

SANDIA REPORT

SAND2010-6978
Unlimited Release

Design Considerations for Concentrating Solar Power Tower Systems Employing Molten Salt

Robert Moore, Milton Vernon, Clifford K. Ho, Nathan P. Siegel, and Gregory J. Kolb

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of Energy's
National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865) 576-8401
Facsimile: (865) 576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: <http://www.osti.gov/bridge>

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone: (800) 553-6847
Facsimile: (703) 605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: <http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online>



Design Considerations for Concentrating Solar Power Tower Systems Employing Molten Salt

Robert Moore, Milton Vernon, Clifford K. Ho, Nathan P. Siegel, and Gregory J. Kolb

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185

Abstract

The Solar Two Project was a United States Department of Energy sponsored project operated from 1996 to 1999 to demonstrate the coupling of a solar power tower with a molten nitrate salt as a heat transfer media and for thermal storage. Thermal storage allows for power production at night and when conditions are unfavorable for collection of solar energy. Over all, the Solar Two Project was very successful; however many operational challenges were encountered. In this work, the major problems encountered in operation of the Solar Two facility were evaluated and alternative technologies identified for use in a future solar power tower operating with a steam Rankine power cycle. Most of the problems were minor and easily corrected. However, certain problems caused by corrosion of construction materials, failure of equipment due to salt freeze-thaw cycling, and leaks in seals resulted in significant program delays and additional cost. Many of the major problems encountered can be addressed with new technologies that were not available a decade ago. These new technologies include better thermal insulation, analytical equipment, pumps and valves specifically designed for molten nitrate salts, and gaskets resistant to thermal cycling and advanced equipment designs. Additionally, new data are available for metal corrosion rates in molten nitrate salts that can be used for equipment design.

Table of Contents

ABSTRACT	4
TABLE OF CONTENTS	6
TABLE OF FIGURES	7
TABLE OF TABLES	8
EXECUTIVE SUMMARY	7
1.0 INTRODUCTION	9
2.0 BACKGROUND	10
2.1 <i>The Solar Two Facility</i>	<i>10</i>
3.0 DESIGN OPTIONS FOR THE NEXT GENERATION SOLAR TOWER	13
3.1 <i>Corrosion Minimization</i>	<i>13</i>
3.2 <i>Advanced Insulation</i>	<i>16</i>
3.3 <i>Advanced Flange Seals</i>	<i>17</i>
3.4 <i>Heat Trace</i>	<i>18</i>
3.5 <i>Pumps and Valves</i>	<i>19</i>
3.6 <i>Steam generator/Heat Exchanger Design Options</i>	<i>20</i>
3.7 <i>Radar Level Sensors</i>	<i>25</i>
3.8 <i>Pretreatment of Nitrate Salt Mixture</i>	<i>25</i>
4 POWER SYSTEM EFFICIENCY IMPROVEMENT MOTIVATION	27
5 STEAM RANKINE POWER CYCLE OPTIONS	29
5.1 <i>Subcritical Steam Rankine Cycle</i>	<i>29</i>
5.2 <i>Supercritical Steam Rankine Cycle</i>	<i>30</i>
5.3 <i>Reheated Supercritical Steam Rankine Cycle</i>	<i>32</i>
5.4 <i>Regenerated Supercritical Steam Rankine Cycle</i>	<i>34</i>
5.5 <i>Regenerated & Reheated Supercritical Steam Rankine Cycle</i>	<i>35</i>
5.6 <i>Steam Rankine Cycle Recommendation</i>	<i>36</i>
6 ADDITIONAL RESERCH NEEDS	41
7 SUMMARY	42
8 REFERENCES	43
9 DISTRIBUTION	47

Table of Figures

Figure 1: Corrosion Rates of Metals in High Temperature Steam (Phillips et al., 2003)	15
Figure 2: Thermal Conductivity of Aerogel Insulation (Aspen Aerogels, Inc.).....	16
Figure 3: Constant Seating Stress Gasket U.S. Patent 6,869,08, Jjenco, Inc.....	18
Figure 4: Block diagram of subcritical steam Rankine cycle showing basic design on the left and one option to avoid salt plugging on the right	30
Figure 5: T-s diagrams for subcritical steam Rankine cycle operating at 6.9 MPa (1000 psi) and 550°C with 39.04% cycle efficiency on left and 600°C with 39.74% cycle efficiency on right.....	30
Figure 6: Block diagram of supercritical steam Rankine cycle showing basic design on the left and one option to avoid salt plugging on the right	31
Figure 7: T-s diagrams for supercritical steam Rankine cycle operating at 25 MPa (3625 psi) and 550°C with 42.21% cycle efficiency on left and 600°C with 43.93% cycle efficiency on right.....	32
Figure 8: Block diagram of reheated supercritical steam Rankine cycle showing basic design on the left and one option to avoid salt plugging on the right	33
Figure 9: T-s diagrams for reheated supercritical steam Rankine cycle operating at 25 MPa (3625 psi) and 550°C with 42.45% cycle efficiency on left and 600°C with 41.87% cycle efficiency on right	33
Figure 10: Block diagram of regenerated supercritical steam Rankine cycle showing basic two stage design on the left and a three stage design on the right.....	34
Figure 11: T-s diagrams for 3 stage regenerated supercritical steam Rankine cycle operating at 25 MPa (3625 psi) and 550°C with 46.41% cycle efficiency on left and 600°C with 47.23% cycle efficiency on right.....	35
Figure 12: Block diagram of regenerated & reheated supercritical steam Rankine cycle showing basic two stage design	36
Figure 13: T-s diagrams for 2 stage regenerated & reheated supercritical steam Rankine cycle operating at 25 MPa (3625 psi) and 550°C with 45.39% cycle efficiency on left and 600°C with 44.29% cycle efficiency on right.....	36
Figure 14: Hypothetical temperature profile through an unmixed heat exchanger with a single channel flow perturbation.	38
Figure 15: Magnitude of flow perturbation that results in a salt channel freeze for unmixed heat exchanger flow as a function of water inlet temperature with salt inlet of 600°C and average ΔT between flows of 50°C.	38
Figure 16: Salt and water (Rankine working fluid) temperature profile as a function of specific enthalpy change through input heat exchanger with water at 25 MPa.	39
Figure 17: Block diagram of 5 stage recuperated supercritical Rankine system utilizing direct contact condenser and dry heat rejection at 25°C (77°F) inlet temperature.	40

Table of Tables

Table 1: Solar Two Major Processing Units.....	11
Table 2: Problems Encountered in Operation of the Solar Two Facility	12
Table 3: Materials Testing in Molten Nitrate Salts.....	14
Table 4: Properties of Aerogel and Ceramic Fiber Insulation.....	16
Table 5: Heat Exchanger Options for the Steam Generator.....	22

Executive Summary

This work was a review of problems and lessons learned from operation of the Solar Two power tower with the objective of identifying advanced technologies and equipment for the design of a future 100MWe solar power tower. The Solar Two project was completed more than a decade ago and there are many new technologies and products available to improve over the Solar Two design. Advanced power conversion systems include both the advanced Rankine cycles and the advanced Brayton cycles, but only the Rankine cycles are discussed in this report.

The Solar Two facility was designed to produce 10 MWe power using a molten nitrate salt mixture (60% sodium nitrate, 40% potassium nitrate) as both the heat transfer media and the thermal storage media. Thermal storage allowed the facility to produce power when collection of solar energy was not possible (e.g., night, cloudy skies). Solar Two operated with a steam Rankine power cycle.

The major problems encountered during operation of the Solar Two facility were caused by corrosion in the molten nitrate salt media, incorrect or inadequate heat trace, inadequate insulation, leaking gaskets and seals, and incorrect heat exchanger design. In some cases, inadequate temperature control led to freeze-thaw cycles of the nitrate salt causing failure of equipment.

Data on corrosion in molten nitrate salt mixtures indicate the presence of impurities, especially chloride and water, contribute significantly to corrosion. In general, the available information indicates that mild steel is acceptable for cold salt processing, and moderate to high chromium stainless steel is acceptable for hot salt processing. These are only guidelines and additional static and dynamic corrosion tests are needed.

The new technologies and products identified in this work that are applicable to a new solar facility include:

- Aerogel insulation with a factor of 2-3 less thermal conductivity than the best ceramic fiber insulation
- Constant Seating Stress Gaskets that are resistant to thermal cycling
- High-temperature, self-regulating heat trace to prevent over heating
- Commercially available valves and pumps designed specifically for molten nitrate salt
- Printed circuit board and microchannel heat exchangers with a very high heat transfer area but that are very compact and light weight
- Commercial scrubbing units for removing NO_x compounds from vent streams for pretreatment of the nitrate salt mixtures
- High temperature radar level detectors are commercially available for temperatures up to 400°C. Higher temperature may be possible by modification of the sensors.
- High temperature stainless steel, Inconel, and Hastelloy filters to filter fluids at high temperatures (up to 925°C)

- High temperature steam turbine for implementation of high-temperature Rankine cycles at the lower 100 MWe power levels

The additional research needs identified in this work are:

- Additional static and dynamic corrosion testing of materials.
- Evaluation of new technologies under operating conditions including constant seating stress gaskets, gasket materials, aerogels, etc.
- Evaluation of new heat trace cables and process control options for electric heat trace.
- Evaluation of high-temperature radar tank level sensors for molten salt tanks.
- Continue evaluation of alternative steam generator/heat exchanger designs
- Evaluation of designs allowing for 24/7 operation of the power generation section of the facility. 24/7 operation would eliminate thermal cycling and prevent many problems with materials and seals.
- Evaluation of insulating the solar receiver during night time or unfavorable conditions. Aerogel insulation is lightweight and can potentially be used to keep the receiver hot when not in operation. This would eliminate the need to empty the receiver and eliminate temperature cycling.
- Evaluation of supercritical fluid power cycles and heat exchanger configurations.
- Development of supercritical steam high-pressure turbine for power systems smaller than 350 MW.

In summary, many new technologies are available to improve solar facility design and avoid potential problems encountered during operation of Solar Two. The major problems encountered during Solar Two operation were caused by thermal cycling and salt freeze-thaw cycles. These problems can be eliminated or minimized by continuous operation (24/7).

1.0 INTRODUCTION

The Solar Two Project was a United States Department of Energy sponsored project to demonstrate the coupling of a solar power tower with a molten nitrate salt heat transfer media. Solar Two was designed to produce 10MWe power and was located in the Mojave Desert near Barstow, CA. The facility operated from 1996 to 1999 with many lessons being learned concerning the use molten nitrate salt. The objective of this work was to review the major problems encountered in the Solar Two Project and evaluate advances in technology that could be used in the design of a future 100 MWe molten nitrate salt solar power tower operating with a steam Rankine power cycle.

The primary objective of the Solar Two Project was to demonstrate the utility of using molten nitrate salt as the heat transfer media and for thermal storage. Thermal storage allows for uninterrupted power generation at night and at times when the sun is not shining. Over all, the Solar Two Project was very successful; however many operational challenges were encountered. Most of the problems were minor and easily corrected. However, certain problems caused by corrosion of construction materials, failure of equipment due to salt freeze-thaw cycling, and leaks in seals resulted in significant program delays and additional cost. Many of the major problems encountered can be addressed with new technologies that were not available a decade ago. These new technologies include better thermal insulation, analytical equipment, pumps and valves specifically designed for molten nitrate salts, and gaskets resistant to thermal cycling and advanced equipment designs. Additionally, new data are available for metal corrosion rates in molten nitrate salts that can be used for equipment design.

Based on the experience gained with the Solar Two Project, a design basis for a scaled-up facility was selected. The criteria included:

- 100 MWe (~250MWt)
- Molten nitrate salt mixture (60% sodium nitrate, 40% potassium nitrate)
- Maximum salt temperature approaching 600°C
- Steam Rankine power cycle
- Dry heat rejection

The steam Rankine power cycle was chosen for this study since it is the most developed power cycle and offers many options to be investigated including (1) Subcritical Rankine cycle, (2) Supercritical Rankine cycle, (3) Reheat Rankine cycle and (4) Feed water preheat Rankine cycle.

