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Advanced Thermal Storage for Central Receivers with Supercritical Coolants

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1 Abstract

The principal objective of the study is to determine if supercritical heat transport fluids in a central receiver power plant, in combination with ceramic thermocline storage systems, offer a reduction in levelized energy cost over a baseline nitrate salt concept. The baseline concept uses a nitrate salt receiver, two-tank (hot and cold) nitrate salt thermal storage, and a subcritical Rankine cycle.

A total of 6 plant designs were analyzed, as follows:

Plant Designation	Receiver Fluid	Thermal Storage	Rankine Cycle
Subcritical nitrate salt	Nitrate salt	Two tank nitrate salt	Subcritical
Supercritical nitrate salt	Nitrate salt	Two tank nitrate salt	Supercritical
Low temperature H_2O	Supercritical H_2O	Two tank nitrate salt	Supercritical
High temperature H_2O	Supercritical H_2O	Packed bed thermocline	Supercritical
Low temperature CO_2	Supercritical CO_2	Two tank nitrate salt	Supercritical
High temperature CO_2	Supercritical CO_2	Packed bed thermocline	Supercritical

Several conclusions have been drawn from the results of the study, as follows:

1) The use of supercritical H_2O as the heat transport fluid in a packed bed thermocline is likely not a practical approach. The specific heat of the fluid is a strong function of the temperatures at values near 400 °C, and the temperature profile in the bed during a charging cycle is markedly different than the profile during a discharging cycle.

2) The use of supercritical CO_2 as the heat transport fluid in a packed bed thermocline is judged to be technically feasible. Nonetheless, the high operating pressures for the supercritical fluid require the use of pressure vessels to contain the storage inventory. The unit cost of the two-tank nitrate salt system is approximately $24/kWht, while the unit cost of the high pressure thermocline system is nominally 10 times as high.

3) For the supercritical fluids, the outer crown temperatures of the receiver tubes are in the range of 700 to 800 °C. At temperatures of 700 °C and above, intermetallic compounds can precipitate between, and within, the grains of nickel alloys. The precipitation leads to an increase in tensile strength, and a decrease in ductility. Whether the proposed tube materials can provide the required low cycle fatigue life for the supercritical H_2O and CO_2 receivers is an open question.

4) A ranking of the plants, in descending order of technical and economic feasibility, is as follows:

i) Supercritical nitrate salt and baseline nitrate salt: equal ratings
ii) Low temperature supercritical H_2O
iii) Low temperature supercritical CO_2
iv) High temperature supercritical CO_2
v) High temperature supercritical H_2O

5) The two-tank nitrate salt thermal storage systems are strongly preferred over the thermocline systems using supercritical heat transport fluids.

2 Introduction

2.1 Objectives

The objectives of the work are to 1) determine if supercritical heat transport fluids in a central receiver power plant, in combination with ceramic thermocline storage systems, offer a reduction in levelized energy cost over a baseline nitrate salt concept, and 2) if so, demonstrate a prototype thermocline storage unit.

Currently, most commercial central receiver plant designs are based on a nitrate salt receiver, with a two-tank (hot and cold) nitrate salt thermal storage system with capacities in the range of 6 to 12 hours. However, nitrate salt components have not been demonstrated at commercial plant sizes, and there are known problems with routine daily operations, such as filling and draining the receiver. To explore alternate approaches with the potential for higher net solar-to-electric efficiencies, the proposed work examined 6 combinations of receiver coolant, thermal storage media, and Rankine cycle conditions, as outlined in Table 1.

Table 1 Plant Designations

Plant Designation	Receiver Fluid	Thermal Storage	Rankine Cycle
Subcritical nitrate salt	Nitrate salt	Two tank nitrate salt	Subcritical
Supercritical nitrate salt	Nitrate salt	Two tank nitrate salt	Supercritical
Low temperature H_2O	Supercritical H_2O	Two tank nitrate salt	Supercritical
High temperature H_2O	Supercritical H_2O	Packed bed thermocline	Supercritical
Low temperature CO_2	Supercritical CO_2	Two tank nitrate salt	Supercritical
High temperature CO_2	Supercritical CO_2	Packed bed thermocline	Supercritical

For the purposes of the study, the location of the plant was assumed to be Barstow, California, and the thermal storage capacity was assumed to be 6 hours of turbine operation. The operating conditions for the subcritical and the supercritical Rankine cycles are presented in Table 2.

Table 2 Rankine Cycle Design Parameters

	Live steam pressure, bar	Live steam temperature, °C	Reheat steam temperature, °C	Feedwater heaters, each	Nominal gross cycle efficiency
Subcritical	125	540	540	6	0.434
Low temperature supercritical	300	590	590	8	0.470
High temperature supercritical	350	650	575	8	0.480

The supercritical receiver designs use a packed bed thermocline for thermal storage. The system consists of a vertical vessel, which is filled with a granular ceramic material, such as quartzite. During charging, hot fluid enters the top of the vessel, and flows down through the packed bed. Energy is stored by transferring heat from the fluid to the filler material. During discharging, the fluid flow is reversed; cold fluid enters the bottom of the vessel, and energy is transferred from the filler material to the fluid.

The principal advantage of a thermocline system over a conventional two-tank design is the substitution of an inexpensive filler material (quartzite) for a relatively more expensive fluid media (nitrate salt). The principal disadvantages of a thermocline system are three:

1) As with any heat transfer process, there is a temperature decay associated with storing energy in the filler material, and a decay associated with removing energy from the filler material. This necessarily leads to a loss in thermodynamic availability, according to the Second Law.

2) Finite temperature differences must be established between the circulating fluid and the filler material to affect the necessary heat transfer. As such, a portion of the bed height is occupied with a permanent temperature gradient, with values between the receiver inlet temperature and the receiver outlet temperature. The depth of the gradient is a significant fraction of the total system height (~25 percent), which increases the height, and the cost, of the system by a comparable amount.

3) The conduction heat transfer processes which establish the temperature gradient will, if left unchecked, produce a gradient which occupies the full height of the bed. The height of the gradient is controlled by allowing the vessel outlet temperature to decay near the end of a discharge cycle, and the temperature to rise near the end of a charge cycle.

Nonetheless, previous studies have shown the use of a thermocline storage system to offer a significant reduction in levelized energy costs compared with a two-tank design [1]. One of the goals of the present study is to determine if these cost benefits are also available with supercritical receiver coolants.

The supercritical fluid pressures proposed in this study range from 150 bar for CO_2 to 300 bar for H_2O. The thermocline storage vessels are then necessarily pressure vessels. The most economical pressure vessel is a commercial section of standard pipe, at the largest diameter possible with the required wall thickness. As such, the standard thermocline vessel for use with CO_2 is a 24 in. stainless steel pipe, Schedule 120, with a length of 12.2 m (40 feet). The standard vessel for use with H_2O is a 24 in. stainless steel pipe, Schedule 160, also with a length of 12.2 m. To achieve the storage capacities required, multiple vessels are installed in parallel.

[1] Pacheco, J. E., et al (Sandia National Laboratories, Albuquerque, New Mexico), "Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants", Journal of Solar Energy Engineering, Proof Copy 002202SLE, May 2002

2.2 Background

2.2.1 Reference Plant Design

Some of the recent work in central receiver plant design has been based on the use of a binary nitrate salt as the receiver coolant, thermal storage medium, and heat transport fluid in the steam generator. The salt is a mixture of 60 percent by weight sodium nitrate ($NaNO_3$), and 40 percent by weight potassium nitrate (KNO_3). The salt has several thermophysical properties which make it suitable as a heat transport fluid and storage medium, including:

- High densities, in the range of 1,700 to 1,900 kg/m^3
- Acceptable thermal conductivities, in the range of 0.50 to 0.56 W/m-C
- Acceptable specific heats, in the range of 1.50 to 1.55 kJ/kg-C
- Low absolute viscosities, in the range of 0.0010 to 0.0036 kg-m/sec
- Very low vapor pressures, on the order of several Pascals.
- Low corrosion rates for carbon steels at temperatures up to 350 °C, and low corrosion rates with stainless steels at temperatures up to 600 °C.

The largest difficulty with nitrate salt is a freezing point of approximately 230 °C. As such, all equipment in contact with the salt must have electric heating, and the thermal insulation throughout the system must be of the highest quality.

The receiver and the thermal storage tanks are vented to the atmosphere. As a result, the salt is continuously exposed to air, and an equilibrium concentration of nitrate and nitrite is established through the following reaction [2]:

$$(Na,K)NO_3 \rightarrow (Na,K)NO_2 + \tfrac{1}{2}O_2$$

A plot of the nitrite concentration as a function temperature is illustrated in Figure 1. The nitrite component is important, as it is a much corrosive agent than the nitrate.

The nitrite component is also subject to decomposition to form the metal oxides, of which the peroxide is the most stable, via the following reaction:

$$2\ (Na,K)NO_2 \rightarrow (Na,K)_2O_2 + O_2 + N_2$$

[2] Bradshaw, R. W., and Goods, S. H. (Sandia National Laboratories, Albuquerque, New Mexico and Livermove, California), "Corrosion of Alloys and Metals by Molten Nitrates", Sandia Report SAND2000-8727, August 2001

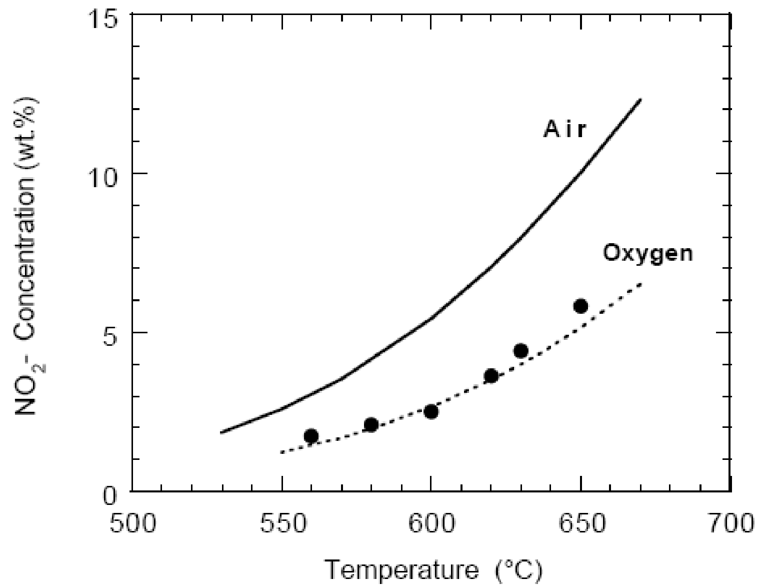

Figure 1 Nitrite Concentration in Binary Nitrate Salt as a Function of Temperature

The oxide concentrations are low at temperatures up to 600 °C, but increase rapidly at higher temperatures. The peroxides are quite corrosive, and at temperatures above 625 °C, they are an excellent agent for continuous chromium depletion from the base metal by a fluxing process [3].

For the salt quantities required in a commercial project, the sodium nitrate component is likely to be supplied from mines in South America. Further, the potassium nitrate component is often manufactured from the sodium nitrate. As such, the salt mixture has a nominal chloride ion content of 0.5 percent by weight. As with the nitrites and oxides, chlorides are corrosive agents.

The freezing point of the salt mixture, together with it's corrosion characteristics, effectively define an operating temperature range of 250 °C to 600 °C. To provide a safety margin on the freezing point, a lower temperature limit of approximately 288 °C is often used. To provide for a nominal film temperature of 600 °C on the inside of the receiver tubes, an upper bulk temperature limit of 565 °C is normally specified. Together with the fluid temperature characteristics of a subcritical Rankine cycle, the following design parameters have been adopted for the reference plant design: 237 °C final feedwater temperature; 288 °C cold salt tank temperature; 125 bar live steam pressure; 540 °C live steam temperature; 540 °C reheat steam temperature; and 565 °C hot salt tank temperature.

[3] Bradshaw, R. W. (Sandia National Laboratories, Livermore, California), "Oxidation and Chromium Depletion of Alloy 800 and 316SS by Molten NaNO3-KNO3 at Temperatures Above 600°C", Sandia Report SAND86-9009, January 1987

2.2.2 Supercritical receiver coolants

The candidate supercritical fluids selected for the study include H_2O and CO_2. The principal advantages to the use of supercritical fluids as the receiver coolant include the following:

- No change of phase on heating
- Elimination of the corrosion characteristics of nitrate salts
- Elimination of electric heat tracing, and daily equipment filling / draining
- Transition to supercritical Rankine cycles, with gross efficiencies up to 48 percent.

2.3 Qualitative Considerations

2.3.1 Nitrate Salt

Nitrate salt does well in the following areas:

- Low vapor pressures allow thin receiver tube walls, which allows both high allowable fluxes and high thermal efficiencies
- The same fluid is the receiver coolant, the thermal storage medium, and the heat transport fluid in the steam generator. As such, there are no temperature decays into, or out of, storage
- Density and specific heat vary by a modest 10 percent and 3 percent, respectively, over the temperature range of interest
- Extensive information is available on material corrosion rates.

Nitrate salt doesn't do well in the following areas:

- Preheating and filling the receiver, a daily occurrence, is something of an art form. The relatively complex hydraulic arrangement is shown in Figure 2.
- All salt equipment must have thermal insulation of the highest quality and reliable electric heat tracing
- Robust flow and pressure instrumentation have yet to be demonstrated.

2.3.2 Supercritical Fluids

Supercritical fluids do well in the following areas:

- Upper temperature limits in the receiver are defined by metal strength limits, rather than corrosion rates

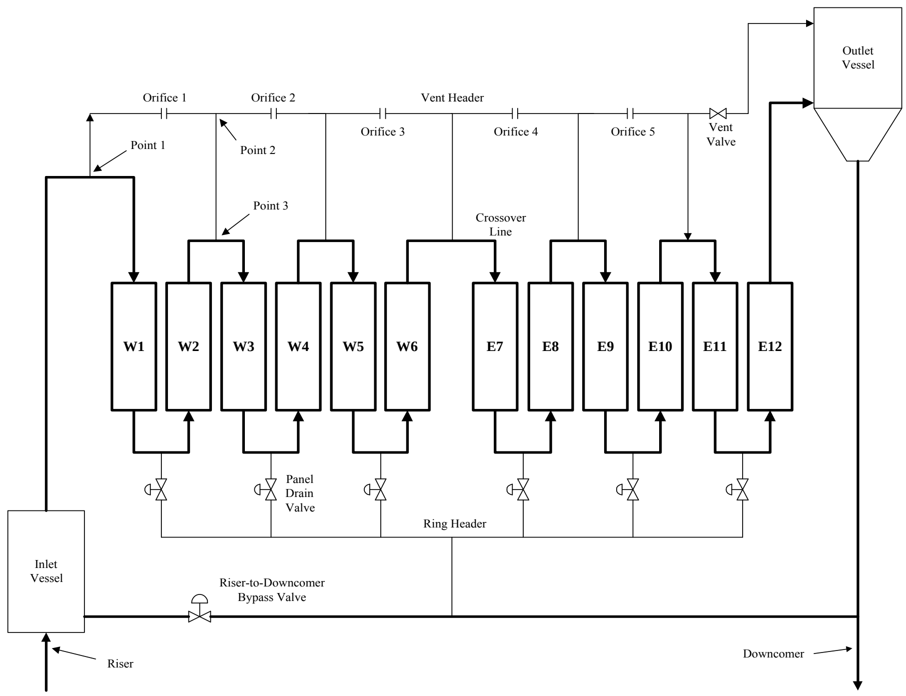

Figure 2 Nitrate Salt Receiver Panel, Vessel, and Piping Arrangement

- Daily receiver filling is not required
- Electric heat trace requirements are minimal
- Rankine cycle efficiencies are 5 to 6 percentage points higher than subcritical cycles
- All heat transfer is single phase.

Supercritical fluids don't do well in the following areas:

- High pressures require relatively thick receiver tube walls, which reduce both allowable fluxes and thermal efficiencies
- Supercritical H_2O has lower, and supercritical CO_2 much lower, fluid densities than nitrate salt, leading to larger equipment sizes and higher circulation pump power demands
- The low temperature supercritical designs require a supercritical fluid-to-salt heat exchanger
- For supercritical H_2O, the specific heat is a strong function of temperature between 375 °C and 425 °C, which significantly complicates the operation of a thermocline storage system.

2.4 Complete Plant Designs

The title of the study is advanced thermal storage systems for use with supercritical receiver coolants. However, thermal storage costs are only in the range of 3 to 8 percent of overall plant capital cost. In effect, the efficiency of the receiver, and as a consequence, the size and the cost of the collector system, will have a much larger influence on the economics of supercritical thermocline storage than the design of the storage system. As a result, much of the work discussed in the following sections concentrated on the design and the cost of supplying of those systems supplying energy to the storage system.

2.5 Receiver Designs

2.5.1 Heliostat Field and Receiver Arrangement

For the proposed site in Barstow, California, the sun elevation angle reaches a maximum value of 32 degrees at noon on the winter solstice, and 79 degrees at noon on the summer solstice. To track the sun, the normal vector from the heliostat surface bisects the angle between the sun and the receiver. As such, the best cosine efficiencies are obtained by locating the heliostats to the North of the receiver. The effect is illustrated schematically in Figure 3.

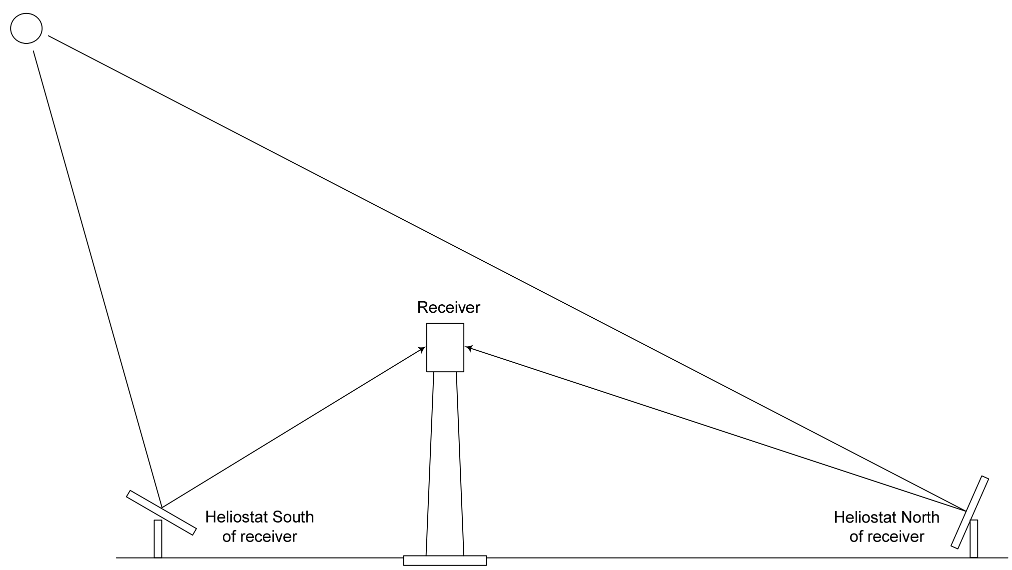

Figure 3 Heliostat Cosine Efficiencies North and South of the Tower

When the receiver capacity approaches 350 MWt, the heliostats in the outermost rows of the collector field are on the order of 2 km from the receiver, and the size of the reflected beam becomes large relative to the size of the absorber. The height of the tower, and the dimensions of the receiver, must also be large to capture the images from the furthest heliostats.

For receiver capacities above 350 MWt, an alternate design approach is to locate the heliostats around the full circumference of the receiver, and to configure the receiver as an external cylinder. As implied in Figure 3, those heliostats located South of the receiver have lower cosine efficiencies, and higher aberration losses, than those located North of the receiver. However, the South heliostats are closer to the receiver, and have a smaller image size. The height of the tower and the dimensions of the receiver are also reduced, as shown in Figure 4 for a 320 MWt receiver capacity. Economic studies conducted by Sandia have shown a nominal parity in the cost of energy for external and cavity designs at a capacity of 320 MWt, and for larger capacities, the external designs were preferred [4].

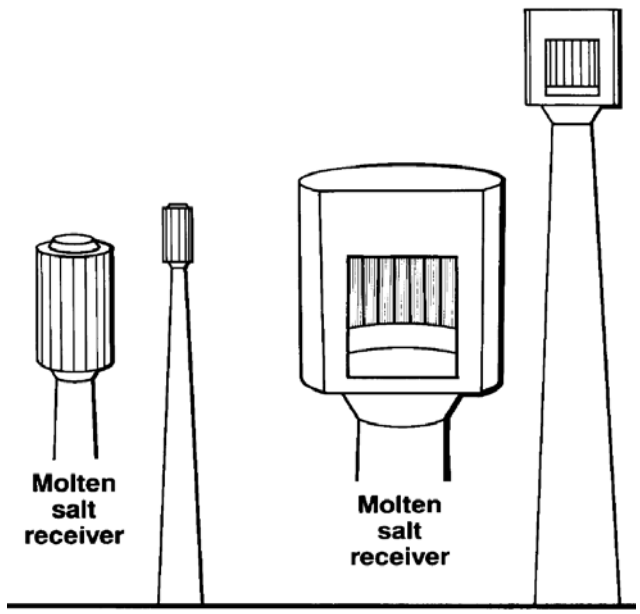

Figure 4 320 MWt External Cylinder and North Cavity Receivers

As noted below in Section 2.5.3, the receiver capacities required for the study are well above 350 MWt, and a surround heliostat field with an external cylindrical receiver was selected as the design approach.

2.5.2 Series and Parallel Panel Flow Arrangements

As shown in Figure 2, the flow path in a nitrate salt receiver consists of several panels in series. The thermal conductivity of the salt is relatively modest; hence, a long heating path is necessary.

Such an arrangement was not found to be suitable for the supercritical fluids. In particular, the decreases in density as the fluid progresses from the inlet temperature to the outlet temperature

[4] Falcone, P. (Sandia National Laboratories, Albuquerque, New Mexico and Livermore, California), "A Handbook for Solar Central Receiver Design", Sandia Report SAND 86-8009, December 1986

were significant. As a result, the fluid velocities near the end of the flow circuit were quite high, and the pressure losses became excessive.

To avoid this problem, the receiver arrangement consists of 24 panels in parallel. The flow in the riser is divided among the panels based on the incident power for that panel. The panel flow enters at the bottom and leaves at the top, with the full rise in temperature occurring in one vertical pass. A schematic flow arrangement is shown in Figure 5. For the supercritical fluids, the combination of density, thermal conductivity, specific heat, and viscosity resulted in Nusselt numbers, and the corresponding convection coefficients, which were sufficiently high to yield acceptable combinations of film temperatures and bulk temperatures along the full tube length.

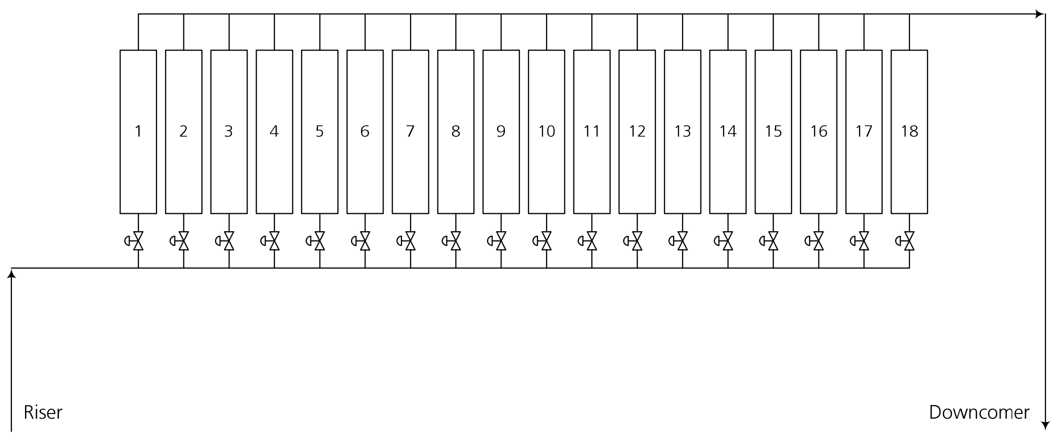

Figure 5 Parallel Flow Arrangement for Supercritical Receivers

2.5.3 Minimum Supercritical Rankine Cycle Size

The minimum size for a commercial supercritical steam turbine is approximately 450 MWe. This is based on, among other factors, the following:

- Turbine blades must be of some minimum length for acceptable aerodynamic efficiency; i.e., to reduce the leakage losses around the tip of the blade. For a given blade length and live steam density, the mass flow rate through, and the power output of, the turbine are then generally defined.

- High pressure equipment is expensive, and some minimum plant size is typically required to justify a reduction in the fuel demand of the heat source.

With a nominal cycle efficiency of 47 percent, and a solar multiple of about 1.8 to supply a storage system with a capacity of 6 hours, the thermal output of the receiver is on the order of 1,700 MWt. A power output this size in a single tower is likely impractical, as the optical efficiencies of the furthest heliostats will be very low.

To keep the heliostat field and tower dimensions within practical values, the plant designs are based on two 50-percent capacity heliostat fields and receivers. The fields are located side-by-side, with a common power block between the fields. The power block is offset to the South of the towers to reduce the distance between the fields, and thereby the length of the heat transport piping between the towers and the power block. The basic arrangement is illustrated in Figure 6.

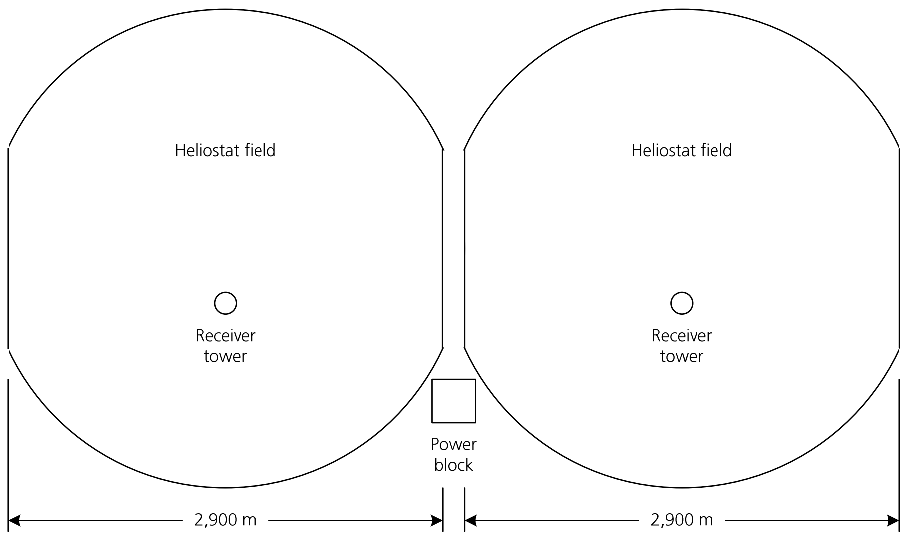

Figure 6 Collector Field Arrangement

2.5.4 Low Cycle Fatigue

Central receivers differ from parabolic trough collectors in two important areas:

- Central receivers do not have an external glass envelope, and associated vacuum space, to reduce convection losses

- Parabolic trough collectors use highly selective surface coatings, with absorbtivities of 94 to 96 percent and emissivities of 8 to 10 percent. However, the coatings are not stable in air at the 600 °C to 700 °C tube temperatures of interest in a central receiver. The latter must use a less effective Pyromark® coating, which has an absorbtivity of about 93 percent but a much higher emissivity of approximately 85 percent.

In general, the unit radiation and convection losses from a central receiver tube are much higher than from a parabolic tube. As a result, the only effective means for reducing the thermal losses in a central receiver is to increase the incident flux on, and thereby reduce the surface area of, the absorber.

The receiver tubes are illuminated from only one side. Since neither the thermal conductivity of the tube wall, nor the internal convection coefficient due to the coolant flow, are infinite, a circumferential and a radial temperature distribution is established in the tube wall. One example is illustrated in Figure 7.

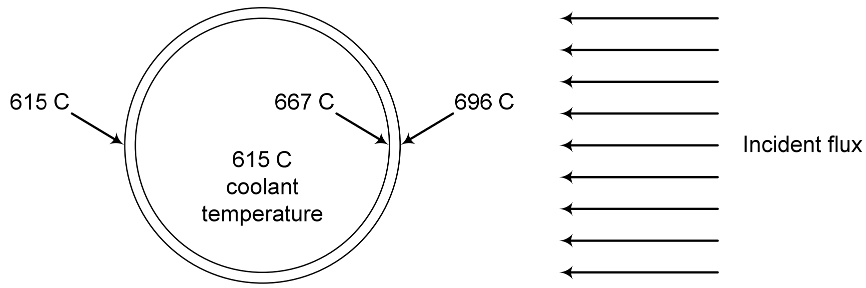

Figure 7 Circumferential and Radial Temperature Distribution in a Receiver Tube

The tube strain is calculated from the following equation [5]:

$$\varepsilon = \alpha\left(\left(\frac{T_{oc} - T_{ic}}{2(1-\nu)}\right) + \left(\frac{T_{oc} + T_{ic}}{2} - T_{avg}\right)\right)$$

where ε is the strain, α is the coefficient of thermal expansion, and ν is Poisson's ratio, T_{oc} is the outer crown temperature, T_{ic} is the inner crown temperature, and T_{avg} is the average circumferential temperature. The average circumferential temperature is given as follows:

$$T_{avg} = T_{fluid} + \frac{\left[\frac{(T_{oc} + T_{ic})}{2}\right] - T_{fluid}}{\pi}$$

where T_{fluid} is the bulk fluid temperature.

The illumination of the tubes on one side, together with the restraint on lateral movement provided by the tube supports, also places the front of the tubes in compression, and the back in tension. The effect is illustrated in Figure 8. At night, the stress distribution is reversed.

Receiver tubes are heated from ambient temperature to normal operating temperature each morning. The tubes also experience partial range heating during the day following a cloud transient. In general, the receiver is designed to withstand the equivalent of 10,000 full range temperature cycles during the 30 year life of the plant. Since the fatigue life of the tubes does not need to be infinite, the tubes can be designed to stresses, and the associated strains, much higher than listed in either Division 1 or Division 2 to Section VIII of the ASME Boiler and Pressure Vessel Code. Using the design approaches presented in Division 1 of Subsection NH, Class 1 Components

[5] Smith, David C. (Science Applications International Corporation, Albuquerque, New Mexico), "Design and Optimization of Tube-Type Receiver Panels for Molten Salt Applications"

in Elevated Temperature Service, to Section III (rather than Section VIII) of the Boiler and Pressure Vessel Code, tube strains can approach, and sometimes enter, the plastic region. For a nitrate salt receiver using tubes with a wall thickness in the range of 1.25 to 1.65 mm, the allowable incident fluxes can approach values as high as 2,500 kWt/m^2.

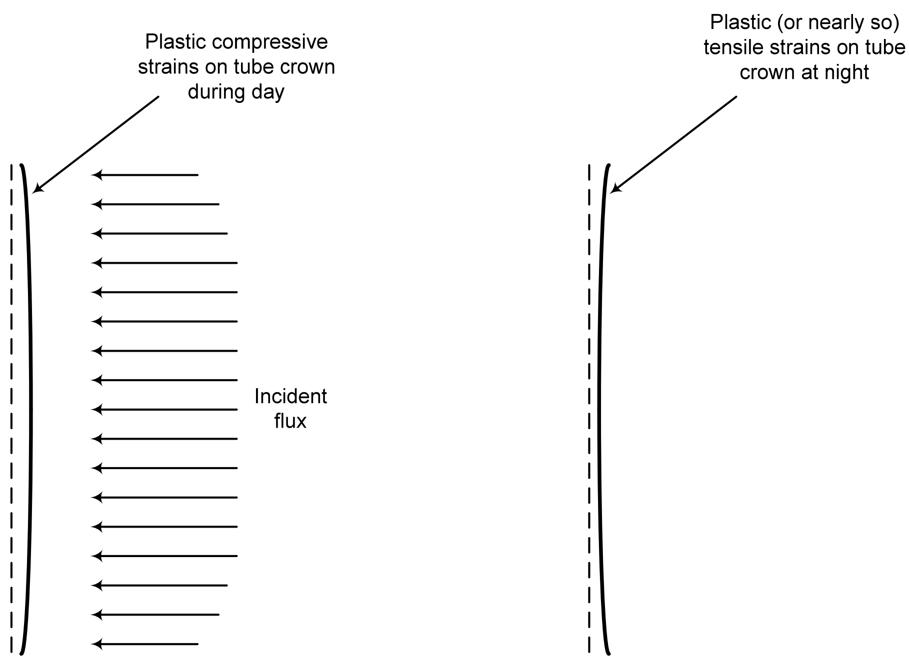

Figure 8 Diurnal Tube Strains in a Receiver Tube

This design approach has important consequences for the study. Nitrate salt receivers operate with fluid pressures in the range of 1 to 20 bar, while the supercritical fluid receivers necessarily operate in the range of 150 to 350 bar. As a result, the tube wall in a supercritical design will be much thicker than a tube wall in a nitrate salt design. Since the tube strains increase with wall thickness, the supercritical receivers must operate with lower incident fluxes than the nitrate salt receivers to achieve the same fatigue life. A direct consequence of a lower incident flux is a larger absorber, higher convection and radiation losses, and a lower thermal efficiency. A detailed examination of the receiver thermal losses for each of the 6 designs is presented in Section 4.5.

2.6 Specific Heat of Supercritical H_2O

For fluid temperatures just above the critical point (i.e., 375 °C to 425 °C), supercritical H_2O has a specific heat which is a strong function of temperature. The effect is illustrated in Figure 9. Within this temperature range, supercritical H_2O can exchange significant quantities of energy with another fluid with only modest changes in the temperature of the supercritical H_2O.

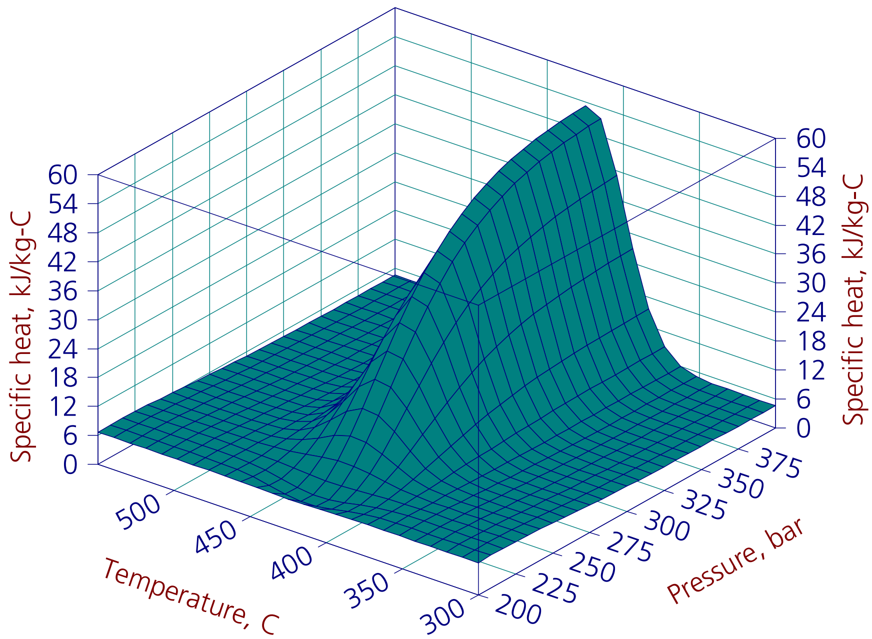

Figure 9 Specific Heat of Supercritical H_2O as a Function of Temperature and Pressure

The variable specific heat influences the plant design in the following areas:

1) In the supercritical fluid-to-salt (or steam) heat exchangers, the temperature profiles on both the fluid and the salt (or steam) sides are non-linear. As such, design approaches based on a log mean temperature difference are not suitable. As discussed below, the heat exchanger designs are based on the NTU (number of transfer units) method, with temperature profiles calculated for each meter of tube length. The heat exchanger length is increased, in increments of 1 m, until the required duty is satisfied.

2) In a thermocline storage system, the circulating fluid temperature at the end of the discharge cycle decays very little from the initial charging temperature. This is an ideal situation, in the sense that a uniform temperature is maintained throughout the discharge process. In contrast, the fluid temperature rise at the end of the charge cycle is very pronounced. This is an undesirable characteristic, as the reduced temperature difference between the filler and the fluid means that heat is not being transferred from the fluid to the bed, and energy extraction is problematic. The performance of the supercritical H_2O thermocline is discussed more completely in Section 3.4.5.

3 Plant Designs

Each of the 6 plant design proceeded through the following steps:

- Development of a Rankine cycle design, and calculation of the gross cycle efficiency, the steam generator duty, and the receiver duty
- Low cycle fatigue analysis of the receiver tubes to determine a potential combination of fluid flow rate, incident flux, absorber height, absorber diameter, tube diameter, and tube wall thickness which satisfies the following: receiver duty; fluid outlet temperature; panel life; maximum film temperature; and pressure loss
- Optimization of the collector field layout, the tower height, and the absorber dimensions to provide the lowest levelized cost of thermal energy
- Calculation of the thermal storage system media quantities and vessel dimensions
- Calculation of the steam generator heat transfer areas

3.1 Subcritical Nitrate Salt

3.1.1 Rankine Cycle

The Rankine cycle for the subcritical nitrate salt plant was based on a 125 bar live steam pressure, with live and reheat steam temperatures of 540 °C. The feedwater heating system consisted of 3 closed low pressure heaters, 1 open deaerating heater, and 2 closed high pressure heaters. An extraction pressure of 35.0 bar to the last high pressure feedwater heater results in a final feedwater temperature of 237 °C.

A design point condenser pressure of 80 millibar was selected, and the low pressure turbine exhaust area was adjusted to provide a nominal exhaust velocity 200 m/sec. The resulting exhaust quality and exhaust loss were 0.953 and 19.8 kJ/kg, respectively.

At the design point, the required live steam flow rate is 350.9 kg/sec, the gross cycle efficiency is 0.434, and the steam generator duty is 1,014 MWt. A heat balance, derived from the GateCycle calculations for the cycle, is shown in Figure 10.

3.1.2 Process Flow Diagram

The basic arrangement of the receivers, the two-tank thermal storage system, and the steam generator is illustrated in Figure 11.

Using the design parameters from the GateCycle calculations for feedwater, live steam, and reheat steam flow rate, pressure, and temperature, an in-house program was used to estimate the following parameters for the steam generator: nitrate salt flow rates; nitrate salt temperature profiles; nitrate salt and water / steam pressure losses; and heat transfer areas.

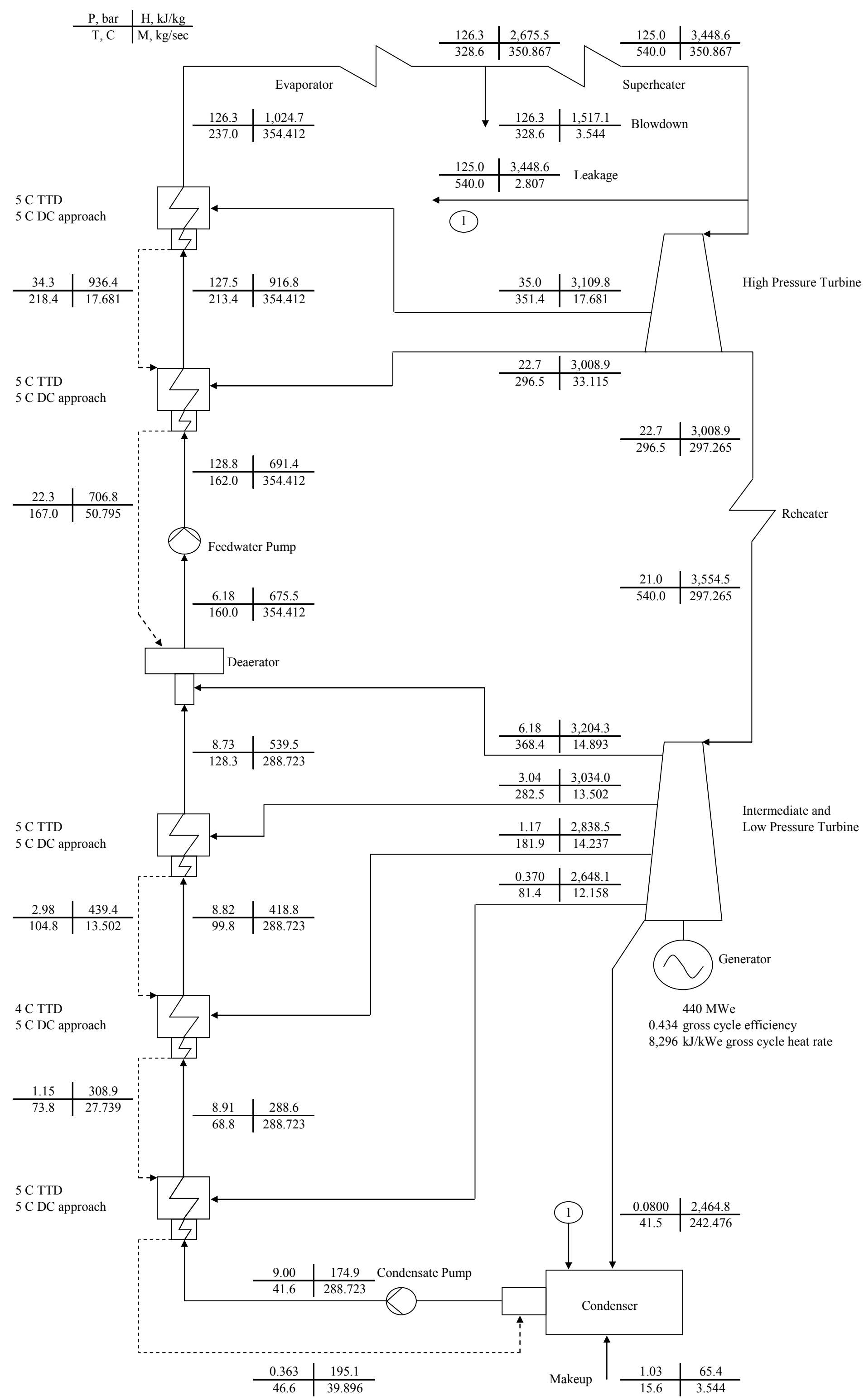

Figure 10 400 MWe Subcritical Rankine Cycle Heat Balance

The steam generator is assumed to be a forced recirculation design, with a nominal blowdown flow rate equal to 1.0 percent of the incoming feedwater flow rate. As the salt enters the steam generator, the flow divides into parallel flow paths through the superheater and the reheater. The exit from the reheater combines with the exit from the superheater, and the combined flow is directed to the evaporator and the preheater. A pinch point temperature of 7 °C in the evaporator is selected to provide a salt temperature of 288 °C at the exit of the preheater.

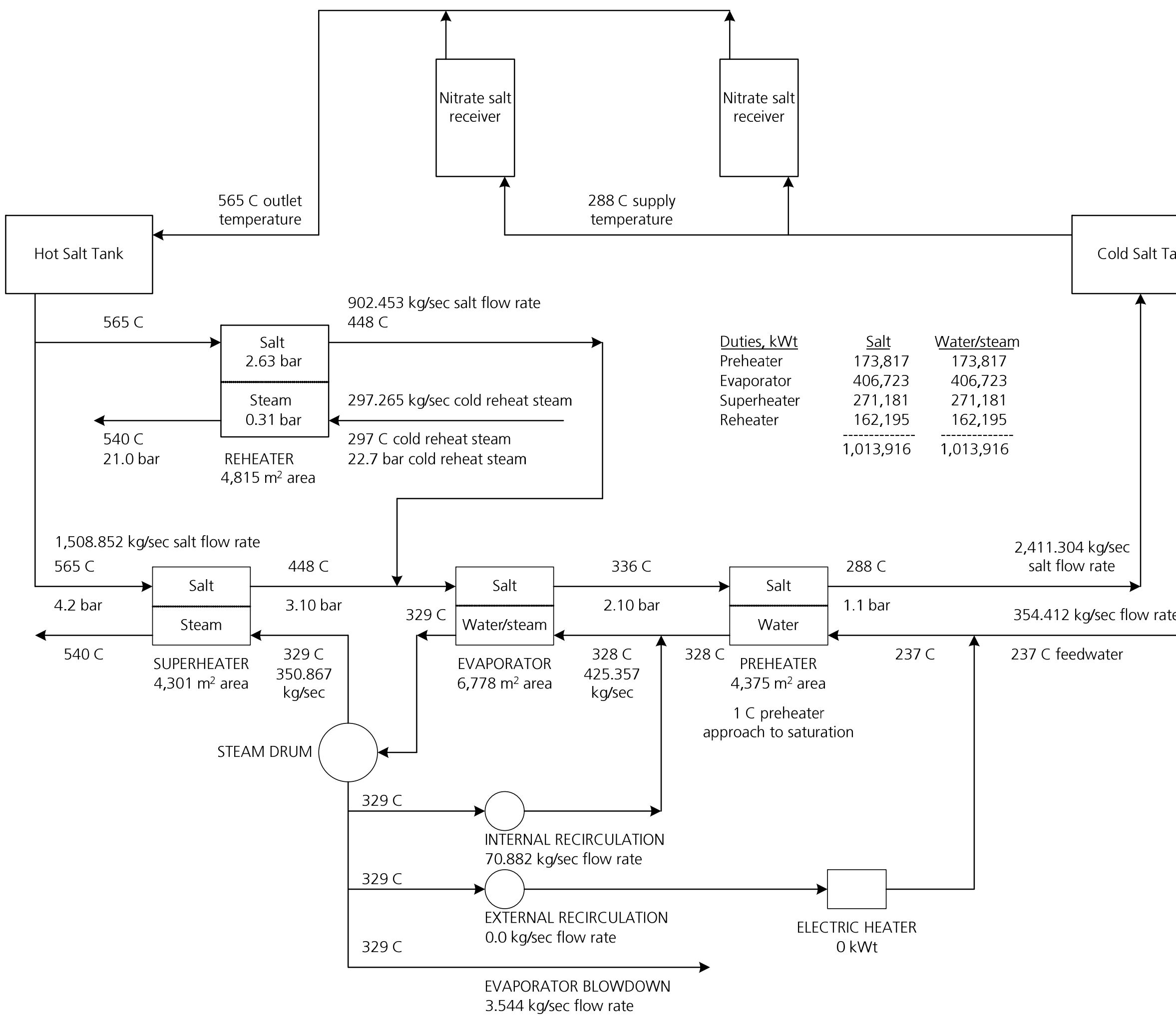

Figure 11 Subcritical Nitrate Salt Receiver Process Flow Diagram

3.1.3 Receiver Design Parameters

A conceptual nitrate salt receiver design has been assembled around the following parameters:

- 910 MWt net output power at noon on the vernal equinox

- Salt inlet and outlet temperatures of 288 °C and 566 °C, respectively
- 1.45 mm tube wall thickness
- Tube diameters as large as possible to reduce the pressure losses, but consistent with the salt pressure at the receiver inlet and a tube wall thickness of 1.45 mm
- 16 panels, in 2 flow paths of 8 panels each
- North-to-South incident panel power ratio of 1.9 at noon on the vernal equinox [6]
- Absorber height-to-diameter ratio of 1.25 [6]
- Incident flux on the center 75 percent of the panel equal to the peak flux. Between the center portion of the flux profile and the top and bottom of the panel, the flux tapered linearly to the edge value. On the North panel, the edge value was 160 kWt/m^2. For the balance of the panels, the edge values were proportional to the peak flux for that panel divided by the peak flux for the North panel [7].

Through a series of iterations among peak incident flux on the North panel, absorber diameter, absorber height, and salt film temperatures on the South panel, a nominal absorber diameter and height of 20 m and 25 m, respectively, were selected.

A low cycle fatigue analysis, shown in Table 3, shows an estimated minimum panel life of 33 years.

The calculations in Table 3 also show inner crown temperatures exceeding 600 °C in panels 6, 7, and 8. Although this temperature is higher than desired, it is judged to be acceptable for two reasons:

- The high temperatures occur for a limited number of hours each year, and involve a limited surface area of the receiver. The quantities of corrosive agents, (Na,K)NO_2 and $(Na,K)_2O_2$, produced will be limited by the time and surface area available for generation. In addition, the nitrites and oxides will be diluted by the very large mass of salt in the storage system.
- The preferred tube materials today are nickel-based alloys, such as Inconel 625LCF. There are limited data available on corrosion rates of 625LCF in nitrate salts at temperatures above 600 °C. However, as shown in Figure 12, the corrosion rates for Inconel 600, an alloy similar to 625LCF, are not dramatically higher at 630 °C than at 600 °C [2].

The unit convection and radiation losses are 40.5 kWt/m^2, and the thermal efficiency, defined as the ratio of absorbed power to incident power, is 0.879.

Table 3 Subcritical Nitrate Salt Receiver Tube Strain and Thermal Efficiency Analysis

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[6] Vant-Hull, L. (University of Houston, Houston, Texas) and Izygon, M. (Tietronix Software, Inc., Houston, Texas), "RCell Analysis for Solar Tres Conceptual Design", Report to Nexant, Inc. on Task 3 - Commercial SPT Conceptual Design Study for Sandia National Laboratories, September 2000

[7] Conversation with Lorin Vant-Hull, University of Houston, August 22, 2009

Salt Properties								
Panel number	1	2	3	4	5	6	7	8
Bulk temperature, C	342	394	442	485	519	545	561	566
Density, kg/m^3	1,872	1,839	1,809	1,782	1,760	1,743	1,733	1,730
Volume flow rate, m^3/sec	0.577	0.587	0.597	0.606	0.614	0.619	0.623	0.624
Velocity, m/sec	3.71	3.77	3.84	3.89	3.94	3.98	4.00	4.01
Re, salt	150,444	202,317	245,055	272,617	290,964	306,343	318,691	323,674
Pr, salt	7.25	5.32	4.34	3.86	3.59	3.39	3.24	3.19
Nu, salt	704	789	848	881	901	918	931	936
h, salt, J/sec-m^2-K	6,726	7,679	8,397	8,859	9,174	9,426	9,615	9,688
Friction factor	0.0167	0.0158	0.0153	0.0150	0.0148	0.0147	0.0146	0.0146
Tube head loss, m	6.17	6.05	6.04	6.11	6.19	6.25	6.28	6.29
Tube (rounded) entrance loss, m	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Tube (rounded) exit loss, m	0.63	0.65	0.68	0.70	0.71	0.73	0.74	0.74
Panel head loss, m	6.83	6.74	6.75	6.84	6.94	7.02	7.05	7.06
Tube Temperatures								
Inner tube crown temperature, C	498	519	545	573	597	614	624	626
Outer tube crown temperature, C	597	603	618	635	651	663	669	668
Average tube circumference temperature, C	408	447	487	523	552	575	588	592
Strain Analysis								
Peak crown flux, W/m^2	1,047,000	953,979	864,533	782,099	709,844	650,547	606,485	579,352
Strain at tube crown	0.00288	0.00240	0.00205	0.00178	0.00157	0.00141	0.00130	0.00124
Fluid pressure, bar	11.2	9.9	8.7	7.4	6.1	4.8	3.6	2.3
Simple hoop stress, MPa	21.7	19.2	16.8	14.3	11.8	9.3	6.9	4.4
Simple hoop strain	0.00012	0.00011	0.00009	0.00008	0.00007	0.00005	0.00004	0.00003
Tube crown and hoop stress strain	0.00300	0.00251	0.00214	0.00186	0.00164	0.00147	0.00134	0.00126
Stress, MPa	542	451	382	329	288	256	233	220
Allowable cycles; crown temperature	33,491	75,351	149,882	264,615	429,820	649,733	898,056	1,120,867
Estimated panel life, years	33	75	150	265	430	650	898	1,121
Panel flux distribution								
- Panel width, m	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
- Panel height, m	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
- Fraction of panel height at peak flux	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
- Flux at panel top/bottom, kWt/m^2	160	146	132	120	108	99	93	89
Panel power, MWt								
- Incident	87.55	79.77	72.29	65.40	59.36	54.40	50.71	48.45
- Reflection loss	5.25	4.79	4.34	3.92	3.56	3.26	3.04	2.91
- Radiation loss	2.59	2.66	2.84	3.08	3.30	3.47	3.55	3.55
- Convection loss	0.79	0.80	0.82	0.84	0.86	0.87	0.88	0.88
	-------	-------	-------	-------	-------	-------	-------	-------
- Total loss	8.63	8.25	8.00	7.84	7.72	7.60	7.48	7.34
- Net power	78.92	71.53	64.29	57.56	51.64	46.80	43.24	41.11

3.1.4 RCell Analyses

The RCell computer code is used to define the optimum combination of heliostat area, heliostat spacing, tower height, and absorber dimensions. The code, developed by the University of Houston, is divided into three systems: the NS; RC; and IH systems.

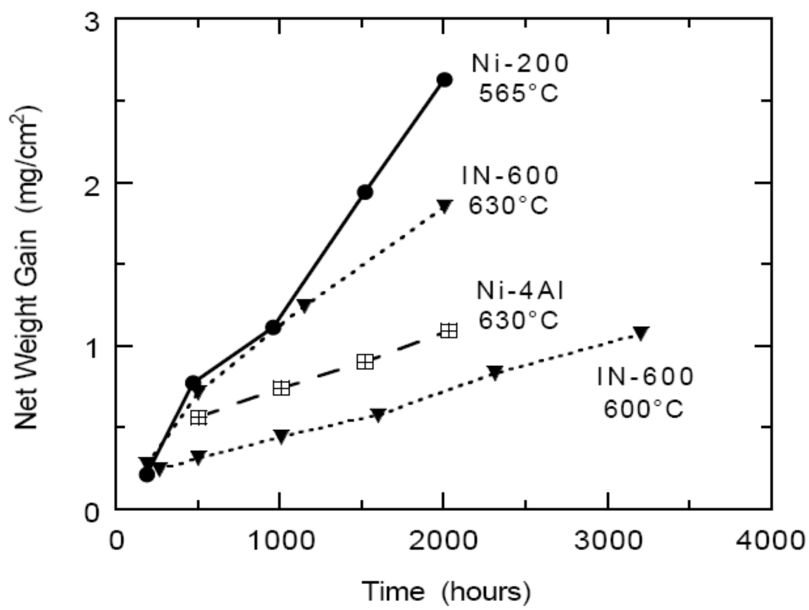

Figure 12 Corrosion Rates for Nickel and Inconel 600 in Nitrate Salt

- The NS code is a cellwise performance model containing a cell model of the collector field where cells are square and have a North-South orientation. Each cell contains a representative heliostat at the center, which may represent many heliostats. The NS code also determines the receiver intercept factors.

- The RC code system contains the primary design method and is a cellwise cost/performance optimization program.

- The IH code system is used for final performance analysis. This model is capable of representing individual heliostat locations.

The optimization program determines the optimum heliostat spacing parameters in each cell, and the optimum boundary location of the collector field using a detailed cost and performance model for the thermal energy available at the base of the tower.

The principal inputs to the code include the following:

- Site latitude, longitude, and elevation. For Barstow, California, the values are 34.9 °, 117.4 °, and 584 m.

- Direct normal radiation and atmospheric attenuation models

- Heliostat mechanical characteristics. The heliostat is a non-inverting design, with glass mirrors and a combined azimuth / elevation drive at the top of a pedestal. The heliostat has 28 facets, each 1.355 m tall and 3.22 m wide, with a 15 mm separation between facets. The net reflective area is 122.17 m^2. The facets are arranged in 4 columns of 7 each, and are cylindrically focused to focal lengths of 2.0, 3.5, and 4.0 to effectively reduce the 3.22 m dimension. The facets are canted, on-axis, to the slant range.

- Heliostat optical errors. The error budget includes the following: 2.6 mrad surface normal, including 1.0 mrad focusing error; and 1.3 mrad tracking error, including 1.0 mrad canting error. These are converted to a beam error by doubling, and then adding in quadrature, to yield a total beam error of 2.90 mrad. No account is taken of gravitational loads, wind deflections, or installation defects.

- Effective heliostat reflectivity. Clean mirror reflectivity is 0.94, and the average dust factor is taken to be 0.95. It is assumed that 98 percent of the heliostats are operational at any time. The inefficiency of the layout process in converting from the RCell cellwise model to the individual heliostat model requires the field efficiency to be reduced by a slippage factor of 2.95 percent. Thus, the effective heliostat reflectivity is 0.8943 (0.94 x 0.95 x 0.98 x 0.9705) before shading, blocking, and cosine losses.

- Receiver allowable incident flux as a function of circumferential position on the absorber, as shown in the Strain Analysis section of Table 3.

- Number and location of the vertical aimpoints

- North-to-south panel power ratio of 1.8 at the design point

- Cost functions for the heliostats, receiver, tower, vertical piping, and receiver coolant circulation pump.

The RCell calculations showed the following combination of parameters as the optimum: a mirror area of 1,793,600 m^2; an optical tower height of 260 m; absorber diameter of 20.0 m; and absorber height of 25.0 m. In RCell, the optical tower height is defined as the difference in elevation between the centerline of the heliostat and the centerline of the absorber.

The distribution of heliostats within the collector field is illustrated in Table 4. The number is each table entry is the number of heliostats within that cell. For example, in the first cell North of the tower, there are 219 heliostats.

The incident flux distribution on the receiver at the design point is show in Figure 13. The peak flux on the North panel is slightly greater than 1,000 kWt/m^2, while the peak flux on the South panel is about 620 kWt/m^2. Station number 0 is the equator on the receiver.

An elevation view of the receiver tower is shown in Figure 14.

The heliostat field efficiency matrix, shown in Table 5, accounts for the following optical effects:

- Heliostat blocking: the losses due to any portion of the reflected image from the heliostat under study illuminating the back of a nearby heliostat

Table 4 Heliostat Distribution in Subcritical Nitrate Salt Plant

0.0	0.0	0.0	0.0	15.4	41.7	60.2	46.7	60.2	41.7	15.4	0.0	0.0	0.0	0.0
0.0	0.0	0.0	42.2	65.1	69.5	72.5	73.6	72.5	69.5	65.1	42.2	0.0	0.0	0.0
0.0	0.0	48.7	68.4	75.7	82.4	87.3	89.1	87.3	82.4	75.7	68.4	48.7	0.0	0.0
0.0	31.8	68.2	78.0	88.9	99.5	107.6	83.0	107.6	99.5	88.9	78.0	68.2	31.8	0.0
0.0	63.6	75.3	88.7	104.7	121.4	134.6	139.5	134.6	121.4	104.7	88.7	75.3	63.6	0.0
7.7	68.7	81.8	99.3	121.8	146.6	164.1	126.7	164.1	146.6	121.8	99.3	81.8	68.7	7.7
13.9	71.5	86.5	107.6	136.7	169.9	185.8	218.9	185.8	169.9	136.7	107.6	86.5	71.5	13.9
10.6	72.4	66.1	111.0	144.3	139.0	176.7	Tower	176.7	139.0	144.3	111.0	66.1	72.4	10.6
0.0	71.2	86.2	107.7	139.5	182.9	203.0	211.8	203.0	182.9	139.5	107.7	86.2	71.2	0.0
0.0	43.8	81.1	99.0	123.8	156.8	190.1	142.3	190.1	156.8	123.8	99.0	81.1	43.8	0.0
0.0	1.6	69.7	87.7	104.7	124.5	142.9	150.8	142.9	124.5	104.7	87.7	69.7	1.6	0.0
0.0	0.0	12.2	69.6	87.5	98.9	108.1	83.8	108.1	98.9	87.5	69.6	12.2	0.0	0.0
0.0	0.0	0.0	3.4	47.5	80.5	85.5	87.3	85.5	80.5	47.5	3.4	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	12.1	14.4	12.1	0.0	0.0	0.0	0.0	0.0	0.0

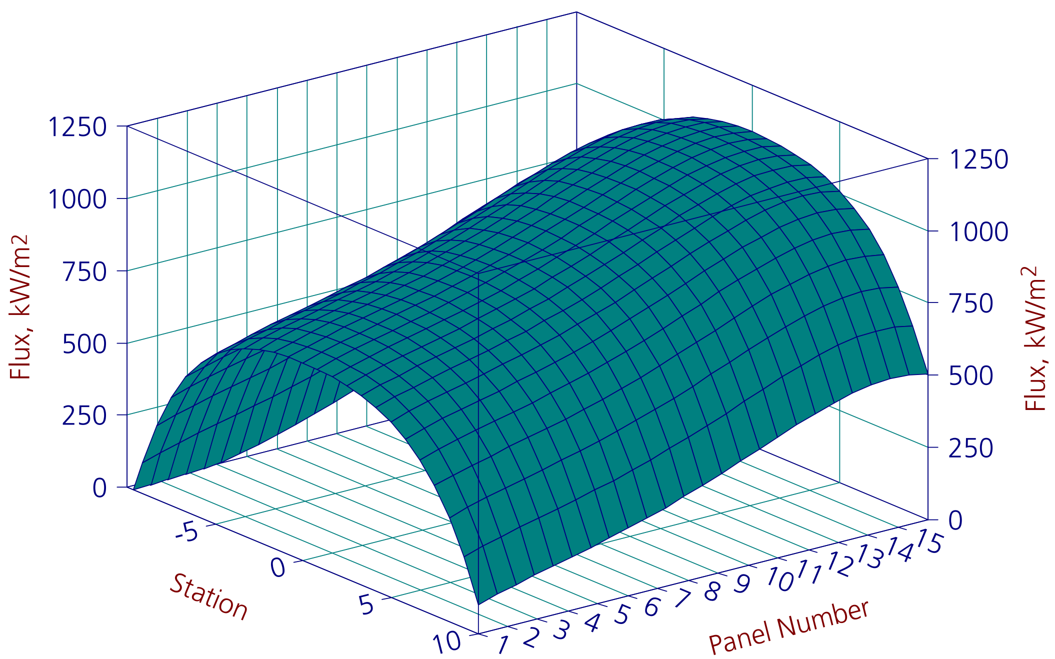

Figure 13 Equinox Noon Incident Flux Distribution on Subcritical Nitrate Salt Receiver

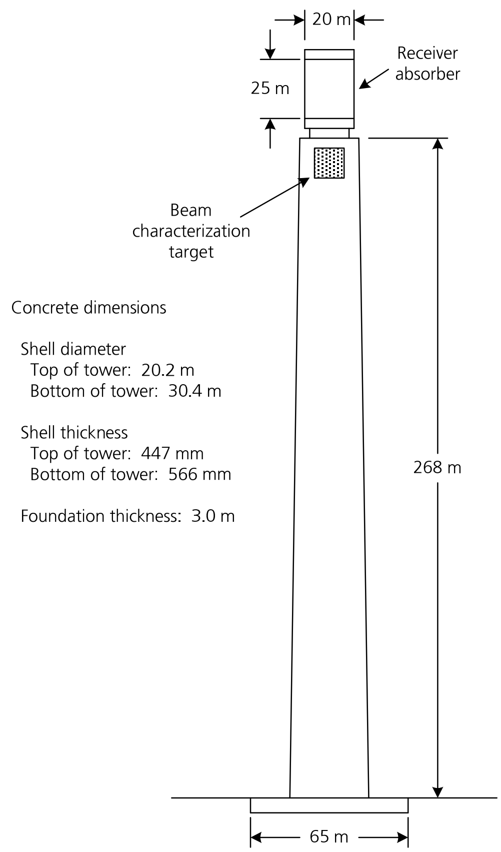

Figure 14 Tower and Foundation Dimensions for Subcritical Nitrate Salt Receiver

Table 5 Field Efficiency Matrix for the Subcritical Nitrate Salt Receiver

AZ / EL	0.000	0.170	0.340	0.510	0.670	0.840	1.000
0.000	0.60919	0.59891	0.59713	0.59421	0.59144	0.58146	0.57271
0.167	0.60597	0.59582	0.59408	0.59166	0.58914	0.57949	0.57002
0.333	0.59752	0.58757	0.58603	0.58354	0.58236	0.57159	0.56184
0.500	0.58203	0.57259	0.57126	0.57020	0.56878	0.55516	0.54434
0.667	0.55649	0.54760	0.54648	0.54464	0.54099	0.52572	0.51333
0.833	0.49417	0.48638	0.48594	0.48282	0.47697	0.46177	0.45314
1.000	0.34612	0.34069	0.34161	0.34949	0.36103	0.36765	0.36617

- Heliostat shading: the losses due to any heliostat casting a shadow on any portion of the heliostat under study
- Atmospheric attenuation: the effect of scattering due to moisture and particles in the air

- Receiver intercept: the fraction of the reflected images which are intercepted by the absorber
- Receiver absorbtivity: the fraction of incident light absorbed on the outside of the receiver tubes.

The matrix values are selected, based on the following:

1) Non-dimensional hour of the day between noon and sunset (first column on the left). Sunset is defined as an elevation angle of 10 degrees above the horizon.

2) Non-dimensional day of the year (first row at the top). Day 0 is defined as winter solstice.

3.1.5 Thermal Storage System

The thermal storage system consists of a cold salt tank, operating at a temperature of 288 °C, and a hot salt tank, operating at a temperature of 565 °C. The stored energy requirement is 6,083 MWht, and the required storage mass, including the stagnant inventory at the bottom of the tanks, is 58,037 metric tons.

Steel plates for fabricating the tanks are available in standard thickness up to 63.5 mm (2.50 inches). To keep the hydrostatic loads such that standard plates can be used, 2 cold tanks and 2 hot tanks are required. The cold tanks have a diameter of 40.4 m and a height of 12.2 m, while the hot tanks have a diameter of 42.4 m and a height of 12.2 m. The tank volumes are sufficient to hold the stagnant inventory from the adjacent tank should a leak develop in one of the tanks.

