale-up of a receiver to a utility size. Both the salt and sodium receivers in a Solar One conversion have critical design characteristics--such as heat flux, tube materials, and average temperature change per tube length--that are representative of a utility-scale receiver. Differences in the design characteristics of the converted plant receiver and utility-scale receiver are not expected to be significant.

Only Option 5 presents the capability for evaluating an advanced heliostat design. Option 5 adds 100 advanced large-area (150 m^2) heliostats to the Solar One heliostat field. However, Option 4 does provide a capability to evaluate an advanced mirror module design through the upgrading of the existing heliostat field.

All options will provide valuable cost data, particularly in the area of operating and maintenance cost. Option 5 will also provide data on the costs of larger area heliostats. Option 3 requires a heat exchanger that has not previously been built and tested.

7.2 Factors Governing Utility Selection

The results of this study indicate that several options exist for reducing the technical and economic risks associated with advanced central receiver systems. The costs of the options are not significantly different, and comparison of the options did not identify a clear technical choice as to the best alternative. Electrical utility preferences should play a strong role in selecting the conversion option. If a successful plant at a power level of 10 MWe will provide sufficient data to effect a utility decision to construct a utility-scale plant without government subsidy, then any one of the options would become very attractive. If the utilities indicate that a larger experiment is needed prior to construction of a utility-scale plant, then none of the options may be appropriate.

A Solar One conversion does offer an attractive approach to testing large-scale components. The conversion options can provide 40-50 MWt to the receiver surface, thereby permitting the testing of relatively large-scale components, such as the receiver and pumps. (In comparison, the CRTF heliostat field is sized to provide 5 MWt). Furthermore, there is the potential for testing some utility-scale equipment at this power level. It may be possible to group a few full-size panels from a utility-scale plant receiver to form the Solar One conversion receiver. Similarly, steam generator tube diameters and lengths equivalent to a utility-scale design could be specified for the Solar One conversion steam generator. Another important consideration, the effect of component interactions during plant startup or cloud passage on plant performance, would also be tested at this increased power level.

The selection of a Solar One conversion option will hinge strongly on three factors: (1) plant configuration (stand-alone or hybrid); (2) capability for evaluating advanced heliostat designs; and (3) heat transfer fluid.

Utilities may also find a solar/fossil hybrid system to be an attractive option. Providing a central receiver electrical generating plant with the capability to burn fossil fuels to supplement the collected solar energy has several potential advantages. This plant concept can be used to increase the number of hours for delivering electrical energy, thus improving the utilization of the turbine-generator and other equipment as well as making better use of the operating and maintenance manpower. The fossil energy can also be used to increase the peak power delivered. In addition, a hybrid plant's output can be easily matched to a utility grid's system load because the hybrid plant can deliver electricity even when solar energy is not available for extended periods. Thus, for a small increase in plant capital cost, a hybrid option can improve the overall flexibility and economics of a plant.

The testing of an advanced heliostat design may also be desirable for a Solar One conversion. This option will provide new information on the fabrication, construction, operation, and maintenance costs of an advanced heliostat design and will allow the supplier and user to develop more confidence in heliostat pricing and warranty positions. The number of new heliostats tested should be sufficient to guarantee realistic manufacturing procedures and provide statistically significant numbers for operations and maintenance evaluation. A quantity of five or ten heliostats would probably be hand built with little or no tooling, whereas 50 to 100 heliostats would require attention to tooling and production techniques. At Solar One, many lessons were learned operating 1818 heliostats that were not found in the earlier testing of two heliostat prototypes.

Finally, utility preferences for a heat transfer fluid are important for a number of reasons. Molten salt and liquid sodium, as heat transfer and storage fluids, affect receiver cost and thermal storage cost in opposite ways. Molten salt has a lower heat transfer capability and a higher thermal storage capability than liquid sodium. Consequently, liquid sodium should produce the lowest cost receiver, and molten salt the lowest cost storage. The approach to achieving the minimum plant cost by combining a sodium receiver with molten salt storage is complicated by the need to transfer heat from one fluid to the other and the need to provide handling and service capabilities for the two different fluids. The costs to solve these complications may reduce the apparent cost advantages of a combined fluid system over a single fluid system. It is important then to consider the advantages of using one or both heat transfer fluids in a utility-scale plant when selecting the configuration for a Solar One system conversion.