Based on the data collected and reviewed in this work, new technologies have been identified for use in a scaled-up solar power tower system. Recommendations are given for equipment designs and additional research needs have been identified. Additionally, thermodynamic analysis were performed for a steam Rankine power cycle. Although beyond the scope of this work, the use of a supercritical fluid instead of steam as the working fluid for power generation is briefly touched upon.

2.0 BACKGROUND

2.1 The Solar Two Facility

Description

The Solar One project was the first research and demonstration project in the United States to prove the technical feasibility of the central receiver concept for generating electric energy on a commercial scale. Solar One was located in the Mojave Desert east of Barstow, CA, with a power output of 10 MWe. Solar energy was used to heat a high temperature heat-transfer molten salt fluid that was used to generate steam to drive a series of turbines for generation of electricity. The subsequent project, Solar Two, involved refitting Solar One to use molten nitrate salt for solar energy collection instead of the heat transfer fluid used in Solar One. A different solar receiver and additional mirrors were also added. The main purpose of the Solar Two project was to reduce the perceived technical and financial risks in using molten nitrate salt technology (Kelly, 2002).

The use of molten nitrate salt has several advantages over more conventional heat transfer fluids. The heat transfer properties of the nitrate salt are such that incident fluxes on the solar receiver up to 1,000 kW/m² can be safely tolerated; this was approximately twice the allowable flux levels for the water steam receiver at Solar One (Kelly, 2000). However, the main advantage is that molten nitrate salt can be used for thermal energy storage allowing overnight operation and uninterrupted operation. 3.3 million pounds of a nitrate salt mixture with a composition of 60% sodium nitrate and 40% potassium nitrate were used in the Solar Two Project. The major processing units for molten nitrate salt and the construction materials for the units for the Solar Two facility are listed in Table 1.

Problems Encountered and Lessons Learned

There are two main reports that document the successes and lessons learned for operation of the Solar Two facility. These are:

Kelly, B. "Lessons Learned, Project History and Operating Experience of the Solar Two Project" SAND2000-2598,

Pacheco, J.E. (editor) "Final Test and Evaluation Results from the Solar Two Project" SNAD2002-0120, January 2002

Table 1: Solar Two Major Processing Units

Process Unit	Description	Construction Materials
Solar Collector	Heat nitrate salt from 290°C to 565°C. Ave flux capacity of 430 kW/m ²	316H s.s.
Steam Generator	Shell and tube preheater and superheater and a kettle type boiler. Heat 100 bar water at 260°C to supply superheated steam at 510°C	Preheater: carbon steel. Boiler: 9Cr-1Mo ferric steel tubes, 2 1/4Cr-1Mo ferric steel, carbon steel shell. Superheater: 300 series s.s.
Thermal Storage Tanks	Cold salt storage tank (290°C) 11.6 m dia. x 7.8 m high. Hot salt storage tank (565°C) 11.6 m dia.x 8.4 m high. The sides and the roof of each tank insulated with 46 cm and 30 cm, respectively of mineral wool blankets overlaid with 5 cm of fiberglass boards. The bottom of the hot tank insulated with 15 cm insulating firebrick on top of 30 cm foamglass insulation.	Cold salt tank: ASTM-A516-70 carbon steel. Hot salt tank: 304 s.s.
Pipes	Schedule 10 and schedule 40 pipe.	Cold salt pipe: ASTM A106 carbon steel. Hot salt pipe: AISI 304/304H s.s.

A third report by Zavoico (2001) also contains useful information. The report draws from the lessons learned in the reports by Kelly and Pacheco and describes a generic solar power tower design using molten nitrate salt.

In general, the problems, solutions and recommendations documented by Kelly and Pacheco can be divided into five main categories and are given in Table 2. There were a total of 94 problems documented and discussed in the two reports. Most of the problems were minor and required only simple modifications of equipment or operational procedures. However, some problems resulted in significant reengineering or replacement of equipment resulting in significant delays of the program schedule. These problems included:

- Corrosion in several process units and pipes
- Incorrect heat tracing resulting in freezing of the nitrate salt mixture
- Tube rupture in the steam generator from freeze-thaw cycles of the nitrate salt mixture
- Leaking valve bodies and pump failures
- Evolution of large amounts of NO_x compounds when pre-treating the nitrate salt mixture. Although not considered a major problem at the time, new US EPA regulations may prevent the release of significant amounts of NO_x compounds in the future.

Table 2: Problems Encountered in Operation of the Solar Two Facility

Problem Area	Problems/Issues Cited
Design problems	49
– Incorrect design	
Operational problems	15
– Incorrect operating procedure.	
– Process control issue	
Materials problems	20
– Corrosion	
– Welds	
– Gaskets	
– Valve seats	
Heat tracing problems	8
– Incorrect heat trace scheme	
– Insulation issue	
Equipment failure	2
– Salt plugging (non corrosion problems)	

A description of the major problems encountered, new design options and technical advances in equipment and materials are discussed in the next section.

3.0 DESIGN OPTIONS FOR THE NEXT GENERATION SOLAR TOWER

3.1 Corrosion Minimization

Nitrate Salt Induced Corrosion

Along with the reports documenting the operation of Solar Two, some literature data are available reporting on corrosion of metals in molten nitrate salts. Table 3 lists the available corrosion data.

Type 304 and 304H were used for the hot salt pipe for Solar Two, and stress corrosion cracking was observed. Kelly (2002) reports stress corrosion cracking can occur for 304 and 316 stainless steel if the following conditions are present:

- Residual tensile stresses due to welding and rolling operations
- Presence of chlorides in the molten nitrate salt
- Presence of water in the molten nitrate salt
- Depletion of chromium. Chromium is soluble in molten nitrate salt

This is in agreement with Kearney et al. (2004) who reports that molten nitrate salt(s) is relatively benign in terms of corrosion. However the industrial grade salt contains impurities, of which the most chemically active are chlorides and perchlorates, known to cause metal corrosion. The authors also state trace moisture in the salt may exacerbate corrosion problems. Goods and Bradshaw (2004) also indicate impurities in molten nitrate salt(s) strongly increase corrosion of 304 and 316 stainless steel.

Kelly (2000) states materials that are immune to stress corrosion cracking are 321 and 347 stainless steel, Inconel, and ferric steels with high chromium content. Kelly recommends using 321 or 347 stainless steel for the hot salt piping in future designs. Failures of the cold salt pipes in Solar Two were due to overheating and carbon steel did not show evidence of corrosion when operated at the nominal design conditions. For the steam generator, both Kelly and Zavoico recommend carbon steel for the preheater, a 9Cr-1Mo stainless steel for the boiler and 321 or 347 stainless steel for the superheater.

The literature data indicate type 321H (18Cr-10Ni-Ti) and 316T s.s. had minimal corrosion in molten nitrate salt after 8000 hr. of static and dynamic testing. (Fabrizi, 2007) Corrosion testing of Inconel 718 and 625 indicated minimal corrosion at temperatures up to 600°C (Bradshaw and Goods, 2000).

Table 3: Materials Testing in Molten Nitrate Salts

SUBJECT	DESCRIPTION	RESULTS	REFERENCE
Solar 2 cold salt pipe corrosion	ASTM A106 Grade B carbon steel	Severe corrosion where pipe was overheated due to incorrect heat trace.	Kelly, 2000
Solar 2 Hot salt pipe corrosion	AISI Type 304/304H s.s. with a min. carbon content of 0.04%. Limited portions fabricated from Typ2 316H and 347 materials	Cracking of Type 304H and 347 s.s. was observed. Four requirements must be met for these materials to fail: 1. Temperatures in excess of 1,000F for more than a few hours, 2. reduction of tensile strength due to welding 3. presence of Cl ⁻ ions (0.3% in Solar 2 testing) and 4. presence of water. Recommendations were to consider (with additional corrosion data) Type 321 or 347 s.s for the hot salt pipe.	Kelly, 2000
Corrosion testing of Inconel 718 and Inconel 625 in nitrate salt mixtures	Accelerated coupon corrosion tests were performed with Inconel 718 and Inconel 625 in molten NaNO ₃ and KNO ₃ mixtures up to 600C	Corrosion was dependant on chlorine impurities in the salt mixtures. Total metal loss after 5000 hours of testing was 9 - 12 microns and 10 to 15 microns for Inconel 718 and Inconel 625 respectively. The corrosion scales, Ni oxide, were reported to be very adherent.	Bradshaw and Goods, 2000
Corrosion testing of Inconel 625 in nitrate salt mixture	Accelerated coupon corrosion tests were performed with Inconel 625 in molten NaNO ₃ and KNO ₃ up to 650C	After 2800 hours at 650C metal loss was 23 microns. The corrosion scale, Ni oxide, formed were very adherent.	Bradshaw and Goods, 2001
Solar 2 receiver corrosion	Receiver tubes were constructed of 316 s.s. and an analysis was performed after 1500 hours of operation.	Minimal corrosion observed. The oxide scales were never greater than 10 microns.	Pacheco 2002
Corrosion on Ni and Ni alloys in molten salt	The authors present a review of corrosion mechanism of Ni and Ni based alloys in molten nitrates, sulfates, carbonates and hydroxides	Corrosion of Ni and Ni alloys in nitrate salts in through a processes closely related to dissolution of passivated metals through a Ni oxide layer.	Tzvetkoff and Gencheva, 2003
Corrosion of carbon and s.s. in nitrate salts	Coupon testing of 304 and 316 s.s. at 570°C and A36 C steel at 316°C in molten nitrate salts	6 - 15 microns/year for 304 and 316 s.s. respectively. 1 - 4 microns for A36 C steel. Small amounts of impurities significantly increased corrosion.	Goods and Bradshaw, 2004
Corrosion of Tantalum in molten nitrate ternary mixture	Corrosion of tantalum at 413 to 503K in molten LiNO ₃ - NaNO ₃ - KNO ₃	Method used to form a passivating Ta oxide layer on tantalum. No high temperature data has been located	Yurinskii, V.P., E.G. Firsova and E.V. Afonicheva 2003
Corrosion of nickel and iron alloys in molten nitrate-nitrite salts at 510 - 705 °C.	More specific information has been requested	Nickel alloys with 15-20% chromium content performed the best. Iron and nickel alloys with low chromium content exhibited significant corrosion. For all materials corrosion increased drastically above 650°C.	Slusser et al (1985)
Corrosion of Nickel in Molten NaNO ₃ -KNO ₃ Eutectic	NiO ₂ passivating film forms at temperatures below 350C. Significant increase in corrosion at higher temperatures	Mechanism of corrosion was not determined at higher temperatures but the authors indicate corrosion is occurring at a higher rate and through a different mechanism.	Baraka, A., R.M.S. Baraka and A. Abdel-Razik (1986)
Static and dynamic corrosion testing of AISI 321H and 316T in molten nitrate salt	Testing of 321H s.s. (18Cr-10Ni-Ti) and 316T s.s. in molten nitrate salt mixture (60/40)	8000 hours of static tests and 8000 hours of dynamic tests at 550°C indicate little corrosion.	Fabrizi, 2007

Based on the results from Solar Two and the literature data some basic conclusions can be made:

- Impurities in the salt, especially chlorides, perchlorates, and water, must be minimized.
- Mild steels are applicable for temperatures up to ~300°C.
- Moderate to high chromium steels are applicable up to temperatures of ~570°C and possibly higher.
- Ni based alloys are resistant to corrosion up to ~650°C.

These conclusions are only guidelines and additional coupon testing, both static and dynamic, are needed to complete the evaluation of metal corrosion in molten nitrate salts. Experiments should be performed with industrial grade salts as well as laboratory reagent grade salts. The effect of chlorides, perchlorate, and water should be quantitatively determined.

Steam Induced Corrosion of Metals

From literature data and experience with the Solar Two facility, it is known that corrosion can be significant for metals in contact with molten nitrate salts. However, steam can also be very corrosive at elevated temperatures. Figure 1 is a graph of corrosion rates as a function of steam temperature for high chromium steel. Corrosion rates are all high above 650°C. The materials are all nickel-chromium alloys. The two alloys with the lowest corrosion rates, given by the green and purple lines, were treated by shot peening a process not applicable to long pipes. The other two alloys show significant corrosion in steam at a temperature of 600°C and above. The current design criteria for the 100 MWe solar tower calls for a steam temperature approaching 600°C.