The steady state heat loss from the 4 tanks is approximately 1,965 kWt. As such, if the storage system is fully charged during the course of a day, the storage efficiency is slightly above 99 percent.

The inventory temperatures are such that concrete cannot be used directly as the foundation material. For the purposes of the study, the foundation design is similar to that used for the thermal storage tanks at the Solar Two central receiver demonstration project. The design is illustrated in Figure 15. Starting from the bottom and moving up, the tank foundation consists of a concrete slab, an insulating concrete slab, foam glass insulation, insulating firebricks, and a steel slip plate. The perimeter of the foundation is somewhat different, consisting of a ring wall of firebricks to support the large loads from the walls and the roof.

Steel pipes, approximately 2 m apart, are embedded in the concrete foundation. One end of the pipe is open to the atmosphere, while the other end is connected to a vertical chimney about 3 m high. Vertical conduction down through the insulation warms the air inside the pipe, and a natural convection flow is established. The air velocities are very low, perhaps 0.05 m/sec, but the heat removal by the air flow is sufficient to maintain the concrete temperatures at safe values.

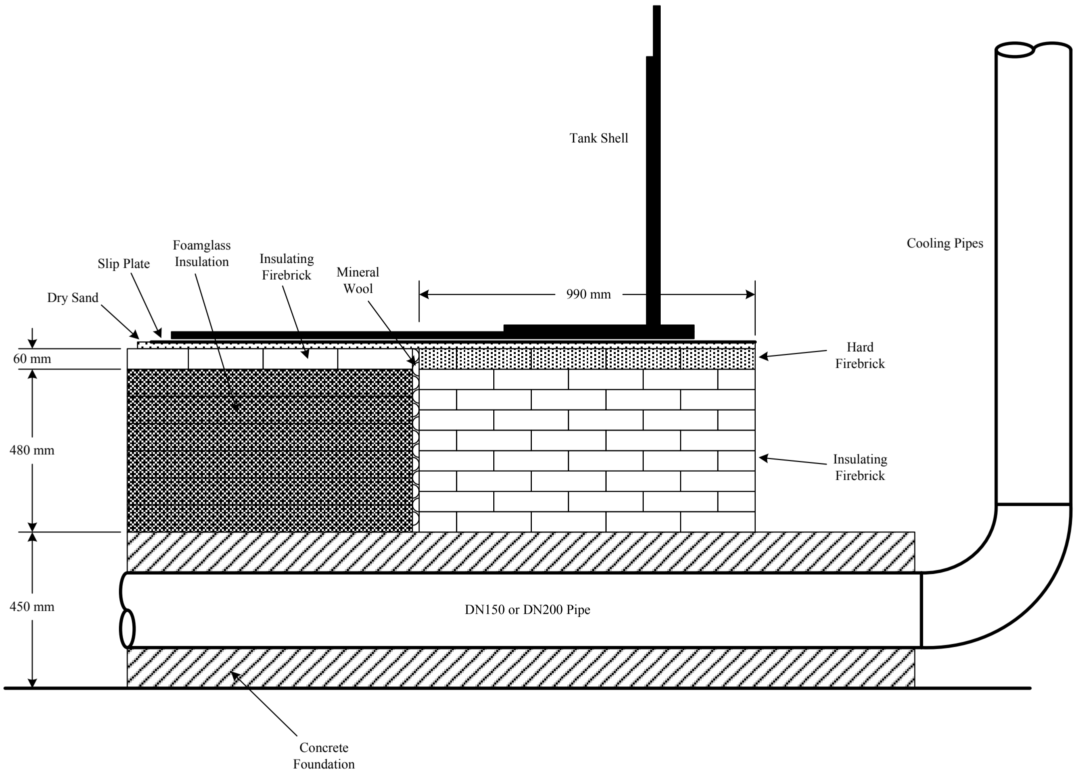

Figure 15 Elevation View of Hot Salt Tank Foundation

3.2 Supercritical Nitrate Salt

3.2.1 Rankine Cycle

The Rankine cycle for the supercritical nitrate salt plant was based on a 301 bar live steam pressure, with live and reheat steam temperatures of 590 °C. The feedwater heating system consisted of 4 closed low pressure heaters, 1 open deaerating heater, and 3 closed high pressure heaters. An extraction pressure of 92 bar to the last high pressure feedwater heater results in a final feedwater temperature of 307 °C.

A design point condenser pressure of 80 millibar was selected, and the low pressure turbine exhaust area was adjusted to provide a nominal exhaust velocity 150 m/sec. The resulting exhaust quality and exhaust loss were 0.929 and 29.6 kJ/kg, respectively.

At the design point, the required live steam flow rate is 350.0 kg/sec, the gross cycle efficiency is 0.4878 and the steam generator duty is 904 MWt. A heat balance, derived from the GateCycle calculations for the cycle, is shown in Figure 16.

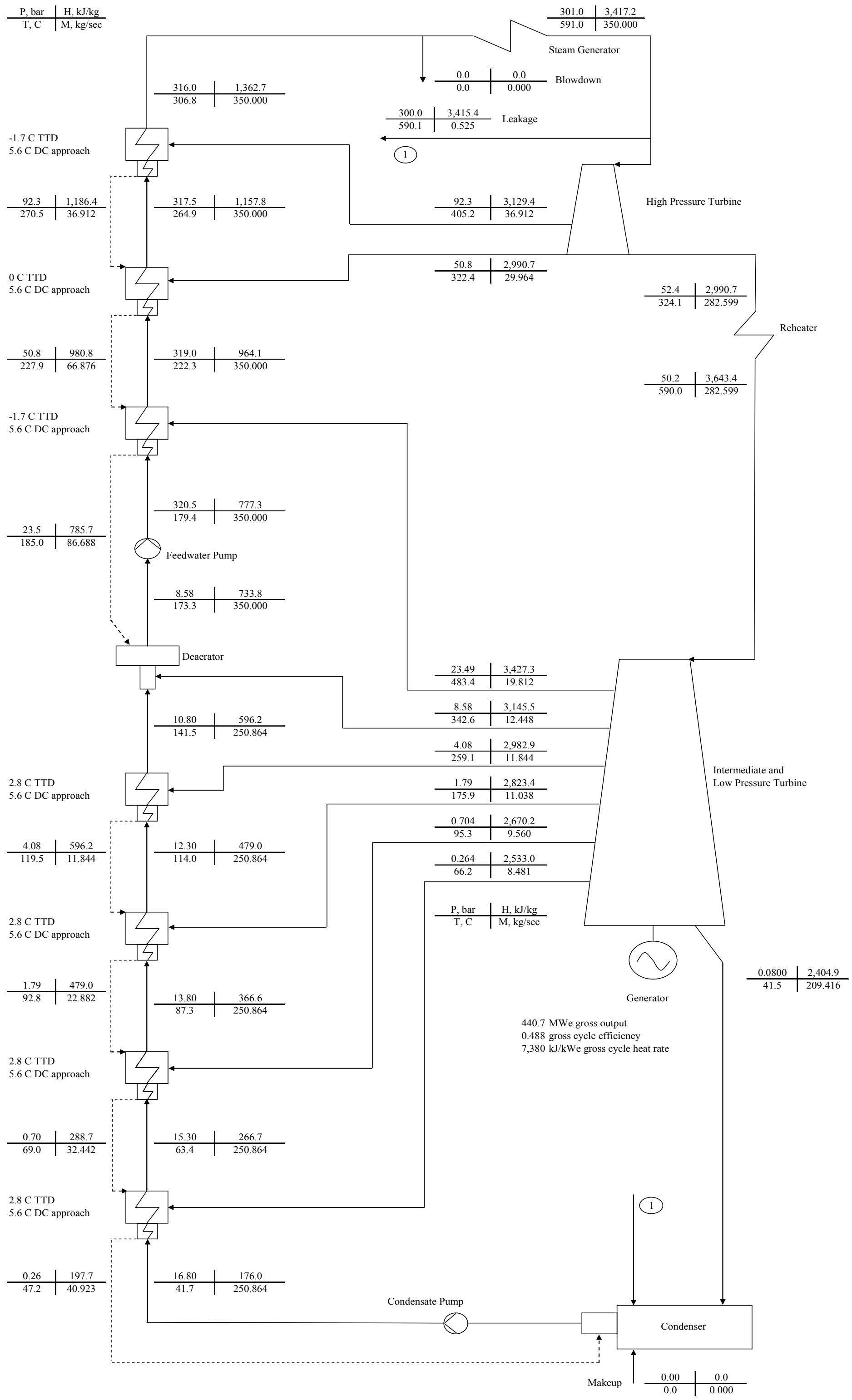

Figure 16 400 MWe Low Temperature Supercritical Rankine Cycle Heat Balance

3.2.2 Process Flow Diagram

The basic arrangement of the receivers, the two-tank thermal storage system, and the steam generator is illustrated in Figure 17.

Using the design parameters from the GateCycle calculations for feedwater, live steam, and reheat steam flow rate, pressure, and temperature, an in-house program was used to estimate the following parameters for the steam generator: nitrate salt flow rates; nitrate salt temperature profiles; nitrate salt and water / steam pressure losses; and heat transfer areas.

The steam generator is a single pass-to-superheat design. As the salt enters the steam generator, the flow divides into parallel flow paths through the supercritical heat exchanger and the reheater. The exit from the supercritical heat exchanger combines with the exit from the reheater prior to returning to the cold salt tank.

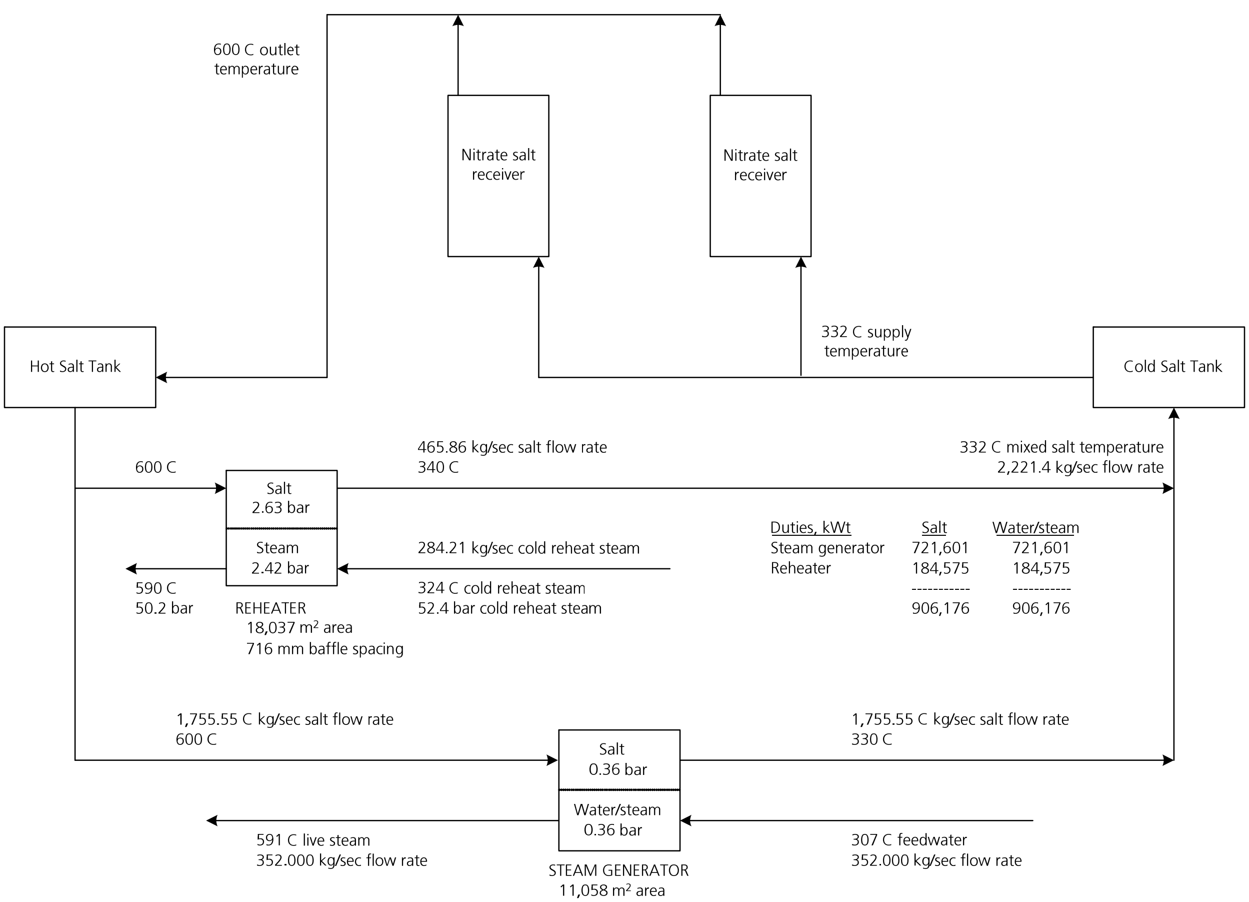

Figure 17 Supercritical Nitrate Salt Process Flow Diagram

To determine the temperature of the salt leaving the supercritical heat exchanger, a heat transfer analysis was conducted along the length of the heat exchanger tube. As noted in Section 2.6, the specific heat of supercritical steam is a strong function of temperature between 375 ° and 425 °C. As such, the temperature profile in the heat exchanger is non-linear, as illustrated in Figure 18. A salt exit temperature of 330 °C ensures the temperature differences along the length of the tube are adequate.

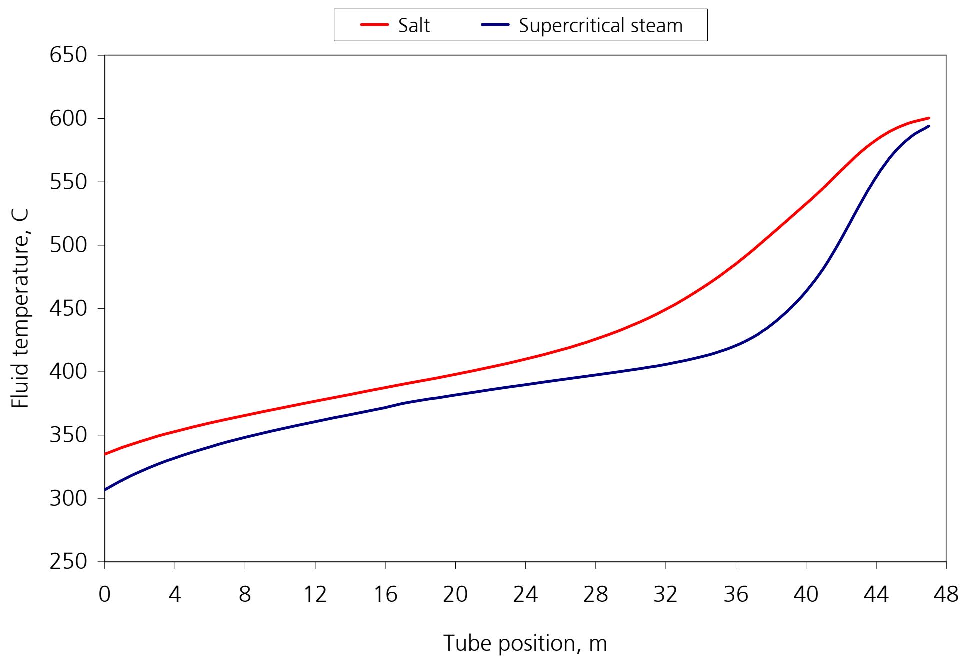

Figure 18 Temperature Profile in Nitrate Salt Supercritical Steam Generator

For subcritical steam, the specific heat is nominally independent of the temperature. As such, the temperature profiles in the reheater are essentially two parallel lines, and the heat transfer calculations are straightforward. To reduce the thermodynamic penalty due to mixing, a salt exit temperature equal to that of the supercritical heat exchanger (330 °C), is preferred. However, the approach temperature at the cold end of the heat exchanger would be only 6 °C, and the surface area would be impractically large. To keep the heat exchanger area within a reason, a salt exit temperature of 340 °C was selected. This results in a mixed salt temperature of 332 °C returning the cold salt tank.

3.2.3 Receiver Design Parameters

A conceptual nitrate salt receiver design has been assembled around the following parameters:

- 812 MWt net output power at noon on the vernal equinox
- Salt inlet and outlet temperatures of 332 °C and 600 °C, respectively

- North-to-South incident panel power ratio of 2.8 at noon on the vernal equinox.

The balance of the design parameters were the same as those used for the subcritical nitrate salt receiver.

Through a series of iterations among peak incident flux on the North panel, absorber diameter, absorber height, and salt film temperatures on the South panel, a nominal absorber diameter and height of 25.2 m and 31.6 m, respectively, were selected.

A low cycle fatigue analysis, shown in Table 6, shows an estimated minimum panel life of 23 years.

Since the receiver outlet temperature is 600 °C, the tube film temperatures in the latter panels are necessarily above 600 °C. To hold the film temperatures comparable to those of the subcritical salt receiver, the supercritical salt receiver design is based on the following:

- The North-to-South incident power ratio has been increased from the previous value of 1.9 to a new value of 2.4. As such, a portion of the duty is shifted from the South side to the North.

- The absorber dimensions are increased from the previous values of 20 m diameter and 25 m height to new values of 25.2 m diameter and 31.6 m height. The larger dimensions reduce the peak fluxes on both the North and the South panels.

Shifting heliostats from the South to the North improves the annual optical efficiency of the collector field. However, increasing the absorber area reduces the receiver thermal efficiency; the efficiency of the subcritical design is 0.879, while the efficiency of the supercritical design is 0.840. The net effect on the annual performance is discussed in Section 4.5.

3.2.4 RCell Analyses

The RCell calculations showed the following combination of parameters as the optimum: a mirror area of 1,627,800 m^2; an optical tower height of 260 m; absorber diameter of 25.2 m; and absorber height of 31.6 m. The distribution of heliostats within the collector field is illustrated in Table 7, and the heliostat field efficiency matrix is shown in Table 8.

Table 6 Supercritical Nitrate Salt Receiver Tube Strain and Thermal Efficiency Analysis

Salt Properties								
Panel number	1	2	3	4	5	6	7	8
Bulk temperature, C	387	436	482	522	555	580	595	600
Density, kg/m^3	1,844	1,812	1,783	1,758	1,737	1,721	1,712	1,708
Volume flow rate, m^3/sec	0.546	0.555	0.564	0.572	0.579	0.585	0.588	0.589
Velocity, m/sec	3.92	3.99	4.06	4.11	4.16	4.20	4.23	4.23
Re, salt	146,556	180,889	204,210	220,335	236,490	255,362	272,794	280,199
Pr, salt	5.54	4.43	3.88	3.56	3.30	3.03	2.83	2.75
Nu, salt	619	670	701	719	738	759	778	786
h, salt, J/sec-m^2-K	8,326	9,178	9,749	10,154	10,534	10,929	11,264	11,400
Friction factor	0.0169	0.0162	0.0159	0.0157	0.0155	0.0153	0.0151	0.0150
Tube head loss, m	11.92	11.87	11.99	12.18	12.32	12.37	12.37	12.36
Tube (rounded) entrance loss, m	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05
Tube (rounded) exit loss, m	0.71	0.73	0.75	0.78	0.80	0.81	0.82	0.82
Panel head loss, m	12.67	12.64	12.79	13.00	13.16	13.23	13.24	13.23
Tube Temperatures								120
Inner tube crown temperature, C	464	498	533	564	590	609	620	622
Outer tube crown temperature, C	522	546	572	597	617	631	639	640
Average tube circumference temperature, C	421	464	505	541	571	593	606	610
Strain Analysis								
Peak crown flux, W/m^2	646,500	568,559	493,614	424,544	364,004	314,320	277,401	254,666
Strain at tube crown	0.00156	0.00129	0.00107	0.00089	0.00075	0.00063	0.00055	0.00050
Fluid pressure, bar	19.1	16.8	14.6	12.3	10.1	7.8	5.5	3.3
Simple hoop stress, MPa	27.3	24.0	20.8	17.6	14.3	11.1	7.9	4.7
Simple hoop strain	0.00015	0.00013	0.00011	0.00010	0.00008	0.00006	0.00004	0.00003
Tube crown and hoop stress strain	0.00171	0.00142	0.00118	0.00099	0.00083	0.00069	0.00059	0.00052
Stress, MPa	316	259	214	177	146	122	104	92
Allowable cycles; crown temperature	794,147	1,626,854	2,687,264	3,285,307	2,535,828	979,915	175,855	23,213
Estimated panel life, years	794	1,627	2,687	3,285	2,536	980	176	23
Panel flux distribution								
- Panel width, m	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
- Panel height, m	31.6	31.6	31.6	31.6	31.6	31.6	31.6	31.6
- Fraction of panel height at peak flux	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
- Flux at panel top/bottom, kWt/m^2	160	160	160	160	160	160	160	160
Panel power, MWt								
- Incident	91.65	80.98	70.72	61.26	52.97	46.17	41.11	38.00
- Reflection loss	6.42	5.67	4.95	4.29	3.71	3.23	2.88	2.66
- Radiation loss	2.86	3.23	3.67	4.11	4.51	4.81	4.99	5.01
- Convection loss	1.11	1.16	1.21	1.26	1.30	1.33	1.34	1.34
	-------	-------	-------	-------	-------	-------	-------	-------
- Total loss	10.38	10.05	9.83	9.66	9.52	9.37	9.21	9.02
- Net power	81.26	70.92	60.89	51.60	43.45	36.79	31.90	28.98

Table 7 Heliostat Distribution in Supercritical Nitrate Salt Plant

0.0	0.0	0.0	0.0	0.0	2.5	10.9	14.6	10.9	2.5	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	6.8	29.4	45.8	57.9	46.5	57.9	45.8	29.4	6.8	0.0	0.0	0.0
0.0	0.0	14.6	44.2	64.3	68.6	71.6	72.6	71.6	68.6	64.3	44.2	0.0	0.0	0.0
0.0	11.5	47.2	67.1	74.2	80.6	85.3	87.0	85.3	80.6	74.2	67.1	47.2	11.5	0.0
0.0	34.2	66.4	75.8	86.2	96.3	103.9	80.1	103.9	96.3	86.2	75.8	66.4	34.2	0.0
7.4	50.9	72.7	85.4	100.3	115.9	128.2	132.8	128.2	115.9	100.3	85.4	72.7	50.9	7.4
13.7	59.5	78.3	94.5	115.3	138.3	155.0	119.8	155.0	138.3	115.3	94.5	78.3	59.5	13.7
13.9	59.7	82.1	101.4	128.1	159.3	176.3	201.5	176.3	159.3	128.1	101.4	82.1	59.7	13.9
8.7	53.9	82.9	103.6	133.9	173.4	177.5	Tower	177.5	173.4	133.9	103.6	82.9	53.9	8.7
0.0	41.0	80.5	99.9	128.5	126.9	197.4	211.8	197.4	126.9	128.5	99.9	80.5	41.0	0.0
0.0	20.7	62.5	68.5	113.4	143.1	174.7	189.1	174.7	143.1	113.4	68.5	62.5	20.7	0.0
0.0	0.0	29.8	65.6	95.6	113.1	129.4	136.5	129.4	113.1	95.6	65.6	29.8	0.0	0.0
0.0	0.0	0.0	23.7	54.3	84.7	97.8	101.0	97.8	84.7	54.3	23.7	0.0	0.0	0.0
0.0	0.0	0.0	0.0	9.9	28.4	40.5	40.6	40.5	28.4	9.9	0.0	0.0	0.0	0.0

Table 8 Field Efficiency Matrix for the Supercritical Nitrate Salt Receiver

AZ / EL	0.000	0.170	0.340	0.510	0.670	0.840	1.000
0.000	0.62788	0.61792	0.61772	0.61613	0.61546	0.60784	0.59966
0.167	0.62420	0.61446	0.61431	0.61338	0.61322	0.60571	0.59766
0.333	0.61405	0.60480	0.60482	0.60447	0.60590	0.59828	0.58979
0.500	0.59610	0.58744	0.58846	0.59036	0.59211	0.58195	0.57258
0.667	0.56883	0.56137	0.56255	0.56456	0.56481	0.55241	0.54118
0.833	0.50676	0.50002	0.50313	0.50306	0.50114	0.48735	0.47860
1.000	0.35661	0.35242	0.35493	0.36521	0.38140	0.38901	0.38752

3.2.5 Thermal Storage System

The thermal storage system consists of a cold salt tank, operating at a temperature of 332 °C, and a hot salt tank, operating at a temperature of 600 °C. The stored energy requirement is 5,412 MWht, and the required storage mass, including the stagnant inventory at the bottom of the tanks, is 53,184 metric tons.

As with the subcritical salt design, 2 cold tanks and 2 hot tanks are required. The cold tanks have a diameter of 38.9 m and a height of 12.2 m, while the hot tanks have a diameter of 40.8 m and a height of 12.2 m. The steady state heat loss from the 4 tanks is approximately 1,950 kWt. As such, if the storage system is fully charged during the course of a day, the storage efficiency is slightly above 99 percent.

3.3 Low Temperature Supercritical H_2O

The low temperature supercritical H_2O design is similar to the supercritical salt receiver design; the principal difference is the replacement of the 2 nitrate salt receivers with 2 supercritical H_2O receivers and 2 supercritical H_2O-to-salt heat exchangers.

3.3.1 Rankine Cycle

The Rankine cycle for the low temperature supercritical H2O plant is the same as for the supercritical nitrate salt plant. The supercritical cycle heat balance, shown in Figure 16, is unchanged.

3.3.2 Process Flow Diagram

The basic arrangement of the receivers, the two-tank thermal storage system, and the steam generator is illustrated in Figure 19. The steam generator design is the same as that used for the supercritical nitrate salt plant.

As with the salt-to-supercritical H_2O steam generator discussed in Section 3.2.2, the variable specific heat of supercritical H_2O imposes a non-uniform temperature profile in the supercritical H_2O-to-salt heat exchangers shown in the process flow diagram. A plot of the fluid temperature profiles as a function of the heat transferred is shown in Figure 20. The curve for the supercritical H_2O is concave, which means the fluid temperatures to and from the heat exchanger are higher than would be the case with a specific heat which is independent of temperature. In general, such a characteristic is undesirable, as it increases the fluid temperatures in the receiver.

Converting the duty profile in Figure 20 to a temperature profile along the length of the tube results in the distributions shown in Figure 21. The required supply temperature to the receiver is 410 °C, and the outlet temperature is 675 °C.

For the required duty of 812 MWt at each tower, 3 heat exchangers, each with an area of 4,780 m^2, are required. The pressure losses on the supercritical H_2O and nitrate salt sides are 0.061 bar and 1.57 bar, respectively.

Thermal energy is transported between the supercritical H_2O-to-salt heat exchangers, located at the towers, and the thermal storage system, located at the central power block, by nitrate salt piping. The cold salt and the hot salt pipe diameters are 28 in. and 30 in., respectively, and the salt circulation pump power demand is 3,310 kWe for each of the 2 loops.

The capacity of each heat transport loop is equal to the 812 MWt duty of the receiver. In theory, the capacity of the loops could be reduced if the thermal storage tanks were located at the tower, and the heat transport system only needed to carry one-half of the steam generator duty. However, the thermal energy source for the steam generator during morning startup would then be the hot salt heat transport pipe. As such, the morning startup transient for the hot salt pipe would be added to the morning startup transient for the steam generator. The capital cost savings from the smaller salt lines were not judged to be sufficient to offset the additional operating complexity, and the entire thermal storage system was located at the central power block.

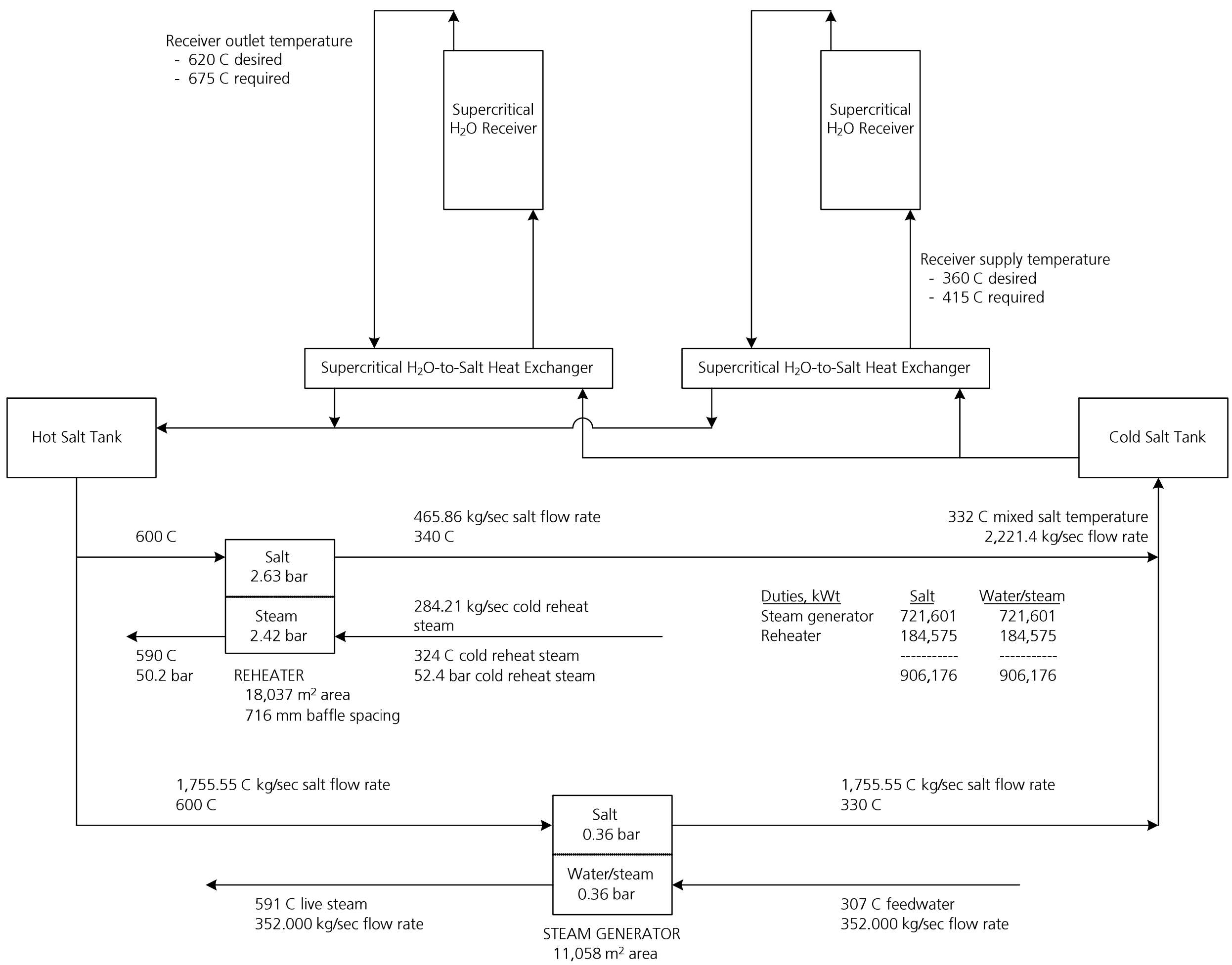

Figure 19 Low Temperature Supercritical H_2O Process Flow Diagram

3.3.3 Receiver Design Parameters

A conceptual low temperature supercritical H_2O receiver design has been assembled around the following parameters:

- 812 MWt net output power at noon on the vernal equinox
- Fluid inlet and outlet temperatures of 410 °C and 675 °C, respectively
- Tube diameters to provide an acceptable compromise between pressure loss and fatigue life. Large tubes provide a low pressure loss. However, as the diameter increases, so does the wall thickness, which has a detrimental effect on the fatigue life. The desired pressure loss is less than 4 bar, while the desired fatigue life is at least 10 years.

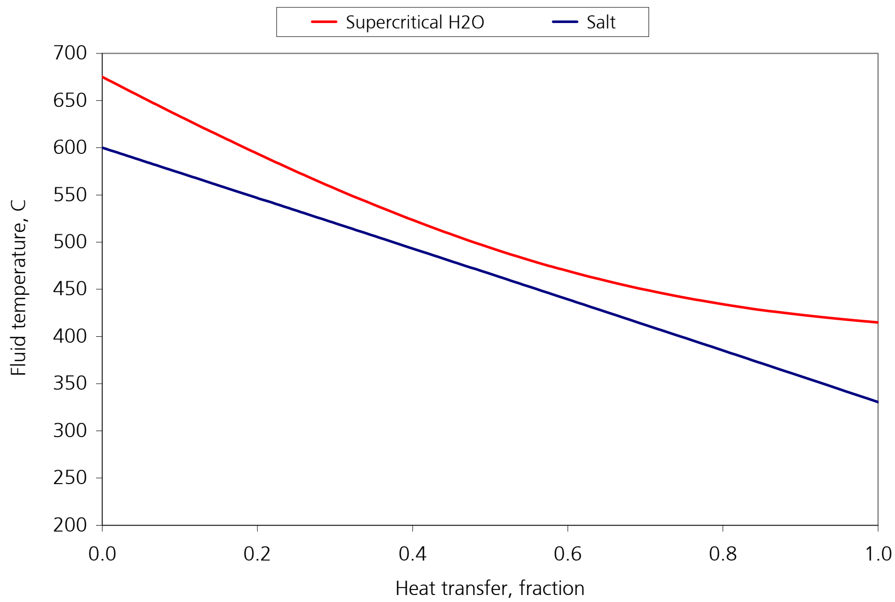

Figure 20 Fluid Temperature Versus Duty in Supercritical H_2O-to-Salt Heat Exchanger

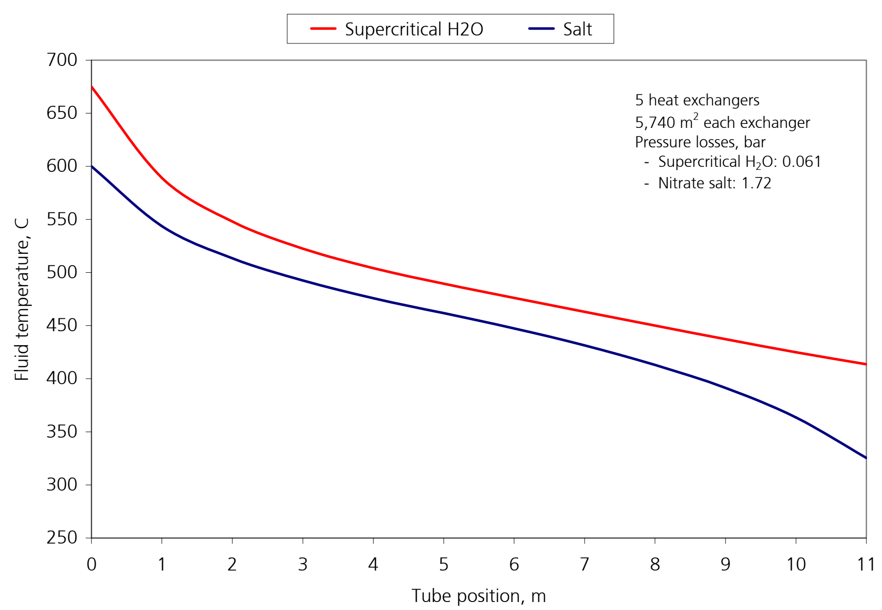

Figure 21 Temperature Profile in Supercritical H_2O-to-Salt Heat Exchanger

- 24 panels in parallel
- North-to-South incident panel power ratio of 1.8 at noon on the vernal equinox

- Incident flux on the center 75 percent of the panel equal to the peak flux. Between the center portion of the flux profile and the top and bottom of the panel, the flux tapered linearly to the edge value. On the North panel, the edge value was 160 kWt/m^2. For the balance of the panels, the edge values were proportional to the peak flux for that panel divided by the peak flux for the North panel [8].

Through a series of iterations among tube dimensions, peak incident fluxes, absorber diameter, and absorber height, the following design parameters were adopted:

- Absorber diameter and height of 21.5 m and 34.4 m, respectively

- 150 tubes per panel; the tube outside diameter is 18.8 mm, and the wall thickness is 2.41 mm

- A peak flux of 614 kWt/m^2 on the North panel, decreasing to 342 kWt/m^2 on the South.

The receiver thermal efficiency is 0.815, and the highest pressure loss is 3.46 bar in the North panel.

A plot of the temperature profile within the North panel is shown in Figure 22. Note that at a vertical position of about 85 percent of the panel height, the combination of tube temperatures and incident flux reach a maximum. At this location, the local fatigue life of the tube reaches a minimum of about 6 years. Although the balance of the tube length has a much longer fatigue life, the minimum local fatigue life will determine the life of the panel.

The corresponding profiles for the South panel are shown in Figure 23. The incident fluxes are slightly more than one-half of those on the North panel, which increases the local fatigue life to about 10 years.

Several characteristics of the low temperature supercritical H_2O receiver are notably different from the subcritical salt receiver, as follows:

- The tube diameters are much smaller, resulting in 3,600 tubes for the supercritical H_2O receiver, but only 1,120 for the salt receiver. The larger number, and smaller sizes, of the supercritical H_2O tubes increases the relative fabrication complexity and cost of the supercritical receiver.

- The incident fluxes are about 60 percent of those for the salt receiver. This results in an absorber which is about 50 percent larger. Since the thermal losses are, to a first order, proportional to the absorber area, the thermal efficiency of the supercritical H_2O receiver is about 6 percentage points lower than the subcritical salt receiver.

As noted in Figure 22, the outer crown temperatures can exceed 800 °C. At temperatures of 700 °C and above, intermetallic compounds precipitate between, and within, the grains of nickel alloys. The precipitation leads to an increase in tensile strength, and a decrease in ductility. As shown in Figure 24, heating Inconel 625LCF to a temperature of 700 °C in air for 1,000 hours results in an increase in tensile strength of about 30 percent, but a decrease in ductility of perhaps

[8] Conversation with Lorin Vant-Hull, University of Houston, August 22, 2009

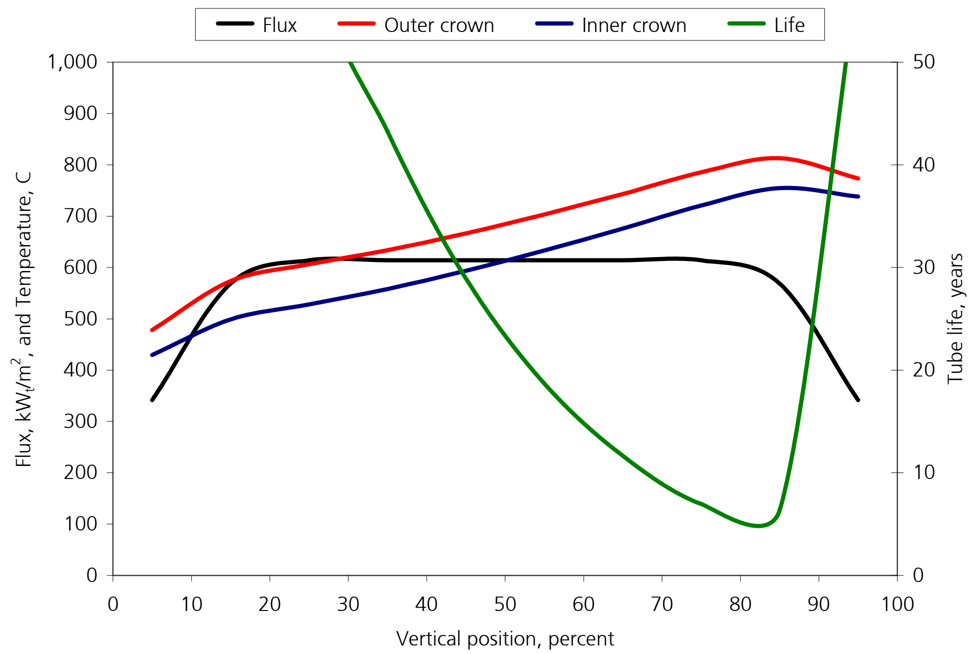

Figure 22 Characteristics of North Panel for Low Temperature Supercritical H_2O Receiver

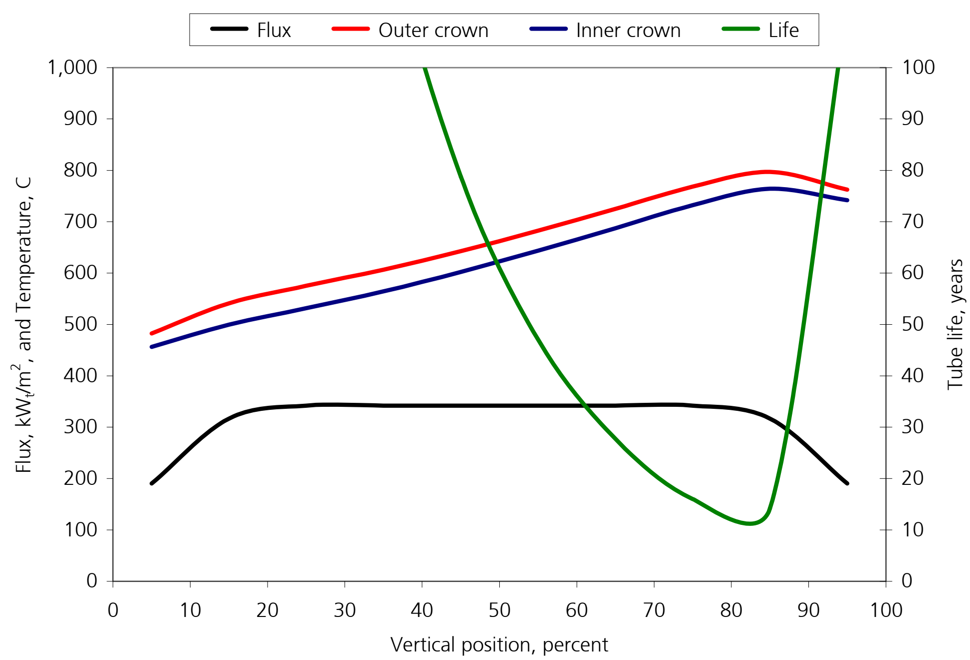

Figure 23 Characteristics of South Panel for Low Temperature Supercritical H_2O Receiver

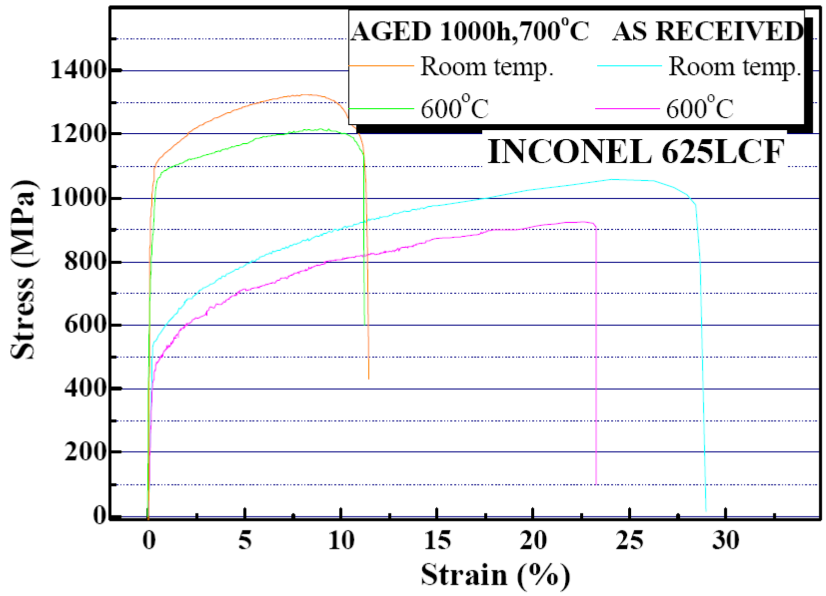

Figure 24 Aged Material Properties for Inconel 625LCF

50 percent [9]. The strain and low cycle fatigue analyses summarized in Figure 22 and Figure 23 were based on data developed at temperatures up to 600 °C. Whether these data can be extrapolated to the temperatures expected for the supercritical H_2O and the supercritical CO_2 receivers is an open question.

3.3.4 RCell Analyses

The RCell calculations showed the following combination of parameters as the optimum: a mirror area of 1,729,332 m^2; an optical tower height of 240 m; absorber diameter of 21.5 m; and absorber height of 34.4 m.

The distribution of heliostats within the collector field is illustrated in Table 9, and the heliostat field efficiency matrix is shown in Table 10.

The cost of the vertical tower piping is greater for the low temperature supercritical H_2O receiver than for the baseline nitrate salt receiver. As a result, the optimum tower height of 240 m is slightly less the optimum height of 260 m for the nitrate salt plant. Generally, the consequence of a lower tower height is a somewhat lower optical efficiency for the collector field. However, the supercritical H_2O receiver absorber is larger than the baseline nitrate salt receiver, which translates into slightly lower spillage losses. The net effect is a field efficiency matrix for the baseline nitrate salt receiver, shown in Table 8, which is almost identical to the low temperature supercritical H_2O receiver, shown in Table 10.

[9] Alvarez-Lara, M., and Perosanz, F. (CIEMAT, Madrid, Spain), "Alloys Selection for Molten Salts Central Receivers for Solar Power Plants", SolarPACES, 2009

Table 9 Heliostat Distribution in Low Temperature Supercritical H_2O Plant

0.0	0.0	0.0	0.0	0.00	17.1	32.0	36.4	32.0	17.1	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	19.6	53.8	67.7	70.7	71.8	70.7	67.7	53.8	19.6	0.0	0.0	0.0
0.0	0.0	25.9	66.7	73.9	80.7	85.6	87.4	85.6	80.7	73.9	66.7	25.9	0.0	0.0
0.0	13.7	66.5	76.3	87.3	98.2	106.7	110.0	106.7	98.2	87.3	76.3	66.5	13.7	0.0
0.0	40.5	73.7	87.2	103.6	121.4	136.1	106.3	136.1	121.4	103.6	87.2	73.7	40.5	0.0
0.0	59.7	80.3	98.0	121.6	149.0	170.0	176.0	170.0	149.0	121.6	98.0	80.3	59.7	0.0
3.2	68.8	85.1	106.6	137.3	174.9	196.5	223.0	196.5	174.9	137.3	106.6	85.1	68.8	3.2
0.0	66.2	86.8	109.9	144.7	191.9	210.5	Tower	210.5	191.9	144.7	109.9	86.8	66.2	0.0
0.0	53.3	84.8	106.5	139.1	140.0	215.6	227.3	215.6	140.0	139.1	106.5	84.8	53.3	0.0
0.0	28.4	79.8	48.8	122.6	156.4	193.7	211.8	193.7	156.4	122.6	48.8	79.8	28.4	0.0
0.0	0.0	52.3	86.4	103.3	123.0	141.4	149.4	141.4	123.0	103.3	86.4	52.3	0.0	0.0
0.0	0.0	5.0	53.4	86.3	97.5	106.6	110.2	106.6	97.5	86.3	53.4	5.0	0.0	0.0
0.0	0.0	0.0	0.0	34.5	65.5	84.0	86.1	84.0	65.5	34.5	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	4.3	3.1	4.3	0.0	0.0	0.0	0.0	0.0	0.0

Table 10 Field Efficiency Matrix for Low Temperature Supercritical H_2O Receiver

AZ / EL	0.000	0.170	0.340	0.510	0.670	0.840	1.000
0.000	0.60961	0.59887	0.59674	0.59405	0.59204	0.58334	0.57468
0.167	0.60608	0.59562	0.59379	0.59129	0.58973	0.58127	0.57288
0.333	0.59750	0.58750	0.58601	0.58354	0.58298	0.57518	0.56624
0.500	0.58248	0.57296	0.57179	0.57046	0.57037	0.55930	0.55043
0.667	0.55819	0.54917	0.54804	0.54678	0.54299	0.53051	0.52058
0.833	0.50172	0.49393	0.49340	0.49181	0.48594	0.47006	0.46203
1.000	0.35938	0.35452	0.35416	0.36159	0.37667	0.37914	0.37772

3.3.5 Thermal Storage System

The thermal storage system is identical to that for the supercritical nitrate salt plant.

3.4 High Temperature Supercritical H_2O

3.4.1 Rankine Cycle

The Rankine cycle for the high temperature supercritical H_2O plant was based on a 350 bar live steam pressure and a live steam temperatures of 650 °C.

For the high temperature supercritical H_2O design, the heat transport fluid must be steam. However, as shown in Figure 6, the nominal distance from the tower to the power block is 1.3 km, and it is impractical to transport cold steam and reheat steam over such long distances. As such, the heat source for the cycle reheater is portion of the supercritical steam from the tower.

As with the other supercritical H_2O heat exchangers described above, the variable specific heat of the supercritical H_2O produces a non-linear temperature profile in the supercritical H_2O-to-reheat steam heat exchanger. A plot of the temperatures along the length of the heat exchanger is shown in Figure 25. To maintain a reasonable temperature difference along the full length of the tube, the maximum reheat steam temperature is on the order of 570 °C to 580 °C. A value of 577 °C was selected for the heat balance calculations.

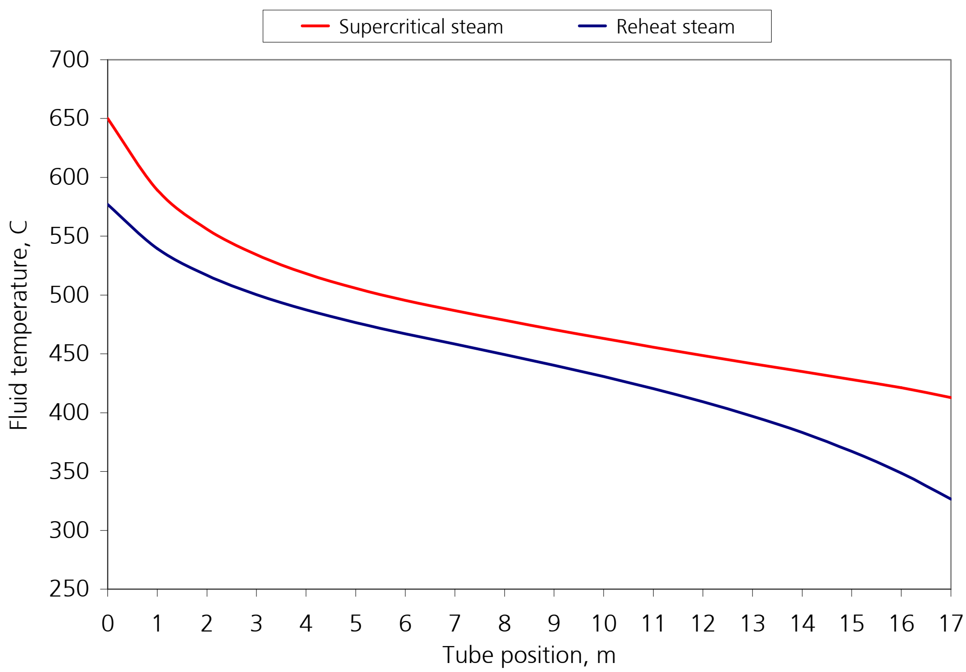

Figure 25 Temperature Profile in Supercritical H_2O-to-Reheat Steam Heat Exchanger

The temperature of the supercritical fluid leaving the heat exchanger is 417 °C. To capture the energy in this stream, the supercritical fluid is mixed with the feedwater leaving the last high pressure feedwater heater.

The feedwater heating system consisted of 4 closed low pressure heaters, 1 open deaerating heater, and 3 closed high pressure heaters. An extraction pressure of 92 bar to the last high pressure feedwater heater results in a feedwater temperature of 307 °C at the exit of the heat exchanger. After the feedwater mixes with the supercritical fluid leaving the reheater, the mixed temperature returning to the tower is 350 °C

A design point condenser pressure of 80 millibar was selected, and the low pressure turbine exhaust area was adjusted to provide a nominal exhaust velocity 200 m/sec. The resulting exhaust quality and exhaust loss were 0.929 and 19.8 kJ/kg, respectively.

At the design point, the required live steam flow rate is 350.0 kg/sec, the gross cycle efficiency is 0.4928 and the steam generator duty is 893 MWt. A heat balance, derived from the GateCycle calculations for the cycle, is shown in Figure 26.

3.4.2 Process Flow Diagram

The basic plant arrangement is illustrated in Figure 27. A supercritical steam line, and the companion feedwater line, are required to transport thermal energy from the receiver to the central power block. To reduce the capacity, and the cost, of the transport piping, the thermocline storage vessels are located at the base of each tower.

3.4.3 Receiver Design Parameters

A conceptual high temperature supercritical H_2O receiver design has been assembled around the following parameters:

- 804 MWt net output power at noon on the vernal equinox
- Fluid inlet and outlet temperatures of 350 °C and 650 °C, respectively

The balance of the design parameters are the same as for the low temperature supercritical H_2O receiver.

Through a series of iterations among tube dimensions, peak incident fluxes, absorber diameter, and absorber height, the following design parameters were adopted:

- Absorber diameter and height of 22.0 m and 36.5 m, respectively
- 170 tubes per panel; the tube outside diameter is 16.4 mm, and the wall thickness is 2.41 mm
- A peak flux of 592 kWt/m^2 on the North panel, decreasing to 329 kWt/m^2 on the South.

The receiver thermal efficiency is 0.829, and the highest pressure loss is 2.03 bar in the North panel.

A plot of the temperature profile within the North panel is shown in Figure 28. As with the low temperature supercritical H2O receiver, the combination of tube temperatures and incident flux reach a maximum at a vertical position of about 85 percent of the panel height. At this location, the local fatigue life of the tube reaches a minimum of about 8 years.

The corresponding profiles for the South panel are shown in Figure 29. The incident fluxes are slightly more than one-half of those on the North panel, which increases the local fatigue life to about 17 years.

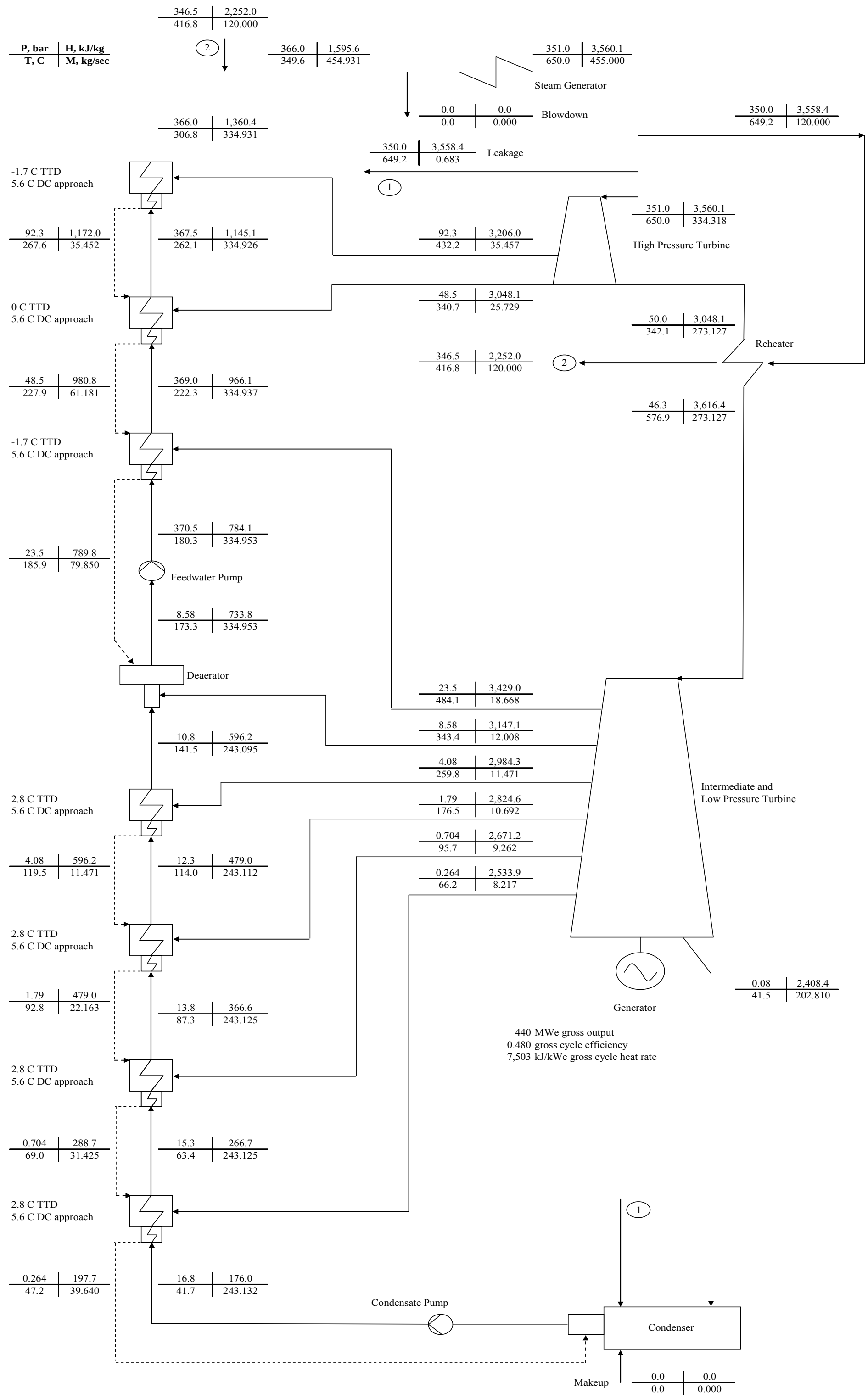

Figure 26 400 MWe High Temperature Supercritical Rankine Cycle Heat Balance

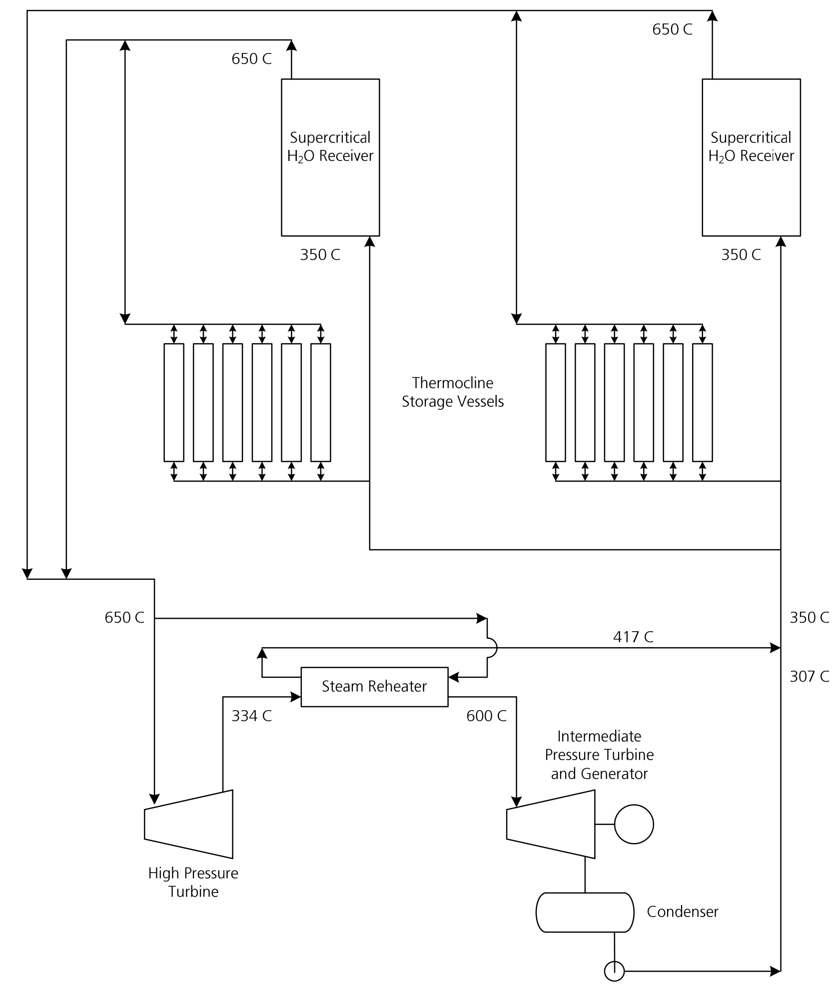

Figure 27 High Temperature Supercritical H_2O Process Flow Diagram

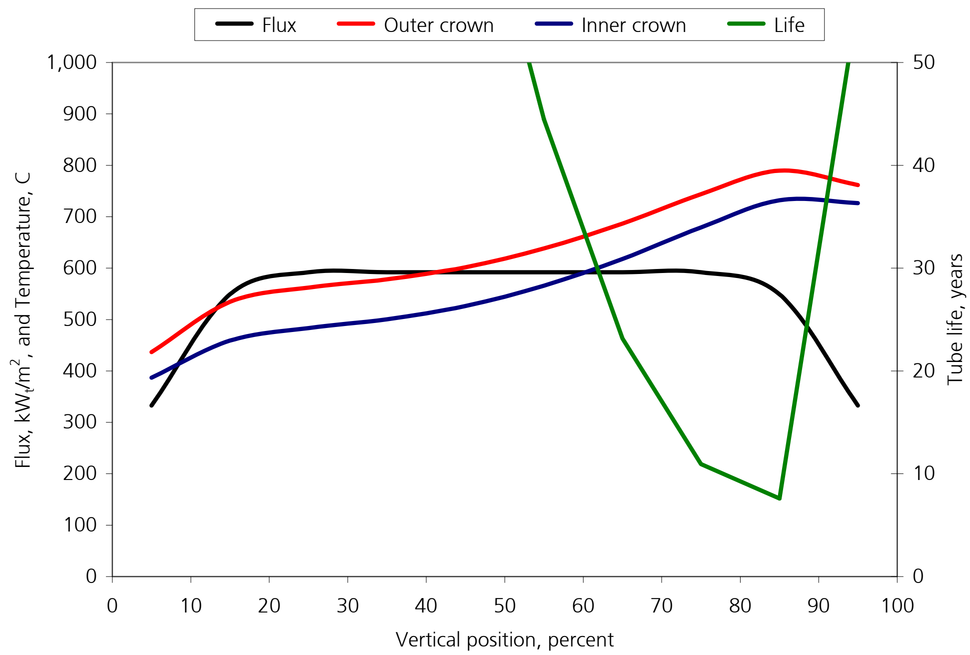

Figure 28 Characteristics of North Panel for High Temperature Supercritical H_2O Receiver

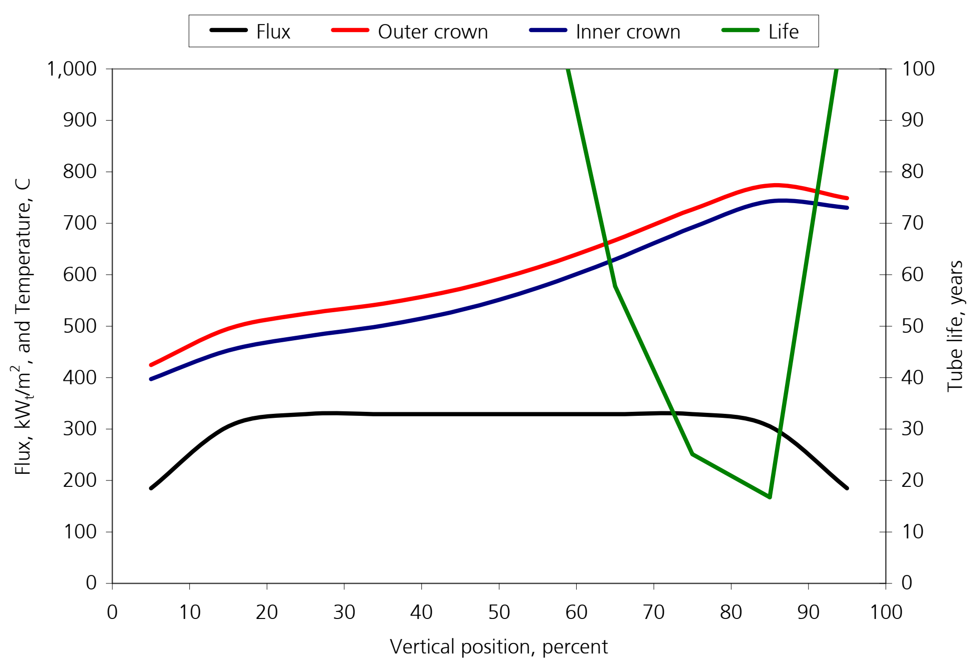

Figure 29 Characteristics of South Panel for High Temperature Supercritical H_2O Receiver

3.4.4 RCell Analyses

The RCell calculations showed the following combination of parameters as the optimum: a mirror area of 1,715,800 m^2; an optical tower height of 250 m; absorber diameter of 22.0 m; and absorber height of 36.5 m. The distribution of heliostats within the collector field is illustrated in Table 11, and the heliostat field efficiency matrix is shown in Table 12.