APPENDIX A

IMPLEMENTATION

Implementation of a Solar One conversion project requires three major activities: Conceptual and Preliminary Design; Final Design and Construction; and Startup, Testing and Evaluation.

A.1 Conceptual and Preliminary Design

The objective of this activity is to complete the conceptual and preliminary design of a Solar One conversion project. The activity includes five tasks:

Task 1: Plant and System Design Requirements and Analyses

(1) review of existing Solar One plant and system design requirements;
(2) update of design requirements for a Solar One conversion;
(3) analyses of design issues, such as materials selection, pump type selection, etc; and
(4) completion of required field surveys and test borings.

Task 2: Plant and System Designs

(1) definition of the plant configuration including equipment and piping layouts;
(2) design of site modifications, such as roads, drainage, and grading;
(3) design of facilities modifications, such as buildings, fences, lighting, sanitary sewers, and fire protection;
(4) description of the converted plant and its major systems;
(5) definition of the plant operating modes and transitions;
(6) definition of the plant and system operating characteristics limits; and
(7) procurement of long-lead items

Task 3: Plant Performance

(1) definition of mass flows over the range of operating conditions; and
(2) definition of energy flows for the design point and on an annual basis.

Task 4: Plant Costs

(1) estimates of final design, construction, plant modification, spare parts, and downtime costs;
(2) definition of a plant final design and construction schedule;
(3) definition of operations and maintenance needs.

Task 5: Environmental Impact Assessment

(1) identification of potential impacts; and
(2) definition of mitigation approaches.

A.2 Final Design and Construction

The objective of this activity is to complete the Solar One conversion project final design and construction. The activity consists of two tasks:

Task 1: Plant and System Designs

(1) description of the final plant and system designs;
(2) integration of all plant systems;
(3) definition of control and evaluation requirements;
(4) completion of required computer simulations;
(5) analyses of failure modes and effects;
(6) development of a maintainability program;
(7) development of a system safety plan; and
(8) preparation of bid-ready construction packages.

Task 2: Plant Construction

(1) procurement, fabrication, and installation of all systems;
(2) checkout and acceptance testing of all systems;
(3) integrated plant acceptance testing; and
(4) operations and maintenance training.

A.3 Startup, Testing and Evaluation

The objectives of the startup, testing, and evaluation activity are to: (1) evaluate the technical feasibility of a Solar One conversion; (2) provide information to reduce technical and economic risks for private sector decisions regarding designs and economics of future central receiver systems; and (3) identify areas where future research and development may lead to significant performance improvements and increased capabilities. The activity consists of three tasks:

Task 1: Plant Technical Feasibility

(1) testing and analysis of the plant operating modes and mode transitions.

Task 2: Information for Future System Designs

(1) testing and analysis of design point performance;
(2) testing and analysis of annual performance;
(3) analysis of lessons learned from design, construction, and operation;
(4) analysis of environmental and safety impacts;
(5) analysis of design and constructions costs; and
(6) analysis of operations and maintenance procedures and costs.

Task 3: Identification of Future Research and Development Needs

(1) assessment of heliostat optical accuracy;
(2) assessment of mirror module corrosion;
(3) assessment of receiver tube life; and
(4) assessment of storage medium and containment material life.