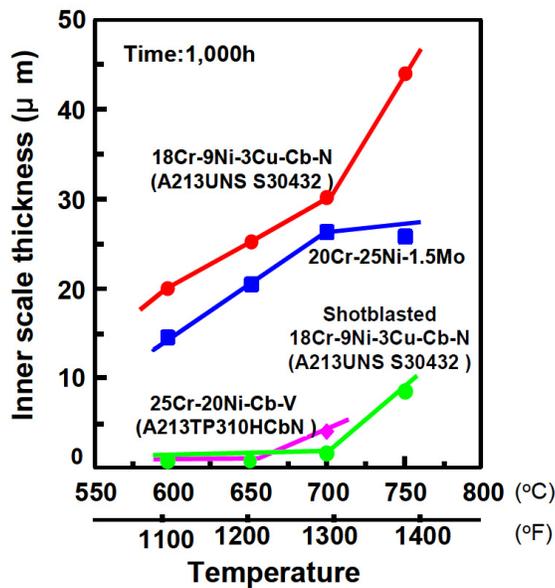


Figure 1: Corrosion Rates of Metals in High Temperature Steam (Phillips et al., 2003)

For power conversion supercritical fluids, carbon dioxide and water may be used instead of subcritical steam. If supercritical fluids are considered then additional materials testing may be required. Many steels corrode in supercritical water and therefore high chromium or Ni based alloys are typically used. However, these alloys may be unacceptable for molten nitrate salts. It is known that chromium is very soluble in molten nitrate salts above temperatures of 550°C, but relatively insoluble at temperatures below 450°C.

3.2 Advanced Insulation

Several problems with inadequate insulation were encountered during the operation of Solar Two. Among the problems was freezing of nitrate salt in the solar receiver tubes. For pipes and areas where thermal insulation is critical there is a new option for insulation. Aerogel insulation has been around for many decades; however its use for routine applications has been cost prohibitive. Due to a new manufacturing method, Aerogel is now relatively inexpensive. For 5 mm thick and 10 mm thick aerogel sheets, the cost is \$1.99 ft² and \$3.67 ft², respectively. Aerogel has the lowest bulk density of any known porous solid and has a thermal conductivity 2-3 times less than the best ceramic fiber insulation. The properties of Aerogel and ceramic fiber blanket insulation are compared in Table 4. For the same insulating value, it would require approximately 3 times the weight using ceramic fiber insulation and the cost is comparable.

Table 4: Properties of Aerogel and Ceramic Fiber Insulation

Material	Thermal conductivity (W/mK)	Density (kg/m ³)	Cost (\$/ft ²)
ceramic blanket	40	128	3.67 (10 mm thick)
Aerogel	12 to 16	112	2-5 (1" thick)

Figure 2 is the thermal conductivity of Aerogel as a function of temperature (Aspen Aerogels, Inc.). Aerogel has a maximum operating temperature of 650°C and a density of 6-8 lb/ft³. Aerogel is available in sheet and blanket form from Aspen Aerogels, Inc. It can be easily cut with a knife or scissors.

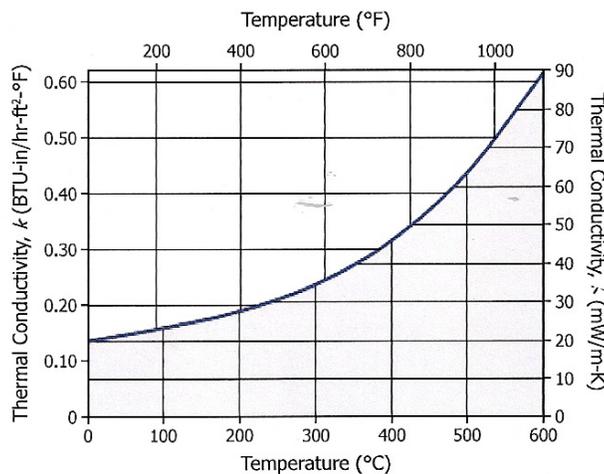


Figure 2: Thermal Conductivity of Aerogel Insulation (Aspen Aerogels, Inc.)

Because of Aerogel's low weight and high insulation properties, a potential application is to use it to insulate the solar receiver during night time or in bad weather. For Solar Two the receiver had to be emptied when not in operation. This resulted in delays in process start up, and for long-term operation this can lead to problems with thermal cycling.

3.3 Advanced Flange Seals

During Solar Two operation leaks through flange/gasket seals were encountered. The leaks were managed by retightening the flange bolts at the operating temperature. (Kelly, 2000) Although this practice is common in industry for long-term operation, short-term operation with thermal cycling will eventually cause the seals to fail. Currently, there are better flange seals available for high-temperature use. Constant Seating Stress Gaskets were developed in 2005 by Jenco, Inc. (U.S. Patent 6,869,008) a diagram of the Constant Seating Stress Gaskets is given in Figure 3. These seals maintain a constant force on the gasket seat and compensate for rotation effects. Any gasket material can be use with this technology including polymers, metals, asbestos and certain minerals.

The concept is described on the Jjenco web site that manufactures the product:

When tightened, every flange exhibits a tendency to rotate about its axial centerline in response to the compressive load provided by the fasteners about its periphery. This phenomenon is referred to as flange rotation, and differs for each flange according to its size, material, and pressure class. The degree to which a given flange rotates is dependent upon the bolt preload, and can be predicted using Finite Element Analysis. The PerfectSealEOS gasket takes advantage of this predictable phenomenon by providing a known point about which the flange face is initially caused to pivot. As the fasteners are further tightened, the flange rotates about this fixed point, compressing the filler material into a groove in the carrier ring in the process, until such time as the flange contacts a second contact point, having then fully captured the filler material within the groove. The relationship between the first and second contact points represents a degree of flange rotation corresponding to the desired bolt preload necessary to effectively seal the joint (Jjenco web site).

This type of seal would need to be tested under the conditions applicable for solar salt.

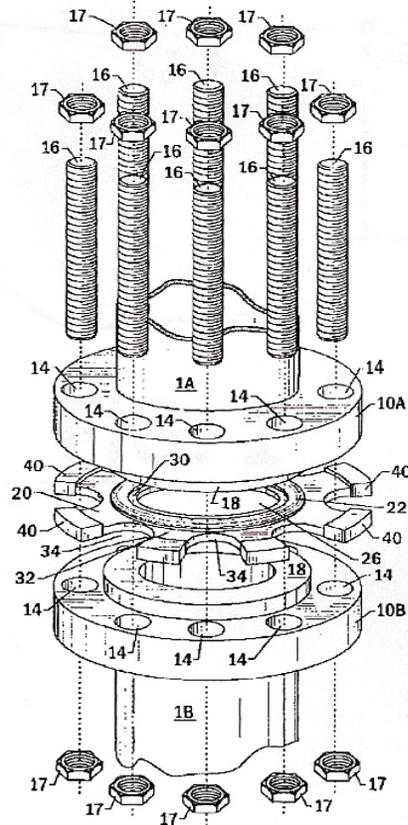


Figure 3: Constant Seating Stress Gasket U.S. Patent 6,869,08, Jjenco, Inc

3.4 Heat Trace

Improper heat trace for Solar Two resulted in overheating of cold salt pipes, the failure of a receiver tube and an evaporator tube, and the failure of valves (Kelly, 2000). Solar Two heat trace was electric. In this work, tracing with steam, mineral oil, silicon oils and aromatic oils was evaluated as alternatives to electric heat trace. The guidelines for using heat trace are given by Pitzer (2003) and are listed below.

- Mineral, silicon and aromatic oils
 - 300 – 400°C
 - Complex piping, pumps, heating unit
 - Leak, corrosion, fluid replacement
 - Complex piping, pumps, heating unit
 - Low heat capacity – multiple heat tracing is required
 - Leak, corrosion, fluid replacement are problems
 -

- Steam
 - Typically low temperature applications (<200°C)
 - Complex piping, pumps, heating unit
 - Leak, corrosion, fluid replacement are problems
 -
- Electric
 - 500°C or higher
 - Easiest method to install and maintain
 - Economical competitive for high temperature applications
 - Best temperature control over other methods

Based on these guidelines and the requirements for molten nitrate salt, 290°C for cold salt and up to 600°C for hot salt, electric heat trace is the only viable option.

More than 15 years have past since electric heat trace was installed at Solar Two. Since then, there have been many advances in heat tracing and process control and monitoring. (Thompson et al., 1998; Sandberg et al., 2000; Sandberg et al., 2001; Driscoll and Johnson, 2009; Barth et al., 2002; Pitzer and Barth, 2006. Also, there are numerous companies that provide installation of high temperature heat trace systems for pilot plant and industrial applications.

Heat tracing engineering is traditionally one of the last activities to take place in the design phase and plant construction timeline (Thompson et al, 1998). However, incorrect heat trace can cause equipment failures and create substantial down time for the facility such as those that occurred for Solar Two. Additionally, heat trace uses a substantial amount of power reducing the overall efficiency of the process. Solar Two heat trace consumed 3 MWh/day. (Pacheco, 2002)

New products are available for future facilities employing molten-salt technology. These include parallel self-regulating cable heaters and parallel resistance constant power heater (Malone, 2009). Parallel self-regulating cable heaters are now available for temperatures up to 300°C. These heater cables cannot overheat unlike the heater cables used for Solar Two. Additionally, parallel self-regulating heaters can be cut to length during installation. This could not be done using the heater cables for Solar Two that had to be special ordered for each pipe section and application. Parallel resistance, metal sheathed, and mineral insulated cable heaters are now available for temperatures up to 425°C. These cable heaters can also be cut to any desired length (Malone, 2009).

3.5 Pumps and Valves

Numerous leaks and failures are reported for the valves and pumps for Solar Two. A small amount of information on molten nitrate salt valves and pumps is available from testing in other solar energy programs and the literature.

Fabrizi (2007) reports the use of valves with sealing bellows in the Italian solar trough project operated by the Italian National Agency for New Technologies, Energy and the Environment. An expansion bellows for use in solar molten salt piping and valves is patented by Litwin (U.S. Patent 6,877,508, 2003). The inventor states the design accommodates cyclic thermal expansion and contraction in the piping and valves.

Commercial molten salt pumps are available for molten nitrate salts at very high temperatures from Friatec - Rheinlutte, Germany. Fabrizio (2007) reports the construction materials for a Friatec pump are reliable based on testing in molten nitrate salt. No corrosion in the pump was observed.

3.6 Steam generator/Heat Exchanger Design Options

Solar Two Steam Generator

The steam generator used in the Solar Two facility consisted of a preheater, evaporator and superheater. The preheater and superheater used a U-tube shell and tube heat exchanger and the evaporator was a kettle type unit. Molten nitrate salt was pumped through the shell side of the preheater and superheater and through the tube side of the boiler. This particular design is similar to a standard fire tube boiler with internal heating. This type of design is proven and easily scaled up in size. (Steingress et al, 2003)

For Solar Two, rupture of a tube in the kettle boiler occurred due to salt freeze-thaw cycling when cold feed water contacted the tube bundle. Upon examination of the kettle tubes, the outer diameters of the tubes near the bottom of the bundle were consistently larger than the diameter of tubes near the top of the bundle. The change was due to plastic deformation from one or more freeze-thaw cycles. A startup feedwater heater was added to the system to ensure feedwater temperature did not drop below 230°C. No other tube ruptures were encountered after this modification. (Kelly, 2000; Pacheco, 2002)

Some fouling was observed in the preheater. It was determined that the partition plate was leaking, causing bypass around the tube bundle. Replacing the gasket eliminated the problem. To prevent any further scaling, a phosphate injection system was added. (Pacheco, 2002)

Kelly (2000) states the Kettle type evaporator should be a suitable option for a nitrate salt system. He recommends that the salt should be moved to the shell side of the evaporator to prevent tube ruptures from freeze-thaw cycles. He further states there are 10 kettle evaporators operating successfully in solar power plants.