Table 11 Heliostat Distribution in High Temperature Supercritical H_2O Plant

0.0	0.0	0.0	0.0	0.0	0.0	5.9	13.8	5.9	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	32.1	61.1	75.3	76.5	75.3	61.1	32.1	0.0	0.0	0.0	0.0
0.0	0.0	3.1	51.5	78.8	86.1	91.4	93.4	91.4	86.1	78.8	51.5	3.1	0.0	0.0
0.0	0.0	49.1	81.3	93.1	105.0	114.2	117.7	114.2	105.0	93.1	81.3	49.1	0.0	0.0
0.0	18.4	78.4	92.9	110.6	130.0	146.0	114.1	146.0	130.0	110.6	92.9	78.4	18.4	0.0
0.0	37.5	85.4	104.5	129.9	159.6	182.3	188.6	182.3	159.6	129.9	104.5	85.4	37.5	0.0
0.0	46.6	90.4	113.5	146.6	187.2	209.5	236.3	209.5	187.2	146.6	113.5	90.4	46.6	0.0
0.0	43.8	92.2	116.9	154.2	205.3	226.1	Tower	226.1	205.3	154.2	116.9	92.2	43.8	0.0
0.0	30.1	90.0	113.1	147.7	149.3	234.0	249.6	234.0	149.3	147.7	113.1	90.0	30.1	0.0
0.0	2.7	74.7	77.6	129.9	165.8	206.2	226.4	206.2	165.8	129.9	77.6	74.7	2.7	0.0
0.0	0.0	27.6	91.5	109.3	130.0	149.4	158.0	149.4	130.0	109.3	91.5	27.6	0.0	0.0
0.0	0.0	0.0	28.1	80.8	103.0	112.5	116.3	112.5	103.0	80.8	28.1	0.0	0.0	0.0
0.0	0.0	0.0	0.0	7.5	40.4	59.0	61.4	59.0	40.4	7.5	0.0	0.0	0.0	0.0

Table 12 Field Efficiency Matrix for High Temperature Supercritical H_2O Receiver

AZ / EL	0.000	0.170	0.340	0.510	0.670	0.840	1.000
0.000	0.61528	0.60465	0.60248	0.59933	0.59691	0.58842	0.57973
0.167	0.61181	0.60129	0.59940	0.59651	0.59464	0.58644	0.57797
0.333	0.60292	0.59286	0.59123	0.58853	0.58789	0.58037	0.57133
0.500	0.58730	0.57772	0.57646	0.57514	0.57531	0.56422	0.55500
0.667	0.56253	0.55350	0.55227	0.55106	0.54715	0.53425	0.52415
0.833	0.50440	0.49643	0.49600	0.49429	0.48818	0.47139	0.46305
1.000	0.35862	0.35388	0.35286	0.36015	0.37636	0.37883	0.37709

3.4.5 Thermocline Storage

Thermocline Model

The temperatures of the fluid and the inventory, as a function of time and location within the bed, were estimated using the Schumann model for heat transfer in a packed bed. The coupled partial differential equations are as follows:

$$(\rho\, c_p)_f\ \varepsilon\ \frac{\partial T_p}{\partial \tau} = \frac{(m c_p)_f}{A}\ \frac{\partial T_p}{\partial x} + h_v (T_b - T_f)$$

$$(\rho\, c_p)_b\ (1-\varepsilon)\ \frac{\partial T_b}{\partial \tau} = h_v (T_f - T_b)$$

In the equations

- r is density (kg/m^3)
- c_p is specific heat (kJ/kg-C)
- e is the void fraction of the bed
- T is temperature (C)
- t is time (sec)
- A is the cross section area of the tank (m^2)
- x is the vertical location within the bed (m)
- the subscript 'f' represents the fluid
- the subscript 'b' represents the bed.

The volumetric heat transfer coefficient, h_v, is given by the following: h_v = 6 h (1-□) S / D_{part}, where

- S is the particle shape factor; for spheres, the factor is 1.0.
- D_{part} is the particle diameter (m)
- h = 1.625 Re $^{0.493}$ Pr $^{1/3}$ k_f / D_{part} for Re < 120
- h = 0.687 Re $^{0.673}$ Pr $^{1/3}$ k_f / D_{part} for Re > 120.
- Re is Reynolds number for the flow inside the tank (VD/n)
- V is the simple salt velocity based on the diameter of an empty tank (m/sec)
- D is the diameter of the tank (m)
- n is the kinematic viscosity of the salt (m^2/sec)
- Pr is the Prandtl number for the fluid ($c_p\mu$/k)
- k is the thermal conductivity of the fluid (W/m-C).

The equations were solved numerically using the modified Euler's method, which calculated the slope of the fluid and bed temperature functions at each time step to predict the temperatures at the next time step. Using the predicted fluid and bed temperatures, the slopes of the temperature functions were then recalculated to improve the accuracy of the predictions.

<u>Temperature Profiles with Nitrate Salt</u>

An example of the temperature profiles established in a thermocline bed after a series of complete charge / discharge cycles is shown in Figure 30. At 0 hours, the vessel is fully charged, as shown by the '0 hour' profile. At the bottom of the vessel, the temperature is 465 °C. Moving up through the bed, the temperature increases, reaching a maximum value of 670 °C at a height of 6 m. The temperature is a uniform value of 670 °C from 6 m to the top of the vessel at 14 m.

The vessel is discharged over a period of 6 hours. At this time, the temperature of the bed is 370 °C from the bottom of the vessel to an elevation of 10 m. From 10 m to the top of the vessel, the bed temperature increases essentially linearly to a value of 560 °C. The quantity of energy stored is effectively the space between the 0 hour and the 6 hour curves.

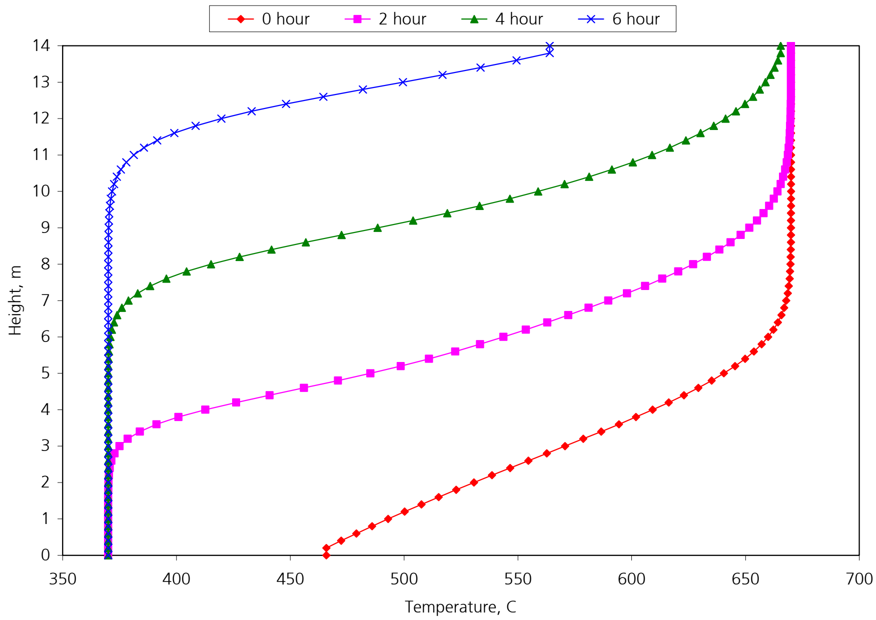

Figure 30 Representative Temperature Profile in Thermocline Vessel

A principal feature of the thermocline is the stability of the curves. As long as the system proceeds through full charge / discharge cycles, the temperature profiles in successive cycles overlap the profiles from the previous cycles.

Temperature Profiles with Supercritical H_2O

Starting with a bed at a uniform temperature of 500 °C, the temperature profile after one complete charge / discharge cycle, using supercritical H_2O as the heat transport fluid, is shown in Figure 31. The temperature profiles are nominally similar to those shown in Figure 30 for a nitrate salt thermocline.

After a second complete charge / discharge cycle, the temperature profile is as shown in Figure 32. Two important changes have occurred in the profiles, as follows:

1) The fluid outlet temperature at the end of the discharge cycle (6 hour curve) has not decayed from the design value of 700 °C. This is an ideal situation, in the sense that a uniform temperature is maintained throughout the discharge process.

2) In contrast, the fluid temperature rise at the end of the charge cycle (0 hour curve) is very large. This is an undesirable characteristic, as heat is not being transferred from the fluid to the bed.

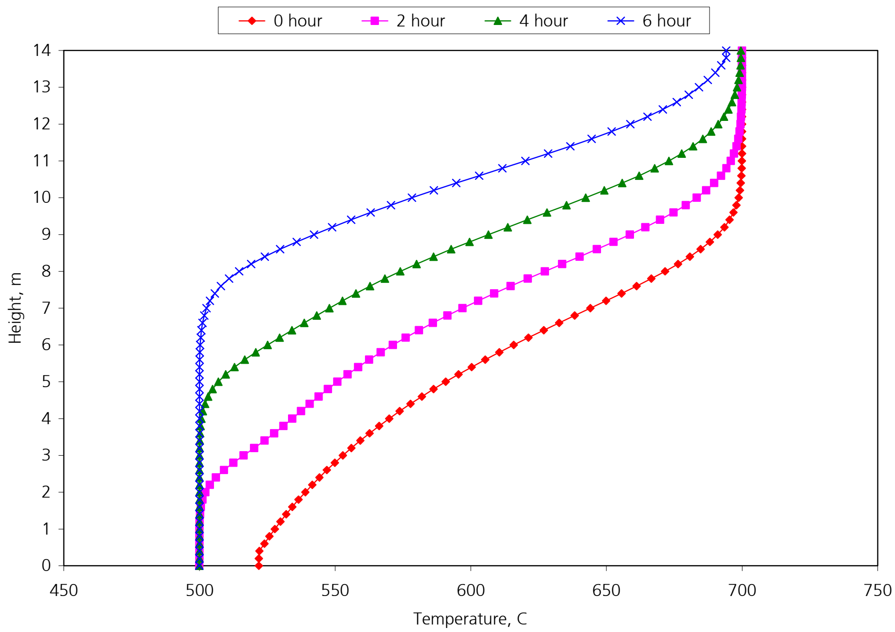

Figure 31 Temperature Profile in Supercritical H_2O Thermocline Vessel - First Cycle

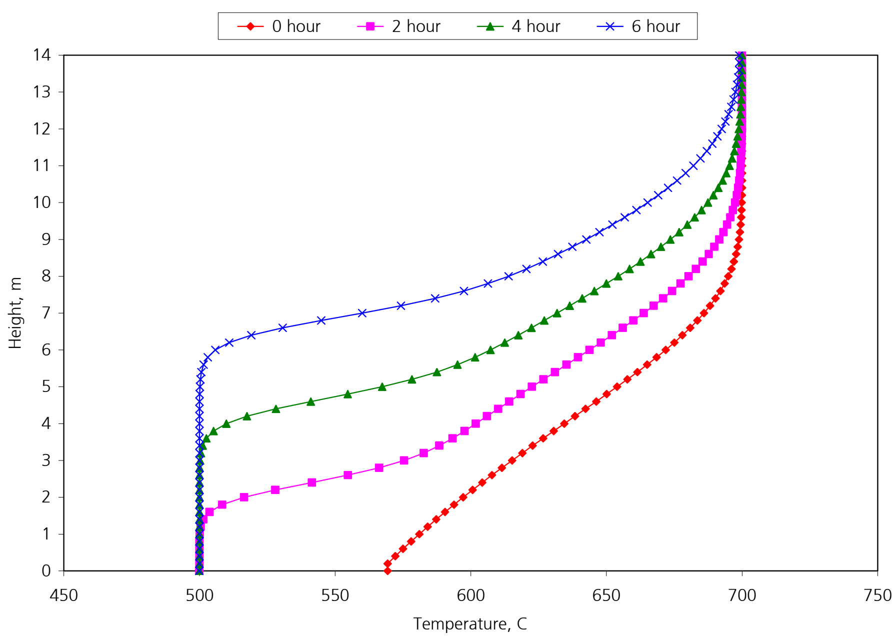

Figure 32 Temperature Profile in Supercritical H_2O Thermocline Vessel - Second Cycle

After a third complete charge / discharge cycle, the temperature profile is as shown in Figure 33. The fluid temperature remains constant throughout the discharge cycle; however, the temperature rise at the end of the charge cycle is more pronounced.

After a fourth complete charge / discharge cycle, the temperature profile is as shown in Figure 34. As with the second and third cycles, the fluid temperature remains constant throughout the discharge cycle. However, the outlet temperature rise at the end of the charge cycle is approaching the normal charging temperature. As such, there is limited energy transfer to the bed, as the temperature difference between the fluid and the bed is approaching 0 °C. Also, the discharge temperature profile (6 hour curve) is moving toward the bottom of the bed. Since the storage capacity is represented by the difference between the 0 hour and the 6 hour curves, the effective storage capacity is simultaneously decreasing. It is anticipated after perhaps 20 complete charge / discharge cycles, the temperature profiles will merge into one vertical line at 700 °C on the abscissa, and the storage system will no longer function.

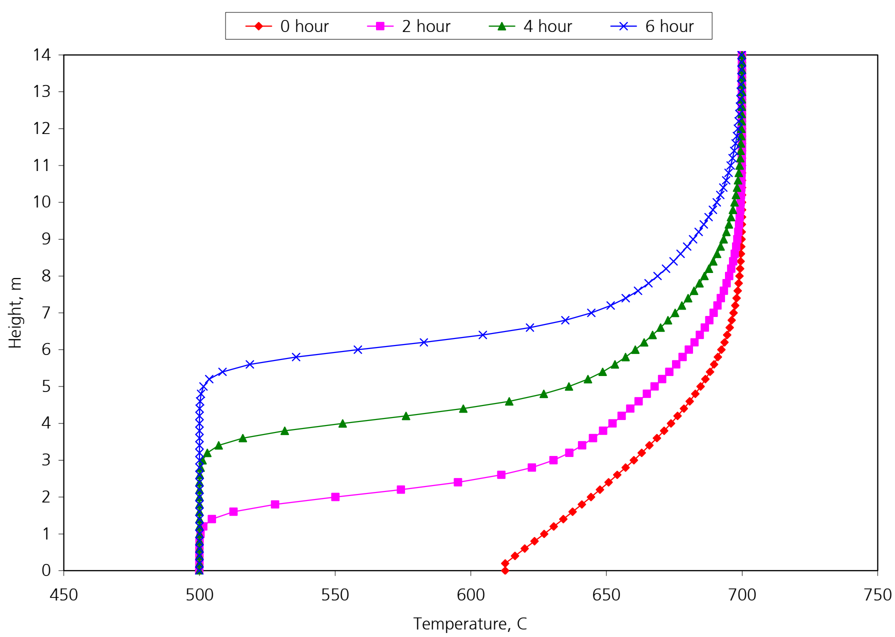

Figure 33 Temperature Profile in Supercritical H_2O Thermocline Vessel - Third Cycle

Analysis of Heat Transfer in Bed

In a packed bed, the energy stored is function of the enthalpy change, while the energy transferred is a function of the temperature difference and residence time. At a pressure of 310 bar, the specific heat and enthalpy of supercritical H_2O as functions of temperature are shown in Table 13.

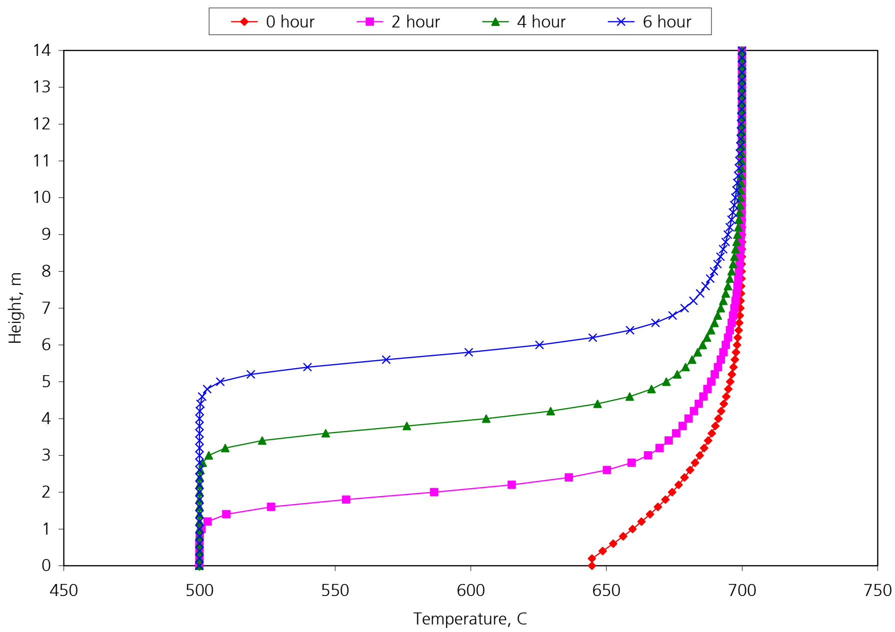

Figure 34 Temperature Profile in Supercritical H_2O Thermocline Vessel - Fourth Cycle

<u>Discharge Cycle - Bottom of the Bed</u> For the purposes of the discussion which follows, and to keep the arithmetic simple, the mass * specific heat of the fluid is assumed to be the same as the mass * specific heat of the bed *at the bottom of the bed*. During a discharge cycle, fluid enters the bottom of the bed at a temperature of 500 °C, and comes in contact with the a portion of the bed at, for example, 520 °C. When the heat transfer is complete, the fluid and bed temperature are both 510 °C. The energy transferred is 42.9 kJ (i.e., 4.29 kJ/C * 10 °C), with an average temperature difference of 10 °C. The 510 °C fluid then moves further up the bed, and the heat transfer process is repeated.

At the next elevation, the fluid temperature is 510 °C and the bed temperature is 530 °C. Since the fluid velocity everywhere in the tank is the same, the residence time at each elevation is the same. To a first order, the heat transfer coefficient is nominally independent of the fluid properties. However, the energy transferred is no longer 42.9 kJ. The specific heat of the fluid has decreased, but specific heat of the bed has not. For a given quantity of energy to be transferred, the delta T of the fluid must increase as the inverse of the specific heat. However, the maximum allowable delta T of the fluid is constrained; the final fluid temperature cannot be greater than the final bed temperature. If 1 kg of fluid at 510 °C mixes with 1 kg of bed at 530 °C, the initial fluid energy is 3,111 kJ, the initial bed energy is 2,339 kJ (based on 4.41 kJ/kg-C * 530 °C), and the final fluid + bed energy is 5,450 kJ. Solving for the mixed temperature yields a value of 520.4 °C, and an energy transfer of 42.4 kJ. Several items become apparent, as follows:

1) The mixed fluid temperature is higher than in a perfect thermocline (i.e., 520.4 °C, rather than 520.0 °C), the temperature difference between the initial bed and the final fluid is less (i.e., 9.6 °C, rather than 10.0 °C), and the energy transferred is less (42.4 kJ, rather than 42.9 kJ).

Table 13 Specific Heat and Enthalpy of Supercritical H_2O at 310 Bar

Fluid temperature, C	Specific heat, kJ/kg-C	Enthalpy, kJ/kg	ΔH / °C
450	7.03	2,797	------
460	6.15	2,863	6.57
470	5.52	2,921	5.82
480	5.05	2,974	5.28
490	4.69	3,023	4.87
500	4.41	3,068	4.55
510	4.18	3,111	4.29
520	4.00	3,152	4.09
530	3.84	3,191	3.92
540	3.70	3,229	3.77
550	3.59	3,265	3.64
560	3.48	3,301	3.53
570	3.40	3,335	3.44
580	3.32	3,369	3.36
590	3.25	3,401	3.28
600	3.19	3,434	3.22
610	3.14	3,465	3.16
620	3.09	3,496	3.11
630	3.05	3,527	3.07
640	3.01	3,557	3.03
650	2.98	3,587	3.00
660	2.95	3,617	2.97
670	2.93	3,647	2.94
680	2.91	3,676	2.92
690	2.89	3,705	2.90
700	2.87	3,733	2.88
710	2.85	3,762	2.86
720	2.84	3,790	2.85
730	2.82	3,819	2.83
740	2.81	3,847	2.82
750	2.80	3,875	2.81

2) Since the specific heat of the fluid continues to decrease as the fluid temperature increases, the trend continues as the fluid moves up the bed.

3) The bed temperature at the '520 °C elevation' is no longer 520.0 °C as in a perfect thermocline. It is now 520.4 °C. The process will then compound on the next charge cycle, since the bed starting point is 520.4 °C, rather than 520.0 °C. The effect is illustrated in Figures 31 and 32. The only mechanism for controlling the bed temperature profile is to push the thermocline zone out the top at the end of a charge cycle, and out the bottom on the end of a discharge cycle. If the bed temperature at the bottom is increasing on successive discharge cycles, the temperature of the fluid exiting the bed at the end of the discharge cycle

should also increase. This is shown on Figure 31, where the red line intersects the abscissa at about 520 °C, and then in Figure 32, where the red line intersects at about 570 °C.

Discharge Cycle - Top of the Bed   During a discharge cycle, fluid flows near the top of the bed at a temperature of, for example, 680 °C, and comes in contact with a portion of the bed at 700 °C. If 1 kg of fluid at 680 °C mixes with 1 kg of bed at 700 °C, the initial fluid energy is 3,676 kJ, the initial bed energy is 3,089 kJ (based on 4.41 kJ/kg-C * 700 °C), and the final fluid + bed energy is 6,764 kJ. Solving for the mixed temperature yields a value of 692.1 °C, and an energy transfer of 35.0 kJ. However, this is a particularly disruptive process for a thermocline. The theoretically perfect bed temperature is 690.0 °C, but with these simplified heat transfer parameters, it is 692.1 °C. During the next charge cycle, the fluid enters the top of the tank at 700 °C. However, rather than transferring energy to a bed at a temperature of 690.0 °C, the heat transfer is to a bed at 692.1 °C. As such, the energy transfer is less than a theoretical thermocline. Further, the temperature at the top of the bed continues to increase through repeated charge / discharge cycles, as shown in the (near) vertical red line in Figure 34.

The principal mechanism for the nonuniformity in the bed temperature profiles during repeated charge / discharge cycles is that the specific heat of the fluid changes with time and vertical position, while the specific heat of the bed is independent of time and position. If, by some coincidence, a bed temperature profile could be established on the first cycle which represented the profile on the N^{th} cycle, the variable specific heat of the fluid would not make any difference to the temperature profiles. However, the basic heat transfer processes for establishing a temperature profile are unstable, and even an N^{th} cycle profile would be disrupted by operating through a partial charge / discharge cycle.

Thermocline calculations using nitrate salt and supercritical CO_2, both of which have nominally constant specific heats, exhibit repeatable temperature profiles over dozens of cycles. Since the only difference between these fluids and supercritical H_2O is the variable specific heat of the latter, the use of supercritical H_2O as a heat transport fluid in a packed bed thermocline was judged to be infeasible. As such, the high temperature supercritical H_2O plant design was also considered infeasible.

3.5 Low Temperature Supercritical CO_2

3.5.1 Rankine Cycle

The process flow diagram for the low temperature supercritical CO_2 plant is shown in Figure 35. The basic design parameters are the same as those in the low temperature supercritical H_2O plant, with the following changes:

- The receiver coolant is CO_2, rather than H_2O
- The receiver outlet temperature is reduced from 675 °C in the low temperature supercritical H_2O plant to 620 °C in the low temperature supercritical CO_2 plant. The specific heat for supercritical CO_2 is nominally independent of temperature. As a result, the temperature profiles in the supercritical CO_2-to-salt heat exchanger are parallel lines, as shown in Figure 36, and the

approach temperatures at each end of the heat exchanger are maintained along the full tube length.

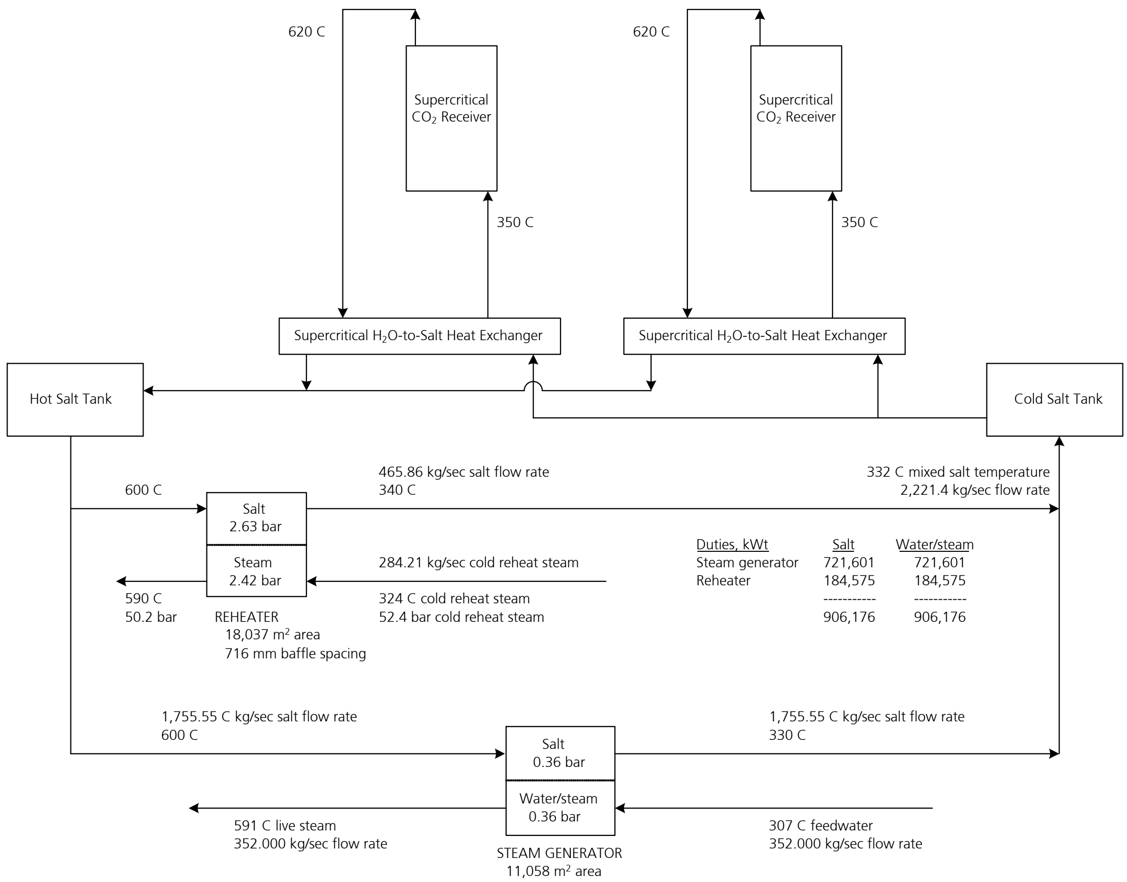

Figure 35 Low Temperature Supercritical CO_2 Process Flow Diagram

3.5.2 Receiver Design Parameters

A conceptual low temperature supercritical CO_2 receiver design has been assembled around the following parameters:

- 812 MWt net output power at noon on the vernal equinox
- Fluid inlet and outlet temperatures of 350 °C and 620 °C, respectively
- Tube diameters to provide an acceptable compromise between pressure loss and fatigue life
- 24 panels in parallel

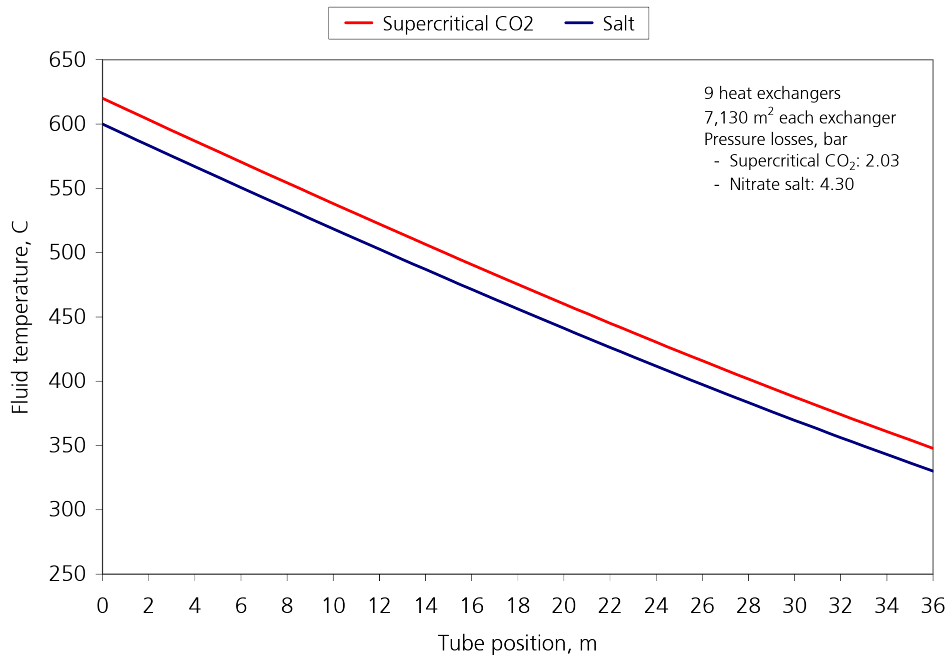

Figure 36 Temperature Profile in Low Temperature Supercritical CO_2-to-Salt Heat Exchanger

- North-to-South incident panel power ratio of 1.9 at noon on the vernal equinox
- Incident flux on the center 75 percent of the panel equal to the peak flux. Between the center portion of the flux profile and the top and bottom of the panel, the flux tapered linearly to the edge value. On the North panel, the edge value was 160 kWt/m^2. For the balance of the panels, the edge values were proportional to the peak flux for that panel divided by the peak flux for the North panel [10].

Through a series of iterations among tube dimensions, peak incident fluxes, absorber diameter, and absorber height, the following design parameters were adopted:

- Absorber diameter and height of 22.0 m and 33.0 m, respectively
- 85 tubes per panel; the tube outside diameter is 32.0 mm, and the wall thickness is 2.16 mm
- A peak flux of 693 kWt/m^2 on the North panel, decreasing to 385 kWt/m^2 on the South.

The receiver thermal efficiency is 0.833, and the highest pressure loss is 4.11 bar in the North panel.

A plot of the temperature profile within the North panel is shown in Figure 37. Note that at a vertical position of about 75 percent of the panel height, the combination of tube temperatures

[10] Conversation with Lorin Vant-Hull, University of Houston, August 22, 2009

and incident flux reach a maximum. At this location, the local fatigue life of the tube reaches a minimum of about 7 years.

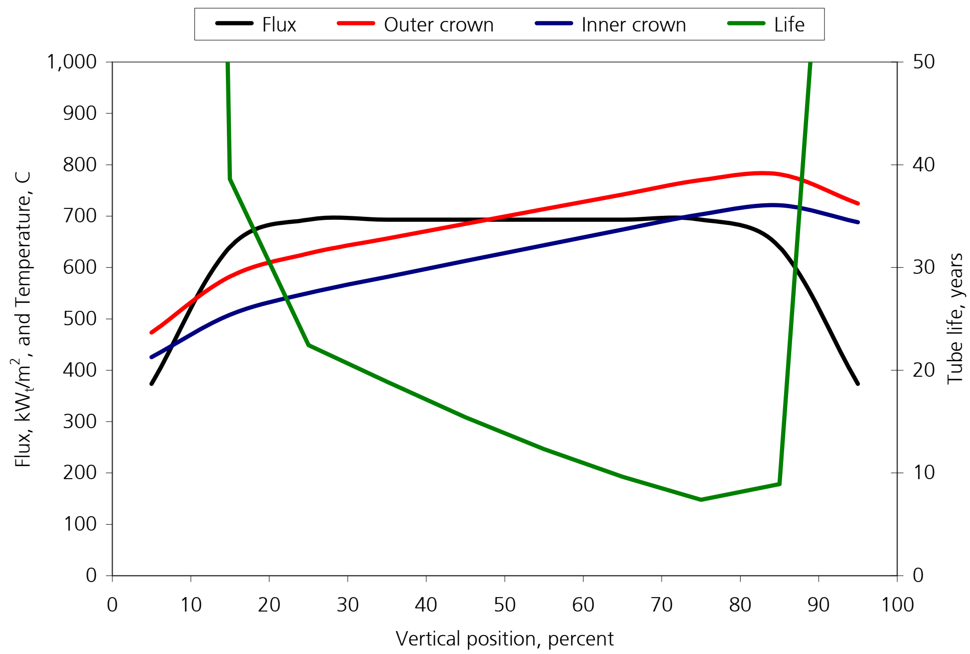

Figure 37 Characteristics of North Panel for Low Temperature Supercritical CO_2 Receiver

The corresponding profiles for the South panel are shown in Figure 38. The incident fluxes are slightly more than one-half of those on the North panel, which increases the local fatigue life to about 27 years.

The heat transfer characteristics of supercritical CO_2 are similar enough to supercritical H_2O that the receiver design parameters, such as allowable flux, fatigue life, and thermal efficiency, are comparable.

One important difference between the supercritical CO_2 and the supercritical H_2O plants is the lower density of supercritical CO_2 at the receiver inlet conditions; approximately 130 kg/m^3 for CO_2, and 660 kg/m^3 for H_2O. As a result, for each bar of pressure loss in the receiver circuit, the circulation pump power requirements for the supercritical CO_2 receiver are about 4 times those for the supercritical H_2O receiver. At the flow rates of interest, the power requirements for the CO_2 circulation pumps can easily reach a rather daunting 20 MWe for each tower.

A corollary to the relatively low density for supercritical CO_2 is the large diameters required for the riser and downcomer piping. Due to the very high cost for circulation, relatively low velocities have been adopted for the tower vertical piping. With an assumed velocity of 12 m/sec in the riser and 14 m/sec in the downcomer, the calculated riser and downcomer diameters are 54 in. and 62 in.,

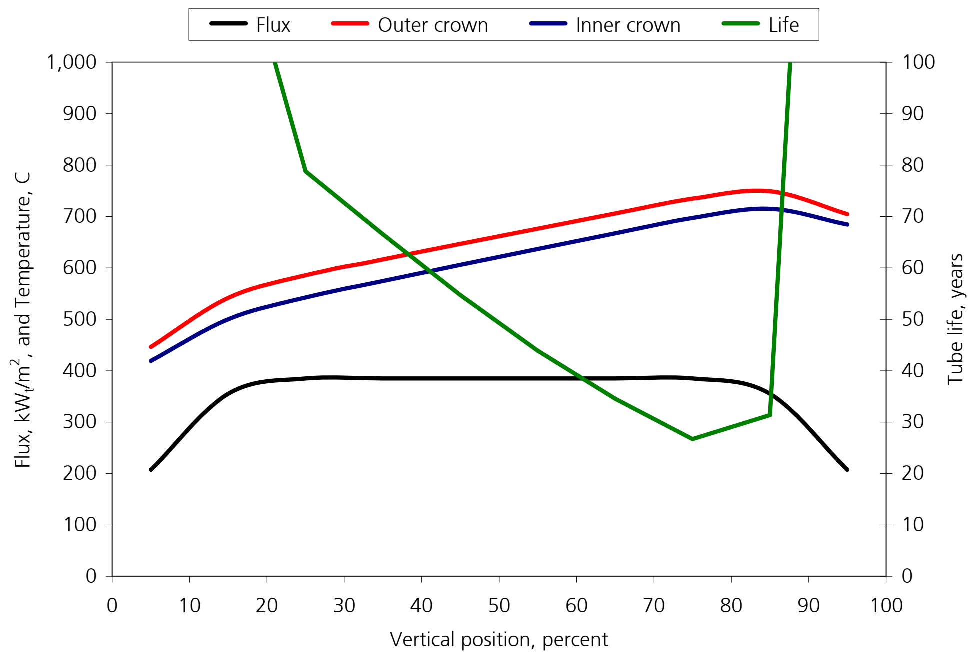

Figure 38 Characteristics of South Panel for Low Temperature Supercritical CO_2 Receiver

respectively. However, the largest commercial pipe which can accommodate the 150 bar pressures required is a 24 in. line. As such, the riser consists of five 24-in. Sch 120 lines, while the downcomer requires seven 24-inch Sch 140 pipes. The mass of stainless steel in the downcomers is some 2,700 metric tons, and to a first order, the cost of the tower vertical piping is on a par with the cost of the receiver.

3.5.3 RCell Analyses

The RCell calculations showed the following combination of parameters as the optimum: a mirror area of 1,780,996 m^2; an optical tower height of 210 m; absorber diameter of 22.0 m; and absorber height of 33.0 m. The distribution of heliostats within the collector field is illustrated in Table 14, and the heliostat field efficiency matrix is shown in Table 15.

Due to the high cost of the CO_2 piping in the tower, the optimum tower height is 210 m, which is well below the optimum height of 260 m for the baseline nitrate salt plant. A direct consequence of a lower tower height is a somewhat lower optical efficiency for the collector field, as shown by a comparison of the field efficiency matrices in Table 8 and Table 15.

An elevation view of the receiver tower is shown in Figure 39. As an illustration of the differences in the optimum tower design resulting from differences in receiver cost and vertical piping cost, a comparison of the towers for the baseline nitrate salt plant and the low temperature supercritical CO_2 plant is shown in Figure 40.

Table 14 Heliostat Distribution in Low Temperature Supercritical CO_2 Plant

0.0	0.0	0.0	0.0	0.0	2.4	12.9	15.8	12.9	2.4	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	11.1	35.9	51.9	53.6	54.2	53.6	51.9	35.9	11.1	0.0	0.0	0.0
0.0	0.0	22.3	52.4	56.6	60.3	62.9	63.8	62.9	60.3	56.6	52.4	22.3	0.0	0.0
0.0	20.8	53.5	59.5	65.7	71.5	75.6	77.2	75.6	71.5	65.7	59.5	53.5	20.8	0.0
3.4	51.2	59.4	67.8	77.2	86.6	93.8	96.6	93.8	86.6	77.2	67.8	59.4	51.2	3.4
22.4	56.5	65.7	77.3	91.4	106.9	120.0	93.9	120.0	106.9	91.4	77.3	65.7	56.5	22.4
35.1	60.1	71.5	86.9	107.5	132.5	154.5	162.6	154.5	132.5	107.5	86.9	71.5	60.1	35.1
41.8	62.7	75.8	94.6	122.0	158.9	191.0	228.1	191.0	158.9	122.0	94.6	75.8	62.7	41.8
39.0	63.6	77.4	97.8	129.3	176.1	208.7	Tower	208.7	176.1	129.3	97.8	77.4	63.6	39.0
29.4	62.6	75.9	95.1	124.5	127.0	206.8	215.3	206.8	127.0	124.5	95.1	75.9	62.6	29.4
11.8	60.0	71.5	43.7	109.9	140.8	175.6	192.9	175.6	140.8	109.9	43.7	71.5	60.0	11.8
0.0	36.6	65.5	77.6	92.8	110.7	127.4	134.8	127.4	110.7	92.8	77.6	65.5	36.6	0.0
0.0	2.6	45.9	67.8	77.6	87.8	96.1	99.3	96.1	87.8	77.6	67.8	45.9	2.6	0.0
0.0	0.0	2.6	38.9	65.5	71.5	76.0	77.7	76.0	71.5	65.5	38.9	2.6	0.0	0.0
0.0	0.0	0.0	0.0	15.9	34.8	45.8	47.0	45.8	34.8	15.9	0.0	0.0	0.0	0.0

Table 15 Field Efficiency Matrix for Low Temperature Supercritical CO_2 Receiver

AZ / EL	0.000	0.170	0.340	0.510	0.670	0.840	1.000
0.000	0.59082	0.58014	0.57761	0.57592	0.57526	0.56756	0.55929
0.167	0.58741	0.57685	0.57519	0.57354	0.57302	0.56518	0.55742
0.333	0.57951	0.56941	0.56827	0.56651	0.56655	0.55954	0.55131
0.500	0.56636	0.55655	0.55570	0.55434	0.55513	0.54593	0.53806
0.667	0.54473	0.53551	0.53444	0.53315	0.53065	0.52029	0.51196
0.833	0.49528	0.48699	0.48631	0.48575	0.48129	0.46828	0.46119
1.000	0.36914	0.36187	0.36225	0.36963	0.38331	0.38576	0.38551

3.5.4 Thermal Storage System

The thermal storage system for the low temperature supercritical CO_2 plant is identical to that for the supercritical nitrate salt and the low temperature supercritical H_2O plants.

3.6 High Temperature Supercritical CO_2

3.6.1 Rankine Cycle

The Rankine cycle for the high temperature supercritical CO_2 plant is identical to that for the high temperature supercritical H_2O plant.

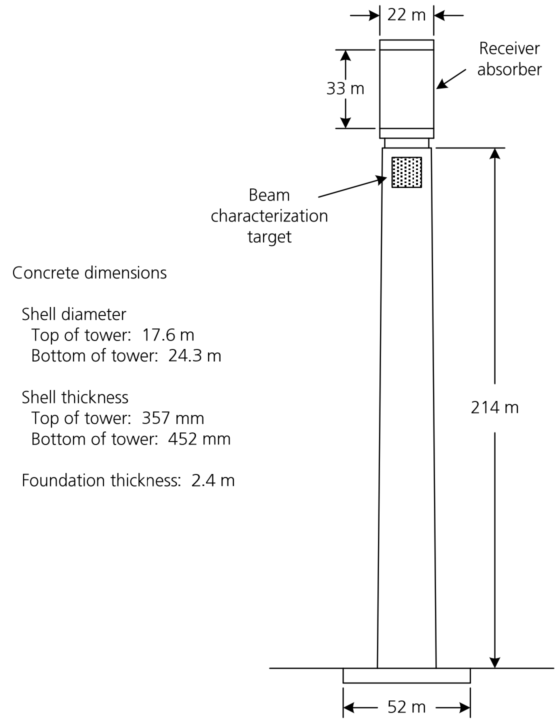

Figure 39 Tower and Foundation Dimensions for Low Temperature Supercritical CO_2 Receiver

3.6.2 Process Flow Diagram

The process flow diagram for the high temperature supercritical CO_2 plant is shown in Figure 41. The basic design parameters are the same as those in the high temperature supercritical H_2O plant, with one principal exception. Due to the very high cost of supercritical CO_2 piping, heat is transported between the towers and the central power block by means of supercritical H_2O. As such, there is a supercritical CO_2-to-supercritical H_2O steam generator located at the base of each tower.

As with the other supercritical H_2O heat exchangers described above, the variable specific heat of the supercritical H_2O produces a non-linear temperature profile in the supercritical CO_2 steam generator. A plot of the fluid temperatures along the length of the heat exchanger is shown in Figure 42. To maintain a reasonable temperature difference along the full length of the tube, receiver inlet and outlet temperatures of 370 °C and 670 °C, respectively, were selected for the performance calculations.

3.6.3 Receiver Design Parameters

A conceptual high temperature supercritical CO_2 receiver design has been assembled around the following parameters:

- 804 MWt net output power at noon on the vernal equinox

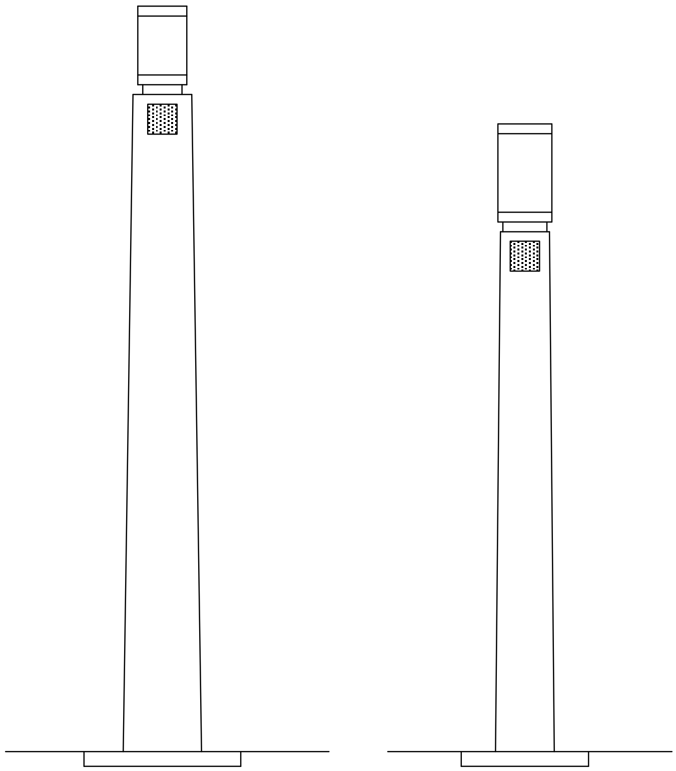

Figure 40 Comparison of Baseline Salt and Low Temperature Supercritical CO_2 Towers

- Fluid inlet and outlet temperatures of 370 °C and 670 °C, respectively

The balance of the parameters are the same as those for the low temperature supercritical CO_2 receiver.

Through a series of iterations among tube dimensions, peak incident fluxes, absorber diameter, and absorber height, the following design parameters were adopted:

- Absorber diameter and height of 20.8 m and 33.0 m, respectively
- 85 tubes per panel; the tube outside diameter is 32.0 mm, and the wall thickness is 2.16 mm
- A peak flux of 657 kWt/m^2 on the North panel, decreasing to 364 kWt/m^2 on the South.

The receiver thermal efficiency is 0.815, and the highest pressure loss is 4.24 bar in the North panel.

A plot of the temperature profile within the North panel is shown in Figure 43. Note that at a vertical position of about 75 percent of the panel height, the combination of tube temperatures and incident flux reach a maximum. At this location, the local fatigue life of the tube reaches a minimum of about 5 years.

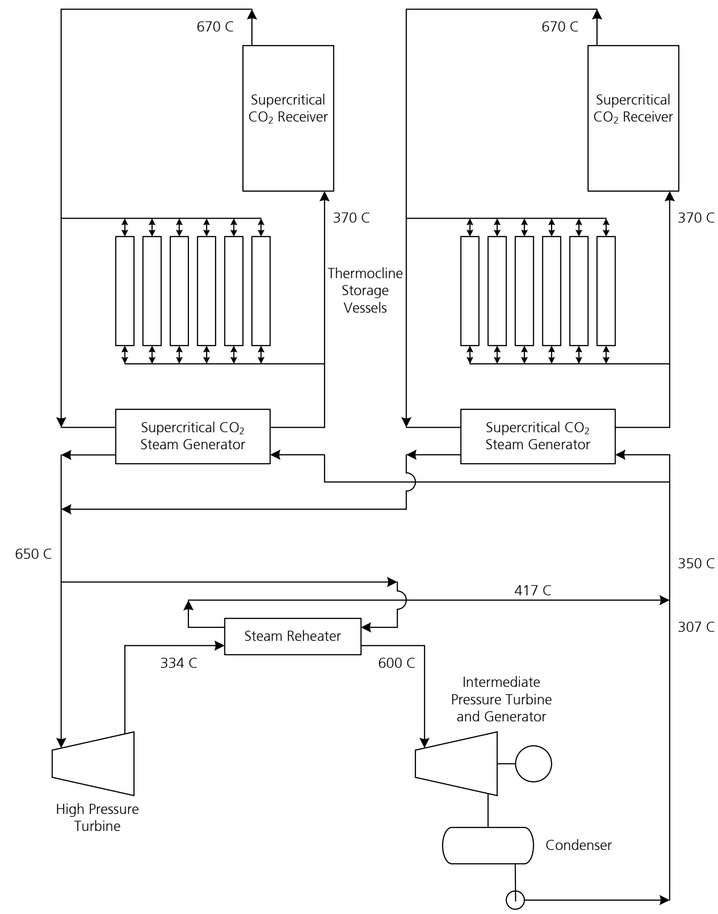

Figure 41 High Temperature Supercritical CO_2 Process Flow Diagram

The corresponding profiles for the South panel are shown in Figure 44 The incident fluxes are slightly more than one-half of those on the North panel, which increases the local fatigue life to about 18 years.

As with the low temperature supercritical CO_2 receiver, the relatively low density of the supercritical CO_2 in the high temperature case leads to comparable circulation pump and vertical piping designs, as follows:

- Two 50-percent capacity circulation pumps at each tower, each with a power demand of 19,950 kWe
- Five risers, each 24-in. Sch 140 carbon steel pipe
- 6 downcomers, each 24-in. stainless steel pipe, with a specialty wall thickness of 73.5 mm.

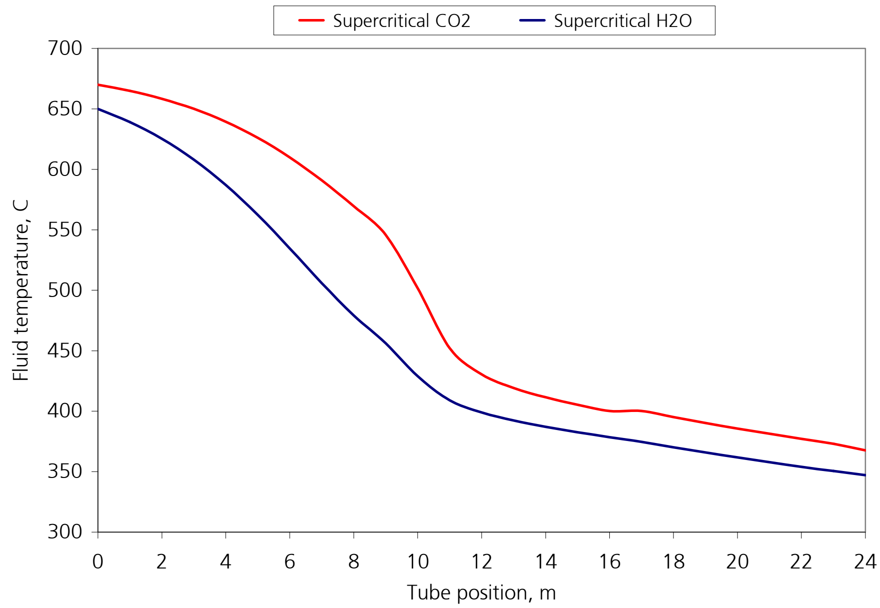

Figure 42 Temperature Profile in Supercritical CO_2-to-Supercritical Steam Generator

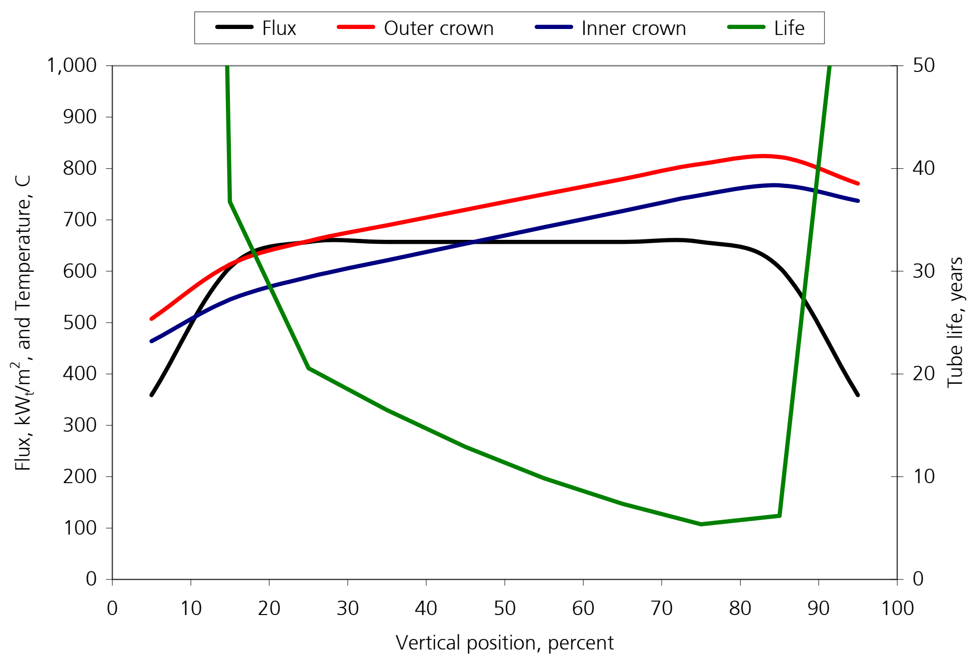

Figure 43 Characteristics of North Panel for High Temperature Supercritical CO_2 Receiver

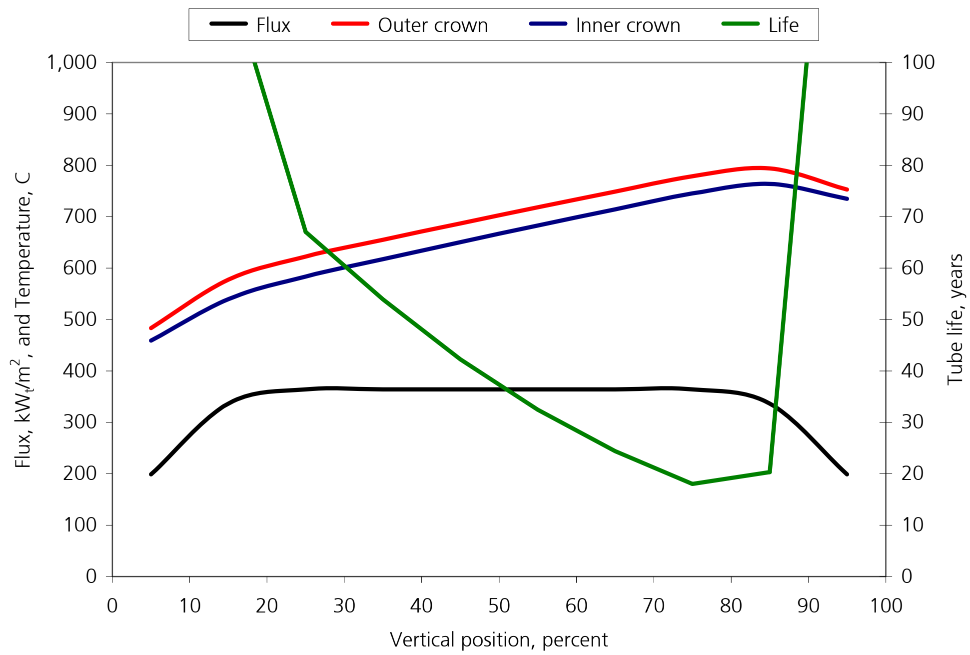

Figure 44 Characteristics of South Panel for High Temperature Supercritical CO_2 Receiver

3.6.4 RCell Analyses

The RCell calculations showed the following combination of parameters as the optimum: a mirror area of 1,774,300 m^2; an optical tower height of 210 m; absorber diameter of 24.0 m; and absorber height of 33.0 m. The distribution of heliostats within the collector field is illustrated in Table 16, and the heliostat field efficiency matrix is shown in Table 17.

Table 16 Heliostat Distribution in High Temperature Supercritical CO_2 Plant

0.0	0.0	0.0	0.0	0.0	9.1	19.0	21.6	19.0	9.1	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	16.7	39.2	52.1	53.7	54.3	53.7	52.1	39.2	16.7	0.0	0.0	0.0
0.0	0.0	27.1	52.5	56.7	60.3	62.8	63.7	62.8	60.3	56.7	52.5	27.1	0.0	0.0
0.0	25.6	53.4	59.4	65.6	71.2	75.3	76.9	75.3	71.2	65.6	59.4	53.4	25.6	0.0
9.3	52.2	59.3	67.6	76.8	86.0	93.0	95.8	93.0	86.0	76.8	67.6	59.3	52.2	9.3
26.2	56.3	65.3	76.8	90.6	105.8	118.5	92.7	118.5	105.8	90.6	76.8	65.3	56.3	26.2
37.2	59.8	71.0	86.1	106.2	130.7	152.3	160.3	152.3	130.7	106.2	86.1	71.0	59.8	37.2
42.5	62.2	75.1	93.5	120.5	156.8	187.0	205.5	187.0	156.8	120.5	93.5	75.1	62.2	42.5
39.3	63.1	76.6	96.7	127.6	173.8	206.8	Tower	206.8	173.8	127.6	96.7	76.6	63.1	39.3
30.2	62.0	75.0	93.9	122.8	125.4	206.9	209.1	206.9	125.4	122.8	93.9	75.0	62.0	30.2
14.1	59.3	70.7	64.7	108.4	138.8	173.3	190.7	173.3	138.8	108.4	64.7	70.7	59.3	14.1
0.0	35.0	64.7	76.5	91.5	109.1	125.5	132.8	125.5	109.1	91.5	76.5	64.7	35.0	0.0
0.0	4.7	42.0	66.8	76.5	86.5	94.6	97.8	94.6	86.5	76.5	66.8	42.0	4.7	0.0
0.0	0.0	4.2	35.2	64.5	70.4	74.8	76.4	74.8	70.4	64.5	35.2	4.2	0.0	0.0
0.0	0.0	0.0	0.0	15.1	31.1	40.4	41.0	40.4	31.1	15.1	0.0	0.0	0.0	0.0

Table 17 Field Efficiency Matrix for High Temperature Supercritical CO_2 Receiver

AZ / EL	0.000	0.170	0.340	0.510	0.670	0.840	1.000
0.000	0.59404	0.58309	0.58049	0.57888	0.57839	0.57171	0.56397
0.167	0.59050	0.57975	0.57810	0.57652	0.57625	0.56942	0.56233
0.333	0.58283	0.57230	0.57140	0.56967	0.57015	0.56408	0.55650
0.500	0.56874	0.55905	0.55880	0.55799	0.55870	0.55042	0.54303
0.667	0.54742	0.53854	0.53800	0.53784	0.53559	0.52474	0.51644
0.833	0.49997	0.49146	0.49110	0.49097	0.48757	0.47450	0.46653
1.000	0.37454	0.36700	0.36690	0.37500	0.38916	0.39254	0.39250

3.6.5 Thermocline Storage

Temperature Profiles with Supercritical CO_2

Unlike supercritical H_2O, the use of supercritical CO_2 as the heat transport fluid in a thermocline results in stable temperature profiles over a series of complete charge / discharge cycles. An example of the temperature profiles, using the 370 °C and 670 °C receiver inlet and outlet temperatures selected for the process flow diagram, is shown in Figure 45.

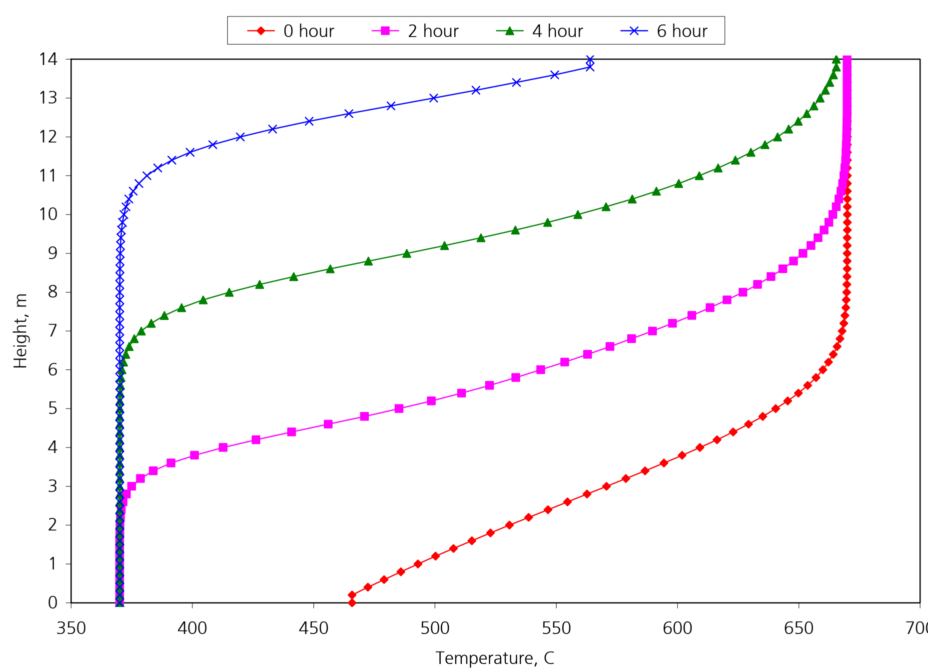

Figure 45 Temperature Profiles in Supercritical CO_2 Thermocline Storage Vessels

The energy utilization is 76 percent, where utilization is defined as the energy extracted during a complete discharge cycle divided by the energy which could be extracted were the entire bed to be cooled to the receiver inlet temperature of 370 °C.

Vessel Design and Arrangement

Since the thermocline vessels operate at a nominal pressure of 150 bar, the least expensive pressure vessel is a commercial section of stainless steel pipe. The largest diameter for which heavy wall pipe is available is 24 inch, and the pipe is available in standard lengths up to 12.2 m (40 ft.). A section of pipe, with a wall thickness of 59.5 mm (Sch 160), is taken to be a standard storage module.

With quartzite as the filler material, the storage capacity of the bed in each vessel is on the order of 0.296 MWht. However, the vessel wall also closely follows the temperature of the bed. As such, the thermal capacity of the vessel itself can be used as a portion of the storage media; this increases the storage capacity of each vessel to about 0.586 MWht.

The required plant storage capacity of 5,357 MWht is divided between the two towers, resulting in 4,600 vessels to be located at each tower. The vessels are divided among 4 quadrants, with 1,200 vessels in each quadrant. Supercritical CO_2 is supplied to 2 adjacent quadrants by a 600 mm hot header at the top of the vessels, and a 600 mm cold header near the bottom. In each quadrant, the vessels are arranged in 40 rows, with 30 vessels in each row. The vessels in each row are supplied by a 38 mm header, stepping down to a 19 mm header. A plan view of the vessel layout within a quadrant is shown in Figure 46, and an elevation view is shown in Figure 47.

Each vessel has an inlet and an outlet isolation valve to be closed in the event of a leak. Since it is essentially impossible to access a vessel for repair or replacement, a vessel is removed from service in the case of a failure. As such, 1,200 vessels are installed in each quadrant, rather than the required number of 1,150, as an allowance for leaks over the life of the project.

Insulating some 4,800 vessels would be a very expensive proposition. In addition, the continuous heat losses from an individual vessel would result in a daily storage efficiencies in the range of only 75 to 80 percent. To avoid these problems, the vessels are installed adjacent to one another in a common enclosure. The vessels are not insulated, and only the outside of the enclosure is insulated. With this arrangement, the daily storage efficiency is greater than 99 percent.

Vertical Conduction in Vessel Wall

Since the vessel itself provides a portion of the storage capacity, an analysis was conducted to determine if the vertical conduction along the vessel wall had a detrimental effect on the storage capacity. Two calculations were performed; one with a bed temperature profile at the end of a discharge cycle; and another with a profile at the end of a charge cycle.

The results of the first analysis are shown in Figure 48. After a 16 hour hold period, the slope of the temperature profile in the vessel wall has increased; i.e., conduction heat transfer is reducing a portion of the desired temperature gradient. A similar effect is seen in Figure 49, which shows the reduction in the sharpness of the temperature profile after a 16 hour hold period at the end of a charge cycle.

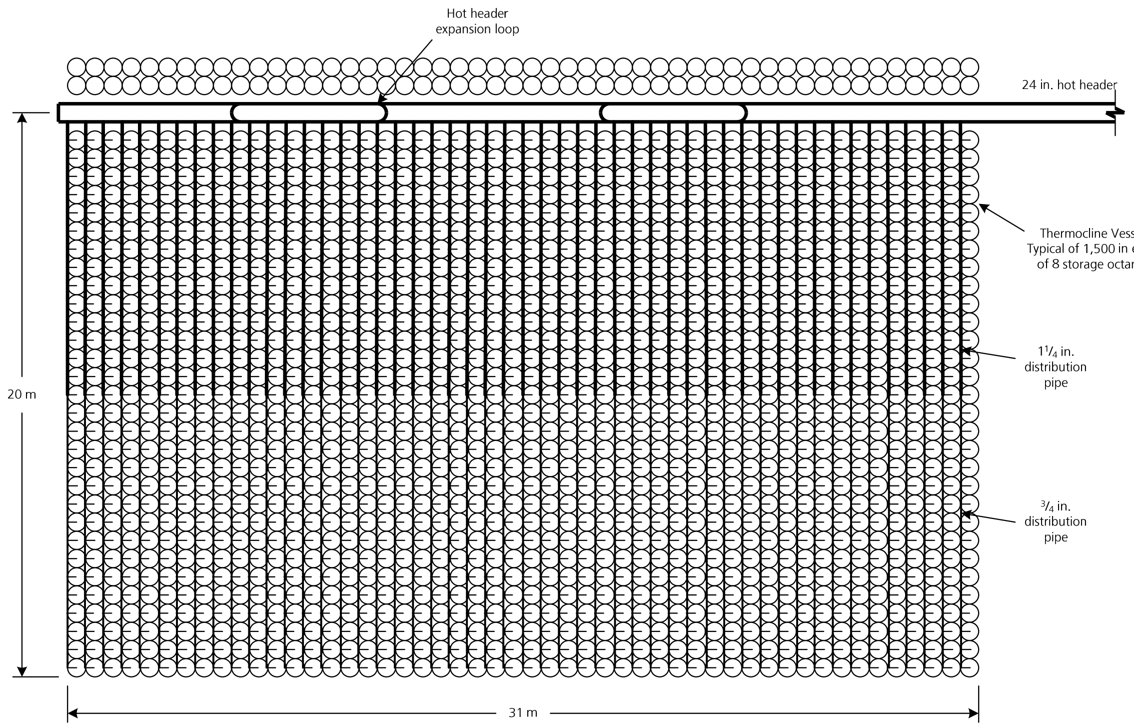

Figure 46 Plan View of Thermocline Vessels in a Quadrant

Although the temperature difference between the top and the bottom of the vessel is a relatively large 300 °C, the integrated conduction heat transfers are relatively modest due to long conduction path lengths of 6 to 10 m. For this phase of the analyses, the effects of conduction along the vessel wall are judged to be within the accuracy of the temperature profile calculations, and the effects are ignored in the annual performance calculations discussed in Section 4.5.

Thermal Ratcheting of Filler Material

Thermal ratcheting occurs if the radial growth of the vessel is greater than the particle size in the bed. In effect, the extra space available during thermal expansion allows the bed to settle. When the vessel contracts during cooling, the resistance of the bed to vertical movement imposes an additional circumferential stress on the vessel wall.