APPENDIX B

PLANT CAPITAL COST SUMMARIES OF

SOLAR ONE CONVERSION OPTIONS

Solar One Conversion Option 1
Molten Salt Stand-Alone

Plant Capital Cost Summary
(1984 $)

Plant direct costs:	
0 Land	100,000
0.1 Acquisition	0
0.3 Permits	50,000
0.5 Survey	50,000
1 Structures and Improvements	500,000
1.1 Offsite Improvements	0
1.3 Onsite Improvements	500,000
2 Collector, Receiver, Storage & Steam Generation	28,632,000
2.1 Collector System	525,000
2.2 Receiver System	14,712,600
2.3 Thermal Transport System	2,664,400
2.4 Thermal Storage System	3,062,500
2.5 Steam Generation System	5,967,500
2.6 Heat Transport Auxiliaries	250,000
2.9 Heat Transport Fluid	1,450,000
3 Turbine-Generator Plant	0
4 Electrical System	4,637,500
4.3 Added Electrical Equipment	0
4.7 Control & Instrumentation Modifications	4,637,500
5 Misc. Plant System & Equipment	0
5.1 Auxiliary Heater	0
Total direct costs:	33,869,500
Design engineering costs:	8,910,000
Const management:	1,500,000
Project management:	1,500,000
Contingencies:	6,870,500
Total indirect costs:	18,780,500
Total (overnight construction):	52,650,000
Sales and use taxes:	600,000
Total at in-service:	53,250,000
Startup costs:	2,000,000
Total capital req:	55,250,000

Solar One Conversion Option 2
Liquid Sodium Stand-Alone

Plant Capital Cost Summary
(1984 $)

Plant direct costs:	
0 Land	100,000
0.1 Acquisition	0
0.3 Permits	50,000
0.5 Survey	50,000
1 Structures and Improvements	500,000
1.1 Offsite Improvements	0
1.3 Onsite Improvements	500,000
2 Collector, Receiver, Storage & Steam Generation	33,555,100
2.1 Collector System	525,000
2.2 Receiver System	13,157,600
2.3 Thermal Transport System	3,346,500
2.4 Thermal Storage System	5,318,500
2.5 Steam Generation System	6,442,500
2.6 Heat Transport Auxiliaries	1,125,000
2.9 Heat Transport Fluid (Sodium)	3,640,000
3 Turbine-Generator Plant	0
4 Electrical System	4,638,000
4.3 Added Electrical Equipment	0
4.7 Control & Instrumentation Modifications	4,638,000
5 Misc. Plant System & Equipment	0
5.1 Auxiliary Heater	0
Total direct costs:	38,793,100
Design engineering costs:	8,910,000
Const management:	1,500,000
Project management:	1,500,000
Contingencies:	7,605,400
Total indirect costs:	19,515,400
Total (overnight construction):	58,308,500
Sales and use taxes:	600,000
Total at in-service:	58,908,500
Startup costs:	2,000,000
Total capital req:	60,908,500

Solar One Conversion Option 3
Liquid Sodium Receiver/Molten Salt Storage Stand-Alone

Plant Capital Cost Summary
(1984 $)

Plant direct costs:	
0 Land	100,000
0.1 Acquisition	0
0.3 Permits	50,000
0.5 Survey	50,000
1 Structures and Improvements	500,000
1.1 Offsite Improvements	0
1.3 Onsite Improvements	500,000
2 Collector, Receiver, Storage & Steam Generation	29,791,100
2.1 Collector System	525,000
2.2 Receiver System	13,157,600
2.3 Thermal Transport System	5,263,500
2.4 Thermal Storage System	3,062,500
2.5 Steam Generation System	5,967,500
2.6 Heat Transport Auxiliaries	250,000
2.9 Heat Transport/Storage Fluids	1,565,000
3 Turbine-Generator Plant	0
4 Electrical System	4,829,500
4.3 Added Electrical Equipment	0
4.7 Control & Instrumentation Modifications	4,829,500
5 Misc. Plant System & Equipment	0
5.1 Auxiliary Heater	0
Total direct costs:	35,220,600
Design engineering costs:	9,110,000
Const management:	1,500,000
Project management:	1,500,000
Contingencies:	7,099,400
Total indirect costs:	19,209,400
Total (overnight construction):	54,430,000
Sales and use taxes:	600,000
Total at in-service:	55,030,000
Startup costs:	2,000,000
Total capital req:	57,030,000

Solar One Conversion Option 4
Molten Salt Stand-Alone With Upgraded Heliostats

Plant Capital Cost Summary
(1984 $)