Zavoico (2001) proposes a design utilizing three shell and tube heat exchangers for the preheater, evaporator and superheater with molten salt on the shell side for all three units. The steam-water mixture exiting the evaporator is separated in a steam drum and the water is recycled back through the evaporator. The steam is sent to the superheater. By moving the molten salt to the

shell side of the boiler, the design of Zavoico eliminates potential problems with salt freeze-thaw cycles that could result in tube rupture. The Zavoico design is similar to a water-tube steam generator. These boilers are commonly used in industry and are easily scaled up in size. (Steingress et al, 2003)

Shell and Tube Heat Exchangers

According to the report of Kelly (2000), shell and tube heat exchangers are the preferred design for use in the steam generator. To prevent tube rupture, it seems logical to pass the molten salt through the shell side of the shell and tube heat exchanger. However, it should be noted that once operational procedures for the Solar Two steam generator were modified after the tube rupture there were no further problems encountered operating with the salt on the tube side. If cold spots and thermal cycling in the steam generator can be eliminated, that may be accomplished by operating the steam generator 24/7. Then other factors need to be considered when designing the system.

The heat transfer coefficients of the molten nitrate salt and water (steam) are within the same order of magnitude and both are relatively low. Therefore, moving the salt to the shell side will not significantly affect heat transfer. However, other factors need to be evaluated. The selection procedure for a shell and tube heat exchanger design is given by Rohsenow (1998). Selecting the tube side and shell side fluids depends on several factors that are summarized below.

- **Maintenance and Cleanability** - The shell is typically very expensive compared to the tube bundle. The tube bundle is typically easy to remove and replace whereas the shell is typically not. Additionally, the shell is typically difficult to clean.
- **Corrosion** - Corrosion may dictate the use of expensive materials; therefore the more corrosive fluids should be placed in the tubes.
- **Pressure** - The highest pressure fluid should be contained in the tubes.
- **Temperature** - The highest temperature fluid should be placed in the tubes. As with pressure, high temperature and pressures require thicker materials. Additionally, more insulation may be required if the highest temperature is on the shell side.
- **Hazardous or expensive fluids** - place on the tube side for safety concerns.
- **Quantity** - The fluid with the smaller quantity being passed through the heat exchanger should be placed in the shell. This may decrease the required surface area needed in the heat exchanger.
- **Viscosity** - Turbulent flow provided much better heat transfer than laminar flow. The fluids should be arranged to obtain turbulent flow in the shell and tubes.

- **Pressure drop** - Pressure drop in the tubes are easily calculated whereas pressure drop of a fluid across the shell side can vary significantly from theoretical values. If pressure drop for a fluid is critical it is best to place it in the tubes. All of these issues need to be considered before selecting the shell side and tube side fluids.

In addition to the above mentioned criteria, shell and tube heat exchangers are typically large and heavy; a necessity to achieve the high surface area needed for good heat transfer. This should be considered when siting the steam generator. The main advantages of shell and tube units are their simplicity and well established design criteria.

Additional Heat Exchanger Options

Other than shell and tube designs other heat exchanger designs are available for use in the steam generator. In the open literature, for molten salts three types of heat exchanger are prevalent: shell and tube, helical coil and printed circuit heat exchangers. Table 5 lists the advantages and disadvantages for these three types of heat exchangers.

Table 5: Heat Exchanger Options for the Steam Generator

Heat Exchanger	Advantages	Disadvantages
Shell and Tube	Proven design. Most common type of heat exchanger. Simple inspections and maintenance Long-term operating history in numerous applications	Large and heavy expensive capital cost
Helical Coil	Proven design. Long-term operating history in numerous applications Better heat transfer than conventional shell and tube design Self cleaning for most applications In use for many industrial applications including the Japanese High Temperature Test Reactor	Significant capital cost Smaller than shell and tube design but still large. However, microchannel units are available.
Printed Circuit (Heatric)	Compact, lightweight design (7 times lighter than a comparable shell and tube design) Very high heat transfer area, very efficient heat transfer Generally subjected to few constraints in thermal design Lower cost than shell and tube and helical coil designs Significant research effort for supercritical CO ₂ Brayten cycle applications	Unproven design for many applications Inspections and maintenance is very difficult Plugging can be a serious problems. Method to clean microchannels is unknow

Helical or Spiral heat Exchangers

Helical coil heat exchangers have higher heat transfer coefficients and therefore require smaller heat transfer surface areas than shell and tube units. The curved flow path results in turbulent flow through the exchanger that would be laminar flow in a straight tube under the same flow conditions. The centrifugal force created by the curved path of the fluid creates a self cleaning

mechanism and can prevent fouling. Because of this self cleaning action, helical heat exchangers are widely used for handling two phase flow (Ramachandran et al., 2008).

Yang et al. (2009) investigated the heat transfer performance and the thermal efficiency of a molten salt receiver with spiral tubes in a solar tower. The authors report three times better heat transfer than with straight tubes. A spiral type heat exchanger is in use in the Japanese Very High Temperature Reactor using molten fluoride salt (Oh et al., 2004).

Printed Circuit Heat Exchangers and Microchannel Plate Fin Heat Exchangers

Printed circuit heat exchanger and microchannel have been proposed for use in high temperature nuclear reactors using helium (Tochon et al., 2004) and molten salt (Forsberg et al., 2004; St. Clair, 2005) as the heat transfer media. Printed circuit heat exchangers are based on chemically etching plate sheets and joining the sheets by diffusion bonding. The major manufacturer of printed circuit heat exchangers is Heatric, Inc.

Plate fin heat exchangers are based on joining corrugated thin films by brazing. NORDON, Inc. is the major manufacturer of plate fin heat exchangers (Pra et al., 2008). Sandia National Laboratories has incorporated printed circuit heat exchangers into the development program of the Super Critical CO₂ Brayton system.

Hybrid Microchannel Heat Exchanger

Printer circuit and/or microchannel heat exchangers may be used for the preheater and superheater sections of the steam generator for a molten solar salt evaporator. However, the use of any very small channel heat exchanger for the boiler is questionable because of fouling issues. The very small channels can be easily plugged with corrosion products. An option is to have microchannels on the molten salt side and larger channels on the steam side of the heat exchanger. This type of hybrid unit is available from Heatrix, Inc.

Two Heat Exchanger Design

Potential damage to the steam generator boiler by corrosion or fouling can be partially controlled by the use of two heat exchangers in series; a low temperature heat exchanger followed by a high temperature heat exchanger. Because corrosion and fouling are much more prevalent at higher temperatures, the low temperature unit may last for an extended period of time with the high temperature unit being periodically replaced (Oh, et al., 2010).

Evaporator Blowdown

If water is used as the working fluid, water will need to be periodically added to the system to replace water in the steam generator from boiler bottoms blowdown. Blowdown is necessary to

remove corrosion products, sludge, etc. that build up over time and control the chemical composition of the water. This is particularly important if chemical additives are used to control water pH, etc. The steam generator for the Solar Two facility was frequently blown down. However, because the evaporator blowdown flow rate was inadequate, significant iron oxide deposits were observed in the superheater (Kelly, 2000). An industrial steam generator using city purified water is blown down every 24 hours. The composition of water to be used in the 100 MWe solar facility is unknown at this time and estimating the frequency of blowdown can not be determined. The best method for determining when to blowdown in a steam generator is to monitor the water composition.

Other Working Fluid Options

Although beyond the scope of this report, the use of a supercritical fluid instead of subcritical water (steam) for the working fluid is worth discussion. For water, three separate heat exchangers are needed to generate superheated steam: 1. water preheating, 2. steam generation and 3. steam superheating. Additionally, there are issues with corrosion, fouling and the need for periodic blowdown. If a supercritical fluid, water or CO₂, is used a single heat exchanger would be required. This is because a phase change does not take place when heating a supercritical fluid. The use of a single heat exchanger would decrease capital and maintenance costs and be far less complicated than the use of three heat exchangers including the process control and monitoring equipment.

Driscoll and Hejzlar (2004) present the design and plant layout for a 300 MWe supercritical CO₂ plant. The study focused on using the next generation nuclear reactor to provide the energy to power the supercritical power cycle. However, other than the primary heat exchanger that couples the nuclear heat source with the supercritical power cycle, some changes in the turbomachinery size, and some changes in operational parameters, many features of the design are relevant to a 100 MWe supercritical CO₂ cycle that could be powered by solar energy. The authors list several references for the design of a supercritical CO₂ power cycle including:

Dostal, V., et al. "A Supercritical Carbon Dioxide Cycle for the Next Generation Reactors." MIT-ANL-YR-100, March 10, 2004

Yang et al., "Annual Report: Qualification of the Supercritical CO₂ Power Conversion Cycle for Advances Reactor Applications" MIT-GFR-012, April 9, 2004

The Dostal et al. (2004) study focused exclusively on plant layout and cost assessment for a supercritical CO₂ Brayton power cycle. Other than the criteria for the power source, the authors based their design on economics and synergism with industrial experience. Capital cost reduction was a main focus of the work, but inspection and plant maintenance were also considered. A layout for their system is presented. Among the features of their system is the use of Heatric printed circuit heat exchangers for the recuperator and pre-cooler. Another study for a supercritical CO₂ Brayton cycle is reported by Pra et al., (2008). The authors also utilize printed circuit heat exchangers in their design.

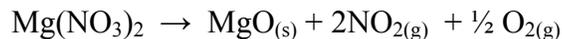
3.7 Radar Level Sensors

Problems were encountered measuring the molten salt level in the cold and hot salt storage tanks for Solar Two. Radar level sensors are now available for high-temperature use and are resistant to heavy build up. Vega, Inc. manufactures a radar level sensor that will operate up to 400°C and 160 bar even in the presence of very heavy build up. The sensor, VEGAPULS 66, has a range up to 35 m. Units that operate at even higher temperatures may be available in the future.

It may be possible to modify a commercial radar sensor for very high temperature operation. Radar will easily penetrate many materials including ceramics, polymers and even certain metal alloys. Some of these materials are good thermal insulators and could possibly be used to keep the radar sensor relatively cool compared to the molten salt. Another possibility is to provide external cooling of temperature sensitive components.

3.8 Pretreatment of Nitrate Salt Mixture

The operating temperature of the nitrate salt mixture for Solar Two was 1050°F (566°C). The salt mixture was from an industrial source and contained 0.05% magnesium nitrate. At a temperature of 900°F (482°C) and above, the magnesium nitrate decomposes according to the following reaction:



Therefore, the salt had to be pretreated before use to remove the $\text{Mg}(\text{NO}_3)_2$. This was accomplished by heating the salt mixture to 1025°F (552°C) for approximately 30 days and venting the NO_x gas. In the vent stacks the NO_x and water vapor formed nitric and nitrous acid that resulted in corrosion of the vent pipe. The pipe was replaced with a stainless steel pipe.

The Solar Two facility was designed to operate at 10 MWe and had a salt inventory of 3.3 million lbs with 9,900 lbs of gas evolved during pretreatment. Assuming a linear relationship, a 100 MWe facility would require 33 million lbs of salt and emit 99,000 lbs of gas during salt pretreatment (Kelly, 2000).

Nitrogen dioxide is considered a very serious health hazard and OSHA has set a 5 ppm ceiling level for worker exposure. NO_x compounds form acid in the lungs and will explode on contact with certain organic compounds. For the first time since 1972, EPA is proposing new regulations for NO_x emissions (U.S. EPA web site). It is unknown how these new regulations will affect pretreatment of salt for a new 100 MWe solar power tower.

Fortunately, removing NO_x compounds from gas streams is a straightforward process and there are commercially available scrubber systems that can be purchased. Ecologix Environmental Systems and Tri-Mer Corporation are just two of the companies that supply NO_x scrubbers. The

scrubbing process consists of removing the NO_x from the gas stream by first scrubbing with water. This converts the NO_x compounds to acids that are subsequently neutralized in the second step using ammonia or another base.

4 POWER SYSTEM EFFICIENCY IMPROVEMENT MOTIVATION

This report examines the use of a steam Rankine cycle for electrical production from the energy stored in the high temperature molten-salt reservoir. The molten-salt is pumped from the high temperature reservoir at 600°C through a heat exchanger and into the low temperature reservoir at 270°C.