The thermocline vessels have an outside diameter of 609.6 mm. If the temperature change between construction and normal operation is 650 C, and if the coefficient of thermal expansion (α) is 14 μm/m-C, the vessel outside diameter at operating temperature will be on the order of 614.7 mm, as calculated by the following equation:

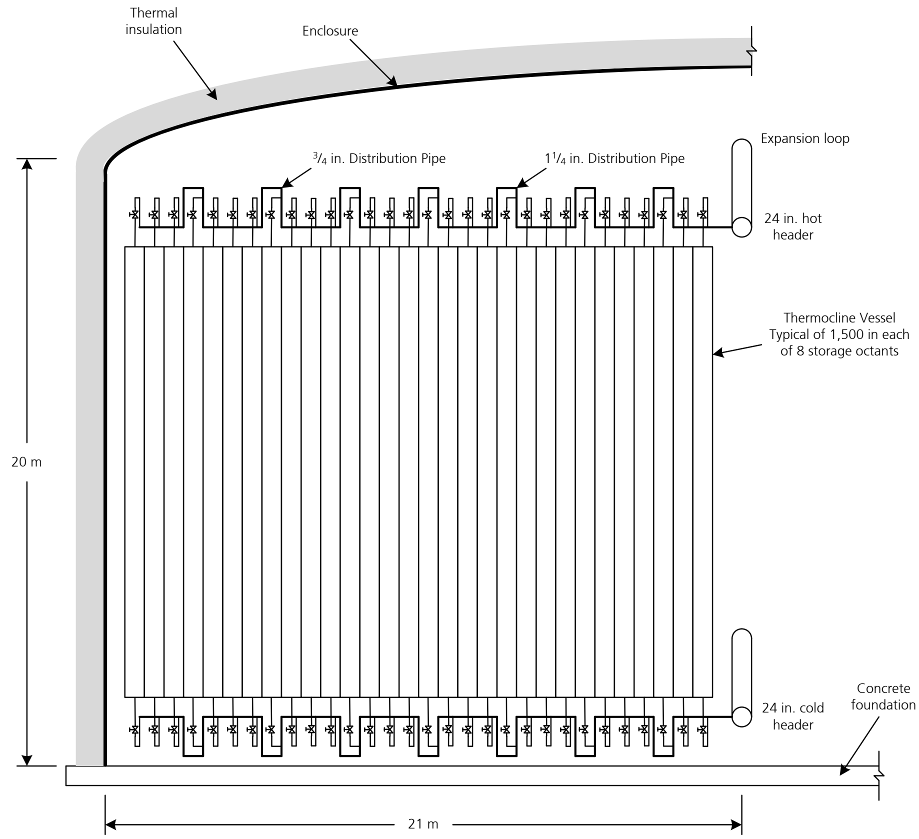

Figure 47 Elevation View of Thermocline Vessels in a Quadrant

$$D_{final} = D_{initial} * (1 + \alpha\Delta T)$$

Selecting a particle size greater than 2.5 mm should prevent settling. Since the thermocline performance with particle diameters of 2.5 mm and 5.0 mm should be comparable, the selection of a nominal particle size of 5 mm should prevent thermal ratcheting without adversely affecting the heat transfer characteristics of the bed.

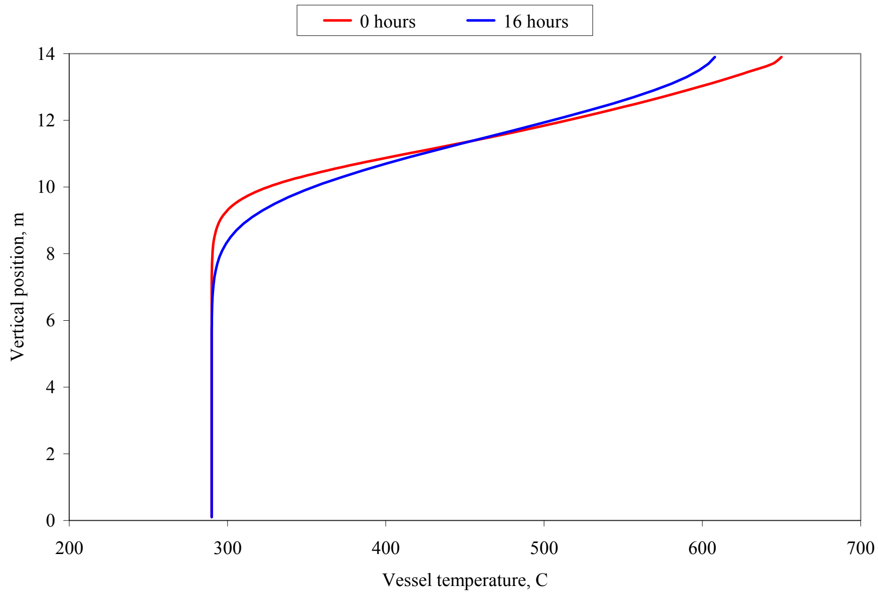

Figure 48 Change in Vertical Temperature Profile in Vessel Wall Following Discharge

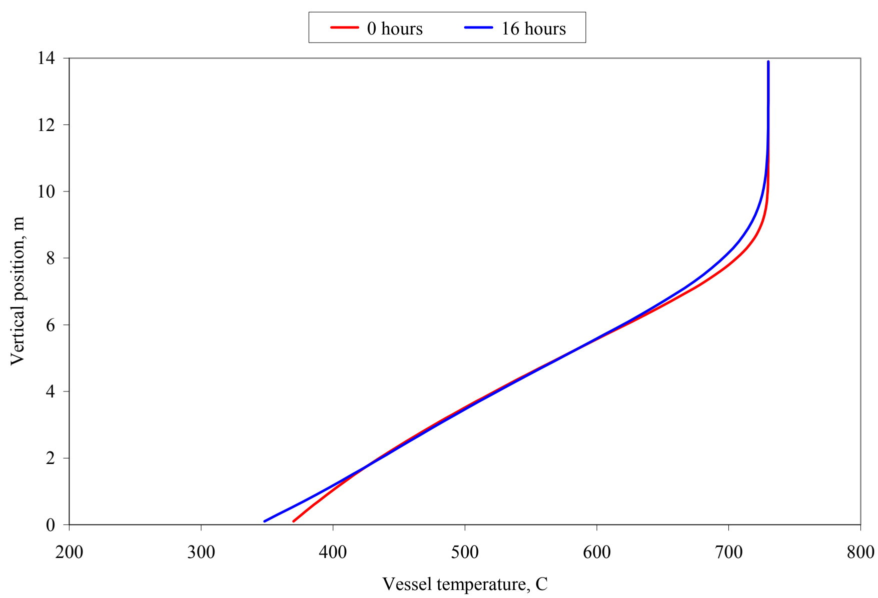

Figure 49 Change in Vertical Temperature Profile in Vessel Wall Following Charge

3.6.6 Daily Startup of Supercritical H_2O Transport Pipeline

Thermal energy is transported from the receiver towers to the central power block by means of a supercritical steam line. To keep the morning startup times and energies to a minimum, steam is trapped in the line overnight by means of isolation valves. The expected decay in pressure and temperature during an overnight shutdown is shown in Figure 50. After a 16 hour shutdown period, the steam temperature and pressure have decayed from initial values of 591 °C and 350 bar to final values of 511 °C and 256 bar, respectively.

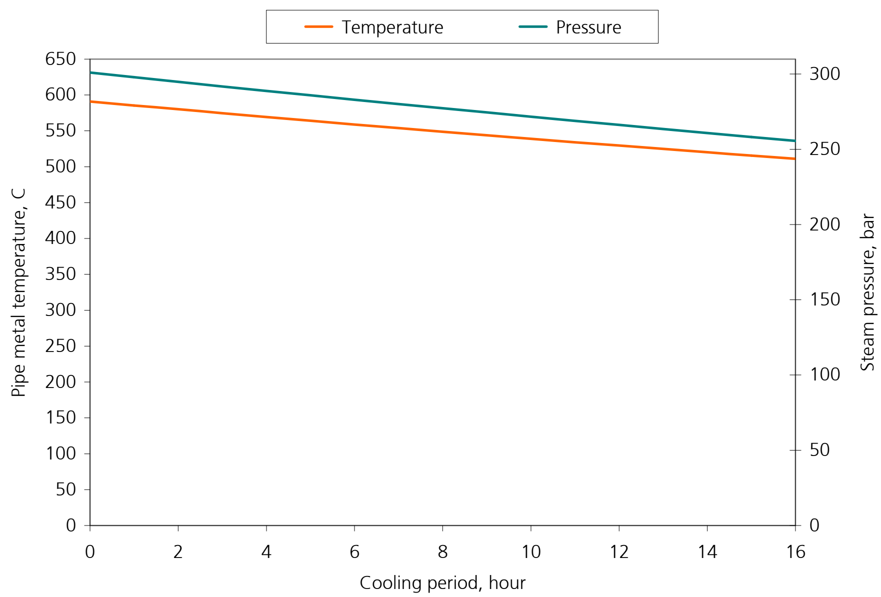

Figure 50 Pipeline Temperature and Pressure Profile Following Daily Shutdown

In the morning, the line is returned by service by introducing supercritical steam from the receiver. A possible reheating profile is shown in Figure 51. The calculations are based on a steam flow equal to 20 percent of the design flow rate at 0 minutes, increasing linearly to the design flow rate during the next 30 minutes. After approximately 90 minutes, the pipe temperature essentially reaches the design supercritical steam temperature of 591 °C. The cumulative energy lost during the 16 hour overnight shutdown period is approximately 26 MWht, which represents about 2 minutes of receiver operation at the design point.

A similar warm-up analysis was conducted, but with the supercritical steam pipeline starting at ambient temperature. As above, supercritical steam is introduced at a flow rate equal to 20 percent of the design flow at 0 minutes, increasing linearly to the design flow rate during the next 30 minutes. The temperature profile is shown in Figure 52. After 2½ hours, the pipe metal temperature is within 10 °C of the normal receiver outlet temperature of 591 °C. The energy required to reheat the pipe and the insulation is about 125 MWht, or about 10 minutes of receiver operation at the design point. As such, the best annual energy efficiency is achieved by isolating the supercritical steam pipeline during each shutdown period.

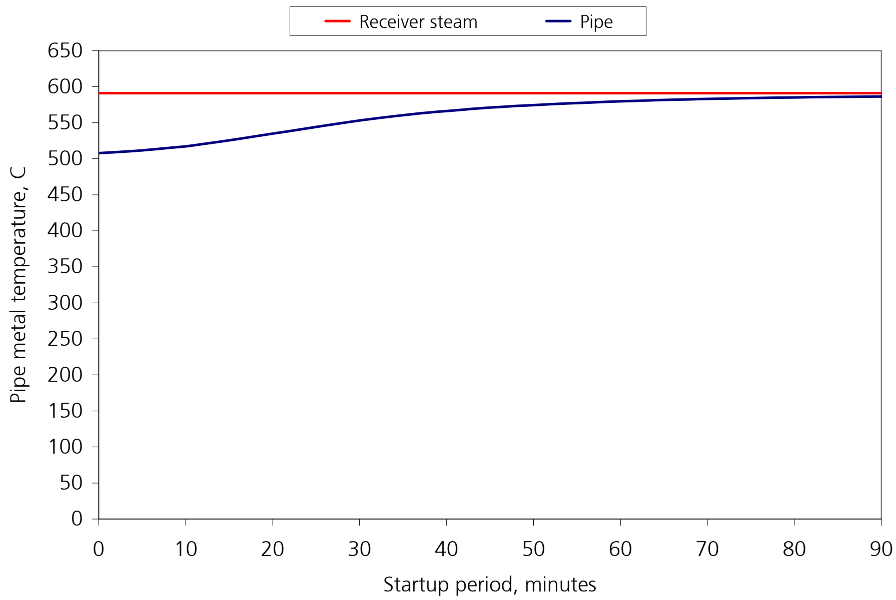

Figure 51 Pipeline Temperature Profile Following Daily Startup

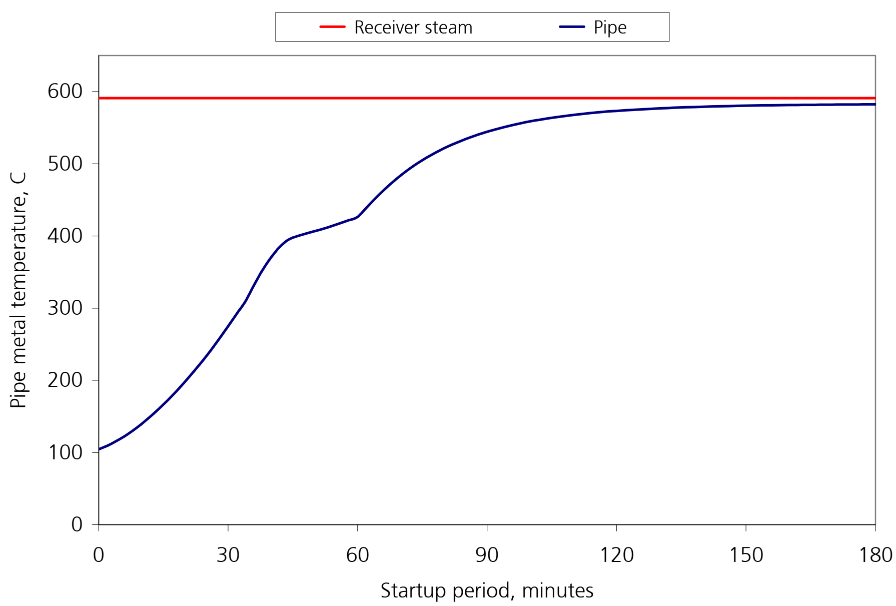

Figure 52 Pipeline Temperature Profile Following Cold Startup

3.7 Compilation of Plant Design Parameters

The principal design parameters for the Rankine cycles, the receiver system, the thermal storage system are compiled in Tables 18 through 23.

Table 18 Summary of Rankine Cycle Design Parameters

	Subcritical nitrate salt	Supercritical nitrate salt	Low temperature supercritical H_2O	High temperature supercritical H_2O	Low temperature supercritical CO_2	High temperature supercritical CO_2
Gross output, MWe	440	440	440	440	440	440
Live steam						
- Pressure, bar	125.0	301	301	351	301	351
- Temperature, C	540	591	591	650	591	650
- Flow rate, kg/sec	350.867	350.000	350.000	455.000	350.000	455.000
Reheat steam						
- Pressure, bar	21.0	50.2	50.2	46.3	50.2	46.3
- Temperature, C	540	590	590	577	590	577
- Flow rate, kg/sec	297.265	282.599	282.599	273.127	282.599	273.127
Feedwater temperature, C	237	307	307	350	307	350
Gross cycle efficiency	0.434	0.488	0.488	0.493	0.488	0.493
Steam generator duty, MWt	1,014	902	902	893	902	893

Table 19 Summary of Receiver Design Parameters

	Subcritical nitrate salt	Supercritical nitrate salt	Low temperature supercritical H_2O	High temperature supercritical H_2O	Low temperature supercritical CO_2	High temperature supercritical CO_2
Receiver output, MWt	910	812	812	804	812	804
Inlet fluid						
- Pressure, bar	11.7	19.6	315	360	150	150
- Temperature, C	288	335	415	350	332	370
- Flow rate, kg/sec	2,159	2,012	640	410	2,322	2,192
Outlet fluid						
- Pressure, bar	1.5	1.5	312	358	147	146
- Temperature, C	566	600	675	655	620	670
Receiver circuit pressure drop, bar	92.4	96.5	11.5	15.1	8.7	9.1
Circulation pump power, kWe						
- Receiver circulation	12,321	12,187	3,590	1,120	18,596	19,941
- Salt transfer to power block	Included	Included	3,306	N/A	3,569	N/A
	---------	---------	---------	---------	---------	---------
- Total	12,321	12,187	6,896	1,120	22,166	19,941
Receiver design						
- Absorber diameter, m	20.00	25.25	21.50	21.25	22.00	20.75
- Absorber height, m	25.00	31.56	34.40	35.06	33.00	33.20
- Peak flux on North panel, kW/m^2	995	647	614	592	619	657
- Peak flux on South panel, kW/m^2	550	255	342	329	346	364
- North-to-South panel power ratio	1.92	2.41	1.93	1.91	1.90	1.94
- Thermal efficiency	0.880	0.840	0.815	0.829	0.824	0.815
Panel design						
- Highest tube temperatures, C						
- Inner crown	623	622	755	732	722	767
- Outer crown	663	640	813	790	776	822
- Panel life, years						
- North panel	46	794	6	8	9	5
- South panel	1,383	23	14	17	27	18
Collector field area, m^2	1,796,300	1,627,775	1,729,332	1,715,796	1,780,996	1,774,326
Tower height, m	260	260	240	250	210	210
Design point optical efficiency	0.606	0.625	0.607	0.595	0.583	0.585

Table 20 Summary of Thermal Storage Design Parameters

	Subcritical nitrate salt	Supercritical nitrate salt	Low temperature supercritical H_2O	High temperature supercritical H_2O	Low temperature supercritical CO_2	High temperature supercritical CO_2
Capacity, MWht	6,083	5,412	5,412	N/A	5,412	5,357
Two Tank Thermal Storage						
- Hot salt tank						
• Inventory temperature, C	565	600	600	N/A	600	N/A
• Number, each	2	2	2	"	2	"
• Diameter, m	42.4	40.8	40.8	"	40.8	"
• Height, m	12.2	12.2	12.2	"	12.2	"
• Insulation thickness, mm	508	536	536	"	536	"
• Heat loss, per tank, kWt	608	597	597	"	597	"
- Cold salt tank						
• Inventory temperature, C	288	332	332	N/A	332	N/A
• Number, each	2	2	2	"	2	"
• Diameter, m	40.4	38.9	38.9	"	38.9	"
• Height, m	12.2	12.2	12.2	"	12.2	"
• Insulation thickness, mm	279	316	316	"	316	"
• Heat loss, per tank, kWt	374	379	379	"	379	"
- Total inventory, metric tons	58,037	53,184	53,184	"	53,184	"
- System heat loss, kWt	1,964	1,953	1,953	"	1,953	"
Thermocline Storage						
- Storage vessel						
• Inventory temperature, C	N/A	N/A	N/A	N/A	N/A	370 to 670
• Number, each	"	"	"	"	"	9,600
• Diameter, m	"	"	"	"	"	0.61
• Height, m	"	"	"	"	"	12.2
• Enclosure insulation thickness, mm	"	"	"	"	"	300
• System heat loss, kWt	"	"	"	"	"	2,136

Table 21 Summary of Principal Heat Exchangers in Low Temperature Plants - Sheet 1 of 2

	Subcritical nitrate salt	Low temperature supercritical H_2O	Low temperature supercritical CO_2
Supercritical fluid-to-salt heat exchanger			
- Duty, MWt	N/A	1,632	1,685
- Temperatures, C			
• Supercritical fluid in	"	675	620
• Nitrate salt out	"	600	600
• Supercritical fluid out	"	415	350
• Nitrate salt in	"	332	332
- Number, each	"	5	9
- Heat transfer area, each, m^2	"	5,737	7,362
- Total heat transfer area, m^2	"	28,687	66,255
- Heat exchanger dimensions			
• Diameter, m	"	1.96	1.23
• Length, m	"	7.5	20.0
- Pressure losses, bar			
• Supercritical fluid	"	0.061	2.028
• Nitrate salt		1.57	4.30
Salt-to-supercritical steam heat exchanger			
- Duty, MWt	N/A	722	722
- Temperatures, C			
• Nitrate salt in	"	600	600
• Supercritical steam out	"	591	591
• Nitrate salt out	"	335	335
• Feedwater in	"	307	307
- Number, each	"	2	2
- Heat transfer area, each, m^2	"	5,529	4,965
- Total heat transfer area, m^2	"	11,058	9,930
- Heat exchanger dimensions			
• Diameter, m	"	1.21	1.15
• Length, m	"	26.5	24.0
- Supercritical fluid pressure loss, bar	"	1.27	1.13
Steam generator reheater			
- Duty, MWt	162	185	185
- Temperatures, C			
• Nitrate salt in	565	600	600
• Hot reheat steam	540	590	590
• Nitrate salt out	448	340	340
• Cold reheat steam	297	324	324
- Number, each	1	2	2
- Heat transfer area, each, m^2	4,301	9,499	9,499
- Total heat transfer area, m^2		18,037	18,037
- Heat exchanger dimensions			
• Diameter, m	3.40	2.18	2.18
• Length, m	5.7	30.5	30.5
- Reheat steam pressure loss, bar	0.31	2.42	2.42

Table 22 Summary of Principal Heat Exchangers in Low Temperature Plants - Sheet 2 of 2

	Subcritical nitrate salt	Low temperature supercritical H_2O	Low temperature supercritical CO_2
Subcritical steam generator preheater			
- Duty, MWt	174	N/A	N/A
- Temperatures, C			
• Nitrate salt in	336	"	"
• Feedwater out	328	"	"
• Nitrate salt out	288	"	"
• Feedwater in	237	"	"
- Number, each	1	"	"
- Heat transfer area, each, m^2	4,375	"	"
- Total heat transfer area, m^2	4,375	"	"
- Heat exchanger dimensions			
• Diameter, m	2.01	"	"
• Length, m	14.39	"	"
- Feedwater pressure loss, bar	0.164	"	"
Subcritical steam generator evaporator			
- Duty, MWt	407	N/A	N/A
- Temperatures, C			
• Nitrate salt in	448	"	"
• Saturated steam out	329	"	"
• Nitrate salt out	336	"	"
• Feedwater in	328	"	"
- Number, each	1	"	"
- Heat transfer area, each, m^2	6,778	"	"
- Total heat transfer area, m^2	6,778	"	"
- Heat exchanger dimensions			
• Diameter, m	3.61	"	"
• Length, m	7.84	"	"
- Saturated steam pressure loss, bar	0.012	"	"
Subcritical steam generator superheater			
- Duty, MWt	271	N/A	N/A
- Temperatures, C			
• Nitrate salt in	565	"	"
• Live steam out	540	"	"
• Nitrate salt out	448	"	"
• Saturated steam in	329	"	"
- Number, each	1	"	"
- Heat transfer area, each, m^2	4,301	"	"
- Total heat transfer area, m^2	4,301	"	"
- Heat exchanger dimensions			
• Diameter, m	2.62	"	"
• Length, m	9.05	"	"
- Reheat steam pressure loss, bar	0.472	"	"

Table 23 Summary of Principal Heat Exchanger in High Temperature Plants

	Supercritical nitrate salt	High temperature supercritical H_2O	High temperature supercritical CO_2
Supercritical fluid-to-steam heat exchanger			
- Duty, MWt	N/A	N/A	816
- Temperatures, C			
• Supercritical fluid in	"	"	670
• Supercritical steam out	"	"	650
• Supercritical fluid out	"	"	370
• Feedwater in	"	"	350
- Number, each	"	"	4
- Heat transfer area, each, m^2	"	"	4,287
- Total heat transfer area, m^2	"	"	17,149
- Heat exchanger dimensions			
• Diameter, m	"	"	1.03
• Length, m	"	"	14
- Pressure losses, bar			
• Supercritical fluid	"	"	0.61
• Feedwater / supercritical steam			0.65
Salt-to-supercritical steam heat exchanger			
- Duty, MWt	718	N/A	N/A
- Temperatures, C			
• Nitrate salt in	600	"	"
• Supercritical fluid out	591	"	"
• Nitrate salt out	335	"	"
• Supercritical fluid in	307	"	"
- Number, each	2	"	"
- Heat transfer area, each, m^2	4,035	"	"
- Total heat transfer area, m^2	8,070	"	"
- Heat exchanger dimensions			
• Diameter, m	1.26	"	"
• Length, m	25.5	"	"
- Supercritical fluid pressure loss, bar	1.44	"	"
Steam generator reheater			
- Duty, MWt	184	155	155
- Temperatures, C			
• Hot fluid in	600	650	650
• Hot reheat steam	590	577	577
• Hot fluid out	335	417	417
• Cold reheat steam	324	342	342
- Number, each	2	1	1
- Heat transfer area, each, m^2		3,107	3,107
- Total heat transfer area, m^2	21,942	3,107	3,107
- Heat exchanger dimensions			
• Diameter, m	2.18	1.58	1.58
• Length, m	17.0	10.5	10.5
- Reheat steam pressure loss, bar	2.96	0.67	0.67

4 Annual Performance Analyses

4.1 SOLERGY Inputs

The annual performance of the 6 plants were estimated through the following steps:

- Weather data

  Annual weather files for Barstow, California, were compiled from data assembled for the 10 MWe Solar One central receiver pilot plant [11], and arranged in the SOLERGY data format. The weather file included values for direct normal radiation, wind direction, wind speed, dew point temperature, barometric pressure, and dry bulb temperature.

- SOLERGY calculations of net plant electric output

  For each of 35,040 15-minute time steps in a year, SOLERGY calculates the following parameters: sun position; direct normal radiation on the heliostat field, using direct normal radiation from the weather file; aggregate cosine optical losses from the heliostats distributed around the receiver tower; mirror reflectivity losses, including losses due to dust; heliostat shading and blocking losses; atmospheric attenuation losses, due to absorption and scattering; receiver spillage losses; incident receiver power; receiver thermal losses due to reflection, convection, and radiation; thermal losses in the tower piping; thermal losses in the storage tanks; gross Rankine cycle thermal-to-electric conversion efficiency; auxiliary electric power demands for the nitrate salt pumps and the Rankine cycle pumps and fans; continuous electric power demands for heat tracing and balance of plant loads; and net electric output.

  Energy flows are also monitored to account for the following: heliostat stowing due to high winds; receiver thermal losses during daily startup; energy not collected during supercritical fluid heat exchanger startup (discussed in Section 4.2.2); receiver thermal losses during cloud transients; heliostat defocusing if the thermal storage system reaches capacity; Rankine cycle thermal losses during daily startup; and Rankine cycle efficiency decay near the end of the thermocline storage discharge (discussed in Section 4.4). The cycle startup energies were a function of the shutdown period for the steam turbine-generator; i.e., a cold start, a warm start, or a hot start. The net thermal input to the Rankine cycle was limited to 105 percent of the design point input (i.e., 1.05 x 440 MWe / 0.434 = 1,065 MWt) based on an estimated upper capacities of the steam turbine, the fluid pumps, and the heat exchangers.

- SOLERGY dispatch logic

  Each of the central receiver designs use thermal storage, and the dispatch logic in SOLERGY operates as follows: 1) in the morning, thermal energy from the receiver is delivered to the storage system; 2) when the energy in storage reaches a value sufficient to operate the turbine for at least 1 hour, the Rankine cycle is started; and 3) Rankine cycle operation continues at full

[11] "Solar One Solar Thermal Central Receive Pilot Plant 1984 Meteorological Data Report", McDonnell Douglas Astronautics Company, Sandia report SAND86-8161, 1986

load until the storage system is fully discharged. On clear days, the turbine need only be started once; however, on cloudy days, multiple turbine starts are possible.

It can be noted SOLERGY has an alternate dispatch logic (MAXOUT), which selects the turbine start and stop times each day to maximize the energy sales revenues based on a time-of-day price schedule. However, the standard dispatch logic was selected for the study for 2 reasons: 1) each plant had the same thermal storage capacity; and 2) only relative levelized energy costs, rather than absolute costs, were of interest.

A summary of the input parameters to the SOLERGY calculations is shown in Appendix B.

4.2 Nitrate Salt Heat Transport Loop Startup Times and Energies

Both of the nitrate salt plants, and the low temperature supercritical H_2O and CO_2 plants, use a nitrate salt piping loop to transport thermal power from the receivers to the central power block. During the evening shutdown, the temperature of the stagnant salt in the heat transport piping decays, as shown in Figure 53. Pipe insulation thickness for the cold and the hot salt lines were 150 mm and 200 mm, respectively, and were selected based on previous economic studies conducted for the Solar Two project.

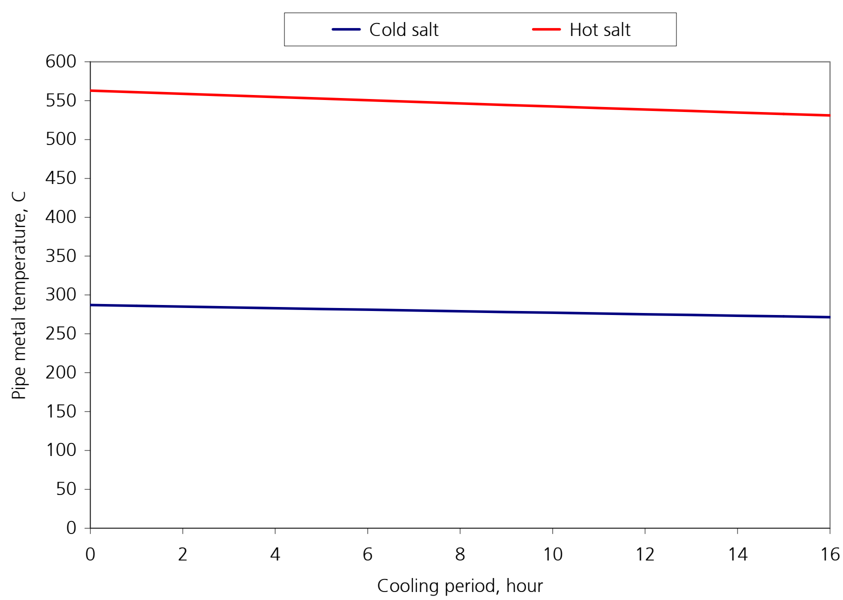

Figure 53 Overnight Temperature Decays in Nitrate Salt Heat Transport Loop

The energy lost during the overnight shutdown is on the order of 46 MWht, or about 3 minutes of receiver operation at the design point output.

4.2.1 Nitrate Salt Receivers

For the subcritical and the supercritical nitrate salt receivers, there are no provisions for salt recirculation at the tower. During morning startup of the receiver, the initial salt outlet temperature is the temperature of the salt in the cold transport line. During the next 15 minutes, the outlet temperature increases to the design value of either 565 °C or 600 °C. As such, the temperature of the salt at the inlet to the hot transport line starts at a value of 533 °C, decreases quickly to the cold transport line temperature of 272 °C, and then increases to the design value over the next 15 minutes. The unit thermal mass of the salt in the transport line is approximately 1,140 kJ/C-m, while the unit thermal mass of the hot salt line is on the order of 110 kJ/C-m. As such, the temperature of the pipe closely follows the temperature of the salt, and the transient temperature profile at the outlet of the hot salt line should mimic the profile at the entrance. At the exit of the hot salt pipe, the flow will need to directed to either the cold salt tank or the hot salt tank, depending on the temperature at that time.

It can be noted the startup transient is no more problematic than for a smaller plant with a single tower. In the small plant, as the temperature of the downcomer is raised to the normal design value, the salt leaving the downcomer is directed to either the cold salt tank or the hot salt tank, depending on the temperature. In effect, the large and the small plant have a similar transient profile, for two reasons:

1) For the thermal transport line in a large plant, the temperature in the hot salt line following an overnight shutdown period is reasonably close to the design value. As a result, almost all of the thermal energy in the line can be captured in the hot salt tank, and a significant quantity of energy is not required to reheat the line each morning to the normal operating temperature.

2) The unit thermal mass of the salt, in kJ/C-m, is much higher than the unit thermal mass of the pipe. As such, the pipe is not effective in storing a significant portion of the energy in the salt, and thereby reducing the thermodynamic availability of the energy.

4.2.2 Supercritical Fluid Receivers

For the low temperature supercritical H_2O and CO_2 receivers, the fluid circulation pump is located at the tower. During receiver startup, the receiver outlet temperature can be matched very closely with the temperatures of the hot salt transport line. In principle, the temperature and energy transients in the transport loop during startup can be minimal.

The difficulty lies in the supercritical heat exchanger. During normal operation, a temperature profile is established along the length of the heat exchanger. At the end of the day, the fluid flows on both sides are stopped. The temperature profile remains in place overnight, as conduction heat transfer rates inside the heat exchanger are typically low.

In an ideal morning startup, the receiver would operate in recirculation until the receiver outlet temperature matched the hot fluid inlet metal temperature on the heat exchanger. The fluid and salt flows would then be established to match the receiver duty. If the flow coordination is perfect, the temperature profile in the heat exchanger will remain essentially unchanged.

In practice, it will be a difficult task to accelerate the salt flow in the transport loop at exactly the rate necessary to maintain the temperature profile. The thermal capacity of the salt is much higher than the thermal capacity of the metal in the heat exchanger, and even a small mismatch in fluid and salt flow rates will quickly revise the temperature profile and produce high transient thermal stresses. Also, at low flow rates, the flows tend not be distributed evenly among the tubes and within the shell; the flows tend to channel, and concentrate in certain regions. The non-uniform flow distribution can produce local regions of high thermal stresses.

To ensure an adequate fatigue life for the heat exchanger, the safest practice would involve the following steps:

1) At the end of the solar day, the fluid flows on both sides of the heat exchanger are stopped.

2) All but one of the receiver panels are isolated, and the supercritical fluid circulation pump is started at a low flow rate. The flow rate is adequate to maintain a uniform flow distribution among the tubes in the supercritical heat exchanger. For the supercritical H_2O and CO_2 heat exchangers, the thermal mass of the H_2O and CO_2 are on the order of 3.5 and 2.5 percent, respectively, of the combined thermal mass of the salt and the steel in the heat exchangers. As such, the flow of high temperature H_2O or CO_2 through the heat exchanger will slowly raise the salt and steel temperatures.

3) As circulation continues, the combined thermal energy in the downcomer and the supercritical heat exchanger is rejected to the environment through the 1 active receiver panel. As such, the temperature of the heat exchanger can be reduced at a typical allowable change rate of 300 to 350 °C/hr.

4) Once the heat exchanger reaches the cold salt temperature of 330 °C, the circulation of the supercritical fluid is stopped.

5) During morning startup, the flow of salt in the heat transport loop is established. Since the temperature of the cold salt line is nominally the same as the supercritical heat exchanger, there are no startup restrictions on the salt flow rate.

6) The supercritical receiver loop is placed in operation, and the receiver outlet temperature is increased at a nominal rate of 350 °C/hr to match the allowable temperature change rate for the supercritical heat exchanger. As such, the nominal startup time is 1 hour for the receiver and the heat exchanger to reach the normal operating temperatures.

7) At the beginning of the morning startup, the temperature of the salt leaving the hot salt transport line is equal to the nominal cold salt temperature of 330 °C. Over the next 1 hour, the temperature of the salt leaving the line increases to the normal operating value. For exit temperatures between 330 °C and 550 °C, the salt is returned to the cold salt storage tank; at higher temperatures, the salt is directed to the hot salt storage tank. In effect, no useful energy is delivered to the hot salt tank for the first 50 minutes of the startup procedure, and a startup period of 3 time steps (45 minutes) is assigned to the supercritical heat exchangers in the SOLERGY calculations.

The thermal energy required to reheat the supercritical H_2O or CO_2 heat exchanger from the initial cold salt temperature to the normal operating temperature represents about 2.5 minutes of receiver output at the design point. For the purposes of the SOLERGY calculations, the reheat energy requirements are set to 33.8 MWht.

4.3 Supercritical CO_2-to-Supercritical H_2O Steam Generator Startup

The high temperature supercritical CO_2 plant uses a supercritical CO_2-to-supercritical H_2O steam generator. The temperature of the feedwater in the heat transport loop is comparable to the temperature of the salt in the nitrate salt heat transport loop discussed above. Also, the combination of density and specific heat of the supercritical H_2O in the heat exchanger is comparable the combination of density and specific heat of the salt in the supercritical fluid heat exchanger discussed above. As such, the operating constraints and procedures discussed above should be generally applicable to the supercritical CO_2 steam generator; a startup period of 3 time steps, and a startup energy of 34 MWht, are assigned to the SOLERGY performance calculations.

4.4 Rankine Cycle Performance with Thermocline Storage

As shown in Figure 45, the fluid outlet temperature from the thermocline storage system decays by as much as 100 °C at the end of a discharge cycle. To examine the effect of lower steam temperatures on the output and efficiency of the Rankine cycles, a series of GateCycle calculations were made for the high temperature supercritical Rankine cycle with inlet steam temperatures between 550 °C and 650 °C. The results are shown in Figure 54. For example, if the steam temperature decays by 100 °C, the cycle output and efficiency decay by 14 percent and 5 percent (i.e., 95 percent of the design efficiency), respectively.

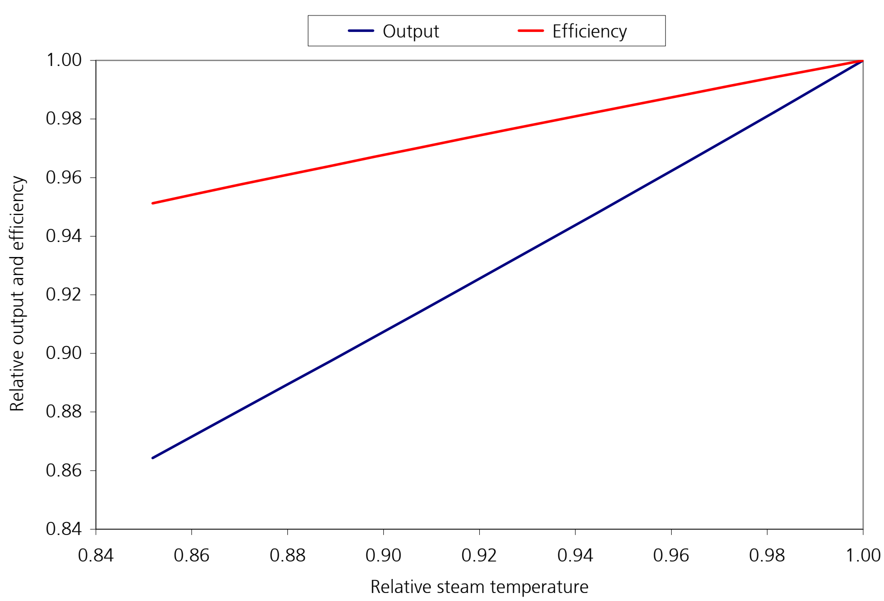

Figure 54 Output and Efficiency of Supercritical Rankine Cycle at Reduced Steam Temperatures

Combining the performance data in the figure above with the temperature profile in Figure 45 results the estimated output and efficiency profile shown in Figure 55. Although the efficiency, and in particular the output, decay near the end of the discharge period, the lower performance occurs only for a limited period. If the efficiency and the output are integrated over the 6 hour discharge period, the weighted values are 0.992 and 0.977, respectively. If the efficiency and the output are further integrated over the annual hours of non-storage and storage operation, the weighted values increase to 0.990 and 0.996, respectively.

For the purposes of the annual performance calculations for the high temperature supercritical CO_2 plant, the annual efficiency as calculated by SOLERGY is multiplied by 0.996 to account for the reduced cycle performance when operating with a thermocline storage system.

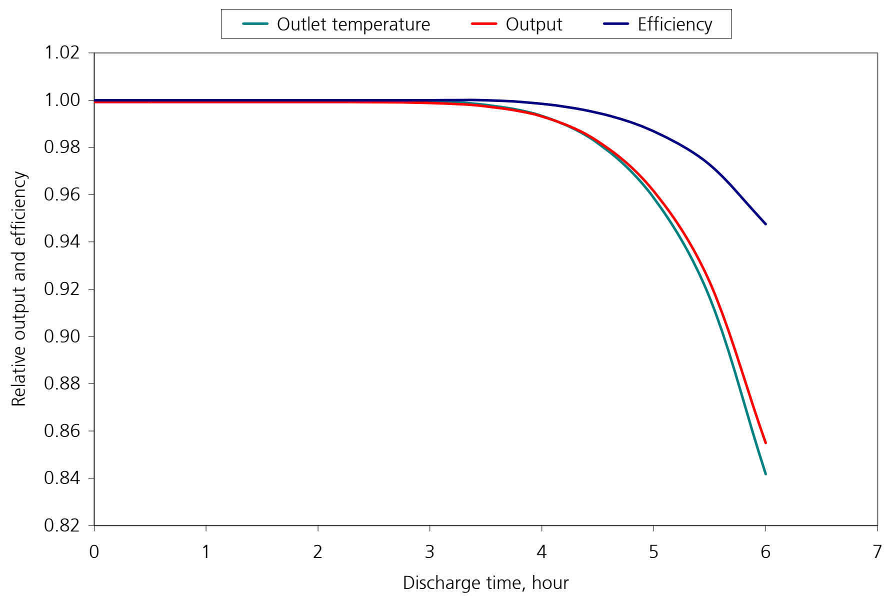

Figure 55 Rankine Cycle Output and Efficiency as a Function of Discharge Time

4.5 Annual Performance Summary

A summary of the annual energy flows is shown in
Figure 56, and a summary of the annual system efficiencies is presented in Table 24.

Several observations from the performance calculations can be made, as follows:

- Switching from a subcritical Rankine cycle to a supercritical cycle results in net increase in the annual plant efficiency. A supercritical cycle require an increase in the receiver operating temperature, which reduces the receiver efficiency; however, the efficiency of the Rankine cycle increases at a faster rate than the efficiency of the receiver decreases.

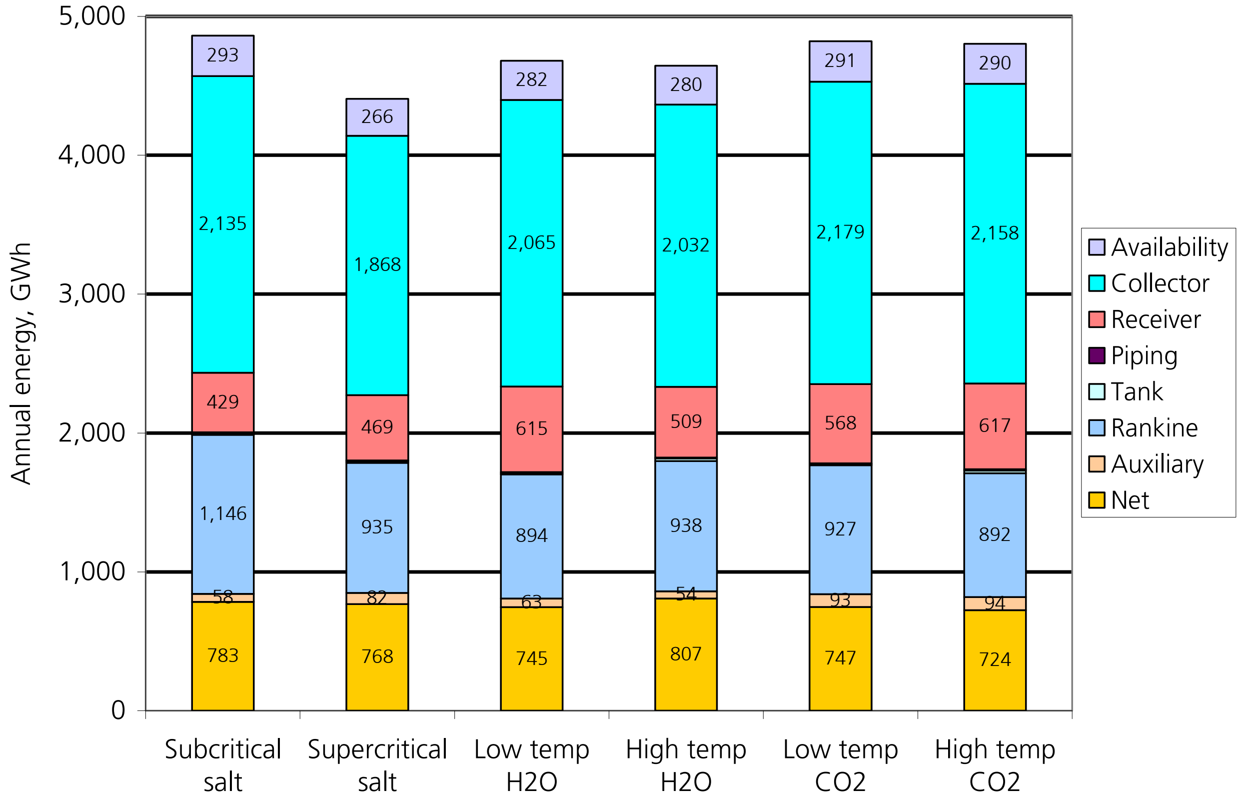

Figure 56 Summary of Annual Plant Performance

- For the low temperature supercritical CO_2 plant, the optical efficiency of the collector field, shown in the table as 'Energy redirected to receiver', is below the corresponding values for the subcritical nitrate salt and the low temperature supercritical H_2O plants. The lower efficiency is a consequence of a lower tower height, which is due to the much higher costs for the vertical supercritical CO_2 piping than the vertical nitrate salt or supercritical H_2O piping.

- Annual thermal storage efficiencies, defined as the annual energy delivered to storage divided by annual energy extracted from storage, are at least 99 percent. Although the dimensions, and the thermal losses, of the thermocline storage system are larger than the two-tank nitrate salt systems, the efficiencies of both systems are high enough that the type of system does not influence the annual performance of the plant.

- If one ignores the technical feasibility of thermocline storage using supercritical H_2O, the highest annual plant efficiency is provided by the high temperature supercritical H_2O plant. This is due, in large part, to the relatively low auxiliary energy demands of the receiver coolant circulation pumps, as noted in Table 19.

Table 24 Summary of Annual System Efficiencies

Category Efficiency	Subcritical nitrate salt	Supercritical nitate salt	Low temperature supercritical H_2O	High temperature supercritical H_2O	Low temperature supercritical CO_2	High temperature supercritical CO_2
Potential energy to collector field	1.000	1.000	1.000	1.000	1.000	1.000
Unavailable energy due to plant outages	------	------	------	------	------	------
Available energy to collector field	0.940	0.940	0.940	0.940	0.940	0.940
Energy redirected to receiver	0.533	0.549	0.530	0.534	0.519	0.522
Energy absorbed by receiver	0.824	0.793	0.736	0.782	0.758	0.738
Energy supplied to thermal storage	0.997	0.996	0.996	0.997	0.996	0.995
Energy withdrawn from thermal storage	0.994	0.994	0.995	0.990	0.995	0.989
Gross electric output	0.423	0.476	0.475	0.479	0.475	0.478
Electric energy for internal plant demands	------	------	------	------	------	------
Net electric output	0.932	0.904	0.922	0.938	0.889	0.885
Cumulative Efficiency						
Potential energy to collector field	1.000	1.000	1.000	1.000	1.000	1.000
Unavailable energy due to plant outages	------	------	------	------	------	------
Available energy to collector field	0.940	0.940	0.940	0.940	0.940	0.940
Energy redirected to receiver	0.501	0.516	0.498	0.502	0.488	0.490
Energy absorbed by receiver	0.412	0.409	0.367	0.392	0.370	0.362
Energy supplied to thermal storage	0.411	0.407	0.366	0.391	0.368	0.360
Energy withdrawn from thermal storage	0.409	0.405	0.364	0.387	0.367	0.356
Gross electric output	0.173	0.193	0.173	0.185	0.174	0.170
Electric energy for internal plant demands	------	------	------	------	------	------
Net electric output	0.161	0.174	0.159	0.174	0.155	0.151

- The annual efficiencies of the low- and the high temperature supercritical CO_2 plants are less than the efficiencies for the corresponding supercritical H_2O plants. This is primarily due to the very large circulation pump power demands for the CO_2 receivers.
- The annual auxiliary energy demand for the supercritical nitrate salt plant is well above the corresponding value for the subcritical nitrate salt plant. The effect can be traced to the annual energy demand of the feedwater pump.

5 Economic Analyses

5.1 Capital Cost Estimates

Capital cost estimates were assembled for the each of the 6 plant designs. The principal estimate categories include direct field costs, indirect field costs, and project related costs.

Direct field costs include all of the expenses for equipment procurement, shipping, sales taxes, installation labor, labor supervision, construction utilities, and site supervision. Indirect field costs include engineering, procurement, construction management, startup, checkout, and the contractor's fee. Project related costs include financing costs, owner's engineering, owner's contingencies, constructor mobilization, interest during construction, initial spare parts, and funded debt reserve.

5.1.1 Direct Field Cost

The bases for the direct field cost estimates were as follows:

- The estimates include the major equipment, bulk materials, installation labor, contingencies, freight, sales taxes, and engineering, procurement, and construction management expenses. The costs are shown in mid-2008 dollars, and exclude project related expenses, such as electric interconnection, permits, licenses, interest during construction, financing fees, and escalation to mid-2010 dollars.

- Prices for the major Rankine cycle equipment were developed from vendor contacts, and an in-house database for fossil and combined cycle plants in the range of 50 MWe to 250 MWe.

- Costs for balance of plant items, such as site work, pumps, tanks, vessels, heat exchangers, structural steel, concrete, switchgear, electric bulk materials, piping, thermal insulation, valves, and instrumentation, were derived from a Bechtel in-house database and from the AspenTech Icarus cost estimating program.

- Heliostat costs were based on installed costs for the 122 m^2 heliostats at the PS10 and PS20 central receiver power plants in Sevilla, Spain.

- Nitrate salt receiver costs were derived from vendor estimates developed for the 137 MWt Solar Tres receiver, and the 460 MWt Eskom receiver. The cost for the 910 MWt baseline nitrate salt receiver was estimated to be $51,545,000. The cost for the 5 other receivers were assumed to scale from the baseline salt receiver as follows:

  $$\text{Receiver cost} = \$4{,}135{,}000 + \$47{,}409{,}000 * (\text{Diameter} / 20.0) * (\text{Height} / 25.0)^{0.6}$$

  where $4,135,000 is a fixed cost for engineering, Diameter is the absorber diameter [m], and Height is the absorber height [m]

  In addition, estimates were made of the mass, and cost, of the Inconel in each receiver, plus the labor costs to fabricate and install the tubes, tube clips, and headers. The sum of the Inconel and labor costs was defined as a 'complexity cost'. For the baseline salt receiver, the unit complexity cost was \$2,281/m^2 of absorber area, as shown in Table 25:

Table 25 Calculation of Unit Complexity Cost for Baseline Nitrate Salt Receiver

28,000	m total straight tube length	2,240	each number of tube-to-header welds
5	percent length allowance for jumper tubes	1.5	man-hour per weld
29,400	m total tube length	65	\$/man-hour rate
1.947	kg tube weight per m	218,400	\$ for tube-to-nozzle welding
57,245	kg total tube weight		
		2,240	each number of nozzles pulled from headers
0.00222	m^2 tube cross section flow area	2	man-hour per nozzle
70	each tubes per header	65	\$/man-hour rate
0.0778	m^2 header cross section flow area	291,200	\$ for nozzle fabrication
0.315	m header diameter		
12	in. nominal header size	14,000	each number of tube clip welds
12	in. selected header diameter	1	man-hour per clip, including leak detection
65	kg/m unit header weight for Sch 30	65	\$/man-hour rate
3.93	m header length	910,000	\$ for tube clip fabrication
256	kg header weight		
8,185	kg total header weight in receiver	1,419,600	\$ for specialty fabrication
65,431	kg total Inconel mass in receiver	3,583,349	\$ for Inconel + specialty fabrication
33	\$/kg unit price for Inconel	2,281	\$/m^2 unit specialty cost
2,163,749	\$ for Inconel in receiver		

Unit complexity costs for the balance of the receivers were estimated as follows:

- Supercritical nitrate salt: \$2,281/m^2
- Low temperature supercritical H_2O: \$4,364/m^2
- High temperature supercritical H_2O: \$4,579/m^2
- Low temperature supercritical CO_2: \$3,223/m^2
- High temperature supercritical CO_2: \$3,295/m^2

The higher unit complexity costs for the supercritical receivers are primarily the reflection of the smaller diameter, and therefore the larger number, of tubes, tube bends, tube clips, and tube-to-header nozzles.

As such, the total receiver cost was estimated using the scaling relationship above, plus the incremental unit complexity cost. For example, the cost for the low temperature supercritical H2O receiver, with absorber height and diameter of 21.5 m and 34.4 m, respectively, was estimated as follows:

$$\text{Cost} = \$4{,}135{,}000 + \$47{,}409{,}000 * (21.5 / 20) * (34.4 / 25)^{0.6} + 21.5 * 34.4 * \pi * (\$4{,}364 - \$2{,}281) = \$70{,}696{,}000$$

- Estimates for the supercritical fluid heat exchangers were derived from the unit costs of the high pressure feedwater heaters and the Therminol steam generator from the Solana parabolic trough power plant, with adjustments to reflect the stainless steels required for the central receiver heat exchangers.

- Estimates for the supercritical fluid receiver circulation pumps were derived from the cost data assembled for the feedwater and the Therminol circulation pumps at the Solana parabolic trough power plant.

- Receiver tower costs were estimated as follows:

    1) As part of the Utilities Study, reasonably detailed tower designs were developed by Black & Veatch for both the 468 MWt and the 936 MWt salt receiver towers.

    2) From the 936 MWt design, the following ratios were developed: tower diameter at top to tower diameter at bottom; shell thickness at top as a fraction of diameter at top; shell thickness at bottom as a fraction of diameter at bottom; foundation diameter as a multiplier of tower diameter at bottom; and foundation thickness as a fraction of foundation diameter.

    3) The above dimensions were used in a tower wind load model, which calculated 1) shell bending stresses along the height of the tower, and 2) minimum soil pressure on the upwind side of the foundation.

    4) Using the optimum tower heights for each of the 6 cases, and using the ratios above, shell and foundation concrete dimensions were developed for each case. The bending loads and soil bearing pressures were then calculated for each of the designs. The loads and pressures were consistent with the loads and pressures from the Black & Veatch case. As such, the calculated concrete dimensions were assumed to be acceptable.

    5) Using the calculated shell and foundation dimensions, and using representative reinforcing steel mass per m^3 of concrete (with different ratios for the shell and the foundation), concrete quantities, reinforcing steel quantities, and concrete form dimensions were developed.

    6) Unit costs for the above items were derived from recent estimates from ABENCS on the Solana project to compile the tower costs.

- Estimates for the nitrate salt thermal storage systems were derived from the preliminary design and cost estimate prepared by Nexant for the AndaSol 1 and 2 parabolic trough projects in Spain, and an in-house, two-tank storage optimization program.

- Direct labor rates by craft, including payroll additives, for a representative desert site near Los Angeles were estimated as follows:

- Mechanical: $38.13 / hr
- Civil: $26.72 / hr
- Steel worker: $38.32 / hr
- Pipe fitter: $42.68 / hr
- Electrician: $29.42 / hr
- Instrument technician: $36.85 / hr

Equipment and material installation costs for items which are distributed among the craft hours were estimated as a percentage of the direct wage rates. These distributable costs included equipment rentals, welding supplies, construction utilities, labor for material handling, and labor for site clean-up. The distributable costs were estimated to be 84.5 percent of the direct labor costs. Thus, the total craft labor rates to the project were estimated as follows:

- Mechanical: $70.35 / hr
- Civil: $49.30 / hr
- Steel worker: $70.70 / hr
- Pipe fitter: $78.84 / hr
- Electrician: $54.28 / hr
- Instrument technician: $67.99 / hr

- A sales tax of 7.75 percent was applied to all equipment and bulk material purchases.
- An allowance for freight, equal to 4 percent of the equipment and materials cost, was included in the estimate
- At this stage of the project, the projects designs are conceptual. As the design progresses through the preliminary and the final design stages, additional details on the major equipment and the bulk material will be developed. As such, conceptual capital cost estimates are necessarily incomplete, as all of the equipment and material have not yet been identified. To account for the capital costs of the items not yet identified, various contingencies, ranging from 5 percent to 15 percent, were applied to the system level costs.

Details of the direct field cost estimate for the subcritical nitrate salt plant are presented in Appendix C. As noted below in Table 29, the thermocline storage systems for the high temperature supercritical plants are very expensive. Details of the direct field costs for the thermocline systems are shown in Appendix D.

5.1.2 Indirect Field Costs

The indirect field costs include final design engineering, procurement, construction management, startup, checkout, and the contractor's fee.

The development of the estimate for final design and procurement is shown in Table 26. The annual personnel costs are based on the following:

- Payroll expenses for vacation, holidays, sick leave, and employer payroll contributions equal to 40 percent of the direct wages

Table 26 Final Design and Procurement Estimate

Position	Number of People	Duration, years	Direct Wage, $/hr	Annual Cost	Total Cost
Project Manager	1	5.0	$60	$384,000	$1,920,000
Project Engineer	1	5.0	$55	$352,000	$1,760,000
Project Administrator	2	5.0	$25	$160,000	$1,600,000
Mechanical					
- Lead	2	5.0	$50	$320,000	$3,200,000
- Engineer	6	2.5	$45	$288,000	$4,320,000
Civil/Structural					
- Lead	1	5.0	$50	$320,000	$1,600,000
- Engineer	4	2.0	$45	$288,000	$2,304,000
Control/Instrumentation					
- Lead	2	5.0	$50	$320,000	$3,200,000
- Engineer	6	2.5	$45	$288,000	$4,320,000
Electrical					
- Lead	2	5.0	$50	$320,000	$3,200,000
- Engineer	6	2.0	$45	$288,000	$3,456,000
Plant Design	4	4.0	$45	$288,000	$4,608,000
Technical Specialists	4	3.0	$55	$352,000	$4,224,000
Procurement					
- Lead	1	4.0	$55	$352,000	$1,408,000
- Buyer	6	2.0	$35	$224,000	$2,688,000
Project Controls	2	5.0	$30	$192,000	$1,920,000

					$45,728,000

- Overhead and contractor profit expenses equal to 120 percent of the sum the direct wages and payroll expenses.

The development of the estimate for construction management and field procurement costs is shown in Table 27. The annual personnel costs are based on the following:

- Payroll expenses for vacation, holidays, sick leave, and employer payroll contributions equal to 40 percent of the direct wages

- Overhead, travel, per diem, relocation, and contractor profit expenses equal to 160 percent of the sum the direct wages and payroll expenses.

The development of the estimate for startup and checkout costs is shown in Table 28. The annual personnel costs are based on the following:

- Payroll expenses for vacation, holidays, sick leave, and employer payroll contributions equal to 40 percent of the direct wages

Table 27 Construction Management and Field Procurement Estimate

Position	Number of People	Duration, years	Direct Wage, $/hr	Annual Cost	Total Cost
Construction Manager	1	3.0	$60	$454,000	$1,362,000
Project Engineer	1	3.0	$55	$416,000	$1,248,000
Project Administrator	2	3.0	$25	$189,000	$1,134,000
Mechanical	2	2.5	$45	$341,000	$1,705,000
Plant Design	1	2.5	$45	$341,000	$852,500
Civil/Structural	1	2.5	$45	$341,000	$852,500
Control/Instrumentation	3	2.5	$45	$341,000	$2,557,500
Electrical	3	2.5	$45	$341,000	$2,557,500
Technical Specialists	4	2.5	$55	$416,000	$4,160,000
Procurement	2	2.5	$40	$303,000	$1,515,000
Project Controls	2	2.5	$30	$227,000	$1,135,000
Warehouse Clerk	1	2.5	$25	$189,000	$472,500

					$19,551,500

Table 28 Startup and Checkout Estimate

Position	Number of People	Duration, years	Direct Wage, $/hr	Annual Cost	Total Cost
Startup Manager	1	2.0	$60	$454,000	$908,000
Project Administrator	1	2.0	$25	$189,000	$378,000
Mechanical	4	2.0	$45	$341,000	$2,728,000
Control/Instrumentation	5	2.0	$45	$341,000	$3,410,000
Electrical	3	2.0	$45	$341,000	$2,046,000
Plant Design	2	2.0	$45	$341,000	$1,364,000
Technical Specialists	4	2.0	$55	$416,000	$3,328,000
Procurement	1	2.0	$40	$303,000	$606,000
Project Controls	2	2.0	$30	$227,000	$908,000
Warehouse Clerk	1	2.0	$25	$189,000	$378,000

					$16,054,000

- Overhead, travel, per diem, relocation, and contractor profit expenses equal to 160 percent of the sum the direct wages and payroll expenses.

For the purposes of the 6 plant estimates, the following have been assumed:

- None of the plant designs are significantly more complex than the others. As a result, the engineering, procurement, construction management, startup, and checkout costs are same for all plants

- The contractor's fee is 5 percent of the sum of the direct field costs, engineering, procurement, construction management, startup and checkout.

5.1.3 Project Related Costs

Project related costs include those expenses incurred by the owner, and fees for project financing. At this stage of the design, most of the project related costs were estimated as percentages of the sum of the direct and indirect field costs, as follows:

- Project development cost: 5.0 percent
- Project development fees: 2.0 percent
- Owner's general and administrative expenses: 2.5 percent
- Constructor mobilization: 1.0 percent
- Initial spare parts: 0.6 percent
- Owner's contingency: 1.5 percent
- Initial working capital: 2.5 percent
- Lender's initiation fee: 1.5 percent
- Lender's closing fee: 0.5 percent

Additional project related costs include funded debt reserve and interest during construction. The former is estimated to be 6 months of debt service, and the latter is estimated at a 6.0 percent interest rate on the construction expenditures from the centroid of the expenditures to the commercial operation date. The expenditure centroid is assumed to be two-thirds of the design and construction period.

5.1.4 Summary of Capital Cost Estimates

A summary of the 6 capital cost estimates is shown in Table 29. Unit costs range from a low of $6,500/kWe for the subcritical nitrate salt plant, to a high of $11,000/kWe for the high temperature supercritical CO_2 plant.

The unit costs for the plants with nitrate salt storage fall within a range of $6,500/kWe to $7,500/kWe, while both of the plants with thermocline storage have a nominal unit cost of $10,500/kWe. Most of the difference in cost is due to the storage system. The unit cost of the two-tank nitrate salt systems is approximately $24/kWht, while the unit cost of the thermocline systems is nominally 10 times as high at $255/kWht. The higher cost is a direct consequence of the higher operating pressure. For the nitrate salt systems, the sum of the unit steel requirement for the cold and the hot tanks is 360 kg/MWht, while the unit steel requirement for the thermocline vessels is a much more daunting 19,400 kg/MWht. Although the performance of the thermocline systems takes credit for the thermal mass provided by the vessel walls, the high fluid pressures, in essence, lead to the substitution of low cost quartzite rock with the more expensive stainless steel.

With supercritical fluid pressures of 150 bar and higher, the stainless steel requirements are such that the storage system is 50 percent more expensive than the collector system. Under such a scenario, the Rankine cycle efficiency in the plants with thermocline storage would need to be on the order of 90 percent to achieve economic parity with the plants using nitrate salt storage. Such efficiencies, of course, are precluded by thermodynamic limitations.

Table 29 Summary of Capital Cost Estimates

Cost Category	Subcritical nitrate salt	Supercritical nitrate salt	Low temperature supercritical H_2O	High temperature supercritical H_2O	Low temperature supercritical CO_2	High temperature supercritical CO_2
Land	31,564	28,603	30,388	30,150	31,296	31,178
Structures and Improvements	20,943	20,622	20,815	20,788	20,913	20,901
Collector System	913,275	827,593	879,227	872,345	905,494	902,103
Receiver System	288,004	343,950	458,735	363,615	552,769	451,411
Thermal Storage System	174,585	169,533	169,533	1,349,383	169,533	1,302,939
Steam Generation System	66,327	65,467	65,461	4,547	65,461	96,256
Electric Power Generation System	351,011	351,875	351,875	359,030	351,875	356,728
Master Control System	4,297	4,297	4,297	4,297	4,297	4,297
Total Field Cost	1,850,006	1,811,941	1,980,330	3,004,156	2,101,638	3,165,813
Engineering, Procurement, and Home Office	52,587	52,587	52,587	52,587	52,587	52,587
Construction Management and Field Procurement	22,484	22,484	22,484	22,484	22,484	22,484
Startup and Checkout	18,462	18,462	18,462	18,462	18,462	18,462
Contractor Fee (5 percent)	97,177	95,274	103,693	154,884	109,759	162,967
Total Indirect Cost	190,711	188,807	197,227	248,418	203,292	256,501
Total Overnight Construction Cost	2,040,717	2,000,748	2,177,557	3,252,573	2,304,930	3,422,314
Development costs (5.0 percent)	102,036	100,037	108,878	162,629	115,246	171,116
Development fees (2.0 percent)	40,814	40,015	43,551	65,051	46,099	68,446
Owner's general and adminstrative costs (2.5 percent)	51,018	50,019	54,439	81,314	57,623	85,558
Constructor mobilization (1.0 percent)	20,407	20,007	21,776	32,526	23,049	34,223
Initial spare parts (0.6 percent)	12,244	12,004	13,065	19,515	13,830	20,534
Owner's contingency (1.5 percent)	30,611	30,011	32,663	48,789	34,574	51,335
Initial working capital (2.5 percent)	51,018	50,019	54,439	81,314	57,623	85,558
Interest during construction (1 year; 7 percent)	169,242	165,927	180,590	269,744	191,154	283,821
Lender's initiation fee (1.5 percent)	30,611	30,011	32,663	48,789	34,574	51,335
Lender's closing fee (0.5 percent)	10,204	10,004	10,888	16,263	11,525	17,112
Funded debt reserve (6 month debt service)	28,060	27,510	29,941	44,723	31,693	47,057
Total Project Related Expenses	546,264	535,565	582,894	870,657	616,989	916,094
Total Capital Cost	2,586,981	2,536,314	2,760,451	4,123,230	2,921,919	4,338,407
Unit Cost, $/kWe	6,467	6,341	6,901	10,308	7,305	10,846

5.2 Operation and Maintenance Cost Estimates

Annual operation and maintenance costs were assembled for the 6 plant designs. The principal point of departure for all of the estimates is the compilation of the historical operation and maintenance data from the SEGS III through VII parabolic trough projects at Kramer Junction, California. The SEGS data include the following:

- Staff descriptions (i.e., plant manager, or equipment operator), number of personnel for each function, and wage rates
- Spare parts and equipment costs for the steam generator, the Rankine cycle, and the balance of plant

- Raw water costs, plus the costs for water treatment chemicals
- Service contract costs, for items such as nitrogen supply, telephones, computers, and vehicle maintenance
- Miscellaneous items, such as site improvements, travel, office supplies, equipment rentals, and service vehicle fuel.