Plant direct costs:	
0 Land	100,000
0.1 Acquisition	0
0.3 Permits	50,000
0.5 Survey	50,000
1 Structures and Improvements	500,000
1.1 Offsite Improvements	0
1.3 Onsite Improvements	500,000
2 Collector, Receiver, Storage & Steam Generation	35,602,000
2.1 Collector System	7,495,000
2.2 Receiver System	14,712,600
2.3 Thermal Transport System	2,664,400
2.4 Thermal Storage System	3,062,500
2.5 Steam Generation System	5,967,500
2.6 Heat Transport Auxiliaries	250,000
2.9 Heat Transport Fluid	1,450,000
3 Turbine-Generator Plant	0
4 Electrical System	4,637,500
4.3 Added Electrical Equipment	0
4.7 Control & Instrumentation Modifications	4,637,500
5 Misc. Plant System & Equipment	0
5.1 Auxiliary Heater	0
Total direct costs:	40,839,500
Design engineering costs:	8,910,000
Const management:	1,500,000
Project management:	1,500,000
Contingencies:	7,912,500
Total indirect costs:	19,822,500
Total (overnight construction):	60,662,000
Sales and use taxes:	812,000
Total at in-service:	61,474,000
Startup costs:	2,000,000
Total capital req:	63,474,000

Solar One Conversion Option 5
Molten Salt Stand-Alone With Added Heliostats

Plant Capital Cost Summary
(1984 $)

Plant direct costs:	
0 Land	100,000
0.1 Acquisition	0
0.3 Permits	50,000
0.5 Survey	50,000
1 Structures and Improvements	500,000
1.1 Offsite Improvements	0
1.3 Onsite Improvements	500,000
2 Collector, Receiver, Storage & Steam Generation	33,301,500
2.1 Collector System	4,787,500
2.2 Receiver System	15,119,600
2.3 Thermal Transport System	2,664,400
2.4 Thermal Storage System	3,062,500
2.5 Steam Generation System	5,967,500
2.6 Heat Transport Auxiliaries	250,000
2.9 Heat Transport Fluid	1,450,000
3 Turbine-Generator Plant	0
4 Electrical System	4,637,500
4.3 Added Electrical Equipment	0
4.7 Control & Instrumentation Modifications	4,637,500
5 Misc. Plant System & Equipment	0
5.1 Auxiliary Heater	0
Total direct costs:	38,539,000
Design engineering costs:	8,910,000
Const management:	1,500,000
Project management:	1,500,000
Contingencies:	7,568,000
Total indirect costs:	19,478,000
Total (overnight construction):	58,017,000
Sales and use taxes:	709,000
Total at in-service:	58,726,000
Startup costs:	2,000,000
Total capital req:	60,726,000

Solar One Conversion Option 6
Molten Salt Hybrid With Salt Heater

Plant Capital Cost Summary
(1984 $)

Plant direct costs:	
0 Land	100,000
0.1 Acquisition	0
0.3 Permits	50,000
0.5 Survey	50,000
1 Structures and Improvements	500,000
1.1 Offsite Improvements	0
1.3 Onsite Improvements	500,000
2 Collector, Receiver, Storage & Steam Generation	27,114,500
2.1 Collector System	525,000
2.2 Receiver System	14,712,600
2.3 Thermal Transport System	2,664,400
2.4 Thermal Storage System	2,175,000
2.5 Steam Generation System	5,967,500
2.6 Heat Transport Auxiliaries	250,000
2.9 Heat Transport Fluid	820,000
3 Turbine-Generator Plant	0
4 Electrical System	4,829,500
4.3 Added Electrical Equipment	0
4.7 Control & Instrumentation Modifications	4,829,500
5 Misc. Plant System & Equipment	6,243,000
5.1 Auxiliary Molten Salt Heater	6,243,000
Total direct costs:	38,787,000
Design engineering costs:	9,660,000
Const management:	1,500,000
Project management:	1,500,000
Contingencies:	7,717,500
Total indirect costs:	20,377,500
Total (overnight construction):	59,164,500
Sales and use taxes:	715,000
Total at in-service:	59,879,500
Startup costs:	2,000,000
Total capital req:	61,879,500

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