The energy needs for power production is inversely proportional to the cycle efficiency. The equation relating the input energy (Q_{in}), cycle efficiency (eff), and output work (W_{out}) is:

$$Q_{in} = \frac{W_{out}}{eff} \quad (1)$$

Increasing the efficiency of the cycle decreases the footprint of the solar collectors, the size of the receiver and the volume of the storage needed for the same system performance.

Every power conversion system must have some heat rejection associated with it. Since the sum of the W_{out} and rejection energy (Q_{rej}) must equal the input energy, a simple equation can be derived relating the Q_{rej} to W_{out} and eff. That equation is:

$$Q_{rej} = \left(\frac{1 - eff}{eff} \right) \cdot W_{out} \quad (2)$$

For the same output, improving the efficiency from 33% to 34% reduces the heat rejection by 4.4%, and improving a 33% efficient system to 40% (a 7% cycle improvement) reduces the heat rejection by 26%. A significant reduction in heat rejection system size and consumables can be obtained from an efficiency improvement.

Capital Payback is a term used to describe the payback of loans and monies to investors for up front monies used in the construction of the facility. Usually the rate structure of a power plant includes Capital Payback, operating expense, fuel cost, taxes and profit. For a Concentrating Solar Power Plant, Capital Payback for the solar collection system (land, mirrors, tracking system, solar collector, and storage system) will be a significant part of the cost for electrical generation. A significant reduction is seen in the capital payback of the solar collector system with an increase in efficiency. A simple equation for the “Capital Payback Reduction” can be derived for the solar collection system since it scales as described in equation 1 above. That equation is:

$$\text{Capital_Payback_Reduction} = \frac{\text{Old_Payback_Rate} - \text{New_Payback_Rate}}{\text{Old_Payback_Rate}} = 1 - \frac{eff_{old}}{eff_{new}} \quad (3)$$

For a 1% improvement in efficiency of a system that was originally 33% efficient, the capital payback is reduced by ~3% and improving the efficiency of a 33% efficient system to 40% (a 7% improvement in efficiency) reduces the capital payback by more than 17%.

5 STEAM RANKINE POWER CYCLE OPTIONS

The Steam Rankine Power cycle has several options that should be considered for a 100 MWe Concentrating Solar Power Plant. These options include subcritical, supercritical, reheat supercritical, recuperated supercritical and the reheat recuperated supercritical. Each of these cycle options will be described, and analyzed for 550°C and 600°C turbine inlet temperatures and nominal 25°C compressor inlet temperature. Cycle analysis was accomplished by calculating the theoretical minimum energy required to pump the fluid and then adjusting the energy input by the pumps isentropic efficiency, calculating the thermal energy input necessary to heat the water to the desired temperature and turbine inlet pressure, calculating the theoretical maximum energy extraction through the turbine expansion and then adjusting the energy extraction by the turbine isentropic efficiency, repeating this step for any reheat stages, calculating the thermal energy necessary to condense the steam, and finally calculating any subcooling necessary to prevent the pump from undergoing cavitation as it pumps the water to the high side pressure. Pressure drops are included in the analysis, which then constrain the performance of piping and heat exchangers. Finally the efficiency of the system is calculated from total energy rejected and total energy input as well as net mechanical energy extracted (turbine – pump) and total energy input. These efficiencies will agree within the uncertainty of the thermodynamic data.

5.1 Subcritical Steam Rankine Cycle

The Subcritical Steam Rankine cycle is the most dominant closed cycle power conversion system in the world. In this cycle the water is pumped from a condenser (1-2 psi, ~25°C) to a high-side pressure below the critical pressure for water (22.09 MPa, 3204 psi), then heated until boiling occurs, heated through boiling and finally heated to the desired temperature. The superheated steam is then expanded through a turbine to the condenser pressure (usually into the phase change dome) where it is condensed and again pumped to repeat the cycle. Figure 4 shows the block diagram for the basic subcritical steam Rankine cycle as well as a block diagram for a subcritical steam Rankine cycle layout to avoid the salt plugging that was observed in the Solar Two demonstration program. In the second configuration (feed water heating), steam is brought from the boiler and injected into the water flow immediately after the first pump to bring the water temperature high enough to avoid salt freezing. The second pump does a small amount of work to overcome the pressure drop in the flow between the second pump and the boiler discharge. The cycle analyses of these layouts are identical, and calculated cycle efficiencies will be the same. One way to look at this is that the state points in the analysis are the same and that the use of the recirculation is a simple way of rising the working fluid's temperature before heating the working fluid with a heat source. Figure 5 shows the T-s diagram for the subcritical Rankine Cycle operating at 6.9 MPa (1000 psi) pump outlet pressure for both 550°C and 600°C turbine inlet temperature. At these conditions cycle efficiencies in the 39% level are achievable

and the quality of the steam from the turbine is relatively high, requiring no further treatment as it goes through the turbine stages.

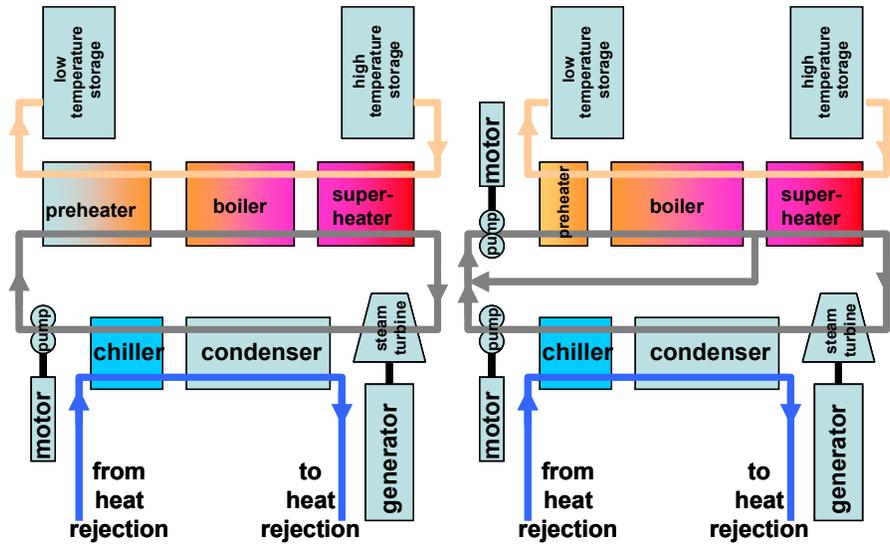


Figure 4: Block diagram of subcritical steam Rankine cycle showing basic design on the left and one option to avoid salt plugging on the right

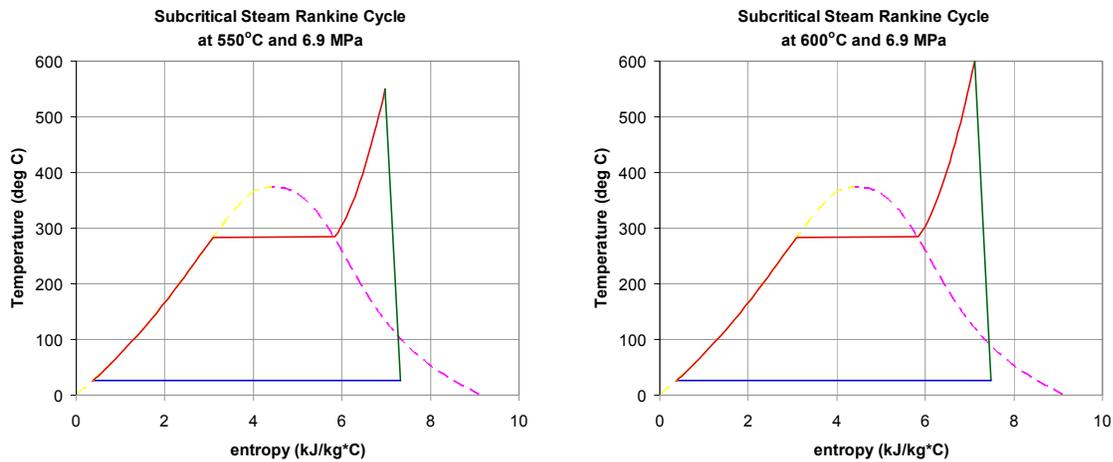


Figure 5: T-s diagrams for subcritical steam Rankine cycle operating at 6.9 MPa (1000 psi) and 550°C with 39.04% cycle efficiency on left and 600°C with 39.74% cycle efficiency on right

5.2 Supercritical Steam Rankine Cycle

The Supercritical Steam Rankine cycle is similar to the subcritical system, except for the high-side pressure and elimination of the need to accomplish steam/water separation during energy input. In this cycle the water is pumped from a condenser (1-2 psi, ~25°C) to a high side pressure

greater than the critical pressure for water then heated to the desired turbine inlet temperature. The supercritical steam is then expanded through a turbine to the condenser pressure (usually into the phase change dome) where it is condensed and again pumped to repeat the cycle. Figure 6 shows the block diagram for the basic supercritical steam Rankine cycle as well as a block diagram for a supercritical steam Rankine cycle layout incorporating feed water heating to avoid the salt plugging that was observed in the Solar Two demonstration program. In the second arrangement, the second pump does little work, only enough to overcome the pressure drop of the flow through the input heat exchanger. The cycle analyses of these layouts are identical, and calculated cycle efficiencies will be the same. Figure 7 shows the T-s diagram for the supercritical Rankine Cycle operating at 25 MPa (3625 psi) pump outlet pressure for both 550°C and 600°C turbine inlet temperature. At these conditions cycle efficiencies in the 42%-43% level are achievable. The quality of the steam from the turbine is relatively low (~76%), and may require a water/steam separator stage before passing the steam flow through the low pressure turbine.

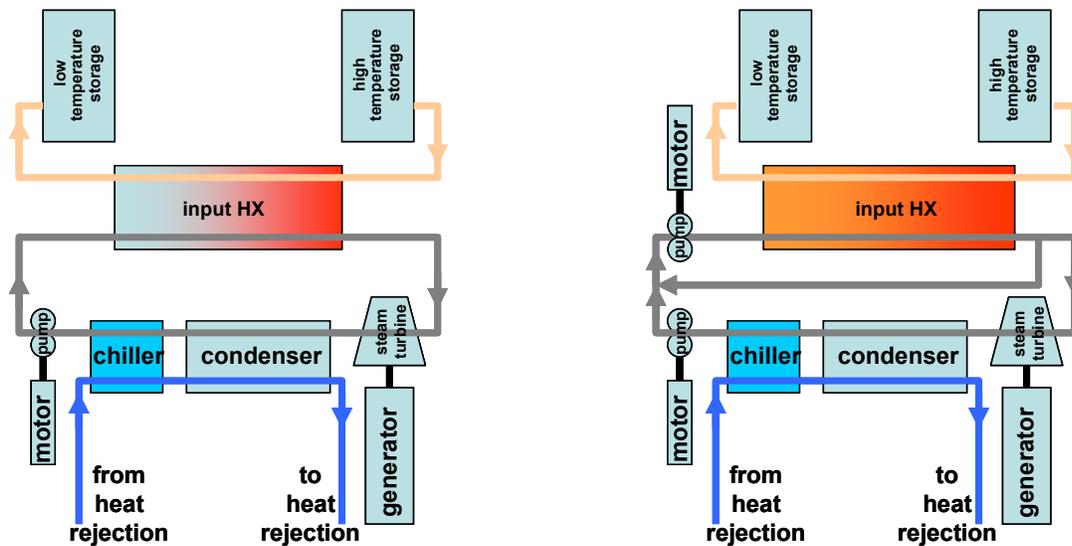


Figure 6: Block diagram of supercritical steam Rankine cycle showing basic design on the left and one option to avoid salt plugging on the right