The staffing plan is shown in Figure 57. The staff requirements are taken to be the same for all 6 projects.

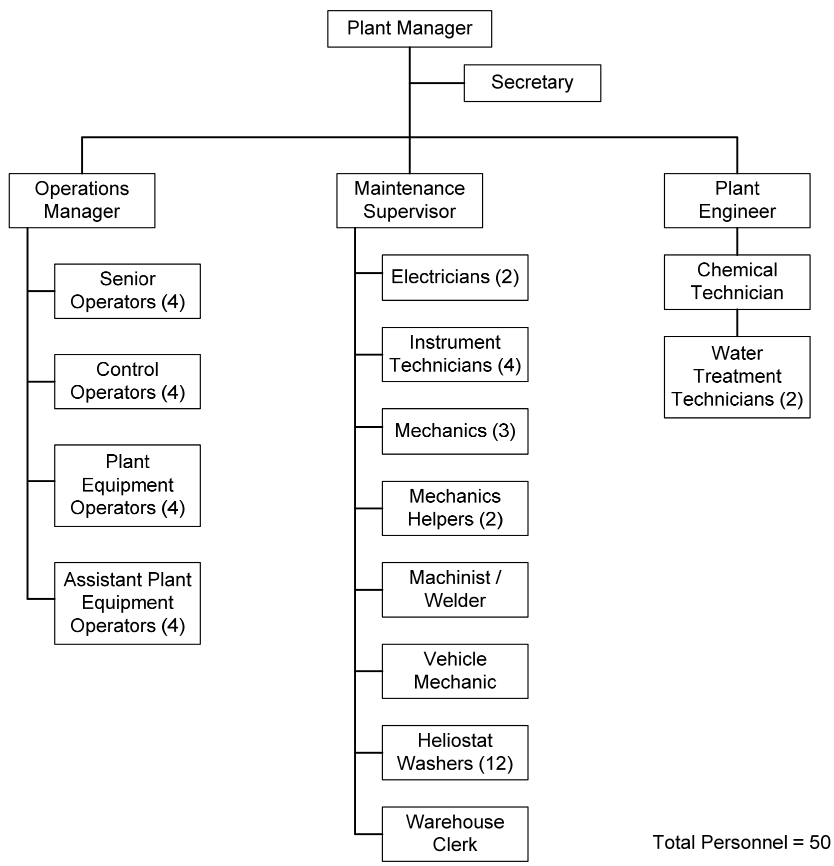

Figure 57 Operation and Maintenance Staffing Plan

The development of the annual personnel expenses for the plant staff is shown Table 30. The annual personnel costs are based on the following:

- Payroll expenses for vacation, holidays, sick leave, and employer payroll contributions equal to 39 percent of the direct wages

- Overhead and contractor profit expenses equal to 45 percent of the sum the direct wages and payroll expenses.

Non-labor operation and maintenance costs are estimated as a percentage of system costs. The development of the non-labor costs for the subcritical nitrate salt plant is shown in

Table 31. Non-labor costs for the other 5 plants are similar.

Table 30 Annual Cost for Operation and Maintenance Staff

Position	Number of personnel	Direct wage, $/hr	Total cost
Plant Manager	1	$60	$252,000
Operations Manager	1	$54	$226,000
- Senior Operators	4	$44	$738,000
- Control Operators	4	$40	$671,000
- Plant Equipment Operators	4	$35	$587,000
- Assistant Plant Equipment Operators	4	$32	$537,000
Maintenance Supervisor	1	$54	$226,000
- Electricians	2	$42	$352,000
- Instrument Technicians	4	$42	$704,000
- Mechanics	3	$32	$402,000
- Mechanics Helpers	2	$25	$210,000
- Machinist / Welder	1	$38	$159,000
- Vehicle Mechanic	1	$28	$117,000
- Heliostat Washers	12	$12	$604,000
- Warehouse Clerk	1	$15	$63,000
Plant Engineer	1	$40	$168,000
Chemical Technician	1	$35	$147,000
Water Treatment Technician	2	$30	$252,000
Secretary	1	$18	$75,000
	-----		---------------
	50		$6,490,000

Table 31 Non-Labor Operation and Maintenance Costs for Subcritical Nitrate Salt Plant

Non-labor costs	
- Heliostat field (0.5 percent of system cost)	$4,570,000
- Receiver system (2.0 percent of system cost)	$5,910,000
- Thermal storage system (1.0 percent of system cost)	$1,750,000
- Steam generation system (1.5 percent of system cost)	$990,000
- Electric power generation system (2.0 percent of system cost)	$6,430,000
- Service contracts	$500,000
- Water	$125,000
- Miscellaneous	$350,000
- Capital equipment	$140,000

Subtotal: Non-labor costs	$20,765,000

5.3 Levelized Cost of Energy Estimates

Estimates of the levelized cost of energy were developed using a 30 year cash flow analysis. Working with various financial parameters and constraints, the model solves for the cash flow in each year of the project required to satisfy the debt, equity, tax, insurance, and operating cost obligations. Future year costs are discounted to obtain a levelized energy cost.

The principal financial inputs to the model include the following:

- Project financing by an independent power producer
- Construction start date of 2009, and commercial operation date of 2012
- Federal and state income tax rates of 35.0 and 5.3 percent, resulting in an effective rate of 38.4 percent
- Property insurance and property tax rates of 0.5 and 0.0 percent, respectively
- Investment tax credit of 30 percent
- Modified accelerated capital recovery, with a 5 year depreciation period
- Debt interest rate and term of 6.0 percent and 12 years, respectively
- Minimum debt coverage ratio of 1.25
- Return on equity of 12.0 percent, with no supplemental investments past the commercial operation date
- No escalation in the sales price of the electric energy.

In general, the incentives offered by the investment tax credit and the accelerated depreciation favor equity financing over debt financing, and the optimum fractions of debt and equity financing are in the range of 37 percent and 63 percent, respectively. As a consequence of the low debt contributions, the debt coverage ratios are readily satisfied, with minimum values of about 1.59 in the last year of the debt term. The discount rate, taken to be the weighted average cost of capital, is a nominal 9.8 percent.

A summary of the levelized cost of energy calculations is shown in Table 32.

5.4 Economic Assessment

Several conclusions can be drawn from the levelized cost of energy estimates, as follows:

- The use of a supercritical Rankine cycle can offer a small improvement in levelized energy cost in comparison with a subcritical Rankine cycle

Table 32 Summary of Levelized Cost of Energy Estimates

	Subcritical nitrate salt	Supercritical nitrate salt	Low temperature supercritical H_2O	High temperature supercritical H_2O	Low temperature supercritical CO_2	High temperature supercritical CO_2
Annual Net Plant Ouput, MWhe	1,566,960	1,535,440	1,490,319	1,613,883	1,494,023	1,447,889
Total Capital Cost, $1000	2,586,981	2,536,314	2,760,451	4,123,230	2,921,919	4,338,407
Annual Operation and Maintenance Cost, $1000	21,205	21,855	24,405	23,365	26,425	26,485
Levelized Cost of Energy, $/kWhe	0.167	0.168	0.183	0.240	0.193	0.284
Relative Levelized Cost of Energy	1.00	1.01	1.09	1.44	1.16	1.70

- A nitrate salt receiver, in combination with nitrate salt storage, is preferred over the combination of a supercritical fluid receiver with nitrate salt storage

- For large thermal storage systems, systems operating at low pressures are strongly preferred over those operating at high pressures.

6 Conclusions

Several conclusions have been drawn from the results of the study, as follows:

1) The use of supercritical H_2O as the heat transport fluid in a packed bed thermocline is likely not a practical approach. The specific heat of the fluid is a strong function of the temperatures at values near 400 °C, and the temperature profile in the bed during a charging cycle is markedly different than the profile during a discharging cycle. It's practical to a remove heat from the bed; however, after a series of charge / discharge cycles, it becomes increasingly difficult to add heat to the bed. After perhaps 20 cycles, the energy utilization of the bed approaches zero. For the purposes of this study, the high temperature supercritical H_2O plant was judged to be infeasible.

2) The use of supercritical CO_2 as the heat transport fluid in a packed bed thermocline is technically feasible, as consecutive charge / discharge cycles lead to repeatable temperature profiles. Nonetheless, the high operating pressures for the supercritical fluid require the use of pressure vessels, rather than atmospheric pressure tanks, to contain the storage inventory. For the nitrate salt storage systems, the sum of the unit steel requirement for the cold and the hot tanks is 360 kg/MWht, while the unit steel requirement for the supercritical CO_2 thermocline vessels is a much more daunting 19,400 kg/MWht. Although the performance of the thermocline systems takes credit for the thermal mass provided by the vessel walls, the high fluid pressures, in essence, lead to the substitution of low cost quartzite rock with the more expensive stainless steel. The unit cost of the two-tank nitrate salt systems is approximately $24/kWht, while the unit cost of the thermocline systems is nominally 10 times as high at $255/kWht.

3) Each of the low temperature supercritical plants use a supercritical fluid-to-salt heat exchanger. During startup each day, the heat exchanger imposes a thermal demand on the net energy collection to bring the heat exchanger to the normal operating temperature. The heat exchanger also imposes a time delay on the startup of the receiver to keep the temperature change rates for the heat exchanger within the limits set by the manufacturer. However, the effects on the annual performance of the startup energy demands and delays are relatively minor, and do not influence the relative rankings among the 6 plant designs.

4) Each of the plant designs require a heat transport loop between the towers and the central power block. As with the supercritical fluid-to-salt heat exchanger, the daily startup energy demands of the heat transport loops have a measurable, but relatively small, influence on the annual plant performance.

5) To achieve reasonable panel fatigue lifetimes for the supercritical receivers, the tube wall thickness should be 2.5 mm, and preferably less. For high pressure systems, this translates into tubes with a small diameter. For example, the low temperature supercritical H_2O receiver has 150 tubes per panel, with a tube outside diameter of 19 mm. In comparison, the baseline nitrate salt receiver has 70 tubes per panel, with a tube outside diameter of 56 mm. No assessment has been made of the practicality of fabricating a panel with tubes 36 m long, but only 19 mm in diameter. Other fabrication considerations not yet addressed include the following:

a) The tubes make the transition between the absorber section and the panel headers through curved sections known as jumper tubes. The jumper tubes connect with the headers at assigned circumferential positions to provide the space necessary for welding. Further, the tube-to-header connections are typically made with a transition nozzle, and the nozzle diameter is greater than the tube diameter. Given a limited number of circumferential positions available, it may or may not be practical to connect some 150 small diameters tubes to a header.

b) A single tube in a panel can experience a failure, and it is desirable to replace a tube without the need to replace the complete panel. Further, it is desirable to weld the replacement tube into position using an automatic orbital welder. Whether such a welder can be accommodated within the limited space available between adjacent circumferential positions on the header has yet to be determined.

c) The wall thickness of the receiver tube is much less than the wall thickness of the upper and lower header. During cloud interruptions, the tube-to-header joints can experience temperature change rates of several 1000 °C per hour. To reduce the magnitude of the transient thermal stresses, the transition between the header and the tube can be formed by pulling a nozzle directly from the header, resulting in a smooth transition in wall thickness. Whether it is possible to pull the required number and location of nozzles from a header has yet to be determined.

d) Pulling nozzles from a header has been demonstrated for salt receivers, where the maximum fluid pressure is perhaps 20 bar. Whether sufficient strength will remain in a header which operates at 350 bar is an item requiring additional examination.

e) The outer crown temperatures are in the range of 700 to 800 °C. At temperatures of 700 °C and above, intermetallic compounds can precipitate between, and within, the grains of nickel alloys. The precipitation leads to an increase in tensile strength, and a decrease in ductility. However, the strain and low cycle fatigue analyses were based on data developed at temperatures up to 600 °C. Whether these data can be extrapolated to the temperatures expected for the supercritical H_2O and the supercritical CO_2 receivers is an open question.

6) The use of a supercritical Rankine cycle offers a net improvement in annual plant efficiency compared with a subcritical Rankine cycle. The minimum supercritical steam turbine size is about 450 MWe. Further, the availability of a large thermal storage system will allow the Rankine cycle to avoid undesirable operation at part load conditions in the morning and afternoon. Given the practical limitations on collector field and receiver sizes, supercritical plants will likely require 2 collector fields and receivers, connected by heat transport loops to a central power block.

7) As a corollary to Item 6, the minimum plant investment in a supercritical central receiver power plant will be on the order of $2 billion.

8) A ranking of the plants, in descending order of technical and economic feasibility, is as follows:

i) Supercritical nitrate salt and baseline nitrate salt: equal ratings
ii) Low temperature supercritical H_2O
iii) Low temperature supercritical CO_2
iv) High temperature supercritical CO_2
v) High temperature supercritical H_2O

9) The two-tank nitrate salt thermal storage systems are strongly preferred over the thermocline systems using supercritical heat transport fluids.

Appendix A
RCELL Analyses

RCELL Analysis in Support of the Abengoa/DoE Study of Advanced Storage Options

Report to Abengoa Solar on

Department of Energy
Advanced Thermal Energy Storage for Central Receivers with Supercritical Coolant
Grant DE-FG36-08GO18149

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TIETRONIX

Introduction

This report documents the results of the study performed by Tietronix Software using the RCELL suite of codes. It is part of the R&D project awarded to Abengoa Solar by the Department of Energy, the goal of which is to investigate a variety of methods to store extremely high-temperature thermal energy for CSP applications. The projects are expected to further DOE's goal of reducing the cost of CSP electricity from today's 13-16 cents per kWhe with no thermal storage to 8-11 cents per kWhe with 6 hours of thermal storage by 2015, and to less than 7 cents per kWhe with 12-17 hours of thermal storage by 2020.

The aim of the project is to:

- Determine if supercritical working/heat transport fluids, either with a conventional two-tank salt storage unit or in combination with ceramic thermocline storage, offer a reduction in levelized energy cost from a reference, subcritical nitrate salt plant design or one designed to work with a supercritical turbine.

- If a system utilizing ceramic thermocline storage shows an advantage, demonstrate a prototype thermocline storage unit

This report describes the specific Task 1.1.2 – Collector Field and Receiver Design, which relates only to the solar portion of the plant, and provides the results obtained for the optimized design of each of the six plant designs considered. The reports will first introduce some of the key concepts of t he RCELL suite of tools, then describe the invariant inputs used for the studies, describe the different plant designs evaluated and finally present the results obtained with the RCELL suite of code to determine the optimum configuration of the solar portion of each of the plants.

Description of the Main RCELL Functions

The RCELL suite of tools was designed to perform a number of functions found necessary in the preliminary design, evaluation, final design, and operation of Central Receiver power plants. The primary functions are:

1. Cellwise basis (NS)
   - Implementation of Hermite coefficients to develop a detailed flux map on the image plane on the receiver and transfer the flux to nodes on the receiver.
   - Producing node files (intercepted flux on each node) to use on RC and IH.
   - Producing Interception factor files from the data for use in RC and IH
   - Instantaneous performance-shading, blocking, cosine computation (SBC)
   - Annual performance and summary

2. Cellwise basis (RC)
   - Cost effective optimization of Heliostat spacings
   - Cost effective optimization of Heliostat fields
   - Cost effective optimization of central receiver systems

- Co-optimization of field and receiver under an allowable flux constraint

3. Individual Heliostat basis (IH)
   - Layout of heliostat field to emulate the optimum Cellwise design
   - Detailed evaluation of receiver flux maps and of SBC.
   - Annual performance summary

To support these functions, a number of detailed models are required. A nominal list of the primary models follows:

- Sun position via Ephemeris (to < 0.1 degree error)
- Site dependent insolation model
- Cellwise structure generator
- Individual heliostat structure generator
- Receiver node structure generator (cylinders, flats/apertures)
- Heliostat (rectangular, split rectangular, round)
- Time step generators
- Shading and blocking processor (rectangular, split rectangular or round, 8 to 24 neighbors, stereographic projections vs. processing of overlapping events)
- Aim point generator, weight functions
- Image radius estimator (Gaussian)
- Image generator - Hermite function approximation
- Receiver flux map / intercept factors
- Receiver temperature and allowable flux model
- An annual mean SBC data base generator
- A file of cellwise intercept factors,
- The RC optimization processor (RCOP)
- The RC iteration model to cause RCOP to converge on a desired parameter, such as design point power, or annual energy
- A spacing coefficient generator
- A heliostat layout processor (uses RCELL spacing coefficients)
- An aim level processor (uses weights)
- An excess flux density eliminator
- A turbidity estimator/projector
- A clear turbid sky insolation generator
- A complete set of parametric costs (receiver, tower, piping, pumps, heliostats, land, wiring, including PVO&M for each)

Here follows a short description of some RCELL computations:

- The optimization is based on a figure of merit (FOM) which is defined as capital cost/annual energy produced rather than Levelized Energy Cost (LEC). Consequently, there is no need to enter or be concerned with details of the future financial markets etc. The only financial decision is the value to use for the long-term net interest rate (real interest less inflation).

This enters into defining the Present Value of the annual O&M to add to the actual capital investment, and is relatively stable at about 3%.

- The optimization can be set to converge to minimize the FOM giving the optimum system for the defined tower and receiver aperture. Alternatively, we can converge to a defined annual energy level or design point power level. By choosing power level at the design point, the receiver size selected defines the average flux density.

- RCELL has been used extensively, and the optimization has been found to be very reliable and remarkably stable. This stability results from the multitude of variables that enter the optimization. If any one of them is changed, the optimization shifts to accommodate the change, e.g. if the heliostat cost is decreased, the system optimization changes to use heliostats LESS efficiently. For example, a shorter tower will be defined as the optimum and more shading and blocking of the cheaper heliostats will be tolerated.

- Because of the way the shading and blocking data is handled, change of heliostat size has no effect on the resulting database nor does change of tower height.

- A standard output for each run is a set of coefficients for the azimuthal and radial separation of heliostats over the entire field. This allows the solar designer to eliminate the cell structure from consideration. Thus, local neighborhoods of neighbors can readily be set up to allow external verification of the optimization results.

- A detailed Gaussian model for interception calculation on a circular target aperture. This model includes effects of sunshape, heliostat size, focus, off-axis aberrations, beam errors, slant range, and receiver orientation and dimensions. It provides results that compare very well with the more accurate but more cumbersome Hermite Coefficient approach, which can handle any reasonable receiver shape.

- By defining an extra tall receiver and aiming all heliostats at the equator, we can use the Hermite Coefficient approach to determine the spillage past the sides of that receiver. By this means, we find a fairly narrow receiver can indeed be tolerated. For the reference case, the spillage from the sides of the receiver drops exponentially from 10% at 12.5 m dia to 1% at 22 m dia. A 19.4 m dia receiver would give a 2% contribution to spillage from the sides (1% each side). By adjusting the length and using a five level aim, we can obtain a flat top distribution at the allowable flux density and an additional 1% spillage (1/2% each, top and bottom to avoid burning the covers) this gives an average of about 75 kW of spillage per meter of circumference (a nominal 100 kW on the North, and 50 kW on the South). We have used 20 to 25m diameter receivers in this study, so side spillage is not an issue.

RCELL Inputs / Outputs Description

The following list presents the invariant inputs, common for each plant design evaluated, the fluid/temperature dependant inputs for the several plants, and the results provided by RCELL.

- Invariant Inputs
  - Site location
  - Radiation and atmospheric attenuation models
  - Heliostat characteristics and cost functions
  - Land and wiring cost functions
  - Tower cost function

- Fluid dependent inputs
  - Design point thermal energy delivered to ground
  - Allowable incident flux as a function of fluid temperature/location
  - Vertical aimpoint weights
  - North-to-South power ratio (trim ratio)
  - Cost functions for the receiver, heat transfer fluid piping, and heat transfer fluid pumping

- Outputs
  - Tower height
  - Receiver height and diameter
  - Collector field area and heliostat distribution
  - Data for performance "waterfall" from sun to storage
  - Summary of subsystem costs at the design point
  - Matrix of solar system efficiency vs. month and hour

The first five outputs come directly from the RC optimization code, the Matrix requires a separate Annual Run, using the NS performance code. For such a preliminary study, it is adequate to describe the density and distribution of heliostats everywhere in the field without defining the actual location of each heliostat.

Site Latitude and Insolation

The proposed area for the site is in the vicinity of Daggett, California. The climate type there is classified as Csa (Mediterranean, dry summer, warm) or BWh (middle latitude desert). The site latitude is 35 degrees, the elevation is 550 meters.

The entire set of data for the Insolation Model is contained in Table 1. (See glossary at end of report for definitions.)

Heliostat Dimensions, Performance and Cost

The heliostat is defined as a non-inverting glass mirror design, with a pedestal mounted elevation / azimuth drive. It carries 28 facets, each 1.355 m tall by 3.220-m wide, with 15-mm separation. The facets are stacked in 4 columns of 7, and are cylindrically focused to 3 focal lengths (ranging from 2 to 3.5 to 4 times the focal height) to effectively reduce the 3.22-m dimension. The facets are canted, on-axis, to slant range. For our purposes, the reflective area is 122.167 m^2, DMIR = (W x H)**0.5, i.e., 11.1246 m, mechanical limits constraint due to a required 200 mm clearance is 1.47* DMIR. A photograph of the heliostat is shown in Figure 1.

Table 1 Insolation Model Summary

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
PPS	.75	.75	.80	.85	.90	.90	.90	.92	.92	.92	.85	.75	0.80
Precipitable H_2O	.73	.65	.72	.87	.99	1.16	1.92	1.97	1.44	.96	.76	.83	cm
Turbidity	.05	.05	.05	.05	.07	.07	.10	.10	.10	.07	.05	.05	
Season	1	1	1	1	2	2	2	2	2	1	1	1	
CSI-DBN	6.854	8.052	9.209	10.11	10.34	10.45	9.500	8.880	8.000	7.460	6.778	6.293	KWhr/day
With clouds	5.140	6.039	8.598	9.309	9.408	8.550	8.170	7.360	6.864	5.761	4.720	5.140	2.652 MWhr
Visual Range at Sea Level	50.	50.	50.	50.	42.	42.	35.	35.	35.	42.	50.	50.	km

Figure 1 Abengoa 122 Square Meter Heliostat

The random error budget is 1.3-mrad surface normal and 0.65 mrad tracking error. The tracking errors are converted to beam errors by doubling, and adding them in quadrature, giving a beam error sigma of 2.90 mrad. No account is taken of gravitational effects, wind effects, installation defects, or other defects, such as canting or focusing errors.

Mirror reflectivity is taken as 0.94 (clean) with an average dust factor of 0.935, resulting in a net average reflectivity for design purposes of 0.88. It is assumed that, on average, 98% of the heliostats are operational. In addition, the inefficiency of the layout process in converting from the Cellwise to individual heliostat model, requires RCELL results to be reduced by a slippage factor, which amounts to 1.8% for the current geometry. Thus, the total loss factor is 0.94 x 0.935 x 0.98 x 0.982 = 0.846, before shading, blocking, and cosine losses.

A summary of the principal heliostat characteristics is as follows:

- Error budget (beam)

   - 2.6 mrad surface normal
   - 1.3 mrad tracking error
   - 1.0 mrad focus errors are included in the surface normal error
   - 1.0 mrad canting errors are included in the tracking error
   - 2.9 mrad total beam error
- 0.94 mirror reflectivity
- 0.935 dust factor
- 0.98 heliostat availability
- 0.982 RCELL slippage factor
- \$210 / m^2 installed heliostat cost

Heliostat operations and maintenance costs were developed during the Utilities Study, based on information from Solar One and Solar Two and O&M studies at the SEGS trough plants. The conclusion was that 50% of the O&M costs should be associated with the number of heliostats, and 50% with the area for the 43-m^2 heliostat at the Solar One pilot plant. Adapting this to the current heliostat results in annual costs (2008 \$) of 73.40 \$/heliostat, plus 1.876 \$/m^2, or for our 122 m^2 heliostat, \$2.47/m^2-year. Applying the present value factor of 19.6 gives an equivalent capital cost of \$48.46/m^2, compared to the heliostat cost of \$210/m^2

The heliostat energy consumption, including the controller, is estimated to be 915 Whe/day, or about 90 watts for the 10.25 hours the sun is above 10 degrees elevation during the average day. It is assumed the heliostats will be operating for 80% of the hours the sun is above this elevation, giving an annual energy requirement of 90 x 0.80 x 3737, or 0.27 MWhr/year for each heliostat. This is converted to a present value by multiplying by FLIFEL = 26, the present value factor for electricity inflating at 2% above nominal inflation. Bulk electricity is assumed to cost \$70/MWhe, so the Present Value O&M adder for electric parasitic energy is \$490.80/heliostat, or \$3.95/m^2 compared to the capital cost of \$210/m^2.

Tower Cost Function

We use the concrete tower cost model developed during the Utilities Study by Black and Veatch (2/24/87), inflated to current costs.

CTOWR = (0.6E6 + 17.72 * THTB**2.392) * (CEI / 320.)
= (1.078E6 + 31.863 * THTB**2.392) * (CEI / 575.4)

Here the THTB (tower height to base) is expressed as [Focal height – Receiver radius – Receiver height / 2 + Elevation of heliostat horizontal axis].

The receiver radius is inserted to account for a transition from concrete to receiver support, which also provides a working platform, and is charged to the receiver.

Radiation and Atmospheric Attenuation

Models for these quantities suitable for use in RCELL have been developed over the years, and were in place for the Utilities Study. They are in basic agreement with other models, but are based on monthly average values of long term average parameters, such as precipitable water (cm of water contained in the water vapor column in the atmosphere above the site), turbidity (related to aerosols in the atmosphere overhead), and percent monthly average cloud cover. The basic insolation model is developed from data taken by Moon in the early 1900's. The atmospheric attenuation is developed from a series of runs using the Air Force attenuation model and database to determine the loss between a heliostat and a receiver at various elevations and ranges. Both these models fit the data with exponential functions, as is appropriate for attenuation problems, and are in good agreement with other models which are less well suited to our purposes. RCELL requires reasonably simple models giving accurate results for any sun position and any receiver elevation and heliostat slant range. For optimization purposes it is important that long-term average values be used rather than data from a recent year or two.

Land and Wiring Costs

The land employed by the field was costed during the Utilities Study at 2,500$/acre in 1986 dollars, which inflates to $4,539/acre in 2008 $. Thus, the current cost is $1.12/m^2. As land is purchased in rectangular blocks, and the field is nearly circular, it is reasonable to multiply by $4/\pi$, giving an effective cost of $1.40/m^2 for the field area.

The wiring cost model assumes that power and optical fiber lines are laid together in shallow trenches. Lines emanate from the tower to field transformers and field controllers scattered regularly in the field. From there they go to array controllers. From each array controller, radial headers are collocated in radial inward and outward trenches to about 10 circles, where they branch to right and left to daisy chain to about 10 heliostats in each branch. For the larger field we are considering here, this model could surely be improved, as could the 30-year-old cost data. Wiring is currently about 5% of the total cost. Transformer and field controller costs could be included, but current estimates are not available for them.

Description of Systems to Assess

The objective of this study is to define systems to directly heat the different working fluids to charge the storage system. Six different systems are considered for this study. They consist of Molten Salt (Nitrate) at Low and High Temperature, Supercritical steam and Supercritical carbon dioxide, each at Low and High Temperatures. The working fluids are set to charge a binary salt two tank storage unit, or in an alternative higher temperature design, to charge a stratified bed storage unit. In each case, the storage unit is to provide sufficient energy at the design point to provide a 1.8 solar multiple to a 400 MWe turbine. Two equal solar plants are defined to provide this duty. Based on the design Rankine cycle efficiency provided by each system the design point power, which must be delivered to the ground by each unit, is defined. An Abengoa spreadsheet is then operated to define the nominal required receiver dimensions, and the maximum allowable flux density around the equator of the receiver based on anticipated vertical flux distributions achieved by the aiming strategy.

A summary of these systems is shown in Table 2. Remarkably, as shown below, the design point power required to be delivered to the receiver by the heliostat field is 1,053 +/- 35 MWt for all cases, in spite of the various differing efficiencies and turbine demands.

Common Receiver Related Factors Defined for Study

200 MWe solar plant design (one of two to supply the 400 MWe turbine)
Various materials/temperatures for the working fluid and heat transfer fluid to ground
Solar multiple of 1.8 (six hours of storage)
Power block parasitics, 10% at design point
Receiver absorbtivity (life time average), 95%
Design point insolation (equinox noon), 950 W/m^2

Table 2 Description of the Parameters and Requirements for the Receiver / Field Designs

Working fluid	Unit	Baseline molten salt	SC molten salt	SC H_2O	SC H_2O	SC CO_2	SC CO_2
Turbine inlet	Temp.	LOW	HIGH	LOW	HIGH	LOW	HIGH
Receiver temp Inlet/Outlet	°C	288/566	335/600	415/675	335/655	332/620	370/670
Storage unit		2-tank molten salt binary nitrate	2-tank molten salt binary nitrate	2-tank molten salt binary nitrate	Packed bed thermocline	2-tank molten salt binary nitrate	Packed bed thermocline
Rankine cycle		125 bar subcritical/ 540°C / 540°C	300 bar / 590°C / 590°C	300 bar / 590°C / 590°C	351 bar / 650°C / 575°C	300 bar / 590°C / 590°C	351 bar / 650°C / 575°C
Gross turbine cycle efficiency	%	43.4	48.8	48.8	49.3	48.8	49.3
Receiver loss Thermal efficiency	kW/m^2 %	28.0 88	34.2 84	47.1 81.5	47.1 82.9	47.1 83.3	47.1 81.5
Receiver demand to storage	MW	912	812	812	804	812	804
Receiver incident radiation	MW	1088.5	1017.5	1048.7	1020.1	1026.1	1038.4
Max allowable incident flux*							
North panels	MW/m^2	995	647	614	592	619	657
South panels	MW/m^2	550	255	342	329	346	364

The lower thermal efficiency reported for the supercritical fluid receivers is due primarily to the larger receiver size associated with the high pressure, thick walled tubing required.

* Estimated by Abengoa using an assumed, but realistic, flux distribution

Description of the Parameters and Requirements for the Receiver/Field Designs

A number of the significant requirements and of the parameters associated with them are tabulated in Table 2 for the low and high temperature systems utilizing the several working fluids studied. These fluids are molten draw salt (a mixture of sodium and potassium nitrates), supercritical steam, and supercritical carbon dioxide. The reference case is a 'low' temperature nitrate salt operating under conditions identical to the Utilities Study, powering a subcritical steam turbine. All other cases power a supercritical steam turbine, achieving significantly higher efficiencies. After accounting for the higher thermal losses experienced by the higher temperature, higher pressure, larger receivers, the incident photon power required by the receiver (from the heliostat field) is surprisingly constant at 1,053 +/- 35 MW.

Development of Cost and Performance Models for Each System

The RCELL optimization routine has as its objective function the ratio (capital cost + present value of O&M) **/** (annual solar system performance). Consequently, to operate the code, appropriate inputs defining the various subsystem costs and performance characteristics are required. Based on specific input values provided by, and on discussions with, the Abengoa project manager, appropriate inputs were developed for each subsystem for each of the six cases. Extensive studies in the 1980's (the Utilities Study) provided a firm base for many of the more basic inputs such as the solar model discussed above, the field wiring model, tower costs, salt receiver costs, and the annual Operations and Maintenance (O&M) costs as a percentage of capital costs for each subsystem. Heliostat characteristics and costs came from an earlier study for Abengoa. It would be appropriate to revisit each of these inputs early in the next phase of this study.

All of these costs are inflated to current dollars by use of the Chemical Engineering Plant Inflation Index (CEI). [Costs are divided by that years CEI, and multiplied by the current years (taken as 2008 for this study) CEI to move them to today's (2008) dollars].

The primary costs analyzed for each case in this study were the receiver costs, vertical piping costs, feed pump costs, and parasitic power. A number of other issues addressed in the Utilities Study were elaborated in more detail based on current information. Parasitic power involved in trace heating of the salt piping was evaluated, but found to be quite small relative to other parasitics. It is assumed that the receiver panels will be preheated as required by the heliostats, as was done at Solar Two.

Solar Core and Roads

RCELL limits the land available to the field due to any constraint via an FLIMIT array, where any available cell is shown as a 4 ($4/4^{th}$ of the cell is available) and restrictions indicated by 3, 2, 1, or 0. A special study with very small cells showed that all heliostats beyond 73 degrees rim angle met the boundary conditions that they contribute positively to the performance of the system. Thus, only the central cell has been assigned a restriction of 0.

Access roads to the solar core are represented by loading field constraints along the line of the road into the FLIMIT array associated with each RCELL summary page. Replacing a 4 with a 3 limits the code to using only ¾ of the land in that cell for heliostats. As the cells are typically about 240 meters on a side, a 30 meter wide road would require 1/8 of the width of the cell. This is accommodated by making every other cell a 3, averaging 1/8 of a cell width restriction, etc. To accomplish a compact plant the two solar fields are assumed to be side by side with the power block between them and to the south. Thus we have WSW and ESE roads 30 m wide. The North road is specified as 10 m wide, so only every 4th cell is reduced to a 3. This alignment of roads minimizes the effect on the flux map resulting from the missing heliostats along the roads.

Power Rating

The power rating (power delivered to the ground by the heliostat field/receiver system) is the product of the turbine design point power, 1/turbine efficiency, 1+fractional power block parasitics, and the solar multiple. The incident radiation required on the receiver to meet this duty is increased by the thermal loss (radiative and convective) and reflectivity (1 - absorbtivity) of the receiver. Taking all these quantities into account for each receiver considered results in an incident radiation requirement of about 1,053 MWt (+/- 35) as shown in Table 2.

Allowable Flux Density and Trim Ratio

For a given receiver duty (outlet temperature, required duty cycles, etc.) the allowable flux density at any point on the receiver is defined not only by the tube material and temperature, but by the working fluid pressure (which defines the wall thickness) and heat transfer characteristics. These and other factors have been implemented in an extensive spreadsheet calculation from Abengoa. By selecting a reasonable vertical flux distribution (flat over 3/4 of the receiver height, dropping to 20% at the ends) and an (A + B*cosine) distribution around the receiver, the maximum allowable flux density to achieve reasonable (10 to 30 year) panel life has been determined.

The challenge of this task is to develop an aiming strategy that can match the assumed vertical distribution and a Trim ratio that delivers the circumferential distribution.

Our aiming strategy defines five vertical aim levels on the receiver (+1, +0.5, 0, -0.5, and -1) to which heliostats are randomly assigned according to weight functions defined to meet the objective. For each heliostat a fairly detailed estimate of the quasi-Gaussian beam radius at the receiver is determined and the shift (from equatorial aim, 0) is determined to bring the edge of the beam (~2 sigma point) to the edge of the receiver. The appropriate aim level (tabulated above) is then applied to define the aim point for that heliostat. By adjusting the weights and a multiplier on the beam radius used, very nearly trapezoidal vertical flux distributions meeting the specifications above are readily achieved. If not, the receiver diameter or height must be increased. If the receiver is abnormally long, more aim levels may be required, but five is generally sufficient.

The trim ratio is defined empirically to meet the required circumferential variation. It is a number (0.0 to about 0.3) applied as a modifier [of the form 1 + RTRIM*cos(azimuth)] to the objective function of the optimizer to disfavor North fields vs. South fields. This imposes a reduction of the allowable shading and blocking in the North, resulting in larger heliostat separations and a more limited northern boundary. The effect on the South is the opposite. Thus, the North-to-South panel power ratio can be modified from a typical value of 2.4 (at Daggett) to a value of 1.0 (not advised). Typical values of RTRIM are 0.1 to 0.13, resulting in North-to-South ratios of about 1.8 to 1.5. Essentially, RTRIM moves heliostats from the North to the South where their annual performance is reduced, but the resulting smaller receiver repays the cost.

Receiver Cost Model

The cost for a baseline molten salt receiver for a subcritical steam turbine was derived from the Utilities Study detailed receiver analysis. That cost model was scaled for inflation from 1986 to current (2008) dollars and scaled to the current nominal baseline receiver dimensions of 20 m dia X 25 m height via the built-in linear, and 0.6 power, dimensional scaling relations. This was developed from the conventional 0.90 power on each dimension by the argument that increases in diameter would require additional welds and perhaps panels, while increases in length would simply require longer tubes and a simple increase in the support structure. The resulting expression is:

Receiver cost (millions of 2008 dollars) = 4.1357 + 47.4088 * (Diam / 20) * (Height / 25)**0.6

This expression developed for a molten salt receiver includes costs of all baseline components above the top of the concrete tower (except for the vertical riser and downcomer piping). For the baseline salt receiver, a current estimate of the actual cost of the Inconel tube and header material is $2.164 million and panel fabrication cost is $1.420 million, for a unit complexity cost of $2,281/m^2 of receiver surface. Thus, about 95% of the 'receiver' cost is in the structure and other operating components, the actual Inconel receiver contributes only a surprisingly small amount. Nevertheless, for the supercritical H_2O receiver the INCREMENTAL unit complexity cost for an equal size receiver is $2,086/m^2, and for the supercritical CO_2 receiver the INCREMENTAL unit complexity cost is $1,045/m^2. These quantities must be added to the baseline receiver cost calculated above. As the typical supercritical receiver area is about 2,500 square meters, this complexity factor adds about $5 or $2.5 million to the respective receiver cost, which is already considerably above the baseline cost due to the larger size associated with the lower allowable flux limits for the supercritical coolants.

Vertical Piping

The vertical piping is a surprising large factor in this study. It incorporates all the costs associated with transporting the working fluid from the outlet of the receiver feed pump to the co-located storage system inlet (piping from the solar core to the power block at the boundary of the field is NOT included in this analysis). Costs of hangers, expansion bellows or 'bends' as appropriate, valves and controllers, insulation, and electric trace heating as required, are included. In some cases, due to high pressures, multiple risers or downcomers are required to maintain a reasonable wall thickness. All these costs are reduced to a single number, dollars/meter of run (a five pipe riser has the same run as a single pipe).

The run for the riser (to the bottom of the receiver: inlet) is typically ~300 m, expressed as:

Receiver focal height – Receiver length / 2 + Heliostat horizontal axis height + 50 metes

The run for the downcomer (from the top of the receiver: outlet) is typically ~330 m, expressed as:

Receiver focal height + Receiver length / 2 + Heliostat horizontal axis height + 50 meters

The additional 50m moves the working fluid away from the tower to a common transfer point to storage.

The piping cost, in 2008 dollars/meter of run, for the several cases studied is tabulated in Table 3.

Table 3 Vertical Piping Costs, per Meter of Run

	Binary salt Lo Temp	Binary salt Hi Temp	SC H_2O Lo Temp	SC H_2O Hi Temp	SC CO_2 Lo Temp	SC CO Hi Temp
Riser - $/m	17,613	17,613	15,519	6,292	53,494	57.141
Downcomer - $/m	13,963	13,963	112,145	62,959	258,346	268,752
Piping cost @300 m & 330 m (millions of $)	9.894	9.894	41.664	22.664	101.204	105.83
Number of risers / downcomers	2/1	2/1	1/1	1/1	5/7	5/6

Taking note of the high cost of the SC H_2O and CO_2 piping, RCELL has optimized at a shorter focal height, reducing these costs by about $2 million and $10 million respectively, but at some cost in added heliostats.

Feed Pump

A different feed pump is required for each of the cases. In the following paragraphs, details of the feed pump costs for each of the systems are presented.

Molten Salt Feed Pump

For the molten salt_cases the feed pump cost model developed during the Utilities Study is simply inflated and scaled to meet our current power levels. The model assumes a friction head of 110 m of salt, adds in the vertical head, scales it with the design point power, and inflates it to current dollars:

CFPUMP = 1.4E6*(((HTX+FHM)/(150. + 70.))*(EQPOWS / 390.))**0.85*(CEI / 320.0)

Where HTX is the focal height, FHM is the friction head in meters, and EQPOWS is the design point power.

The parasitic power requirement is also scaled from the Utilities Study where it is estimated as a fraction of the annual total thermal power delivered to storage, the static head, and the friction head in meters of salt (AEL is the receiver height).

The molten salt parasitic Feed Pump Power =

FPARA = 0.0267*ATPOW *(0.79* (HTX + AEL)+ 0.56*FHM) / 366.

Thus, the pump power is about 2.67% of the annual thermal energy, 0.79 accounts for reduced flow over the year, and 0.56 arises because the friction loss varies as the cube of the flow velocity.

Finally, the present value of the electricity demand is determined by converting this thermal power to electricity at the turbine efficiency and the power block parasitic ratio, then multiplying by the present value factor for electricity over 30 years inflated at 2% over standard inflation (FLIFEL), the cost of a kWhe, and inflating to current dollars:

PVFPP = FPARA * 0.434 / 1.1 * FLIFEL * 0.07 * CEI / 575.4

The same equations were applied for the high temperature molten salt case, but the turbine efficiency is replaced by 0.488 for the supercritical steam turbine.

Low Temperature Supercritical H2O feed pump

This feed pump is scaled from a feed pump used for a similar duty at the Solana parabolic trough plant. The power required to overcome friction losses in the receiver circuit (riser, receiver, downcomer and storage heat exchanger) is compared to the Solana pump power, and the pump cost is scaled as the 0.7 power of the ratio. A 260 m run carrying 880 MWth requires a pump power of 4,196 kWe, so scaling the Solana pump leads to a base cost in early 2009 dollars (CEI estimated at 536) of:

(4,196 kWe / 1,350 kWe)**0.7 * ($971,000) = $2,156,000.

Using a feed pump piping length from the ground to the top of the receiver, plus 50 m to the storage heat exchanger, given by:

Total piping length = TPL = FH + AEL/2 + DMIR/2 + 50

then gives for the LowT SC H2O feed pump:

FPCOST = 2.156*E6 * (((TPL / 260) * 0.75 + 0.25) * (EQPOWS / 880))**0.7 * (CEI / 536)

The annual average power required for this feed pump is:

FPP = [(TPL / 260) * 0.75 + 0.25] * (EQPOWS / 880) * 3,590 kWe

And the PVO&M for the feed pump electricity = FPP * 26 * 0.07 * 3737 * 0.80.

High Temperature Supercritical H2O feed pump

The receiver circulation pump power is reduced from 4,196 to 1,120 kWe, so the costs are reduced accordingly. It is assumed the higher temperature/pressure duty can be accommodated.

Low Temperature Supercritical CO2 Feed Pump

The low temperature supercritical CO_2 feed pump is considered to be essentially the same as the Solana pump, but the duty is higher because friction losses are independently calculated due to the differing characteristics of CO_2. As a result, two larger and more expensive half-power pumps are required, as follows:

The mean annual power requirement for the LowT SC CO_2 Feed pump power =

FPP = 2 * [(TPL / 260) * 0.44 + 0.56] *(EQPOWS / 880) * 10,197 kWe

The cost for these pumps is estimated at:

LowT SC CO_2 feed pump cost = 2 * 4,014,709 * (0.5 * FPP / 10,197)**0.7

And the Present Value O&M equation is the same as for the supercritical H_20 case.

High Temperature Supercritical CO2 Feed Pump

The pump power and costs equations are taken to be the same as for the low temperature case.

Operations and Maintenance

Because the annual operations and maintenance costs for different subsystems of the plant vary considerably, RCELL is equipped to assign a different percent of its capital cost to each element. These percentages were considered carefully during the Utilities Study, and we see no reason to change them at this time; i.e., tower 0.2%; receiver 2%; vertical piping 1%; and feed pump 5%. During a detailed design study, these percentages and the wiring cost model should be re-evaluated, and the final design optimizations re-run.

We add the present value of operations and maintenance (PVO&M) to the capital cost for each subsystem in order to evaluate the objective function for the optimization. The present value factor (a multiplier on the annual cost) may be computed based on the assumed discount factor and the interest rate using the standard formula. This turns out to be essentially equivalent to using a net interest rate, which historically tends to vary closely around 3%, independent of the variations in the discount factor and interest rate. Thus, we assume a 3% net interest rate and a 30-year life for the plant to obtain a present value factor of 19.6 (called FLIFE in the code). This present value factor is multiplied by the annual O&M cost associated with each subsystem and summed to obtain the total PVO&M to be added to the capital cost. It amounts to about 25% of the capital cost.

Current circumstances suggest electricity cost will inflate faster than the economy. Assuming the added inflation is 2% (3%) results in a present value factor of 25.5 (30), which we designate as FLIFEL when dealing with electrical parasitics of the heliostats and feed pumps.

Heliostats operations and maintenance associated costs have been described in the Heliostats section above. It amounts to nearly 20% of the total cost associated with the heliostat field.

Table 4 Conceptual Design Study Results

Baseline - Low T Salt, Subcritical turbine cycle:

Design Point Power: 910MWth (into working fluid)
Configuration: Circular field
Receiver Type: Cylindrical
Aimpoint strategy: Multi-aimpoints
Flux Restriction: N995kW/m^2 S 550W/m^2 *Sizing of the optimum Heliostats Field:*

- Number of Heliostats: 14704
- Land Area: 0.7 10^7 m^2
- Tower Height: 260 m
- Receiver Dimensions: H=25 m D=20 m
- Equinox Noon Power: 910 MWt
- Grand Cost Total ($): 646.25 Millions
- Figure of Merit: 335.798
- Design Point Efficiencies
  - Cosine = 0.802
  - Outage = 0.98
  - Reflectivity= 0.88
  - S&B = 0.993 (slippage = 0.986 => 0.979)
  - Atmospheric Attenuat. = 0.92180
  - Intercept. = 0.898
  - Receiver Absorptivity = 0.92
  - Thermal Losses = 44 MW
  - Total = 0.492
- Annual Efficiencies:
  - Cosine = 0.764
  - Outage = 0.98
  - Reflectivity = 0.88
  - Field Slippage = 0.986
  - S&B = 0.9577
  - Atm. Att. x Intercept = 0.887
  - Receiver Absorptivity = 0.92
- Annual Energy:
  - In the Fluid = 1924.53 GWh

Hi T Salt, Supercritical turbine cycle:

Design Point Power: 910MWth (into working fluid)
Configuration: Circular field
Receiver Type: Cylindrical
Aimpoint strategy: Multi-aimpoints
Flux Restriction: N:647kW/m^2 S:255kW/m^2
Sizing of the optimum Heliostats Field:

- Number of Heliostats: 13347
- Land Area: 0.663 10^7 m^2
- Tower Height: 260 m
- Receiver Dimensions: H=31.56 m D=25.25 m
- Equinox Noon Power: 812 MWt
- Grand Cost Total ($): 628.85 Millions
- Figure of Merit: 374.396
- Design Point Efficiencies
  - Cosine = 0.815
  - Outage = 0.98
  - Reflectivity = 0.88
  - S&B = 0.997 (slippage=0.986 => 0.983)
  - Atmospheric Attenuat. = 0.92234
  - Intercept. = 0.903
  - Receiver Absorptivity = 0.92
  - Thermal Losses = 86 MW
  - Total = 0.479
- Annual Efficiencies:
  - Cosine = 0.773
  - Outage = 0.98
  - Reflectivity = 0.88
  - Field Slippage = 0.986
  - S&B = 0.965
  - Atm. Att. x Intercept = 0.903
  - Receiver Absorptivity = 0.92
- Annual Energy:
  - In the Fluid = 1679.631 GWh

LowT Supercritical Steam:
Design Point Power: 812MWth (into working fluid)
Configuration: Circular field
Receiver Type: Cylindrical
Aimpoint strategy: Multi-aimpoints
Flux Restriction: N:614kW/m^2 S:342kW/m^2
Sizing of the optimum Heliostats Field:

- Number of Heliostats: 14213
- Land Area: 0.739 10^7 m^2
- Tower Height: 240 m
- Receiver Dimensions: H=34.4m D=21.5m
- Equinox Noon Power: 812 MWt
- Grand Cost Total ($): 677.48 Millions
- Figure of Merit: 405.89
- Design Point Efficiencies
    - Cosine = 0.794
    - Outage = 0.98
    - Reflectivity = 0.88
    - S&B = 0.994 (slippage = 0.985 => 0.979)
    - Atmospheric Attenuat. = 0.918
    - Intercept. = 0.906
    - Receiver Absorptivity = 0.92
    - Thermal Losses = 109 MW
    - Total = 0.4523
- Annual Efficiencies:
    - Cosine = 0.757
    - Outage = 0.98
    - Reflectivity = 0.88
    - Field Slippage = 0.985
    - S&B = 0.962
    - Atm. Att. x Intercept = 0.896
    - Receiver Absorptivity = 0.92
- Annual Energy:
    - In the Fluid = 1669.13 GWh

HiT Supercritical Steam:
Design Point Power: 812MWth (into working fluid)
Configuration: Circular field
Receiver Type: Cylindrical
Aimpoint strategy: Multi-aimpoints
Flux Restriction: N:592kW/m^2 S:329kW/m^2
Sizing of the optimum Heliostats Field:

- Number of Heliostats: 14100
- Land Area: 0.711 10^7 m^2
- Tower Height: 250 m
- Receiver Dimensions: H=36.5m D=22m
- Equinox Noon Power: 804 MWt
- Grand Cost Total ($): 637.21 Millions
- Figure of Merit: 388.102
- Design Point Efficiencies
    - Cosine = 0.797
    - Outage = 0.98
    - Reflectivity = 0.88
    - S&B = 0.995 (slippage = 0.985 => 0.980)
    - Atmospheric Attenuat.= 0.92161
    - Intercept. = 0.909
    - Receiver Absorptivity = 0.92
    - Thermal Losses = 118 MW
    - Total = 0.453
- Annual Efficiencies:
    - Cosine = 0.760
    - Outage = 0.98
    - Reflectivity = 0.88
    - Field Slippage = 0.985
    - S&B = 0.963
    - Atm. Att. x Intercept = 0.889
    - Receiver Absorptivity = 0.92
- Annual Energy:

In the Fluid = 1641.85 GWh

LowT Supercritical CO_2:
Design Point Power: 812MWth (into working fluid)
Configuration: Circular field
Receiver Type: Cylindrical
Aimpoint strategy: Multi-aimpoints
Flux Restriction: N:619kW/m^2 S:346kW/m^2
Sizing of the optimum Heliostats Field:

- Number of Heliostats: 14642
- Land Area: 0.8833 10^7 m^2
- Tower Height: 210 m
- Receiver Dimensions: H=33 m D=22 m
- Equinox Noon Power: 812 MWt
- Grand Cost Total ($): 736.47 Millions
- Figure of Merit: 438.06
- Design Point Efficiencies
  - Cosine = 0.781
  - Outage = 0.98
  - Reflectivity = 0.88
  - S&B = 0.989 (slippage = 0.982 => 0.971)
  - Atmospheric Attenuat. = 0.91761
  - Intercept. = 0.899
  - Receiver Absorptivity = 0.92
  - Thermal Losses = 107 MWt
  - Total = 0.4387
- Annual Efficiencies:
  - Cosine = 0.747
  - Outage = 0.98
  - Reflectivity = 0.88
  - Field Slippage = 0.982
  - S&B = 0.961
  - Atm. Att. x Intercept = 0.888
  - Receiver Absorptivity = 0.92
- Annual Energy:
  - In the Fluid = 1681.21GWh

HiT Supercritical CO_2:
Design Point Power: 812MWth (into working fluid)
Configuration: Circular field
Receiver Type: Cylindrical
Aimpoint strategy: Multi-aimpoints
Flux Restriction: N:657kW/m^2 S:364kW/m^2
Sizing of the optimum Heliostats Field:

- Number of Heliostats: 14590
- Land Area: 0. 8954 10^7 m^2
- Tower Height: 210 m
- Receiver Dimensions: H=33 m D=24 m
- Equinox Noon Power: 804 MWt
- Grand Cost Total ($): 746.54 Millions
- Figure of Merit: 450.
- Design Point Efficiencies
  - Cosine = 0.781
  - Outage = 0.98
  - Reflectivity = 0.88
  - S&B = 0.990 (slippage = 0.982 => 0.972)
  - Atmospheric Attenuat. = 0.91713
  - Intercept. = 0.902
  - Receiver Absorptivity = 0.92
  - Thermal Losses = 118 MWt
  - Total = 0.4336
- Annual Efficiencies:
  - Cosine = 0.747
  - Outage = 0.98
  - Reflectivity = 0.88
  - Field Slippage = 0.982
  - S&B = 0.964
  - Atm. Att. x Intercept = 0.891
  - Receiver Absorptivity = 0.92
- Annual Energy:
  - In the Fluid = 1659.0 GWh

Table 5 Comparison of Optimized Systems

Responding to the variations in input parameters for the several systems, RCELL has produced different optimum designs. The primary variables affecting these designs are enumerated in earlier sections of the document. Both cost and performance variations are effective. For example, the very high cost of the vertical piping for the CO2 system results in a significantly shorter tower, a somewhat larger number of heliostats which extend to lower rim angles, and hence require more land area. The lower allowable flux density associated with the higher-temperature and higher-pressure receivers require a larger receiver area with proportionate increases in receiver cost but improved interception for more distant heliostats. It is reasonable to tabulate a number of factors resulting from the study, evaluated at the design point or annual average, as appropriate.

Working fluid	Unit	Salt Baseline	Salt Advanced	SC H_2O	SC H_2O	SC CO_2	SC CO_2
Turbine inlet	Temp.	LOW	HIGH	LOW	HIGH	LOW	HIGH
Focal height	M	260	260	240	250	210	210
V piping cost	M$	11.622	10.98	42.96	21.78	85.07	89.08
Receiver diam.	M	20	25.25	23	22	22	22
Receiver height	M	25	31.56	36.8	36.5	33	33
Receiver cost	M$	51.54	72.97	78.437	74.84	71.34	71.34
N/S power		1.98	2.13	2.02	1.81	1.7	1.84
Trim ratio		+0.1	+0.1	+0.1	+0.1	+0.12	+0.12
Ave Visual Range Multiplier		0.92180	0.92234	0.918	0.92161	0.91761	0.91713
Ave Interception X AVRM		0.89750	0.90250	0.89639	0.89941	0.88821	0.89145
Annual S&B efficiency		0.95766	0.96516	0.96298	0.96304	0.96087	0.96377
# heliostats		14,704	13,385	14,843	14,101	14.642	14,590
Glass area	Km^2	1.7963	1.6353	1.8133	1.7226	1.7888	1.7825
Land area	Km^2	7.0005	6.6574	8.0144	7.1097	8.8329	8.9540
Capital cost	M$	488.76	472.98	542.26	496.96	575.59	578.355
PVO&M	M$	119.47	119.17	131.23	120.03	141.79	142.27
PV electric	M$	38.09	38.08	37.49	20.217	26.887	25.92
Figure of Merit $/annual-MWh		335.80	374.60	413.144	388.102	442.14	449.992
RC Run	ABEN	081409A	110609	82509F	111809A	092709B’	112209D

These values have been excerpted from the Summary Pages, which follow in Appendix A for each run.

Annual and Diurnal System and Field Efficiency

For each of the systems optimized above, the system parameters were transferred to the NS annual performance code via the field array and the set of coefficients defining the heliostat radial and azimuthal separations everywhere in the field. The NS code then establishes the configuration defined by RCELL and sets up a timing array to step through each of the seven days from solstice to solstice in 7 equal steps from noon to "sunset" (10 degrees above the horizon). The symmetric days and hours need not be evaluated so long as the field has essential symmetry (no slope, no time of day pricing, no asymmetric constraints). At each time step the solar model is operated to find the sun position and intensity, applying appropriate weights to account for the vernal and autumnal attenuation and cloud cover. Using this insolation data, the fully dressed representative heliostat in each cell is used to generate cosine, shading, and blocking data. Weighted sums of this data (including the vernal and autumnal cloud coverage) are used to generate a flux map, evaluate the total power to each panel (sum over vertical nodes), and the receiver sum. This material is then processed to provide a substantial number of inputs of value to the receiver designer.

At the current stage of development the time dependent efficiency of the field at providing incident energy on the receiver is of value to use in the SOLERGY code developed by Sandia to evaluate the actual energy expected from the system at each instant of each day of the year. In a final design the panel power during typical days, the gradient across each panel, receiver asymmetry ratios, etc. have been required by, and provided to, receiver designers to assure success of their designs under real life conditions. A representative sample of these outputs is summarized in Appendix C for the molten salt receiver. Others are very similar.

Appendix A: Summary Results Page from RCELL Code for Each System

These summaries first define the heliostat and give the glass area and land area in the field. The first three of these five arrays are tabulated in quarters of the cell occupied, so a 4 represents a full cell. The first one shows the a priori limits placed on the field to account for the roads, solar core, and area available to the optimizer. The second depicts the area selected by the optimizer without regard to the limits, and the third shows the actual area of the allowed and optimized field. The fourth indicates cell in which mechanical limits are imposed and reveals which neighbor is at fault. The fifth is used in case the field contains more than one plane.

Following a definition of the focal height, receiver dimensions, and trim ratio used in the run is an array showing the number of heliostats placed in each cell of the field. Both this and the preceding arrays are distorted by the fact that the print cells are not square.

After citing the thermal loss/m2 assigned to the receiver, RCELL prints a summary of the performance and costs of the optimal design at the design point (here chosen as equinox noon). As the model insolation at that point is typical lower than the value defined for the design, a second EQN power is quoted along with the designated design point insolation. The next line provides the annual thermal energy provided by the system using the clear sky model insolation for the site, corrected by the monthly average cloud cover and turbidity. This is the denominator in the objective function for the optimization. The parasitic powers quoted on this line are the thermal energy required to provide the parasitic electricity for the heliostats and feed pumps. They are neither added nor subtracted from the annual thermal energy, but are used to compute the electrical load below.

The balance of the summary is pretty self-evident, with the final figure of merit being the ratio of the total capital plus PVO&M costs divided by the annual thermal energy. For an unconstrained design (which would have a smaller receiver due to relaxation of the flux density constraint), the figure of merit would be converged to Finput. Here instead, Finput is adjusted to provide the desired design point power from the existing receiver.

Baseline – Low T Salt, Subcritical Turbine Cycle:

```
NGON =   4  ; MAX.  NUMBER OF HELIOS./CELL=   415.0   ; HGLASS/DMIR**2 =  0.9872   ; TOTAL GLASS = 0.17963E+07
                     14703.9 HELIOS    AHELI= 122.1668    ASEG= 122.1668    ; TOTAL LAND  = 0.70005E+07

         F-LIMIT            OPTIMUM          ALLOWED          M-LIMIT          PLANES

  044444444444440  000000000000000  000000000000000  000000000000000  111111111111111
  444444434444444  000013444310000  000013434310000  000000000000000  111111111111111
  444444444444444  000344444443000  000344444443000  000000000000000  111111111111111
  444444444444444  003444444444300  003444444444300  000000000000000  111111111111111
  444444434444444  024444444444420  024444434444420  000000000000000  111111111111111
  444444444444444  044444444444440  044444444444440  000000000000000  111111111111111
  444444434444444  144444444444441  144444434444441  000000000000000  111111111111111
  444444444444444  144444444444441  144444444444441  000000000000000  111111111111111
  443443404344344  144444444444441  143443404344341  000000707000000  111111111111111
  444444444444444  044444444444440  044444444444440  000000353000000  111111111111111
  444444434444444  034444444444430  034444434444430  000000070000000  111111111111111
  444444444444444  004444444444400  004444444444400  000000000000000  111111111111111
  444444434444444  001444444444100  001444434444100  000000000000000  111111111111111
  444444444444444  000034444430000  000034444430000  000000000000000  111111111111111
  444444434444444  000000111000000  000000111000000  000000000000000  111111111111111
  044444444444440  000000000000000  000000000000000  000000000000000  111111111111111
                 X=X=X=X=X=   TRIM = TRIM * (1 + (    0.1000) * COS(AZ)) OPTION ACTIVE   =*=*=*=*=*
* * * * * * * * * * * * * * NUMBER OF HELIOSTATS PER CELL ; HT =  260.0 FOCAL HEIGHT ; AND APERTURE=1570.80 M2
             CYLINDER LENGTH =  25.00 M; DIA.  =  20.00 M
             REDUCED  LENGTH =  25.00 M; DIA.  =  20.00 M

     0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
     0.0   0.0   0.0   0.0  14.7  41.0  59.8  46.6  59.8  41.0  14.7   0.0   0.0   0.0   0.0
     0.0   0.0   0.0  41.4  65.0  69.9  73.3  74.6  73.3  69.9  65.0  41.4   0.0   0.0   0.0
     0.0   0.0  48.2  68.7  76.5  83.0  88.0  90.1  88.0  83.0  76.5  68.7  48.2   0.0   0.0
     0.0  31.3  68.9  78.9  89.2  99.5 107.3  82.7 107.3  99.5  89.2  78.9  68.9  31.3   0.0
     0.0  63.4  76.0  88.8 104.0 120.8 134.9 140.6 134.9 120.8 104.0  88.8  76.0  63.4   0.0
     7.3  68.5  81.9  98.6 121.0 146.5 175.1 120.0 175.1 146.5 121.0  98.6  81.9  68.5   7.3
    13.0  71.1  86.1 107.2 136.0 178.9 186.7 208.8 186.7 178.9 136.0 107.2  86.1  71.1  13.0
     9.9  72.0  65.9 110.6 141.9 128.7 188.5   0.0 188.5 128.7 141.9 110.6  65.9  72.0   9.9
     0.0  70.5  86.1 107.9 137.6 184.6 217.5 182.7 217.5 184.6 137.6 107.9  86.1  70.5   0.0
     0.0  42.4  81.3  99.7 123.2 156.8 193.0 145.8 193.0 156.8 123.2  99.7  81.3  42.4   0.0
     0.0   1.4  68.4  88.3 106.0 127.2 150.0 158.9 150.0 127.2 106.0  88.3  68.4   1.4   0.0
     0.0   0.0  10.8  67.8  88.4 101.6 112.5  84.9 112.5 101.6  88.4  67.8  10.8   0.0   0.0
     0.0   0.0   0.0   3.3  45.0  79.3  85.2  86.1  85.2  79.3  45.0   3.3   0.0   0.0   0.0
     0.0   0.0   0.0   0.0   0.0   0.0  10.6  13.0  10.6   0.0   0.0   0.0   0.0   0.0   0.0
     0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BLOSS =    28.000 KW/M2
PERFORMANCE SUMMARY AND COST BREAKDOWN FOR OPTIMIZED COLLECTOR FIELD -TRIM LINE AT  1.000

   EQNOON POWER    =   818.330   910.048 IN MW - (SCALED TO  950.0W/M2)
   ANNUAL ENERGY   =  1924.5339 IN GWH  PARAS.=  14.3882 HELIOS  40.3106 FPUMPS
   FIXED COSTS     =     5.2329 IN $M
   TOTAL TOWER COST=    88.5226; TOW 17.2940; REC 51.5448; V P 11.6241; PUMP  8.0597 IN $M FOR  950.0 EQUINOON POWER
   SUM PV O&M COSTS=    31.3773;     0.6848;     20.4118;     2.3016;      7.9791; PV OF O&M COSTS IN $M
   LAND COST       =     9.9907 IN $M;  PV OF O&M COST =   0.000 IN $M
   WIRING COST     =     7.7870 IN $M;  PV OF O&M COST =   0.000 IN $M
   HELIOSTAT COST  =   377.2284 IN $M;  PV OF O&M COST =  88.096 IN $M
   CAPITAL COST TOT=   488.7617 IN $M;  PV O&M COST TOT= 119.473 IN $M; PV OF PARA COST=  38.019 IN $M
   GRAND COST TOTAL=   646.2540 IN $M
   FIGURE OF MERIT =   335.798 IN $/MWH , FOR FINPUT=     281.973 ,AND FSTAR=     310.748
```
[1]

[1] For more explanation on this results page, see SAND88-7029 "The University of Houston Central Receiver Code System: Concepts, Updates, and Start-Up Kits", Pitman, C.L., Vant-Hull, L. L., March 1989

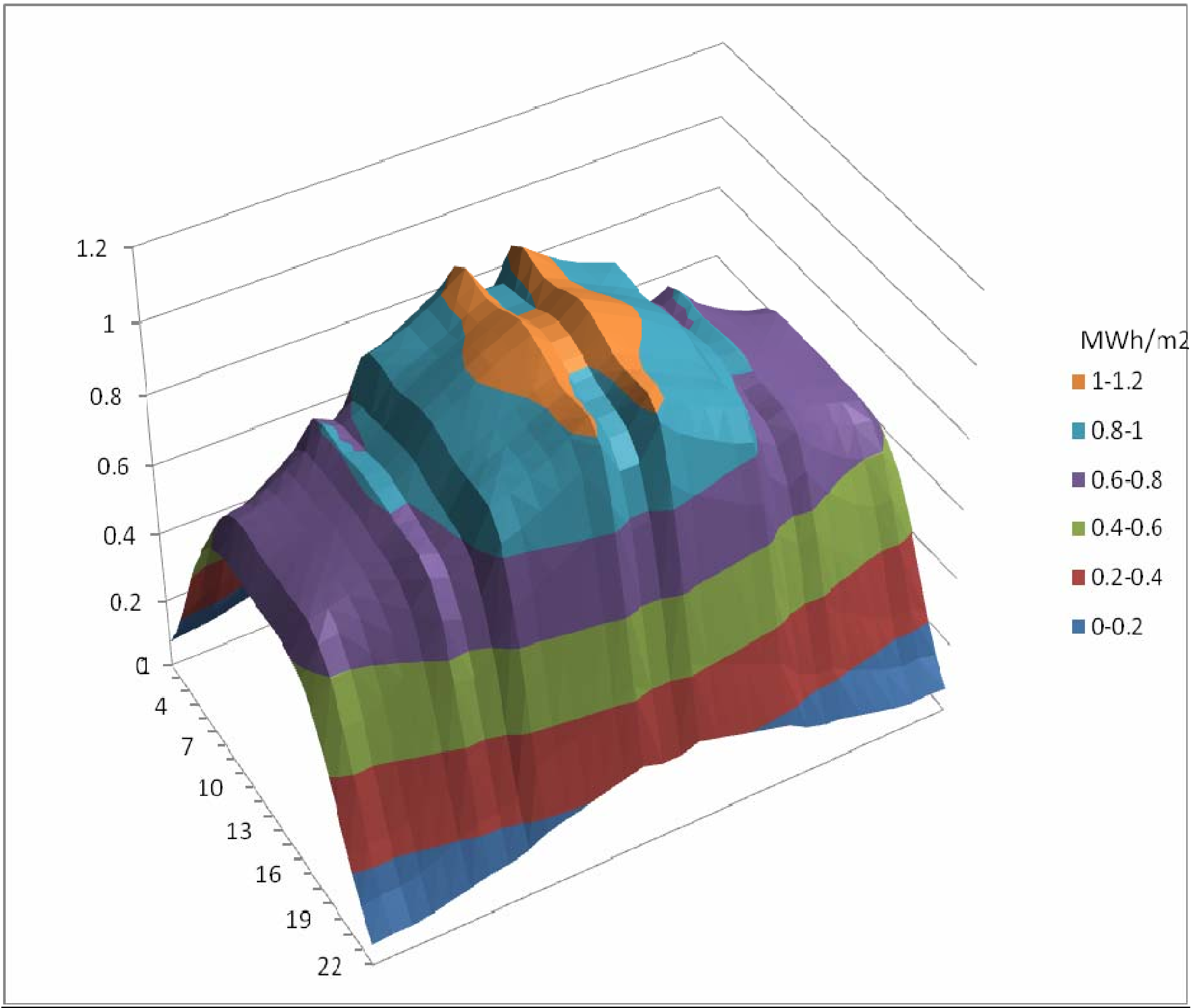

Figure 2 Example of Fluxmap Obtained by RCELL Using 5 Aim Levels

The central notch is due to heliostats deleted to build the North road. The notches due to the East, West, and South roads have been mitigated in later layouts by moving the roads to the WSW and ESE and eliminating the South road.

LowT Supercritical Steam:

NGON = 4 ; MAX. NUMBER OF HELIOS./CELL= 471.5 ; HGLASS/DMIR**2 = 0.9872 ; TOTAL GLASS = 0.17363E+07
14212.6 HELIOS AHELI= 122.1668 ASEG= 122.1668 ; TOTAL LAND = 0.73930E+07

F-LIMIT	OPTIMUM	ALLOWED	M-LIMIT	PLANES
044444434444440	000000000000000	000000000000000	000000000000000	111111111111111
444444444444444	000001222100000	000001222100000	000000000000000	111111111111111
444444444444444	000134444431000	000134444431000	000000000000000	111111111111111
444444444444444	002444444444200	002444444444200	000000000000000	111111111111111
444444444444444	014444444444410	014444444444410	000000000000000	111111111111111
444444434444444	034444444444430	034444434444430	000000000000000	111111111111111
444444444444444	044444444444440	044444444444440	000000000000000	111111111111111
444444444444444	044444444444440	044444444444440	000000000000000	111111111111111
444444404444444	044444444444440	044444404444440	000000707000000	111111111111111
444443444344444	034444444444430	034443444344430	000000757000000	111111111111111
444244444442444	024444444444420	024244444442420	000000000000000	111111111111111
434444444444434	003444444444300	003444444444300	000000000000000	111111111111111
444444444444444	000344444443000	000344444443000	000000000000000	111111111111111
444444444444444	000023444320000	000023444320000	000000000000000	111111111111111
444444444444444	000000000000000	000000000000000	000000000000000	111111111111111
044444444444440	000000000000000	000000000000000	000000000000000	111111111111111

X=X=X=X=X= TRIM = TRIM * (1 + (0.1200) * COS(AZ)) OPTION ACTIVE =*=*=*=*=*

* * * * * * * * * * * * * * NUMBER OF HELIOSTATS PER CELL ; HT = 240.0 FOCAL HEIGHT ; AND APERTURE=2323.52 M2

CYLINDER LENGTH = 34.40 M; DIA. = 21.50 M
REDUCED LENGTH = 34.40 M; DIA. = 21.50 M

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	16.6	31.5	35.9	31.5	16.6	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	19.2	53.6	68.4	71.7	73.0	71.7	68.4	53.6	19.2	0.0	0.0	0.0
0.0	0.0	25.7	67.2	74.8	81.4	86.4	88.5	86.4	81.4	74.8	67.2	25.7	0.0	0.0
0.0	13.7	67.3	77.5	87.9	97.8	105.6	108.5	105.6	97.8	87.9	77.5	67.3	13.7	0.0
0.0	40.8	75.0	87.5	102.5	118.7	133.6	104.4	133.6	118.7	102.5	87.5	75.0	40.8	0.0
0.0	60.1	81.0	97.2	118.6	147.8	172.8	193.9	172.8	147.8	118.6	97.2	81.0	60.1	0.0
3.0	68.9	85.0	104.5	135.2	176.4	194.3	220.8	194.3	176.4	135.2	104.5	85.0	68.9	3.0
0.0	66.2	86.6	108.0	142.6	197.5	209.4	0.0	209.4	197.5	142.6	108.0	86.6	66.2	0.0
0.0	53.0	85.0	105.7	136.7	139.5	222.1	241.2	222.1	139.5	136.7	105.7	85.0	53.0	0.0
0.0	27.5	79.7	49.0	122.8	156.8	200.0	229.0	200.0	156.8	122.8	49.0	79.7	27.5	0.0
0.0	0.0	50.8	86.2	104.0	125.2	147.2	154.8	147.2	125.2	104.0	86.2	50.8	0.0	0.0
0.0	0.0	4.6	51.5	85.9	98.7	109.0	111.3	109.0	98.7	85.9	51.5	4.6	0.0	0.0
0.0	0.0	0.0	0.0	32.5	63.7	82.0	82.2	82.0	63.7	32.5	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	4.2	2.7	4.2	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

BLOSS = 47.100 KW/M2
PERFORMANCE SUMMARY AND COST BREAKDOWN FOR OPTIMIZED COLLECTOR FIELD -TRIM LINE AT 1.000

EQNOON POWER = 723.123 812.005 IN MW - (SCALED TO 950.0W/M2)
ANNUAL ENERGY = 1669.1258 IN GWH PARAS.= 11.9721 HELIOS 33.9412 FPUMPS
FIXED COSTS = 5.1603 IN $M
TOTAL TOWER COST= 128.3774; TOW 13.5247; REC 70.7044; V P 41.9823; PUMP 2.1660 IN $M FOR 950.0 EQUINOON POWER
SUM PV O&M COSTS= 38.9914; 0.5356; 27.9989; 8.3125; 2.1444; PV OF O&M COSTS IN $M
LAND COST = 10.5510 IN $M; PV OF O&M COST = 0.000 IN $M
WIRING COST = 7.5517 IN $M; PV OF O&M COST = 0.000 IN $M
HELIOSTAT COST = 364.6252 IN $M; PV OF O&M COST = 85.153 IN $M
CAPITAL COST TOT= 516.2655 IN $M; PV O&M COST TOT= 124.144 IN $M; PV OF PARA COST= 37.071 IN $M
GRAND COST TOTAL= 677.4810 IN $M
FIGURE OF MERIT = 405.890 IN $/MWH , FOR FINPUT= 276.868 ,AND FSTAR= 371.643

LowT Supercritical CO2:

```
NGON =   4  ; MAX.  NUMBER OF HELIOS./CELL=   451.2   ; HGLASS/DMIR**2 =  0.9872   ; TOTAL GLASS = 0.17888E+07
                  14642.1 HELIOS    AHELI= 122.1668    ASEG= 122.1668    ; TOTAL LAND  = 0.88329E+07

        F-LIMIT            OPTIMUM          ALLOWED          M-LIMIT          PLANES

  044444434444440   000000111000000   000000111000000   000000000000000   111111111111111
  444444444444444   000134444431000   000134444431000   000000000000000   111111111111111
  444444444444444   002444444444200   002444444444200   000000000000000   111111111111111
  444444444444444   024444444444420   024444444444420   000000000000000   111111111111111
  444444444444444   044444444444440   044444444444440   000000000000000   111111111111111
  444444434444444   244444444444442   244444434444442   000000000000000   111111111111111
  444444444444444   344444444444443   344444444444443   000000000000000   111111111111111
  444444444444444   344444444444443   344444444444443   000000030000000   111111111111111
  444444404444444   344444444444443   344444404444443   000000707000000   111111111111111
  444443444344444   244444444444442   244443444344442   000000737000000   111111111111111
  444244444442444   144444444444441   144244444442441   000000000000000   111111111111111
  434444444444434   034444444444430   034444444444430   000000000000000   111111111111111
  444444444444444   003444444444300   003444444444300   000000000000000   111111111111111
  444444444444444   000344444443000   000344444443000   000000000000000   111111111111111
  444444444444444   000012333210000   000012333210000   000000000000000   111111111111111
  044444444444440   000000000000000   000000000000000   000000000000000   111111111111111
                    X=X=X=X=X=   TRIM = TRIM * (1 + (    0.1200) * COS(AZ)) OPTION ACTIVE   =*=*=*=*=*
* * * * * * * * * * * * * * NUMBER OF HELIOSTATS PER CELL ; HT =  210.0 FOCAL HEIGHT ; AND APERTURE=2280.80 M2
             CYLINDER LENGTH =  33.00 M; DIA.  =  22.00 M
             REDUCED  LENGTH =  33.00 M; DIA.  =  22.00 M

                      0.0   0.0   0.0   0.0   0.0   2.1  12.0  14.7  12.0   2.1   0.0   0.0   0.0   0.0   0.0
                    0.0   0.0   0.0  10.4  34.5  50.7  52.7  53.4  52.7  50.7  34.5  10.4   0.0   0.0   0.0
                    0.0   0.0  21.6  51.5  56.6  60.6  63.4  64.5  63.4  60.6  56.6  51.5  21.6   0.0   0.0
                    0.0  20.3  53.2  60.2  66.4  72.5  76.9  78.7  76.9  72.5  66.4  60.2  53.2  20.3   0.0
                    3.3  51.1  60.2  68.8  78.1  87.0  94.0  97.2  94.0  87.0  78.1  68.8  60.2  51.1   3.3
                   22.1  57.1  66.7  78.4  91.6 106.3 119.6  93.7 119.6 106.3  91.6  78.4  66.7  57.1  22.1
                   34.7  60.7  72.8  87.2 106.2 131.7 158.5 171.7 158.5 131.7 106.2  87.2  72.8  60.7  34.7
                   41.2  63.1  76.5  93.3 119.8 160.2 183.2 236.4 183.2 160.2 119.8  93.3  76.5  63.1  41.2
                   38.2  64.2  78.2  96.6 127.1 177.4 209.9   0.0 209.9 177.4 127.1  96.6  78.2  64.2  38.2
                   28.5  62.9  76.6  94.6 122.6 126.7 210.9 234.3 210.9 126.7 122.6  94.6  76.6  62.9  28.5
                   11.1  59.3  72.2  44.0 109.6 141.1 182.5 207.2 182.5 141.1 109.6  44.0  72.2  59.3  11.1
                    0.0  35.0  65.1  78.1  94.1 112.9 132.7 139.7 132.7 112.9  94.1  78.1  65.1  35.0   0.0
                    0.0   2.4  44.1  67.1  78.7  90.3  99.4 100.5  99.4  90.3  78.7  67.1  44.1   2.4   0.0
                    0.0   0.0   2.3  37.0  64.5  71.8  76.3  76.6  76.3  71.8  64.5  37.0   2.3   0.0   0.0
                    0.0   0.0   0.0   0.0  14.5  32.6  43.2  43.3  43.2  32.6  14.5   0.0   0.0   0.0   0.0
                    0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

BLOSS =    47.100 KW/M2
PERFORMANCE SUMMARY AND COST BREAKDOWN FOR OPTIMIZED COLLECTOR FIELD -TRIM LINE AT  1.000

   EQNOON POWER    =  722.367   812.022 IN MW - (SCALED TO  950.0W/M2)
   ANNUAL ENERGY   =  1681.2091 IN GWH  PARAS.=  12.3339 HELIOS  20.9656 FPUMPS
   FIXED COSTS     =     5.0622 IN $M
   TOTAL TOWER COST=   168.7571; TOW  9.8572; REC 65.7379; V P 85.0661; PUMP  8.0959 IN $M FOR  950.0 EQUINOON POWER
   SUM PV O&M COSTS=   51.8684;     0.3903;     26.0322;     16.8431;      8.6028; PV OF O&M COSTS IN $M
   LAND COST       =    12.6058 IN $M;  PV OF O&M COST =   0.000 IN $M
   WIRING COST     =     7.9203 IN $M;  PV OF O&M COST =   0.000 IN $M
   HELIOSTAT COST  =   375.6431 IN $M;  PV OF O&M COST = 87.726 IN $M
   CAPITAL COST TOT=   569.9886 IN $M;  PV O&M COST TOT= 139.594 IN $M; PV OF PARA COST=  26.887 IN $M
   GRAND COST TOTAL=   736.4696 IN $M
   FIGURE OF MERIT =  438.059 IN $/MWH , FOR FINPUT=     292.781 ,AND FSTAR=     438.310
```

HiT Molten Salt:

NGON = 4 ; MAX. NUMBER OF HELIOS./CELL= 415.0 ; HGLASS/DMIR**2 = 0.9872 ; TOTAL GLASS = 0.16306E+07
13347.0 HELIOS AHELI= 122.1668 ASEG= 122.1668 ; TOTAL LAND = 0.66321E+07

F-LIMIT	OPTIMUM	ALLOWED	M-LIMIT	PLANES
044444444444440	000000111000000	000000111000000	000000000000000	111111111111111
444444434444444	000123444321000	000123434321000	000000000000000	111111111111111
444444444444444	001344444443100	001344444443100	000000000000000	111111111111111
444444444444444	013444444444310	013444444444310	000000000000000	111111111111111
444444434444444	024444444444420	024444434444420	000000000000000	111111111111111
444444444444444	134444444444431	134444444444431	000000000000000	111111111111111
444444434444444	144444444444441	144444434444441	000000000000000	111111111111111
444444444444444	134444444444431	134444444444431	000000000000000	111111111111111
444444404444444	134444444444431	134444404444431	000000707000000	111111111111111
444443444344444	024444444444420	024443444344420	000000353000000	111111111111111
444344444443444	013444444444310	013344444443310	000000070000000	111111111111111
434444444444434	002344444443200	002344444443200	000000000000000	111111111111111
444444444444444	000134444431000	000134444431000	000000000000000	111111111111111
444444444444444	000012222210000	000012222210000	000000000000000	111111111111111
444444444444444	000000000000000	000000000000000	000000000000000	111111111111111
044444444444440	000000000000000	000000000000000	000000000000000	111111111111111

X=X=X=X=X= TRIM = TRIM * (1 + (0.1000) * COS(AZ)) OPTION ACTIVE =*=*=*=*=*

* * * * * * * * * * * * * * NUMBER OF HELIOSTATS PER CELL ; HT = 260.0 FOCAL HEIGHT ; AND APERTURE=2503.50 M2

CYLINDER LENGTH = 31.56 M; DIA. = 25.25 M
REDUCED LENGTH = 31.56 M; DIA. = 25.25 M

0.0	0.0	0.0	0.0	0.0	2.3	10.3	14.0	10.3	2.3	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	6.5	28.7	45.4	57.6	46.4	57.6	45.4	28.7	6.5	0.0	0.0	0.0
0.0	0.0	14.3	44.0	64.3	68.5	71.6	72.9	71.6	68.5	64.3	44.0	14.3	0.0	0.0
0.0	11.4	47.2	67.4	74.0	80.0	84.8	86.8	84.8	80.0	74.0	67.4	47.2	11.4	0.0
0.0	34.6	67.1	76.2	85.7	94.9	102.3	78.8	102.3	94.9	85.7	76.2	67.1	34.6	0.0
7.4	51.5	73.5	85.3	99.3	115.5	129.5	135.1	129.5	115.5	99.3	85.3	73.5	51.5	7.4
13.6	59.9	78.7	94.2	116.0	141.2	159.8	113.6	159.8	141.2	116.0	94.2	78.7	59.9	13.6
13.6	60.0	82.2	102.7	131.4	166.4	173.2	193.8	173.2	166.4	131.4	102.7	82.2	60.0	13.6
8.4	54.2	83.8	105.8	122.3	177.4	188.5	0.0	188.5	177.4	122.3	105.8	83.8	54.2	8.4
0.0	41.2	81.8	102.8	119.3	126.6	207.4	182.7	207.4	126.6	119.3	102.8	81.8	41.2	0.0
0.0	20.5	63.5	70.5	115.2	146.4	176.9	194.3	176.9	146.4	115.2	70.5	63.5	20.5	0.0
0.0	0.0	29.4	66.6	90.4	107.8	132.7	141.8	132.7	107.8	90.4	66.6	29.4	0.0	0.0
0.0	0.0	0.0	23.0	54.9	86.0	100.2	96.1	100.2	86.0	54.9	23.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	9.4	27.7	40.7	40.2	40.7	27.7	9.4	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

BLOSS = 34.200 KW/M2
PERFORMANCE SUMMARY AND COST BREAKDOWN FOR OPTIMIZED COLLECTOR FIELD -TRIM LINE AT 1.000

EQNOON POWER = 726.527 812.949 IN MW - (SCALED TO 950.0W/M2)
ANNUAL ENERGY = 1679.6313 IN GWH PARAS.= 11.2430 HELIOS 35.8159 FPUMPS
FIXED COSTS = 5.2329 IN $M
TOTAL TOWER COST= 107.6360; TOW 16.3676; REC 72.9711; V P 10.9747; PUMP 7.3226 IN $M FOR 950.0 EQUINOON POWER
SUM PV O&M COSTS= 38.9671; 0.6482; 28.8965; 2.1730; 7.2494; PV OF O&M COSTS IN $M
LAND COST = 9.4650 IN $M; PV OF O&M COST = 0.000 IN $M
WIRING COST = 7.1647 IN $M; PV OF O&M COST = 0.000 IN $M
HELIOSTAT COST = 342.4187 IN $M; PV OF O&M COST = 79.967 IN $M
CAPITAL COST TOT= 471.9173 IN $M; PV O&M COST TOT= 118.934 IN $M; PV OF PARA COST= 37.996 IN $M
GRAND COST TOTAL= 628.8476 IN $M
FIGURE OF MERIT = 374.396 IN $/MWH , FOR FINPUT= 259.177 ,AND FSTAR= 346.386

HiT Supercritical Steam:

```
NGON =   4  ; MAX.  NUMBER OF HELIOS./CELL=   511.6   ; HGLASS/DMIR**2 =  0.9872   ; TOTAL GLASS = 0.17226E+07
             14100.6 HELIOS    AHELI= 122.1668    ASEG= 122.1668    ; TOTAL LAND  = 0.71097E+07


        F-LIMIT                OPTIMUM            ALLOWED            M-LIMIT             PLANES


  044444434444440  000000000000000  000000000000000  000000000000000  111111111111111
  444444444444444  000000010000000  000000010000000  000000000000000  111111111111111
  444444444444444  000023444320000  000023444320000  000000000000000  111111111111111
  444444444444444  000344444443000  000344444443000  000000000000000  111111111111111
  444444444444444  003444444444300  003444444444300  000000000000000  111111111111111
  444444434444444  014444444444410  014444434444410  000000000000000  111111111111111
  444444444444444  024444444444420  024444444444420  000000000000000  111111111111111
  444444444444444  034444444444430  034444444444430  000000000000000  111111111111111
  444444404444444  024444444444420  024444404444420  000000707000000  111111111111111
  444443444344444  024444444444420  024443444344420  000000757000000  111111111111111
  444344444443444  004444444444400  004344444443400  000000000000000  111111111111111
  434444444444434  001444444444100  001444444444100  000000000000000  111111111111111
  444444444444444  000144444441000  000144444441000  000000000000000  111111111111111
  444444444444444  000002333200000  000002333200000  000000000000000  111111111111111
  444444444444444  000000000000000  000000000000000  000000000000000  111111111111111
  044444444444440  000000000000000  000000000000000  000000000000000  111111111111111
                    X=X=X=X=X=    TRIM = TRIM * (1 + (     0.1200) * COS(AZ)) OPTION ACTIVE    =*=*=*=*=*=*
* * * * * * * * * * * * * * NUMBER OF HELIOSTATS PER CELL ; HT =  250.0 FOCAL HEIGHT ; AND APERTURE=2522.70 M2
             CYLINDER LENGTH =  36.50 M; DIA.  =  22.00 M
             REDUCED  LENGTH =  36.50 M; DIA.  =  22.00 M

                         0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
                         0.0   0.0   0.0   0.0   0.0   0.0   5.2  13.4   5.2   0.0   0.0   0.0   0.0   0.0   0.0
                         0.0   0.0   0.0   0.0  31.7  61.5  76.2  77.6  76.2  61.5  31.7   0.0   0.0   0.0   0.0
                         0.0   0.0   3.0  51.7  79.6  86.7  92.1  94.4  92.1  86.7  79.6  51.7   3.0   0.0   0.0
                         0.0   0.0  49.6  82.5  93.7 104.4 112.8 116.5 112.8 104.4  93.7  82.5  49.6   0.0   0.0
                         0.0  18.5  79.8  93.9 109.5 127.4 143.0 111.7 143.0 127.4 109.5  93.9  79.8  18.5   0.0
                         0.0  37.7  86.2 103.8 126.9 158.5 185.2 205.5 185.2 158.5 126.9 103.8  86.2  37.7   0.0
                         0.0  46.3  90.4 111.7 144.9 189.7 206.6 232.7 206.6 189.7 144.9 111.7  90.4  46.3   0.0
                         0.0  43.3  92.1 115.5 153.3 208.3 227.2   0.0 227.2 208.3 153.3 115.5  92.1  43.3   0.0
                         0.0  29.6  90.2 112.8 146.2 149.1 241.0 261.7 241.0 149.1 146.2 112.8  90.2  29.6   0.0
                         0.0   2.6  74.0  78.2 130.8 167.2 211.9 243.1 211.9 167.2 130.8  78.2  74.0   2.6   0.0
                         0.0   0.0  26.3  90.5 110.1 132.0 155.2 162.5 155.2 132.0 110.1  90.5  26.3   0.0   0.0
                         0.0   0.0   0.0  26.4  79.4 103.7 114.8 117.1 114.8 103.7  79.4  26.4   0.0   0.0   0.0
                         0.0   0.0   0.0   0.0   6.8  38.1  56.5  57.2  56.5  38.1   6.8   0.0   0.0   0.0   0.0
                         0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
                         0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BLOSS =    47.100 KW/M2
PERFORMANCE SUMMARY AND COST BREAKDOWN FOR OPTIMIZED COLLECTOR FIELD -TRIM LINE AT  1.000

   EQNOON POWER    =   715.131    804.000 IN MW - (SCALED TO  950.0W/M2)
   ANNUAL ENERGY   =  1641.8519 IN GWH  PARAS.=  11.7573 HELIOS  13.0274 FPUMPS
   FIXED COSTS     =     5.1958 IN $M
   TOTAL TOWER COST=   112.3938; TOW 14.7481; REC 74.8411; V P 21.7838; PUMP  1.0207 IN $M FOR  950.0 EQUINOON POWER
   SUM PV O&M COSTS=    35.5448;      0.5840;      29.6371;      4.3132;      1.0105; PV OF O&M COSTS IN $M
   LAND COST       =    10.1466 IN $M;  PV OF O&M COST =   0.000 IN $M
   WIRING COST     =     7.4756 IN $M;  PV OF O&M COST =   0.000 IN $M
   HELIOSTAT COST  =   361.7510 IN $M;  PV OF O&M COST =  84.482 IN $M
   CAPITAL COST TOT=   496.9628 IN $M;  PV O&M COST TOT= 120.026 IN $M; PV OF PARA COST=  20.217 IN $M
   GRAND COST TOTAL=   637.2059 IN $M
   FIGURE OF MERIT =   388.102 IN $/MWH , FOR FINPUT=     270.987 ,AND FSTAR=     387.285
```

HiT Supercritical CO_2:

```
NGON =   4  ; MAX.  NUMBER OF HELIOS./CELL=   451.2   ; HGLASS/DMIR**2 =  0.9872   ; TOTAL GLASS = 0.17825E+07
          14590.3 HELIOS    AHELI= 122.1668    ASEG= 122.1668    ; TOTAL LAND  = 0.89540E+07


         F-LIMIT              OPTIMUM             ALLOWED             M-LIMIT             PLANES

  044444434444440   000001222100000   000001222100000   000000000000000   111111111111111
  444444444444444   000134444431000   000134444431000   000000000000000   111111111111111
  444444444444444   002444444444200   002444444444200   000000000000000   111111111111111
  444444444444444   024444444444420   024444444444420   000000000000000   111111111111111
  444444444444444   144444444444441   144444444444441   000000000000000   111111111111111
  444444434444444   244444444444442   244444434444442   000000000000000   111111111111111
  444444444444444   344444444444443   344444444444443   000000000000000   111111111111111
  444444444444444   344444444444443   344444444444443   000000000000000   111111111111111
  444444404444444   344444404444443   344444404444443   000000707000000   111111111111111
  444443444344444   244444444444442   244443444344442   000000333000000   111111111111111
  444344444443444   144444444444441   144344444443441   000000000000000   111111111111111
  434444444444434   034444444444430   034444444444430   000000000000000   111111111111111
  444444444444444   003444444444300   003444444444300   000000000000000   111111111111111
  444444444444444   000244444442000   000244444442000   000000000000000   111111111111111
  444444444444444   000012333210000   000012333210000   000000000000000   111111111111111
  044444444444440   000000000000000   000000000000000   000000000000000   111111111111111
                    X=X=X=X=X=   TRIM = TRIM * (1 + (    0.1200) * COS(AZ)) OPTION ACTIVE    =*=*=*=*=*
* * * * * * * * * * * * * * NUMBER OF HELIOSTATS PER CELL ; HT =  210.0 FOCAL HEIGHT ; AND APERTURE=2488.14 M2
            CYLINDER LENGTH =  33.00 M; DIA.  =  24.00 M
            REDUCED  LENGTH =  33.00 M; DIA.  =  24.00 M

                          0.0   0.0   0.0   0.0   0.0   8.4  17.7  20.2  17.7   8.4   0.0   0.0   0.0   0.0   0.0
                        0.0   0.0   0.0  15.8  38.0  50.8  52.7  53.4  52.7  50.8  38.0  15.8   0.0   0.0   0.0
                        0.0   0.0  26.3  51.9  56.5  60.5  63.2  64.3  63.2  60.5  56.5  51.9  26.3   0.0   0.0
                        0.0  25.0  53.2  60.0  66.1  72.1  76.4  77.8  76.4  72.1  66.1  60.0  53.2  25.0   0.0
                        9.0  52.2  60.1  68.6  77.6  86.4  93.3  96.4  93.3  86.4  77.6  68.6  60.1  52.2   9.0
                       26.0  57.0  66.5  77.9  90.8 105.3 118.1  92.6 118.1 105.3  90.8  77.9  66.5  57.0  26.0
                       36.9  60.6  72.0  86.5 104.8 130.3 157.0 169.8 157.0 130.3 104.8  86.5  72.0  60.6  36.9
                       42.1  63.0  75.6  92.5 118.4 158.9 177.6 207.1 177.6 158.9 118.4  92.5  75.6  63.0  42.1
                       38.7  63.5  77.2  95.2 125.6 175.1 209.9   0.0 209.9 175.1 125.6  95.2  77.2  63.5  38.7
                       29.5  62.7  76.1  93.6 120.9 125.0 214.6 232.1 214.6 125.0 120.9  93.6  76.1  62.7  29.5
                       13.4  59.2  71.2  65.3 108.1 138.7 179.3 203.0 179.3 138.7 108.1  65.3  71.2  59.2  13.4
                        0.0  33.9  64.3  76.8  92.3 110.8 129.8 136.1 129.8 110.8  92.3  76.8  64.3  33.9   0.0
                        0.0   4.3  40.7  66.6  77.3  88.4  97.0  98.1  97.0  88.4  77.3  66.6  40.7   4.3   0.0
                        0.0   0.0   3.9  33.9  63.5  70.4  74.8  74.9  74.8  70.4  63.5  33.9   3.9   0.0   0.0
                        0.0   0.0   0.0   0.0  14.0  29.4  38.4  37.9  38.4  29.4  14.0   0.0   0.0   0.0   0.0
                          0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
BLOSS =    47.100 KW/M2
PERFORMANCE SUMMARY AND COST BREAKDOWN FOR OPTIMIZED COLLECTOR FIELD -TRIM LINE AT  1.000

   EQNOON POWER    =  713.840   803.894 IN MW - (SCALED TO  950.0W/M2)
   ANNUAL ENERGY   =  1659.0049 IN GWH  PARAS.=  12.1656 HELIOS  19.6059 FPUMPS
   FIXED COSTS     =     5.0622 IN $M
   TOTAL TOWER COST=   178.2356; TOW  9.7460; REC 71.3381; V P 89.0845; PUMP  8.0670 IN $M FOR  950.0 EQUINOON POWER
   SUM PV O&M COSTS=    54.8528;      0.3859;      28.2499;      17.6387;       8.5782; PV OF O&M COSTS IN $M
   LAND COST       =    12.7787 IN $M;  PV OF O&M COST =   0.000 IN $M
   WIRING COST     =     7.9632 IN $M;  PV OF O&M COST =   0.000 IN $M
   HELIOSTAT COST  =   374.3150 IN $M;  PV OF O&M COST =  87.416 IN $M
   CAPITAL COST TOT=   578.3547 IN $M;  PV O&M COST TOT= 142.269 IN $M; PV OF PARA COST=  25.916 IN $M
   GRAND COST TOTAL=   746.5389 IN $M
   FIGURE OF MERIT =   449.992 IN $/MWH , FOR FINPUT=     285.693 ,AND FSTAR=     450.430
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[2]

[2] For more explanation on this results page, see SAND88-7029 "The University of Houston Central Receiver Code System: Concepts, Updates, and Start-Up Kits", Pitman, C.L., Vant-Hull, L.L., March 1989

Appendix B: Summary Annual Results from NS Code, Baseline Salt Receiver

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ANNUAL SUMMARY OF INSOLATION , UNIVERSITY OF HOUSTON , ANNUAL INSOLATION=   3.09258 MWH/M2  FOR SUN ABOVE 10 DEGREES
                                                                                                              DAILY INTEGRAL
    HOUR =     0.00    1.05    2.09    3.14    4.18    5.23    6.28    0.00    0.00
DAY =  93    936.20  930.82  913.67  880.98  823.73  717.95  477.39    0.00    0.00  10.467
    HOUR =     0.00    1.02    2.04    3.06    4.07    5.09    6.11    0.00    0.00
DAY = 124    886.28  880.49  861.37  825.11  762.12  647.68  398.55    0.00    0.00  9.469
     62      948.31  943.00  926.06  893.83  837.39  733.20  496.64    0.00    0.00  10.356
    HOUR =     0.00    0.95    1.90    2.85    3.81    4.76    5.71    0.00    0.00
DAY = 155    885.20  879.01  859.96  823.87  761.24  647.60  400.81    0.00    0.00  8.835
     31      981.77  976.83  961.06  931.03  878.26  780.19  553.24    0.00    0.00  10.126
    HOUR =     0.00    0.86    1.72    2.59    3.45    4.31    5.17    0.00    0.00
DAY = 186    879.93  872.79  853.68  817.60  755.42  644.13  410.13    0.00    0.00  7.958
      0      985.08  980.11  964.25  934.10  881.46  784.77  567.99    0.00    0.00  9.219
    HOUR =     0.00    0.77    1.53    2.30    3.06    3.83    4.59    0.00    0.00
DAY = 216    909.64  902.53  884.96  851.91  795.28  695.19  490.20    0.00    0.00  7.433
    336      969.10  964.05  947.99  917.68  865.49  772.25  576.62    0.00    0.00  8.061
    HOUR =     0.00    0.68    1.36    2.04    2.71    3.39    4.07    0.00    0.00
DAY = 246    921.59  916.21  900.10  870.02  819.21  731.68  562.01    0.00    0.00  6.781
    306      930.79  925.72  909.65  879.65  829.02  741.92  573.51    0.00    0.00  6.861
    HOUR =     0.00    0.64    1.28    1.92    2.56    3.20    3.85    0.00    0.00
DAY = 276    904.73  899.68  883.72  854.10  804.59  720.99  565.25    0.00    0.00  6.300

ANNUAL SUMMARY OF COSINES , ANNUAL AVER COSINE=  0.7604
    HOUR =     0.00    1.05    2.09    3.14    4.18    5.23    6.28    0.00    0.00
DAY =  93     0.8160  0.8114  0.7978  0.7759  0.7469  0.7124  0.6749  0.0000  0.0000  0.7714
    HOUR =     0.00    1.02    2.04    3.06    4.07    5.09    6.11    0.00    0.00
DAY = 124     0.8149  0.8104  0.7972  0.7758  0.7474  0.7135  0.6763  0.0000  0.0000  0.8077
    HOUR =     0.00    0.95    1.90    2.85    3.81    4.76    5.71    0.00    0.00
DAY = 155     0.8096  0.8055  0.7933  0.7737  0.7472  0.7154  0.6798  0.0000  0.0000  0.8254
    HOUR =     0.00    0.86    1.72    2.59    3.45    4.31    5.17    0.00    0.00
DAY = 186     0.7973  0.7938  0.7835  0.7667  0.7440  0.7162  0.6846  0.0000  0.0000  0.8230
    HOUR =     0.00    0.77    1.53    2.30    3.06    3.83    4.59    0.00    0.00
DAY = 216     0.7798  0.7770  0.7689  0.7556  0.7375  0.7151  0.6893  0.0000  0.0000  0.7836
    HOUR =     0.00    0.68    1.36    2.04    2.71    3.39    4.07    0.00    0.00
DAY = 246     0.7630  0.7609  0.7547  0.7445  0.7305  0.7131  0.6928  0.0000  0.0000  0.7456
    HOUR =     0.00    0.64    1.28    1.92    2.56    3.20    3.85    0.00    0.00
DAY = 276     0.7560  0.7542  0.7488  0.7398  0.7275  0.7121  0.6941  0.0000  0.0000  0.7368

ANNUAL SUMMARY OF FMIRR , UNIVERSITY OF HOUSTON (EFFECT OF SHADING AND BLOCKING)
    HOUR =     0.00    1.05    2.09    3.14    4.18    5.23    6.28    0.00    0.00
DAY =  93     0.9715  0.9735  0.9792  0.9844  0.9827  0.9251  0.7105  0.0000  0.0000  0.0000
    HOUR =     0.00    1.02    2.04    3.06    4.07    5.09    6.11    0.00    0.00
DAY = 124     0.9736  0.9754  0.9803  0.9850  0.9828  0.9251  0.7083  0.0000  0.0000  0.0000
    HOUR =     0.00    0.95    1.90    2.85    3.81    4.76    5.71    0.00    0.00
DAY = 155     0.9790  0.9801  0.9845  0.9868  0.9817  0.9208  0.7045  0.0000  0.0000  0.0000
    HOUR =     0.00    0.86    1.72    2.59    3.45    4.31    5.17    0.00    0.00
DAY = 186     0.9872  0.9879  0.9890  0.9896  0.9783  0.9093  0.7078  0.0000  0.0000  0.0000
    HOUR =     0.00    0.77    1.53    2.30    3.06    3.83    4.59    0.00    0.00
DAY = 216     0.9919  0.9921  0.9920  0.9879  0.9656  0.8848  0.7138  0.0000  0.0000  0.0000
    HOUR =     0.00    0.68    1.36    2.04    2.71    3.39    4.07    0.00    0.00
DAY = 246     0.9903  0.9895  0.9855  0.9722  0.9393  0.8529  0.7090  0.0000  0.0000  0.0000
    HOUR =     0.00    0.64    1.28    1.92    2.56    3.20    3.85    0.00    0.00
DAY = 276     0.9856  0.9837  0.9780  0.9605  0.9233  0.8388  0.7055  0.0000  0.0000  0.0000

ANNUAL SUMMARY OF FAREA , UNIVERSITY OF HOUSTON , ANNUAL TOTAL REFLECTED POWER/MIRROR=   2.14936 MWH/M2
               includes cosine, shading and blocking
    HOUR =     0.00    1.05    2.09    3.14    4.18    5.23    6.28    0.00    0.00
DAY =  93     0.7932  0.7900  0.7806  0.7620  0.7311  0.6490  0.4524  0.0000  0.0000  7.7279
    HOUR =     0.00    1.02    2.04    3.06    4.07    5.09    6.11    0.00    0.00
DAY = 124     0.7939  0.7907  0.7808  0.7624  0.7317  0.6502  0.4533  0.0000  0.0000  7.0143
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     HOUR =     0.00    0.95    1.90    2.85    3.81    4.76    5.71    0.00    0.00
DAY = 155     0.7930  0.7896  0.7802  0.7618  0.7305  0.6489  0.4553  0.0000  0.0000  6.5365
     HOUR =     0.00    0.86    1.72    2.59    3.45    4.31    5.17    0.00    0.00
DAY = 186     0.7868  0.7837  0.7739  0.7572  0.7245  0.6396  0.4610  0.0000  0.0000  5.8377
     HOUR =     0.00    0.77    1.53    2.30    3.06    3.83    4.59    0.00    0.00
DAY = 216     0.7728  0.7700  0.7616  0.7447  0.7075  0.6205  0.4688  0.0000  0.0000  5.3349
     HOUR =     0.00    0.68    1.36    2.04    2.71    3.39    4.07    0.00    0.00
DAY = 246     0.7543  0.7514  0.7417  0.7200  0.6791  0.5938  0.4719  0.0000  0.0000  4.7061
     HOUR =     0.00    0.64    1.28    1.92    2.56    3.20    3.85    0.00    0.00
DAY = 276     0.7434  0.7396  0.7294  0.7058  0.6633  0.5822  0.4698  0.0000  0.0000  4.2925

 VISUAL RANGE EFFICIENCIES  MONTH
      1      2      3      4      5      6      7      8      9     10     11     12 ANNUAL AVG

   0.932  0.933  0.932  0.931  0.922  0.921  0.905  0.905  0.910  0.924  0.932  0.932  0.932

******************* TOTAL CLOUDLESS ANNUAL INCIDENT RECEIVER POWER , UNIVERSITY OF HOUSTON
***********************************
TOTAL ANNUAL RECEIVER POWER=  0.3114E+07 IN MWH FOR RECEIVER DIAMETER=  20.00  AND HEIGHT=  25.00 METERS    KWH
     HOUR =     0.000     1.046     2.092     3.139     4.185     5.231     6.277     0.000     0.000
DAY =  93     1.032E+09 1.023E+09 9.920E+08 9.338E+08 8.376E+08 6.465E+08 2.984E+08 0.000E+00 0.000E+00 1.074E+07
     HOUR =     0.000     1.019     2.037     3.056     4.074     5.093     6.111     0.000     0.000
DAY = 124     9.618E+08 9.518E+08 9.198E+08 8.602E+08 7.625E+08 5.742E+08 2.452E+08 0.000E+00 0.000E+00 9.585E+06
      62     1.048E+09 1.038E+09 1.007E+09 9.491E+08 8.533E+08 6.623E+08 3.114E+08 0.000E+00 0.000E+00 1.065E+07
     HOUR =     0.000     0.951     1.903     2.854     3.805     4.757     5.708     0.000     0.000
DAY = 155     9.587E+08 9.479E+08 9.163E+08 8.572E+08 7.592E+08 5.721E+08 2.473E+08 0.000E+00 0.000E+00 8.921E+06
      31     1.094E+09 1.084E+09 1.054E+09 9.966E+08 9.012E+08 7.095E+08 3.516E+08 0.000E+00 0.000E+00 1.047E+07
     HOUR =     0.000     0.862     1.724     2.586     3.448     4.310     5.172     0.000     0.000
DAY = 186     9.498E+08 9.383E+08 9.062E+08 8.492E+08 7.501E+08 5.630E+08 2.573E+08 0.000E+00 0.000E+00 8.001E+06
       0     1.089E+09 1.080E+09 1.049E+09 9.940E+08 8.969E+08 7.032E+08 3.655E+08 0.000E+00 0.000E+00 9.456E+06
     HOUR =     0.000     0.766     1.532     2.297     3.063     3.829     4.595     0.000     0.000
DAY = 216     9.782E+08 9.670E+08 9.377E+08 8.824E+08 7.817E+08 5.976E+08 3.175E+08 0.000E+00 0.000E+00 7.414E+06
     336     1.052E+09 1.043E+09 1.014E+09 9.598E+08 8.591E+08 6.706E+08 3.773E+08 0.000E+00 0.000E+00 8.103E+06
     HOUR =     0.000     0.678     1.357     2.035     2.714     3.392     4.071     0.000     0.000
DAY = 246     9.750E+08 9.655E+08 9.361E+08 8.777E+08 7.785E+08 6.067E+08 3.695E+08 0.000E+00 0.000E+00 6.591E+06
     306     9.850E+08 9.757E+08 9.462E+08 8.876E+08 7.880E+08 6.153E+08 3.771E+08 0.000E+00 0.000E+00 6.669E+06
     HOUR =     0.000     0.641     1.282     1.923     2.564     3.205     3.845     0.000     0.000
DAY = 276     9.423E+08 9.322E+08 9.027E+08 8.435E+08 7.458E+08 5.855E+08 3.696E+08 0.000E+00 0.000E+00 6.005E+06

ANNUAL SUMMARY OF SYSTEM EFFICIENCIES ,  UNIVERSITY OF HOUSTON

     HOUR =     0.000     1.046     2.092     3.139     4.185     5.231     6.277     0.000     0.000
DAY =  93     0.60055   0.59828   0.59130   0.57728   0.55380   0.49044   0.34042   0.00000   0.00000   0.55892
     HOUR =     0.000     1.019     2.037     3.056     4.074     5.093     6.111     0.000     0.000
DAY = 124     0.59104   0.58873   0.58154   0.56780   0.54489   0.48284   0.33502   0.00000   0.00000   0.55132
     HOUR =     0.000     0.951     1.903     2.854     3.805     4.757     5.708     0.000     0.000
DAY = 155     0.58987   0.58732   0.58033   0.56665   0.54314   0.48110   0.33599   0.00000   0.00000   0.54992
     HOUR =     0.000     0.862     1.724     2.586     3.448     4.310     5.172     0.000     0.000
DAY = 186     0.58785   0.58551   0.57816   0.56564   0.54076   0.47600   0.34166   0.00000   0.00000   0.54758
     HOUR =     0.000     0.766     1.532     2.297     3.063     3.829     4.595     0.000     0.000
DAY = 216     0.58564   0.58350   0.57710   0.56411   0.53532   0.46819   0.35277   0.00000   0.00000   0.54326
     HOUR =     0.000     0.678     1.357     2.035     2.714     3.392     4.071     0.000     0.000
DAY = 246     0.57619   0.57390   0.56639   0.54942   0.51757   0.45157   0.35802   0.00000   0.00000   0.52933
     HOUR =     0.000     0.641     1.282     1.923     2.564     3.205     3.845     0.000     0.000
DAY = 276     0.56722   0.56429   0.55635   0.53787   0.50482   0.44228   0.35610   0.00000   0.00000   0.51906

ANNUAL SUMMARY OF SYSTEM EFFICIENCIES/COSI ,  UNIVERSITY OF HOUSTON

     HOUR =     0.000     1.046     2.092     3.139     4.185     5.231     6.277     0.000     0.000
DAY =  93     0.73594   0.73733   0.74112   0.74397   0.74147   0.68842   0.50438   0.00000   0.00000   0.72459
     HOUR =     0.000     1.019     2.037     3.056     4.074     5.093     6.111     0.000     0.000
DAY = 124     0.72532   0.72647   0.72949   0.73186   0.72905   0.67676   0.49539   0.00000   0.00000   0.68256
     HOUR =     0.000     0.951     1.903     2.854     3.805     4.757     5.708     0.000     0.000
DAY = 155     0.72863   0.72917   0.73151   0.73243   0.72686   0.67254   0.49425   0.00000   0.00000   0.66628
     HOUR =     0.000     0.862     1.724     2.586     3.448     4.310     5.172     0.000     0.000
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DAY = 186      0.73731  0.73758  0.73790  0.73777  0.72686  0.66466  0.49905  0.00000  0.00000  0.66538
   HOUR =     0.000    0.766    1.532    2.297    3.063    3.829    4.595    0.000    0.000
DAY = 216      0.75104  0.75093  0.75053  0.74656  0.72587  0.65471  0.51178  0.00000  0.00000  0.69330
   HOUR =     0.000    0.678    1.357    2.035    2.714    3.392    4.071    0.000    0.000
DAY = 246      0.75520  0.75427  0.75052  0.73801  0.70853  0.63325  0.51677  0.00000  0.00000  0.70994
   HOUR =     0.000    0.641    1.282    1.923    2.564    3.205    3.845    0.000    0.000
DAY = 276      0.75024  0.74818  0.74303  0.72707  0.69394  0.62110  0.51306  0.00000  0.00000  0.70446
******************* TOTAL CLOUDLESS ANNUAL ABSORBED RECEIVER POWER , UNIVERSITY OF HOUSTON
************************************
 ABSORBTIVITY IS   0.92   LOSSES ARE  43.9823 MW
TOTAL ANNUAL RECEIVER POWER=  0.2700E+07 IN MWH FOR RECEIVER DIAMETER=  20.00  AND HEIGHT=  25.00 METERS    KWH
   HOUR =     0.000    1.046    2.092    3.139    4.185    5.231    6.277    0.000    0.000
DAY =  93     9.058E+08 8.968E+08 8.686E+08 8.151E+08 7.266E+08 5.508E+08 2.305E+08 0.000E+00 0.000E+00 9.330E+06
   HOUR =     0.000    1.019    2.037    3.056    4.074    5.093    6.111    0.000    0.000
DAY = 124     8.409E+08 8.317E+08 8.022E+08 7.474E+08 6.575E+08 4.843E+08 1.816E+08 0.000E+00 0.000E+00 8.281E+06
    62      9.203E+08 9.111E+08 8.825E+08 8.292E+08 7.410E+08 5.653E+08 2.425E+08 0.000E+00 0.000E+00 9.257E+06
   HOUR =     0.000    0.951    1.903    2.854    3.805    4.757    5.708    0.000    0.000
DAY = 155     8.381E+08 8.281E+08 7.991E+08 7.446E+08 6.545E+08 4.823E+08 1.835E+08 0.000E+00 0.000E+00 7.705E+06
    31      9.624E+08 9.530E+08 9.253E+08 8.729E+08 7.851E+08 6.087E+08 2.795E+08 0.000E+00 0.000E+00 9.134E+06
   HOUR =     0.000    0.862    1.724    2.586    3.448    4.310    5.172    0.000    0.000
DAY = 186     8.298E+08 8.193E+08 7.898E+08 7.372E+08 6.461E+08 4.740E+08 1.927E+08 0.000E+00 0.000E+00 6.906E+06
     0      9.582E+08 9.492E+08 9.209E+08 8.705E+08 7.811E+08 6.030E+08 2.923E+08 0.000E+00 0.000E+00 8.244E+06
   HOUR =     0.000    0.766    1.532    2.297    3.063    3.829    4.595    0.000    0.000
DAY = 216     8.559E+08 8.456E+08 8.187E+08 7.678E+08 6.752E+08 5.058E+08 2.481E+08 0.000E+00 0.000E+00 6.417E+06
   336      9.241E+08 9.155E+08 8.892E+08 8.391E+08 7.464E+08 5.729E+08 3.032E+08 0.000E+00 0.000E+00 7.050E+06
   HOUR =     0.000    0.678    1.357    2.035    2.714    3.392    4.071    0.000    0.000
DAY = 246     8.530E+08 8.442E+08 8.172E+08 7.635E+08 6.723E+08 5.142E+08 2.959E+08 0.000E+00 0.000E+00 5.706E+06
   306      8.622E+08 8.537E+08 8.265E+08 7.726E+08 6.810E+08 5.221E+08 3.029E+08 0.000E+00 0.000E+00 5.777E+06
   HOUR =     0.000    0.641    1.282    1.923    2.564    3.205    3.845    0.000    0.000
DAY = 276     8.229E+08 8.136E+08 7.865E+08 7.320E+08 6.421E+08 4.947E+08 2.960E+08 0.000E+00 0.000E+00 5.186E+06

ANNUAL SUMMARY OF SYSTEM EFFICIENCIES ,  UNIVERSITY OF HOUSTON

   HOUR =     0.000    1.046    2.092    3.139    4.185    5.231    6.277    0.000    0.000
DAY =  93     0.52692  0.52469  0.51778  0.50391  0.48041  0.41784  0.26301  0.00000  0.00000  0.48548
   HOUR =     0.000    1.019    2.037    3.056    4.074    5.093    6.111    0.000    0.000
DAY = 124      0.51673  0.51443  0.50720  0.49334  0.46987  0.40723  0.24812  0.00000  0.00000  0.47630
   HOUR =     0.000    0.951    1.903    2.854    3.805    4.757    5.708    0.000    0.000
DAY = 155      0.51562  0.51308  0.50605  0.49224  0.46822  0.40562  0.24935  0.00000  0.00000  0.47497
   HOUR =     0.000    0.862    1.724    2.586    3.448    4.310    5.172    0.000    0.000
DAY = 186      0.51360  0.51122  0.50384  0.49110  0.46579  0.40074  0.25592  0.00000  0.00000  0.47263
   HOUR =     0.000    0.766    1.532    2.297    3.063    3.829    4.595    0.000    0.000
DAY = 216      0.51246  0.51028  0.50386  0.49086  0.46238  0.39628  0.27568  0.00000  0.00000  0.47018
   HOUR =     0.000    0.678    1.357    2.035    2.714    3.392    4.071    0.000    0.000
DAY = 246      0.50410  0.50184  0.49447  0.47793  0.44693  0.38271  0.28676  0.00000  0.00000  0.45823
   HOUR =     0.000    0.641    1.282    1.923    2.564    3.205    3.845    0.000    0.000
DAY = 276      0.49536  0.49252  0.48473  0.46679  0.43466  0.37368  0.28524  0.00000  0.00000  0.44830

ANNUAL SUMMARY OF SYSTEM EFFICIENCIES/COSI ,  UNIVERSITY OF HOUSTON

   HOUR =     0.000    1.046    2.092    3.139    4.185    5.231    6.277    0.000    0.000
DAY =  93     0.64571  0.64663  0.64897  0.64941  0.64321  0.58651  0.38969  0.00000  0.00000  0.62938
   HOUR =     0.000    1.019    2.037    3.056    4.074    5.093    6.111    0.000    0.000
DAY = 124      0.63413  0.63478  0.63624  0.63589  0.62867  0.57078  0.36688  0.00000  0.00000  0.58967
   HOUR =     0.000    0.951    1.903    2.854    3.805    4.757    5.708    0.000    0.000
DAY = 155      0.63691  0.63700  0.63788  0.63626  0.62660  0.56703  0.36679  0.00000  0.00000  0.57547
   HOUR =     0.000    0.862    1.724    2.586    3.448    4.310    5.172    0.000    0.000
DAY = 186      0.64418  0.64400  0.64306  0.64053  0.62609  0.55956  0.37382  0.00000  0.00000  0.57431
   HOUR =     0.000    0.766    1.532    2.297    3.063    3.829    4.595    0.000    0.000
DAY = 216      0.65719  0.65670  0.65529  0.64963  0.62696  0.55415  0.39995  0.00000  0.00000  0.60004
   HOUR =     0.000    0.678    1.357    2.035    2.714    3.392    4.071    0.000    0.000
DAY = 246      0.66072  0.65956  0.65522  0.64199  0.61182  0.53668  0.41391  0.00000  0.00000  0.61458
   HOUR =     0.000    0.641    1.282    1.923    2.564    3.205    3.845    0.000    0.000
DAY = 276      0.65520  0.65302  0.64739  0.63099  0.59750  0.52476  0.41096  0.00000  0.00000  0.60842
```

ANNUAL SUMMARY OF INCIDENT PANEL POWER IN MW +++ U*H uses U of H insolation model above

DAYS HOUR SOUTH TO EAST TO NORTH
93 0.00 25.934 28.674 28.324 28.787 29.658 30.394 31.715 30.797 31.577 34.306 34.664 35.318 35.841 36.515 38.049 35.614
93 1.05 26.559 29.693 29.744 30.461 31.491 32.353 33.742 32.766 33.519 36.209 36.337 36.689 36.868 37.105 38.072 35.205
continues for each day and hour in Insolation table
ANNUAL SUMMARY OF INCIDENT PANEL POWER IN MW +++ U*H

DAYS HOUR NORTH TO WEST TO SOUTH last number in each row is integral over the full receiver (all 32 panels)
93 0.00 35.614 38.049 36.515 35.841 35.318 34.664 34.306 31.577 30.797 31.715 30.394 29.658 28.787 28.324 28.674 25.934
1032.337
93 1.05 34.707 36.549 34.606 33.580 32.780 31.926 31.424 28.789 28.062 28.976 27.894 27.544 27.191 27.320 28.269 26.110
1022.541
93 2.09 32.988 34.291 31.969 30.575 29.501 28.491 27.904 25.443 24.897 26.079 25.530 25.624 25.719 26.296 27.598
continues for each day and hour in Insolation table25.821 991.972
ANNUAL SUMMARY OF ABSORBED PANEL POWER IN MW +++ U*H

DAYS HOUR SOUTH TO EAST TO NORTH

tables above corrected for reflection and thermal loss

93 0.00 22.485 25.005 24.684 25.110 25.911 26.588 27.803 26.959 27.677 30.187 30.516 31.119 31.599 32.219 33.631 31.391
93 1.05 23.059 25.943 25.990 26.650 27.597 28.391 29.668 28.770 29.463 31.938 32.055 32.380 32.544 32.763 33.652 31.014

ANNUAL SUMMARY OF ABSORBED PANEL POWER IN MW +++ U*H

DAYS HOUR NORTH TO WEST TO SOUTH
93 0.00 31.391 33.631 32.219 31.599 31.119 30.516 30.187 27.677 26.959 27.803 26.588 25.911 25.110 24.684 25.005 22.485
905.768
93 1.05 30.556 32.250 30.463 29.519 28.783 27.998 27.536 25.111 24.443 25.283 24.288 23.966 23.641 23.760 24.633 22.647
896.755
93 2.09 28.975 30.173 28.037 26.754 25.767 24.837 24.297 22.033 21.531 22.619 22.113 22.199 22.287 22.818 24.016

ANNUAL SUMMARY OF DIMENSIONLESS PANEL GRADIENTS +++ U*H

DAYS HOUR SOUTH TO EAST TO NORTH
93 0.00 0.000 0.106 -0.013 0.017 0.031 0.026 0.045 -0.031 0.026 0.087 0.011 0.020 0.015 0.019 0.043 -0.069
93 1.05 0.018 0.118 0.002 0.025 0.035 0.028 0.044 -0.031 0.024 0.081 0.004 0.010 0.005 0.007 0.027 -0.082

ANNUAL SUMMARY OF DIMENSIONLESS PANEL GRADIENTS +++ U*H

DAYS HOUR NORTH TO WEST TO SOUTH
93 0.00 0.000 0.069 -0.043 -0.019 -0.015 -0.020 -0.011 -0.087 -0.026 0.031 -0.045 -0.026 -0.031 -0.017 0.013 -0.106
93 1.05 -0.015 0.054 -0.057 -0.031 -0.025 -0.028 -0.017 -0.092 -0.027 0.034 -0.040 -0.013 -0.014 0.005 0.036 -0.084

ANNUAL SUMMARY OF RECEIVER ASYMMETRY RATIOS , UNIVERSITY OF HOUSTON

HOUR = 0.00 1.05 2.09 3.14 4.18 5.23 6.28 0.00 0.00
DAY = 93 1.518 1.499 1.536 1.810 2.180 2.447 2.790 0.000 0.000
HOUR = 0.00 1.02 2.04 3.06 4.07 5.09 6.11 0.00 0.00
DAY = 124 1.572 1.554 1.566 1.831 2.216 2.541 3.068 0.000 0.000
HOUR = 0.00 0.95 1.90 2.85 3.81 4.76 5.71 0.00 0.00
DAY = 155 1.715 1.709 1.691 1.862 2.251 2.654 3.163 0.000 0.000
HOUR = 0.00 0.86 1.72 2.59 3.45 4.31 5.17 0.00 0.00
DAY = 186 1.942 1.951 1.947 2.085 2.298 2.639 3.144 0.000 0.000
HOUR = 0.00 0.77 1.53 2.30 3.06 3.83 4.59 0.00 0.00
DAY = 216 2.255 2.269 2.276 2.365 2.504 2.652 2.851 0.000 0.000
HOUR = 0.00 0.68 1.36 2.04 2.71 3.39 4.07 0.00 0.00
DAY = 246 2.532 2.545 2.563 2.560 2.686 2.750 3.067 0.000 0.000
HOUR = 0.00 0.64 1.28 1.92 2.56 3.20 3.85 0.00 0.00
DAY = 276 2.645 2.656 2.672 2.666 2.732 2.781 3.028 0.000 0.000

ANNUAL SUMMARY OF RECEIVER PANEL MAXIMA IN KW OVER PANEL NUMBER OF MAXIMA , UNIVERSITY OF HOUSTON
HOUR = 0.00 1.05 2.09 3.14 4.18 5.23 6.28 0.00 0.00

DAY = 93 33.65 33.76 33.02 32.57 30.48 23.58 10.19 0.00 0.00
18.11 14.75 14.61 10.42 10.35 10.11 12.32 0.00 0.00
HOUR = 0.00 1.02 2.04 3.06 4.07 5.09 6.11 0.00 0.00
DAY = 124 31.67 31.76 30.98 30.01 27.72 20.98 8.22 0.00 0.00
18.11 14.77 14.63 10.45 10.35 10.08 12.64 0.00 0.00
HOUR = 0.00 0.95 1.90 2.85 3.81 4.76 5.71 0.00 0.00
DAY = 155 32.63 32.74 31.92 30.14 27.76 21.41 8.25 0.00 0.00
18.09 14.80 14.67 12.04 10.43 10.05 13.34 0.00 0.00
HOUR = 0.00 0.86 1.72 2.59 3.45 4.31 5.17 0.00 0.00
DAY = 186 33.73 33.79 32.95 31.19 27.58 21.40 8.66 0.00 0.00
18.08 14.83 14.73 14.62 11.33 10.37 14.69 0.00 0.00
HOUR = 0.00 0.77 1.53 2.30 3.06 3.83 4.59 0.00 0.00
DAY = 216 36.33 36.23 35.54 33.57 29.44 22.74 10.87 0.00 0.00
18.08 14.85 14.78 14.71 12.47 11.48 15.07 0.00 0.00
HOUR = 0.00 0.68 1.36 2.04 2.71 3.39 4.07 0.00 0.00
DAY = 246 36.88 36.80 36.12 34.05 30.22 23.18 13.03 0.00 0.00
18.08 14.85 14.78 14.62 13.30 12.57 14.84 0.00 0.00
HOUR = 0.00 0.64 1.28 1.92 2.56 3.20 3.85 0.00 0.00
DAY = 276 35.78 35.70 35.02 33.03 29.04 22.40 13.03 0.00 0.00
18.04 14.88 14.77 14.59 13.54 12.99 14.73 0.00 0.00

ANNUAL SUMMARY OF RECEIVER PANEL MINIMA IN KW OVER PANEL NUMBER OF MINIMA , UNIVERSITY OF HOUSTON
HOUR = 0.00 1.05 2.09 3.14 4.18 5.23 6.28 0.00 0.00
DAY = 93 22.17 22.52 21.50 17.99 13.98 9.63 3.65 0.00 0.00
32.50 32.33 24.82 24.67 24.48 24.25 24.03 0.00 0.00
HOUR = 0.00 1.02 2.04 3.06 4.07 5.09 6.11 0.00 0.00
DAY = 124 20.14 20.44 19.78 16.39 12.51 8.26 2.68 0.00 0.00
32.50 32.32 24.91 24.76 24.58 24.38 24.14 0.00 0.00
HOUR = 0.00 0.95 1.90 2.85 3.81 4.76 5.71 0.00 0.00
DAY = 155 19.03 19.16 18.88 16.19 12.33 8.07 2.61 0.00 0.00
32.50 32.30 28.79 25.01 24.85 24.66 24.62 0.00 0.00
HOUR = 0.00 0.86 1.72 2.59 3.45 4.31 5.17 0.00 0.00
DAY = 186 17.37 17.32 16.92 14.96 12.00 8.11 2.75 0.00 0.00
32.50 32.30 32.12 28.48 27.30 25.04 24.88 0.00 0.00
HOUR = 0.00 0.77 1.53 2.30 3.06 3.83 4.59 0.00 0.00
DAY = 216 16.11 15.97 15.61 14.19 11.75 8.57 3.81 0.00 0.00
32.50 32.30 32.10 29.06 28.55 27.56 27.26 0.00 0.00
HOUR = 0.00 0.68 1.36 2.04 2.71 3.39 4.07 0.00 0.00
DAY = 246 14.56 14.46 14.09 13.30 11.25 8.43 4.25 0.00 0.00
32.50 32.31 32.12 29.53 29.06 28.92 28.65 0.00 0.00
HOUR = 0.00 0.64 1.28 1.92 2.56 3.20 3.85 0.00 0.00
DAY = 276 13.53 13.44 13.11 12.39 10.63 8.05 4.30 0.00 0.00
32.50 32.32 32.13 31.96 29.30 29.17 28.90 0.00 0.00

ANNUAL SUMMARY OF INCIDENT PANEL POWER IN MW FOR A CONSTANT DIRECT BEAM INTENSITY AT ALL TIMES OF 950.0 WATTS/M2 +++ U*H

DAYS HOUR SOUTH TO EAST TO NORTH
93 0.00 26.316 29.096 28.741 29.212 30.095 30.842 32.182 31.251 32.043 34.811 35.175 35.839 36.369 37.053 38.610 36.139
93 1.05 27.106 30.305 30.357 31.089 32.140 33.020 34.437 33.441 34.210 36.955 37.085 37.445 37.628 37.870 38.857 35.931

Appendix C: Glossary

Csa	Mediterranean Climate in Classification of Major Climatic Types According to the Koppen-Geiger-Pohl Scheme C: Mid-latitude climate s: Dry summer a: Temperature of warmest month 22 degrees Celsius or above
%PS	Percent Possible Sun
CSI	Clear Sky Insolation
DBI	Direct Beam Insolation in kWhr/day
With Clouds	13th number is MWhr/year
B500	Measured turbidity at 500 nm
ATF	Atmospheric Turbidity Factor
VR	Visual range at sea level, corrected to site elevation in code.
Rain	Rain condition: w for wet; d for dry
DMIR	Reference dimension for heliostat (Square root of height * width)
DREC	Diameter of receiver
HREC	Height of receiver
fh	Focal height of receiver centerline (above plane of heliostat elevation axis)
CEI	Cost Escalation Index, taken from Chemical Engineering Plant Cost Index

Appendix B
SOLERGY Input Parameters

Table B1: SOLERGY Input Parameters – Page 1 of 3

		Subcritical nitrate salt	Supercritical nitrate salt	Low temperature supercritical H_2O	High temperature supercritical H_2O	Low temperature supercritical CO_2	High temperature supercritical CO_2
Site Parameters							
ALAT	degrees site latitude	34.9	34.9	34.9	34.9	34.9	34.9
ALONG	degrees site longitude	117.0	117.0	117.0	117.0	117.0	117.0
ZONE	Pacific time zone	8	8	8	8	8	8
Collector Field							
FS	m^2 field size (mirror area)	1,796,300	1,627,775	1,780,996	1,774,326	1,729,332	1,715,796
ELIM	degrees minimum sun elevation angle	0	0	0	0	0	0
RFLCTY	heliostat reflectivity	1.000	1.000	1.000	1.000	1.000	1.000
Receiver							
EPS	receiver absorbtivity	0.93	0.93	0.93	0.93	0.93	0.93
RS	MWt receiver thermal rating	912	812	812	804	812	804
ALPHAR	hr^{-1} receiver cooldown parameter	0.2	0.2	0.2	0.2	0.2	0.2
TREQD	hr. time delay for receiver startup	0.5	0.5	0.75	0.75	0.75	0.25
EREQD	MWht to preheat the receiver	56.6	56.6	86.8	67.8	86.8	34.0
RMF	receiver minimum flow	0.13	0.13	0.13	0.13	0.13	0.13
PLXLR	MWt hot receiver convection + radiation loss						
2.23	m/sec wind speed	62	80	99	115	117	97
4.47		63	82	102	118	120	100
8.94		64	86	109	126	128	107
13.4		66	90	116	133	136	114
17.9		68	93	123	141	144	122
Piping							
YXLP	fraction of heat lost in piping system	0.00251	0.00305	0.00305	0.00416	0.00305	0.00237
Thermal Storage							
PTSMAX	MWt maximum power to storage	1,004	894	894	884	894	884
PFSMAX	MWt maximum power to steam generator	532	474	474	469	474	469
	hour storage capacity	8	8	8	8	8	8
EMAX	MWht thermal storage capacity	4,055	3,791	3,791	3,750	3,791	3,750
EMIN	MWht minimum value of stored energy	0	0	0	0	0	0
ES	MWht energy in storage at time = 0	0	0	0	0	0	0
TNKLF	MWt heat loss from storage tanks	1.114	0.916	0.916	2.084	0.916	2.084