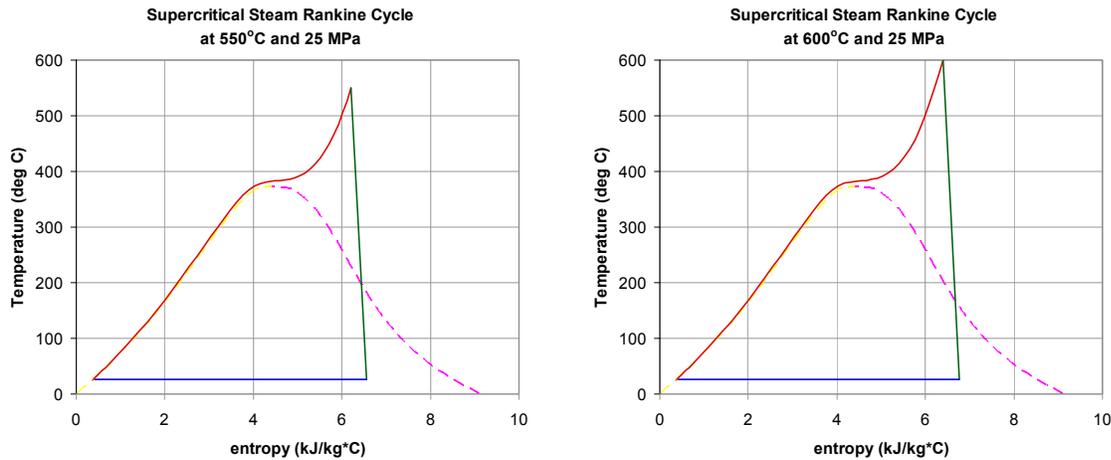


Figure 7: T-s diagrams for supercritical steam Rankine cycle operating at 25 MPa (3625 psi) and 550°C with 42.21% cycle efficiency on left and 600°C with 43.93% cycle efficiency on right

5.3 Reheated Supercritical Steam Rankine Cycle

The Reheated Supercritical Steam Rankine cycle is similar to the Supercritical system, except for the inclusion of a second heating stage following the initial expansion through the high pressure turbine. In this cycle the water is pumped from a condenser (1-2 psi, ~25°C) to a high-side pressure greater than the critical pressure for water then heated to the desired turbine inlet temperature. The supercritical steam is then partially expanded through a high pressure turbine to an intermediate pressure. The steam is then reheated to the second turbine inlet temperature and then expanded to the condenser pressure (usually into the phase change dome) where it is condensed and again pumped to repeat the cycle. Figure 8 shows the block diagram for the basic reheated supercritical steam Rankine cycle as well as a block diagram for a reheated supercritical steam Rankine cycle layout incorporating feed water heating to avoid the salt plugging that was observed in the Solar Two demonstration program. As with the previous two layouts, the second pump does little work, only work necessary to overcome the pressure drop seen in the first input heat exchanger. The cycle analyses of these layouts are identical, and calculated cycle efficiencies will be the same. Figure 9 shows the T-s diagram for the supercritical Rankine Cycle operating at 25 MPa (3625 psi) pump outlet pressure for both 550°C and 600°C turbine inlet temperature. At these conditions cycle analysis shows that reheating does not significantly improve cycle efficiencies (and for 600°C operation actually degrades efficiency), and either the first turbine discharge temperature will have to be raised (salt temperature returning to low temperature tank will have to go up) or the high side pressure will have to be raised to see the benefits from simple reheating.

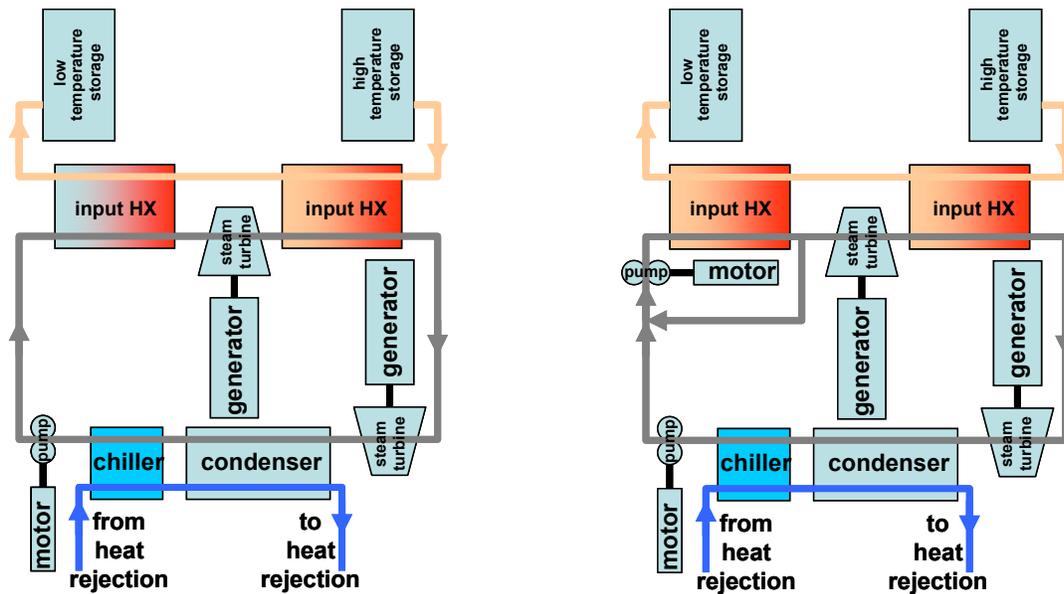


Figure 8: Block diagram of reheated supercritical steam Rankine cycle showing basic design on the left and one option to avoid salt plugging on the right

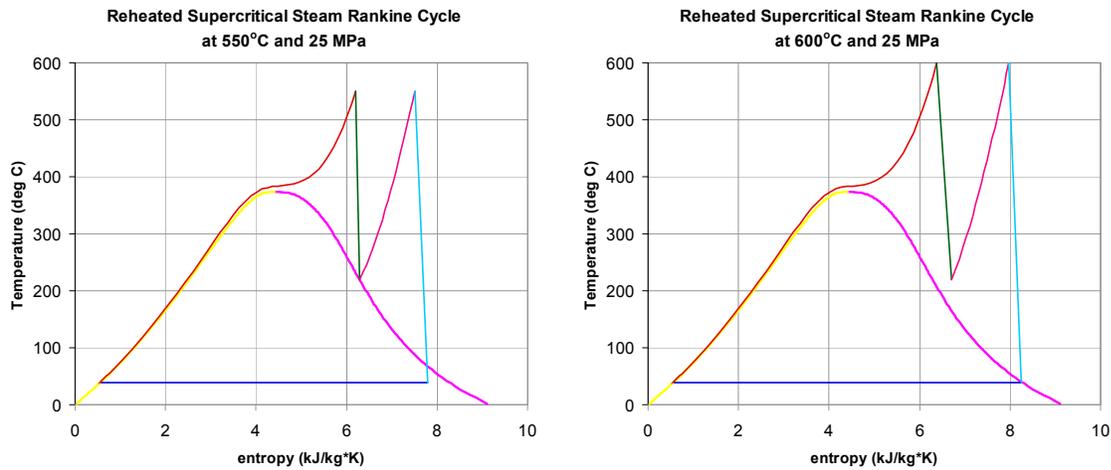


Figure 9: T-s diagrams for reheated supercritical steam Rankine cycle operating at 25 MPa (3625 psi) and 550°C with 42.45% cycle efficiency on left and 600°C with 41.87% cycle efficiency on right

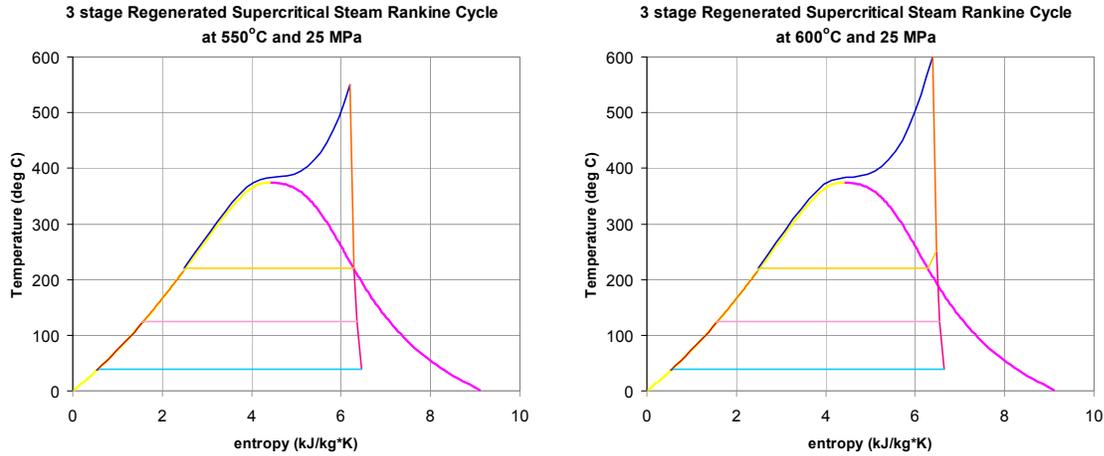


Figure 11: T-s diagrams for 3 stage regenerated supercritical steam Rankine cycle operating at 25 MPa (3625 psi) and 550°C with 46.41% cycle efficiency on left and 600°C with 47.23% cycle efficiency on right

5.5 Regenerated & Reheated Supercritical Steam Rankine Cycle

The Regenerated & Reheated Supercritical Steam Rankine cycle is a combination of the reheat cycle and the regenerated cycle. In this cycle the water is pumped from a condenser (1-2 psi, ~25°C) to an intermediate pressure where it is then heated using steam injection, then pumped to the final operating pressure (greater than the critical pressure for water). The water is finally heated, using the solar salt, to the desired turbine inlet temperature. The supercritical steam is then partially expanded through a high pressure turbine to an intermediate pressure, where some of the steam is used for heating of the water and the remaining steam is reheated using the solar salt to a new elevated temperature. The steam is finally expanded through more turbine sections to the condenser pressure (usually into the phase change dome). Figure 12 shows the block diagram for the basic regenerated & reheated supercritical steam Rankine cycle. Figure 13 shows the T-s diagram for the two-stage regenerated & reheated supercritical Rankine Cycle operating at 25 MPa (3625 psi) pump outlet pressure for both 550°C and 600°C turbine inlet temperature. At these conditions combining regeneration and reheating does not add to the efficiency of the cycle, because of the added entropy in the heat rejection stage of the cycle.

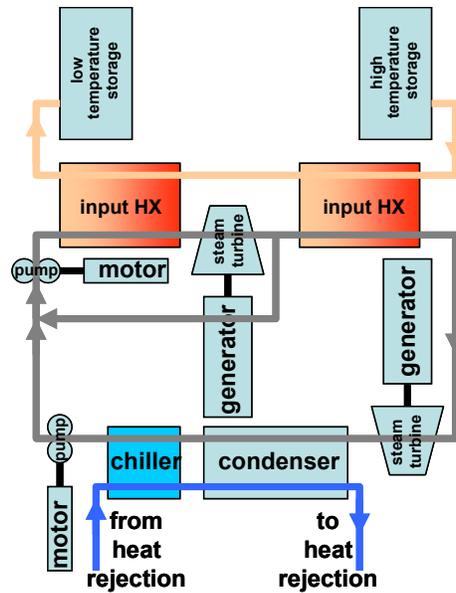


Figure 12: Block diagram of regenerated & reheated supercritical steam Rankine cycle showing basic two stage design

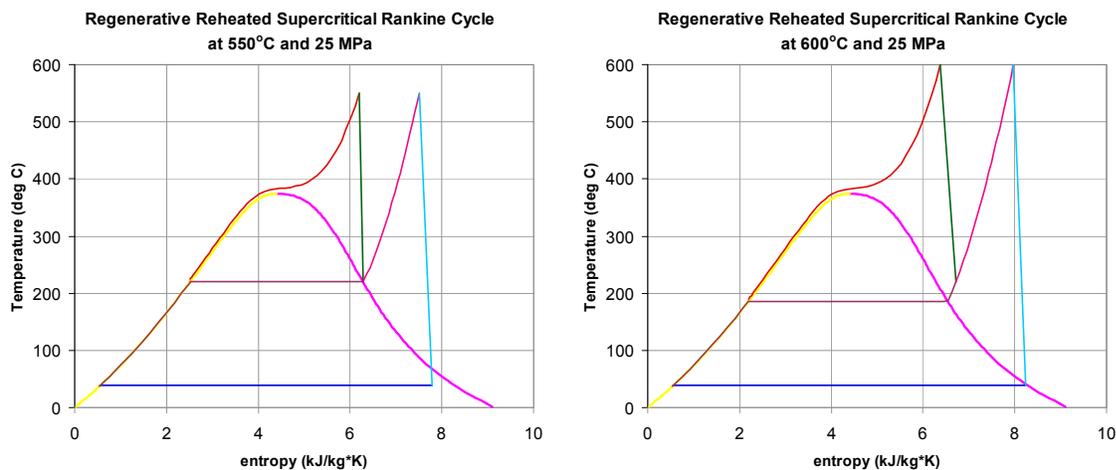


Figure 13: T-s diagrams for 2 stage regenerated & reheated supercritical steam Rankine cycle operating at 25 MPa (3625 psi) and 550°C with 45.39% cycle efficiency on left and 600°C with 44.29% cycle efficiency on right.

5.6 Steam Rankine Cycle Recommendation

The Recuperated Supercritical Steam Rankine cycle provides the greatest efficiency steam Rankine cycle given the operating conditions. It also provides the least complexity in interfacing with the Concentrating Solar Facility, with potentially only one heat exchanger that the salt must flow through. As a result, this reports recommendation that, if the steam Rankine cycle is to be

used for concentrating solar power systems, this cycle should be developed for the 100 MWe output power range.

Today the Supercritical Steam Rankine system is developed for power levels at-and-above 350MW_e for temperatures at-and-below 610°C. The lower limit on power level is driven by the volumetric flow rate requirements from the high pressure axial flow turbine and the turbine operating at the 60 Hz generator frequency. The upper temperature limit is driven by material corrosion (see section 3.1). Since the operating temperature for the solar driven system will be below the operating temperatures already demonstrated, temperature should not be a major development issue for this system. The operating power level is an issue for the solar driven supercritical steam Rankine. The lower limit on the power level for the supercritical steam Rankine system is limited due to the size (smallness) of the high pressure axial turbine blades.

Three approaches can be taken to reduce the lower power levels of the supercritical steam Rankine system. The first of these would be to incorporate partial admission into the turbine design. Partial admission is when flow is permitted in only a portion of the circumference. This approach allows the same HP turbine design to be used for lower power output. The second approach is to utilize a radial turbine for the HP stage, which allows much smaller flow areas and much higher tip speeds to extract more power per stage. In general, radial turbines are used when you want greater ΔP but less flow rate. The third approach is to incorporate a higher speed turbine in the design and either reduce the generator speed through a gearbox or incorporate electrical generation through high speed electrical switching circuitry. These approaches can be combined.

Input Heat eXchangers (HX) must be used in the steam Rankine system. These heat exchangers isolate the liquid solar salt from the water Rankine fluid, while at the same time permitting energy transfer between the two fluids. On the water side of the heat exchanger, the flow versus pressure drop in all of the channels is well behaved and any momentary perturbation in flow will always result in a restoring force that returns the flow to its original level. On the salt side of the heat exchanger, there is the possibility that the water inlet temperature is cool enough that a momentary salt flow reduction will result in the salt cool-down to the point where the viscosity increase will result in a pressure rise greater than the pressure drop associated with the reduced mass flow rate. If that occurs, and the water temperature is low enough, then the salt in the effected channel will freeze. Figure 14 shows a hypothetical salt/steam temperature profile through an unmixed flow heat exchanger with a single channel perturbation. Figure 15 shows the potential salt freezing areas for an unmixed heat exchanger given both laminar and turbulent flow. To ensure that the heat exchanger salt channels will not freeze, one must maintain the water inlet temperature at 200°C or higher.

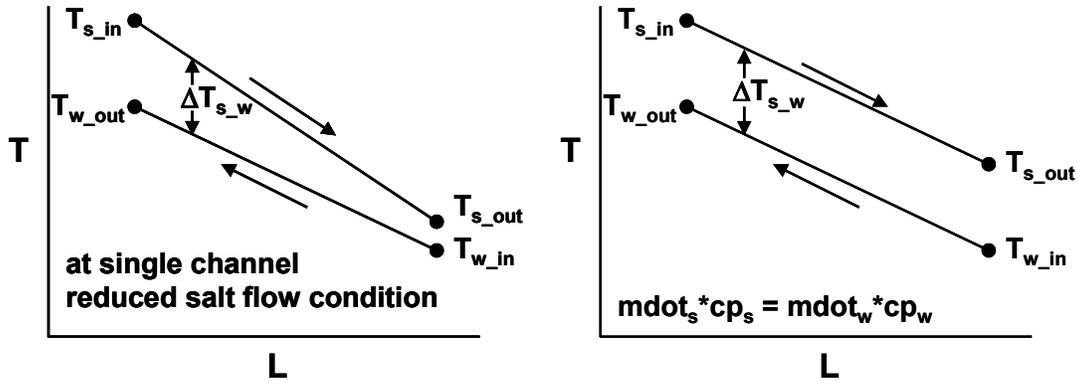


Figure 14: Hypothetical temperature profile through an unmixed heat exchanger with a single channel flow perturbation.

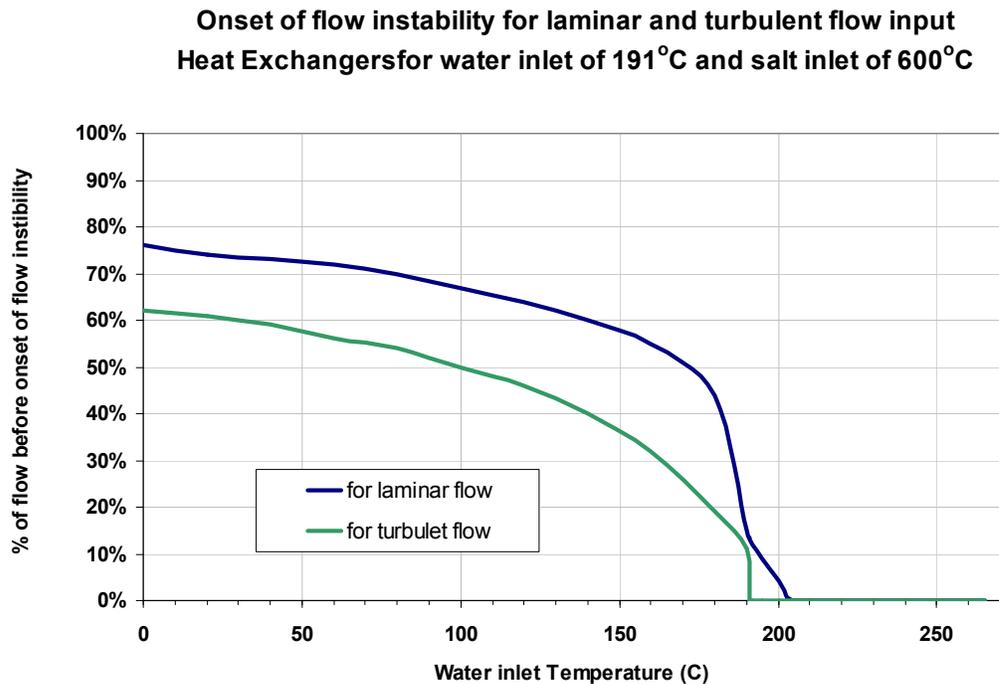


Figure 15: Magnitude of flow perturbation that results in a salt channel freeze for unmixed heat exchanger flow as a function of water inlet temperature with salt inlet of 600°C and average ΔT between flows of 50°C.

Options for input HX include the standard tube-in-shell, spiral tube-in-shell, and printed circuit. Recently SNL has purchased a series of smaller printed circuit heat exchangers (PCHE) and the rough cost for a simple manifold design was about \$2.5/m³. For the 100MWe solar facility a PCHE will transfer slightly over 200 MW_{th}, at a top and bottom ΔT of 50°C will be about 1.7 m³ in volume, and at \$2.5M/m³ will cost about \$4.25M. It must be pointed out that within a heat exchanger the enthalpy lost from the hotter fluid must be gained by the cooler fluid and at no time can the temperature profile through the heat exchanger flip (cooler fluid be hotter than the

hotter fluid). Figure 16 shows the temperature profile of the Solar Salt and the Rankine working fluid (H₂O). Even though the ΔT at both ends of the heat exchanger is 50°C, the two fluids come within 20°C of each other when the water has heated to ~625K and the two fluids are nearly 125C of each other when the water has heated to ~700K.

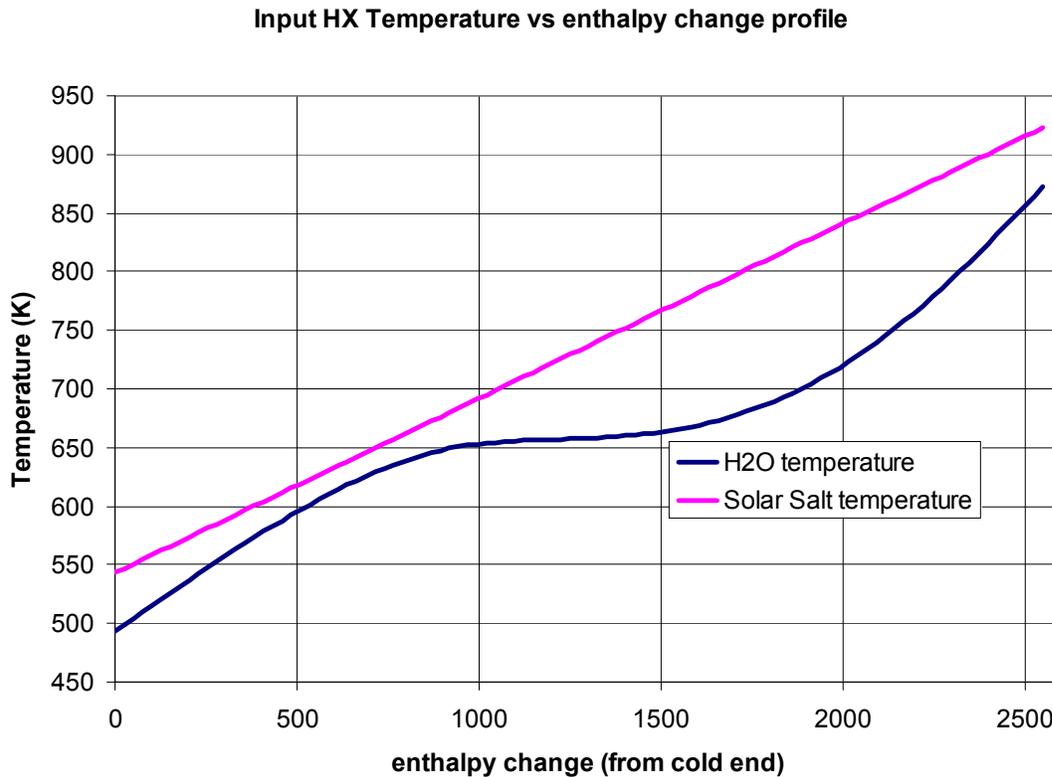


Figure 16: Salt and water (Rankine working fluid) temperature profile as a function of specific enthalpy change through input heat exchanger with water at 25 MPa.

Although the input heat exchanger is required as a result of the desire not to mix the power conversion system fluid (water) with the Solar Systems storage fluid (Solar Salt), the heat rejection system does not have that same constraint. The heat rejection system can use water to move the reject energy from the condenser to the ultimate heat sink. The mixing of the heat rejection system water and the Rankine system water should not be a significant issue. The advantage of mixing the two waters is the high condenser efficiency obtained from a direct contact heat exchanger. In a direct contact heat exchanger the water is injected as droplets at some reduced temperature. As the steam contacts the droplet, the steam is condensed on the droplet's surface and the surface climbs to the steam temperature. As the temperature profile relaxes in the droplet more steam is condensed until the droplet reaches the collection pool at the bottom of the condenser. This approach to condensation provides both a large surface area and a large heat transfer coefficient within the condenser for energy transfer. Figure 17 shows in a schematic form such a condenser attached to a 5 stage recuperated supercritical Rankine cycle operated with dry heat rejection with inlet air at 25°C (77°F).