Table B1 SOLERGY Input Parameters – Page 2 of 3

		Subcritical nitrate salt	Supercritical nitrate salt	Low temperature supercritical H_2O	High temperature supercritical H_2O	Low temperature supercritical CO_2	High temperature supercritical CO_2
Steam Generator							
DLF	MWt steam generator heat loss	0.16	0.16	0.16	0.16	0.16	0.16
REFPC	MWt reference power for steam generator thermal loss	507	451	474	469	474	469
TSTOR	hr steam generator startup time	0.25	0.25	0.25	0.25	0.25	0.25
PWARMD	MWt maximum power to steam generator during startup	50.7	45.1	47.4	46.9	47.4	46.9
PWARMC	MWt maximum allowable power to thermal storage	1,004	894	894	884	894	884
Steam Turbine							
	MWe gross plant rating	220	220	220	220	220	220
	gross Rankine cycle efficiency	0.434	0.488	0.488	0.493	0.488	0.493
TBHWS	hr. time between hot startup and warm startup	5	5	5	5	5	5
TBWCS	hr. time between warm startup and cold startup	60	60	60	60	60	60
SDH	hr. hot turbine synchronization delay	0.25	0.25	0.25	0.25	0.25	0.25
SDW	hr. warm turbine synchronization delay	0.5	0.50	0.50	0.50	0.50	0.50
SDC	hr. cold turbine synchronization delay	1.00	1.00	1.00	1.00	1.00	1.00
RDH	hr. hot turbine ramp delay	0.25	0.25	0.25	0.25	0.25	0.25
RDW	hr. warm turbine ramp delay	0.75	0.75	0.75	0.75	0.75	0.75
RDC	hr. cold turbine ramp delay	1.5	1.5	1.5	1.5	1.5	1.5
TPFSL	MWt thermal power for rated turbine operation	507	451	474	469	474	469
TMFS	minimum turbine flow fraction	0.15	0.15	0.15	0.15	0.15	0.15
ESMIN1	MWht minimum to start turbine; receiver in operation	253	226	237	234	237	234
ESMIN2	MWht minimum to start turbine; receiver not in operation	253	226	237	234	237	234
ESMAX1	MWht maximum to start turbine; receiver in operation	253	226	237	234	237	234

Table B1 SOLERGY Input Parameters – Page 3 of 3

Auxiliary Power		Subcritical nitrate salt	Supercritical nitrate salt	Low temperature supercritical H_2O	High temperature supercritical H_2O	Low temperature supercritical CO_2	High temperature supercritical CO_2
PA(1)	MWe heliostat drive and field transformer power, per m^2	7.60E-07	7.60E-07	7.60E-07	7.60E-07	7.60E-07	7.60E-07
PA(2)	MWhe heliostat stow / unstow energy	8.00E-06	8.00E-06	8.00E-06	8.00E-06	8.00E-06	8.00E-06
PA(3)	1st cold salt pump parasitic equation coefficient	-0.0380	-0.041	0	0	0	0
PA(4)	2nd cold salt pump parasitic equation coefficient	8.3920	8.356	0	0	0	0
PA(5)	3rd cold salt pump parasitic equation coefficient	-6.5470	-7.132	0	0	0	0
PA(6)	4th cold salt pump parasitic equation coefficient	10.4760	11.411	19.605	22.994	7.286	2.175
PA(7)	turbine plant parasitic equation coefficient	-1.0568	-0.1494	-0.1494	-0.1494	-0.1494	-0.1494
PA(8)	turbine plant parasitic equation coefficient	5.8480	10.902	10.902	10.902	10.902	10.902
PA(9)	solar multiple	1.8	1.8	1.8	1.8	1.8	1.8
PA(10)	MWe hot salt pump parasitic power demand	0.612	0.604	0.604	0	0.604	0
PA(11)	without head tank, PA(11) equals PA(10	0.612	0.604	0.604	0	0.604	0
PA(12)	without head tank, PA(12) equals PA(10	0.612	0.604	0.604	0	0.604	0
PA(13)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(14)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(15)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(16)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(17)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(18)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(19)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(20)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(21)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(22)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(23)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(24)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(25)	dry cooling tower equation coefficients	0	0	0	0	0	0
PA(26)	MWt cold receiver convection + radiation loss	6.4	13.7	0	0	0	0
PA(27)	each time steps for receiver hold during cold flow	3	3	0	0	0	0
PA(28)	MWe overnight auxiliary power demand	0.376	0.376	0.376	0.376	0.376	0.376
PA(29)	MWe maintenance period auxiliary power demand	0.376	0.376	0.376	0.376	0.376	0.376

Appendix C
Subcritical Nitrate Salt Plant Total Field Cost Estimate

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	----------------------------- $ ------------------------------ Material	Labor	S/C	Total
====	==	====	===	=======	======	=====	=====	=====	=======	=======	========	========
0	LAND	3,946	AC		8,000						31,564,470	31,564,470
1	STRUCTURES AND IMPROVEMENTS											
1	SITE IMPROVEMENTS											
	Clear and Grub	3,097	AC		624						1,932,690	1,932,690
	Roads - Grading	75,600	SY		0.52						39,310	39,310
	Roads - 8 in. base	12,500	CY		12.48						156,000	156,000
	Roads - 3 in. asphalt	49,300	SY		6.24						307,630	307,630
	Roads - 6 ft. shoulders	21,400	SY		4.16						89,020	89,020
	Roads - Oil only	5,300	SY		0.52						2,760	2,760
	Railroad Spur	0	LF		78.00						0	0
	Site Fences	49,000	LF		12.48						611,520	611,520
	Evaporation Pond - Grading	16,900	SY		0.52						8,790	8,790
	Evaporation Pond - Excavation (Kramer Junction: 150 MWe, 200 m x 660 m)	50,800	CY			26.72	0.13	6,604		389,240		389,240
	Evaporation Pond - Hypalon liner	367,000	SF	3.69		26.72	0.33	119,275	1,354,964	7,030,050		8,385,014
2	PIPING											
	Yard Piping - Excavation	15,000	CY		2.60						39,000	39,000
	Yard Piping - Back Fill	15,000	CY		5.20						78,000	78,000
	Domestic Water	2,600	LF			42.68	1.04	2,705	12,600	202,600		215,200
	Fire Protection	6,700	LF			42.68	1.04	6,968	53,800	521,900		575,700
	Primary Water Treatment	1,200	LF			42.68	1.85	2,221	13,100	166,350		179,450
	Raw Water	5,000	LF			42.68	0.68	3,403	49,000	254,880		303,880
	Sanitary Sewer and Drains	1,500	LF			42.68	0.65	975	7,000	73,030		80,030
3	MAINTENANCE / WAREHOUSE BUILDING	14,000	SF		85						1,190,000	1,190,000
4	CONTROL / ELECTRICAL / ADMINISTRATION BUILDING	4,400	SF		255						1,122,000	1,122,000
5	WATER TREATMENT	3,750	SF		155						581,250	581,250
6	ELECTRIC AND CONTROL											
	- Turbine-Generator	2,750	SF		285						783,750	783,750
	- Cooling Tower	900	SF		285						256,500	256,500
7	SECURITY / GATEHOUSE	150	SF		104						15,600	15,600
									----------	----------	------------	------------
	Subtotal - Structures and Improvements								1,490,464	8,638,050	7,213,820	17,342,334
	Sales Tax								110,294			
									----------	----------	------------	------------
1	TOTAL - STRUCTURES AND IMPROVEMENTS								1,600,758	8,638,050	7,213,820	17,452,628
2	COLLECTOR SYSTEM											
1	Collector System - 1,796,300 m^2; complete including foundations and controls	3,592,600	M^2		224				0	0	803,305,360	803,305,360
2	Electric Power Distribution and Field Wiring (power, control, and grounding)	3,592,600	M^2		7.50				0	0	26,944,500	26,944,500
									---------------	---------------	---------------	---------------
	Subtotal - Collector System								0	0	830,249,860	830,249,860
	Sales Tax								0			
									---------------	---------------	---------------	---------------
2	TOTAL - COLLECTOR SYSTEM								0	0	830,249,860	830,249,860

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	---------- $ ---------- Material	Labor	S/C	Total
0	LAND	3,946	AC		8,000						31,564,470	31,564,470
1	STRUCTURES AND IMPROVEMENTS											
1	SITE IMPROVEMENTS											
	Clear and Grub	3,097	AC		624						1,932,690	1,932,690
	Roads - Grading	75,600	SY		0.52						39,310	39,310
	Roads - 8 in. base	12,500	CY		12.48						156,000	156,000
	Roads - 3 in. asphalt	49,300	SY		6.24						307,630	307,630
	Roads - 6 ft. shoulders	21,400	SY		4.16						89,020	89,020
	Roads - Oil only	5,300	SY		0.52						2,760	2,760
	Railroad Spur	0	LF		78.00						0	0
	Site Fences	49,000	LF		12.48						611,520	611,520
	Evaporation Pond - Grading	16,900	SY		0.52						8,790	8,790
	Evaporation Pond - Excavation (Kramer Junction: 150 MWe, 200 m x 660 m)	50,800	CY			26.72	0.13	6,604		389,240		389,240
	Evaporation Pond - Hypalon liner	367,000	SF	3.69		26.72	0.33	119,275	1,354,964	7,030,050		8,385,014
2	PIPING											
	Yard Piping - Excavation	15,000	CY		2.60						39,000	39,000
	Yard Piping - Back Fill	15,000	CY		5.20						78,000	78,000
	Domestic Water	2,600	LF			42.68	1.04	2,705	12,600	202,600		215,200
	Fire Protection	6,700	LF			42.68	1.04	6,968	53,800	521,900		575,700
	Primary Water Treatment	1,200	LF			42.68	1.85	2,221	13,100	166,350		179,450
	Raw Water	5,000	LF			42.68	0.68	3,403	49,000	254,880		303,880
	Sanitary Sewer and Drains	1,500	LF			42.68	0.65	975	7,000	73,030		80,030
3	MAINTENANCE / WAREHOUSE BUILDING	14,000	SF		85						1,190,000	1,190,000
4	CONTROL / ELECTRICAL / ADMINISTRATION BUILDING	4,400	SF		255						1,122,000	1,122,000
5	WATER TREATMENT	3,750	SF		155						581,250	581,250
6	ELECTRIC AND CONTROL											
	- Turbine-Generator	2,750	SF		285						783,750	783,750
	- Cooling Tower	900	SF		285						256,500	256,500
7	SECURITY / GATEHOUSE	150	SF		104						15,600	15,600
	Subtotal - Structures and Improvements								1,490,464	8,638,050	7,213,820	17,342,334
	Sales Tax								110,294			
1	TOTAL - STRUCTURES AND IMPROVEMENTS								1,600,758	8,638,050	7,213,820	17,452,628
2	COLLECTOR SYSTEM											
1	Collector System - 1,796,300 m^2; complete including foundations and controls	3,592,600	M^2		224				0	0	803,305,360	803,305,360
2	Electric Power Distribution and Field Wiring (power, control, and grounding)	3,592,600	M^2		7.50				0	0	26,944,500	26,944,500
	Subtotal - Collector System								0	0	830,249,860	830,249,860
	Sales Tax								0			
2	TOTAL - COLLECTOR SYSTEM								0	0	830,249,860	830,249,860

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	------ $ ------ Material	Labor	S/C	Total
3	RECEIVER SYSTEM											
G	PUMPS AND DRIVERS											
1	Cold Salt Pump Extended shaft turbine pump, 4 stage 6,000 gpm, 1584 lb_m/sec, 1260 ft total developed head 4,500 bhp motor variable speed drive	6	EA	1,806,775		38.13	494	2,964	10,840,650	208,520		11,049,170
2	Spare Pump and Motor (without variable speed drive) 6,000 gpm, 1584 lb_m/sec, 1260 ft total developed head 2,500 bhp motor variable speed drive	1	EA	1,210,539		38.13	0	0	1,210,540	0		1,210,540
3	Pump Heating Shell	1	EA	236,641		38.13	0	0	236,640	0		236,640
	Subtotal - Pumps and Drivers								12,287,830	208,520		12,496,350
T	SPECIAL EQUIPMENT											
1	Nitrate Salt Receiver 910 MWt, external cylinder, nickel alloy steel tubes and headers, 20 m dia. x 25 m absorber height, 2 flow circuits, 12 passes per circuit, includes inlet and outlet vessels, piping, valves, insulation, heat tracing, installation, and checkout	2	EA		51,545,000						103,090,000	103,090,000
2	Tower Elevator	2	EA	654,439	10,000	38.13	585	1,170	1,308,880	82,310	20,000	1,411,190
3	Receiver Maintenance Crane: 5 ton	2	EA	239,200		38.13	650	1,300	478,400	91,450	0	569,850
	Subtotal - Special Equipment								1,787,280	173,760	103,110,000	105,071,040
J	INSTRUMENTATION											
1	Nitrate Salt Pipe Temperatures (Electric heat trace system) Type K thermocouple, Type 304 stainless steel braided sheath Welded tab; with A/D converter/transmitter	128	EA	627		36.85	29.9	3,827	80,271	264,330		344,601
2	Thermocouple Low Energy Process Interface Unit	2	EA	20,696		36.85	52	104	41,392	7,180		48,572
3	Loop Check	128	EA			36.85	3.25	416		28,730		28,730
4	Calibration and Testing	128	EA			36.85	3.51	449		31,010		31,010
5	Operator Station (in control room, provided by others)	1	LT		34,895						34,895	34,895
	Subtotal - Instrumentation								121,663	331,250	34,895	487,808

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
L	PIPING											
1	Vertical Pipe and Fittings: Nitrate Salt											
	22" Pipe - Carbon steel A 106 Grade B, Sch 60 (Riser)	5,732	LF	246		42.68	3.20	18,343	1,412,250	1,373,890		2,786,140
	22" Pipe - Carbon steel A 106 Grade B, Sch 60 (Cold salt pump discharge)	480	LF	246		42.68	3.20	1,536	118,260	115,050		233,310
	28" Pipe - Stainless steel A 213 Type 347H, Sch 20 (Downcomer)	4,094	LF	611		42.68	4.58	18,753	2,501,310	1,404,600		3,905,910
	28" Pipe - Stainless steel A 213 Type 347H, Sch 20 (Diversion to cold salt tank)	320	LF	611		42.68	4.58	1,466	195,490	109,800		305,290
	2" Pipe - Carbon steel A106 Grade B, Sch 80 (Compressed air supply)	5,732	LF	6		42.68	0.70	4,013	35,930	300,570		336,500
2	Vertical Pipe Welds											
	22" Pipe - Carbon steel A 106 Grade B, Sch 60 (Riser)	717	EA			42.68	19.20	13,757		1,030,400		1,030,400
	22" Pipe - Carbon steel A 106 Grade B, Sch 60 (Cold salt pump discharge)	60	EA			42.68	19.20	1,152		86,280		86,280
	28" Pipe - Stainless steel A 213 Type 347H, Sch 20 (Downcomer)	512	EA			42.68	22.30	11,413		854,830		854,830
	28" Pipe - Stainless steel A 213 Type 347H, Sch 20 (Diversion to cold salt tank)	40	EA			42.68	22.30	892		66,810		66,810
	2" Pipe - Carbon steel A106 Grade B, Sch 80 (Compressed air supply)	1,146	EA			42.68	1.60	1,834		137,370		137,370
3	Valves for Vertical Piping											
	22 in. gate, carbon steel, 900 lb, motor operated, bellows seal (Salt isolation)	4	EA	57,339					229,360			229,360
	22 in. check, carbon steel, 900 lb class (Salt isolation)	4	EA	41,589					166,350			166,350
	28 in. gate, stainless steel, 150 lb class, motor operated (Cold salt tank diversion)	3	EA	75,603					226,810			226,810
	2 in. gate, carbon steel, 150 lb class (Compressed air supply)	8	EA	213					1,710			1,710
4	Vertical Piping Miscellaneous Piping Items and Operations											
	Hangers and supports (20% of installation manhours; $4/ft for material)	1	LT	65,436		42.68		14,632	65,440	1,095,920		1,161,360
	Waste allowance (10% of piping material)	1	LT	426,324					426,320			426,320
	Testing and inspection (7.5% of installation manhours)	1	LT			42.68		5,487		410,970		410,970
	Material handling (5% of installation manhours)	1	LT			42.68		3,658		273,980		273,980
	Freight (3% of material)	1	LT	146,624					146,620			146,620
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	Subtotal - Vertical Piping								5,525,850	7,260,470		12,786,320
5	Horizontal Pipe and Fittings: Nitrate Salt											
	28" Pipe - Carbon steel A 106 Grade B, Sch 60 (Horizonal riser)	11,811	LF	297		42.68	3.20	37,795	3,513,320	2,830,840		6,344,160
	30" Pipe - Stainless steel A 213 Type 347H, Sch 20 (Horizontal downcomer)	13,780	LF	655		42.68	4.58	63,110	9,030,070	4,726,930		13,757,000
	2" Pipe - Carbon steel A106 Grade B, Sch 80 (Compressed air supply)	9,843	LF	6		42.68	0.70	6,890	61,690	516,060		577,750
6	Horizontal Pipe Welds											
	28" Pipe - Carbon steel A 106 Grade B, Sch 60 (Horizonal riser)	1,476	EA			42.68	19.20	28,346		2,123,110		2,123,110
	30" Pipe - Stainless steel A 213 Type 347H, Sch 20 (Horizontal downcomer)	1,722	EA			42.68	22.30	38,410		2,876,900		2,876,900
	2" Pipe - Carbon steel A106 Grade B, Sch 80 (Compressed air supply)	1,969	EA			42.68	1.60	3,150		235,930		235,930
7	Valves for Horizontal Piping											
	28 in. gate, carbon steel, 900 lb, motor operated, bellows seal (Salt isolation)	4	EA	57,339					229,360			229,360
	30 in. gate, stainless steel, 150 lb class, motor operated (Salt isolation)	4	EA	75,603					302,410			302,410
	2 in. gate, carbon steel, 150 lb class (Compressed air supply)	8	EA	213					1,710			1,710

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	---- $ ---- Material	Labor	S/C	Total
====	==	====	===	=======	======	=====	=====	=====	=======	=======	========	========
8	Horizontal Piping Miscellaneous Piping Items and Operations											
	Hangers and supports (20% of installation manhours; $4/ft for material)	1	LT	141,732		42.68		35,540	141,730	2,661,960		2,803,690
	Waste allowance (10% of piping material)	1	LT	1,260,508					1,260,510			1,260,510
	Testing and inspection (7.5% of installation manhours)	1	LT			42.68		13,328		998,230		998,230
	Material handling (5% of installation manhours)	1	LT			42.68		8,885		665,490		665,490
	Freight (3% of material)	1	LT	394,157					394,160			394,160
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	Subtotal - Horizontal Piping								14,934,960	17,635,450		32,570,410
M	STRUCTURAL STEEL											
	Light structural steel	100	T	1,872		38.32	52	5,200	187,200	366,810		554,010
	Deck plate	3,000	SF	37		38.32	1.69	5,070	109,820	357,640		467,460
	Stair tower	2,047	LF	64		38.32	0.75	1,544	130,940	108,910		239,850
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	Subtotal - Structural Steel								427,960	833,360		1,261,320
N	INSULATION											
1	Piping: Stainless steel foil jacket; 25 mm mineral fiber blanket; calcium silicate block insulation; outer aluminum jacket											
	22" pipe, 6 in. thick, 1.1 fitting factor (Riser)	6,306	ELF	106		42.68	1.24	7,842	665,280	462,210		1,127,490
	22" Pipe, 6 in. thick, 1.1 fitting factor (Cold salt pump discharge)	528	ELF	106		42.68	1.24	657	55,710	38,720		94,430
	28" Pipe, 8 in. thick, 1.1 fitting factor (Downcomer)	4,504	ELF	177		42.68	2.03	9,151	797,500	539,360		1,336,860
	28" Pipe, 8 in. thick, 1.1 fitting factor (Cold salt tank diversion)	352	ELF	177		42.68	2.03	715	62,330	42,140		104,470
	28" pipe, 6 in. thick, 1.1 fitting factor (Horizontal riser)	12,992	ELF	126		42.68	1.51	19,656	1,637,990	1,158,520		2,796,510
	30" pipe, 8 in. thick, 1.1 fitting factor (Horizontal downcomer)	15,157	ELF	186		42.68	2.17	32,865	2,820,160	1,937,060		4,757,220
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	Subtotal - Insulation								6,038,970	4,178,010	0	10,216,980
P	ELECTRICAL											
1	Power Distribution											
	Substation transformer, 4000 / 5000 kVA, 4.16 kV - 480 V, OA / FA (480 V power for heat trace circuits: Receiver ovens and tower piping)	1	EA	78,000		29.42	429	429	78,000	26,440		104,440
	Heat trace power transformers, 50 kVA, 480 V - 50 V, AA	15	EA	2,600		29.42	33	488	39,000	30,050		69,050
	480 V motor control center	1	LT	94,016		29.42	338	338	94,016	20,830		114,846
	150 A combination starters for heat trace circuits	16	EA	Included in MCC price								
	Size 3 combination starters	4	EA	Included in MCC price								
	4.16 kV switchgear, 750 A main breaker, 4 each current limiting fuses and contactors (2 salt pump contactors + 2 substation contactors)	1	LT	83,225		29.42	312	312	83,225	19,230		102,455
	480 V switchgear, 3000 A main breaker and transition section to MCC	1	LT	41,600		29.42	91	91	41,600	5,610		47,210
	480 V disconnect switches, 100 A	40	EA	484		29.42	7	260	19,344	16,030		35,374
	Distribution transformer, 45 kVA, 480 V - 240 V	1	EA	2,080		29.42	33	33	2,080	2,000		4,080
	Heat trace power distribution panel	2	EA	2,600		29.42	39	78	5,200	4,810		10,010
	Lighting panel; 42 circuits	1	EA	1,638		29.42	39	39	1,638	2,400		4,038
	480 V disconnect switches, 30 A	2	EA	218		29.42	7	13	437	800		1,237
	Start / stop switches	2	EA	239		29.42	13	26	478	1,600		2,078
	Variable frequency drive (installation only)	1	EA	104		29.42	78	78	104	4,810		4,914

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	---- $ ---- Material	Labor	S/C	Total
====	==	====	===	=======	======	=====	=====	=====	=======	=======	========	========
3	Electric Heat Tracing											
	22" pipe, 9 active and 2 spare cables (Riser)	63,055	FT	35		29.42	0.33	20,493	2,206,929	1,263,180		3,470,109
	22" Pipe, 9 active and 2 spare cables (Cold salt pump discharge)	5,280	FT	35		29.42	0.33	1,716	184,800	105,770		290,570
	28" Pipe, 6 active and 2 spare cables (Downcomer)	32,756	FT	35		29.42	0.33	10,646	1,146,457	656,200		1,802,657
	28" Pipe, 6 active and 2 spare cables (Diversion to cold salt tank)	2,560	FT	35		29.42	0.33	832	89,600	51,280		140,880
	28" Pipe, 11 active and 2 spare cables (Horizontal riser)	129,921	FT	35		29.42	0.33	42,224	4,547,244	2,602,710		7,149,954
	30" Pipe, 6 active and 2 spare cables (Horizontal riser)	110,236	FT	35		29.42	0.33	35,827	3,858,268	2,208,360		6,066,628
	22 in. gate, 2 active and 2 spare cables, bellows seal (Salt isolation)	3	EA	499		29.42	26	78	1,498	4,810		6,308
	22 in. check, 2 active and 2 spare cables, bellows seal (Salt isolation)	3	EA	499		29.42	26	78	1,498	4,810		6,308
	28 in. gate, 3 active and 1 spare cable (Cold salt tank diversion)	1	EA	624		29.42	13	13	624	800		1,424
	28 in. gate, 3 active and 1 spare cable (Horizontal riser salt isolation)	4	EA	499		29.42	26	104	1,997	6,410		8,407
	30 in. gate, 3 active and 1 spare cable (Horizontal downcomer salt isolation)	4	EA	499		29.42	26	104	1,997	6,410		8,407
	Nitrate salt pump transition to top of salt tank	6	EA	1,248		29.42	26	156	7,488	9,620		17,108
	¾ in. rigid steel conduit	72,200	FT	1.96		29.42	0.24	17,108	141,695	1,054,520		1,196,215
	Electric power distribution cable, 12 gauge	360,999	FT	0.29		29.42	0.004	1,408	105,123	86,780		191,903
4	Lighting											
	Stanchions - 35 ft. poles	12	EA	1,323		29.42	18.7	224	15,875	13,820		29,695
	Pendant lights	20	EA	526		29.42	2.3	46	10,525	2,820		13,345
	Staircase lighting	100	EA	312		29.42	5.4	542	31,200	33,390		64,590
	Receptacles	50	EA	17		29.42	2.5	124	832	7,610		8,442
	Photocell	2	EA	125		29.42	2.2	4	250	270		520
	Lighting contactor	2	EA	458		29.42	10.8	22	915	1,340		2,255
	Junction boxes	30	EA	84		29.42	16.3	488	2,527	30,050		32,577
	Panelboards	2	EA	936		29.42	29.3	59	1,872	3,610		5,482
	¾ in. rigid steel conduit	7,170	FT	2.80		29.42	0.18	1,273	20,070	78,460		98,530
	2 conductor, 12 gauge wire	14,340	FT	0.29		29.42	0.0039	56	4,176	3,450		7,626
5	Welding Receptacle	24	EA	550		29.42	4	94	13,200	5,790		18,990
6	Communication Stations											
	GAI-Tronics page/party station	2	EA	1,050		29.42	10.40	21	2,101	1,280		3,381
	Horn	2	EA	234		29.42	5.20	10	468	640		1,108
	U bracket for horn	2	EA	73					146			146
	5 party line cable	1,320	FT	2.86		29.42	0.09	124	3,775	7,620		11,395
	Single line cable	1,320	FT	0.52		29.42	0.04	48	686	2,960		3,646
	¾ in. rigid steel conduit	320	FT	2.80		29.42	0.18	57	896	3,500		4,396
7	Fire / Smoke Detectors											
	Emergency shutdown stations	10	EA	78		29.42	2.60	26	780	1,600		2,380
	Photoelectric smoke detectors	16	EA	156		29.42	2.60	42	2,496	2,560		5,056
	Thermal detectors	16	EA	156		29.42	2.60	42	2,496	2,560		5,056
	Strobe light and horn	4	EA	104		29.42	2.60	10	416	640		1,056
	Electric wire, 16 gauge	4,000	FT	0.29		29.42	0.012	47	1,165	2,880		4,045
	¾ in. rigid steel conduit	1,000	FT	2.80		29.42	0.18	178	2,799	10,940		13,739
	Terminal box	2	EA	416		29.42	6.50	13	832	800		1,632
8	Instrument Conduit											
	¾ in. rigid steel conduit	6,000	FT	2.80		29.42	0.18	1,065	16,795	65,660		82,455
	Terminations	2,000	EA	14.55		29.42	0.65	1,300	29,099	80,130		109,229
	Instrument wiring	60,000	FT	1.06		29.42	0.014	866	63,648	53,370		117,018

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	------------ $ ------------ Material	Labor	S/C	Total
====	==	====	===	=======	======	=====	=====	=====	=======	=======	========	========
9	Cable Trays											
	12 in. power cable tray	800	FT	10		29.42	0.35	278	8,187	17,120		25,307
	12 in. instrument cable tray	800	FT	10		29.42	0.35	278	8,187	17,120		25,307
	24 in. 4.16 kV power cable tray	600	FT	11		29.42	0.49	294	6,883	18,130		25,013
	36 in. power cable tray	600	FT	15		29.42	0.67	404	9,273	24,900		34,173
	Tray covers	2,800	FT	Included		29.42	0.00	0	0	0		0
	Support columns	16	EA	312		29.42	39.0	624	4,992	38,460		43,452
	Support sleepers	12	EA	104		29.42	6.5	78	1,248	4,810		6,058
10	Wire and Cable											
	4.16 kV											
	3 conductor, 0000 gauge	1,500	FT	14.03		29.42	0.020	30	21,044	1,850		22,894
	Terminations	30	EA	1.67		29.42	0.153	5	50	280		330
	480 V											
	3 conductor, 12 gauge	4,620	FT	0.29		29.42	0.004	18	1,345	1,110		2,455
	3 conductor, 4 gauge	3,960	FT	3.03		29.42	0.007	29	11,985	1,800		13,785
	3 conductor, 0 gauge	10,200	FT	4.78		29.42	0.013	129	48,797	7,960		56,757
	3 conductor, 0000 gauge	6,400	FT	9.53		29.42	0.019	122	60,969	7,500		68,469
	Terminations	440	EA	1.11		29.42	0.117	51	490	3,170		3,660
	Control and instrument											
	7 conductor, 14 gauge	5,940	FT	1.52		29.42	0.018	108	9,019	6,660		15,679
	Twisted pair, 16 gauge	1,200	FT	1.06		29.42	0.014	17	1,273	1,070		2,343
	Twisted pair, 16 gauge, thermocouple	3,000	FT	1.06		29.42	0.014	43	3,182	2,670		5,852
	25 pair, 16 gauge	2,640	FT	7.55		29.42	0.061	162	19,933	9,960		29,893
	25 conductor, 14 gauge	1,800	FT	3.95		29.42	0.040	73	7,114	4,470		11,584
	Terminations	1,402	EA	14.55		29.42	0.650	911	20,399	56,170		76,569
	Termination boxes	4	EA	416		29.42	13.0	52	1,664	3,210		4,874
	Armored cable connections	50	EA	52		29.42	1.3	65	2,600	4,010		6,610
11	Cathodic Protection											
	Graphite anodes											
	Drilling	600	LF			29.42	1.05	632		38,940		38,940
	Anodes	20	EA	478		29.42	7.3	147	9,570	9,040		18,610
	Junction box	6	EA	783		29.42	8.4	50	4,700	3,100		7,800
	Rectifier	2	EA	5,984		29.42	182	364	11,970	22,440		34,410
	Test station	4	EA	73		29.42	2.17	9	290	530		820
	Reference cell	4	EA	52		29.42	5.42	22	210	1,340		1,550
	Electric cable, 3 conductor, armored, underground											
	6 gauge	900	FT	0.98		29.42	0.36	328	880	20,190		21,070
	8 gauge	750	FT	0.63		29.42	0.36	273	480	16,830		17,310
12	Grounding											
	Structural steel											
	1 conductor, 00 gauge, bare cable	500	FT	1.52		29.42	0.325	162	759	10,010		10,769
	Cadwelds	20	EA	10		29.42	1.49	30	210	1,830		2,040
	Grounding rods	10	EA	31		29.42	2.6	26	310	1,600		1,910
	Substation transformer											
	1 conductor, 00 gauge, bare cable	80	FT	1.52		29.42	0.325	26	121	1,600		1,721
	Cadwelds	24	EA	10		29.42	1.49	36	250	2,200		2,450

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	------------- $ ------------- Material	Labor	S/C	Total
====	==	====	===	=======	======	=====	=====	=====	=======	=======	========	========
	Pipe rack											
	1 conductor, 00 gauge, bare cable	330	FT	1.52		29.42	0.325	107	501	6,610		7,111
	Cadwelds	36	EA	10		29.42	1.49	53	370	3,300		3,670
	Grounding rods	6	EA	31		29.42	2.6	16	190	960		1,150
	Mechanical equipment											
	Nitrate salt pumps	6	EA	10		29.42	1.30	8	60	480		540
	Motor operated valves	24	EA	10		29.42	1.30	31	250	1,920		2,170
	1 conductor, 00 gauge, bare cable	800	FT	1.52		29.42	0.200	160	1,214	9,870		11,084
	1 conductor, 2 gauge, bare cable	1,200	FT	1.04		29.42	0.200	240	1,248	14,810		16,058
13	Testing	1	LT	5,200		29.42	311	311	5,200	19,160		24,360
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	Subtotal - Electrical								19,216,764	13,211,220		32,427,984
Q	CONCRETE WORK											
1	Receiver Tower											
	Formwork	Slip formed; included with concrete										
	Reinforcing steel	4,967	T	832		26.72	26	129,135	4,132,311	7,611,180		11,743,491
	Concrete	29,216	CY	306		26.72	1.95	56,971	8,941,862	3,357,870		12,299,732
	Embedded metals	292,160	LB	1.56		26.72	w/ forms		455,770			455,770
2	Tower Foundation											
	Formwork	38,865	SF	1.56		26.72	0.46	17,684	60,629	1,042,270		1,102,899
	Reinforcing steel	2,591	T	832		26.72	26	67,366	2,155,712	3,970,540		6,126,252
	Concrete	25,910	CY	306		26.72	1.95	50,525	7,930,026	2,977,910		10,907,936
	Embedded metals	259,100	LB	1.56		26.72	w/ forms		404,196			404,196
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	Subtotal - Concrete Work								24,080,506	18,959,770	0	43,040,276
S	SITEWORK											
	Excavation	31,092	CY			26.72	0.33	10,105		595,580		595,580
	Backfill and Compaction	5,182	CY	8		26.72	1.17	6,063	43,114	357,350		400,464
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	Subtotal - Sitework								43,114	952,930	0	996,044
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	Subtotal - Receiver System								84,464,898	63,744,740	102,673,615	250,883,253
	Sales Tax								6,250,402			6,250,402
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3	TOTAL - RECEIVER SYSTEM								90,715,301	63,744,740	102,673,615	257,133,656

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
4	THERMAL STORAGE SYSTEM											
D	TANKS											
1	Cold Salt Storage Tank Vertical cylindrical tank, self supporting roof, atmospheric pressure 135 ft diameter x 40 ft height, ASTM A 516, Grade 70, carbon steel 1,050,000 lb approximate weight Includes internal salt distribution piping	3	EA		3,462,990						10,388,970	10,388,970
2	Hot Salt Storage Tank Vertical cylindrical tank, self supporting roof, atmospheric pressure 141 ft diameter x 40 ft height, ASTM A 240, Type 347, stainless steel 1,140,000 lb approximate weight Includes internal salt distribution piping	3	EA		7,954,342						23,863,025	23,863,025
	Subtotal - Tanks										34,251,995	34,251,995
T	SPECIAL EQUIPMENT											
1	Nitrate Salt Inventory $0.476/lb for salt mixture, delivered $0.025/lb for handling, melting, and loading the inventory	179,178,327	LB	0.476	0.026				85,337,720		4,658,636	89,996,356
2	Maintenance Crane 15 ton capacity, 10 ft span	3	EA	100,984		38.13	309	928	302,950	65,280		368,230
	Subtotal - Special Equipment								85,640,670	65,280	4,658,636	90,364,586
J	INSTRUMENTATION											
1	Storage Tank Level Transmitters Sitrans LC500 capacitance detectors	6	EA	1,435		36.85	23.4	140	8,611	9,670		18,281
2	Storage Tank Inventory Temperatures Type K thermocouple, Type 304 stainless steel braided sheath Ceramic insulation, suitable for immersion; with transmitter With A/D converter/transmitter	96	EA	627		36.85	29.9	2,870	60,204	198,230		258,434
3	Thermocouple Low Energy Process Interface Unit	6	EA	20,696		36.85	52	312	124,176	21,550		145,726
4	Loop Check	120	EA			36.85	3.25	390		26,940		26,940
5	Calibration and Testing	80	EA			36.85	3.51	281		19,410		19,410
6	Operator Station (in control room, provided by others)	1	LT		34,895						34,895	34,895
	Subtotal - Instrumentation								192,991	275,800	34,895	503,686

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	---------- $ ---------- Material	Labor	S/C	Total
====	===	====	===	=======	======	=====	=====	=====	=======	=======	========	========
M	STRUCTURAL STEEL											
	Heavy steel (elevated platform)	372	T	1,404		38.32	13	4,833	521,910	340,920		862,830
	Light structural steel	57	T	1,872		38.32	52	2,986	107,490	210,630		318,120
	Deck plate	2,200	SF	37		38.32	1.69	3,718	80,540	262,270		342,810
	Stair tower	540	LF	64		38.32	0.75	407	34,540	28,710		63,250
	Subtotal - Structural Steel								744,480	842,530		1,587,010
N	INSULATION											
1	Tanks											
	Cold tank - 12 in. calcium silicate and mineral wool	84,122	ESF	17		42.68	0.42	35,468	1,426,100	2,656,550		4,082,650
	Hot tank - 14 in. calcium silicate and mineral wool	90,203	ESF	20		42.68	0.45	40,219	1,775,970	3,012,400		4,788,370
	Subtotal - Insulation								3,202,070	5,668,950	0	8,871,020
P	ELECTRICAL											
1	Power Distribution											
	Substation transformer, 4000 / 5000 kVA, 4.16 kV - 480 V, OA / FA (480 V power to tank immersion heaters)	1	EA	78,000		29.42	429	429	78,000	26,440		104,440
	480 V motor control center	1	LT	94,016		29.42	338	338	94,016	20,830		114,846
	400 A combination starters for cold tank immersion heaters	4	EA	Included in MCC price								
	400 A combination starters for hot tank immersion heaters	4	EA	Included in MCC price								
	Size 3 combination starters	4	EA	Included in MCC price								
	480 V disconnect switches, 100 A	16	EA	484		29.42	7	104	7,738	6,410		14,148
	Distribution transformer, 45 kVA, 480 V - 240 V	1	EA	2,080		29.42	33	33	2,080	2,000		4,080
	Heat trace power distribution panel	2	EA	2,600		29.42	39	78	5,200	4,810		10,010
	Lighting panel; 42 circuits	1	EA	1,638		29.42	39	39	1,638	2,400		4,038
	480 V disconnect switches, 30 A	2	EA	218		29.42	7	13	437	800		1,237
	Start / stop switches	8	EA	239		29.42	13	104	1,914	6,410		8,324
2	Storage Tank Immersion Heaters											
	Cold tank - 125 kW, 3 phase, 480 V, 150 A	12	EA	8,036		29.42	65	780	96,440	48,080		144,520
	Hot tank - 175 kW, 3 phase, 480 V, 210 A	12	EA	9,941		29.42	65	780	119,290	48,080		167,370
	Silicon controlled recitifier control packages	24	EA	416		29.42	26	624	9,984	38,460		48,444
4	Lighting											
	Stanchions - 35 ft. poles	6	EA	1,323		29.42	18.7	112	7,937	6,910		14,847
	Pendant lights	10	EA	526		29.42	2.3	23	5,262	1,410		6,672
	Staircase lighting	5	EA	312		29.42	5.4	27	1,560	1,670		3,230
	Receptacles	2	EA	17		29.42	2.5	5	33	300		333
	Photocell	1	EA	125		29.42	2.2	2	125	130		255
	Lighting contactor	1	EA	458		29.42	10.8	11	458	670		1,128
	Junction boxes	1	EA	84		29.42	16.3	16	84	1,000		1,084
	Panelboards	1	EA	936		29.42	29.3	29	936	1,800		2,736
	¾ in. rigid steel conduit	1,260	FT	1.96		29.42	0.24	299	2,473	18,400		20,873
	2 conductor, 12 gauge wire	2,520	FT	0.29		29.42	0.0039	10	734	610		1,344
5	Welding Receptacle	6	EA	550		29.42	4	23	3,300	1,420		4,720

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

				----- Unit Cost ------		Labor	MH	Total	------------------------------ $	-------------------------------		
Code	Description	Qty	Unit	Material	S/C	$ Rate	Rate	MH	Material	Labor	S/C	Total
6	Communication Stations											
	GAI-Tronics page/party station	1	EA	1,050		29.42	10.40	10	1,050	640		1,690
	Horn	1	EA	234		29.42	5.20	5	234	320		554
	U bracket for horn	1	EA	73					73			73
	5 party line cable	330	FT	2.86		29.42	0.09	31	944	1,900		2,844
	Single line cable	330	FT	0.52		29.42	0.04	12	172	740		912
	¾ in. rigid steel conduit	80	FT	1.96		29.42	0.24	19	157	1,170		1,327
7	Fire / Smoke Detectors											
	Emergency shutdown stations	3	EA	78		29.42	2.60	8	234	480		714
	Photoelectric smoke detectors	12	EA	156		29.42	2.60	31	1,872	1,920		3,792
	Thermal detectors	12	EA	156		29.42	2.60	31	1,872	1,920		3,792
	Strobe light and horn	3	EA	104		29.42	2.60	8	312	480		792
	Electric wire, 16 gauge	1,200	FT	0.29		29.42	0.012	14	349	870		1,219
	¾ in. rigid steel conduit	1,200	FT	1.96		29.42	0.24	284	2,355	17,530		19,885
	Terminal box	3	EA	416		29.42	6.50	20	1,248	1,200		2,448
8	Instrument Conduit											
	¾ in. rigid steel conduit	1,500	FT	1.96		29.42	0.24	355	2,944	21,910		24,854
	Terminations	60	EA	14.55		29.42	0.65	39	873	2,400		3,273
	Instrument wiring	1,800	FT	1.06		29.42	0.014	26	1,909	1,600		3,509
9	Cable Trays											
	12 in. power cable tray	480	FT	10		29.42	0.35	167	4,912	10,270		15,182
	12 in. instrument cable tray	660	FT	10		29.42	0.35	229	6,754	14,120		20,874
	Tray covers	1,140	FT	Included		29.42	0.00	0	0	0		0
	Support columns	33	EA	312		29.42	39.0	1,287	10,296	79,330		89,626
	Support sleepers	24	EA	104		29.42	6.5	156	2,496	9,620		12,116
10	Wire and Cable											
	<u>480 V</u>											
	3 conductor, 0 gauge	5,000	FT	4.78		29.42	0.013	63	23,920	3,900		27,820
	Terminations	60	EA	1.11		29.42	0.117	7	67	430		497
	<u>Control and instrument</u>											
	7 conductor, 14 gauge	5,940	FT	1.52		29.42	0.018	108	9,019	6,660		15,679
	Twisted pair, 16 gauge	1,200	FT	1.06		29.42	0.014	17	1,273	1,070		2,343
	Twisted pair, 16 gauge, thermocouple	3,000	FT	1.06		29.42	0.014	43	3,182	2,670		5,852
	Terminations	1,402	EA	14.55		29.42	0.650	911	20,399	56,170		76,569
	Termination boxes	4	EA	416		29.42	13.0	52	1,664	3,210		4,874
	Armored cable connections	50	EA	52		29.42	1.3	65	2,600	4,010		6,610
11	Cathodic Protection											
	Graphite anodes											
	Drilling	100	LF			29.42	1.05	105		6,490		6,490
	Anodes	10	EA	478		29.42	7.3	73	4,780	4,520		9,300
	Junction box	1	EA	783		29.42	8.4	8	780	520		1,300
	Rectifier	1	EA	5,984		29.42	182	182	5,980	11,220		17,200
	Test station	2	EA	73		29.42	2.17	4	150	270		420
	Reference cell	2	EA	52		29.42	5.42	11	100	670		770

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
	Electric cable, 3 conductor, armored, underground											
	6 gauge	300	FT	0.98		29.42	0.36	109	290	6,730		7,020
	8 gauge	240	FT	0.63		29.42	0.36	87	150	5,380		5,530
12	Grounding											
	<u>Tanks and structural steel</u>											
	1 conductor, 00 gauge, bare cable	500	FT	1.52		29.42	0.325	162	759	10,010		10,769
	Cadwelds	20	EA	10		29.42	1.49	30	210	1,830		2,040
	Grounding rods	10	EA	31		29.42	2.6	26	310	1,600		1,910
	<u>Substation transformer</u>											
	1 conductor, 00 gauge, bare cable	80	FT	1.52		29.42	0.325	26	121	1,600		1,721
	Cadwelds	24	EA	10		29.42	1.49	36	250	2,200		2,450
	<u>Mechanical equipment</u>											
	1 conductor, 00 gauge, bare cable	440	FT	1.52		29.42	0.200	88	668	5,430		6,098
	1 conductor, 2 gauge, bare cable	530	FT	1.04		29.42	0.200	106	551	6,540		7,091
	Lighting protection for elevated platform	820	FT	3.12		29.42	0.200	164	2,558	10,120		12,678
13	Testing	1	LT	5,200		29.42	311	311	5,200	19,160		24,360
	Subtotal - Electrical								565,677	579,870		1,145,547
Q	<u>CONCRETE WORK</u>											
1	Elevated Platform											
	Formwork	2,710	SF	1.56		26.72	0.46	1,233	4,228	72,680		76,908
	Reinforcing steel	54	T	832		26.72	26	1,409	45,094	83,060		128,154
	Concrete	542	CY	306		26.72	1.95	1,057	165,885	62,290		228,175
	Embedded metals	2,710	LB	1.56		26.72	w/ forms		4,228			4,228
2	Tank Foundations											
	Formwork	9,934	SF	1.56		26.72	0.46	4,520	15,497	266,400		281,897
	Reinforcing steel	454	T	832		26.72	26	11,815	378,089	696,390		1,074,479
	Concrete	4,544	CY	306		26.72	1.95	8,861	1,390,842	522,290		1,913,132
	Embedded metals	5,680	LB	1.56		26.72	w/ forms		8,861			8,861
	Subtotal - Concrete Work								2,012,723	1,703,110	0	3,715,833
S	<u>SITEWORK</u>											
	Excavation	8,739	CY			26.72	0.65	5,680		334,790		334,790
	Backfill and Compaction	5,826	CY	8		26.72	1.17	6,816	48,471	401,740		450,211
	Foamglas (tank foundation insulation)	84,373	CF	21		26.72	0.10	8,125	1,804,966	478,870		2,283,836
	Refractory brick, with mortar (tank perimeter foundation)	234,599	EA	1.6		26.72	0.07	15,249	365,974	898,770		1,264,744
	Sand (tank foundation)	228	CY	21		26.72	1.30	296	4,741	17,470		22,211
	Subtotal - Sitework								2,224,151	2,131,640	0	4,355,791
X	<u>PAINTING</u>											
	Structural steel (allowance)	35,200	SF		0.52						18,304	18,304

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	---- $ ---- Material	Labor	S/C	Total
	Subtotal								94,582,762	11,267,180	38,963,830	144,813,772
	Sales Tax								6,999,124			6,999,124
4	TOTAL - THERMAL STORAGE SYSTEM								101,581,886	11,267,180	38,963,830	151,812,897
5	STEAM GENERATION SYSTEM											
E	<u>HEAT EXCHANGERS</u>											
1	Steam Generator											
	U-tube / straight shell, 2 tube & 2 shell passes											
	- Preheater - Carbon steel shell and tubes, 24,300 ft^2 per shell	2	EA	909,371		38.13	351	702	1,819,000	49,390		1,868,390
	- Superheater - Stainless steel shell and tubes, 23,800 ft^2 per shell	2	EA	4,446,106		38.13	377	754	8,892,000	53,040		8,945,040
	- Reheater - Stainless steel shell and tubes, 26,300 ft^2 per shell	2	EA	4,909,557		38.13	481	962	9,819,000	67,680		9,886,680
	- Evaporator - Chrome-moly steel shell and tubes, 37,500 ft^2 per shell	2	EA	5,611,383		38.13	624	1,248	11,223,000	87,800		11,310,800
	Steam drum - Carbon steel	2	EA	5,611,383		38.13	624	1,248	11,223,000	87,800		11,310,800
2	Blowdown Heat Exchanger	2	EA						Included in T/G price			0
3	Heat Transport Fluid Heater	0	EA	3,692,000		38.13	62,790	0	0	0		0
	2 50-percent capacity; 1,090 million Btu/hr each; natural gas fired											
	550 F / 1050 F nitrate salt inlet / outlet temperatures											
	Complete with air preheater, induced draft fans, and forced draft fans											
	Includes $1/kWt for NOx selective catalytic reduction system											
	and $0.35/kWt for CO oxidation catalyst system											
	Subtotal - Heat Exchangers								42,976,000	345,710	0	43,321,710
G	<u>PUMPS AND DRIVERS</u>											
1	Hot Salt Pump	2	EA	1,453,712		38.13	494	988	2,907,420	69,510		2,976,930
	Extended shaft turbine pump, 1 stage, stainless steel											
	11,300 gpm, 2725 lb_m/sec, 200 ft total developed head											
	1,250 bhp motor variable speed drive											
2	Spare Hot Salt Pump and Motor (without variable speed drive)	1	EA	973,987		38.13	0	0	973,990	0		973,990
	11,300 gpm, 2725 lb_m/sec, 200 ft total developed head											
	1,250 bhp motor variable speed drive											
3	Cold Salt Attemperation Pump	1	EA	184,036		38.13	156	156	184,040	10,970		195,010
	Extended shaft turbine pump, 1 stage											
	2050 gpm, 250 lb_m/sec, 200 ft total developed head											
	250 bhp motor variable speed drive											
4	Spare Attemperation Salt Pump and Motor (without variable speed drive)	1	EA	123,304		38.13	0	0	123,300	0		123,300
	Extended shaft turbine pump, 1 stage											
	2050 gpm, 250 lb_m/sec, 200 ft total developed head											
	250 bhp motor variable speed drive											

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
5	Startup Boiler Feedwater Pump - Horizontal, multi-stage 250 gpm, 3000 ft tdh, 250 bhp electric motor, Variable speed drive, CS impeller and bowl	1	EA	65,000		38.13	299	299	65,000	21,030		86,030
6	Evaporator Recirculation Pump - Horizontal, single-stage, canned rotor 11600 gpm, 100 ft tdh, 250 bhp electric motor, Variable speed drive, CS impeller and bowl	2	EA	156,000		38.13	299	598	312,000	42,070		354,070
	Subtotal - Pumps and Drivers								4,565,750	63,100	0	4,628,850
J	INSTRUMENTATION											
1	Nitrate Salt Pump Discharge Flow Meters Venturi flow meters with Kaman KD-1911 impedance pressure transducers	5	EA	8,601		36.85	31.2	156	43,004	10,770		53,774
2	Nitrate Salt Pump Discharge Pressure Transmitters Kaman KD-1911 impedance pressure transducers	5	EA	8,601		36.85	31.2	156	43,004	10,770		53,774
3	Nitrate Salt System Temperatures Type K thermocouple, located in stainless steel thermowell Industrial protection head assembly With A/D converter/transmitter	24	EA	690		36.85	29.9	718	16,548	49,590		66,138
4	Nitrate Salt Pipe Temperatures (Electric heat trace system) Type K thermocouple, Type 304 stainless steel braided sheath Welded tab; with A/D converter/transmitter	128	EA	627		36.85	29.9	3,827	80,271	264,330		344,601
5	Loop Check	162	EA			36.85	3.25	527		36,400		36,400
6	Calibration and Testing	162	EA			36.85	3.51	569		39,300		39,300
7	Operator Station (in control room, provided by others)	1	LT		34,895						34,895	34,895
	Subtotal - Instrumentation								182,828	411,160	34,895	628,883
L	PIPING											
1	Nitrate Salt and Recirculation Water Pipe and Fittings											
	22" Pipe - Stainless steel A 213 Type 347, Std wall (Hot salt pump discharge)	150	LF	360		42.68	4.16	624	54,040	46,740		100,780
	30" Pipe - Stainless steel A 213 Type 347, Std wall (Hot salt pump discharge)	200	LF	494		42.68	4.58	916	98,720	68,610		167,330
	24" Pipe - Stainless steel A 213 Type 347, Std wall (Superheater inlet)	160	LF	394		42.68	4.16	666	62,980	49,880		112,860
	18" Pipe - Stainless steel A 213 Type 347, Std wall (Reheater inlet)	160	LF	294		42.68	3.56	570	46,980	42,690		89,670
	24" Pipe - Stainless steel A 213 Type 347, Std wall (Superheater to evaporator)	80	LF	394		42.68	4.16	333	31,490	24,940		56,430
	18" Pipe - Stainless steel A 213 Type 347, Std wall (Reheater to evaporator)	80	LF	294		42.68	3.56	285	23,490	21,350		44,840
	30" Pipe - Chrome-moly steel A 213 Type 347, Std (Evaporator to preheater)	80	LF	494		42.68	4.58	366	39,490	27,410		66,900
	30" Pipe - Carbon steel A106 Grade B, Std Wall (Preheater outlet)	240	LF	148		42.68	2.29	550	35,540	41,190		76,730
	6" Pipe - Carbon steel A106 Grade B, Sch 40 (Cold salt attemperation)	240	LF	24		42.68	0.86	206	5,680	15,430		21,110
	24" Pipe - Carbon steel A106 Grade B, Sch 100 (Steam drum recirculation)	120	LF	459		42.68	5.10	612	55,020	45,840		100,860

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
5	Startup Boiler Feedwater Pump - Horizontal, multi-stage 250 gpm, 3000 ft tdh, 250 bhp electric motor, Variable speed drive, CS impeller and bowl	1	EA	65,000		38.13	299	299	65,000	21,030		86,030
6	Evaporator Recirculation Pump - Horizontal, single-stage, canned rotor 11600 gpm, 100 ft tdh, 250 bhp electric motor, Variable speed drive, CS impeller and bowl	2	EA	156,000		38.13	299	598	312,000	42,070		354,070
	Subtotal - Pumps and Drivers								4,565,750	63,100	0	4,628,850
J	INSTRUMENTATION											
1	Nitrate Salt Pump Discharge Flow Meters Venturi flow meters with Kaman KD-1911 impedance pressure transducers	5	EA	8,601		36.85	31.2	156	43,004	10,770		53,774
2	Nitrate Salt Pump Discharge Pressure Transmitters Kaman KD-1911 impedance pressure transducers	5	EA	8,601		36.85	31.2	156	43,004	10,770		53,774
3	Nitrate Salt System Temperatures Type K thermocouple, located in stainless steel thermowell Industrial protection head assembly With A/D converter/transmitter	24	EA	690		36.85	29.9	718	16,548	49,590		66,138
4	Nitrate Salt Pipe Temperatures (Electric heat trace system) Type K thermocouple, Type 304 stainless steel braided sheath Welded tab; with A/D converter/transmitter	128	EA	627		36.85	29.9	3,827	80,271	264,330		344,601
5	Loop Check	162	EA			36.85	3.25	527		36,400		36,400
6	Calibration and Testing	162	EA			36.85	3.51	569		39,300		39,300
7	Operator Station (in control room, provided by others)	1	LT		34,895						34,895	34,895
	Subtotal - Instrumentation								182,828	411,160	34,895	628,883
L	PIPING											
1	Nitrate Salt and Recirculation Water Pipe and Fittings											
	22" Pipe - Stainless steel A 213 Type 347, Std wall (Hot salt pump discharge)	150	LF	360		42.68	4.16	624	54,040	46,740		100,780
	30" Pipe - Stainless steel A 213 Type 347, Std wall (Hot salt pump discharge)	200	LF	494		42.68	4.58	916	98,720	68,610		167,330
	24" Pipe - Stainless steel A 213 Type 347, Std wall (Superheater inlet)	160	LF	394		42.68	4.16	666	62,980	49,880		112,860
	18" Pipe - Stainless steel A 213 Type 347, Std wall (Reheater inlet)	160	LF	294		42.68	3.56	570	46,980	42,690		89,670
	24" Pipe - Stainless steel A 213 Type 347, Std wall (Superheater to evaporator)	80	LF	394		42.68	4.16	333	31,490	24,940		56,430
	18" Pipe - Stainless steel A 213 Type 347, Std wall (Reheater to evaporator)	80	LF	294		42.68	3.56	285	23,490	21,350		44,840
	30" Pipe - Chrome-moly steel A 213 Type 347, Std (Evaporator to preheater)	80	LF	494		42.68	4.58	366	39,490	27,410		66,900
	30" Pipe - Carbon steel A106 Grade B, Std Wall (Preheater outlet)	240	LF	148		42.68	2.29	550	35,540	41,190		76,730
	6" Pipe - Carbon steel A106 Grade B, Sch 40 (Cold salt attemperation)	240	LF	24		42.68	0.86	206	5,680	15,430		21,110
	24" Pipe - Carbon steel A106 Grade B, Sch 100 (Steam drum recirculation)	120	LF	459		42.68	5.10	612	55,020	45,840		100,860

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
2	Pipe Welds											
	22" Pipe - Stainless steel A 213 Type 347, Std wall (Hot salt pump discharge)	19	EA			42.68	17.64	331		24,790		24,790
	30" Pipe - Stainless steel A 213 Type 347, Std wall (Hot salt pump discharge)	25	EA			42.68	22.30	558		41,790		41,790
	24" Pipe - Stainless steel A 213 Type 347, Std wall (Superheater inlet)	32	EA			42.68	17.64	564		42,240		42,240
	18" Pipe - Stainless steel A 213 Type 347, Std wall (Reheater inlet)	20	EA			42.68	13.64	273		20,450		20,450
	24" Pipe - Stainless steel A 213 Type 347, Std wall (Superheater to evaporator)	10	EA			42.68	17.64	176		13,180		13,180
	18" Pipe - Stainless steel A 213 Type 347, Std wall (Reheater to evaporator)	10	EA			42.68	13.64	136		10,190		10,190
	30" Pipe - Chrome-moly steel A 213 Type 347, Std (Evaporator to preheater)	10	EA			42.68	22.30	223		16,700		16,700
	30" Pipe - Carbon steel A106 Grade B, Std Wall (Preheater outlet)	30	EA			42.68	11.15	335		25,090		25,090
	6" Pipe - Carbon steel A106 Grade B, Sch 40 (Cold salt attemperation)	30	EA			42.68	2.40	72		5,390		5,390
	24" Pipe - Carbon steel A106 Grade B, Sch 100 (Steam drum recirculation)	15	EA			42.68	33.00	495		37,080		37,080
3	Valves											
	22 in. Gate, Stainless steel, 600 lb class, Air operated (Hot salt pump discharge)	3	EA	163,301					489,900			489,900
	18 in. Globe, Stainless steel, 300 lb class, Air operated (Reheater flow control)	1	EA	244,951					244,950			244,950
	22 in. Check, Stainless steel, 600 lb class (Hot salt pump discharge)	3	EA	118,446					355,340			355,340
	6 in. Check, Carbon steel, 600 lb class (Attemperation pump discharge)	1	EA	2,023					2,020			2,020
	6 in. Gate, Carbon steel, 600 lb class (Attemperation pump discharge)	1	EA	2,023					2,020			2,020
	16 in. Gate, Carbon steel, 900 lb class	4	EA	27,314					109,250			109,250
4	Miscelleneous Piping and Operations											
	Hangers and supports (20% of installation manhours; $4/ft for material)	1	LT	6,040		42.68	1658	1,658	6,040	124,180		130,220
	Waste allowance (10% of piping material)	1	LT	45,343					45,340			45,340
	Testing and inspection (7.5% of installation manhours)	1	LT			42.68	622	622		46,590		46,590
	Material handling (5% of installation manhours)	1	LT			42.68	415	415		31,080		31,080
	Freight (3% of material)	1	LT	13,603					13,600			13,600
	Subtotal - Piping								1,721,890	822,830	0	2,544,720
N	INSULATION											
1	Steam Generator Heat Exchangers											
	8 in. calcium silicate, aluminum jacket, 1.2 fitting factor	9,500	ESF	11		42.68	0.36	3,400	109,070	254,660		363,730
2	Pipe: Calcium silicate with aluminum jacket											
	- 22" x 8" thick, 1.2 fitting factor	180	ELF	150		42.68	1.62	292	26,990	21,870		48,860
	- 30" x 8" thick, 1.2 fitting factor	240	ELF	186		42.68	2.17	520	44,650	38,950		83,600
	- 24" x 8" thick, 1.2 fitting factor	192	ELF	159		42.68	1.76	338	30,530	25,320		55,850
	- 18" x 8" thick, 1.2 fitting factor	192	ELF	132		42.68	1.36	261	25,290	19,550		44,840
	- 24" x 8" thick, 1.2 fitting factor	96	ELF	159		42.68	1.76	169	15,270	12,660		27,930
	- 18" x 8" thick, 1.2 fitting factor	96	ELF	132		42.68	1.36	131	12,650	9,810		22,460
	- 30" x 8" thick, 1.2 fitting factor	96	ELF	133		42.68	1.60	154	12,760	11,530		24,290
	- 30" x 6" thick, 1.2 fitting factor	288	ELF	133		42.68	1.60	462	38,270	34,600		72,870
	- 6" x 6" thick, 1.2 fitting factor	288	ELF	49		42.68	0.58	167	14,210	12,510		26,720
	- 24" x 4" thick, 1.2 fitting factor	144	ELF	112		42.68	1.33	192	16,180	14,380		30,560
	Subtotal - Insulation								345,870	455,840	0	801,710

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	---- $ ---- Material	Labor	S/C	Total
P	ELECTRICAL											
1	Power Distribution											
	Distribution transformer, 500 / 600 kVA, 4.16 kV - 480 V, AA / FA	1	EA	69,784		29.42	33	33	69,784	2,000		71,784
	(3Φ power to salt attemperation and feedwater pumps)											
	480 V motor control center	3	LT	5,200		29.42	104	312	15,600	19,230		34,830
	Size 1 combination starters	3	EA	1,560					4,680			4,680
	Size 3 combination starters	1	EA	2,496					2,496			2,496
	4.16 kV switchgear, 300 A main breaker, 2 each current limiting fuses	1	LT	43,823		29.42	312	312	43,823	19,230		63,053
	and contactors (1 hot salt pump contactor + 1 substation contactor)											
	480 V switchgear, 300 A main breaker and transition section to MCC	1	LT	3,120		29.42	52	52	3,120	3,210		6,330
	480 V disconnect switches, 100 A	3	EA	484		29.42	7	20	1,451	1,200		2,651
	Lighting panel; 15 circuits	1	EA	1,638		29.42	39	39	1,638	2,400		4,038
	480 V disconnect switches, 30 A	10	EA	218		29.42	7	65	2,184	4,010		6,194
	Start / stop switches	3	EA	239		29.42	13	39	718	2,400		3,118
	Variable frequency drive (installation only)	3	EA	104		29.42	78	234	312	14,420		14,732
2	Electric Heat Tracing											
	22" pipe, 4 active and 2 spare cables (Hot salt pump discharge)	900	FT	35		29.42	0.33	293	31,500	18,030		49,530
	30" Pipe, 6 active and 2 spare cables (Hot salt pump discharge)	1,600	FT	35		29.42	0.33	520	56,000	32,050		88,050
	24" Pipe, 5 active and 2 spare cables (Superheater inlet)	1,120	FT	35		29.42	0.33	364	39,200	22,440		61,640
	18" Pipe, 4 active and 2 spare cables (Reheater inlet)	960	FT	35		29.42	0.33	312	33,600	19,230		52,830
	24" Pipe, 5 active and 2 spare cables (Superheater to evaporator)	560	FT	35		29.42	0.33	182	19,600	11,220		30,820
	18" Pipe, 4 active and 2 spare cables (Reheater to evaporator)	480	FT	35		29.42	0.33	156	16,800	9,620		26,420
	30" Pipe, 6 active and 2 spare cables (Evaporator to preheater)	640	FT	35		29.42	0.33	208	22,400	12,820		35,220
	30" Pipe, 6 active and 2 spare cables (Preheater outlet)	1,920	FT	35		29.42	0.33	624	67,200	38,460		105,660
	6" Pipe, 2 active and 2 spare cables (Cold salt attemperation)	960	FT	35		29.42	0.33	312	33,600	19,230		52,830
	Steam generator heat exchangers	6,562	FT	35		29.42	0.33	2,133	229,659	131,450		361,109
	10 vessels, 10 m cable length, 20 cables per vessel											
	Large valves, 3 active and 2 spare cables, bellows seal	8	EA	624		29.42	26	208	4,992	12,820		17,812
	Small valves, 2 active and 2 spare cables, bellows seal	1	EA	499		29.42	26	26	499	1,600		2,099
	Nitrate salt pump transition to top of salt tank	6	EA	1,248		29.42	26	156	7,488	9,620		17,108
	¾ in. rigid steel conduit	1,919	FT	1.96		29.42	0.24	455	3,767	28,030		31,797
	Electric power distribution cable, 12 gauge	9,597	FT	0.29		29.42	0.004	37	2,795	2,310		5,105
3	Lighting											
	Stanchions	16	EA	312		29.42	6.5	104	4,992	6,410		11,402
	Pendant lights	10	EA	312		29.42	6.5	65	3,120	4,010		7,130
	Staircase lighting	5	EA	312		29.42	6.5	33	1,560	2,000		3,560
	Photocell	1	EA	125		29.42	2.6	3	125	160		285
	Lighting contactor	1	EA	458		29.42	13.0	13	458	800		1,258
	Receptacles	6	EA	52		29.42	2.6	16	312	960		1,272
	1 in. rigid steel conduit	1,125	FT	2.07		29.42	0.26	291	2,324	17,960		20,284
	1 1/2 in. rigid steel conduit	210	FT	2.84		29.42	0.31	64	597	3,970		4,567
	2 conductor, 12 gauge wire	7,170	FT	0.29		29.42	0.012	84	2,088	5,170		7,258
4	Welding Receptacle	1	EA	281		29.42	13	13	280	800		1,080