6 ADDITIONAL RESEARCH NEEDS

Based on the results from the Solar Two project and the literature that have been reviewed in this work, additional research needs have been identified. These include:

- Additional static and dynamic corrosion testing of materials.
- Evaluation of new technologies under operating conditions including constant seating stress gaskets, gasket materials, aerogels, etc.
- Evaluation of new heat trace cables and process control options for electric heat trace.
- Evaluation of high-temperature radar tank level sensors for molten salt tanks.
- Continued evaluation of alternative steam generator/heat exchanger designs
- Evaluation of designs and equipment allowing for 24/7 operation of the power generation section of the facility. 24/7 operation would eliminate thermal cycling and prevent many problems with materials and seals. All potential equipment should be tested by thermal cycling.
- Evaluation of insulating the solar receiver during night time or unfavorable conditions. Aerogel insulation is lightweight and can potential be used to keep the receiver hot when not in operation. This would eliminate the need to empty the receiver and eliminate temperature cycling and significantly shorten startup time.
- Evaluation of chemical buffer systems for steam in the steam Rankine power cycle. Buffers are typically used for corrosion and fouling minimization.
- Evaluation of supercritical fluid, CO₂ and water, power cycles and heat exchanger configurations.

7 SUMMARY

In this work, new technologies were identified & thermodynamic power cycle analysis were performed for a future 100 MWe solar power tower using molten nitrate salt operating with a steam Rankine power cycle. Literature data along with lessons learned from operation of the 10 MWe Solar Two power tower were used to determine the specific needs for the future solar tower. The new technologies identified include:

- Corrosion data for materials of construction. In general the available data indicate that mild steel for cold salt processing is appropriate, while moderate to high chromium stainless steel is appropriate for hot salt processing
- Advanced Aerogel insulation - lowest thermal conductivity of any insulating material. Now cost effective due to a new manufacturing method. Use in critical areas where maximum insulation and light weight are needed.
- Constant Seating Stress Gaskets. Provide constant force on the gasket to compensate for thermal cycling. Use where thermal cycling may be a problem.
- Higher temperature self regulating heat trace is now commercially available. Use on cold & hot salt piping & equipment.
- Commercially available valves & pumps for molten nitrate salt (not available at the time of Solar Two operation).
- Printed circuit board & microchannel heat exchangers. Extremely high heat transfer area, very compact & light weight & are presently in use for very high temperature gasses & liquids.
- Commercial scrubbing units for removing NO_x compounds from vent streams. Very large amounts of NO_x compounds will be generated from pretreatment of the nitrate salt mixture. It is unknown if the NO_x compounds can be released to the environment at this time. US EPA is revising regulations on NO_x release at this time.
- High temperature radar level detectors are commercially available for temperatures up to 400°C. Higher temperature may be possible by modification of the sensors.
- At the operating conditions of the proposed solar facility, a simple recuperated supercritical Rankine cycle offers the highest efficiency of the Rankine cycle options. This cycle is not currently developed and development will have a significant improvement in both the capital required for future power conversion systems and overall system efficiency.

Each of the new technologies identified in this work needs to be tested in the presence of molten nitrate salt & to determine the effect of thermal cycling. Serious consideration should be given to continuous operation of the solar facility (24/7). This was a main focus of the Solar Two project. Many problems caused by thermal cycling can be eliminated if full time operation is possible.

8 REFERENCES

Aiming M., K. Kim, Gu.Young Han, Y. Kang, T.Beom Seo. "Heat transfer Characteristics of High Temperature Molten salt Storage for Solar Thermal Power Generation" Proceedings of ISES Solar World Congress 2007: Solar Energy and Human Settlement

Baraka, A., R.M.S. Baraka and A. Abdel-Razik "The Corrosion Behavior of Nickel in Molten $\text{NaNO}_3\text{-KNO}_3$ Eutectic" (1986) Surface Technology vol. 26 p. 199-206

Barth, R., C. Bonorden, P. House and B. Johnsen "Heat Tracing Technology for the 21st Century" IEE Industrial Applications Magazine Jan, Feb 2002

Bohn, M.S. "Air Molten Salt-Direct Contact Heat Exchanger" (1985) Journal of Solar Energy 107(3) p. 208-214

Bradshaw, R.W. and N.P. Siegel, N.P. "Molten Nitrate Salt Development for Thermal Energy Storage in Parabolic Trough Solar Power Systems" (2008) Proceedings of the 2nd International Conference on Energy Sustainability, ES 2008 (2009) Vol.2, p.631-637

Bradshaw, R.W. "Corrosion Resistance of Stainless Steels During Thermal Cycling in Alkali Nitrate Molten Salts" SAND2001-8518, September 2001

Bradshaw, R.W. "Thermal-Convection Loop Study of the Corrosion of Incoloy 800 in Molten $\text{NaNO}_3\text{-KNO}_3$ " Corrosion 43(3) p. 173-178

Bradshaw, R.W. "Corrosion of 316SS and Incoloy 800 in Molten $\text{NaNO}_3\text{-KNO}_3$ " (1983) Proceeding of the Electrochemical Society vol. 83-81 p. 455-471

Clair, R. "Summary of the MIT-Tokyo Tech." Symposium on Innovative Nuclear Energy Systems, November 2-5 2005 Cambridge, MA

Driscoll, M.J and P. Hejzlar "300 MWe Supercritical CO_2 Plant Layout and Design" Topical Mass. Institute of Technology MIT-GFR-014 June 2004.

Driscoll, T. and B. Johnson "Safety and Safety Factors: The Impact of Heat Tracing Systems Designs" European Conference on Electrical and Instrumentation Applications in the Petroleum Chemical Industry, Spain, May 26-28 2009

Forsburg, C.W, P.Peterson and H. Zhao "An Advanced Molten Salt Reactor Using High-Temperature Reactor Technology" Proceedings of the ICAPP'04 Pittsburgh, PA June 13-17 2004

Goods, S.H. and R.W. Bradshaw “Corrosion of Stainless Steels and Carbon Steel by Molten Mixtures of Commercial Nitrate Salts” (2004) Journal of Materials Engineering and Performance 13(1) p. 78-87

Goods, S.H., “Corrosion Characteristics of Incoloy Alloy 800 in Molten nitrate Salts” SAND-81-8665, 1983.

Hayner, G.O. “Next generation Nuclear Plant Materials Research and Development Program Plan.” US DOE INEEL/EXT-04-02347 Rev. 1. September 2004

Jjenco web site at <http://www.jjenco.com/perfectsealeos.htm>

Kelly, B. Lessons Learned, Project History and Operating Experience of the Solar Two Project. SAND2000-2598 2000

Kearney, D., B. Kelly, U. Herrman, R. Cable, J. Pacheco, R. Mahoney, H. Price, D. Blake, P. Nava and N. Potrovitza “Engineering Aspects of a Molten Salt Heat Transfer Fluid in a Trough Solar Field” Energy 29 2004 pp. 861-870

Litwin, R.Z. “Expansion Bellows for use in Solar Molten Salt Piping and Valves” U.S Patent 6,877,508, April 2005

Malone, N. “Applying the Heat - An Overview of Industrial Heat Tracing” Process Industry news Feb. 10, 2009

Oh, C.H., E. Kim and M. Patterson “Design of Heat Exchanger for the Next Generation Nuclear Plant.” Transactions of the ASME 132, 2010

Oh, C.H., E. Kim and M. Patterson “Design Option of Heat Exchanger for the Next Generation Nuclear Plant” Journal of Engineering for Gas Turbines and Power 132, 2010

Pra, F., P. Tochon, C. Mauget, J. Fokkens and S. Willemsen “Promising Designs of Compact Heat Exchangers for Modular HTRs using the Brayton Cycle” Nuclear Engineering and Design 238 2008 pp. 3160-3173

Pacheco, J.E. Final Test and Evaluation Results from the Solar Two Project. SAND2002-0120, 2002

Personal communication with Watlow engineers

Phillips, S., N. Shinotsuka, K. Yamamoto and Y. Fukuda “Application of High Steam Temperature Countermeasures in High Sulfur Coal-Fired Boilers.
http://www.hitachipowersystems.us/supportingdocs/forbus/hpsa/technical_papers/EP2003B.pdf

Pitzer, K. “The Relative Merits and Limitations of Thermal Fluid, Electric and Steam Heat Tracing Systems” Thermon Corp., 2003

Pitzer, K. and R. Barth “New Directions in Pipe heat-Tracing Designs” Insulation Outlook 2006

Pra, F., P. Tochon, C. Mauget, J. Fokkens and S. Willemsen “Promising Designs of Compact Heat exchangers for Modular HTR’s Using the Brayton Cycle” Nuclear Engineering and Design 238 2008 pp. 3160-3173

Ramachadran, S., P. Kalaichelvi and S. Sundaram “Heat Transfer Studies in a Spiral Plate Heat Exchanger for Water-Palm Oil Two Phase Systems” Brazilian Journal of Chemical Engineering 25(3) 2008 pp. 483-490

Reilly, H.E. and G.J. Kolb “An Evaluation of the Molten-Salt Power Towers Including Results of the Solar Two Project, SAND2001-3674, November 2001

Rohsenow, W.M., J.P. Hartnett and Y.I. Cho (Editors) “Handbook of Heat Transfer, 3rd Edition” McGraw-Hill, New York, NY. 1998

Sandberg, C., B. Holmes and J. Berer “Control and Monitoring of Electric Heat Tracing” 48th Annual Petroleum and Chemical Industry Conference, Toronto, Canada, Sept. 24-26, 2001

Sandberg, C. “Electrical Heat-Trace Can Minimize Piping Temperature Variations” SyncroFlo Piping Systems Solutions, August 29, 2000

Slusser, J.W., J.B. Titcomb, M.T. Heffelfinger and B.R. Dunbobbin. “Corrosion in Molten nitrate-Nitrite Salts” (1985) Journal of Metals 37(7) p. 24-27

Smith, D.C., S.A. Saloff and T.P. Staed “Design and Testing of an Advanced Molten Salt Central Receiver” (1987) Solar Energy Vol.1, p 479-487

Steingress, F.M., H.J. Frost and D.R. Walker “High Pressure Boilers, 3rd Edition” American Technical Publishers, Inc. Homewood, IL 2003

St Clair, R. “Summary of the MIT-Tokto Tech Symposium on Innovative Nuclear Systems” Cambridge, MA Nov. 2-4, 2005

Thompson, J., E. Shuler and P. Van Hoorickx “Advances in Electrical heat Tracing Engineering Reducing Installed Cost and Improved Reliability” IEEE, Paper no. PCIC-98-08

U.S. Environmental Protection Agency “New EPA Rule Will Require Use of Best Technologies to Reduce Greenhouse Gases from Large Facilities/Small Businesses and Farms Exempt.” US EPA web site. 09/30/2009

Wright, J. and M.S. Bohn “Direct Contact Thermal-Storage Research” Energy Storage Contractors Review Meeting, August 23, 1982

Yang, M, X. Yang, X. Yang and J. Ding “Heat Transfer Enhancement and Performance of the Molten Salt Receiver of a Solar Power Tower” Applied Energy. Revised article in press 2009

Yurinskii, V.P. “Anodic Oxidation of Metals in Molten Nitrates” (1989) Plenum Publishing Corporation, UDC 541.135

Zavoico, A.B. “Solar Power Tower Design Basis Document, Revision 0” SAND2001-2100, July 2001

9 Distribution

All Electronic Copies:

C. K. Ho, MS1127 (Org 6123) ckho@sandia.gov
N. P. Siegal, MS1127 (Org 6123) npsiege@sandia.gov
G. J. Kolb, MS1127 (Org 6123) gjkolb@sandia.gov
G. E. Rochau, MS1136 (Org 6221) gerocha@sandia.gov
R.C. Moore, MS1136 (Org 6221) rcmoore@sandia.gov
M. E. Vernon, MS1136 (Org 6221) meverno@sandia.gov
Technical Library, (Org 9536) libref@sandia.gov