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	---- $ ---- Material	Labor	S/C	Total
5	Communication Stations											
	GAI-Tronics page/party station	2	EA	1,050		29.42	10.40	21	2,101	1,280		3,381
	Horn	2	EA	234		29.42	5.20	10	468	640		1,108
	U bracket for horn	2	EA	73					146			146
	5 party line cable	660	FT	2.86		29.42	0.09	62	1,888	3,810		5,698
	Single line cable	660	FT	0.52		29.42	0.04	24	343	1,480		1,823
	1 in. rigid steel conduit	160	FT	2.07		29.42	0.26	41	331	2,550		2,881
6	Fire / Smoke Detectors											
	Emergency shutdown stations	2	EA	78		29.42	2.60	5	156	320		476
	Photoelectric smoke detectors	8	EA	156		29.42	2.60	21	1,248	1,280		2,528
	Thermal detectors	8	EA	156		29.42	2.60	21	1,248	1,280		2,528
	Strobe light and horn	2	EA	104		29.42	2.60	5	208	320		528
	Electric wire, 16 gauge	550	FT	0.29		29.42	0.012	6	160	400		560
	1 in. rigid steel conduit	840	FT	2.07		29.42	0.26	218	1,735	13,410		15,145
	Terminal box	1	EA	416		29.42	6.50	7	416	400		816
7	Instrument Conduit											
	1 3/4 in. rigid steel conduit	3,500	FT	2.84		29.42	0.31	1,073	9,957	66,130		76,087
	2 1/2 in. flexible connections to instruments	70	EA	21		29.42	2.60	182	1,456	11,220		12,676
8	Cable Trays											
	12 in. power cable tray	300	FT	10		29.42	0.35	104	3,070	6,420		9,490
	12 in. instrument cable tray	400	FT	10		29.42	0.35	139	4,093	8,560		12,653
	24 in. 4.16 kV power cable tray	330	FT	11		29.42	0.49	162	3,785	9,970		13,755
	36 in. power cable tray	330	FT	15		29.42	0.67	222	5,100	13,700		18,800
	Tray covers	1,360	FT	Included		29.42	0.00	0	0	0		0
	Support columns	22	EA	300		29.42	39.0	858	6,600	52,890		59,490
	Support sleepers	12	EA	100		29.42	6.5	78	1,200	4,810		6,010
9	Wire and Cable											
	4.16 kV											
	3 conductor, 0000 gauge	1,500	FT	14.03		29.42	0.020	30	21,044	1,850		22,894
	Terminations	20	EA	1.67		29.42	0.153	3	33	190		223
	480 V											
	3 conductor, 6 gauge	2,400	FT	1.70		29.42	0.006	14	4,068	880		4,948
	Terminations	40	EA	1.11		29.42	0.098	4	45	240		285
	Control and instrument											
	7 conductor, 14 gauge	5,940	FT	1.52		29.42	0.018	108	9,019	6,660		15,679
	Twisted pair, 16 gauge	1,200	FT	1.06		29.42	0.014	17	1,273	1,070		2,343
	Twisted pair, 16 gauge, thermocouple	5,000	FT	1.06		29.42	0.014	72	5,304	4,450		9,754
	25 pair, 16 gauge	2,640	FT	7.55		29.42	0.061	162	19,933	9,960		29,893
	25 conductor, 14 gauge	2,200	FT	3.95		29.42	0.040	89	8,694	5,460		14,154
	Terminations	1,600	EA	17.19		29.42	0.845	1,352	27,506	83,340		110,846
	Termination boxes	8	EA	416		29.42	13.0	104	3,328	6,410		9,738
	Armored cable connections	150	EA	52		29.42	1.3	195	7,800	12,020		19,820

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
10	Cathodic Protection											
	Graphite anodes	2	EA	910		29.42	9.75	20	1,820	1,200		3,020
	Rectifier	2	EA	931		29.42	7.80	16	1,860	960		2,820
	Test station	2	EA	73		29.42	2.60	5	150	320		470
	Reference cell	2	EA	52		29.42	6.50	13	100	800		900
	Electric cable	300	FT	0.83		29.42	0.20	60	250	3,730		3,980
11	Grounding											
	<u>Vessels and structural steel</u>											
	1 conductor, 00 gauge, bare cable	1,050	FT	1.52		29.42	0.325	341	1,594	21,030		22,624
	Cadwelds	20	EA	10		29.42	1.49	30	210	1,830		2,040
	Grounding rods	10	EA	31		29.42	2.6	26	310	1,600		1,910
	<u>Switchgear</u>											
	1 conductor, 00 gauge, bare cable	125	FT	1.52		29.42	0.325	41	190	2,510		2,700
	Cadwelds	12	EA	10		29.42	1.49	18	120	1,100		1,220
	<u>Pipe racks</u>											
	1 conductor, 00 gauge, bare cable	330	FT	1.52		29.42	0.325	107	501	6,610		7,111
	Cadwelds	36	EA	10		29.42	1.49	53	370	3,300		3,670
	Grounding rods	6	EA	31		29.42	2.6	16	190	960		1,150
	<u>Mechanical equipment</u>											
	Nitrate salt pumps	2	EA	10		29.42	1.30	3	20	160		180
	Feedwater pumps	3	EA	10		29.42	1.30	4	30	240		270
	Nitrate salt heaters	0	EA	10		29.42	1.30	0	0	0		0
	Motor operated valves	8	EA	10		29.42	1.30	10	80	640		720
	Heat exchangers and steam drum	6	EA	10		29.42	1.30	8	60	480		540
	1 conductor, 00 gauge, bare cable	600	FT	1.52		29.42	0.200	120	911	7,400		8,311
	1 conductor, 2 gauge, bare cable	730	FT	1.04		29.42	0.200	146	759	9,010		9,769
12	Testing	1	LT	5,200		29.42	311	311	5,200	19,160		24,360
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	Subtotal - Electrical								899,242	895,710		1,794,952
Q	<u>CONCRETE WORK</u>											
1	Steam Generator Heat Exchangers											
	Concrete	193	CY	234		26.72	1.95	376	45,090	22,160		67,250
	Forms	2,891	SF	1.56		26.72	0.46	1,315	4,510	77,510		82,020
	Reinforcing Steel	14	T	832		26.72	26	376	12,025	22,150		34,175
	Embedded Metal	964	LB	1.56		26.72	w/ forms		1,503			1,503
2	Nitrate Salt Heaters											
	Concrete	0	CY	234		26.72	1.95	0	0	0		0
	Forms	0	SF	1.56		26.72	0.46	0	0	0		0
	Reinforcing Steel	0	T	832		26.72	26	0	0	0		0
	Embedded Metal	0	LB	1.56		26.72	w/ forms		0			0
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	Subtotal - Concrete Work								63,128	121,820	0	184,948

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	------------ $ ------------ Material	Labor	S/C	Total
====	==	====	===	=======	======	=====	=====	=====	=======	=======	========	========
S	SITEWORK											
	Excavation	96	CY			26.72	0.65	63		3,690		3,690
	Backfill	48	CY	8		26.72	1.17	56	401	3,320		3,721
									-------	--------	--------	--------
	Subtotal - Sitework								401	7,010	0	7,411
X	PAINTING											
	Structural steel (allowance)	12,000	SF		0.52						6,240	6,240
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	Subtotal - Steam Generation System								50,755,109	3,123,180	41,135	53,919,424
	Sales Tax								3,755,878			3,755,878
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5	TOTAL - STEAM GENERATION SYSTEM								54,510,987	3,123,180	41,135	57,675,302
6	ELECTRIC POWER GENERATION SYSTEM											
C	COLUMNS AND VESSELS											
1	Instrument Air Filters - Replaceable cartridge, 150 psig design pressure	2	EA	2,860		26.72	26	52	5,720	3,660		9,380
	5 micron filter, 33 scfm											
2	Compressed Air Receivers - Vertical, cylindrical, carbon steel with dished heads,	2	EA	10,400		26.72	78	156	20,800	10,970		31,770
	4 ft. diameter x 15' 6" tall, 200 ft^3 capacity											
3	Air Dryer - Dual tower desiccant dryer with automatic regeneration controls	1	LT	8,320		26.72	104	104	8,320	7,320		15,640
	200 scfm, 110 psig											
4	Liquid N_2 Storage - 1000 gallons, 400 psig, includes 300 scfm vaporizer	1	EA	10,400		26.72	104	104	10,400	7,320		17,720
5	Open Deaerating Feedwater Heater	1	EA	452,400		26.72	208	208	452,400	14,630		467,030
	Tray and spray type, with external vent, 150 psig design pressure											
	8 ft. diameter x 22 ft. long, carbon steel, 0.800 in. wall, 14,500 lb											
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	Subtotal - Columns and Vessels								497,640	43,900	0	541,540
D	TANKS											
1	Fuel Oil Storage - 5000 gallon, horizontal, double walled fiberglass, underground	1	EA	19,760		26.72	78	78	19,760	5,490		25,250
2	Diesel Generator Day - 200 gallon, horizontal, carbon steel	1	EA	12,480		26.72	26	26	12,480	1,830		14,310
	Above ground with concrete catch basin											
3	Lubricating Oil Conditioner - centrifugal oil purifier, 7.5 bhp drive, 480 V	1	EA	62,920		26.72	208	208	62,920	14,630		77,550
	Includes two 36 kW oil heaters											
4	Demineralizer - 50 gpm, skid mounted, dual string with cation, ion, and	1	LT	447,200		26.72	2,600	2,600	447,200	182,910		630,110
	mixed bed ion exchangers, degas tower, includes piping, valves, and											
	regeneration control, 1 bhp air blower and 15 bhp pumps											

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	---- $ ---- Material	Labor	S/C	Total
5	Hyprochlorinator - 120 gallon / 60 gallon per day, panel mounted feeder with water powered metering pump, plastic tank, water analyzer, and controls	1	EA	5,720		26.72	208	208	5,720	14,630		20,350
6	Lime Grit Hopper - 12 ft^3, 20 in. diameter x 3 ft high, flat bottom, open top Carbon steel with outlet side gate valve	1	EA	2,600		26.72	31	31	2,600	2,180		4,780
7	Sand Filters - 35 ft^3, vertical flow with plastic internals, 100 gpm flow rate	2	EA	1,768		26.72	26	52	3,540	3,660		7,200
8	Soda Ash Mixing - 100 gallons, 30 in. diameter x 48 in. high, plastic Wing top with gauge glass and level switches	1	EA	520		26.72	26	26	520	1,830		2,350
9	Liquid Coagulant Mixing - 100 gallons, 30 in. diameter x 48 in. high, plastic Floating lip with gauge glass and level switches	1	EA	520		26.72	26	26	520	1,830		2,350
10	Chemical Feed - 300 gallon, 48 in. diameter x 4 ft 6 in. high, 304 stainless steel with gauge glass and level switches, 2 with floating lid, 1 with wing lid	3	EA	13,728		26.72	31	94	41,180	6,610		47,790
11	Sodium Phosphate Dissolving Funnel - 100 gallon, 30 in. diameter x 4 ft high 304 stainless steel, 'V' bottom with outlet strainer	1	EA	2,288		26.72	26	26	2,290	1,830		4,120
12	Lime Soda Softener - 28,500 gallons, cone bottom, open top Carbon steel with plastic lining and internals, 18 ft. diameter x 16 ft. high	1	EA	78,000		26.72	156	156	78,000	10,970		88,970
13	Service Water Storage - 10,000 gallons, cone roof, fiberglass 12 ft. diameter x 13 ft. high	1	EA	18,720		26.72	83	83	18,720	5,840		24,560
14	Sludge Thickener - 3,000 gallons, cone bottom, open top Carbon steel with plastic lining and internals, 7 ft. 6 in. diameter x 10 ft. high	1	EA	15,600		26.72	229	229	15,600	16,110		31,710
15	Supernatant Storage - 400 gallon nominal capacity, vertical with cone roof 4 ft. diameter x 6 ft. high	1	EA	2,080		26.72	31	31	2,080	2,180		4,260
16	Sulfuric Acid Storage - 6,000 gallons, horizontal cylindrical, carbon steel 7 ft. diameter x 21 ft long	1	EA	14,872		26.72	78	78	14,870	5,490		20,360
17	Potable Water Storage - 1,000 gallon, horizontal cylindrical, carbon steel 4 ft. diameter x 12 ft 6 in. long, 150 psi design pressure	1	EA	7,384		26.72	78	78	7,380	5,490		12,870
18	Liquid Coagulant Storage - 350 gallons, horizontal cylindrical, carbon steel 42 in. diameter x 72 in. long	1	EA	1,040		26.72	31	31	1,040	2,180		3,220
19	Caustic Soda Storage - 3,500 gallons, horizontal cylindrical, carbon steel 5 ft. diameter x 23 ft. 6 in. long, 8 kWe 480 V immersion heater	1	EA	12,688		26.72	104	104	12,690	7,320		20,010
20	Soda Ash Storage Bin - 10,000 lb capacity, vertical cylindrical, cone top and hopper bottom, bottom discharge duct, slide gate valve Carbon steel, 5 ft. diameter x 10 ft. high, 8 ft ground clearance	1	EA		41,600						41,600	41,600

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
21	Quick Lime Storage Bin - 9,600 lb capacity, vertical cylindrical, cone top and hopper bottom, bottom discharge duct, slide gate valve Carbon steel, 5 ft. diameter x 10 ft. high, 8 ft ground clearance	1	EA		41,600						41,600	41,600
	Subtotal - Tanks								749,110	293,010	83,200	1,125,320
E	HEAT EXCHANGERS											
1	Feedwater Heaters - Horizontal, closed, integral desuperheater and drain cooler											
	Low pressure 1 - 9,000 ft^2	1	EA	582,314		38.13	130	130	582,310	9,150		591,460
	Low pressure 2 - 9,300 ft^2	1	EA	598,277		38.13	195	195	598,280	13,720		612,000
	Low pressure 3 - 7,300 ft^2	1	EA	469,182		38.13	195	195	469,180	13,720		482,900
	High pressure 1 - 15,300 ft^2	1	EA	1,033,249		38.13	208	208	1,033,250	14,630		1,047,880
	High pressure 2 - 8,600 ft^2	1	EA	582,112		38.13	351	351	582,110	24,690		606,800
2	Main Condenser - 1,950,000 lb/hr inlet steam, 2.5 in. HgA 193,000 gpm circulating water flow rate, 101,000 ft^2 heat transfer area	1	EA	4,096,560		38.13	1,144	1,144	4,096,560	80,480		4,177,040
3	Cooling Towers - Wet, mechanical draft, 58,000 gpm circ water flow rate Circulating water: 95 F to 76 F @ 104 F dry bulb / 65 F wet bulb 8 cells; 300 kWe, 2 speed fan in each cell	18	EA	90,187		38.13	870	15,655	1,623,370	1,101,330		2,724,700
4	Cooling Towers - Air Cooled Condenser 70 F ambient, 2.5 in. HgA condenser pressure 47 modules, 200 bhp fan per module, 7100 kWe design point power demand Budgetary price, and module labor manhours, from SPX	0	EA	933,111		38.13	2,500	0	0	0		0
5	Gland Steam Condenser - Straight tube heat exchanger Steam on shell side, water on tube side, 2,500 lb/hr steam at 3.0 psia 400 ft^2 surface area, carbon steel shell, stainless steel tubes	1	EA	8,320		38.13	52	52	8,320	3,660		11,980
	Subtotal - Heat Exchangers								8,993,380	1,261,380	0	10,254,760
G	PUMPS AND DRIVERS											
1	Condensate - 3 x 50 %, 2400 gpm, 301 ft tdh, 114 ^{o}F, 250 bhp motor, 480 V 1750 rpm, multi-stage vertical turbine, mounted in below-grade cans (Solana: 200 bhp; $161,000)	3	EA	195,748		26.72	299	897	587,240	63,100		650,340
2	Feedwater - 3 x 50 %, 3200 gpm, 4525 ft tdh, 312 ^{o}F, 4500 bhp 4.16 kV motor, variable speed drive, multi-stage horizontal turbine (Solana: 1,000 bhp; $583,000)	3	EA	1,737,603		26.72	1105	3,315	5,212,810	233,210		5,446,020
3	Component Cooling Water - 2 x 100 %, 9600 gpm, 225 ft tdh, 650 bhp, 4.16 kV Double suction, single state, horizontal split case, centrifugal Cast iron case and impeller	2	EA	156,000		26.72	494	988	312,000	69,510		381,510
4	Sludge Transfer - 2 x 100 %, 70 gpm, 20 ft tdh, 5 bhp motor, 480 V, 1100 rpm Centrifugal, vertical, split, rubber-lined, cast iron case, V belt drive, TEFC motor	2	EA	2,080		26.72	33	65	4,160	4,570		8,730

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
5	Sludge Disposal - 2 x 100 %, 25 gpm, 100 ft tdh, 7.5 bhp, 480 V motor Centrifugal, vertical, split, rubber-lined, cast iron case, V belt drive, TEFC motor	2	EA	3,120		26.72	33	65	6,240	4,570		10,810
6	Blowdown Makeup - 2 x 100 %, 18 gpm, 3600 ft tdh, 25 bhp, 480 V motor Positive displacement, variable speed drive	2	EA	3,640		26.72	98	195	7,280	13,720		21,000
7	Service Water - 2 x 100 %, 250 gpm, 350 ft tdh, 30 bhp, 480 V motor Double suction, single stage, horizontal split case centrifugal Cast iron case with 316 stainless steel shaft and impeller	2	EA	8,580		26.72	98	195	17,160	13,720		30,880
8	Circulating Water - 4 x 33 %, 64,300 gpm, 52 ft tdh, 1250 bhp motor 480 V, 1800 rpm, multi-stage vertical turbine, can type	4	EA	876,986		26.72	306	1,222	3,507,940	85,970		3,593,910
9	Turbine Oil Pit Sump - 25 gpm, 50 ft tdh, 3/4 bhp, 480 V, 1750 rpm Positive displacement, with level switch	2	EA	4,576		26.72	33	65	9,150	4,570		13,720
10	Oily Waste Sump - 100 gpm, 50 ft tdh, 2 bhp, 480 V, 1750 rpm Positive displacement, with level switch	2	EA	10,400		26.72	33	65	20,800	4,570		25,370
11	Fire Water - 1000 gpm, 300 ft tdh, 125 bhp motor, 480 V Single stage centrifugal, NFPA access and control panel	2	EA	34,320		26.72	299	598	68,640	42,070		110,710
12	Fire Water Pressure Maintenance - 20 gpm, 300 ft tdh, 5 bhp motor, 480 V Single stage centrifugal	1	EA	2,288		26.72	33	33	2,290	2,320		4,610
13	Supernatant Transfer - 5 gpm, 50 ft tdh, fractional hp, 480 V Single stage, vertical split case, cast iron case and impeller	2	EA	1,144		26.72	33	65	2,290	4,570		6,860
14	Soda Ash Injection - 1 gpm, 30 ft tdh, 0.1 bhp, 480 V	2	EA	572		26.72	33	65	1,140	4,570		5,710
15	Lime Injection - 1 gpm, 30 ft tdh, 0.1 bhp, 480 V	2	EA	572		26.72	33	65	1,140	4,570		5,710
16	Coagulant Transfer - 2 gpm, 30 ft tdh, 0.1 bhp, 480 V	2	EA	1,144		26.72	33	65	2,290	4,570		6,860
17	Acid Injection - 0 to 50 gpm, 60 psi, 1/2 bhp, 120 V Positive displacement, 316 stainless steel	2	EA	4,576		26.72	33	65	9,150	4,570		13,720
18	Coagulant Aid Charging - 0 to 5 gpm, 30 psi, fractional bhp, 120 V Positive displacement, 316 stainless steel	2	EA	4,576		26.72	33	65	9,150	4,570		13,720
19	Caustic Feed - 0 to 50 gpm, 60 psi, 3/4 bhp, 120 V Positive displacement, 316 stainless steel	2	EA	4,576		26.72	33	65	9,150	4,570		13,720
20	Ammonia Solution Feed - 0 to 10 gpm, 250 psi, 3/4 bhp, 120 V Positive displacement, 316 stainless steel	2	EA	5,720		26.72	33	65	11,440	4,570		16,010
21	Hydrazine Feed - 0 to 10 gpm, 250 psi, 3/4 bhp, 120 V Positive displacement, 316 stainless steel	2	EA	5,720		26.72	33	65	11,440	4,570		16,010
22	Sodium Phosphate Feed - 0 to 10 gpm, 1800 psi, 15 bhp, 480 V Positive displacement, 316 stainless steel	2	EA	8,320		26.72	98	195	16,640	13,720		30,360

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
23	Hydrazing Dispensing - 8 gpm, 15 cfm air drive at 90 psig, Reciprocating drive, stainless steel drum, 48 in. riser tube	1	EA	3,432		26.72	33	33	3,430	2,320		5,750
24	Ammonia Dispensing - 8 gpm, 15 cfm air drive at 90 psig, Reciprocating drive, stainless steel drum, 48 in. riser tube	1	EA	3,432		26.72	33	33	3,430	2,320		5,750
25	Diesel Generator Fuel Oil Supply - 2 gpm, 150 ft tdh, 1/4 bhp, 120 V Positive displacement	1	EA	1,040		26.72	33	33	1,040	2,320		3,360
	Subtotal - Pumps and Drivers								9,837,440	603,710	0	10,441,150
K	COMPRESSORS AND DRIVERS											
1	Air Compressors - 2 x 100 %, rotary screw compressor 750 actual ft^3/min delivery, 110 psig, 200 bhp, 480 V Inter- and after-coolers, carbon steel shell, stainless steel tubes Cooling water - 20 gpm, 10 psi	2	EA	108,121		26.72	208	416	216,240	29,270		245,510
2	Vacuum Pumps - 900 actual ft^3/min, 300,000 ft total developed head 75 bhp motor, single stage, positive displacement with liquid seal rotor Discharge with water trap silencer	6	EA	41,600		26.72	208	1,248	249,600	87,800		337,400
3	Gland Steam Condenser Air Exhauster - Horizontal shaft axial blower 500 ft^3/min, 5,000 ft total developed head, 7.5 bhp motor, 480 V	2	EA	5,200		26.72	52	104	10,400	7,320		17,720
	Subtotal - Compressors and Drivers								476,240	124,390	0	600,630
T	SPECIAL EQUIPMENT											
1	Turbine Generator Package Steam Turbine - 2 cylinder (HP and IP/LP), downward exhaust 440 MWe, 1800 rpm, 1815 psia / 1,005 F / 1,005 F, 2.5 in. HgA exhaust 3,450,000 lb/hr main steam flow rate Generator - 2 pole, air cooled, 490 MVA, 0.9 lagging power factor 13.8 kV, 20500 A each phase Exciter - Direct drive, solid state Turbine turbine gear and motor Automatic voltage and stability control panel Generator gas control panel Lube oil reservoir - 10,000 gallons, carbon steel tank Lube oil coolers - Straight tube / straight shell, 300 gpm oil flow Lube oil vapor extractor - 15 bhp, 175 cfm Primary oil pumps - Vertical centrifugal, single stage pump 250 bhp, 480 V motor, mounted on oil reservoir Emergency oil pumps - Vertical centrifugal, single stage pump 250 bhp, 125 V DC motor, mounted on oil reservoir Turning gear oil pumps - Vertical centrifugal, single stage pump 50 bhp, 480 V motor, mounted on oil reservoir Jacking oil pumps - Positive displacement, horizontal 50 bhp, 480 V motor, mounted on oil reservoir Electro-hydraulic control unit - Skid mounted with oil reservoir	1	LT	167,024,000	234,000	38.13	10,679	10,679	167,024,000	751,270	234,000	168,009,270

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
23	Hydrazing Dispensing - 8 gpm, 15 cfm air drive at 90 psig, Reciprocating drive, stainless steel drum, 48 in. riser tube	1	EA	3,432		26.72	33	33	3,430	2,320		5,750
24	Ammonia Dispensing - 8 gpm, 15 cfm air drive at 90 psig, Reciprocating drive, stainless steel drum, 48 in. riser tube	1	EA	3,432		26.72	33	33	3,430	2,320		5,750
25	Diesel Generator Fuel Oil Supply - 2 gpm, 150 ft tdh, 1/4 bhp, 120 V Positive displacement	1	EA	1,040		26.72	33	33	1,040	2,320		3,360
	Subtotal - Pumps and Drivers								9,837,440	603,710	0	10,441,150
K	COMPRESSORS AND DRIVERS											
1	Air Compressors - 2 x 100 %, rotary screw compressor 750 actual ft^3/min delivery, 110 psig, 200 bhp, 480 V Inter- and after-coolers, carbon steel shell, stainless steel tubes Cooling water - 20 gpm, 10 psi	2	EA	108,121		26.72	208	416	216,240	29,270		245,510
2	Vacuum Pumps - 900 actual ft^3/min, 300,000 ft total developed head 75 bhp motor, single stage, positive displacement with liquid seal rotor Discharge with water trap silencer	6	EA	41,600		26.72	208	1,248	249,600	87,800		337,400
3	Gland Steam Condenser Air Exhauster - Horizontal shaft axial blower 500 ft^3/min, 5,000 ft total developed head, 7.5 bhp motor, 480 V	2	EA	5,200		26.72	52	104	10,400	7,320		17,720
	Subtotal - Compressors and Drivers								476,240	124,390	0	600,630
T	SPECIAL EQUIPMENT											
1	Turbine Generator Package Steam Turbine - 2 cylinder (HP and IP/LP), downward exhaust 440 MWe, 1800 rpm, 1815 psia / 1,005 F / 1,005 F, 2.5 in. HgA exhaust 3,450,000 lb/hr main steam flow rate Generator - 2 pole, air cooled, 490 MVA, 0.9 lagging power factor 13.8 kV, 20500 A each phase Exciter - Direct drive, solid state Turbine turbine gear and motor Automatic voltage and stability control panel Generator gas control panel Lube oil reservoir - 10,000 gallons, carbon steel tank Lube oil coolers - Straight tube / straight shell, 300 gpm oil flow Lube oil vapor extractor - 15 bhp, 175 cfm Primary oil pumps - Vertical centrifugal, single stage pump 250 bhp, 480 V motor, mounted on oil reservoir Emergency oil pumps - Vertical centrifugal, single stage pump 250 bhp, 125 V DC motor, mounted on oil reservoir Turning gear oil pumps - Vertical centrifugal, single stage pump 50 bhp, 480 V motor, mounted on oil reservoir Jacking oil pumps - Positive displacement, horizontal 50 bhp, 480 V motor, mounted on oil reservoir Electro-hydraulic control unit - Skid mounted with oil reservoir	1	LT	167,024,000	234,000	38.13	10,679	10,679	167,024,000	751,270	234,000	168,009,270

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
	Seal oil pumps - 150 gpm, 200 ft total developed head, 25 bhp, 480 V Cast iron case, carbon steel shaft and impeller, TEFC motor											
2	Turbine Crane - Step leg gantry with double girder bridge 90 ft center-to-center width, 110 ft. long, 80 ton main hook, 20 ton auxiliary	1	EA	769,600		26.72	884	884	769,600	62,190		831,790
3	Shop and Warehouse Bridge Crane - 2 ton, single girder, top riding rail mounted conductor, pendant operating hoist 5 hp crane motor, 2 1/2 hp bridge motor	1	EA	20,592		26.72	208	208	20,590	14,630		35,220
4	Soda Ash Mixing Tank Agitator - Tank mounted, stainless steel 1/3 bhp motor drive, 120 V, 2 in. propeller	1	EA	1,040		26.72	26	26	1,040	1,830		2,870
5	Lime Paste Slaker - 200 lb/hr lime / water mixer (2:1 ratio) with classifier and grit discharge, 480 V motor drive	1	EA	3,640		26.72	52	52	3,640	3,660		7,300
	Subtotal - Special Equipment								167,818,870	833,580	234,000	168,886,450
P	PIPING AND INSTRUMENTATION											
1	Main Steam - 24 in., Sch 120, stainless steel	350	LF	1,786		42.68	11.80	4,130	625,190	309,340		934,530
	Welds	25	EA			42.68	82.00	2,050		153,540		153,540
2	Hot Reheat Steam - 54 in., XS wall, stainless steel	450	LF	1,188		42.68	7.20	3,240	534,810	242,680		777,490
	Welds	32	EA			42.68	120.96	3,888		291,210		291,210
3	Cold Reheat Steam - 42 in., XS wall, carbon steel	350	LF	277		42.68	2.80	980	96,800	73,400		170,200
	Welds	25	EA			42.68	16.00	400		29,960		29,960
4	Condensate - 16 in., Sch 40, carbon steel	350	LF	103		42.68	1.65	578	36,150	43,290		79,440
	Welds	25	EA			42.68	9.90	248		18,580		18,580
5	Feedwater - 18 in., Sch 100, carbon steel	500	LF	260		42.68	2.80	1,400	129,770	104,860		234,630
	Welds	36	EA			42.68	20.50	732		54,830		54,830
6	Circulating Water - 72 in., concrete lined carbon steel	900	LF	358		42.68	4.50	4,050	322,630	303,340		625,970
	Welds	64	EA			42.68	27.43	1,763		132,050		132,050
7	Feedwater Heater Extraction Steam - 24 in., Std wall, carbon steel	800	LF	118		42.68	2.08	1,664	94,470	124,630		219,100
	Welds	80	EA			42.68	8.82	706		52,880		52,880
8	Feedwater Heater Drains - 10 in., Sch 40, carbon steel	800	LF	51		42.68	1.25	1,000	40,420	74,900		115,320
	Welds	100	EA			42.68	3.52	352		26,360		26,360
9	Process Water - 3 in., Sch 40, carbon steel	6,500	LF	9		42.68	0.70	4,550	61,460	340,790		402,250
	Welds	813	EA			42.68	1.60	1,300		97,370		97,370
10	Service Water - 2 in., Sch 80, carbon steel	6,000	LF	6		42.68	0.70	4,200	37,600	314,580		352,180
	Welds	750	EA			42.68	1.60	1,200		89,880		89,880

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
	Seal oil pumps - 150 gpm, 200 ft total developed head, 25 bhp, 480 V Cast iron case, carbon steel shaft and impeller, TEFC motor											
2	Turbine Crane - Step leg gantry with double girder bridge 90 ft center-to-center width, 110 ft. long, 80 ton main hook, 20 ton auxiliary	1	EA	769,600		26.72	884	884	769,600	62,190		831,790
3	Shop and Warehouse Bridge Crane - 2 ton, single girder, top riding rail mounted conductor, pendant operating hoist 5 hp crane motor, 2 1/2 hp bridge motor	1	EA	20,592		26.72	208	208	20,590	14,630		35,220
4	Soda Ash Mixing Tank Agitator - Tank mounted, stainless steel 1/3 bhp motor drive, 120 V, 2 in. propeller	1	EA	1,040		26.72	26	26	1,040	1,830		2,870
5	Lime Paste Slaker - 200 lb/hr lime / water mixer (2:1 ratio) with classifier and grit discharge, 480 V motor drive	1	EA	3,640		26.72	52	52	3,640	3,660		7,300
	Subtotal - Special Equipment								167,818,870	833,580	234,000	168,886,450
P	PIPING AND INSTRUMENTATION											
1	Main Steam - 24 in., Sch 120, stainless steel	350	LF	1,786		42.68	11.80	4,130	625,190	309,340		934,530
	Welds	25	EA			42.68	82.00	2,050		153,540		153,540
2	Hot Reheat Steam - 54 in., XS wall, stainless steel	450	LF	1,188		42.68	7.20	3,240	534,810	242,680		777,490
	Welds	32	EA			42.68	120.96	3,888		291,210		291,210
3	Cold Reheat Steam - 42 in., XS wall, carbon steel	350	LF	277		42.68	2.80	980	96,800	73,400		170,200
	Welds	25	EA			42.68	16.00	400		29,960		29,960
4	Condensate - 16 in., Sch 40, carbon steel	350	LF	103		42.68	1.65	578	36,150	43,290		79,440
	Welds	25	EA			42.68	9.90	248		18,580		18,580
5	Feedwater - 18 in., Sch 100, carbon steel	500	LF	260		42.68	2.80	1,400	129,770	104,860		234,630
	Welds	36	EA			42.68	20.50	732		54,830		54,830
6	Circulating Water - 72 in., concrete lined carbon steel	900	LF	358		42.68	4.50	4,050	322,630	303,340		625,970
	Welds	64	EA			42.68	27.43	1,763		132,050		132,050
7	Feedwater Heater Extraction Steam - 24 in., Std wall, carbon steel	800	LF	118		42.68	2.08	1,664	94,470	124,630		219,100
	Welds	80	EA			42.68	8.82	706		52,880		52,880
8	Feedwater Heater Drains - 10 in., Sch 40, carbon steel	800	LF	51		42.68	1.25	1,000	40,420	74,900		115,320
	Welds	100	EA			42.68	3.52	352		26,360		26,360
9	Process Water - 3 in., Sch 40, carbon steel	6,500	LF	9		42.68	0.70	4,550	61,460	340,790		402,250
	Welds	813	EA			42.68	1.60	1,300		97,370		97,370
10	Service Water - 2 in., Sch 80, carbon steel	6,000	LF	6		42.68	0.70	4,200	37,600	314,580		352,180
	Welds	750	EA			42.68	1.60	1,200		89,880		89,880

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	---------- $ ---------- Material	Labor	S/C	Total
11	Instrument Air - 2 in., Sch 80, carbon steel	6,000	LF	6		42.68	0.70	4,200	37,600	314,580		352,180
	Welds	750	EA			42.68	1.60	1,200		89,880		89,880
12	Service Air - 2 in., Sch 80, carbon steel	6,000	LF	6		42.68	0.70	4,200	37,600	314,580		352,180
	Welds	750	EA			42.68	1.60	1,200		89,880		89,880
13	Demineralized Water - 6 in., Sch 40, carbon steel	1,200	LF	24		42.68	0.86	1,032	28,410	77,300		105,710
	Welds	150	EA			42.68	2.40	360		26,960		26,960
14	Lubricating Oil - 2 in., Sch 80, carbon steel	1,000	LF	6		42.68	0.70	700	6,270	52,430		58,700
	Welds	125	EA			42.68	1.60	200		14,980		14,980
15	Chemical Feed - 1 in., Sch 80, stainless steel	2,500	LF	9		42.68	1.40	3,500	22,590	262,150		284,740
	Welds	313	EA			42.68	3.20	1,000		74,900		74,900
16	Fuel Oil - 1 in., Sch 80, carbon steel	400	LF	3		42.68	0.70	280	1,080	20,970		22,050
	Welds	50	EA			42.68	1.60	80		5,990		5,990
17	Nitrogen - 2 in., Sch 80, carbon steel	2,200	LF	6		42.68	0.70	1,540	13,790	115,350		129,140
	Welds	275	EA			42.68	1.60	440		32,960		32,960
18	Carbon Dioxide - 2 in., Sch 80, carbon steel	1,200	LF	6		42.68	0.70	840	7,520	62,920		70,440
	Welds	150	EA			42.68	1.60	240		17,980		17,980
19	Auxiliary Steam - 6 in., Sch 40, carbon steel	1,800	LF	24		42.68	0.86	1,548	42,610	115,940		158,550
	Welds	225	EA			42.68	2.40	540		40,450		40,450
20	Miscellaneous Process - 2 in., Sch 80, carbon steel	12,000	LF	6		42.68	0.70	8,400	75,210	629,160		704,370
	Welds	1,500	EA			42.68	1.60	2,400		179,760		179,760
21	Nonmetallic Piping											
	3 in.; unit price includes fittings	4,825	LF	0.84		42.68	0.55	2,664	4,050	199,530		203,580
	Fused joints	120	EA			42.68	0.47	57		4,270		4,270
	4 in.; unit price includes fittings	150	LF	1.52		42.68	0.59	88	230	6,590		6,820
	Fused joints	5	EA			42.68	0.43	2		150		150
	4 in.; unit price includes fittings	595	LF	35.15		42.68	2.17	1,289	20,920	96,550		117,470
	Bolted connections	40	EA			42.68	3.25	129		9,660		9,660
	6 in.; unit price includes fittings	1,350	LF	3.36		42.68	0.68	914	4,540	68,460		73,000
	Fused joints	46	EA			42.68	0.71	33		2,470		2,470
	6 in.; unit price includes fittings	120	LF	17.28		42.68	1.42	170	2,070	12,730		14,800
	Bolted connections	4	EA			42.68	4.23	17		1,270		1,270
	8 in.; unit price includes fittings	1,845	LF	5.51		42.68	0.81	1,502	10,170	112,500		122,670
	Fused joints	56	EA			42.68	0.87	49		3,670		3,670
	8 in.; unit price includes fittings	20	LF	39.57		42.68	2.54	51	790	3,820		4,610
	Bolted connections	2	EA			42.68	5.85	12		900		900
	20 in.; unit price includes fittings	20	LF	446		42.68	9.36	187	8,920	14,010		22,930
	Bolted connections	4	EA			42.68	15.60	62		4,640		4,640
	24 in.; unit price includes fittings	3,750	LF	31.32		42.68	2.92	10,957	117,440	820,680		938,120
	Fused joints	152	EA			42.68	3.00	456		34,150		34,150
	36 in.; unit price includes fittings	50	LF	751		42.68	10.64	532	37,550	39,850		77,400
	Bolted connections	8	EA			42.68	28.77	216		16,180		16,180

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
====	====	====	===	=======	======	=====	=====	=====	=======	=======	========	========
	48 in.; unit price includes fittings	100	LF	801		42.68	9.05	905	80,080	67,780		147,860
	Bolted connections	2	EA			42.68	39.00	78		5,840		5,840
	48 in.; unit price includes fittings	160	LF	195		42.68	9.27	1,483	31,190	111,080		142,270
	Fused joints	10	EA			42.68	6.83	68		5,090		5,090
	54 in.; unit price includes fittings	960	LF	271		42.68	15.19	14,584	259,910	1,092,340		1,352,250
	Fused joints	62	EA			42.68	9.93	619		46,360		46,360
22	Pneumatic Tubing	72,000	FT	0.36		36.85	0.065	4,680	26,208	323,250		349,458
23	Raceway for Pneumatic Tubing	9,000	FT	1.30		36.85	0.195	1,755	11,700	121,220		132,920
24	Loop Checks	1,800	EA			36.85	3.25	5,850		404,060		404,060
25	Calibration and Testing	1,200	EA			36.85	3.51	4,212		290,920		290,920
26	Valves (150% of piping material)	1	LT	3,377,970					3,377,970			3,377,970
	Butterfly valves for circulating water line; 60 in.; motor operated	0	EA	66,310		42.68	156	0	0	0		0
27	Instrumentation (35% of piping + valves; 45 MH/$1000 of instrumentation)	1	LT	2,186,001		42.68	98,370	98,370		7,367,900		7,367,900
28	Miscelleneous Piping and Operations											
	Hangers and supports (20% of installation manhours; $4/ft for material)	1	LT	623,978		42.68	44,864	44,864	623,980	3,360,310		3,984,290
	Waste allowance (10% of piping material)	1	LT	624,572					624,570			624,570
	Testing and inspection (7.5% of installation manhours)	1	LT			42.68	16,824	16,824		1,260,120		1,260,120
	Material handling (5% of installation manhours)	1	LT			42.68	11,216	11,216		840,080		840,080
	Freight (3% of material)	1	LT	187,372					187,370			187,370
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	Subtotal - Piping and Instrumentation								7,681,638	22,166,020	0	29,847,658
	Contingency - Piping and Instrumentation (25 percent)								1,920,410	5,541,505	0	
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	Subtotal - Piping and Instrumentation								9,602,048	27,707,525	0	37,309,573
M	STRUCTURAL STEEL											
1	Structural Steel - Supports, Pipe Racks, Cable Trays	290	T	1,560					452400			452400
2	Gratings and Ladders	26	T	2,080					54,080			54,080
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	Subtotal - Structural Steel								506,480	0	0	506,480
N	INSULATION											
1	Equipment											
	Feedwater Pumps	1,500	SF	3.27		26.72	0.18	273	4,910	16,090		21,000
	Condenser Air Ejectors	760	SF	3.27		26.72	0.18	138	2,488	8,130		10,618
	Feedwater Heaters	8,600	SF	4.64		26.72	0.26	2,277	39,917	134,210		174,127
	Deaerator	1,500	SF	4.64		26.72	0.26	397	6,962	23,400		30,362
	Miscellaneous Equipment	24,000	SF	4.64		26.72	0.26	6,353	111,396	374,440		485,836

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	------ $ ------ Material	Labor	S/C	Total
====	===	====	===	=======	======	=====	=====	=====	=======	=======	========	========
2	Piping											
	Main Steam - 24 in. x 8 in.; 1.58 fitting factor	553	ELF	159		26.72	2.29	1,265	87,933	74,560		162,493
	Hot Reheat Steam - 54 in. x 8 in.; 1.58 fitting factor	711	ELF	292		26.72	4.62	3,288	207,878	193,790		401,668
	Cold Reheat Steam - 42 in. x 6 in.; 1.58 fitting factor	553	ELF	173		26.72	2.76	1,529	95,831	90,120		185,951
	Feedwater - 18 in. x 4 in.; 1.58 fitting factor	790	ELF	57		26.72	1.15	911	44,824	53,690		98,514
	Feedwater Heater Extraction Steam - 24 in. x 4 in.; 1.93 fitting factor	1,544	ELF	71		26.72	1.43	2,202	109,528	129,790		239,318
	Feedwater Heater Drains - 10 in. x 4 in.; 1.93 fitting factor	1544	ELF	37		26.72	0.81	1,249	57,791	73,620		131,411
	Auxiliary Steam - 6 in. x 4 in.; 1.93 fitting factor	3,474	ELF	28		26.72	0.65	2,249	95,853	132,560		228,413
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	Subtotal - Insulation								865,313	1,304,400	0	2,169,713
P	<u>ELECTRICAL</u>											
1	Power Distribution											
	230 kV Substation (scaled from 280 MWe Solana substation)	1	EA		9,002,312	29.42	1,300	1,300	0	80,130	9,002,312	9,082,442
	Main Transformer - 13.8 / 230 kV, 490 / 540 MVA, OA, 55 / 65 C	1	EA	7,229,129		29.42	1,625	1,625	7,229,130	100,160		7,329,290
	Generator Main Bus - 6500 A, 13.8 kV, 3 phase, non-segregated	240	LF	4,784		29.42	31.20	7,488	1,148,160	461,560		1,609,720
	Auxiliary Transformer - 230 / 13.8 kV, 44 / 50 MVA, OA, 55 / 65 C	1	EA	2,359,697		29.42	650	650	2,359,700	40,070		2,399,770
	Load Center Transformer - 13.8 kV / 4160 V, 1.0 / 1.12 MVA, AA, 55 / 65 C	3	EA	193440		29.42	117	351	580,320	21,640		601,960
	Load Center Transformer - 13.8 kV / 480 V, 1.0 / 1.12 MVA, AA, 55 / 65 C	3	EA	93600		29.42	117	351	280,800	21,640		302,440
	Indoor Transition Section and Auxiliary Cubicle	2	EA	20800		29.42			41,600			41,600
	Outdoor Transition Section and Auxiliary Cubicle	2	EA	24,960		29.42			49,920			49,920
	Metalclad Switchgear - 4160 V											
	700 A air circuit breaker, indoor (480 V transformers)	1	EA	18,200		29.42	46.8	47	18,200	2,900		21,100
	450 A air circuit breaker, indoor (Heat transport fluid pumps)	3	EA	14,560		29.42	46.8	140	43,680	8,630		52,310
	350 A air circuit breaker, indoor (Feedwater pump)	2	EA	13,520		29.42	46.8	94	27,040	5,790		32,830
	300 A air circuit breaker, indoor (Circulating water pumps)	4	EA	12,480		29.42	46.8	187	49,920	11,530		61,450
	200 A air circuit breaker, indoor (Nitrate salt pumps)	4	EA	9,360		29.42	46.8	187	37,440	11,530		48,970
	Air Circuit Breakers - 480 V											
	Indoor, 1600 A	2	EA	20,800		29.42	18.2	36	41,600	2,220		43,820
	Indoor, 800 A	10	EA	14,560		29.42	13.0	130	145,600	8,010		153,610
	Outdoor, 1600 A (TES)	12	EA	20,800		29.42	22.1	265	249,600	16,330		265,930
	Outdoor, 800 A (TES)	12	EA	14,560		29.42	15.6	187	174,720	11,530		186,250
	Motor Control Centers - 4160 V											
	Indoor	3	EA	364,000		29.42	208	624	1,092,000	38,460		1,130,460
	Outdoor	3	EA	260,000		29.42	260	780	780,000	48,080		828,080
	Motor Control Centers - 480 V											
	Indoor	3	EA	124,800		29.42	208	624	374,400	38,460		412,860
	Outdoor	3	EA	130,000		29.42	260	780	390,000	48,080		438,080
	Motor Control Center - 125 V DC	1	EA	20,800		29.42	208	208	20,800	12,820		33,620
	Distribution Panels											
	480 V, 3 phase	3	EA	1,040		29.42	15.6	47	3,120	2,900		6,020
	208 / 120 V, single phase	3	EA	832		29.42	15.6	47	2,500	2,900		5,400
	125 V DC	1	EA	1,040		29.42	15.6	16	1,040	990		2,030
	480 V Power Receptables	60	EA	104		29.42	2.3	137	6,240	8,440		14,680
	Local Control Stations	50	EA	156		29.42	3.4	172	7,800	10,600		18,400
	480-208/120V Dry Type Transformers											
	9 kVA	10	EA	1,872		29.42	9.4	94	18,720	5,790		24,510
	15 kVA	20	EA	2,600		29.42	16	312	52,000	19,230		71,230
	30 kVA	5	EA	3,120		29.42	31	156	15,600	9,620		25,220
	45 kVA	5	EA	3,640		29.42	47	234	18,200	14,420		32,620

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	----- $ ----- Material	Labor	S/C	Total
====	===	====	===	=======	======	=====	=====	=====	=======	=======	========	========
	Duplex Receptables, 120 V	120	EA	8		29.42	1.14	137	1,000	8,440		9,440
	Switches, 120 V	120	EA	8		29.42	1.14	137	1,000	8,440		9,440
	Relay and Meter Boards	10	LF	8,320		29.42	46.8	468	83,200	28,850		112,050
	Battery and Racks, 60 Cells, 125 V DC	1	EA	31,200		29.42	208	208	31,200	12,820		44,020
	Battery Charger, 125 V DC	2	EA	20,800		29.42	52	104	41,600	6,410		48,010
	Uninterruptible Power Supply, 100 kVA, 0.5 hours	1	LT	260,000		29.42	520	520	260,000	32,050		292,050
	Emergency Diesel-Generator, 3000 kVA	1	EA	1,092,000		29.42	3,900	3,900	1,092,000	240,400		1,332,400
	Telephone Switchboard and Equipment	1	LT	83,200		29.42	1,040	1040	83,200	64,110		147,310
	Plant Intercom	1	LT	26,000		29.42	1,040	1,040	26,000	64,110		90,110
	Security System	1	LT	11,440		29.42	520	520	11,440	32,050		43,490
	Fire Detection System	1	LT	364,000		29.42	416	416	364,000	25,640		389,640
	Lighting Fixtures - Low pressure sodium	100	EA	364		29.42	3.12	312	36,400	19,230		55,630
	Roadway Lights with 30 ft. Poles	60	EA	780		29.42	31.2	1,872	46,800	115,390		162,190
	Emergency Lighting Fixtures with 2 Lamps and Battery	48	EA	416		29.42	3.12	150	19,970	9,250		29,220
	Lighting Transformer, 30 kVA, 3 phase 480 / 277 V, Indoor	2	EA	3,640		29.42	31.2	62	7,280	3,820		11,100
	Lighting Transformer, 30 kVA, 3 phase, 480 / 277 V, Outdoor	3	EA	3,640		29.42	31.2	94	10,920	5,790		16,710
	Lighting Panel, 480 / 277 V, 3 phase, 24 circuits, Indoor	2	EA	2,808		29.42	31.2	62	5,620	3,820		9,440
	Lighting Panel, 480 / 277 V, 3 phase, 24 circuits, Outdoor	3	EA	3,432		29.42	31.2	94	10,300	5,790		16,090
2	Bulk Materials											
	Cable Trays - Separate power and instrumentation, with supports and covers	8,000	LF	11.47		29.42	0.490	3,921	91,770	241,690		333,460
	Rigid Metal Conduit - Various sizes	30,000	LF	4.39		29.42	0.359	10,756	131,640	663,000		794,640
	Nonmetallic Conduit - Various sizes	40,000	LF	2.08		29.42	0.130	5,200	83,200	320,530		403,730
	Power Cable - 600 V, 1/C #6 and larger	75,000	LF	5.77		29.42	0.014	1,060	432,900	65,340		498,240
	Power Cable - 600 V, multi-conductor, #8 and smaller	450,000	LF	1.12		29.42	0.005	2,184	505,440	134,620		640,060
	Power Cable - 1/C, 4.16 kV	60,000	LF	9.86		29.42	0.015	889	591,550	54,800		646,350
	Terminations - 480 V and instrumentation	18,000	EA	1.11		29.42	0.098	1,755	20,030	108,180		128,210
	Terminations - 4.16 kV	200	EA	1.67		29.42	0.139	28	330	1,730		2,060
	Conduit - Lighting	2,000	LF	2.84		29.42	0.307	613	5,690	37,790		43,480
	Conduit - Communications	1,000	LF	2.84		29.42	0.307	307	2,840	18,920		21,760
	Instrument and Control Wiring											
	7 conductor, 14 gauge	50,000	FT	1.52		29.42	0.0182	910	75,920	56,090		132,010
	Twisted pair, 16 gauge	80,000	FT	1.06		29.42	0.01	1,154	84,864	71,160		156,024
	Twisted pair, 16 gauge, thermocouple	100,000	FT	1.06		29.42	0.01	1,443	106,080	88,950		195,030
	25 pair, 16 gauge	20,000	FT	7.55		29.42	0.06	1,225	151,008	75,480		226,488
	25 conductor, 14 gauge	30,000	FT	3.95		29.42	0.040	1,209	118,560	74,520		193,080
	Terminations	2,000	EA	17.19		29.42	0.845	1,690	34,382	104,170		138,552
	Termination boxes	25	EA	416		29.42	13.0	325	10,400	20,030		30,430
	Armored cable connections	100	EA	52.00		29.42	1.30	130	5,200	8,010		13,210
	Lighting Wiring - 1 C THHN	12,000	LF	0.29		29.42	0.01	140	3,490	8,630		12,120
	Lighting Wiring - Metalclad cable	4,000	LF	1.25		29.42	0.21	832	4,990	51,280		56,270
	Communications Cable - Multiconductor	2,000	LF	1.06		29.42	0.02	36	2,120	2,220		4,340
	Communications Cable - Metalclad	46,000	LF	1.25		29.42	0.21	9,568	57,410	589,770		647,180
	Grounding - Wire, rods, cadwelds, and pads	80,000	LF	2.08		29.42	0.156	12,480	166,400	769,270		935,670
	Lightning Protection (allowance)	1	LT	10,400		29.42	1,040	1,040	10,400	64,110		74,510
	Cathodic Protection (allowance)	1	LT		104,000						104,000	104,000
	Heat Tracing - Freeze protection for water systems	1	LT	36,400		29.42	837	837	36,400	51,590		87,990
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	Subtotal - Electrical								20,124,794	5,432,750	9,106,312	34,663,856
	Contingency - Electrical (50 percent)								10,062,397	2,716,375	4,553,156	

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
	Subtotal - Electrical								30,187,192	8,149,125	13,659,468	51,995,785
Q	CONCRETE WORK											
1	Turbine-Generator Foundation											
	Concrete	1,200	CY	234		26.72	1.95	2,340	280,800	137,920		418,720
	Forms	9,600	SF	1.56		26.72	0.46	4,368	14,980	257,450		272,430
	Reinforcing Steel	72	T	832		26.72	26	1,872	59,904	110,340		170,244
	Embedded Metal	18,000	LB	1.56		26.72	w/ forms		28,080			28,080
2	Wet Cooling Tower Foundation											
	Concrete	444	CY	234		26.72	1.95	867	104,000	51,100		155,100
	Forms	27,556	SF	1.56		26.72	0.46	12,538	42,990	738,990		781,980
	Reinforcing Steel	53	T	832		26.72	26	1,387	44,373	81,730		126,103
	Embedded Metal	1,778	LB	1.56		26.72	w/ forms		2,773			2,773
3	Miscellaneous Footings and Foundations											
	Concrete	3,000	CY	234.00		26.72	1.95	5,850	702,000	344,800		1,046,800
	Forms	15,000	SF	1.56		26.72	0.46	6,825	23,400	402,260		425,660
	Reinforcing Steel	180	T	832		26.72	26	4,680	149,760	275,840		425,600
	Embedded Metal	15,000	LB	1.56		26.72	w/ forms		23,400			23,400
	Subtotal - Concrete Work								1,476,461	2,400,430	0	3,876,891
S	SITEWORK											
1	Turbine-Generator Foundation											
	Excavation	1,500	CY			26.72	0.65	975		57,470		57,470
	Backfill and Compaction	720	CY	8.32		26.72	1	842	5,990	49,650		55,640
2	Wet Cooling Tower Foundation											
	Excavation	889	CY			26.72	0.65	578		34,050		34,050
	Backfill and Compaction	593	CY	8.32		26.72	1.17	693	4,930	40,860		45,790
3	Miscellaneous Footings and Foundations											
	Excavation	3,750	CY			26.72	0.65	2,438		143,670		143,670
	Backfill and Compaction	938	CY	8.32		26.72	1.17	1,097	7,800	64,650		72,450
4	Fuel Oil Tank											
	Excavation	150	CY			26.72	0.65	98		5,750		5,750
	Backfill and Compaction	100	CY	8.32		26.72	1.17	117	832	6,900		7,732
	Subtotal - Sitework								19,553	403,000	0	422,553
	Subotal								231,029,725	43,124,450	13,976,668	288,130,843
	Sales Tax								17,096,200			17,096,200
6	TOTAL - ELECTRIC POWER GENERATION SYSTEM								248,125,925	43,124,450	13,976,668	305,227,043

400 MWe Subcritical Nitrate Salt Plant Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
7	<u>MASTER CONTROL SYSTEM</u>											
1	Distributed Control System 2,750 I/O Points, 4 operator stations, 6 programmable logic controllers DCS and PLC software	1	LT			36.85	5,200	5,200	3,000,000	359,160		3,359,160
	Sales Tax								222,000			222,000
7	TOTAL - MASTER CONTROL SYSTEM								3,222,000	359,160		3,581,160

Appendix D
Direct Field Cost Estimate for Supercritical CO_2 Thermocline Storage System

Thermocline Storage System Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
4	THERMAL STORAGE SYSTEM											
C	COLUMNS AND VESSELS											
1	Thermocline Vessels 24 in. pipe, Sch 120, ASTM A 213 Type 316H, stainless steel 40 feet long, 1.812 in wall thickness, 430 lb_m/ft, 18000 lb_m/vessel 1,500 vessels per octant; 8 octants	480,000	LF	1,786		42.68	2.95	1,416,000	857,405,950	106,058,190		963,464,140
2	Vessel supports Light structural steel; 5 percent of vessel mass	2,880	T	1,872		38.32	52	149,760	5,391,360	10,564,050		15,955,410
	Subtotal - Columns and Vessels								862,797,310	116,622,240		979,419,550
T	SPECIAL EQUIPMENT											
1	Quartzite Inventory $0.035/lb for crushed rock, delivered $0.025/lb for handling and loading the inventory	183,301,950	LB	0.036	0.026				6,672,190		4,765,851	11,438,041
	Subtotal - Special Equipment								6,672,190	0	4,765,851	11,438,041
J	INSTRUMENTATION											
1	Storage Tank Inventory Temperatures Type K thermocouple, Type 304 stainless steel braided sheath Ceramic insulation, suitable for immersion; with transmitter	24,000	EA	268		36.85	5.2	124,800	6,439,680	8,619,920		15,059,600
2	Thermocouple Low Energy Process Interface Unit	60	EA	20,696		36.85	52	3,120	1,241,760	215,500		1,457,260
3	Loop Check	24,000	EA			36.85	3.25	78,000		5,387,450		5,387,450
4	Calibration and Testing	8,000	EA			36.85	3.51	28,080		1,939,480		1,939,480
5	Operator Station (in control room, provided by others)	1	LT		34,895						34,895	34,895
	Subtotal - Instrumentation								7,681,440	16,162,350	34,895	23,878,685
L	PIPING											
1	CO_2 Supply and Return Headers											
	24" Pipe - Stainless steel A 213 Type 304H, Sch 120 (Primary header)	1,302	LF	1,786		42.68	11.80	15,362	2,325,420	1,150,610		3,476,030
	1¼" Pipe - Stainless steel A 213 Type 304H, Sch 160 (Secondary header)	12,800	LF	12		42.68	1.40	17,920	151,440	1,342,210		1,493,650
	¾" Pipe - Stainless steel A 213 Type 304H, Sch 160 (Tertiary header)	12,800	LF	12		42.68	1.40	17,920	151,440	1,342,210		1,493,650

Thermocline Storage System Total Field Cost Estimate

				Unit Cost		Labor	MH	Total	$			
Code	Description	Qty	Unit	Material	S/C	$ Rate	MH Rate	MH	Material	Labor	S/C	Total
2	Pipe Welds											
	24" Pipe - Stainless steel A 213 Type 304H, Sch 120 (Primary header)	163	EA			42.68	82.00	13,344		999,460		999,460
	1¼" Pipe - Stainless steel A 213 Type 304H, Sch 160 (Secondary header)	1,600	EA			42.68	3.20	5,120		383,490		383,490
	¾" Pipe - Stainless steel A 213 Type 304H, Sch 160 (Tertiary header)	2,560	EA			42.68	3.20	8,192		613,580		613,580
3	Valves											
	24 in. gate, stainless steel, 900 lb, motor operated (Octant isolation)	16	EA	172,018					2,752,290			2,752,290
	¾ in. gate, stainless steel, 900 lb class (Vessel isolation)	24,000	EA	358					8,594,560			8,594,560
4	Miscellaneous Piping Items and Operations											
	Hangers and supports (20% of installation manhours; $4/ft for material)	1	LT	107,607		42.68		15,572	107,610	1,166,310		1,273,920
	Waste allowance (10% of piping material)	1	LT	262,830					262,830			262,830
	Testing and inspection (7.5% of installation manhours)	1	LT			42.68		5,839		437,370		437,370
	Material handling (5% of installation manhours)	1	LT			42.68		3,893		291,580		291,580
	Freight (3% of material)	1	LT	419,255					419,250			419,250
	Subtotal - Piping								14,764,840	7,726,820		22,491,660
M	STRUCTURAL STEEL											
	Light structural steel; thermocline vessel enclosure; allowance	150	T	1,872		38.32	52	7,800	280,800	550,210		831,010
	Deck plate	2,200	SF	37		38.32	1.69	3,718	80,540	262,270		342,810
	Stair tower	540	LF	64		38.32	0.75	407	34,540	28,710		63,250
	Subtotal - Structural Steel								395,880	841,190		1,237,070
N	INSULATION											
1	Thermocline Enclosure											
	Similar to insulation on field fabricated tank	282,445	ESF	17		42.68	0.42	119,088	4,788,240	8,919,670		13,707,910
	12 in. calcium silicate and mineral wool											
	62 m wide, 40 m deep, 20 m high, 2 enclosures eash											
	Subtotal - Insulation								4,788,240	8,919,670	0	13,707,910
P	ELECTRICAL											
1	Power Distribution											
	Lighting panel; 42 circuits	1	EA	1,638		29.42	39	39	1,638	2,400		4,038
	480 V disconnect switches, 30 A	2	EA	218		29.42	7	13	437	800		1,237
	Start / stop switches	8	EA	239		29.42	13	104	1,914	6,410		8,324

Thermocline Storage System Total Field Cost Estimate

Code	Description	Qty	Unit	----- Unit Cost ------ Material	S/C	Labor $ Rate	MH Rate	Total MH	------ $ ------ Material	Labor	S/C	Total
4	Lighting											
	Stanchions - 35 ft. poles	6	EA	1,323		29.42	18.7	112	7,937	6,910		14,847
	Pendant lights	10	EA	526		29.42	2.3	23	5,262	1,410		6,672
	Staircase lighting	5	EA	312		29.42	5.4	27	1,560	1,670		3,230
	Receptacles	2	EA	17		29.42	2.5	5	33	300		333
	Photocell	1	EA	125		29.42	2.2	2	125	130		255
	Lighting contactor	1	EA	458		29.42	10.8	11	458	670		1,128
	Junction boxes	1	EA	84		29.42	16.3	16	84	1,000		1,084
	Panelboards	1	EA	936		29.42	29.3	29	936	1,800		2,736
	¾ in. rigid steel conduit	1,260	FT	1.96		29.42	0.24	299	2,473	18,400		20,873
	2 conductor, 12 gauge wire	2,520	FT	0.29		29.42	0.0039	10	734	610		1,344
5	Welding Receptacle	6	EA	550		29.42	4	23	3,300	1,420		4,720
6	Communication Stations											
	GAI-Tronics page/party station	1	EA	1,050		29.42	10.40	10	1,050	640		1,690
	Horn	1	EA	234		29.42	5.20	5	234	320		554
	U bracket for horn	1	EA	73					73			73
	5 party line cable	330	FT	2.86		29.42	0.09	31	944	1,900		2,844
	Single line cable	330	FT	0.52		29.42	0.04	12	172	740		912
	¾ in. rigid steel conduit	80	FT	1.96		29.42	0.24	19	157	1,170		1,327
7	Fire / Smoke Detectors											
	Emergency shutdown stations	3	EA	78		29.42	2.60	8	234	480		714
	Photoelectric smoke detectors	12	EA	156		29.42	2.60	31	1,872	1,920		3,792
	Thermal detectors	12	EA	156		29.42	2.60	31	1,872	1,920		3,792
	Strobe light and horn	3	EA	104		29.42	2.60	8	312	480		792
	Electric wire, 16 gauge	1,200	FT	0.29		29.42	0.012	14	349	870		1,219
	¾ in. rigid steel conduit	1,200	FT	1.96		29.42	0.24	284	2,355	17,530		19,885
	Terminal box	3	EA	416		29.42	6.50	20	1,248	1,200		2,448
8	Instrument Conduit											
	¾ in. rigid steel conduit	2,500	FT	1.96		29.42	0.24	592	4,906	36,510		41,416
	Terminations	100	EA	14.55		29.42	0.65	65	1,455	4,010		5,465
	Instrument wiring	3,000	FT	1.06		29.42	0.014	43	3,182	2,670		5,852
9	Cable Trays											
	12 in. power cable tray	480	FT	10		29.42	0.35	167	4,912	10,270		15,182
	12 in. instrument cable tray	660	FT	10		29.42	0.35	229	6,754	14,120		20,874
	Tray covers	1,140	FT	Included		29.42	0.00	0	0	0		0
	Support columns	33	EA	312		29.42	39.0	1,287	10,296	79,330		89,626
	Support sleepers	24	EA	104		29.42	6.5	156	2,496	9,620		12,116

Thermocline Storage System Total Field Cost Estimate

				----- Unit Cost ------		Labor	MH	Total	------------------------------ $ ------------------------------			
Code	Description	Qty	Unit	Material	S/C	$ Rate	Rate	MH	Material	Labor	S/C	Total
====	==	====	===	=======	======	=====	=====	=====	=======	=======	========	========
10	Wire and Cable											
	Control and instrument											
	Twisted pair, 16 gauge, thermocouple	2,208,661	FT	1.06		29.42	0.014	31,871	2,342,948	1,964,520		4,307,468
	Average long run = 0.5*31 m; average short run = 0.5*20 m											
	Terminations	96,000	EA	14.55		29.42	0.650	62,400	1,396,762	3,846,330		5,243,092
	Termination boxes	120	EA	416		29.42	13.0	1,560	49,920	96,160		146,080
	Armored cable connections	50	EA	52		29.42	1.3	65	2,600	4,010		6,610
11	Cathodic Protection											
	Graphite anodes											
	Drilling	100	LF			29.42	1.05	105		6,490		6,490
	Anodes	10	EA	478		29.42	7.3	73	4,780	4,520		9,300
	Junction box	1	EA	783		29.42	8.4	8	780	520		1,300
	Rectifier	1	EA	5,984		29.42	182	182	5,980	11,220		17,200
	Test station	2	EA	73		29.42	2.17	4	150	270		420
	Reference cell	2	EA	52		29.42	5.42	11	100	670		770
	Electric cable, 3 conductor, armored, underground											
	6 gauge	300	FT	0.98		29.42	0.36	109	290	6,730		7,020
	8 gauge	240	FT	0.63		29.42	0.36	87	150	5,380		5,530
12	Grounding											
	Enclosure and structural steel											
	1 conductor, 00 gauge, bare cable	2,000	FT	1.52		29.42	0.325	650	3,036	40,050		43,086
	Cadwelds	20	EA	10		29.42	1.49	30	210	1,830		2,040
	Grounding rods	10	EA	31		29.42	2.6	26	310	1,600		1,910
13	Testing	1	LT	5,200		29.42	311	311	5,200	19,160		24,360
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	Subtotal - Electrical								3,884,980	6,239,090		10,124,070
Q	CONCRETE WORK											
1	Vessel Foundation											
	Formwork	4,016	SF	1.56		26.72	0.46	1,827	6,265	107,690		113,955
	Reinforcing steel	395	T	832		26.72	26	10,282	329,034	606,040		935,074
	Concrete	3,955	CY	306		26.72	1.95	7,712	1,210,390	454,530		1,664,920
	Embedded metals	98,869	LB	1.56		26.72	w/ forms		154,235			154,235
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	Subtotal - Concrete Work								1,699,923	1,168,260	0	2,868,183

Thermocline Storage System Total Field Cost Estimate

Code	Description	Qty	Unit	Unit Cost Material	Unit Cost S/C	Labor $ Rate	MH Rate	Total MH	$ Material	$ Labor	$ S/C	$ Total
S	SITEWORK											
	Excavation	4,746	CY			26.72	0.65	3,085		181,810		181,810
	Backfill and Compaction	791	CY	8		26.72	1.17	925	6,581	54,540		61,121
	Foamglas (concrete isolation)	26,694	CF	21		26.72	0.10	2,571	571,070	151,510		722,580
	Subtotal - Sitework								577,651	387,860	0	965,511
X	PAINTING											
	Structural steel (allowance)	35,200	SF		0.52						18,304	18,304
	Subtotal								903,262,454	158,067,480	4,819,050	1,066,148,984
	Sales Tax								66,841,422			66,841,422
4	TOTAL - THERMAL STORAGE SYSTEM								970,103,876	158,067,480	4,819,050	1,132,990,406